That Spin O Boson Changes Everything

The Standard Model and the Energy Frontier



Department of Physics Colloquium Case Western Reserve University

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Chip Brock

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The ATLAS Collaboration: Two-particle Bose-Einstein correlations

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C. Belanger-Champagne⁸⁶, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵⁴, L. Bellagamba^{20a}, A. Bellerive²⁹, M. Bellomo⁸⁵, K. Belotskiy⁹⁷, O. Beltramello³⁰, O. Benary¹⁵⁴, D. Benchekroun^{136a}, K. Bendtz^{147a,147b}, N. Benekos¹⁶⁶,

K. Benslama¹³¹, S. Bentvelsen¹⁰⁶, D. Berge¹⁰⁶, E. Bergeaas Kuutmann¹⁶⁷, N. Berger⁵, F. Berghaus¹⁷⁰, J. Beringer¹⁵,
 C. Bernard²², P. Bernat⁷⁷, C. Bernius⁷⁸, F.U. Bernlochner¹⁷⁰, T. Berry⁷⁶, P. Berta¹²⁸, C. Bertella⁸⁴,
 G. Bertoli^{147a,147b}, F. Bertolucci^{123a,123b}, C. Bertsche¹¹², D. Bertsche¹¹², M.I. Besana^{90a}, G.J. Besjes¹⁰⁵,
 O. Bessidskaia Bylund^{147a,147b}, M. Bessner⁴², N. Besson¹³⁷, C. Betancourt⁴⁸, S. Bethke¹⁰⁰, W. Bhimji⁴⁶,

M. Biglietti^{135a}, J. Bilbao De Mendizabal⁴⁹, H. Bilokon⁴⁷, M. Bindi⁵⁴, S. Binet¹¹⁶, A. Bingul^{19c}, C. Bini^{133a,133b}

C. W. Diack J. S. Diack J. Black J. Diack J. D. Blackouri J. C. Blachard J. S. Diackard J. K. Blackard, K. Balakard, K. Bolekard, K. Bolekard, K. Bolekard, K. Balakard, K.

A. Bogouch^{91,*}, C. Bohm^{147a}, J. Bohm¹²⁶, V. Boisvert⁷⁶, T. Bold^{38a}, V. Boldea^{26a}, A.S. Boldyrev⁹⁸, M. Bomben⁷⁹

M. Bona⁷⁵, M. Boonekamp¹³⁷, A. Borisov¹²⁹, G. Borissov⁷¹, M. Borri⁸³, S. Borroni⁴², J. Bortfeldt⁹⁹,
 V. Bortolotto^{135a,135b}, K. Bos¹⁰⁶, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁶, J. Boudreau¹²⁴, J. Bouffard²

J. Brown⁵⁵, P.A. Bruckman de Renstrom³⁹, D. Bruncko^{145b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni²

A.C. Bundock⁷³, H. Burchar³⁰, S. Burdin⁷³, B. Burgherave¹⁰⁷, S. Burke¹³⁰, I. Burmeister⁴³, E. Busato³⁴,
 D. Büscher⁴⁸, V. Büscher⁸², P. Bussey⁵³, C.P. Buszello¹⁶⁷, B. Butler⁵⁷, J.M. Butler²², A.I. Butt³, C.M. Buttar⁵³,

D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, A. Calandri¹³⁷, G. Calderini⁷⁹, P. Calfayan⁹⁹, R. Calkins¹⁰⁷, L.P. Caloba^{24a}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro⁴⁹, S. Camarda⁴², D. Cameron¹¹⁸, L.M. Caminada¹⁵

B. I. Caloba , D. Cameroli, S. Cameroli, K. Camardol 1010, S. Camarda, D. Cameroli, J. M. Camindata, R. Campanal Armadan¹², S. Campana³⁰, M. Campanell⁷⁷, A. Campoverde¹⁴⁹, V. Canale¹⁰³,1035, A. Canepa^{160a}, M. Cano Bret⁷⁵, J. Cantero⁸¹, R. Cantrill^{125a}, T. Cao⁴⁰, M.D.M. Capeans Garrido³⁰, I. Caprini^{26a}, M. Caprini^{26a}

M. Bruschi^{20a}, L. Bryngemark⁸⁰, T. Buanes¹⁴, Q. Buat¹⁴³, F. Bucci⁴⁹, P. Buchholz¹⁴², R.M. Buckingham¹¹⁹

C.W. Black¹⁵¹, J.E. Black¹⁴⁴, K.M. Black²², D. Blackburn¹³⁹, R.E. Blair⁶, J.-B. Blanchard¹³⁷, T. Blazek^{145a},

E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁶, N. Bousson¹¹³, S. Boutouil^{136d}, A. Boveia³¹ J. Boyd³⁰, I.R. Boyko⁶⁴, I. Bozic^{13a}, J. Bracinik¹⁸, A. Brandt⁸, G. Brandt¹⁵, O. Brandt^{58a}, U. Bratzler¹⁵⁷, B. Brau⁸⁵, J.E. Brau¹¹⁵, H.M. Braun^{176,*}, S.F. Brazzale^{165a,165c}, B. Brelier¹⁵⁹, K. Brendlinger¹²¹, A.J. Brandt⁸, S. B. Brau⁸⁵, J.E. Brau¹¹⁵, H.M. Braun^{176,*}, S.F. Brazzale^{165a,165c}, B. Brelier¹⁵⁹, K. Brendlinger¹²¹, A.J. Brandt⁸, S. B. Brau⁸⁵, J.E. Brau¹¹⁵, H.M. Braun^{176,*}, S.F. Brazzale^{165a,165c}, B. Brelier¹⁵⁹, K. Brendlinger¹²¹, A.J. Brandt⁸, S. B. Brau⁸⁵, J.E. Braz¹¹⁵, H.M. Brau^{87,*}, S.F. Brazzale^{165a,165c}, B. Brelier¹⁵⁹, K. Brendlinger¹²¹, A.J. Bradt⁸⁵, S.F. Brazzale^{165a,165c}, B. Brat¹⁵⁰, K. Brendlinger¹²¹, A.J. Bradt⁸⁵, S.F. Brazzale^{165a,165c}, B. Brelier¹⁵⁹, K. Bradt⁸⁵, S.F. Brazzale^{165a,165c}, B. Br

B. Brau, J. B. Brau, J. K. Bristow¹⁴⁶, T.M. Bristow⁴⁶, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹ C. Bromberg⁸⁹, J. Bronner¹⁰⁰, G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b}, J. Brosamer¹⁵, E. Bros

A.G. Buckley⁵³, S.I. Buda^{26a}, I.A. Budagov⁶⁴, F. Buehrer⁴⁸, L. Bugge¹¹⁸, M.K. Bugge¹¹⁸, O. Bulekov⁹⁷

J.M. Butterworth⁷⁷, P. Butti¹⁰⁶, W. Buttinger²⁸, A. Buzatu⁵³, M. Byszewski¹⁰, S. Cabrera Urbán¹⁶⁸

N. Barlow²⁸, B.M. Barnett¹³⁰, R.M. Barnett¹⁵, Z. Barnovska⁵, A. Baroncelli¹³⁵a, G. Barone⁴⁹, A.J. Barr¹¹⁹, F. Barreiro⁸¹, J. Barreiro Guimarães da Costa⁵⁷, R. Bartoldus¹⁴⁴, A.E. Barton⁷¹, P. Bartos^{145a}, V. Bartsch¹⁵⁰

A. Bassalat¹¹⁶, A. Basye¹⁶⁶, R.L. Bates⁵³, J.R. Batley²⁸, M. Battaglia¹³⁸, M. Battistin³⁰, F. Bauer¹³⁷

Y. Benhammou¹⁵⁴, E. Benhar Noccioli⁴⁹, J.A. Benitez Garcia^{160b}, D.P. Benjamin⁴⁵, J.R. Bensinger²³

R.M. Bianchi¹²⁴, L. Bianchini²³, M. Bianco³⁰, O. Biebel⁹⁹, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹¹

V.A. Bednyakov⁶⁴, C.P. Bee¹⁴⁹, L.J. Beemster¹⁰⁶, T.A. Beermann¹⁷⁶, M. Begel²⁵, J.K. Behr¹¹⁹

E. Badescu^{26a}, P. Bagiacchi^{133a,133b}, P. Bagnaia^{133a,133b}, Y. Bai^{33a}, T. Bain³⁵, J.T. Baines¹³⁰, O.K. Baker¹⁷⁷

O.S. AbouZeid¹⁵⁹, H. Abramowicz¹⁵⁴, H. Abreu¹⁵³, R. Abreu³⁰, Y. Abulaiti^{147a,147b}, B.S. Acharya^{165a,165b,a}

H. Akerstedt^{147a,147b}, T.P.A. Åkesson⁸⁰, G. Akimoto¹⁵⁶, A.V. Akimov⁹⁵, G.L. Alberghi^{20a,20b}, J. Albert¹⁷⁰,

L. Adamczyk^{38a}, D.L. Adams²⁵, J. Adelman¹⁷⁷, S. Adomeit⁹⁹, T. Adye¹³⁰, T. Agatonovic-Jovin^{13a}

J.A. Aguilar-Saavedra^{125a,125f}, M. Agustoni¹⁷, S.P. Ahlen²², F. Ahmadov^{64,b}, G. Aielli^{134a,134}

The ATLAS Collaboration

 ck^{63} hn^{48} akle¹²¹ ard^{30} es^{125a} sen^{148} 106 akida⁶⁵ tifel⁸⁶ wic^{13a}

R. Brock⁸

17

 ura^{155}

when I'm done:

- whole-field planning in particle physics
- the untenable nature of the "Standard Model"
- how the Higgs Boson informs the next steps in collider physics

it takes a village to plan in HEP

Snowmass"

organized by DPF next to last comprehensive one in 2001

"P5"

Particle Physics Project Prioritization Panel

sub-panel of HEPAP

Two vehicles:

Two vehicles:

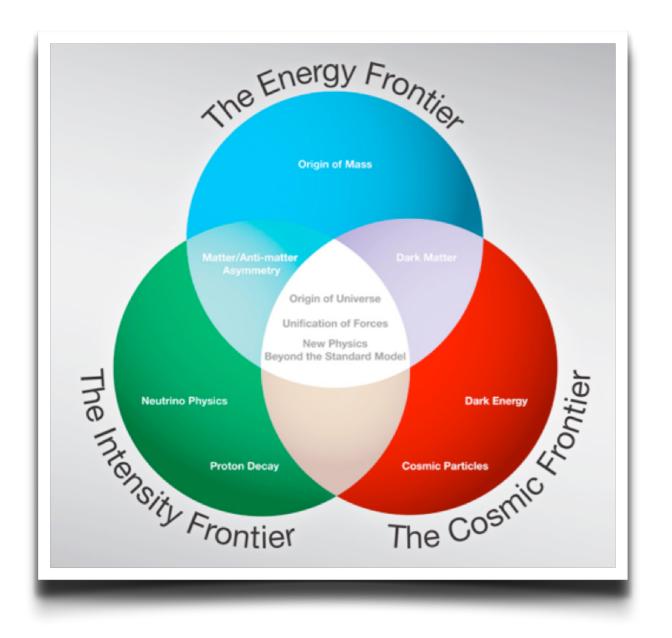
"Snowmass" Workshopsorganized by DPF
previous one in 2001

"P5"

Particle Physics Project Prioritization Panel

sub-panel of HEPAP

Notorious P5 Review: 2008



Three **Frontiers**

- "the circles" -

2008 P5



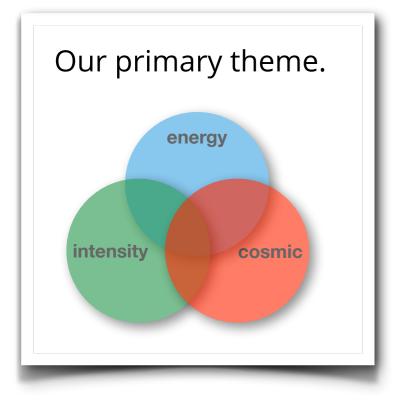
US Particle Physics: Scientific Opportunities A Strategic Plan for the Next Ten Years

Report of the Particle Physics Project Prioritization Panel

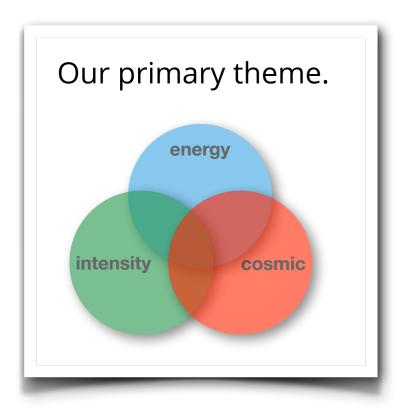
29 May 2008

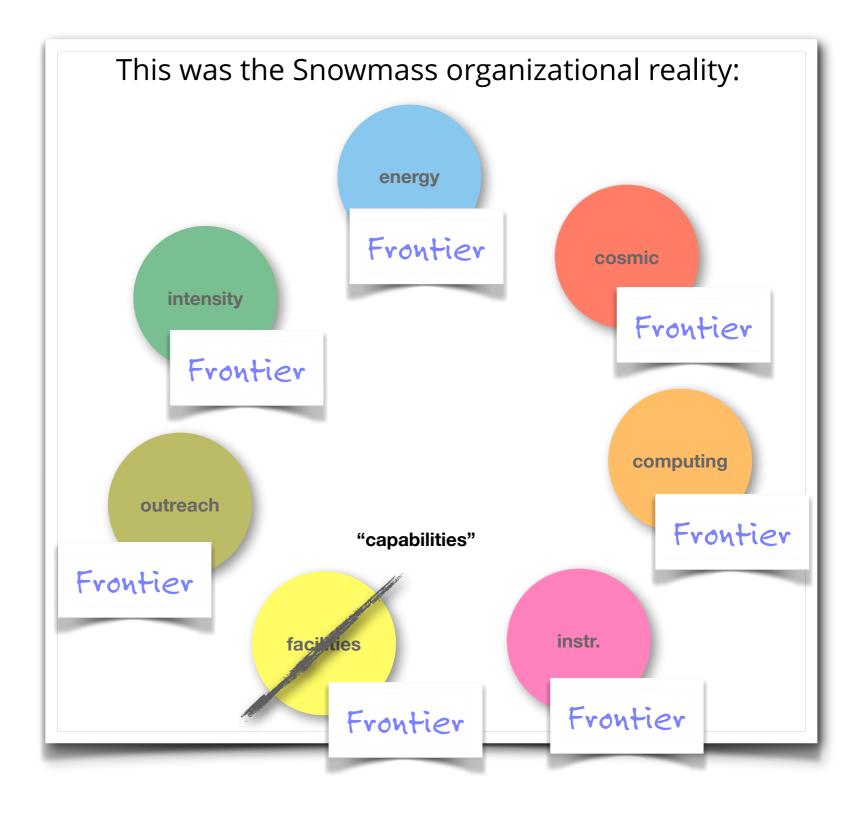
By 2012 it was time for a P5. This time, it was different.

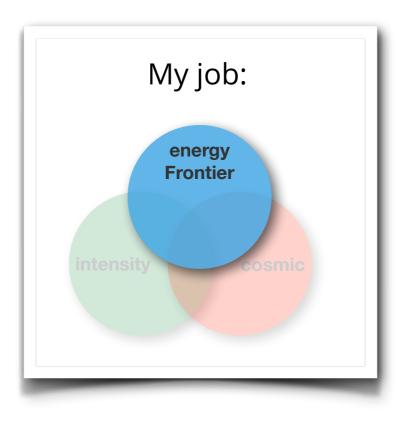
Snowmass → P5 after LHC's first run



DPF started organizing in 2012

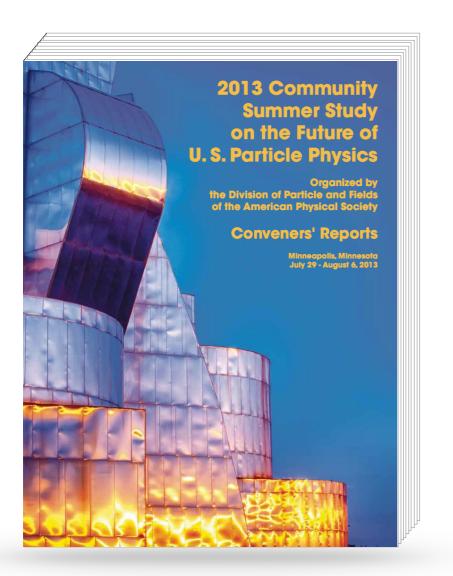


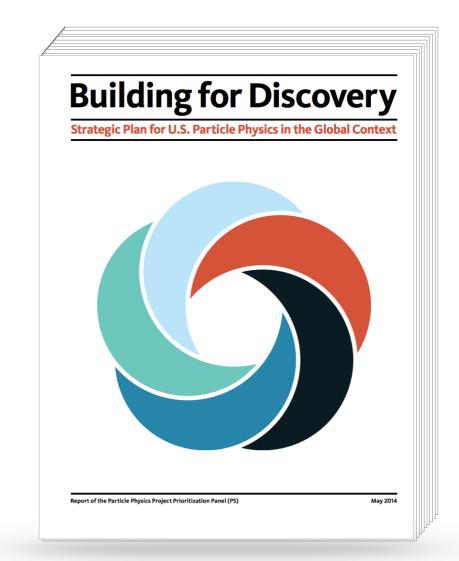


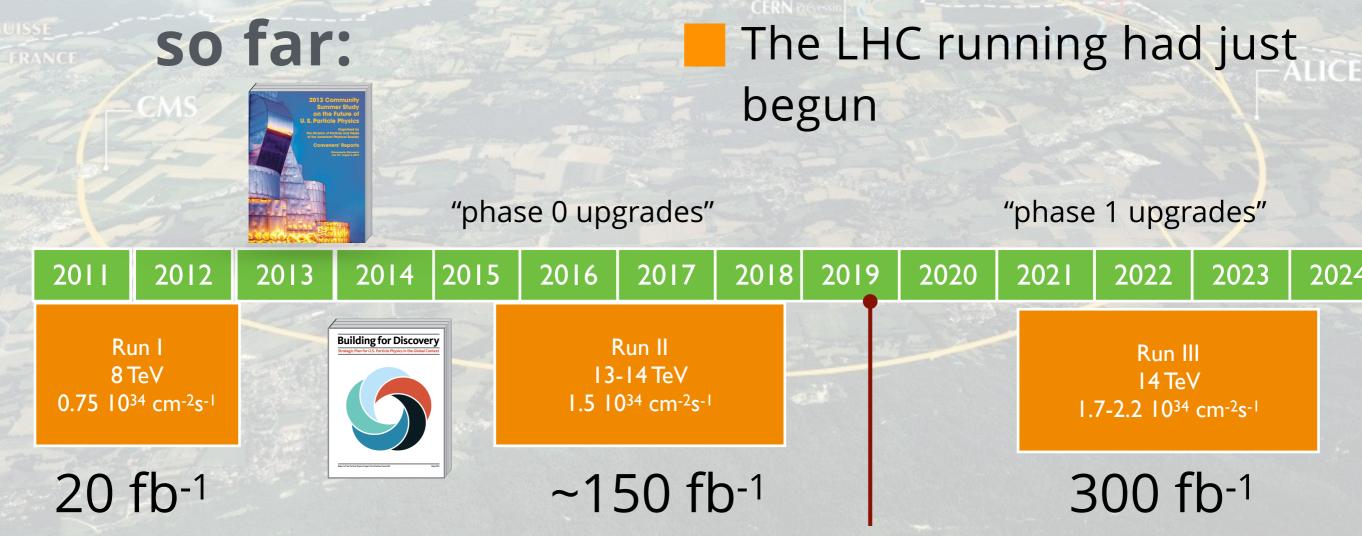


We worked together & apart: Sept 2012-August 2013: "Snowmass" October 2013-May 2014: P5

8







-

ORFT PUNK ONE MORE TIME

HIRIS





First, European Strategy for Particle Physics



First, European Strategy for Particle Physics



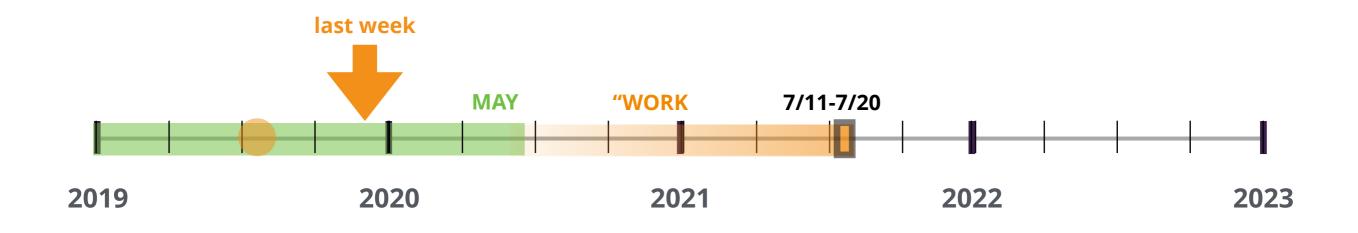
First, European Strategy for Particle Physics

Then, US Snowmass Study



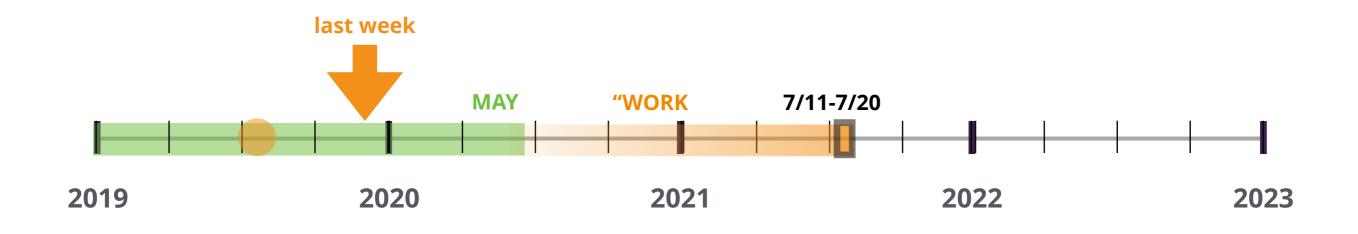
First, European Strategy for Particle Physics

Then, US Snowmass Study



First, European Strategy for Particle Physics

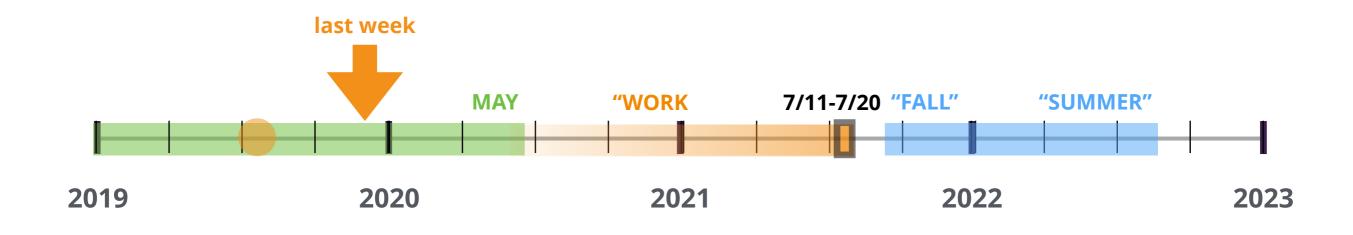
Then, US Snowmass Study



First, European Strategy for Particle Physics

Then, US Snowmass Study

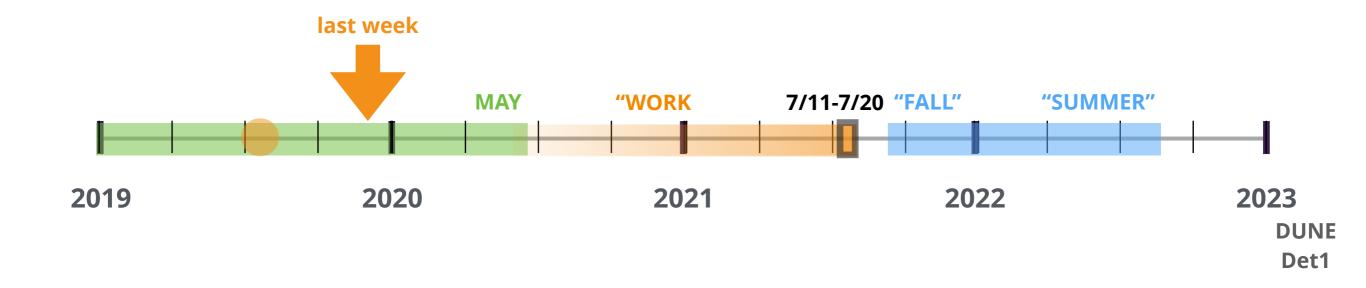
Finally, HEPAP P5 Study



First, European Strategy for Particle Physics

Then, US Snowmass Study

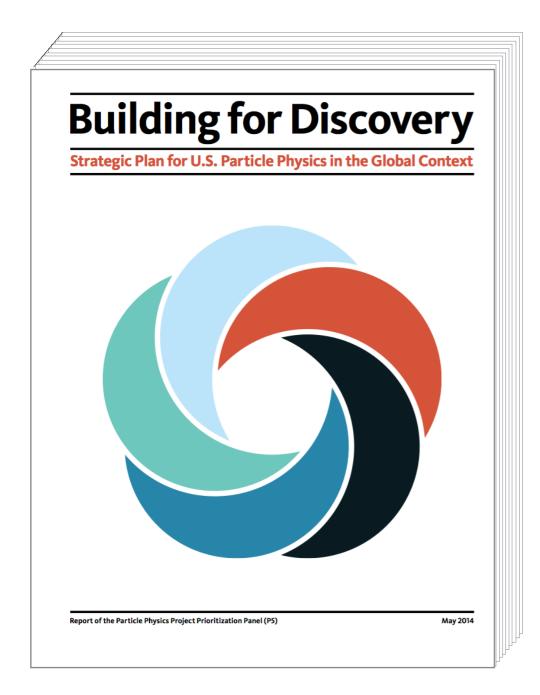
Finally, HEPAP P5 Study

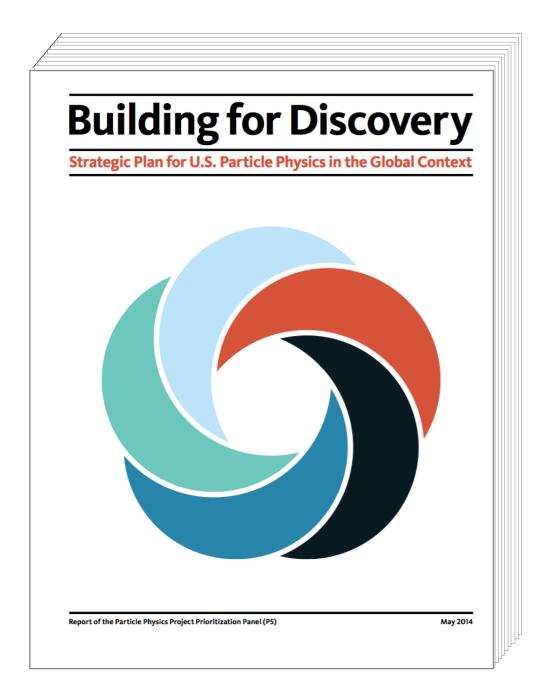


First, European Strategy for Particle Physics

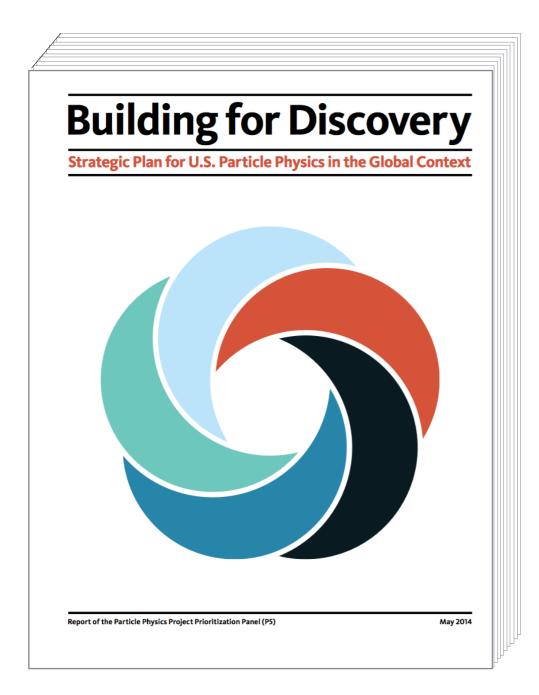
Then, US Snowmass Study

Finally, HEPAP P5 Study

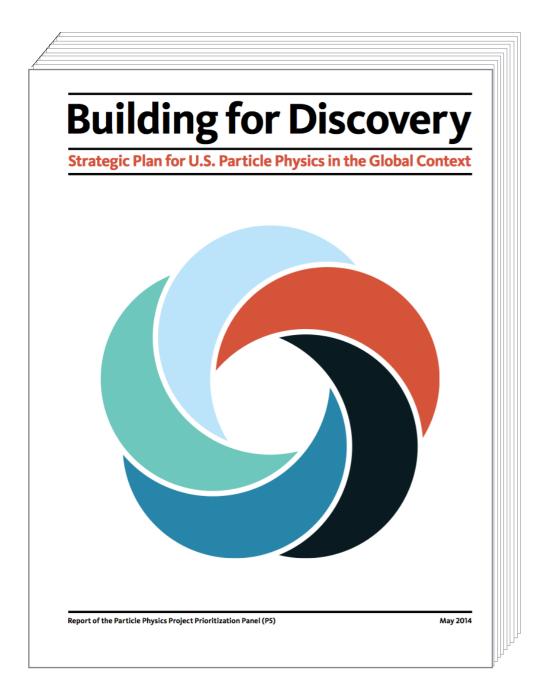




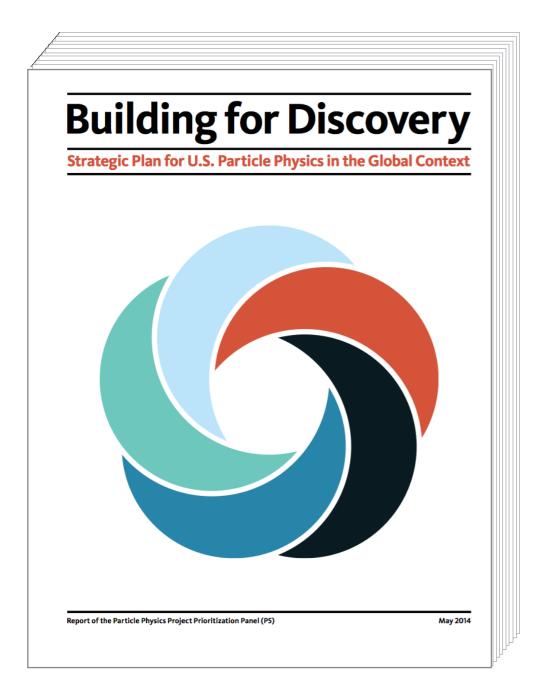




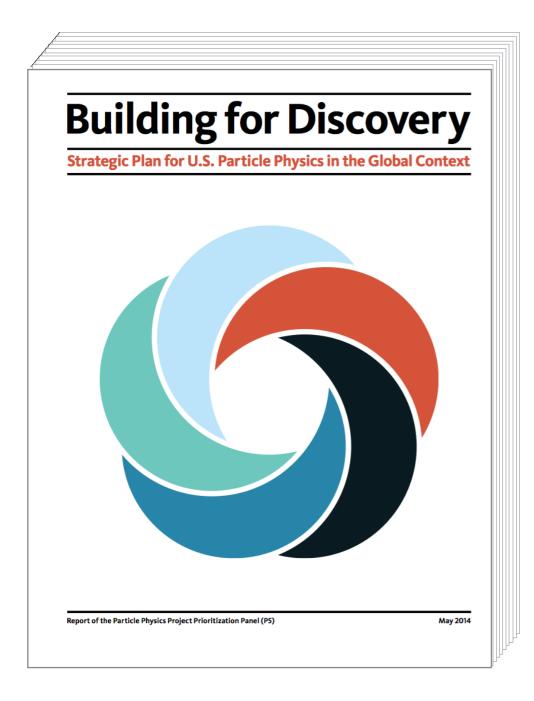
•Use the **Higgs boson** as a new tool for discovery



- •Use the **Higgs boson** as a new tool for discovery
- Pursue the physics associated with neutrino mass



- •Use the **Higgs boson** as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter

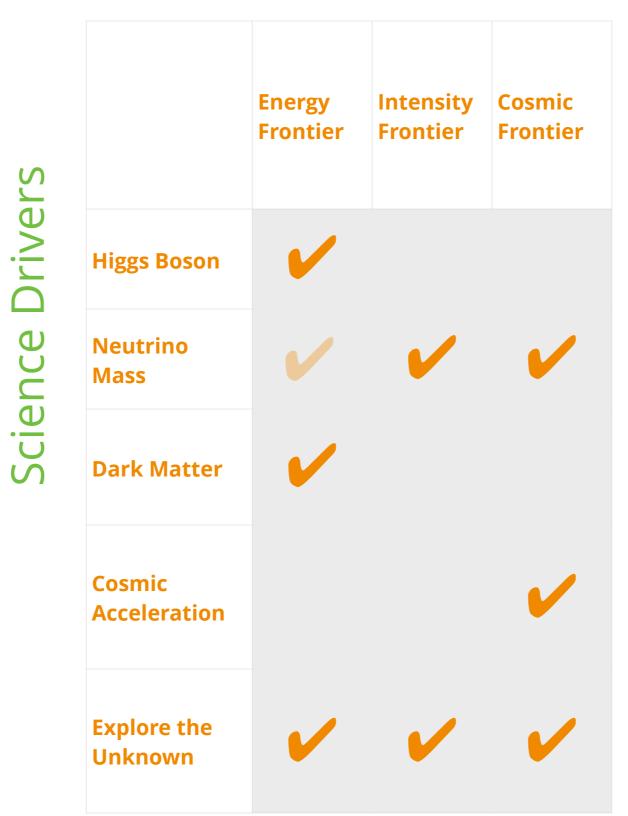


- •Use the **Higgs boson** as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand **cosmic acceleration**: dark energy and inflation

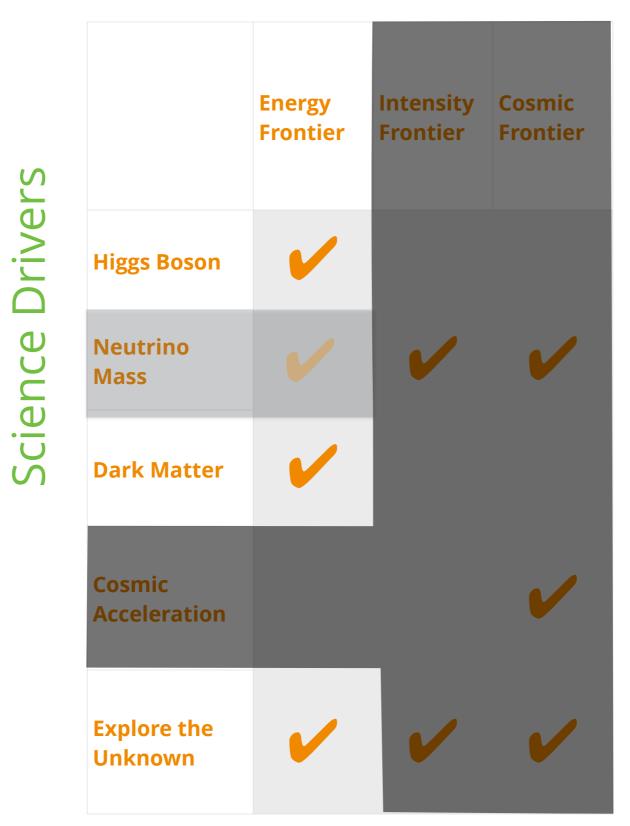


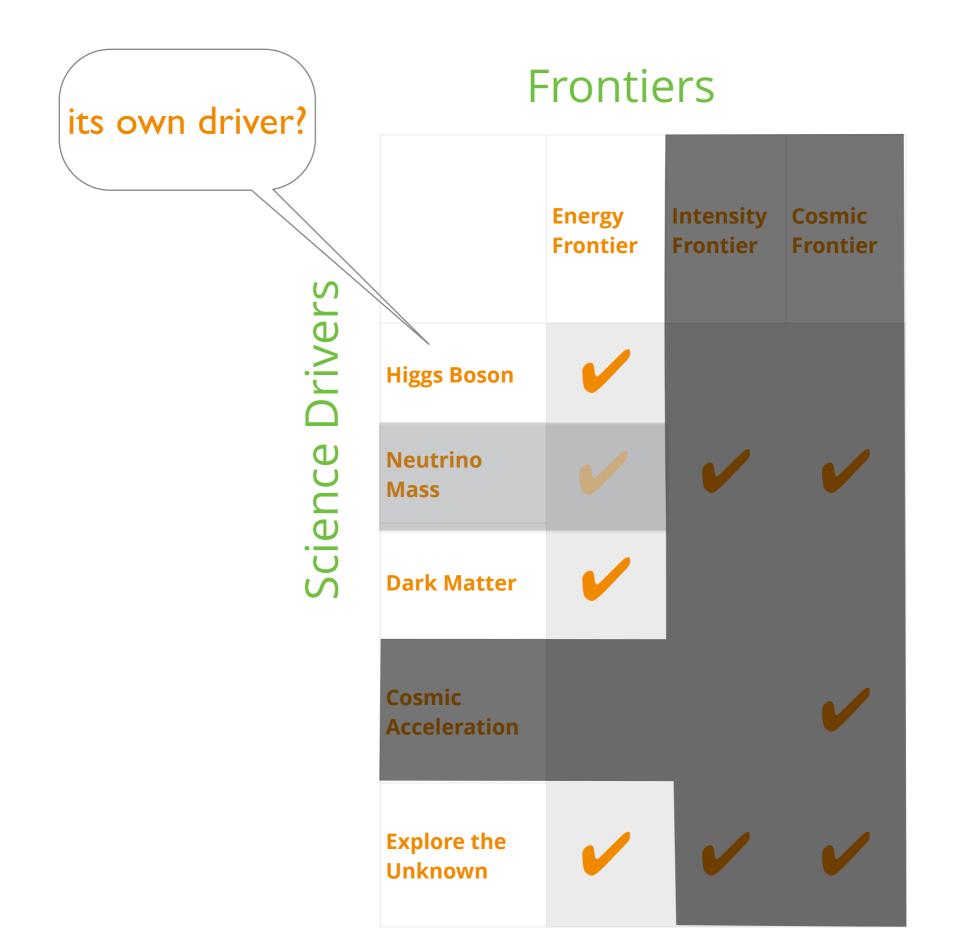
- •Use the **Higgs boson** as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of **dark matter**
- Understand **cosmic acceleration**: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

Frontiers



Frontiers





particle physics



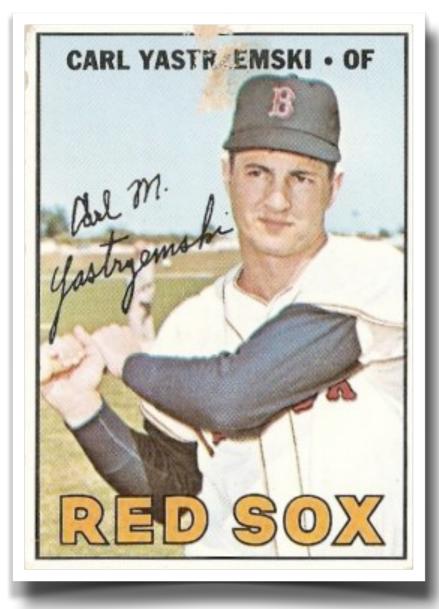
Why the Standard Model victory laps?

history was made





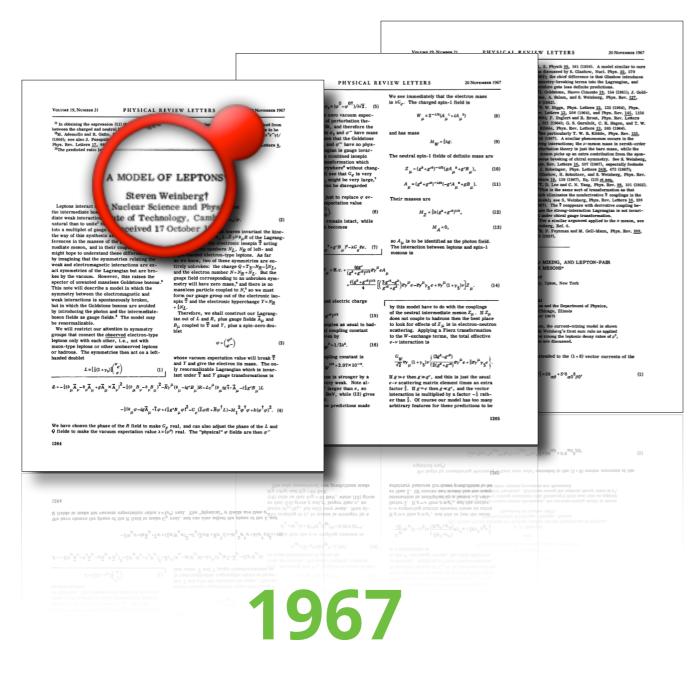
history was made



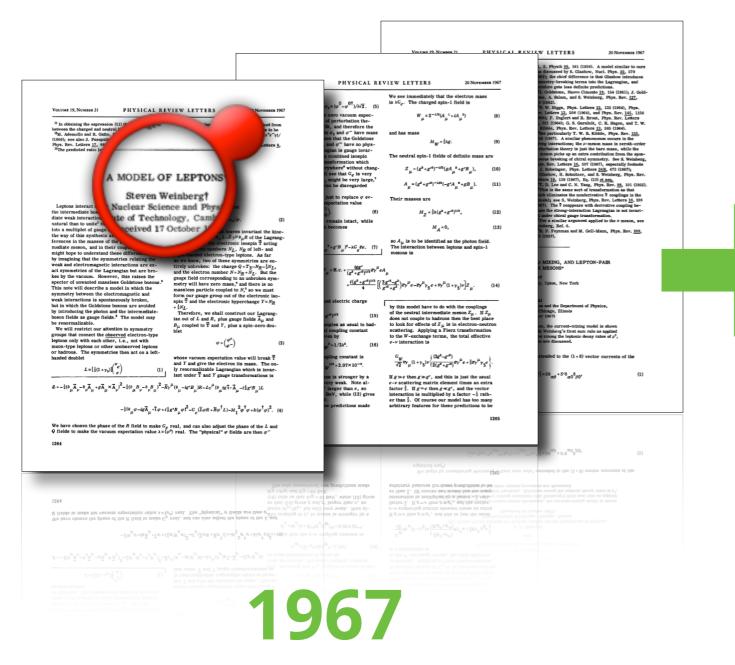


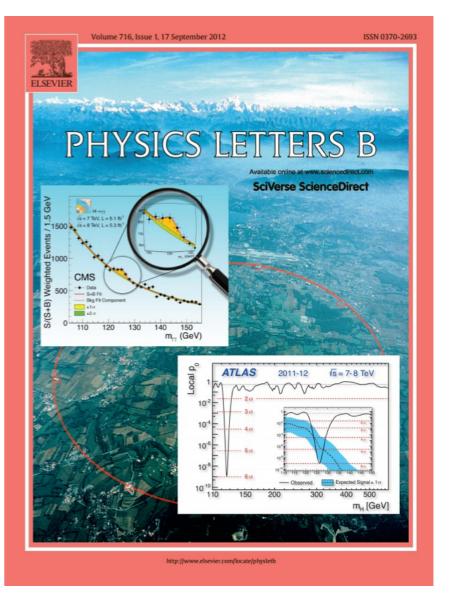






2012

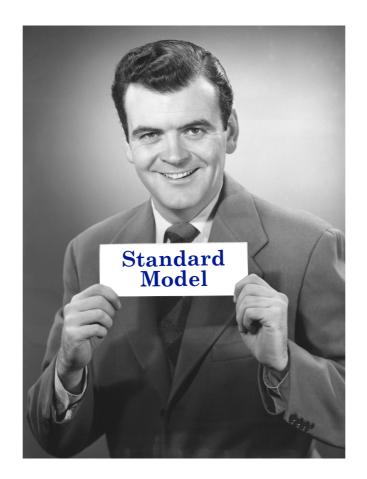




2012

30,000 ft View of the Standard Model





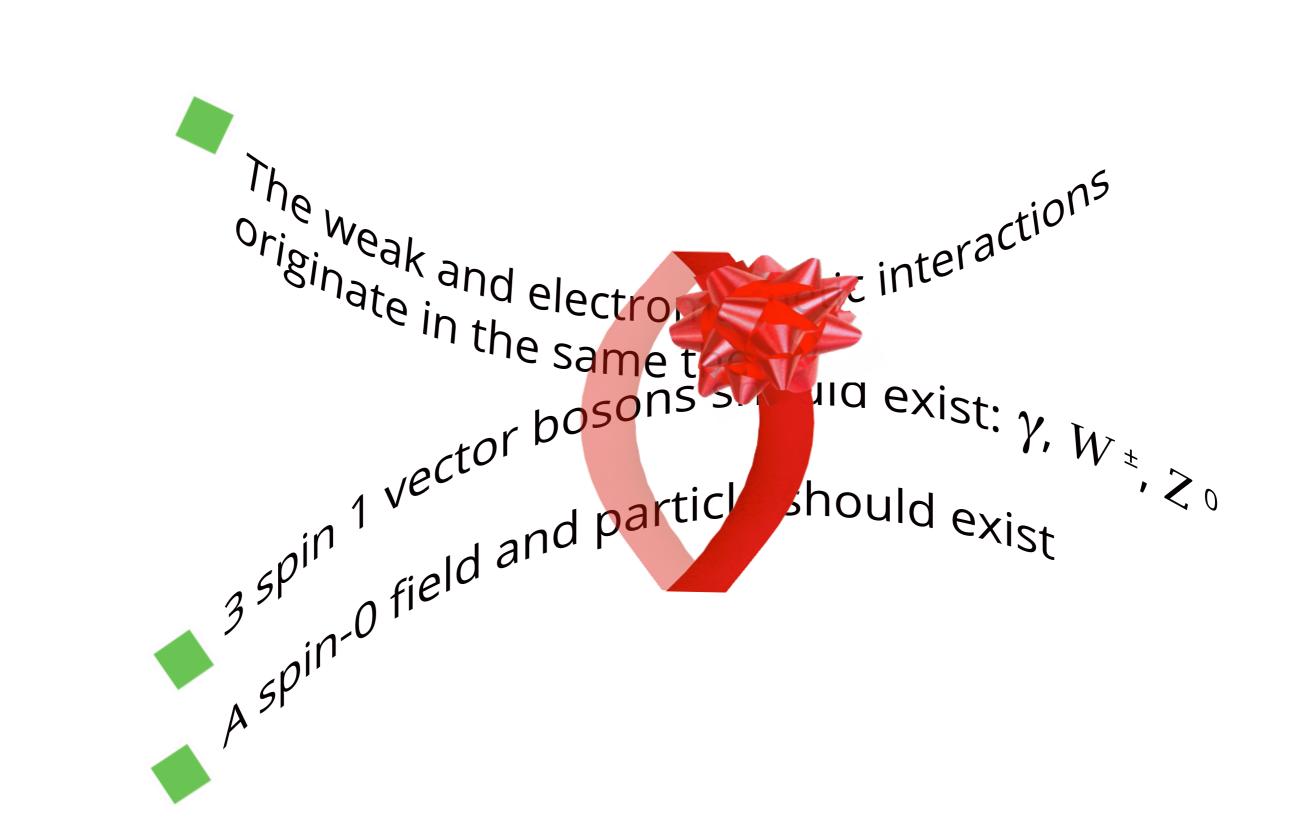
guided research

guided research



Because: 3 SM predictions

The weak and electroma, etic interactions originate in the same the *y*3 spin 1 vector bosons should exist: *γ*, *W*[±], *Z*⁰
A spin-0 field and particle should exist

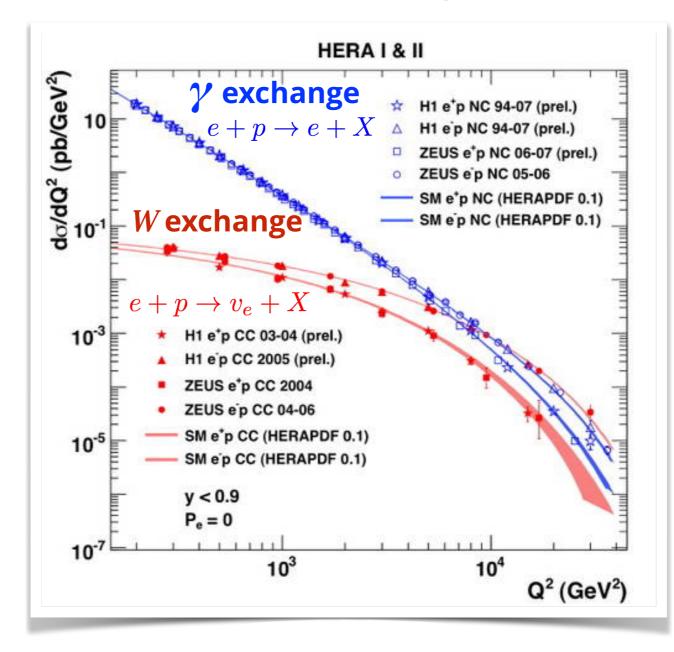


1/3 SM predictions

The weak and electromagnetic interactions originate in the same theory

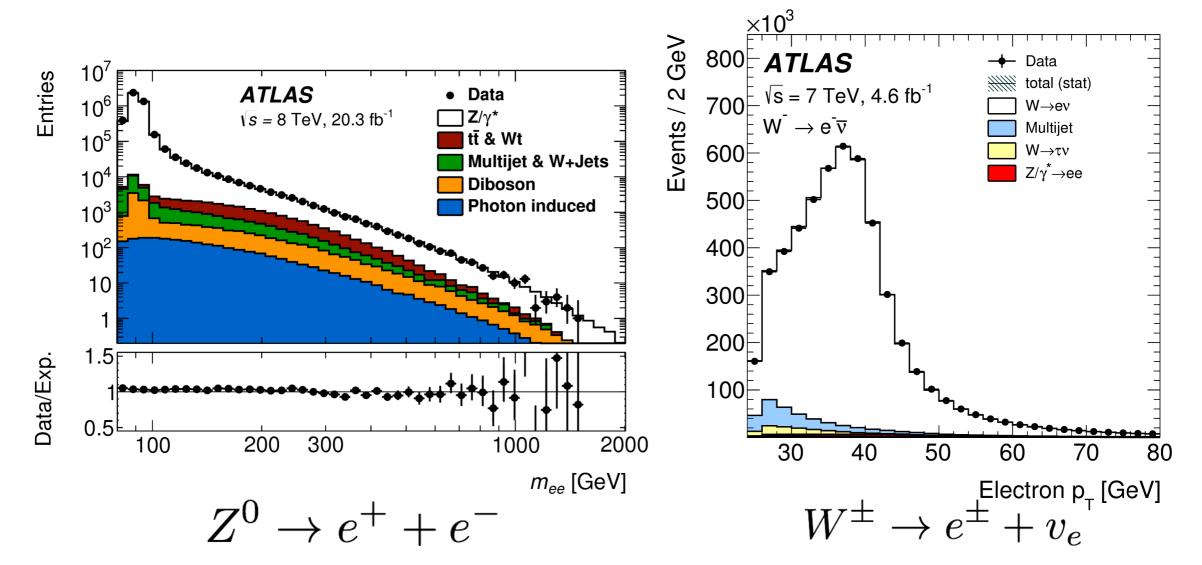
1/3 SM predictions

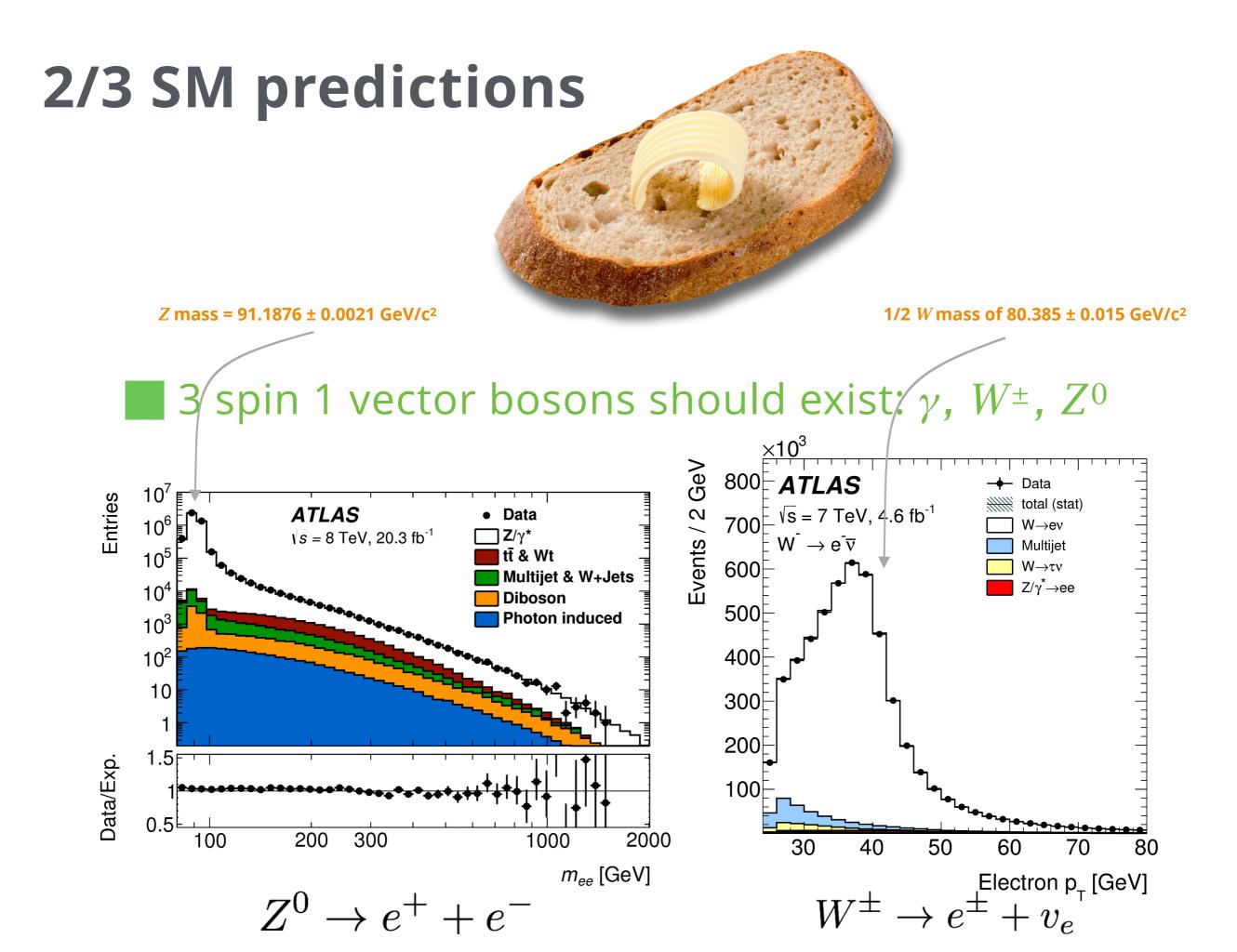
The weak and electromagnetic interactions originate in the same theory





3 spin 1 vector bosons should exist: γ , W^{\pm} , Z^{0}





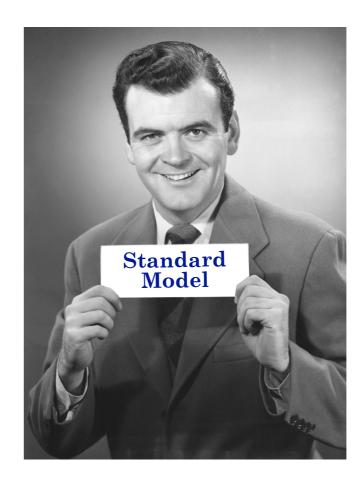
3/3 SM predictions

A spin-0 field and particle should exist and so began a story



4th of July, 2012

the 2012 discovery



completed the story unrelenting 40 year effort.



We're schizophrenic about the Standard Model

Like the nursery rhyme

THERE was a little girl who had a little curl Right in the middle of her forehead; When she was good, she was very, very good, And when she was bad she was horrid.



when the SM is good, it's very good

Like the nursery rhyme

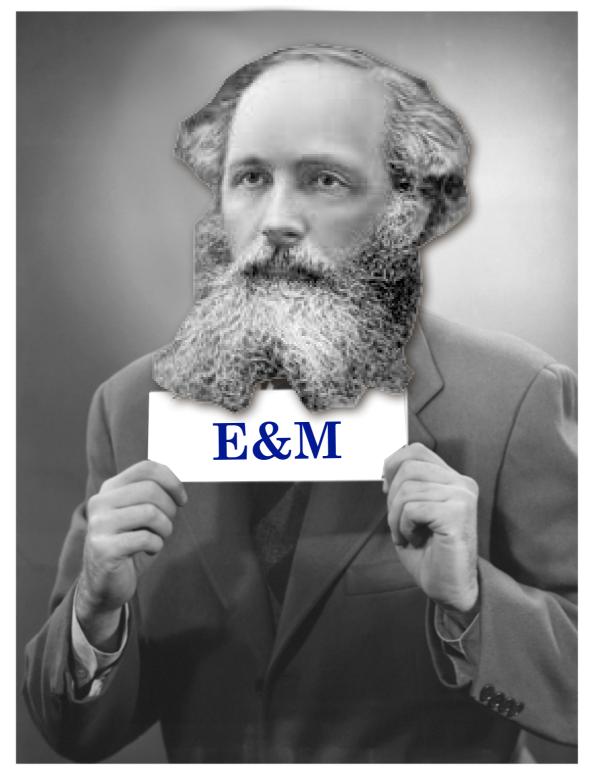
THERE was a little girl who had a little curl Right in the middle of her forehead; When she was good, she was very, very good, And when she was bad she was horrid.

when the SM is good,

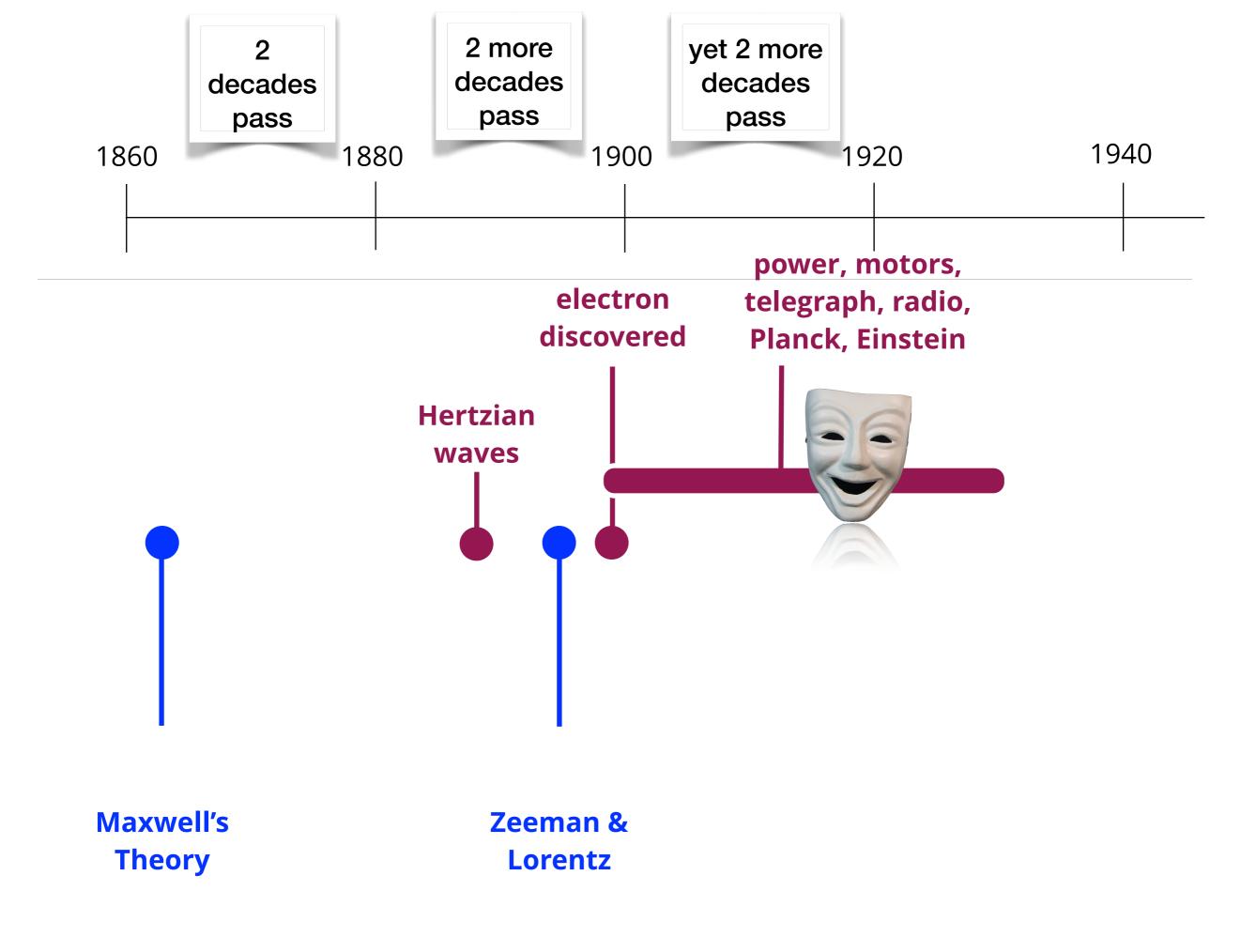
it's very good

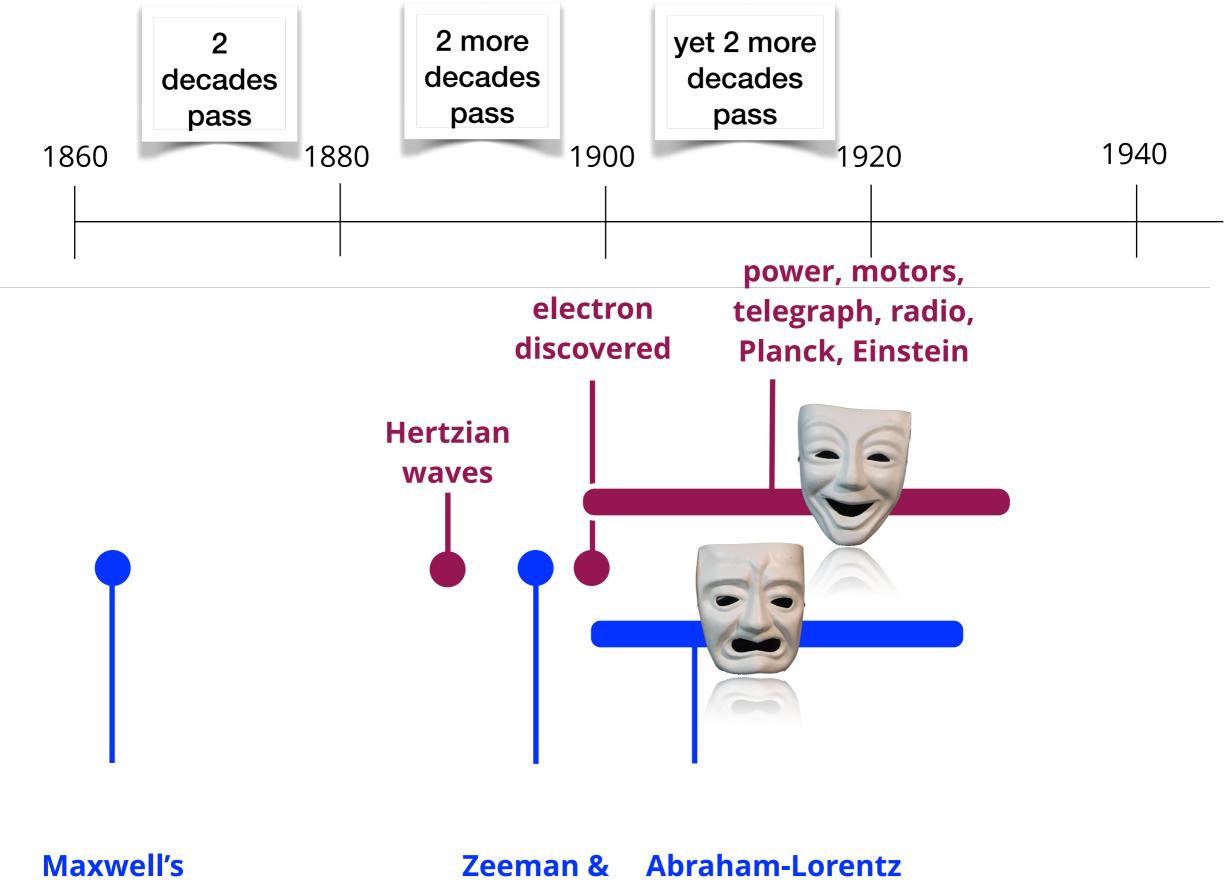
when it's bad

it's very...confusing



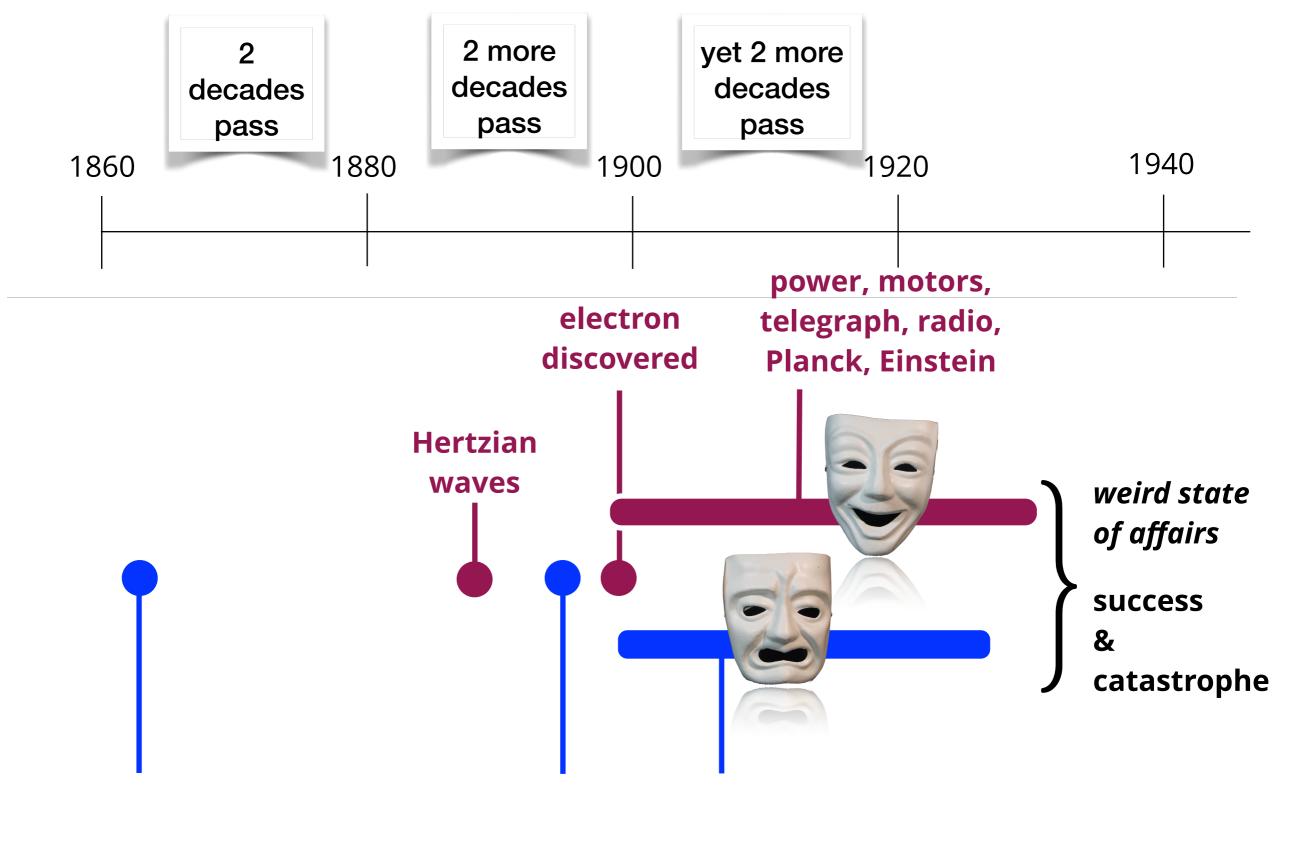




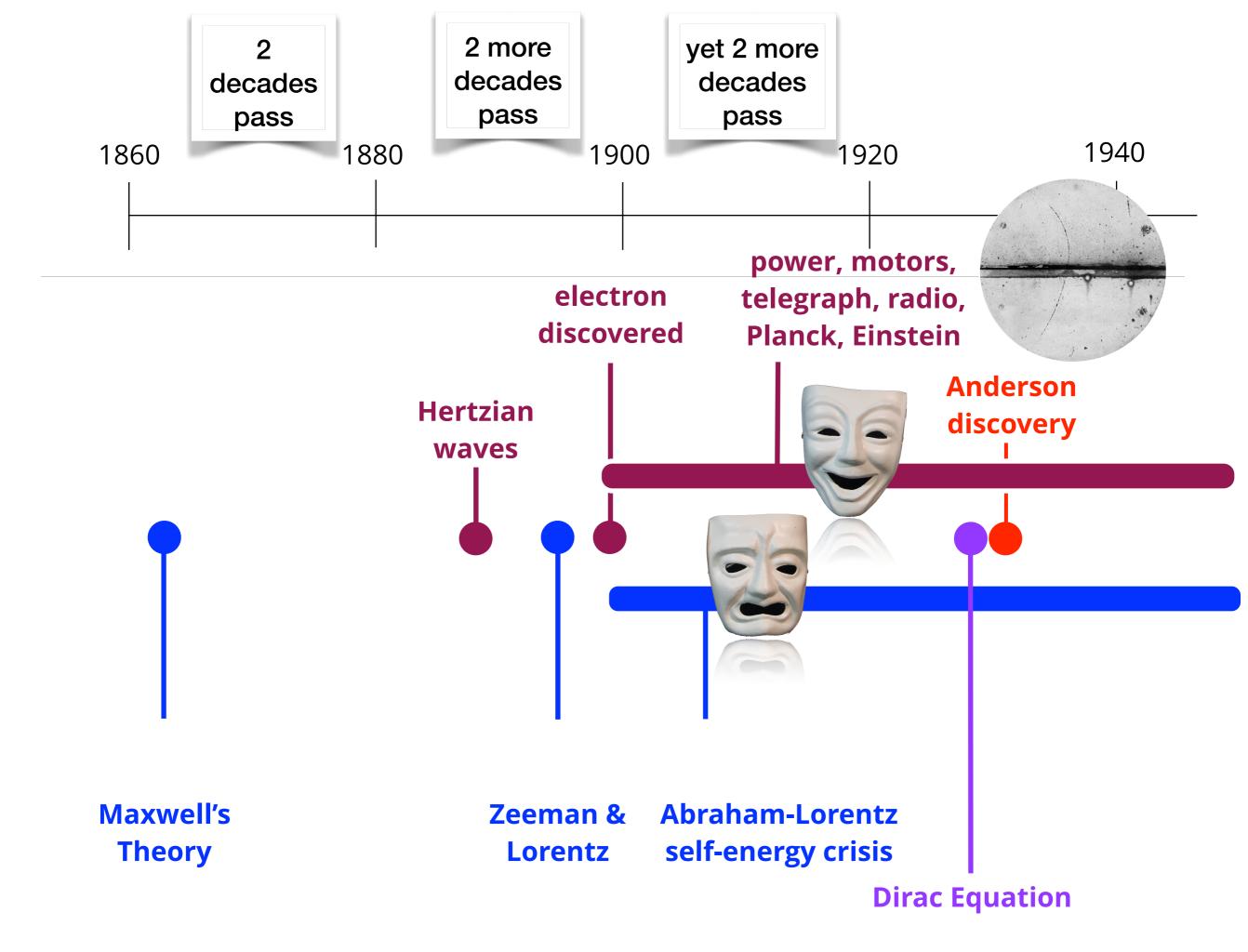


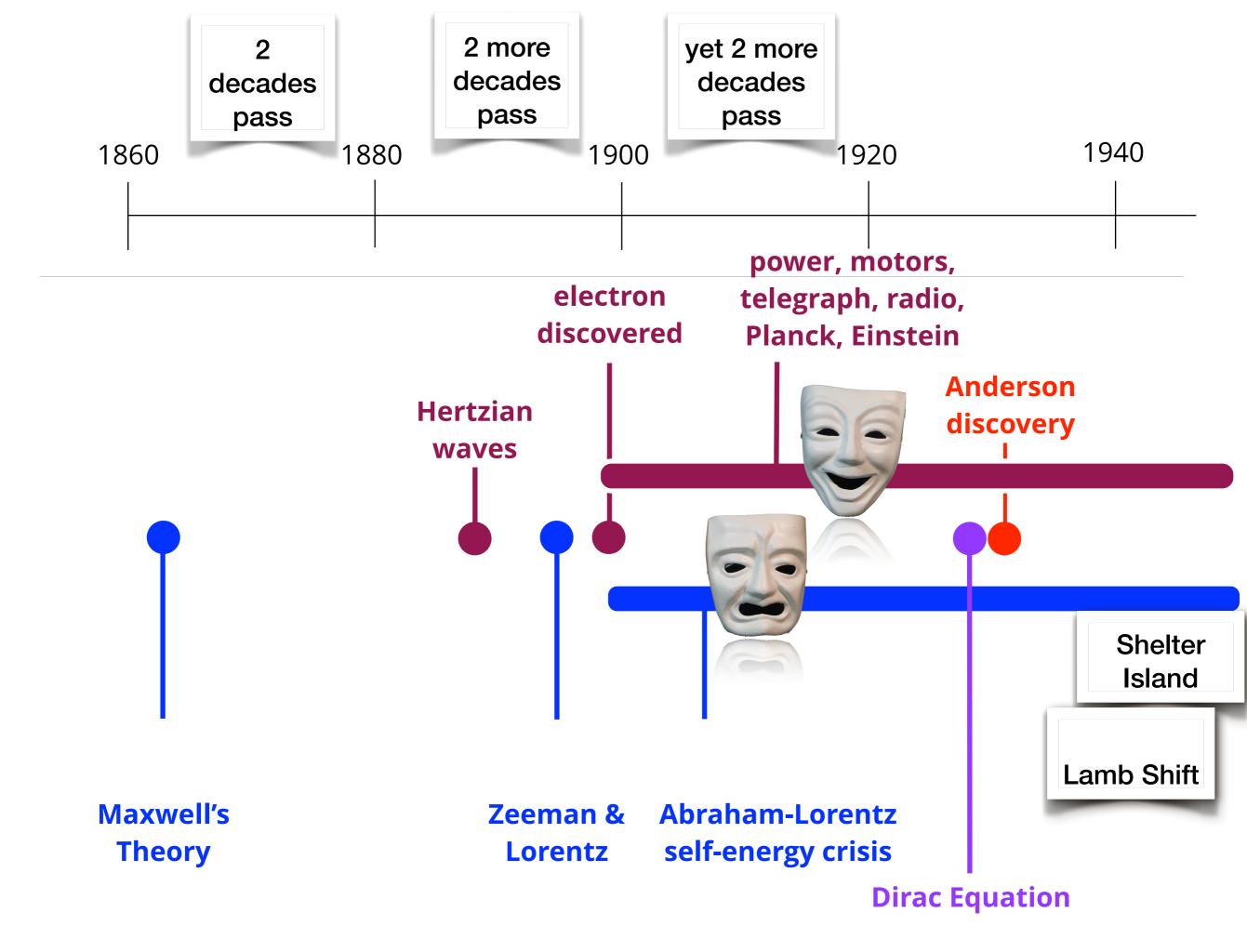
Theory

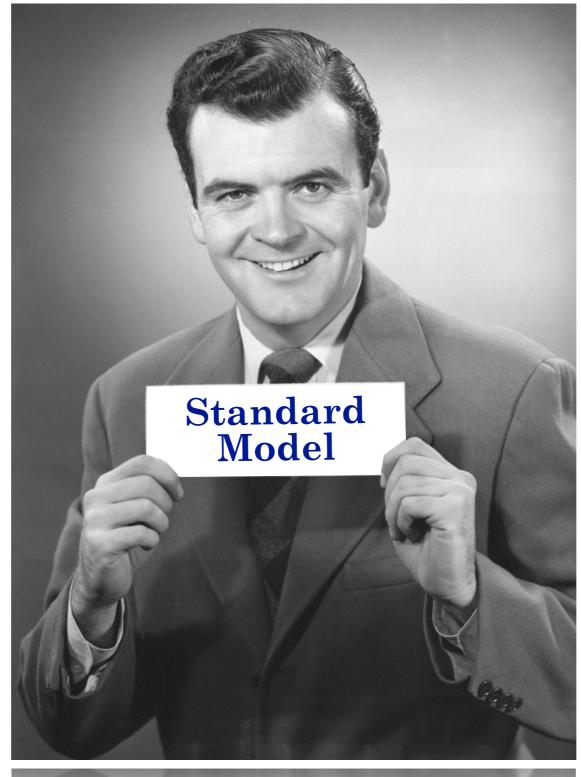
self-energy crisis Lorentz



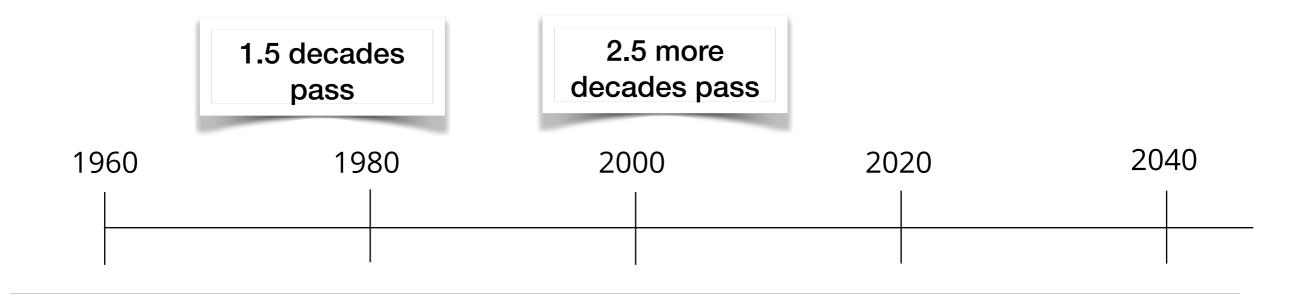
Maxwell's Theory Zeeman & Abraham-Lorentz Lorentz self-energy crisis

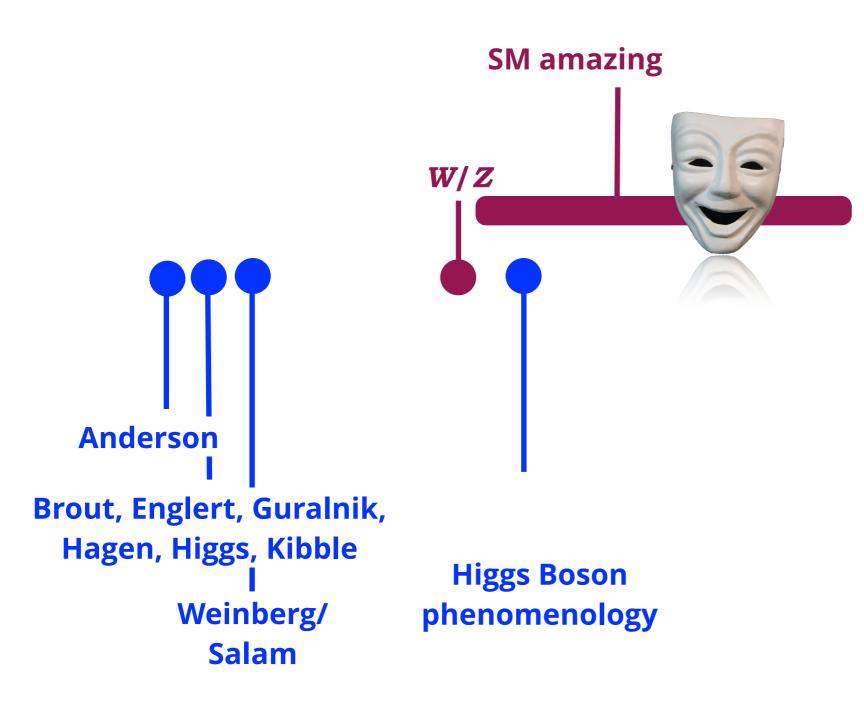


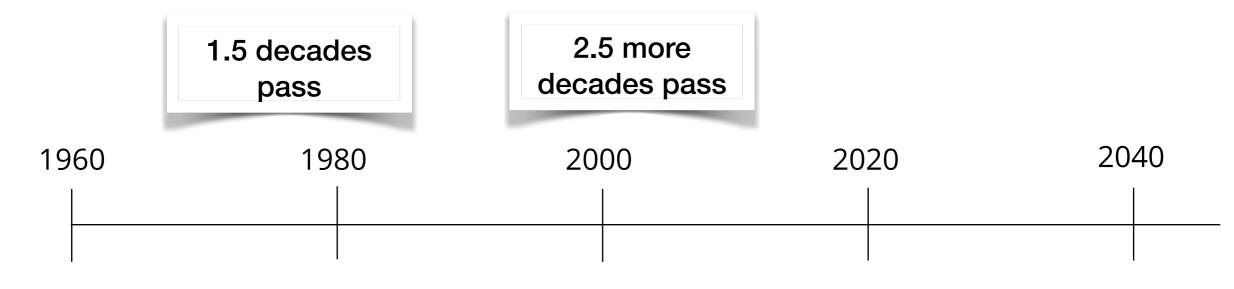


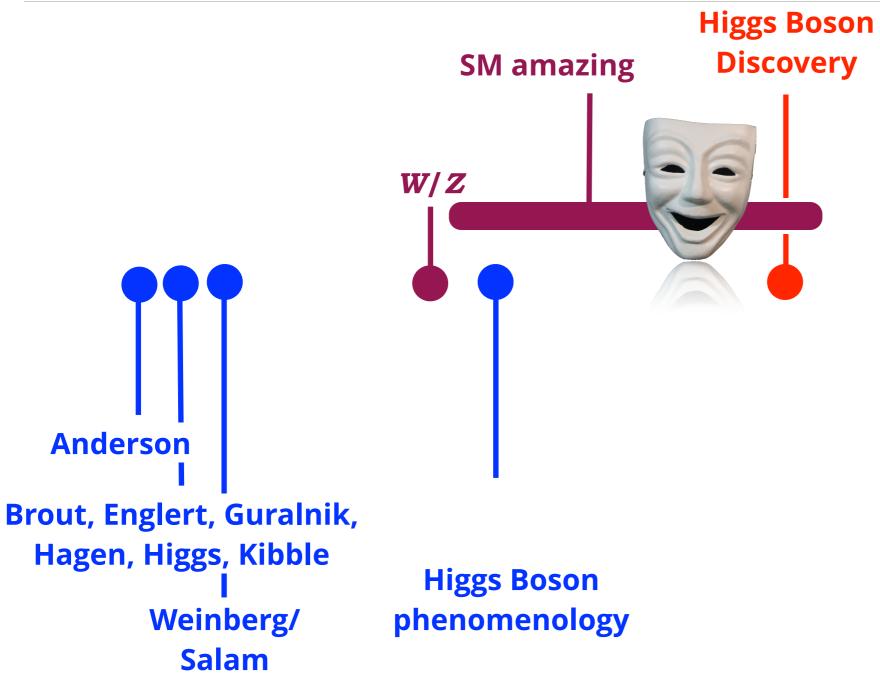


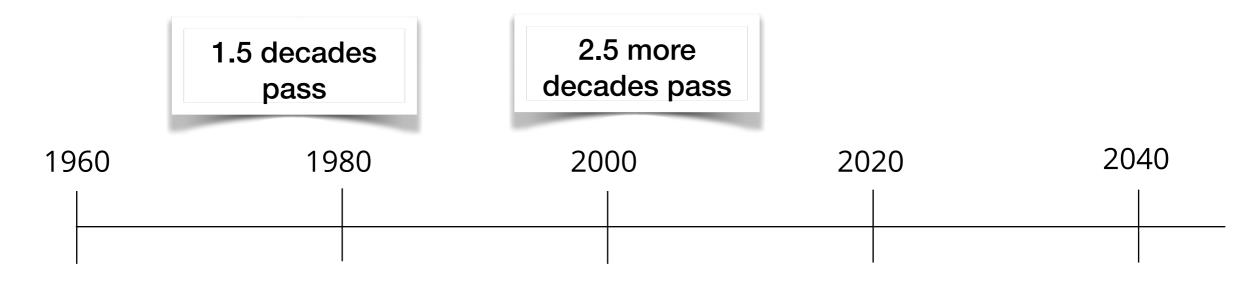


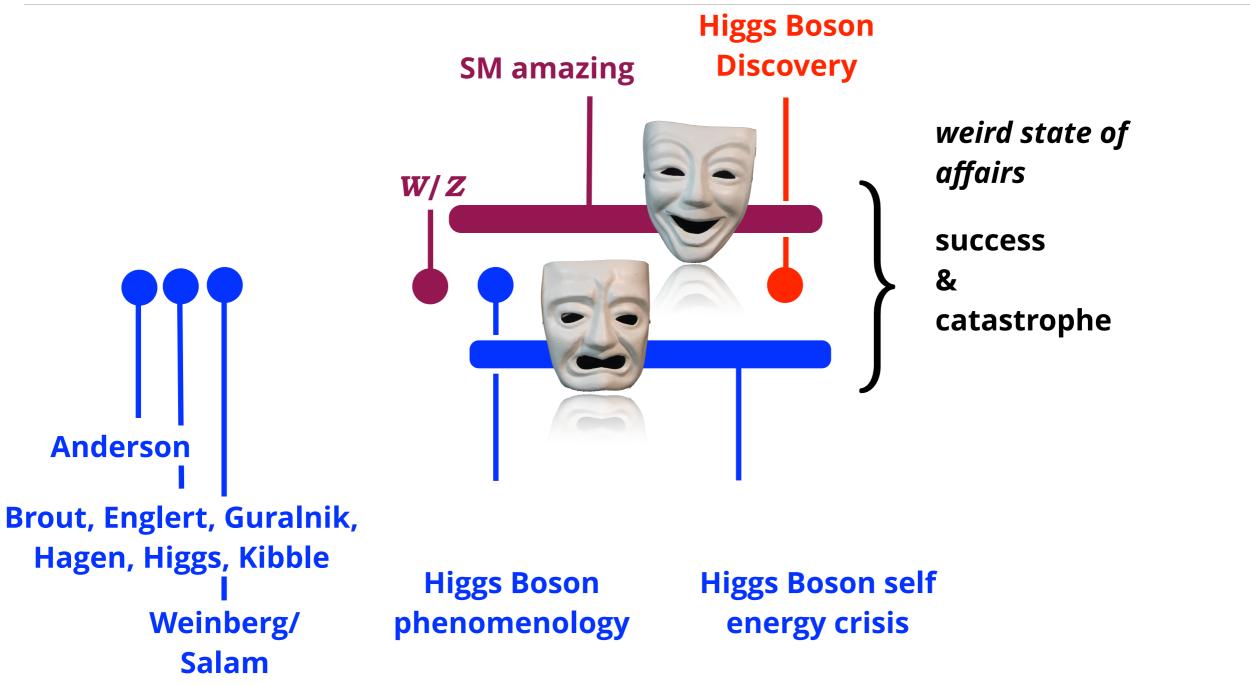


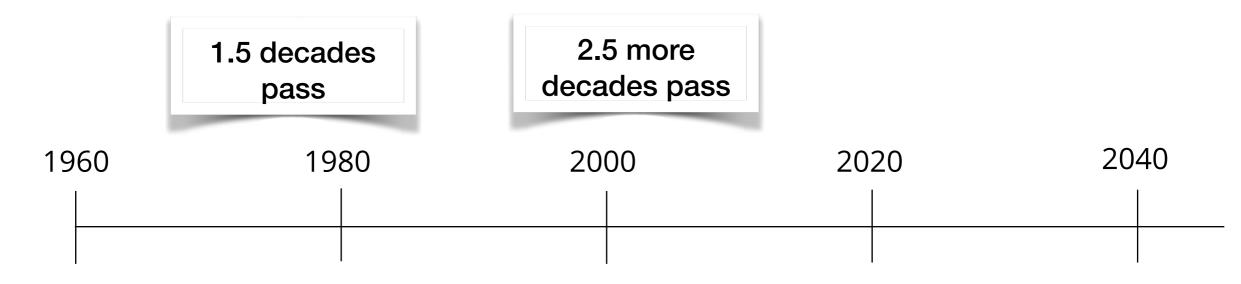


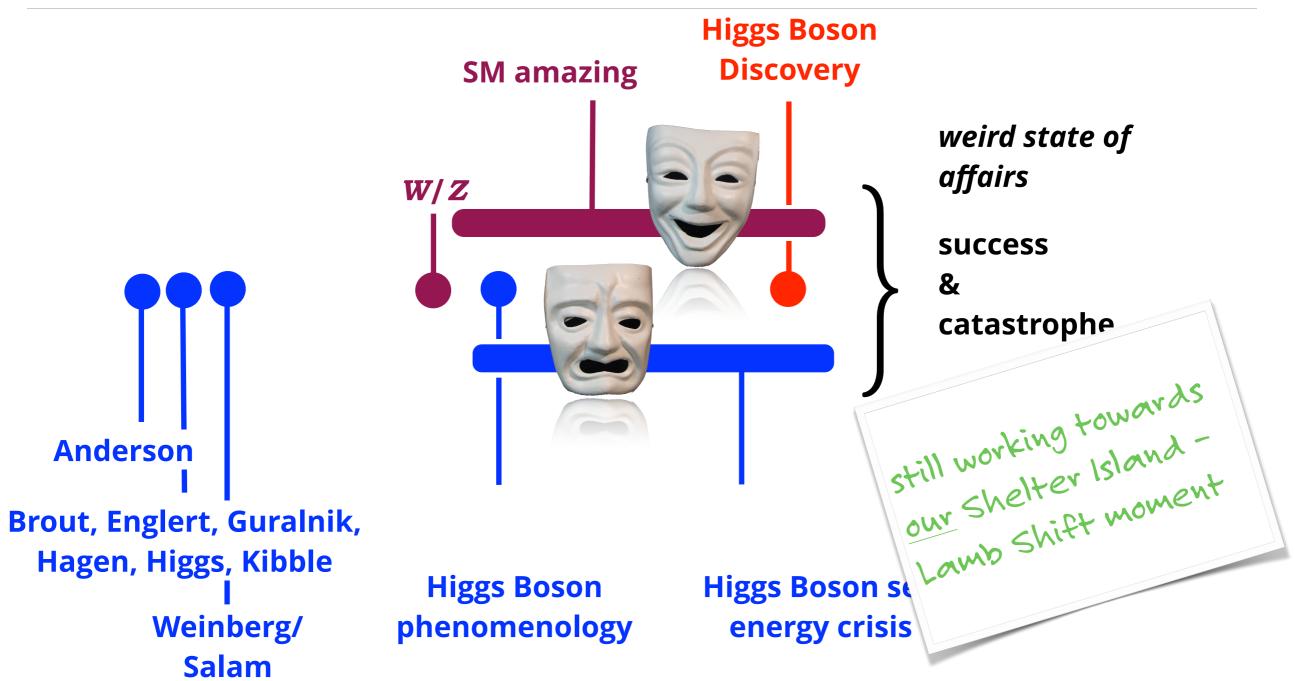












The Standard Model ingredients:

The Gauge Principle circa 1918, 1954 demand of a symmetry

Spontaneous
 Symmetry Breaking
 circa 1950, 1964
 effective theory of
 phase transitions

the players:









ETWENTY CENTS



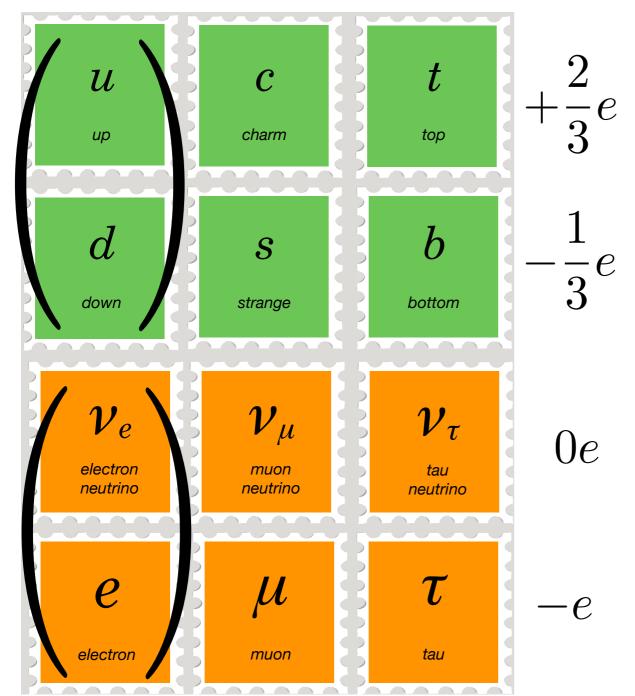




spin 1/2

the players:

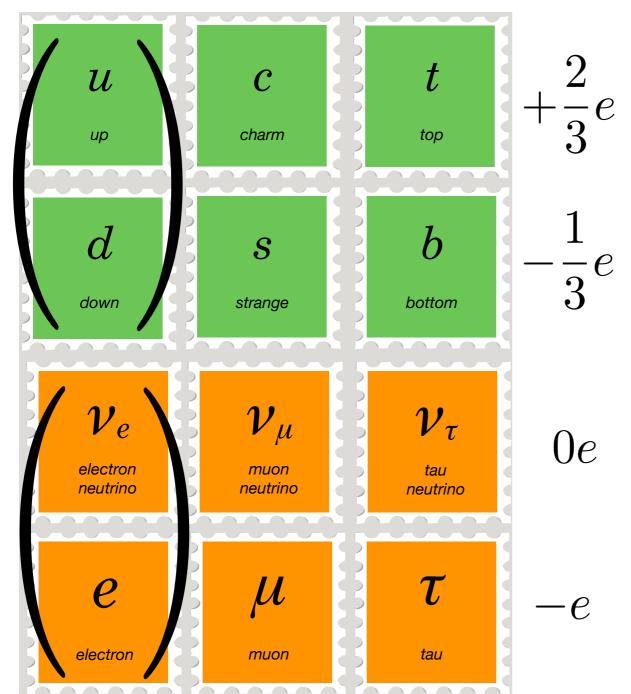
quarks



& their interactions

spin 1/2

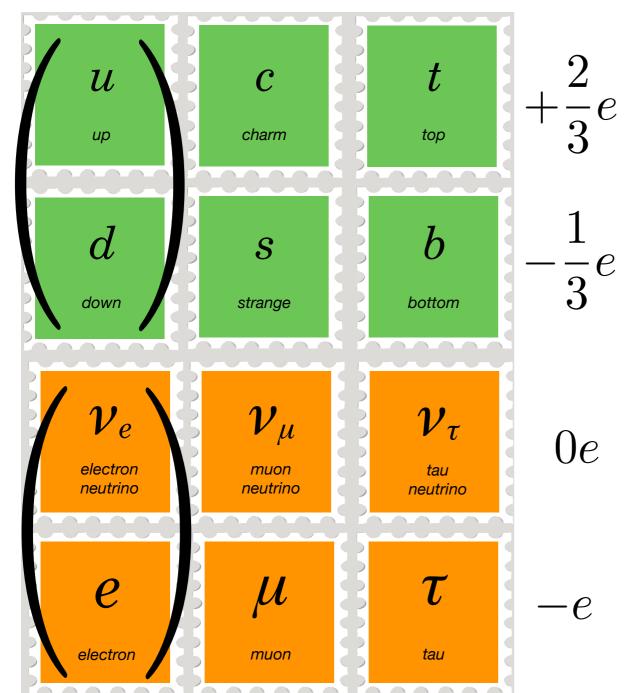
the players:



quarks

spin 1/2

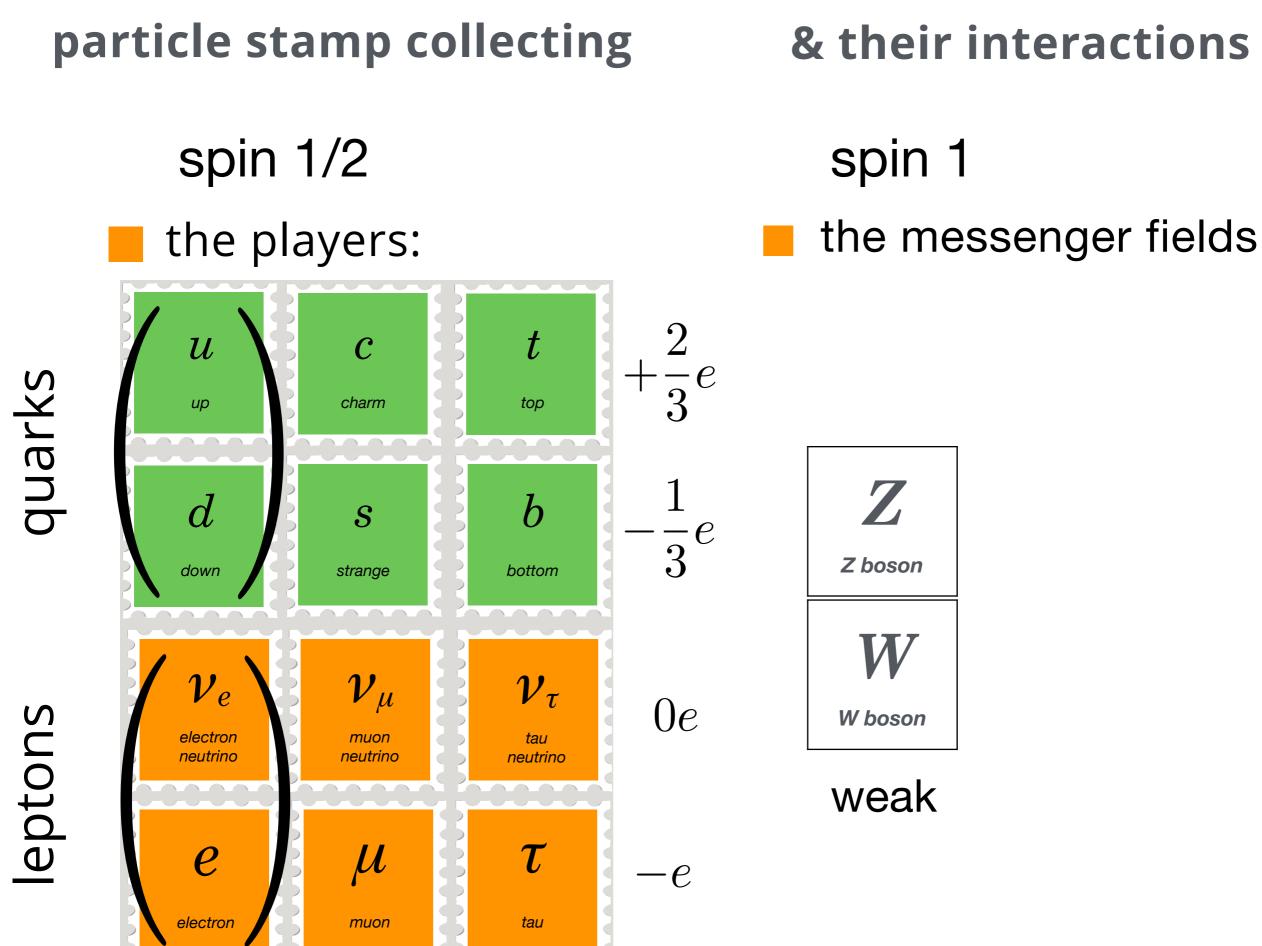
the players:

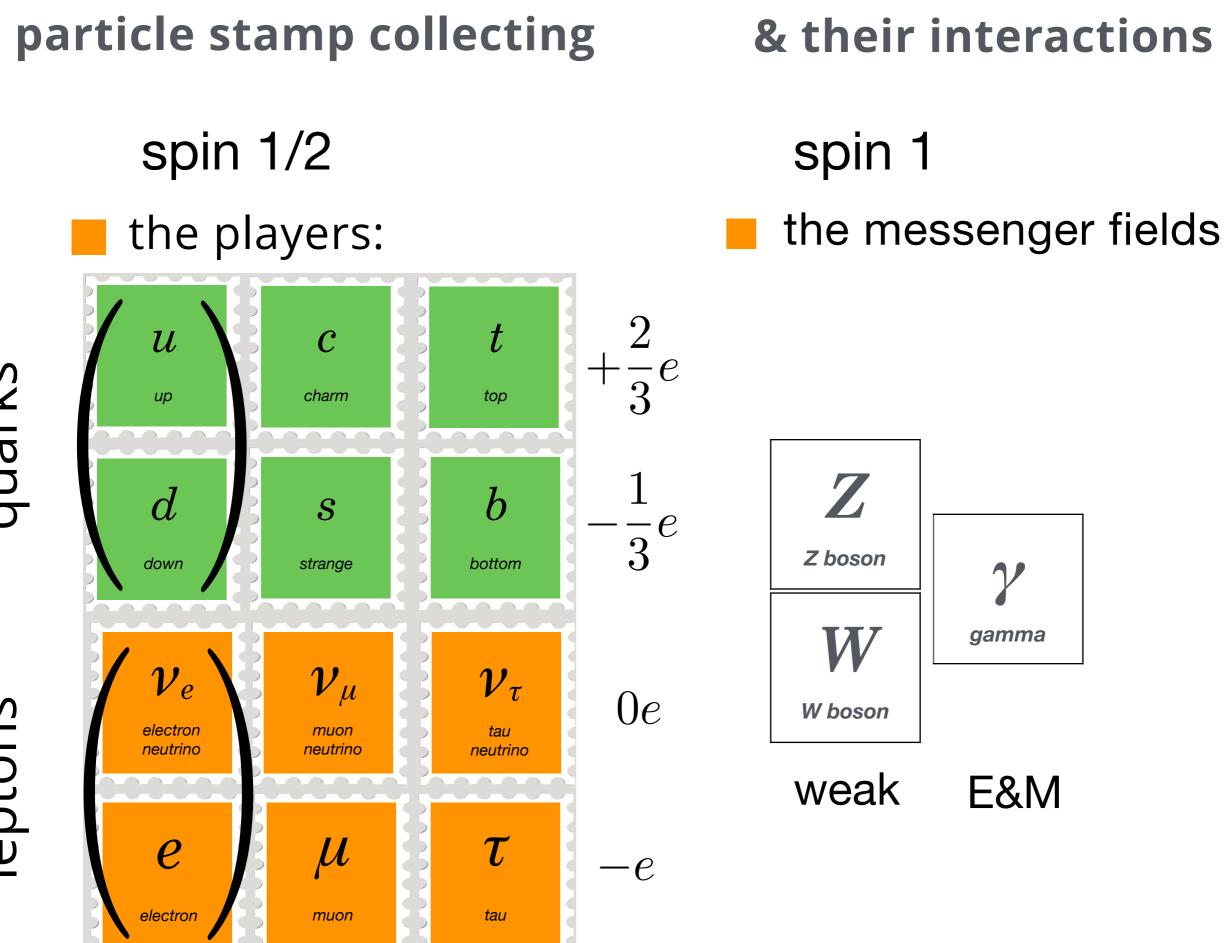


& their interactions

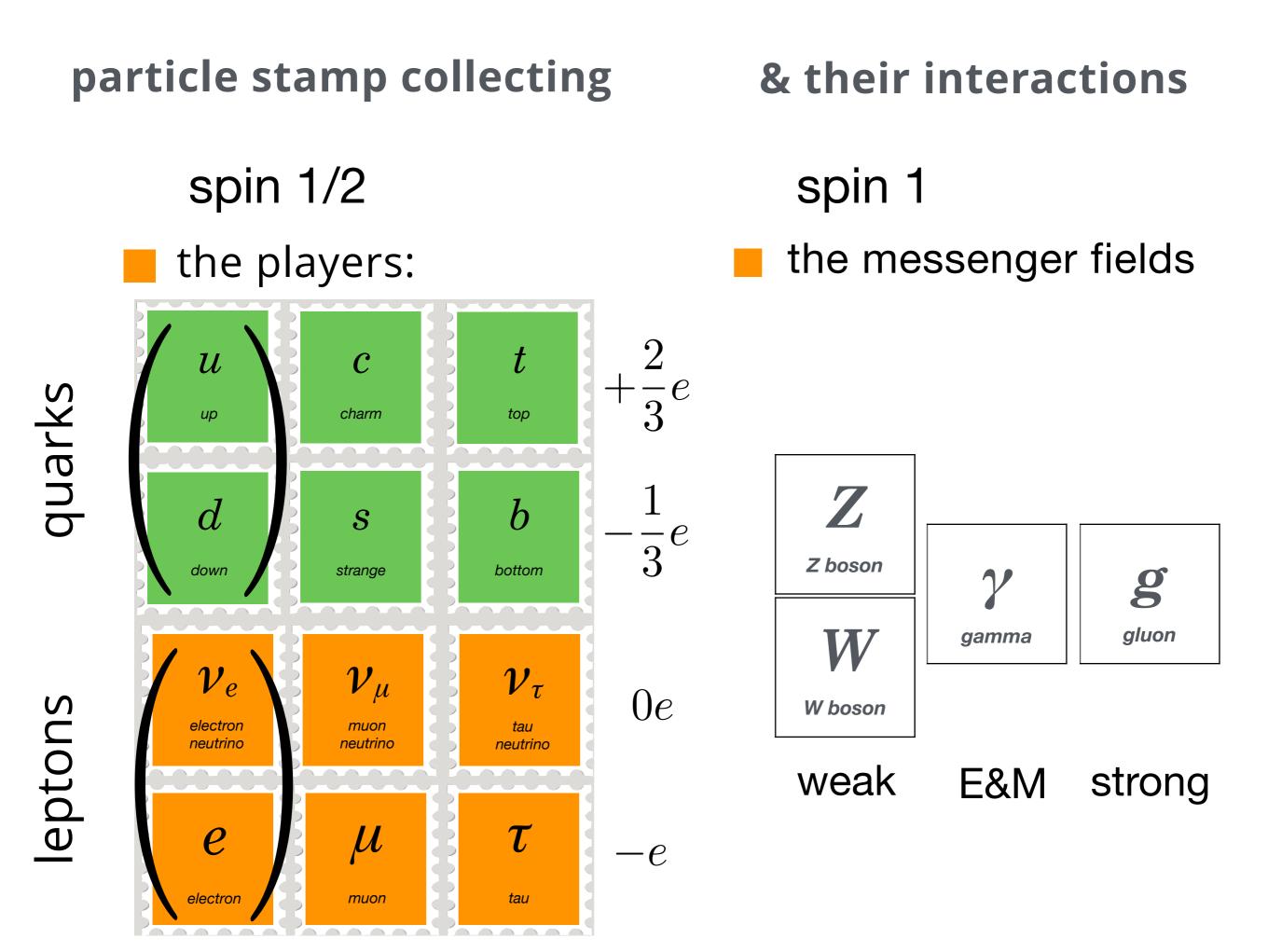
spin 1 the messenger fields

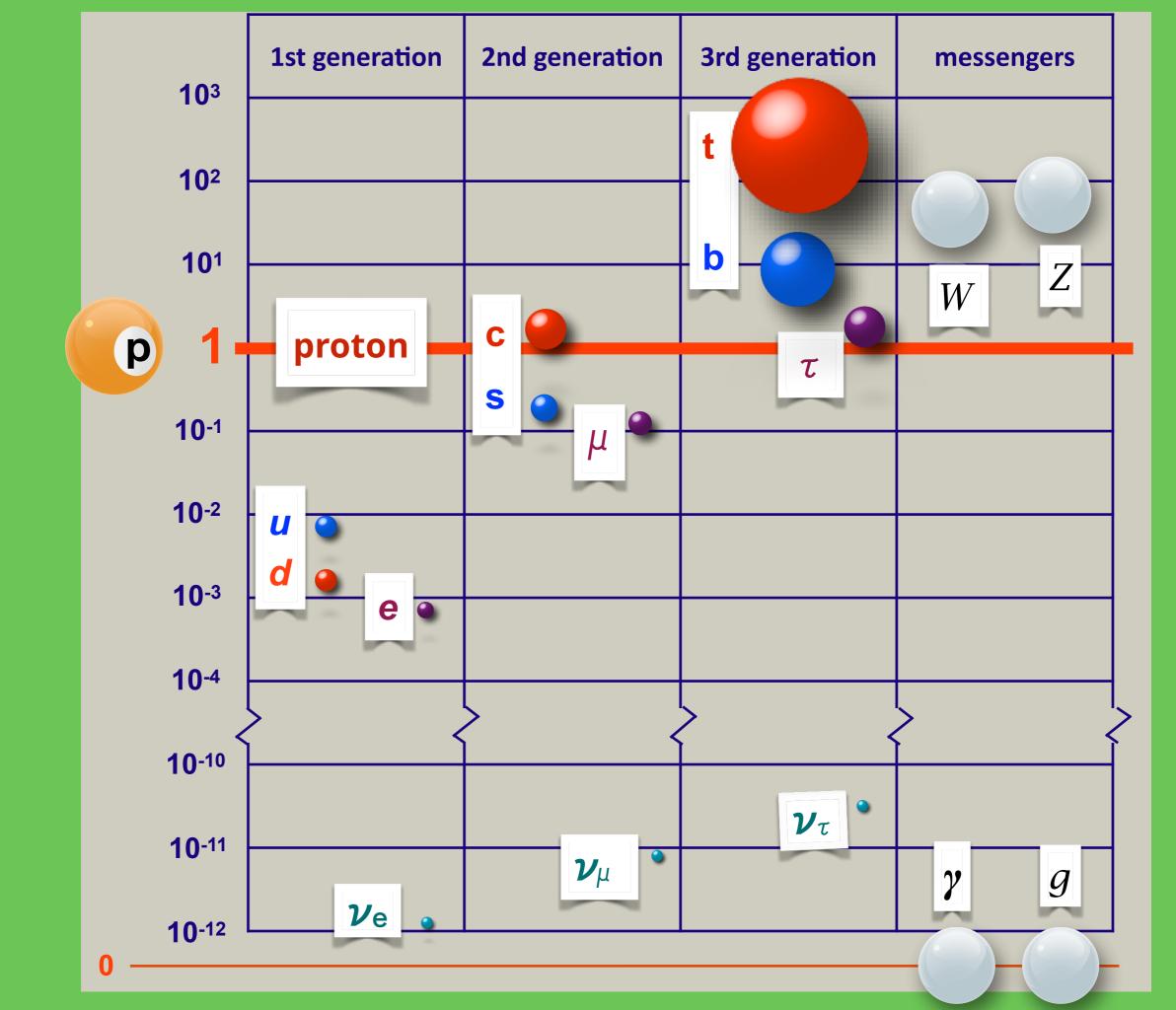
quarks

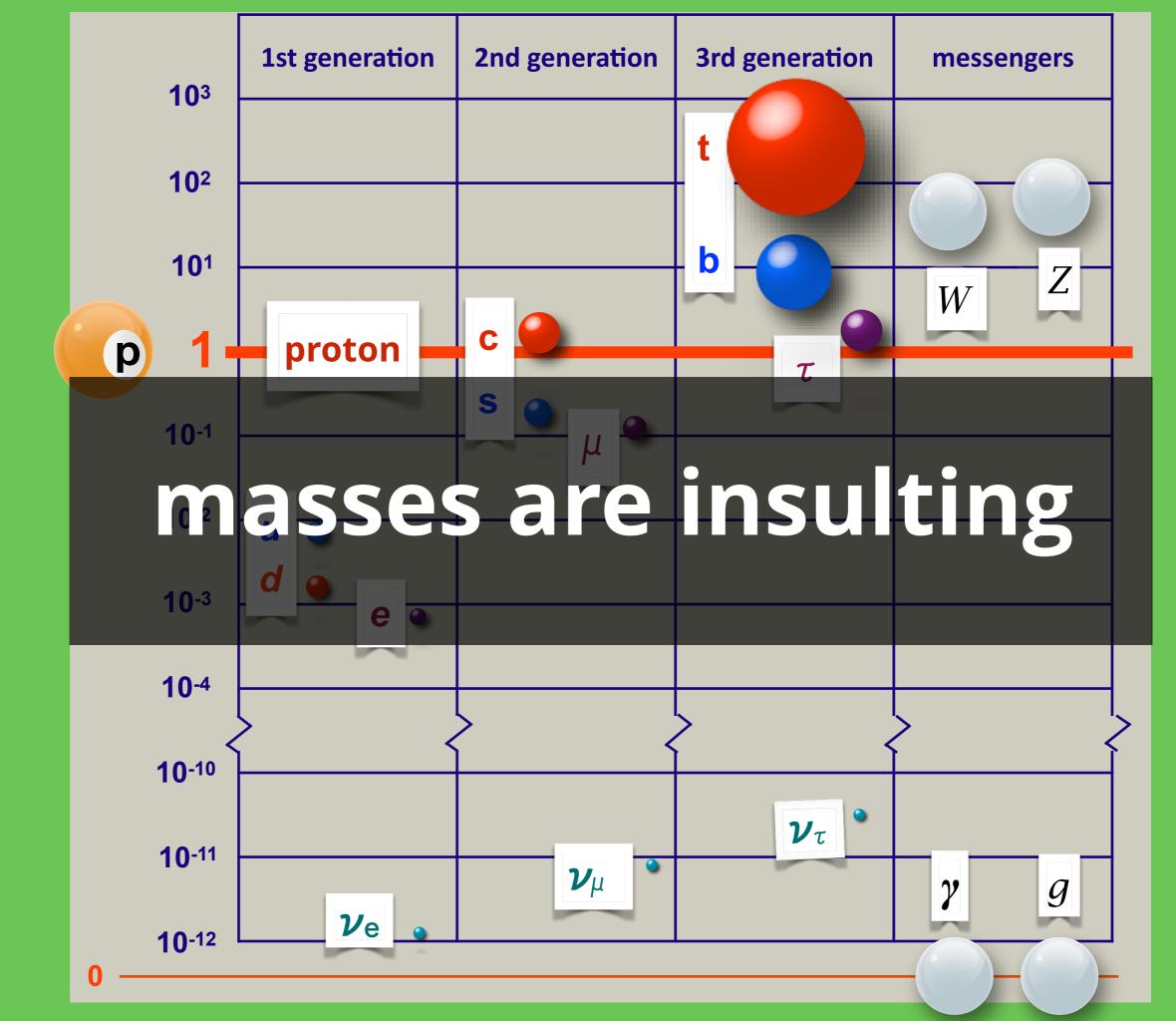




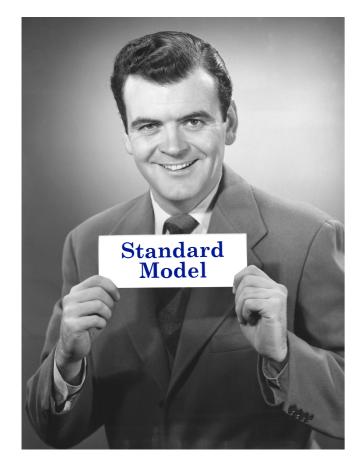
quarks







what's great about the Standard Model?



1. the Gauge Principle



Extremely powerful and pretty.

- $\blacksquare Q$: generator of a group, with "charge" q
- θ a parameter

Extremely powerful and pretty.

Q: generator of a group, with "charge" q $U(Q) = e^{iQ\theta}$. A parameter

Extremely powerful and pretty.

Q: generator of a group, with "charge" q $U(Q) = e^{iQ\theta}$

 $\psi(x) \to e^{iQ\theta}\psi(x) \quad \psi(x) \to e^{iQ\theta(x)}\psi(x)$ Global Local

Extremely powerful and pretty.

Q: generator of a group, with "charge" q $U(Q) = e^{iQ\theta}$

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Invariance of the Local sort demands



Invariance of the Local sort demands

- the existence of a massless spin-1 field,
- $A_{\mu}(x)$



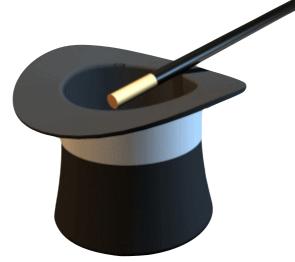
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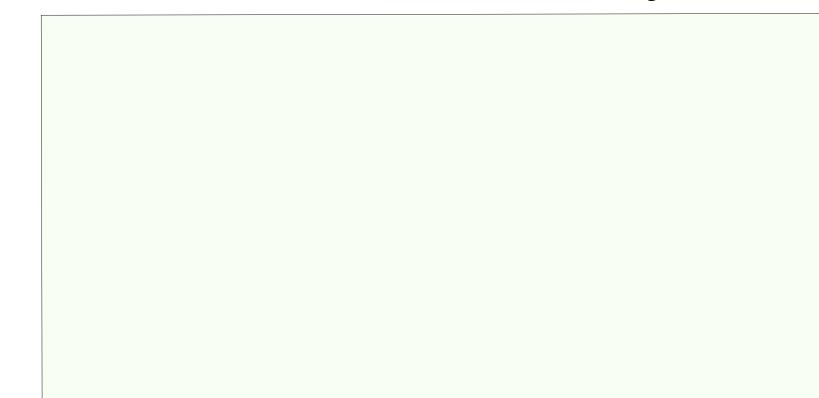
- the existence of a massless spin-1 field, $A_{\mu}(x)$
- and prescribes coupling: $\psi(x): qA_{\mu}(x)\overline{\psi}(x)\gamma^{\mu}\psi(x)$



The demand of a symmetry forces the photon to exist!

Gauge Principle piece:

"Unfolds" rather neatly

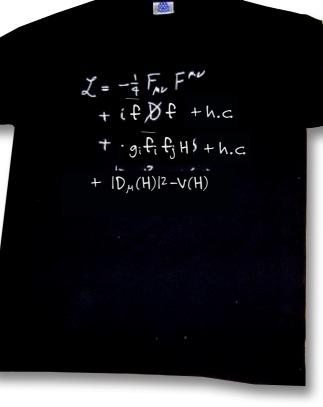


$$\begin{split} &- \left[a_{0} a_{0}^{2} a_{0}^{2} a_{0}^{2} + a_{0}^{2} a_{0}^{$$

Gauge Principle piece:

"Unfolds" rather neatly



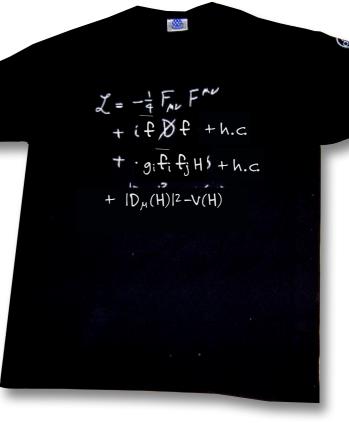


Gauge Principle piece:

"Unfolds" rather neatly

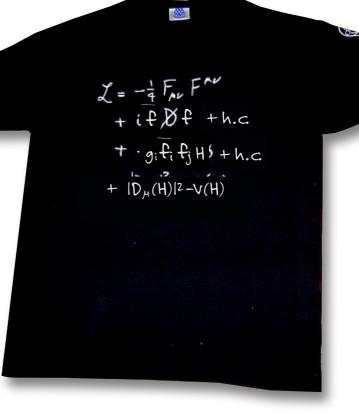
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$+i\bar{\psi}D\psi$$

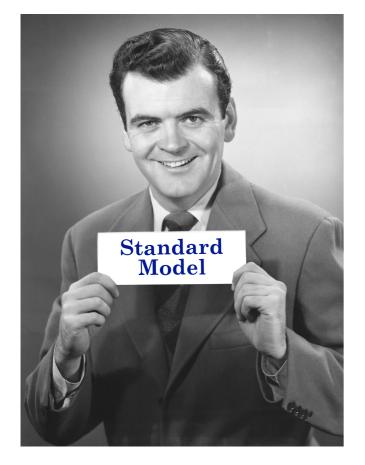


8 **Gauge Principle piece:** Z = - = FAL FAL + if Øf + h.c. $+ \cdot g_i f_i f_j H_{i} + h.c.$ "Unfolds" rather neatly + $|D_{\mu}(H)|^2 - V(H)$ W^{\pm}, Z^0, γ $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \underset{W^{\pm}, Z^{0}, \gamma}{\overset{\mathcal{N}}{\longrightarrow}} \mathcal{L}$ W^{\pm}, Z^0, γ $+i\bar{\psi}D\psi$

Gauge Principle piece: "Unfolds" rather neatly W^{\pm}, Z^0, γ $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \underset{W^{\pm}, Z^{0}, \gamma}{\overset{\mathcal{N}}{\longrightarrow}}$



that's really great this Standard Model

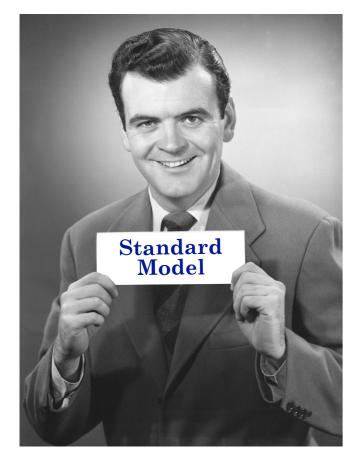


the Gauge Principle:

Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0010	-0.4	-0.2
$\Gamma(had)$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	_	
$\Gamma(inv)$ [MeV]	499.0 ± 1.5	501.69 ± 0.06		
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	_	
$\sigma_{\rm had}[{\rm nb}]$	41.541 ± 0.037	41.477 ± 0.009	1.7	1.7
R_e	20.804 ± 0.050	20.744 ± 0.011	1.2	1.3
R_{μ}	20.785 ± 0.033	20.744 ± 0.011	1.2	1.3
R_{τ}	20.764 ± 0.045	20.789 ± 0.011	-0.6	-0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.0030	0.17227 ± 0.00004	-0.1	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	-0.7	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0, au)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	-2.6	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	-0.9	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	-0.5	-0.5
$\bar{s}_{\ell}^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.23200 ± 0.00076		0.7	0.6
	0.2287 ± 0.0032		-0.9	-0.9
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.1
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_{μ}	0.142 ± 0.015		-0.4	-0.3
$A_{ au}$	0.136 ± 0.015		-0.8	-0.7
	0.1439 ± 0.0043		-0.8	-0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	-0.6	-0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4	- 0.4
Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	-0.1	-0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		-0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053 73 20 \pm 0.35	-0.0474 ± 0.0005 73 23 ± 0.02	1.3	1.3
$Q_W(Cs)$ $Q_W(Tl)$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_{τ} [fs]	-116.4 ± 3.6 291.13 ± 0.43	-116.88 ± 0.03 290.75 ± 2.51	0.1 0.1	0.1 0.1

The most accurate and precise scientific model in history

that's really great this Standard Model



the Gauge Principle:

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$A_{FB}^{(0,c)}$	0.			
	0			
$A_{FB}^{(0,s)}$	0			
$ar{s}_\ell^2(A_{FB}^{(0,q)})$	the hand states of the			
	0.	A DE AND AND A DE AND		
	C	AND THE ADDRESS OF		
A_e	0.1	1		
	0.1			
	0.1	and the second s	0.0	
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$ au_{ au}$ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_{\mu}-2-\frac{lpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

The most accurate and precise scientific model in history

"Standard Model"

"Standard Model"

standard |'standərd| noun

1 a level of quality or attainment

"Standard Model"

standard |'standərd| model |'mädl| noun

1 a level of quality or attainment

noun

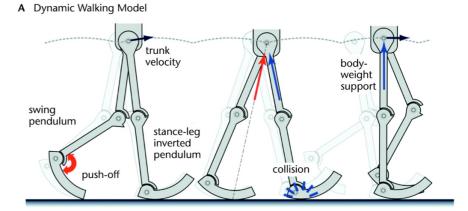
2 ... a simplified description, esp. a mathematical one, of a system or process, to assist calculations and predictions

what's embarrassing about the Standard Model?

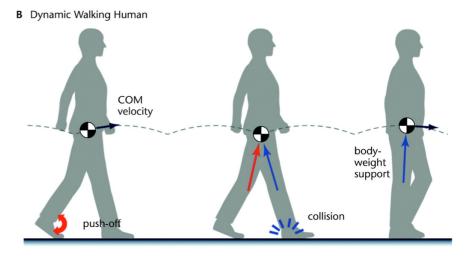


it's not a dynamical theory

SM as an effective theory



I can draw free-body diagrams and make a SM of walking

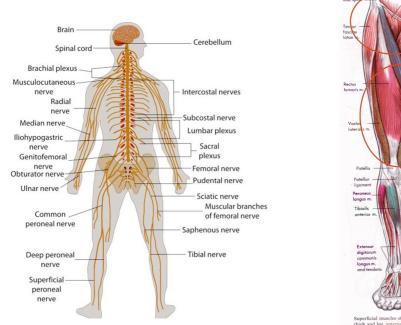


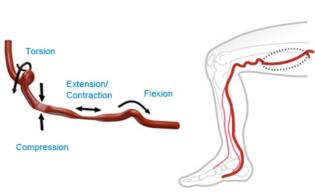
swing pendulum push-off

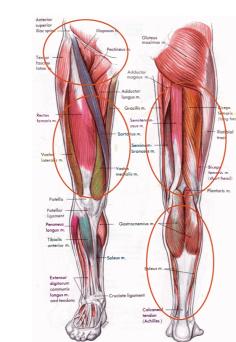
> bodyweight support

collision

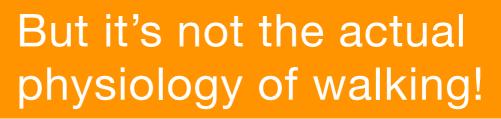
I can draw free-body diagrams and make a SM of walking







Superficial muscles of the right thigh and leg, posterior view.

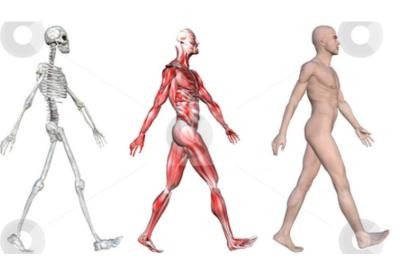


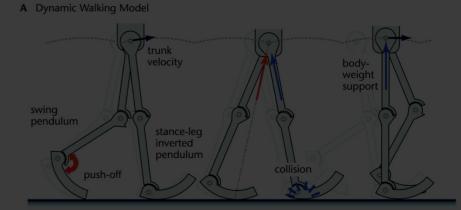
A Dynamic Walking Model

B Dynamic Walking Human

push

COM velocity



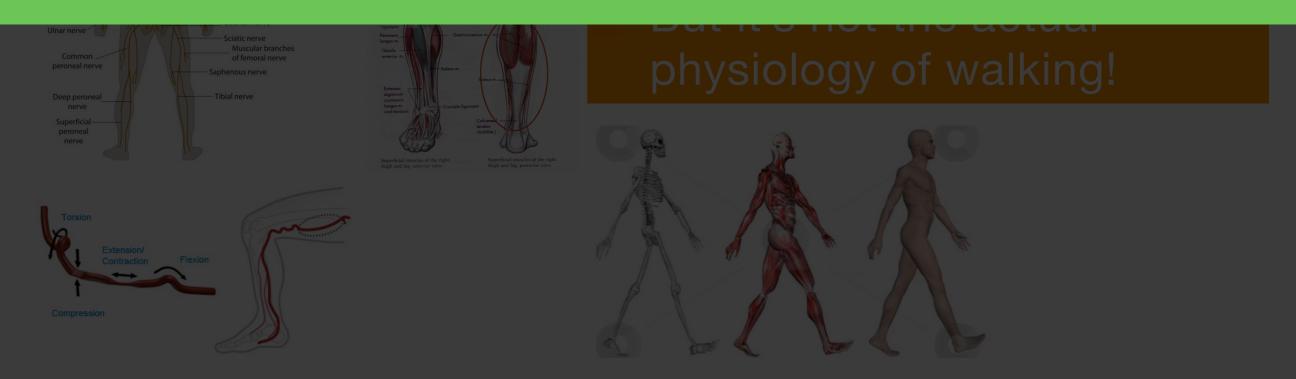


B Dynamic Walking Human

COM velocity

I can draw free-body diagrams and make a SM of walking

SM is an effective theory



what's confusing about the Standard Model?



2. Spontaneous Symmetry Breaking

the story of the Higgs Boson

How?



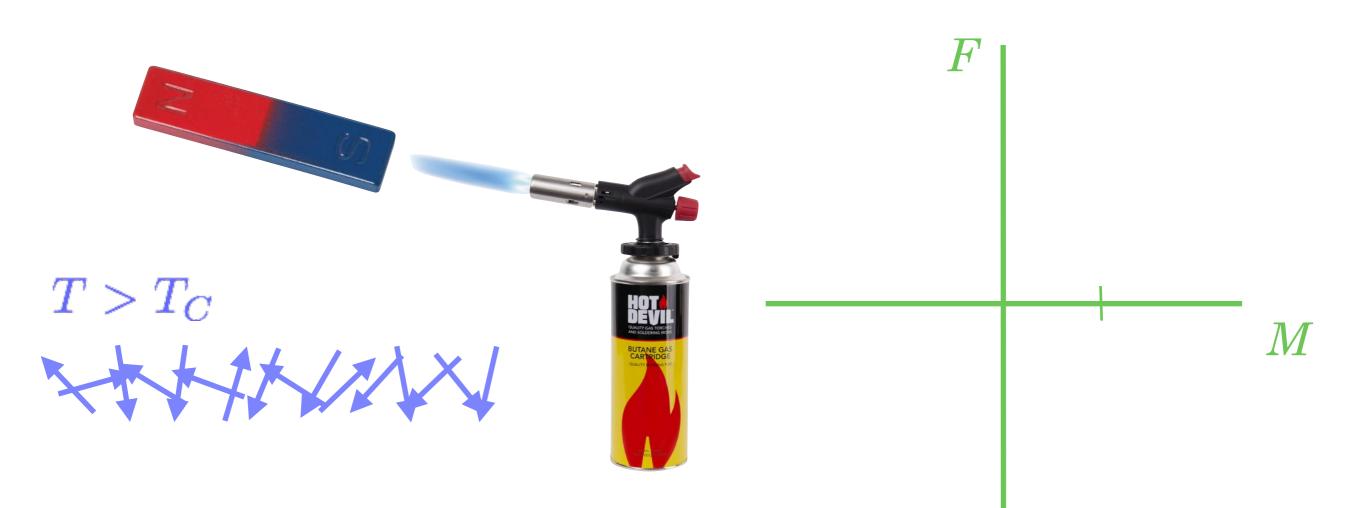
How? a meaningless operation?

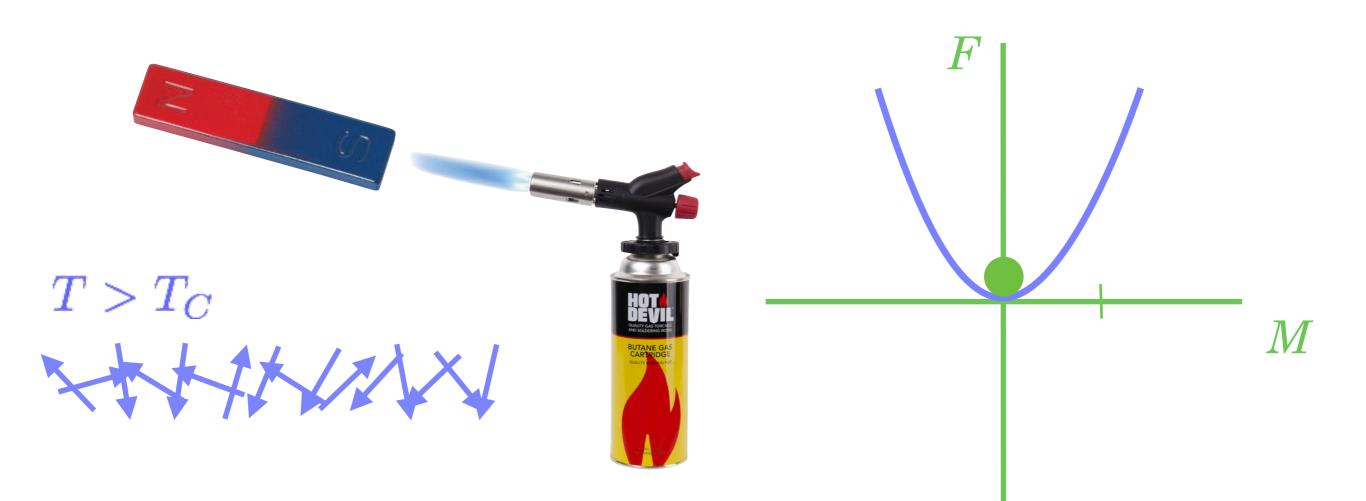
$\mathcal{L} =$ blah blah blah + μ^2 blah + blah blah blah blah

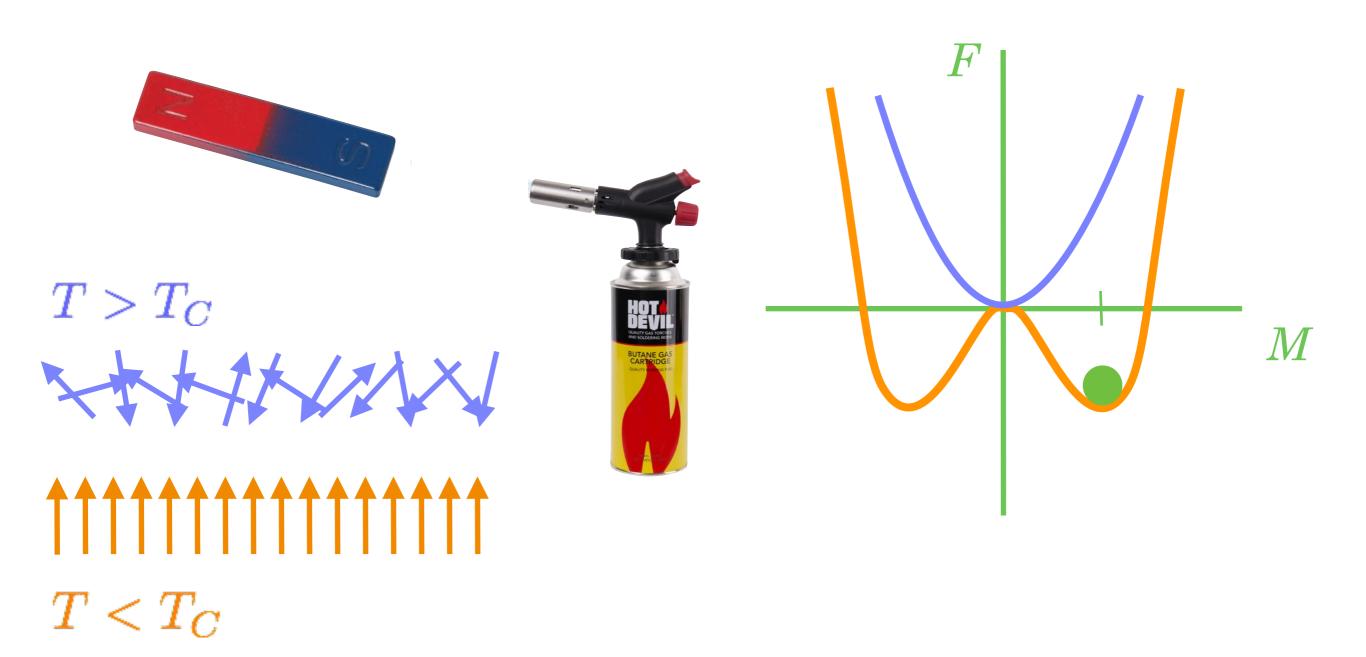
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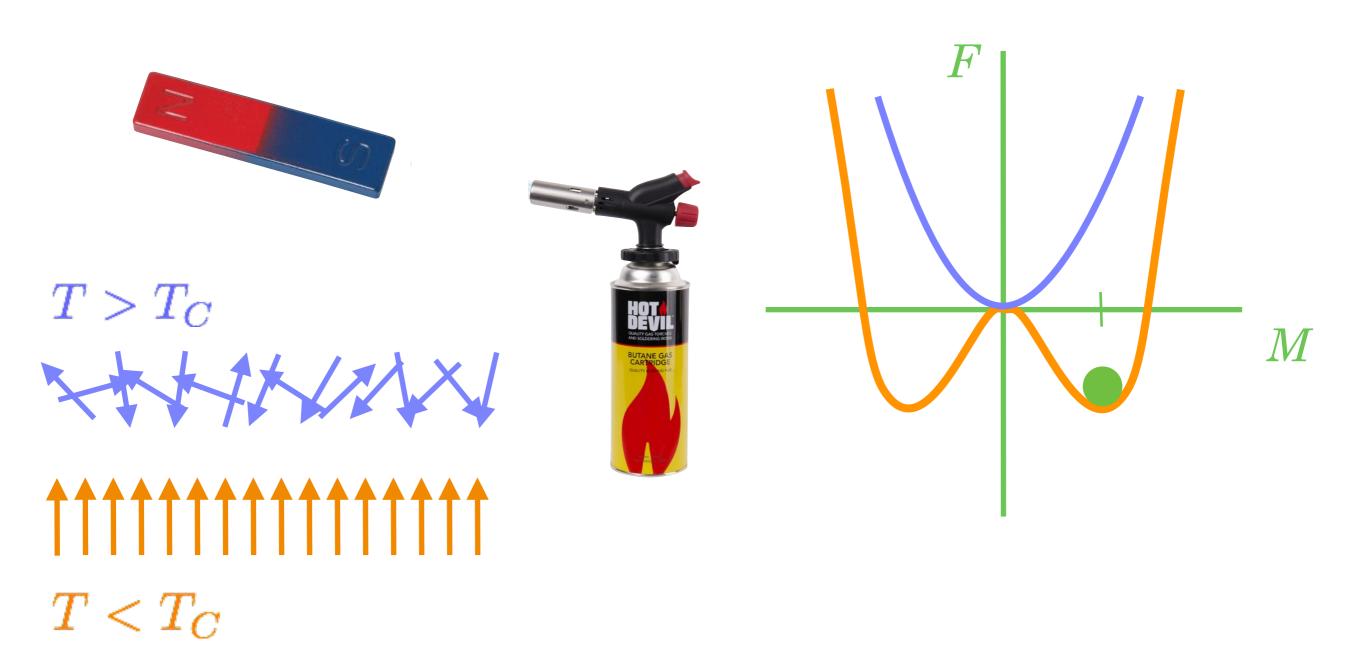






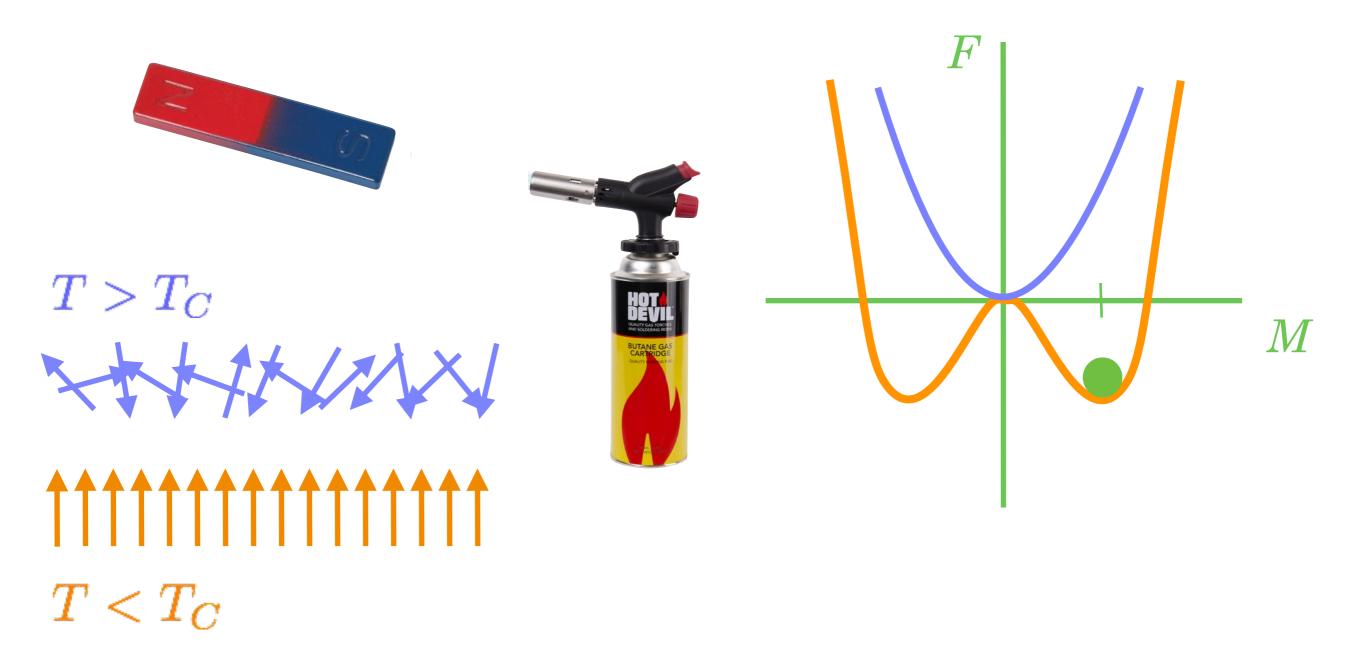






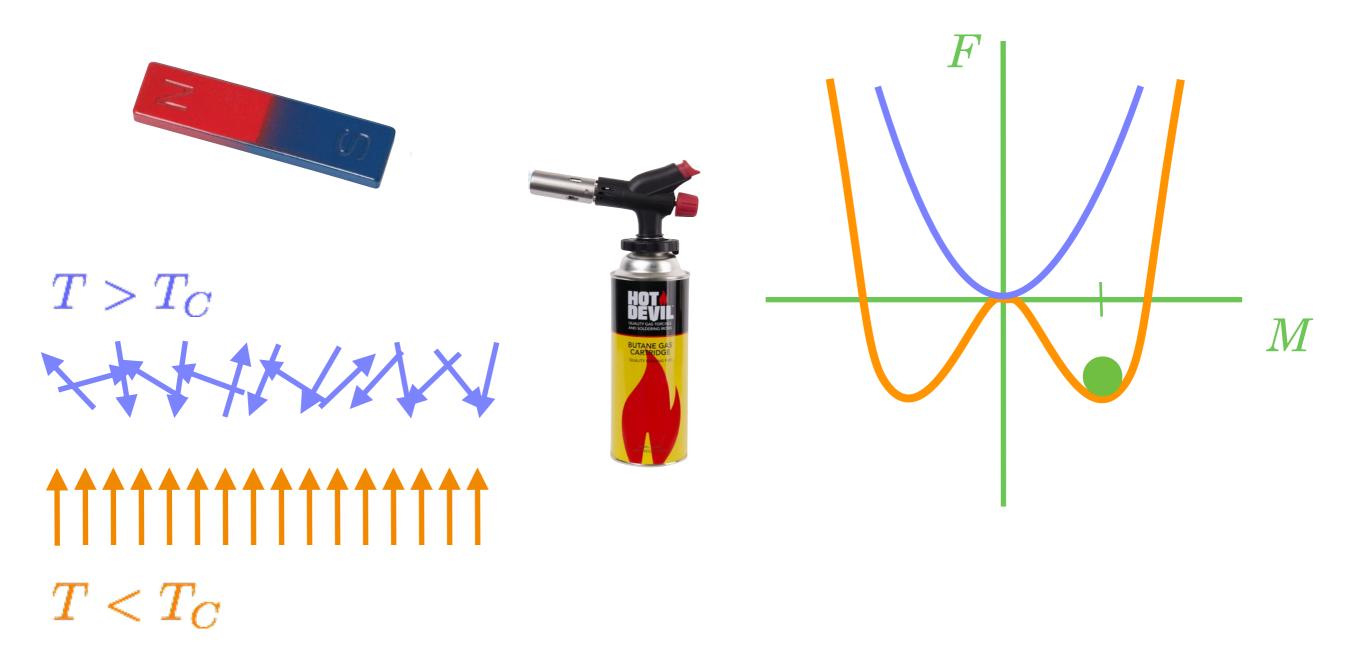


 $\mathcal{L} = \text{blah blah} + (T - T_C) \times \text{blah} + \text{blah blah blah}$





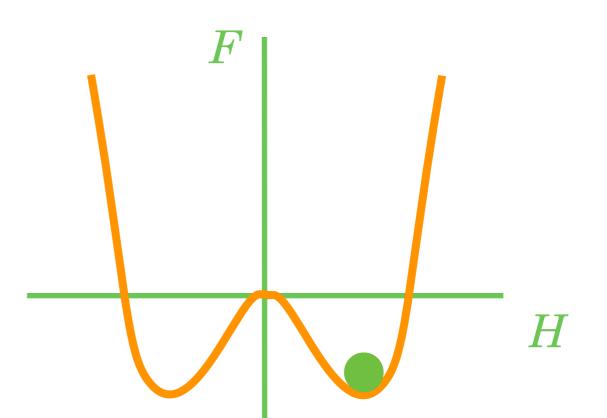
 $\mathcal{L} = \text{blah blah} + (T - T_C) \times \text{blah} + \text{blah blah blah}$



in the SM

We live in the broken symmetry world

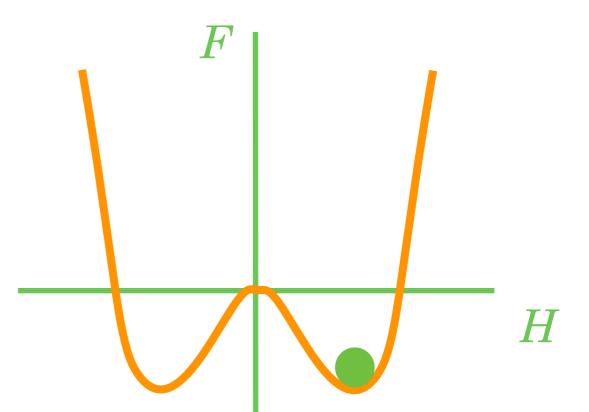
& trying to discover how



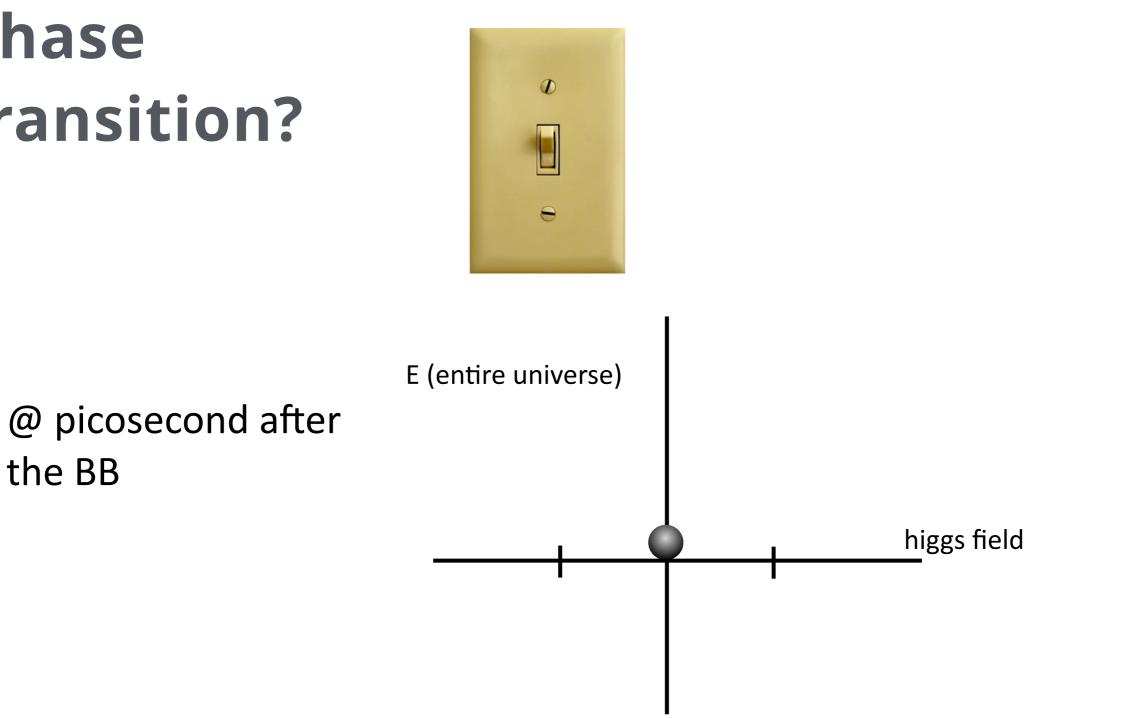
in the SM

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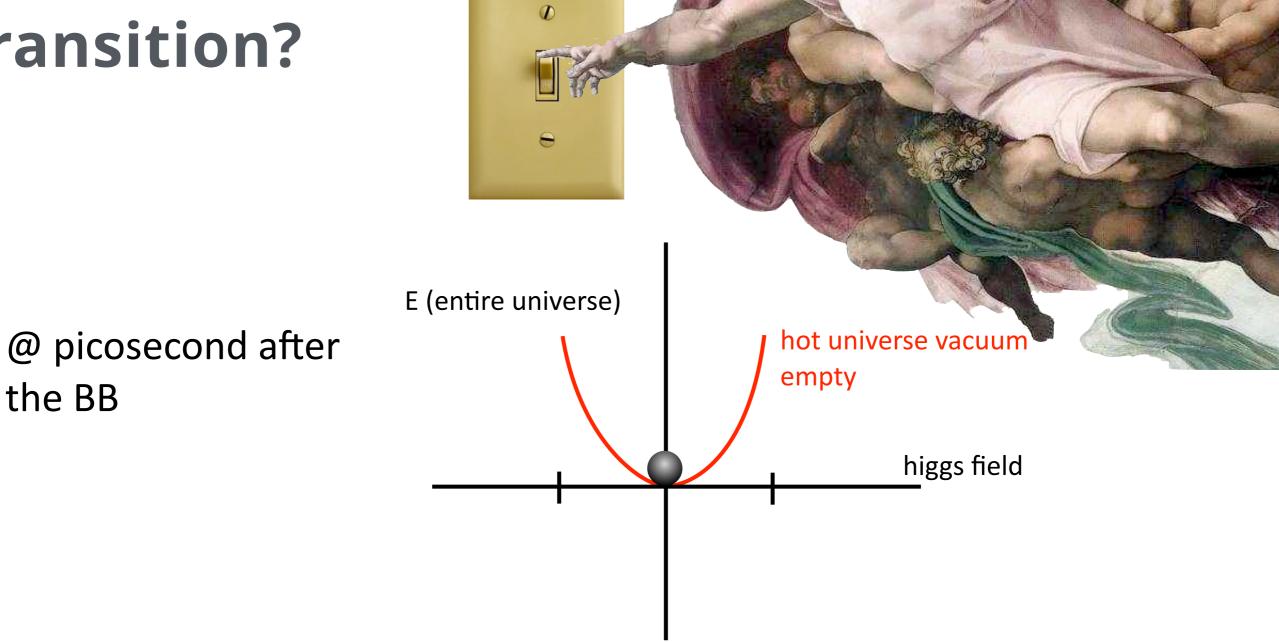
& trying to discover how

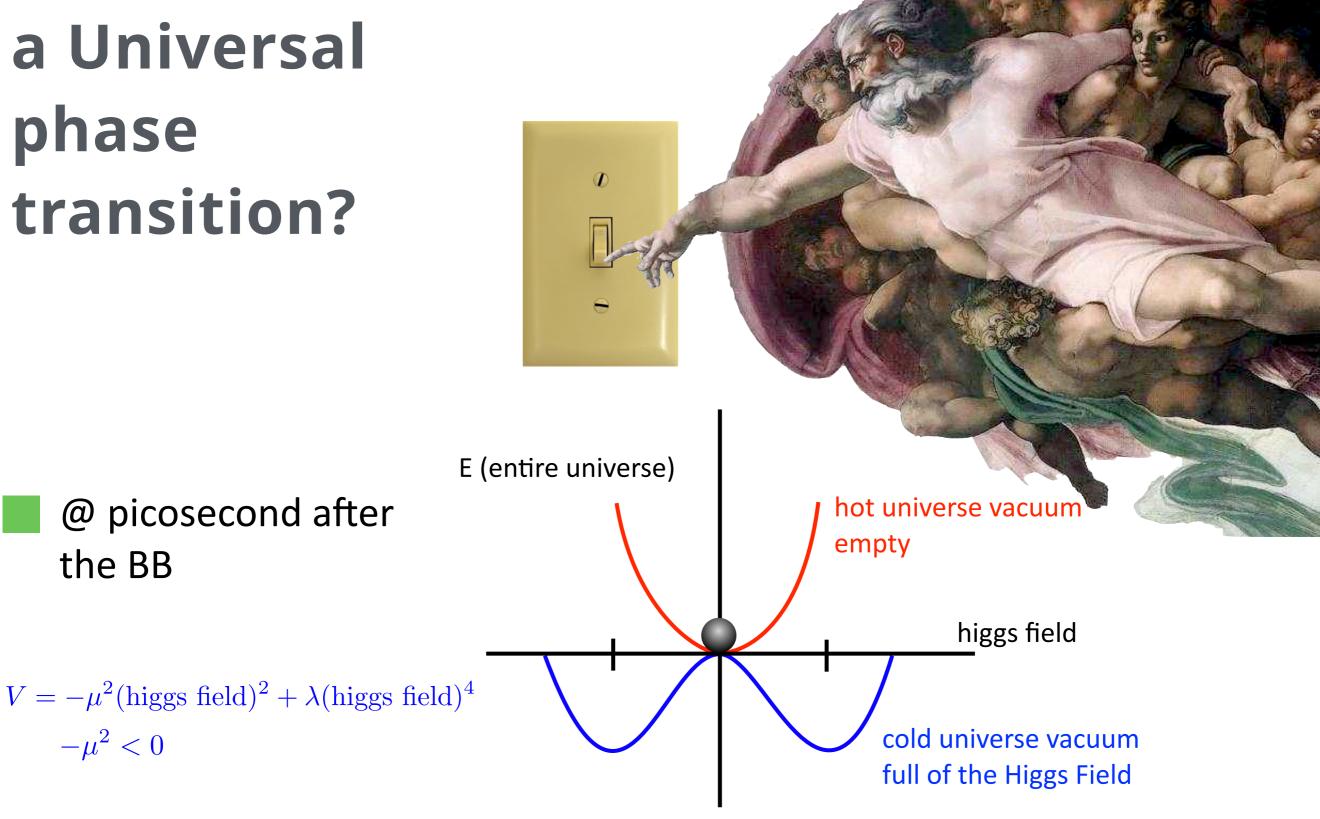


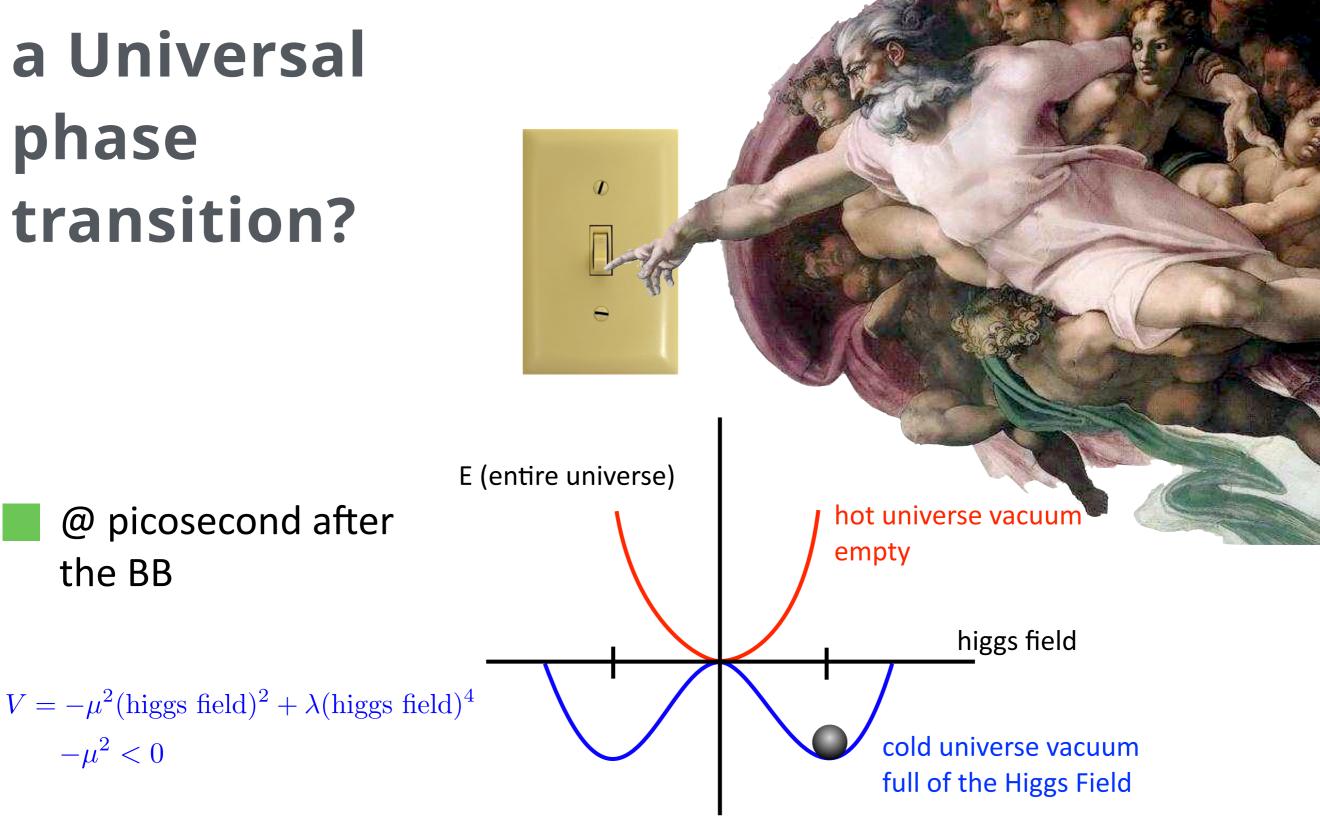
the BB

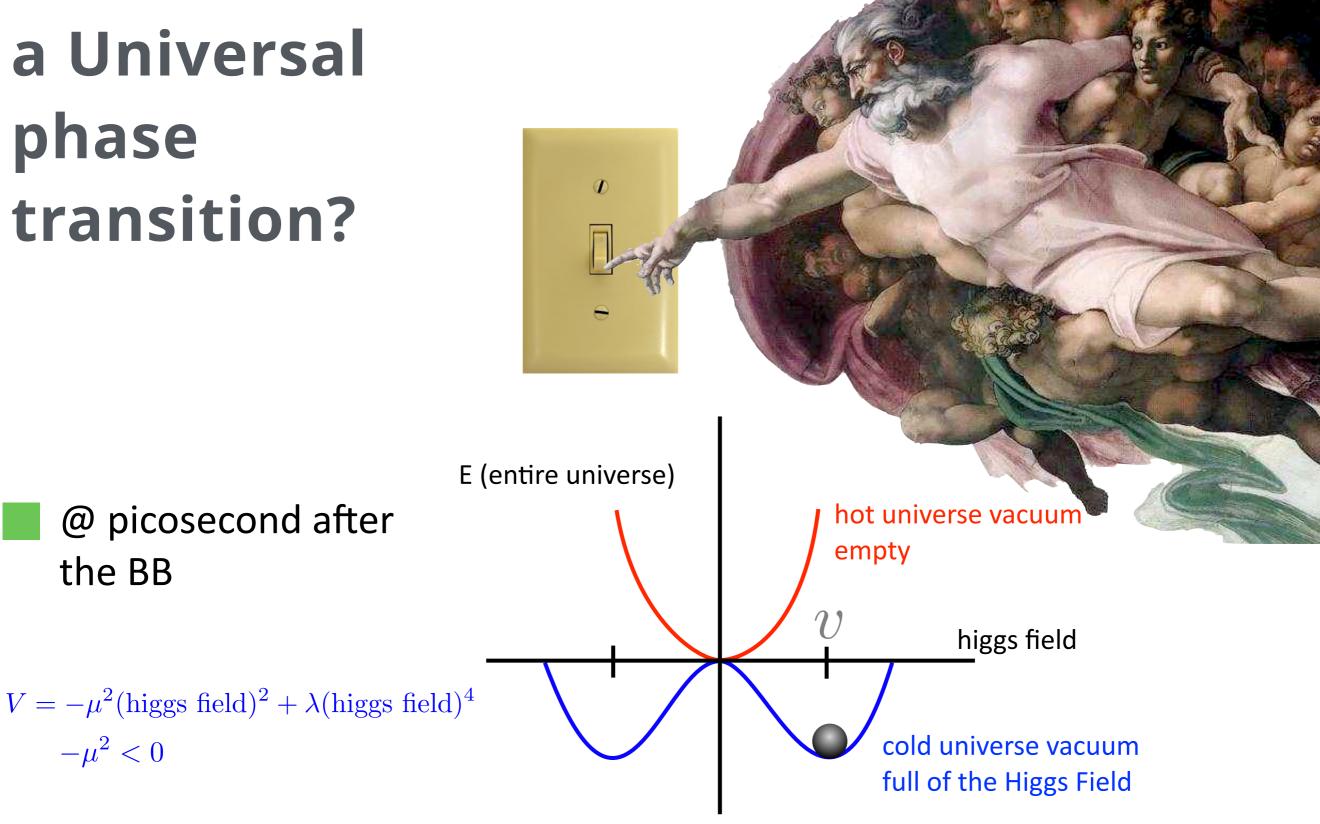


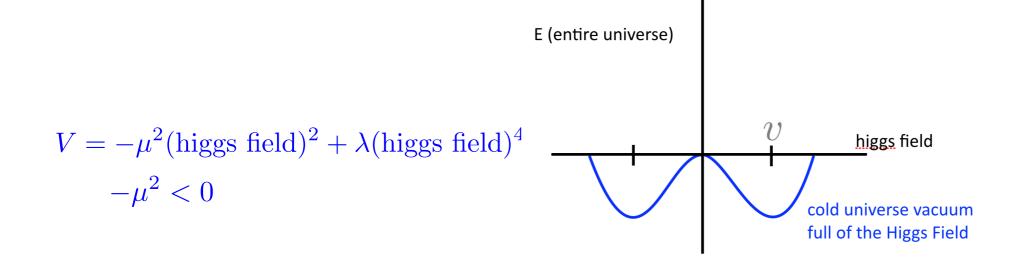
the BB

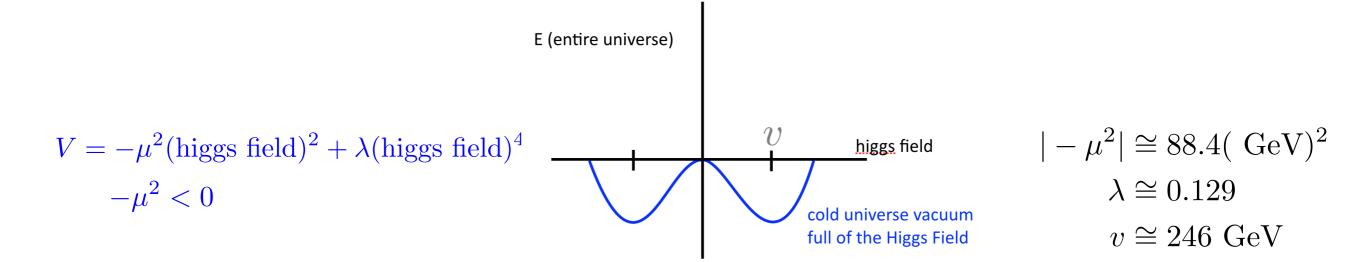














v = 246 GeV...it's <u>on</u>.



0 a^0 0 B^0 + \\\\\\ B^+ - ~~~~~ *B*- ϕ ϕ^*

 $t = 10^{-12} s$ $t = 10^{+18} s$

*a*⁰ 0**WW**

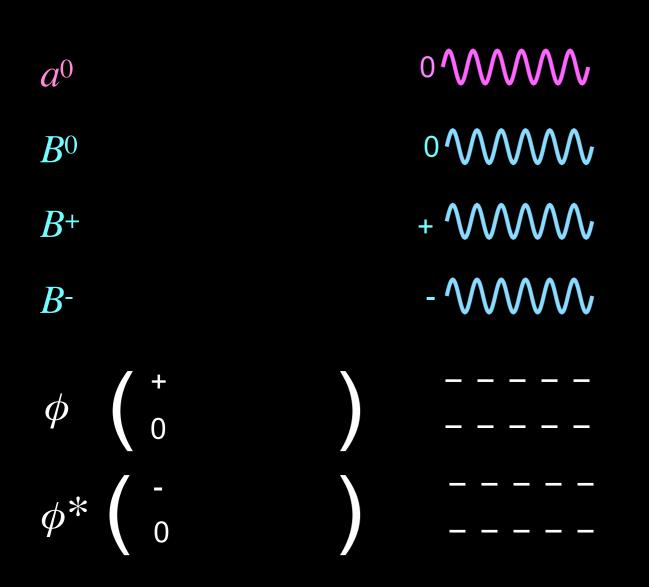
- *B*⁰ 0 **WW**
- *B*⁺ + WWW
- *B* - WWW

$$\phi \begin{pmatrix} + - - - - - \\ 0 - - - - \end{pmatrix}$$

$$\phi^* \begin{pmatrix} - - - - - \\ 0 - - - - \end{pmatrix}$$

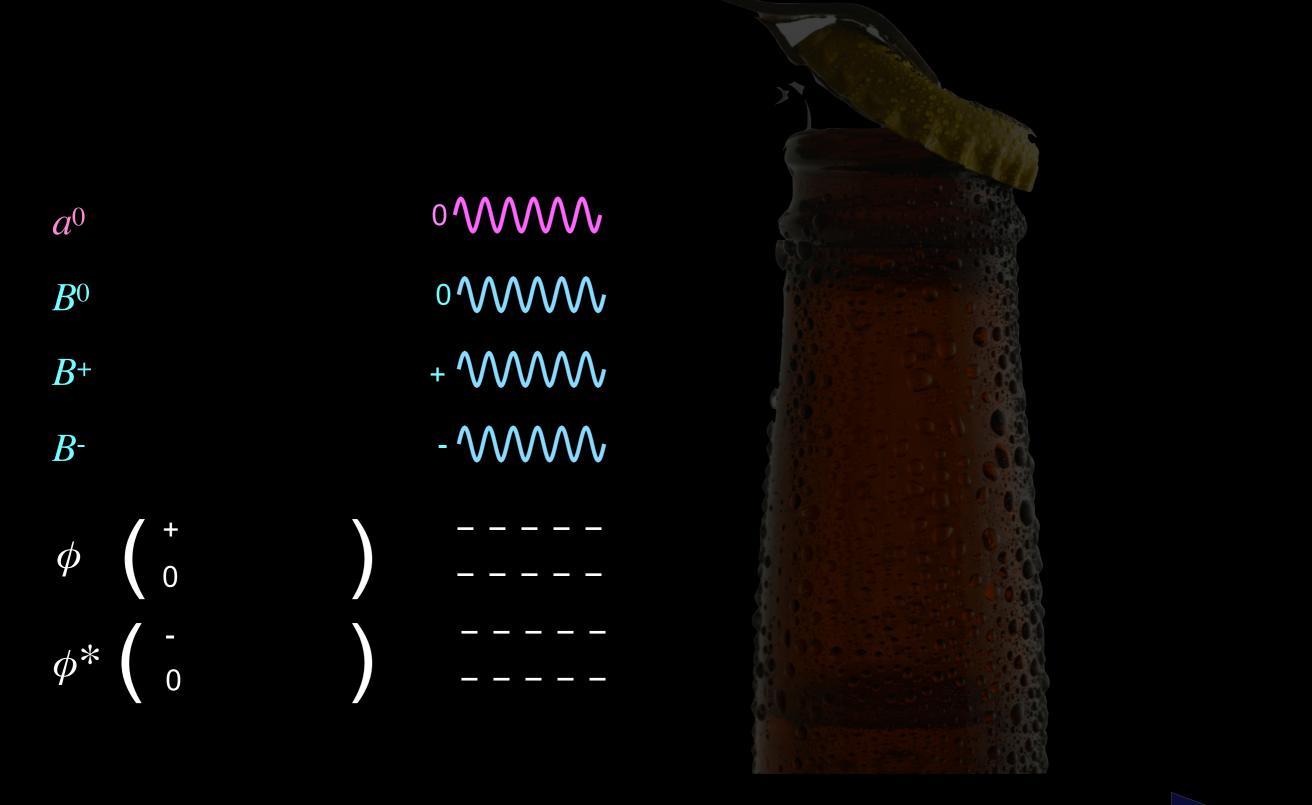
t = the beginning 0 s

$t = 10^{-12} s$ $t = 10^{+18} s$

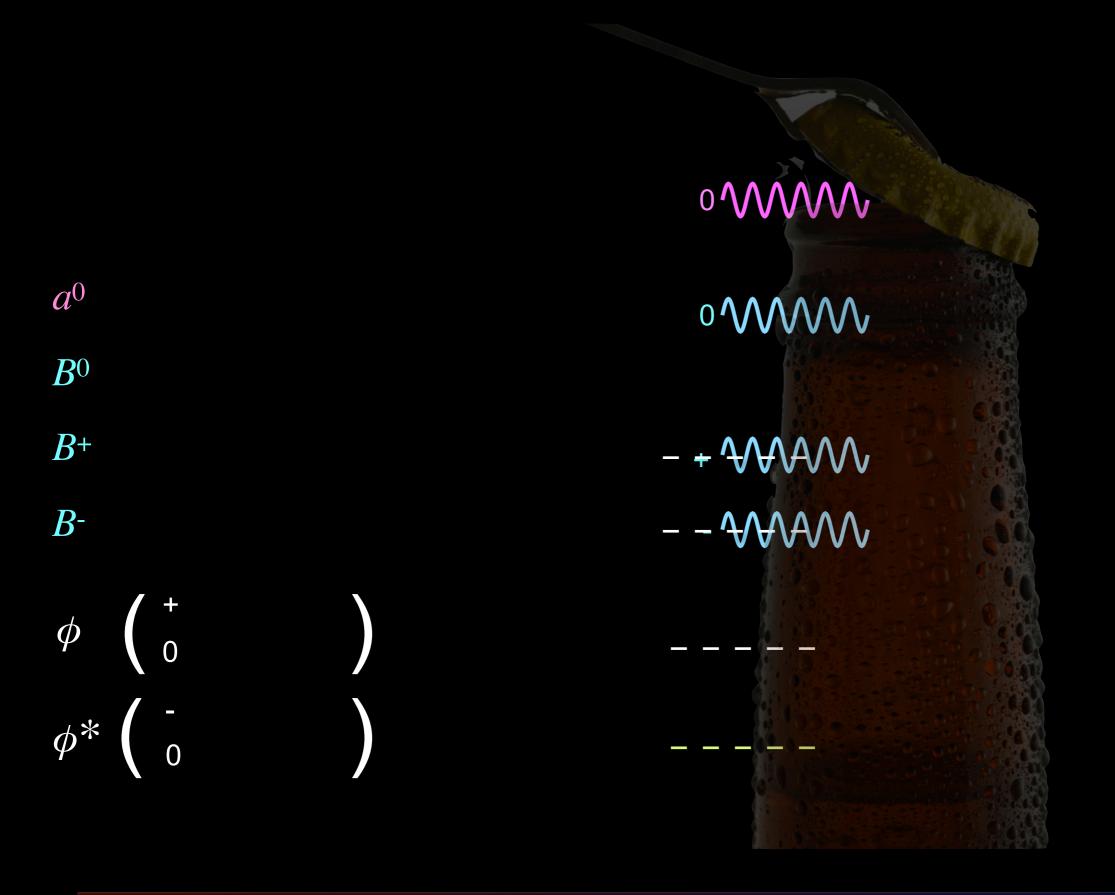


$t = 10^{-12} s$ $t = 10^{+18} s$

t = the beginning 0 s

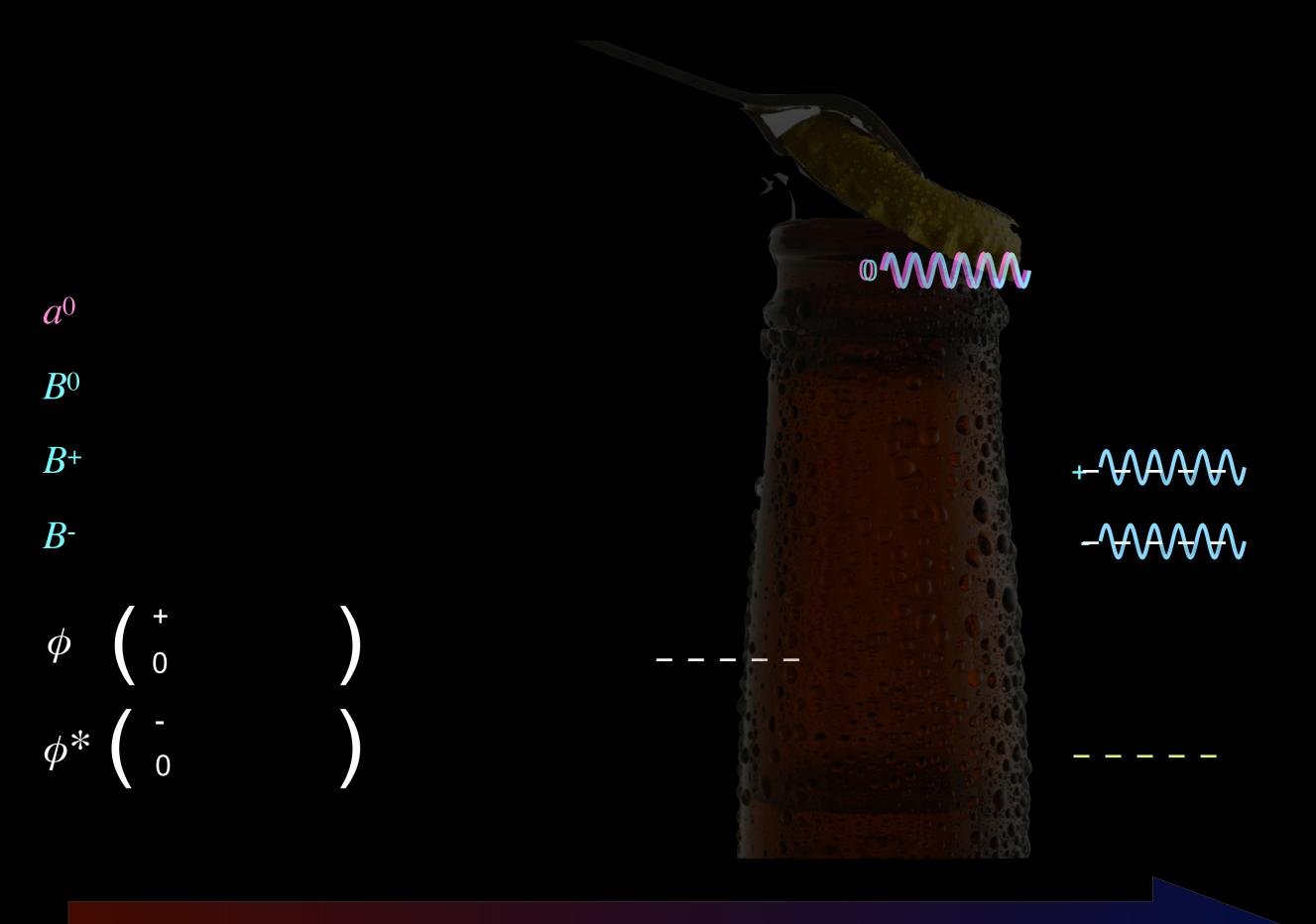


 $t = 10^{-12} s$ $t = 10^{+18} s$



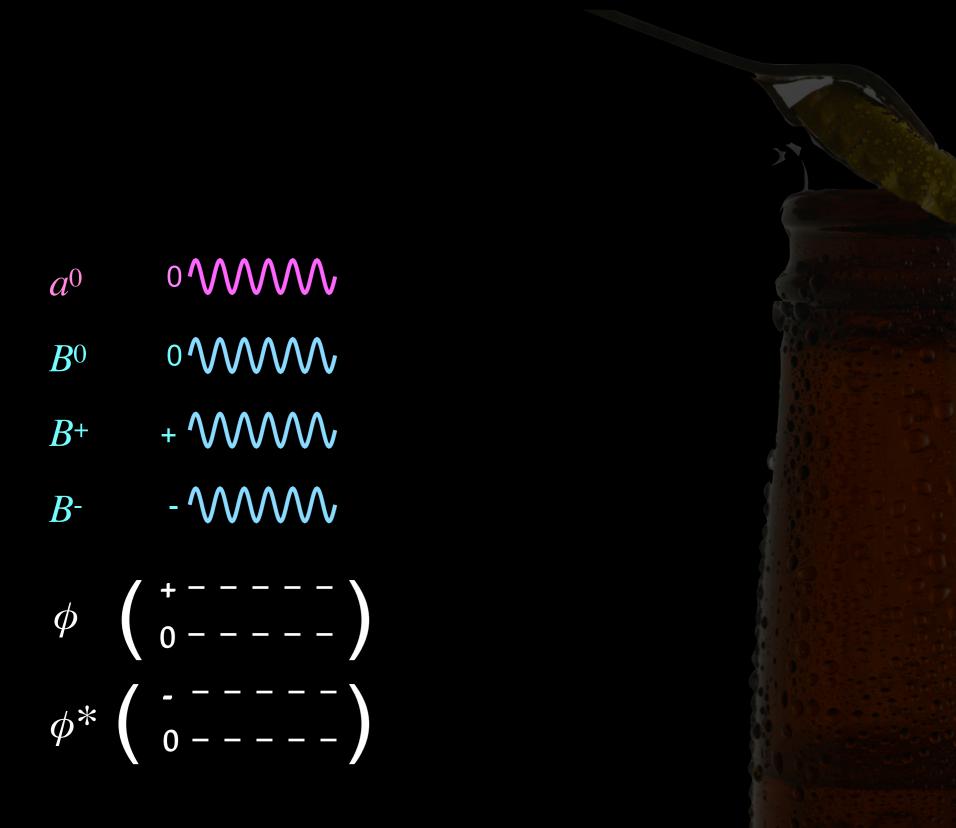
 $t = 10^{-12} s$ $t = 10^{-12} s$

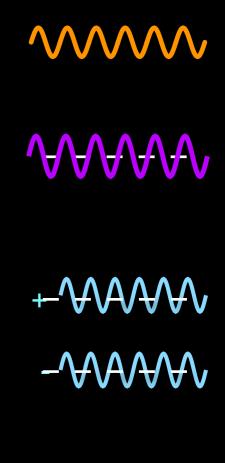
 $t = 10^{+18}s$



 $t = 10^{-12} s$

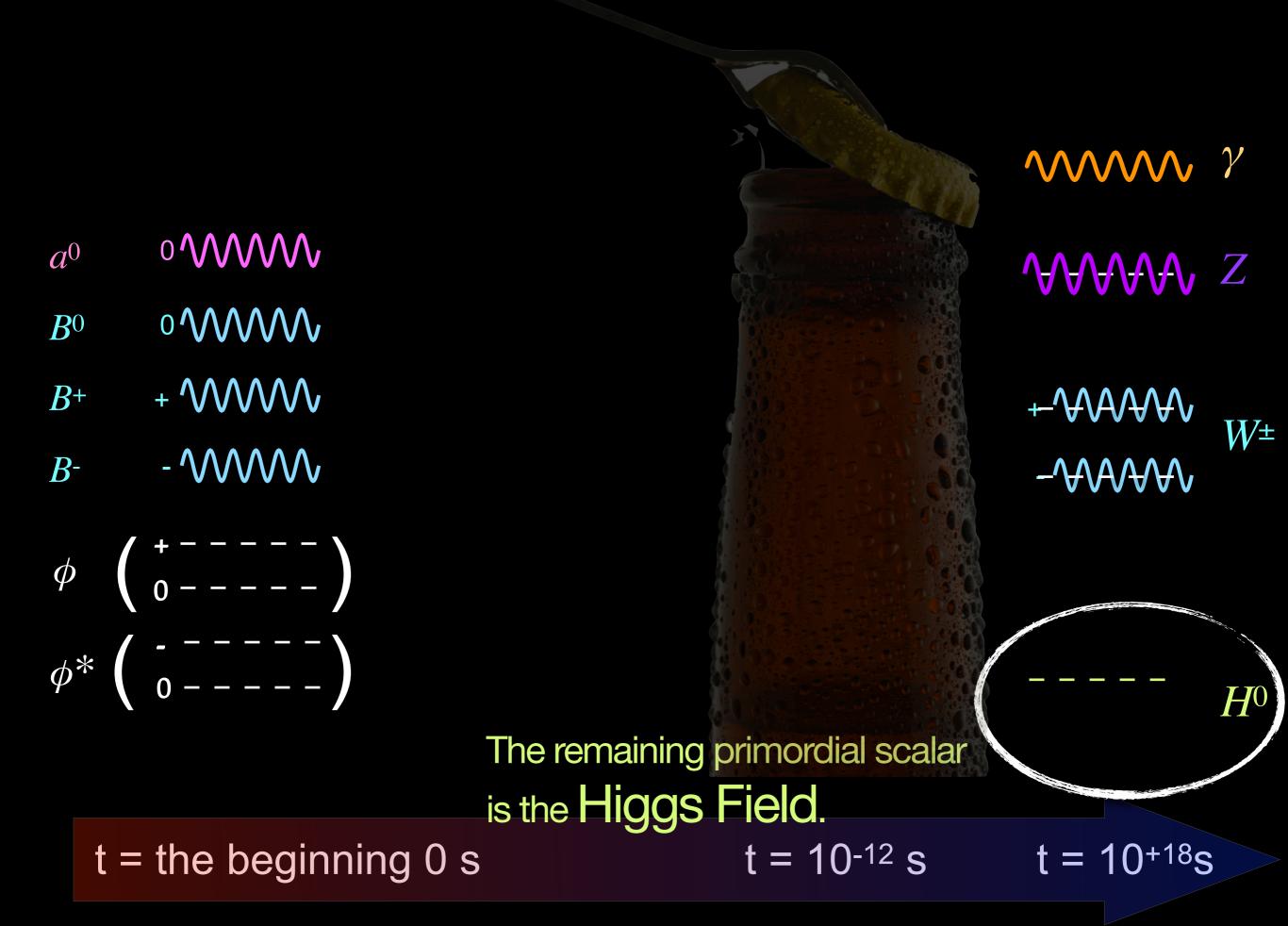
 $t = 10^{+18}s$





 $t = 10^{-12} s$

 $t = 10^{+18}s$



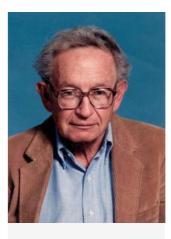
The Standard Model ingredients:

The Gauge Principle circa 1918, 1954 demand of a symmetry

Spontaneous
 Symmetry Breaking
 circa 1950, 1964
 effective theory of
 phase transitions

The Standard Model ingredients:

Sportango Principle Symmetry Breaking Circa 1918, 1954 circa 1950, 1964 demand of a symmetry effective theory of phase transitions



Anderson

The Standard Model ingredients:



Higgs Kibble

Guralnik Hagen Englert Brout

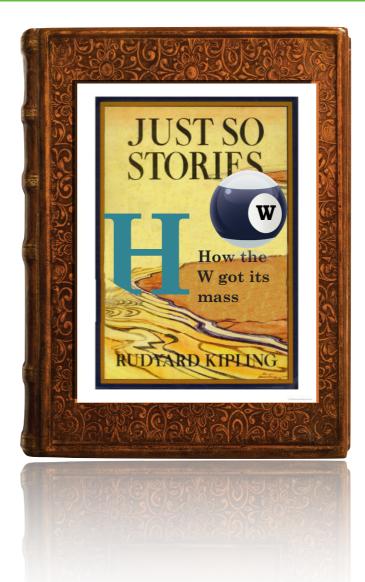


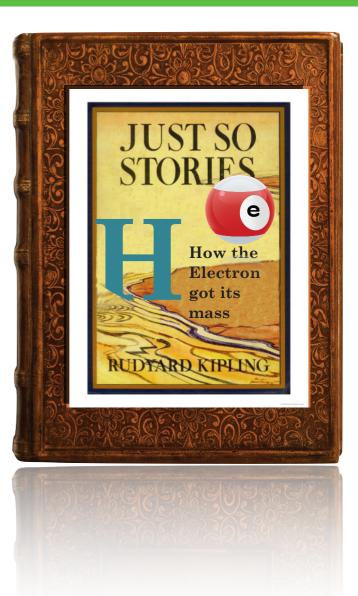
Weinberg Salam Glashow

what's exciting about the Standard Model?



its historical significance & Higgs Field



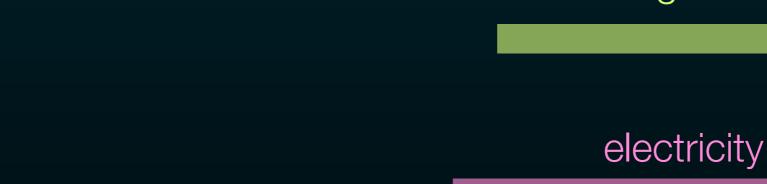


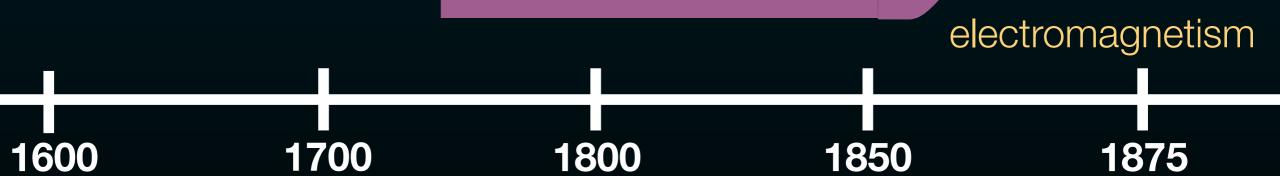
Galilean mechanics

Newtonian gravity

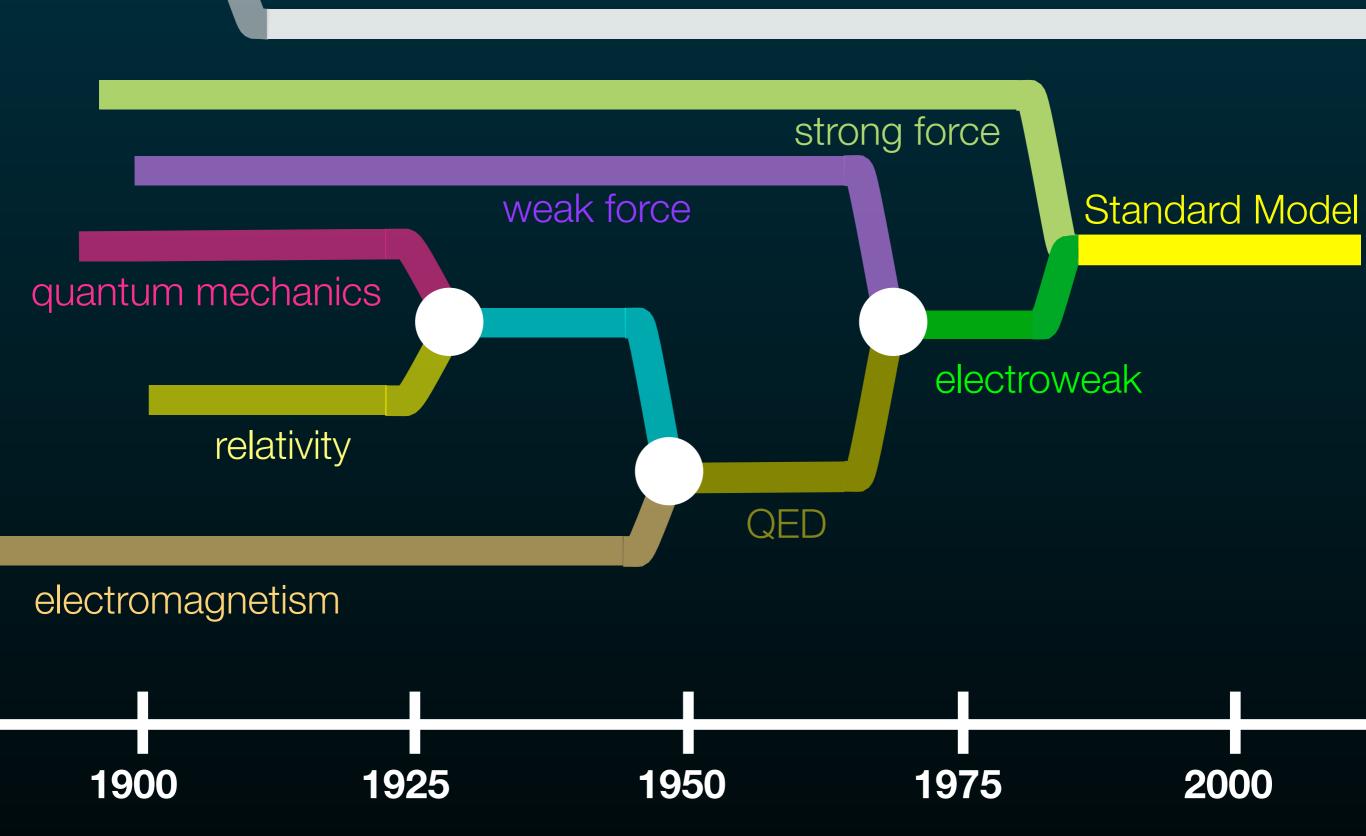
Copernicus/Kepler astronomy

magnetism





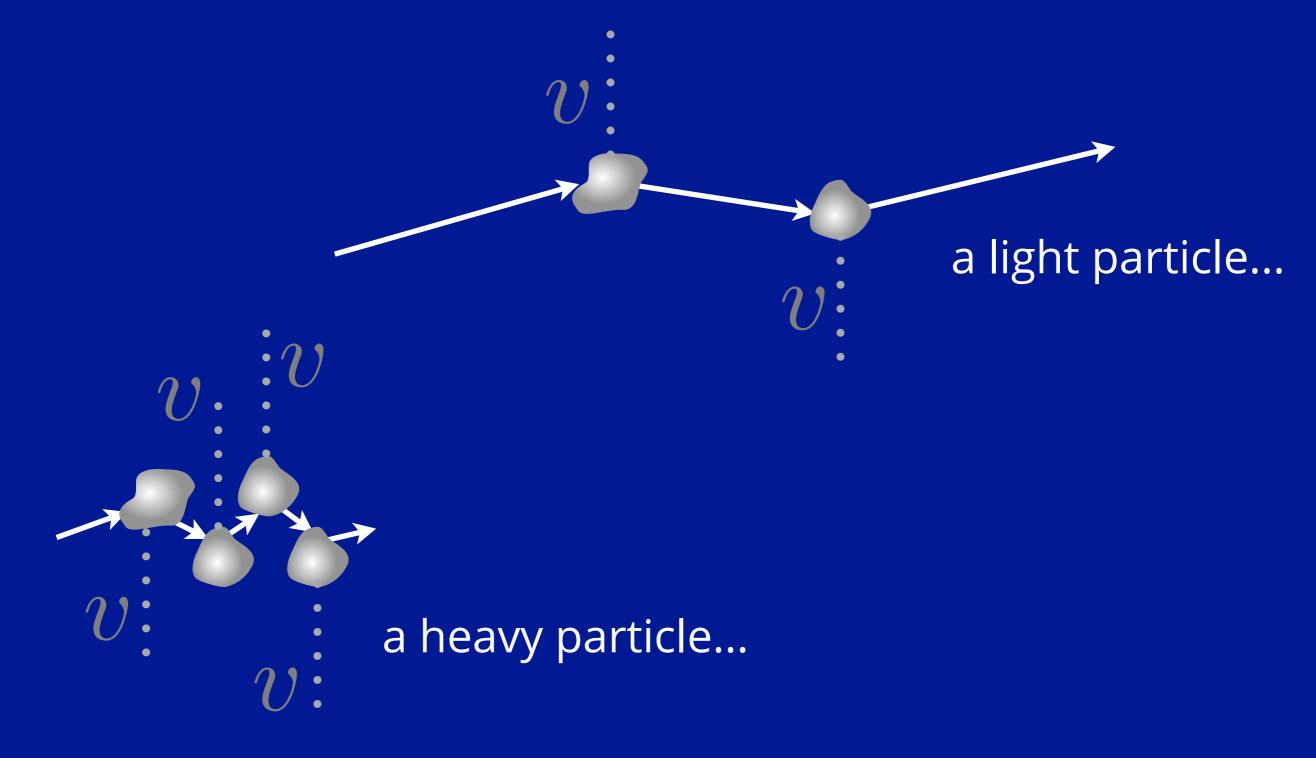
General Relativity



The job of the Higgs **Field** is special.

field generates mass

of the charged fermions

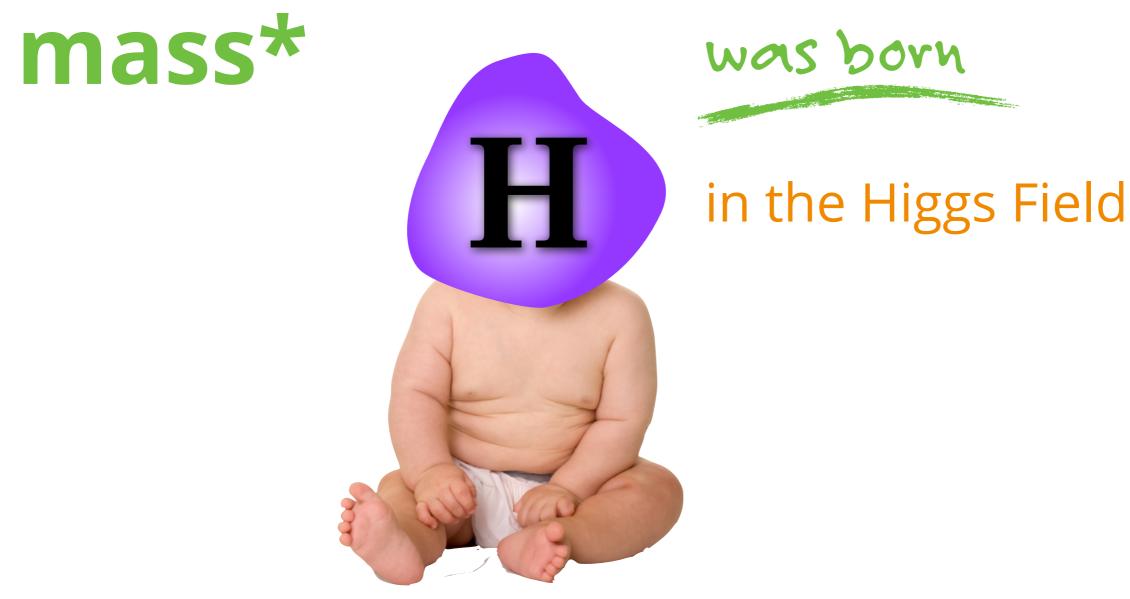








*<u>charged fermions</u> and W/Z!



*<u>charged fermions</u> and W/Z!

what's challenging about the Standard Model?



all things Higgs

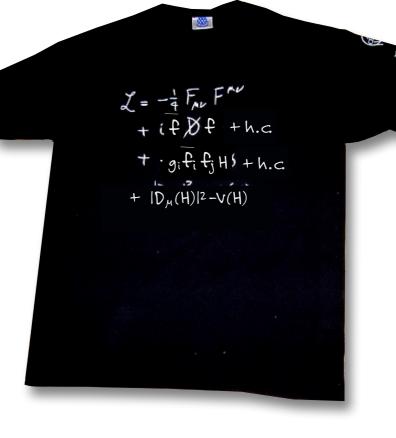




0+ Higgs Boson is not your father's particle!

Higgs Field piece:

 $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \underset{W^{\pm}, Z^{0}, \gamma}{\overset{W^{\pm}, Z^{0}, \gamma}}{\overset{W^{\pm}, Z^{0}, \gamma}}{\overset{W^{0}, Z^{0}, \gamma}}{\overset{W^{0}, Z^{0}, Z^{0}, \gamma}}{\overset{W^{0}, Z^{0}, Z^{0}, \gamma}}{$



8 **Higgs Field piece:** Z= -== FAL FAL + (f))f + h.c. $+ \cdot g_i f_i f_j H_{\beta} + h.c.$ "Unfolds" rather neatly + $|D_{\mu}(H)|^2 - V(H)$ W^{\pm}, Z^0, γ $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \underset{W^{\pm}, Z^{0}, \gamma}{\overset{\mathcal{N}}{\longrightarrow}}$

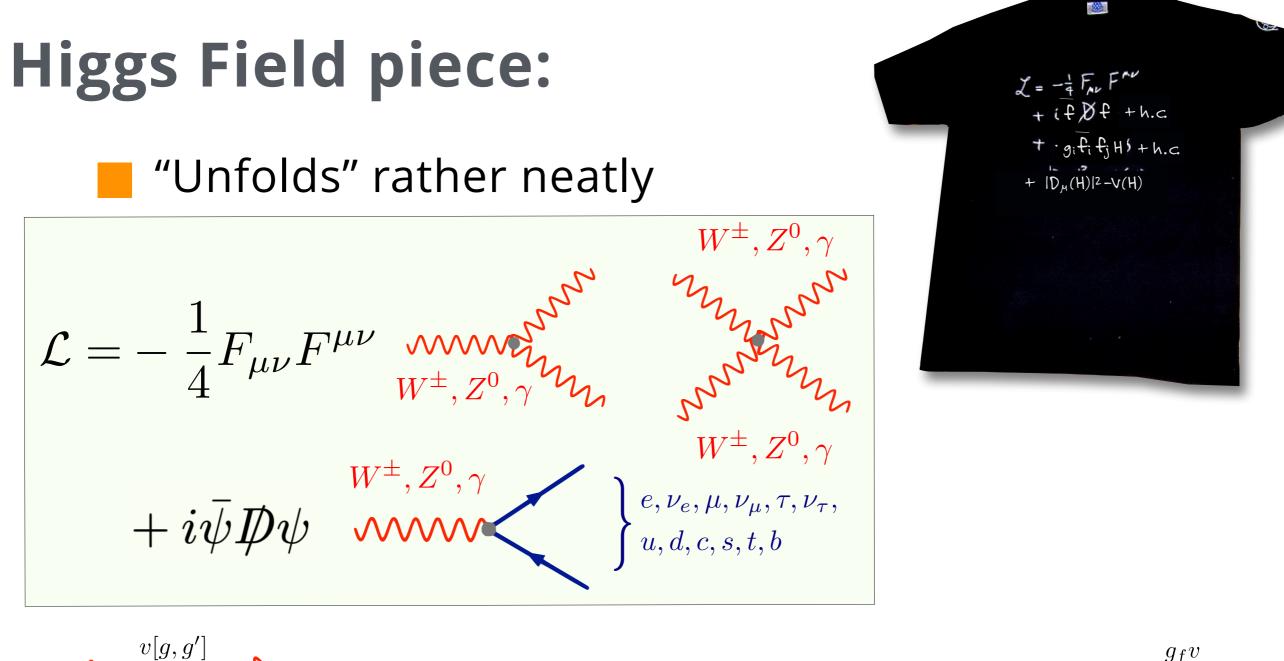
$$+|D_{\mu}H|^2 - \lambda v^2 H^2 + \lambda v H^3 - \frac{\lambda}{4}H^4 + g_i \bar{f}_{Li} f_{Ri}H$$

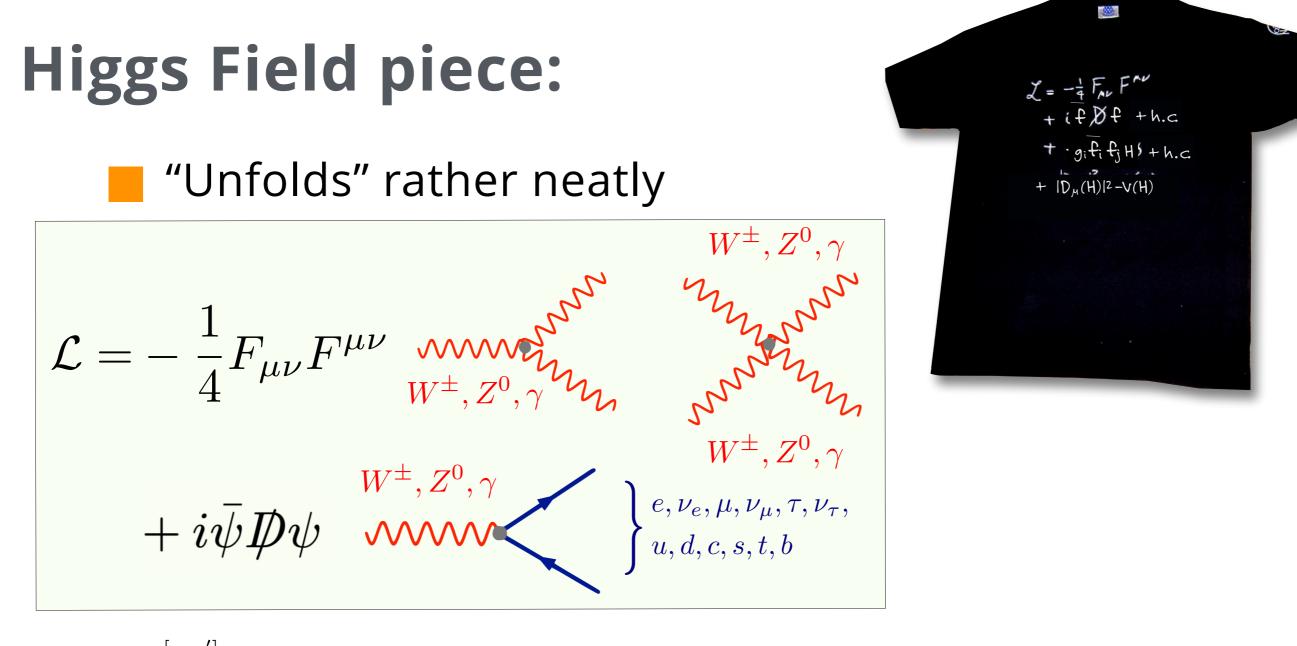
8 **Higgs Field piece:** Z= -== FAL FAL + if Øf + h.c. $+ \cdot g_i f_i f_j H_{\beta} + h.c.$ "Unfolds" rather neatly + $|D_{\mu}(H)|^{2} - V(H)$ W^{\pm}, Z^0, γ $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \underset{W^{\pm}, Z^{0}, \gamma}{\overset{\mathcal{N}}{\longrightarrow}} \mathcal{L}$

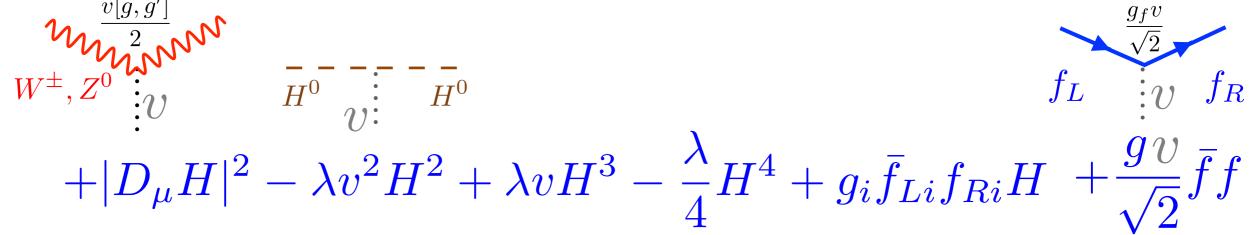
$$+|D_{\mu}H|^{2}-\lambda v^{2}H^{2}+\lambda vH^{3}-\frac{\lambda}{4}H^{4}+g_{i}\bar{f}_{Li}f_{Ri}H +\frac{gv}{\sqrt{2}}\bar{f}f$$

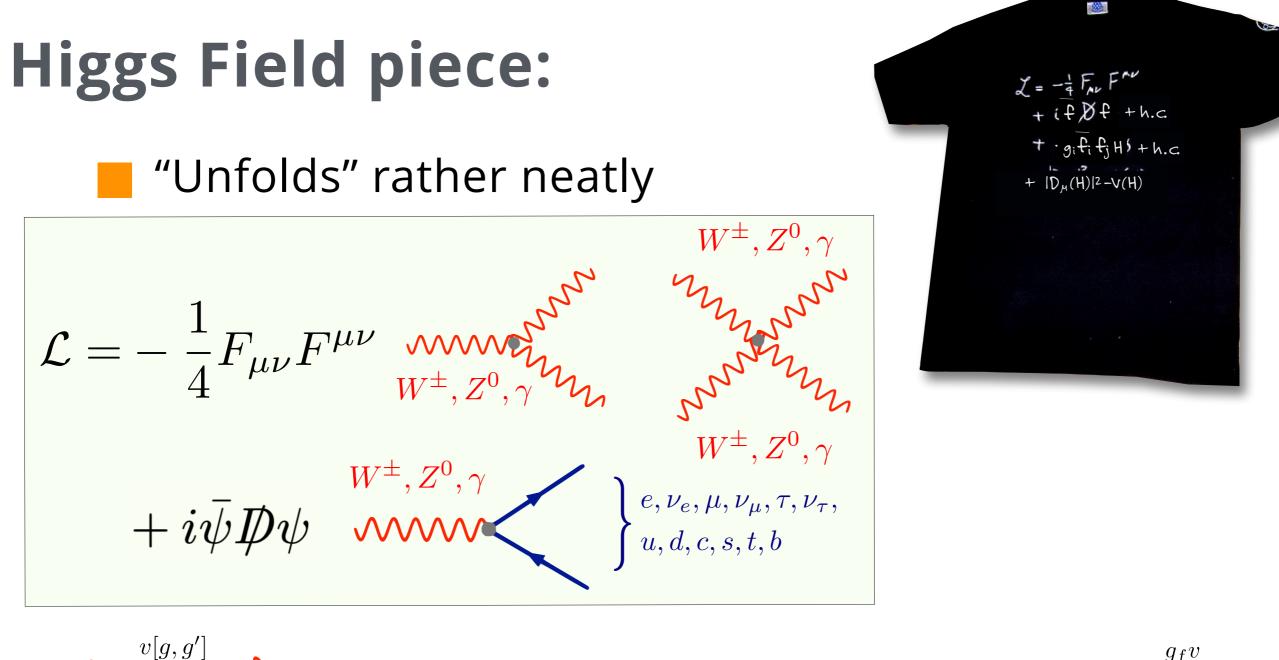
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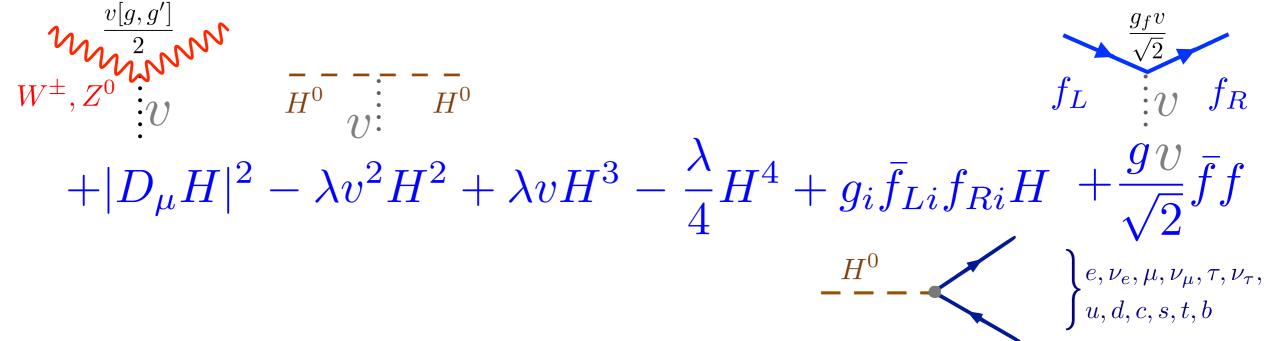
$$+|D_{\mu}H|^{2} - \lambda v^{2}H^{2} + \lambda vH^{3} - \frac{\lambda}{4}H^{4} + g_{i}\bar{f}_{Li}f_{Ri}H + \frac{gv}{\sqrt{2}}\bar{f}f$$

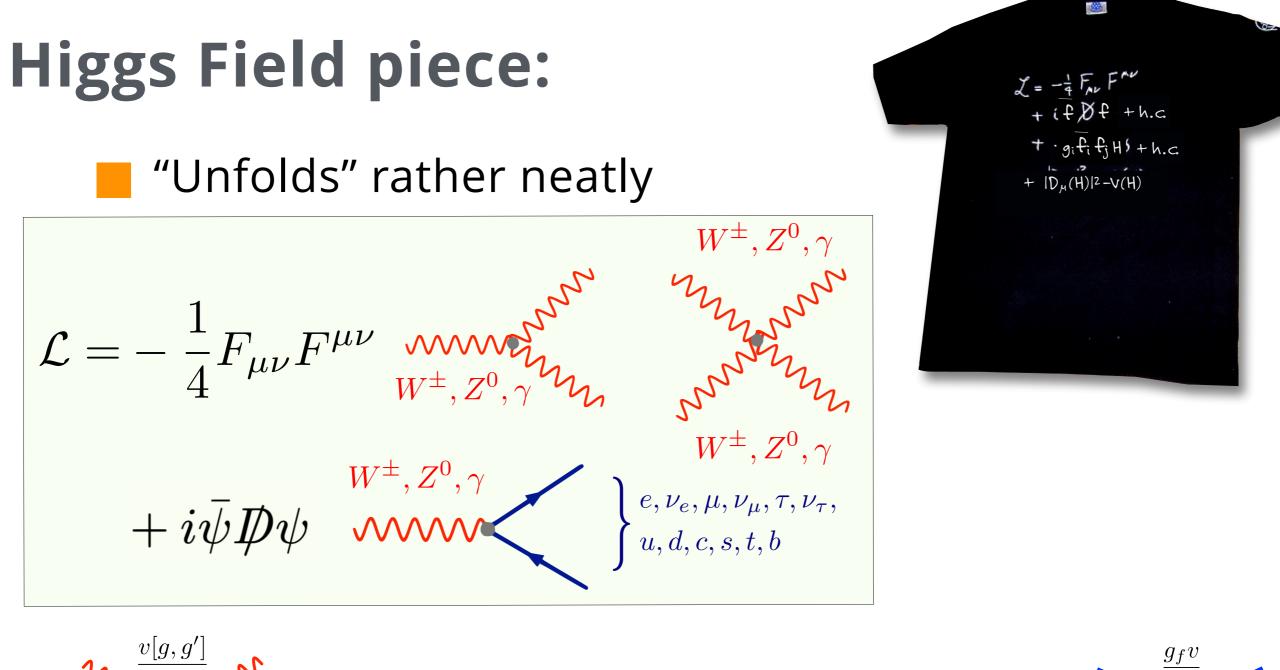


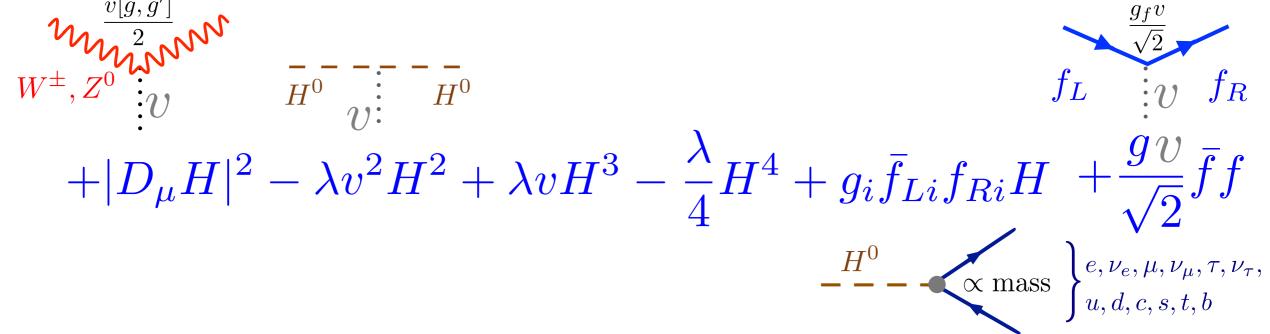


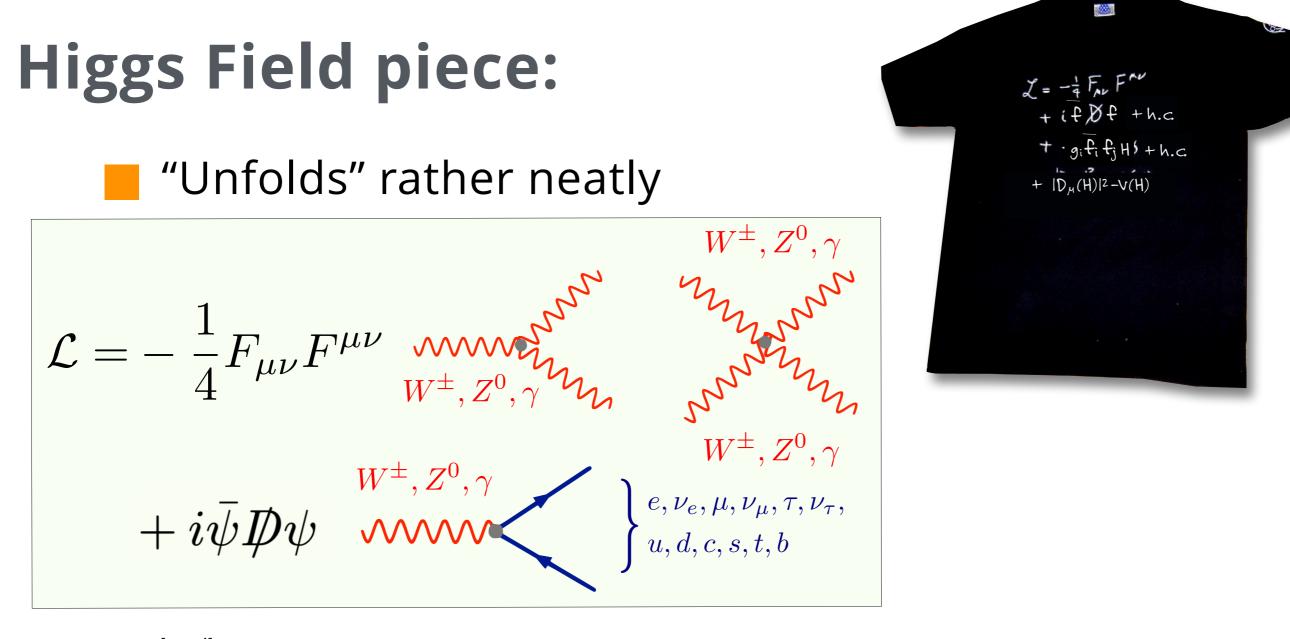


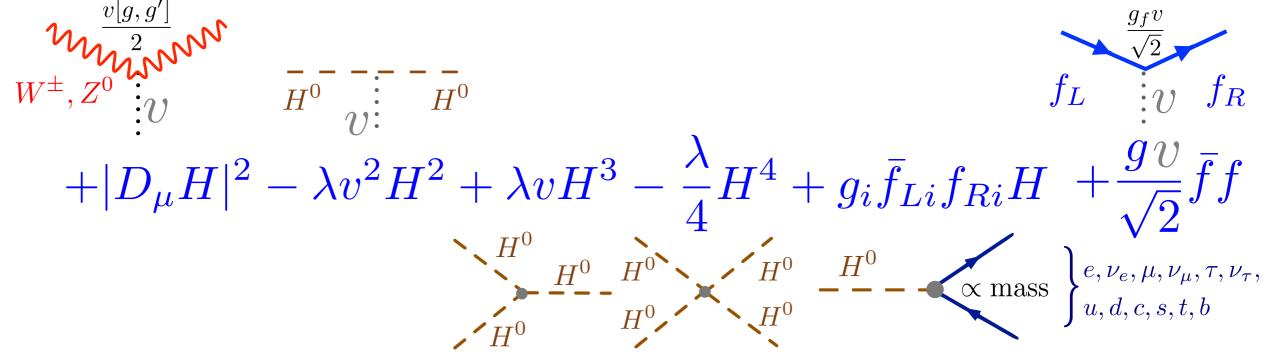


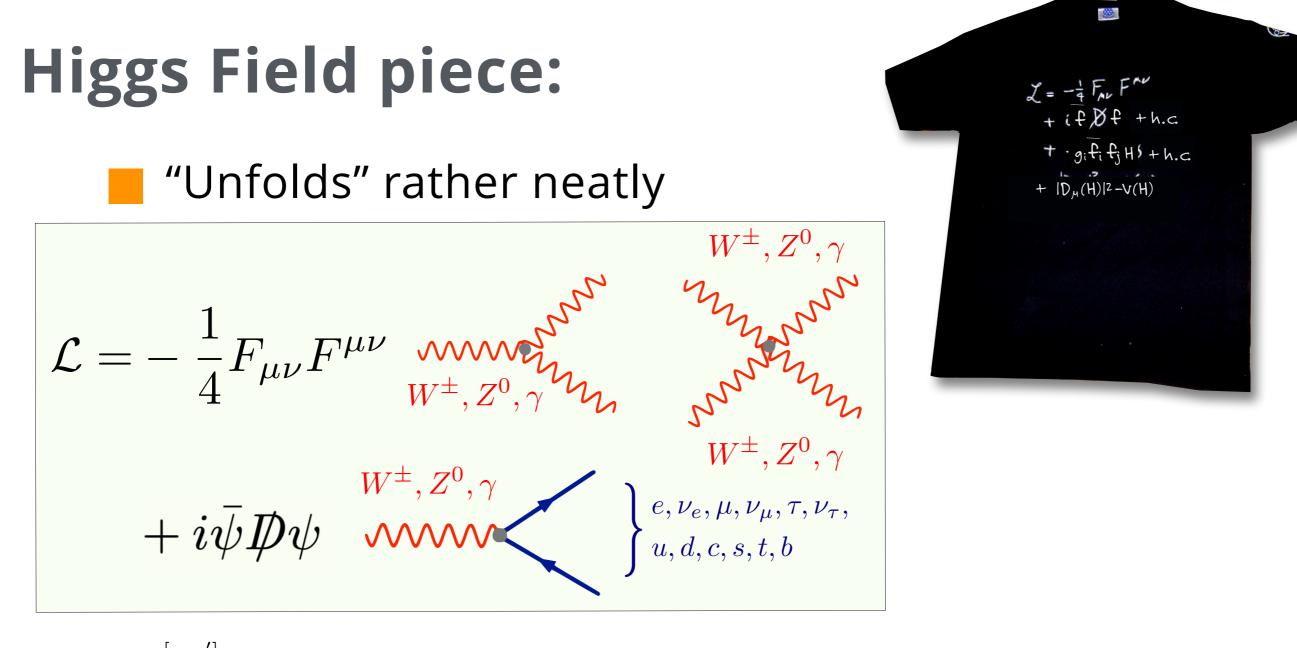


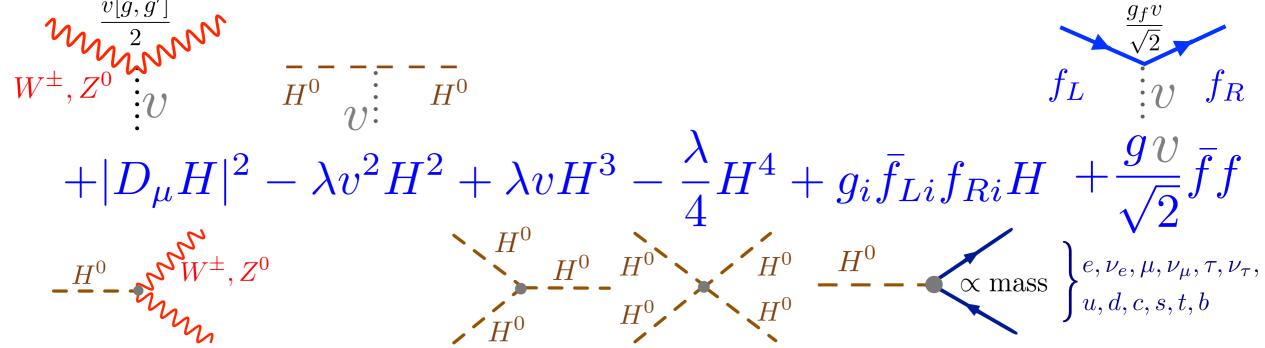










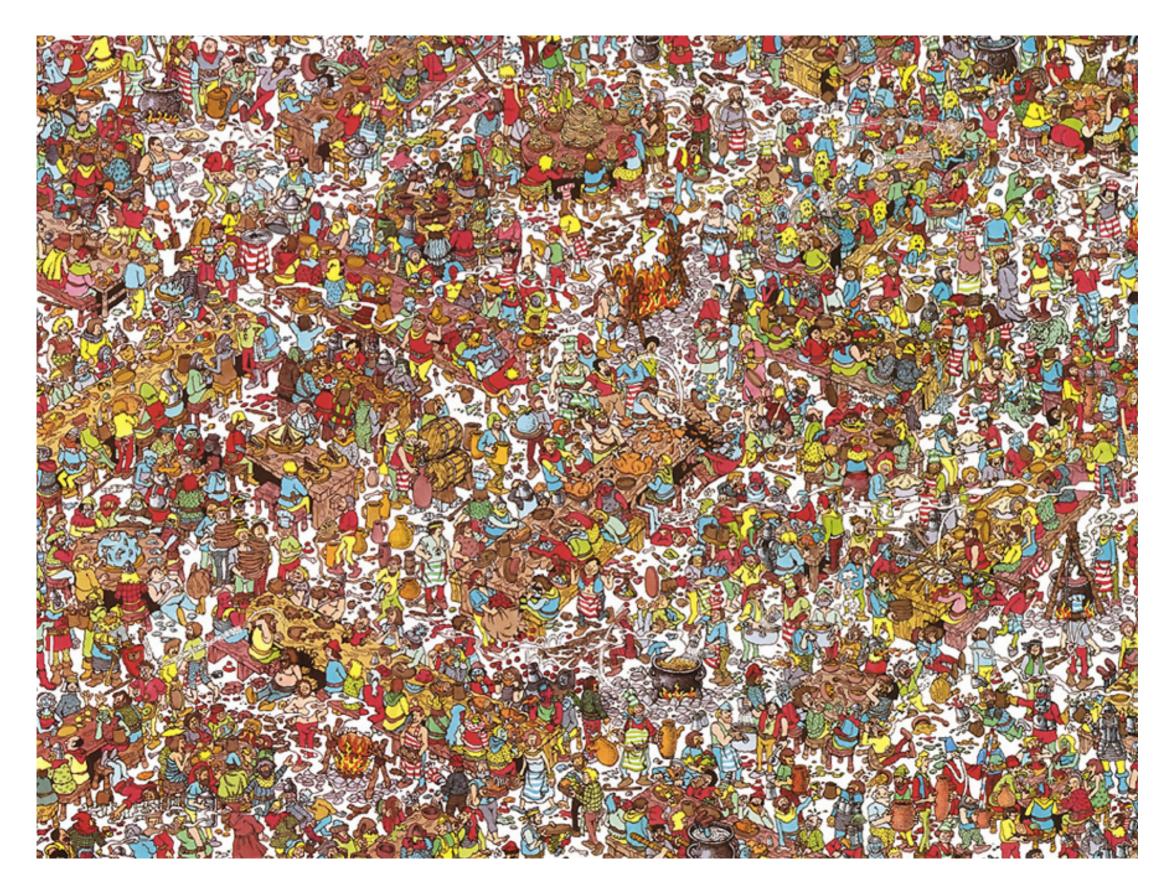


Let's talk about the Higgs Boson.

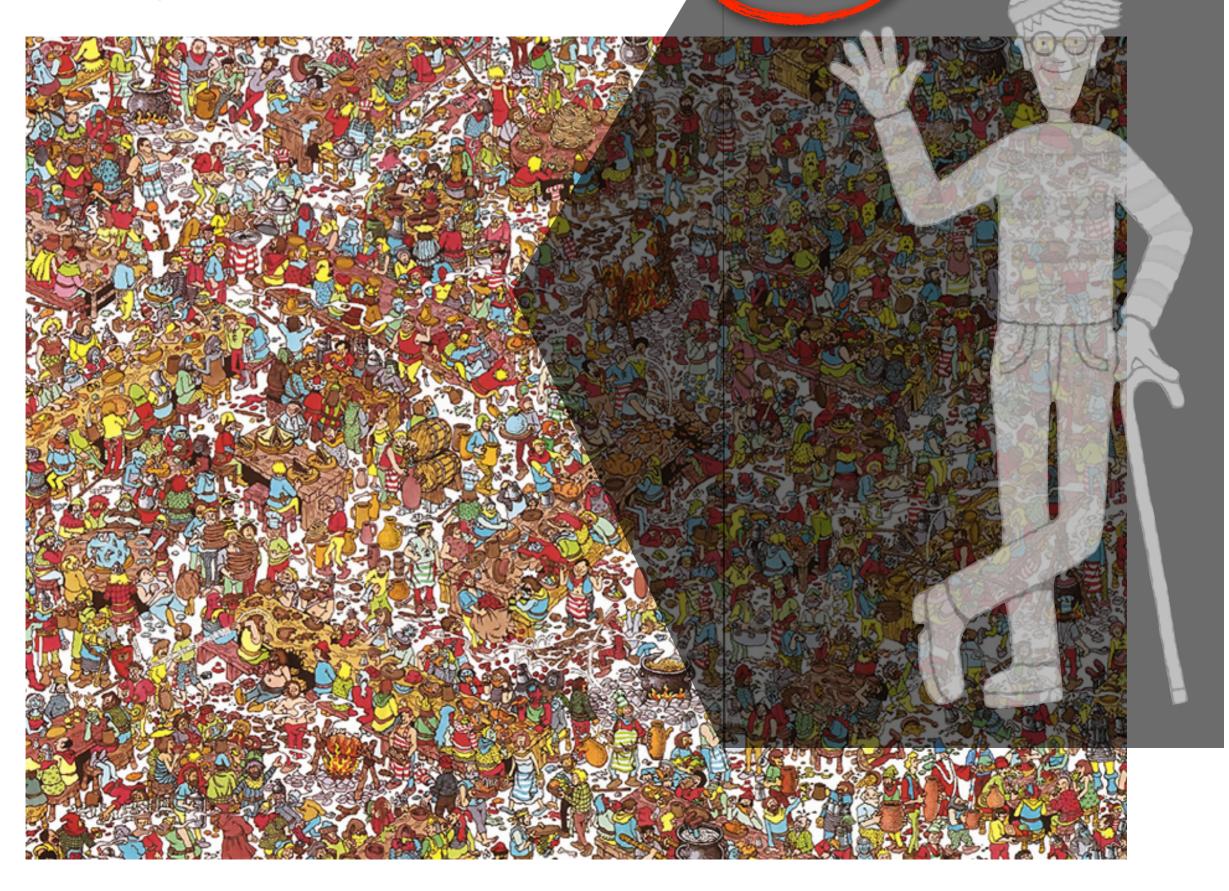
What happened in July, 2012?



the Object Itself?



the Object Itself? is...



hazy

Higgs particle

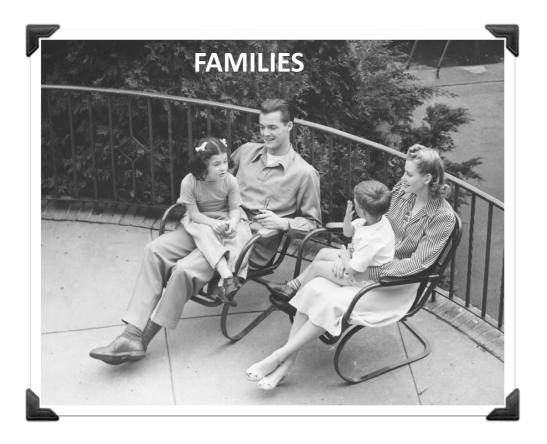




quantum numbers of the vacuum



How many things are only one thing?



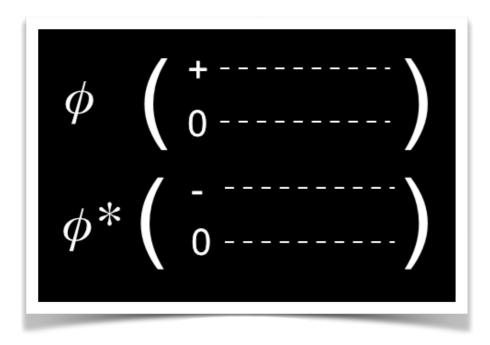
 $\left(\begin{array}{c} u \\ d \end{array}\right) \quad \left(\begin{array}{c} c \\ s \end{array}\right) \quad \left(\begin{array}{c} t \\ b \end{array}\right)$ $\left(\begin{array}{c}\nu_e\\e\end{array}\right)\quad \left(\begin{array}{c}\nu_\mu\\\mu\end{array}\right)\quad \left(\begin{array}{c}\nu_\tau\\\tau\end{array}\right)$

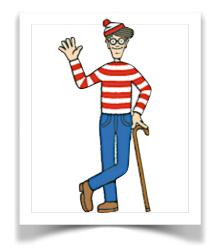
 W^{\pm}, Z^0, γ, g

an elementary *singlet*

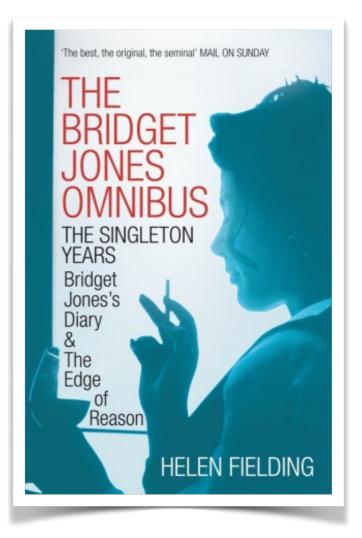


or part of a *doublet*





an elementary singleton?



the "Higgs" Potential.

Our future mission: to unpack it.

 $V = V_0 - |D_{\mu}H|^2 + \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 - g_i \bar{f}_{Li} f_{Ri} H$

the "Higgs" Potential.

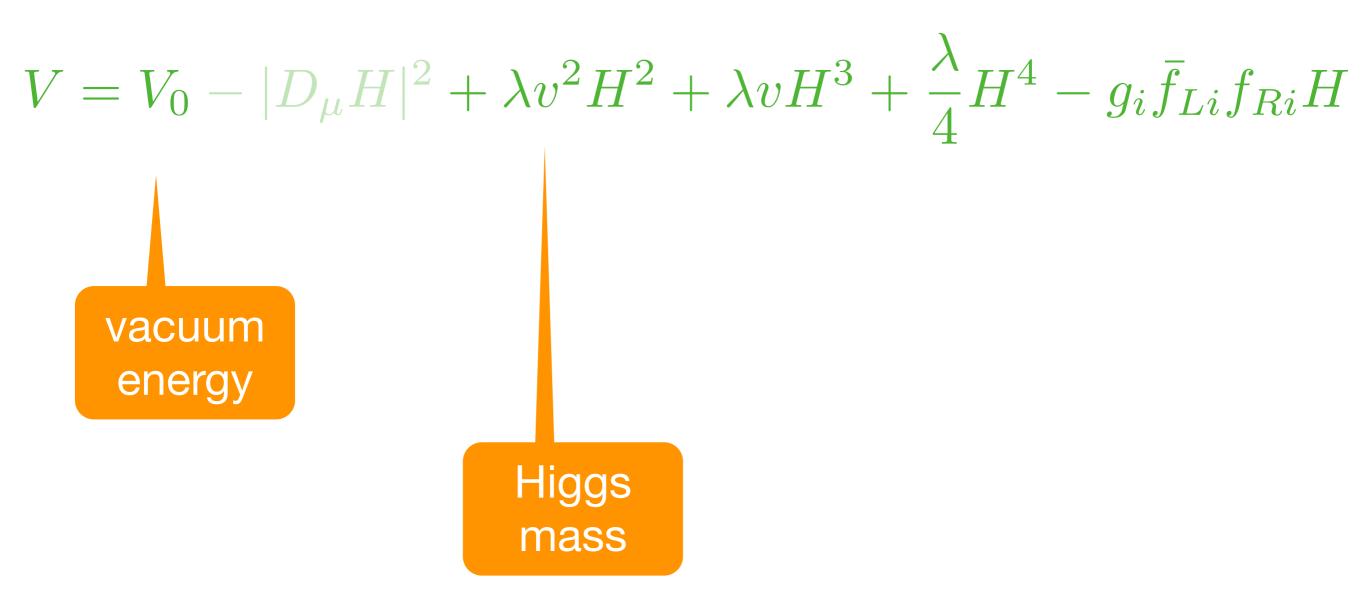
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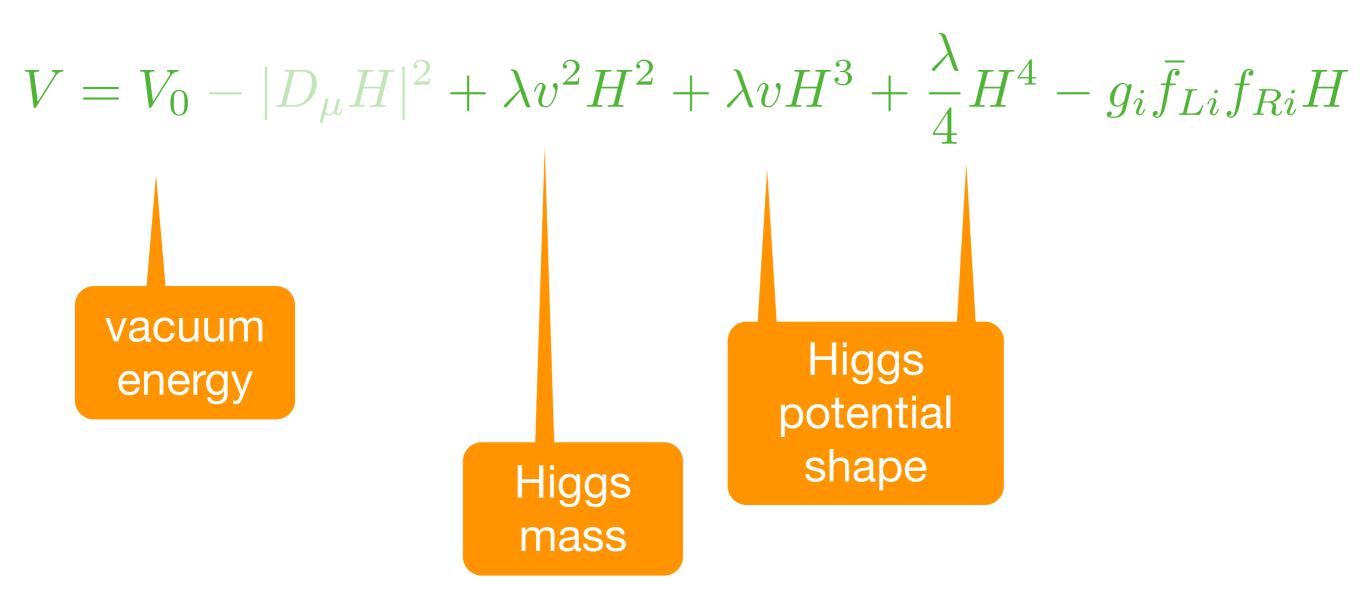
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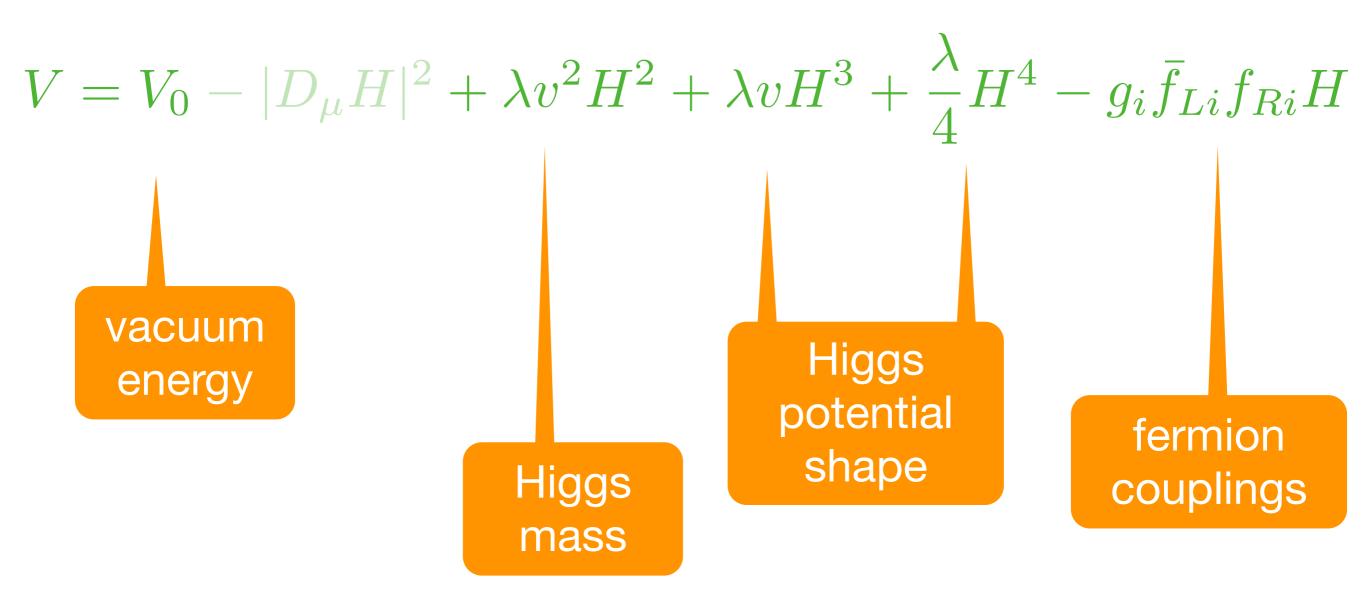
the "Higgs" Potential.

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the "Higgs" Potential.

Our future mission: to unpack it.

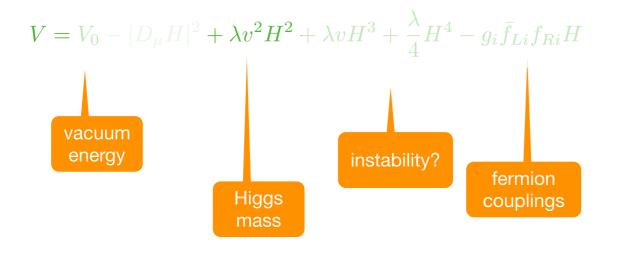






loops

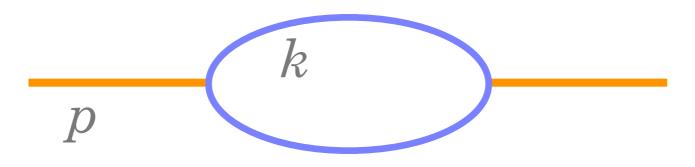




in relativistic quantum field theory

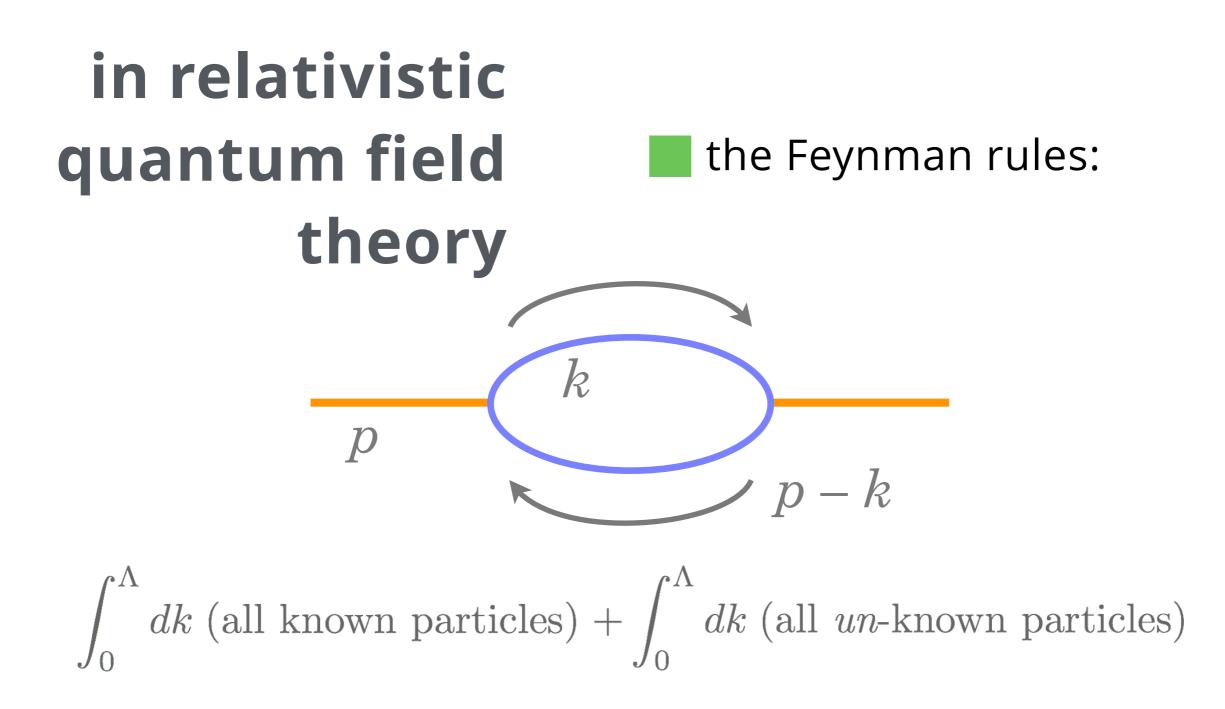


in relativistic quantum field I the Feynman rules: theory

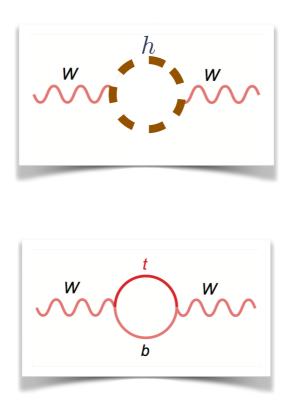


in relativistic quantum field the Feynman rules: theory p k p-k

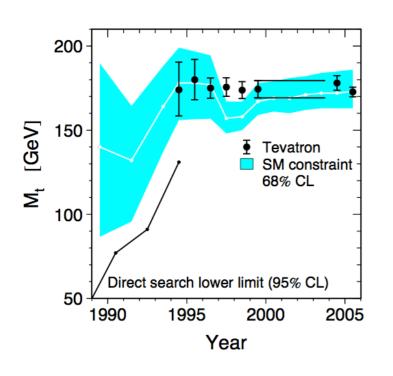
in relativistic quantum field the Feynman rules: theory k p -k $\int^{\Lambda} dk \text{ (all known particles)}$

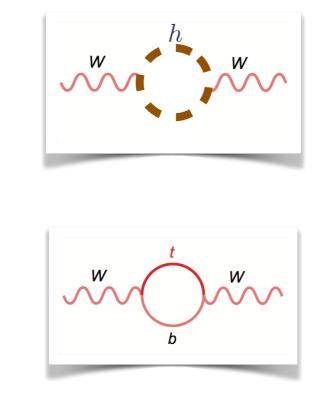


"Loops" are at the core of our language traditionally highly predictive highly accurate



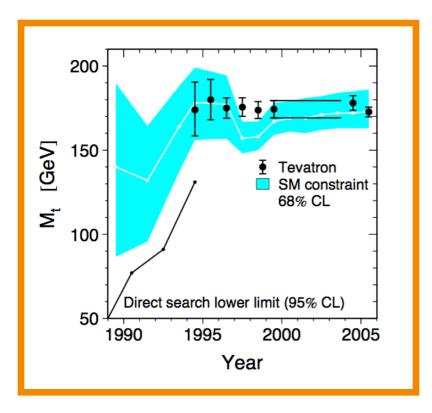
"Loops" are at the core of our language traditionally highly predictive highly accurate

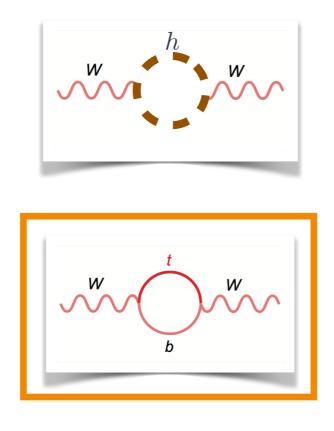




EW fits: top quark

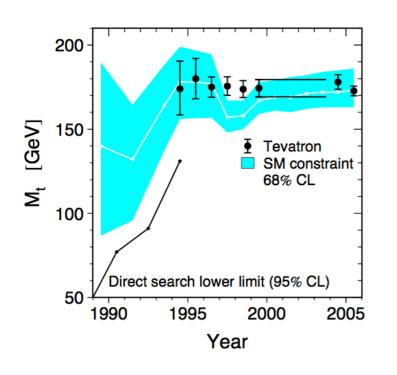
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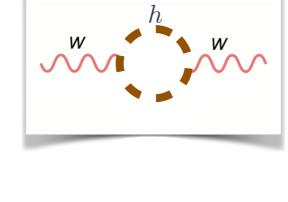


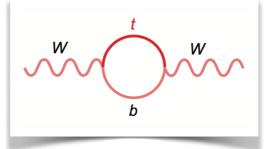


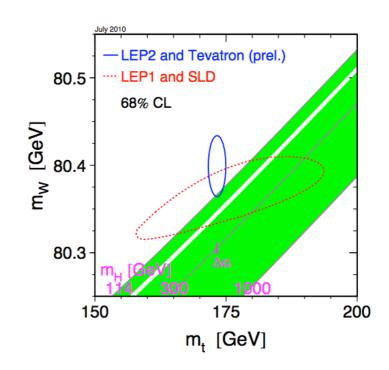
EW fits: top quark

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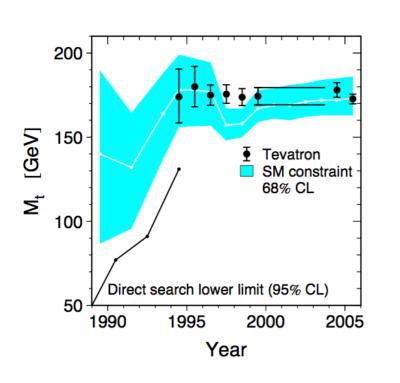




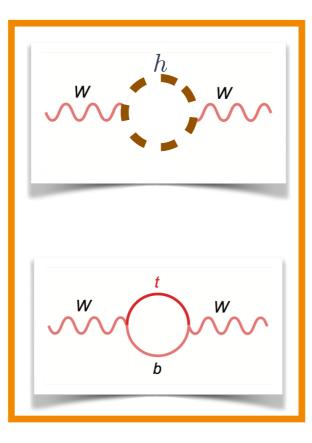
EW fits: top quark

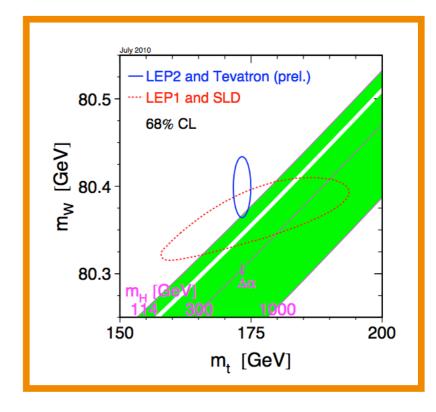
EW fits: Higgs boson

"Loops" are at the core of our language traditionally highly predictive highly accurate



EW fits: top quark





EW fits: Higgs boson

How about a spin 0, elementary particle?

First-ever spin 0 elementary particle.

$$V = \lambda v^2 H^2$$

$$M_H^2 = M_{\rm tree}^2 + \delta M^2$$

 $\delta M^2 \propto \frac{c}{16\pi^2} g^2 \Lambda^2$

3 kinds of loops

$$V = \lambda v^2 H^2$$

$$M_H^2 = M_{\text{tree}}^2 + \begin{pmatrix} H \\ H \end{pmatrix} + \begin{pmatrix} t \\ H \end{pmatrix} + \begin{pmatrix} W, Z \end{pmatrix} + \begin{pmatrix} W, Z \\ H \end{pmatrix} + \begin{pmatrix} W, Z \end{pmatrix} + \begin{pmatrix} W, Z \\ H \end{pmatrix} + \begin{pmatrix} W, Z \end{pmatrix}$$

$$M_{H} \sim 125 \ {\rm GeV/c^2}$$
 $M_{\rm physical}^2$

Top loop is big and negative

$$V = \lambda v^2 H^2$$

$$M_H^2 = M_{\text{tree}}^2 + \begin{pmatrix} H \\ H \end{pmatrix} + \begin{pmatrix} H \\ H \end{pmatrix} + \begin{pmatrix} H \\ H \end{pmatrix} + \begin{pmatrix} W \\ H \end{pmatrix} + \begin{pmatrix} W$$

$$M_{H} \sim 125 \text{ GeV/c}^2 \qquad M_{\text{physical}}^2$$

$$m_t^2 \qquad M_H^2$$

$$M_H^2$$

$$M_H^2$$

Requiring a large, opposing tree value

$$V = \lambda v^2 H^2$$

$$M_H^2 = M_{\text{tree}}^2 + \begin{pmatrix} H \\ H \\ H \end{pmatrix} + \begin{pmatrix} - H \\ H \end{pmatrix} + \begin{pmatrix} W, Z \\ H \end{pmatrix} + \begin{pmatrix} W, Z \\ H \\ H \end{pmatrix} + \begin{pmatrix} W, Z \\ H \\ H \end{pmatrix} + \begin{pmatrix} W, Z \\ H \end{pmatrix} + \begin{pmatrix} W, W \end{pmatrix} + \begin{pmatrix} W,$$

$$M_H \sim 125 \, \text{GeV/c}^2$$
 M_{physical}^2 M_{tree}^2 M_{tree}^2

An enormous fine-tuning

$$V = \lambda v^2 H^2$$

$$M_H^2 = M_{\text{tree}}^2 + \begin{pmatrix} H \\ H \end{pmatrix} + \begin{pmatrix} t \\ H \end{pmatrix} + \begin{pmatrix} W, Z \end{pmatrix} + \begin{pmatrix} W, Z \\ H \end{pmatrix} + \begin{pmatrix} W, Z \\ H \end{pmatrix} + \begin{pmatrix} W, Z \end{pmatrix} + \begin{pmatrix} W, W \end{pmatrix} +$$

$$m_t^2 \qquad M_{H^2 \sim 125 \text{ GeV/c}^2} \qquad M_{\text{physical}}^2 \qquad M_{\text{tree}}^2 \qquad \text{un-fine} \\ M_H^2 \qquad M_H^2 \qquad M_{\text{tree}}^2 \qquad \text{un-fine} \\ M_{W,Z}^2 \qquad M_{W,Z}^2 \qquad M_{W,Z}^2 \qquad M_{W,Z}^2 \qquad \text{un-fine} \\ M_{W,Z}^2 \qquad M_{W,Z}^2 \qquad$$

An enormous fine-tuning

$$V = \lambda v^2 H^2$$

$$M_H^2 = M_{\text{tree}}^2 + \begin{pmatrix} H \\ H \end{pmatrix} + \begin{pmatrix} H \\ H \end{pmatrix} + \begin{pmatrix} H \\ H \end{pmatrix} + \begin{pmatrix} W, Z \end{pmatrix} + \begin{pmatrix} W, W \end{pmatrix} + \begin{pmatrix} W, Z \\ H \end{pmatrix} + \begin{pmatrix} W, Z \end{pmatrix} + \begin{pmatrix} W, W \end{pmatrix} + \begin{pmatrix} W$$

$$m_{t}^{2} \qquad M_{H} \sim 125 \text{ GeV/c}^{2} \qquad M_{physical}^{2} \qquad M_{tree}^{2} \qquad \text{un-fine} \\ M_{H}^{2} \qquad M_{H}^{2} \qquad \text{un-fine} \\ M_{W,Z}^{2} \qquad \text{un-fine} \\ \text{tuning?} \\ \text{un-fine} \\ \text{un-fine} \\ \text{tuning?} \\ \text{un-fine} \\ \text{un-fin$$

if next scale is I the Planck Scale?

 $M_{H}^{2} = 125^{2}$

"coincidence"?



There's no coincidence in science.



Perhaps a huge hint?

of something "BSM"?

no shortage of ideas

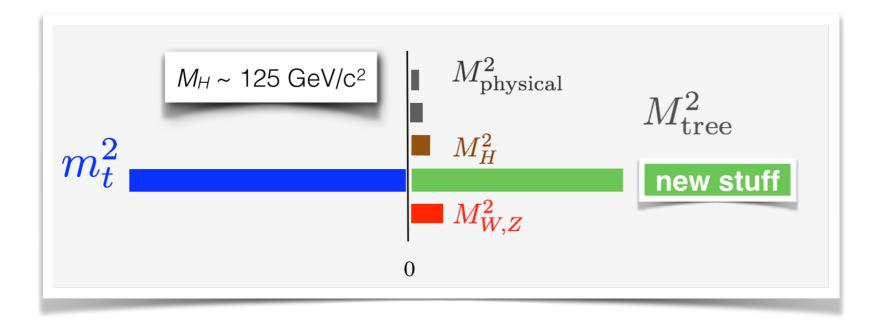
$$M_H \sim 125 \, {\rm GeV/c^2}$$
 $M_{\rm physical}^2$ $M_{\rm tree}^2$
 m_t^2 M_H^2
 M_H^2

Perhaps a huge hint?

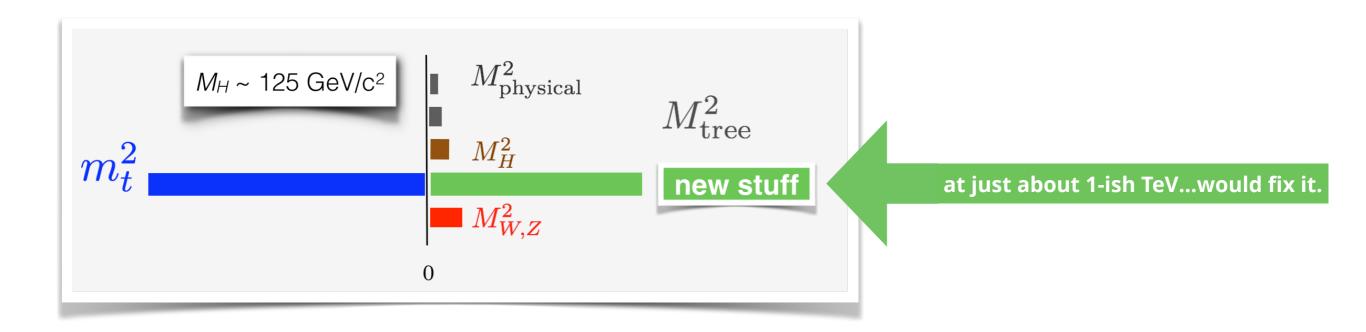
of something "BSM"?

no shortage of ideas

$$\begin{array}{c} M_{H} \sim 125 \ {\rm GeV/c^2} \end{array} \qquad M_{\rm physical}^2 \qquad \qquad M_{\rm tree}^2 \\ m_t^2 \qquad \qquad M_H^2 \qquad \qquad M_{\rm tree}^2 \\ M_H^2 \qquad \qquad M_{\rm W,Z}^2 \end{array}$$



looking for new physics at the ~1 TeV scale



looking for new physics at the ~1 TeV scale



looking for new physics at the ~1 TeV scale

"natural"



Broadly speaking, categories of new stuff:

- Supersymmetric theories –
- Little Higgs-like theories -
- **Composite Higgs -**
- **Extra dimensional theories**

- a Bose-like stop
- a Vector-top
- a Cooper Pair-like H



Broadly speaking, categories of new stuff:

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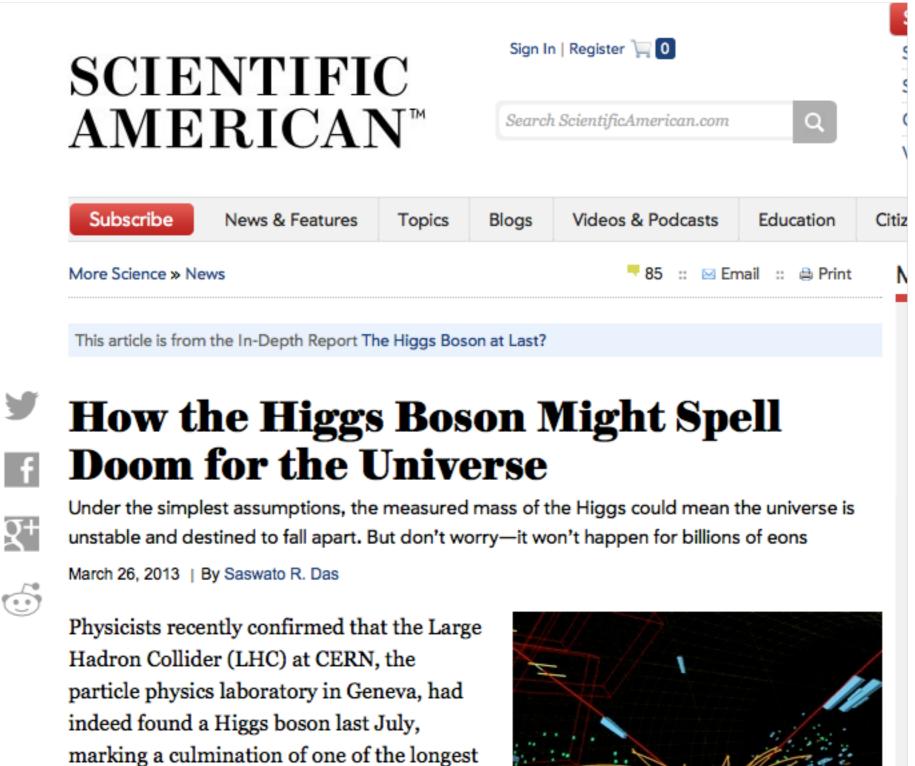
a Cooper Pair-like H

or we tend to default to ideas like:

the multiverse or...

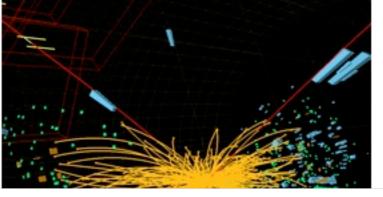
anthropomorphism





and most expensive searches in science. The

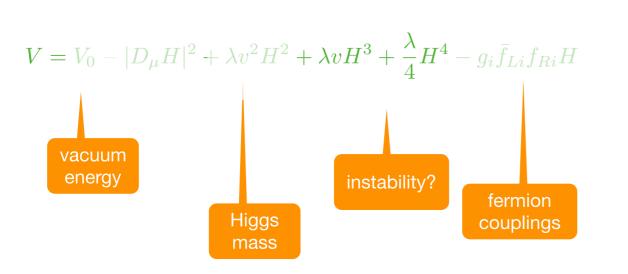
C 11



doom?



doom?

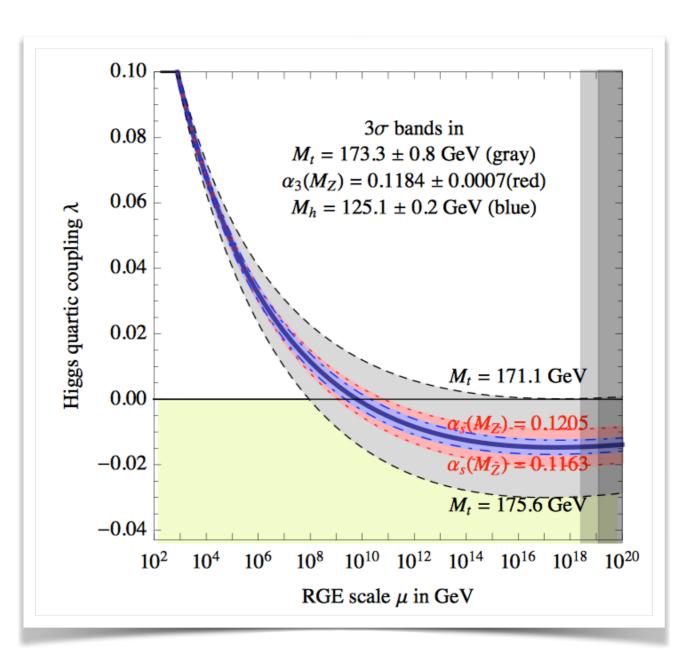




 $V = \lambda v H^3 + \frac{\lambda}{4} H^4$

Another consequence of a spin 0 fundamental particle.

The shape of the vacuum potential could change...and the bottom could fall out.



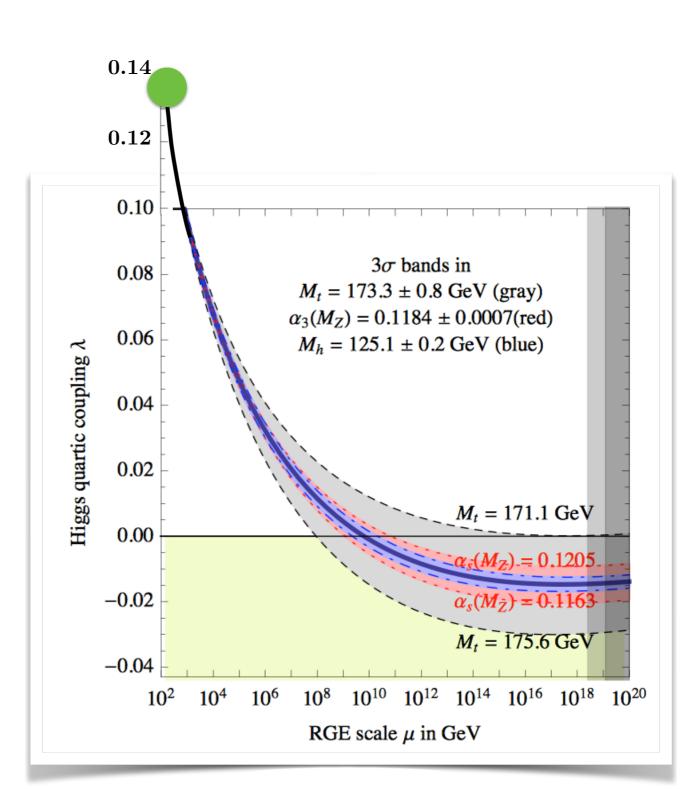
arXiv:1307.3536

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia

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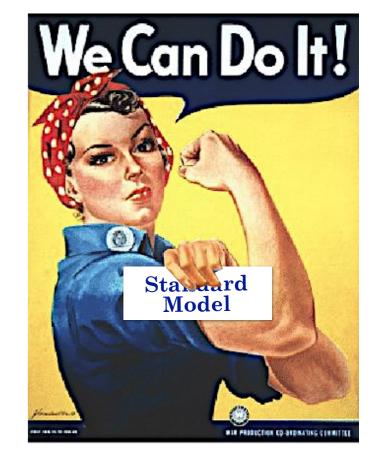
The Standard Model is just weird.



These are: the best of times

and the best of times!





the Snowmass "Energy Frontier"

with Michael Peskin



EF working groups

EF1: The Higgs Boson

Jianming Qian (Michigan), Andrei Gritsan (Johns Hopkins), Heather Logan (Carleton), Rick Van Kooten (Indiana), Chris Tully (Princeton), Sally Dawson (BNL)

EF2: Precision Study of Electroweak Interactions

Doreen Wackeroth (Buffalo), Ashutosh Kotwal (Duke)

EF3: Fully Understanding the Top Quark

Robin Erbacher (UC Davis), Reinhard Schwienhorst (MSU),

Kirill Melnikov (Johns Hopkins), Cecilia Gerber (UIC), Kaustubh Agashe (Maryland)

EF4: The Path Beyond the Standard Model–New Particles, Forces, and Dimensions (& Flavor and CP Violation at high energy)

Daniel Whiteson (Irvine), Liantao Wang (Chicago), Yuri Gershtein (Rutgers), Meenakshi Narain (Brown), Markus Luty (UC Davis) [Soeren Prell (ISU), Michele Papucci (LBNL), Marina Artuso (Syracuse)]

EF5: Quantum Chromodynamics and the Strong Interactions

Ken Hatakeyama (Baylor), John Campbell (FNAL), Frank Petriello (Northwestern), Joey Huston (MSU)

characterizing future collider physics 52 conclusions for all 13 facilities

we evaluated:

4 hadron colliders

- **7** electron colliders
- 1 muon collider
- 1 photon-photon collider



A three-pronged research program:

Mass, CP, and especially couplings

Measure properties of the Higgs boson.

Measure properties of the: *t*, *W*, and *Z*

Search for TeV-scale particles

A three-pronged research program:

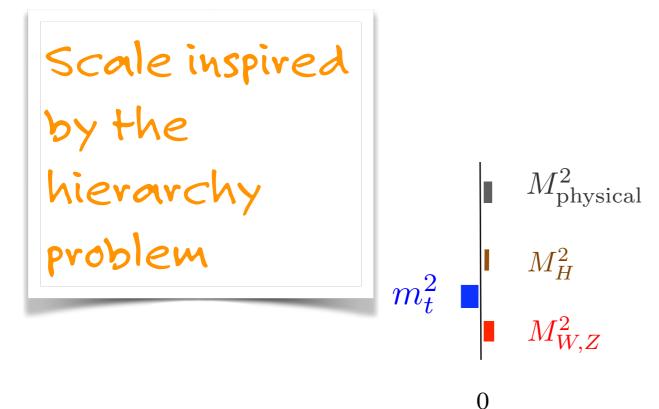


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A three-pronged research program:



Measure properties of the Higgs boson.

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Search for TeV-scale particles









is it alone?





a part of a family?





a part of a family?

different in tiny details?



is it alone?

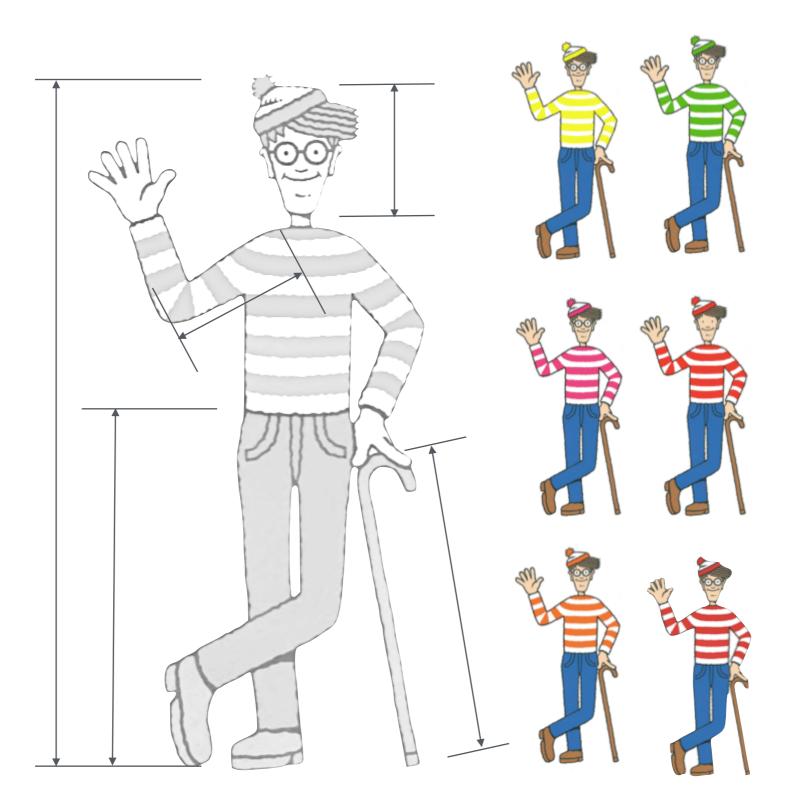


a part of a family?

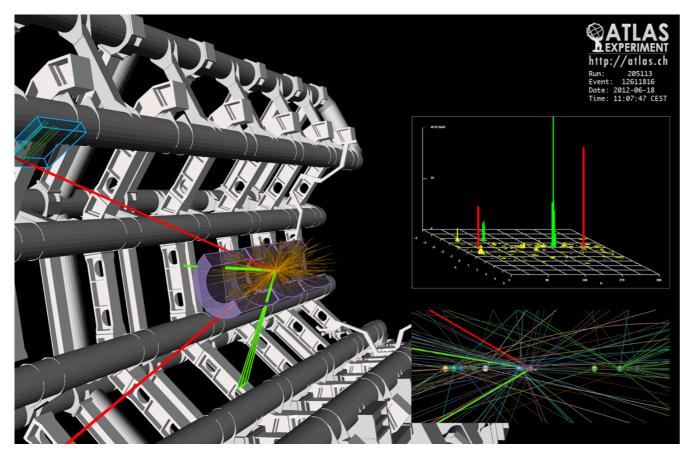
different in tiny details?





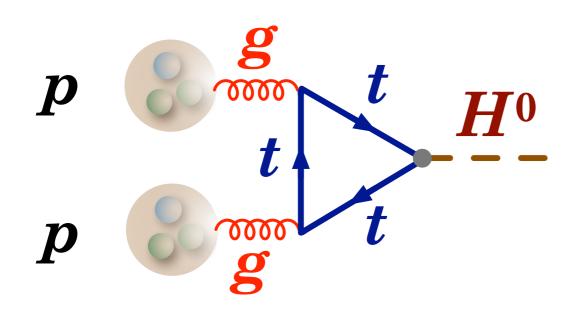


ATLAS

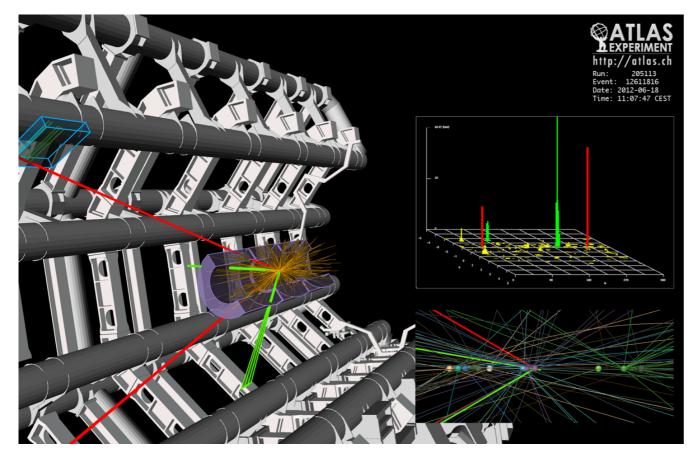


Golden Channel



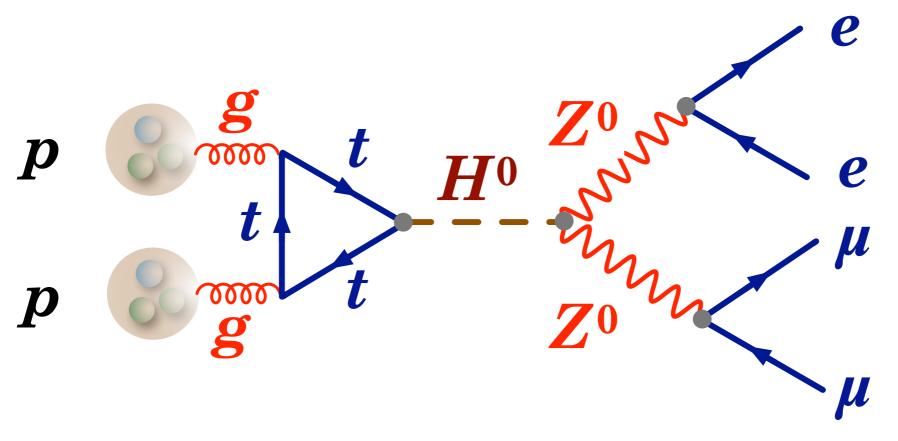


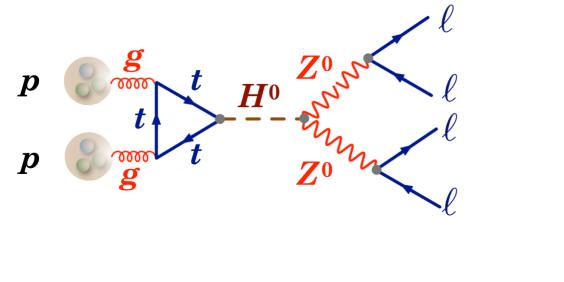
ATLAS



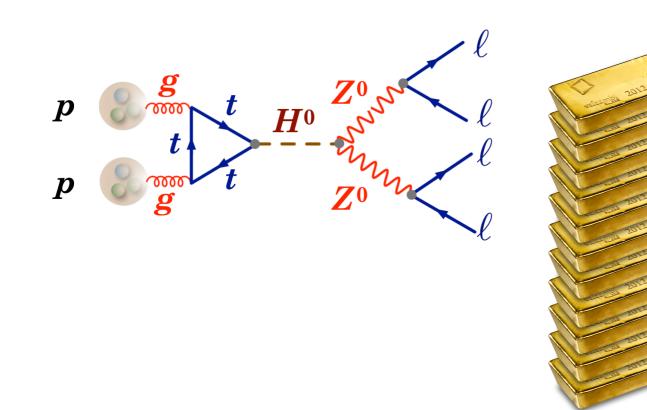
Golden Channel

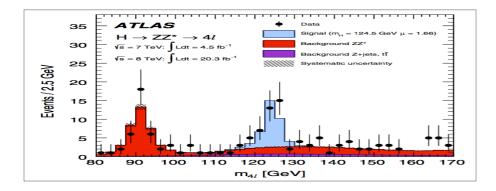


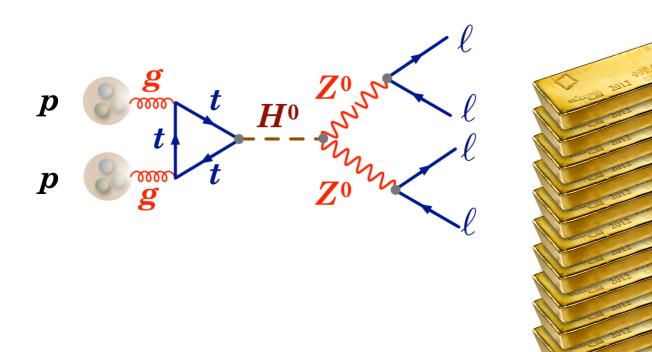


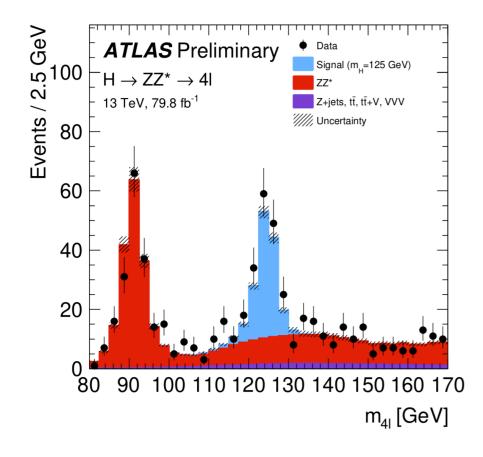


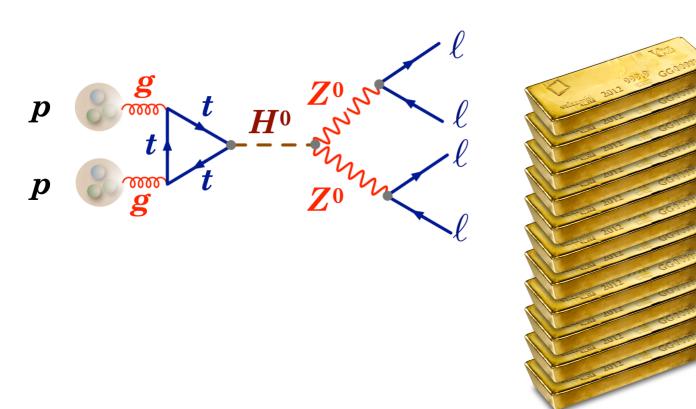


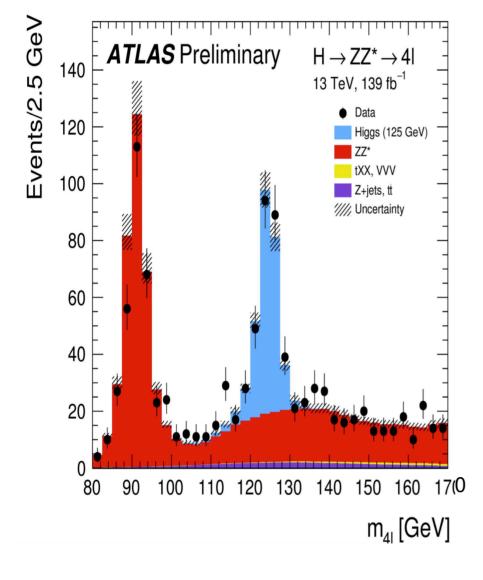


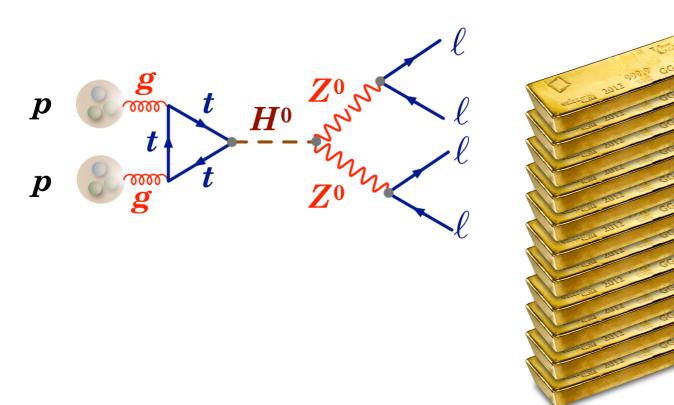


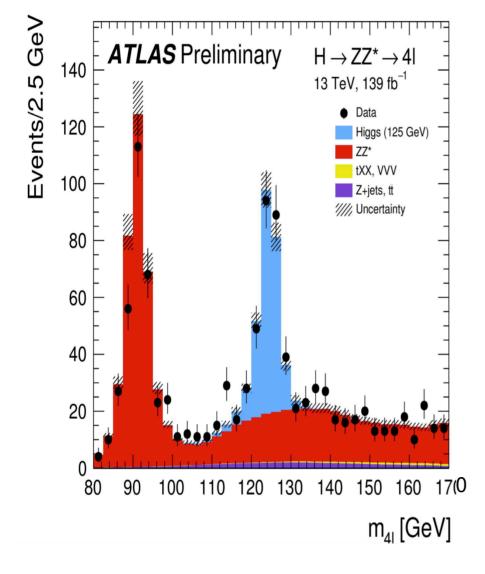


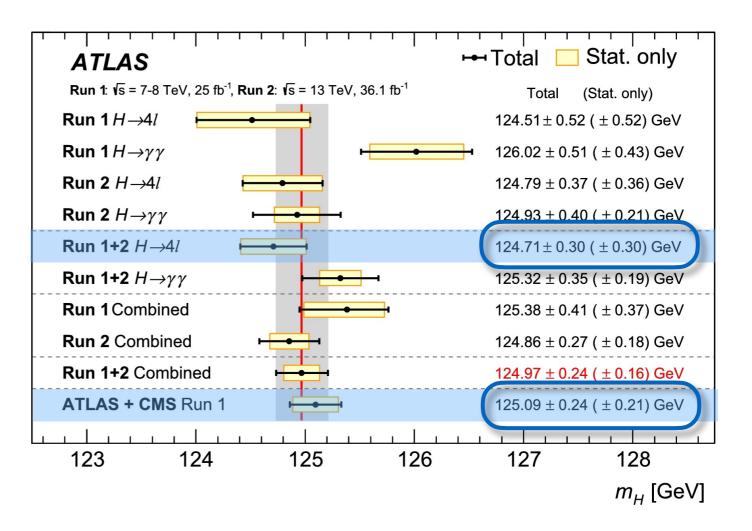


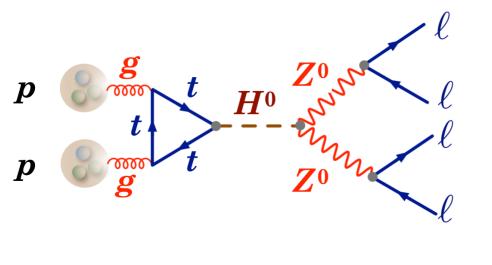






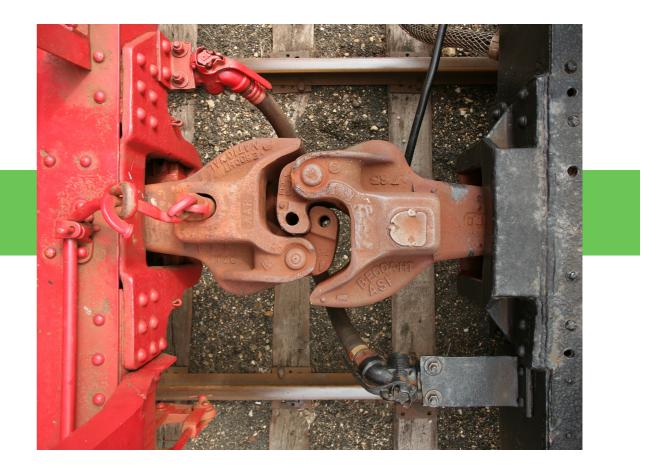




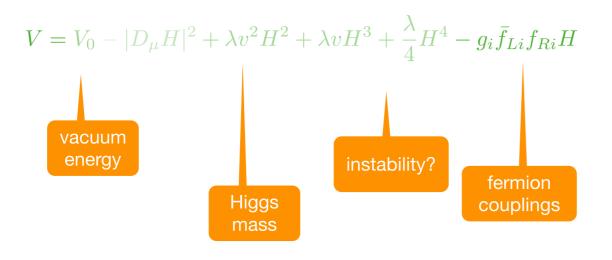


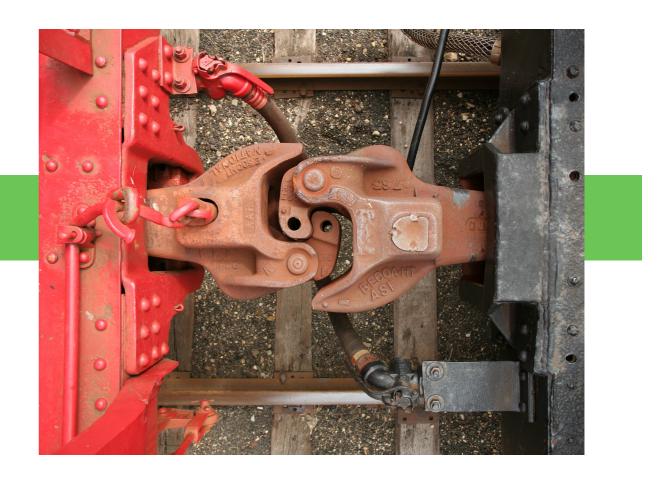


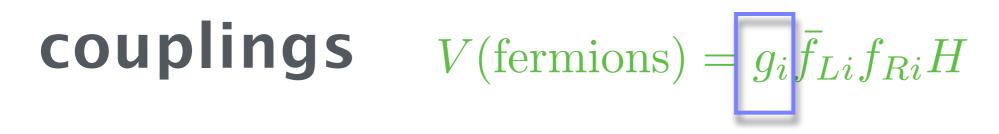
couplings



couplings

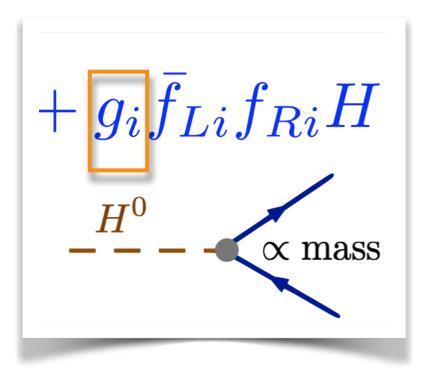


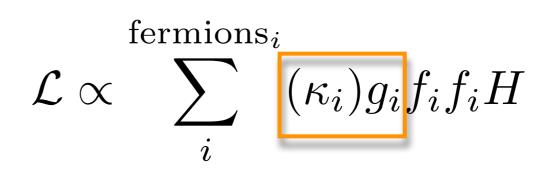




Higgs discovery spawned an industry

precision fitting

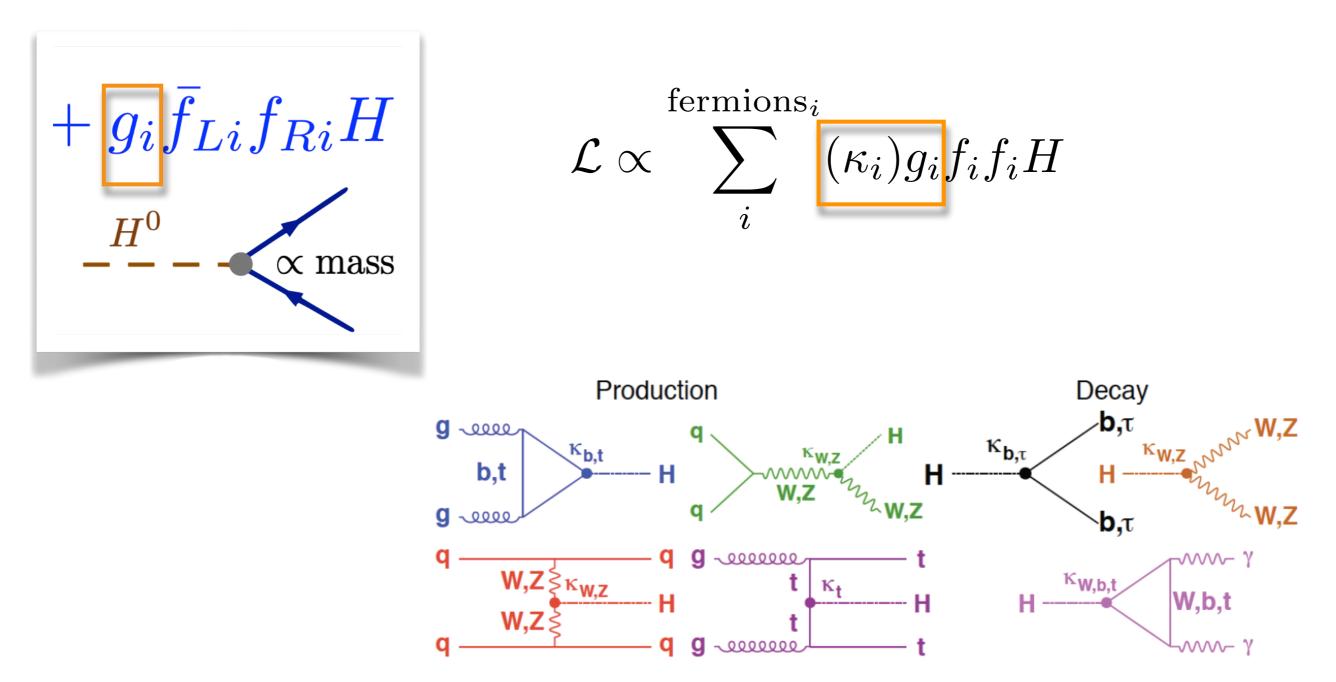


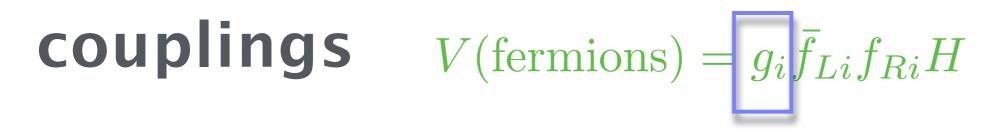




Higgs discovery spawned an industry

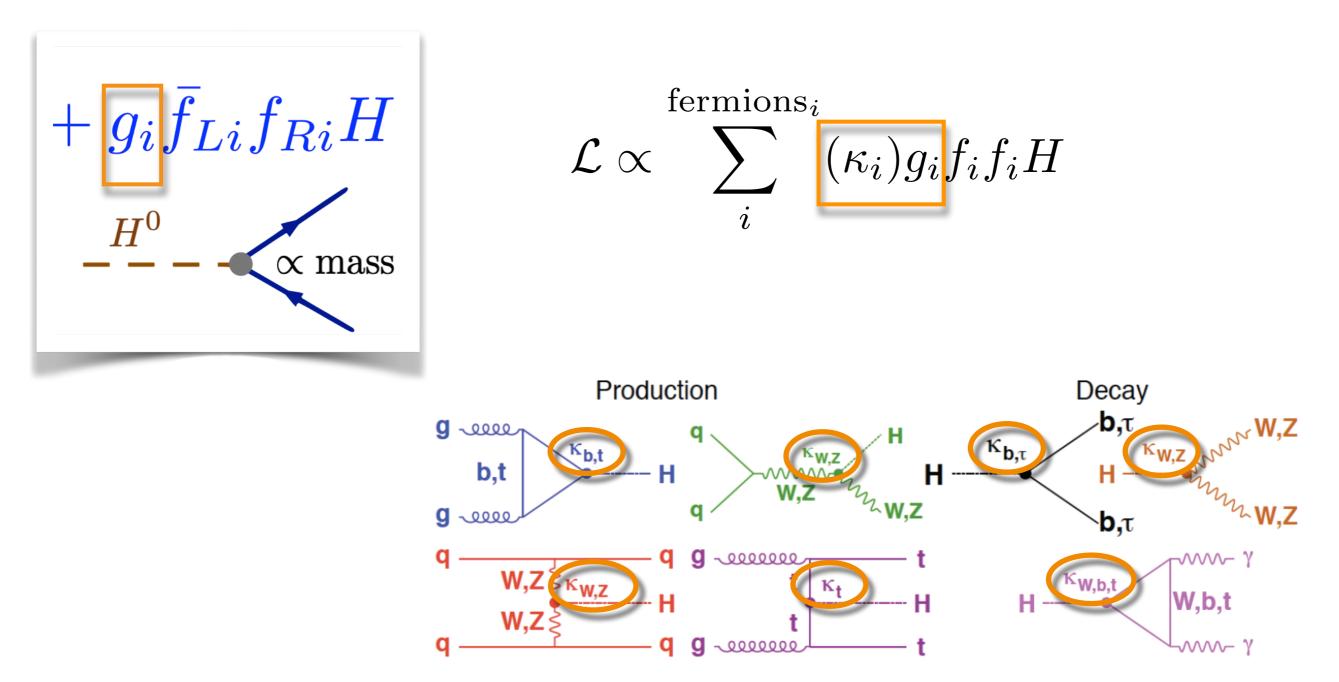
precision fitting





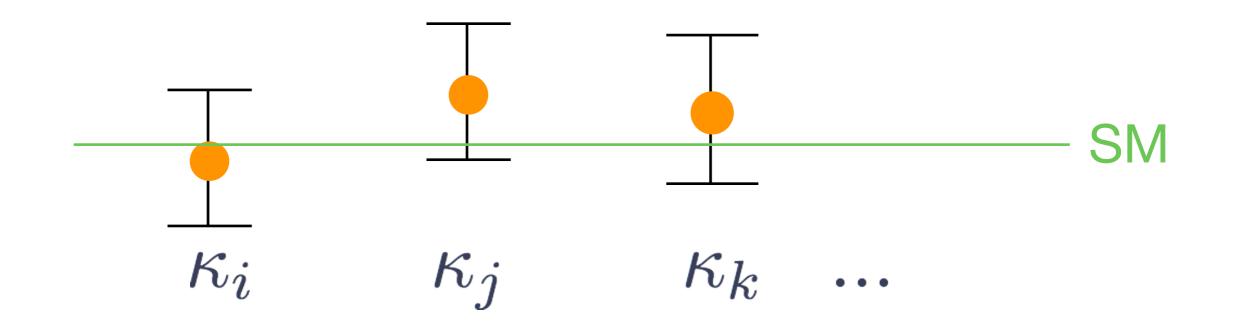
Higgs discovery spawned an industry

precision fitting



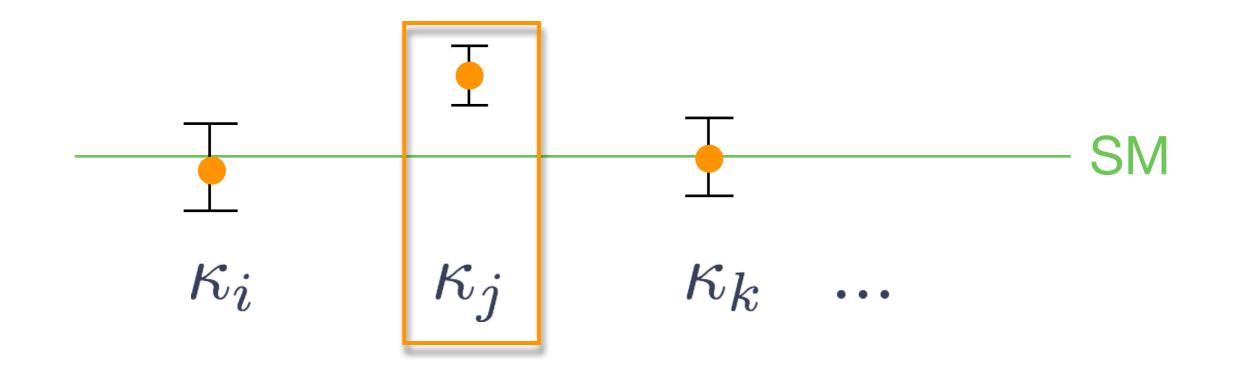
a campaign

Measure the couplings of Higgs... to **everything**

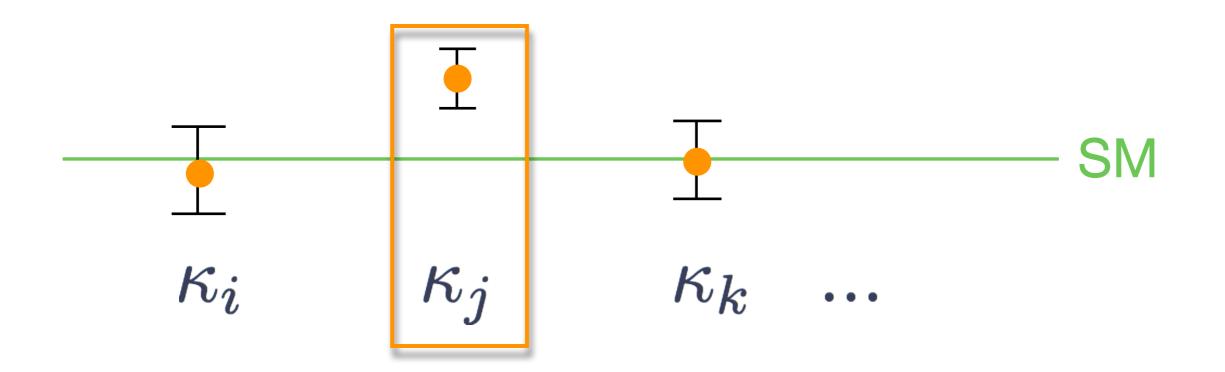


a campaign

Measure the couplings of Higgs... to **everything**



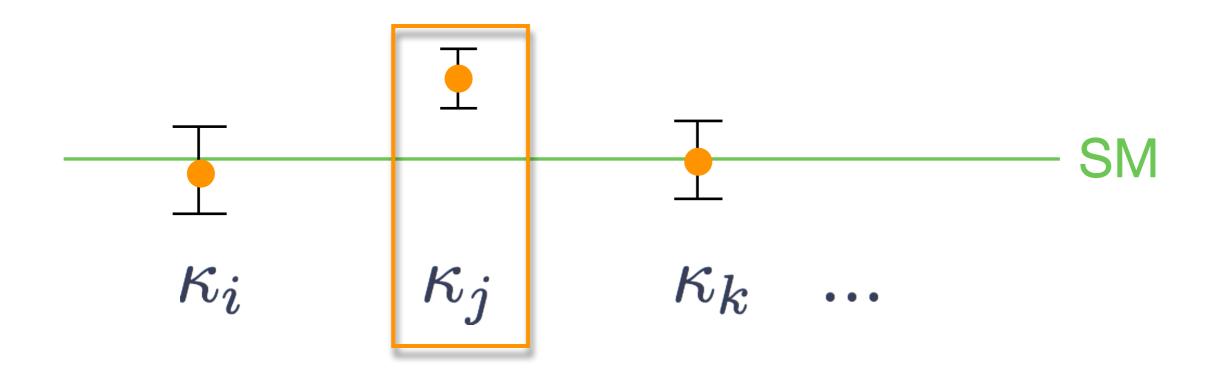
how well?



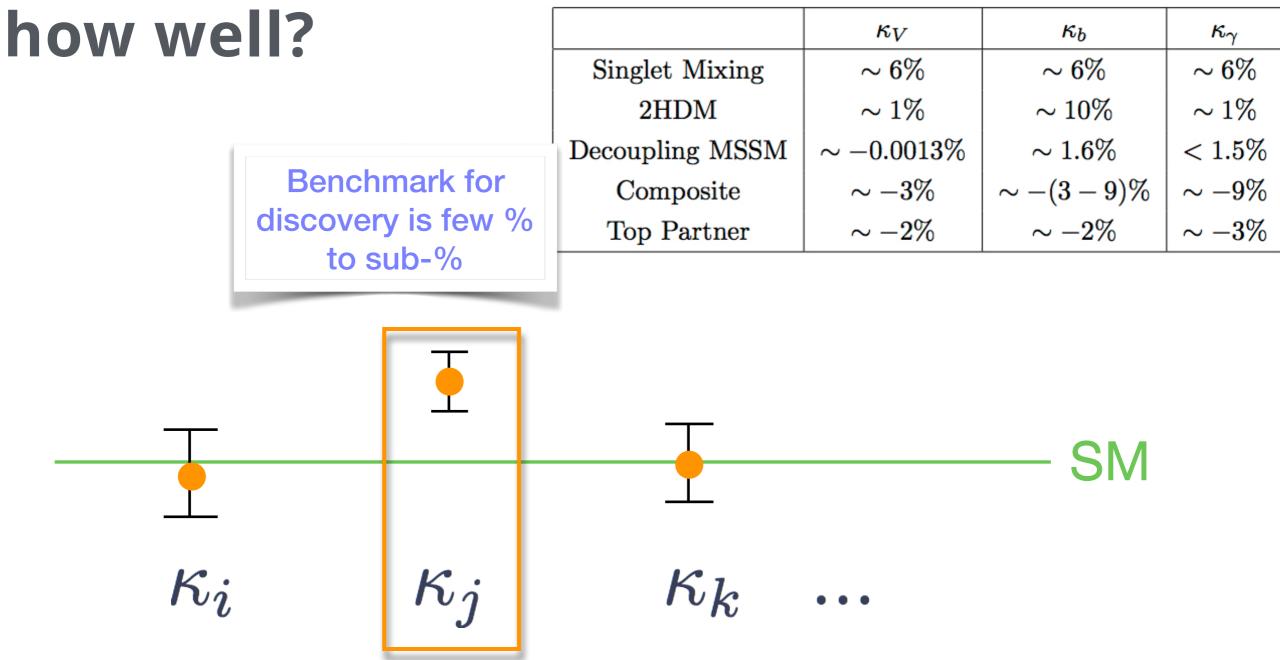
how well?

Beyond the Standard Model Predictions @ 1TeV:

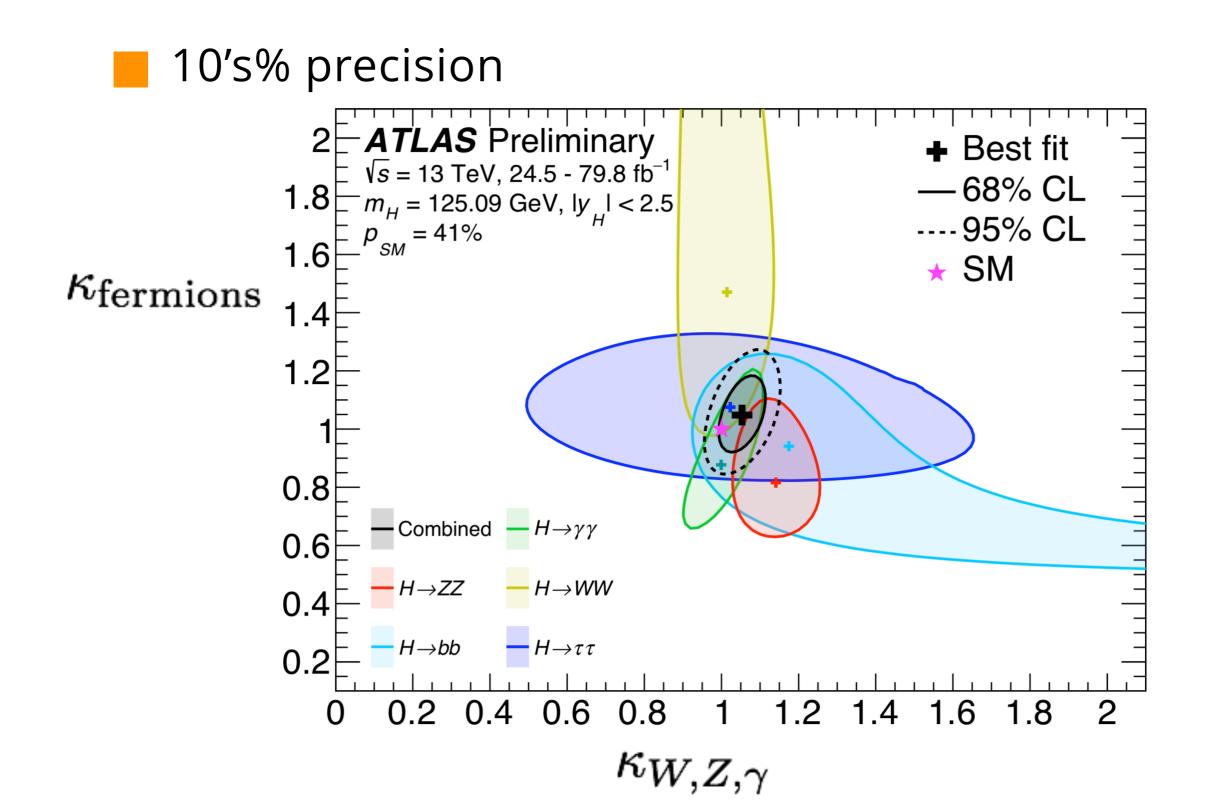
	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	< 1.5%
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



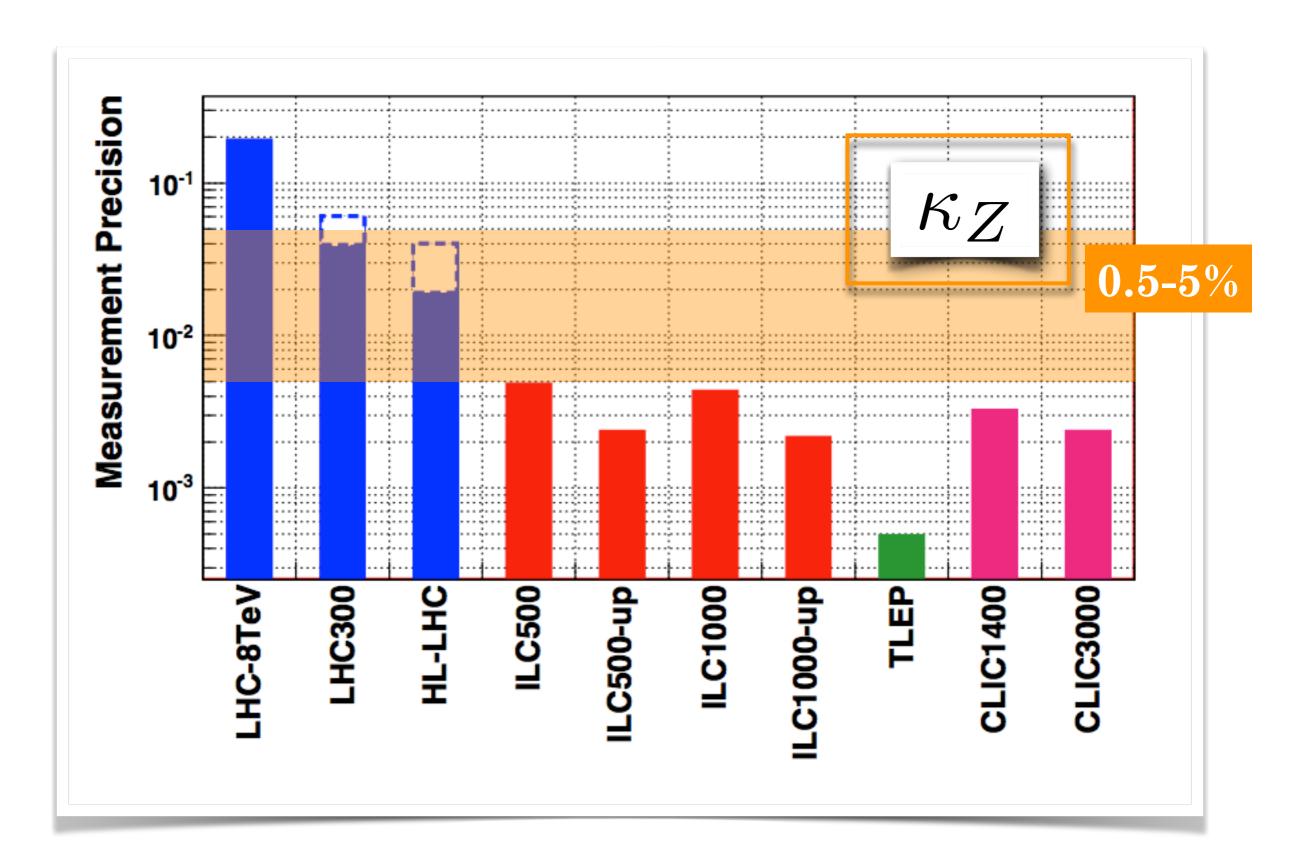
Beyond the Standard Model Predictions @ 1TeV:



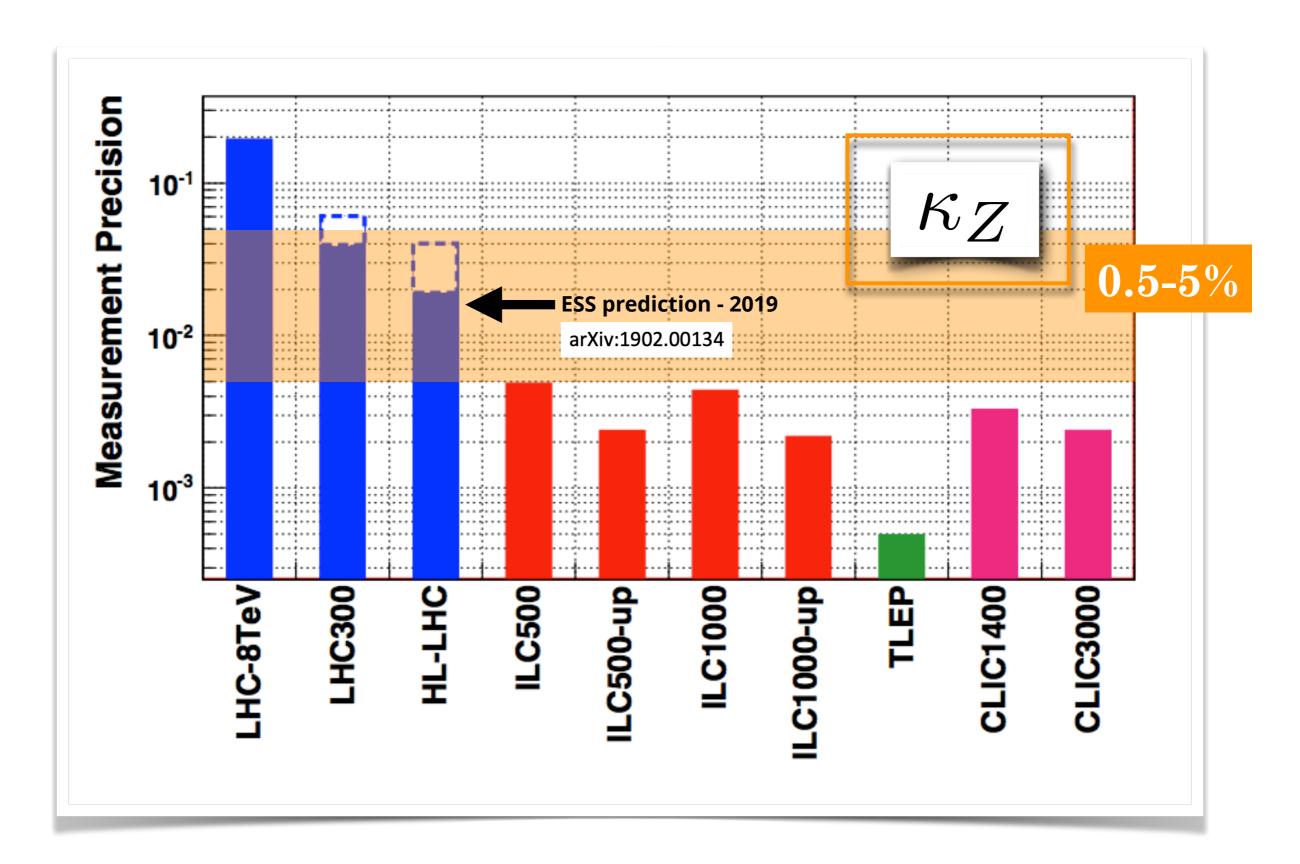
LHC Status in the couplings:



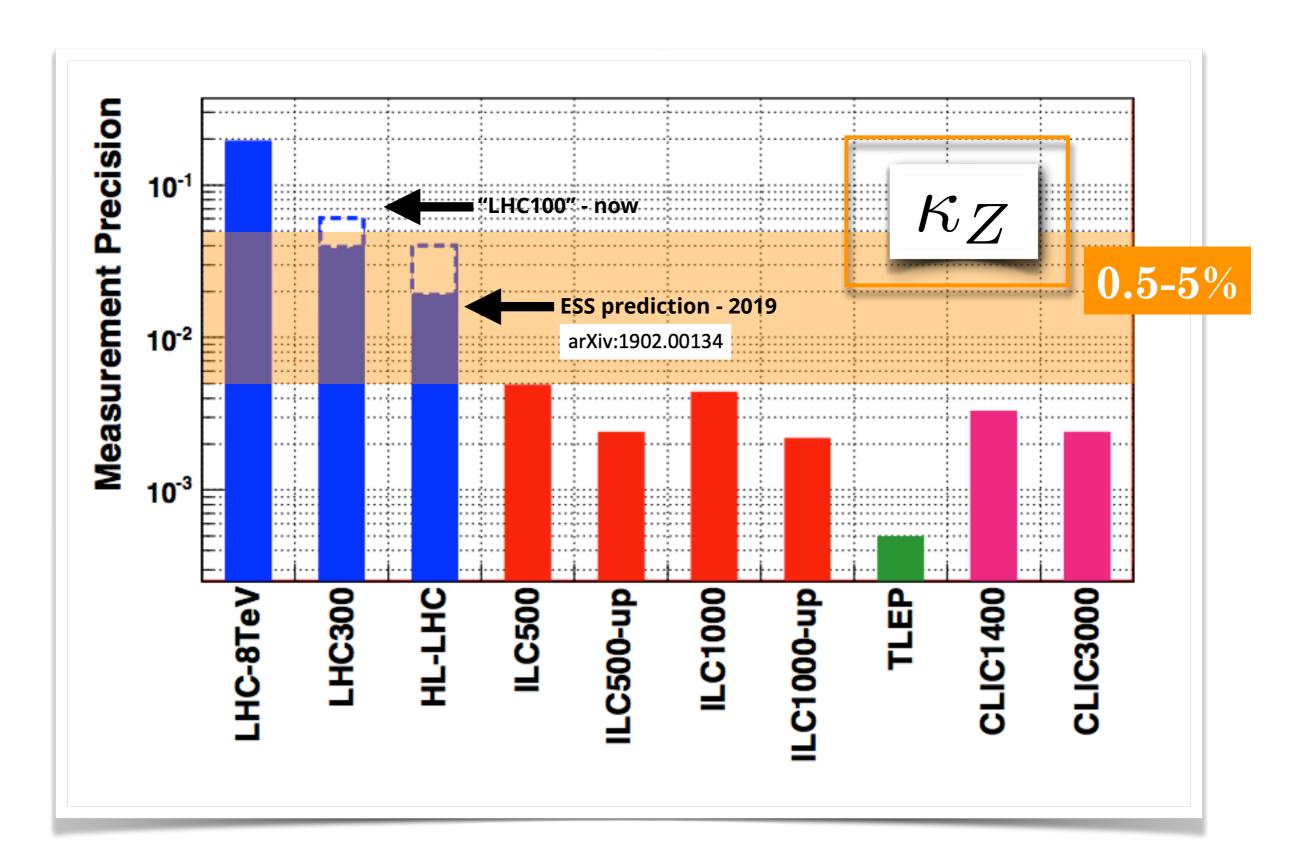
Extrapolating to future machines

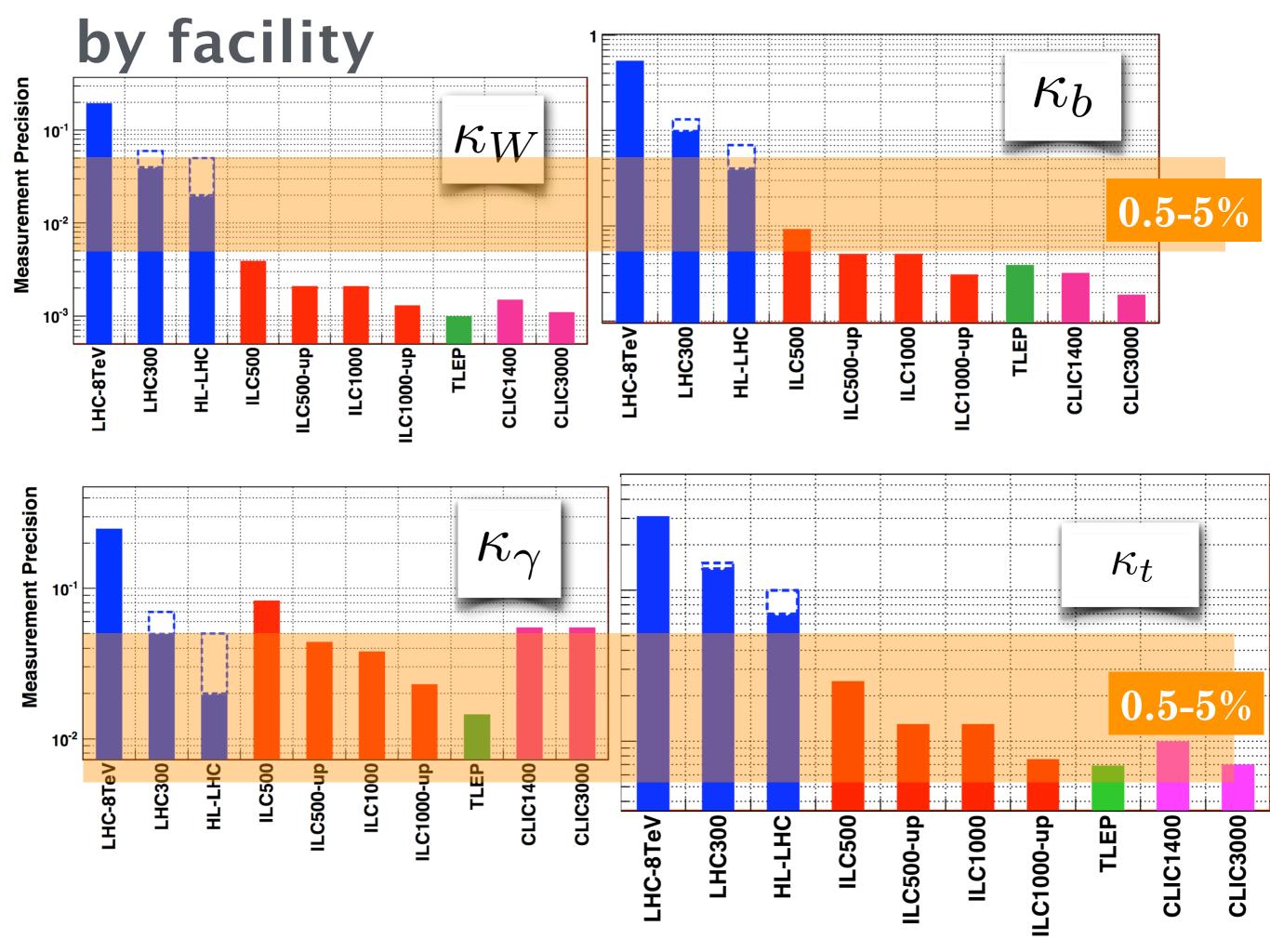


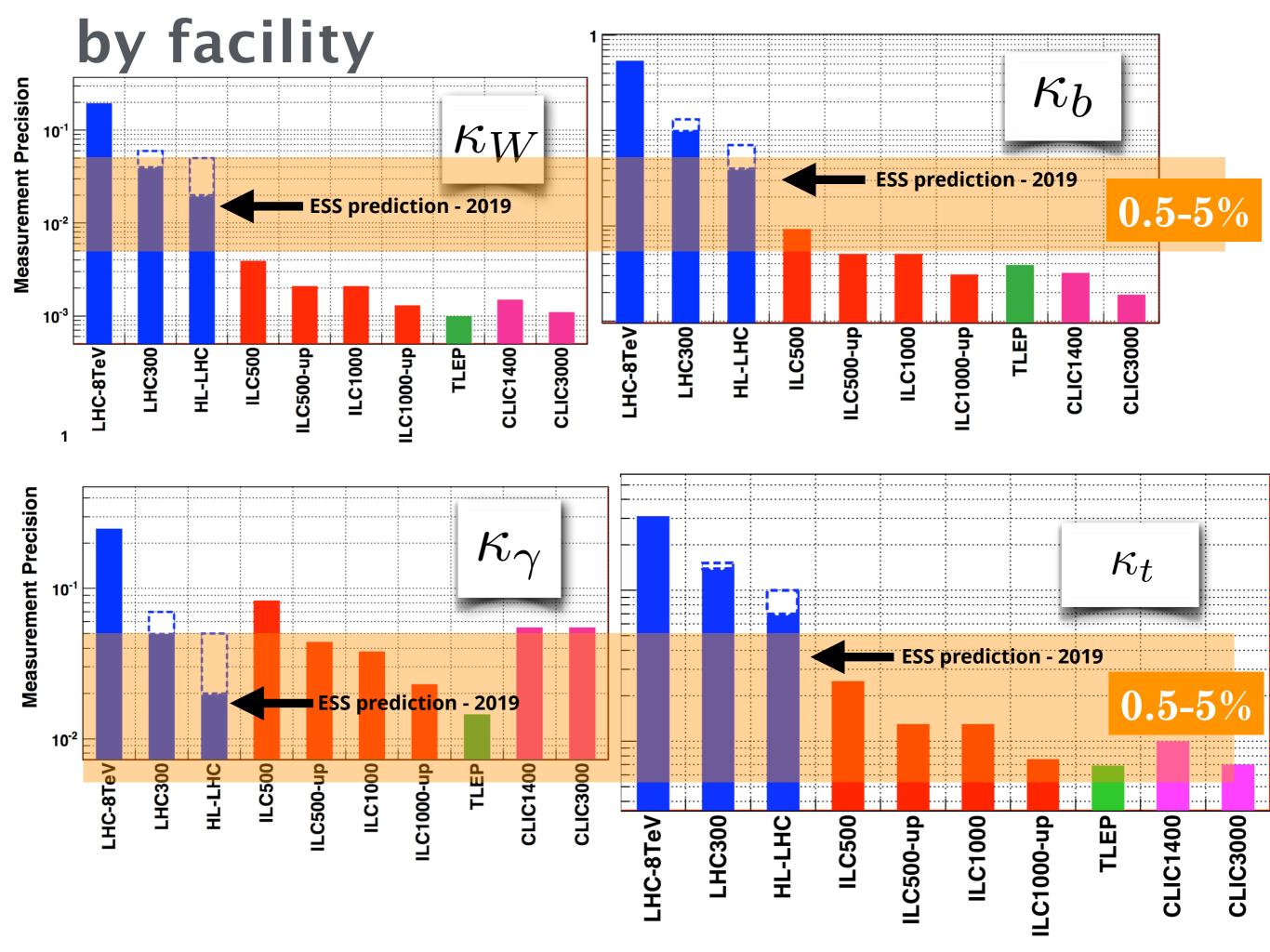
Extrapolating to future machines

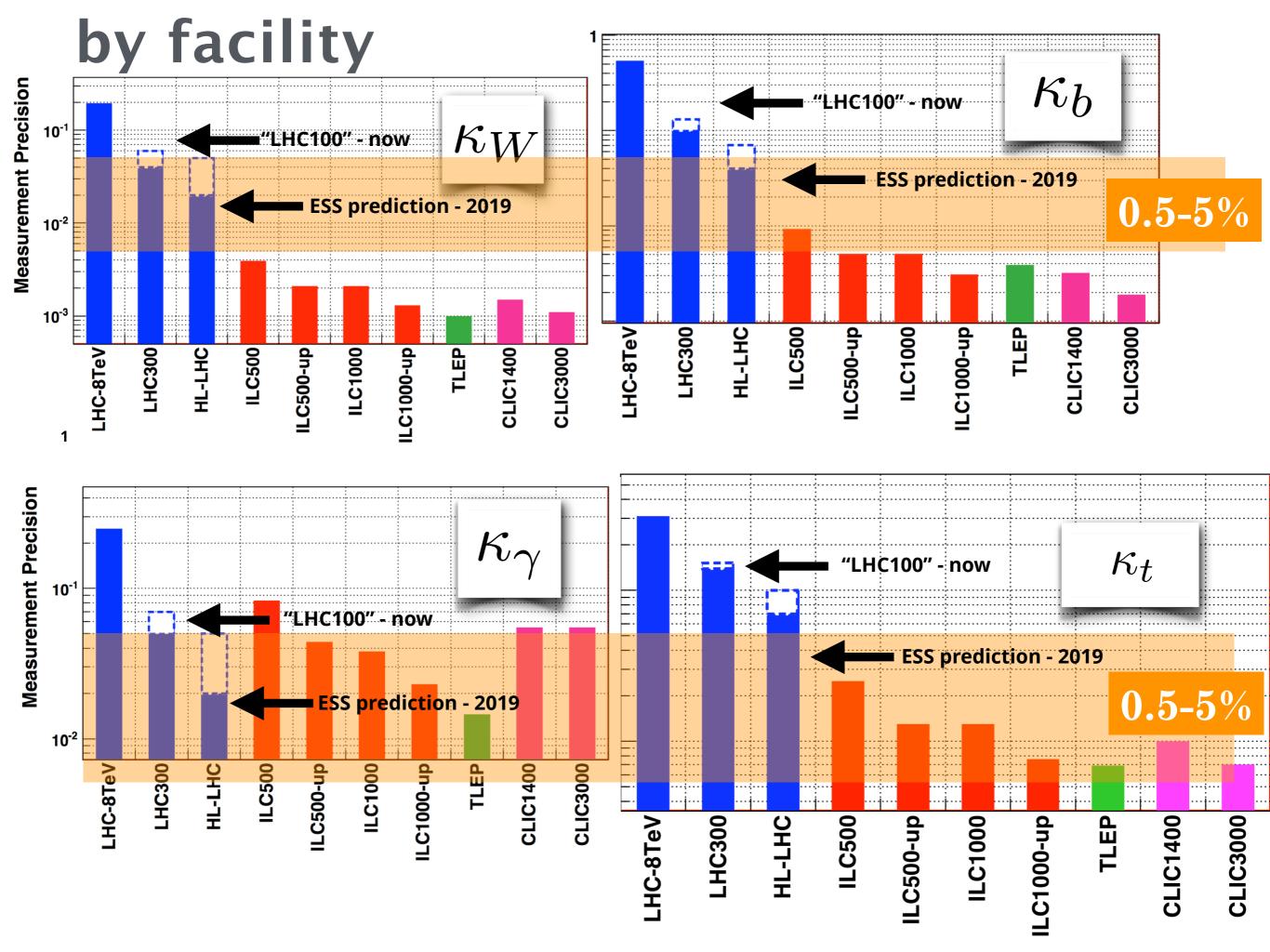


Extrapolating to future machines



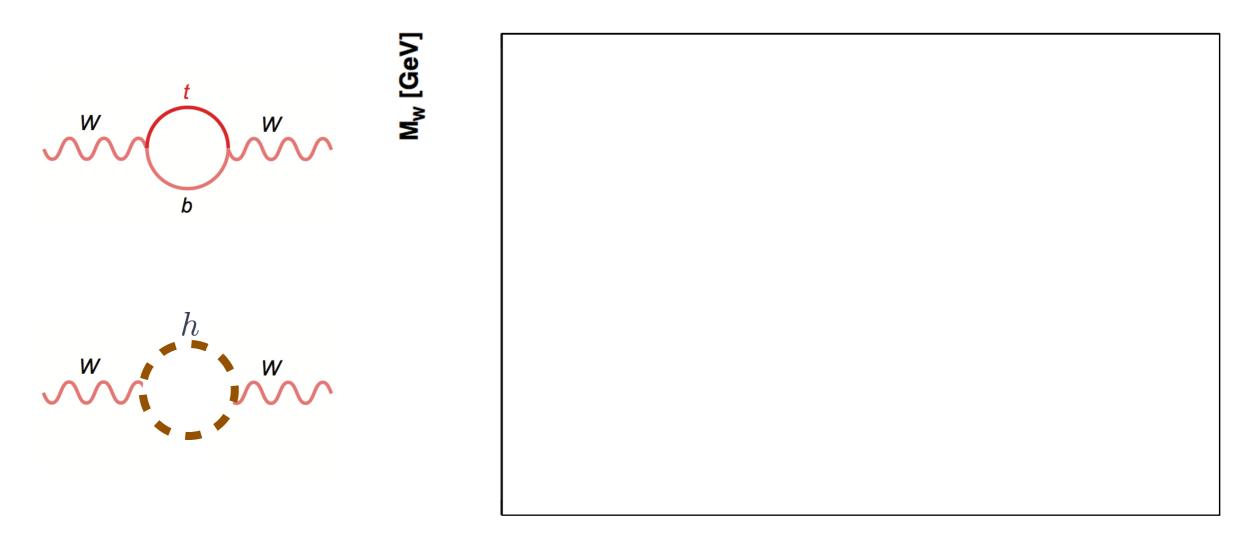




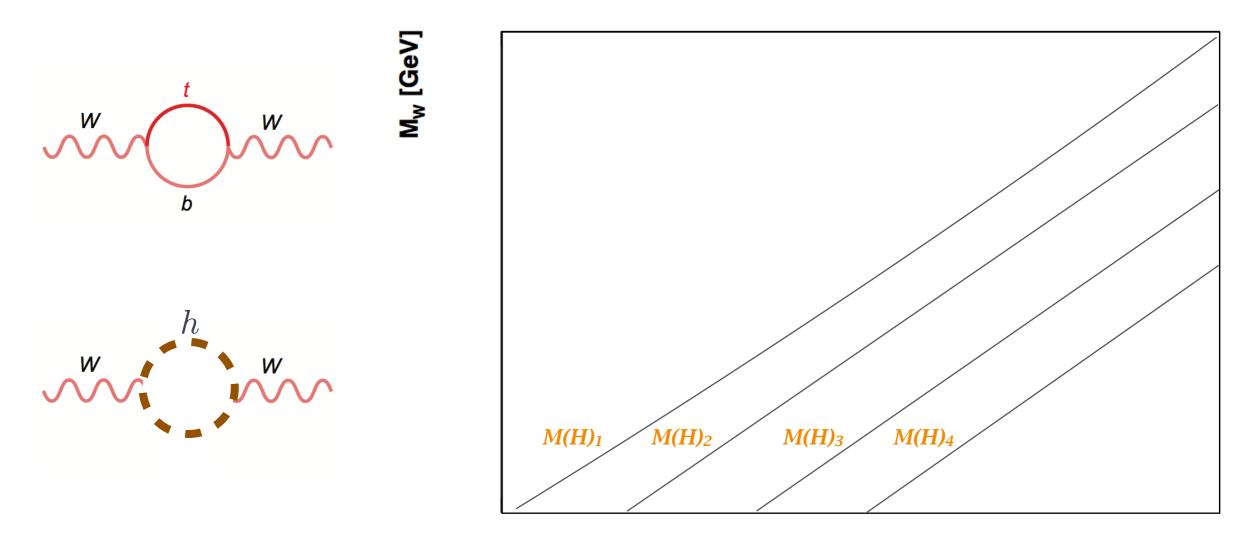


The precision Higgs Boson program is in full swing.

Precision Study of Electroweak Physics

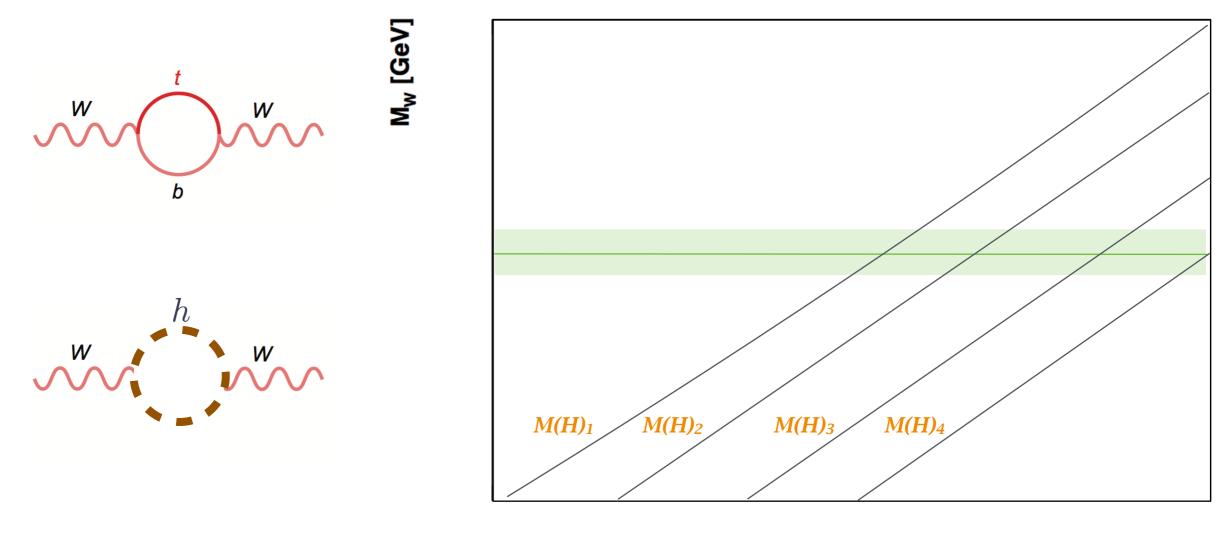


Correlating the Spin 1 messengers, leptons, quarks, and the Higgs boson



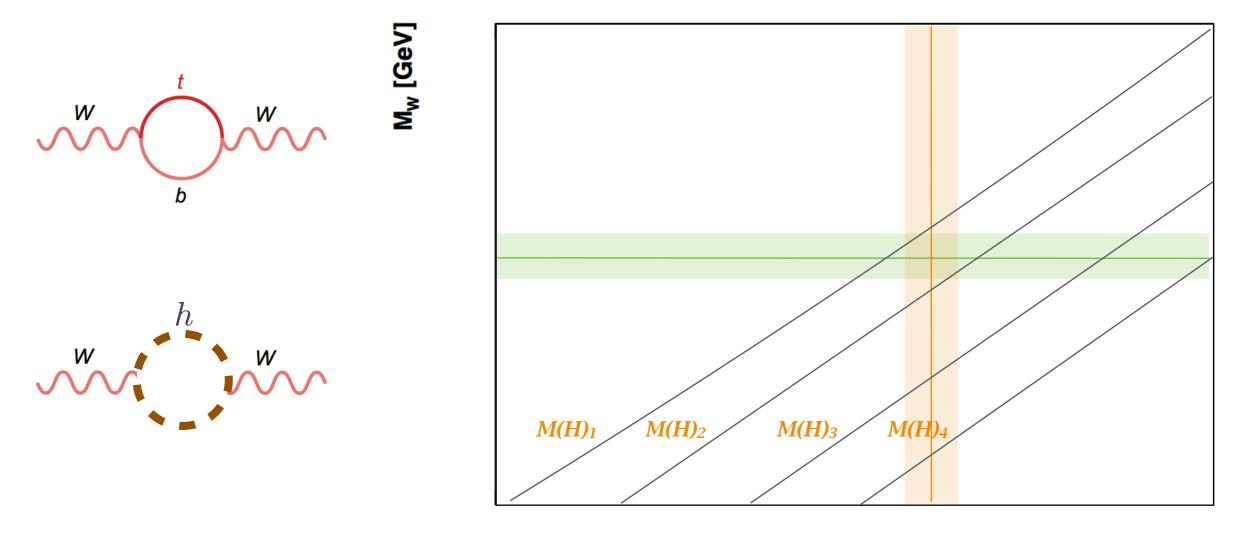
m_t [GeV]

Correlating the Spin 1 messengers, leptons, quarks, and the Higgs boson

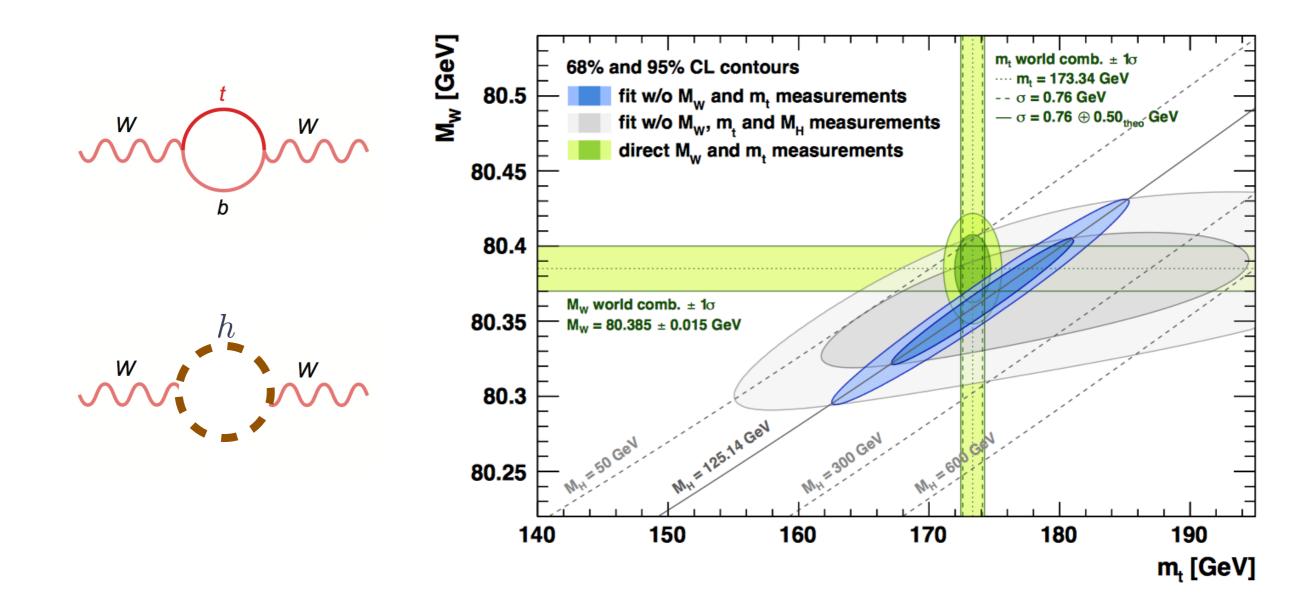


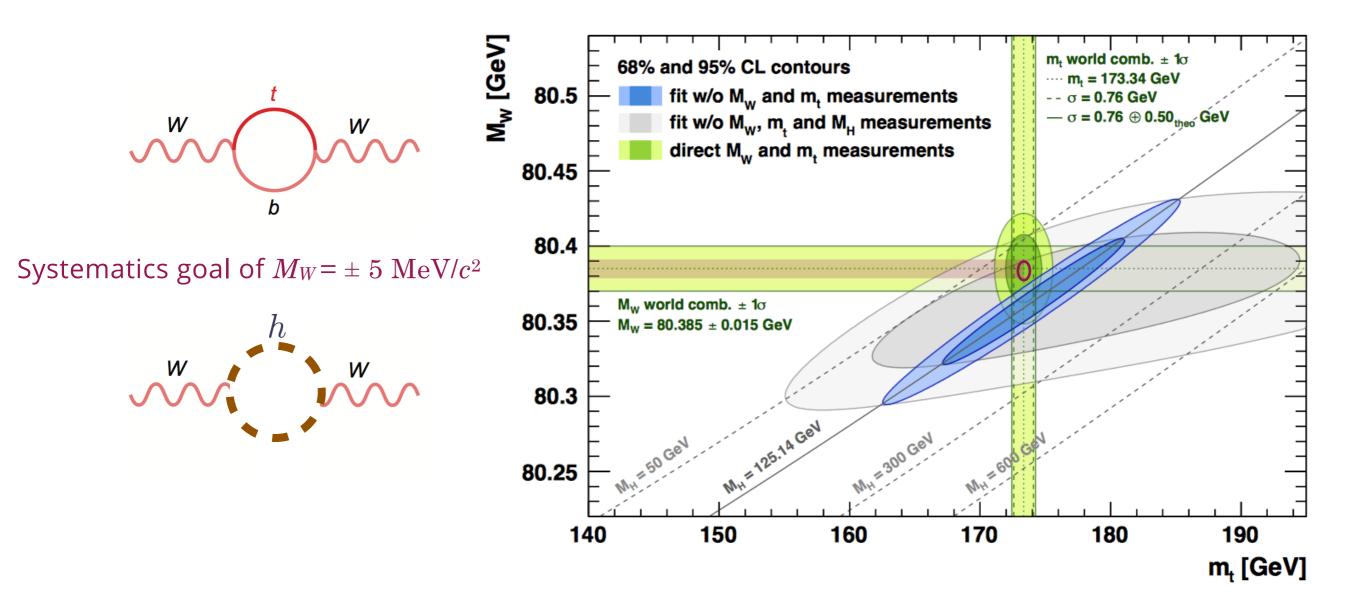
m_t [GeV]

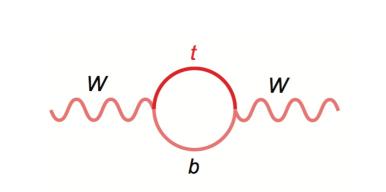
Correlating the Spin 1 messengers, leptons, quarks, and the Higgs boson



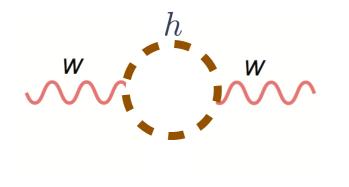
m_t [GeV]

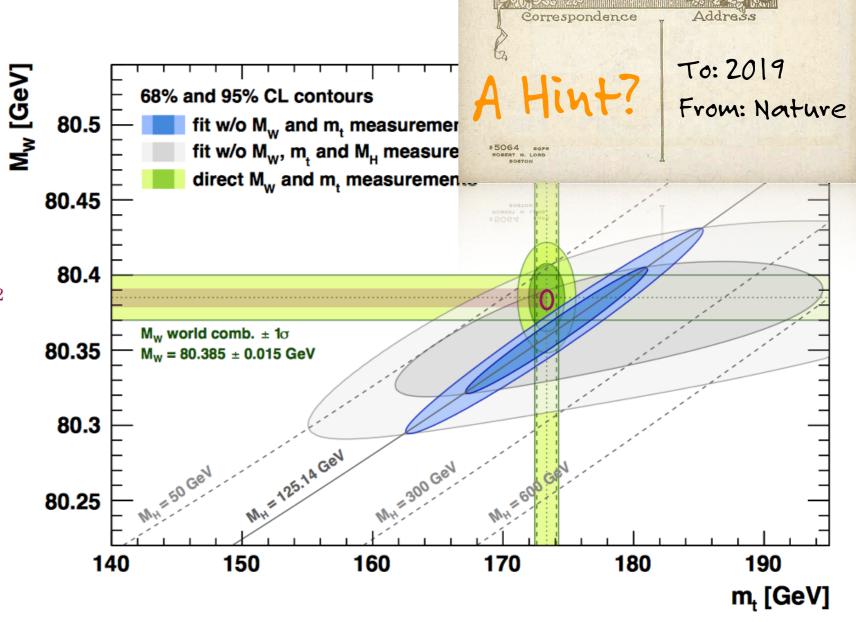






Systematics goal of M_W = $\pm~5~{
m MeV}/c^2$





Fully Understanding the Top Quark

why measure *m*^t precisely?

why measure *m*_t precisely?

EW precision observables

keep up with M_W precision

why measure *m*^t precisely?

 EW precision observables keep up with *M_W* precision
 fundamental parameter largest coupling to Higgs stability argument sensitivity

why measure *m*^t precisely?

$$V = \lambda v H^3 + \frac{\lambda}{4} H^4$$

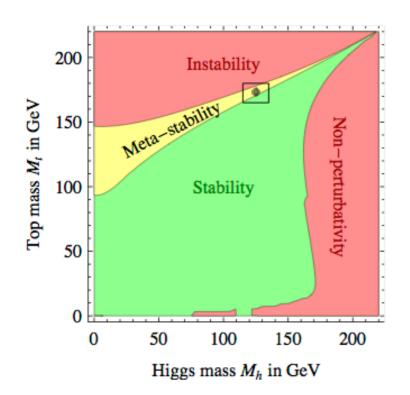
EW precision observables

keep up with M_W precision

fundamental parameter

largest coupling to Higgs stability argument sensitivity

why measure *m*_t precisely?



$$V = \lambda v H^3 + \frac{\lambda}{4} H^4$$

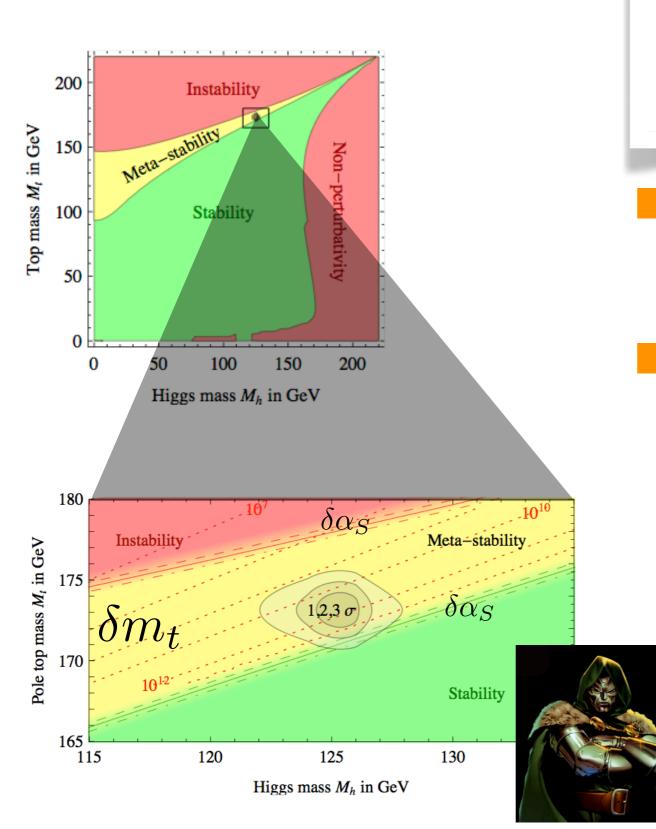
EW precision observables

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largest coupling to Higgs stability argument sensitivity

why measure *m*_t precisely?



$$V = \lambda v H^3 + \frac{\lambda}{4} H^4$$

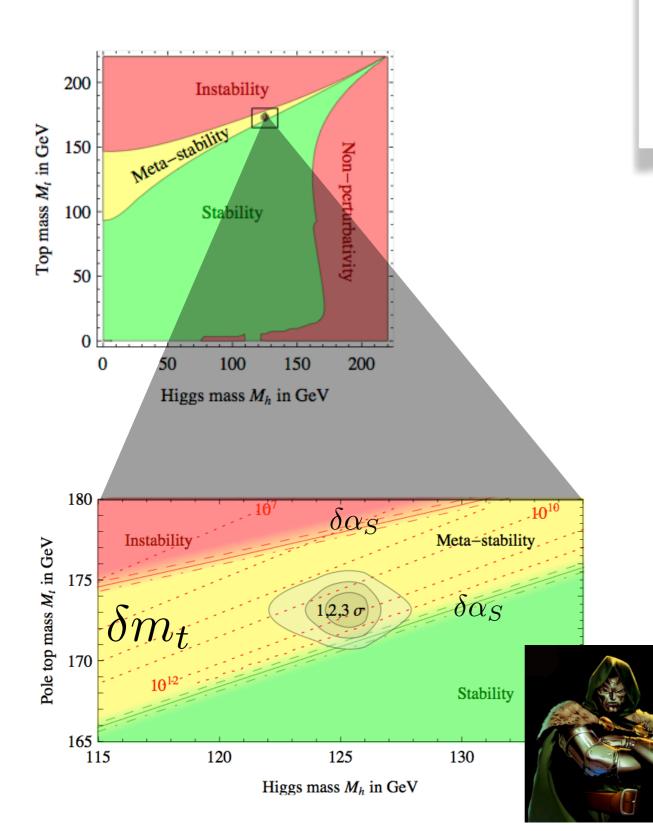
EW precision observables

keep up with M_W precision

fundamental parameter

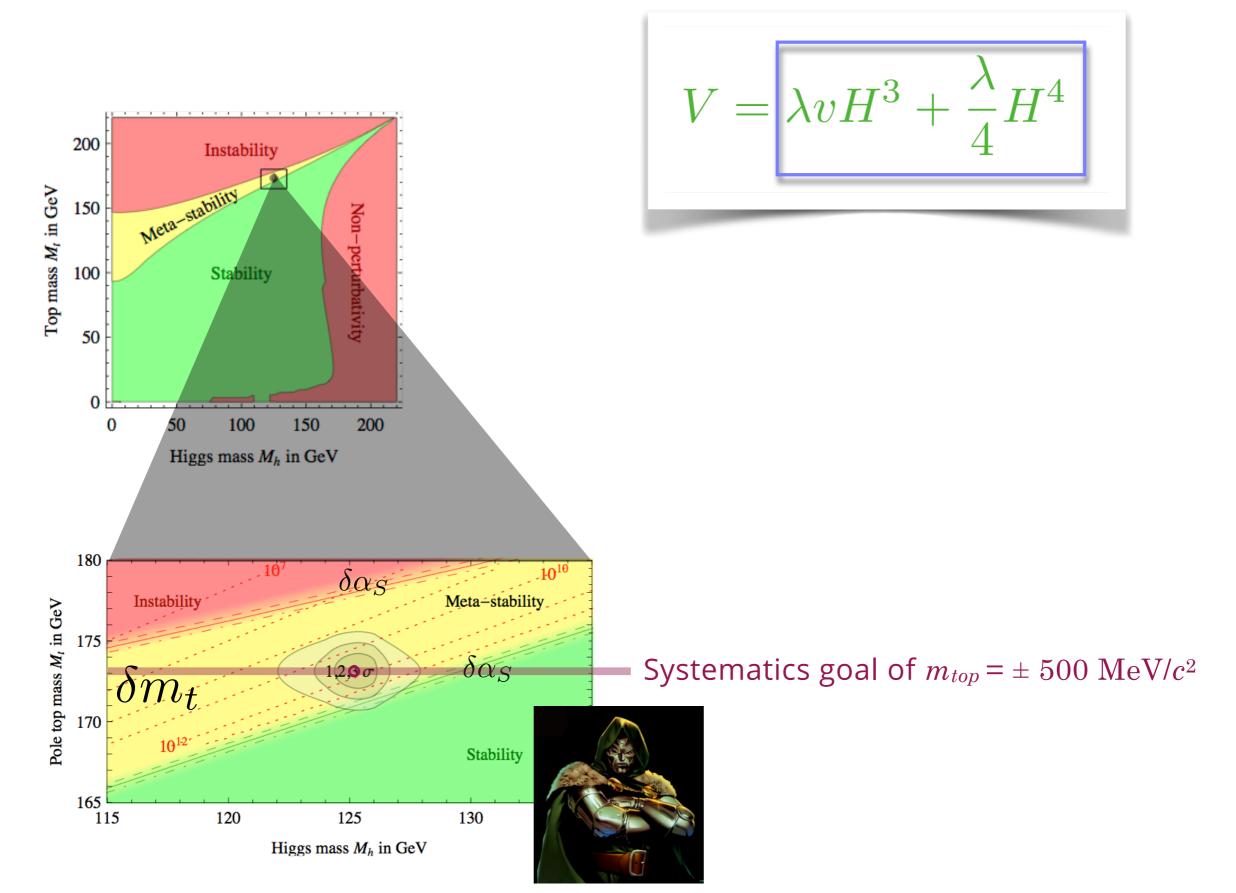
largest coupling to Higgs stability argument sensitivity

why measure *m*^t precisely?

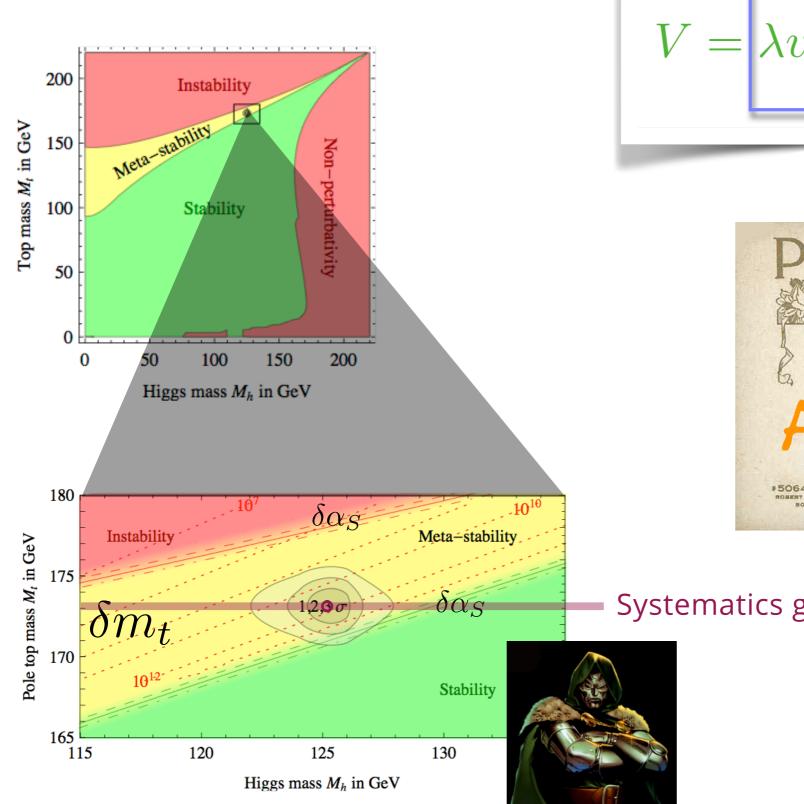


$$V = \lambda v H^3 + \frac{\lambda}{4} H^4$$

why measure *m*_t precisely?



why measure *m*^t precisely?



$$V = \lambda v H^3 + \frac{\lambda}{4} H^4$$



Systematics goal of m_{top} = \pm 500 MeV/ c^2

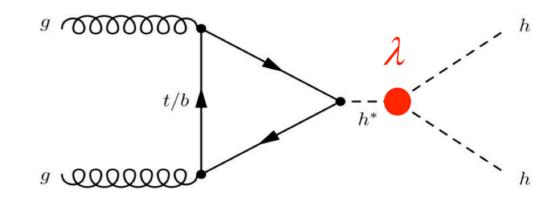
OBTW...that potential shape?

from higgs-higgs self-coupling



very hard...

maybe 50% precision at HL-LHC



The Path Beyond the Standard Model

history suggests

new families Expansion of the gauge groups Compositeness Beyond the Standard Model: motivation from non-zero neutrino mass, the hierarchy problem, the antimatter problem, & the dark matter problem



Dominated by prospects for new particles @ TeV-ish mass and/or:



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

ATLAS Preliminary $\sqrt{s} = 8, 13 \text{ TeV}$

St	atus: May 2019					$\int \mathcal{L} dt = (3.2 - 139) \text{fb}^{-1}$	$\sqrt{s} = 8, 13 \text{ TeV}$
	Model	<i>ℓ</i> , γ	Jets †	$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$	∫£ dt[ft		Reference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH high $\sum p_T$ ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WW \rightarrow q$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{ll} qqq & 0 \ e,\mu \\ & 1 \ e,\mu \end{array} \geq$	$1 - 4 j$ $- 2j$ $\geq 2j$ $\geq 3j$ $- 2J$ $2J$ $\pm 1 b, \geq 1J/2$ $\geq 2 b, \geq 3j$		36.1 36.7 37.0 3.2 3.6 36.7 36.1 139 36.1 36.1	MD TeV scale 7.7 TeV $n = 2$ MS 8.6 TeV $n = 3 \text{ HLZ NLO}$ $n = 6$ Mth 8.9 TeV $n = 6$ $m = 3 \text{ TeV}$, rot BH $n = 6$ $m = 3 \text{ TeV}$, rot BH $m = 6$ $m = 0$ $m = 6$ $m = 0$ $m = 0$ $m = 6$ $m = 6$ $m = 10$ $m = 10$ $m = 15\%$ $m = 11$ $m = 15\%$	1711.03301 1707.04147 1703.09127 1606.02265 1512.02586 1707.04147 1808.02380 ATLAS-CONF-2019-003 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{Leptophobic} Z' \to bb \\ \operatorname{Leptophobic} Z' \to tt \\ \operatorname{SSM} W' \to \ell\nu \\ \operatorname{SSM} W' \to \tau\nu \\ \operatorname{HVT} V' \to WZ \to qqqq \text{ m} \\ \operatorname{HVT} V' \to WH/ZH \text{ model} \\ \operatorname{LRSM} W_R \to tb \\ \operatorname{LRSM} W_R \to \mu N_R \end{array}$	1 <i>e</i> , μ 1 τ nodel B 0 <i>e</i> , μ		- 2j Yes Yes - -	139 36.1 36.1 139 36.1 139 36.1 36.1 36.1 80	Z' mass 5.1 TeV Z' mass 2.42 TeV Z' mass 2.1 TeV Z' mass 3.0 TeV Y' mass 3.0 TeV W' mass 6.0 TeV W' mass 3.7 TeV V' mass 3.6 TeV V' mass 3.6 TeV V' mass 3.6 TeV V' mass 3.6 TeV V' mass 3.293 TeV W _R mass 3.25 TeV W _R mass 5.0 TeV	1903.06248 1709.07242 1805.09299 1804.10823 CERN-EP-2019-100 1801.06992 ATLAS-CONF-2019-003 1712.06518 1807.10473 1904.12679
CI	CI qqqq CI ℓℓqq CI tttt	_ 2 e, μ ≥1 e,μ	2 j _ ≥1 b, ≥1 j	– – Yes	37.0 36.1 36.1	Λ 21.8 TeV $\eta_{LL}^ \Lambda$ 40.0 TeV $\eta_{LL}^ \Lambda$ 2.57 TeV $ C_{4t} = 4\pi$	1703.09127 1707.02424 1811.02305
MQ	Axial-vector mediator (Dirac Colored scalar mediator (D $VV_{\chi\chi}$ EFT (Dirac DM) Scalar reson. $\phi \rightarrow t\chi$ (Dirac	irac DM) 0 e, μ 0 e, μ	$\begin{array}{c} 1-4 \ j \\ 1-4 \ j \\ 1 \ J, \leq 1 \ j \\ 1 \ b, \ 0\mbox{-}1 \ J \end{array}$	Yes Yes Yes Yes	36.1 36.1 3.2 36.1	$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	1711.03301 1711.03301 1608.02372 V 1812.09743
ΓØ	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen	1,2 e 1,2 μ 2 τ 0-1 e,μ	≥ 2 j ≥ 2 j 2 b 2 b	Yes Yes - Yes	36.1 36.1 36.1 36.1	LQ mass 1.4 TeV $\beta = 1$ LQ mass 1.56 TeV $\beta = 1$ LQ" mass 1.03 TeV $\mathcal{B}(LQ_3^u \to b\tau) = 1$ LQ_3^d mass 970 GeV $\mathcal{B}(LQ_3^u \to t\tau) = 0$	1902.00377 1902.00377 1902.08103 1902.08103
Heavy quarks	$ \begin{array}{l} VLQ \ TT \rightarrow Ht/Zt/Wb + \\ VLQ \ BB \rightarrow Wt/Zb + X \\ VLQ \ T_{5/3} \ T_{5/3} \ T_{5/3} \rightarrow Wt \\ VLQ \ Y \rightarrow Wb + X \\ VLQ \ B \rightarrow Hb + X \\ VLQ \ QQ \rightarrow WqWq \\ \end{array} $	multi-channel + X $2(SS)/\geq 3 e, \mu$	≥1 b, ≥1 j ≥ 1 b, ≥ 1j	Yes	36.1 36.1 36.1 36.1 79.8 20.3	T mass 1.37 TeV SU(2) doublet B mass 1.34 TeV SU(2) doublet $T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$ Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ B mass 1.21 TeV $\kappa_B = 0.5$	1808.02343 1808.02343 1 1807.11883 1812.07343 ATLAS-CONF-2018-024 1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton γ^*	1 γ - 3 e,μ 3 e,μ,τ	2j 1j 1b,1j –		139 36.7 36.1 20.3 20.3	q* mass 6.7 TeV only u^* and d^* , $\Lambda = m(q^*)$ q* mass 5.3 TeV only u^* and d^* , $\Lambda = m(q^*)$ b* mass 2.6 TeV $\Lambda = 3.0 \text{ TeV}$ t* mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$ v* mass 1.6 TeV $\Lambda = 1.6 \text{ TeV}$	ATLAS-CONF-2019-007 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana v Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles Magnetic monopoles $\sqrt{s} = 8 \text{ TeV}$	$ 1 e, \mu \\ 2 \mu \\ 2,3,4 e, \mu (SS) \\ 3 e, \mu, \tau \\ - \\ - \\ \sqrt{s} = 13 \text{ TeV} $	≥ 2 j 2 j) - - - - - -	Yes 	79.8 36.1 36.1 20.3 36.1 34.4	N° mass560 GeVN _R mass3.2 TeVH ^{±±} mass870 GeVH ^{±±} mass870 GeVH ^{±±} mass1.22 TeVmulti-charged particle mass1.22 TeVmonopole mass2.37 TeV10 ⁻¹ 1	1812.03673

Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

full data

†Small-radius (large-radius) jets are denoted by the letter j (J).

partial data

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

 $\sqrt{s} = 8, 13 \text{ TeV}$

 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$

Model ℓ, γ Jets; E_T^{miss}	-	5		Reference
$\begin{array}{llllllllllllllllllllllllllllllllllll$	36.1 Mp Tevsca 36.7 Ms Tevsca 37.0 Mth State 3.2 Mth State 3.6 Mth State 36.7 GKK mass State 36.1 GKK mass State 36.1 GKK mass State 36.1 KK mass State 36.1 KK mass State	7.7 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV 4.1 TeV 2.3 TeV .6 TeV 3.8 TeV 1.8 TeV	$\begin{array}{l} n = 2 \\ n = 3 \; \text{HLZ NLO} \\ n = 6 \\ n = 6, \; M_D = 3 \; \text{TeV}, \; \text{rot BH} \\ n = 6, \; M_D = 3 \; \text{TeV}, \; \text{rot BH} \\ k/\overline{M}_{PI} = 0.1 \\ k/\overline{M}_{PI} = 1.0 \\ k/\overline{M}_{PI} = 1.0 \\ \Gamma/m = 15\% \\ \hline \text{Tier (1,1)}, \; \mathcal{B}(A^{(1,1)} \to tt) = 1 \end{array}$	1711.03301 1707.04147 1703.09127 1606.02265 1512.02586 1707.04147 1808.02380 ATLAS-CONF-2019-003 1804.10823 1803.09678
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	139 Z' mass 36.1 Z' mass 36.1 Z' mass 36.1 Z' mass 36.1 Z' mass 139 W' mass 36.1 W' mass 80 W_R mass	5.1 TeV 2.42 TeV 2.1 TeV 3.0 TeV 6.0 TeV 3.7 TeV 3.6 TeV 2.93 TeV 3.25 TeV 5.0 TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$ $m(N_R) = 0.5$ TeV, $g_L = g_R$	1903.06248 1709.07242 1805.09299 1804.10823 CERN-EP-2019-100 1801.06992 ATLAS-CONF-2019-003 1712.06518 1807.10473 1904.12679
$ \overrightarrow{O} \begin{array}{c} CI qqqq & - & 2j & - \\ CI \ell \ell qq & 2e, \mu & - & - \\ CI tttt & \geq 1e, \mu & \geq 1b, \geq 1j \end{array} $	37.0 Λ Ξ 36.1 Λ Ξ 36.1 Λ Ξ	2.57 TeV	21.8 TeV η_{LL}^- 40.0 TeV η_{LL}^- $ C_{4t} = 4\pi$	1703.09127 1707.02424 1811.02305
Axial-vector mediator (Dirac DM) $0 e, \mu$ $1-4 j$ YesColored scalar mediator (Dirac DM) $0 e, \mu$ $1-4 j$ Yes $VV_{\chi\chi}$ EFT (Dirac DM) $0 e, \mu$ $1 J, \leq 1 j$ YesScalar reson. $\phi \rightarrow t\chi$ (Dirac DM) $0-1 e, \mu$ $1 b, 0-1 J$ Yes		55 TeV .67 TeV 3.4 TeV	$\begin{array}{l} g_q{=}0.25, \ g_{\chi}{=}1.0, \ m(\chi) = 1 \ {\rm GeV} \\ g{=}1.0, \ m(\chi) = 1 \ {\rm GeV} \\ m(\chi) < 150 \ {\rm GeV} \\ y = 0.4, \ \lambda = 0.2, \ m(\chi) = 10 \ {\rm GeV} \end{array}$	1711.03301 1711.03301 1608.02372 1812.09743
OrgScalar LQ 1st gen $1,2 e$ $\geq 2 j$ YesScalar LQ 2nd gen $1,2 \mu$ $\geq 2 j$ YesScalar LQ 3rd gen 2τ $2 b$ $-$ Scalar LQ 3rd gen $0-1 e, \mu$ $2 b$ Yes		TeV 56 TeV	$egin{aligned} eta &= 1 \ eta &= 1 \ \mathcal{B}(\mathrm{LQ}_3^u o b au) &= 1 \ \mathcal{B}(\mathrm{LQ}_3^u o t au) &= 1 \ \mathcal{B}(\mathrm{LQ}_3^d o t au) &= 0 \end{aligned}$	1902.00377 1902.00377 1902.08103 1902.08103
$ \begin{array}{lll} & \mbox{VLQ } TT \rightarrow Ht/Zt/Wb + X & \mbox{multi-channel} \\ & \mbox{VLQ } BB \rightarrow Wt/Zb + X & \mbox{multi-channel} \\ & \mbox{VLQ } T_{5/3} T_{5/3}] T_{5/3} \rightarrow Wt + X & \mbox{2} (SS)/\geq 3 \ e,\mu \geq 1 \ b,\geq 1 \ j & \mbox{Yes} \\ & \mbox{VLQ } Y \rightarrow Wb + X & \mbox{1} \ e,\mu & \geq 1 \ b,\geq 1 \ j & \mbox{Yes} \\ & \mbox{VLQ } B \rightarrow Hb + X & \mbox{0} \ e,\mu,2 \ \gamma & \geq 1 \ b,\geq 1 \ j & \mbox{Yes} \\ & \mbox{VLQ } QQ \rightarrow WqWq & \mbox{1} \ e,\mu & \geq 4 \ j & \mbox{Yes} \\ \end{array} $		TeV .64 TeV 1.85 TeV	SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ $\kappa_B = 0.5$	1808.02343 1808.02343 1807.11883 1812.07343 ATLAS-CONF-2018-024 1509.04261
SolutionExcited quark $q^* \rightarrow qg$ -2 jExcited quark $q^* \rightarrow q\gamma$ 1 γ 1 jExcited quark $b^* \rightarrow bg$ -1 b, 1 jExcited lepton ℓ^* 3 e, μ -Excited lepton γ^* 3 e, μ, τ -	139 q* mass 36.7 q* mass 36.1 b* mass 20.3 t* mass 20.3 v* mass 20.3 v* mass	6.7 TeV 5.3 TeV 2.6 TeV 3.0 TeV .6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	ATLAS-CONF-2019-007 1709.10440 1805.09299 1411.2921 1411.2921
Type III Seesaw LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Multi-charged particles Magnetic monopoles $\sqrt{s} = 8 \text{ TeV}$ $1 e, \mu \ge 2 j$ $2 \mu = 2 j$ 	79.8 N ⁰ mass 560 GeV 36.1 N _R mass 870 GeV 36.1 H ^{±±} mass 870 GeV 20.3 H ^{±±} mass 400 GeV 36.1 multi-charged particle mass 1.22 Te 34.4 monopole mass 1.21 Te 10 ⁻¹ 1	3.2 TeV 2.37 TeV 1 1	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$ DY production, $ q = 5e$ DY production, $ g = 1g_D$, spin 1/2 Mass scale [TeV]	ATLAS-CONF-2018-020 1809.11105 1710.09748 1411.2921 1812.03673 1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

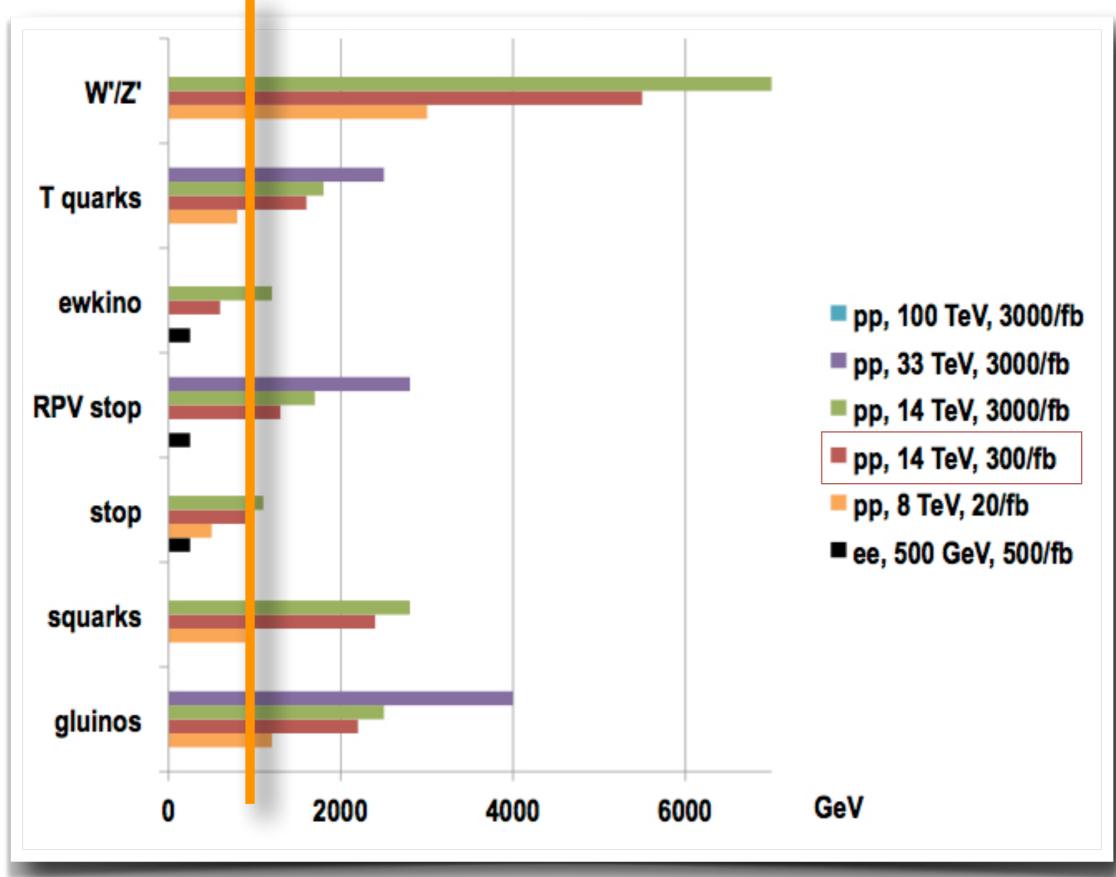
†Small-radius (large-radius) jets are denoted by the letter j (J).

Model	Signature	$\int \mathcal{L} dt$ [fb]	Mass limit		Reference
$\tilde{q}\tilde{q},\tilde{q}\! ightarrow\!q\tilde{\chi}_{1}^{0}$	$\begin{array}{ccc} 0 \ e, \mu & ext{2-6 jets} & E_T^{ ext{miss}} \\ ext{mono-jet} & ext{1-3 jets} & E_T^{ ext{miss}} \end{array}$	36.1 36.1		1.55 $m(\tilde{\chi}_1^0) < 100 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1712.02332 1711.03301
$\tilde{g}\tilde{g},\tilde{g}\! ightarrow\!qar{q}\tilde{\chi}^0_1$	$0 e, \mu$ 2-6 jets E_T^{miss}		ğ ğ Forbidden	2.0 $m(\tilde{\chi}_1^0)$ <200 GeV $m(\tilde{\chi}_1^0)$ =900 GeV	1712.02332 1712.02332
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$\begin{array}{ccc} 3 \ e, \mu & 4 \ { m jets} \\ e e, \mu \mu & 2 \ { m jets} & E_T^{{ m miss}} \end{array}$	36.1 36.1	ğ ğ	1.85 $m(\tilde{\chi}_1^0)$ = 800 GeV 1.2 $m(\tilde{\chi}_1^0)$ = 50 GeV	1706.03731 1805.11381
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	$\begin{array}{ccc} 0 \ e, \mu & \ 7 \ -11 \ { m jets} & \ E_T^{ m miss} \\ { m SS} \ e, \mu & \ 6 \ { m jets} \end{array}$	36.1 139	reg reg	1.8 $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ 1.15 $m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	1708.02794 ATLAS-CONF-2019-015
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	$\begin{array}{ccc} \text{0-1} \ e, \mu & \text{3} \ b & E_T^{\text{miss}} \\ \text{SS} \ e, \mu & \text{6 jets} \end{array}$		5 75 75 75	2.25 $m(\tilde{\chi}^0)$ 200 GeV 1.25 $m(\tilde{\chi}^0)$ 200 GeV	ATLAS-CONF-2018-041 ATLAS-CONF-2019-015
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / i \tilde{\chi}_1^{\pm}$	Multiple Multiple Multiple	36.1 36.1 139	\$\bar{b}_1\$ Forbidden 0.9 \$\bar{b}_1\$ Forbidden 0.58-0.82 \$\bar{b}_1\$ Forbidden 0.74	$\begin{array}{c} m(\tilde{\chi}_{1}^{0}){=}300\text{GeV},BR(b\tilde{\chi}_{1}^{0}){=}1\\ m(\tilde{\chi}_{1}^{0}){=}300\text{GeV},BR(b\tilde{\chi}_{1}^{0}){=}BR(t\tilde{\chi}_{1}^{-}){=}0.5\\ m(\tilde{\chi}_{1}^{0}){=}200\text{GeV},m(\tilde{\chi}_{1}^{+}){=}300\text{GeV},BR(t\tilde{\chi}_{1}^{+}){=}1\end{array}$	1708.09266, 1711.03301 1708.09266 ATLAS-CONF-2019-015
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	$0 e, \mu$ $6 b$ E_T^{miss}	139	\$\tilde{b}_1\$ Forbidden \$\tilde{b}_1\$ 0.23-0.48	0.23-1.35 $ \Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, \ m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV} \\ \Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, \ m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV} $	SUSY-2018-31 SUSY-2018-31
$b_1b_1, b_1 \rightarrow bX_2^{\circ} \rightarrow bhX_1^{\circ}$ $\tilde{i}_1\tilde{i}_1, \tilde{i}_1 \rightarrow Wb\tilde{\chi}_1^0 \text{ or } t\tilde{\chi}_1^0$ $\tilde{i}_1\tilde{i}_1, \tilde{i}_1 \rightarrow Wb\tilde{\chi}_1^0$ $\tilde{i}_1\tilde{i}_1, \tilde{i}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	$\begin{array}{cccc} 0\text{-}2 \ e, \mu & 0\text{-}2 \ \text{jets}/1\text{-}2 \ b \ E_T^{\text{miss}} \\ 1 \ e, \mu & 3 \ \text{jets}/1 \ b & E_T^{\text{miss}} \\ 1 \ \tau + 1 \ e, \mu, \tau & 2 \ \text{jets}/1 \ b & E_T^{\text{miss}} \end{array}$	36.1 139 36.1	<i>i</i> ₁	0 $m(\tilde{\chi}_1^0)=1 \text{ GeV}$ $m(\tilde{\chi}_1^0)=400 \text{ GeV}$ $m(\tilde{\tau}_1)=800 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520 ATLAS-CONF-2019-017 1803.10178
$ \begin{array}{c} \tilde{t}_{1}t_{1}, t_{1} \rightarrow Wb\tilde{\chi}_{1} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow \tilde{\tau}_{1}b\nu, \tilde{\tau}_{1} \rightarrow \tau\tilde{G} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow c\tilde{\chi}_{1}^{0} / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_{1}^{0} \end{array} $	0 e, μ 2 c E_T^{miss} 0 e, μ mono-jet E_T^{miss}	36.1	\vec{c} 0.85 \vec{i}_1 0.46 \vec{i}_1 0.43	$\begin{array}{c} m(\tilde{\chi}_{1}^{0}) \!=\! 0 \; GeV \\ m(\tilde{\iota}_{1},\tilde{c}) \!=\! m(\tilde{\chi}_{1}^{0}) \!=\! 50 \; GeV \\ m(\tilde{\iota}_{1},\tilde{c}) \!=\! m(\tilde{\chi}_{1}^{0}) \!=\! 5 \; GeV \end{array}$	1805.01649 1805.01649 1711.03301
$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$ $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	$\begin{array}{cccc} 1-2 \ e, \mu & 4 \ b & E_T^{\text{miss}} \\ 3 \ e, \mu & 1 \ b & E_T^{\text{miss}} \end{array}$	36.1 139	<i>i</i> ₂ 0.32-0.88 <i>i</i> ₂ Forbidden	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\iota}_1)-m(\tilde{\chi}_1^0)=180 \text{ GeV}$ $m(\tilde{\chi}_1^0)=360 \text{ GeV}, m(\tilde{\iota}_1)-m(\tilde{\chi}_1^0)=40 \text{ GeV}$	1706.03986 ATLAS-CONF-2019-016
$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	$\begin{array}{ccc} \textbf{2-3} \ e, \mu & E_T^{\text{miss}} \\ ee, \mu \mu & \geq 1 & E_T^{\text{miss}} \end{array}$	36.1 139	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} = 0.6 $ $ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} = 0.205 $	$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5$ GeV	1403.5294, 1806.02293 ATLAS-CONF-2019-014
$ ilde{\chi}_1^{\pm} ilde{\chi}_1^{\mp}$ via WW $ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via Wh	$\begin{array}{ccc} 2 \ e, \mu & E_T^{\text{miss}} \\ 0 \ -1 \ e, \mu & 2 \ b/2 \ \gamma & E_T^{\text{miss}} \end{array}$	139 139		${ m m}(ilde{\chi}_1^0){=}0$ ${ m m}(ilde{\chi}_1^0){=}70~{ m GeV}$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-019, ATLAS-CONF-2019
$ \vec{\sum}_{\mathbf{D}} \vec{X}_{1}^{\pm} \vec{X}_{1}^{\mp} \text{ via } \tilde{\ell}_{L} / \tilde{v} $ $ \vec{\tau}, \tilde{\tau} \to \tau \tilde{\chi}_{1}^{0} $	$\begin{array}{ccc} 2 \ e, \mu & E_T^{\text{miss}} \\ 2 \ \tau & E_T^{\text{miss}} \end{array}$	139 139	$\tilde{\chi}_{1}^{\pm}$ 1. $\tilde{\tau}$ [$\tilde{\tau}_{L}, \tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	$m(\tilde{\chi}^0_1)=0$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-018
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R},\tilde{\ell}{\rightarrow}\ell\tilde{\chi}^0_1$	$\begin{array}{ccc} 2 \ e, \mu & 0 \ \text{jets} & E_T^{\text{miss}} \\ 2 \ e, \mu & \geq 1 & E_T^{\text{miss}} \end{array}$		ℓ 0.7 ℓ 0.256	$m(ilde{\mathcal{X}}_1^0)=0$ $m(ilde{\mathcal{X}}_1^0)=10~GeV$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-014
ĤĤ, Ĥ→hĜ/ZĜ	$\begin{array}{lll} 0 \ e, \mu & \geq 3 \ b & E_T^{\rm miss} \\ 4 \ e, \mu & 0 \ {\rm jets} & E_T^{\rm miss} \end{array}$	36.1 36.1	H 0.13-0.23 0.29-0.88 H 0.3	$BR(\tilde{\chi}^0_1 \to h\tilde{G})=1$ $BR(\tilde{\chi}^0_1 \to Z\tilde{G})=1$	1806.04030 1804.03602
Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet E_T^{miss}	36.1	$ \tilde{\chi}_{1}^{\pm} = 0.46 $ $ \tilde{\chi}_{1}^{\pm} = 0.15 $	Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	Multiple Multiple	36.1 36.1	\tilde{g} \tilde{g} [$\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}$]	2.0 m(χ̃ ⁰)=100 GeV	1902.01636,1808.04095 1710.04901,1808.04095
LFV $pp \rightarrow \tilde{\nu}_{\tau} + X, \tilde{\nu}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$ $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{T}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	$e\mu, e\tau, \mu\tau$ 4 e, μ 0 jets E_T^{miss}	3.2 36.1	\tilde{v}_{τ} $\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0} [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$ 0.82	1.9 $\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$ 1.33 $m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$	1607.08079 1804.03602
$\begin{array}{c} x_1 x_1 / x_2 \rightarrow w w/Z \ell \ell \ell \ell \nu \nu \\ \tilde{g} \tilde{g}, \tilde{g} \rightarrow q q \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q q q \end{array}$	4-5 large- <i>R</i> jets Multiple	36.1 36.1	$\tilde{g} = [m(\tilde{\chi}_1^0)=200 \text{ GeV}, 1100 \text{ GeV}]$	1.3 1.9 Large λ_{112}''' 05 2.0 $m(\tilde{\chi}_1^0)$ =200 GeV, bino-like	1804.03568 1804.03568 ATLAS-CONF-2018-003
$\widetilde{t}\widetilde{t}, \ \widetilde{t} \to t \widetilde{\chi}_1^0, \ \widetilde{\chi}_1^0 \to t bs$ $\widetilde{t}_1 \widetilde{t}_1, \ \widetilde{t}_1 \to bs$	Multiple 2 jets + 2 <i>b</i>	36.1 36.7		05 $m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003 1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	$\begin{array}{ccc} 2 e, \mu & 2 b \\ 1 \mu & \text{DV} \end{array}$	36.1 136	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.4-1.45 B R($\tilde{t}_1 \rightarrow be/b\mu$)>20% B R($\tilde{t}_1 \rightarrow q\mu$)=100%, $\cos\theta_t$ =1	1710.05544 ATLAS-CONF-2019-006

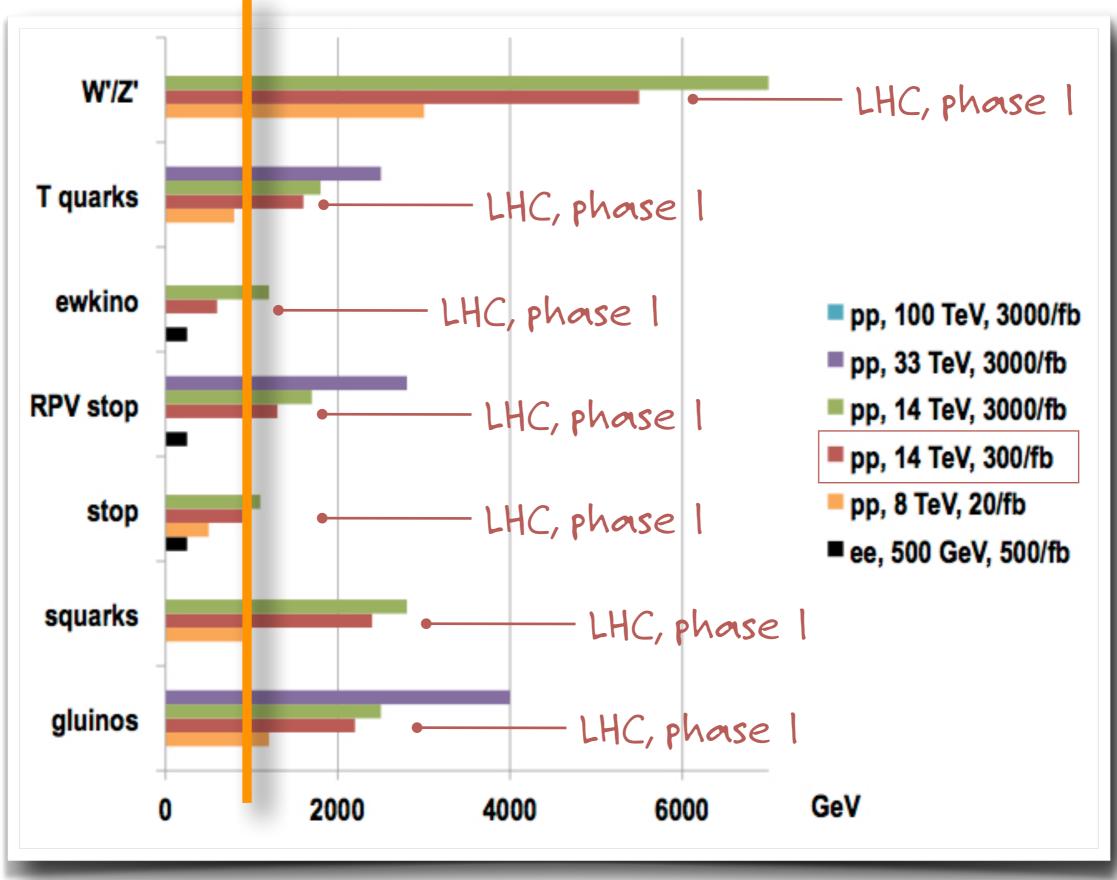
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Model		Signatur	e j	L dt [fb	-1]	Mass limit				Reference
$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i> mono-je	2-6 jets t 1-3 jets	E_T^{miss} E_T^{miss}	36.1 36.1	 <i>q</i> [2×, 8× Degen.] <i>q</i> [1×, 8× Degen.] 	0.43	0.9	1.55	m(𝔅 ¹)<100 GeV m(𝔅)-m(𝔅 ¹)=5 GeV	1712.02332 1711.03301
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2-6 jets	E_T^{miss}	36.1	ĩg ĩ		Forbidden	2.0 0.95-1.6		1712.02332 1712.02332
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	З <i>е</i> , µ <i>ее, µ</i> µ	4 jets 2 jets	E_T^{miss}	36.1 36.1	8 785 75		ronbidden	1.85	$m(\tilde{\chi}_1^0) < 800 \text{ GeV}$ $m(\tilde{\chi}_1^0) < 800 \text{ GeV}$ $m(\tilde{\chi}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$	1706.03731 1805.11381
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 <i>e</i> ,μ SS <i>e</i> ,μ	7-11 jets	E_T^{miss}	36.1 139	s g z			1.8	$m(\tilde{\chi}_{1}^{0})$ <400 GeV	1708.02794 ATLAS-CONF-2019-015
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	0-1 <i>e</i> ,μ SS <i>e</i> ,μ	3 <i>b</i>	$E_T^{\rm miss}$	79.8 139	g řg				.25 $m(\tilde{\chi}) \cdot m(\tilde{\chi}_1^0) = 200 \text{ GeV}$ $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{\chi}) \cdot m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2013-015 ATLAS-CONF-2018-041 ATLAS-CONF-2019-015
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^\pm$		Multiple Multiple Multiple		36.1 36.1 139	$egin{array}{cccc} egin{array}{cccc} egin{array}{ccccc} eta_1 & & Fc \ eta_1 & & eta_1 \ eta_1 & & eta_1 \ eta_1 & & eta_1 \end{array} \end{array}$	rbidden Forbidden Forbidden	0.9 0.58-0.82 0.74		$\begin{array}{c} m(\tilde{x}_1^0) {=} 300 \ GeV, BR(b\tilde{x}_1^0) {=} 1\\ m(\tilde{x}_1^0) {=} 300 \ GeV, BR(b\tilde{x}_1^0) {=} BR(b\tilde{x}_1^\pm) {=} 0.5\\ {}^0_1) {=} 200 \ GeV, m(\tilde{x}_1^\pm) {=} 300 \ GeV, BR(b\tilde{x}_1^\pm) {=} 1\end{array}$	1708.09266, 1711.03301 1708.09266 ATLAS-CONF-2019-015
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow l$	$i\tilde{\chi}_1^0$ 0 e,μ	6 <i>b</i>	$E_T^{\rm miss}$	139	$egin{array}{ccc} ilde{b}_1 & Forbidden \ ilde{b}_1 \end{array}$	0.23-0.48		0.23-1.35	$\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV}$	SUSY-2018-31 SUSY-2018-31
$ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t $ $ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 $ $ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 b \nu, \tilde{\tau}_1 - $	$1 e, \mu$ $\tau \tilde{G}$ $1 \tau + 1 e, \mu$	3 jets/1 b μ,τ 2 jets/1 b	E_T^{miss} E_T^{miss}	36.1 139 36.1	\tilde{t}_1 \tilde{t}_1 \tilde{t}_1	0.44-0		1.16	$m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=400 \text{ GeV}$ $m(\tilde{\tau}_{1})=800 \text{ GeV}$	1506.08616, 1709.04183, 1711.1152 ATLAS-CONF-2019-017 1803.10178
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c}$	$\rightarrow c \tilde{\chi}_1^0 \qquad \qquad 0 \ e, \mu$ $0 \ e, \mu$	2 c mono-jet	E_T^{miss} E_T^{miss}	36.1 36.1	\tilde{c} \tilde{l}_1 \tilde{l}_1	0.46 0.43	0.85		$m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$ $m(\tilde{\iota}_{1},\tilde{c})-m(\tilde{\chi}_{1}^{0})=50 \text{ GeV}$ $m(\tilde{\iota}_{1},\tilde{c})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$	1805.01649 1805.01649 1711.03301
$ \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z $	1-2 <i>e</i> , μ 3 <i>e</i> , μ	4 <i>b</i> 1 <i>b</i>	E_T^{miss} E_T^{miss}	36.1 139	$ ilde{t}_2 \\ ilde{t}_2 \\$	Forbidden	0.32-0.88 0.86		$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=180 \text{ GeV}$ $m(\tilde{\chi}_1^0)=360 \text{ GeV}, m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=40 \text{ GeV}$	1706.03986 ATLAS-CONF-2019-016
${ ilde \chi}_1^\pm { ilde \chi}_2^0$ via WZ	2-3 e, µ ee, µµ	≥ 1	E_T^{miss} E_T^{miss}	36.1 139			0.6		$m(\tilde{\chi}_1^{\pm})=0$ $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^{0})=5$ GeV	1403.5294, 1806.02293 ATLAS-CONF-2019-014
$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp} \text{ via } WW$ $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \text{ via } Wh$ $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp} \text{ via } \tilde{\ell}_{L}/\tilde{v}$	2 e,μ 0-1 e,μ 2 e,μ	2 <i>b</i> /2 γ	E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139	$ \begin{array}{c} \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm} / \tilde{\chi}_{2}^{0} \\ \tilde{\chi}_{1}^{\pm} \end{array} $ Forbidden	0.42	0.74		$\begin{array}{c} m(\tilde{\chi}_{1}^{0}){=}0\\ m(\tilde{\chi}_{1}^{0}){=}70 \ GeV\\ m(\tilde{\ell},\tilde{\nu}){=}0.5(m(\tilde{\chi}_{1}^{+}){+}m(\tilde{\chi}_{1}^{0})) \end{array}$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-019, ATLAS-CONF-201 ATLAS-CONF-2019-008
$ \begin{array}{c} \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} \text{via} \tilde{\ell}_{L} / \tilde{\nu} \\ \tilde{\tau} \tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_{1}^{0} \\ \tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} \end{array} $	2 τ 2 e,μ 2 e,μ	0 jets ≥ 1	E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139	$\tilde{\tau}$ [$\tilde{\tau}_L, \tilde{\tau}_{R,L}$] $\tilde{\ell}$	0.16-0.3 0.12-0.39	0.7		$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=10 \text{ GeV}$	ATLAS-CONF-2019-018 ATLAS-CONF-2019-008 ATLAS-CONF-2019-014
$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$	0 e, µ 4 e, µ	$\geq 3 b$ 0 jets	$E_T^{\rm miss} \\ E_T^{\rm miss}$	36.1 36.1	<u>Й</u> 0.13-0.23 <u>Й</u>	0.3	0.29-0.88		$\begin{array}{l} BR(\tilde{\chi}^0_1 \to h\tilde{G}){=}1\\ BR(\tilde{\chi}^0_1 \to Z\tilde{G}){=}1 \end{array}$	1806.04030 1804.03602
Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod.,	ong-lived $ ilde{\chi}_1^{\pm}$ Disapp. t	rk 1 jet	$E_T^{\rm miss}$	36.1		0.46			Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
Stable \tilde{g} R-hadron Metastable \tilde{g} R-ha	fron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	Multiple Multiple		36.1 36.1	\tilde{g} \tilde{g} [$\tau(\tilde{g})$ =10 ns, 0.2 ns]			2.0	2.4 m($\tilde{\chi}_1^0$)=100 GeV	1902.01636,1808.04095 1710.04901,1808.04095
LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}$				3.2	ν _τ			1.9	λ'_{311} =0.11, $\lambda_{132/133/233}$ =0.07	1607.08079
$ \begin{aligned} \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 &\to WW/Z \\ \tilde{g} \tilde{g}, \tilde{g} \to qq \tilde{\chi}_1^0, \tilde{\chi}_1^0 \to \end{aligned} $		0 jets 4-5 large- <i>R</i> je Multiple	E_T^{miss}	36.1 36.1 36.1	$ \begin{array}{l} \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0] \\ \tilde{g} [m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV}, 1100] \\ \tilde{g} [\lambda_{112}'' = 2e{-}4, 2e{-}5] \end{array} $		0.82	1.33 1.3 1.9 5 2.0	$m(\tilde{\chi}_1^0)$ =100 GeV Large χ_{112}'' $m(\tilde{\chi}_1^0)$ =200 GeV, bino-like	1804.03602 1804.03568 ATLAS-CONF-2018-003
$\begin{array}{l} \widetilde{t}\widetilde{t}, \ \widetilde{t} \rightarrow t\widetilde{\chi}_1^0, \ \widetilde{\chi}_1^0 \rightarrow tb, \\ \widetilde{t}_1\widetilde{t}_1, \ \widetilde{t}_1 \rightarrow bs \end{array}$		Multiple 2 jets + 2 b	,	36.1 36.7	$\tilde{g} = [\lambda'_{323} = 2e-4, 1e-2]$ $\tilde{t}_1 = [qq, bs]$	0.5	5 1.0 0.61	5	$m(\tilde{\chi}_1^0){=}200$ GeV, bino-like	ATLAS-CONF-2018-003 1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 <i>e</i> ,μ 1 μ	2 <i>b</i> DV		36.1 136	\tilde{t}_1 \tilde{t}_1 [1e-10< λ'_{23k} <1e-8, 3		1.0	0.4-1.45 1.6	$\begin{array}{l} BR(\tilde{i}_1 \rightarrow be/b\mu) > 20\% \\ BR(\tilde{i}_1 \rightarrow q\mu) = 100\%, \cos\theta_t = 1 \end{array}$	1710.05544 ATLAS-CONF-2019-006

The TeV scale is in sight-almost history

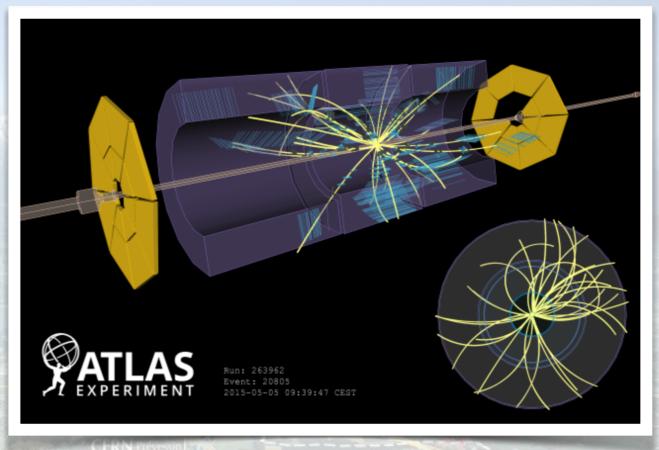


The TeV scale is in sight-almost history









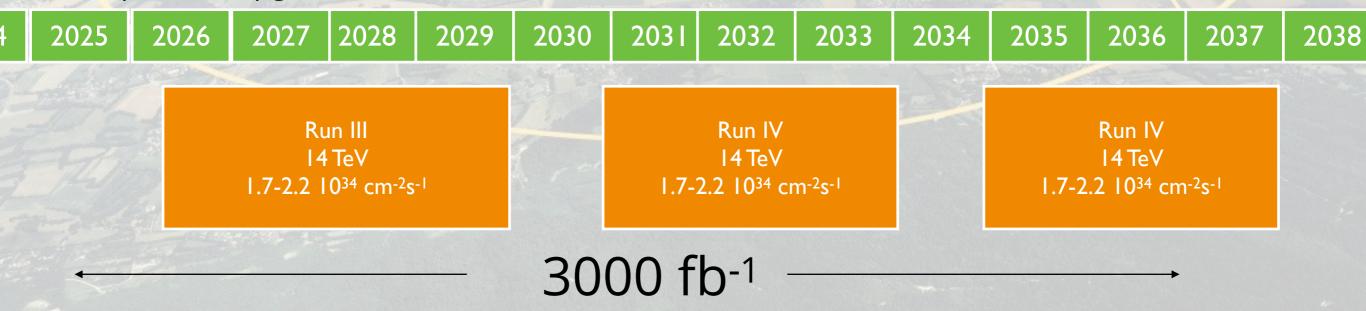
buckle in

The LHC running is just beginning



I'll be an old man rocking

"phase 2 upgrades"



2 things and then conclusions

thing 1: mass.

Rine

Let's be clear.

We collider types say we know about Mass.

Really?

Really?

As long as we know nothing about the neutral fermions or about 85% of the gravitating

universe

Really?

As long as we know nothing about the neutral fermions

or

about 85% of the gravitating universe

We don't know the Mass story.

As long as we know nothing

Understanding Mass is still^{ons} Really "all hands on deck" – EF, IF, and CF

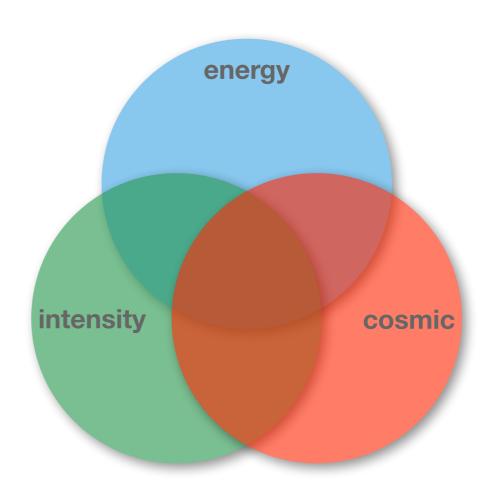
We don't know the Mass story.

thing 2: the circles.

200

The Bumper Sticker Frontier

they're pithy



I'm rethinking...

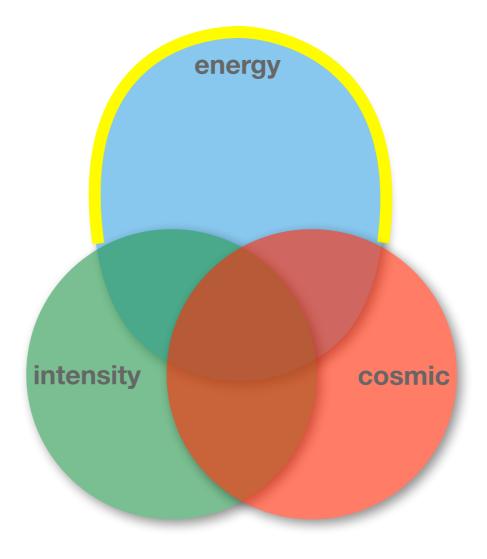
maybe an apt metaphor

energy intensity cosmic

"Frontier"

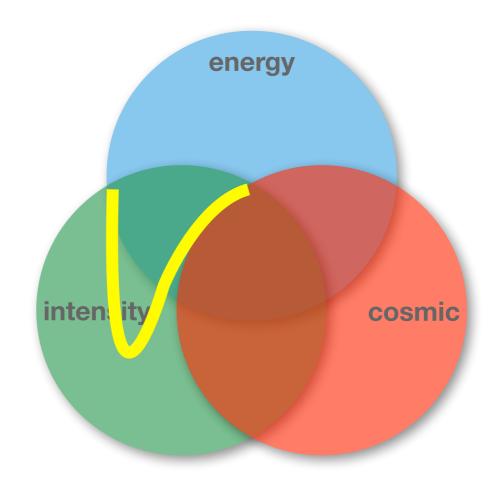
The new physics will bulge somewhere!

a unique "Frontier"



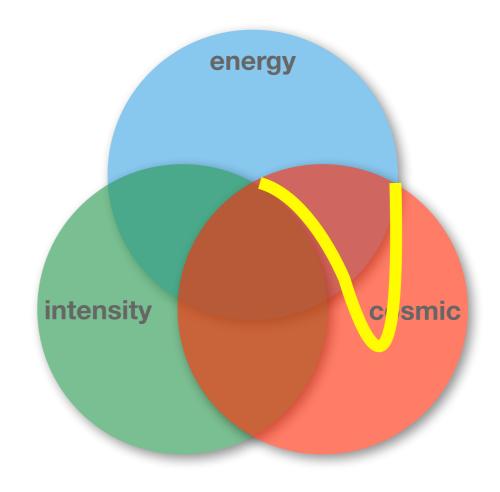
The new physics will bulge somewhere!

a shared "Frontier"



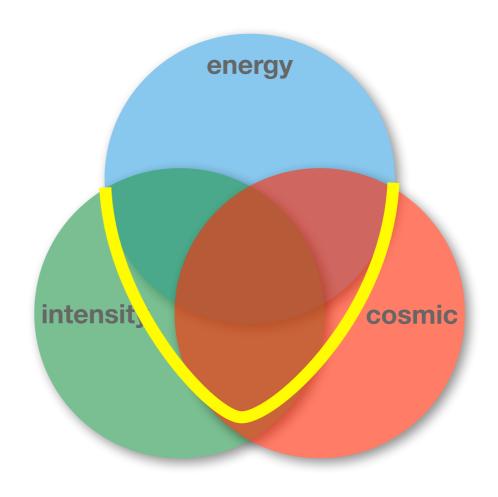
The new physics will bulge somewhere!

a shared "Frontier"



but probably everywhere

a shared "Frontier"





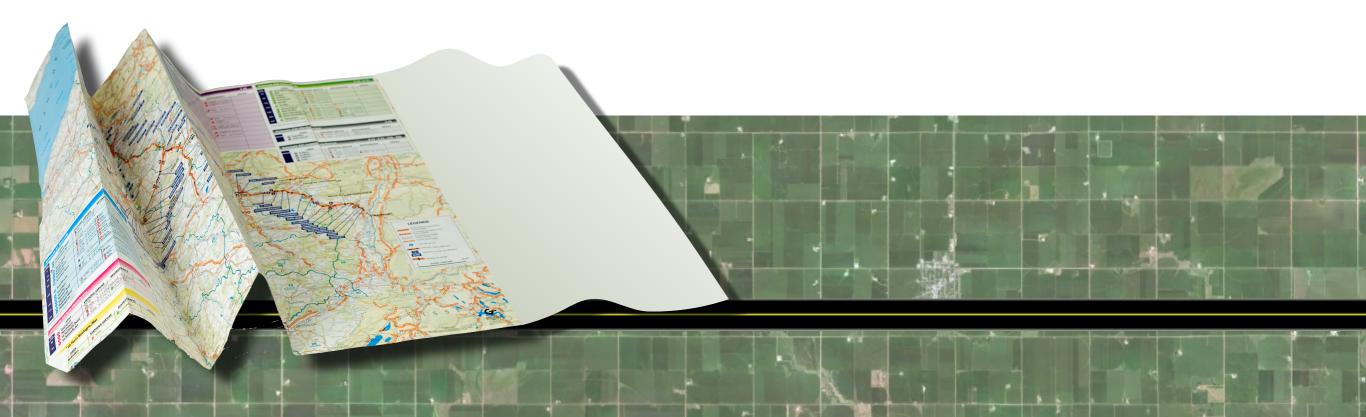
The Higgs particle changes everything.



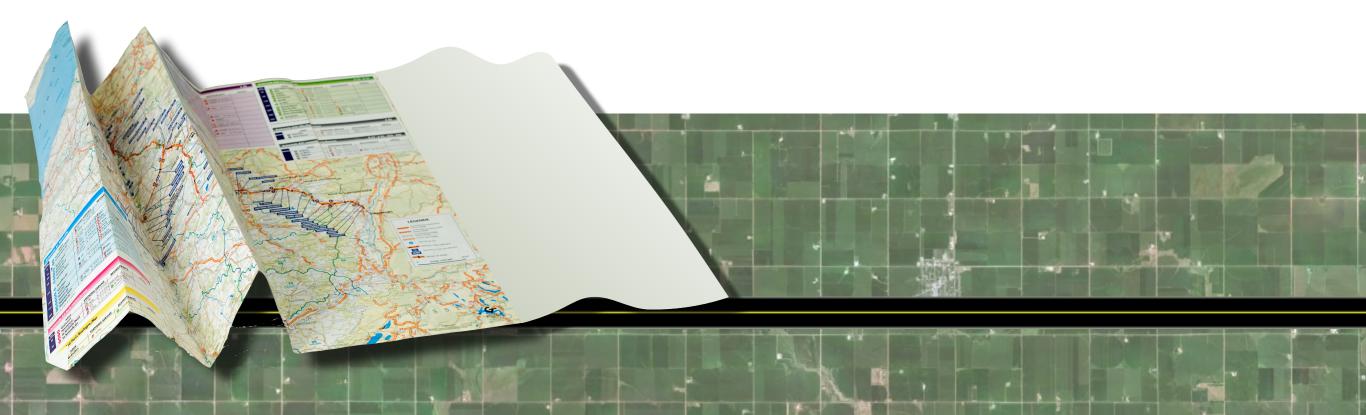
SM guided research



un-guided research?



over-guided research?

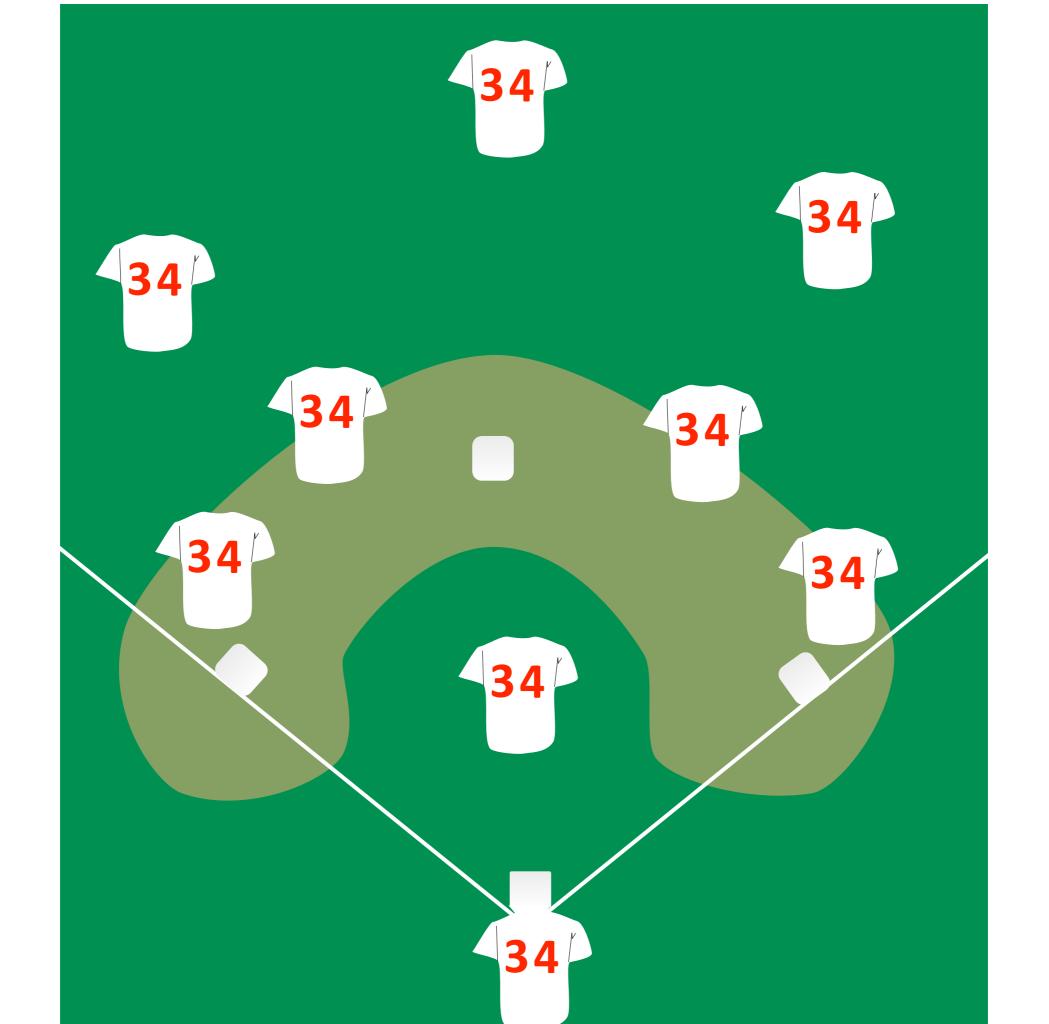


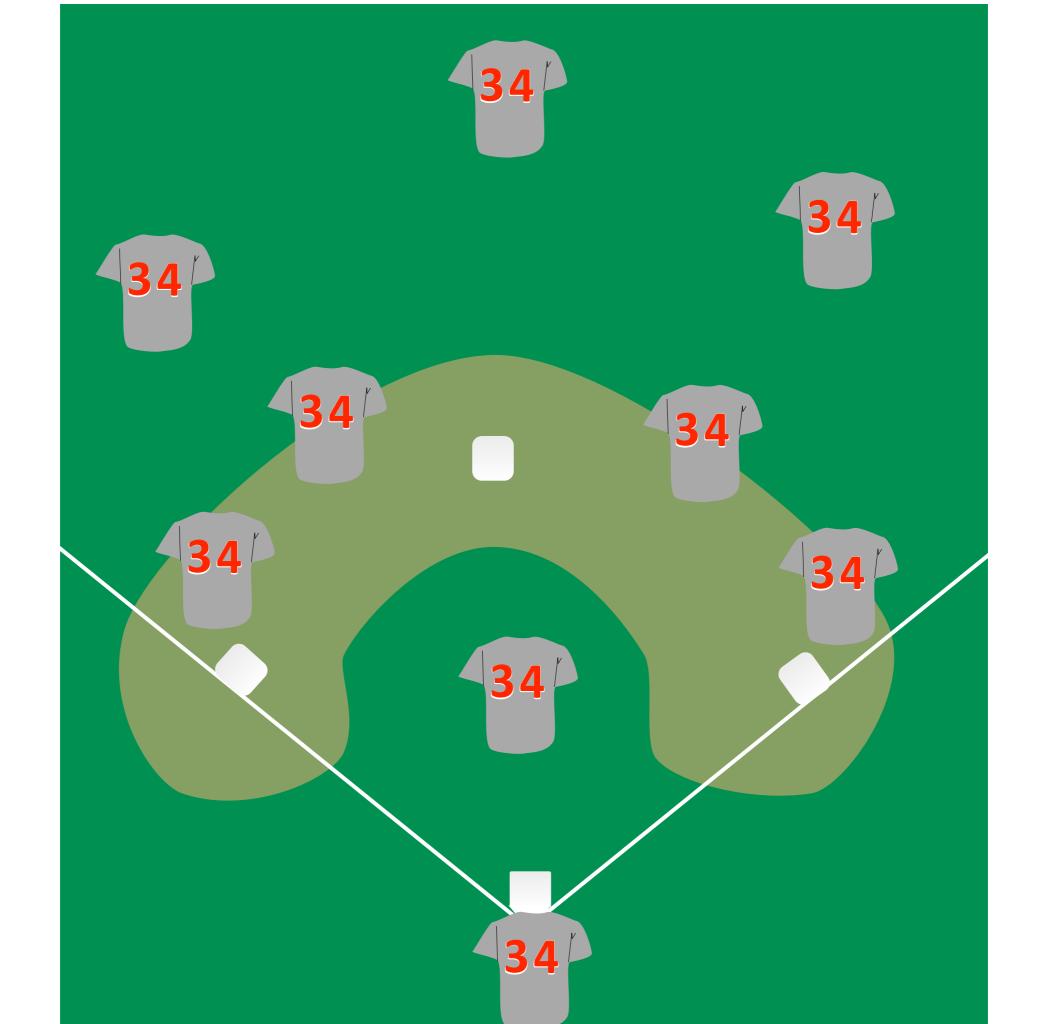
over-guided research?



We're exploring.

"Frontier"

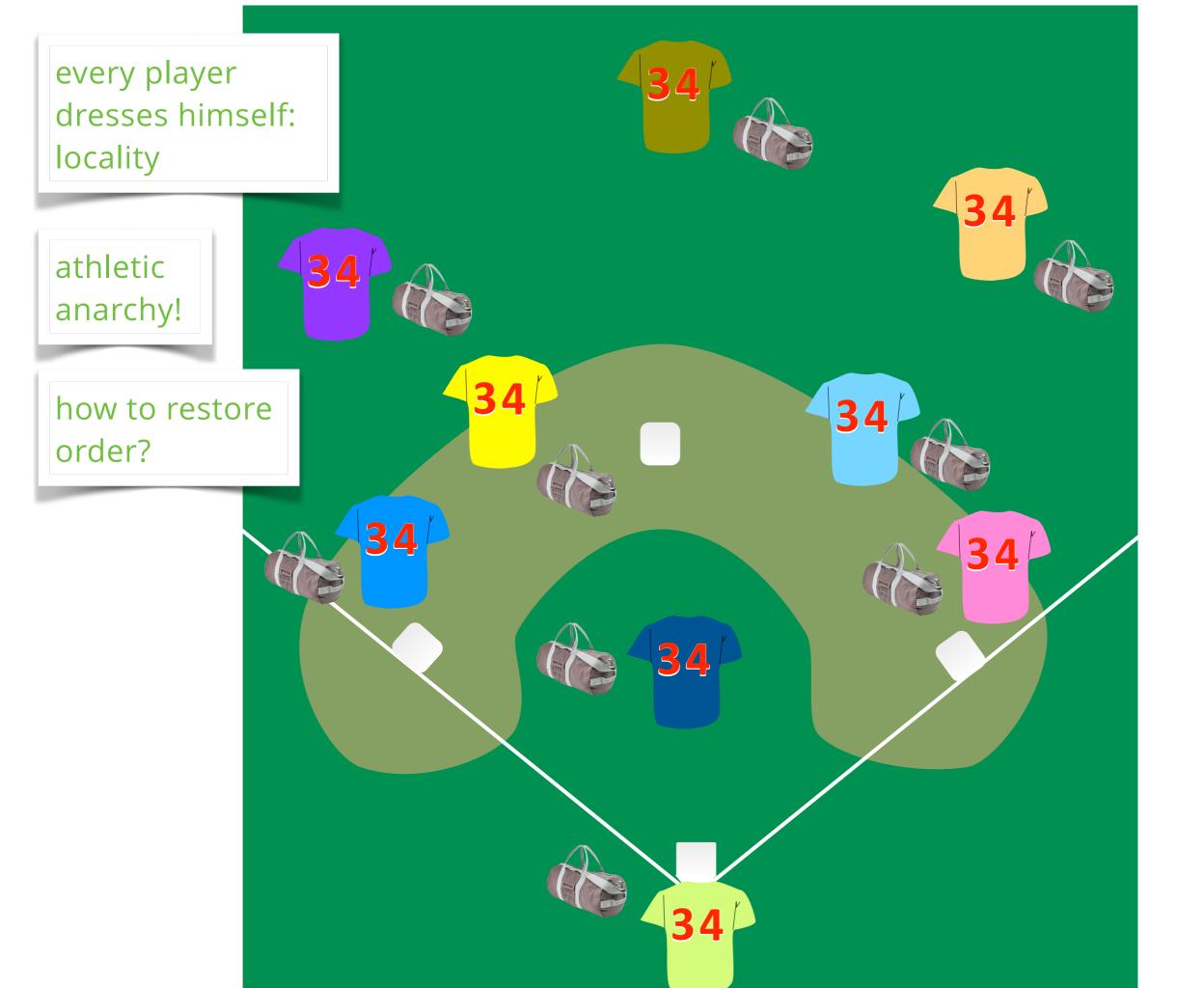


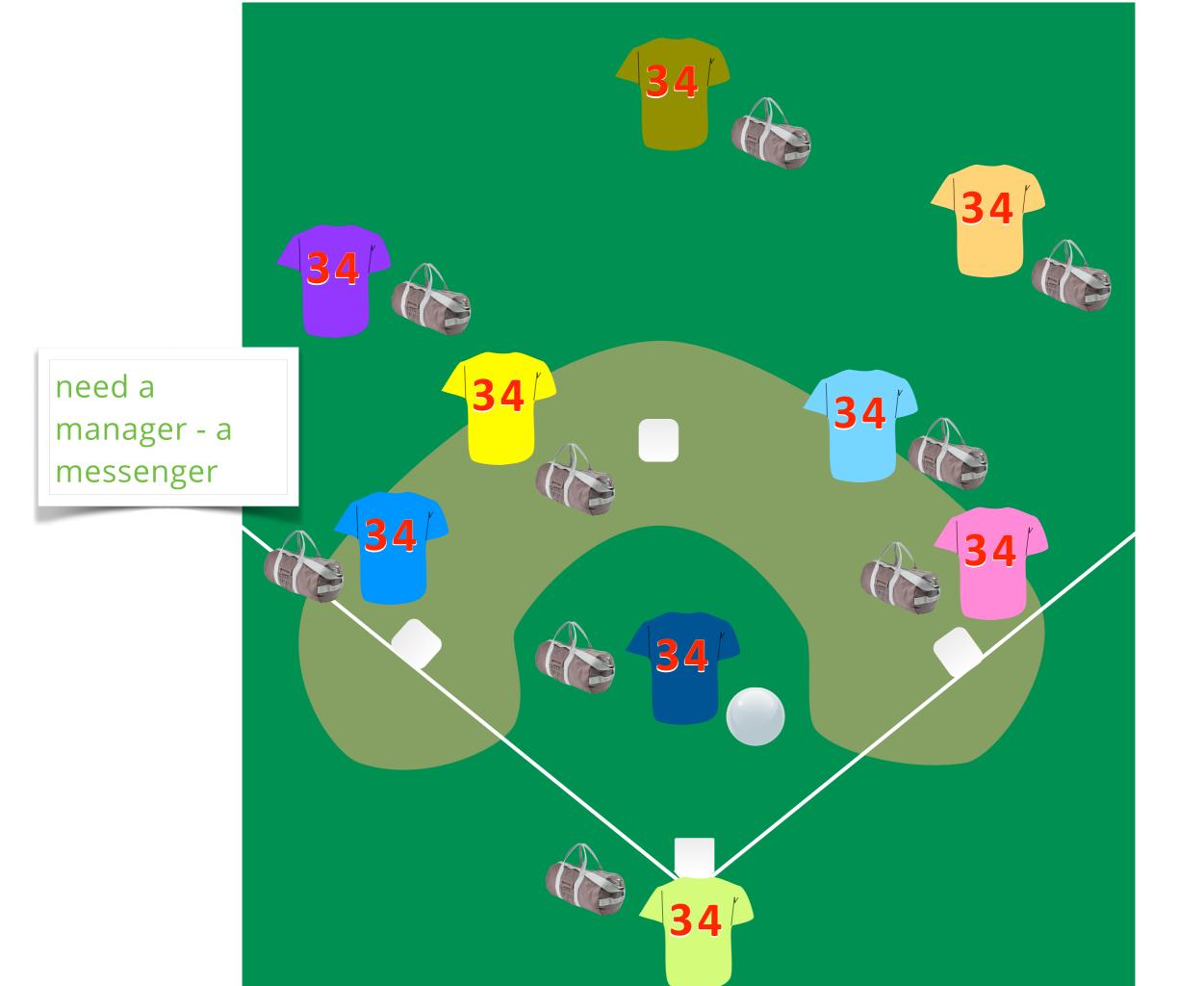


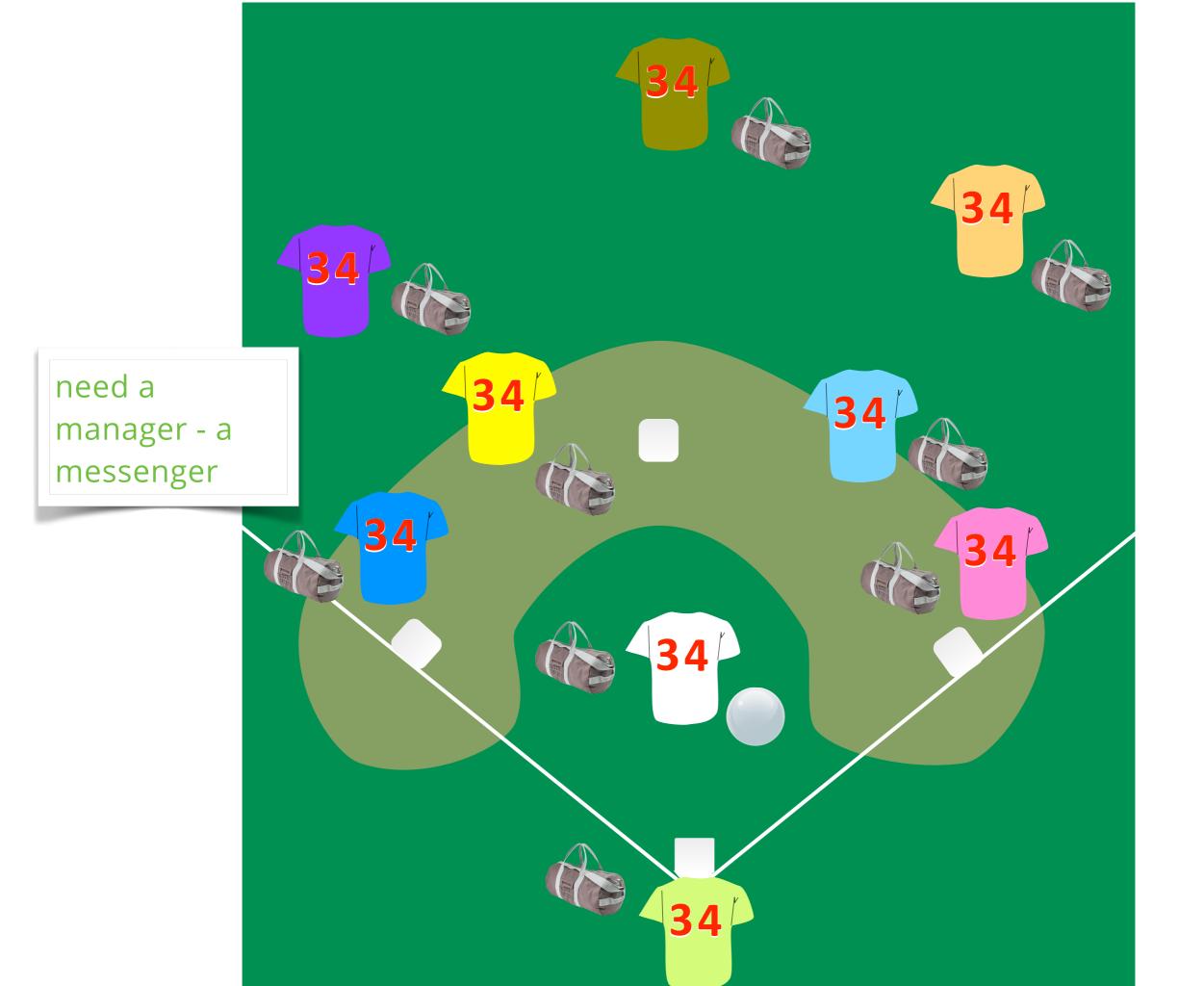


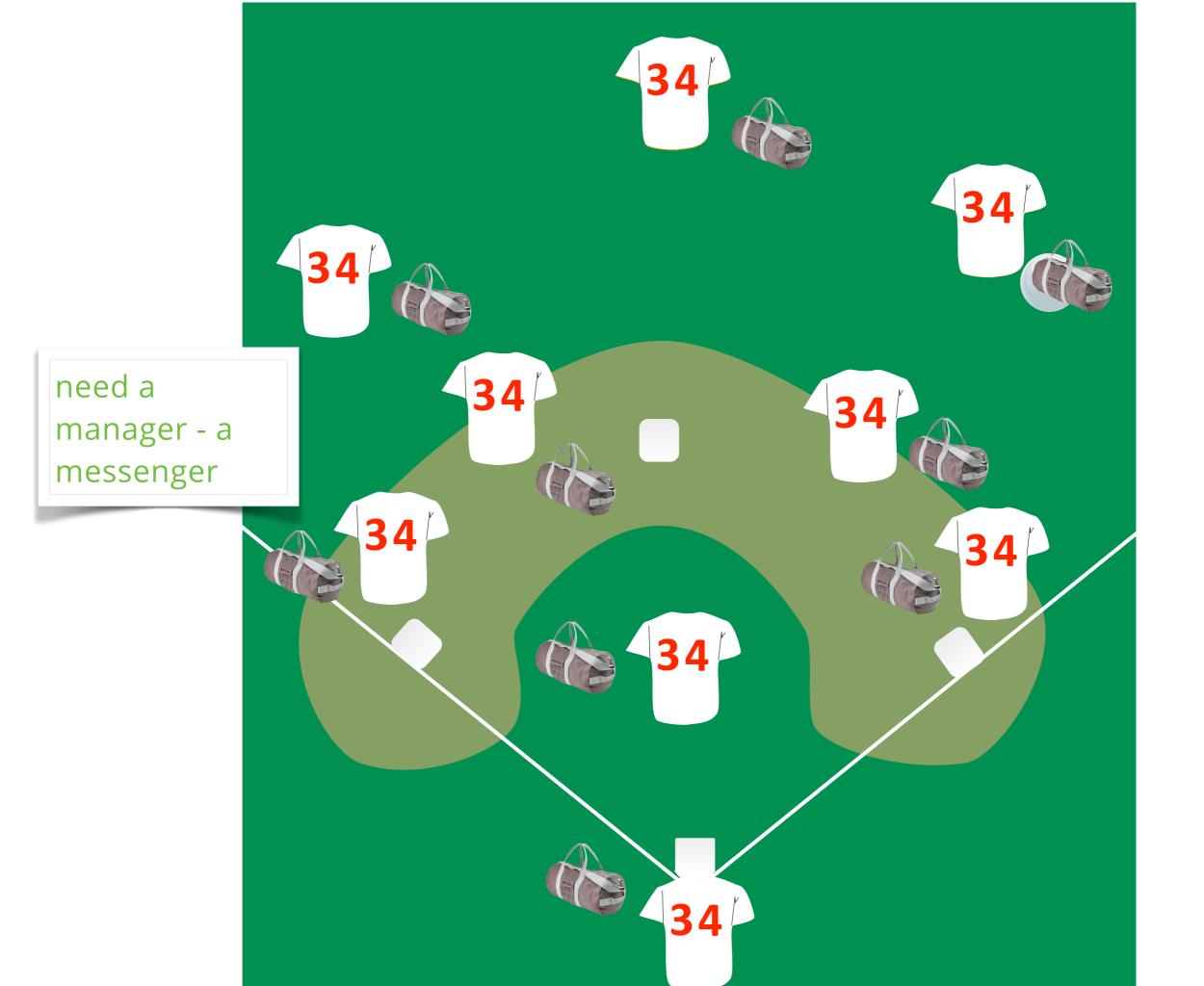


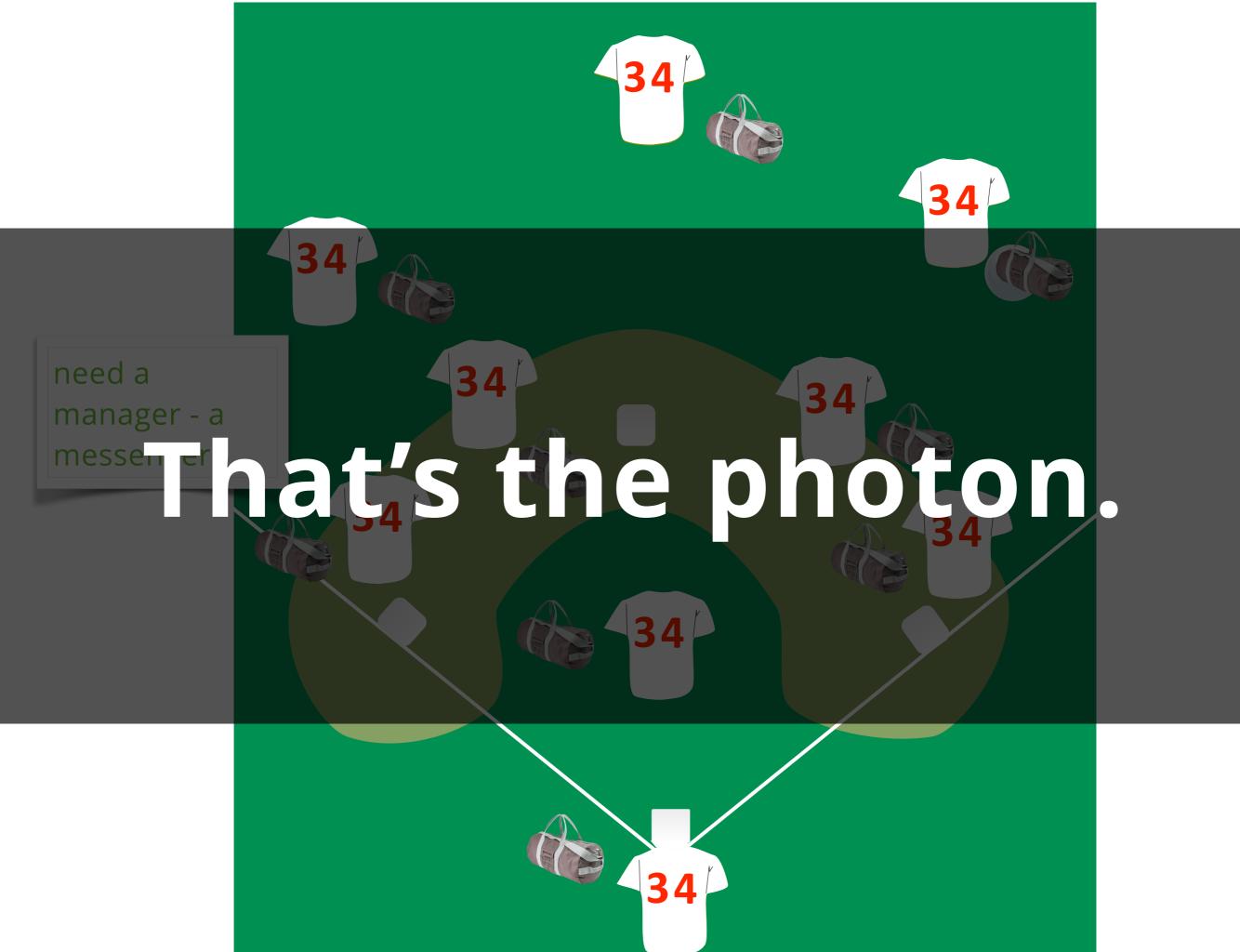




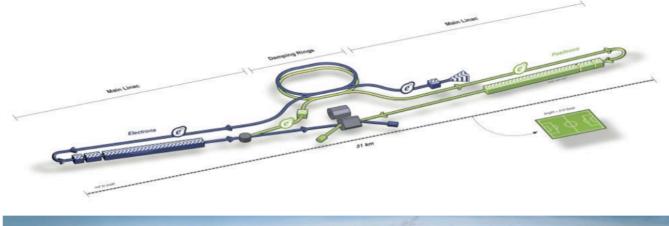




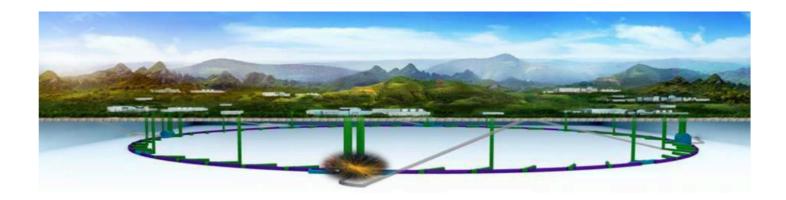




Electron-Positron Collider Proposals









Japan ILC 250: 2032

International Linear Collider

CERN CLIC 350: 2035

Compact Linear Collider

China CEPC: 2030

Circular Electron Positron Collider

CERN FCC-ee: 2039

Future Circular Collider

e⁺e⁻ Collider

Electroweak production

cross sections are predicted with (sub)percent level precisions in most cases

Relative low rate

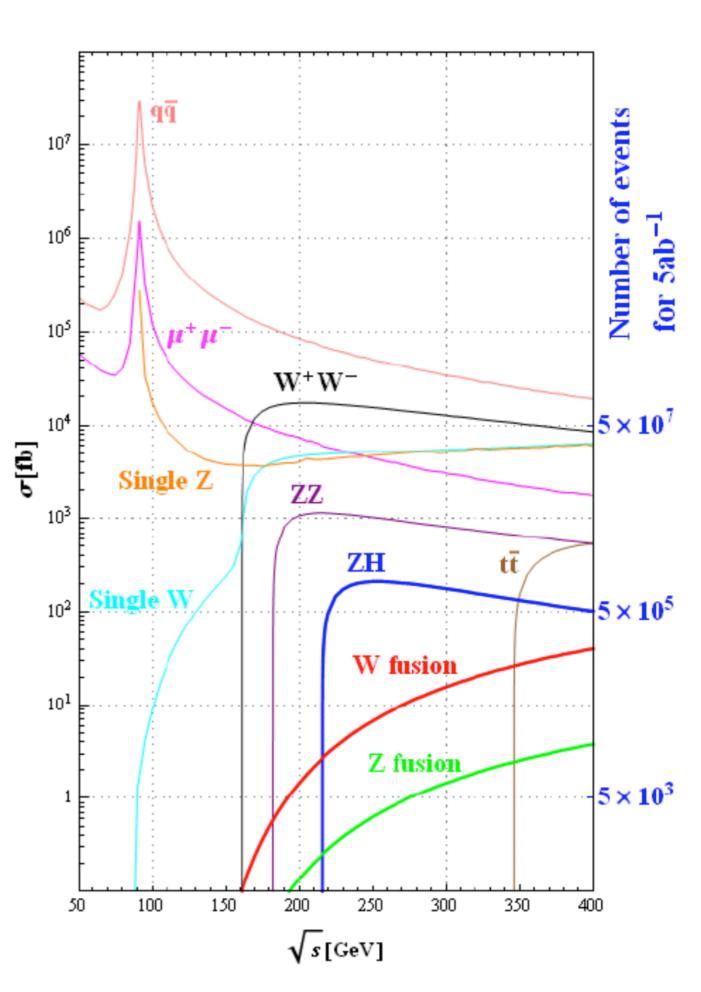
can trigger on every event

Well defined collision energy

allow for the "missing" mass reconstruction (*eg* recoiling mass)

Clean events, smaller background small number of processes

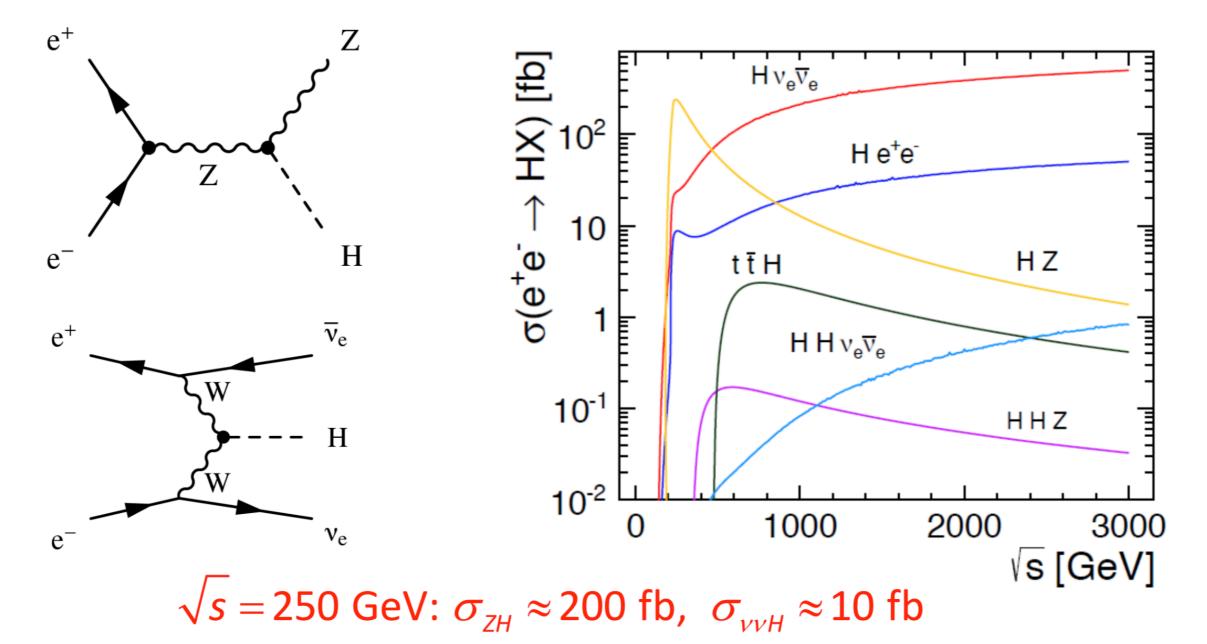
Ideal for precisions: measurements or searches



Higgs Boson Production in e⁺e⁻ Collisions

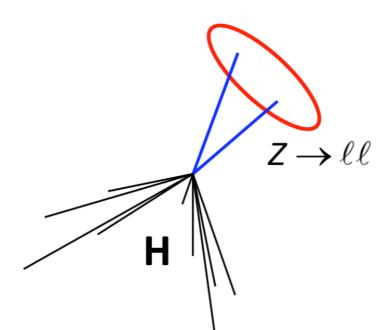
At $\sqrt{s} \square 240 - 250$ GeV, $ee \rightarrow ZH$ production is maximum and dominates with a smaller contribution from $ee \rightarrow vvH$.

Beyond that, the cross section decreases asymptotically as 1/s for $ee \rightarrow ZH$ and increases logarithmically for $ee \rightarrow vvH$.



Higgs Boson Tagging

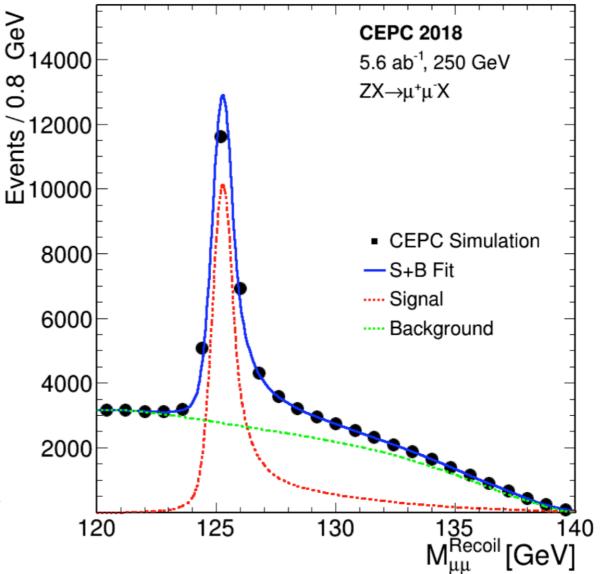
Unique to lepton colliders, the energy and momentum of the Higgs boson in $ee \rightarrow ZH$ can be measured by looking at the Z kinematics only: $E_{_H} = \sqrt{s} - E_{_Z}, \quad \vec{p}_{_H} = -\vec{p}_{_Z}$



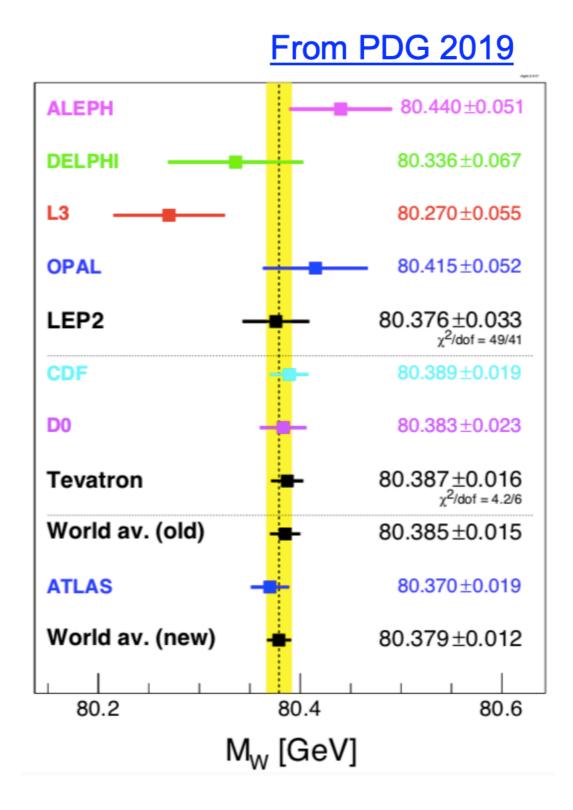
Recoil mass reconstruction:

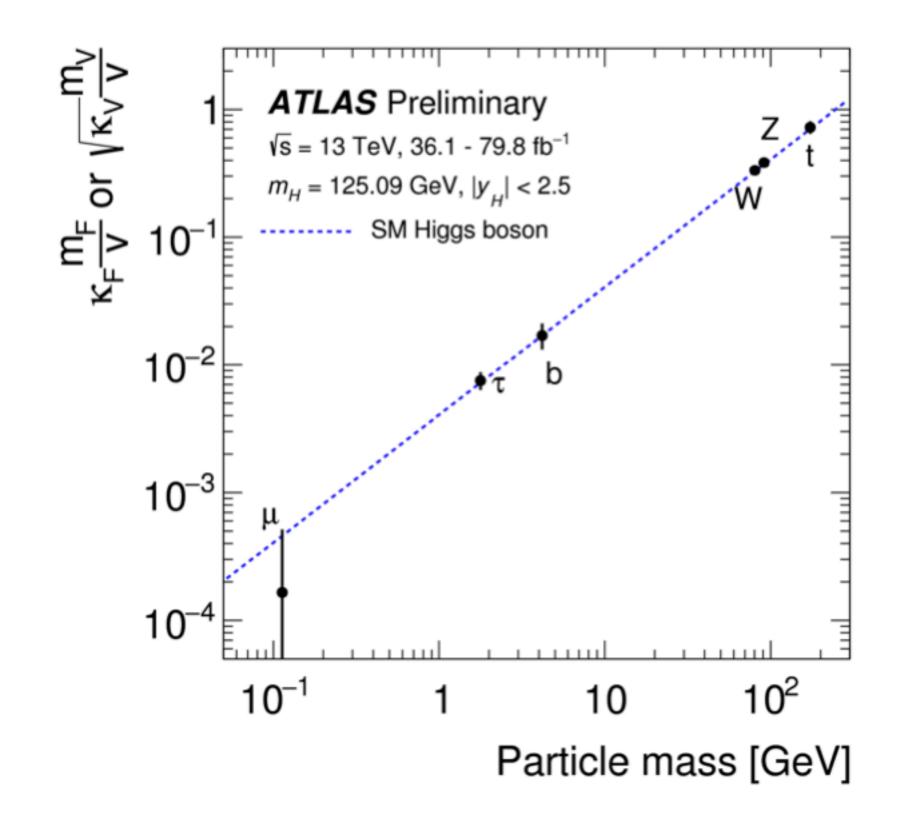
$$m_{\rm recoil}^2 = \left(\sqrt{s} - E_Z\right)^2 - \left|\vec{p}_Z\right|^2$$

⇒ Identifying the Higgs boson without looking at it. Measuring $\sigma(ee \rightarrow ZH)$ independent of its decay !



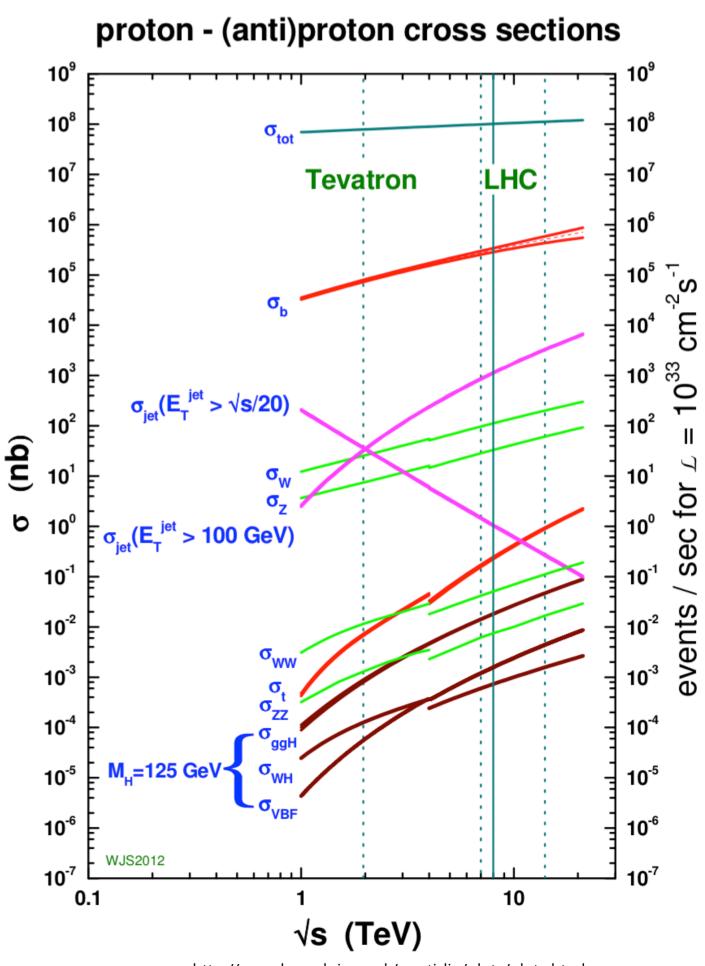
LHC always measures $\sigma \times BR$, no model-independent way to distangle decay from production!





is a generational event

Run 1 to Run 2 bigger science increment than Run 2 to Run 3



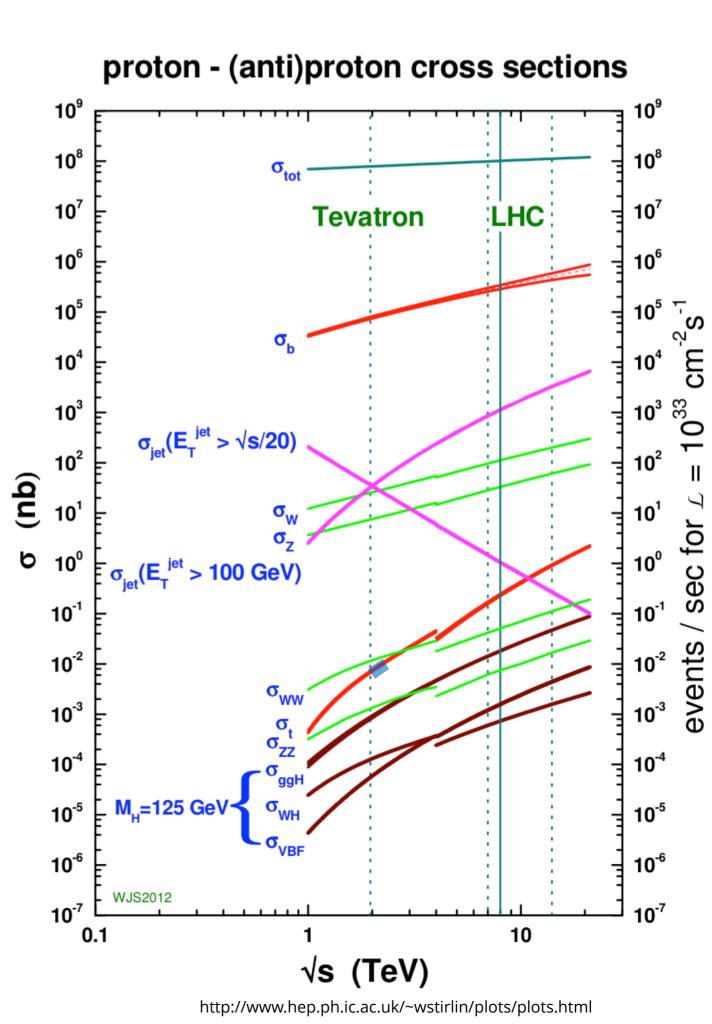
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

is a generational event

Run 1 to Run 2 bigger science increment than Run 2 to Run 3

from:

< 1 tT event/s @ tevatron



is a generational event

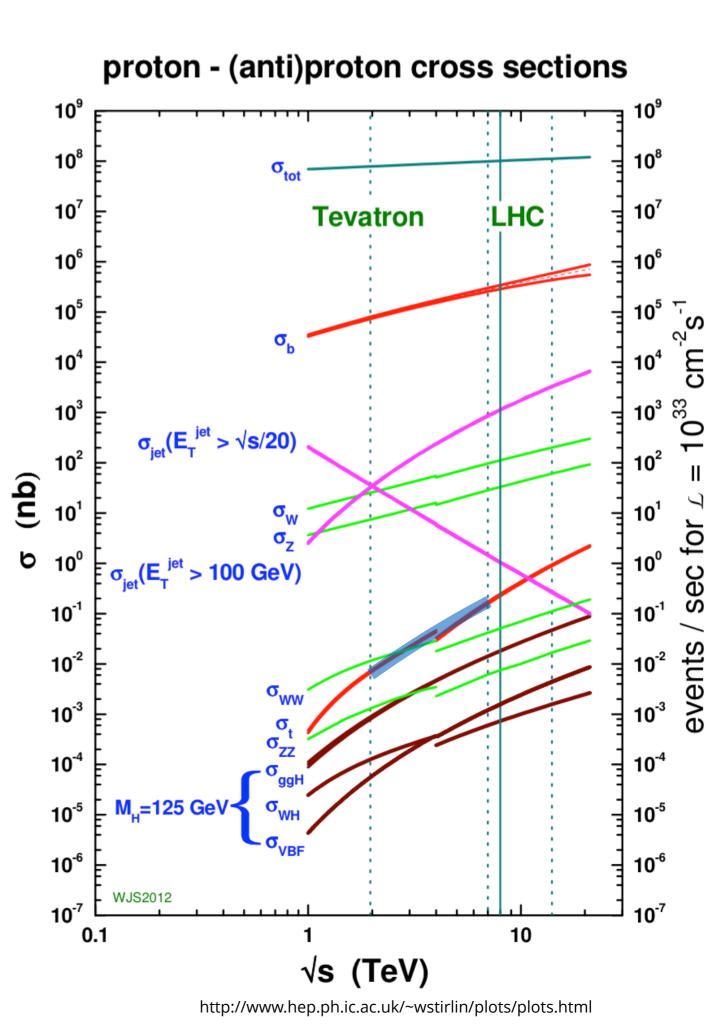
Run 1 to Run 2 bigger science increment than Run 2 to Run 3

from:

< 1 tT event/s @ tevatron

to:

2 tT events/s in Run 1



is a generational event

Run 1 to Run 2 bigger science increment than Run 2 to Run 3

from:

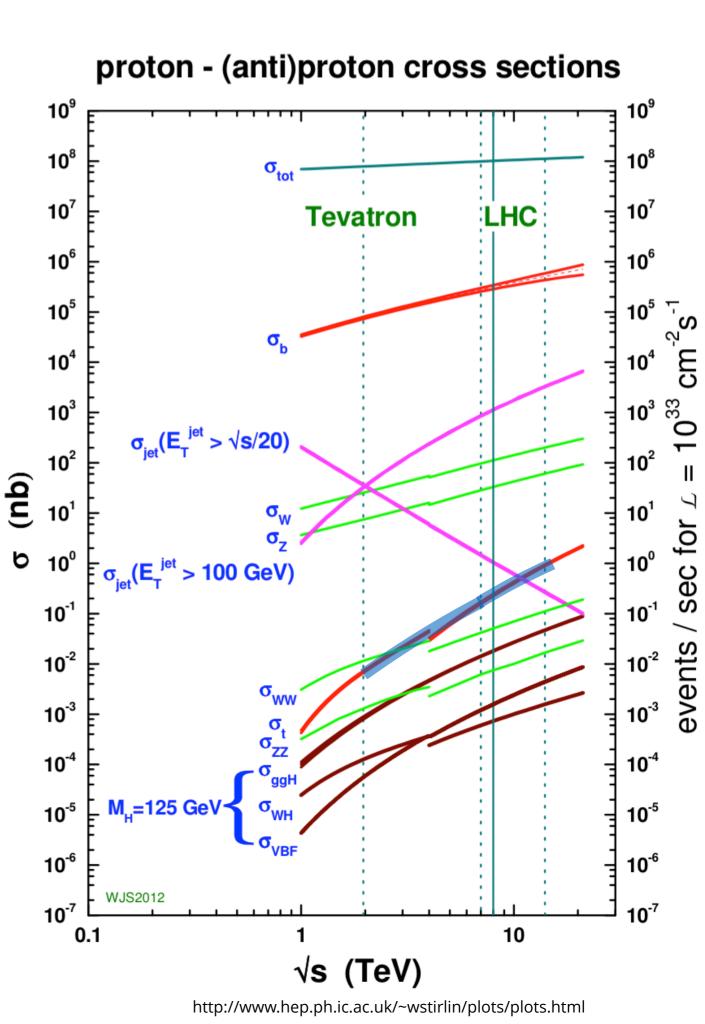
< 1 tT event/s @ tevatron

to:

2 tT events/s in Run 1

to:

13 tT events/s in Run 2



is a generational event

Run 1 to Run 2 bigger science increment than Run 2 to Run 3

from:

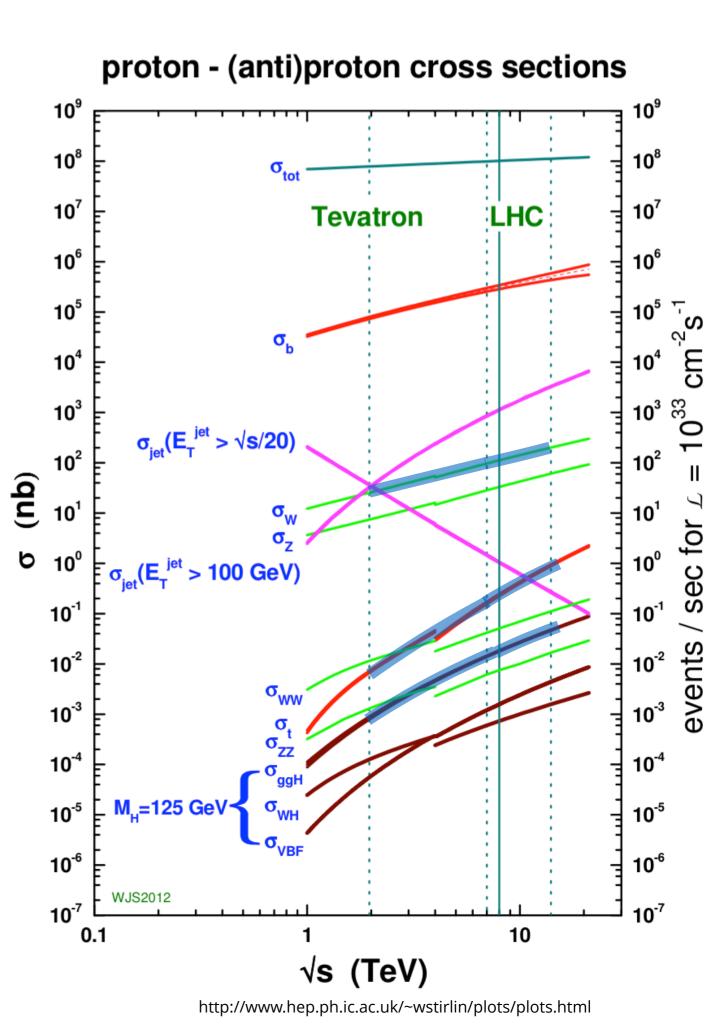
< 1 tT event/s @ tevatron

to:

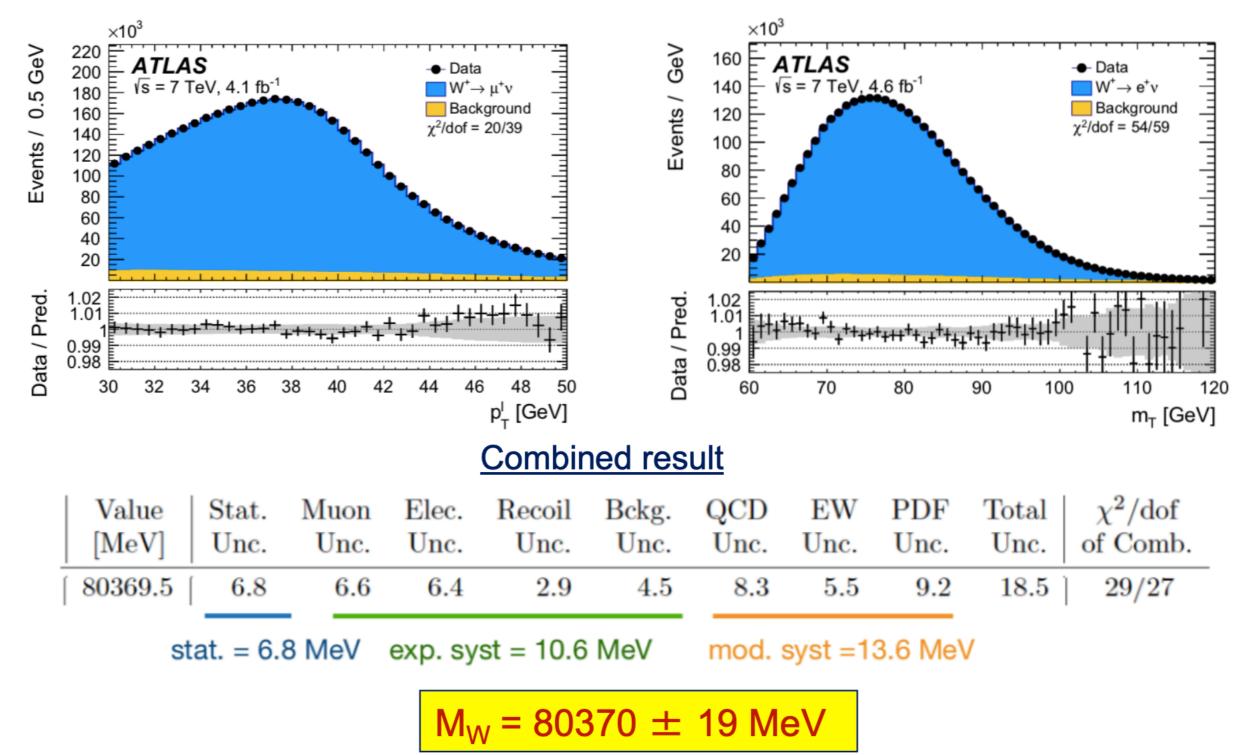
2 tT events/s in Run 1

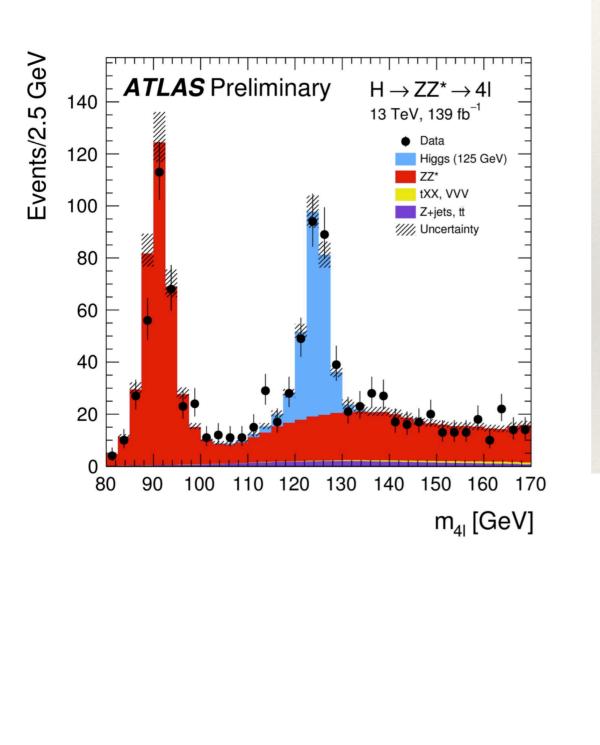
to:

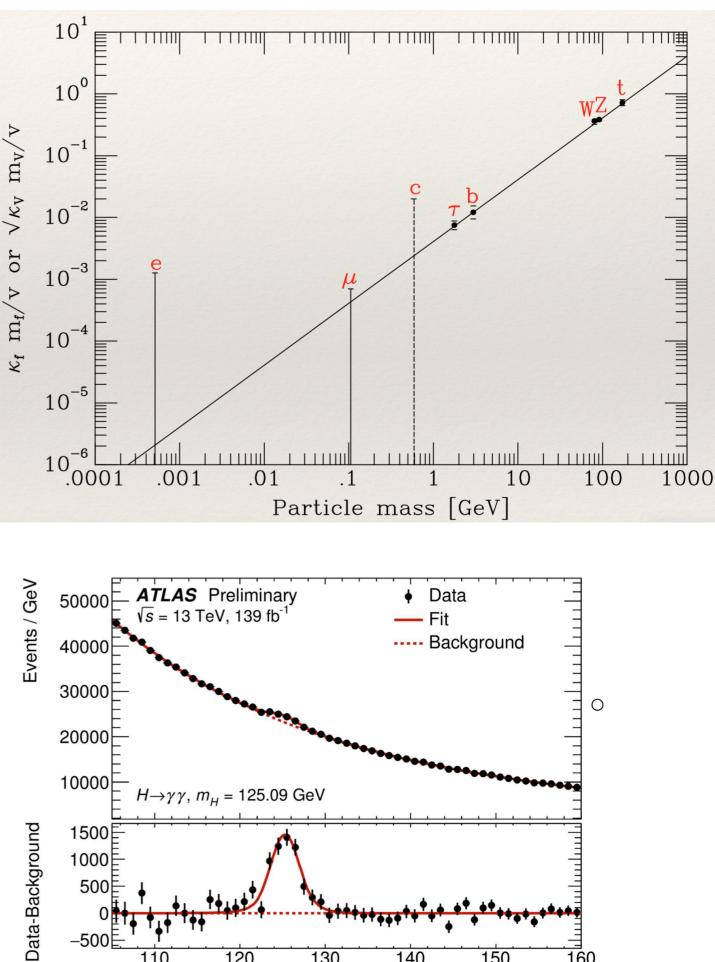
13 tT events/s in Run 2



- Fit from MC templates with different mass generated in steps of 1 10 MeV
- 28 χ² fits, separeted for lepton type (μ,e), W charge (+/-), rapidity interval (4 for μ, 3 for e) and fit variable (m_T, p_T).
- Many other fits were performed as consistency checks by varying fit range, etc ...



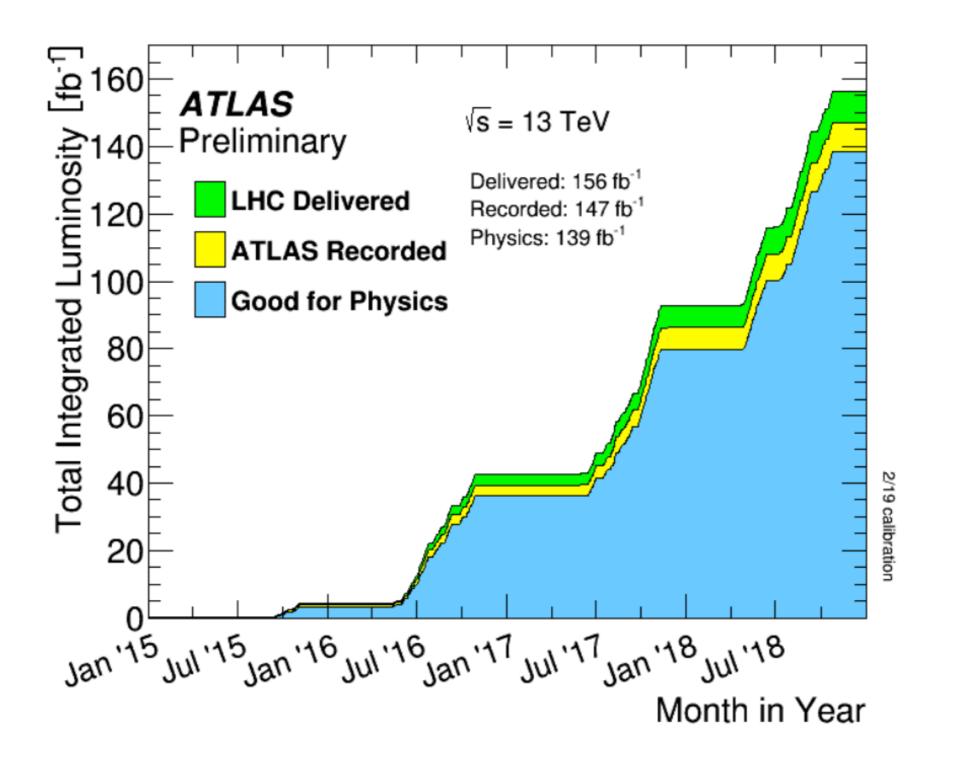




____ 160

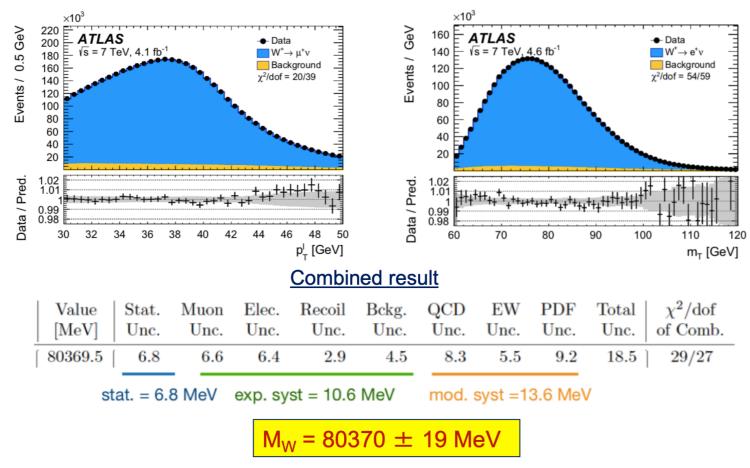
 $m_{\gamma\gamma}$ [GeV]

-500

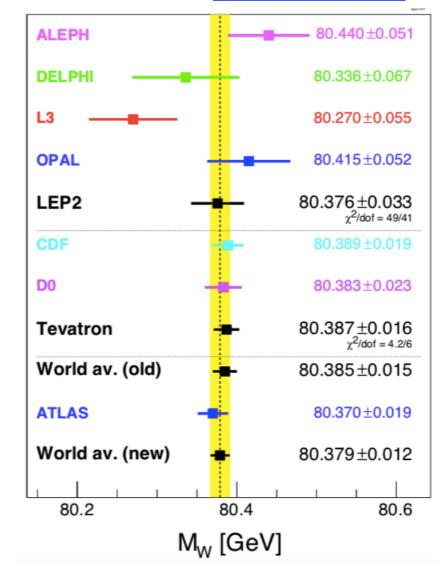


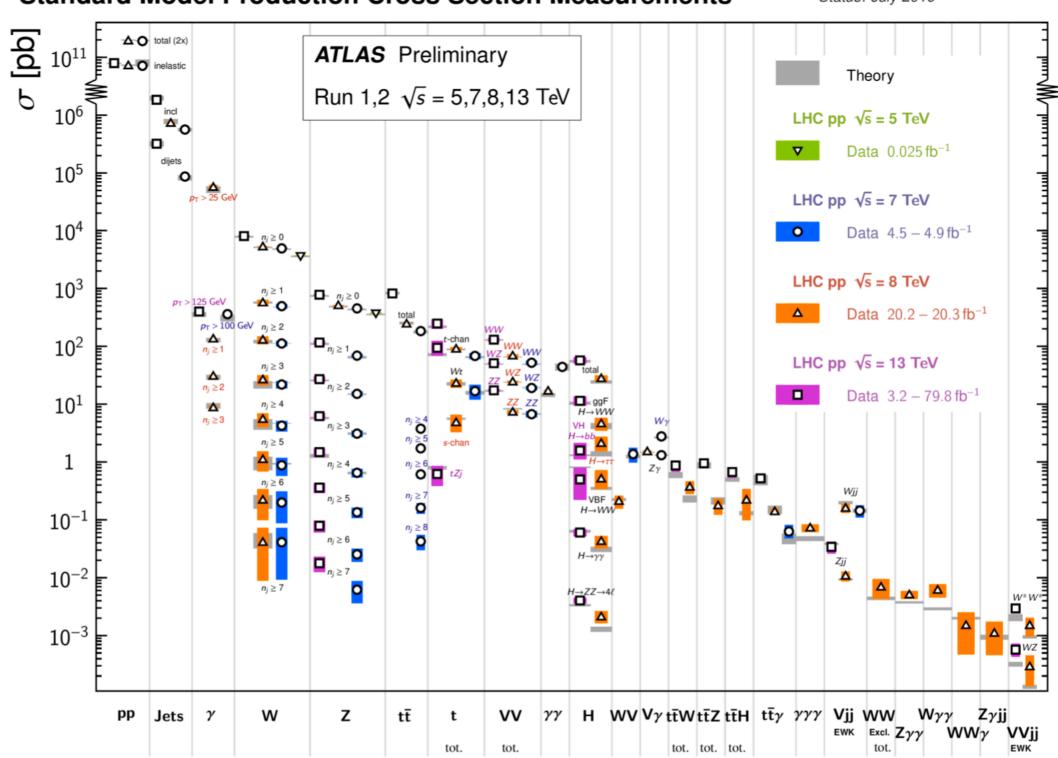
W mass

- Fit from MC templates with different mass generated in steps of 1 10 MeV
- 28 χ² fits, separeted for lepton type (μ,e), W charge (+/-), rapidity interval (4 for μ, 3 for e) and fit variable (m_T, p_T^I).
- Many other fits were performed as consistency checks by varying fit range, etc …



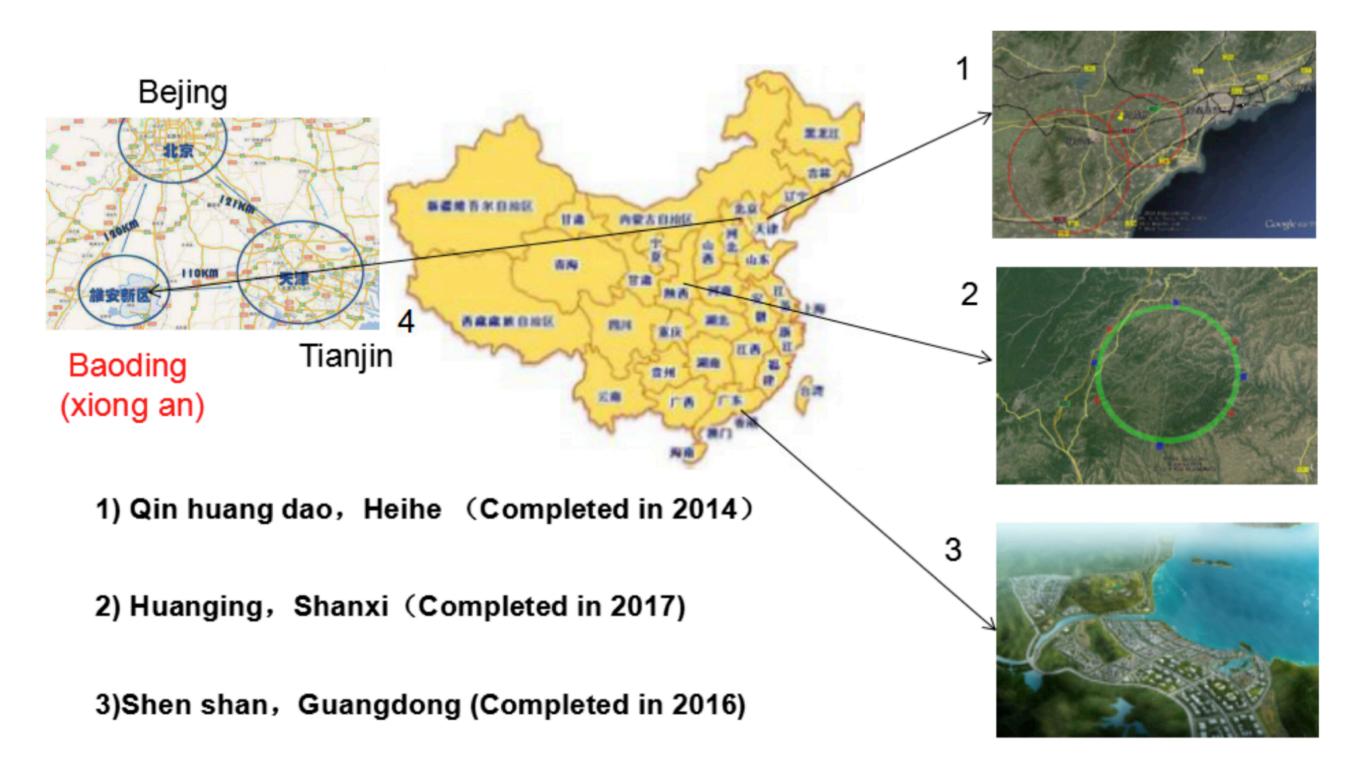
From PDG 2019





Standard Model Production Cross Section Measurements Status: July 2019

100 km circular tunnel in China

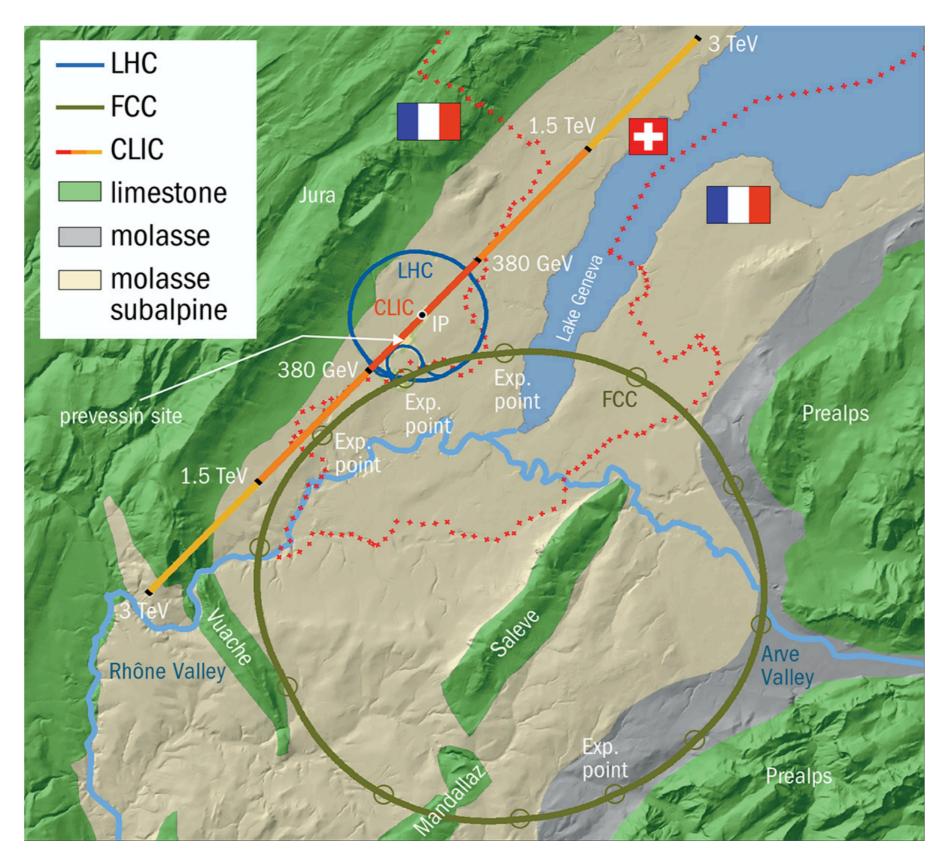


4) Baoding (Xiong an), Hebei (Started in August 2017, near Beijing ~200km to the south)

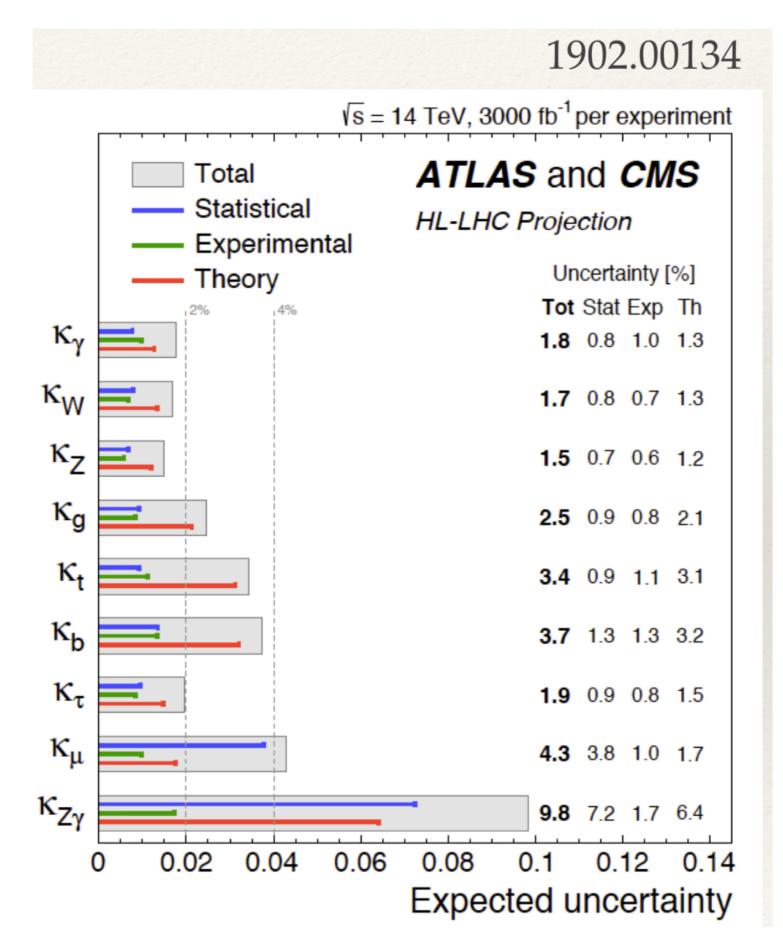
International Linear electron-positron Collider in Japan

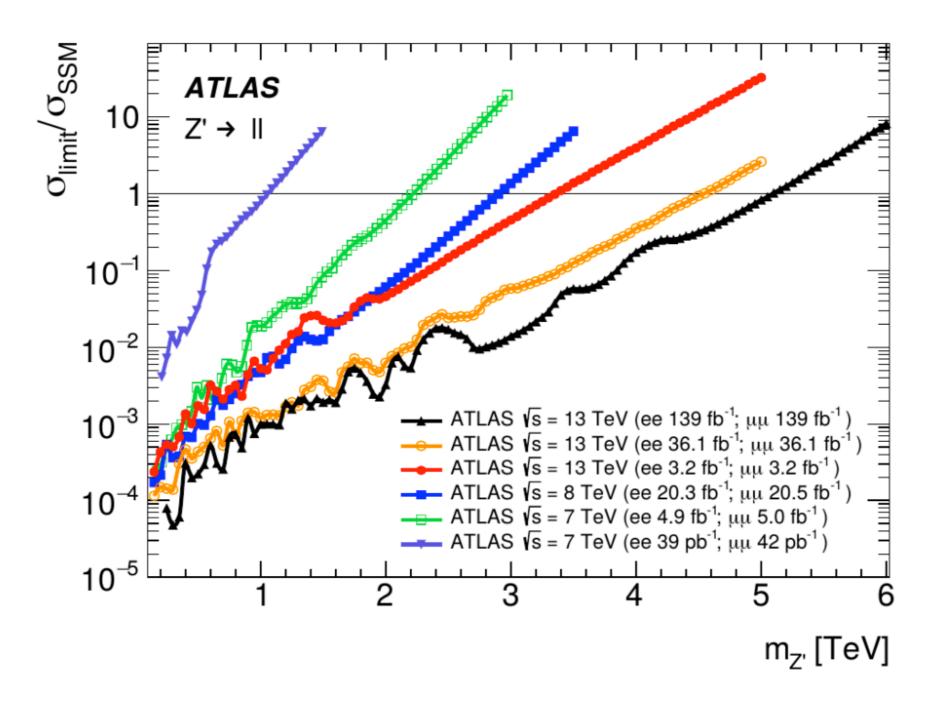


100 km Future Circular Collider or Compact Linear Collider at CERN

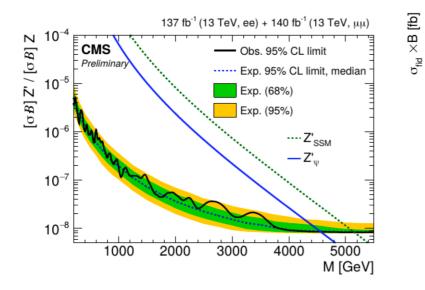


High-luminosity LHC 2026-2035

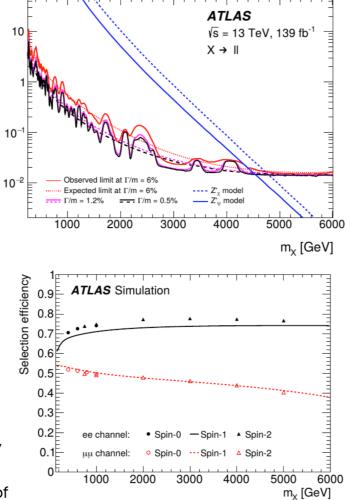


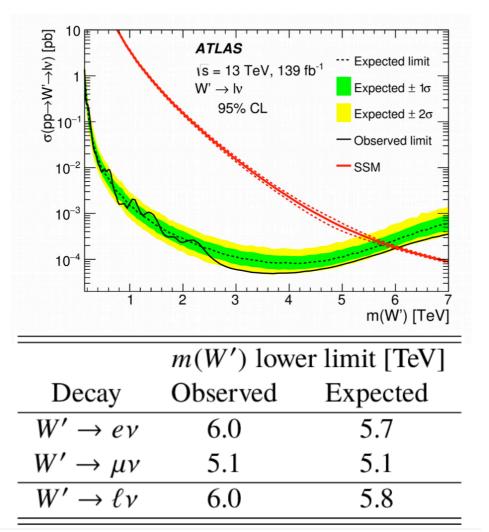


Z'/W'



- Observed limits on $Z'_{\psi} \rightarrow II$:
 - CMS 4.56, ATLAS 4.5 TeV
- Easily reinterpretable to any model
 - ATLAS fiducial σ×B limits applicable to spin-0/1/2 signals
 - CMS efficiency ee (μμ) 60-67 (93)%
 - Available in ee and µµ channels
- No unfolded results available yet, but possibility to "fold" new BSM models
 - Parametrisation of dilepton resolution as a function of $m_{\!\scriptscriptstyle \rm I\!I}$ available on HEPdata





SM

