That Spin 0 Boson Changes Everything

The Standard Model and the Energy Frontier

Department of Physics Colloquium
Case Western Reserve University
October 24, 2019

Chip Brock

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14 The ATLAS Collaboration: Two-particle Bose–Einstein correlations
The ATLAS Collaboration
G. Aad[84], B. Abbott[112], J. Abdallah[152], S. Abdel Khalek[116], O. Abdinov[11], R. Aben[106], B. Abi[113], M. Abolins[89],
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M. Cano Bret[75], J. Cantero[81], R. Cantrill[125a], T. Cao[40], M.D.M. Capeans Garrido[30], I. Caprini[26a], M. Caprini[26a],

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
REM
MORE MEN WEAR BOND CLOTHES THAN ANY OTHER CLOTHES IN AMERICA

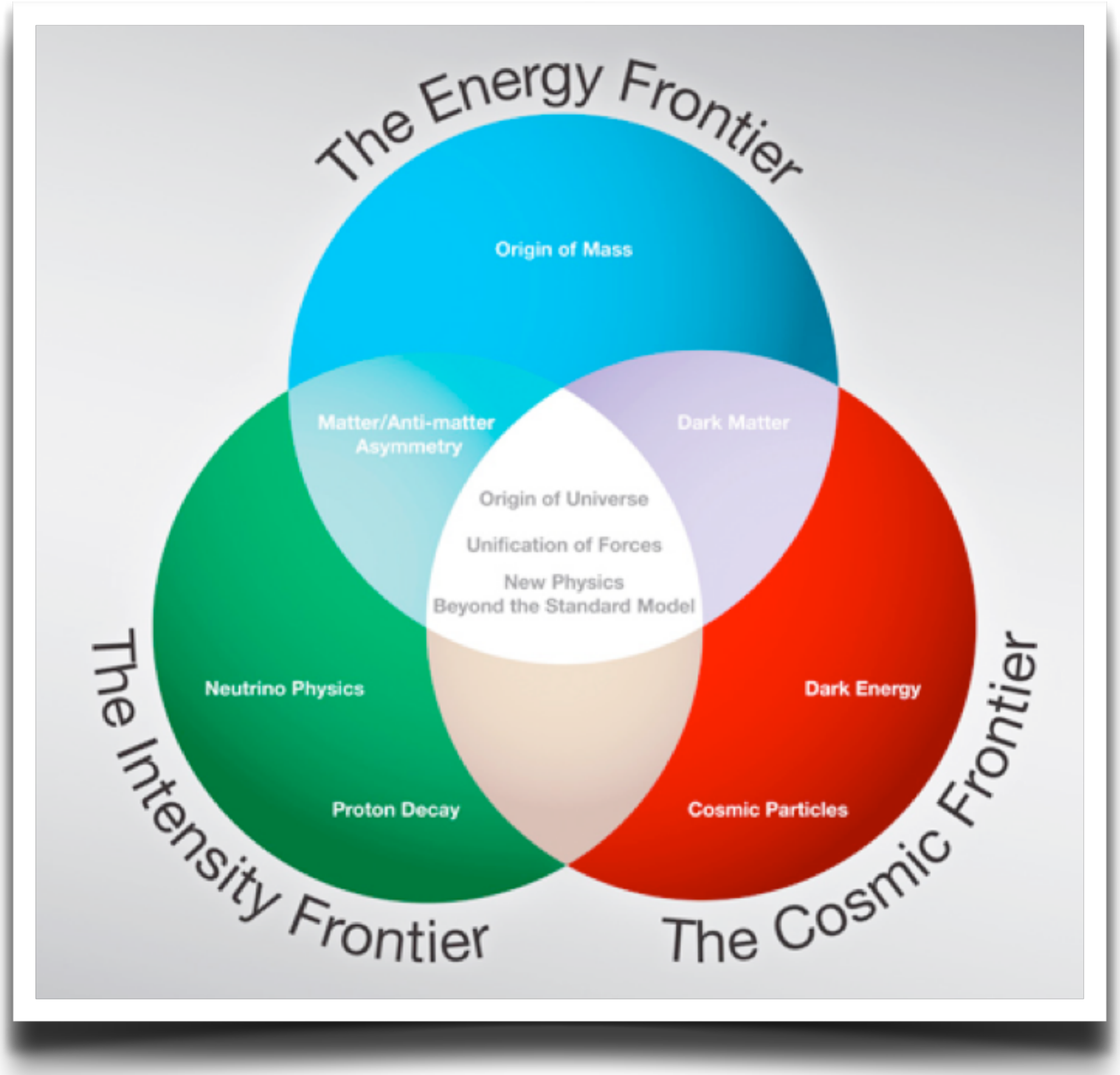
Two vehicles:

- **“Snowmass”**
  - organized by DPF
  - next to last comprehensive one in 2001
- **“P5”**
  - Particle Physics Project Prioritization Panel
  - sub-panel of HEPAP

Two vehicles:

- **"Snowmass" Workshops**
  - organized by DPF
  - previous one in 2001
- **"P5"**
  - **P**article **P**hysics **P**roject **P**rioritization **P**anel
  - sub-panel of HEPAP

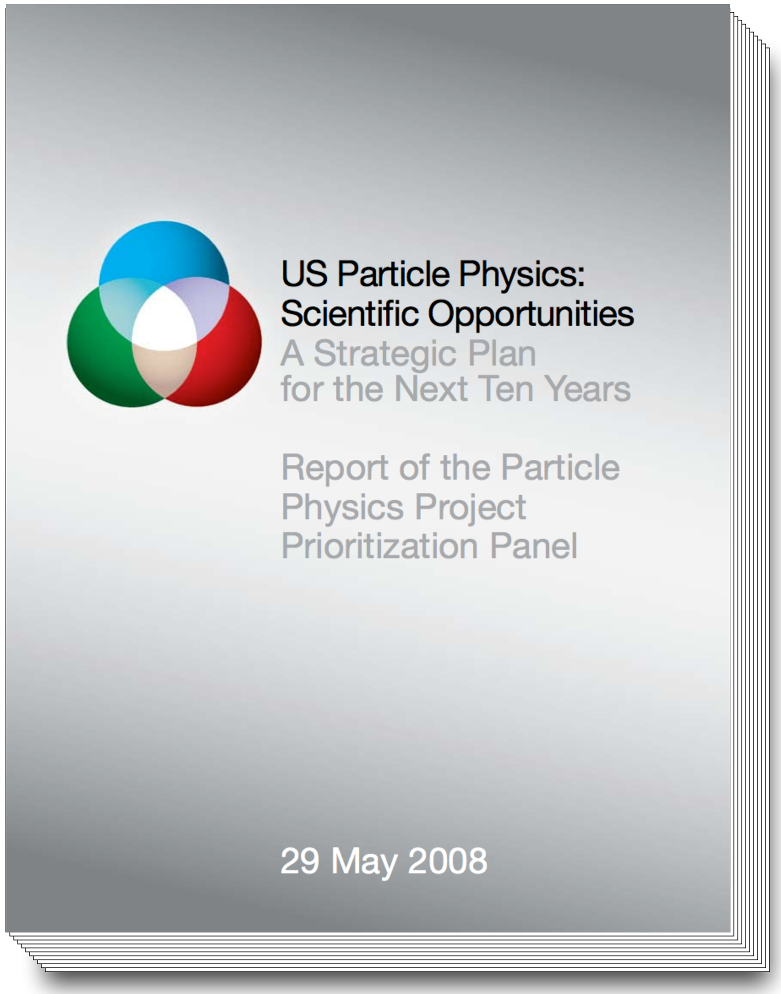
Notorious P5 Review: 2008



- Three **Frontiers**

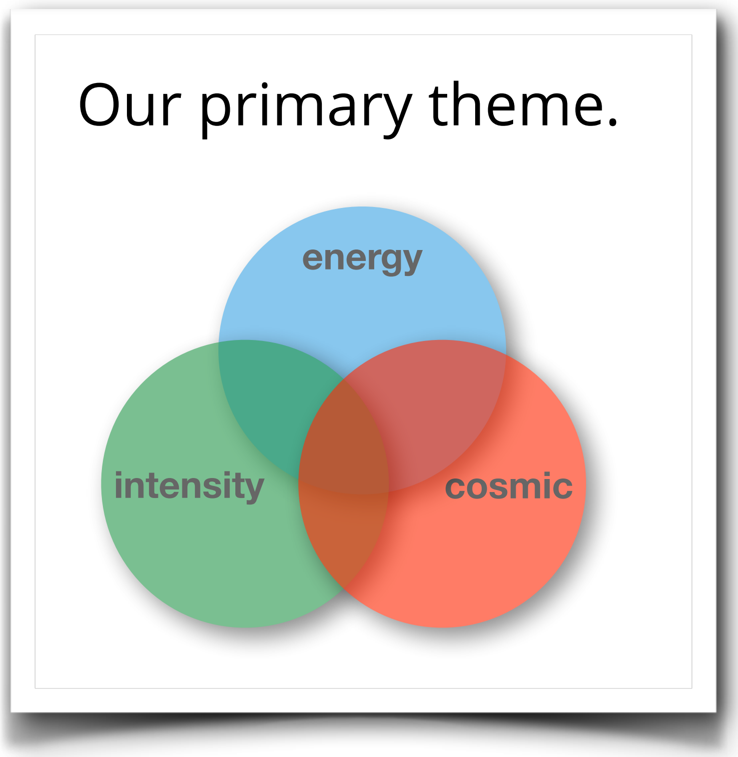
  – "the circles" –

  2008 P5



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

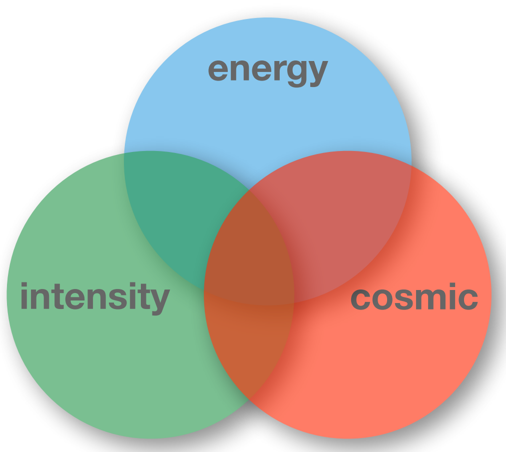
Snowmass → P5 after LHC's first run



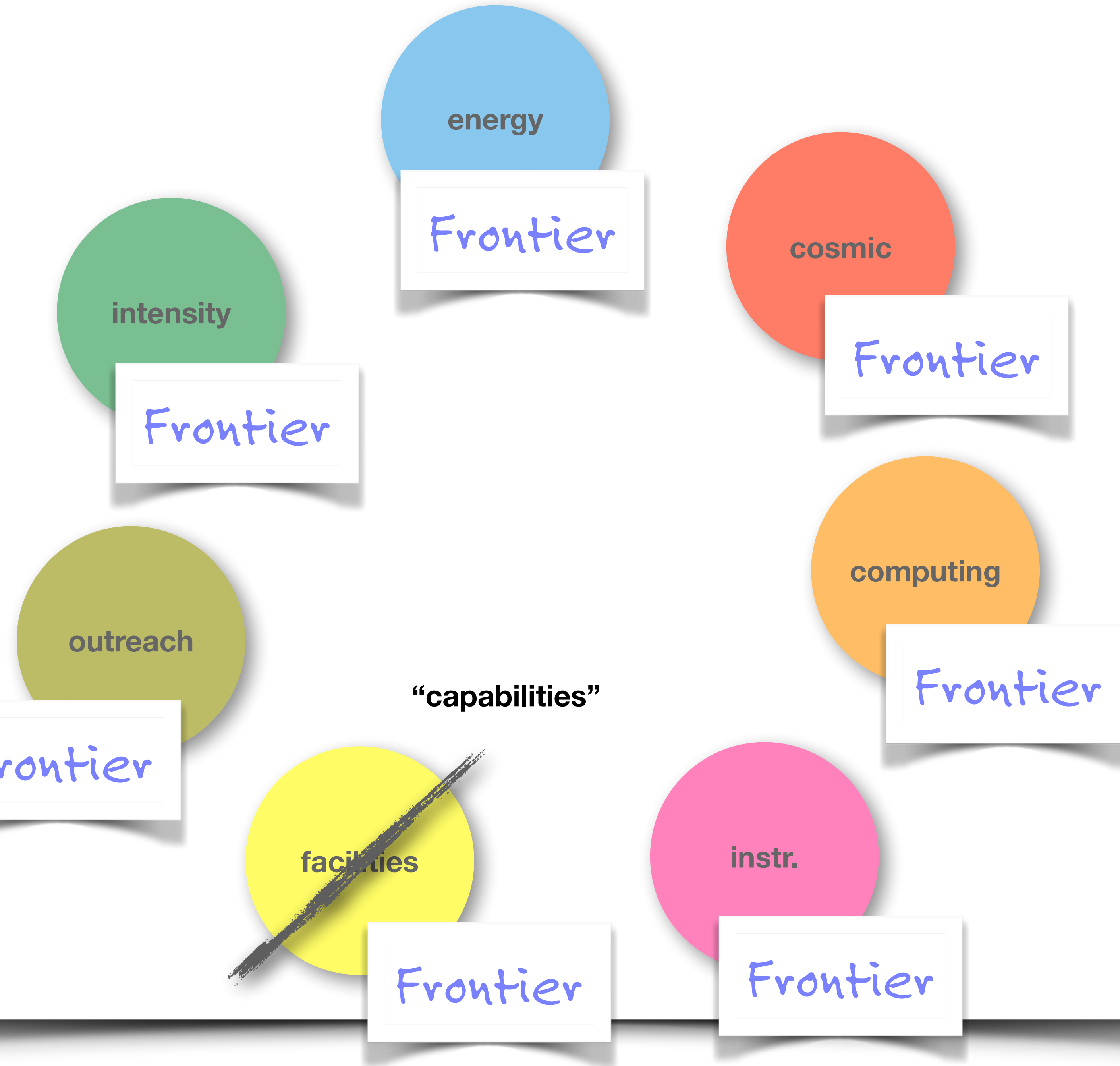
- DPF started organizing

  in 2012

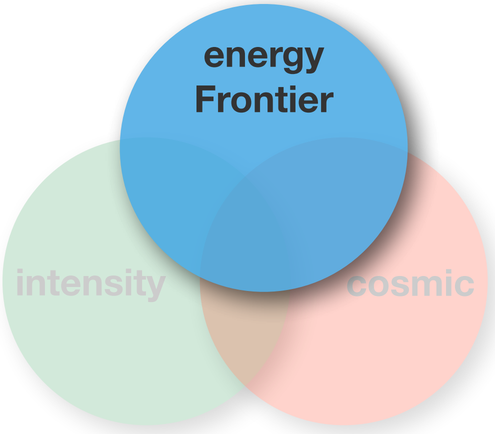
Our primary theme.



This was the Snowmass organizational reality:



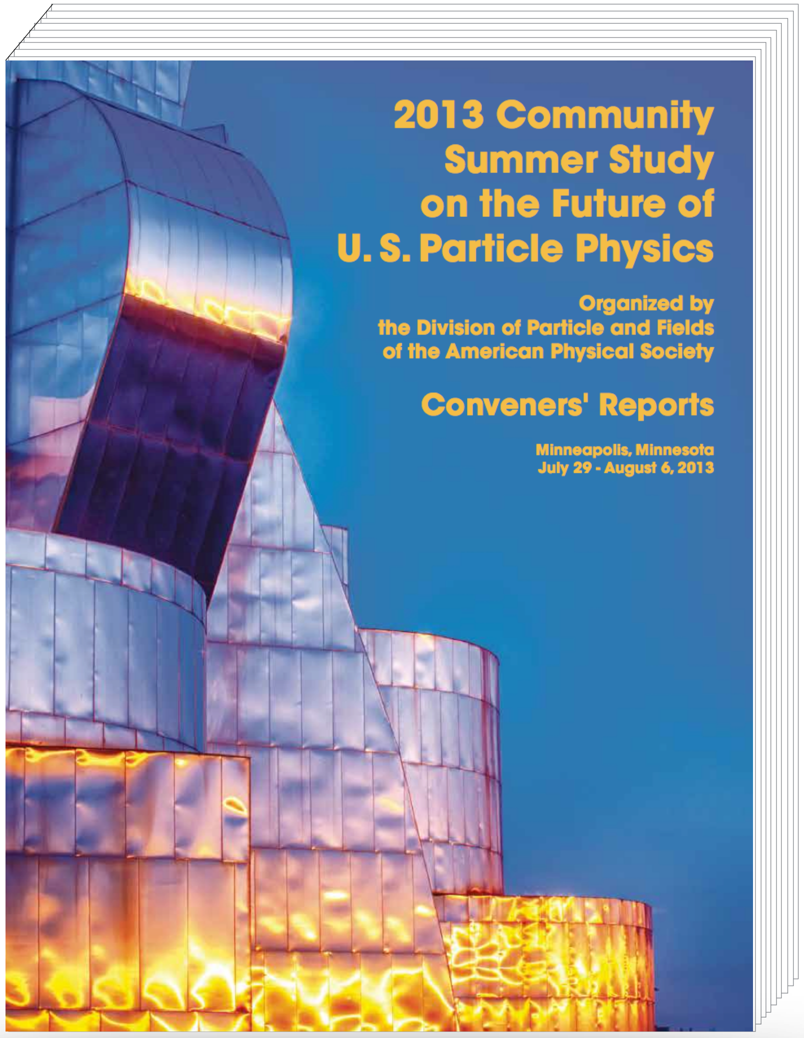
My job:



We worked together & apart:

Sept 2012-August 2013: “Snowmass”

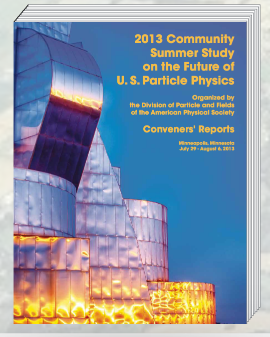
October 2013-May 2014: P5



&

so far:

- The LHC running had just begun



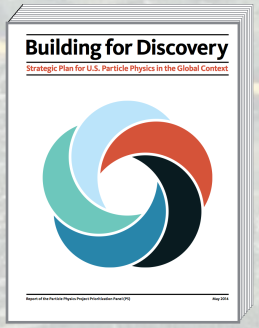
"phase 0 upgrades"

"phase 1 upgrades"

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024

Run I
8 TeV
0.75 10^{34} $cm^{-2}s^{-1}$

20 fb^{-1}



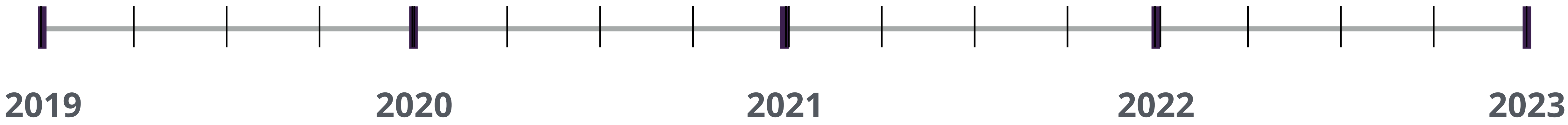
Run II
13-14 TeV
1.5 10^{34} $cm^{-2}s^{-1}$

~150 fb^{-1}

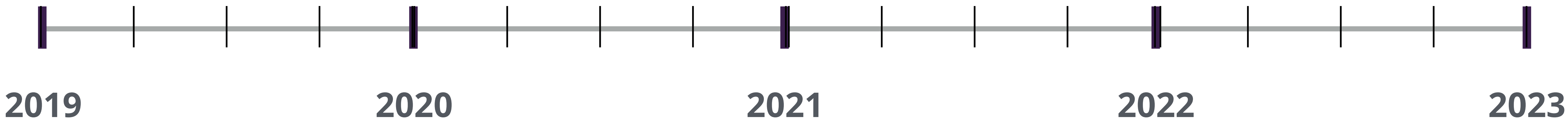
Run III
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

300 fb^{-1}


DAFT PUNK ONE MORE TIME

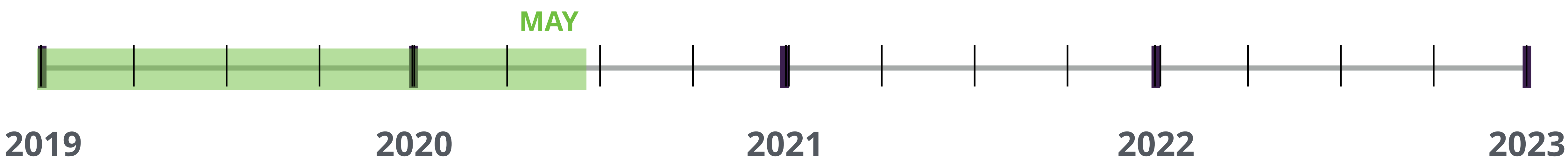


let’s do it again,
“updates”



let’s do it again,
“updates”

- First, European Strategy for Particle Physics



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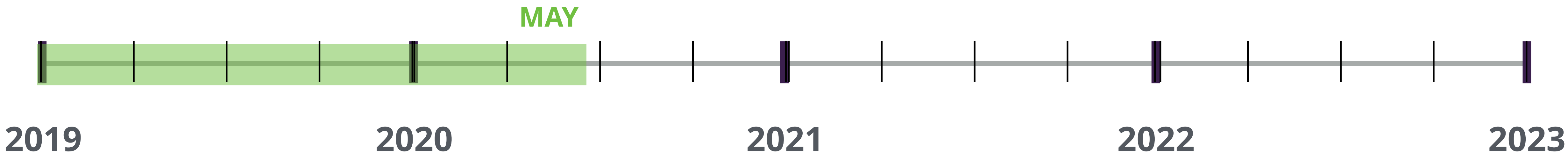
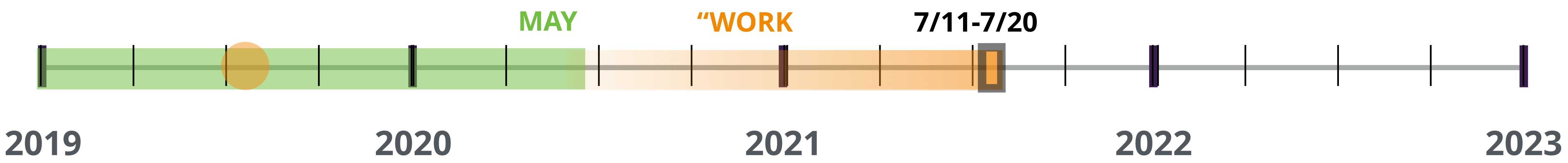
First, European Strategy for Particle Physics



let’s do it again, “updates”

- First, European Strategy for Particle Physics
- Then, US Snowmass Study



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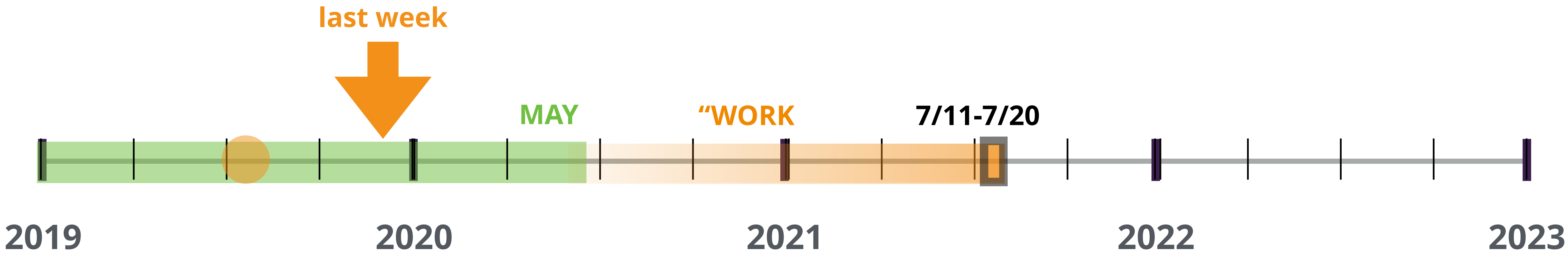

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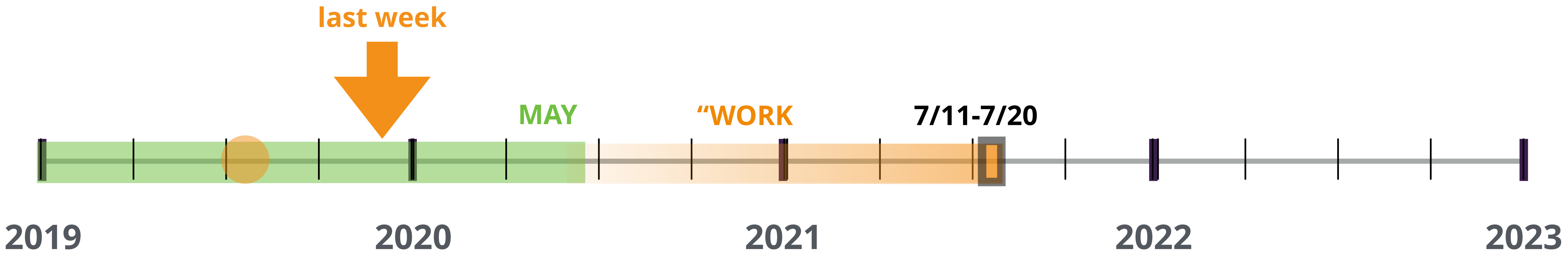
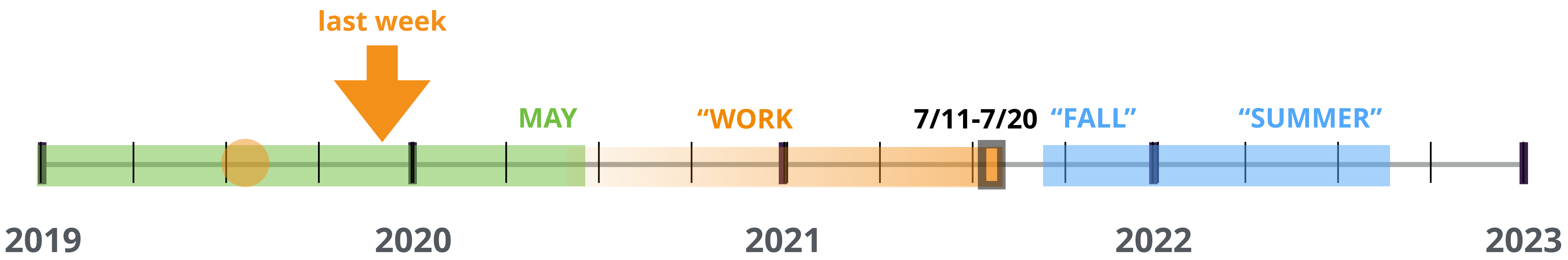


let's do it again, "updates"

- First, European Strategy for Particle Physics
- Then, US Snowmass Study
- Finally, HEPAP P5 Study



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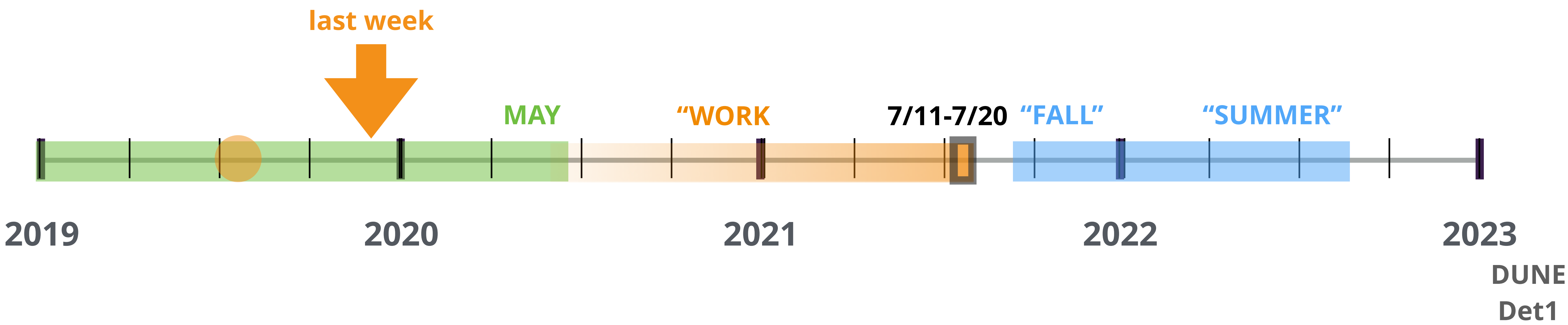

let's do it again, "updates"

- First, European Strategy for Particle Physics
- Then, US Snowmass Study
- Finally, HEPAP P5 Study


Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context
Report of the Particle Physics Project Prioritization Panel (P5)
May 2014

- "Science Drivers":

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

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- Pursue the physics associated with **neutrino mass**

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  - Understand **cosmic acceleration**: dark energy and inflation

"Science Drivers":

- 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

Science Drivers

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	✔		
Neutrino Mass	✔	✔	✔
Dark Matter	✔		
Cosmic Acceleration			✔
Explore the Unknown	✔	✔	✔

Frontiers

Science Drivers

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	✔		
Neutrino Mass	✔	✔	✔
Dark Matter	✔		
Cosmic Acceleration			✔
Explore the Unknown	✔	✔	✔

its own driver?

Frontiers

Science Drivers

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	✔		
Neutrino Mass	✔	✔	✔
Dark Matter	✔		
Cosmic Acceleration			✔
Explore the Unknown	✔	✔	✔

particle physics


HIGGS
ticl
e p
phys
HIGGS

Why the Standard Model victory laps?

between **1967 - 2012**

- history was made

1967 **2012**

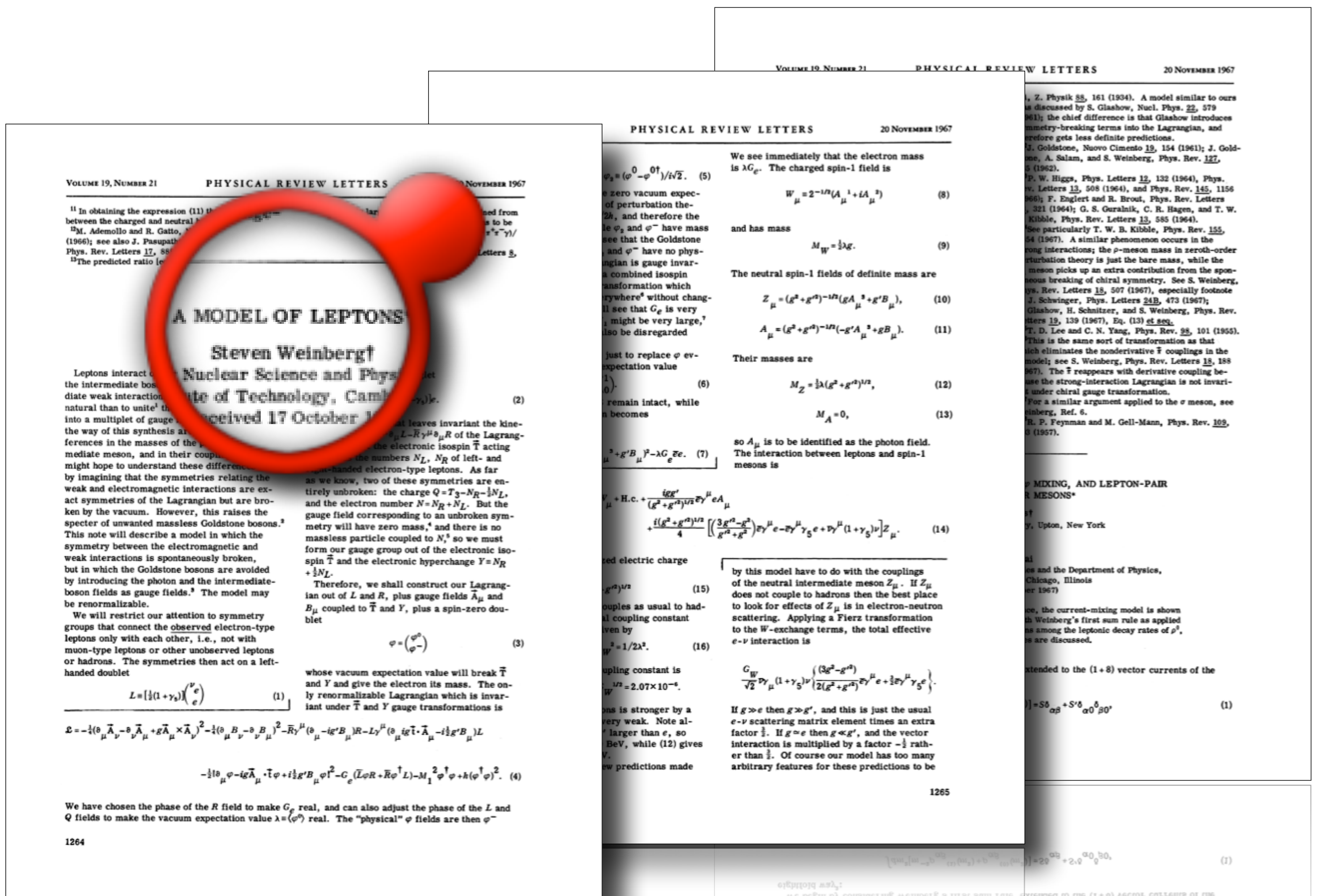
between **1967 - 2012**

- history was made

1967

2012

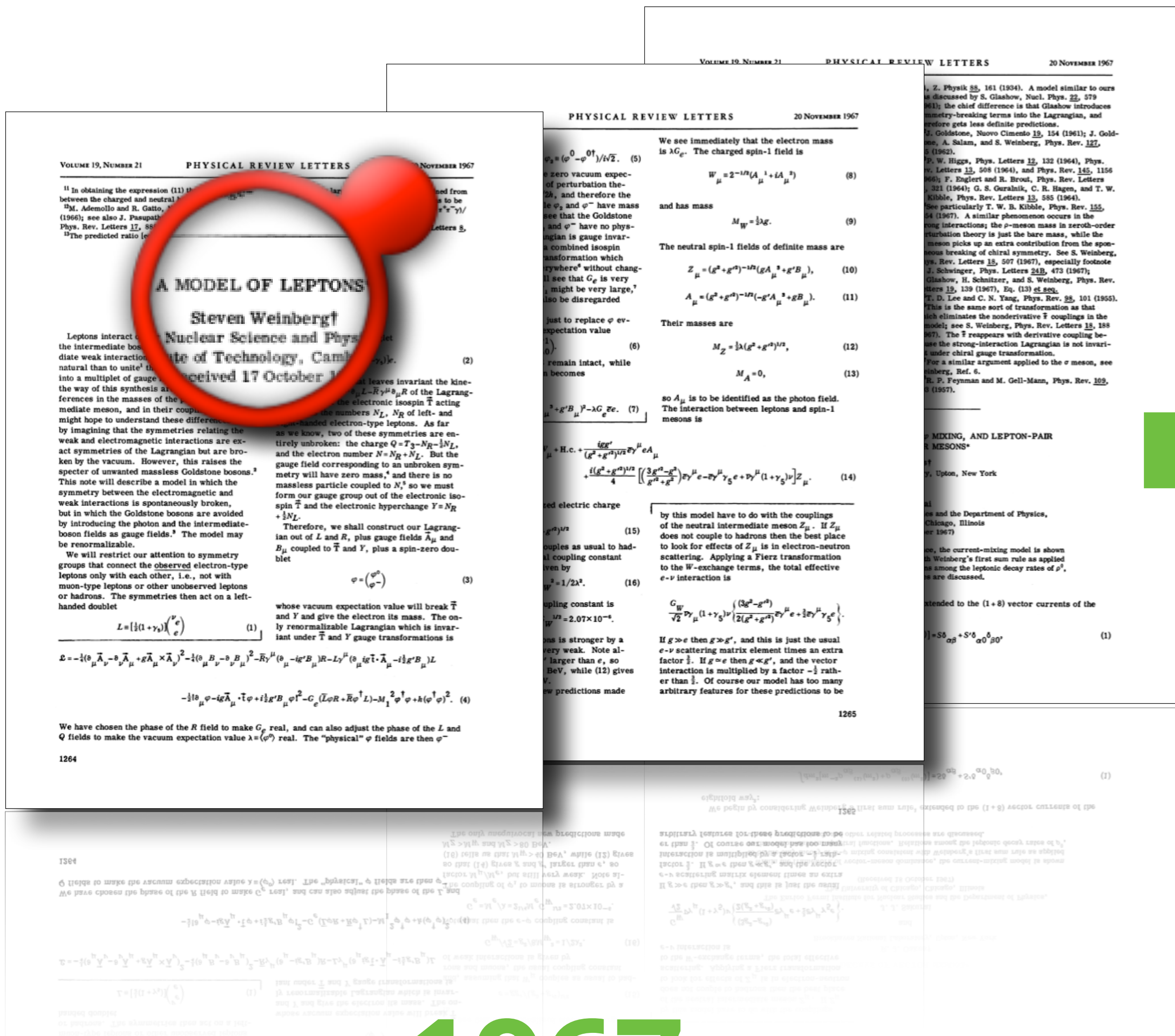
between **1967 - 2012**



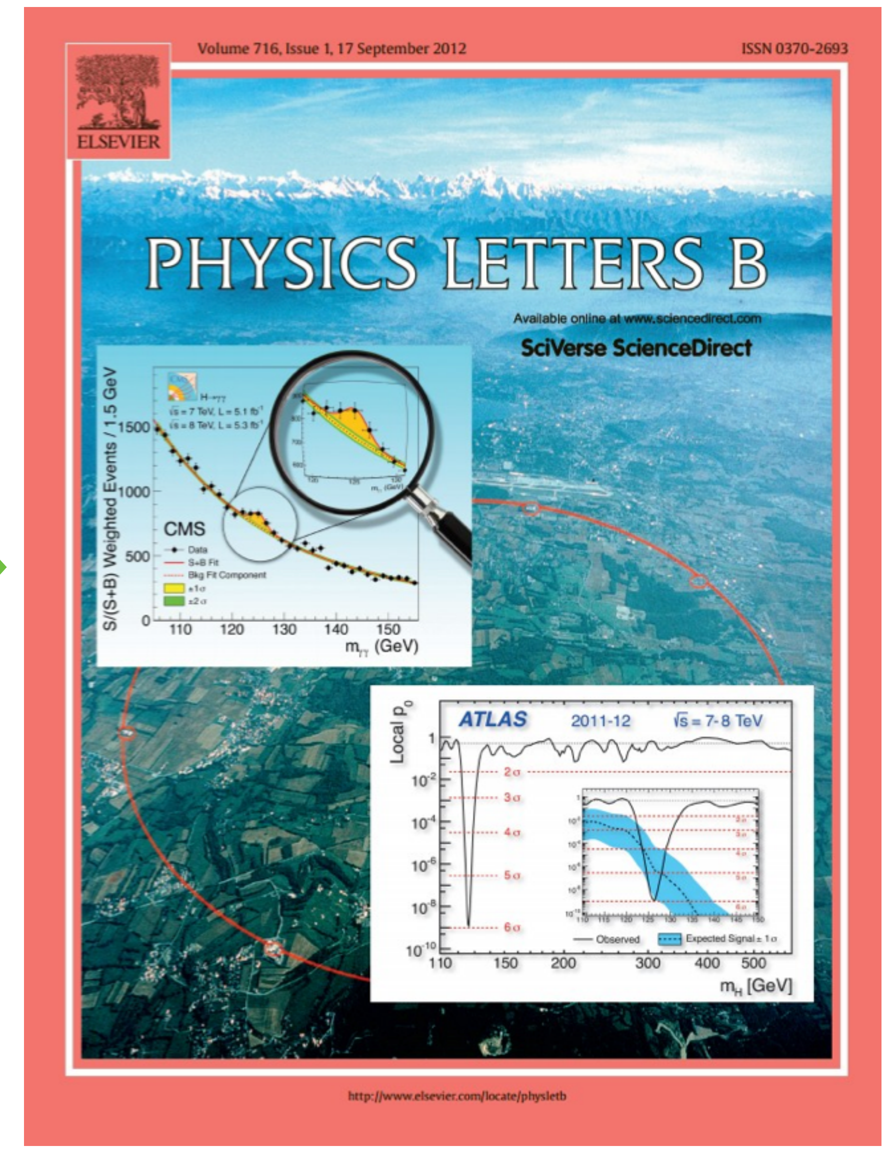
1967

2012

between **1967 - 2012**



1967



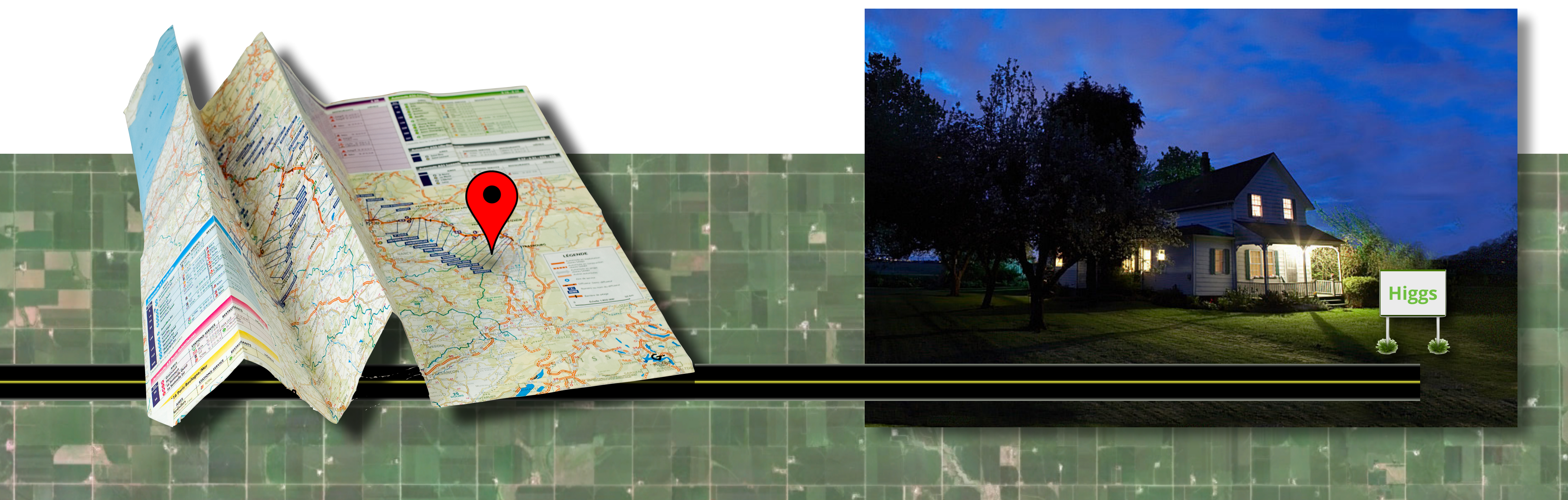
2012

30,000 ft View of the Standard Model

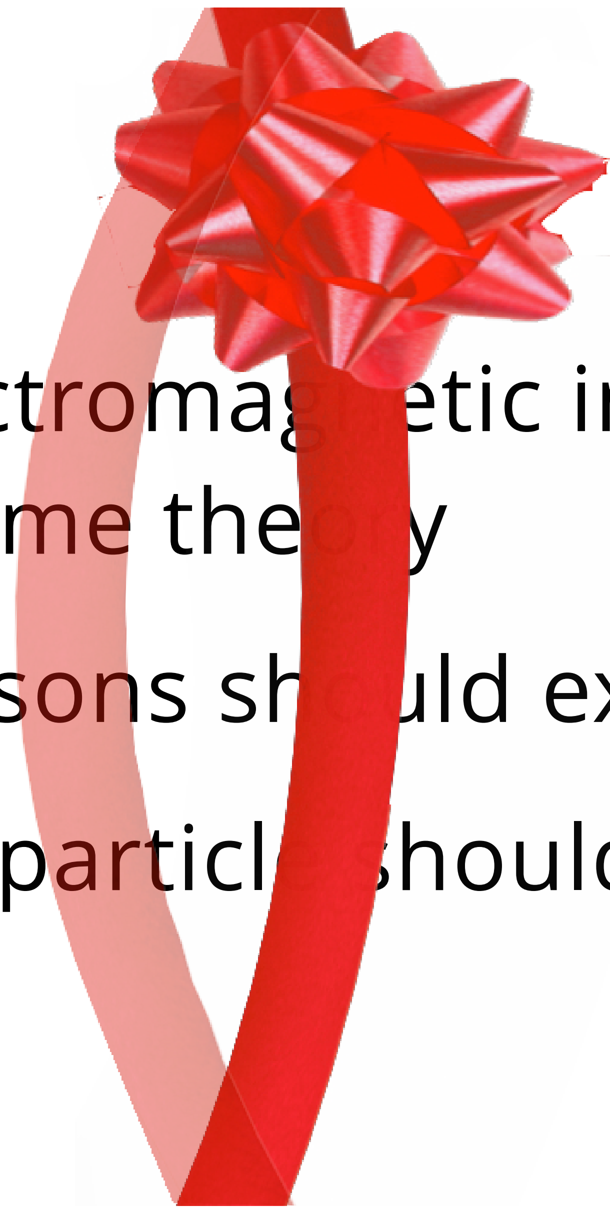

Standard
Model

guided research

guided research



Because: 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
- A spin-0 field and particle should exist

- The weak and electromagnetic interactions originate in the same theory

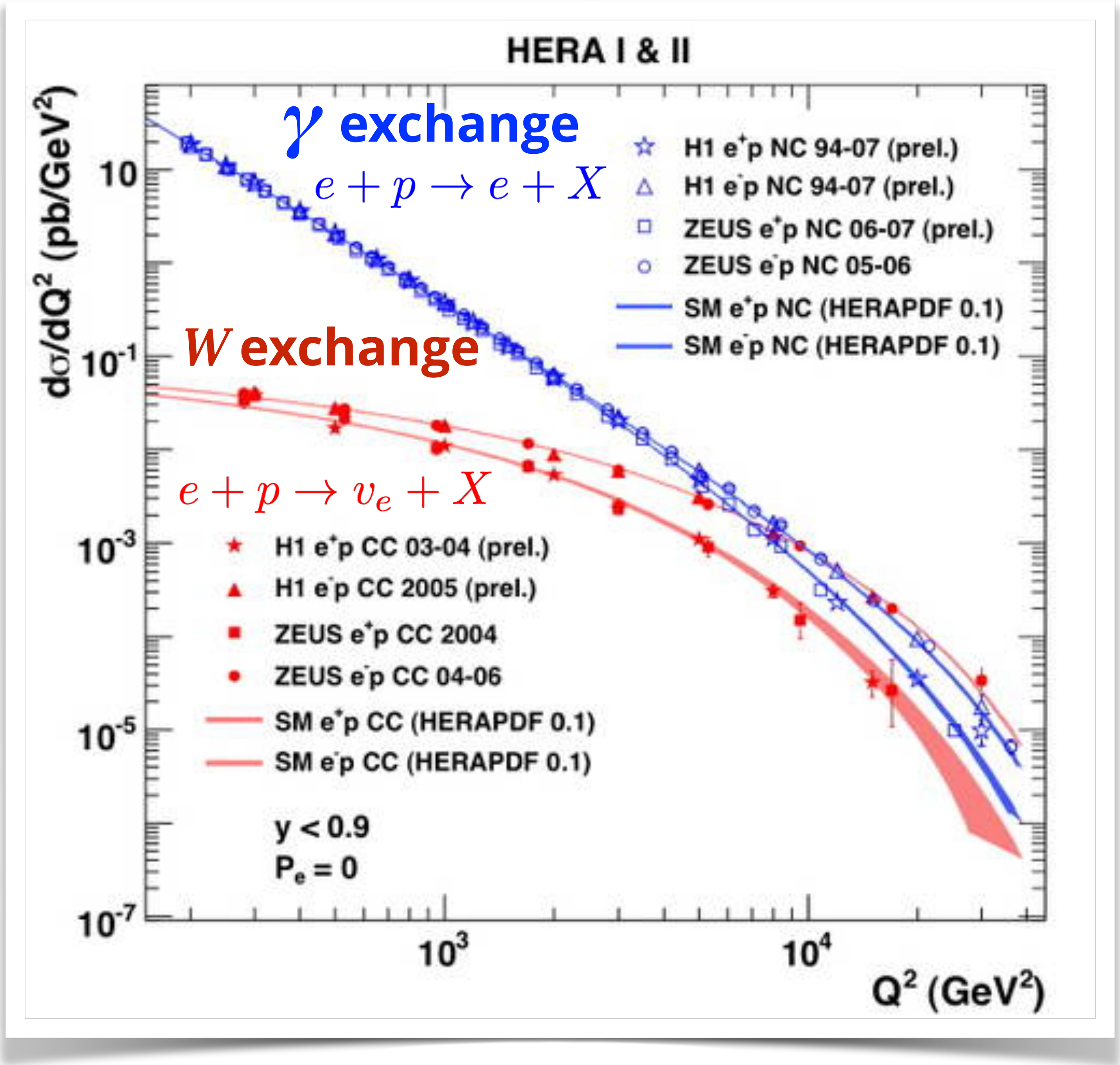
- *3 spin 1 vector* bosons should exist: γ, $W^{\pm}$, Z^{0}
- *A spin-0 field and* particle should exist

1/3 SM predictions

- The weak and electromagnetic interactions originate in the same theory

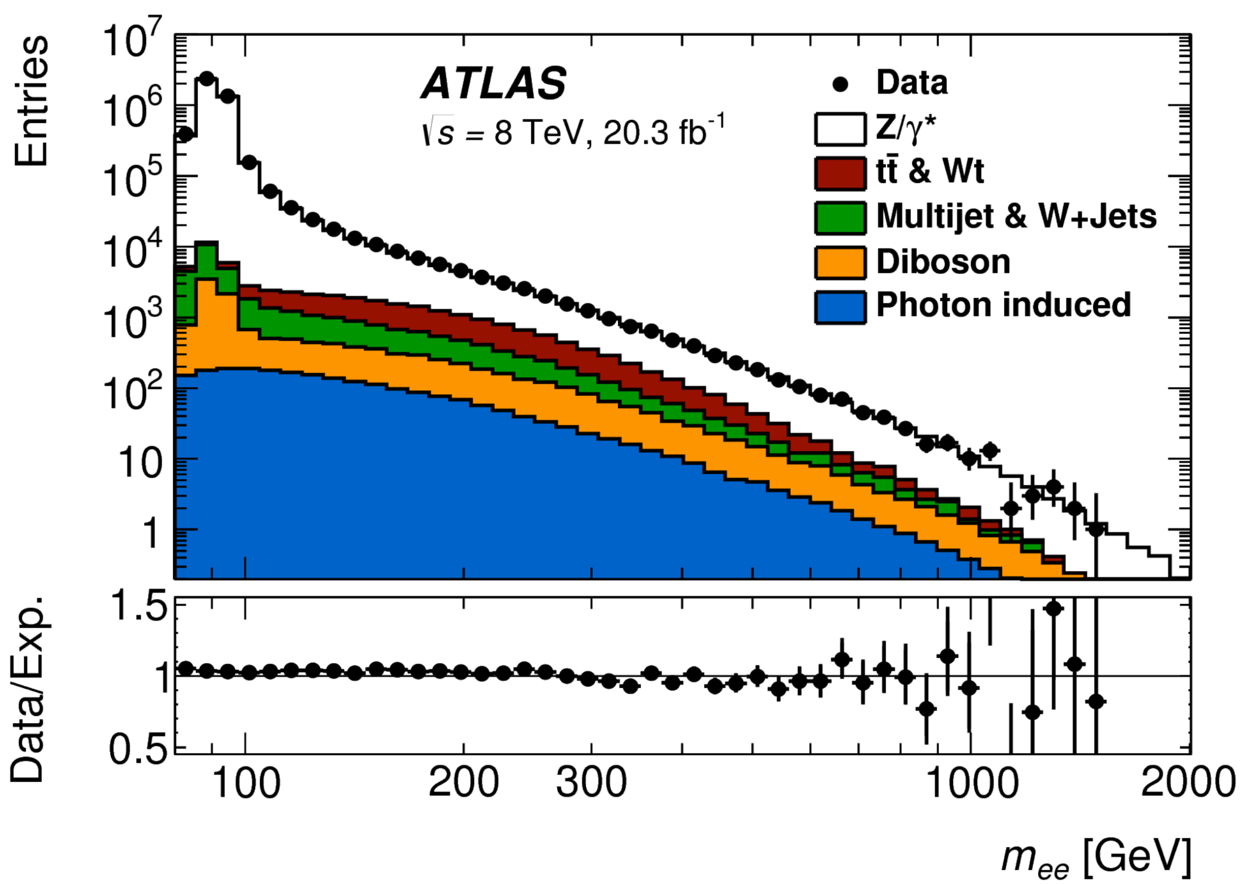
1/3 SM predictions

- The weak and electromagnetic interactions originate in the same theory

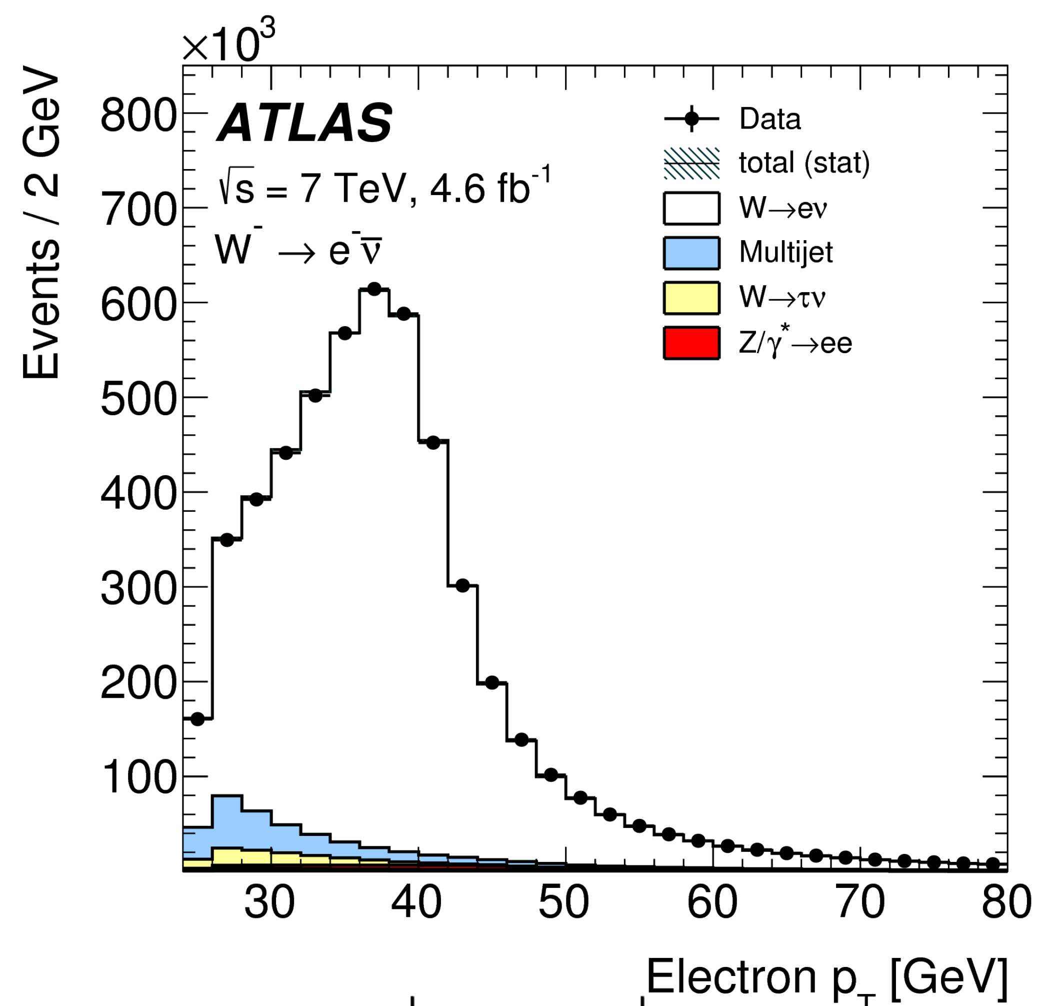


2/3 SM predictions

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



$$Z^0 \rightarrow e^+ + e^-$$



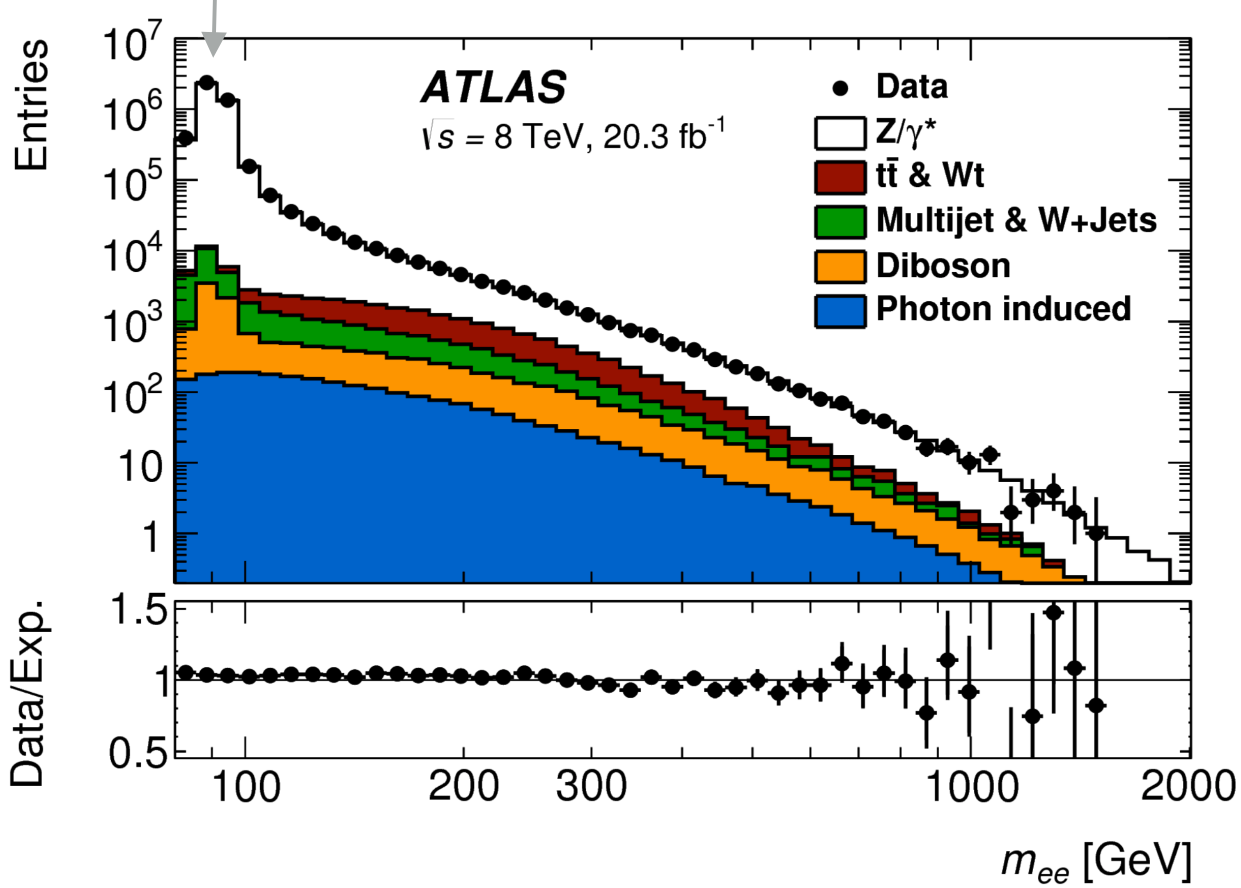
$$W^{\pm} \rightarrow e^{\pm} + v_e$$

2/3 SM predictions

Z mass = 91.1876 ± 0.0021 GeV/c²

1/2 *W* mass of 80.385 ± 0.015 GeV/c²

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



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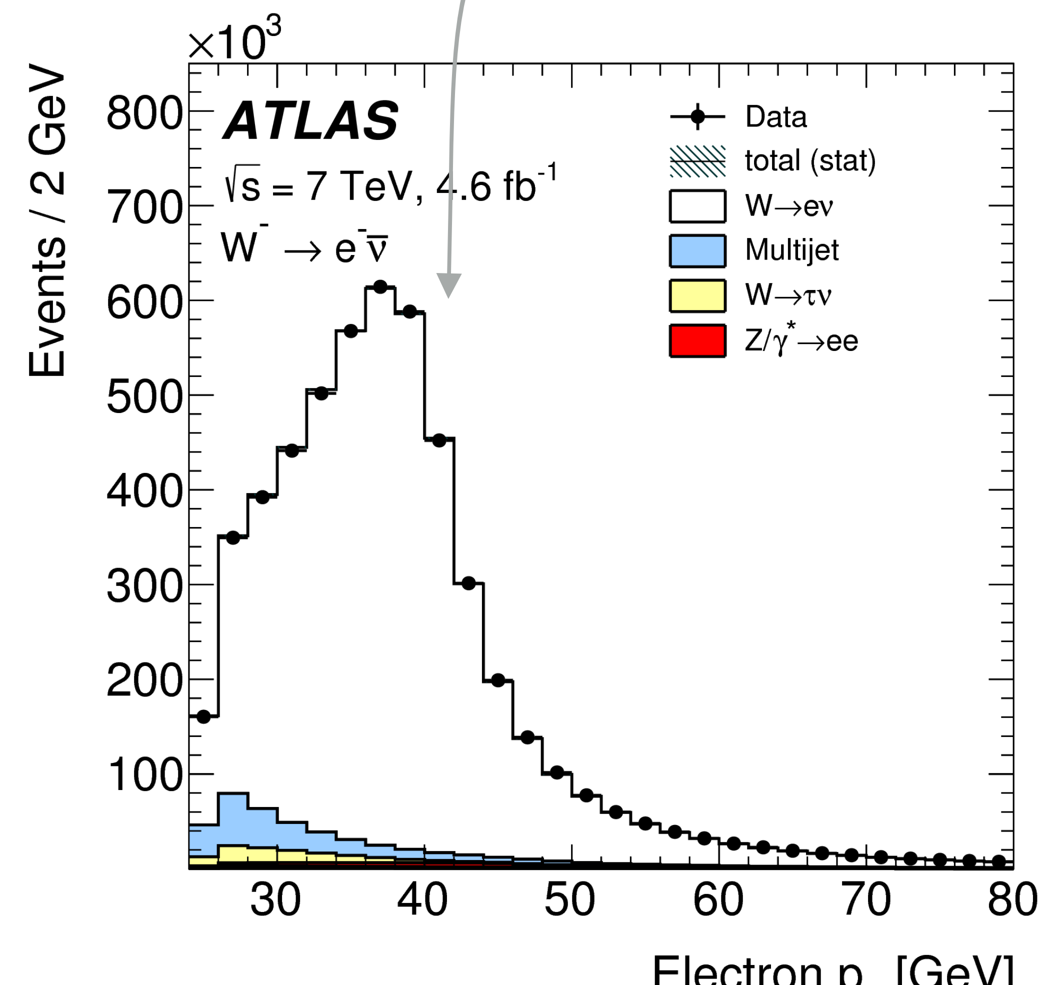


$$W^{\pm} \rightarrow e^{\pm} + v_e$$

3/3 SM predictions

- A spin-0 field and particle should exist

  and so began a story

4th of July, 2012

the 2012 discovery

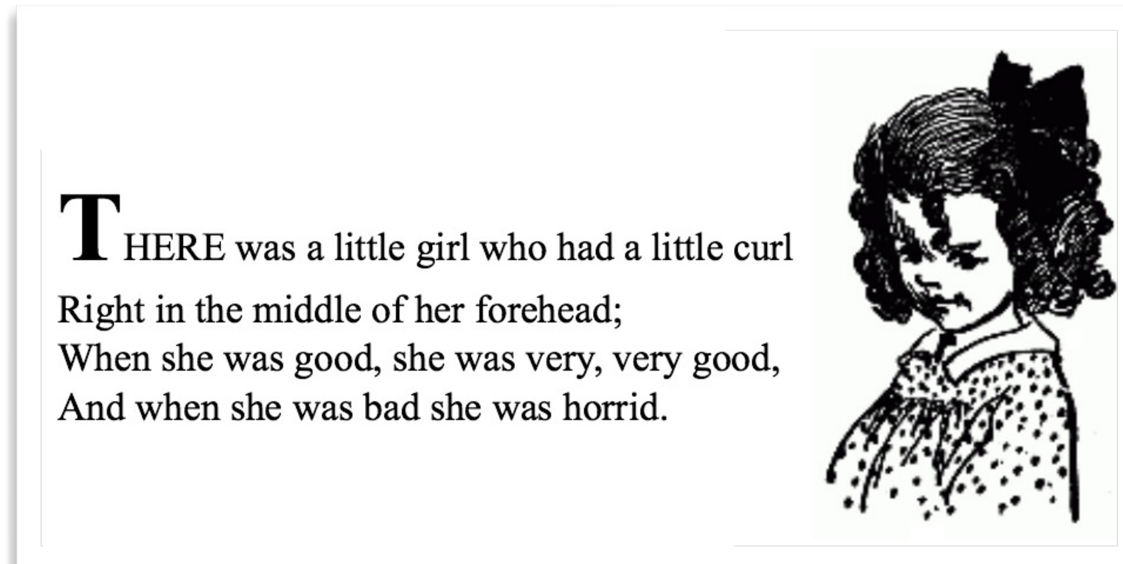
- completed the story

unrelenting 40 year effort.


STANDARD MODEL HAS BEEN PLACED ON THE
NATIONAL
REGISTER
OF HISTORIC
THEORIES
BY THE
UNITED STATES DEPARTMENT OF THE INTERIOR

We’re schizophrenic about the Standard Model

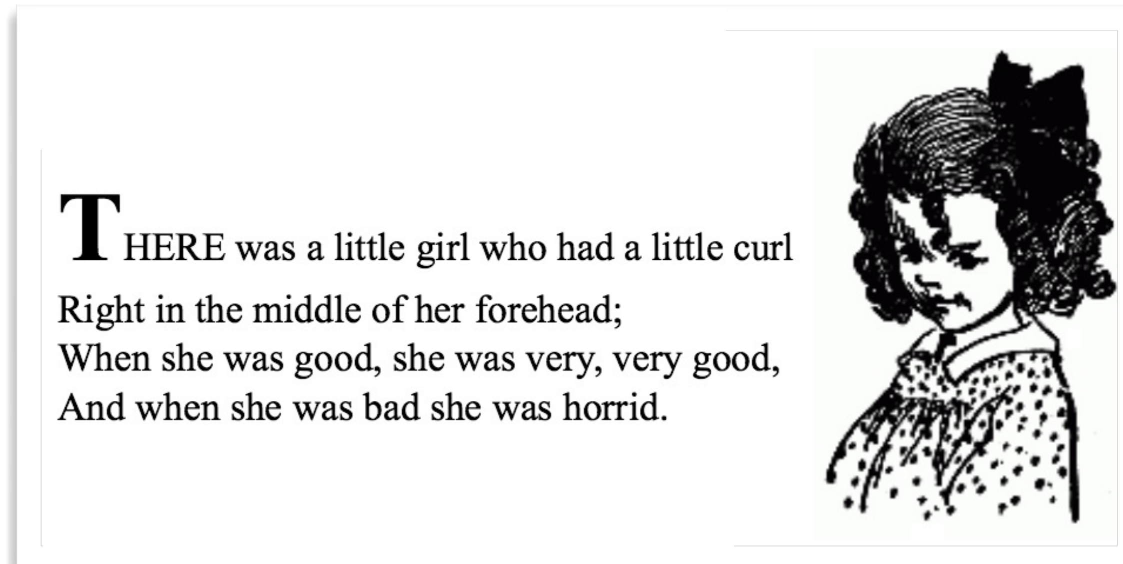
Like the nursery rhyme


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

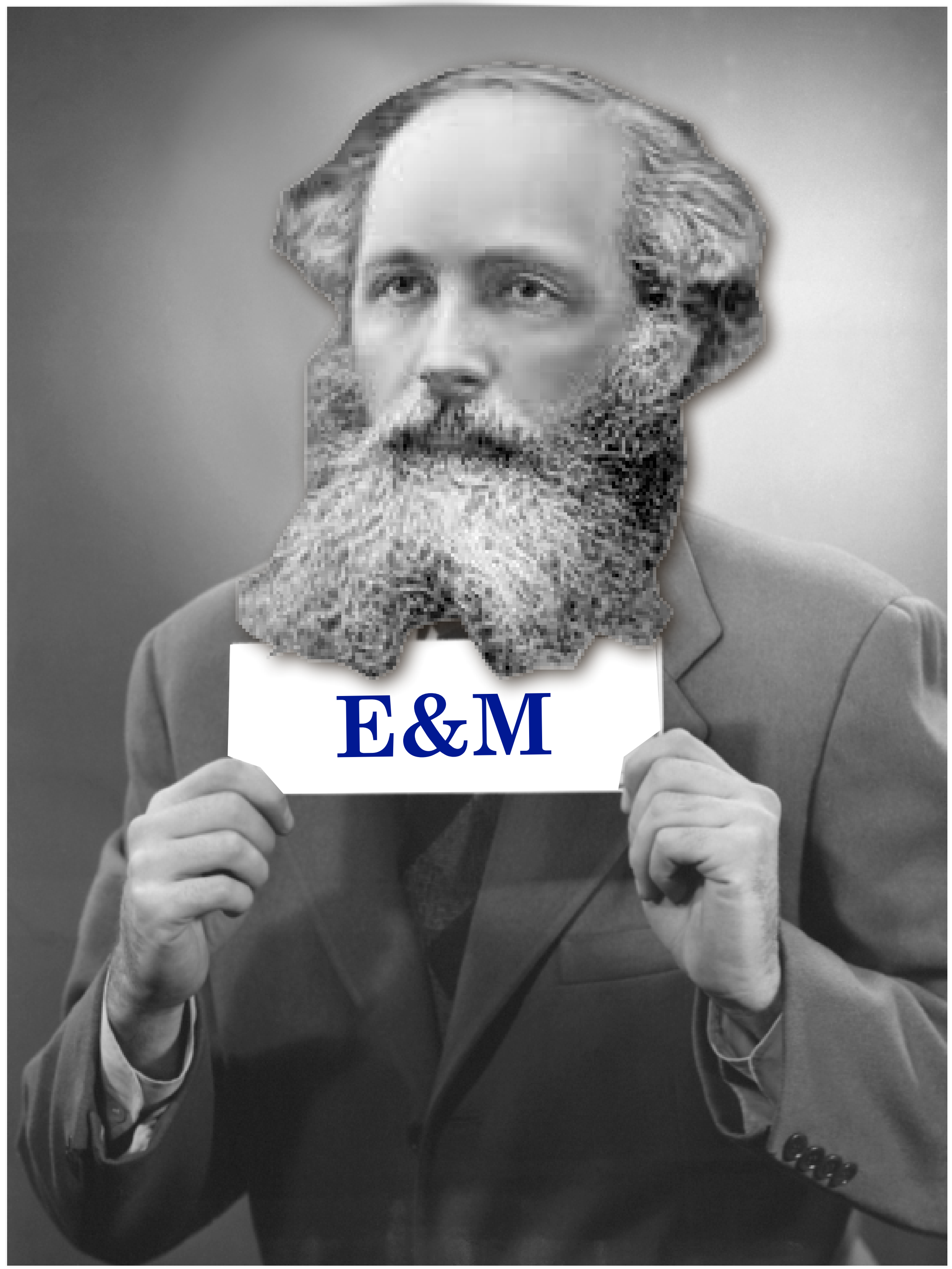


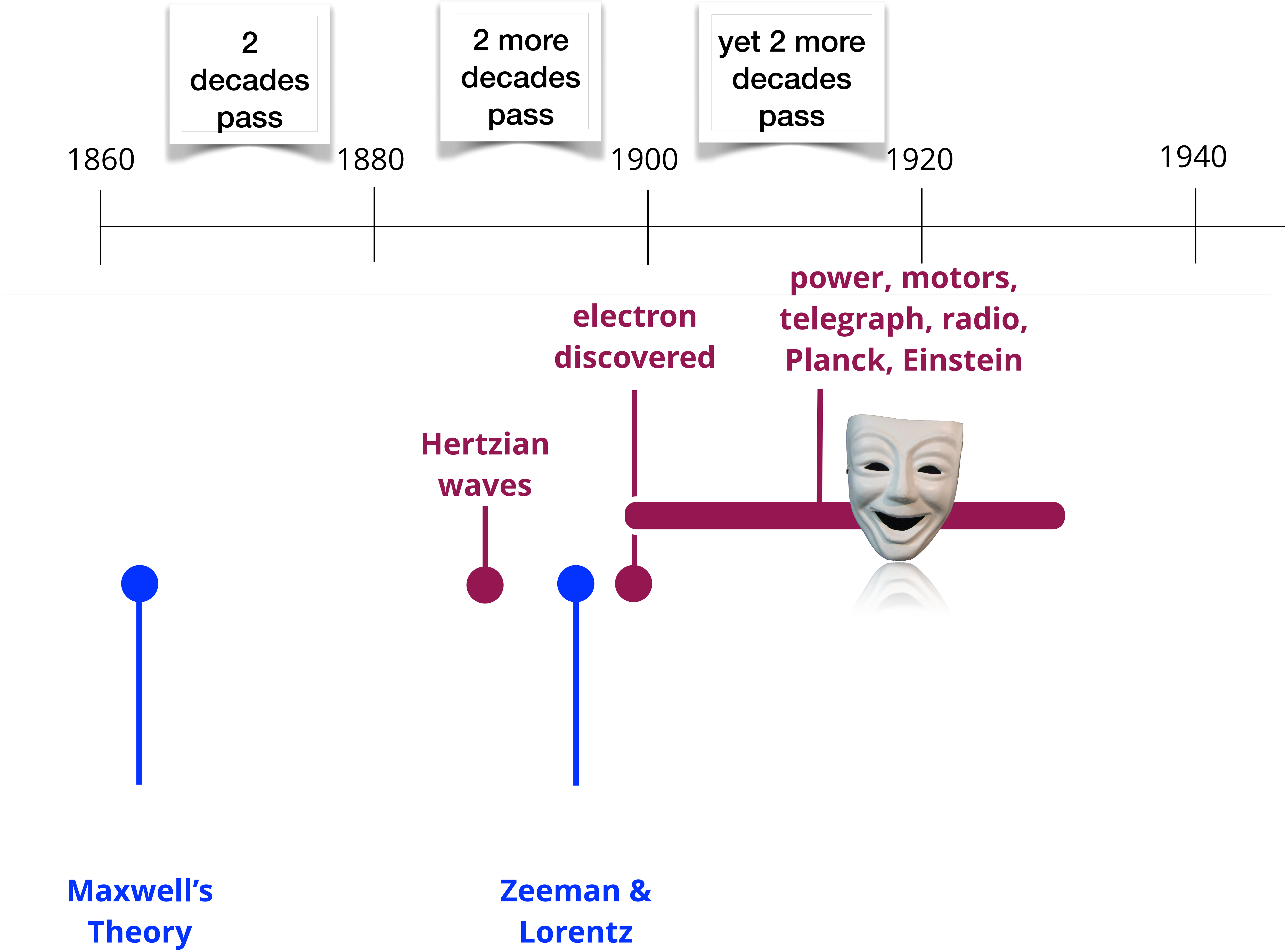
- when the SM is good,

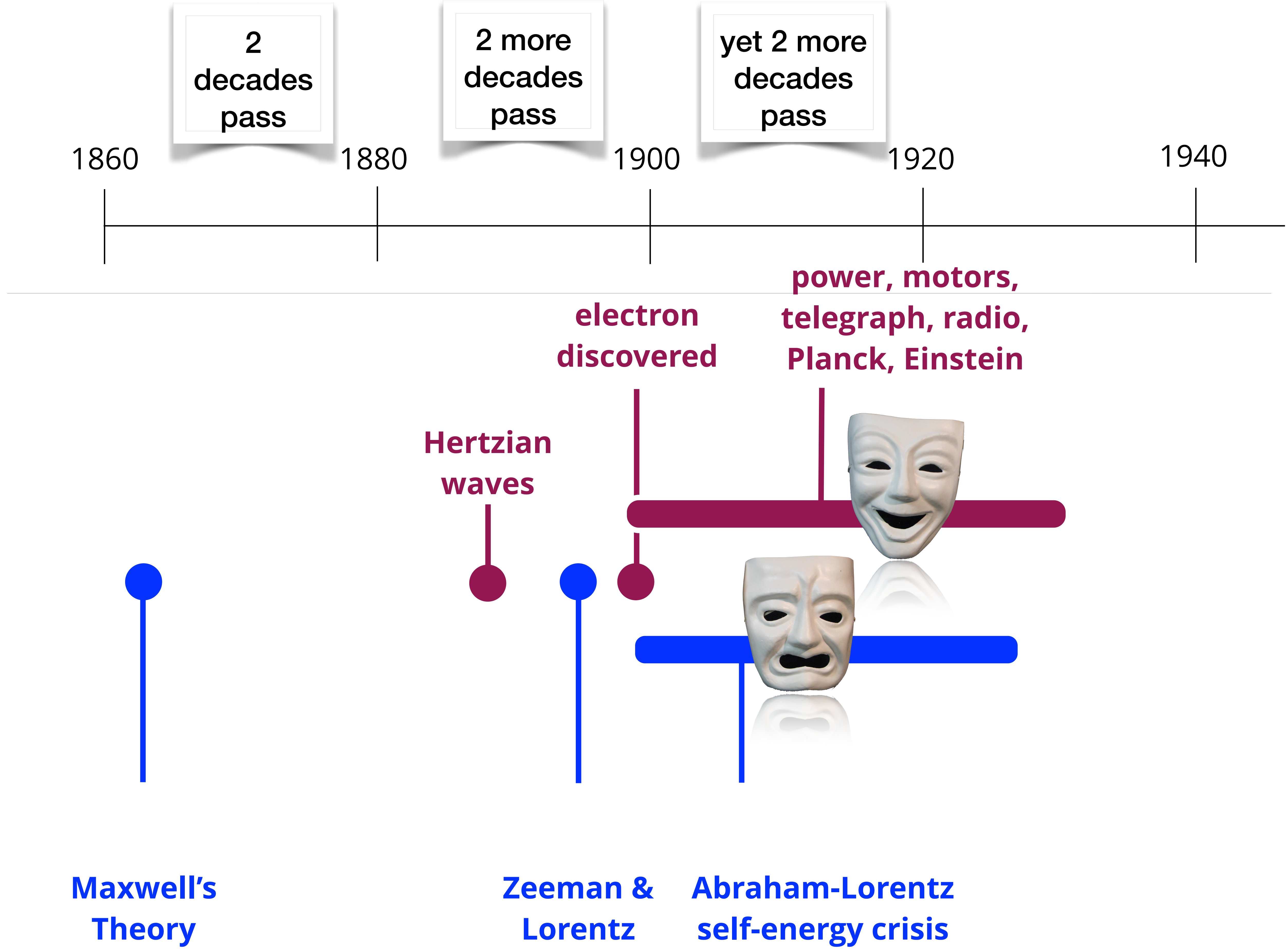
  it's very good

- when it's bad

  it's very...confusing


E&M


2 decades pass
2 more decades pass
yet 2 more decades pass
1860
1880
1900
1920
1940
power, motors, telegraph, radio, Planck, Einstein
electron discovered
Hertzian waves
Maxwell's Theory
Zeeman & Lorentz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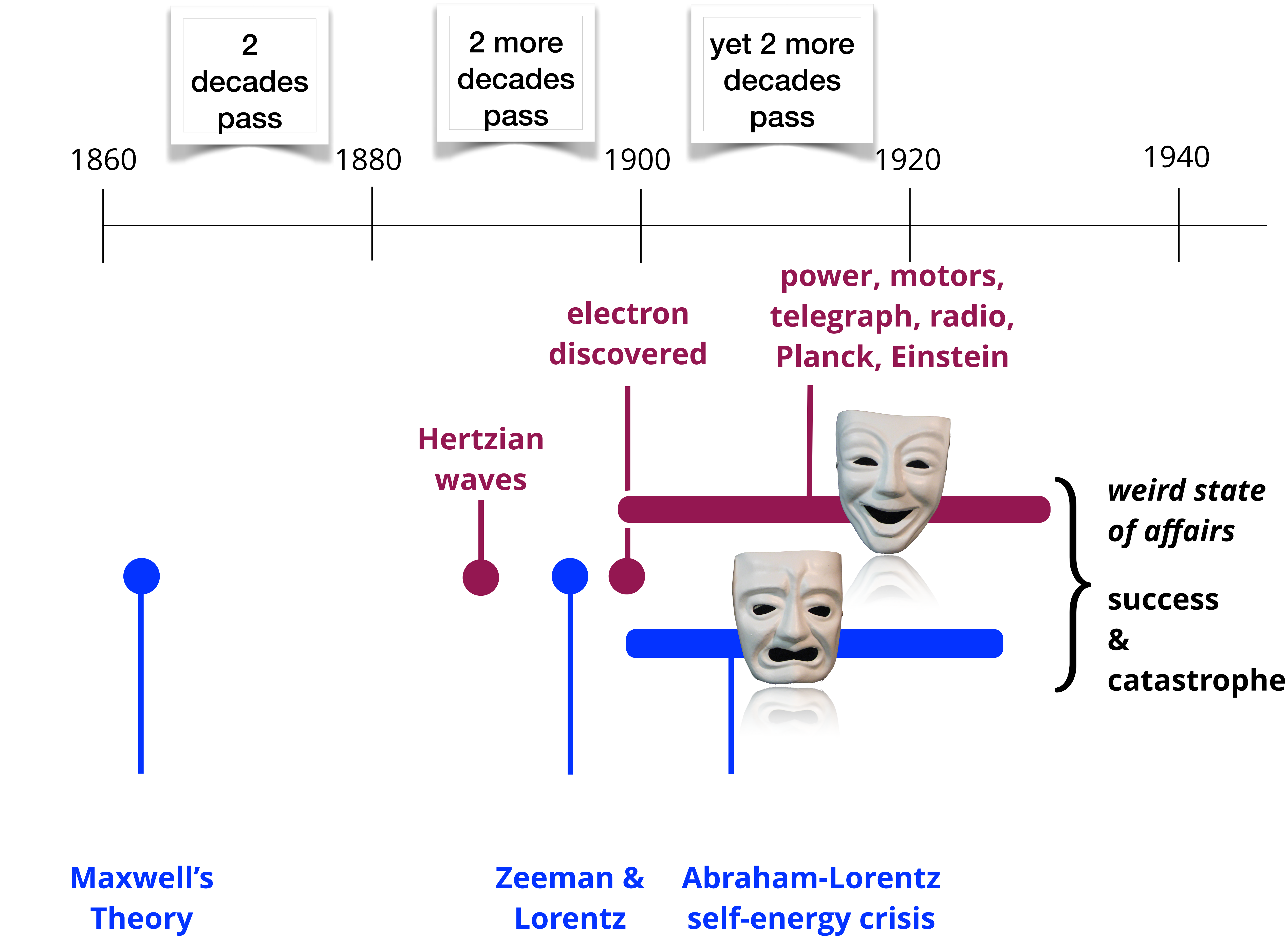
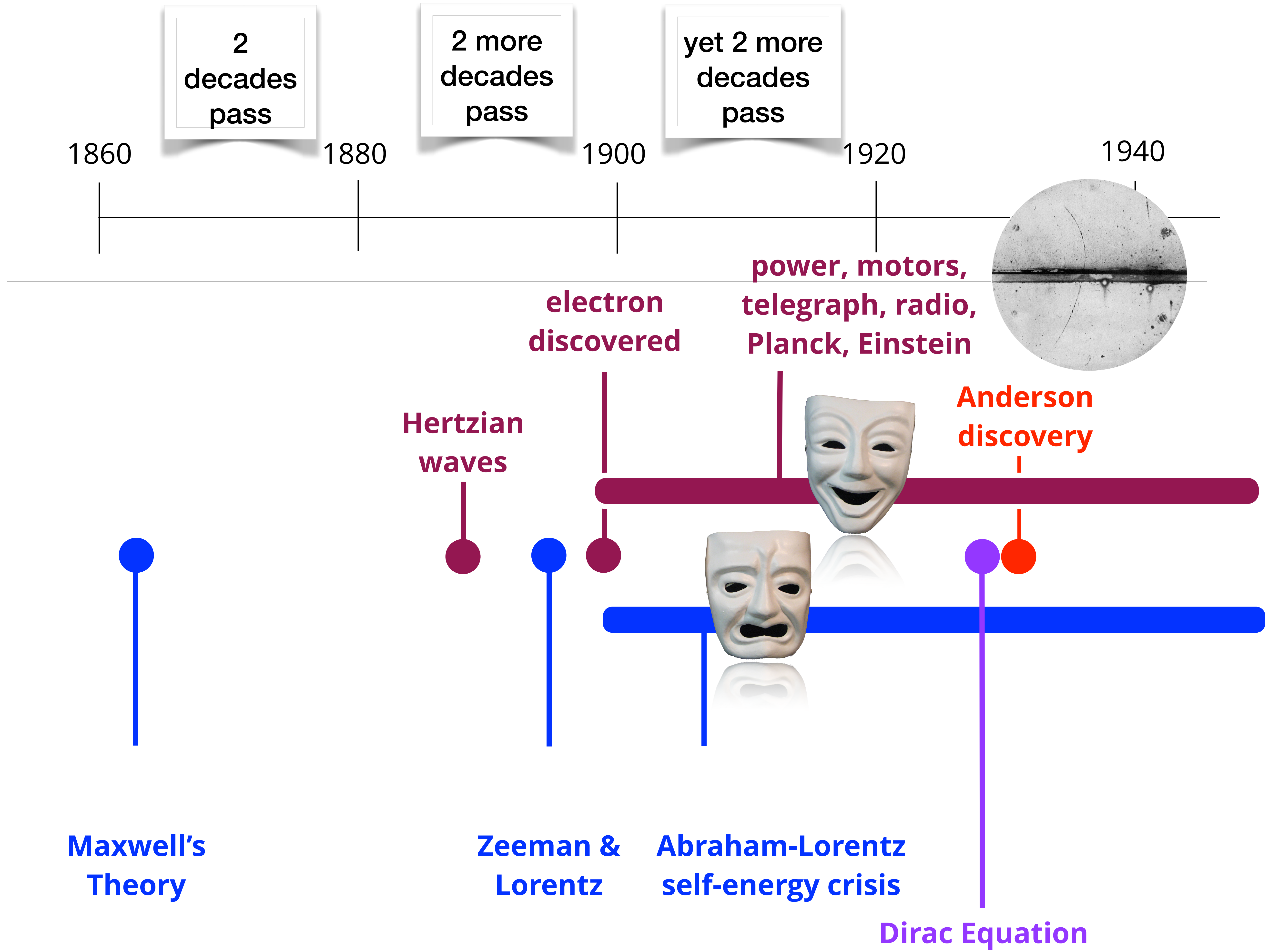
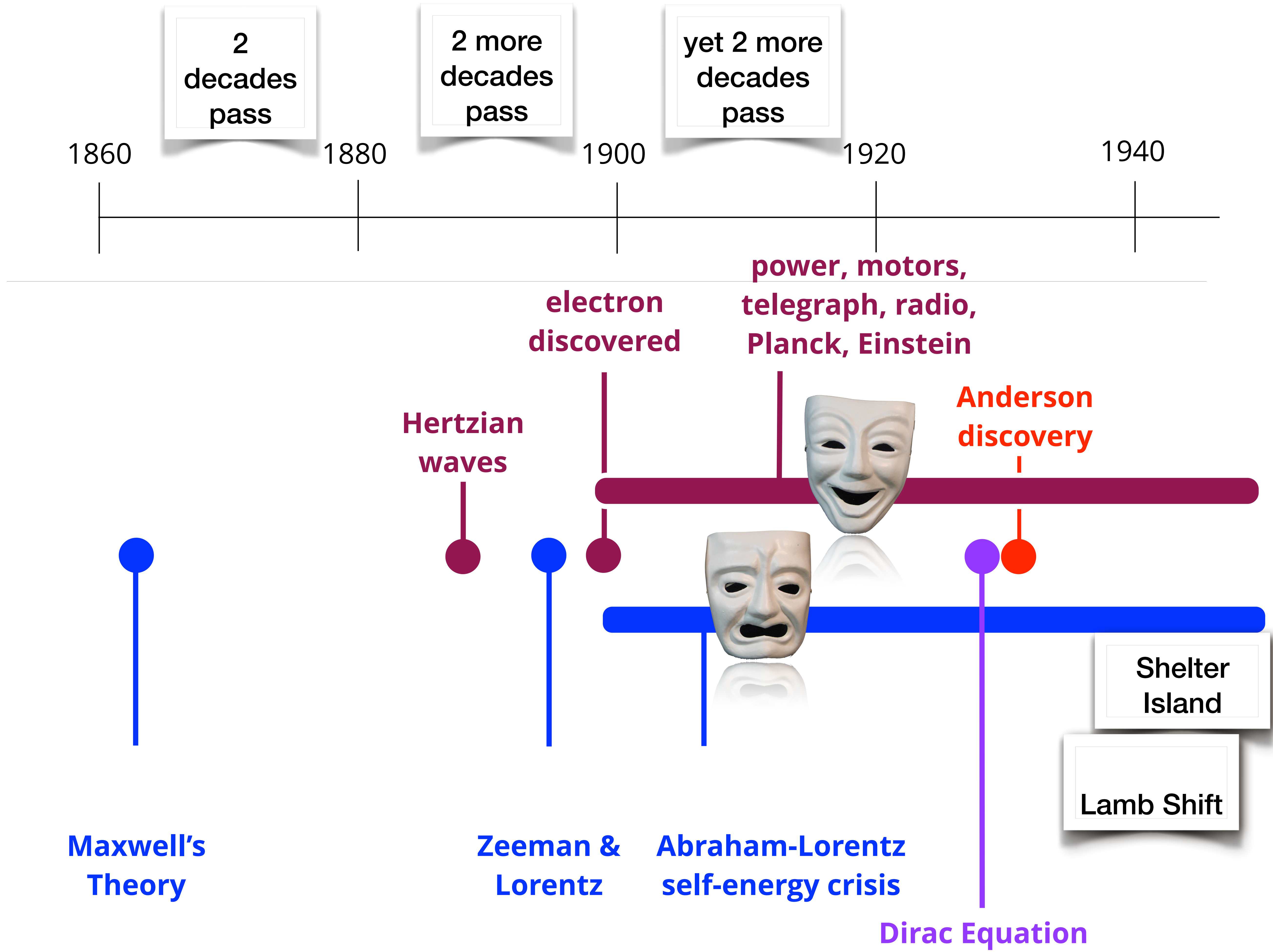
Abraham-Lorentz self-energy crisis



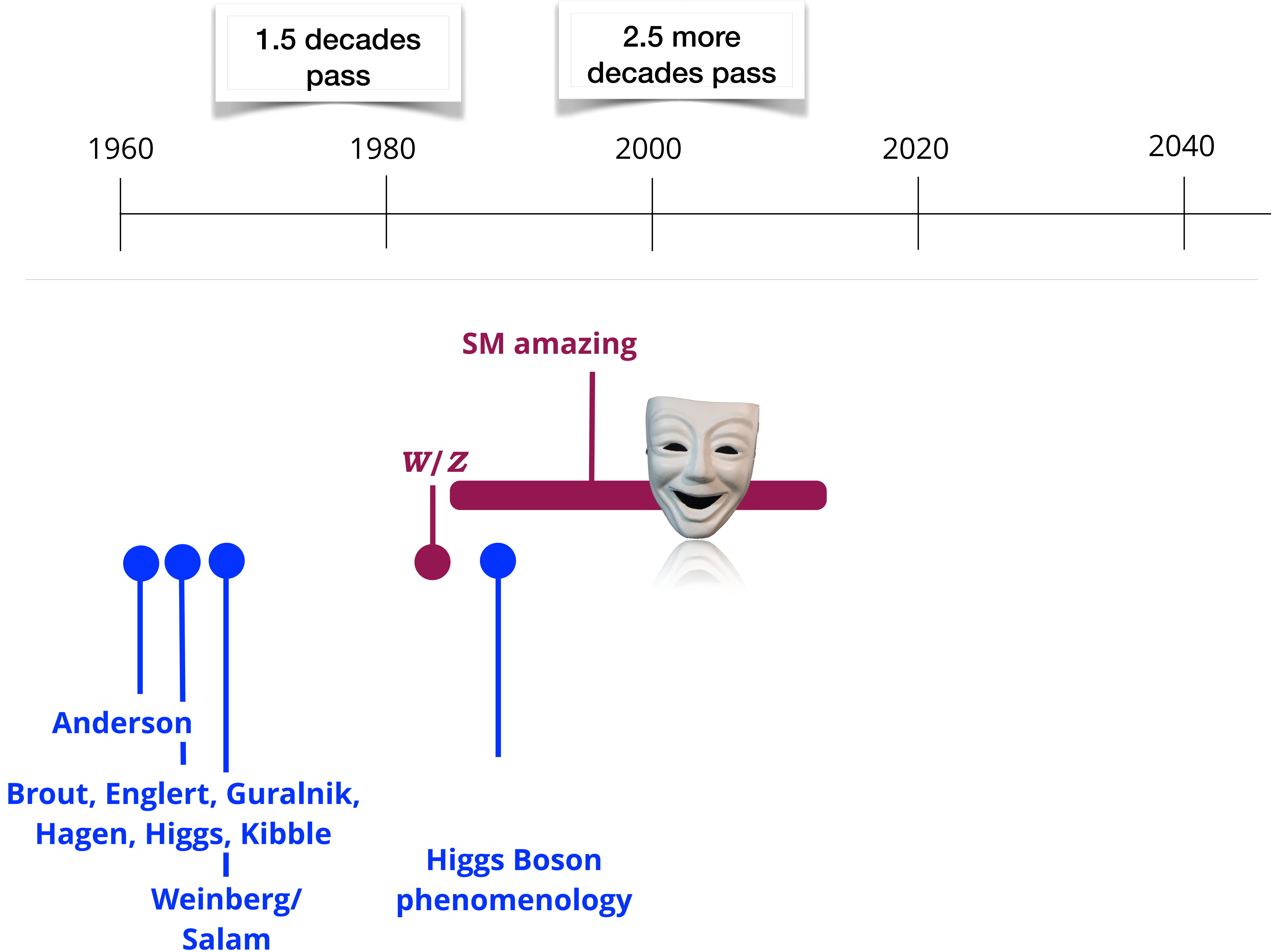
2 decades pass
2 more decades pass
yet 2 more decades pass
1860
1880
1900
1920
1940
power, motors, telegraph, radio, Planck, Einstein
electron discovered
Hertzian waves
weird state of affairs
success & catastrophe
Maxwell's Theory
Zeeman & Lorentz
Abraham-Lorentz self-energy crisis



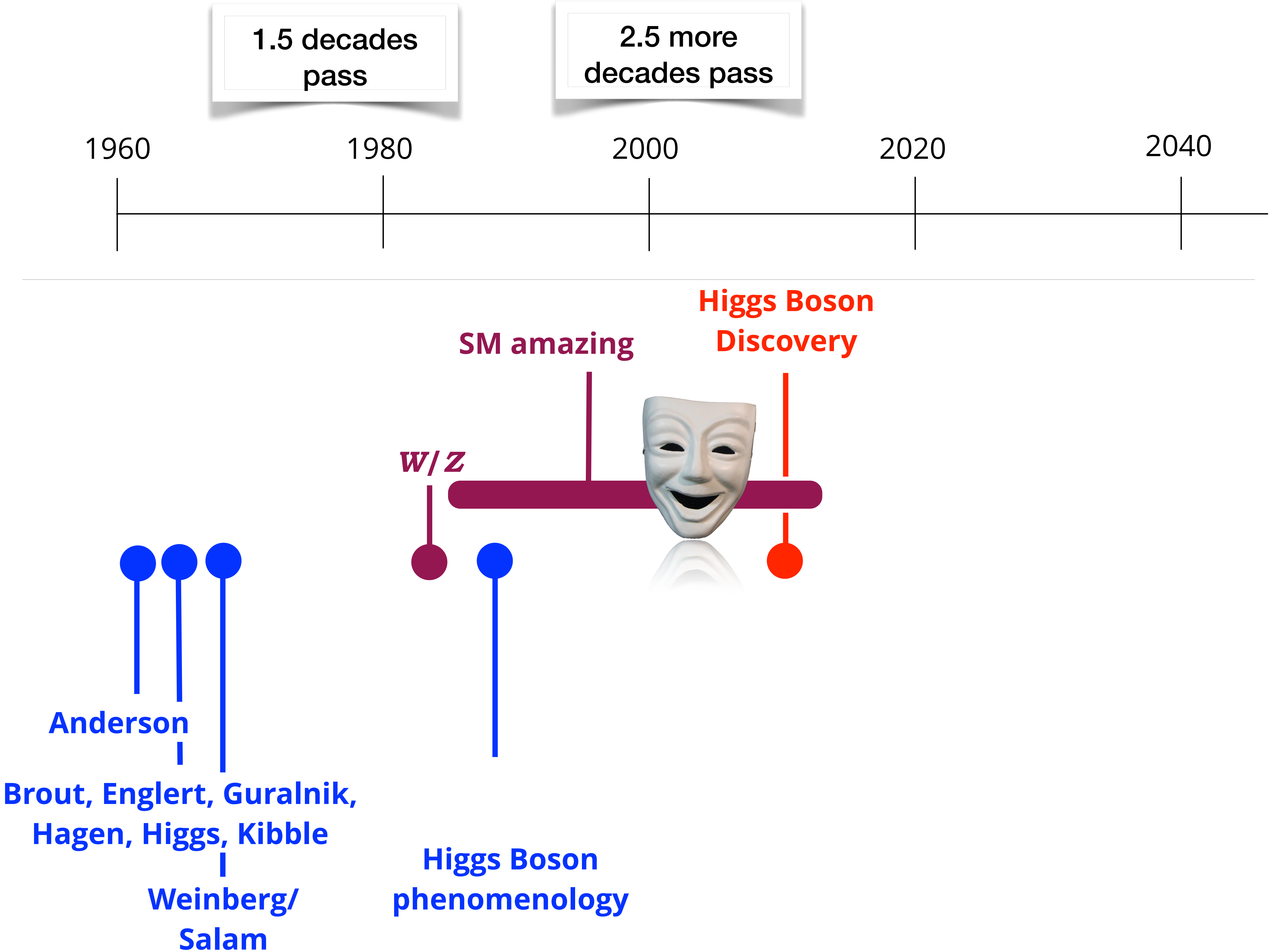
2 decades pass
2 more decades pass
yet 2 more decades pass
1860
1880
1900
1920
1940
electron discovered
power, motors, telegraph, radio, Planck, Einstein
Hertzian waves
Anderson discovery
Maxwell's Theory
Zeeman & Lorentz
Abraham-Lorentz self-energy crisis
Dirac Equation


2 decades pass
2 more decades pass
yet 2 more decades pass
1860
1880
1900
1920
1940
power, motors, telegraph, radio, Planck, Einstein
electron discovered
Hertzian waves
Anderson discovery
Shelter Island
Lamb Shift
Maxwell's Theory
Zeeman & Lorentz
Abraham-Lorentz self-energy crisis
Dirac Equation


Standard
Model



1.5 decades pass
2.5 more decades pass
1960
1980
2000
2020
2040
SM amazing
W/Z
Anderson
Brout, Englert, Guralnik, Hagen, Higgs, Kibble
Weinberg/ Salam
Higgs Boson phenomenology



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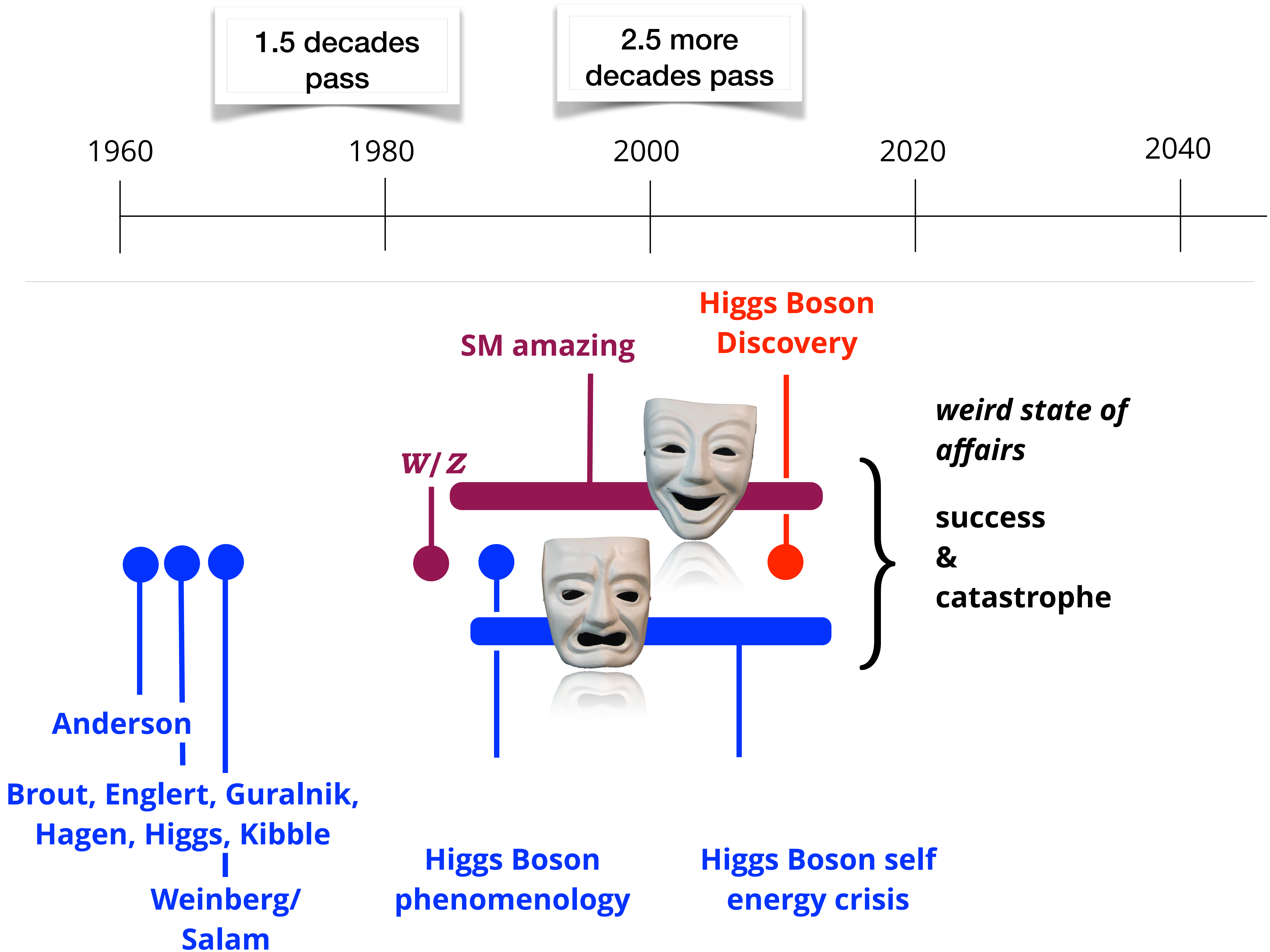
1.5 decades pass
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1960
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Higgs Boson Discovery
SM amazing
W/Z
weird state of affairs
success
&
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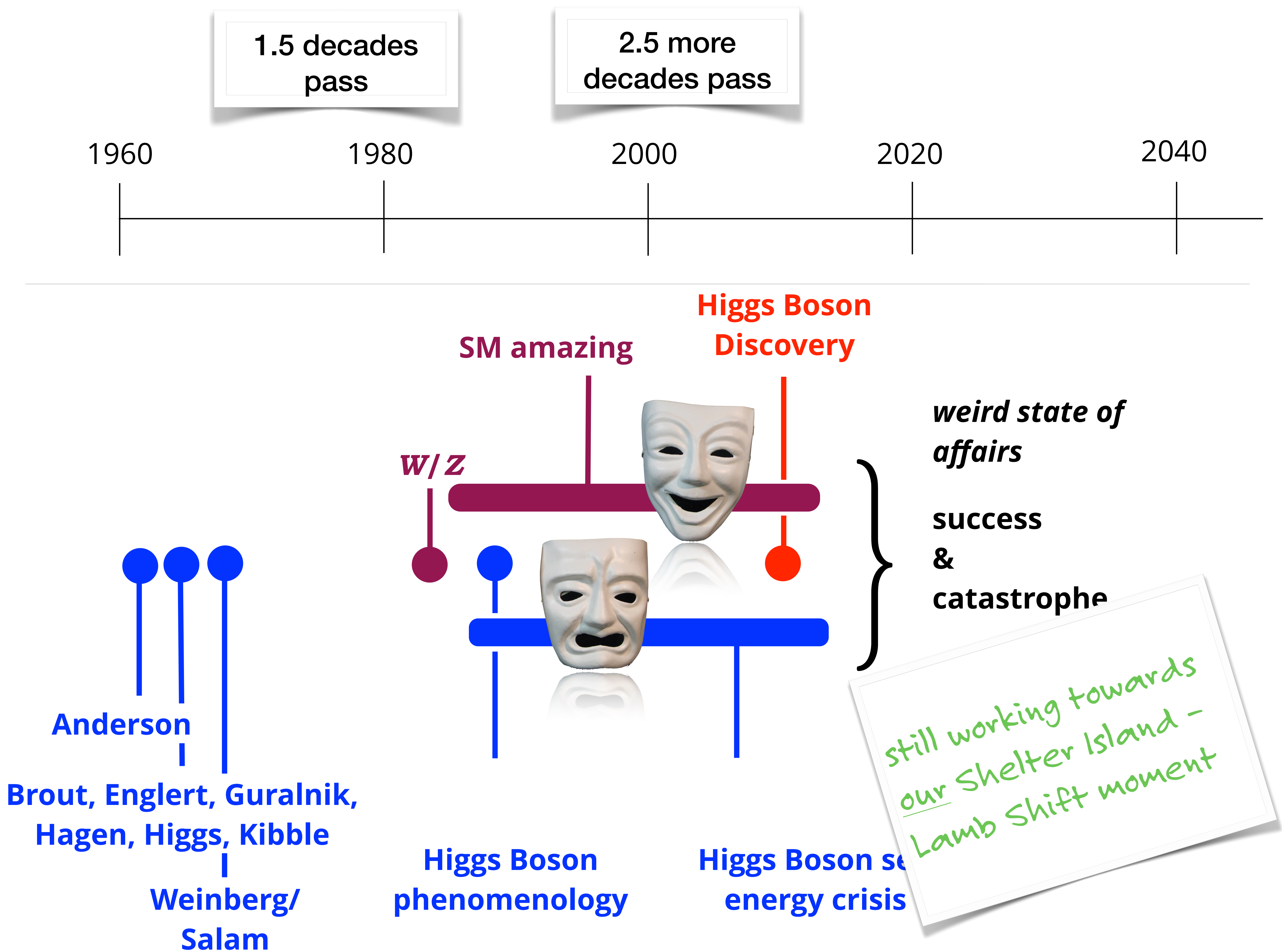
Higgs Boson phenomenology
Higgs Boson self energy crisis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1960
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SM amazing
Higgs Boson Discovery
W/Z
weird state of affairs
success
&
catastrophe
still working towards our Shelter Island – Lamb Shift moment
Anderson
Brout, Englert, Guralnik, Hagen, Higgs, Kibble
Weinberg/ Salam
Higgs Boson phenomenology
Higgs Boson se
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

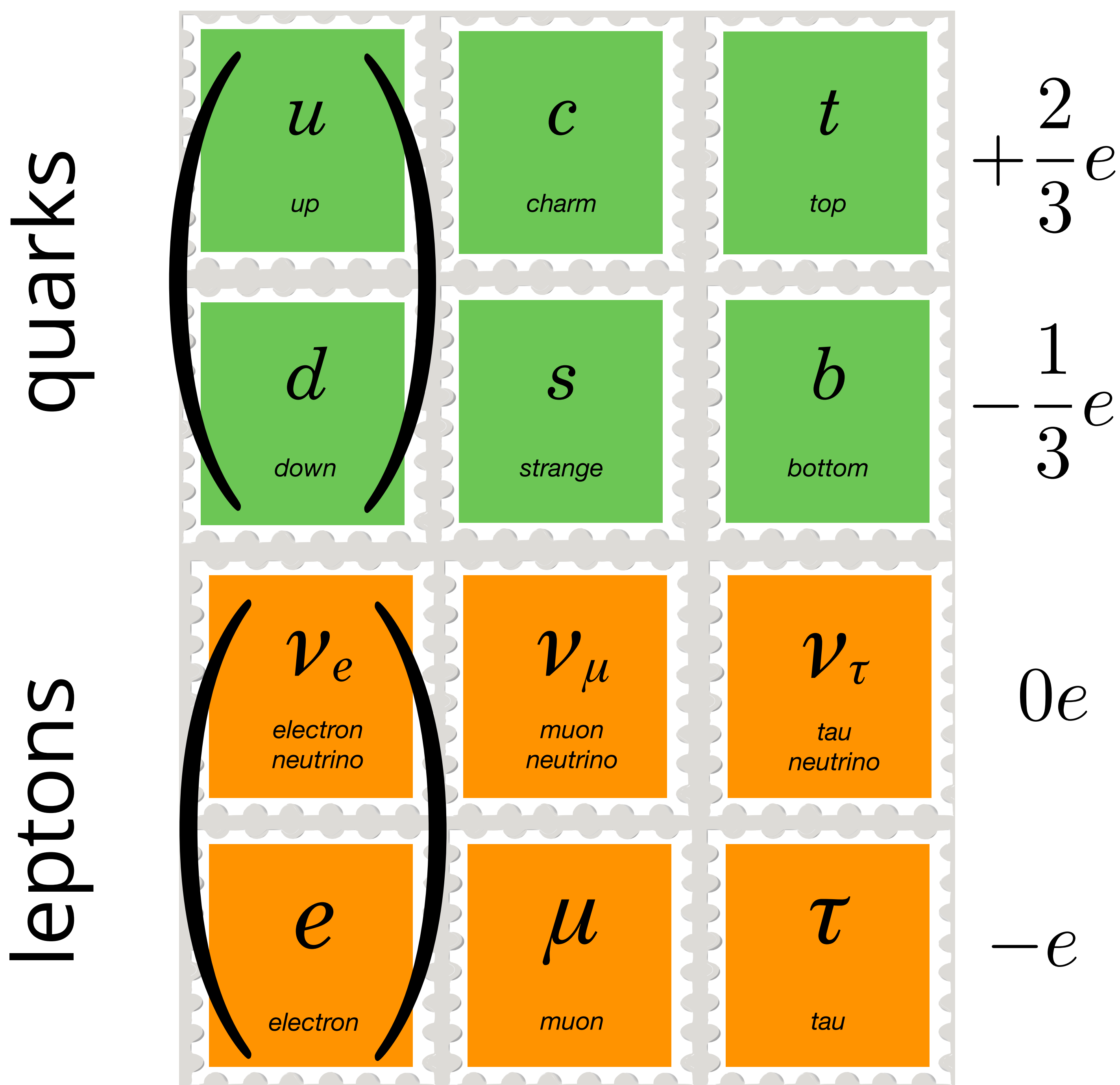
particle stamp collecting

- the players:

particle stamp collecting

spin 1/2

- the players:

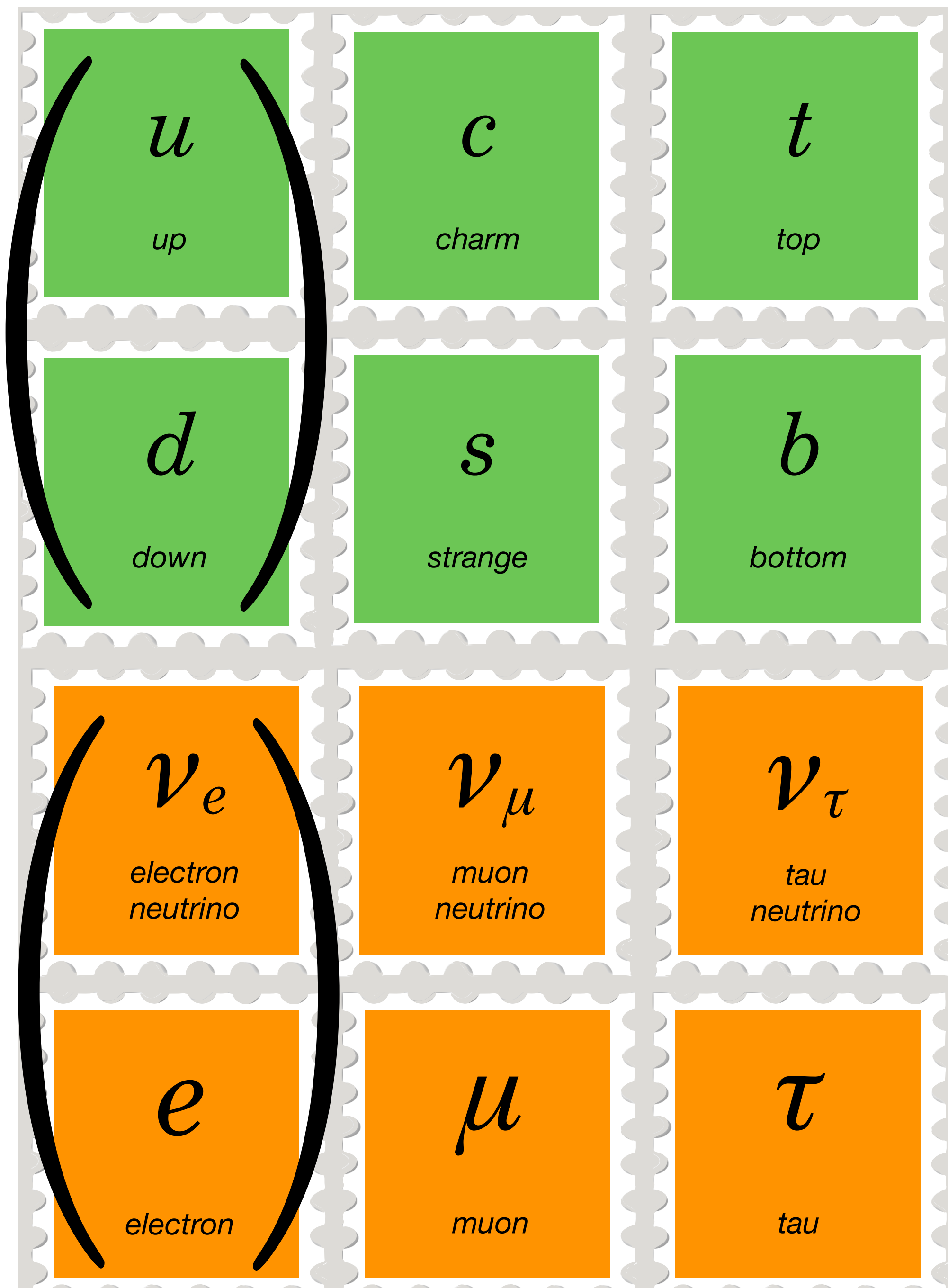


particle stamp collecting & their interactions

spin 1/2

- the players:

quarks



leptons

$+\frac{2}{3}e$

$-\frac{1}{3}e$

$0e$

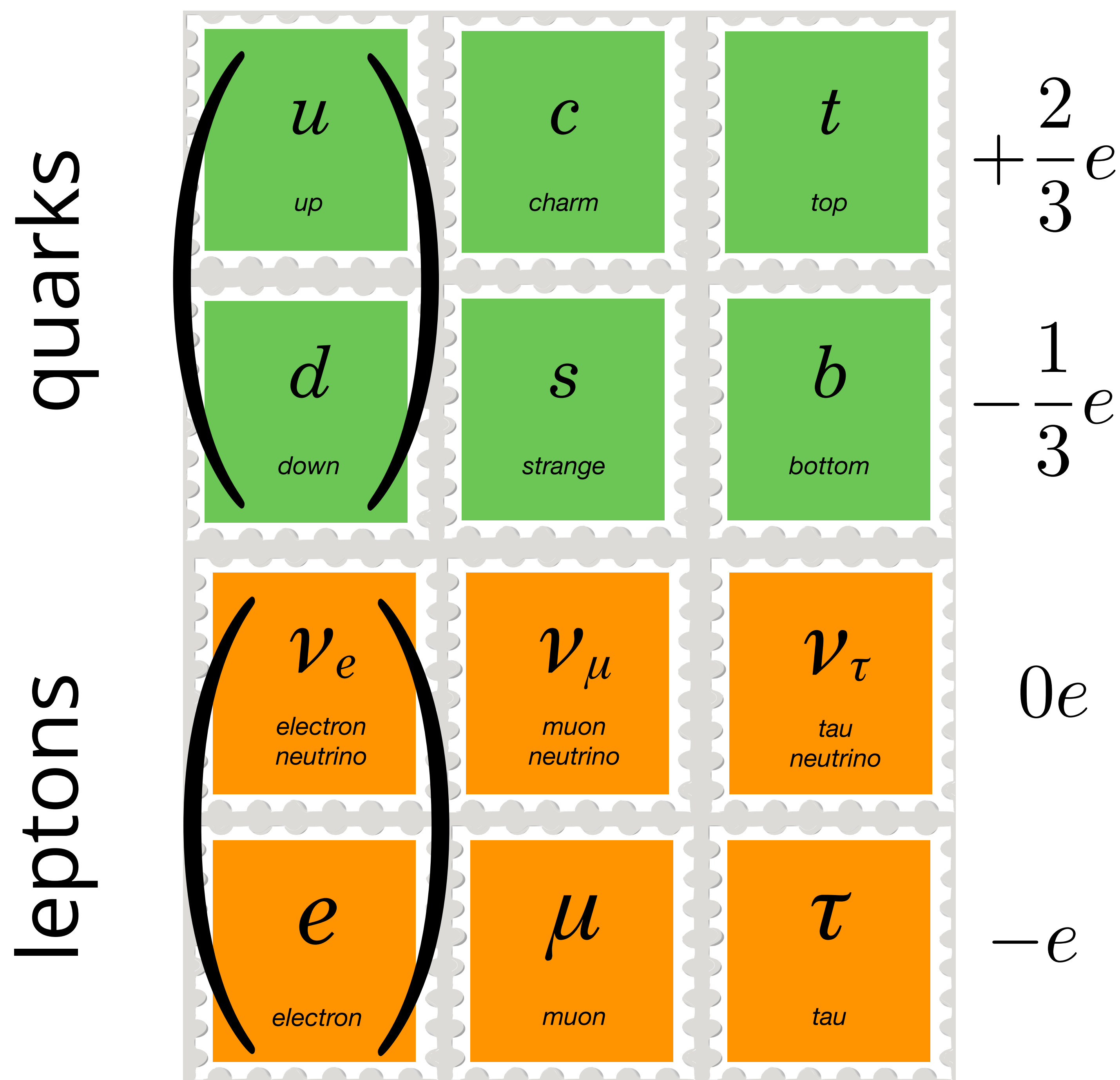
$-e$

particle stamp collecting

& their interactions

spin 1/2

- the players:



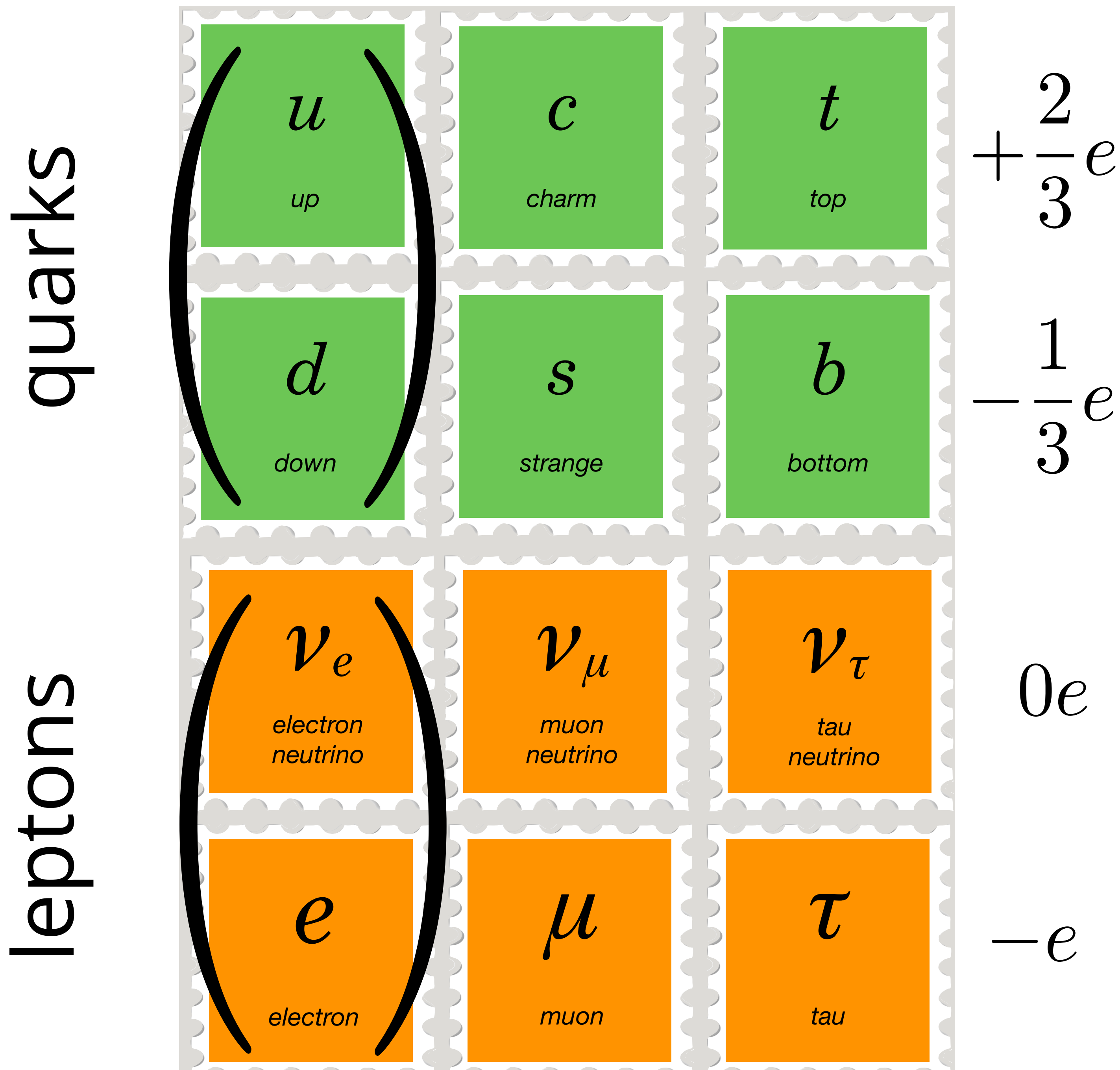
spin 1

- the messenger fields

particle stamp collecting & their interactions

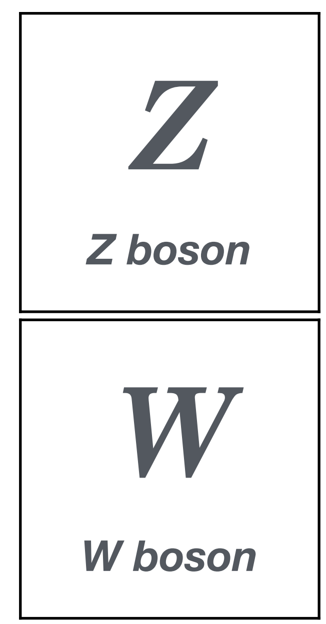
spin 1/2

- the players:



spin 1

- the messenger fields

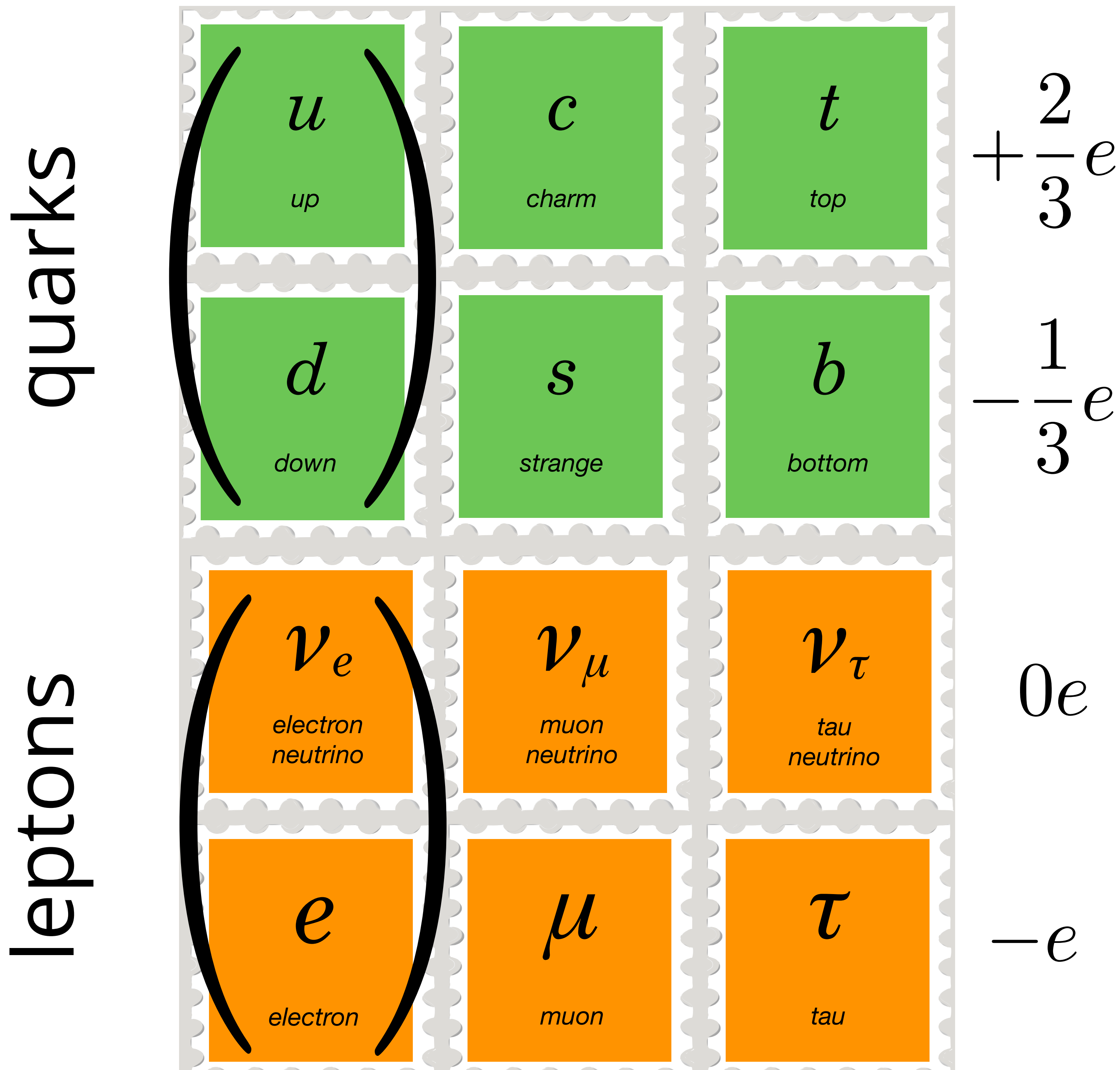


weak

particle stamp collecting & their interactions

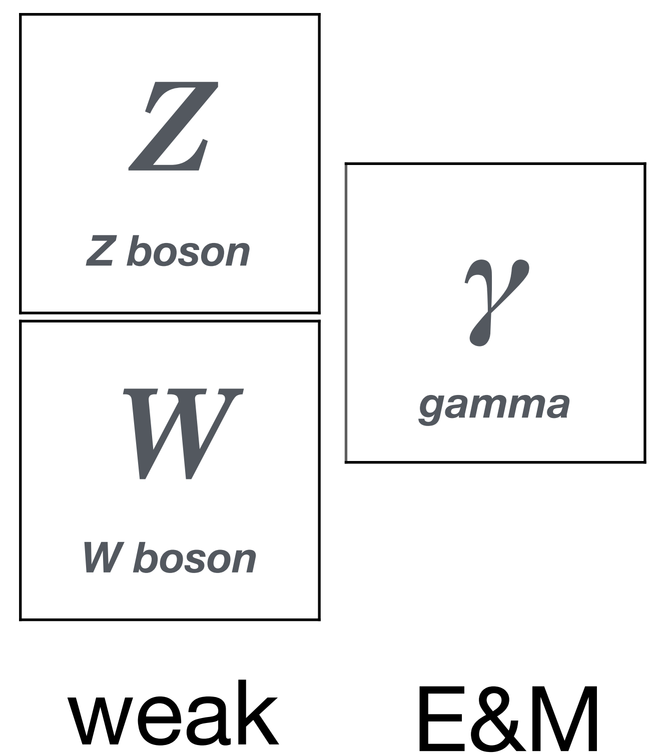
spin 1/2

- the players:



spin 1

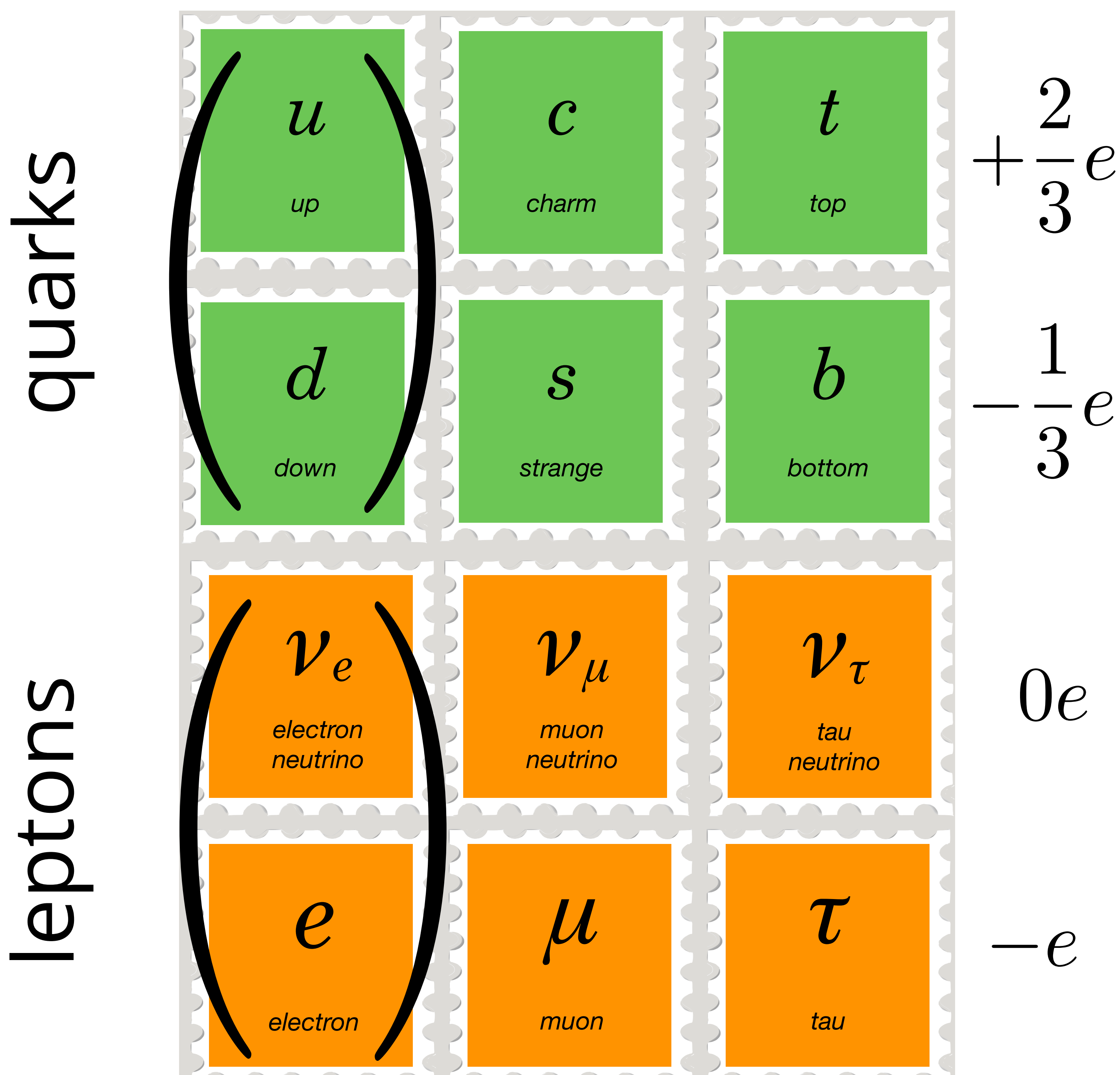
- the messenger fields



particle stamp collecting & their interactions

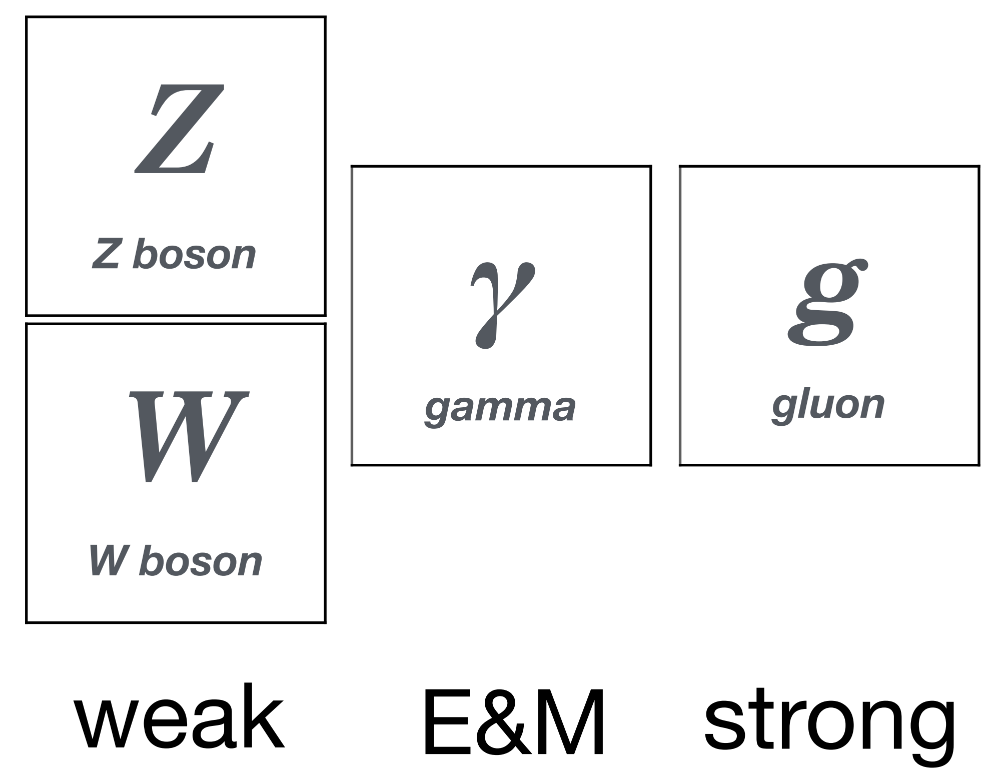
spin 1/2

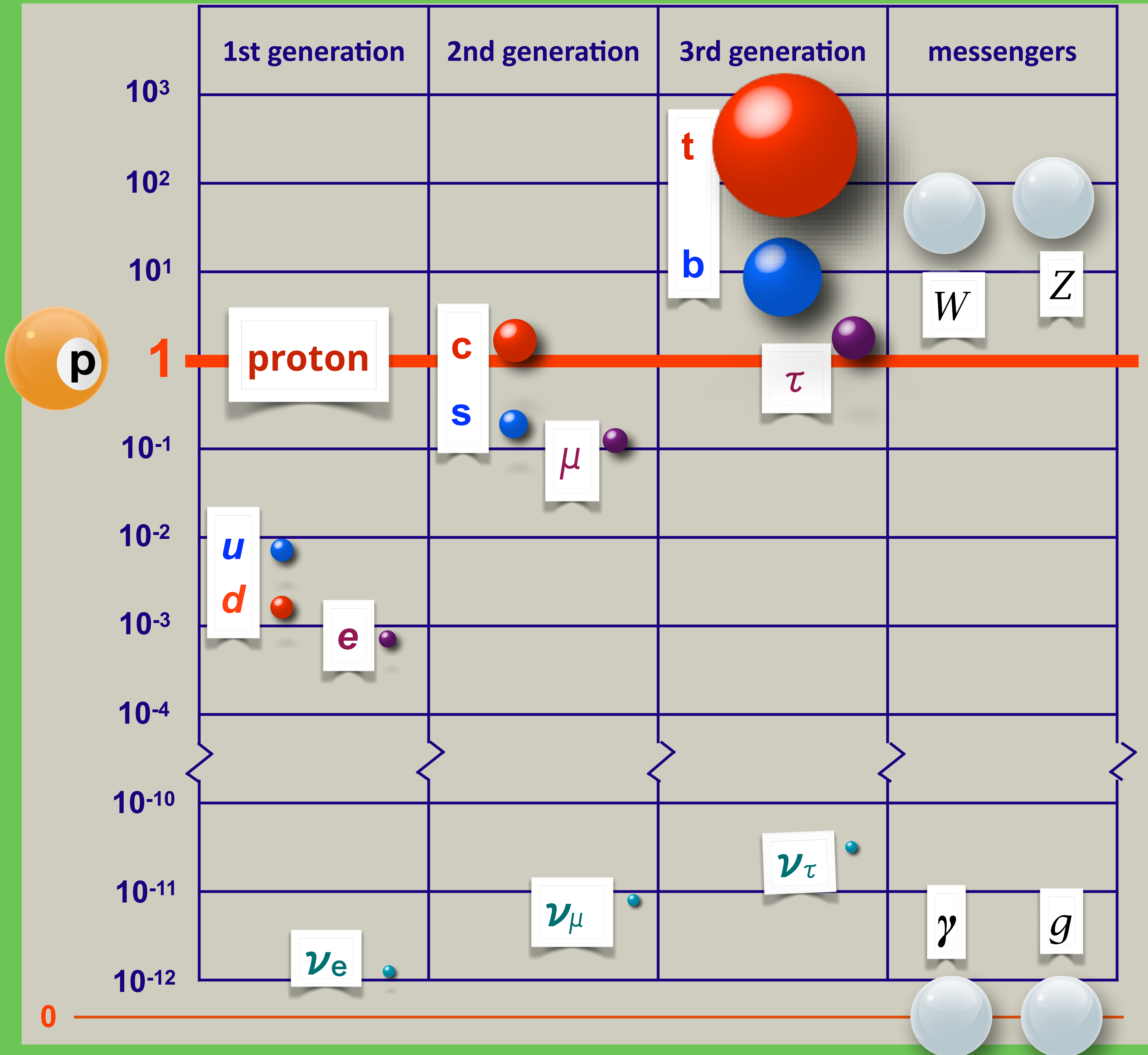
- the players:



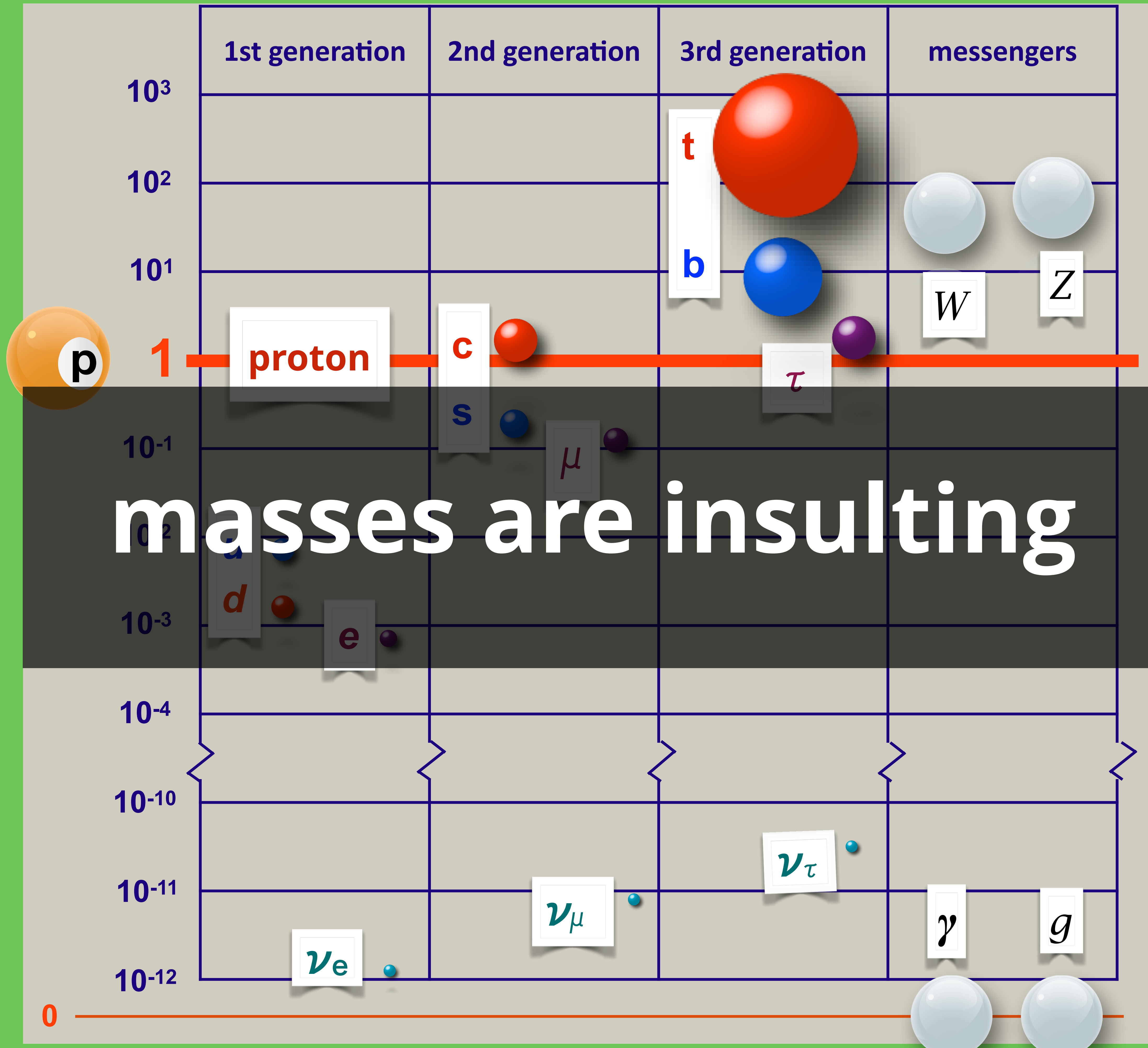
spin 1

- the messenger fields





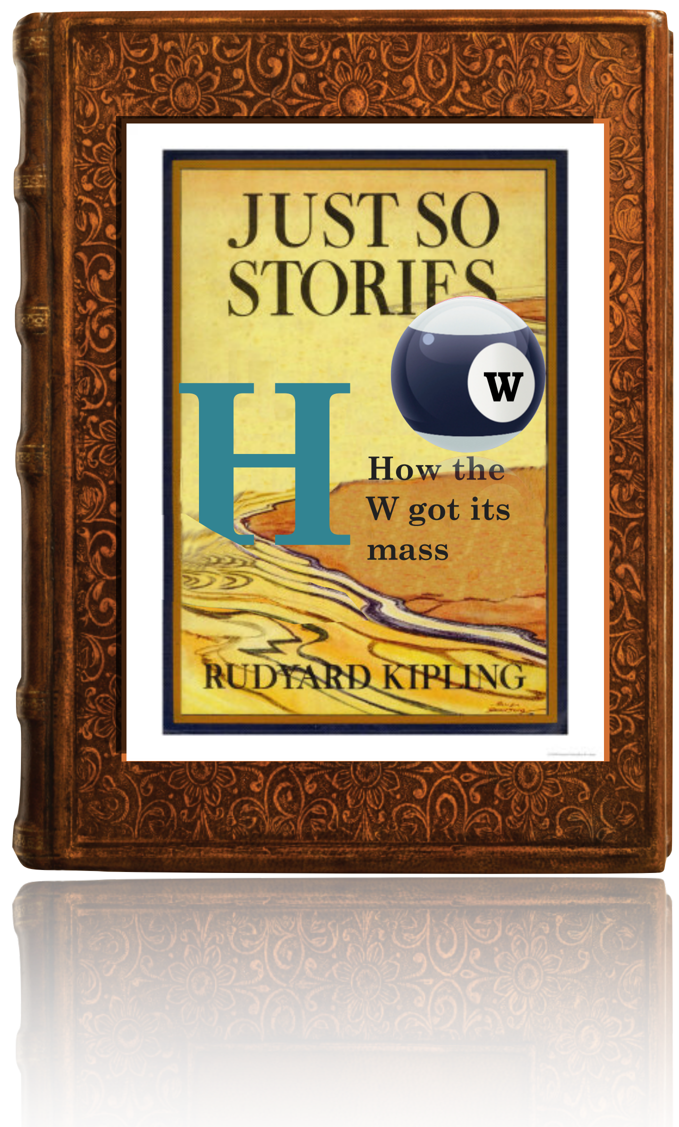
1st generation
2nd generation
3rd generation
messengers
10³
10²
10¹
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻¹⁰
10⁻¹¹
10⁻¹²
0
p
proton
u
d
e
c
s
μ
t
b
τ
W
Z
νe
νμ
ντ
γ
g


masses are insulting
1st generation
2nd generation
3rd generation
messengers
10³
10²
10¹
1
10⁻¹
10⁻³
10⁻⁴
10⁻¹⁰
10⁻¹¹
10⁻¹²
0
p
proton
c
s
t
b
τ
μ
d
e
W
Z
νe
νμ
ντ
γ
g

what's great

about the Standard Model?

1. the Gauge Principle



Gauge Principle

Extremely powerful and pretty.

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

Demand Invariance…

Gauge Principle

Extremely powerful and pretty.

- Q: generator of a group, with “charge” q
- θ a parameter

$$\left.\right\} U(Q) = e^{iQ\theta}$$

Demand Invariance…

Gauge Principle

Extremely powerful and pretty.

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

$$\left.\begin{matrix} \\ \\ \end{matrix}\right\} U(Q) = e^{iQ\theta}$$

Demand Invariance…

$$\psi(x) \to e^{iQ\theta}\psi(x) \qquad \psi(x) \to e^{iQ\theta(x)}\psi(x)$$

Global **Local**

Gauge Principle

Extremely powerful and pretty.

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

$$\left.\right\} U(Q) = e^{iQ\theta}$$

Demand Invariance...

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

Global

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

Local

it’s a kind of magic*

it’s a kind of magic*

* Ask me afterwards for my tried-and-true baseball analogy for the Gauge Principle

it’s a kind of magic*

Invariance of the **Local** sort demands

* Ask me afterwards for my tried-and-true baseball analogy for the Gauge Principle

it's a kind of magic*

Invariance of the **Local** sort demands

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

*** Ask me afterwards for my tried-and-true baseball analogy for the Gauge Principle**

it’s a kind of magic*

Invariance of the **Local** sort demands

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

*** Ask me afterwards for my tried-and-true baseball analogy for the Gauge Principle**

it's a kind of magic*

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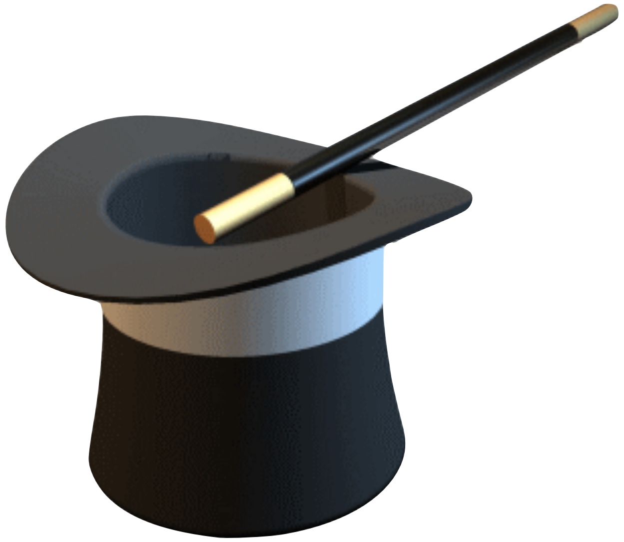
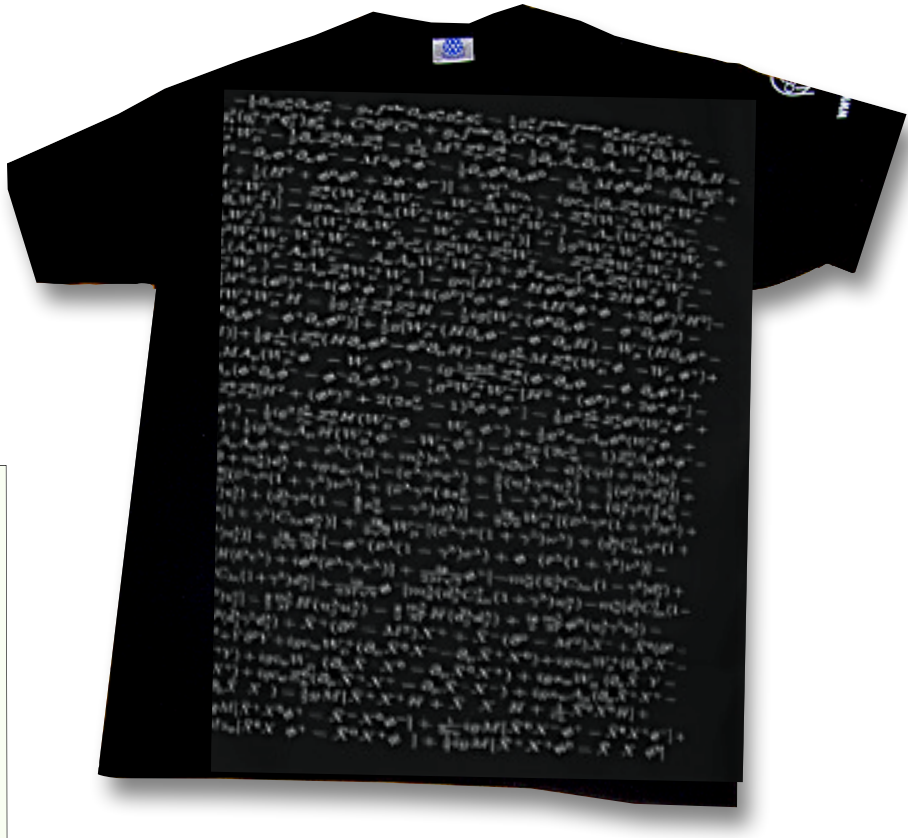


- **The demand of a symmetry forces the photon to exist!**

*** Ask me afterwards for my tried-and-true baseball analogy for the Gauge Principle**

Gauge Principle piece:

- “Unfolds” rather neatly



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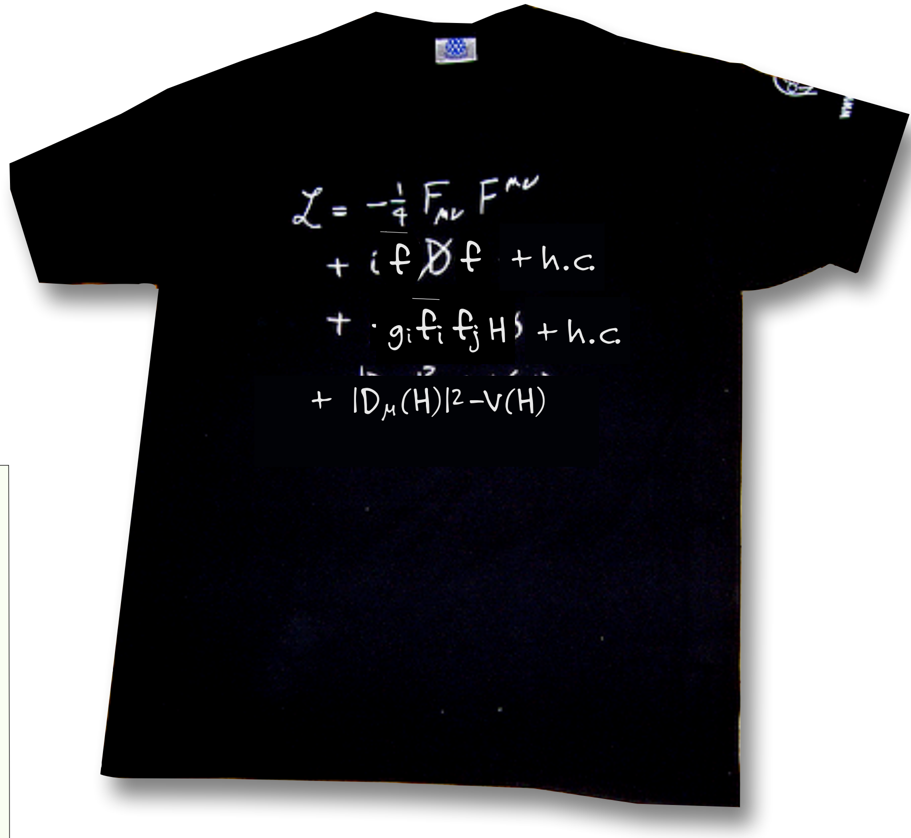
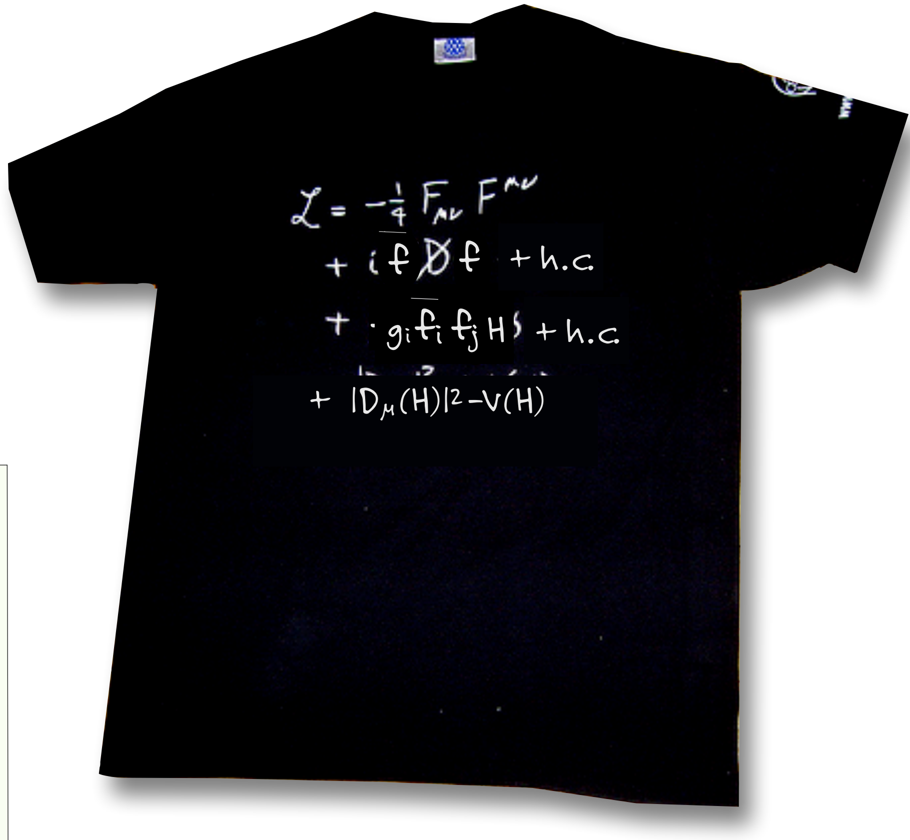


Gauge Principle piece:

- "Unfolds" rather neatly

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

$$+ i\bar{\psi}\not{D}\psi$$



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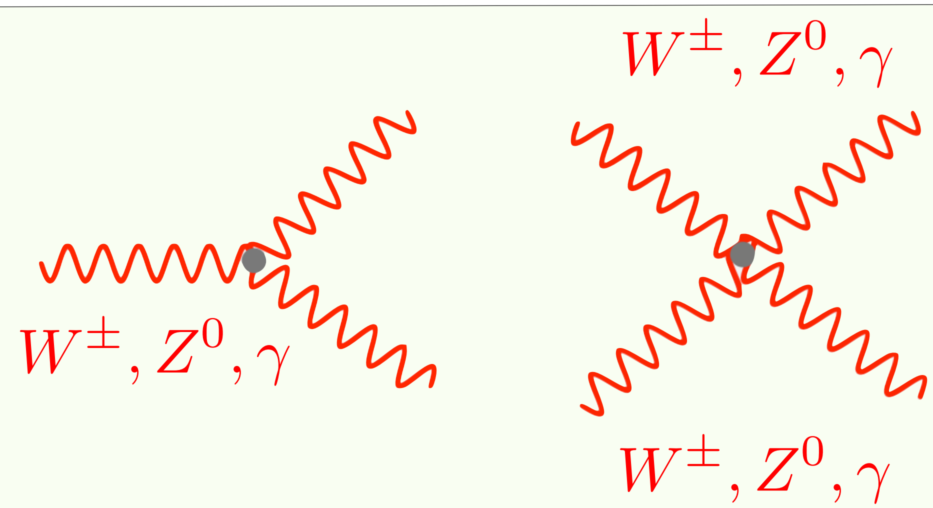
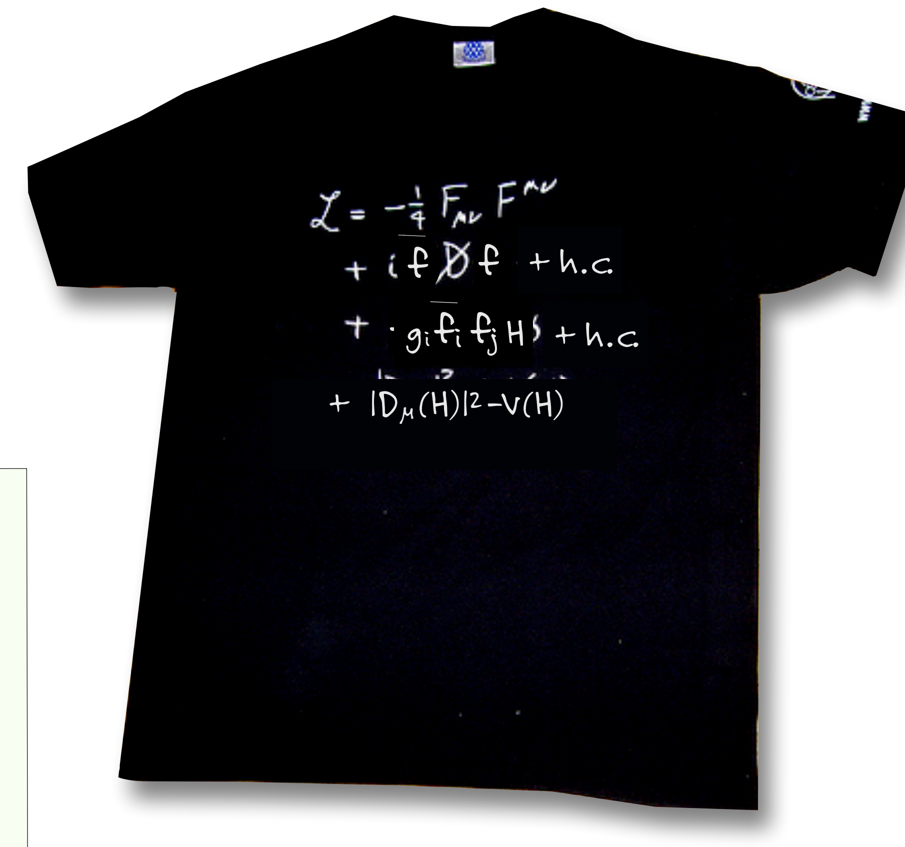


$$+\, i\bar{\psi}\not{D}\psi$$



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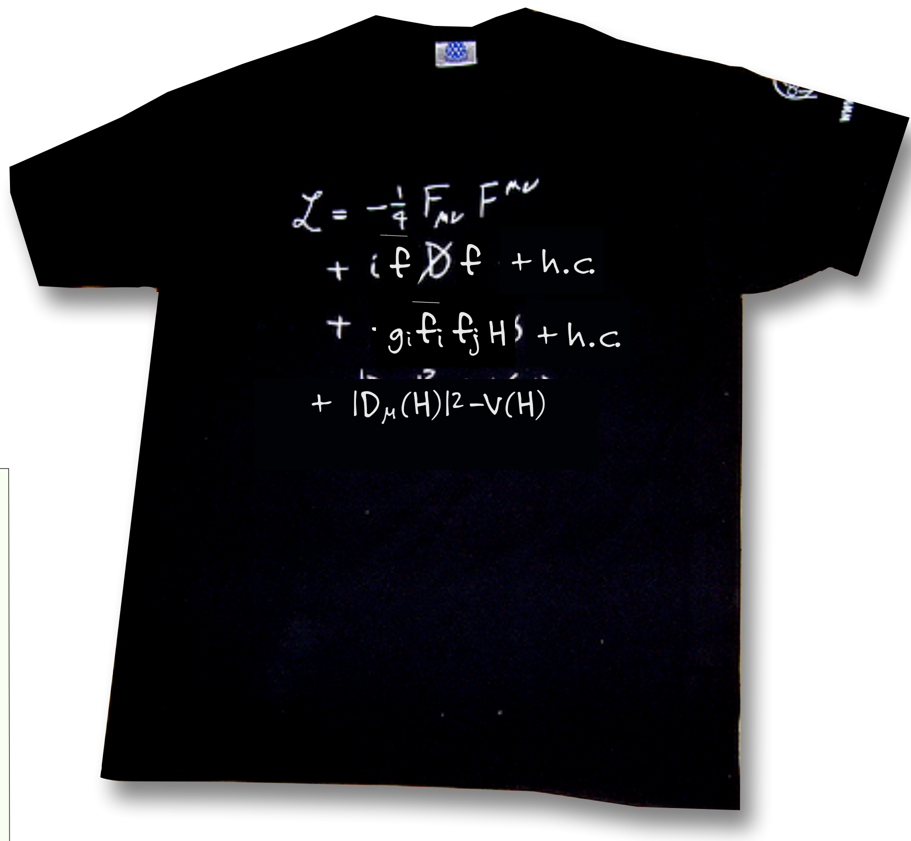

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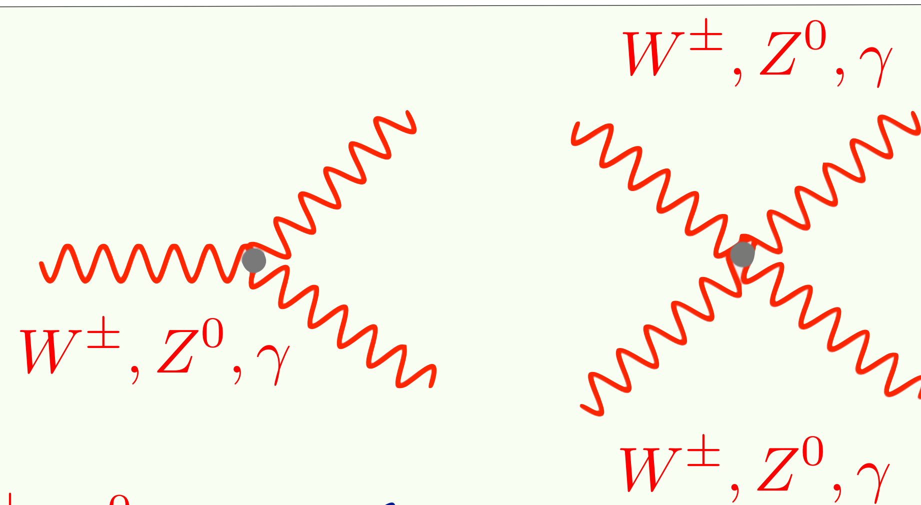
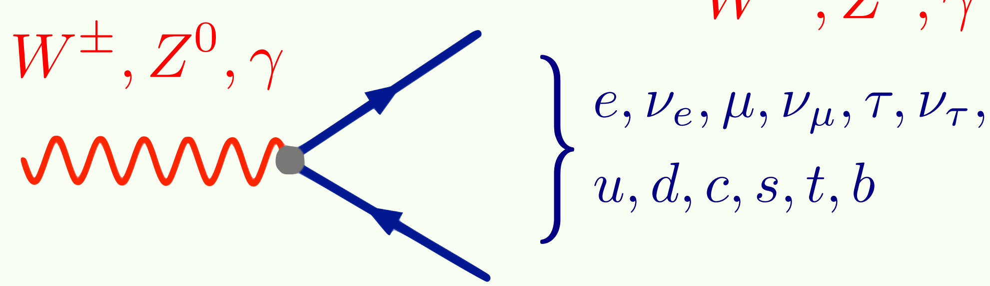


$$+ i\bar{\psi} \not{D} \psi$$



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
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had} [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
$A_{FB}^{(0,\tau)}$	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_τ	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

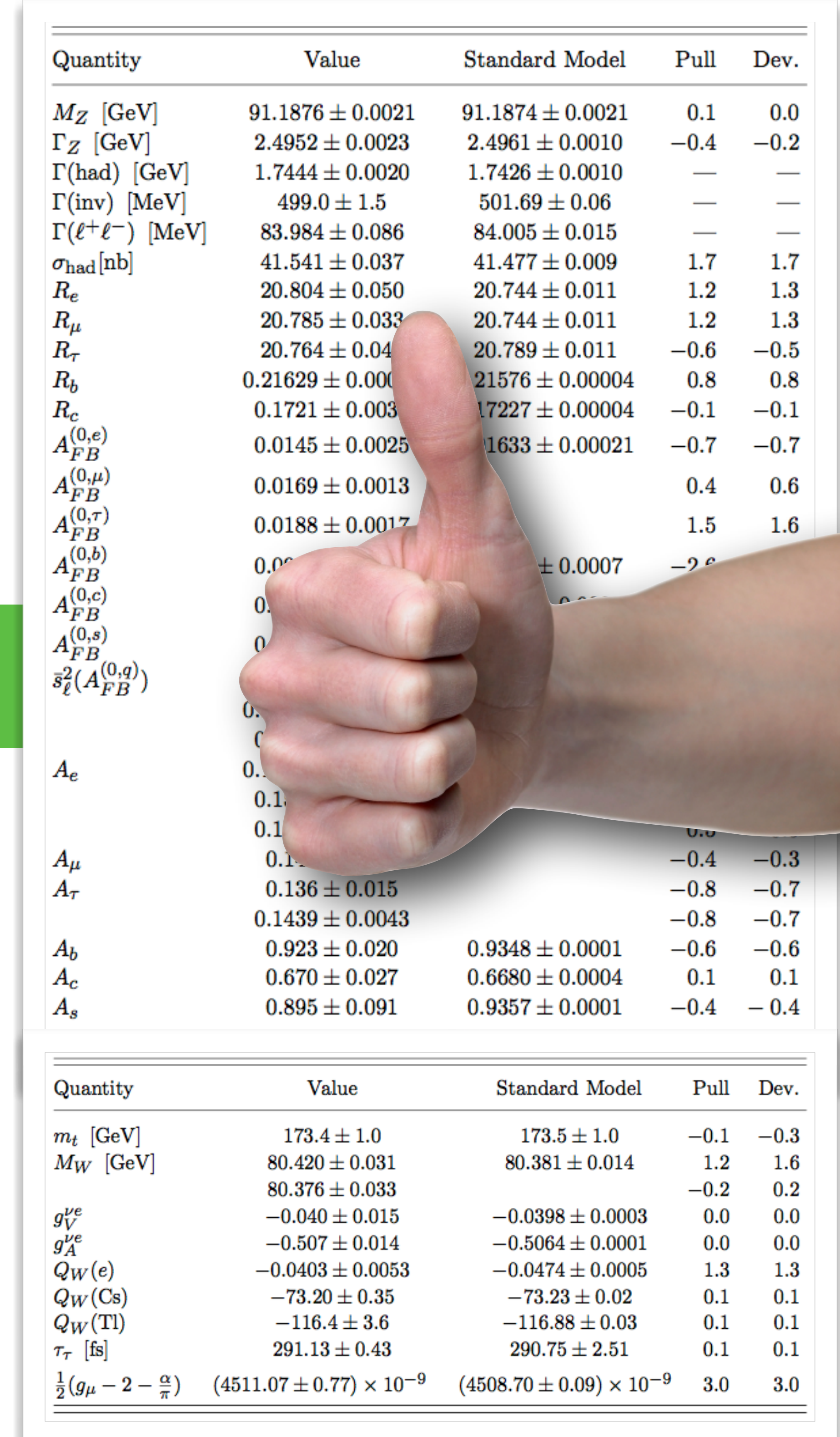
Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	−0.1	−0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		−0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\text{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

The most accurate and precise scientific model in history

that’s really great

this Standard Model

the Gauge Principle:



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$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had} [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 ± 0.04[illegible]	20.789 ± 0.011	−0.6	−0.5
R_b	0.21629 ± 0.000[illegible]	[illegible]21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.003[illegible]	[illegible]17227 ± 0.00004	−0.1	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	[illegible]1633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013	[illegible]	0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017	[illegible]	1.5	1.6
$A_{FB}^{(0,b)}$	0.0[illegible]	[illegible] ± 0.0007	−2.[illegible]	[illegible]
$A_{FB}^{(0,c)}$	0.[illegible]	[illegible]	[illegible]	[illegible]
$A_{FB}^{(0,s)}$	0[illegible]	[illegible]	[illegible]	[illegible]
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	[illegible]	[illegible]	[illegible]	[illegible]
	0.[illegible]	[illegible]	[illegible]	[illegible]
	0[illegible]	[illegible]	[illegible]	[illegible]
A_e	0.[illegible]	[illegible]	[illegible]	[illegible]
	0.1[illegible]	[illegible]	[illegible]	[illegible]
	0.1[illegible]	[illegible]	[illegible]	[illegible]
A_μ	0.1[illegible]	[illegible]	−0.4	−0.3
A_τ	0.136 ± 0.015	[illegible]	−0.8	−0.7
	0.1439 ± 0.0043	[illegible]	−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	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\text{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

The most accurate and precise scientific model in history

“Standard Model”

“Standard Model”

standard |ˈstandərd|
noun

1 a level of quality or attainment

“Standard Model”

standard **|ˈstandərd|**
noun

1 a level of quality or attainment

model **|ˈmädl|**
noun

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

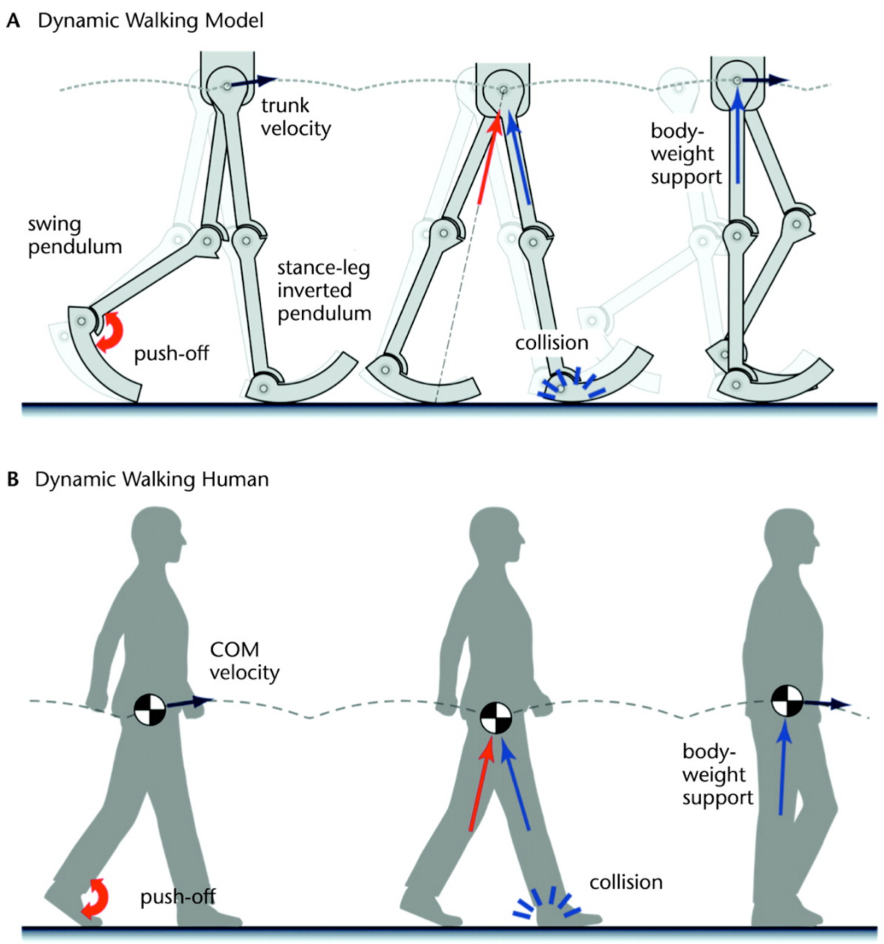
what's embarrassing

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



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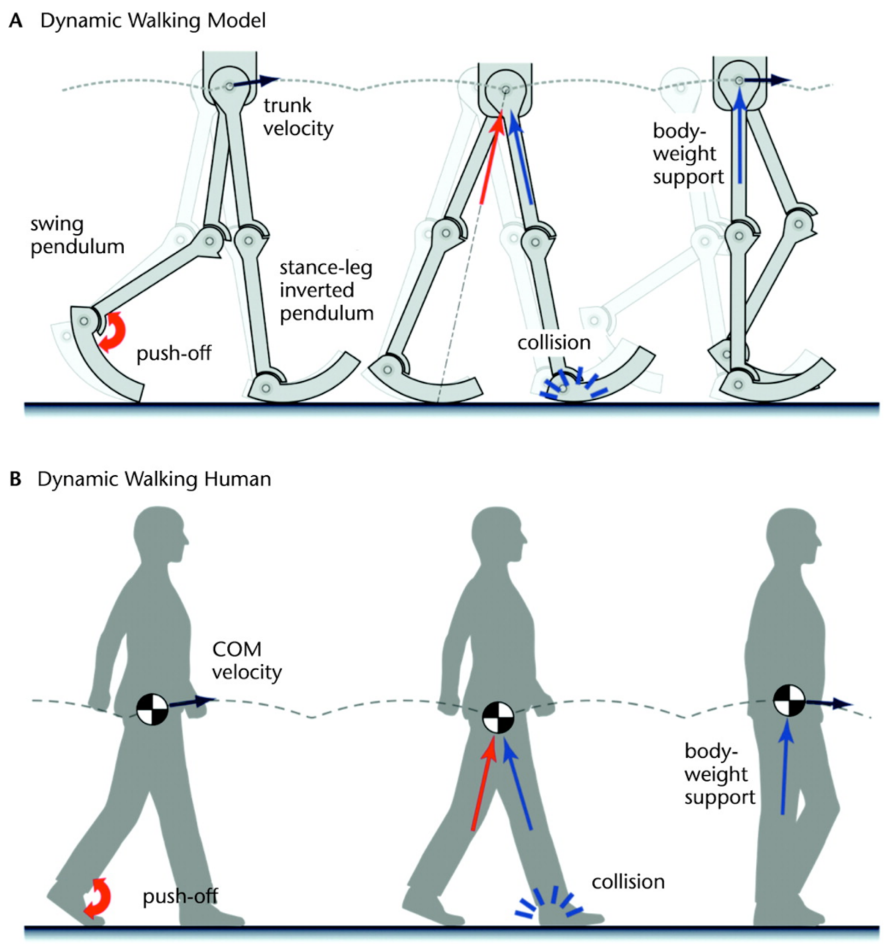
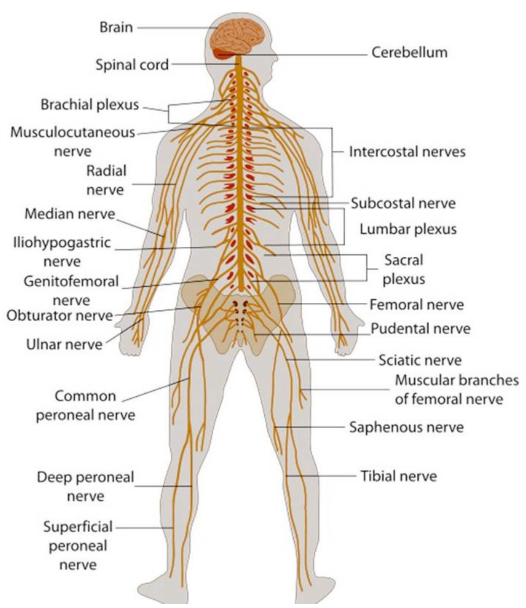
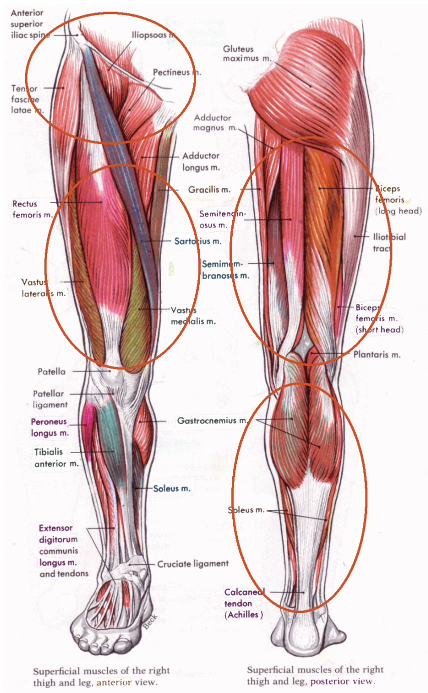
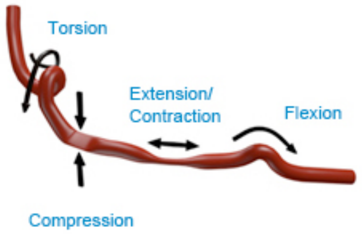
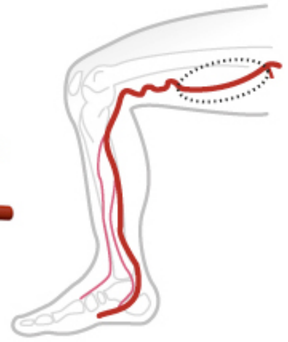


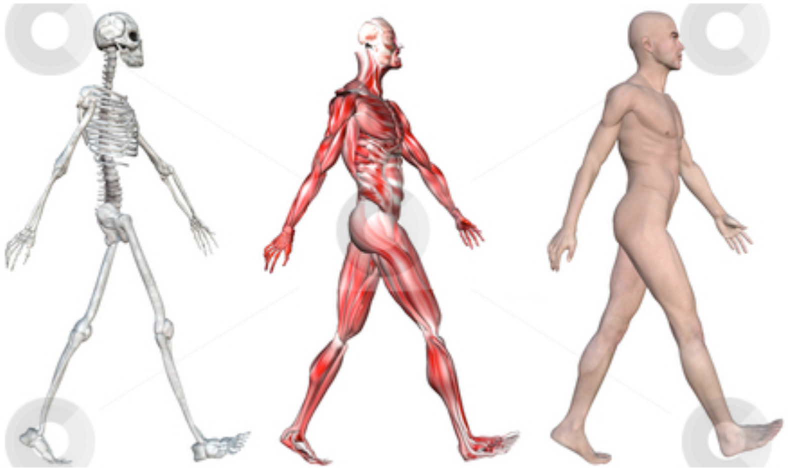




But it’s not the actual physiology of walking!

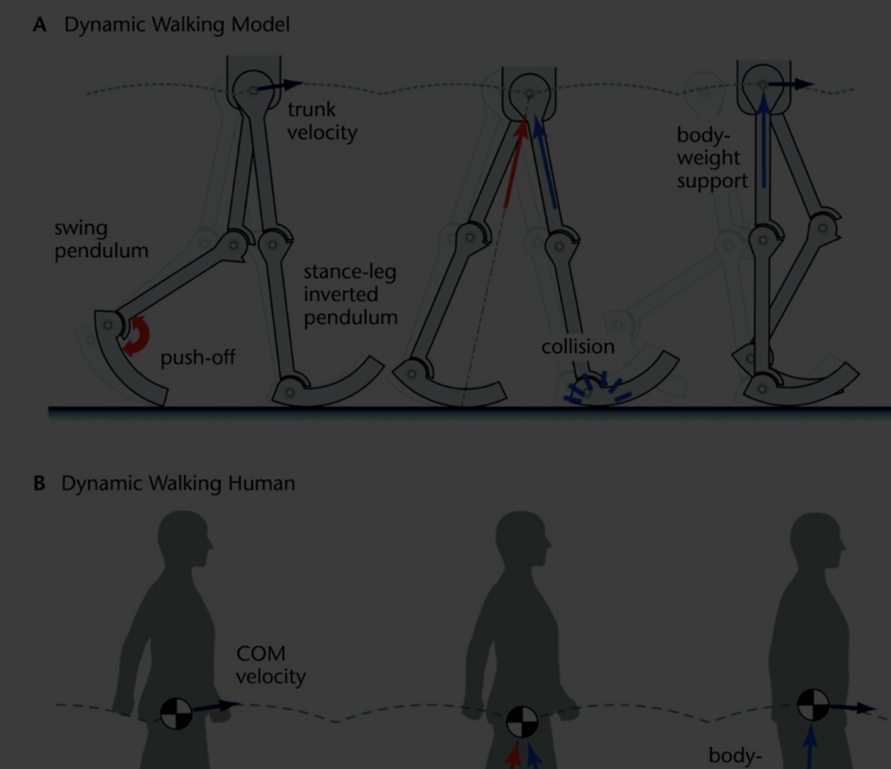


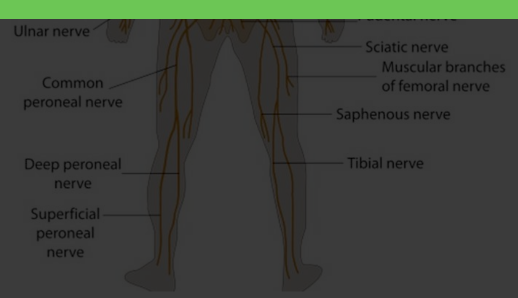


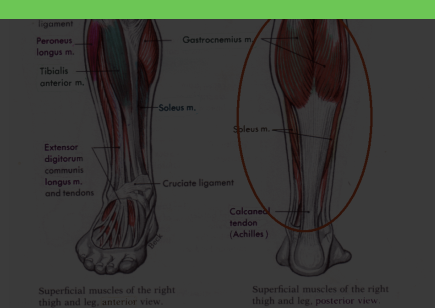


SM is an effective theory

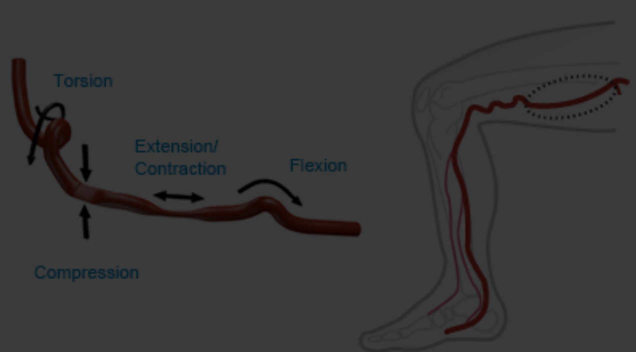
I can draw free-body diagrams and make a SM of walking

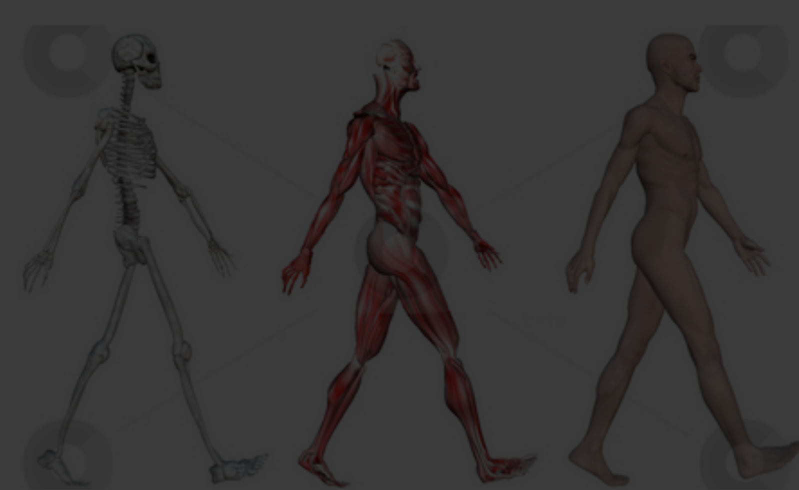






physiology of walking!





what's confusing

about the Standard Model?

2. Spontaneous Symmetry Breaking

- the story of the Higgs Boson

How?

- a meaningless operation?

How?

a meaningless operation?

$$\mathcal{L} = \text{ blah blah blah } + \mu^2 \text{ blah } + \text{ blah blah blah}$$

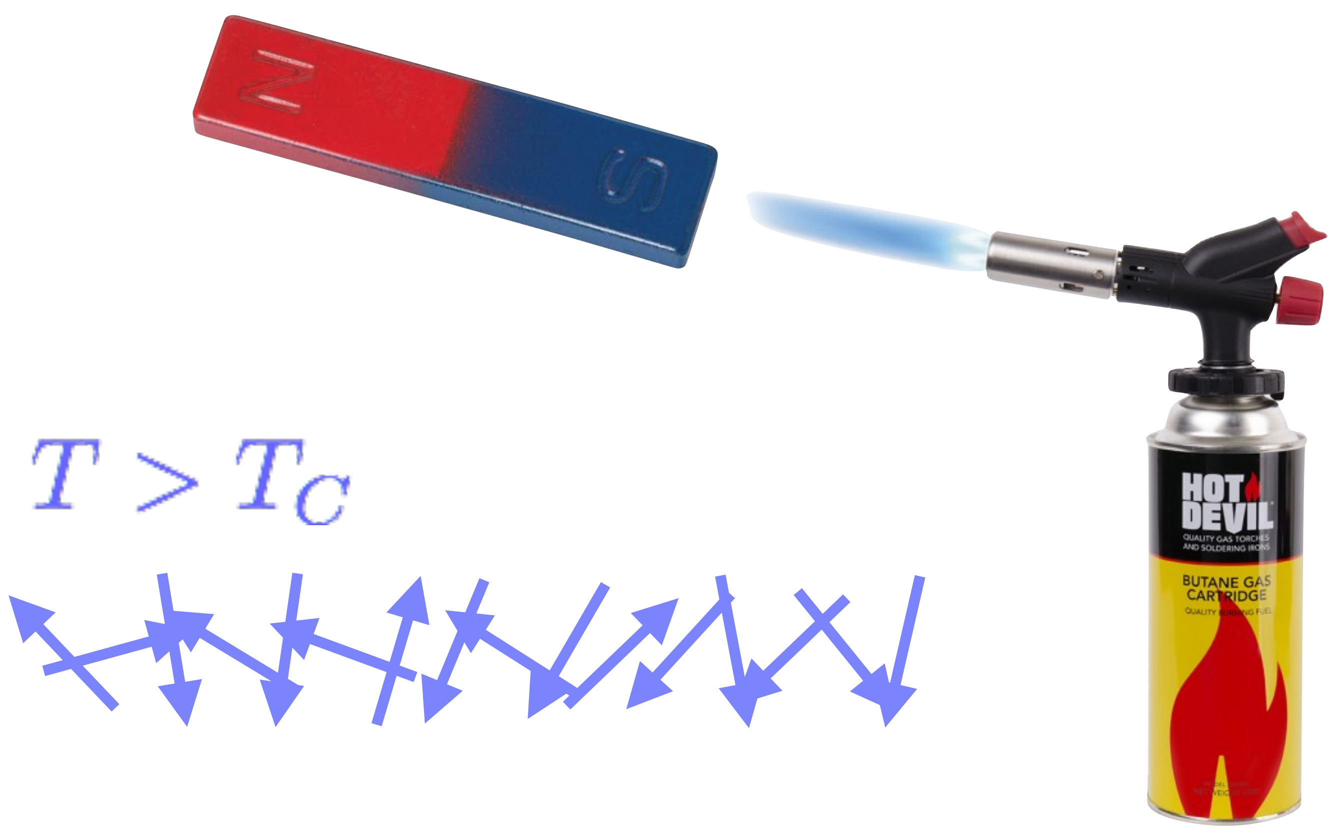
How?

- a meaningless operation?

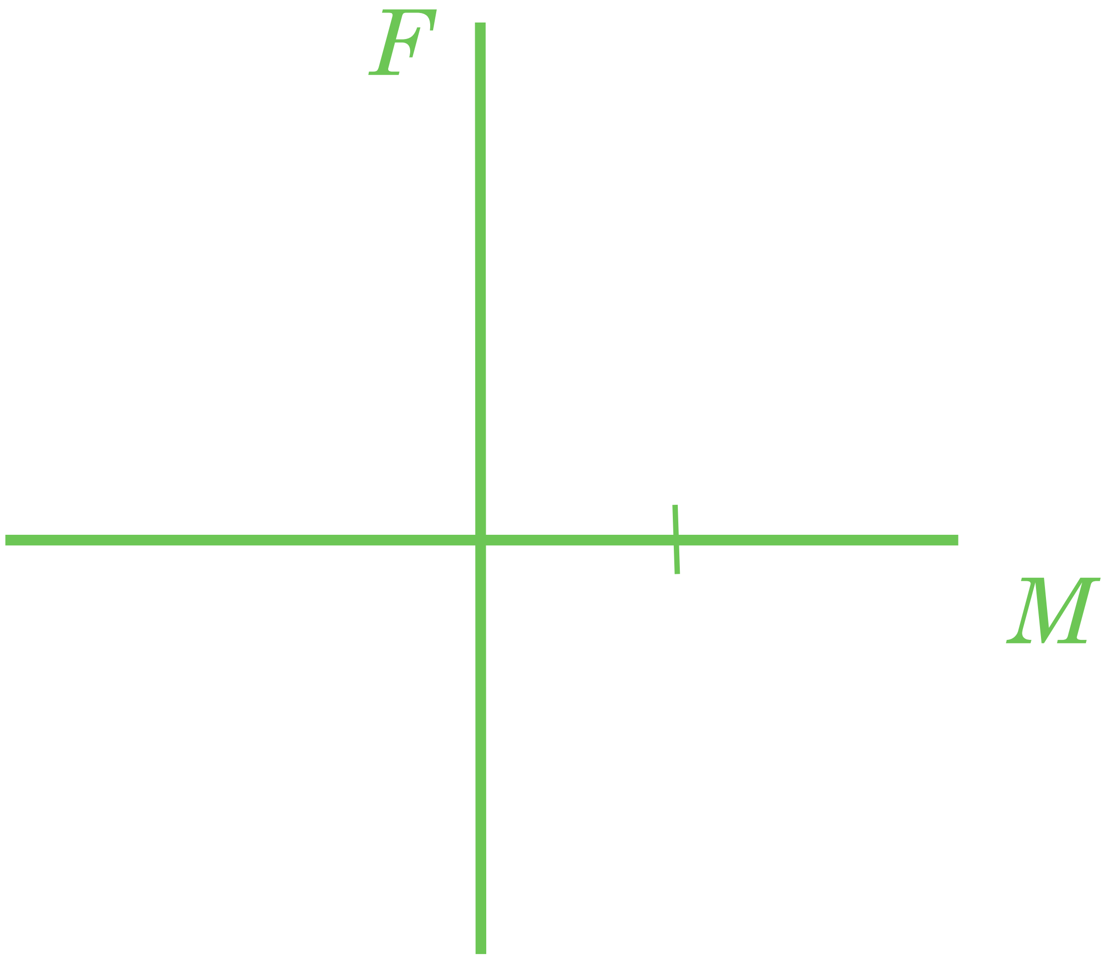
$$\mathcal{L} = \text{ blah blah blah } + \mu^2 \text{ blah } + \text{ blah blah blah}$$

$$\mathcal{L} = \text{ blah blah blah } - \mu^2 \text{ blah } + \text{ blah blah blah}$$

SSB is like a magnet



$T > T_C$



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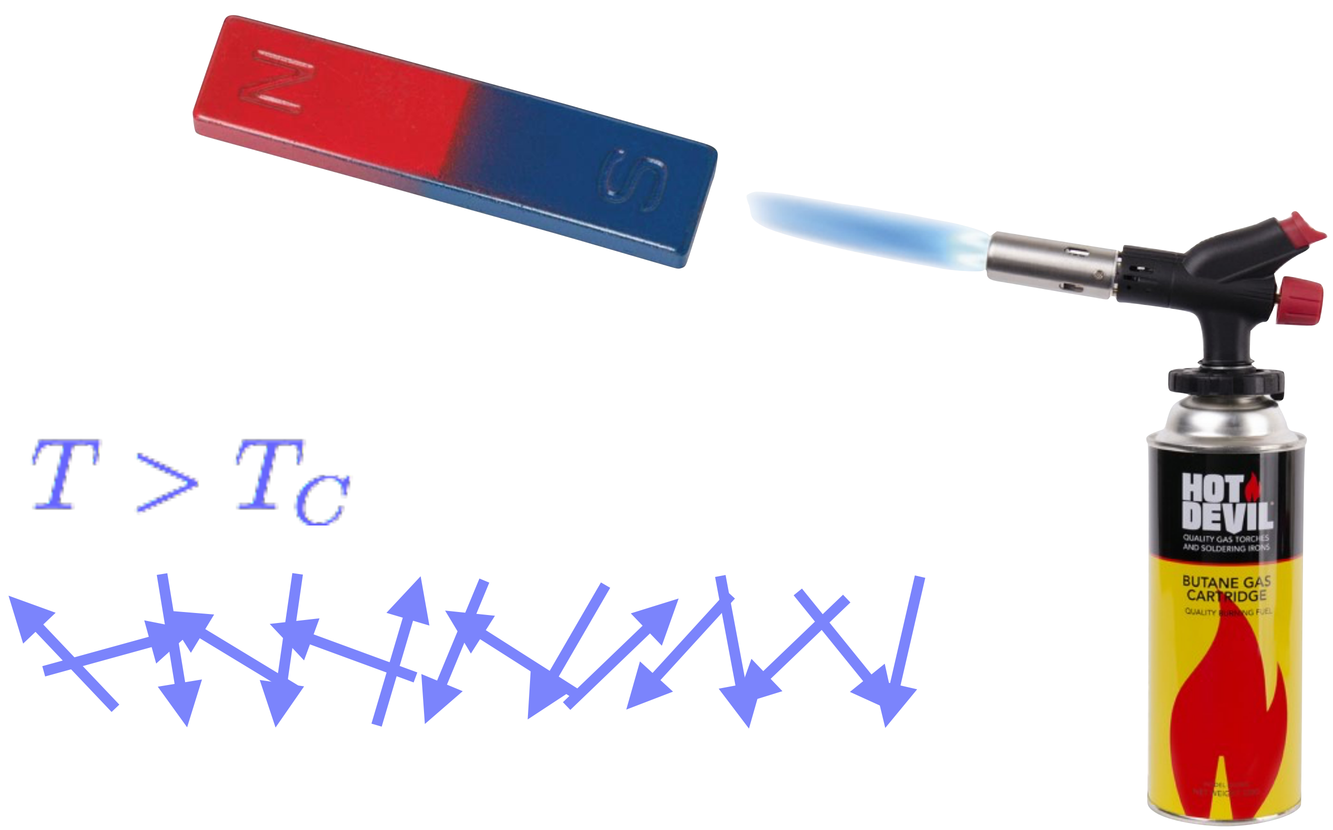

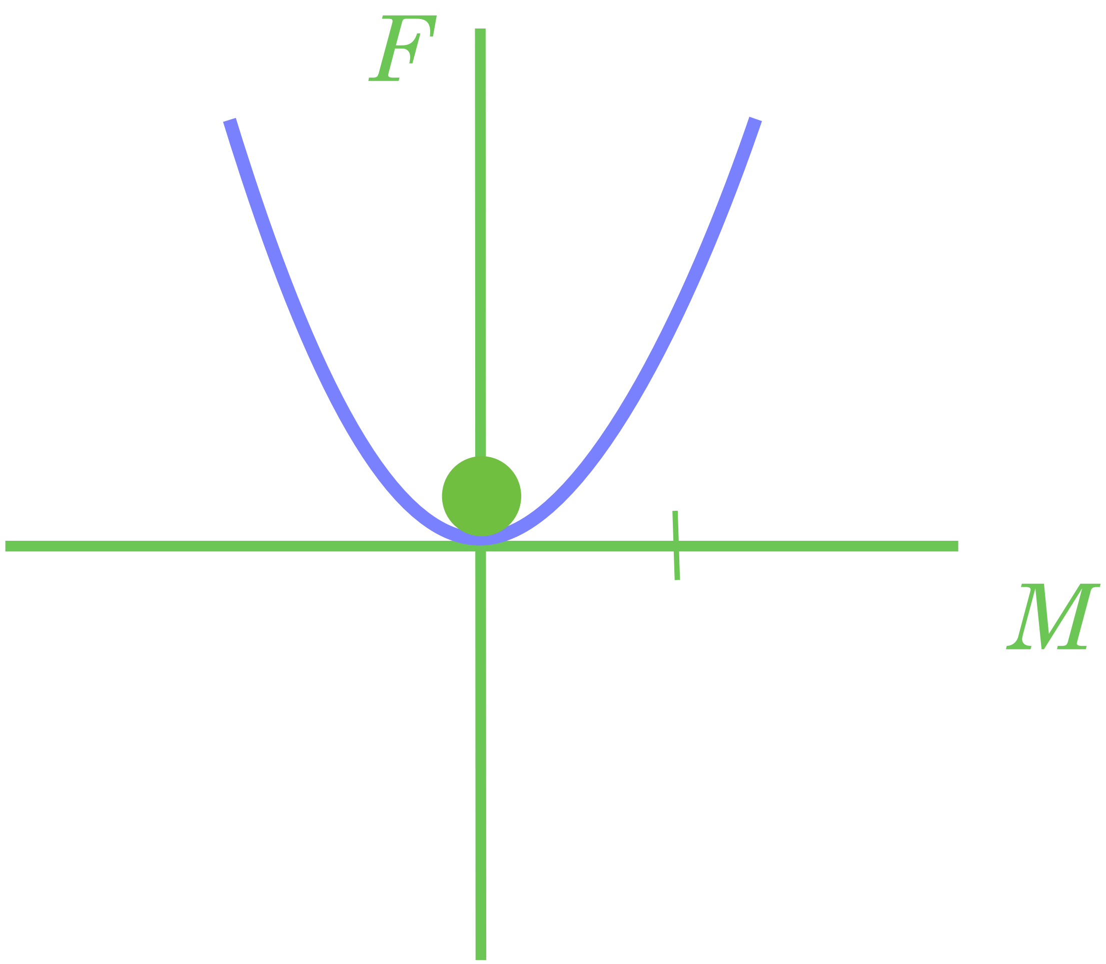

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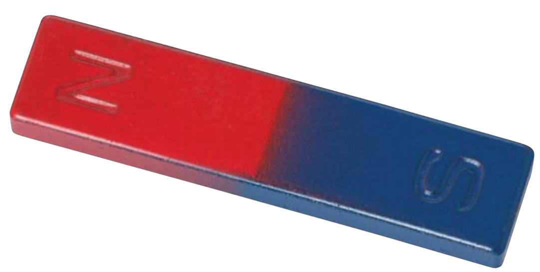

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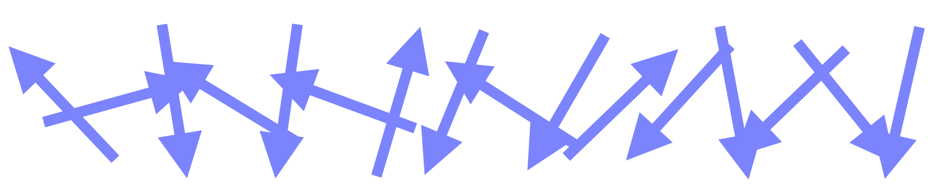

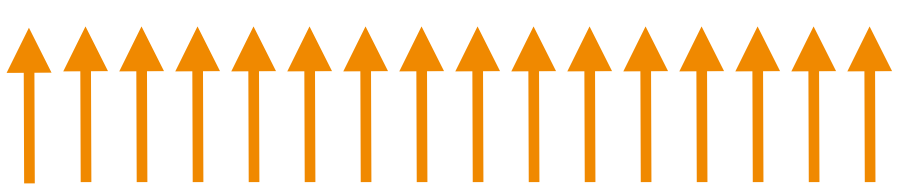

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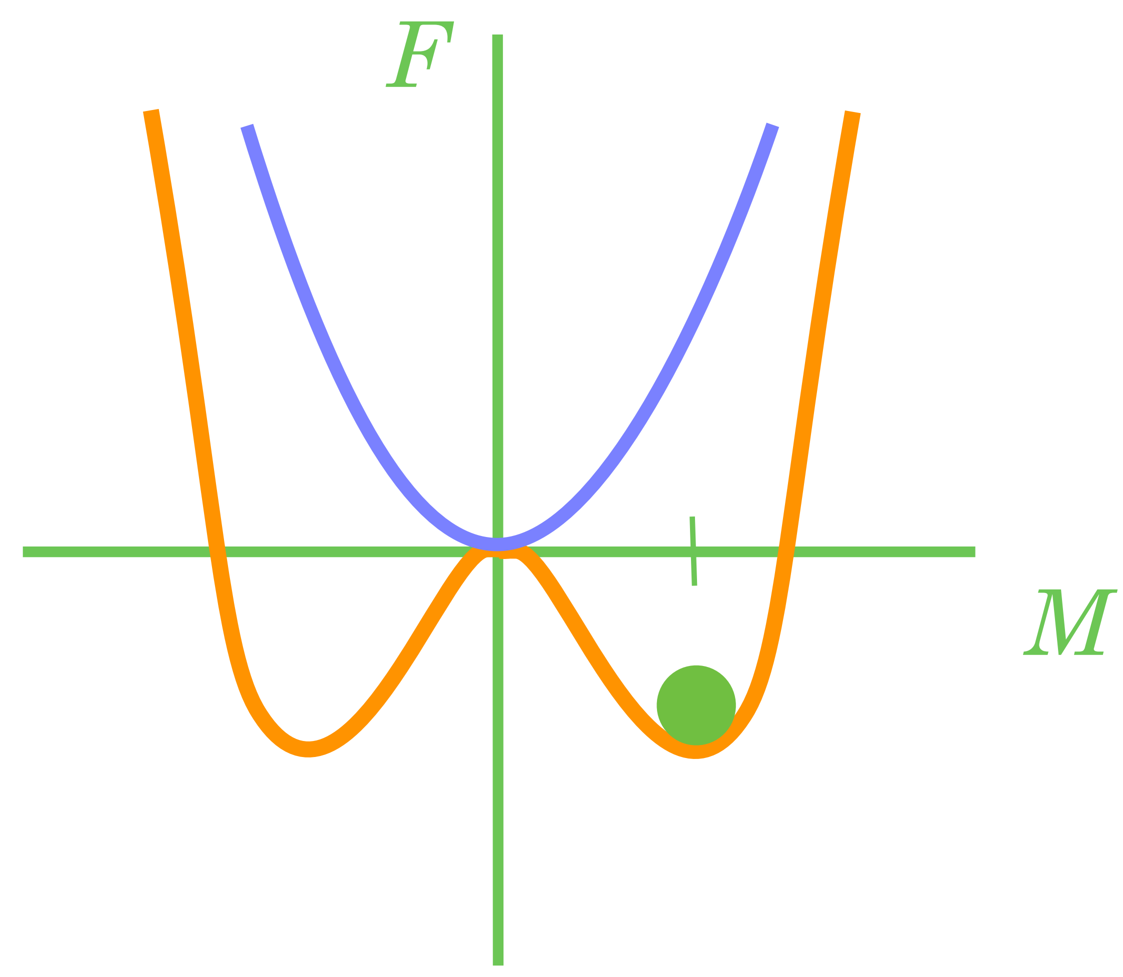

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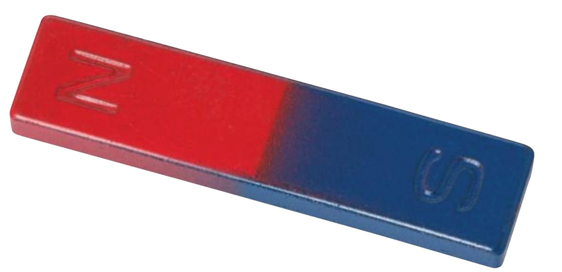

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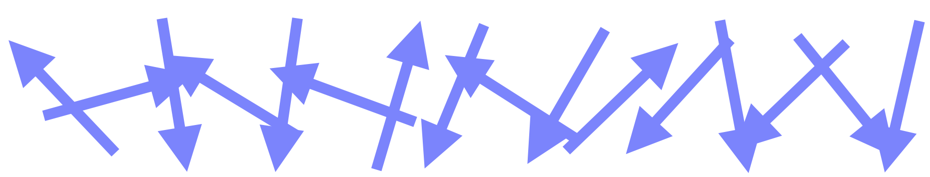

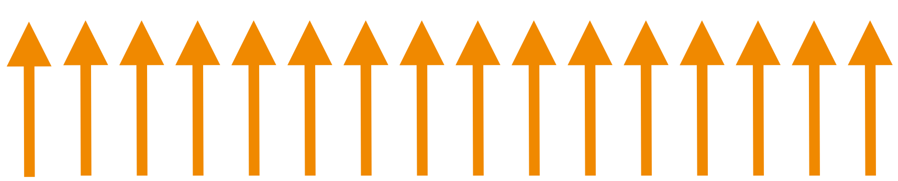

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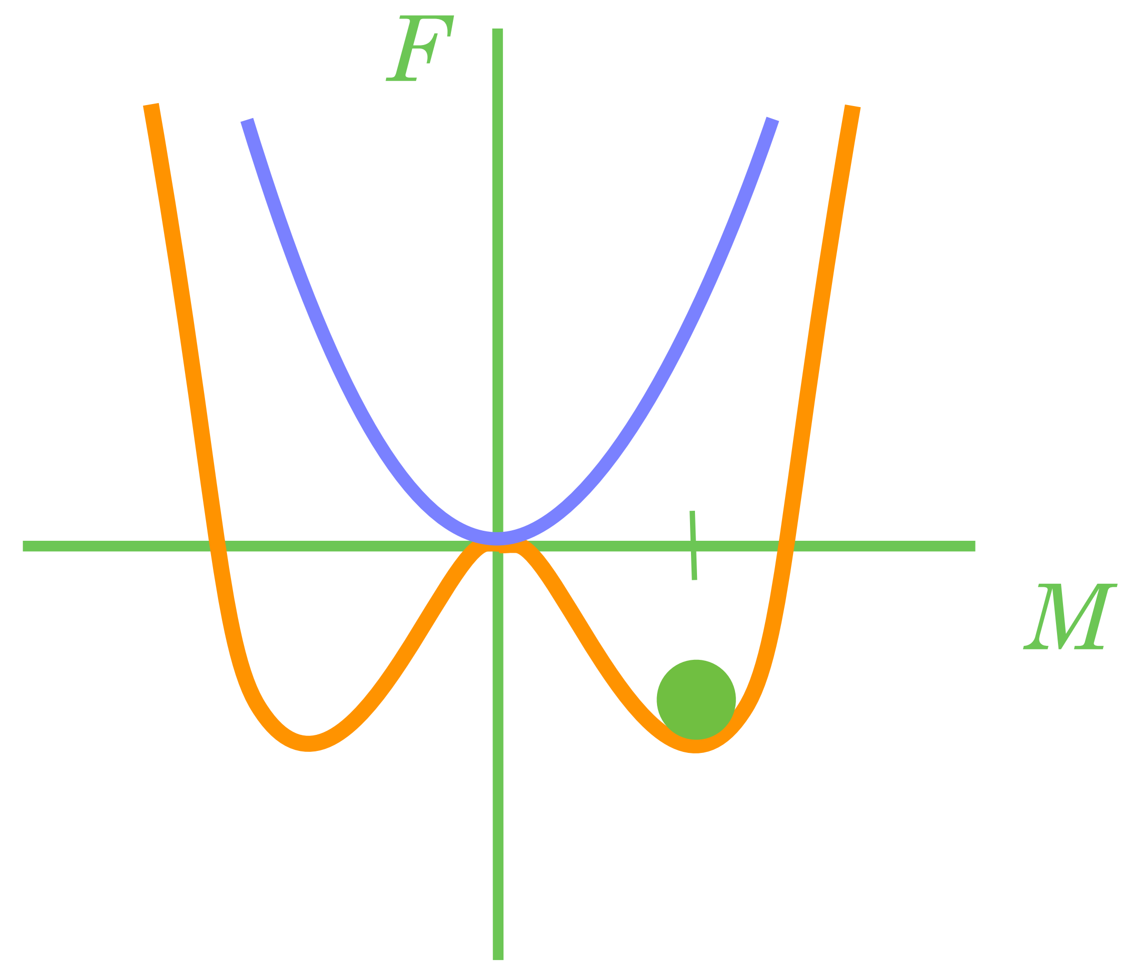
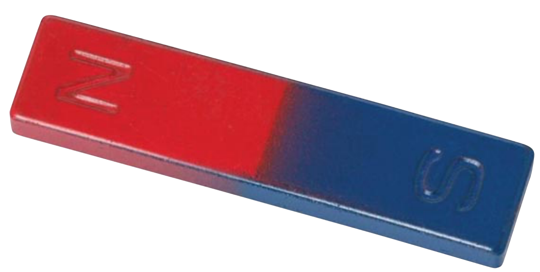
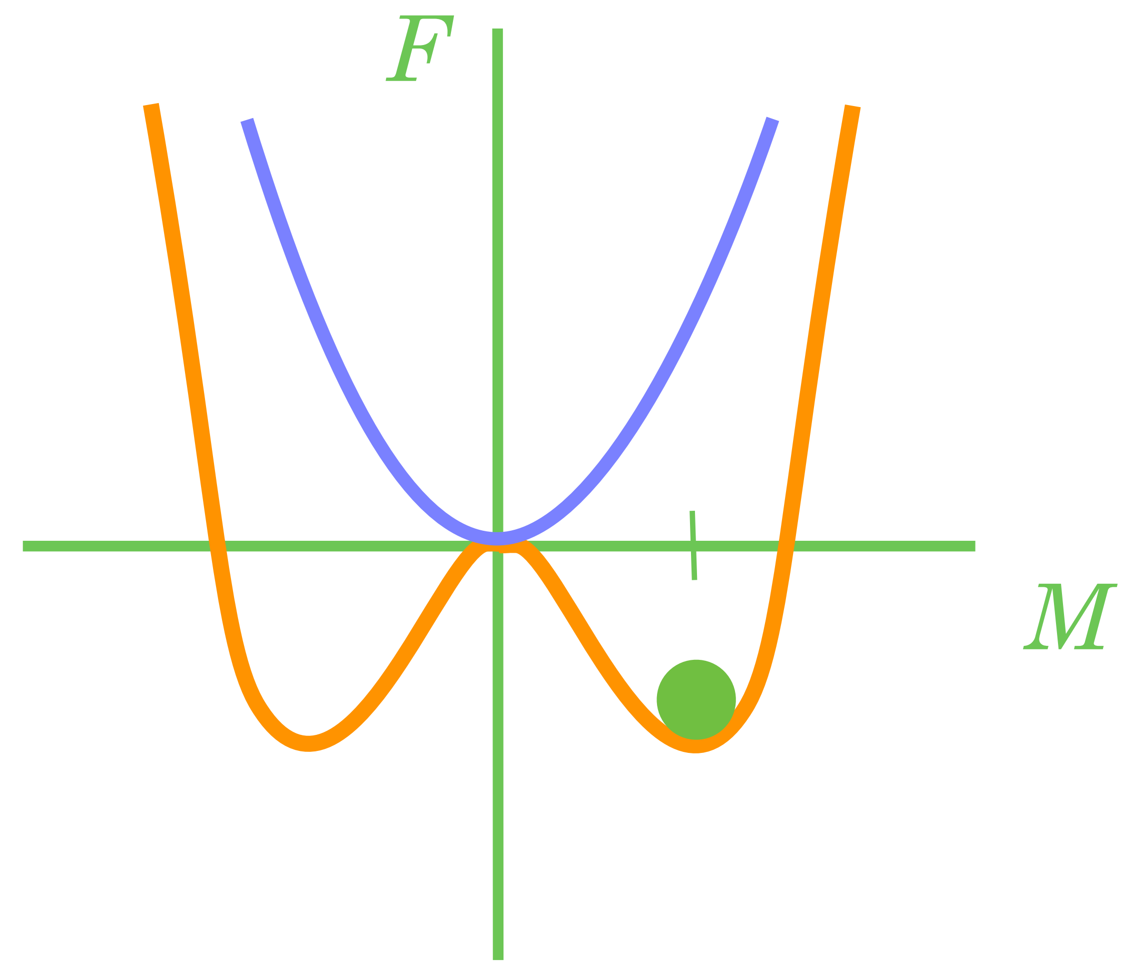


SSB is like a magnet

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





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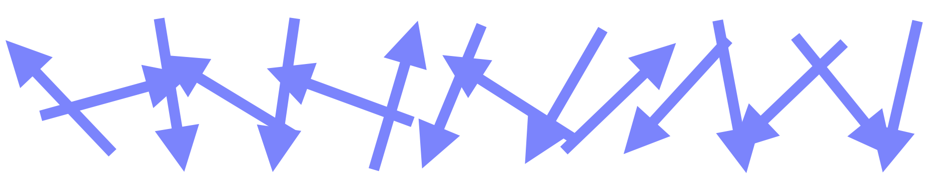

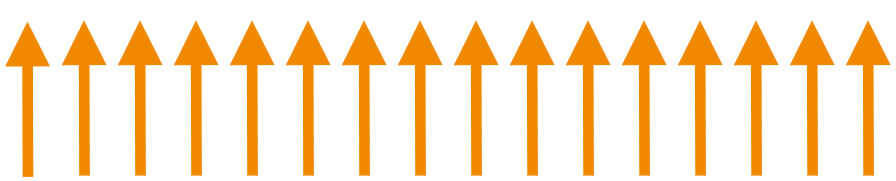

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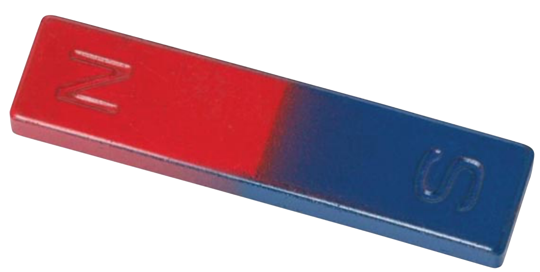

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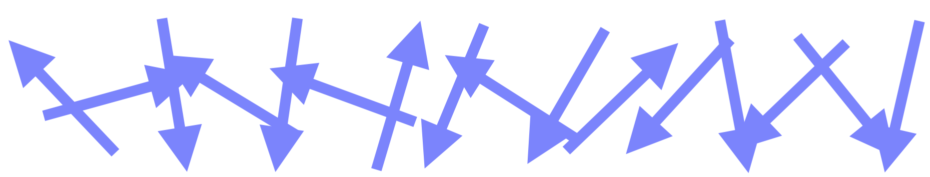
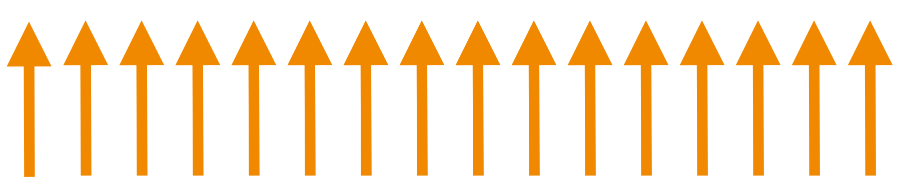
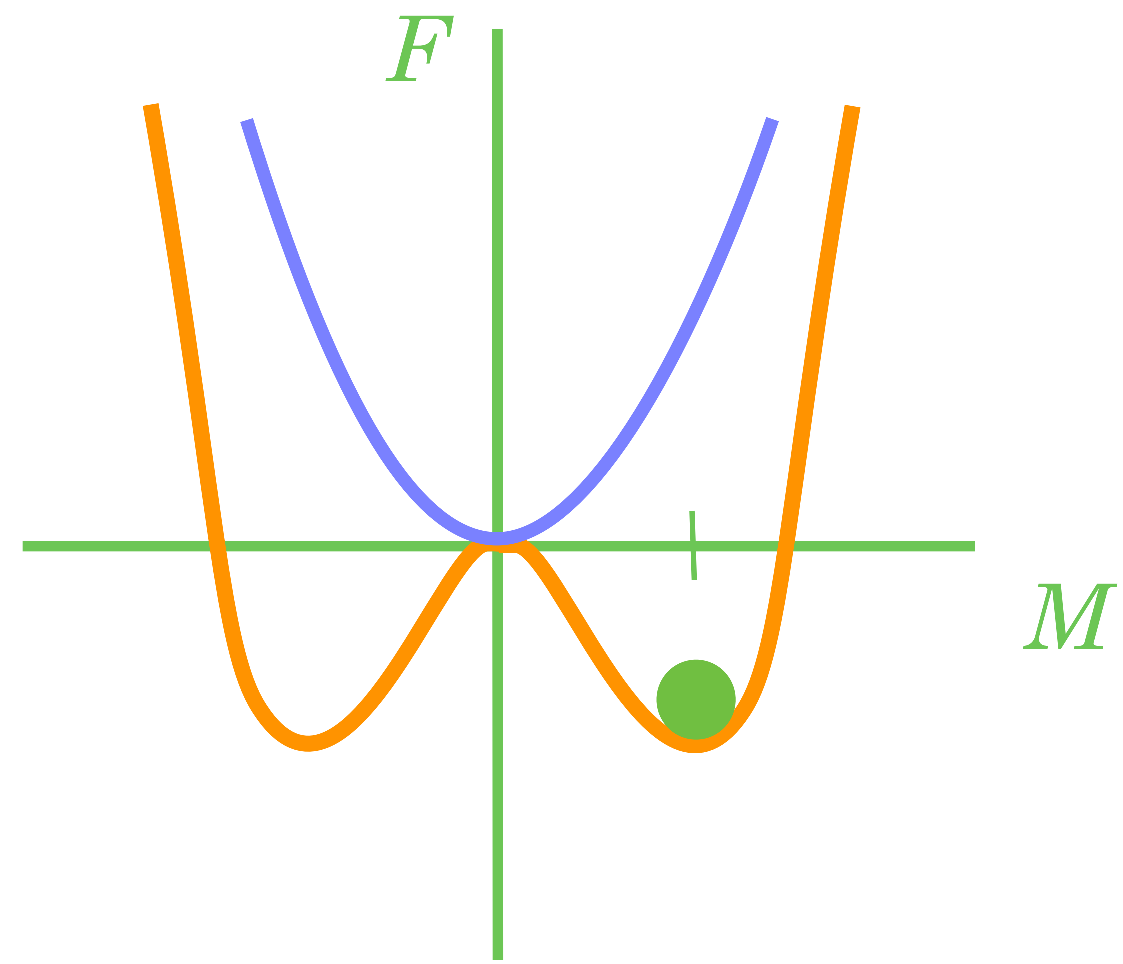




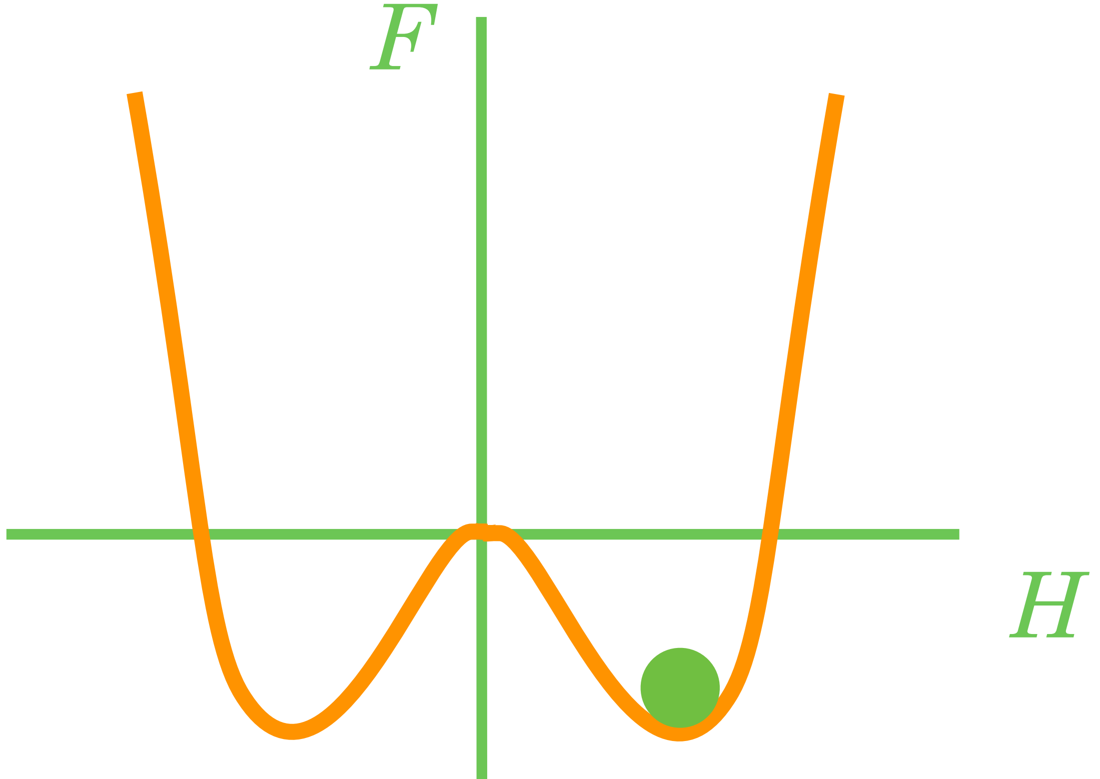
$T < T_C$



in the SM

- We live in the broken symmetry world

& trying to discover how

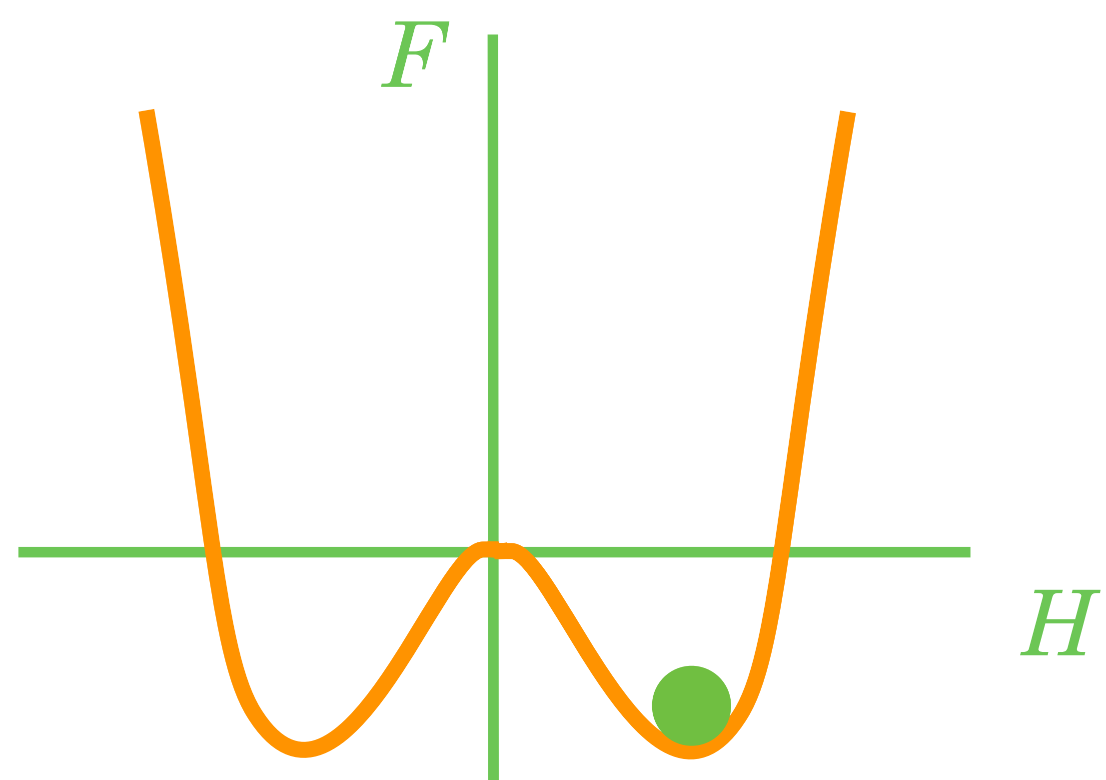


in the SM

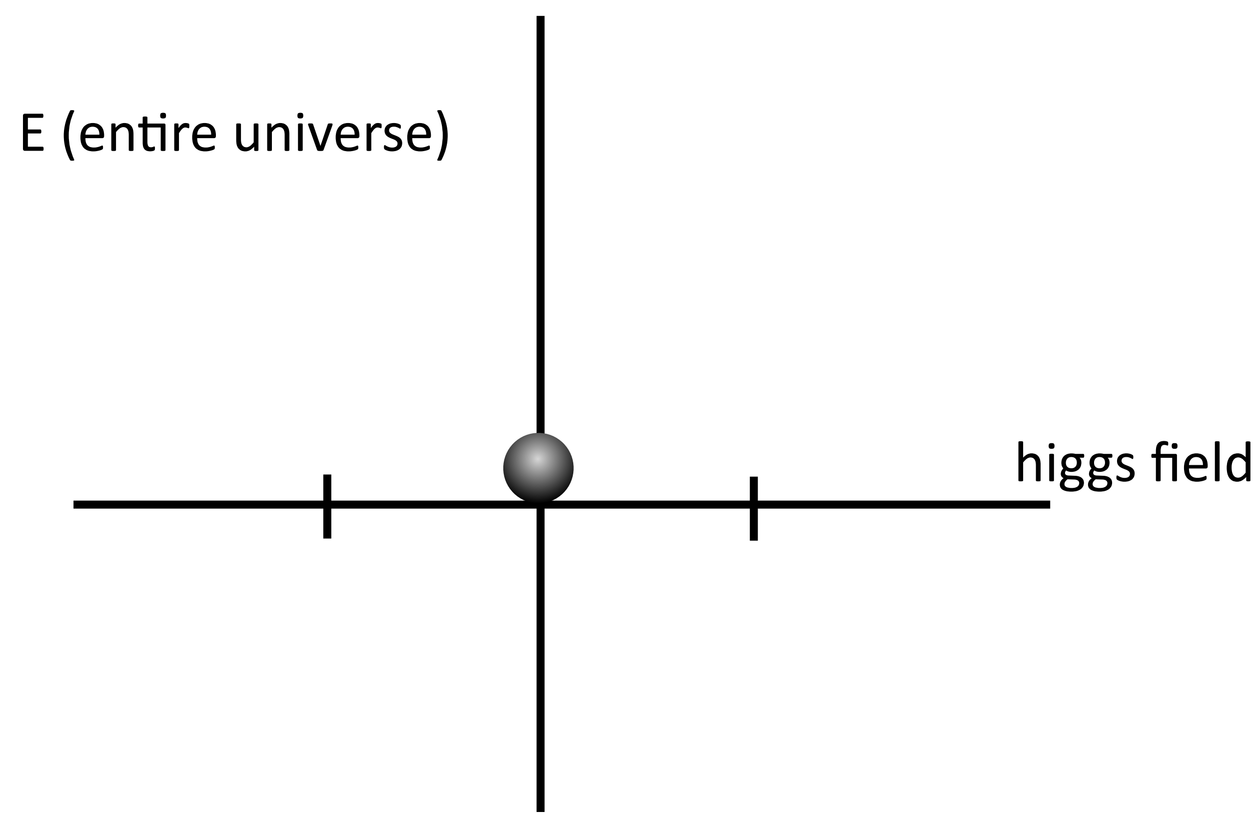
?

- We live in the broken symmetry world

& trying to discover how

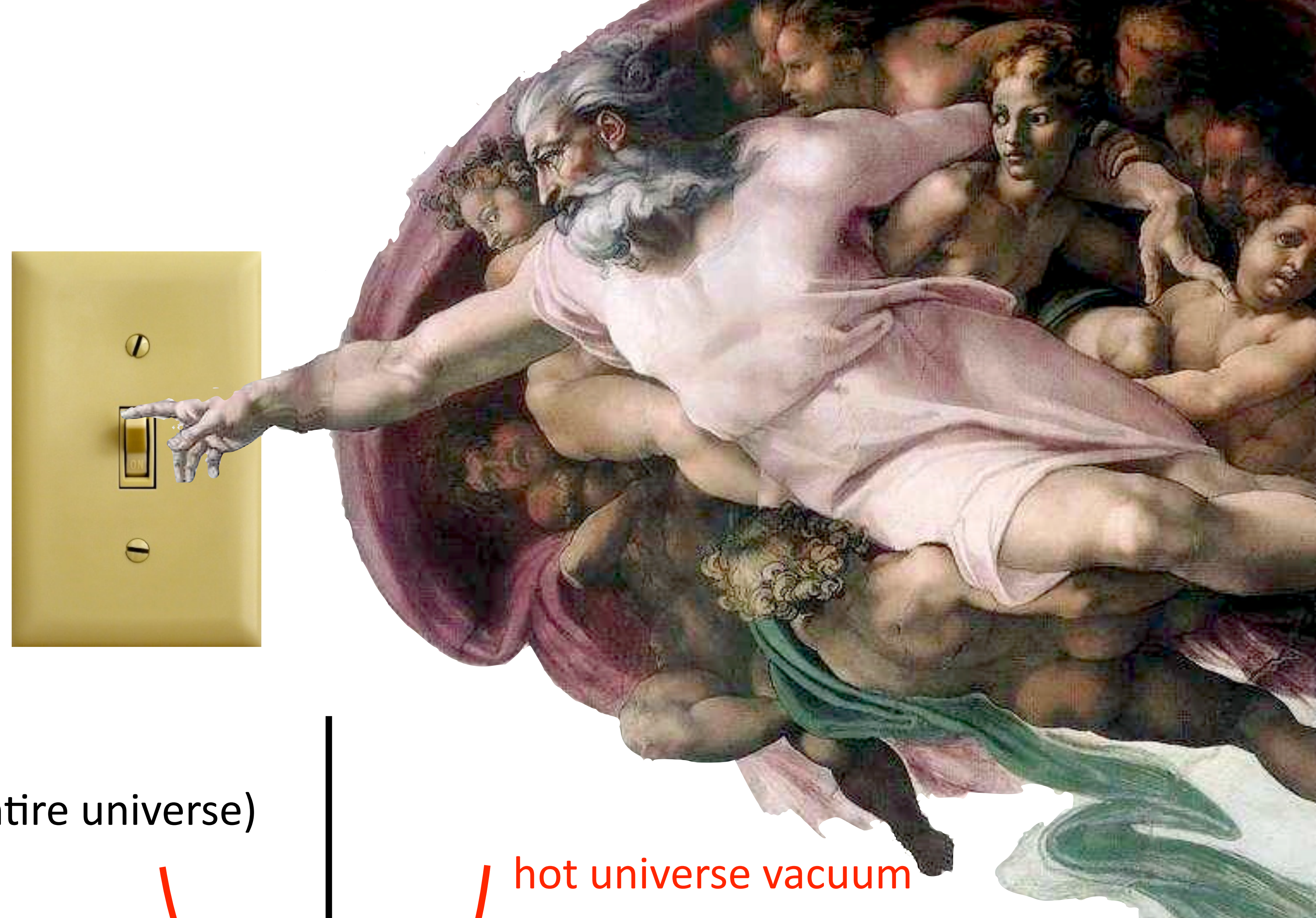


a Universal phase transition?



- @ picosecond after the BB

a Universal phase transition?



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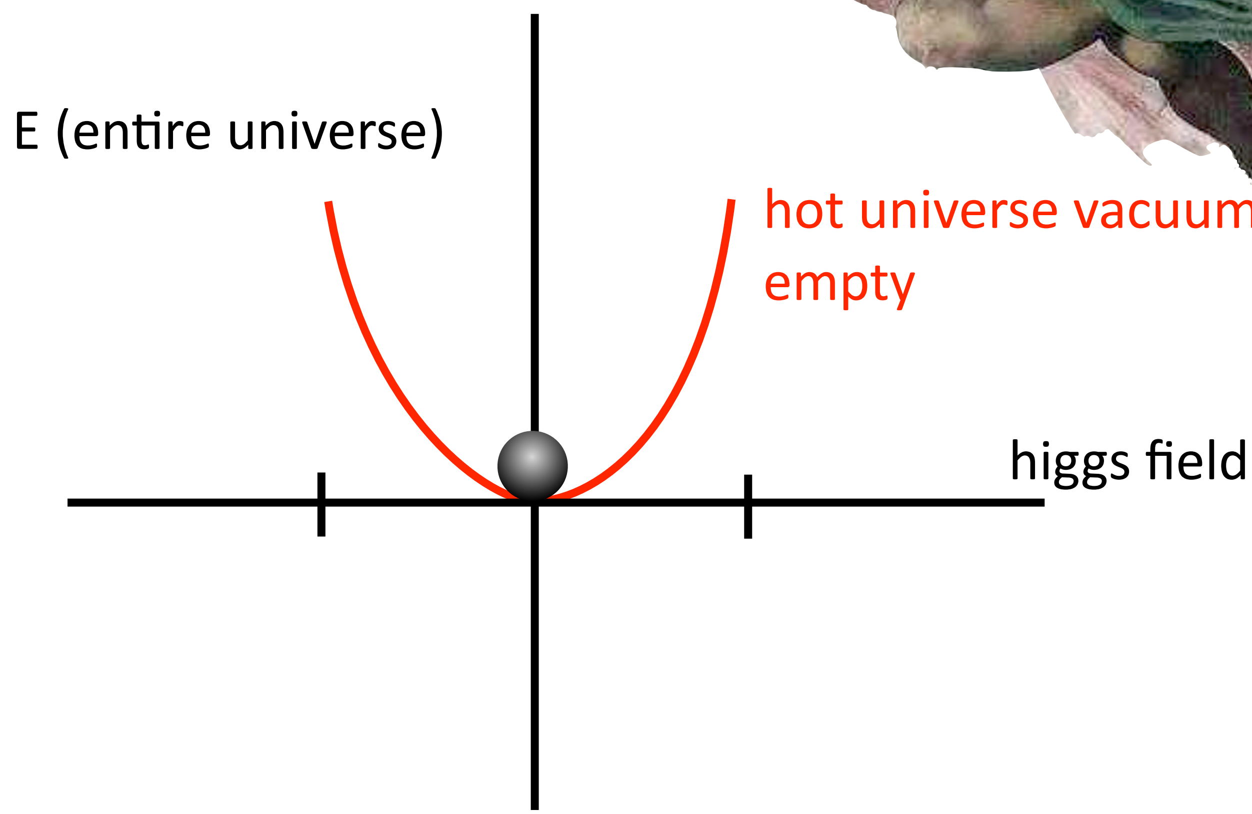

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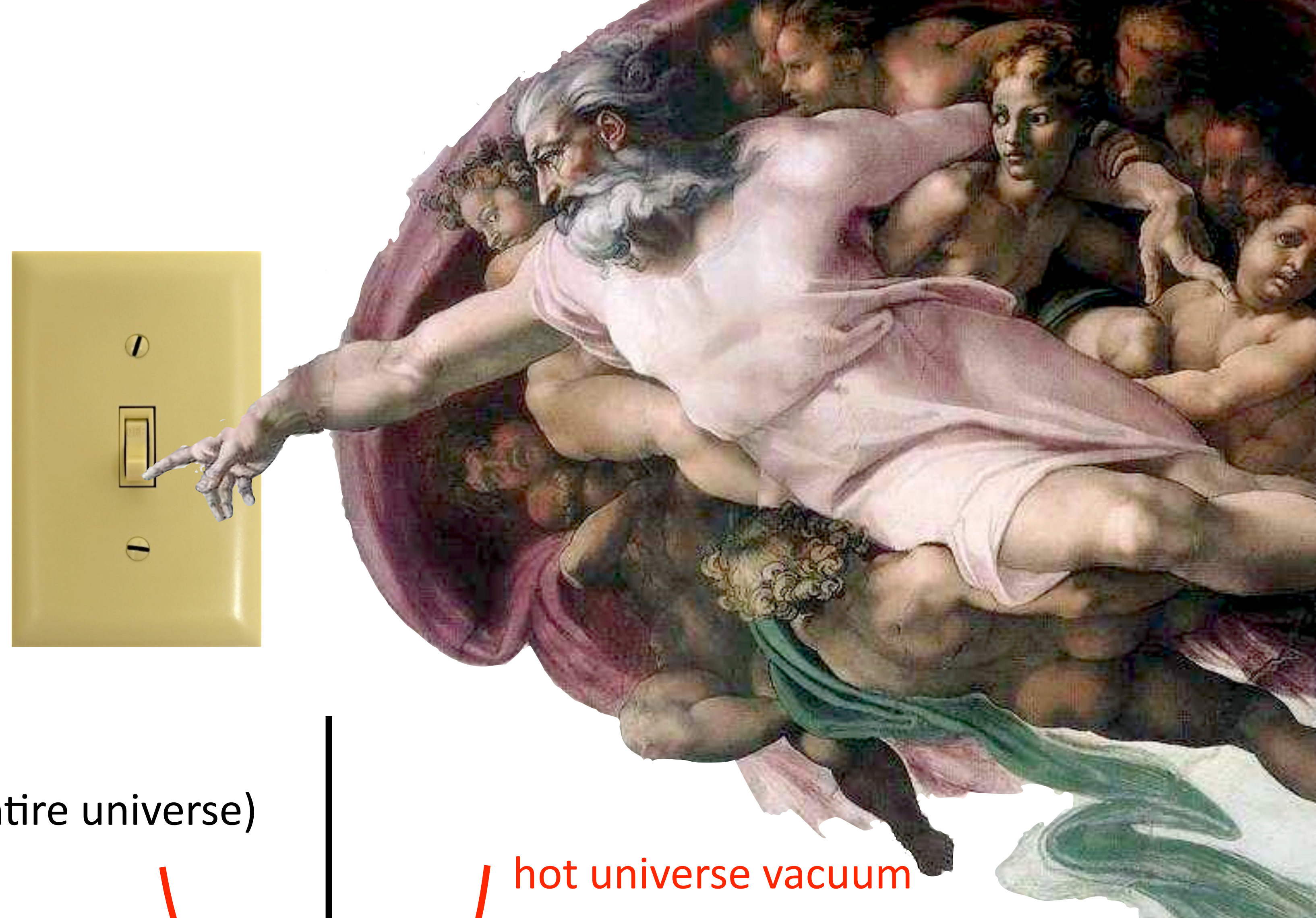
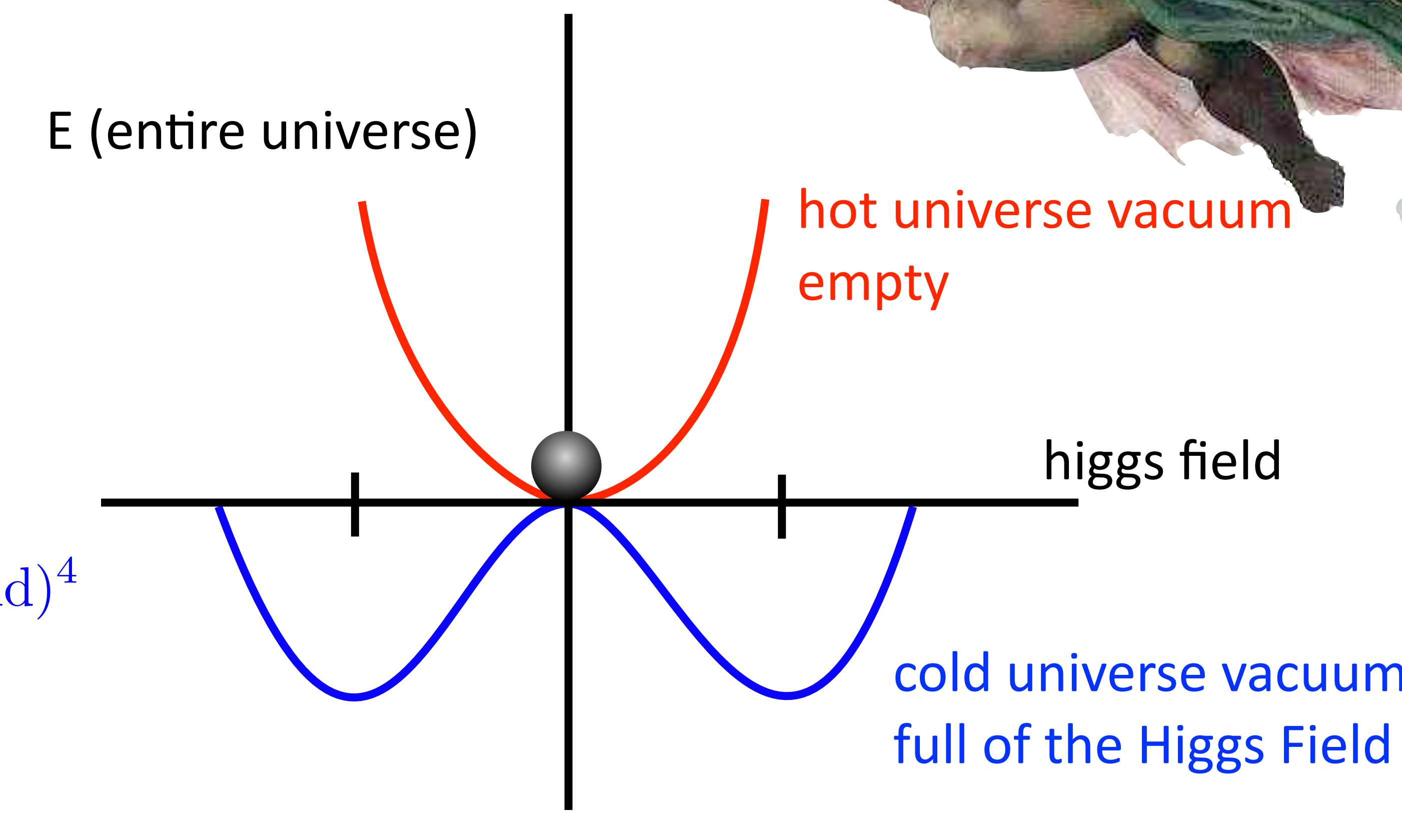


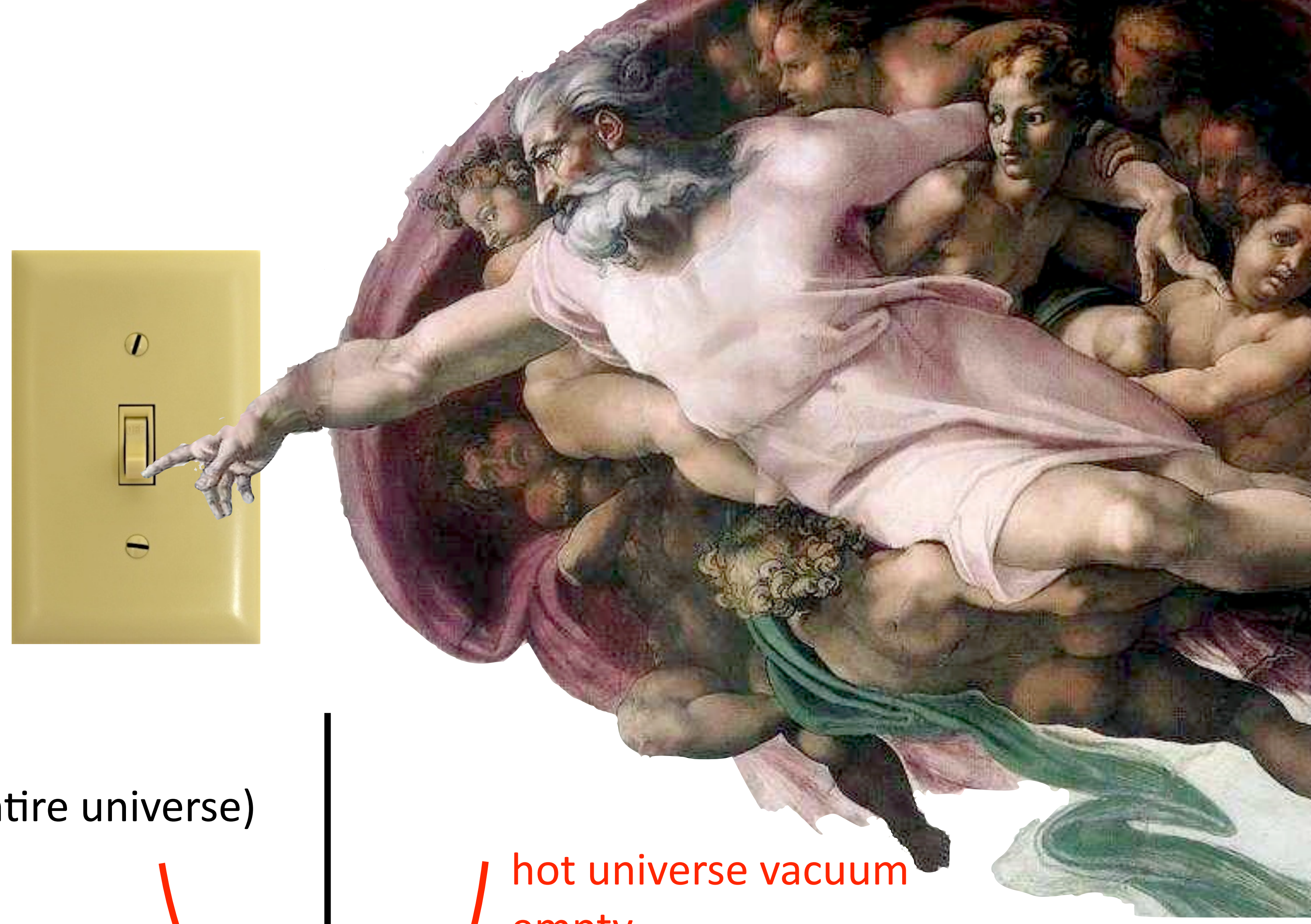
- @ picosecond after the BB

$$V = -\mu^2(\text{higgs field})^2 + \lambda(\text{higgs field})^4$$

$$-\mu^2 < 0$$



a Universal phase transition?



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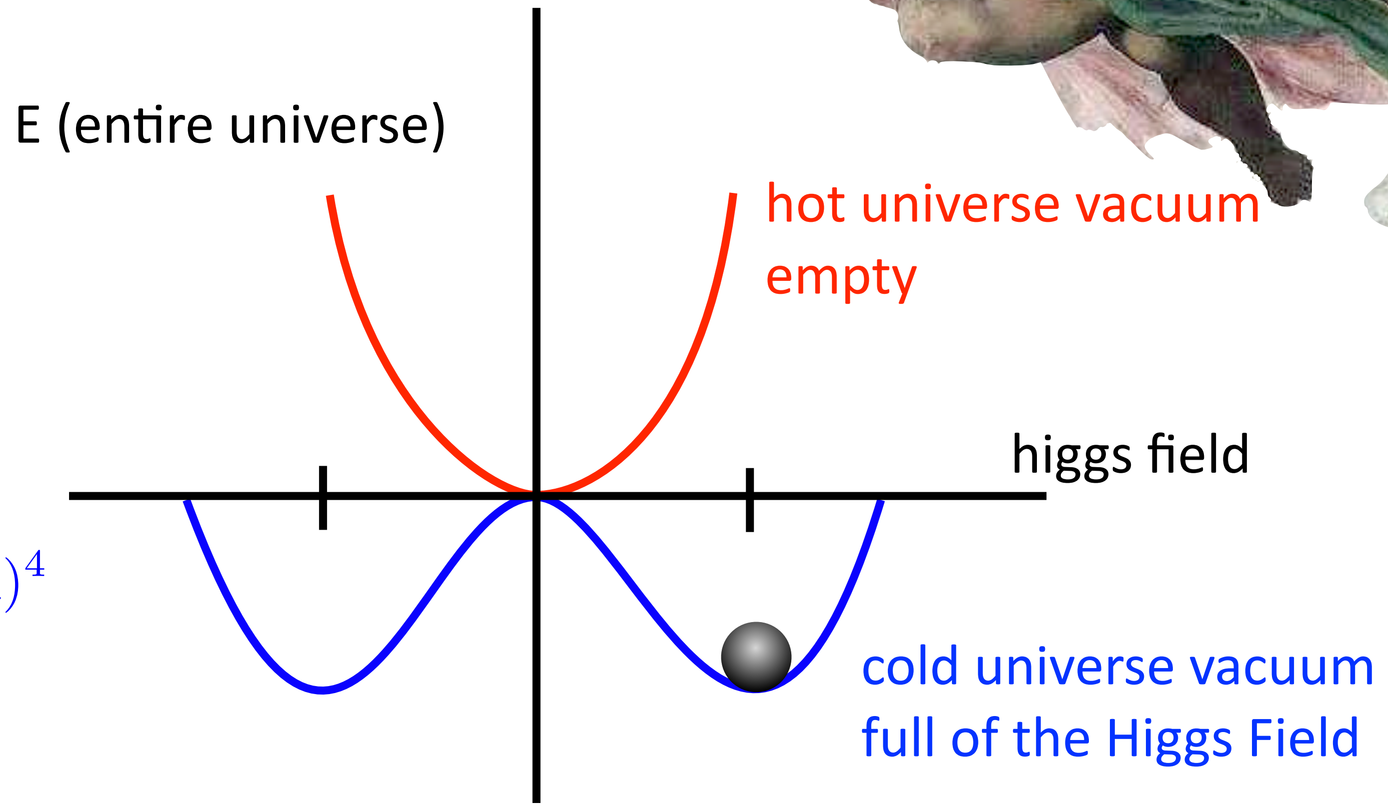

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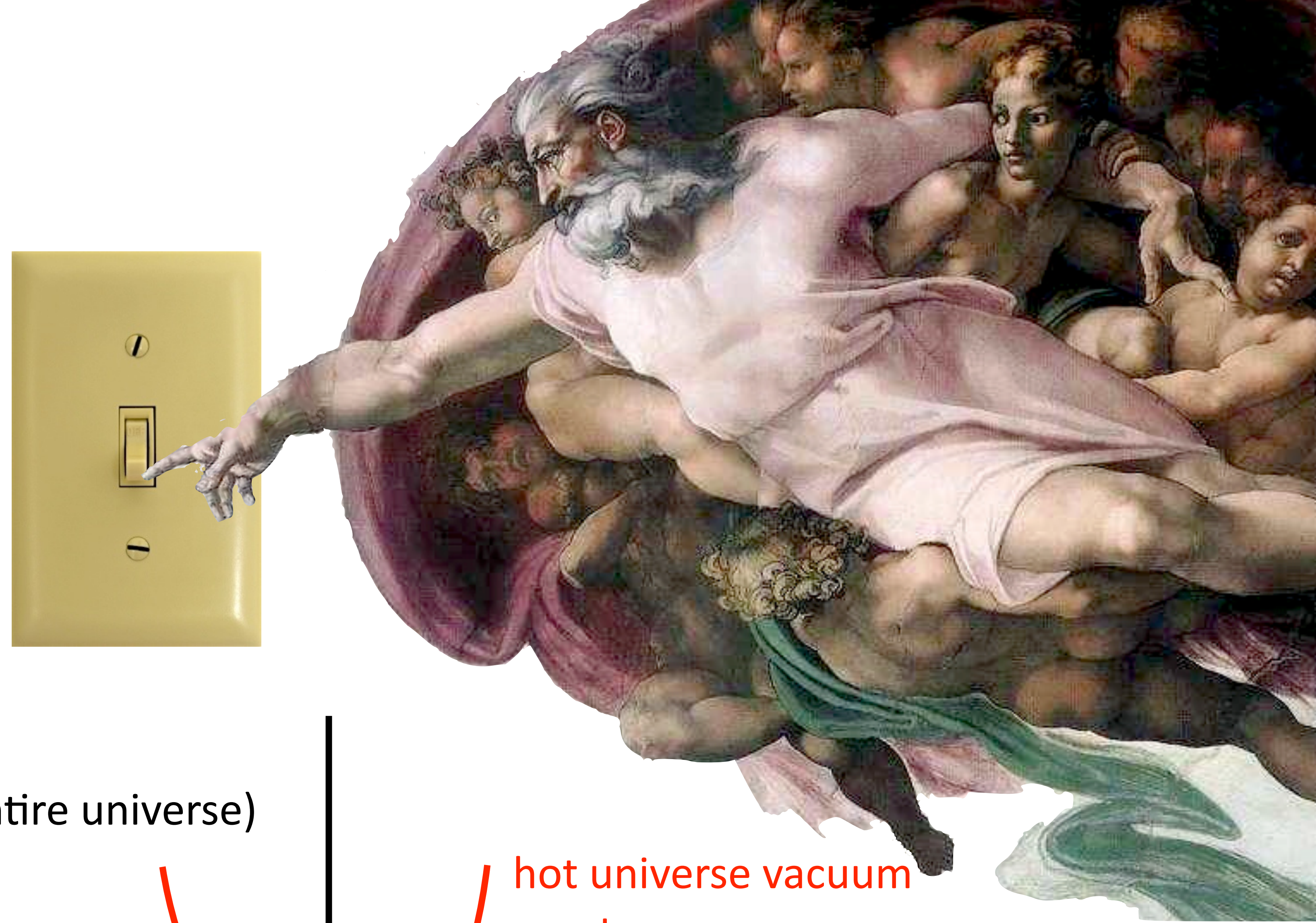

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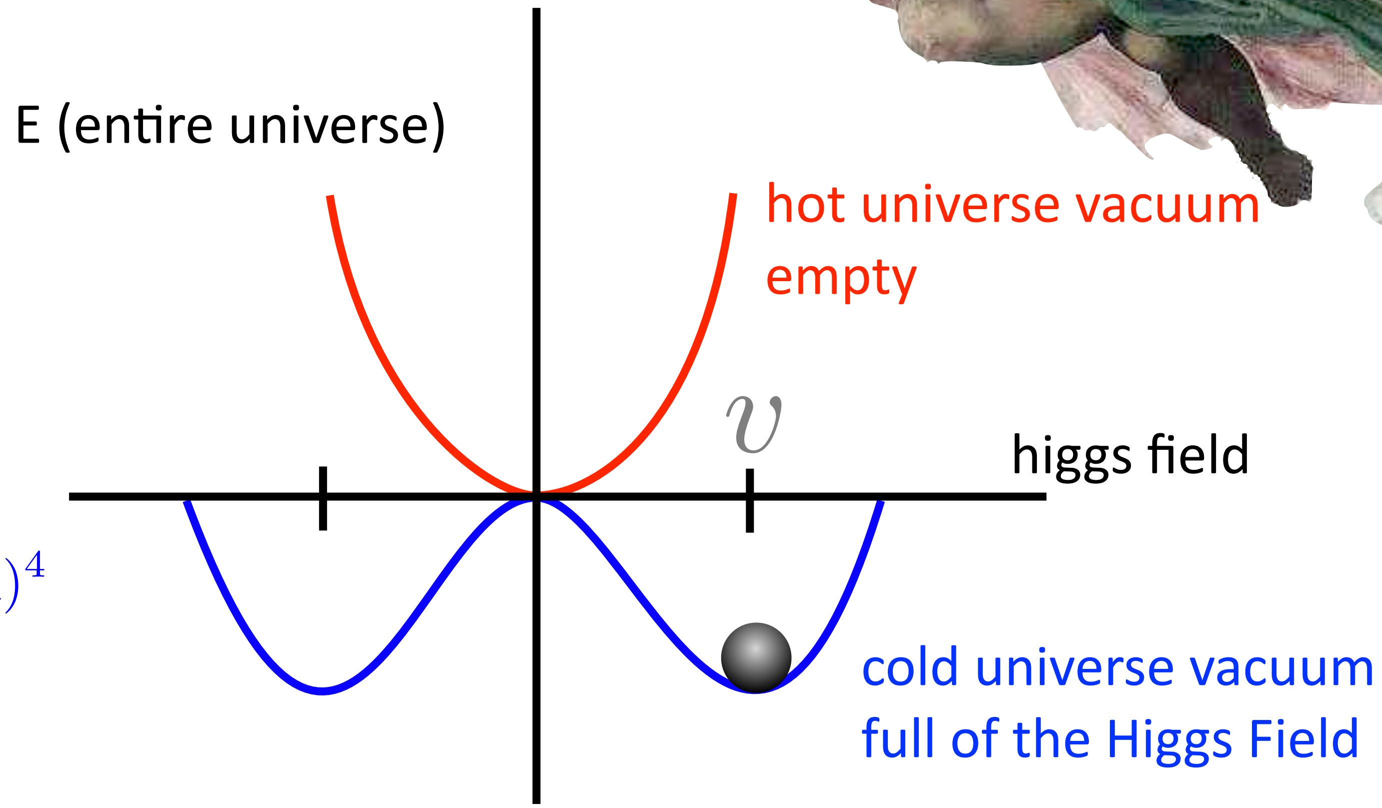

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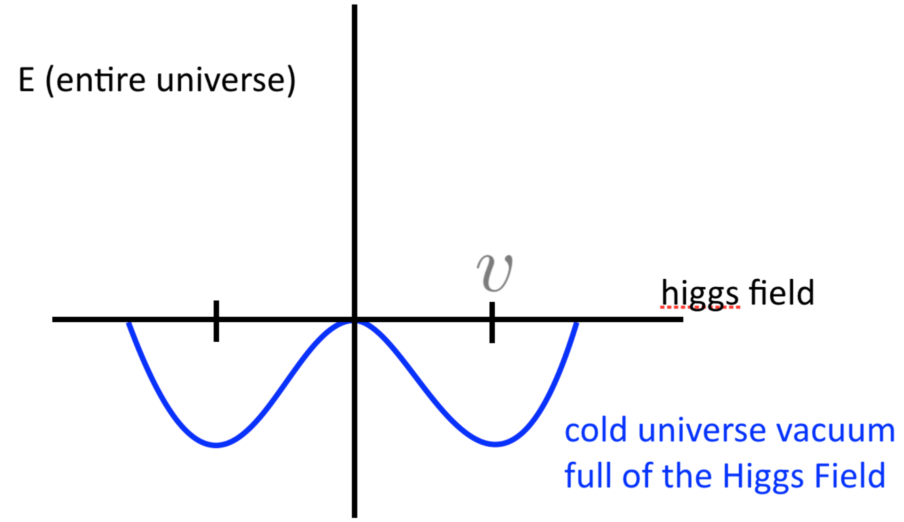

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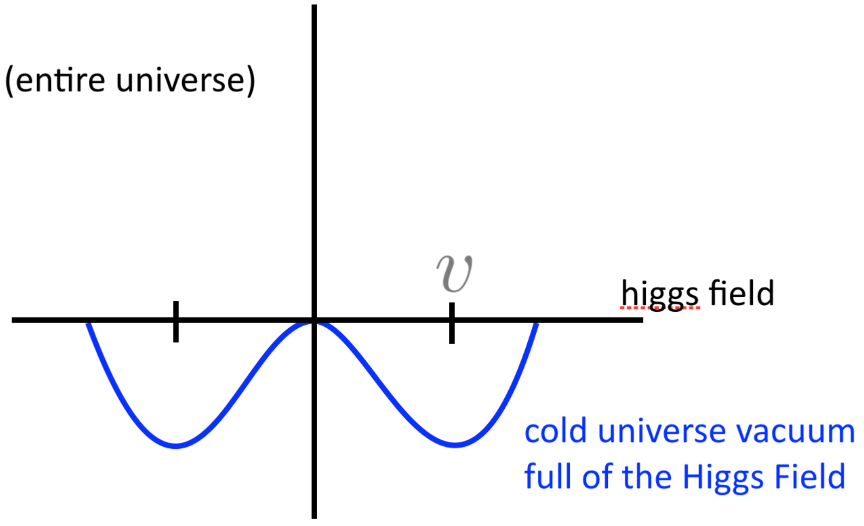


$$|-\mu^2| \cong 88.4(\text{ GeV})^2$$

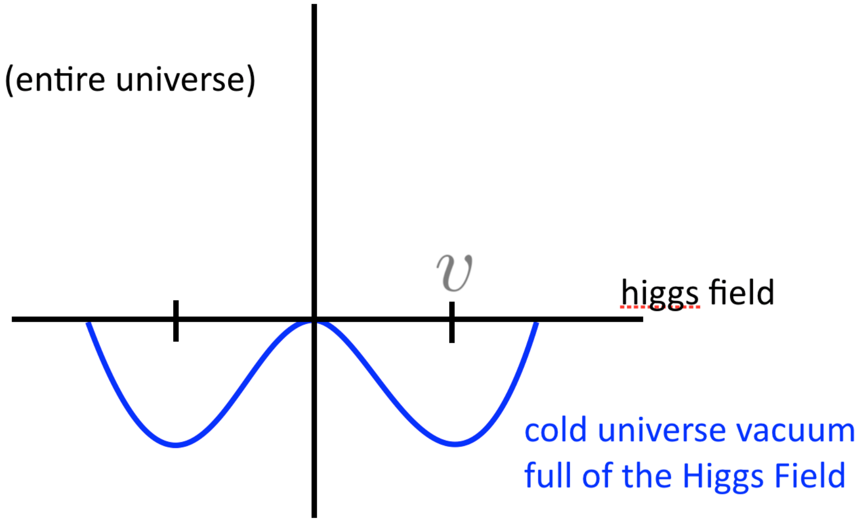
$$\lambda \cong 0.129$$

$$v \cong 246 \text{ GeV}$$

$v = 246$ GeV…it's <u>on</u>.

$$V = -\mu^2(\text{higgs field})^2 + \lambda(\text{higgs field})^4$$

$$-\mu^2 < 0$$



$$|-\mu^2| \cong 88.4(\text{ GeV})^2$$

$$\lambda \cong 0.129$$

$$v \cong 246 \text{ GeV}$$

a^0 0

B^0 0

B^+ +

B^- -

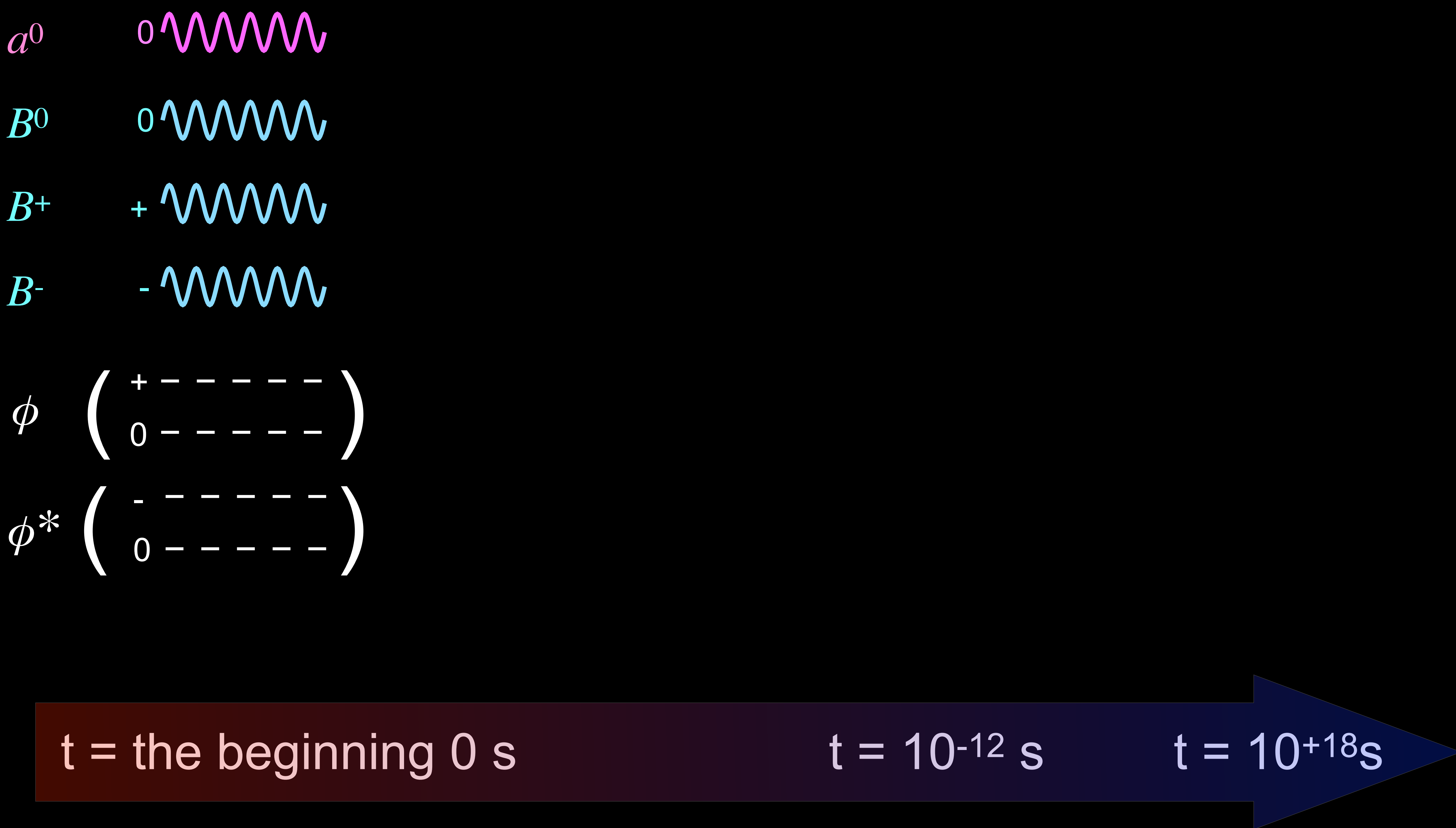
ϕ (+ / 0)

ϕ^* (- / 0)

t = the beginning 0 s

t = 10^{-12} s

t = 10^{+18}s



a^0 0
B^0 0
B^+ +
B^- -
ϕ + 0
ϕ^* - 0
t = the beginning 0 s
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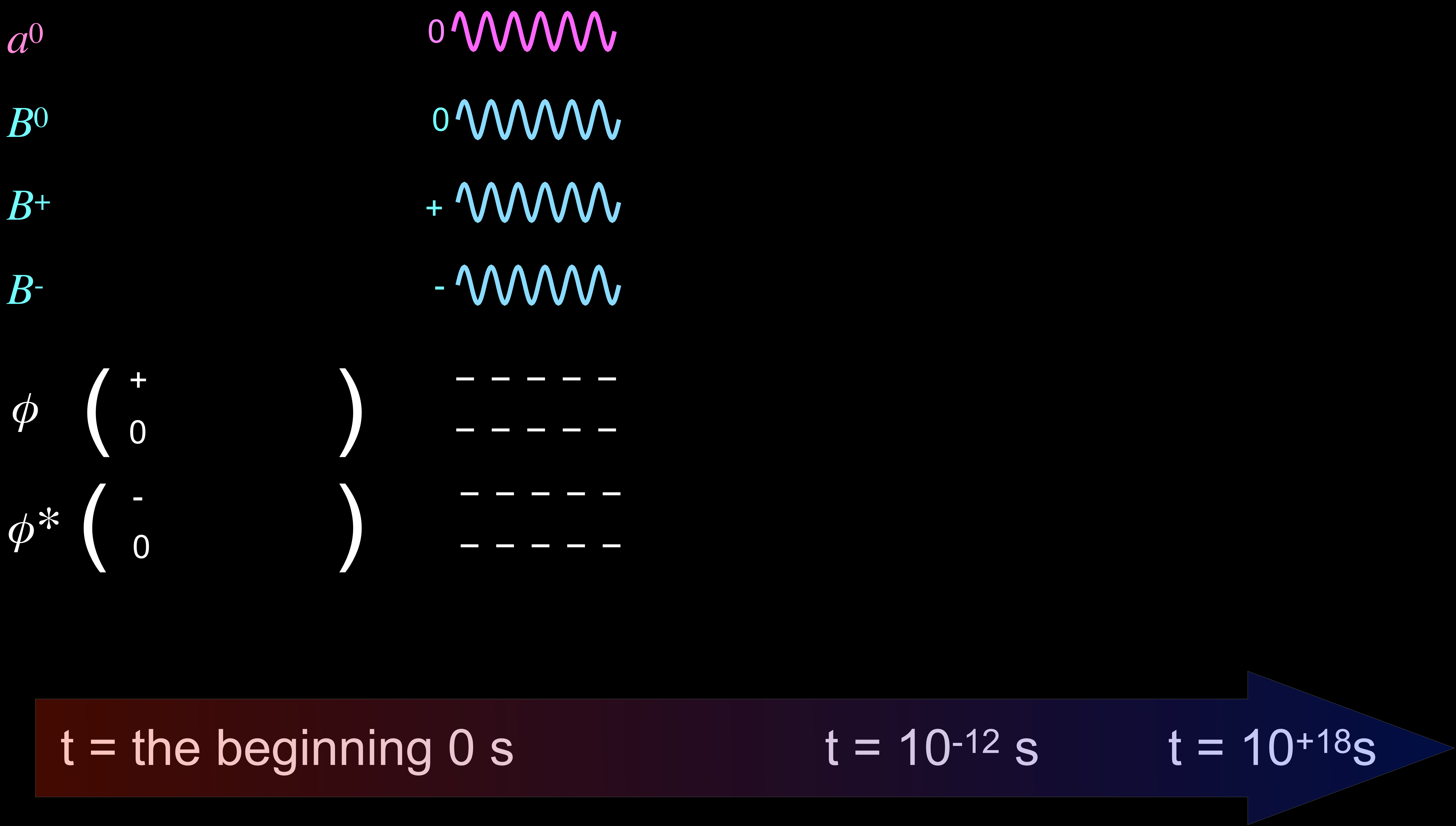


a^0
0
B^0
0
B^+
+
B^-
-
ϕ (+ 0)
ϕ^* (- 0)
t = the beginning 0 s
t = 10^{-12} s
t = 10^{+18}s

a^0 0

B^0 0

B^+ +

B^- -

ϕ $\begin{pmatrix} + \\ 0 \end{pmatrix}$

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

t = the beginning 0 s　　t = 10^{-12} s　　t = 10^{+18} s

a^0

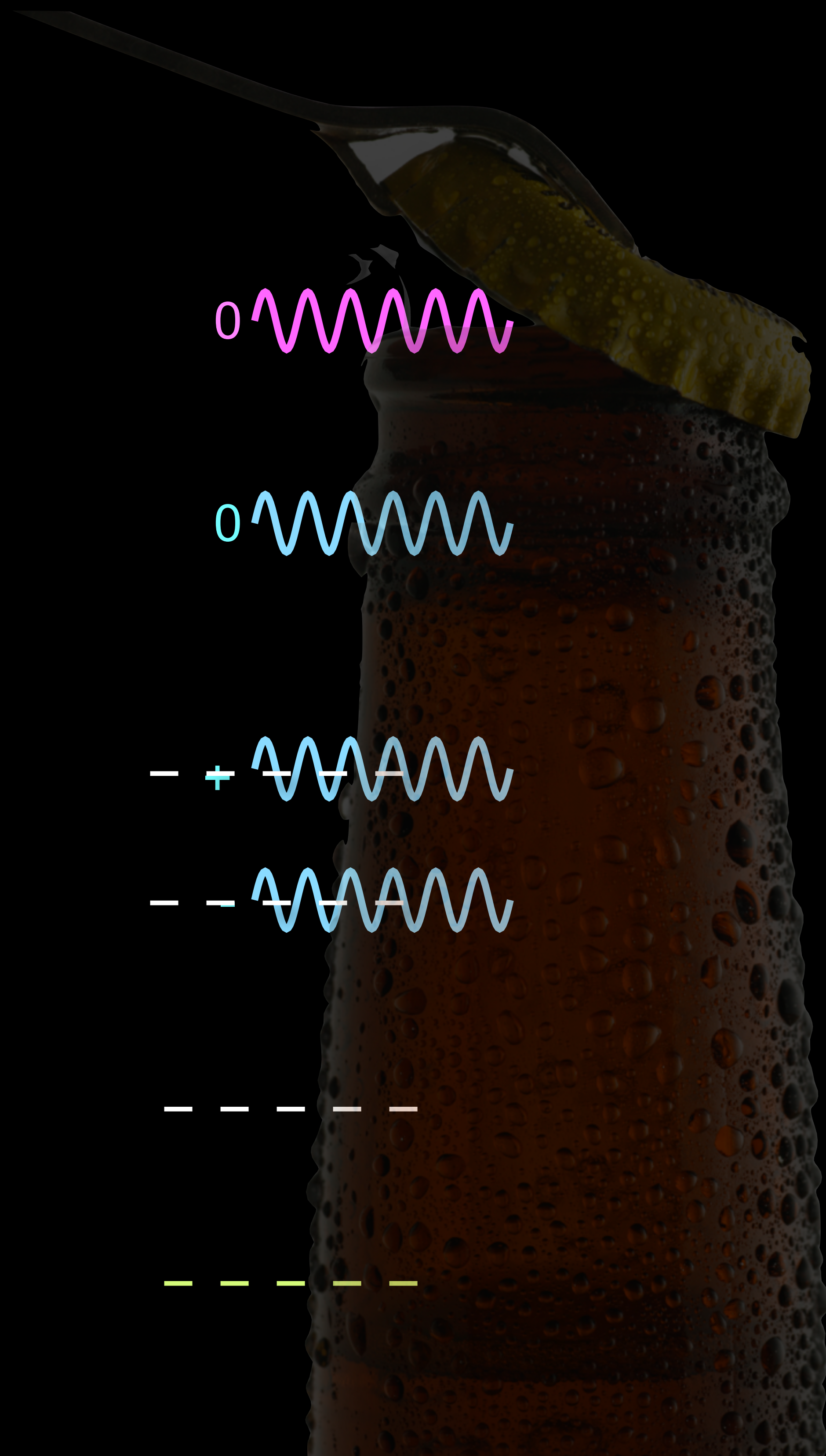
B^0

B^+

B^-

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

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



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a^0

B^0

B^+

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

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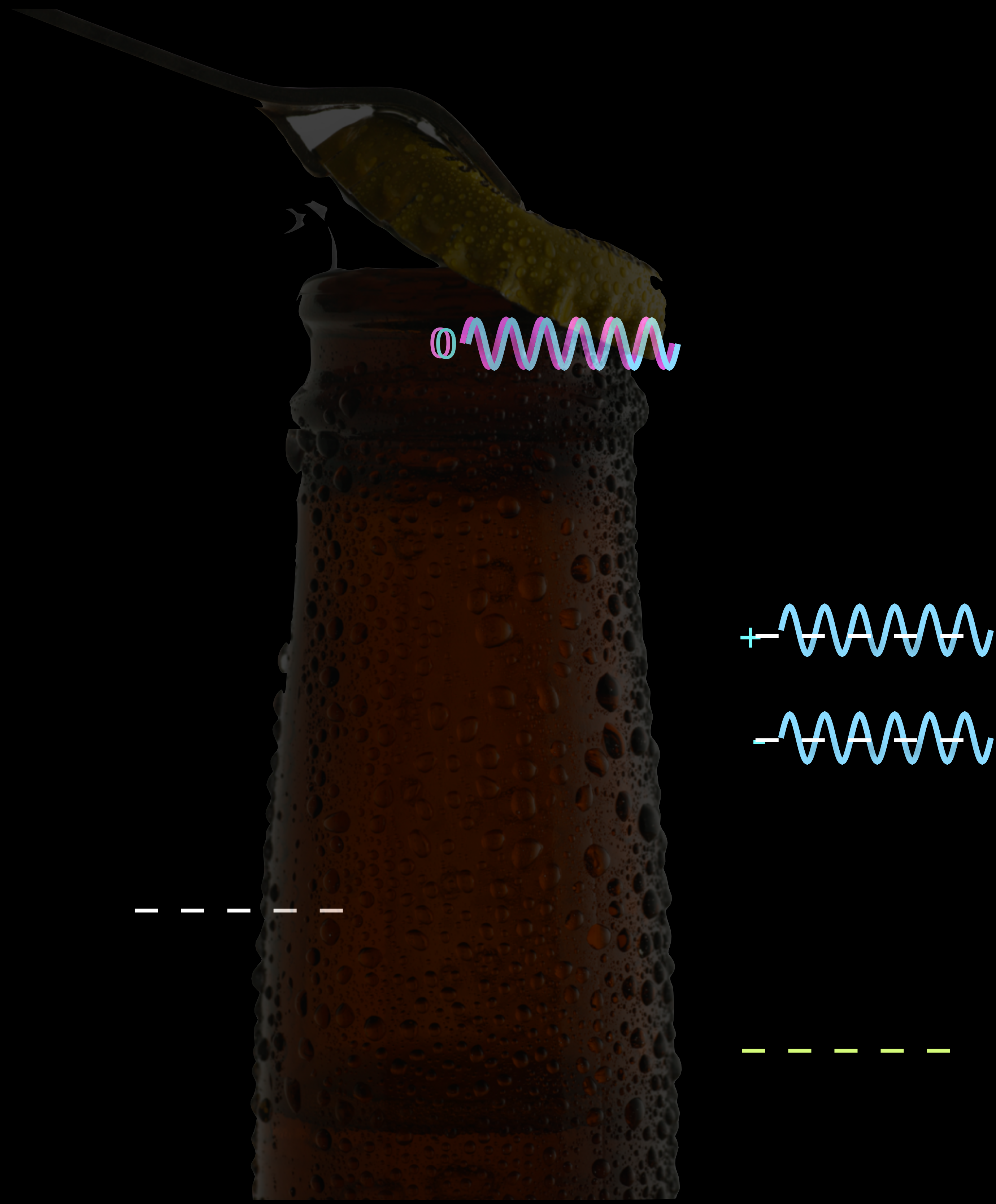
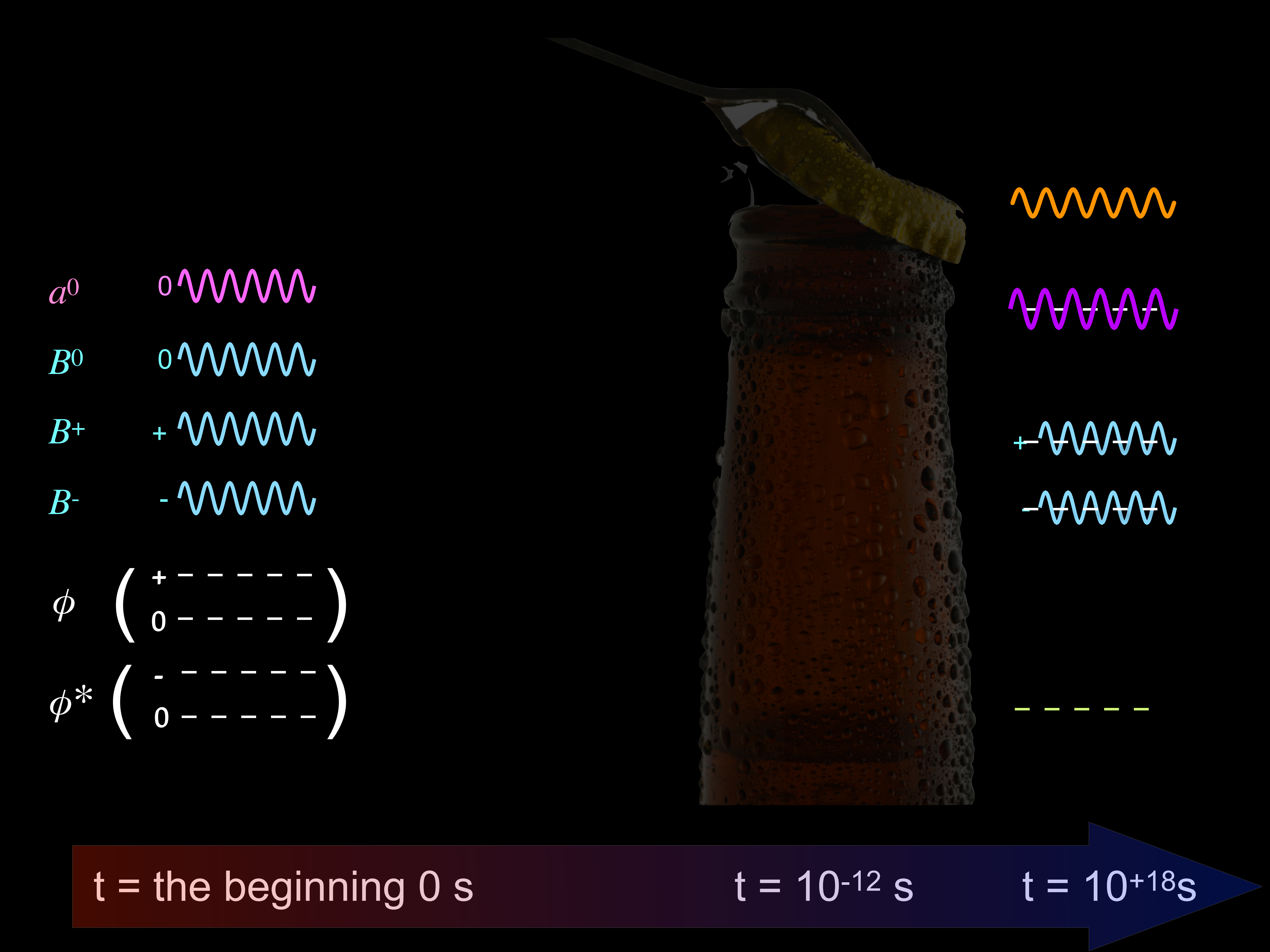
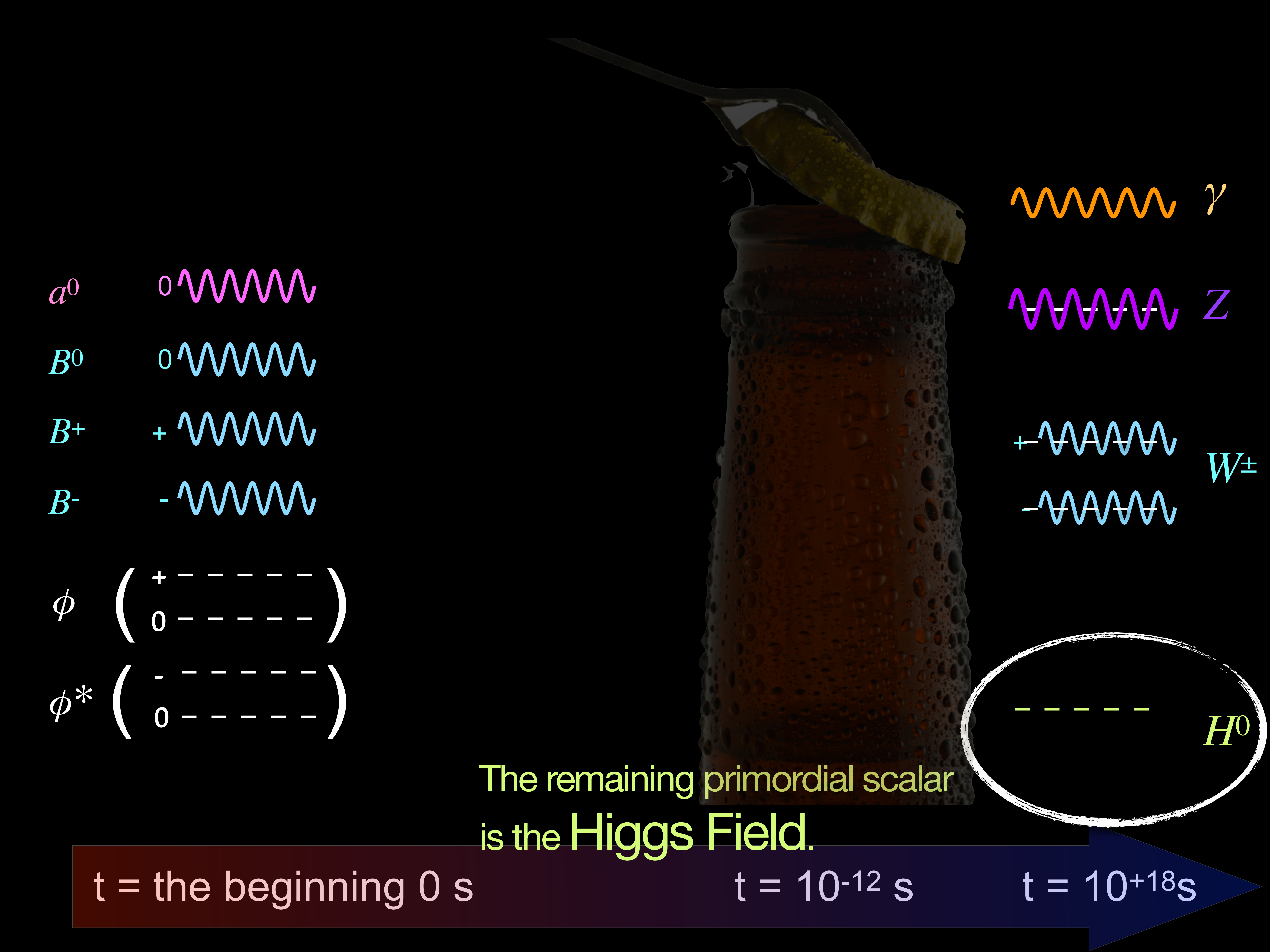


t = the beginning 0 s   t = 10^{-12} s   t = 10^{+18}s



a^0 0
B^0 0
B^+ +
B^- -
ϕ (+ 0)
ϕ^* (- 0)
+
-
t = the beginning 0 s
t = 10^{-12} s
t = 10^{+18}s



γ
Z
W±
a0
B0
B+
B-
φ
φ*
H0
The remaining primordial scalar
is the Higgs Field.
t = the beginning 0 s
t = 10-12 s
t = 10+18s

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

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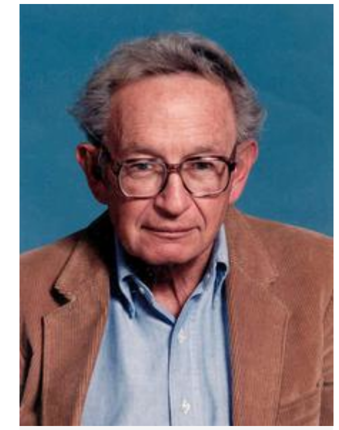
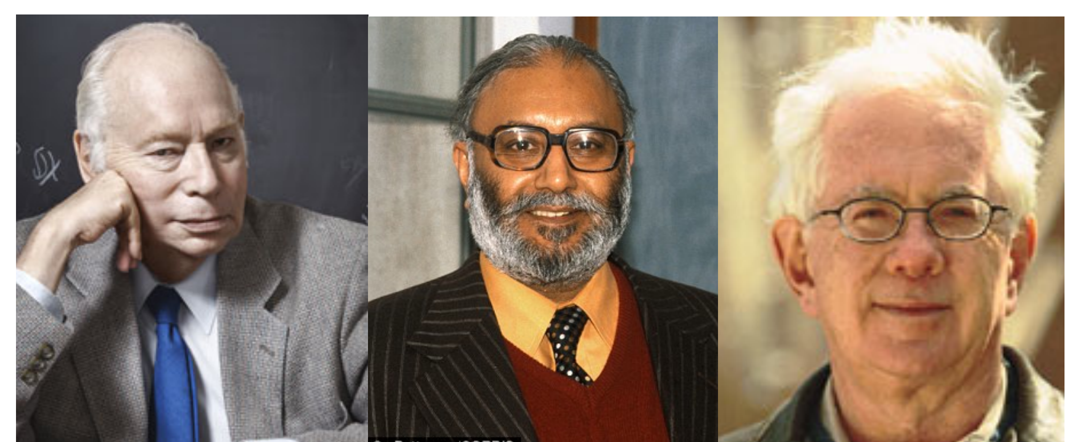


Anderson

Higgs Kibble Guralnik Hagen Englert Brout

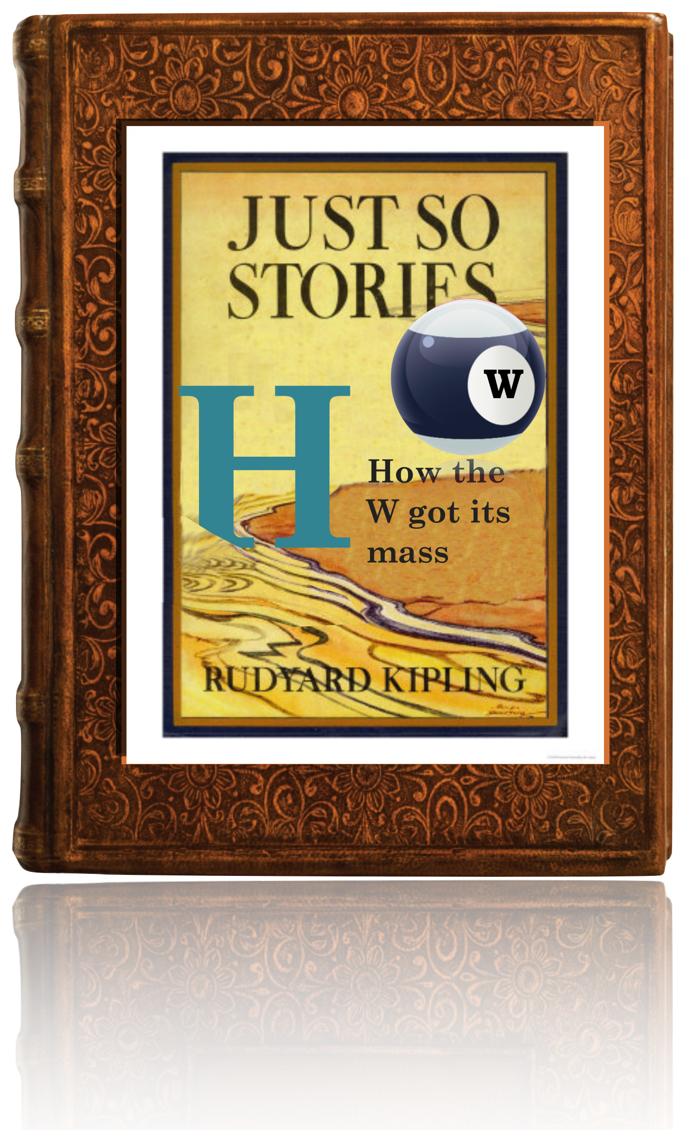


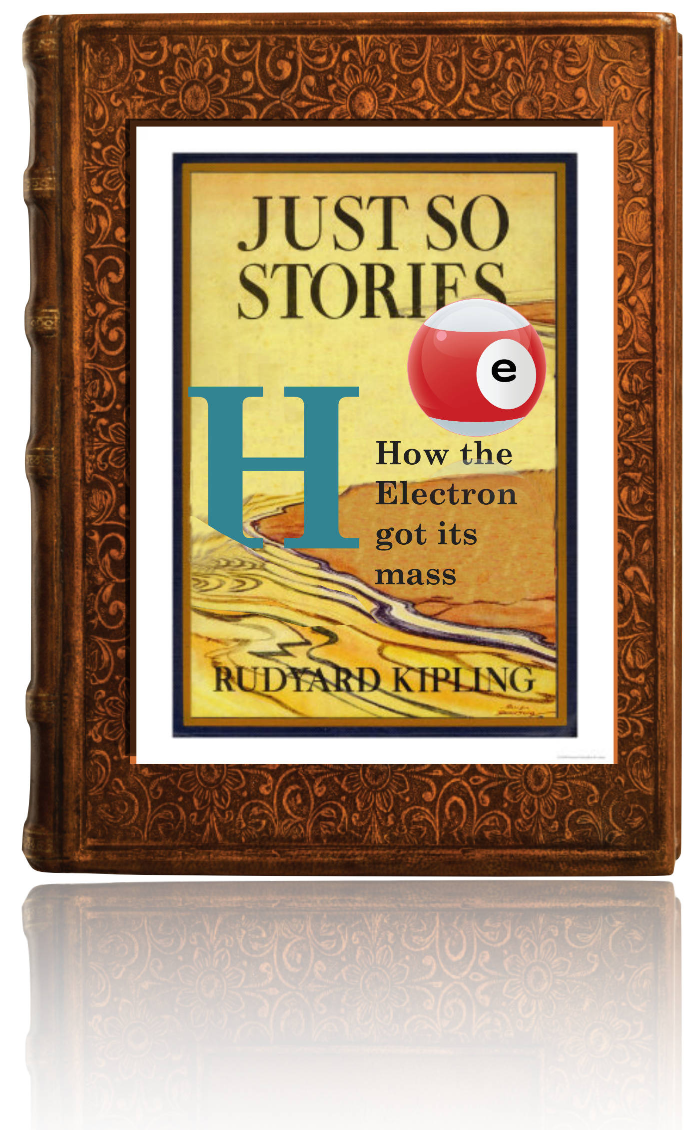
Weinberg Salam Glashow

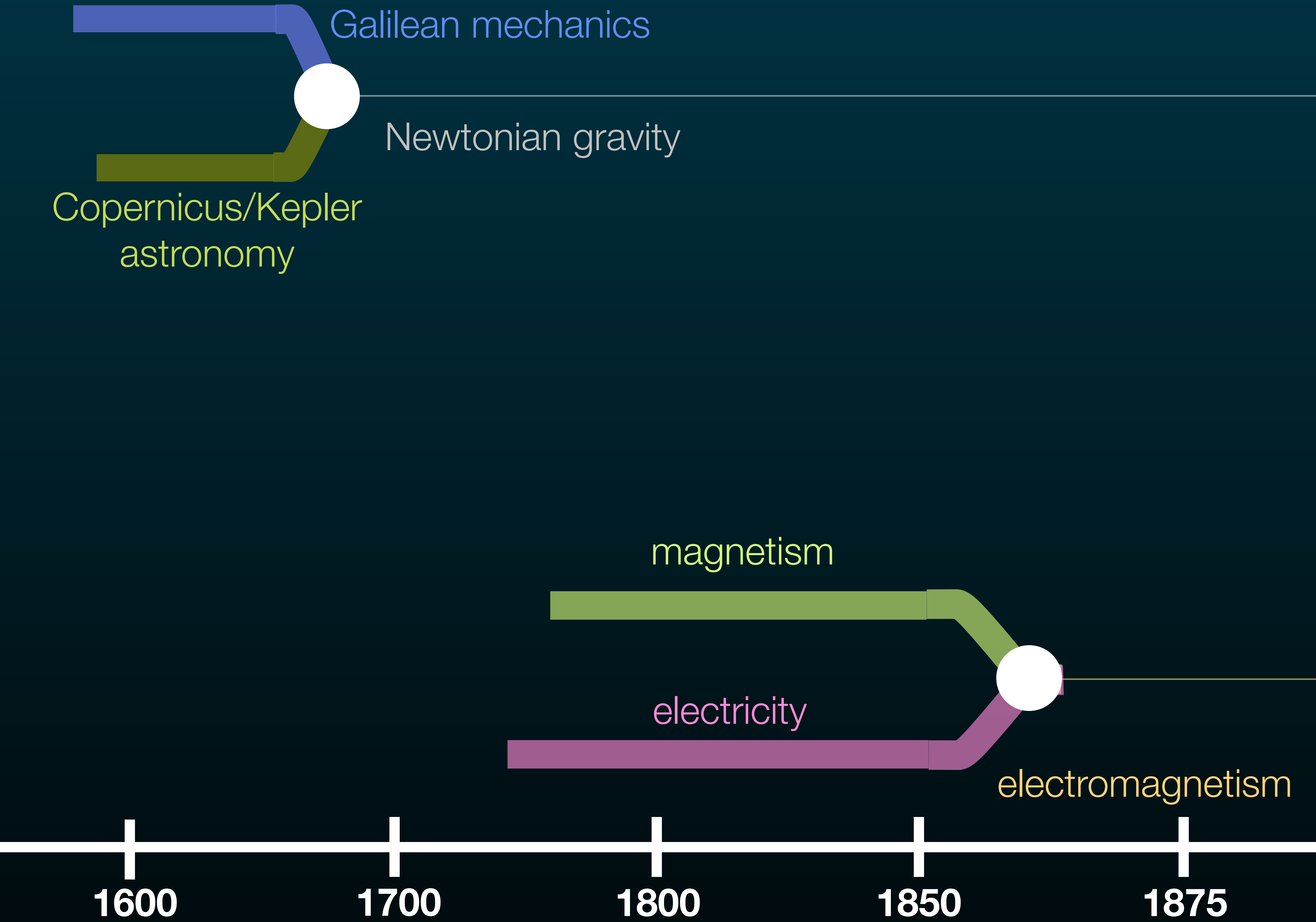
what's exciting

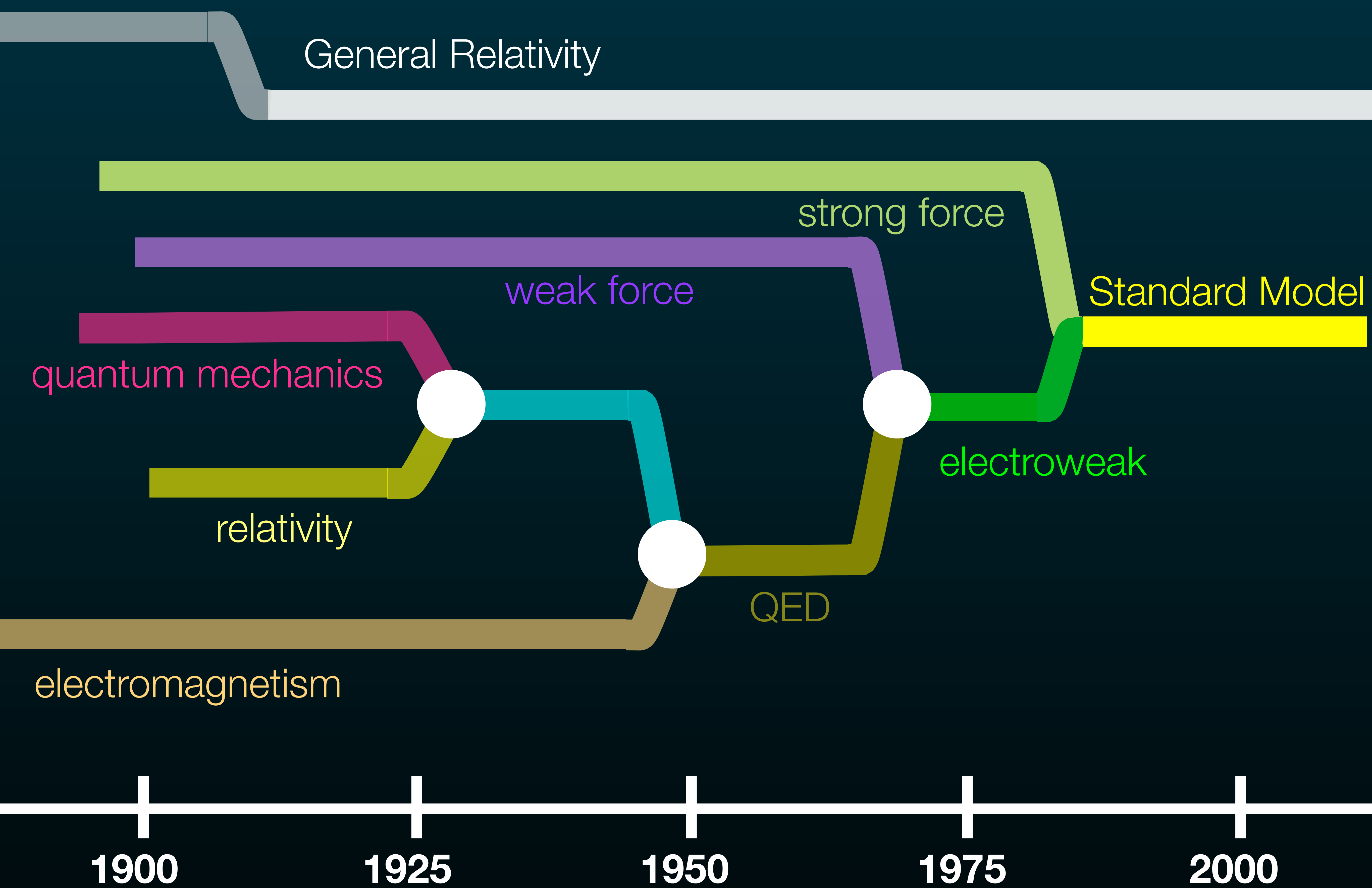
about the Standard Model?

its historical significance & Higgs Field






Galilean mechanics
Newtonian gravity
Copernicus/Kepler
astronomy
magnetism
electricity
electromagnetism
1600
1700
1800
1850
1875

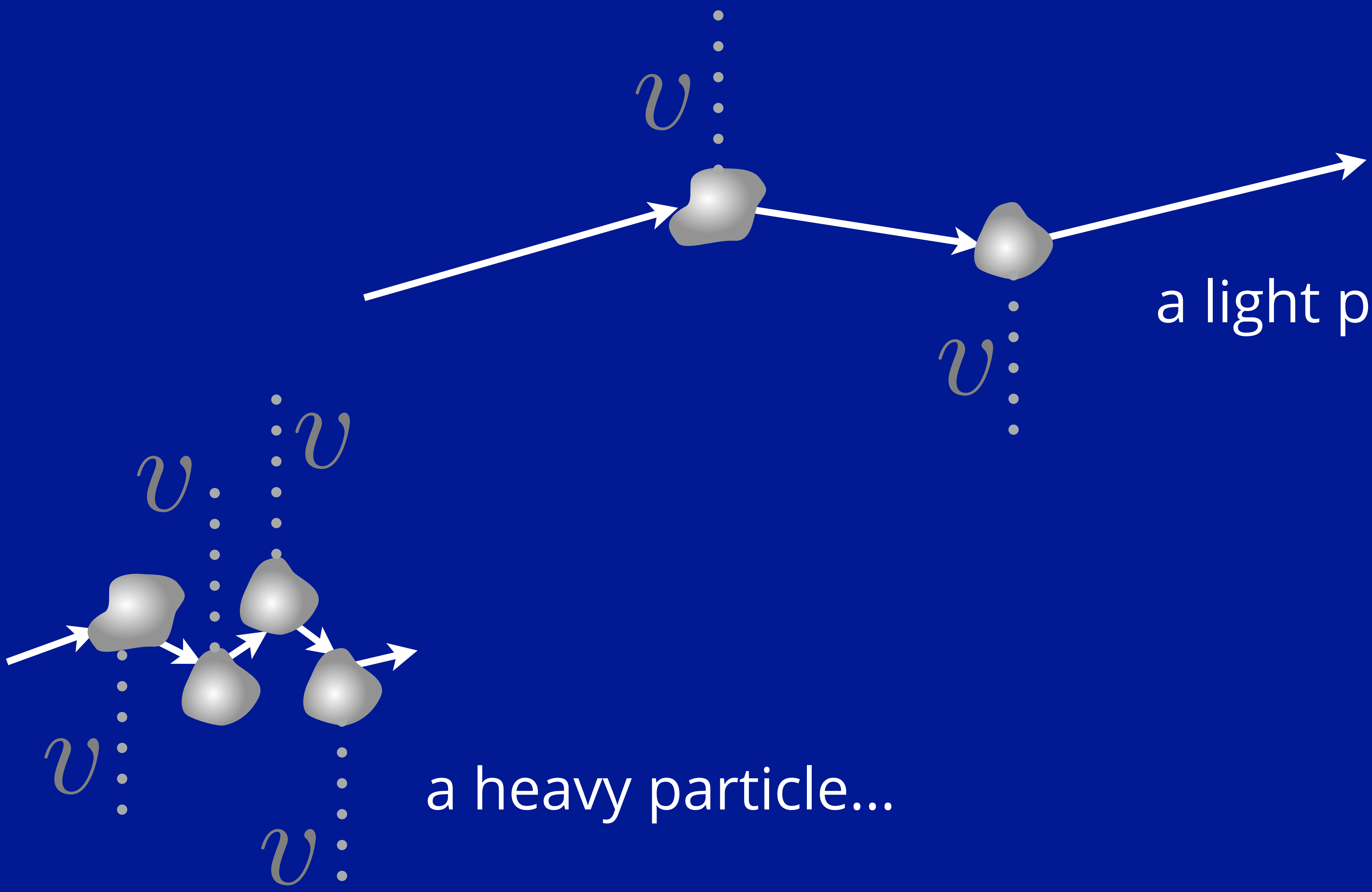


General Relativity
strong force
weak force
Standard Model
quantum mechanics
electroweak
relativity
QED
electromagnetism
1900
1925
1950
1975
2000

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

field generates mass

of the charged fermions



a heavy particle...

mass*

*charged fermions and W/Z!

mass*

was born

in the Higgs Field

*charged fermions and W/Z!

what's challenging

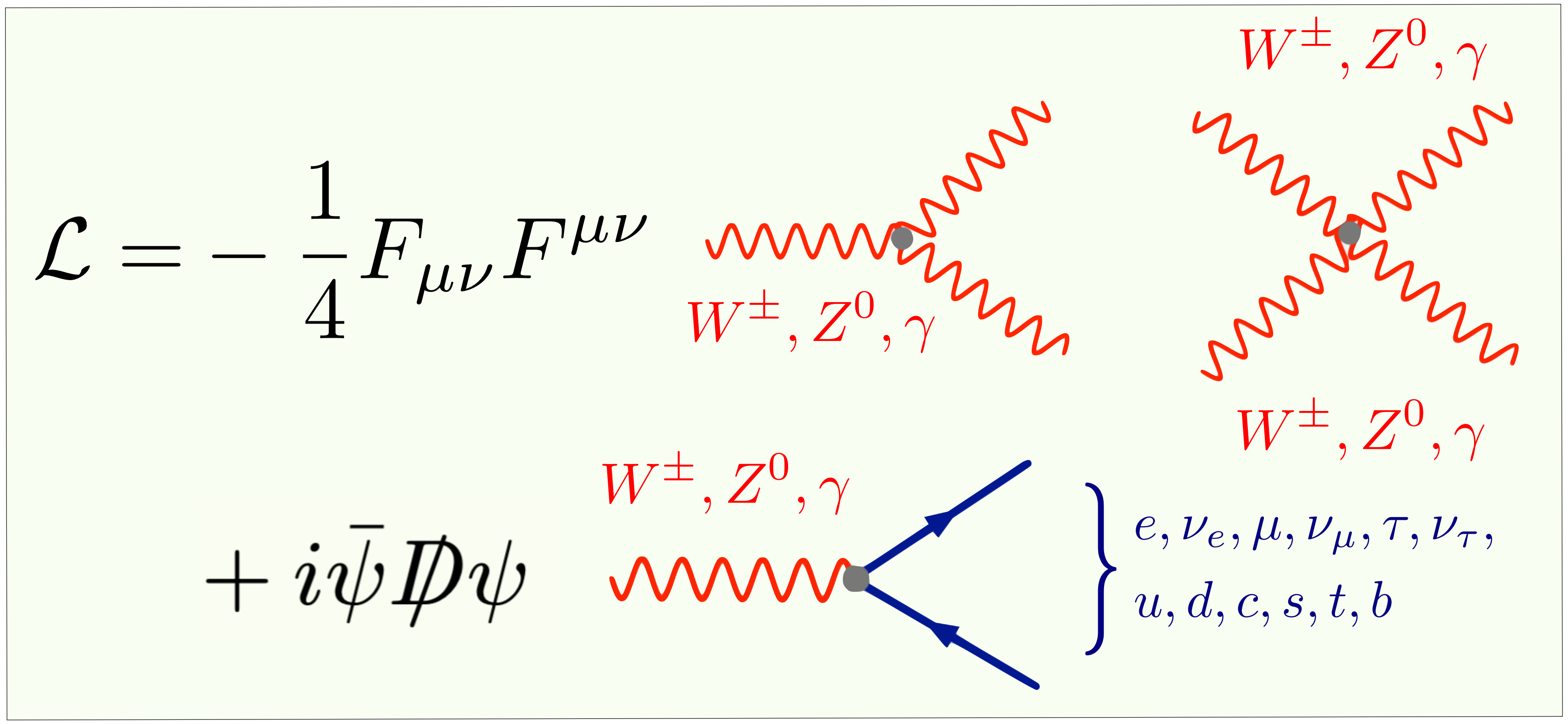
about the Standard Model?

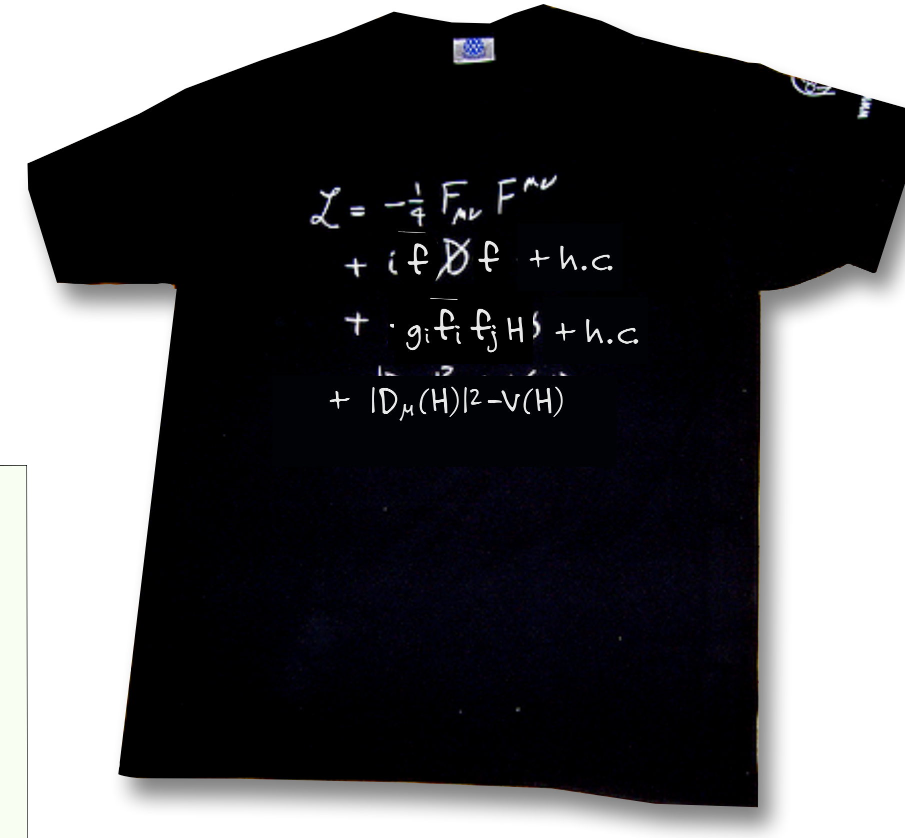
all things Higgs

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

Higgs Field piece:

- "Unfolds" rather neatly





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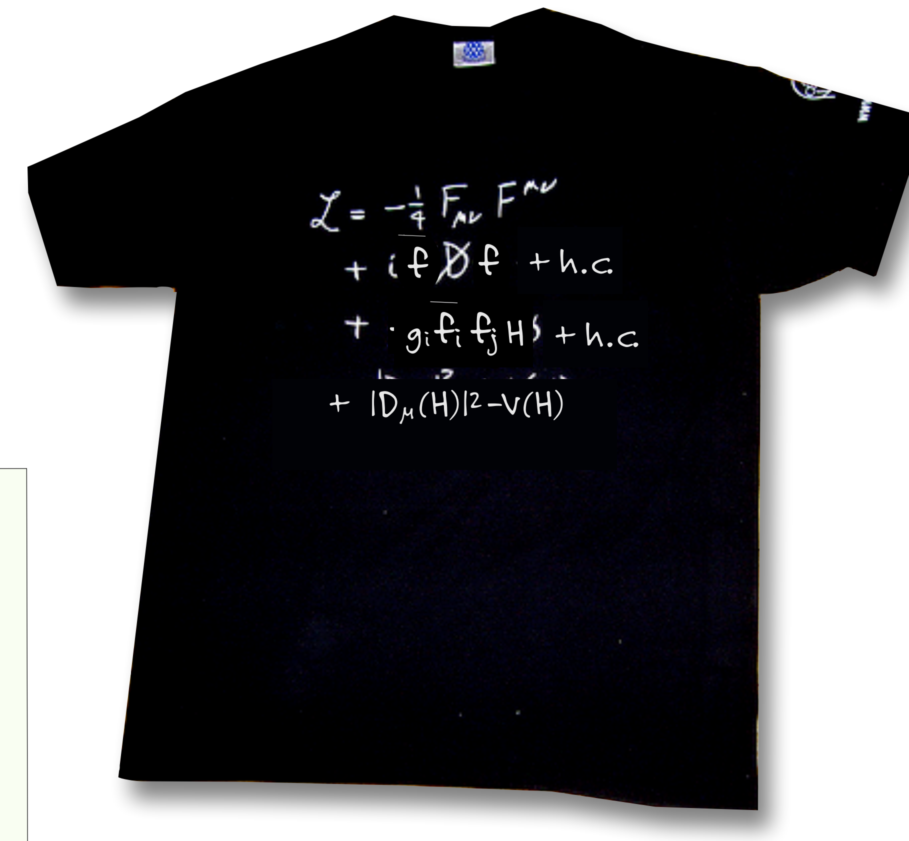

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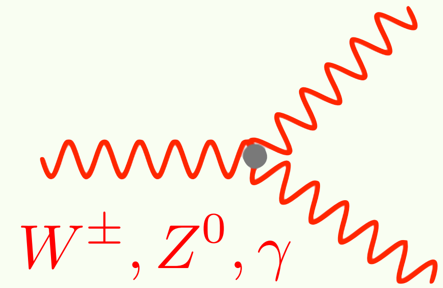

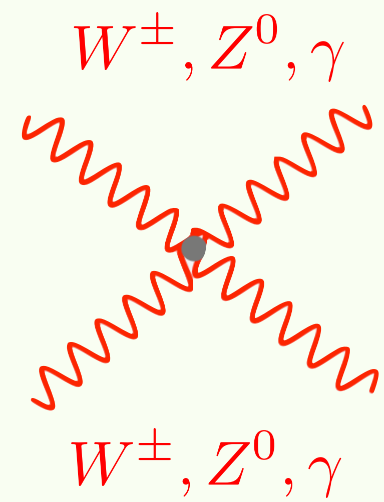

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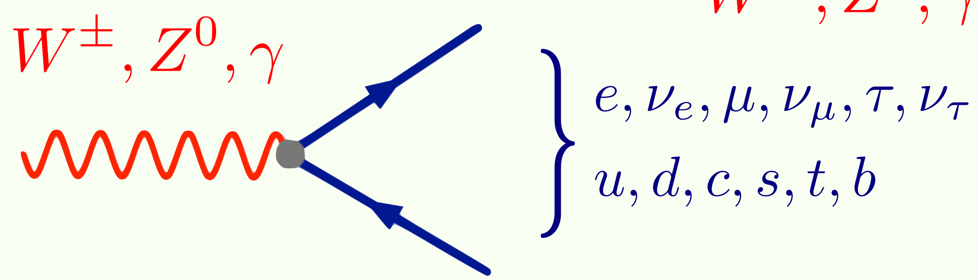

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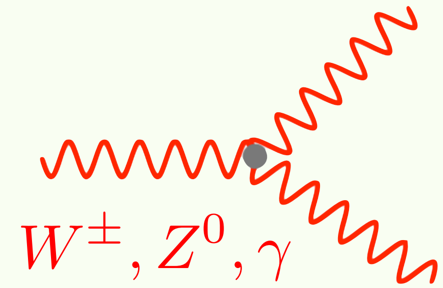

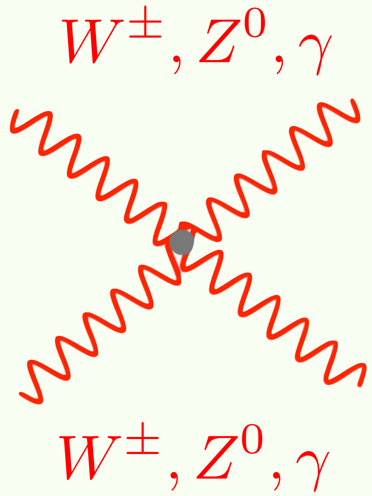

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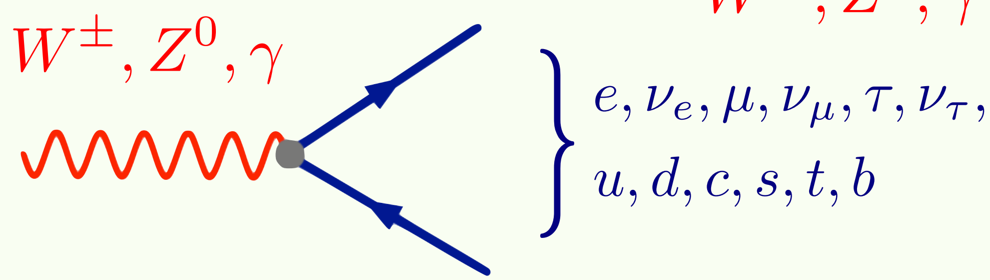

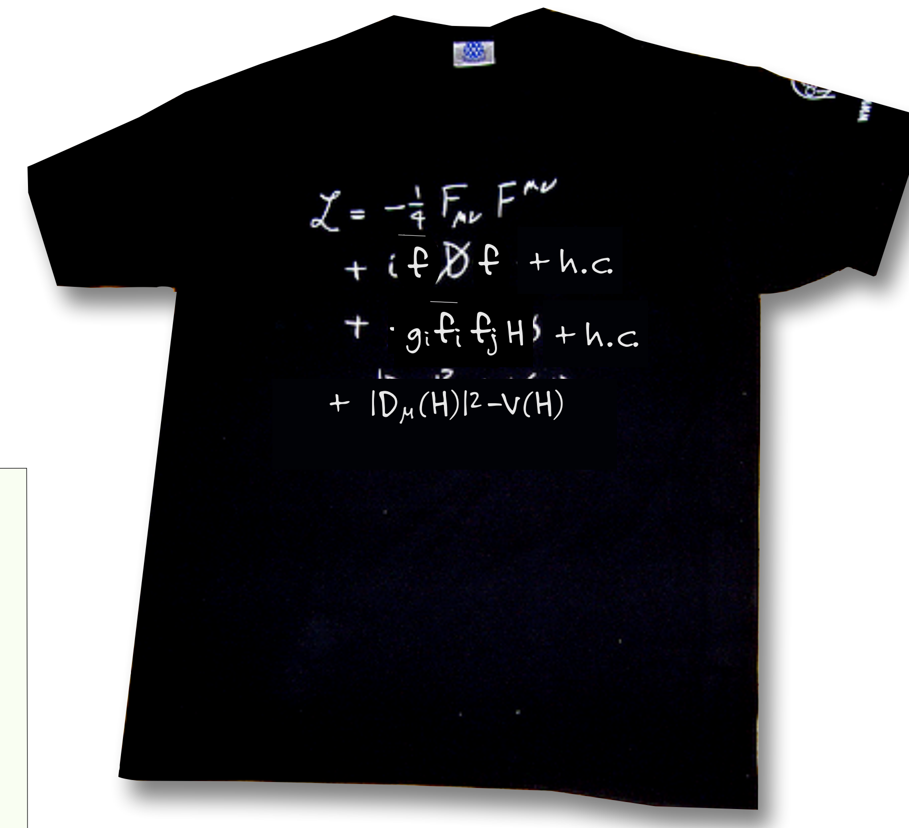

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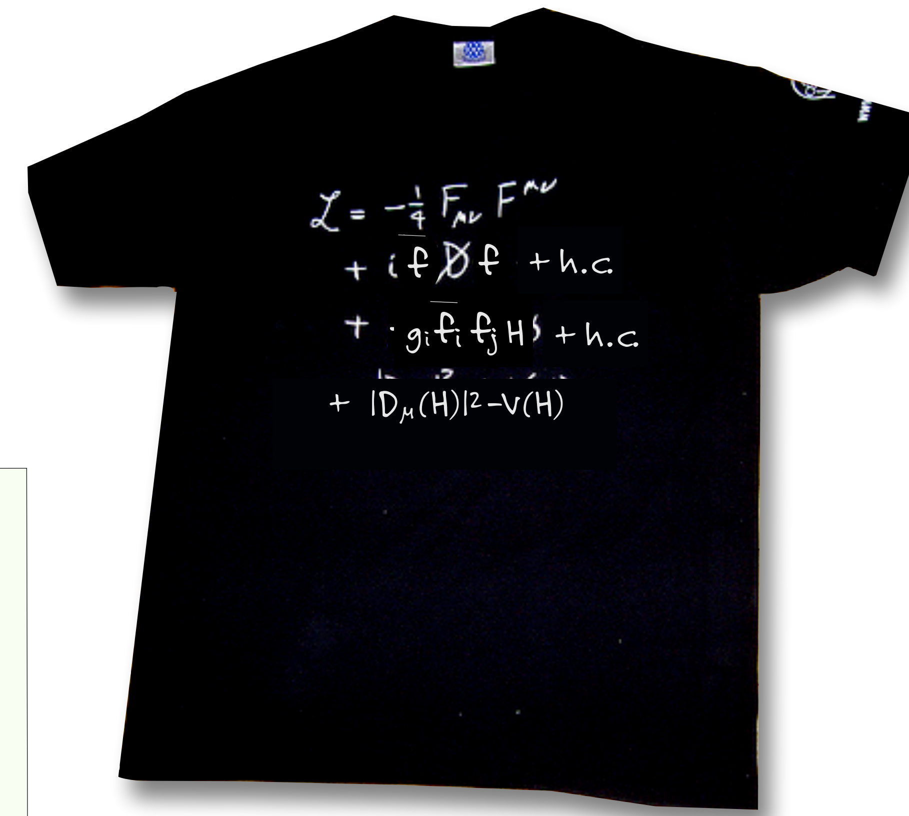

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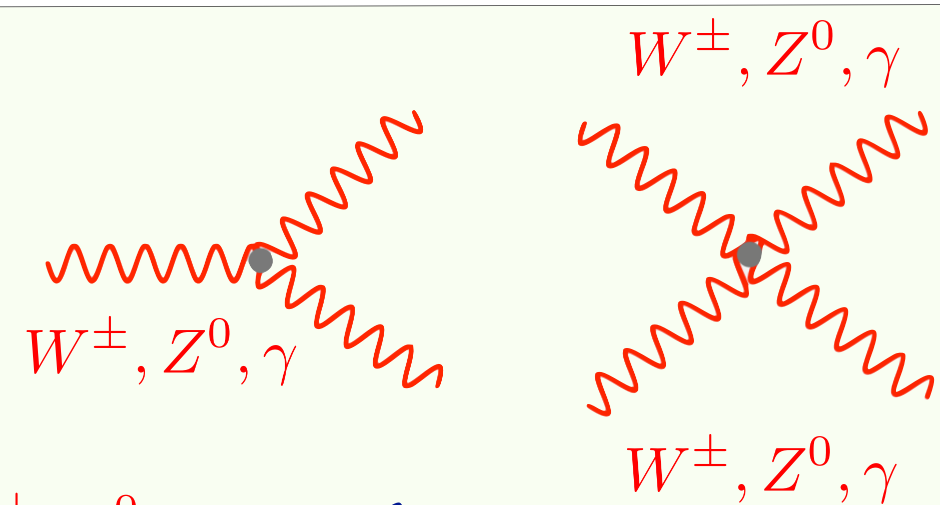

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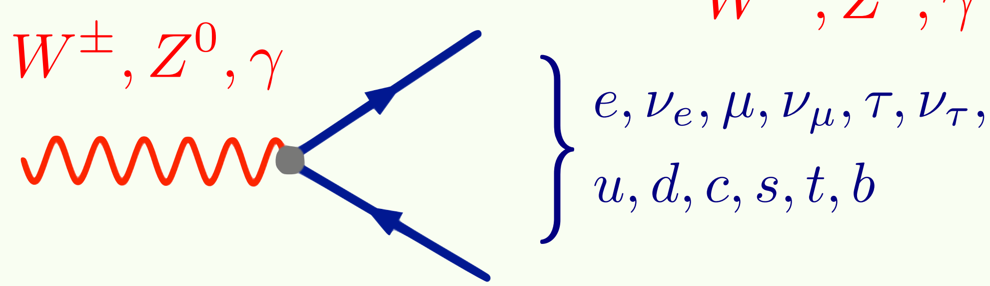

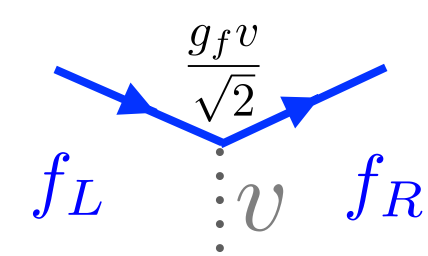

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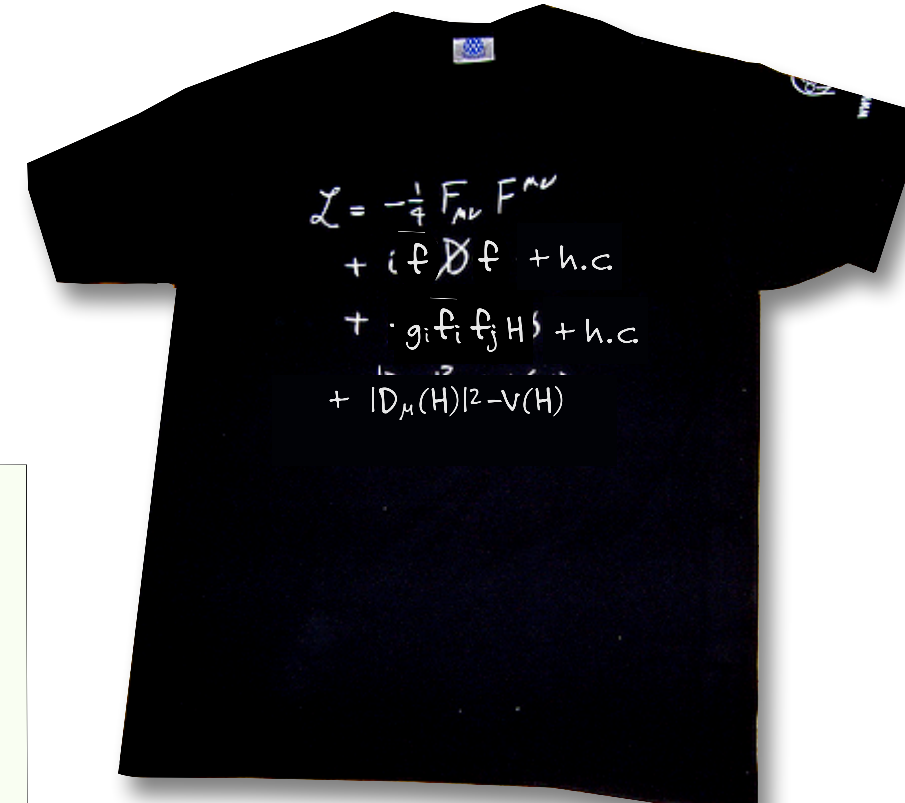

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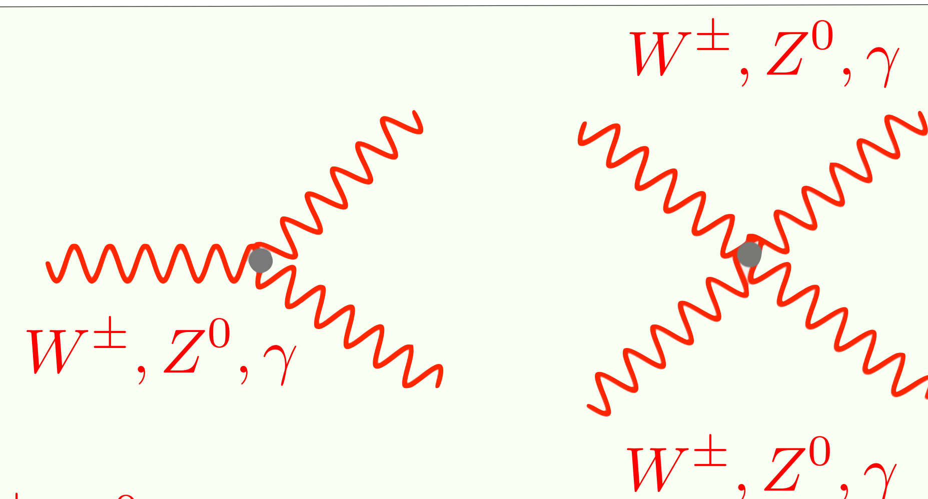

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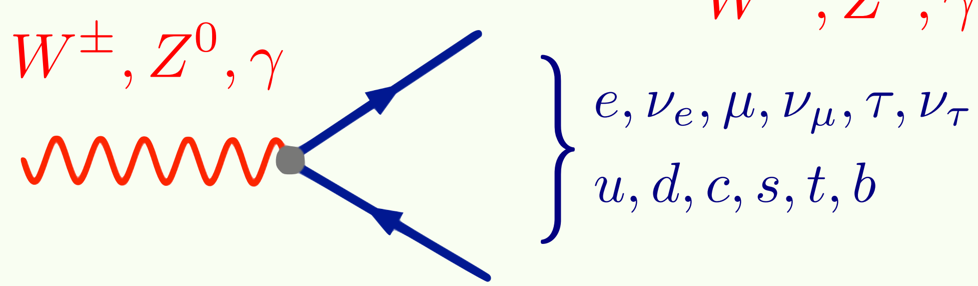

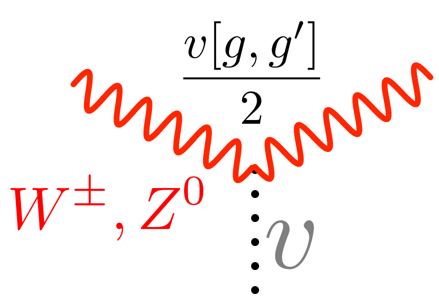

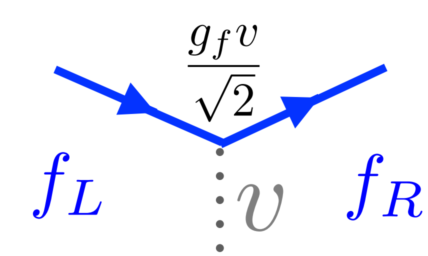

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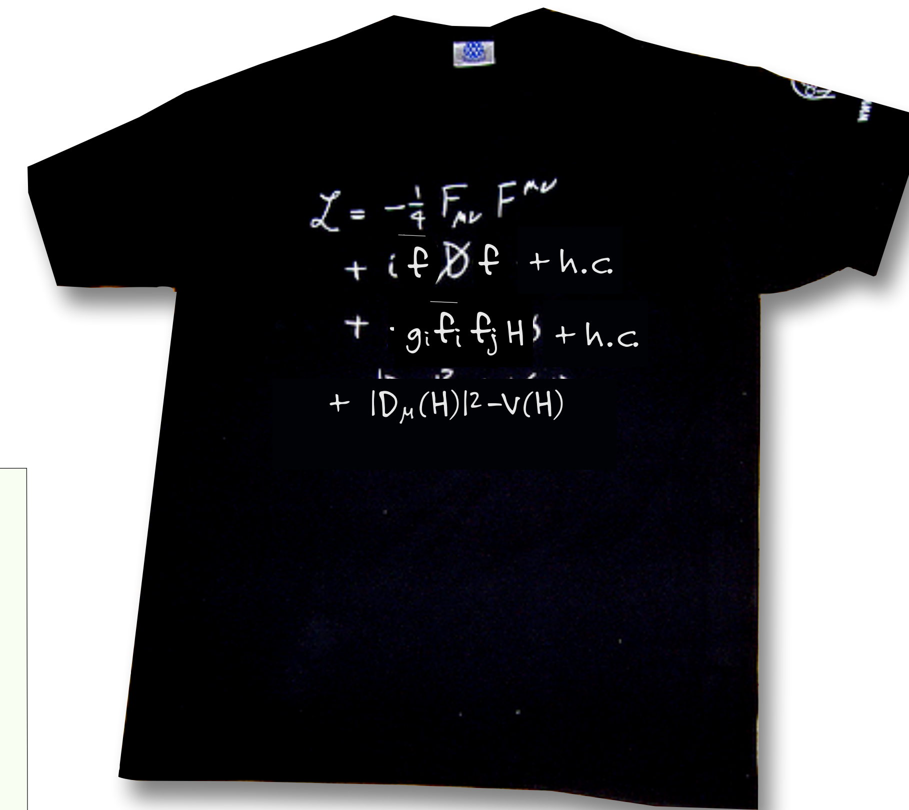

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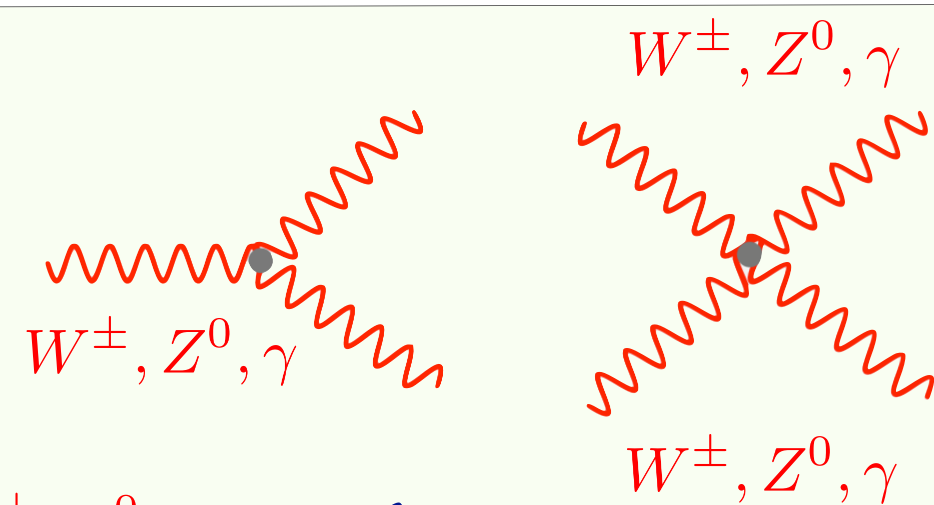

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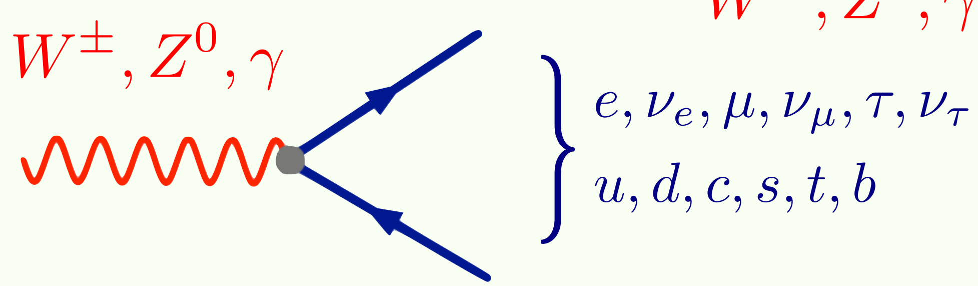

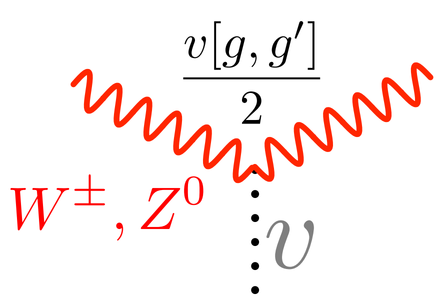

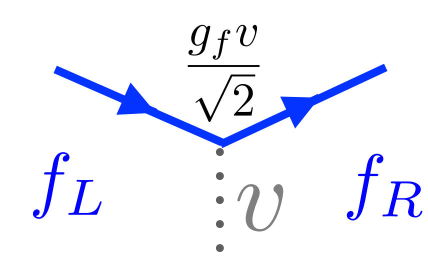

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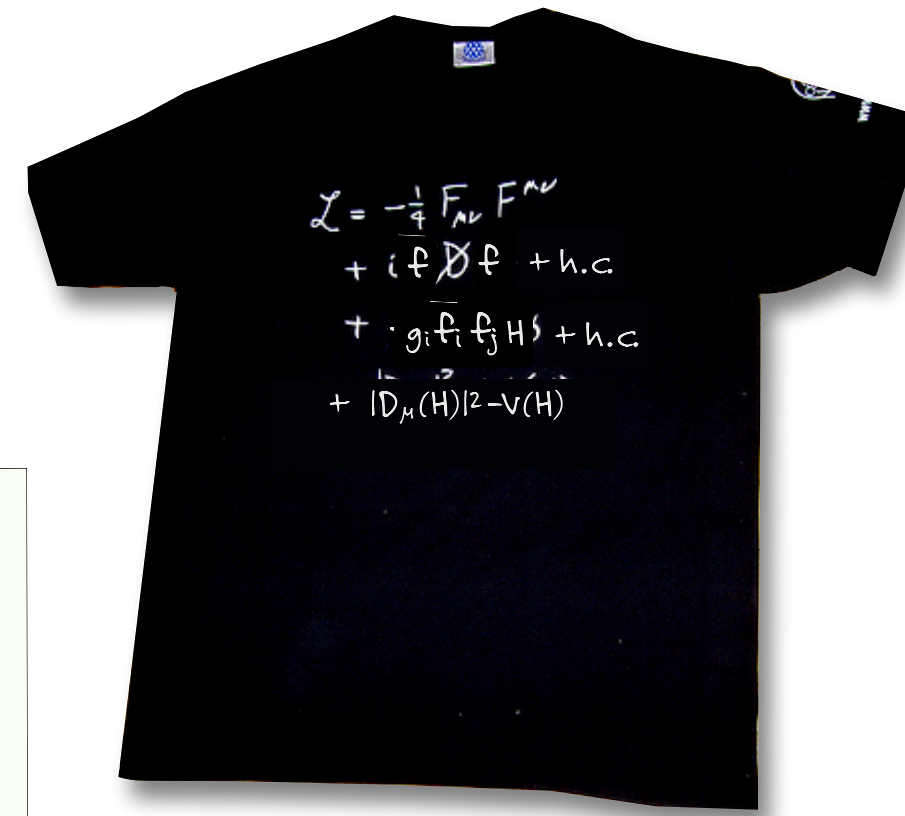

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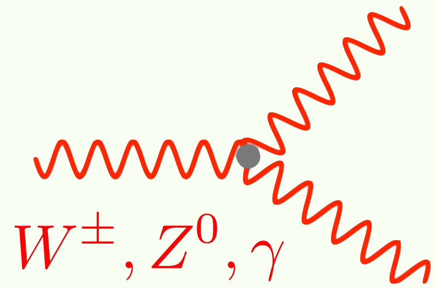

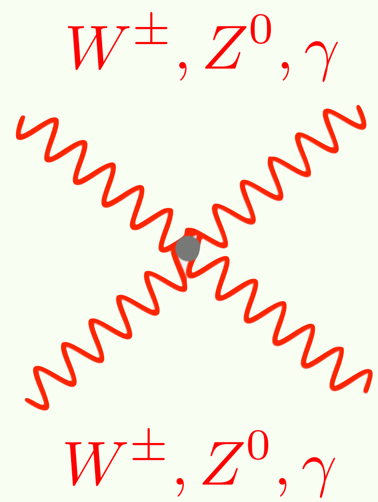

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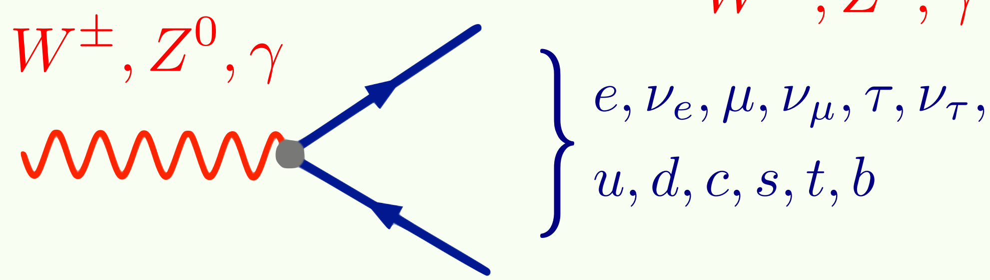

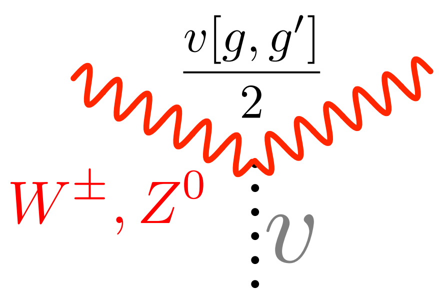

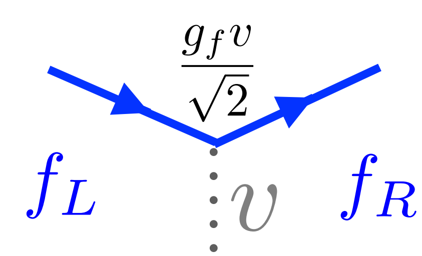

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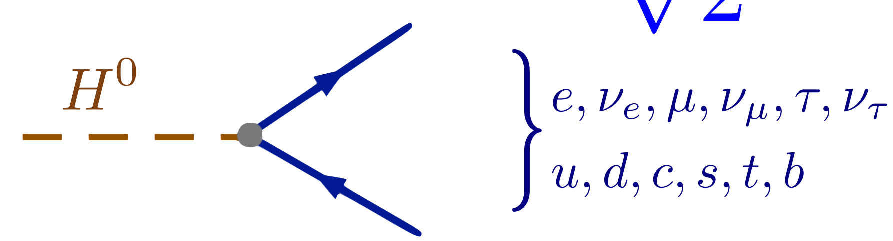

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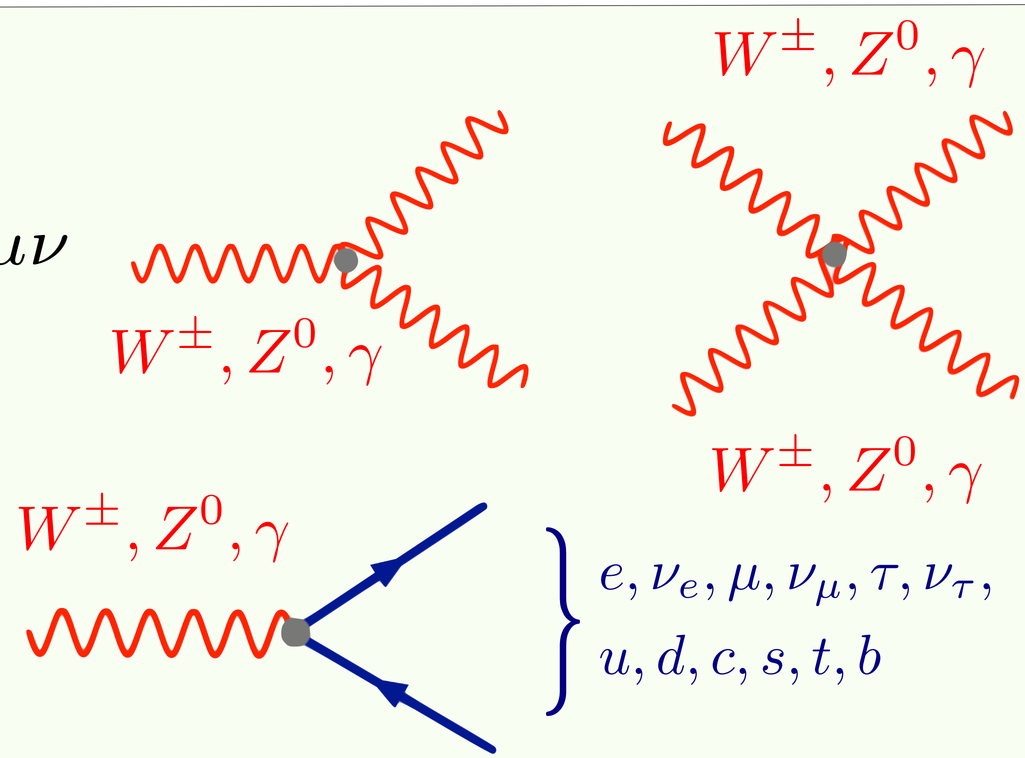

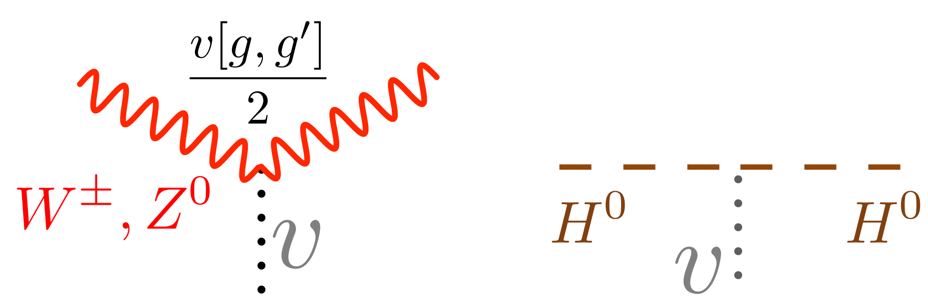

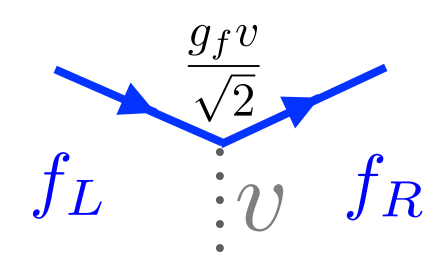

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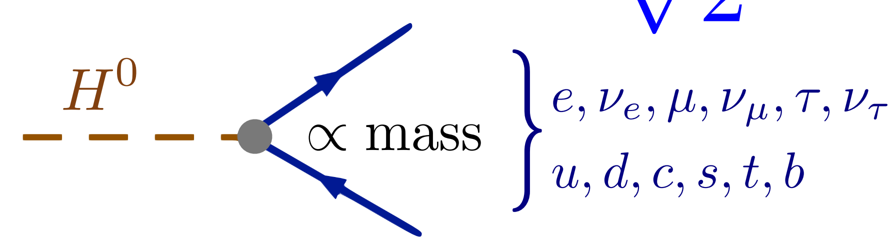

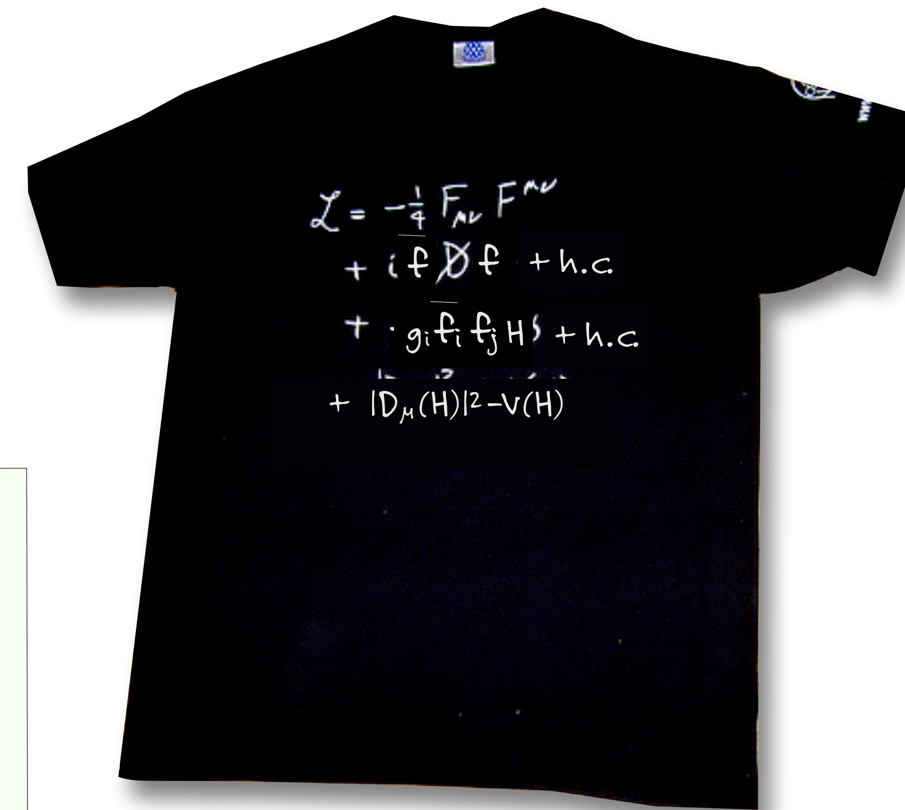

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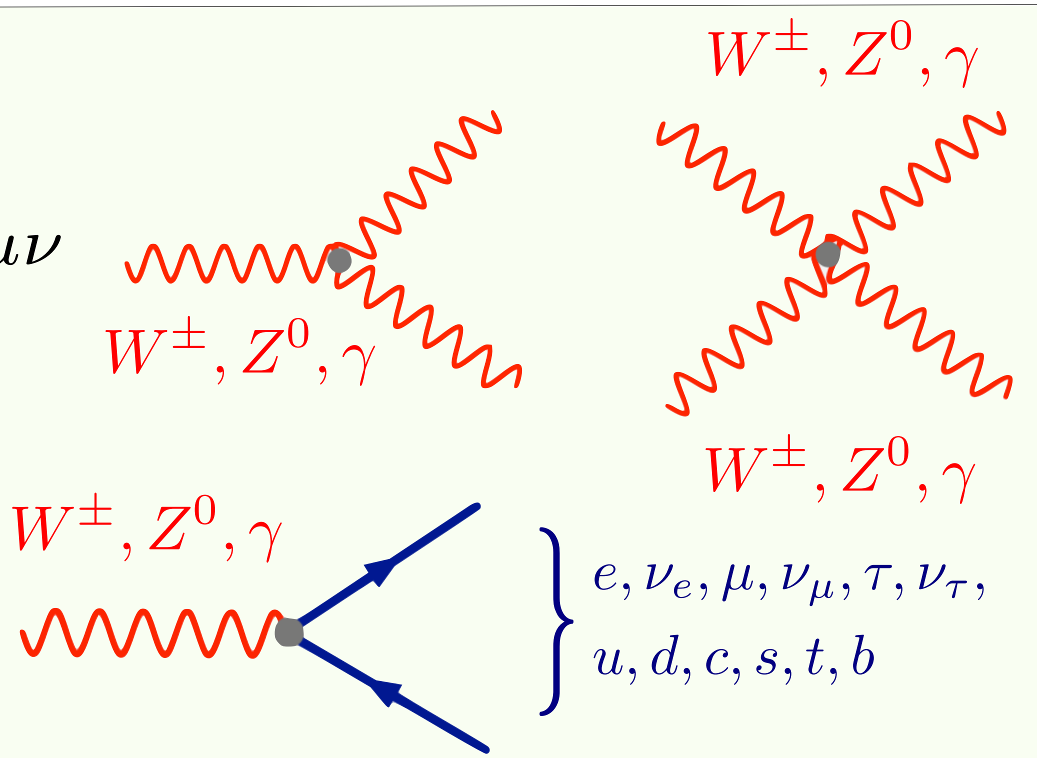

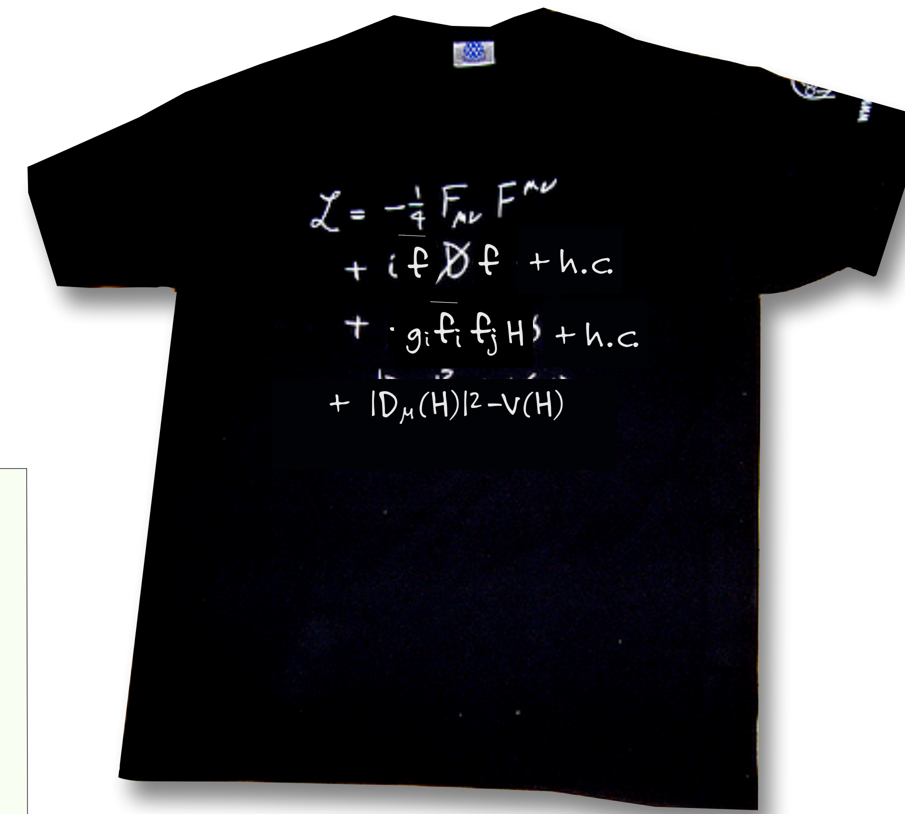

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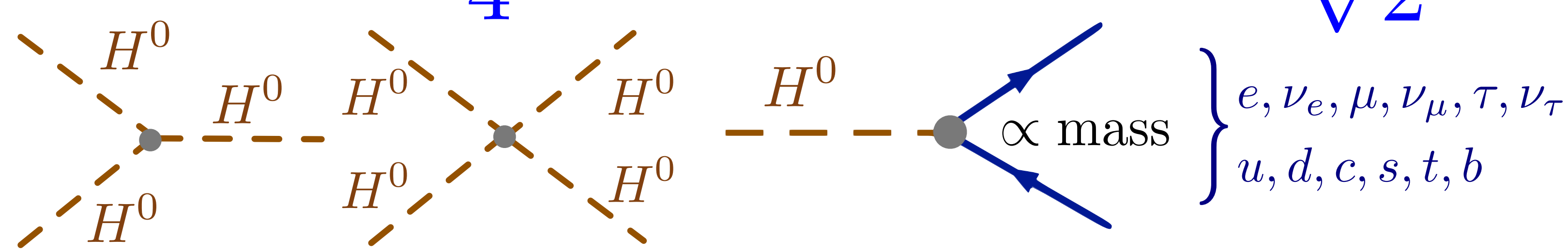

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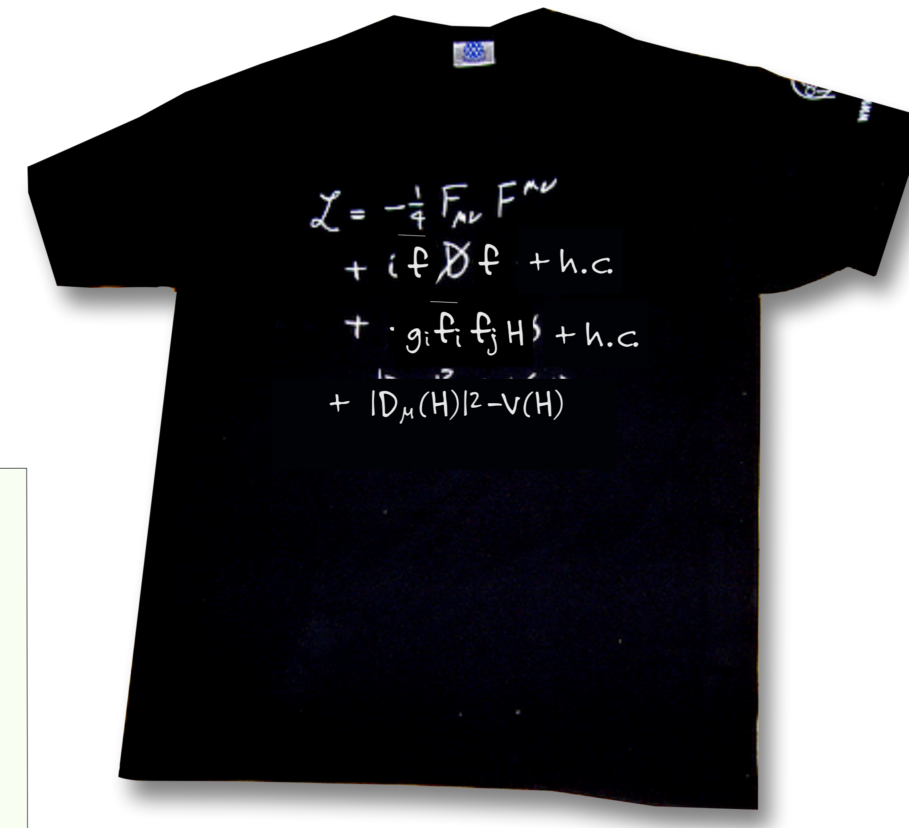

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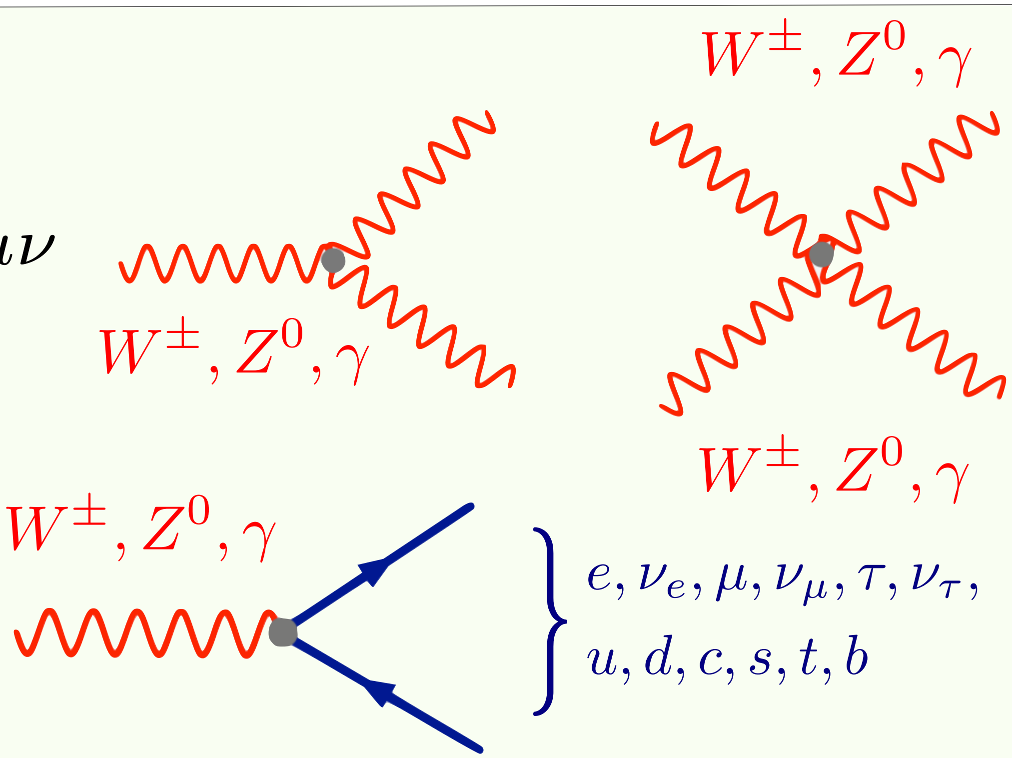

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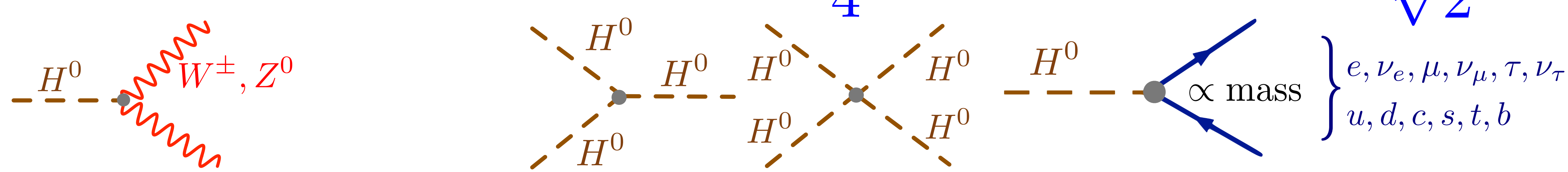
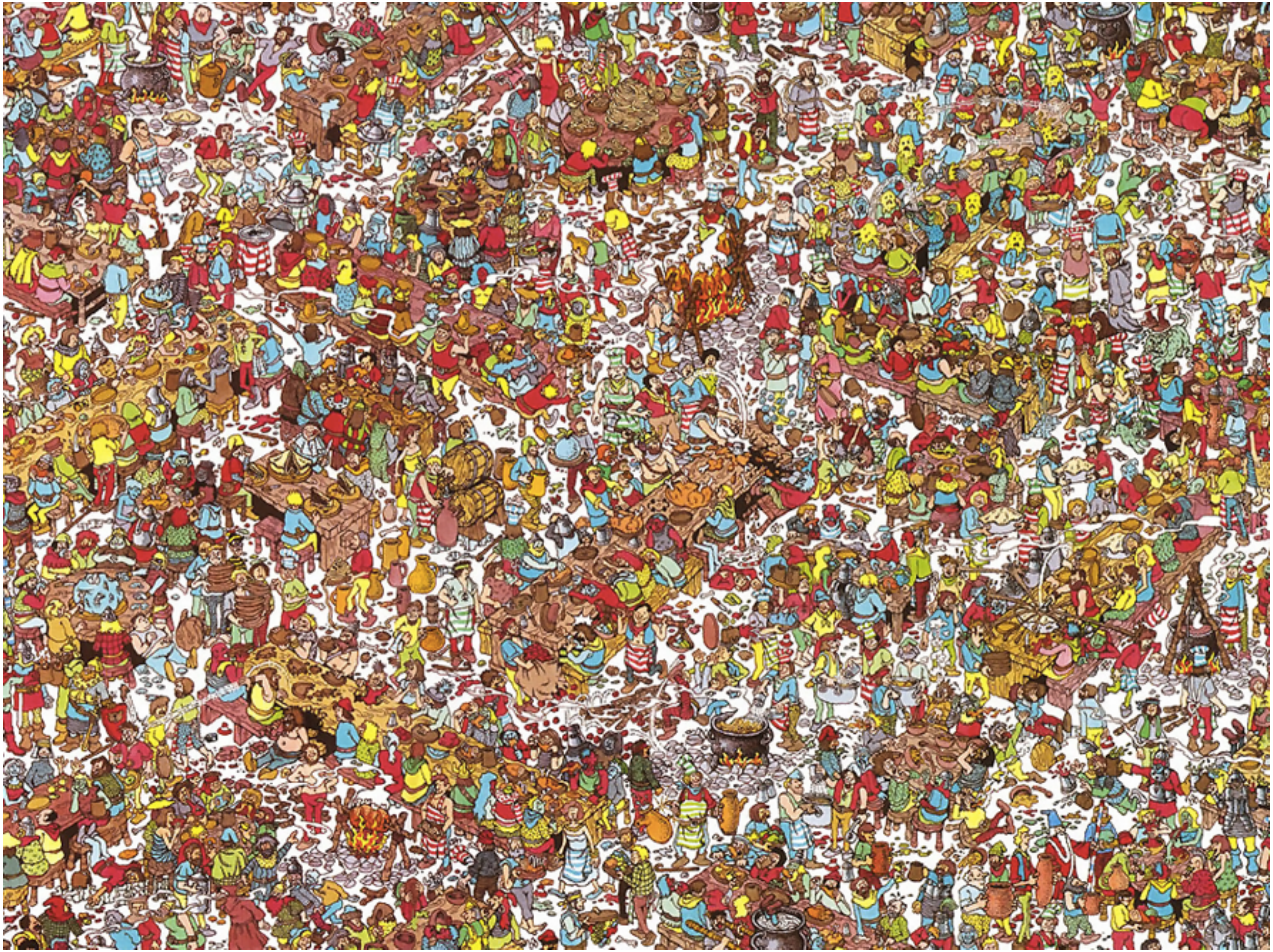


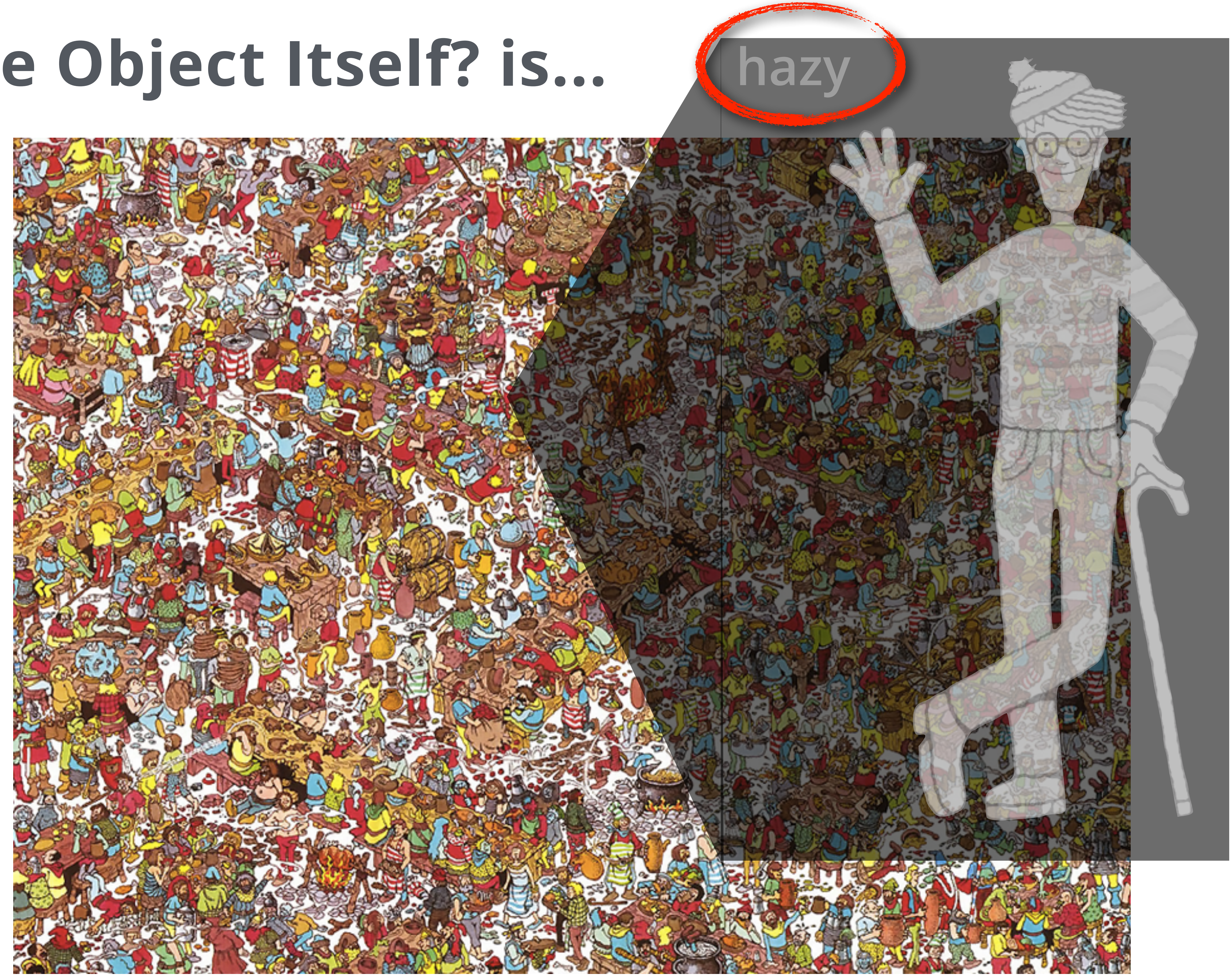
Let’s talk about the Higgs Boson.

What happened in July, 2012?

the Object Itself?



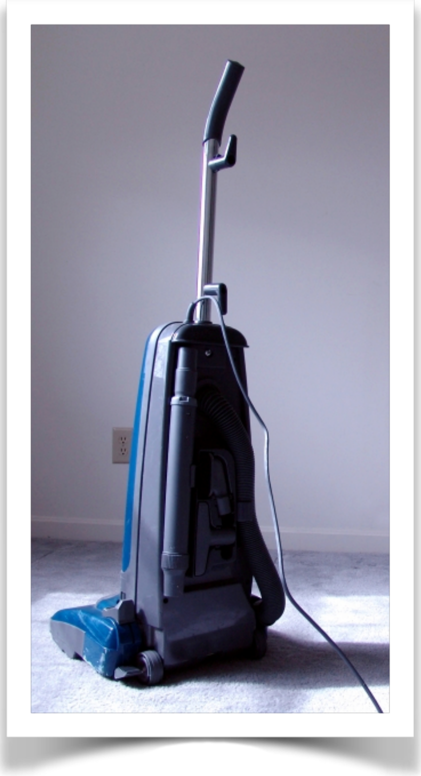
the Object Itself? is...



Higgs particle

strange.

- **quantum numbers of the vacuum**



How many things are only one thing?

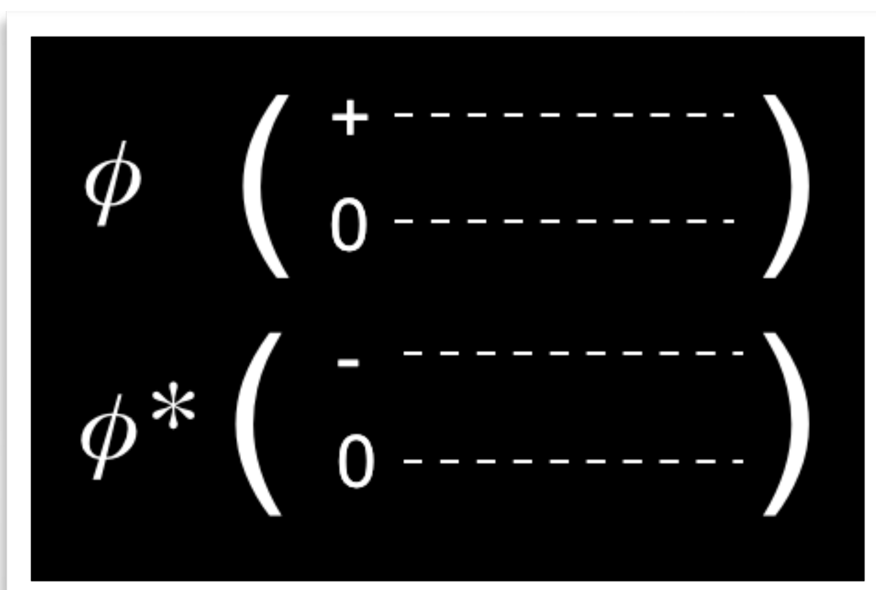
$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

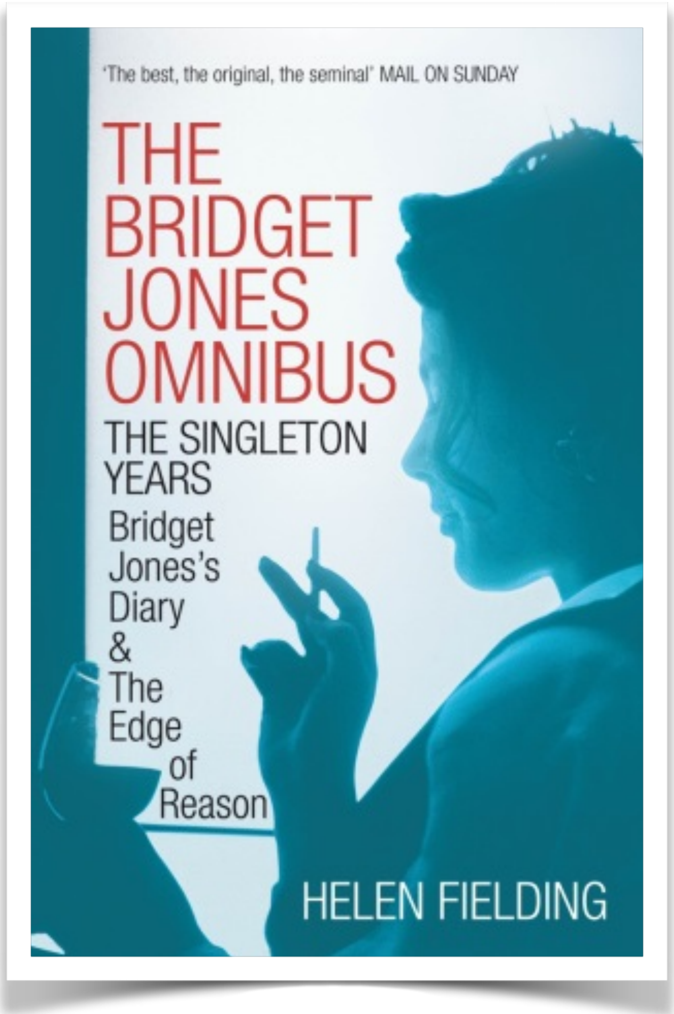
$$W^\pm, Z^0, \gamma, g$$

- **an elementary *singlet***

- or part of a ***doublet***



- an elementary *singleton*?



Much confusion centers on

- the "Higgs" Potential.

  Our future mission: to unpack it.

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

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vacuum energy

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vacuum energy

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- vacuum energy
- Higgs mass
- Higgs potential shape
- fermion couplings

loops

loops

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vacuum energy

Higgs mass

instability?

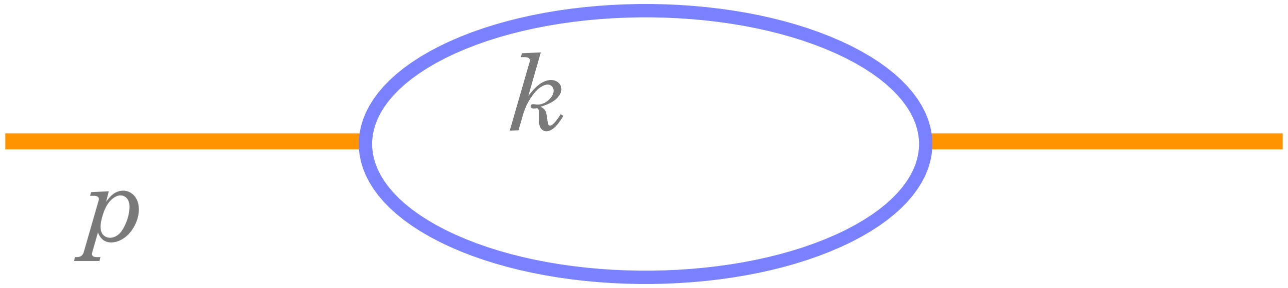
fermion couplings

in relativistic quantum field theory

- the Feynman rules:

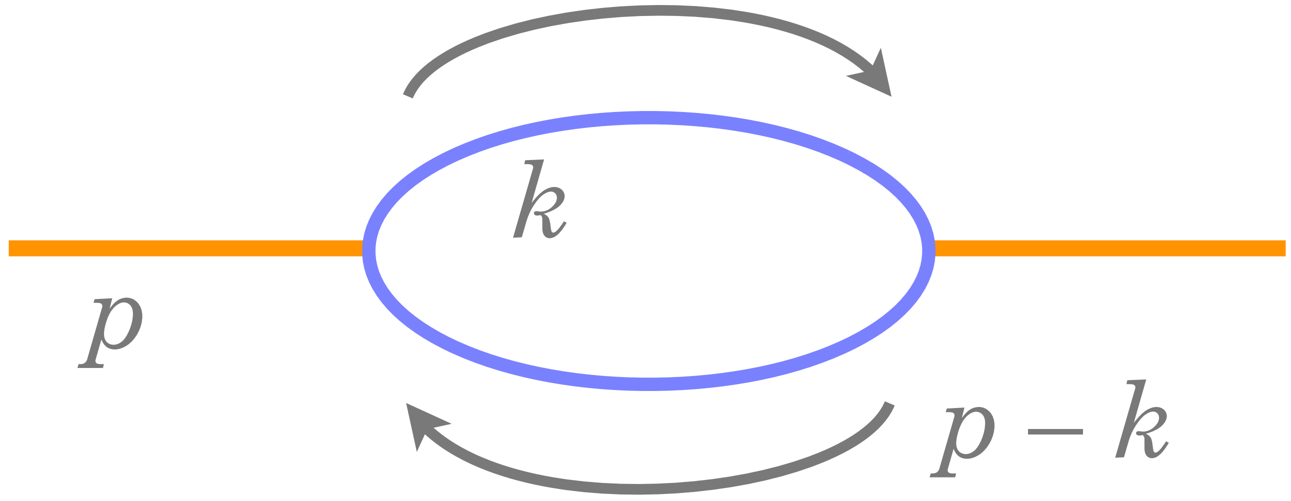
in relativistic quantum field theory

- the Feynman rules:



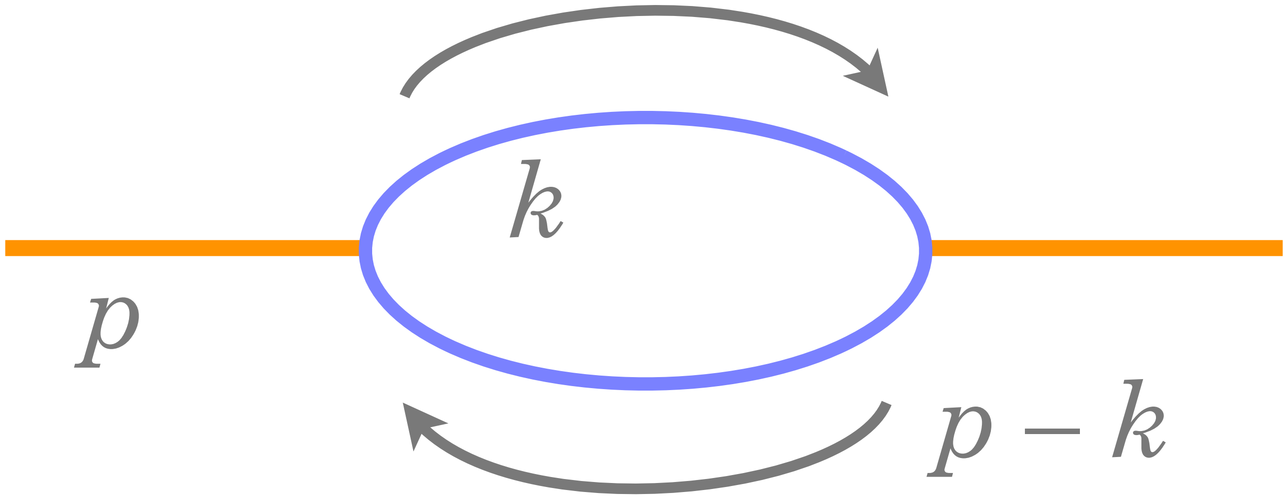
in relativistic quantum field theory

- the Feynman rules:



in relativistic quantum field theory

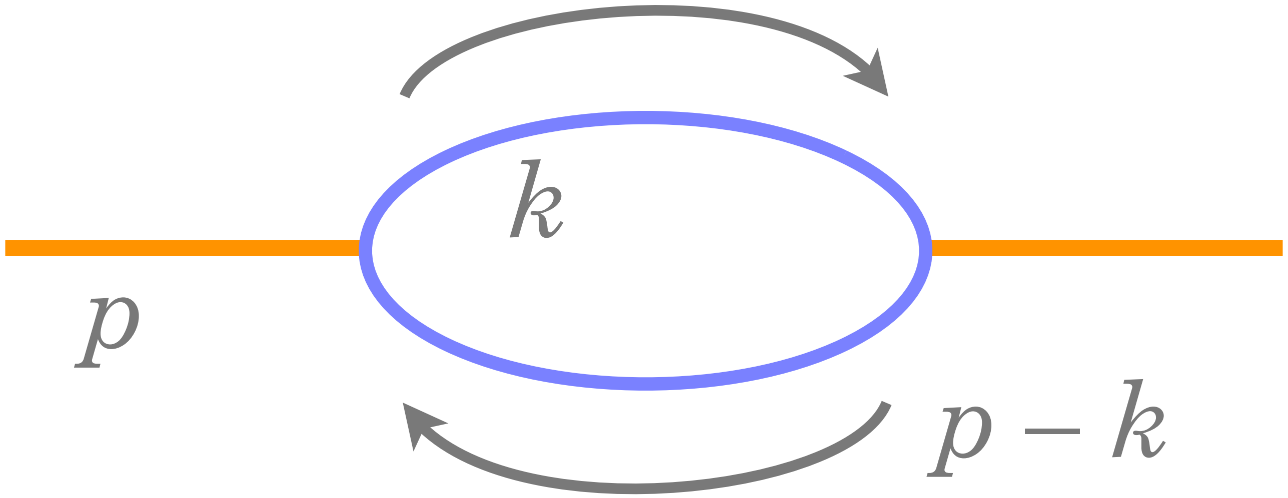
- the Feynman rules:



$$\int_0^\Lambda dk \text{ (all known particles)}$$

in relativistic quantum field theory

the Feynman rules:



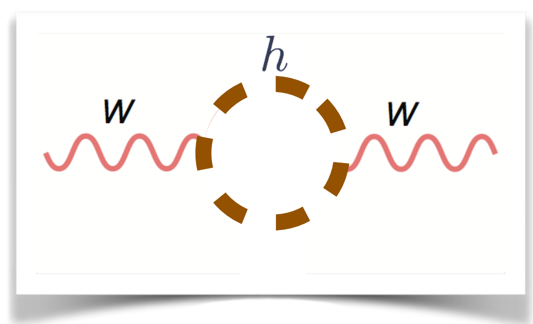
$$\int_0^\Lambda dk\ (\text{all known particles}) + \int_0^\Lambda dk\ (\text{all } \textit{un}\text{-known particles})$$

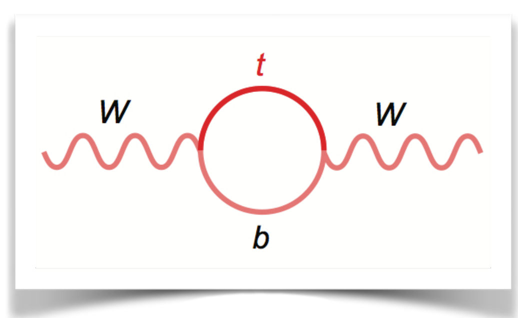
not mysticism

- "Loops" are at the core of our language

  traditionally highly predictive

  highly accurate





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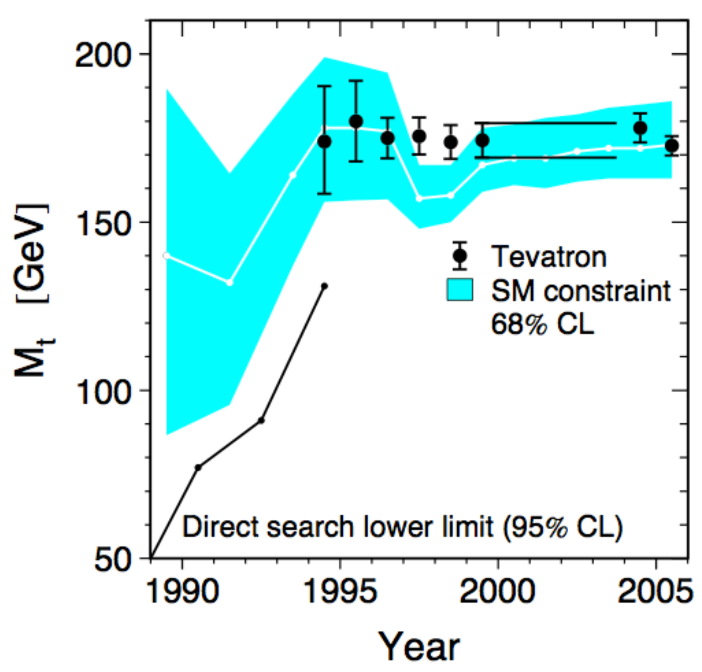

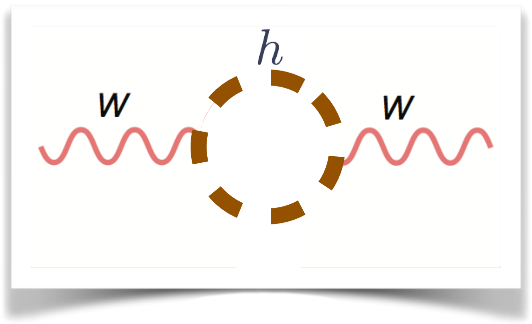

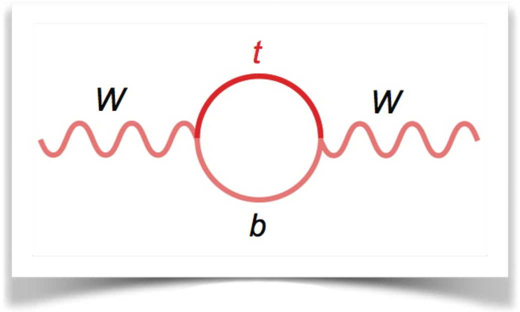

EW fits: top quark

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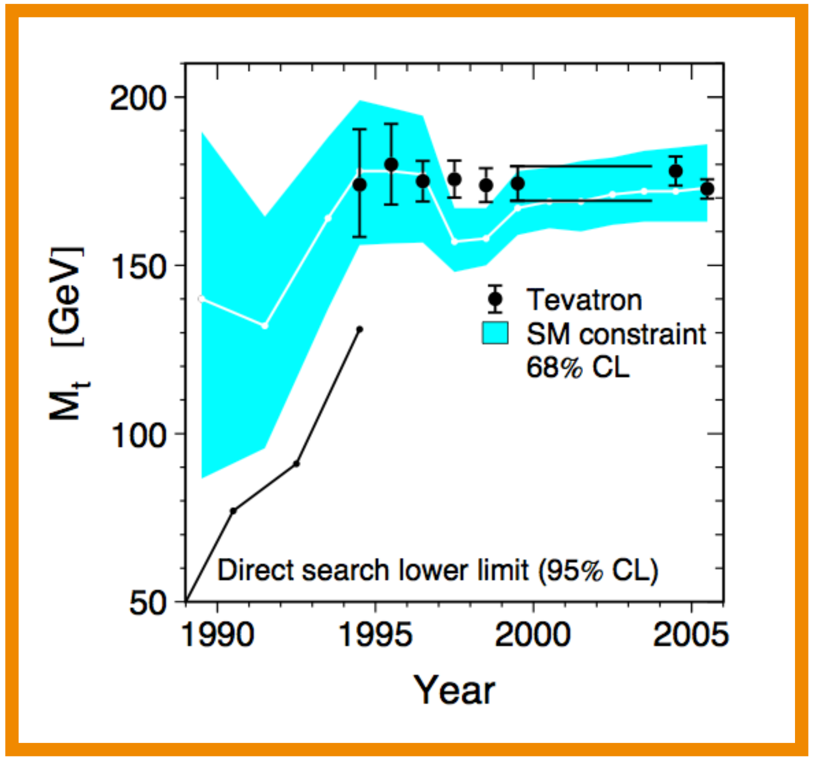

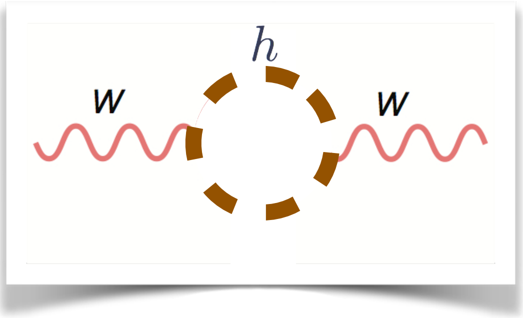

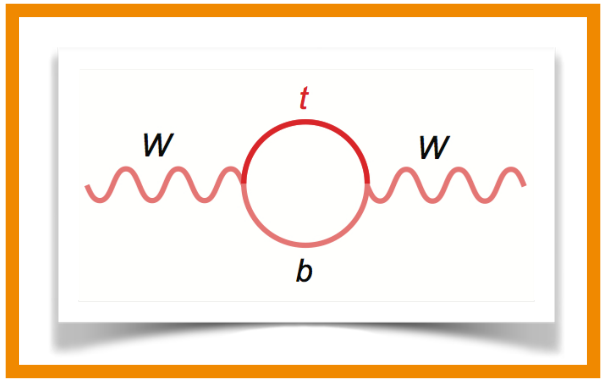

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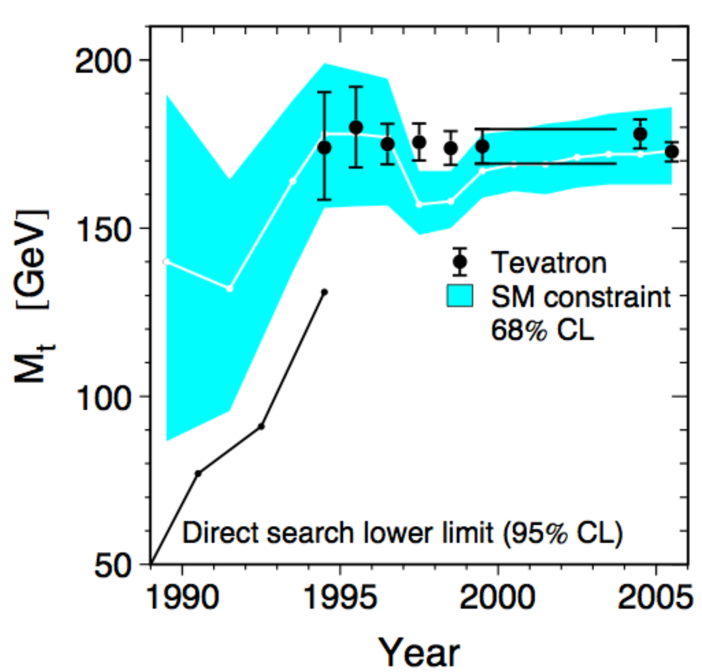

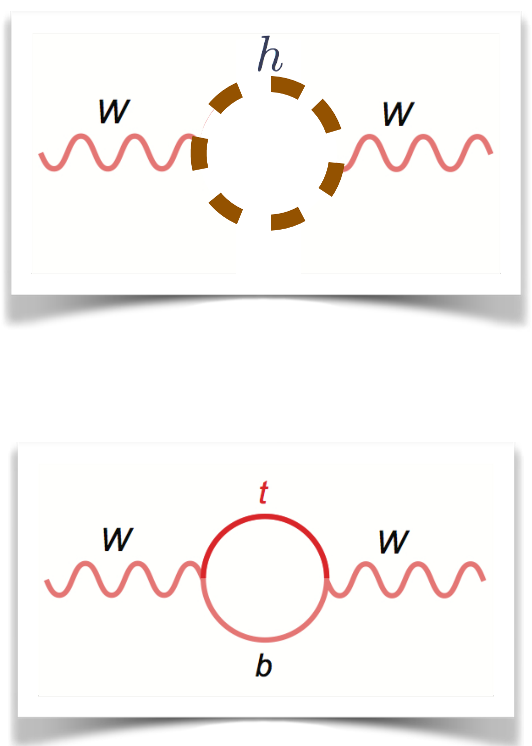

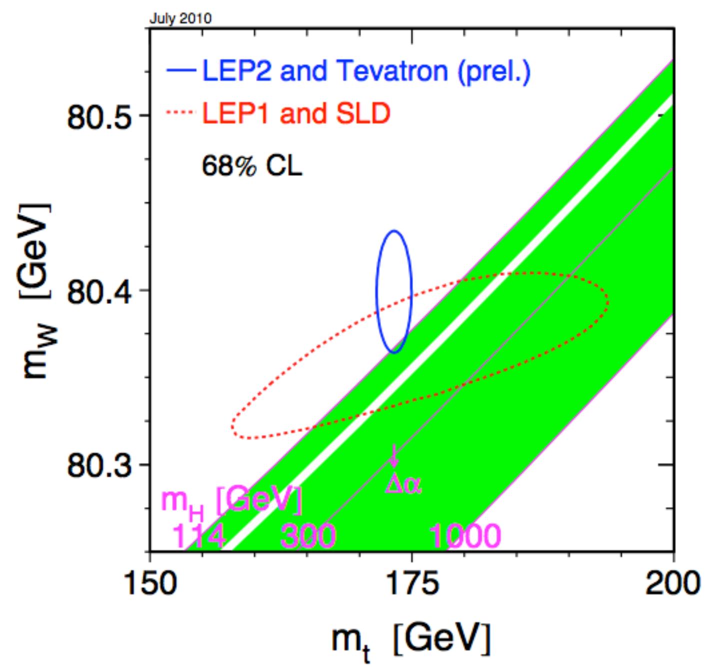

EW fits: top quark

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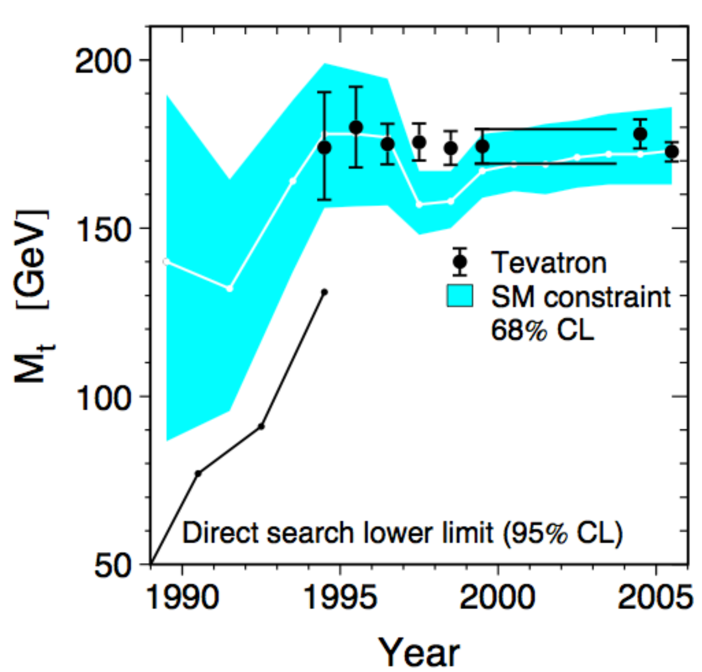
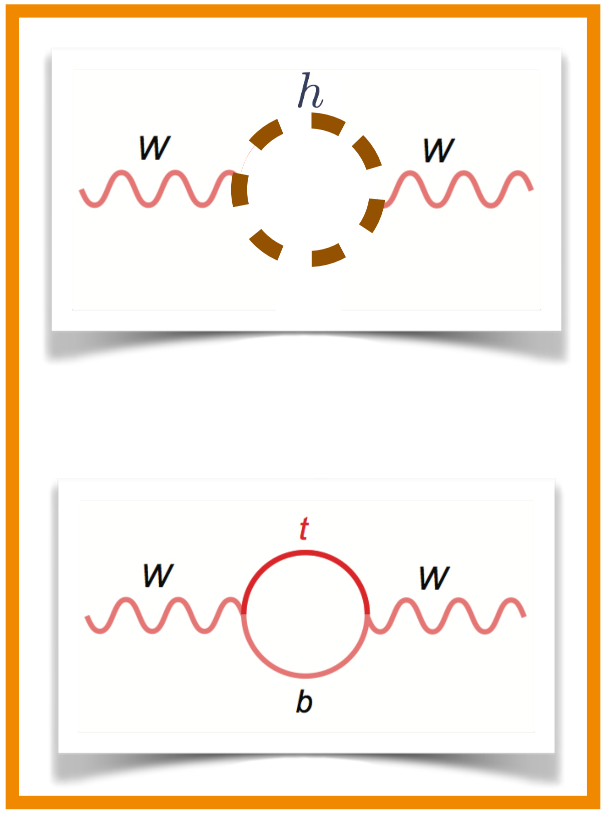
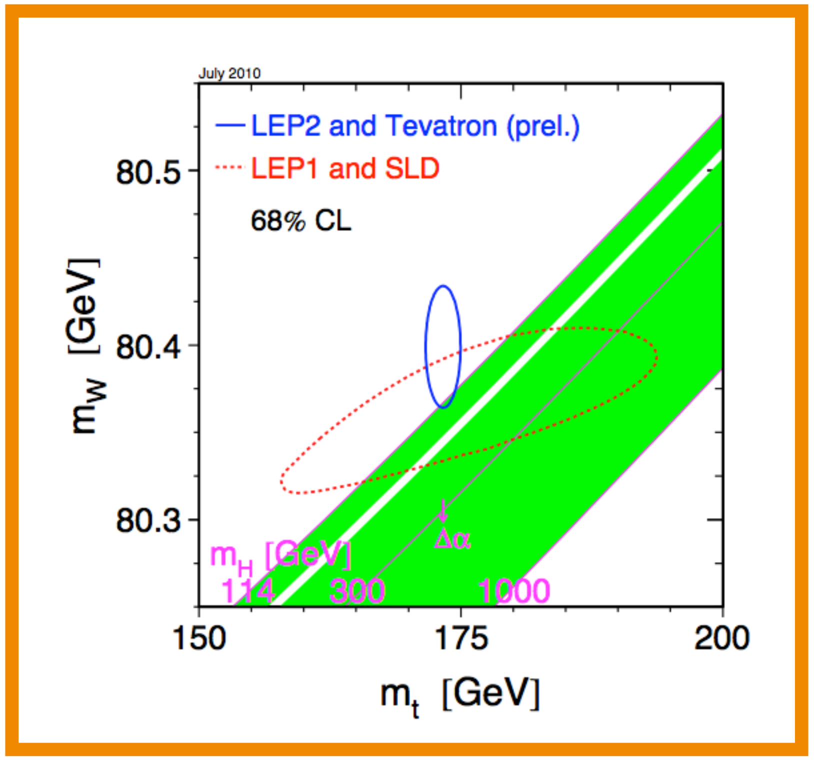






EW fits: top quark

EW fits: Higgs boson

How about

- a spin 0, elementary particle?

First-ever spin 0 elementary particle.

$$V = \boxed{\lambda v^2 H^2}$$

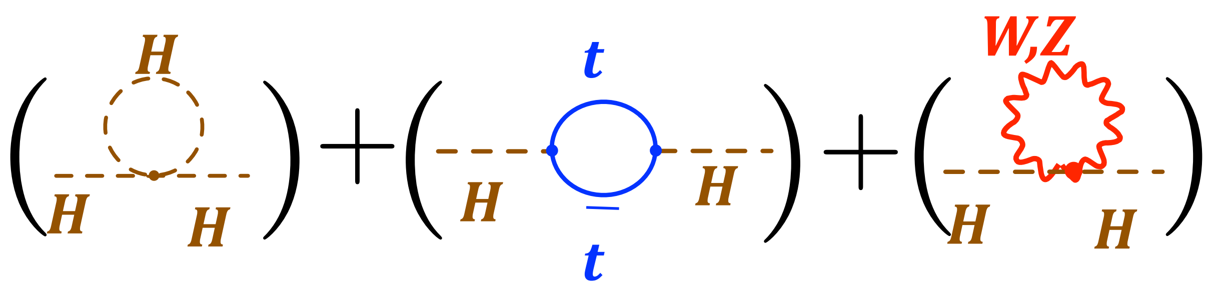
$$M_H^2 = M_{\text{tree}}^2 + \ \delta M^2$$

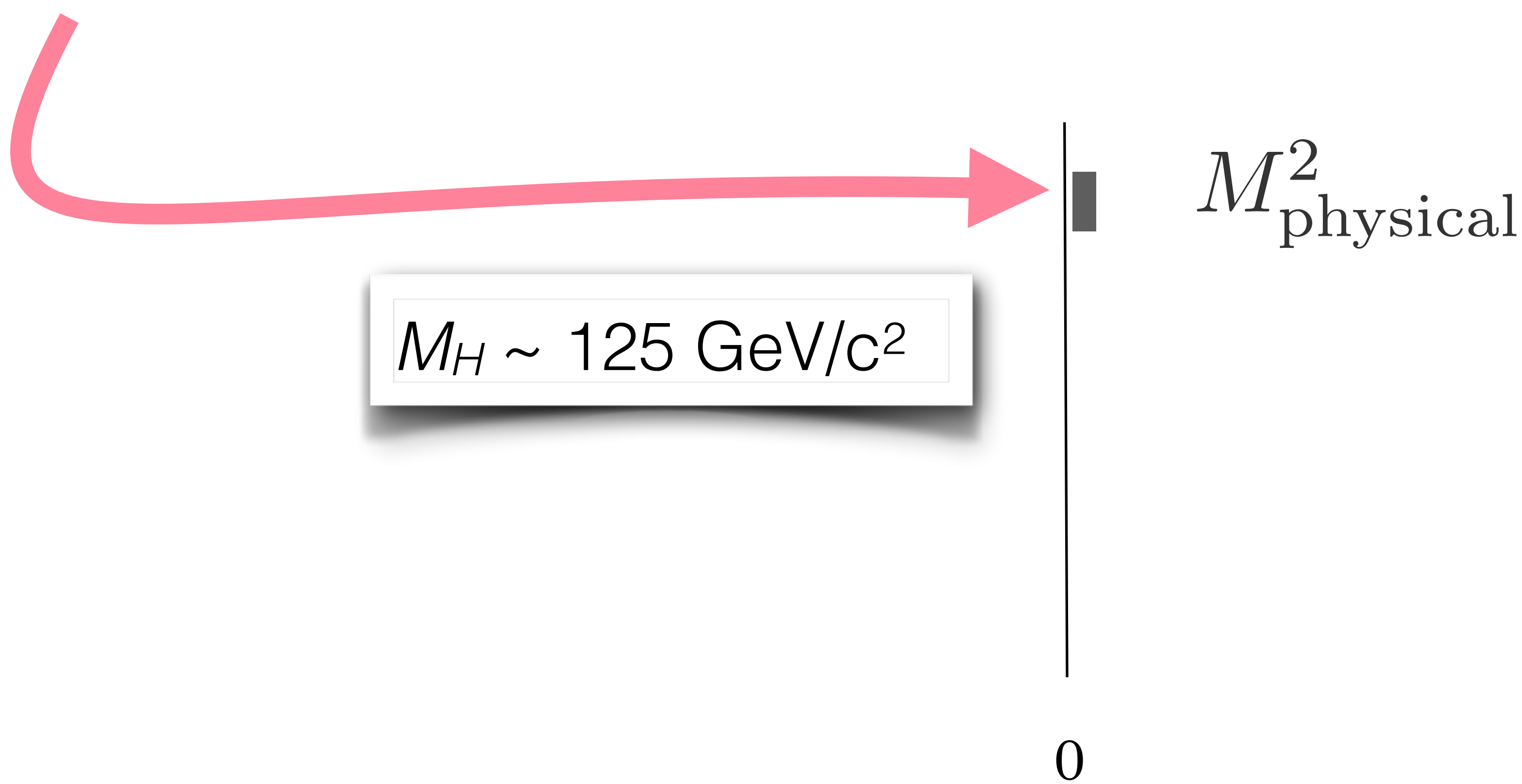
$$\delta M^2 \propto \frac{c}{16\pi^2} g^2 \Lambda^2$$

3 kinds of loops

$$V = \boxed{\lambda v^2 H^2}$$

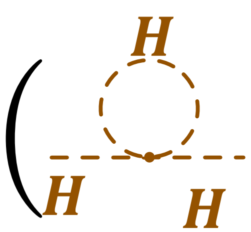
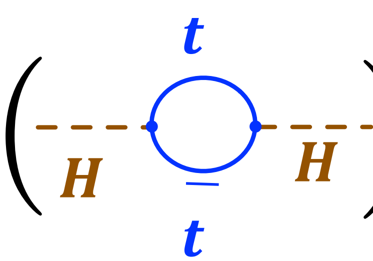
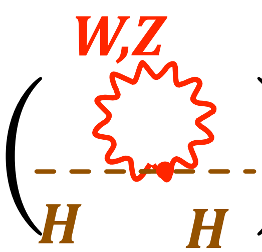
$$M_H^2 = M_{\text{tree}}^2 + (\ldots) + (\ldots) + (\ldots)$$

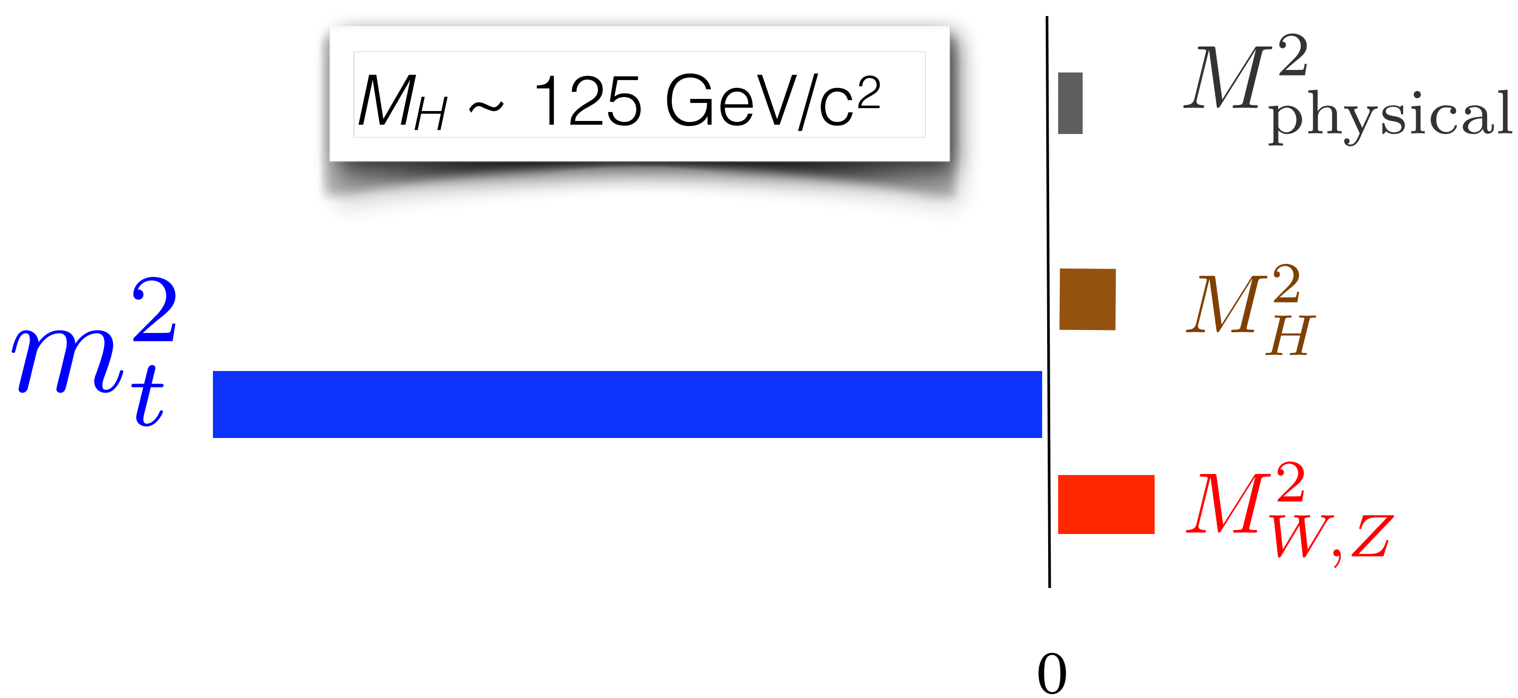




Top loop is big and negative

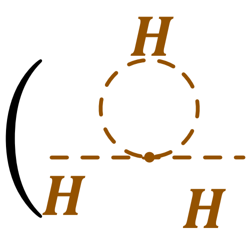
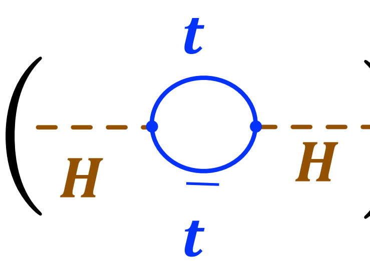
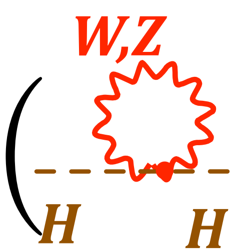
$$V = \boxed{\lambda v^2 H^2}$$

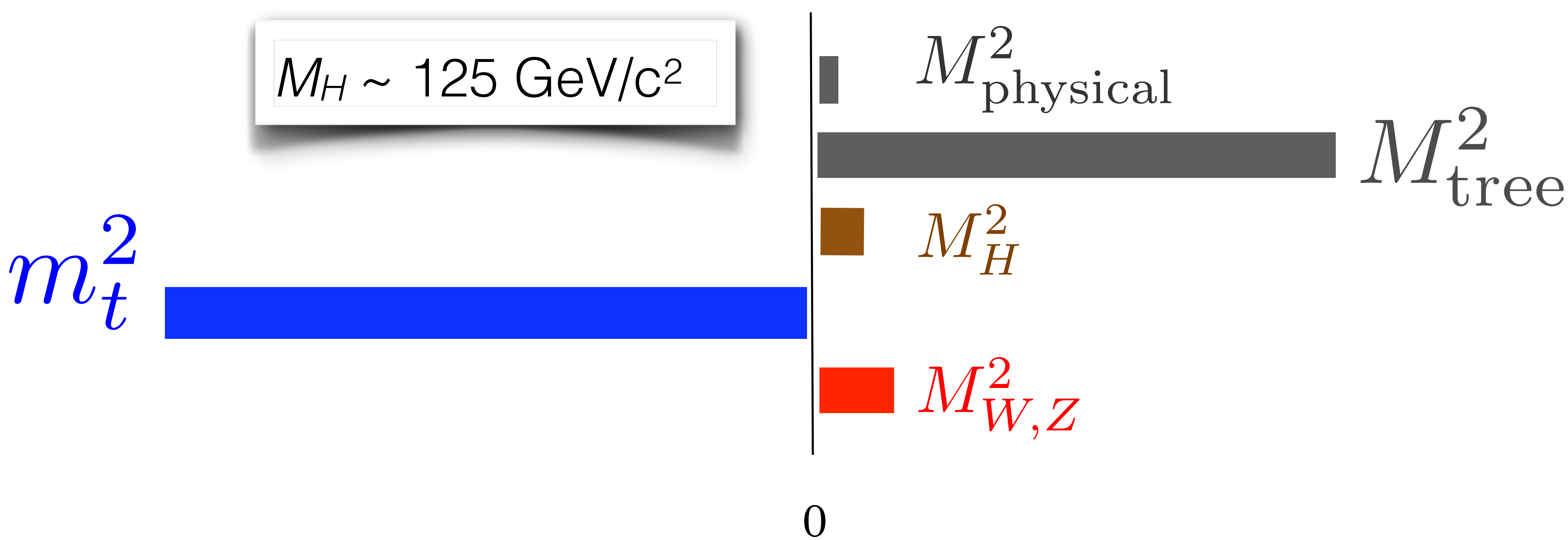
$M_H^2 = M_{\text{tree}}^2 + ($  $) + ($  $) + ($  $)$



Requiring a large, opposing tree value

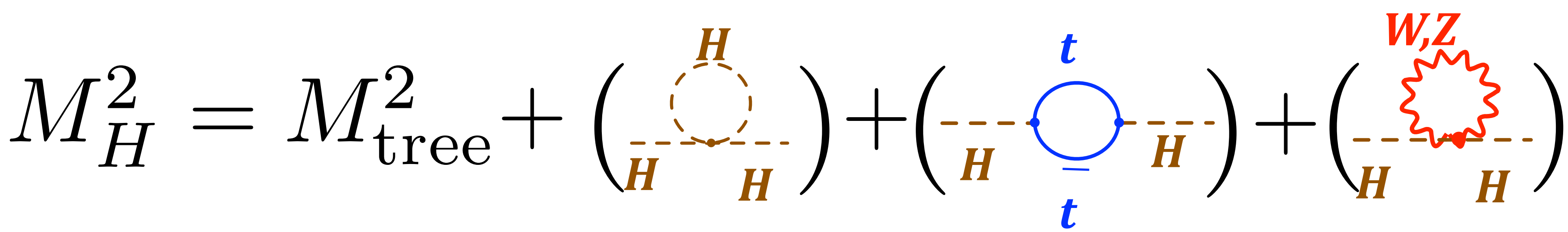
$$V = \boxed{\lambda v^2 H^2}$$

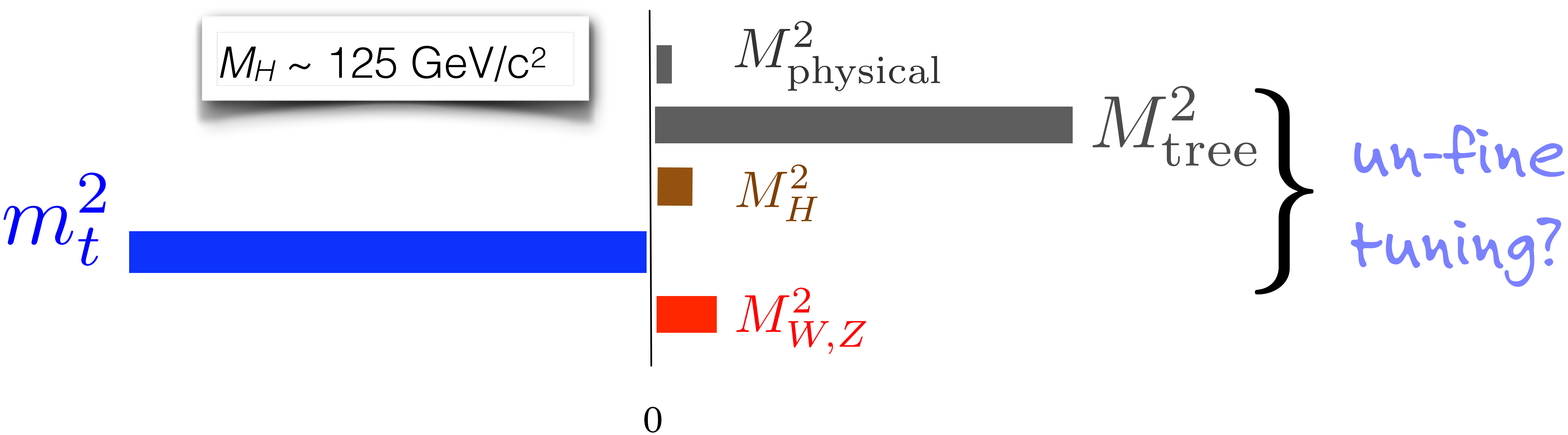
$M_H^2 = M_{\text{tree}}^2 + \Big($  $\Big) + \Big($  $\Big) + \Big($  $\Big)$



An enormous fine-tuning

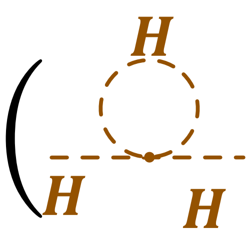
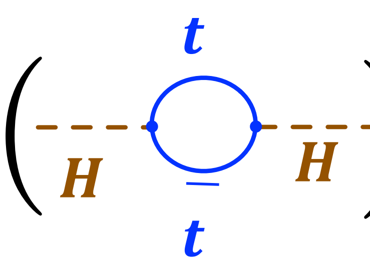
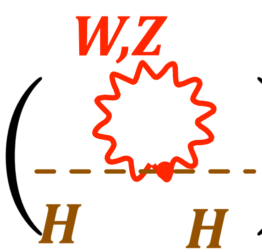
$$V = \boxed{\lambda v^2 H^2}$$



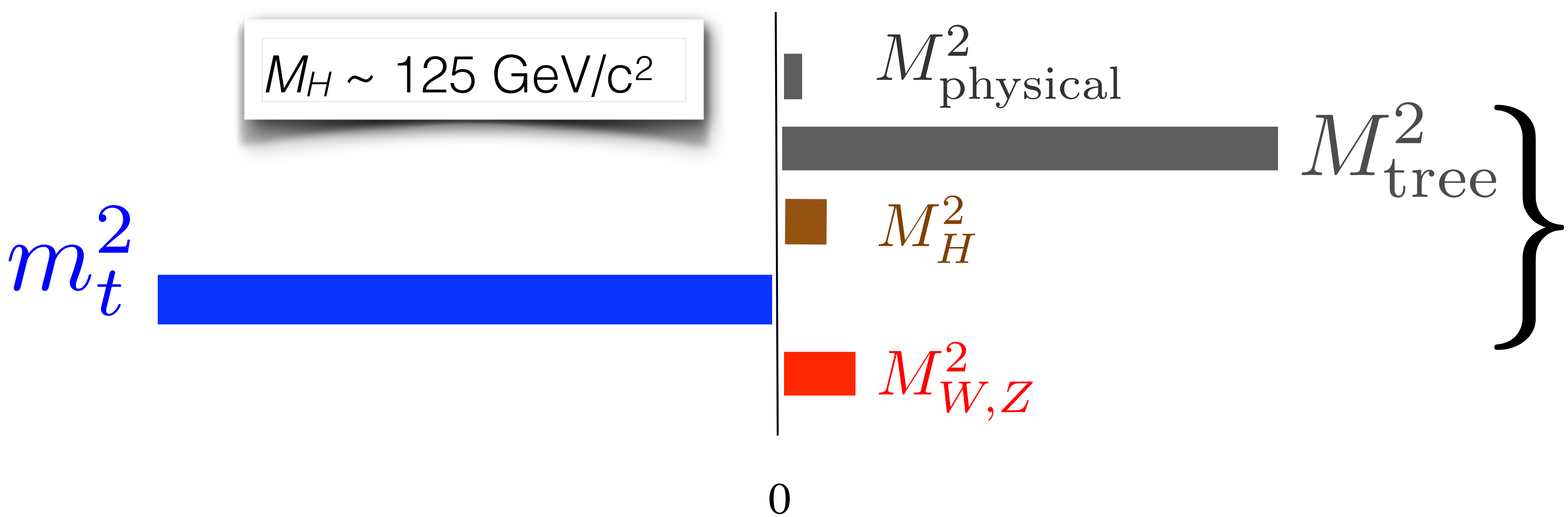


An enormous fine-tuning

$$V = \boxed{\lambda v^2 H^2}$$

$$M_H^2 = M_{\text{tree}}^2 + \Big($$  $$\Big) + \Big($$  $$\Big) + \Big($$  $$\Big)$$

$M_H \sim 125$ GeV/c²



un-fine tuning?

"hierarchy problem"

if next scale is the Planck Scale?

$$M_H^2 = \begin{matrix}\textbf{(nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n60,000)} \\ - \\ \textbf{(nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n44,375)}\end{matrix}$$

$$M_H^2 = \mathbf{125^2}$$

“coincidence”?

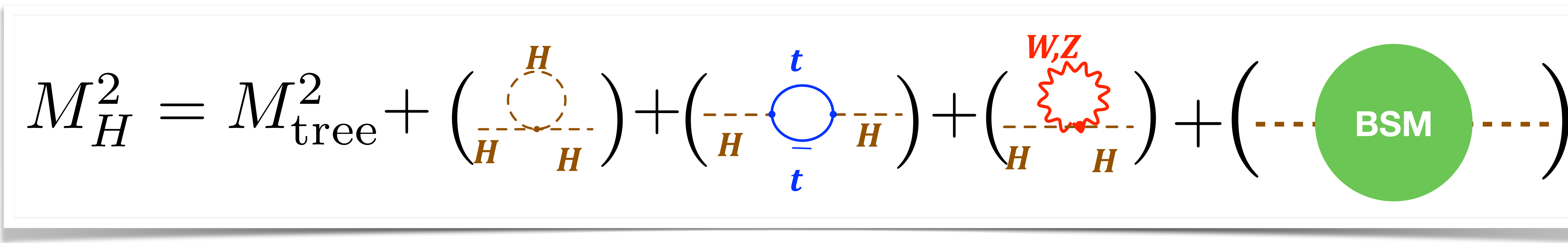
There’s no coincidence in science.

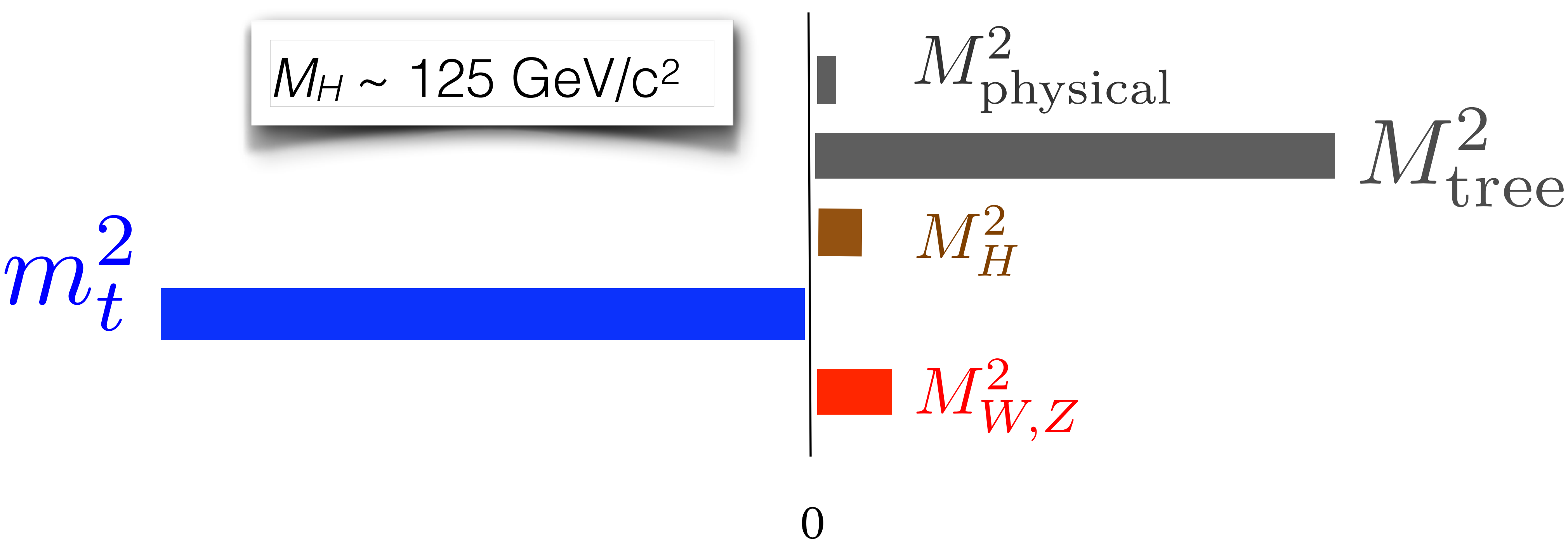

POST CARD
Correspondence
Address
Hints?
To: 2019
From: Nature
#5064
ROBERT H. LORD
BOSTON

Perhaps a huge hint?

of something “BSM”?

no shortage of ideas





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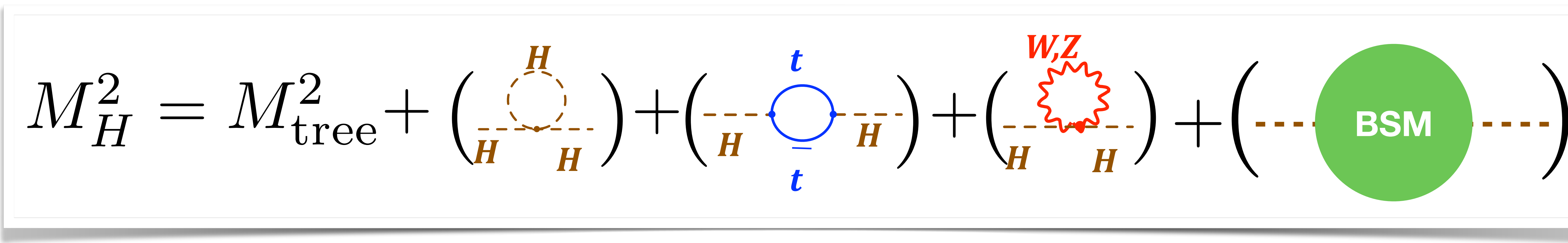
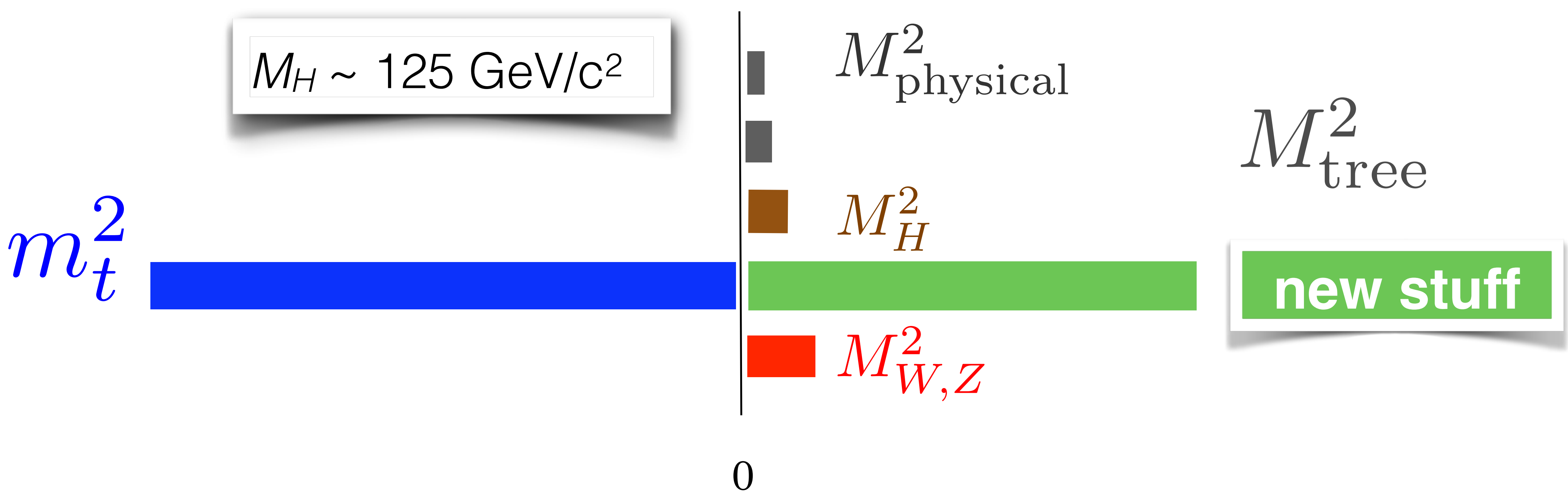
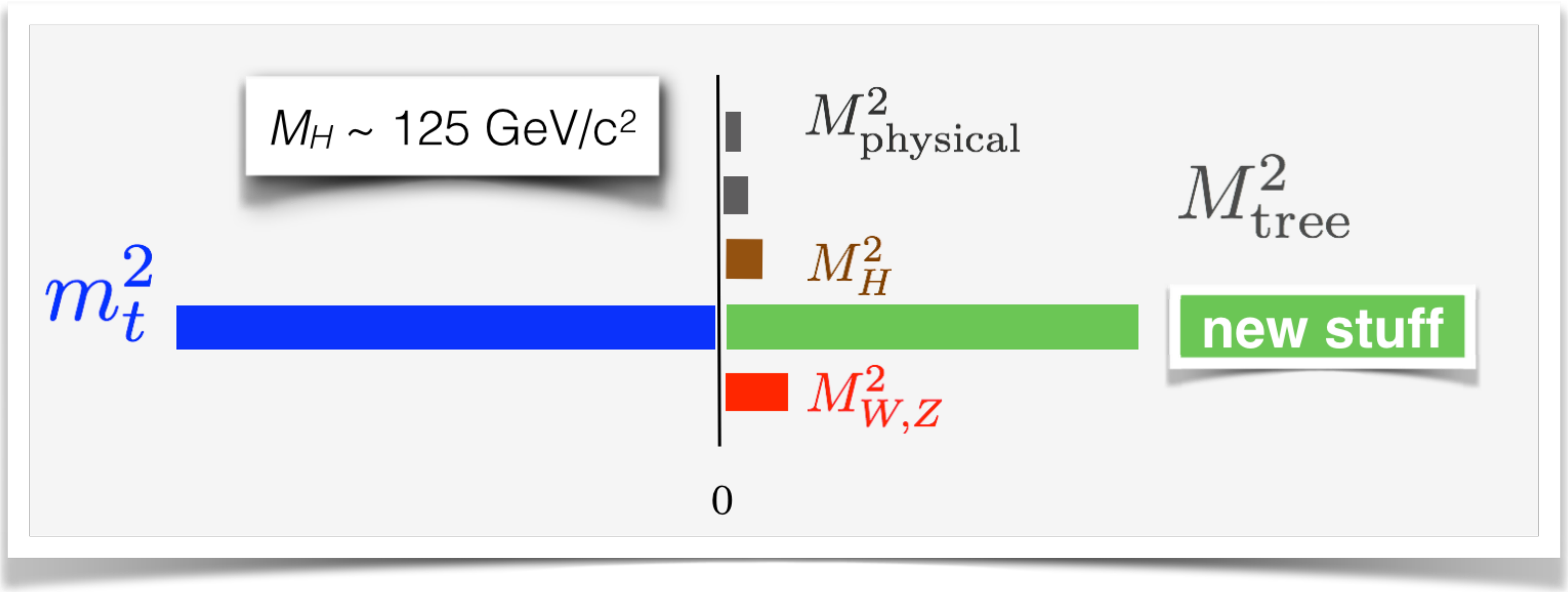
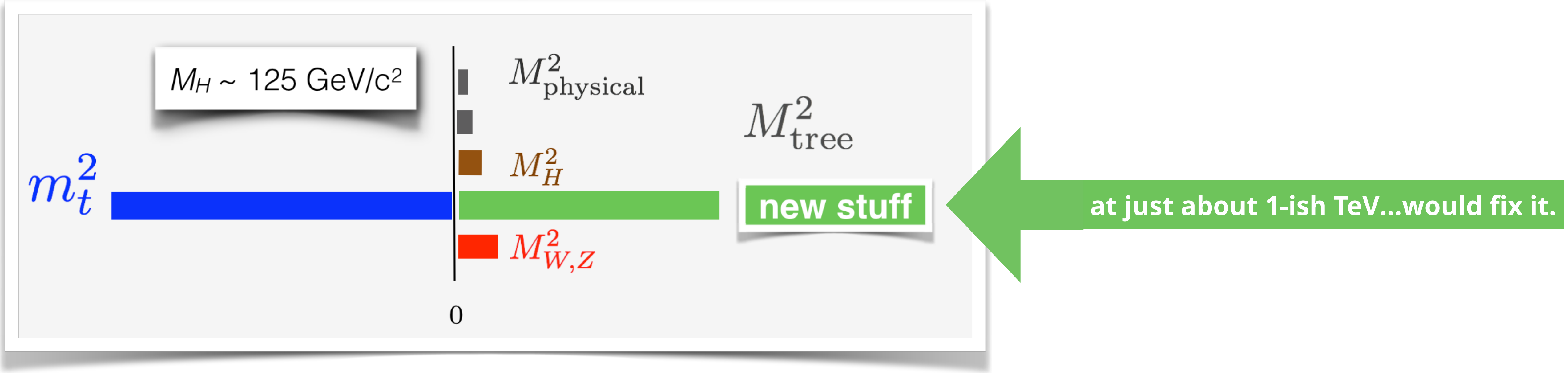






looking for new physics at the ~1 TeV scale



looking for new physics at the ~1 TeV scale

looking for new physics at the ~1 TeV scale

"natural"

new stuff

Broadly speaking, categories of new stuff:

Supersymmetric theories –	a Bose-like stop
Little Higgs-like theories –	a Vector-top
Composite Higgs –	a Cooper Pair-like H
Extra dimensional theories	

new stuff

Broadly speaking, categories of new stuff:

Supersymmetric theories – a Bose-like stop

Little Higgs-like theories – a Vector-like top

Composite Higgs – a Cooper Pair-like H

Extra dimensional theories

- **or we tend to default to ideas like:**

the multiverse or...

anthropomorphism

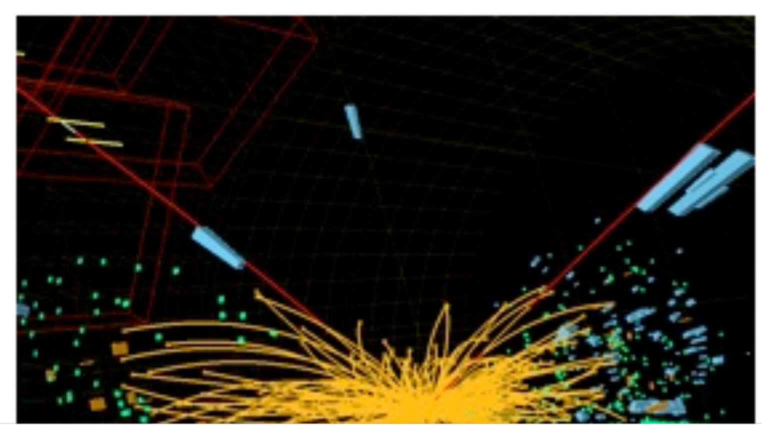
SCIENTIFIC AMERICAN™

This article is from the In-Depth Report The Higgs Boson at Last?

How the Higgs Boson Might Spell Doom for the Universe

Under the simplest assumptions, the measured mass of the Higgs could mean the universe is unstable and destined to fall apart. But don't worry—it won't happen for billions of eons

March 26, 2013 | By Saswato R. Das



Physicists recently confirmed that the Large Hadron Collider (LHC) at CERN, the particle physics laboratory in Geneva, had indeed found a Higgs boson last July, marking a culmination of one of the longest and most expensive searches in science. The

doom?

doom?

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

vacuum energy

Higgs mass

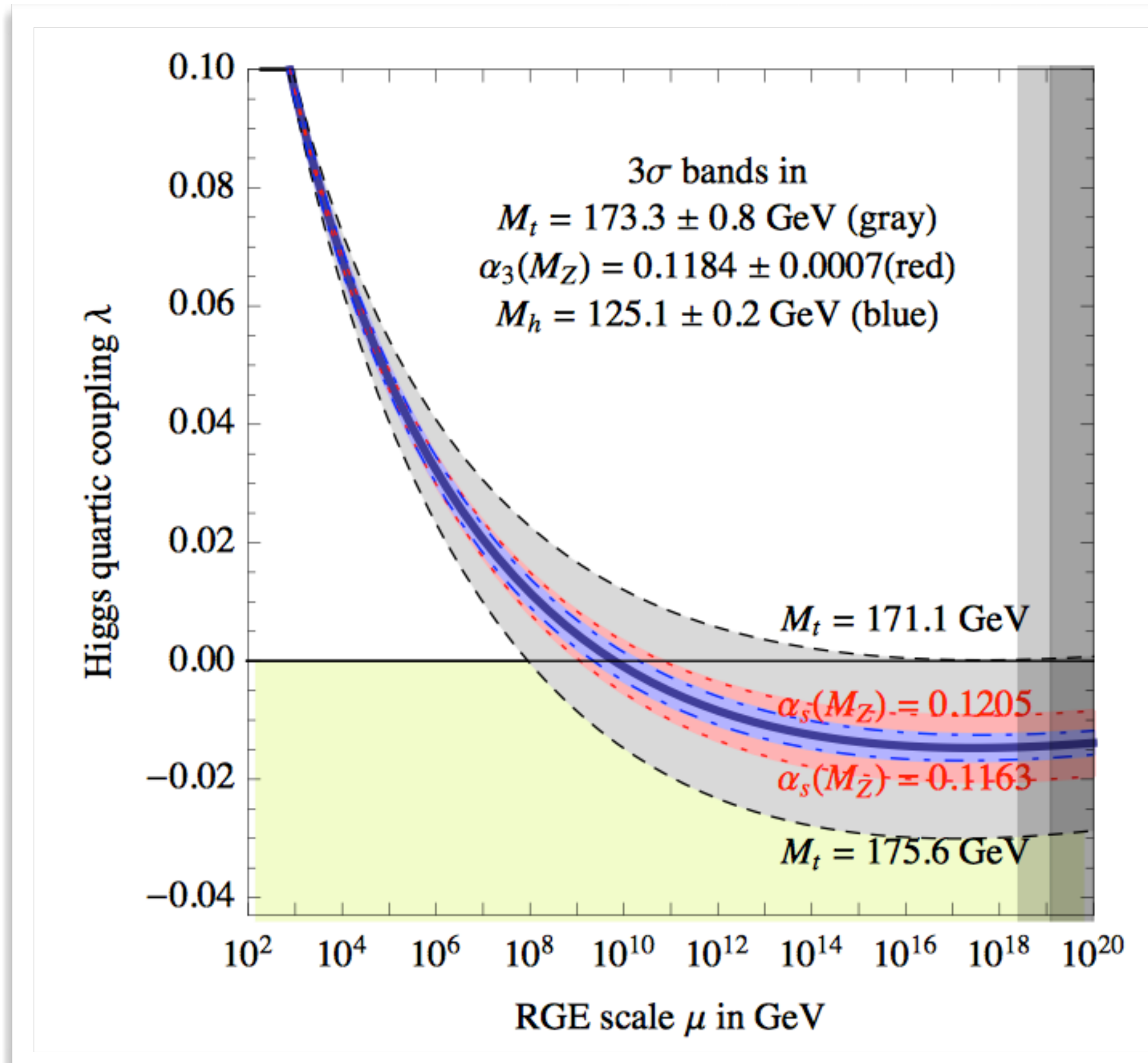
instability?

fermion couplings

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

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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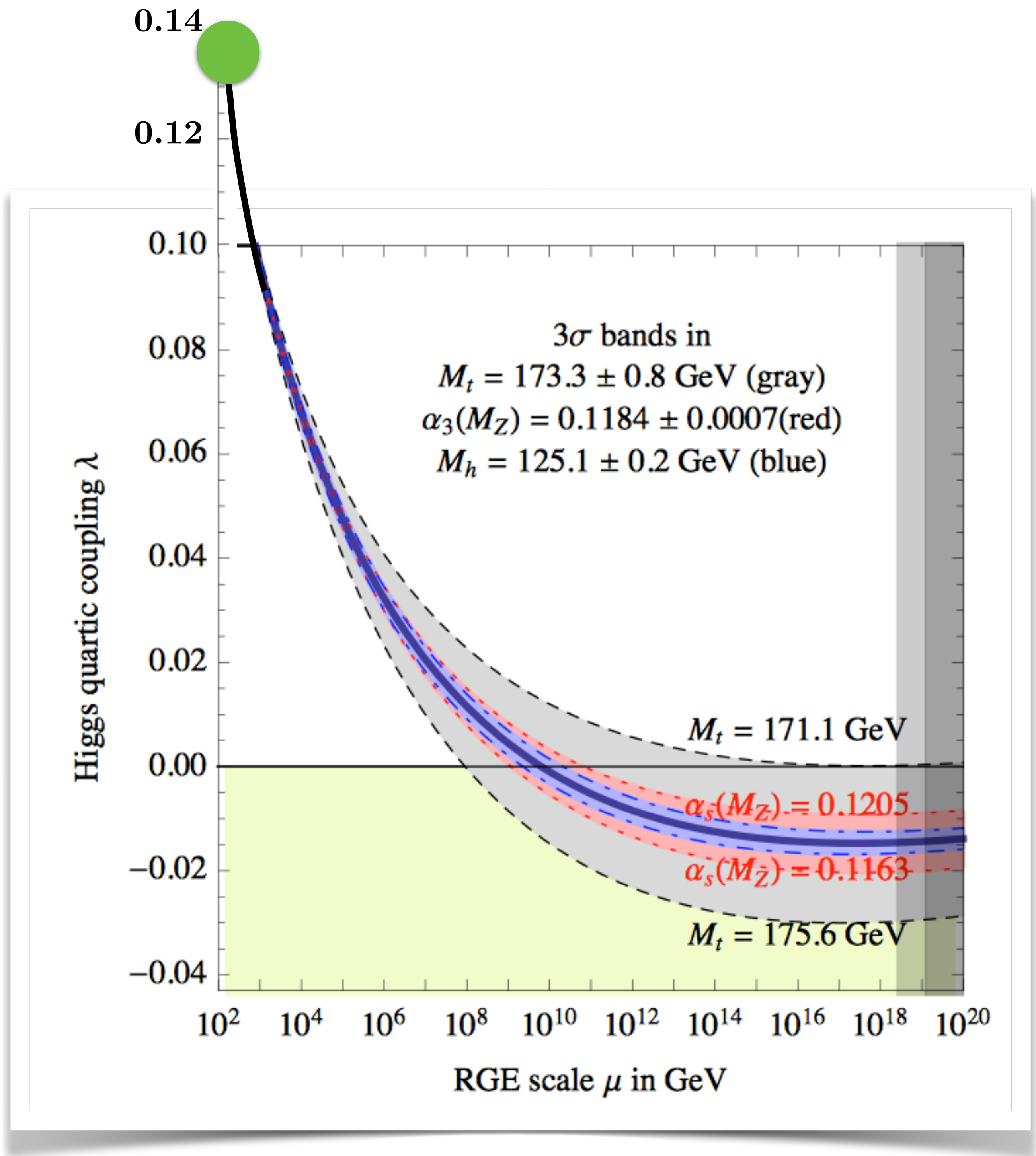


arXiv:1307.3536

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

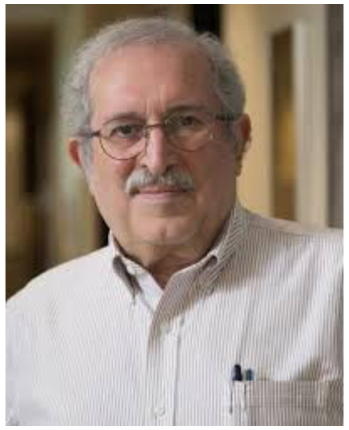
The Standard Model is just weird.

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

Conclusions

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:

They talk to the Higgs Field

- Measure properties of the Higgs boson.
- Measure properties of the: t, W, and Z
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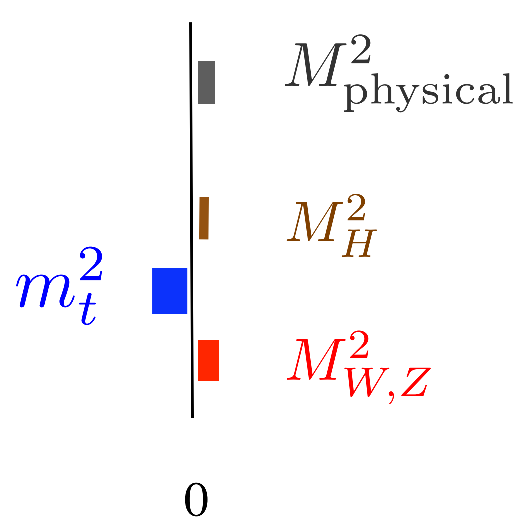
A three-pronged research program:

- Measure properties of the Higgs boson.
- Measure properties of the: t, W, and Z
- Search for TeV-scale particles

Scale inspired by the hierarchy problem



let's

the future:

The Higgs Boson

is it alone?

is it alone?

a part of a family?

is it alone?

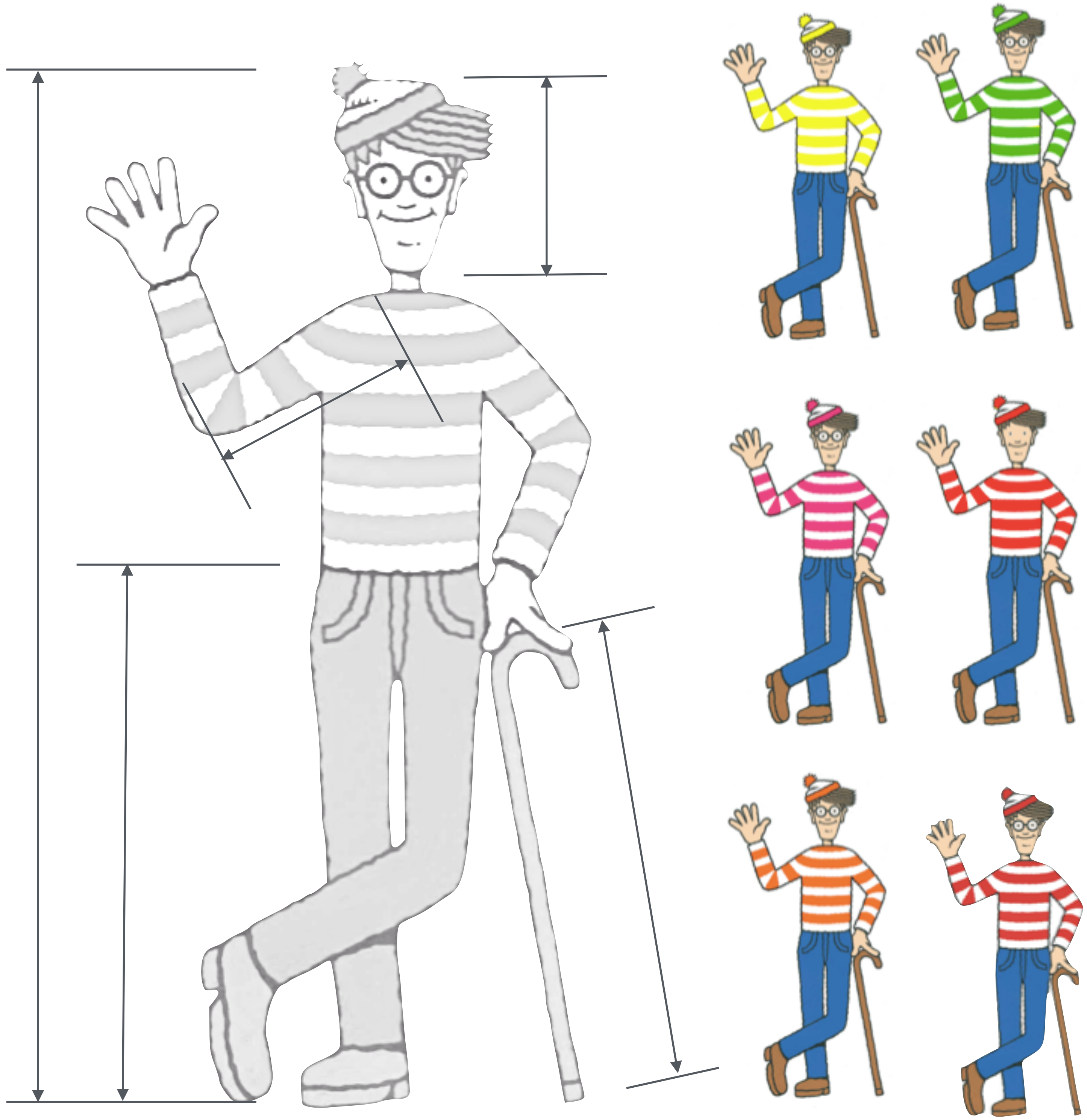
a part of a family?

different in tiny details?

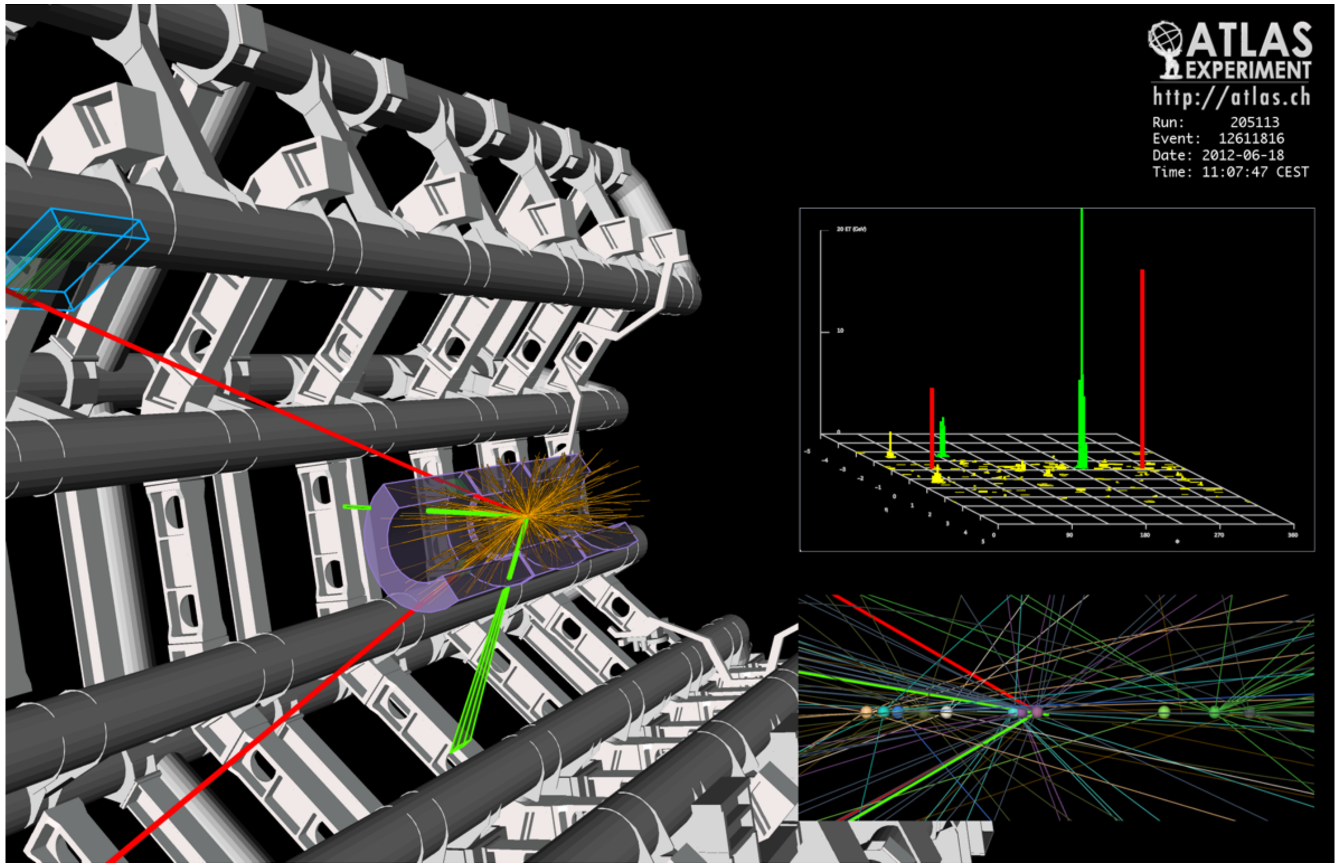
is it alone?

a part of a family?

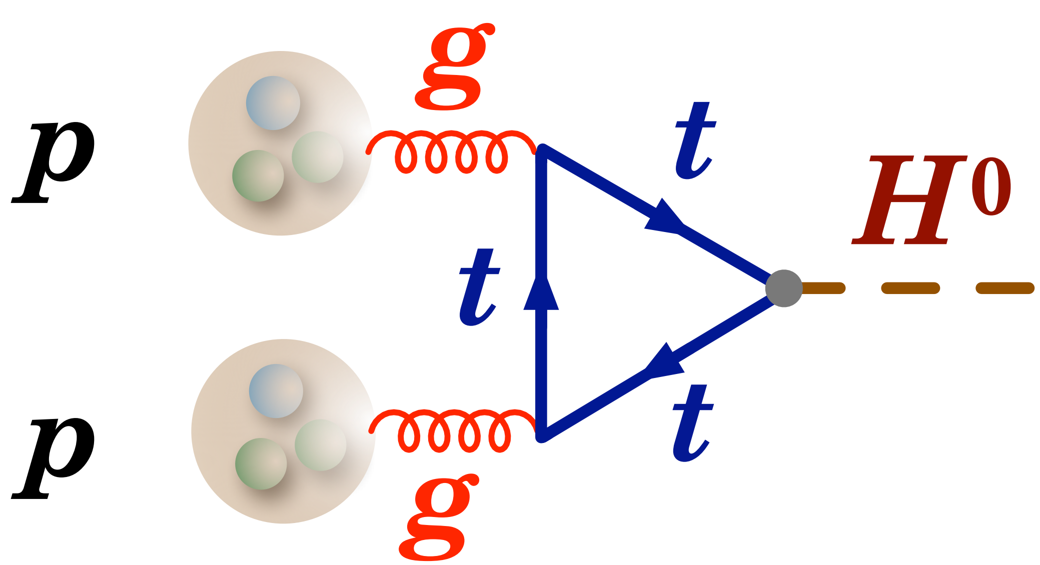
different in tiny details?



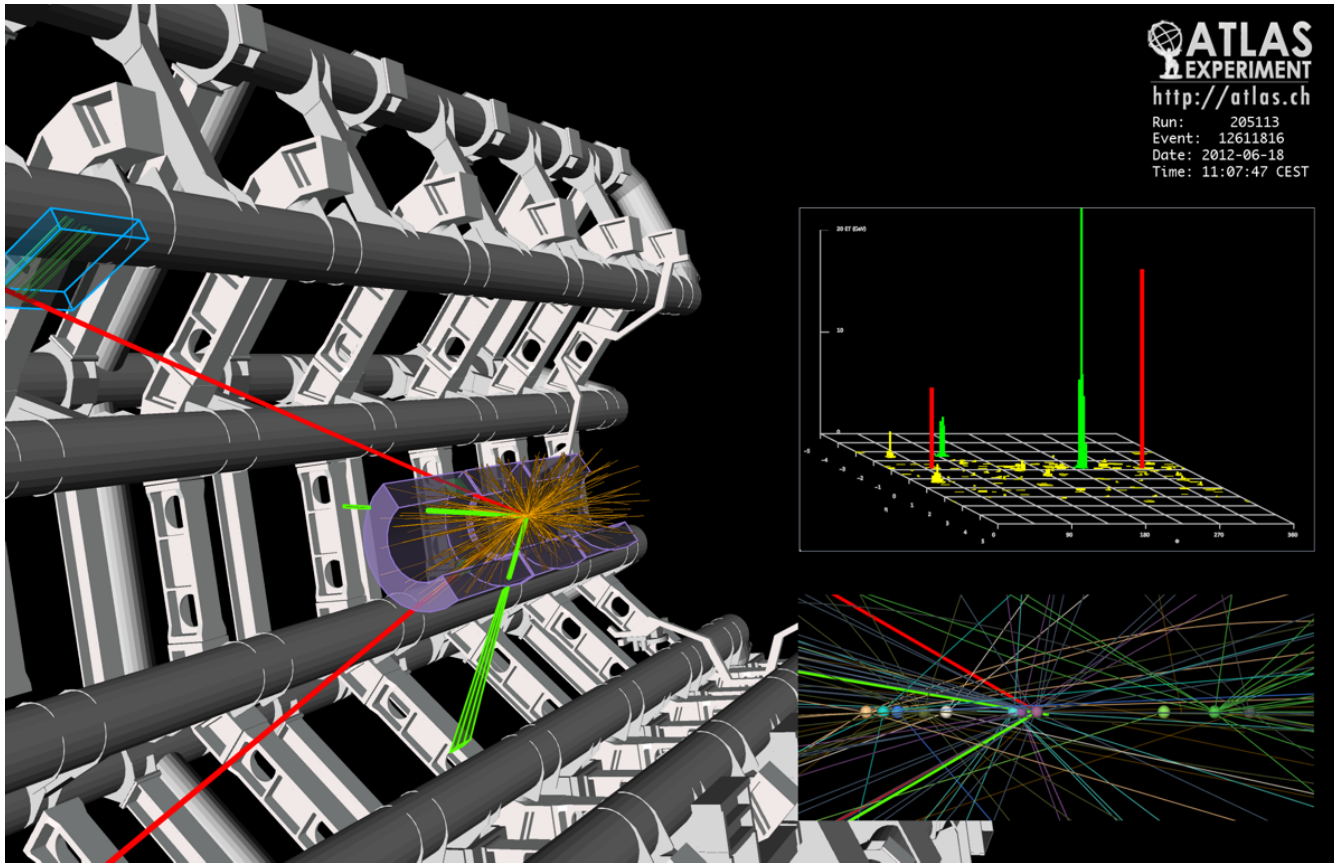
ATLAS



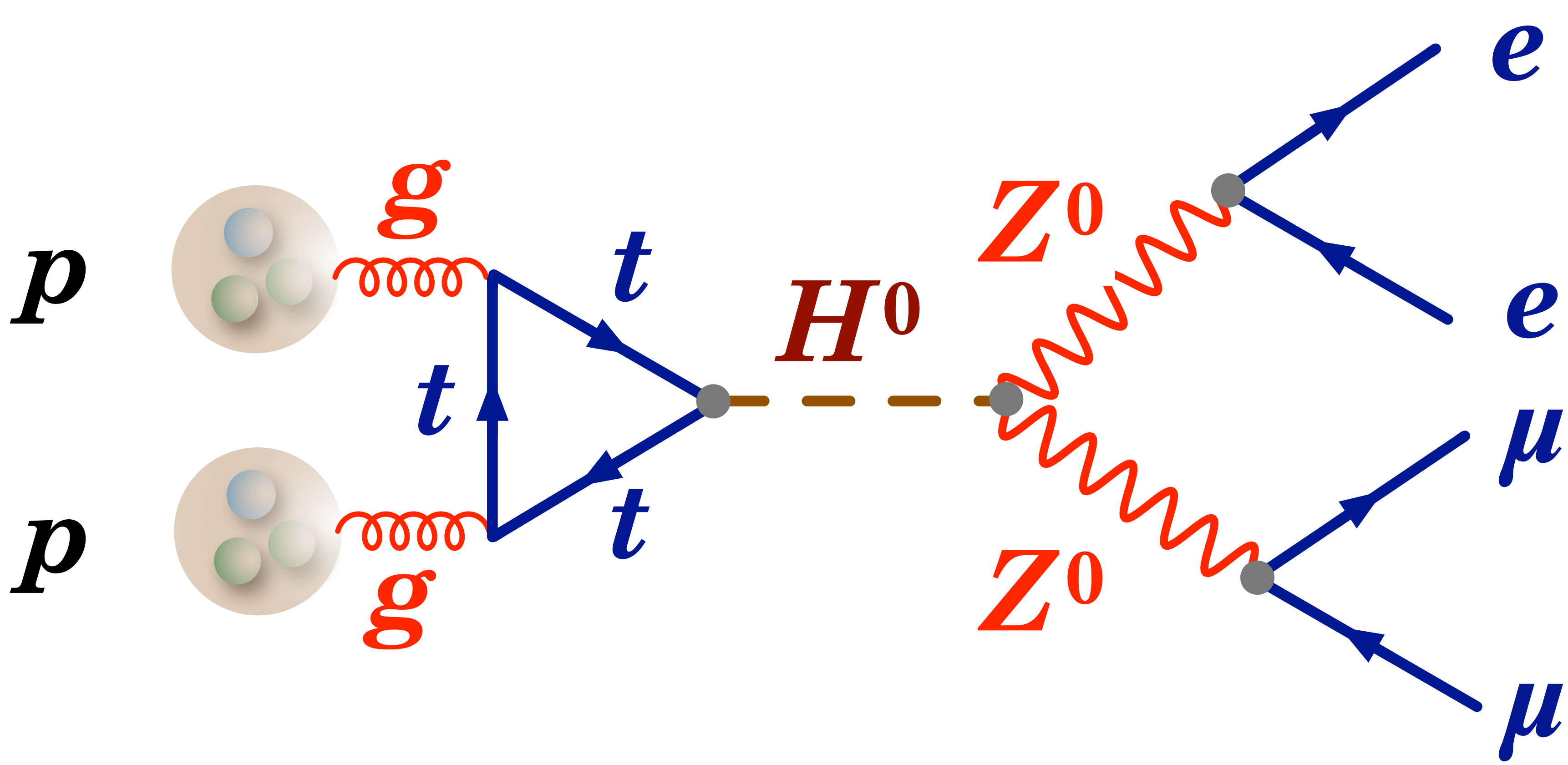
Golden Channel

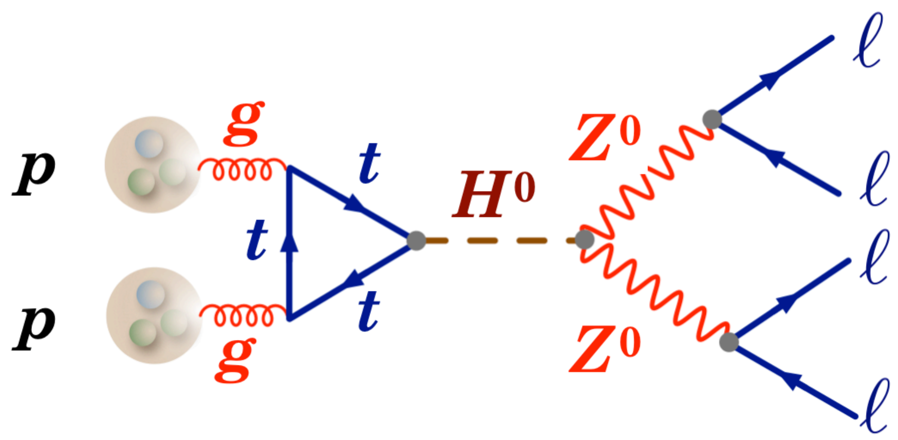


ATLAS

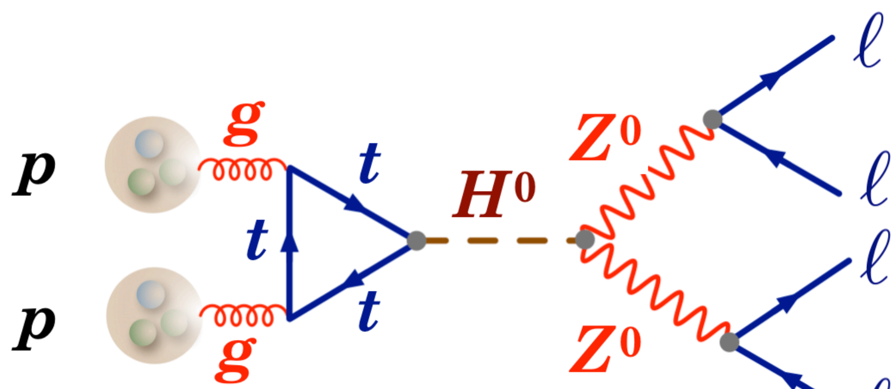


Golden Channel





p
p
g
g
t
t
t
H⁰
Z⁰
Z⁰
ℓ
ℓ
ℓ
ℓ



p
p
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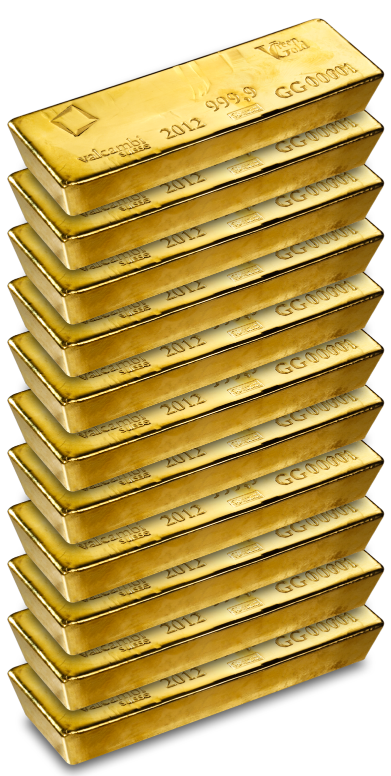
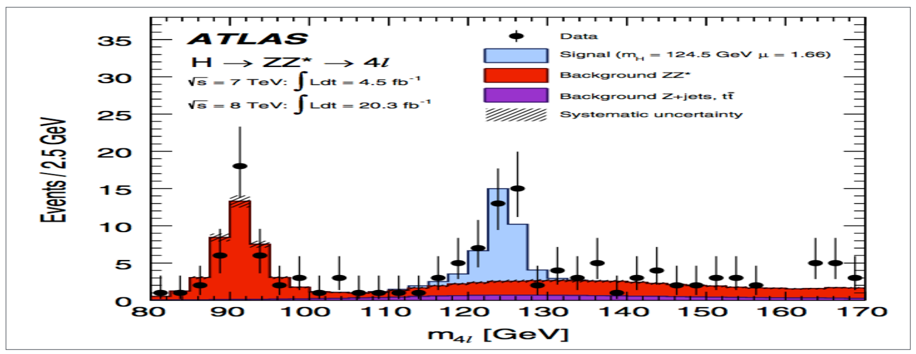
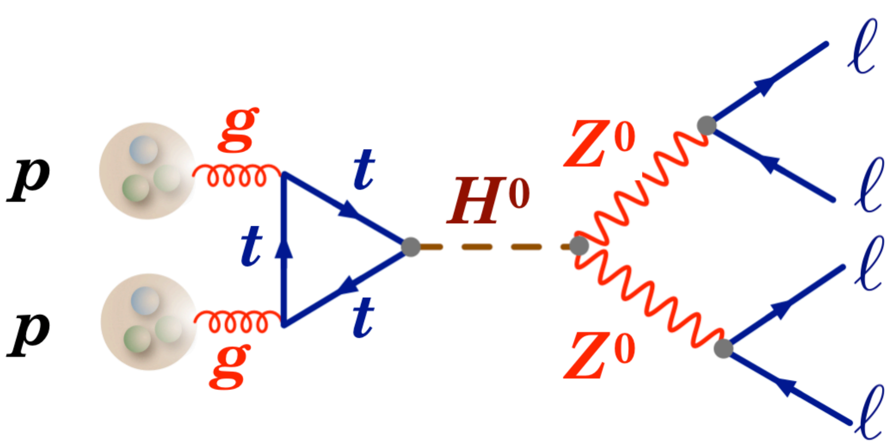
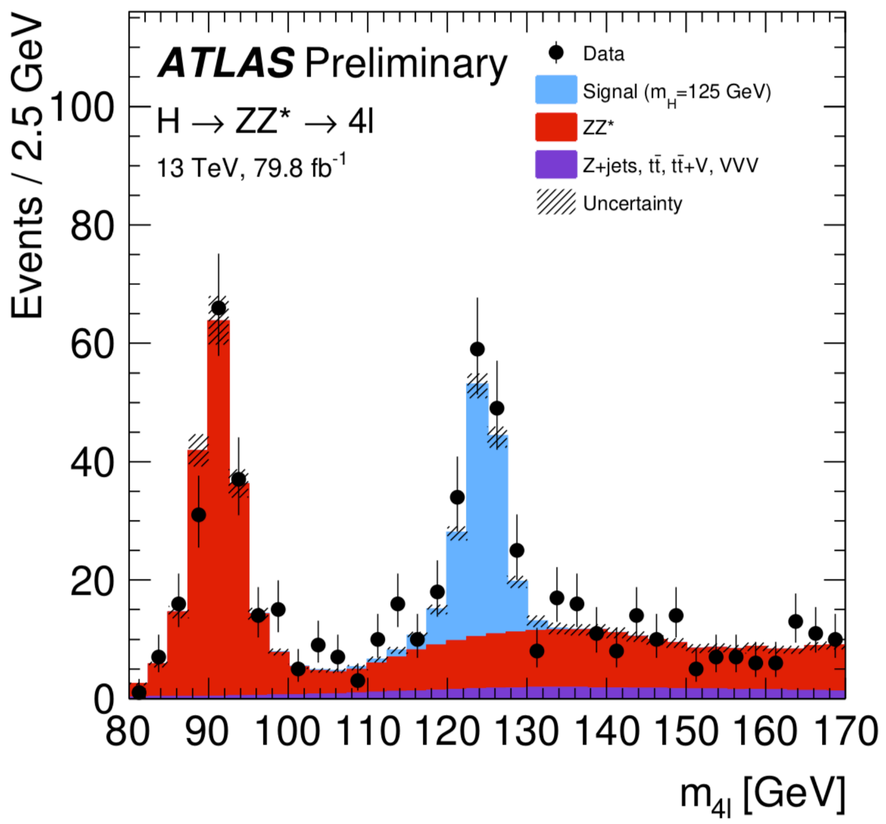
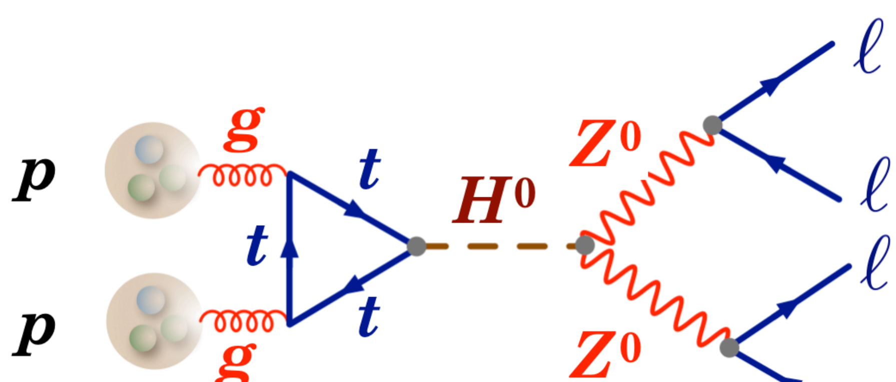
t
t
H⁰
Z⁰
Z⁰
ℓ
ℓ
ℓ
ℓ

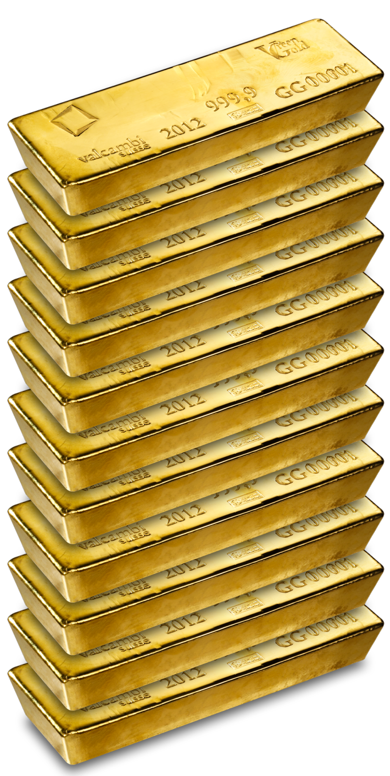


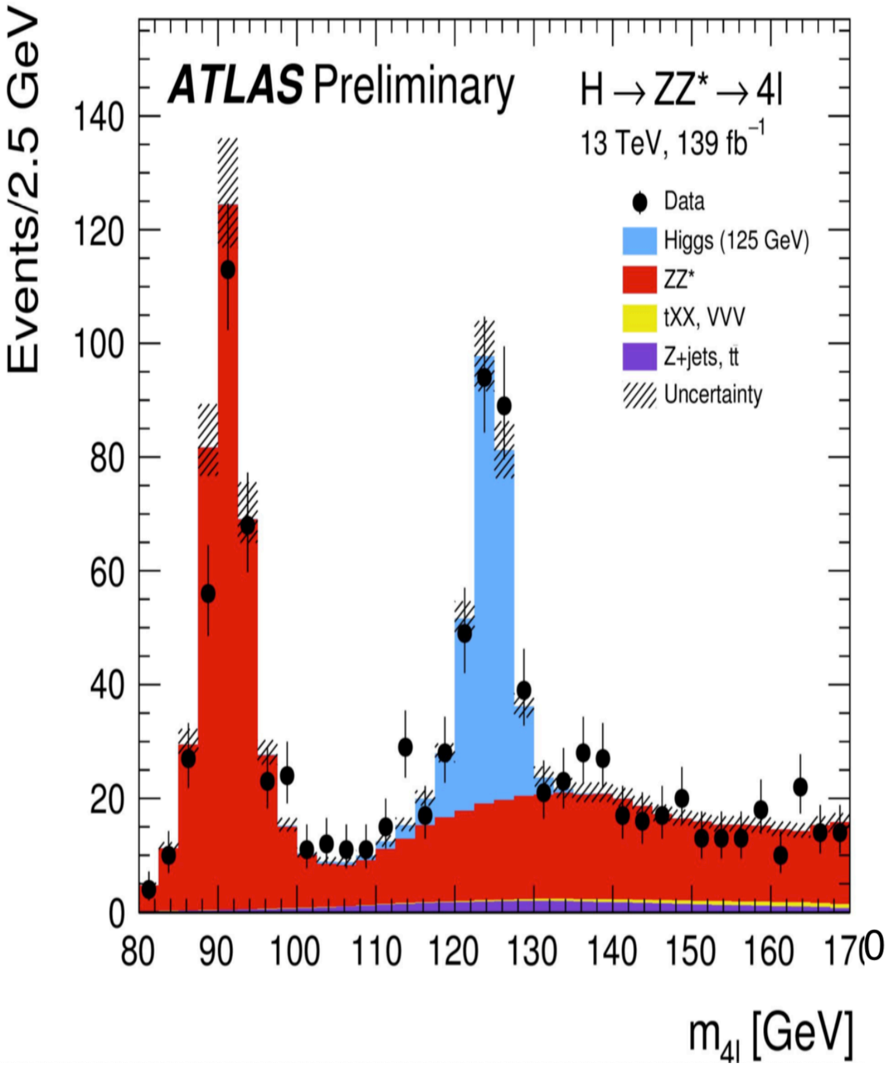

ATLAS
H → ZZ* → 4l
√s = 7 TeV: ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.3 fb⁻¹
Data
Signal (m_H = 124.5 GeV μ = 1.66)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
Events / 2.5 GeV
m_4l [GeV]
0 5 10 15 20 25 30 35
80 90 100 110 120 130 140 150 160 170

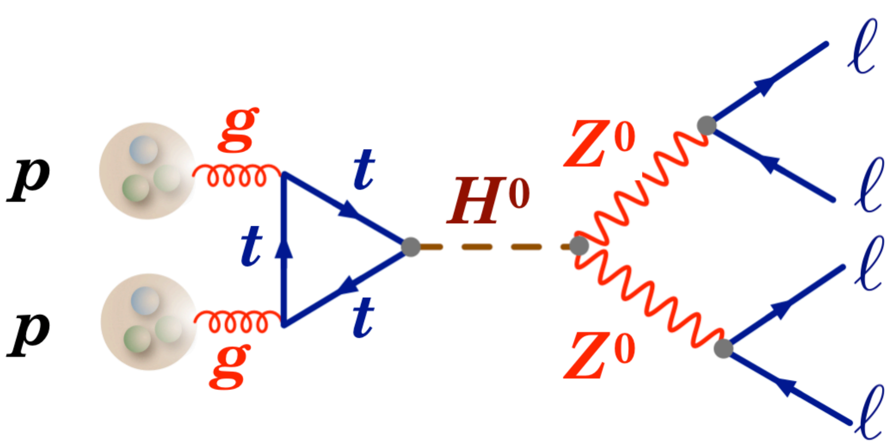

p
p
g
g
t
t
t
H⁰
Z⁰
Z⁰
ℓ
ℓ
ℓ
ℓ

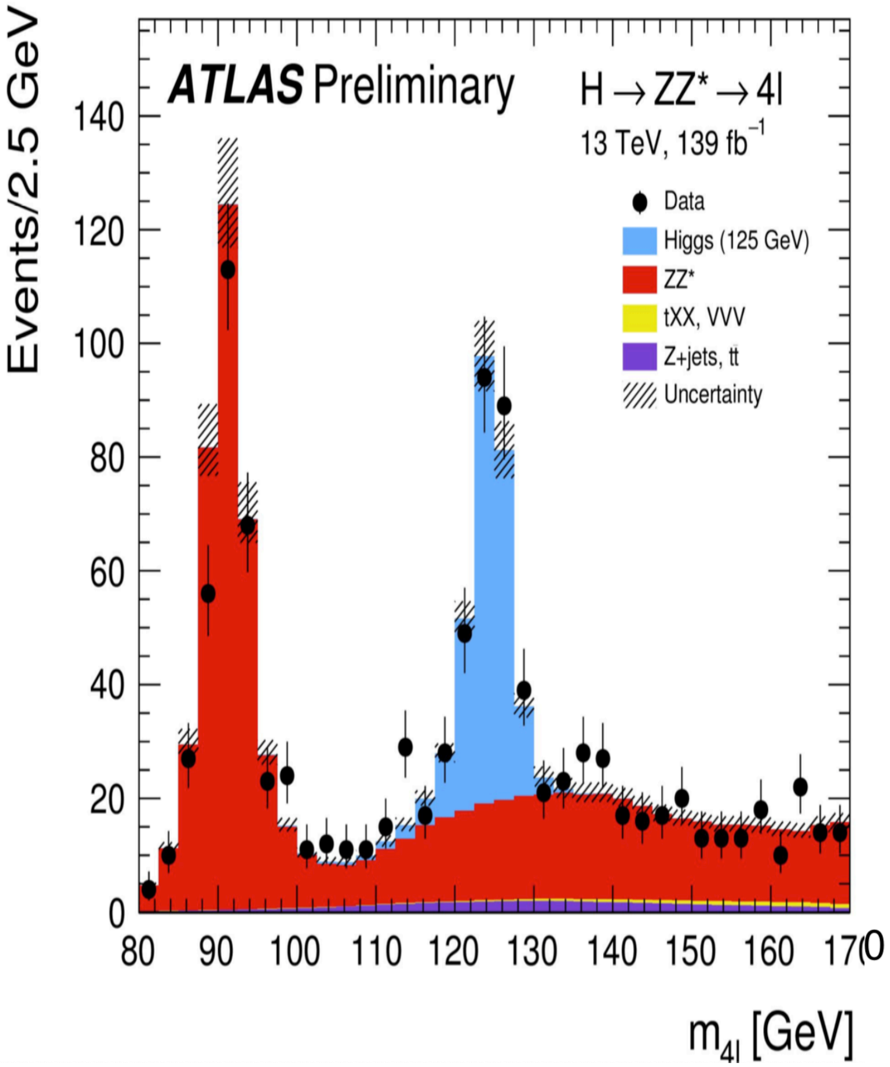

ATLAS Preliminary
H → ZZ* → 4l
13 TeV, 79.8 fb-1
Data
Signal (mH=125 GeV)
ZZ*
Z+jets, tt̄, tt̄+V, VVV
Uncertainty
Events / 2.5 GeV
m4l [GeV]
0
20
40
60
80
100
80
90
100
110
120
130
140
150
160
170

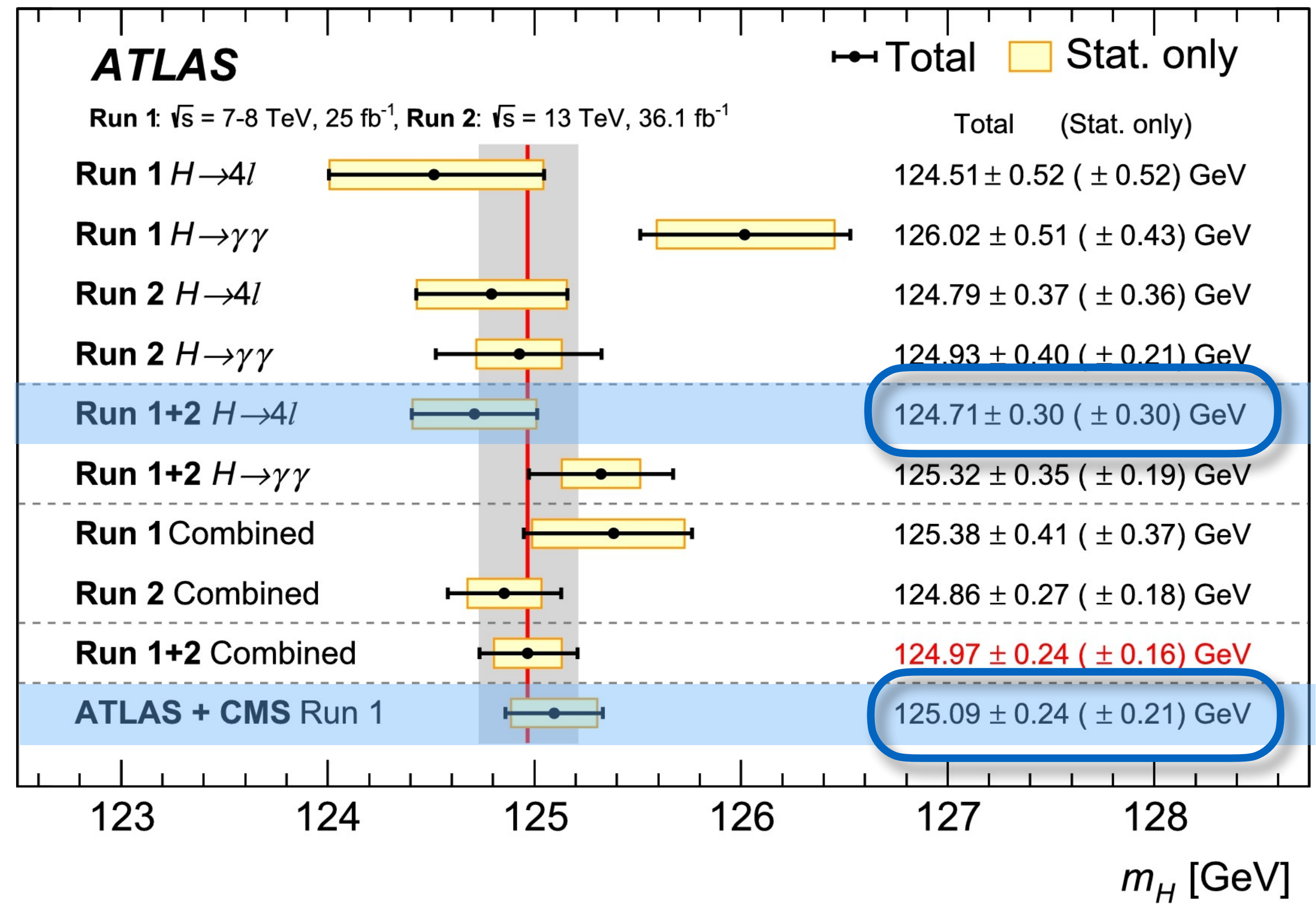

p
p
g
g
t
t
t
H0
Z0
Z0
ℓ
ℓ
ℓ
ℓ

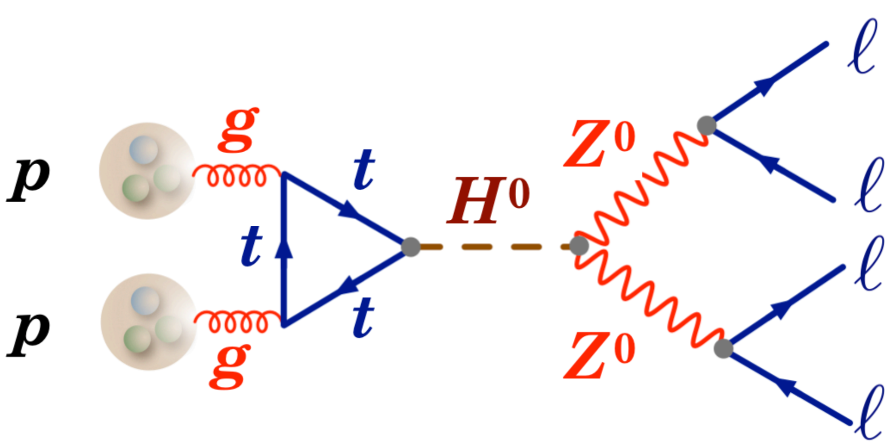



ATLAS Preliminary
H → ZZ* → 4l
13 TeV, 139 fb⁻¹
Data
Higgs (125 GeV)
ZZ*
tXX, VVV
Z+jets, tt
Uncertainty
Events/2.5 GeV
m4l [GeV]
0
20
40
60
80
100
120
140
80
90
100
110
120
130
140
150
160
170

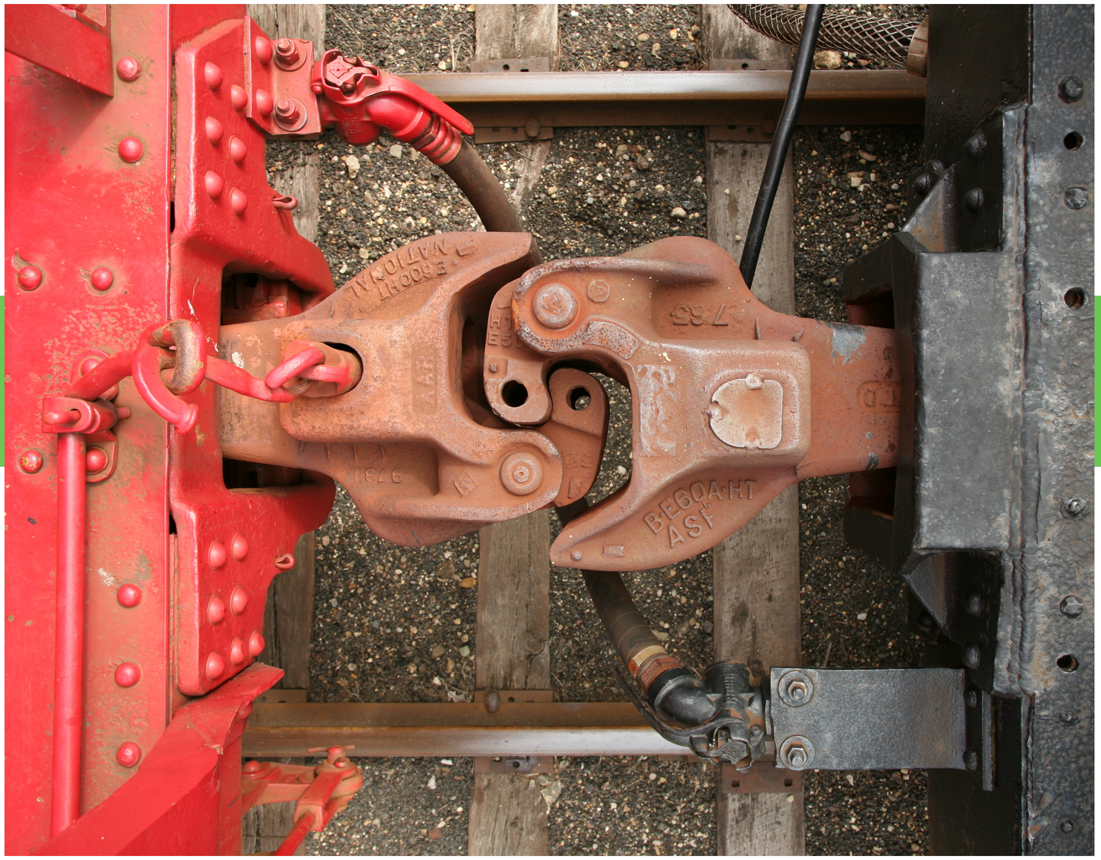

p
p
g
g
t
t
t
H⁰
Z⁰
Z⁰
ℓ
ℓ
ℓ
ℓ


ATLAS Preliminary
H → ZZ* → 4l
13 TeV, 139 fb^{-1}
Data
Higgs (125 GeV)
ZZ*
tXX, VVV
Z+jets, tt
Uncertainty
Events/2.5 GeV
0
20
40
60
80
100
120
140
80
90
100
110
120
130
140
150
160
170
m$_{4l}$ [GeV]

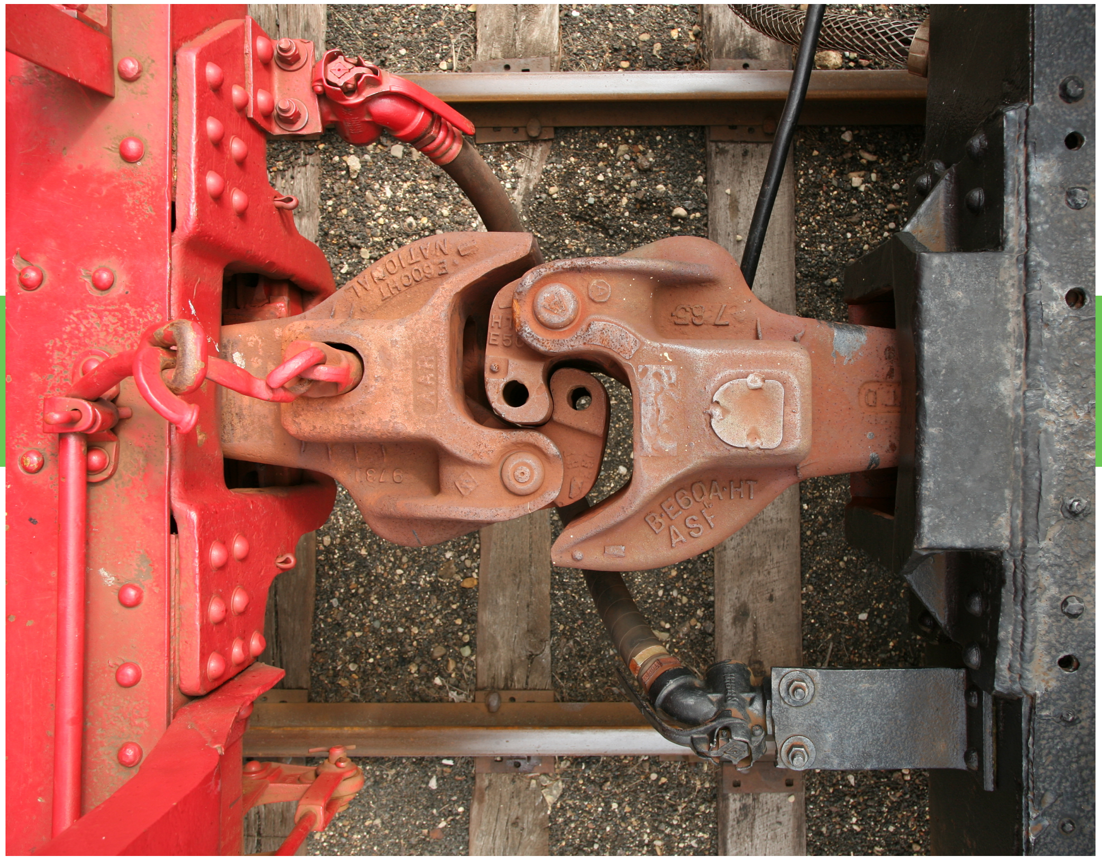

ATLAS
Total
Stat. only
Run 1: √s = 7-8 TeV, 25 fb^{-1}, Run 2: √s = 13 TeV, 36.1 fb^{-1}
Total (Stat. only)
Run 1 H→4l 124.51 ± 0.52 (± 0.52) GeV
Run 1 H→γγ 126.02 ± 0.51 (± 0.43) GeV
Run 2 H→4l 124.79 ± 0.37 (± 0.36) GeV
Run 2 H→γγ 124.93 ± 0.40 (± 0.21) GeV
Run 1+2 H→4l 124.71 ± 0.30 (± 0.30) GeV
Run 1+2 H→γγ 125.32 ± 0.35 (± 0.19) GeV
Run 1 Combined 125.38 ± 0.41 (± 0.37) GeV
Run 2 Combined 124.86 ± 0.27 (± 0.18) GeV
Run 1+2 Combined 124.97 ± 0.24 (± 0.16) GeV
ATLAS + CMS Run 1 125.09 ± 0.24 (± 0.21) GeV
123
124
125
126
127
128
m$_H$ [GeV]


p
p
g
g
t
t
t
H^0
Z^0
Z^0
ℓ
ℓ
ℓ
ℓ

couplings



couplings



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

vacuum energy

Higgs mass

instability?

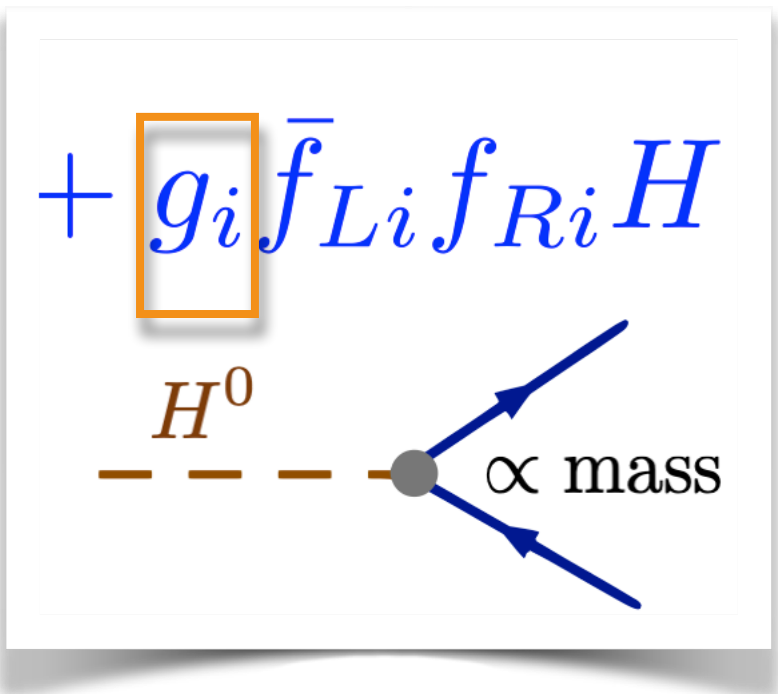
fermion couplings

couplings

$$V(\text{fermions}) = g_i \bar{f}_{Li} f_{Ri} H$$

Higgs discovery spawned an industry

precision fitting



$$\mathcal{L} \propto \sum_{i}^{\text{fermions}_i} (\kappa_i) g_i f_i f_i H$$

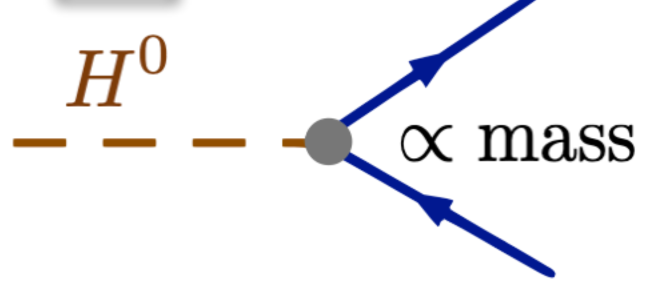
couplings

$$V(\text{fermions}) = g_i \bar{f}_{Li} f_{Ri} H$$

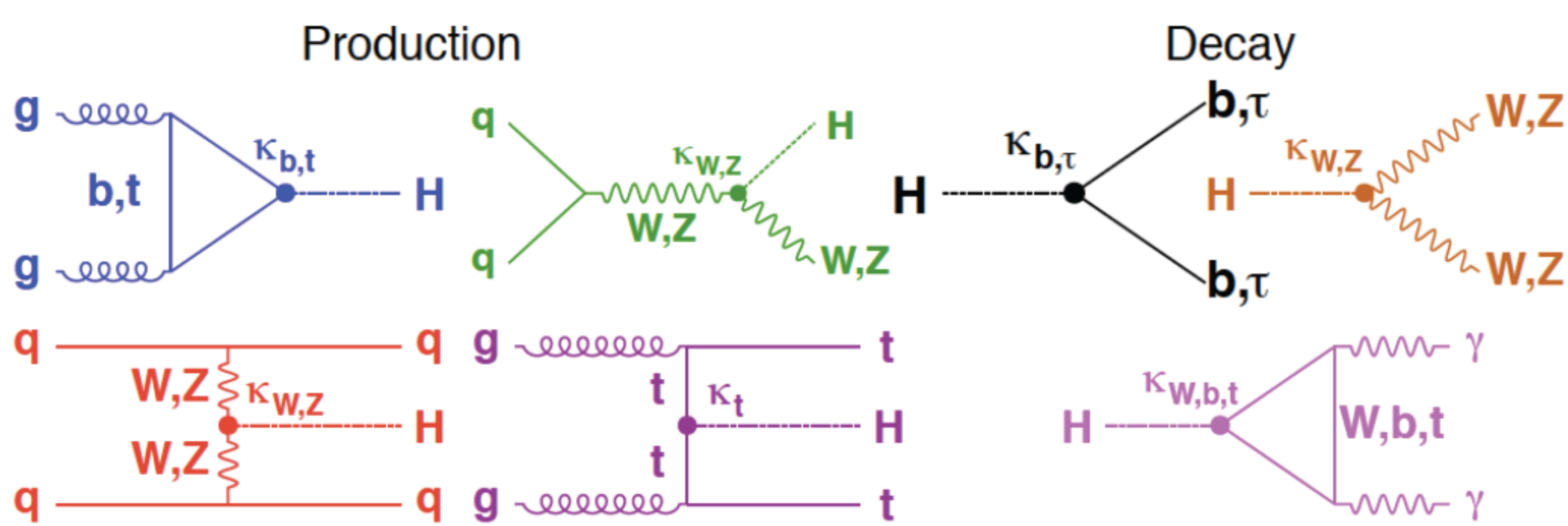
Higgs discovery spawned an industry

precision fitting

$$+ g_i \bar{f}_{Li} f_{Ri} H$$



$$\mathcal{L} \propto \sum_{i}^{\text{fermions}_i} (\kappa_i) g_i f_i f_i H$$

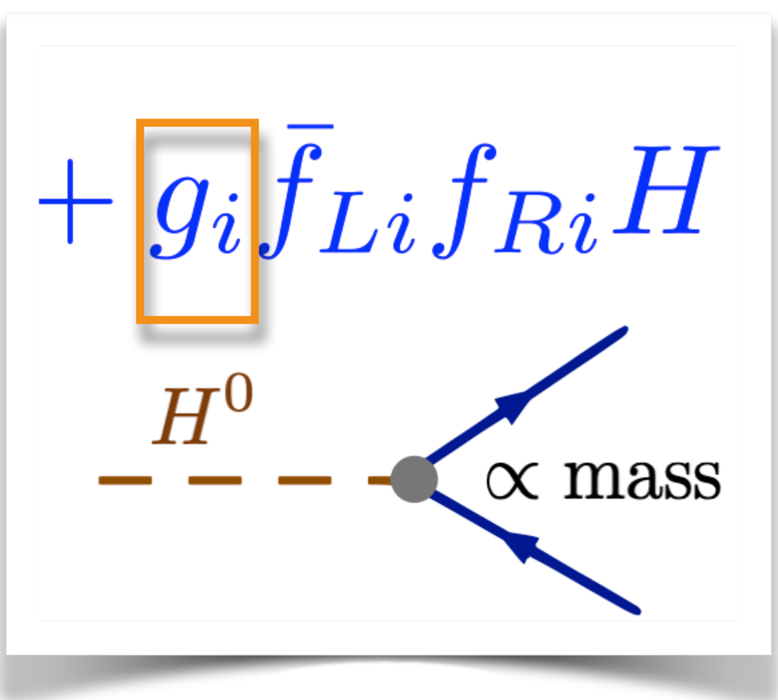


couplings

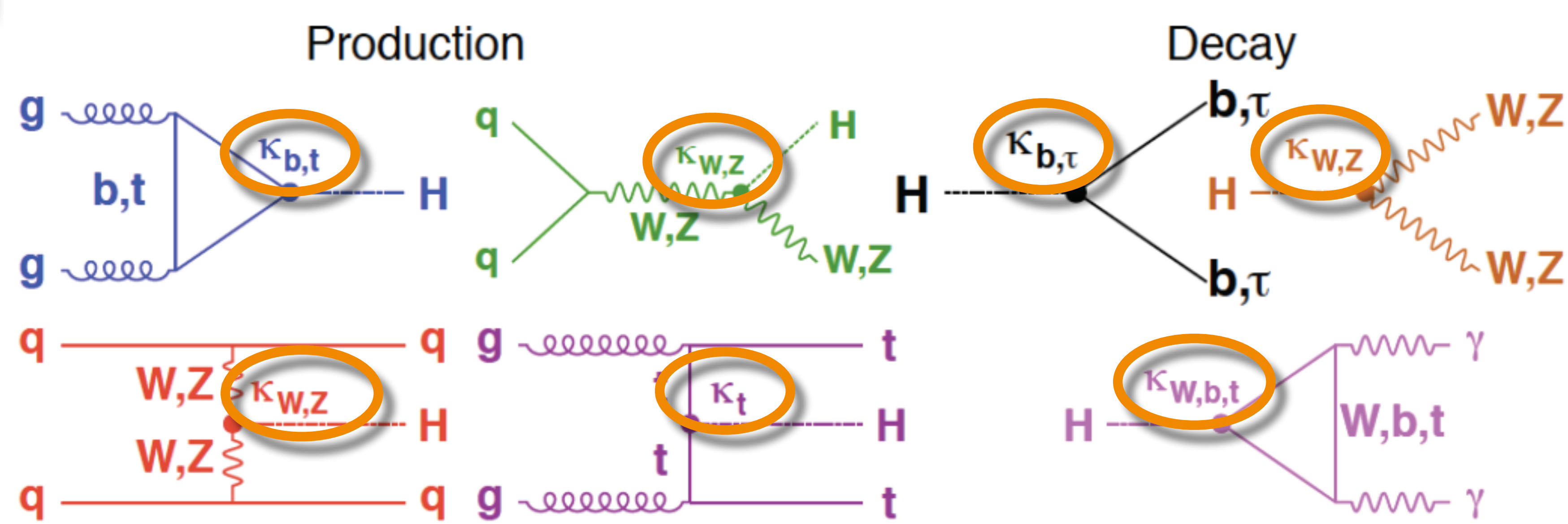
$$V(\text{fermions}) = g_i \bar{f}_{Li} f_{Ri} H$$

Higgs discovery spawned an industry

precision fitting

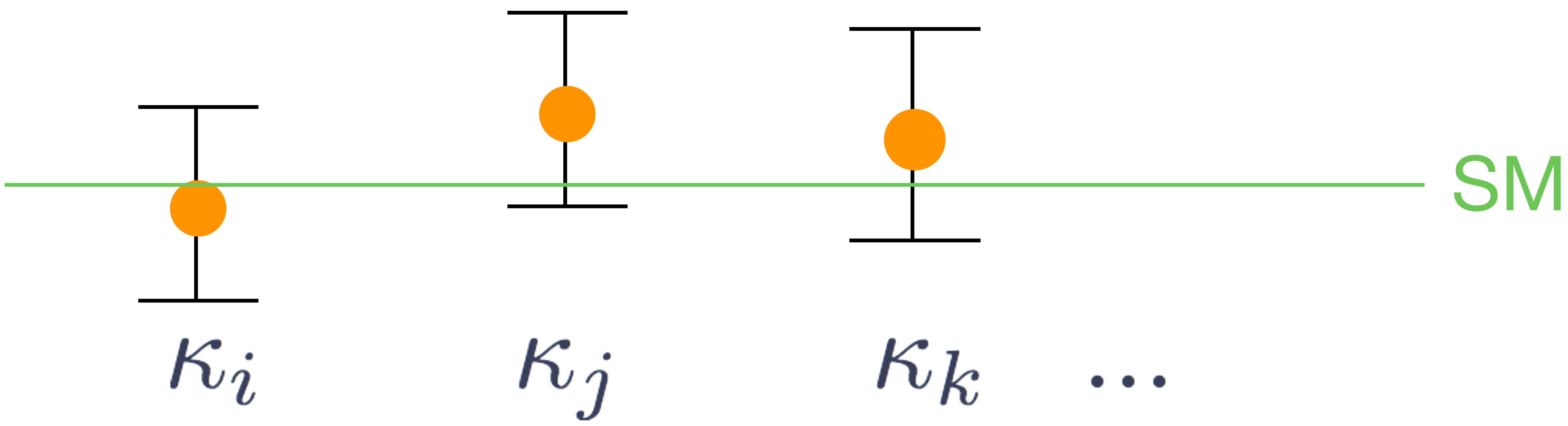


$$\mathcal{L} \propto \sum_{i}^{\text{fermions}_i} (\kappa_i) g_i f_i f_i H$$



a campaign

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



a campaign

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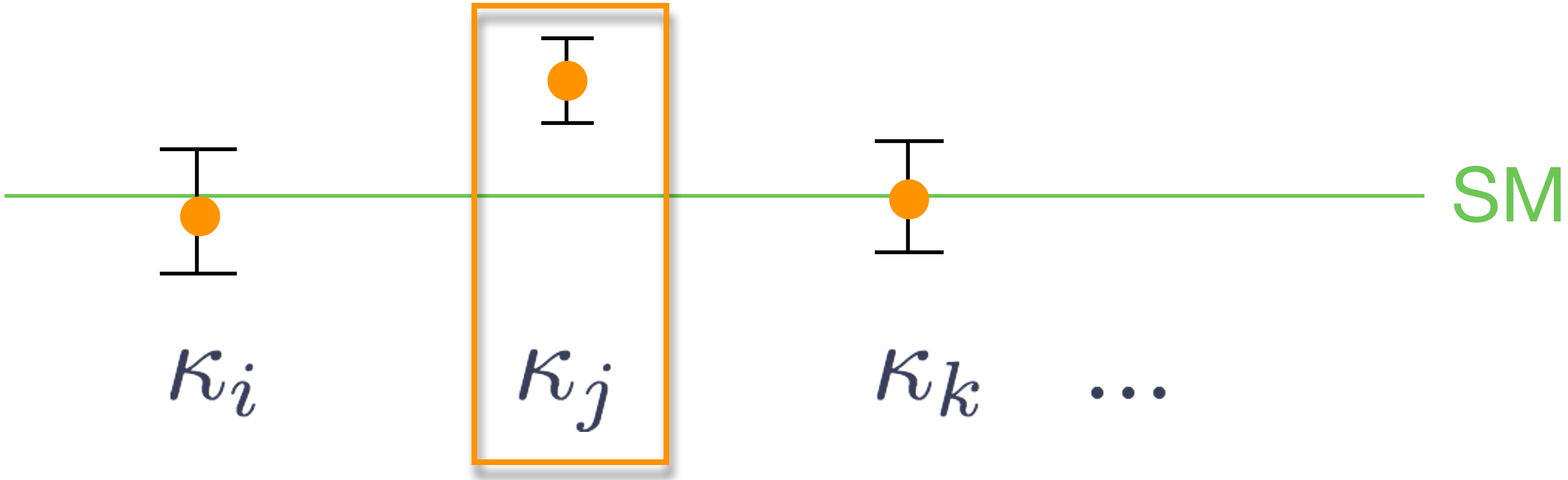
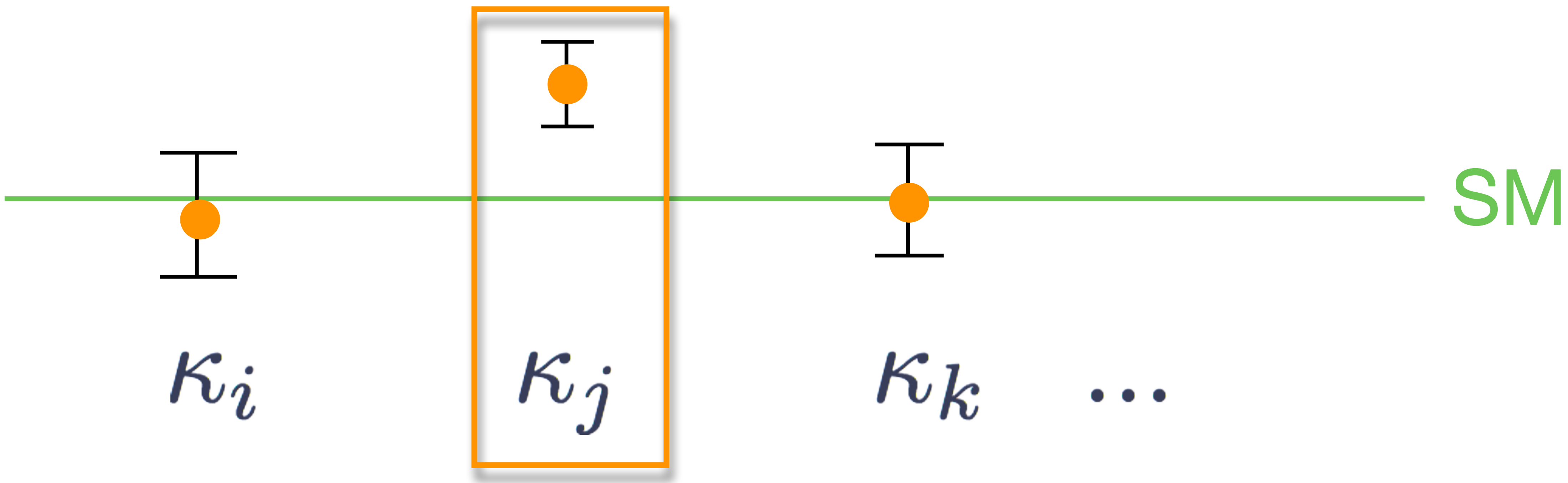


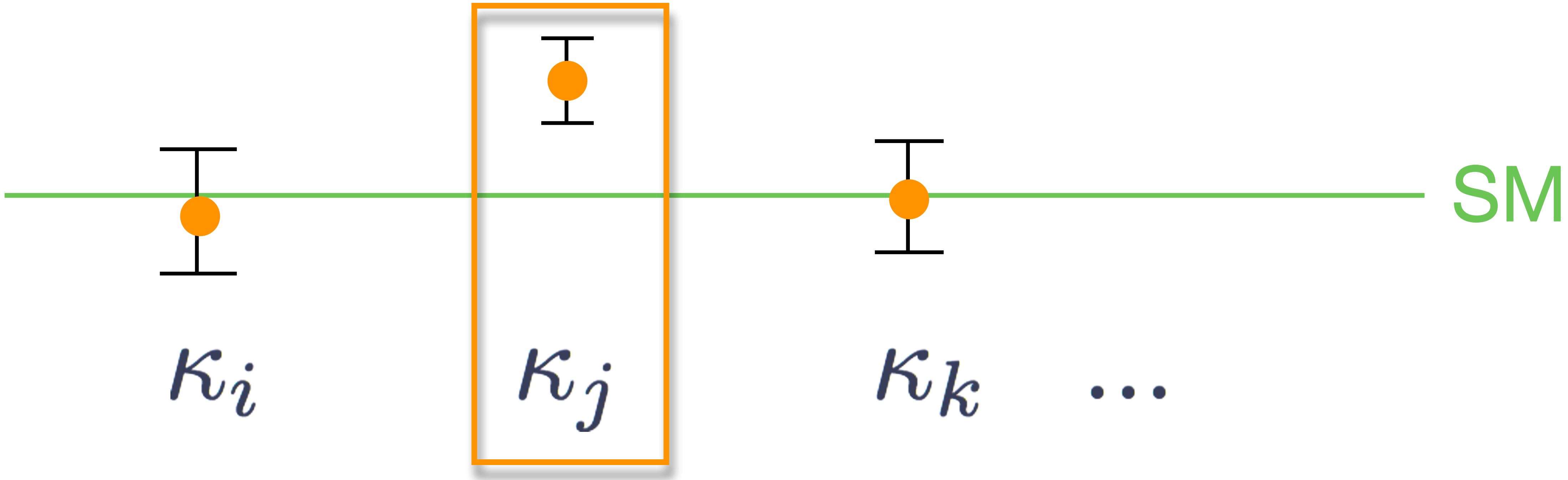
how well?



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	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



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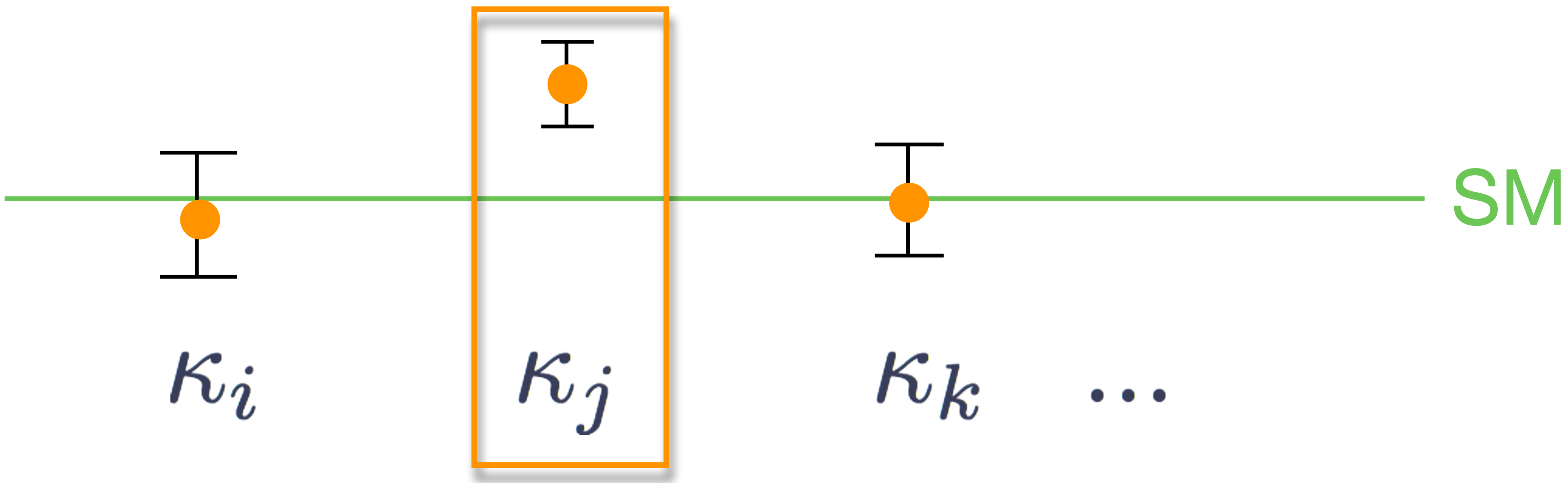
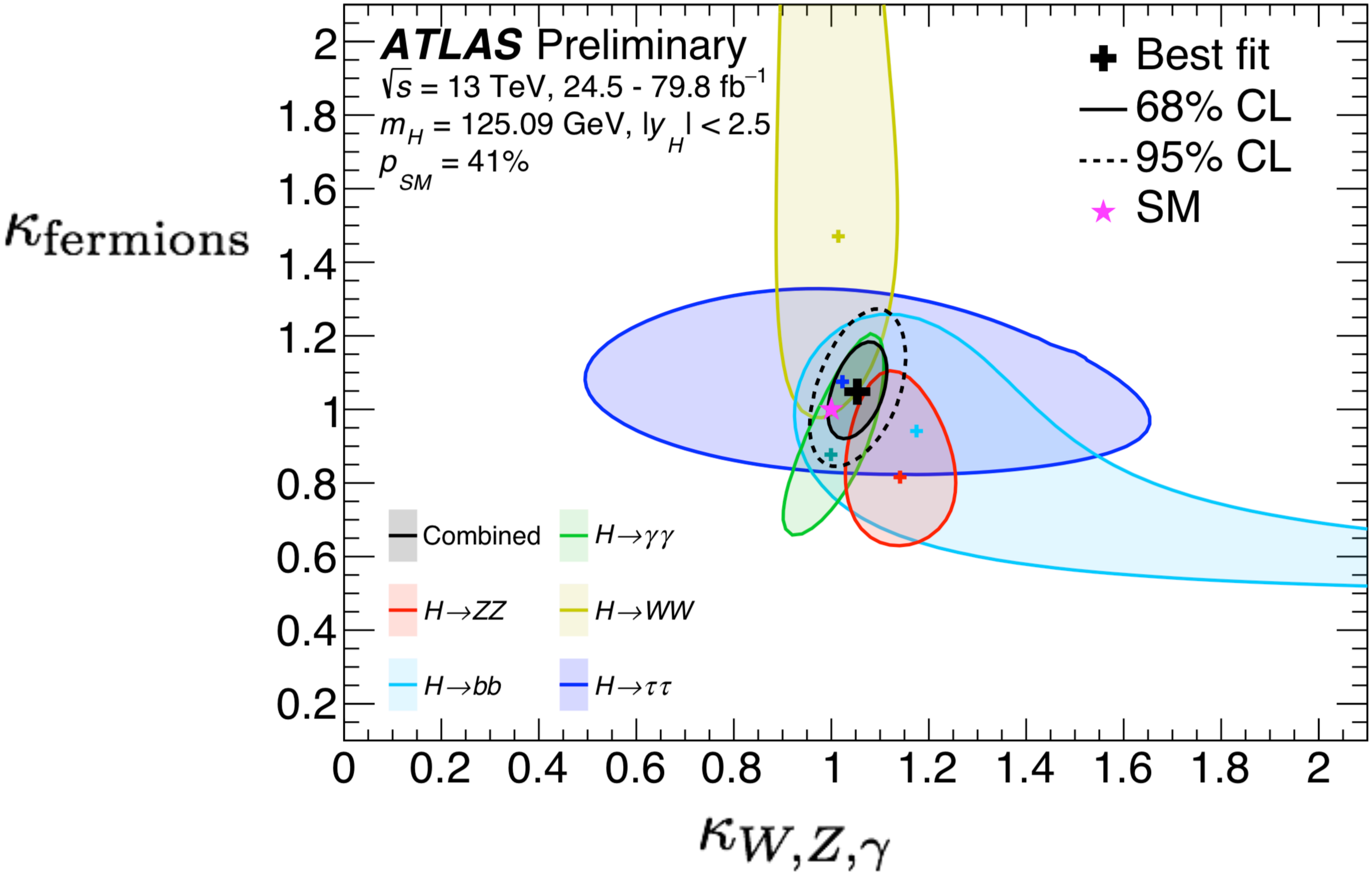
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Benchmark for discovery is few % to sub-%

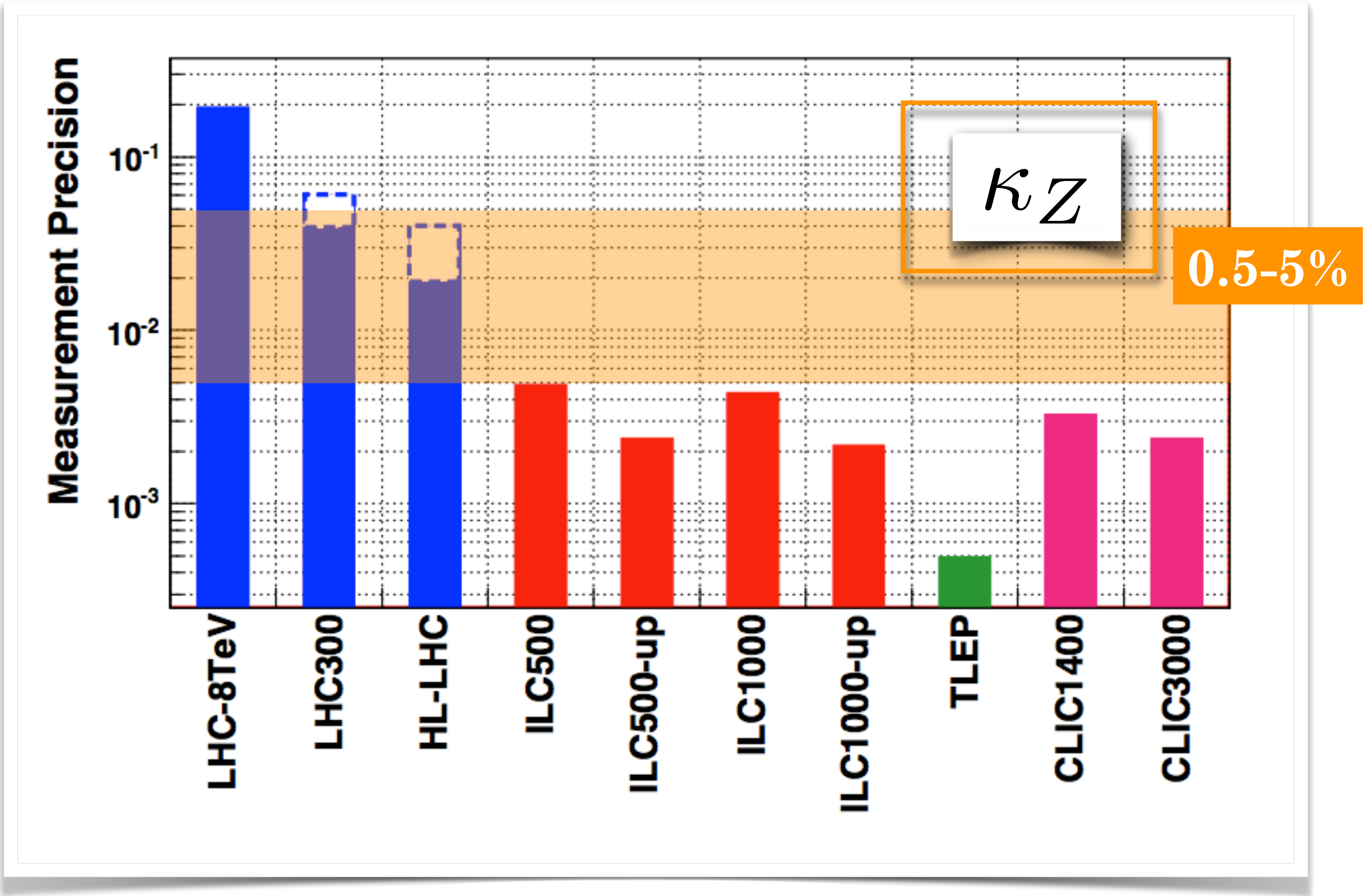


LHC Status in the couplings:

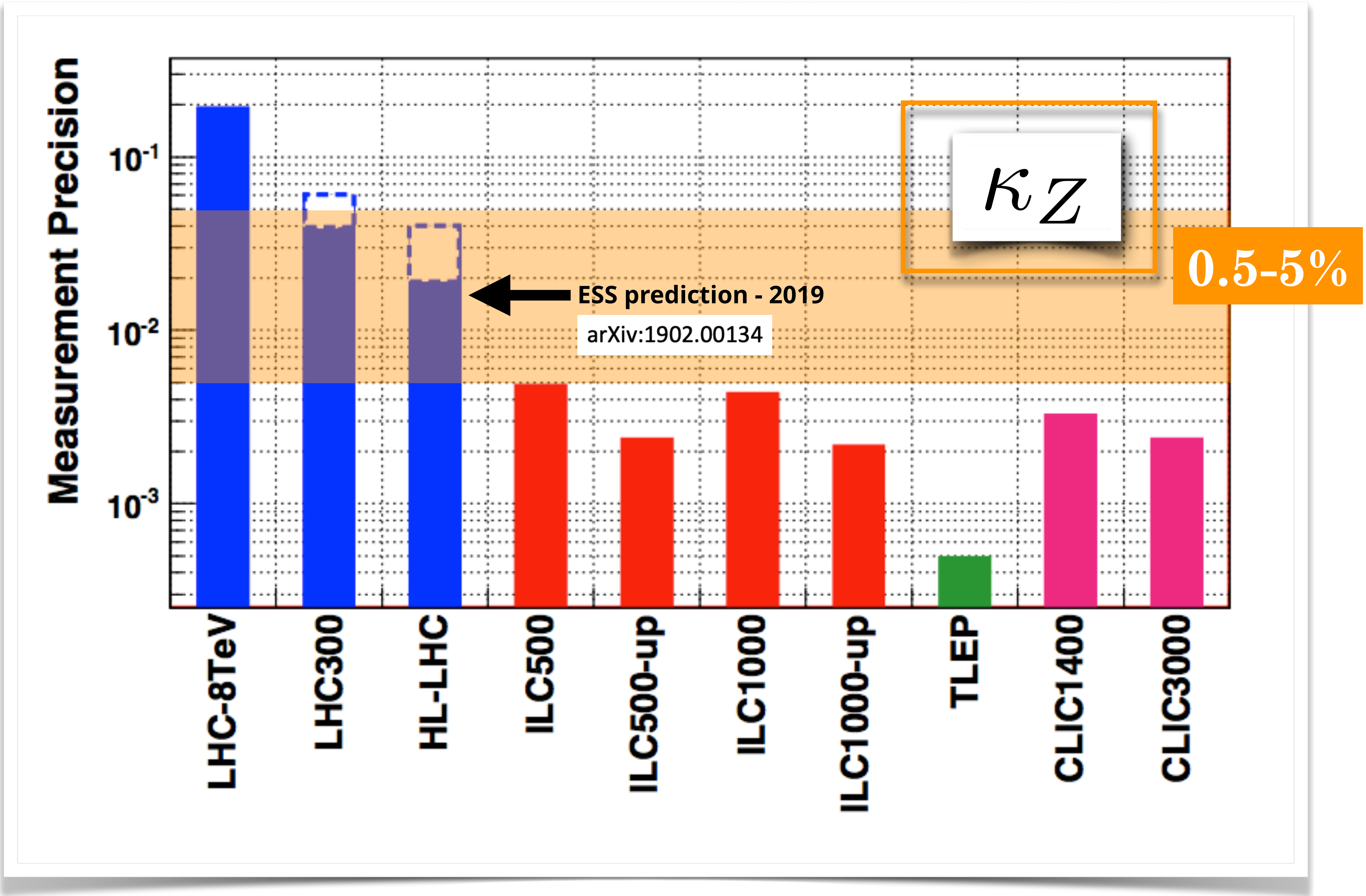
- 10's% precision



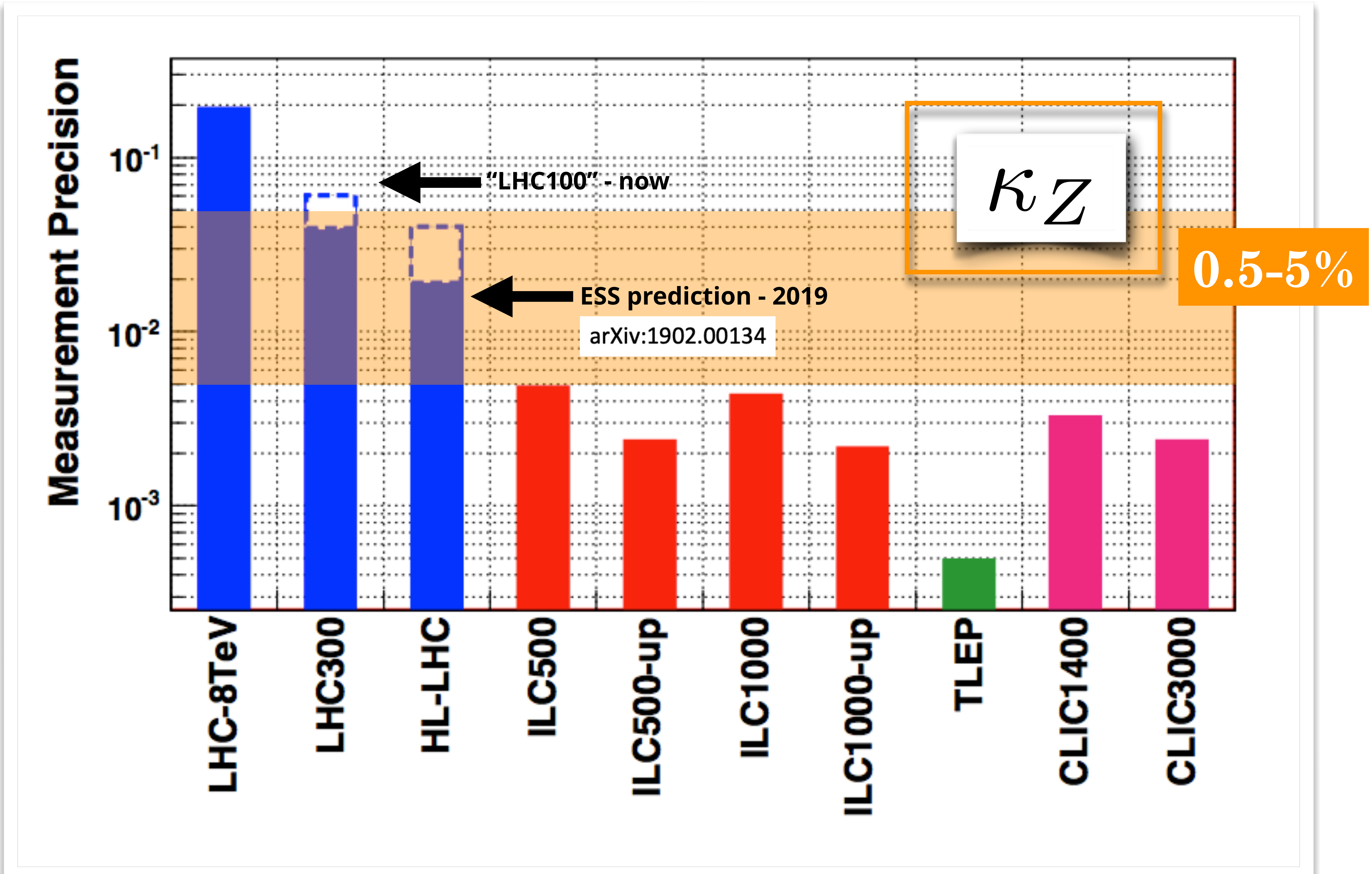
Extrapolating to future machines



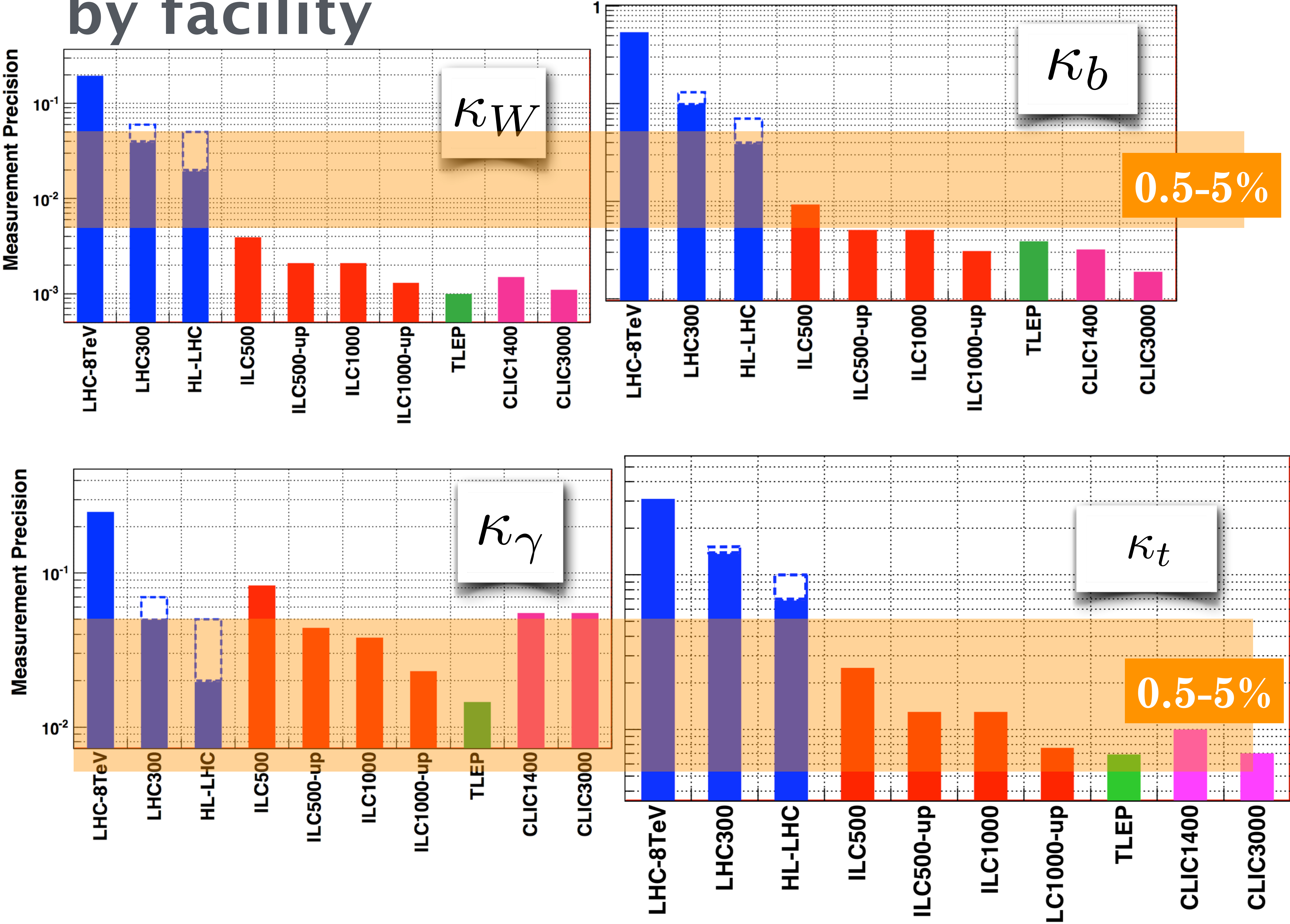
Extrapolating to future machines



Extrapolating to future machines

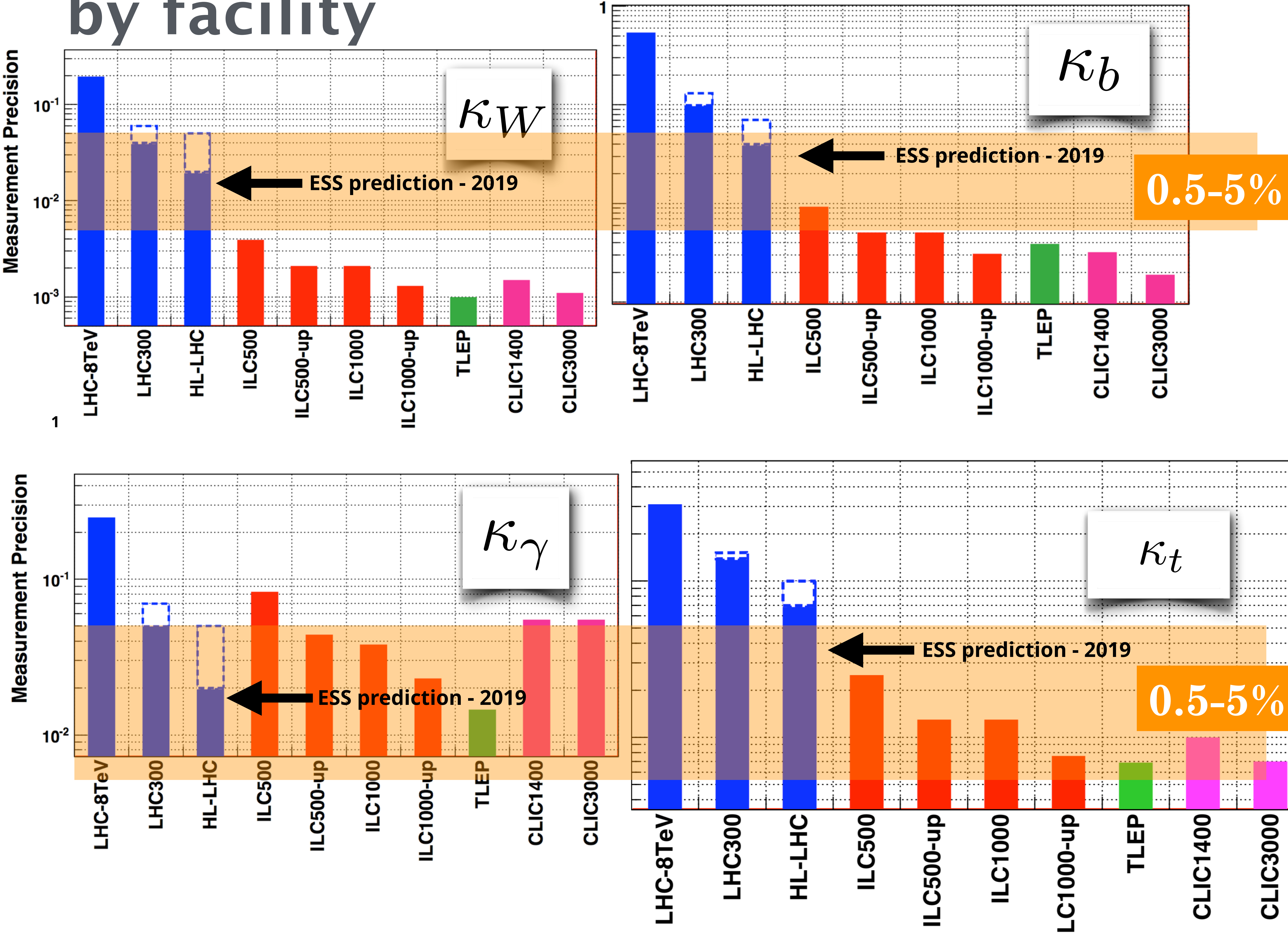


by facility



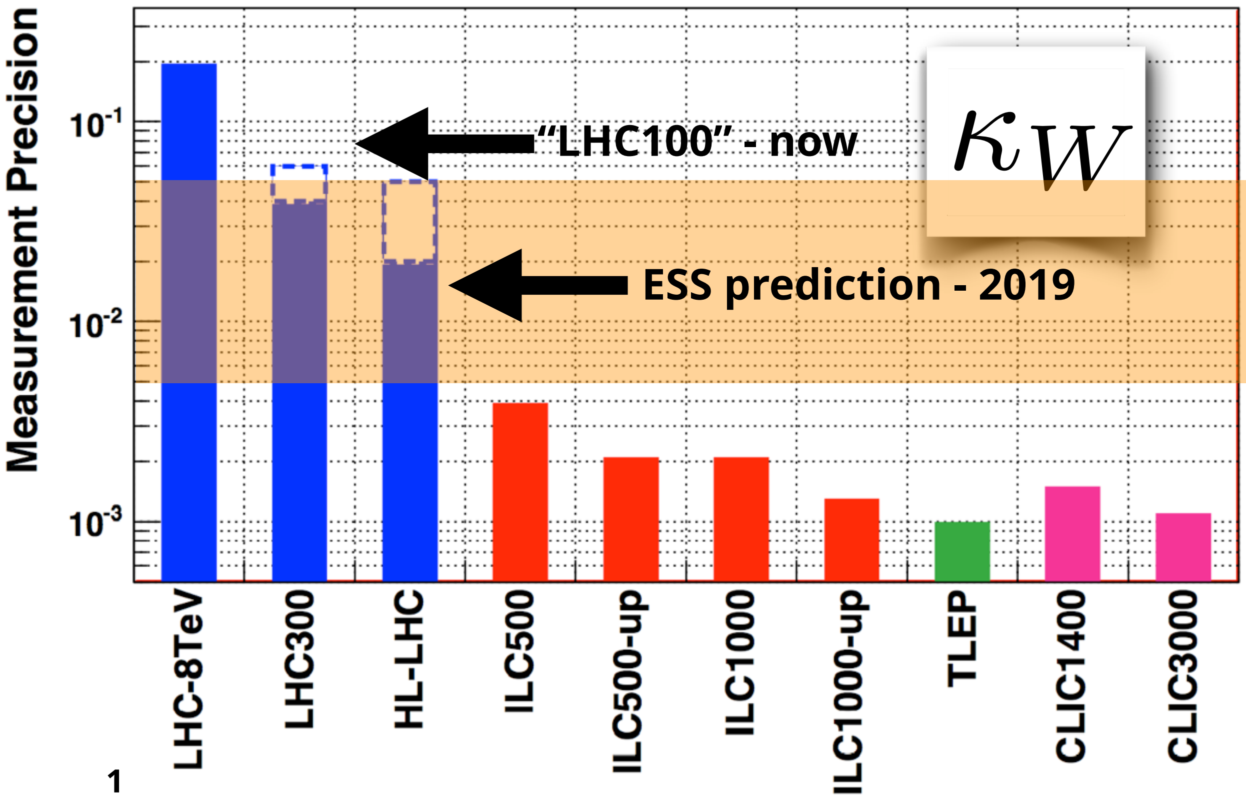
Measurement Precision
κ_W
κ_b
κ_γ
κ_t
0.5-5%
0.5-5%
1
10^{-1}
10^{-2}
10^{-3}
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000

by facility

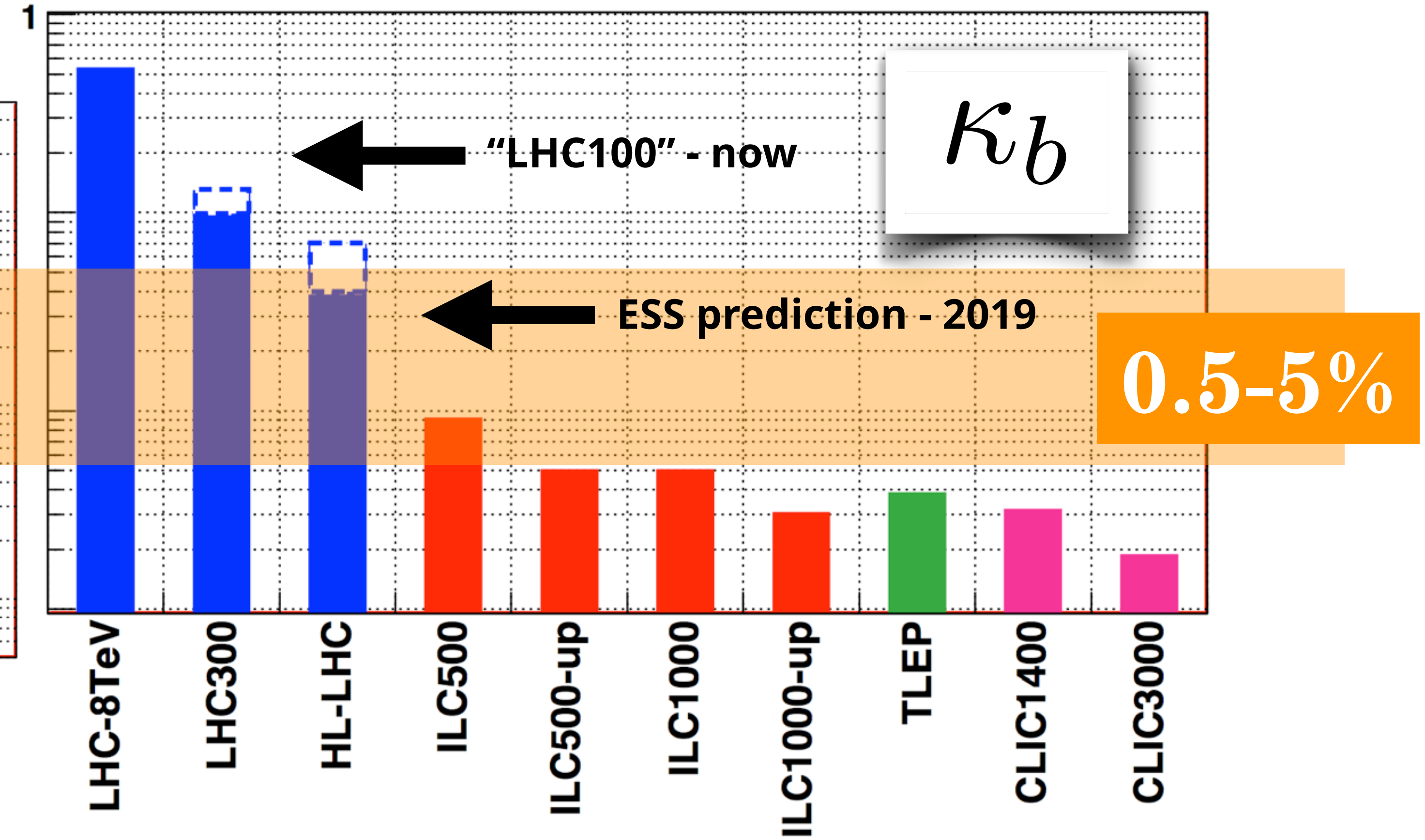


Measurement Precision
κ_W
κ_b
κ_γ
κ_t
ESS prediction - 2019
0.5-5%
10^{-1}
10^{-2}
10^{-3}
1
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000

by facility



Measurement Precision
10^-1
10^-2
10^-3
1
κ_W
"LHC100" - now
ESS prediction - 2019
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000



1
κ_b
"LHC100" - now
ESS prediction - 2019
0.5-5%
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
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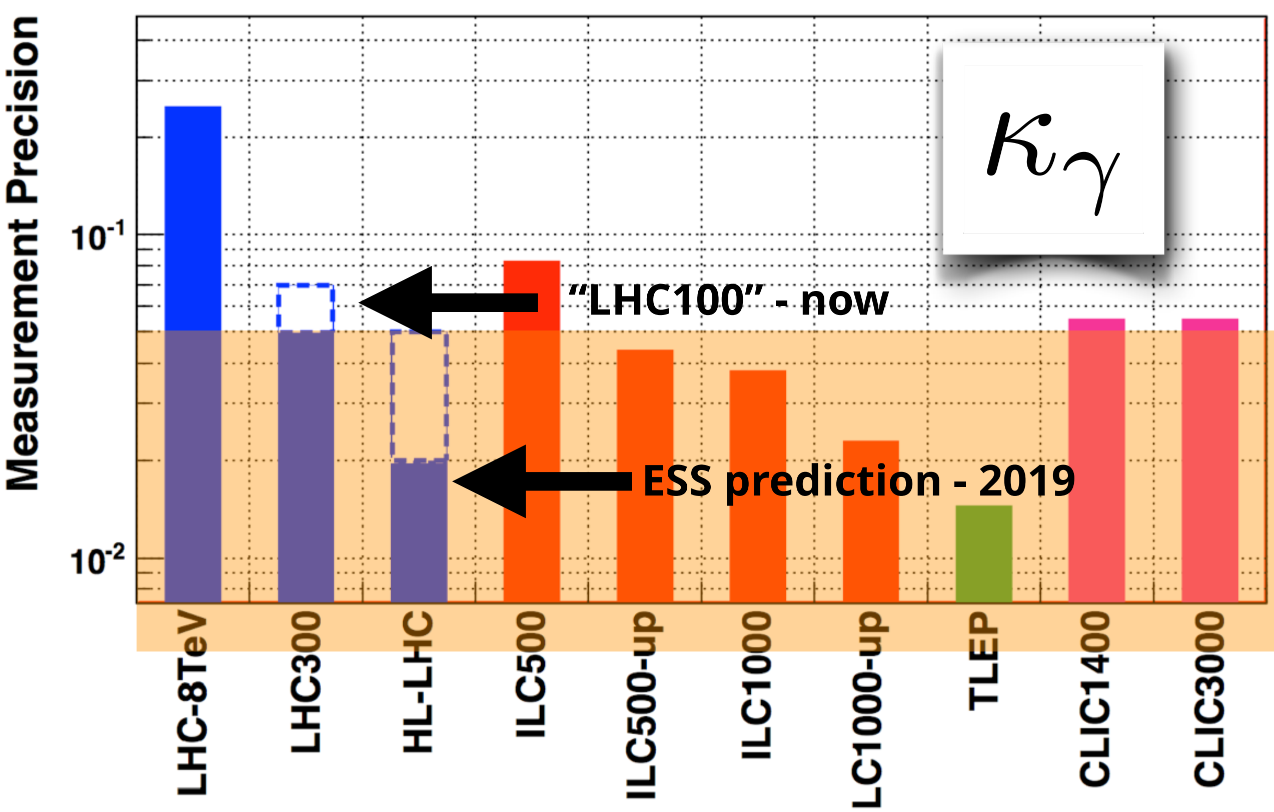
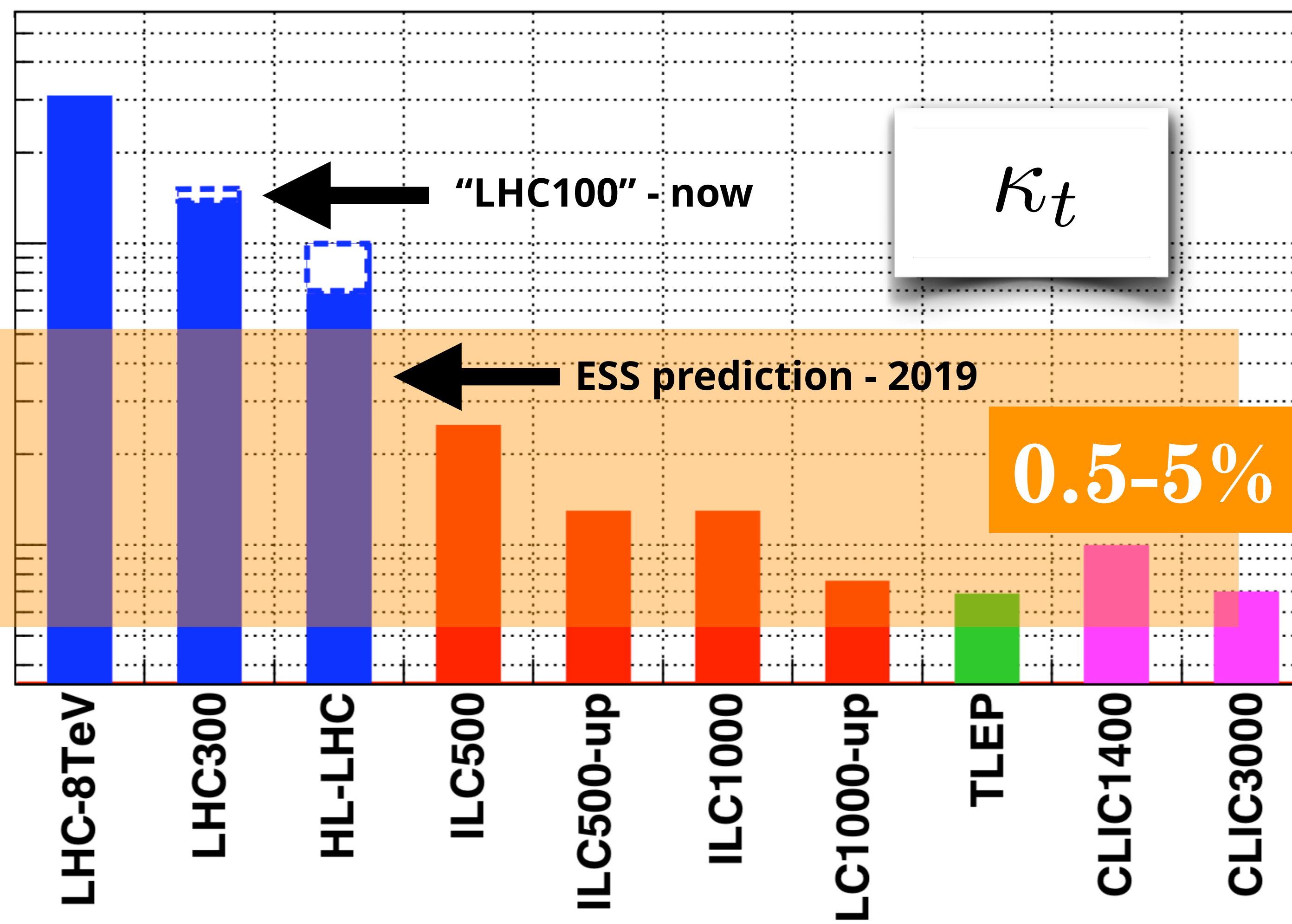


Measurement Precision
10^-1
10^-2
κ_γ
"LHC100" - now
ESS prediction - 2019
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000



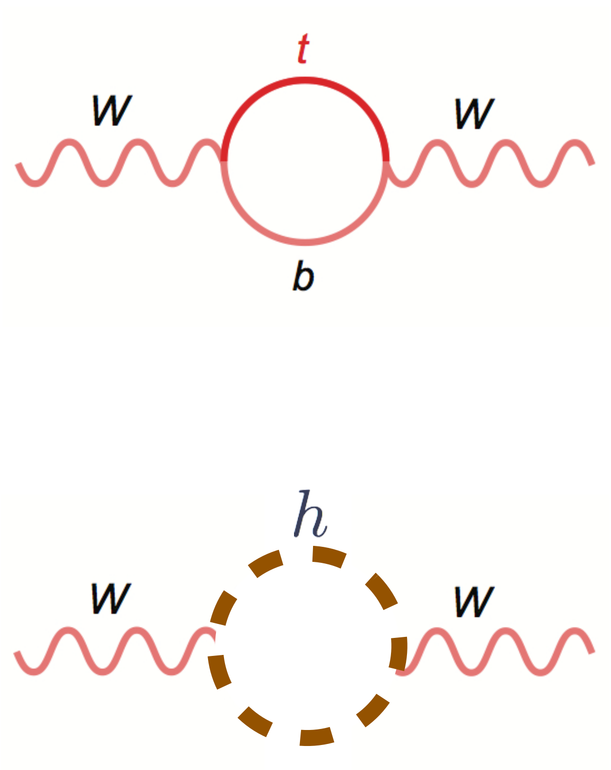
κ_t
"LHC100" - now
ESS prediction - 2019
0.5-5%
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000

The precision Higgs Boson program is in full swing.

Precision Study of Electroweak Physics

Electroweak Precision Observables

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



Electroweak Precision Observables

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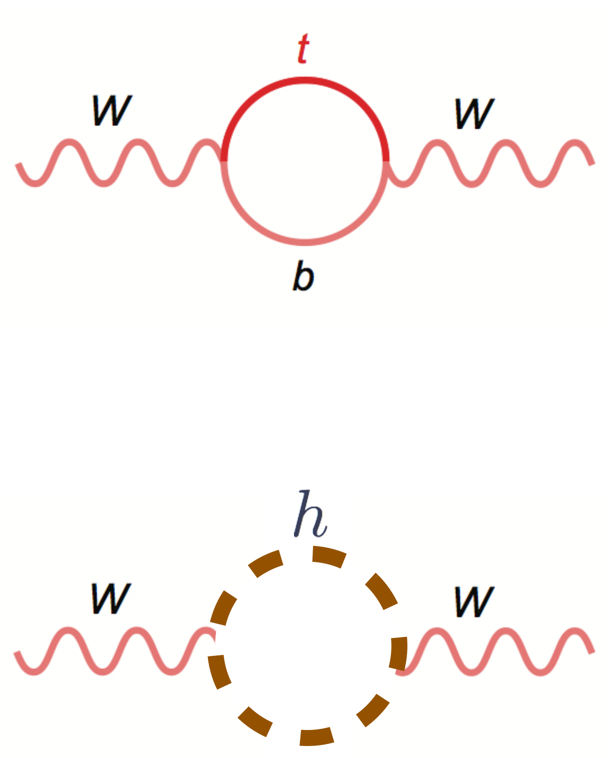

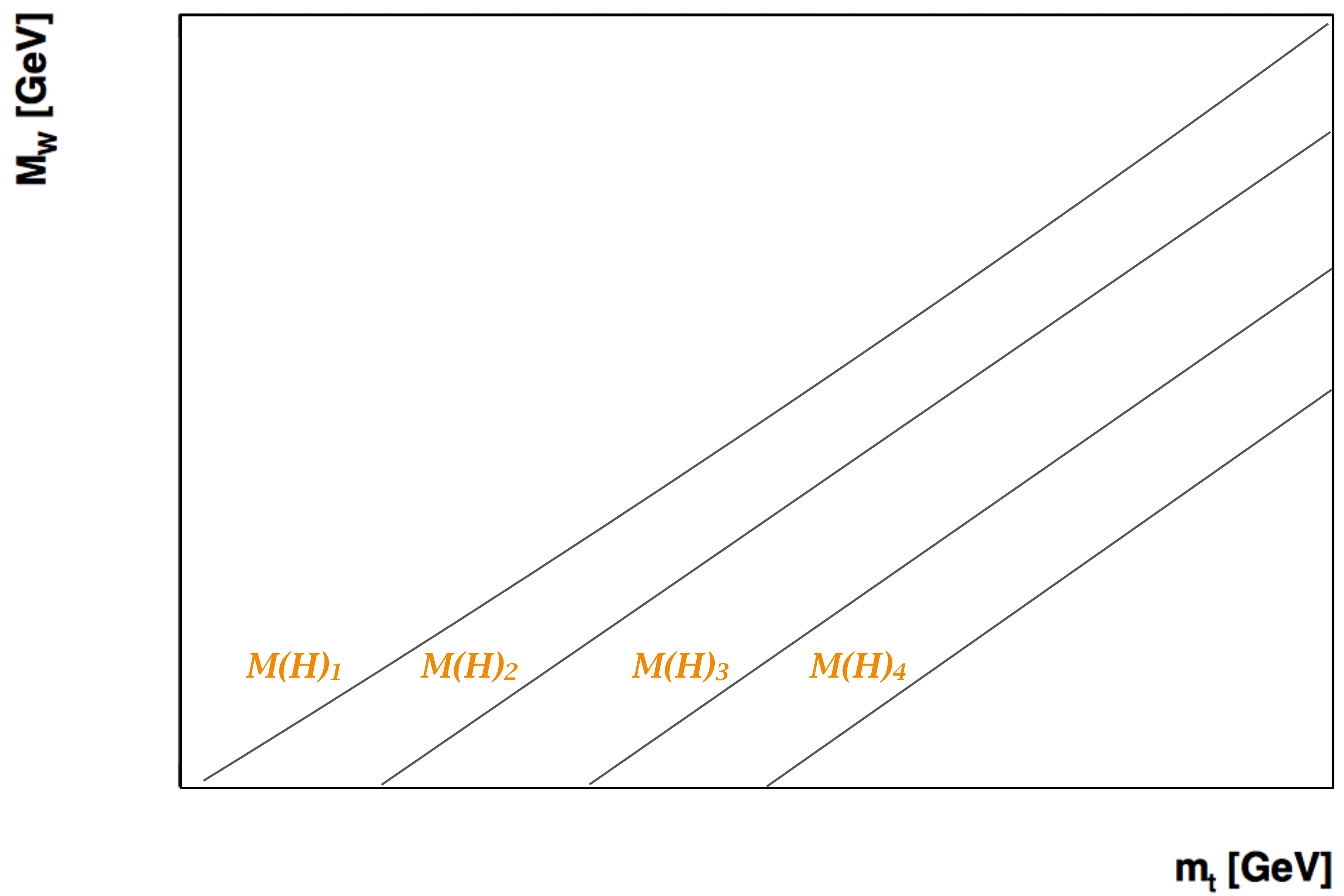

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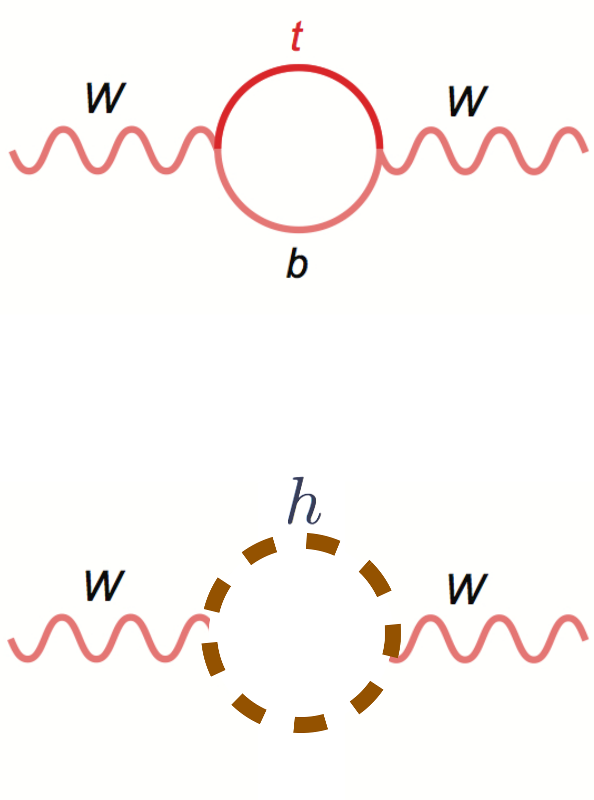

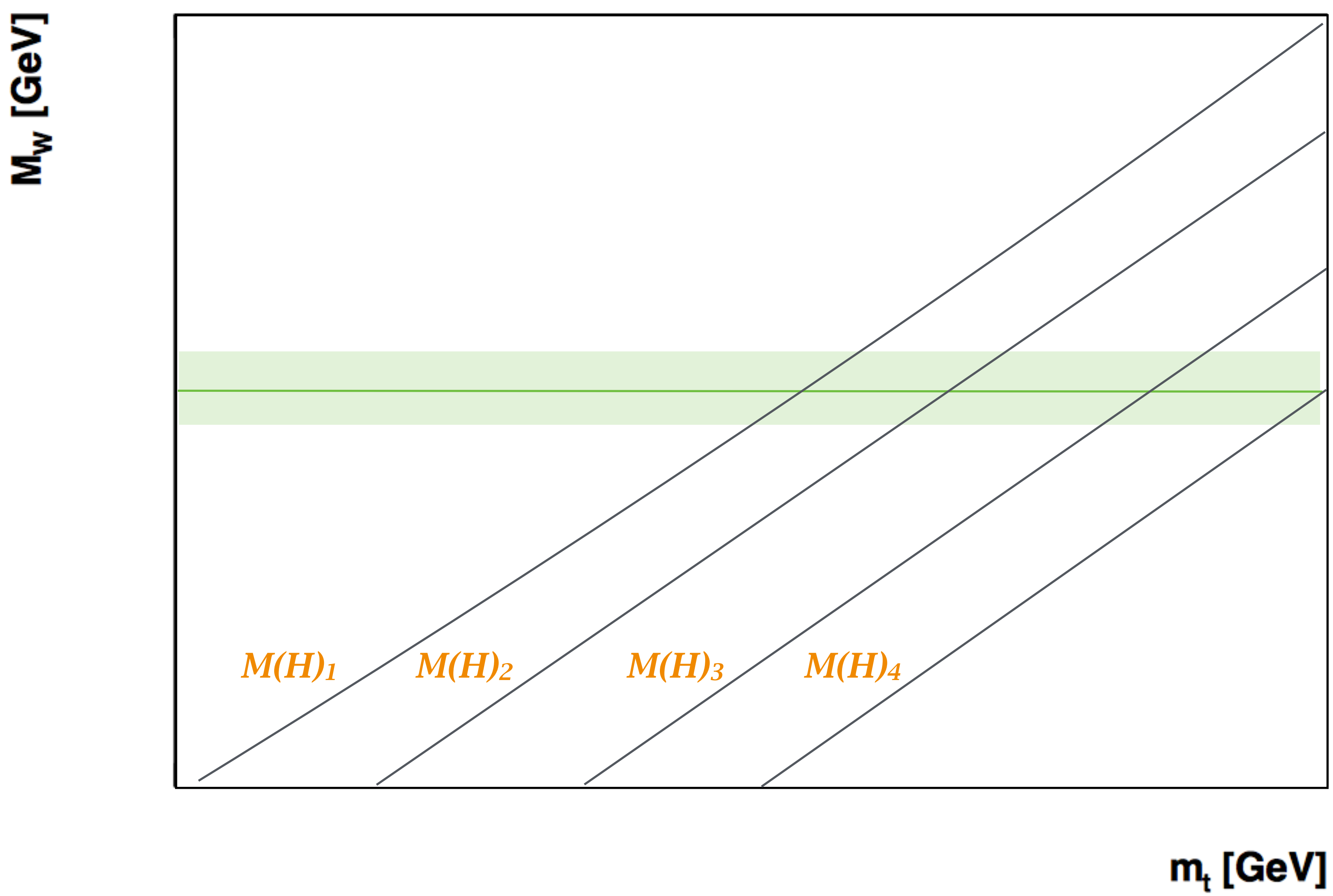

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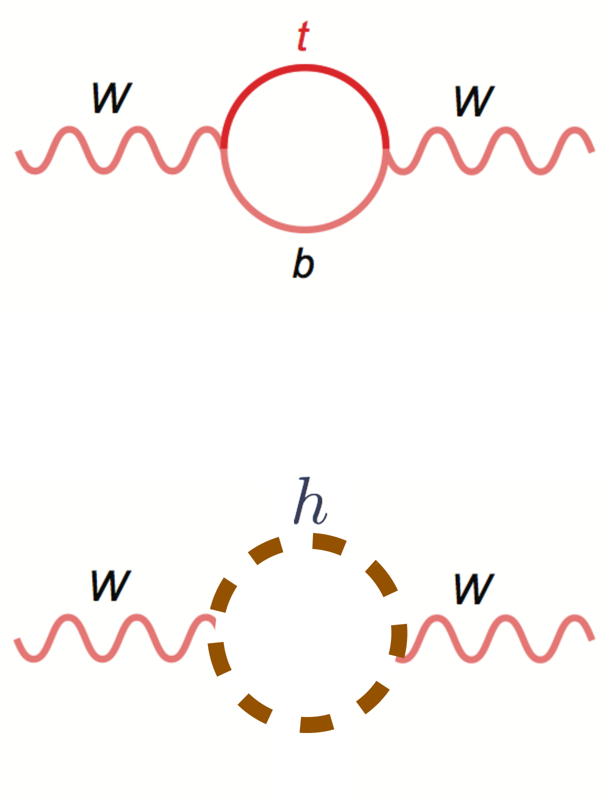

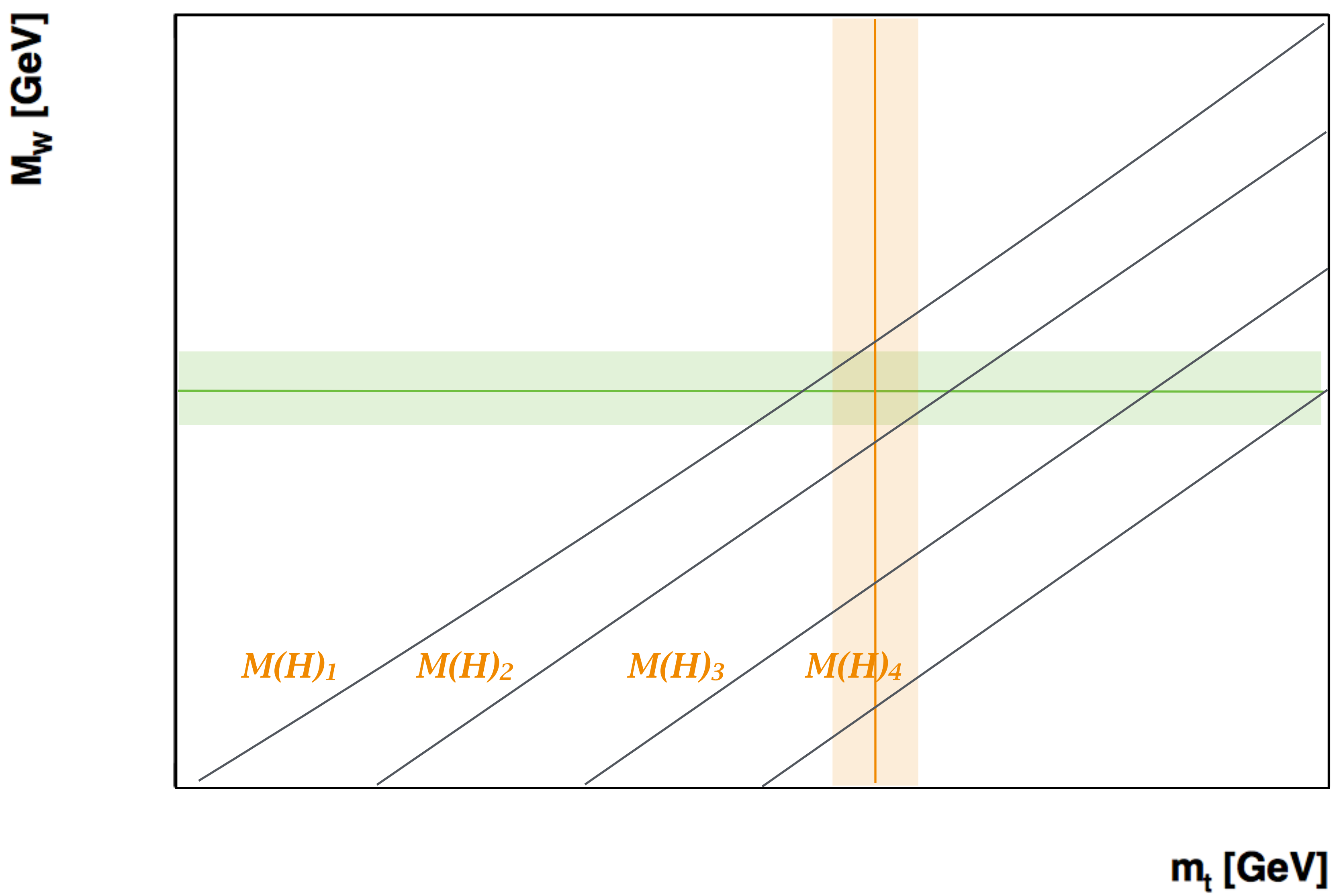

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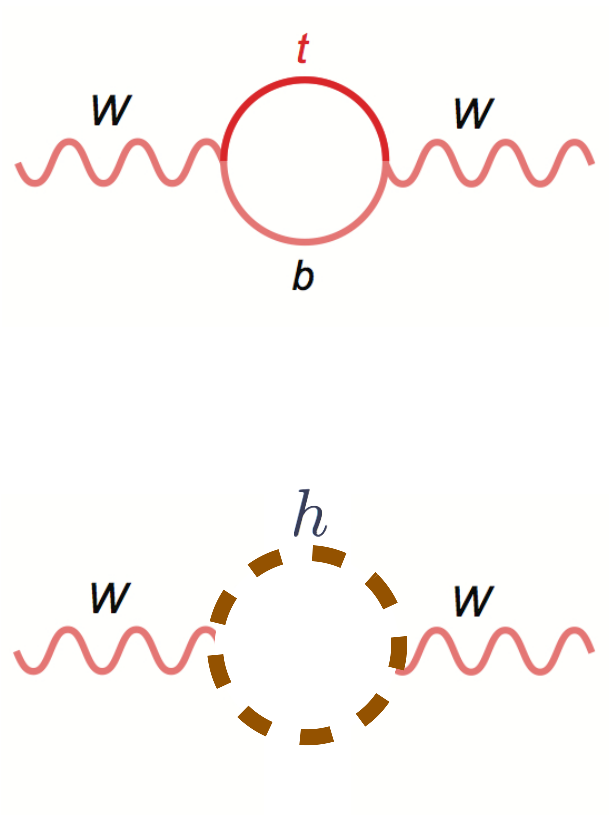

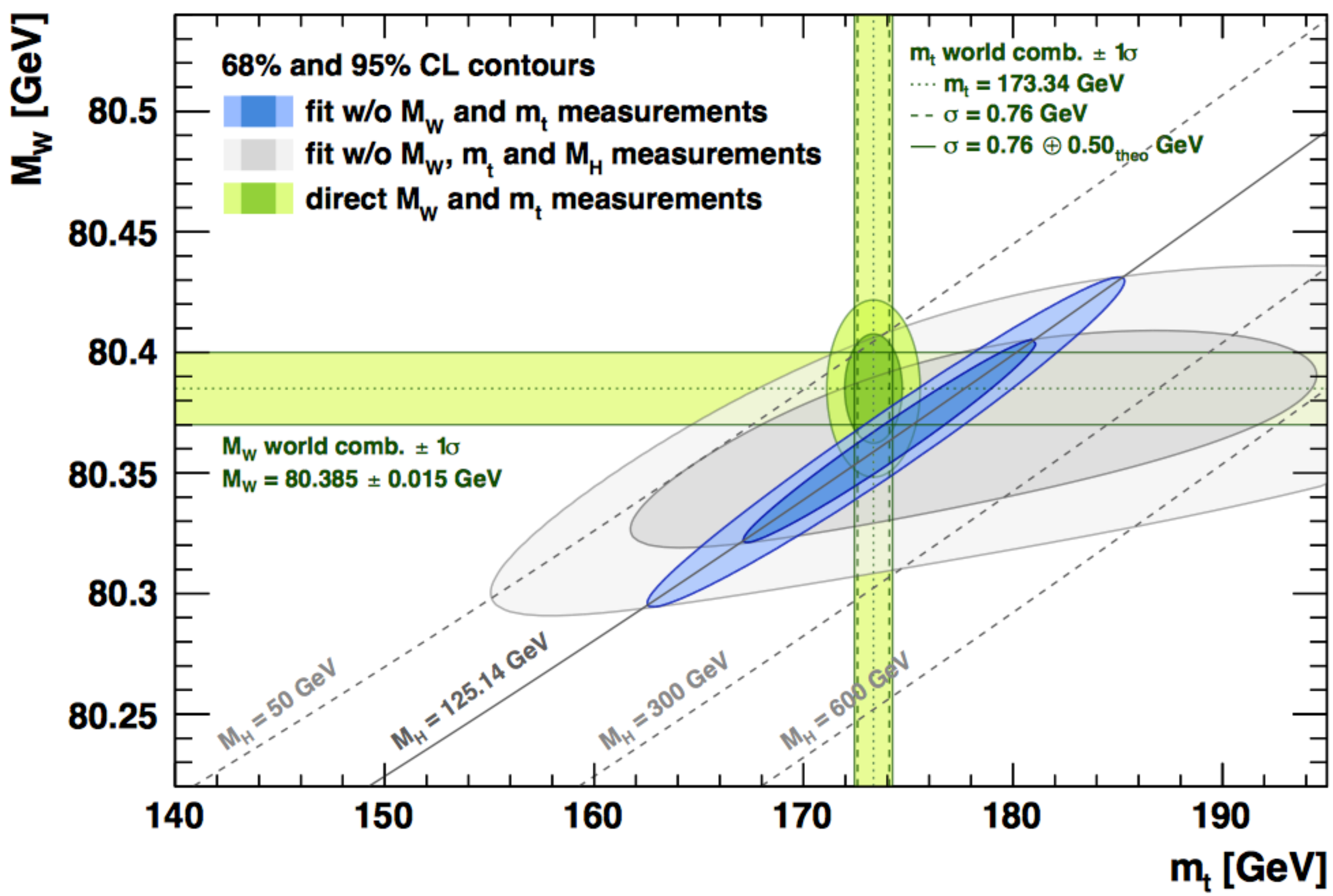

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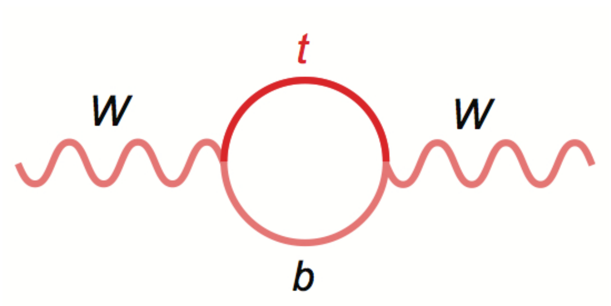
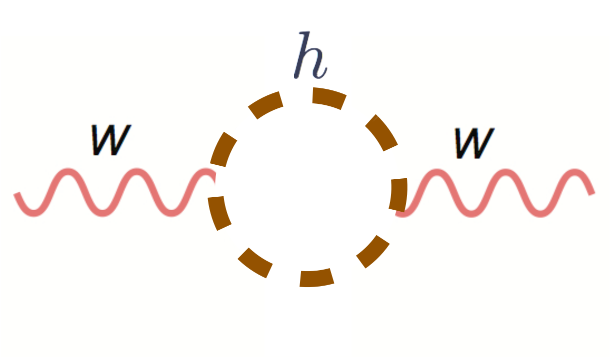
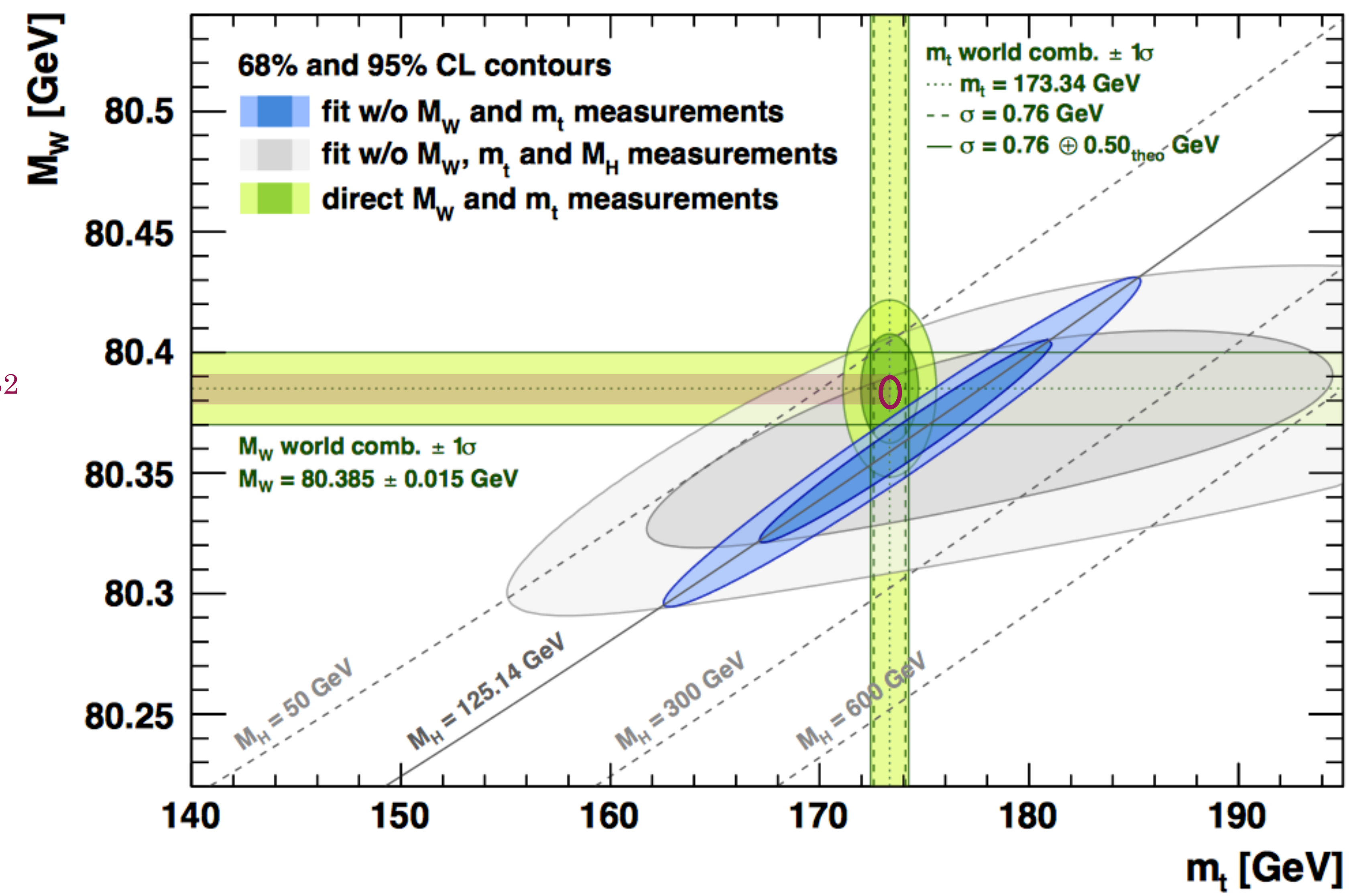


Systematics goal of $M_W = \pm\ 5\ \mathrm{MeV}/c^2$





Electroweak Precision Observables

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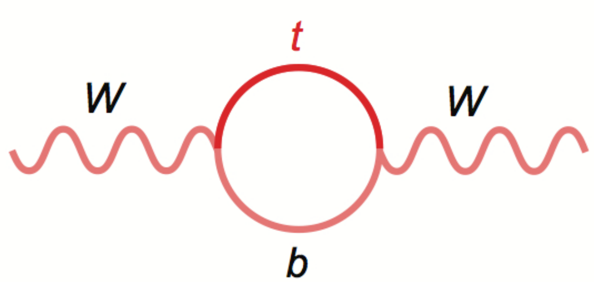

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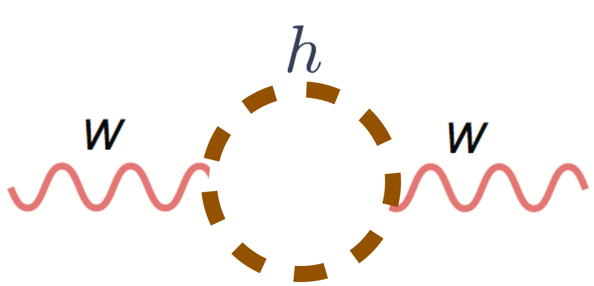
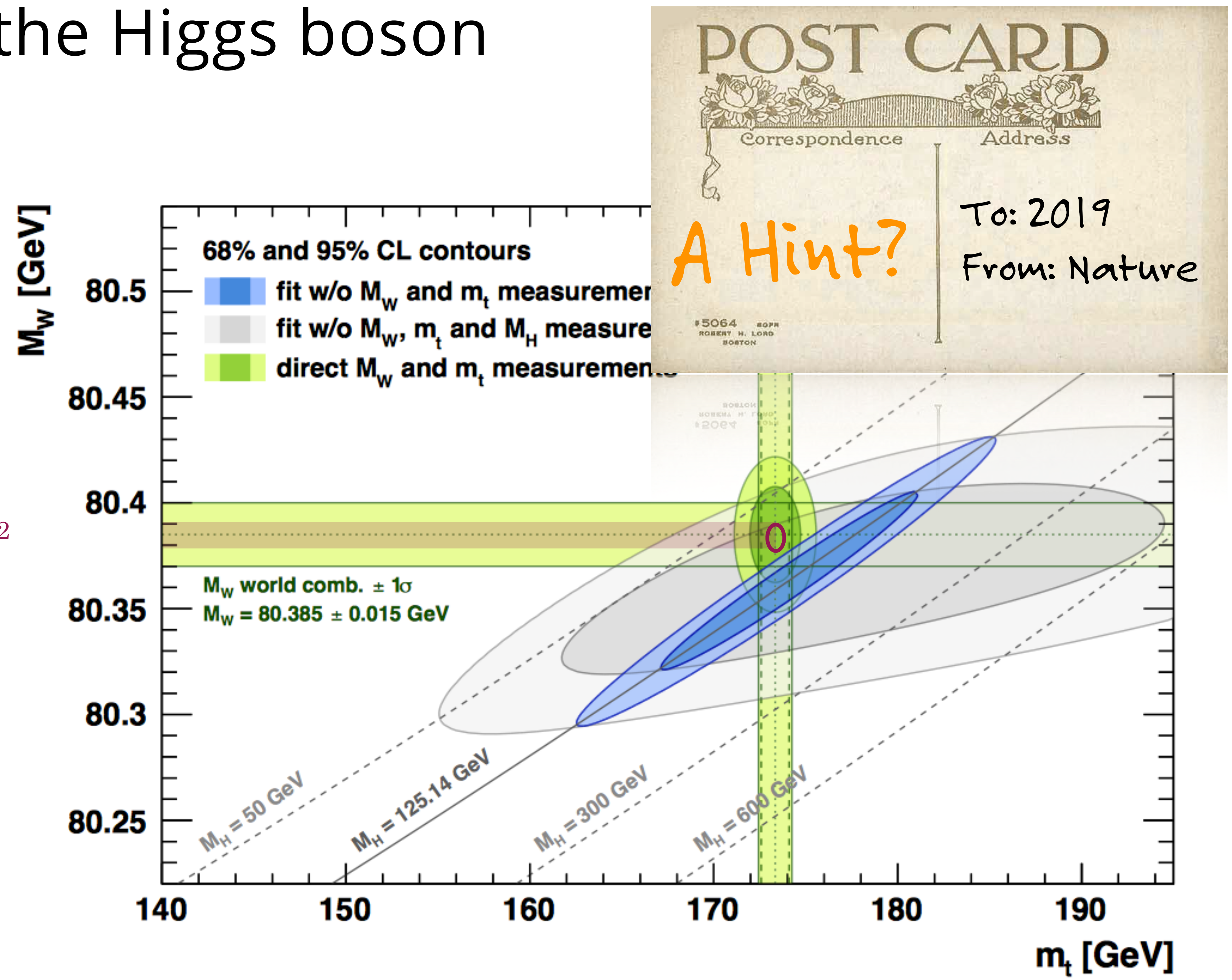




Fully Understanding the Top Quark

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

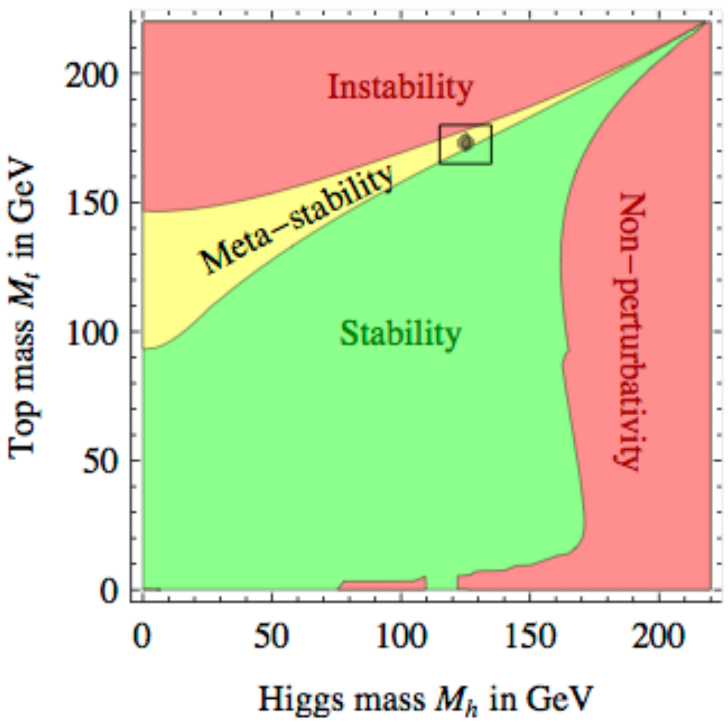
  keep up with M_W precision

- fundamental parameter

  largest coupling to Higgs

  stability argument sensitivity

why measure m_t precisely?



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

- 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

  keep up with M_W precision

- fundamental parameter

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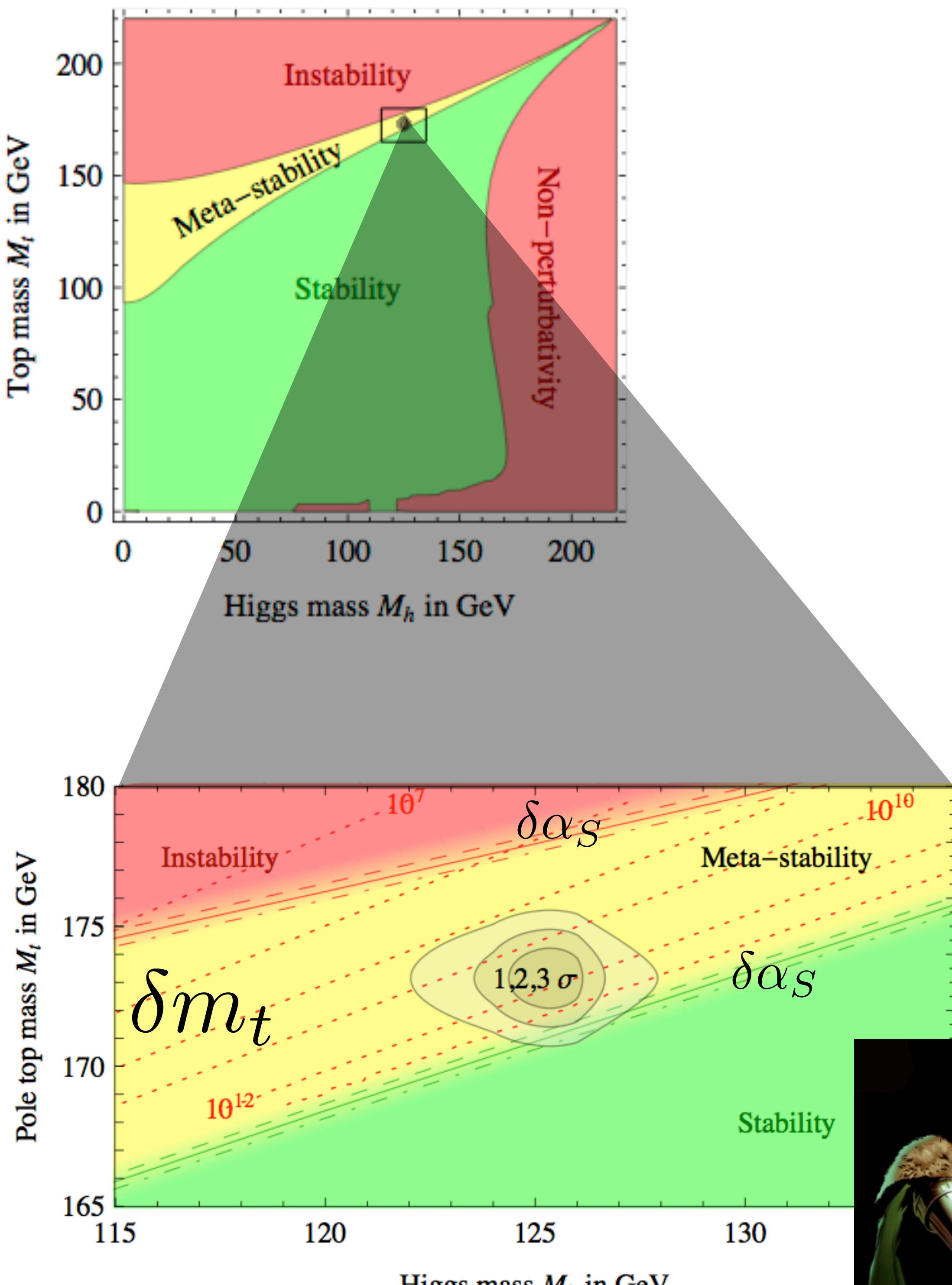
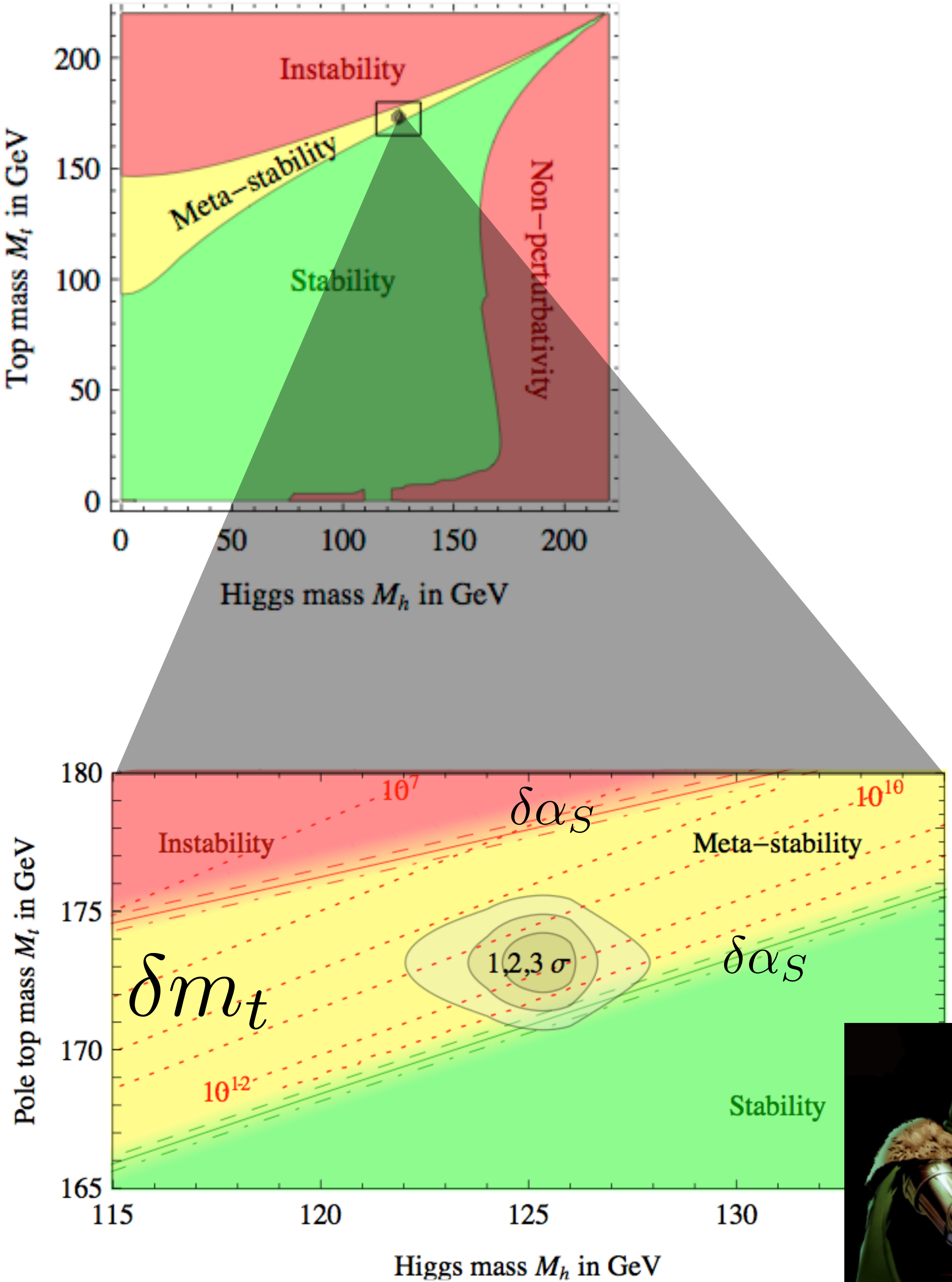


why measure m_t precisely?

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



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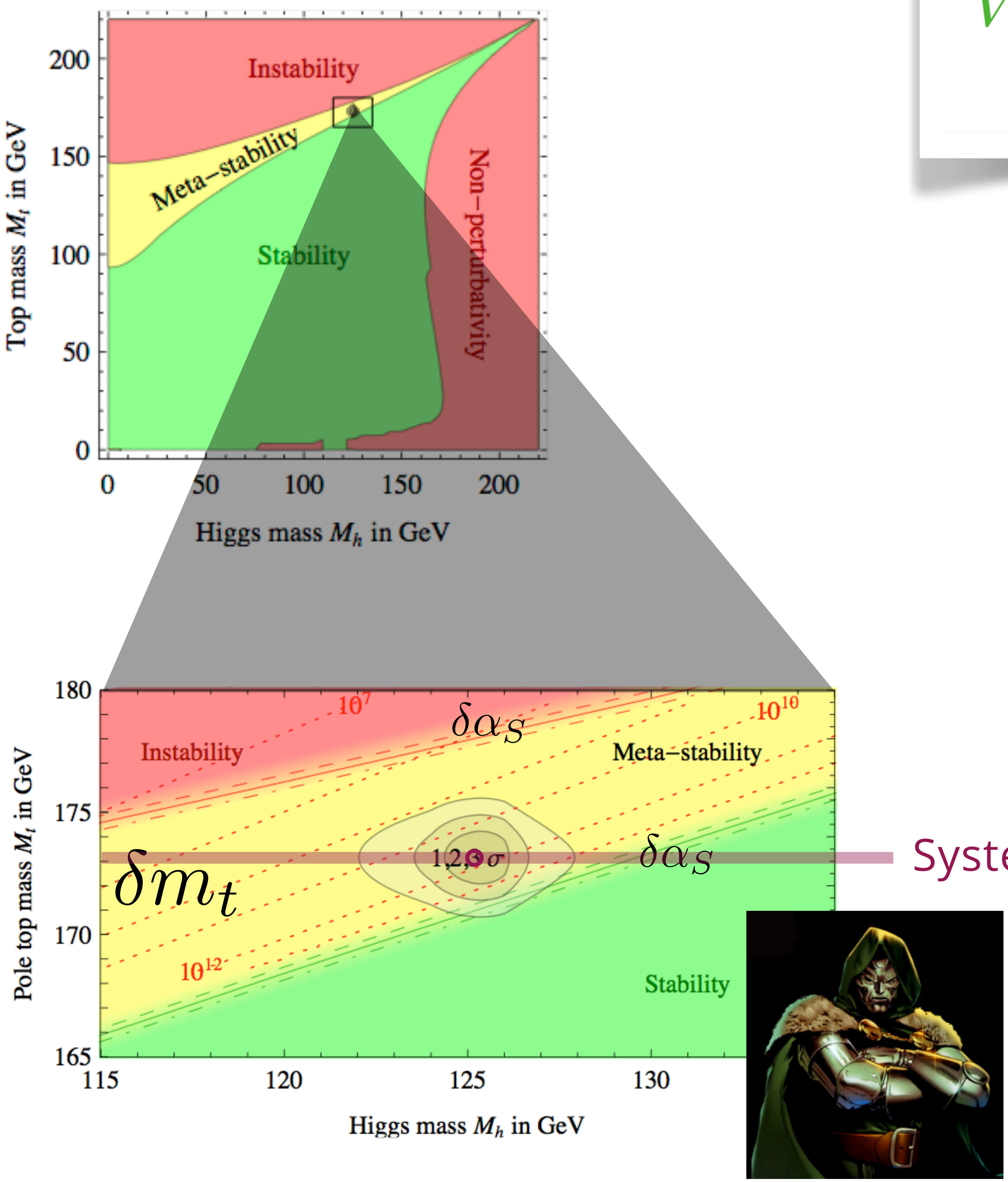
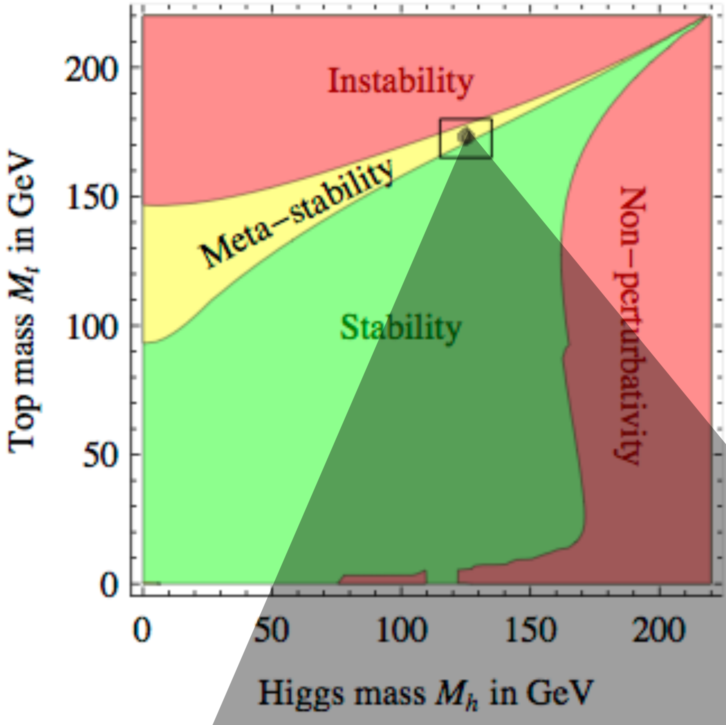
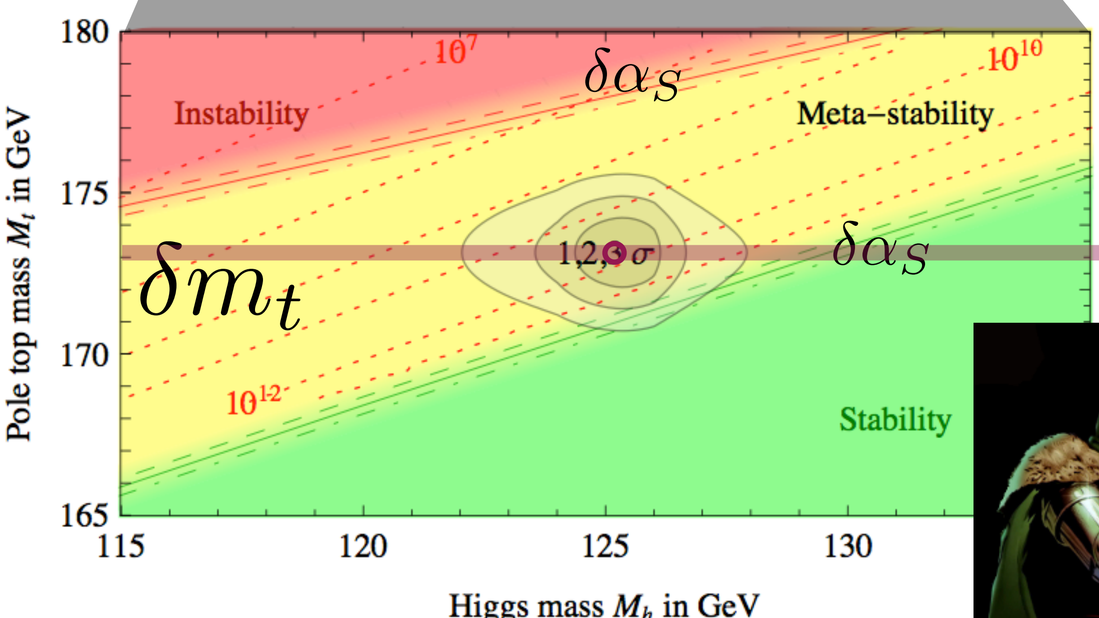


Systematics goal of $m_{top} = \pm\ 500\ \mathrm{MeV}/c^2$

why measure m_t precisely?

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





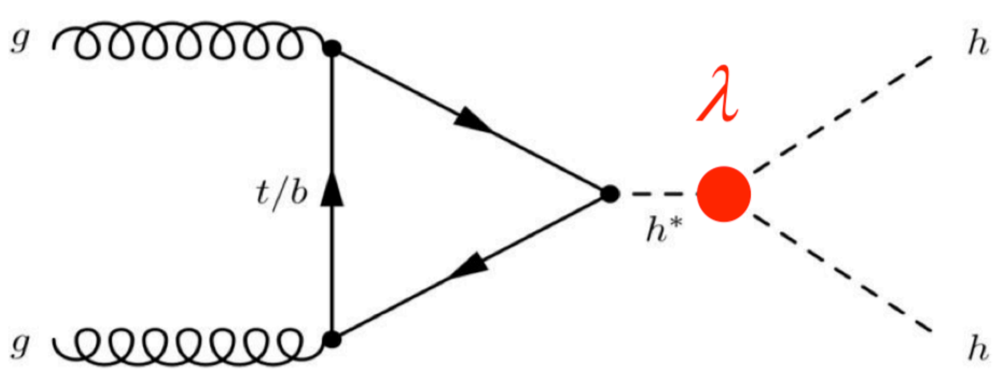
Systematics goal of $m_{top} = \pm$ 500 MeV/c^2

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

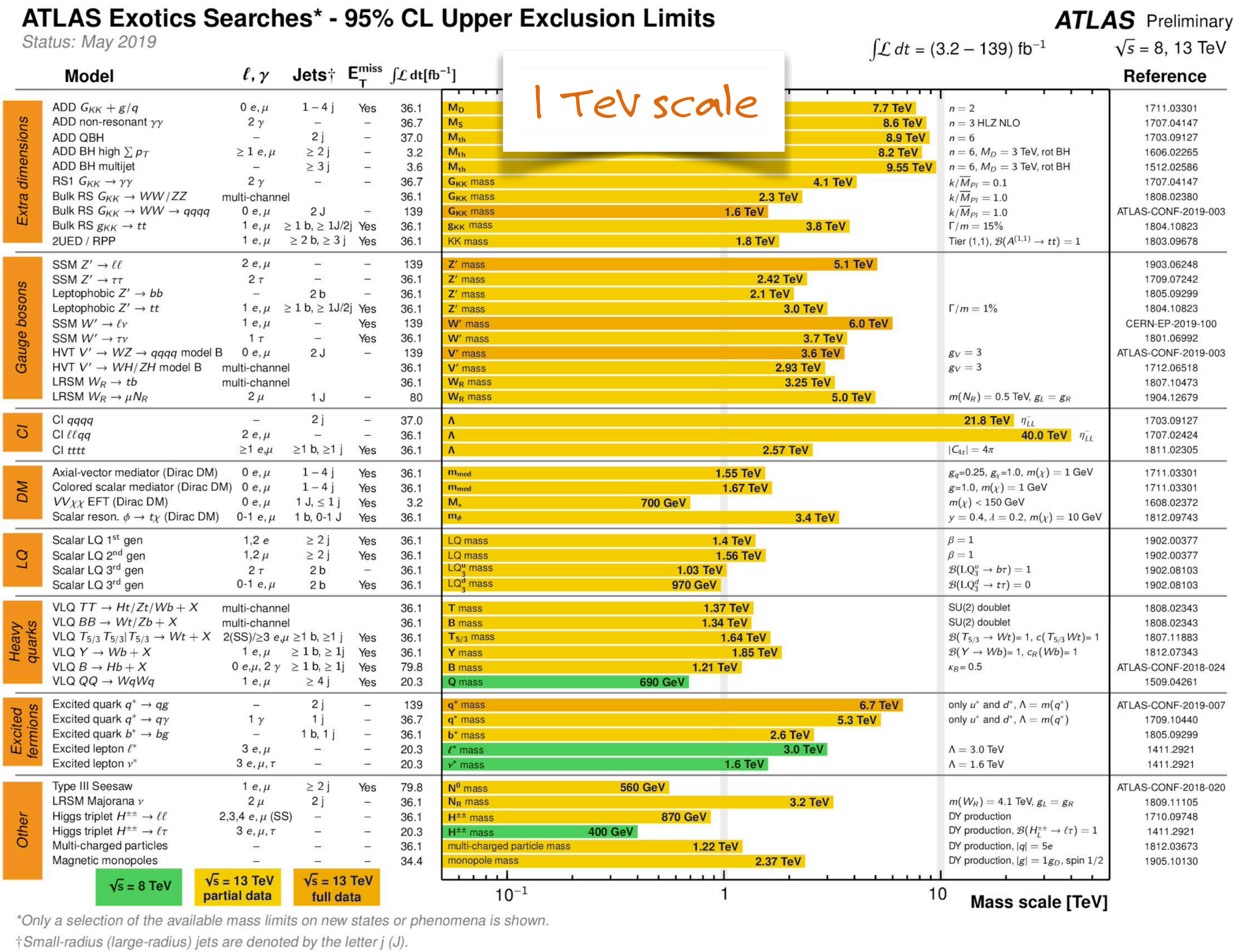
Beyond the Standard Model:

motivation from non-zero neutrino mass, the hierarchy problem, the antimatter problem, & the dark matter problem

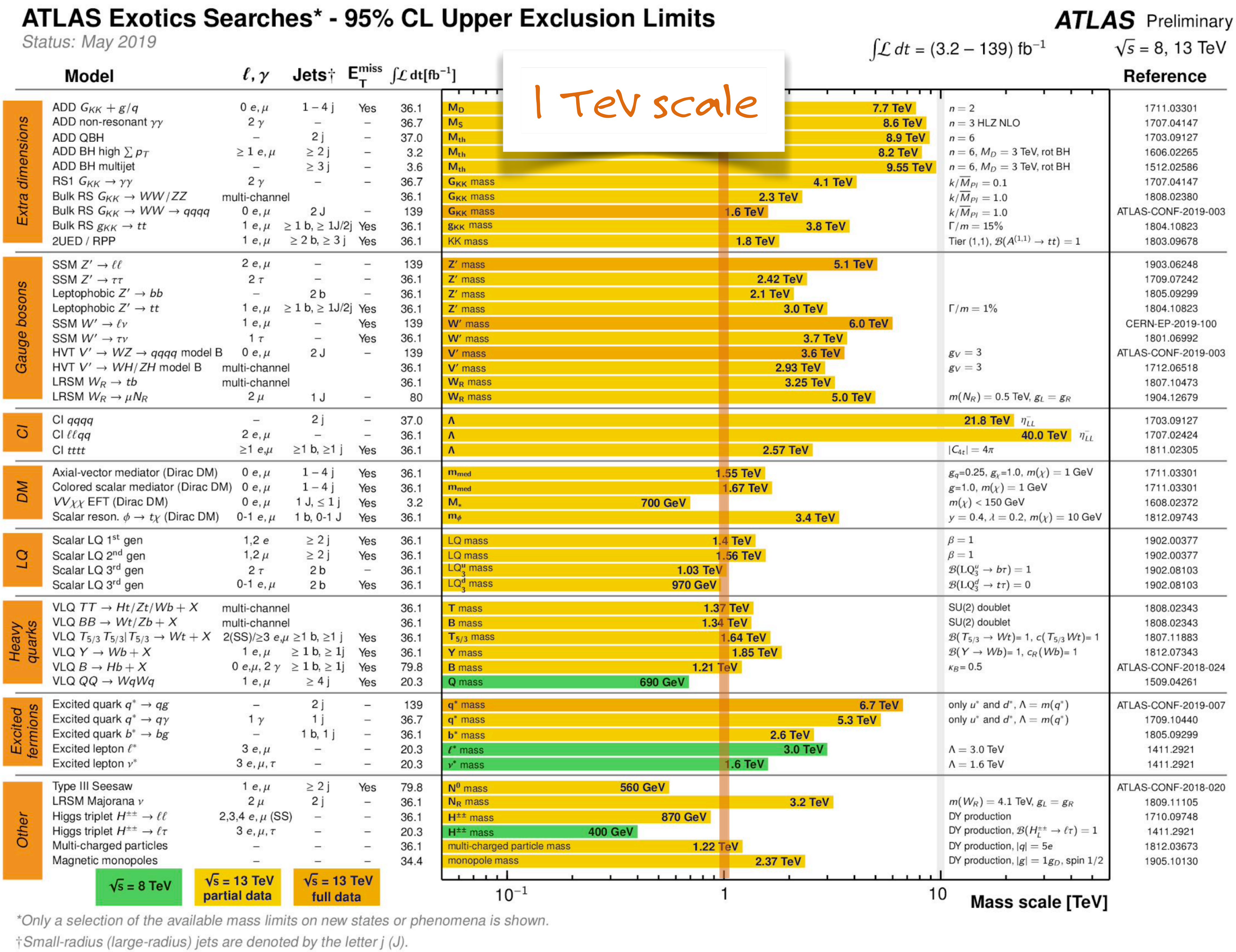
Dominated by prospects for new particles @ TeV-ish mass

and/or:

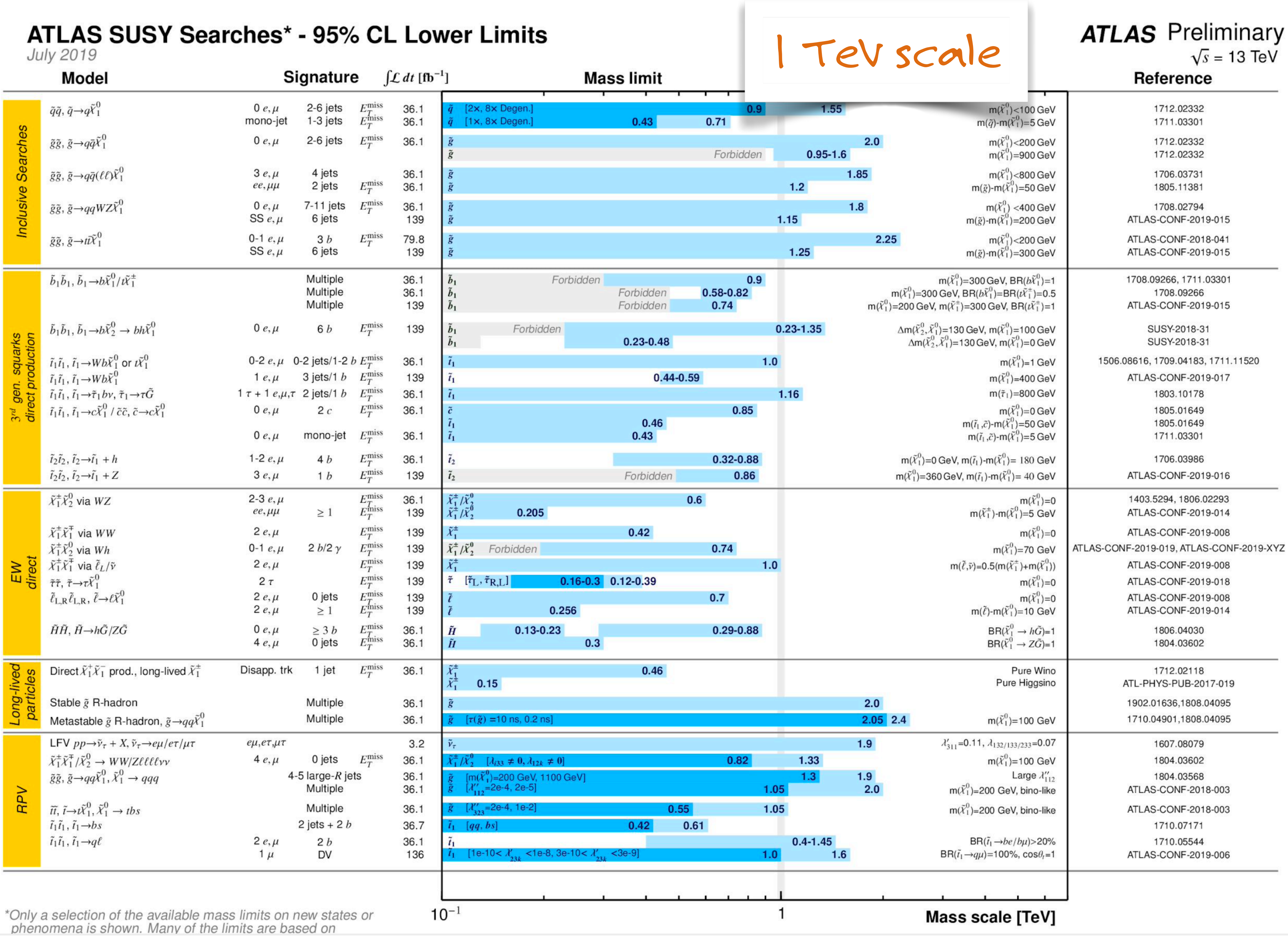
new particle LHC searches



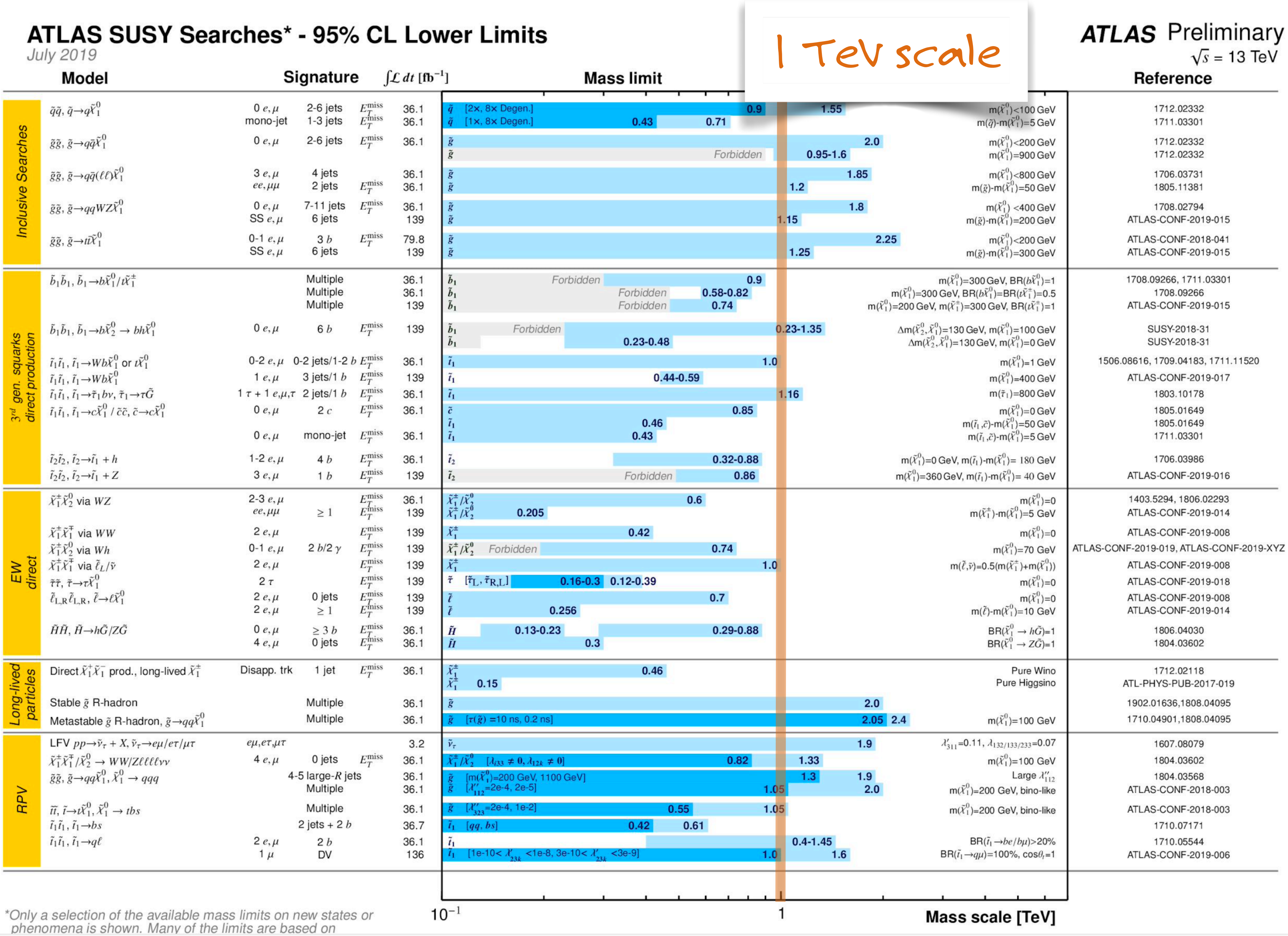
new particle LHC searches



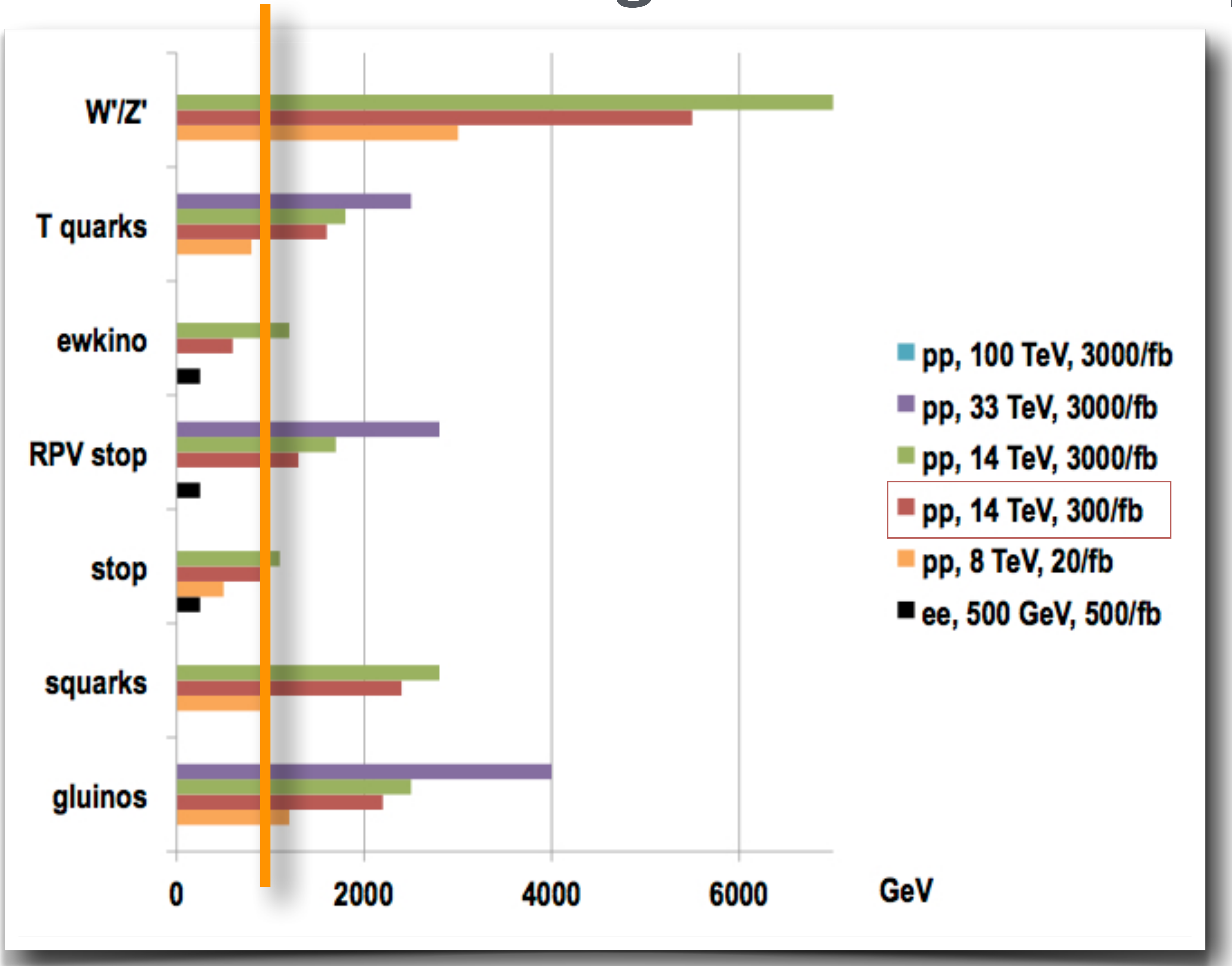
new particle LHC searches



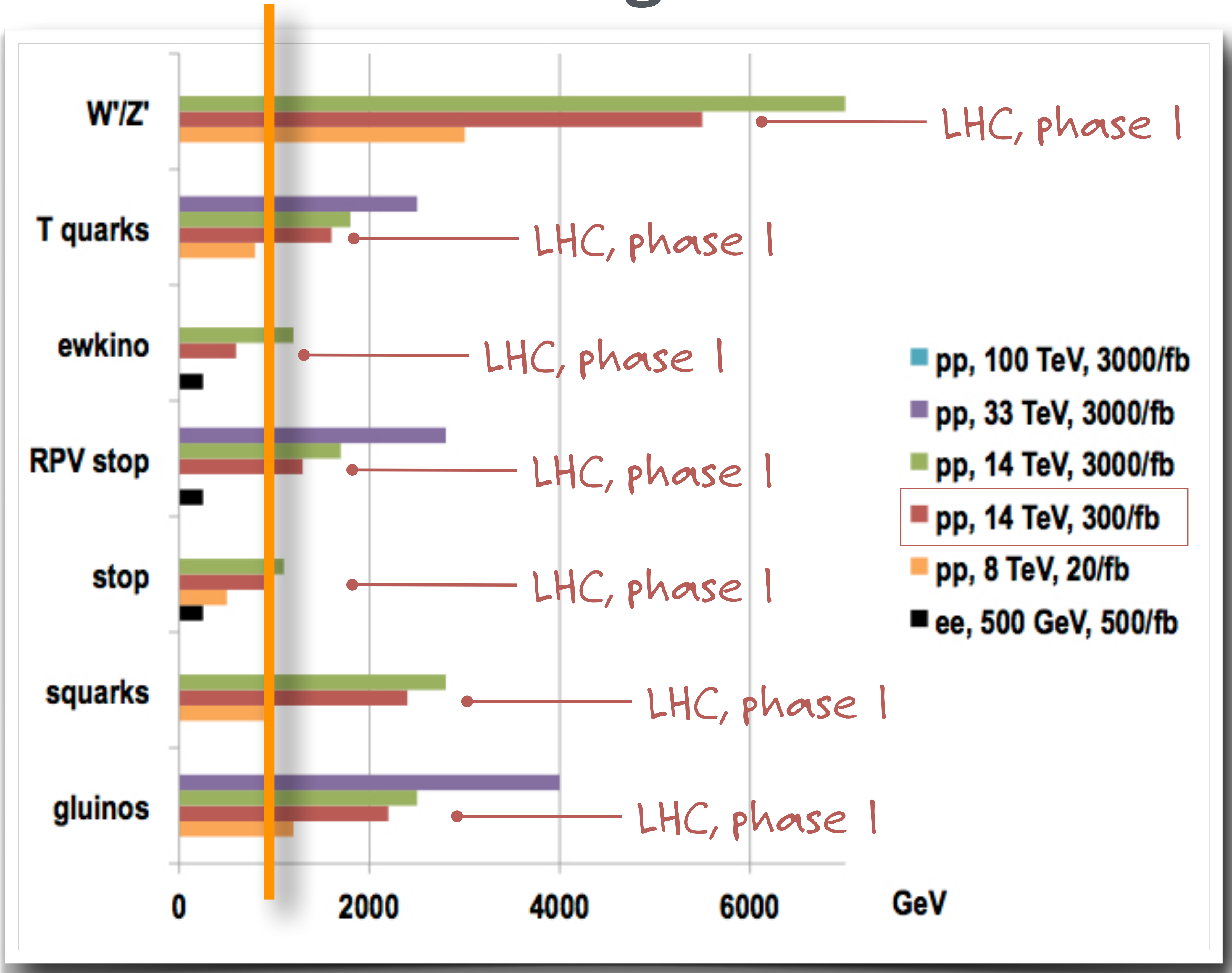
new particle LHC searches



The TeV scale is in sight–almost history

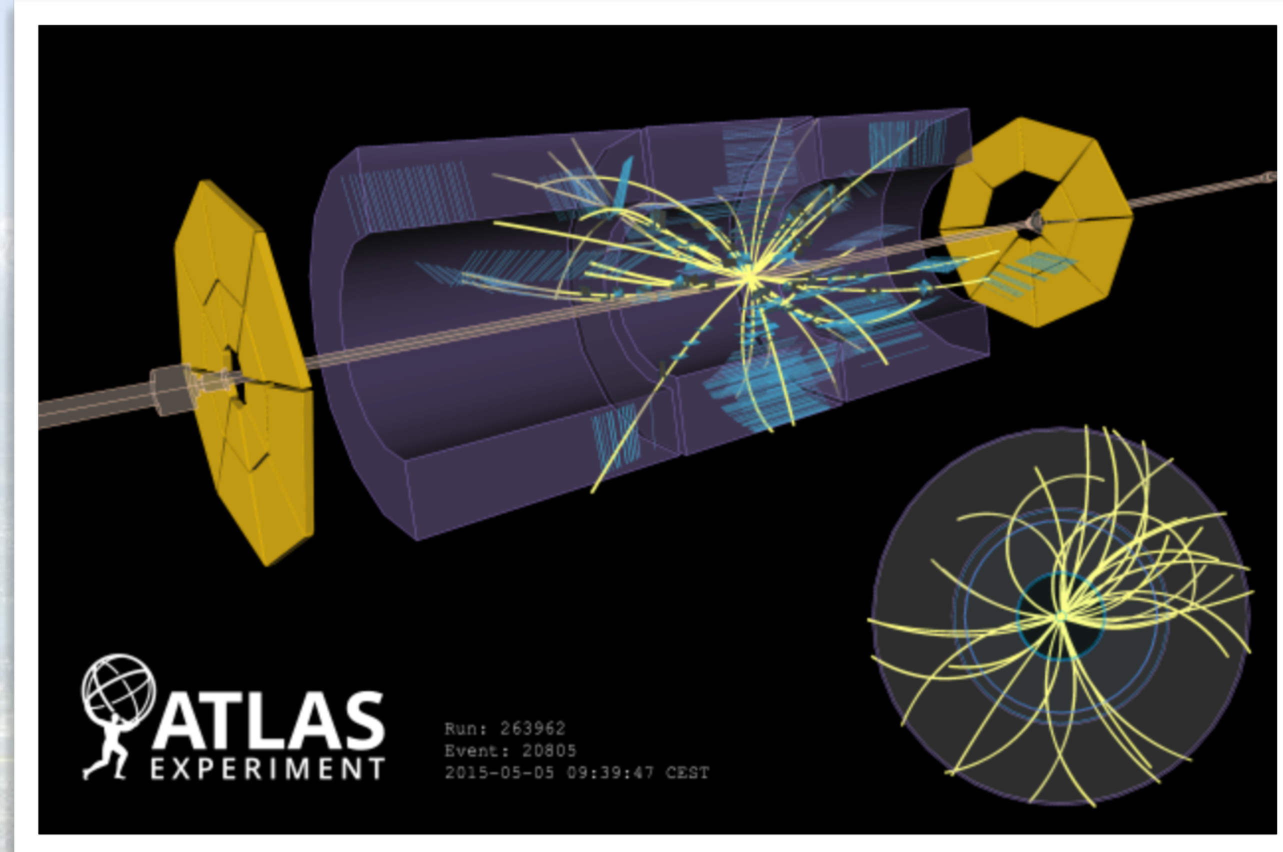


The TeV scale is in sight–almost history



the future

5%



buckle in

- The LHC running is just beginning

"phase 0 upgrades"

"phase 1 upgrades"

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024

Run I
8 TeV
0.75 10^{34} $cm^{-2}s^{-1}$

Run II
13-14 TeV
1.5 10^{34} $cm^{-2}s^{-1}$

Run III
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

20 fb^{-1}

~150 fb^{-1}

300 fb^{-1}

I’ll be an old man rocking

“phase 2 upgrades”

4	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038

Run III
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

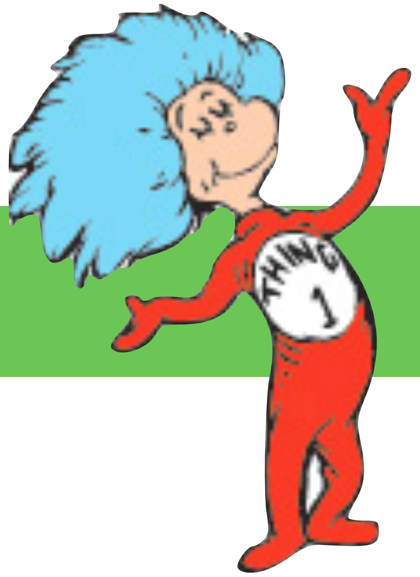
Run IV
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

Run IV
14 TeV
1.7-2.2 10^{34} $cm^{-2}s^{-1}$

← $3000\ fb^{-1}$ →

2 things and then conclusions

thing 1: mass.



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.

Really?

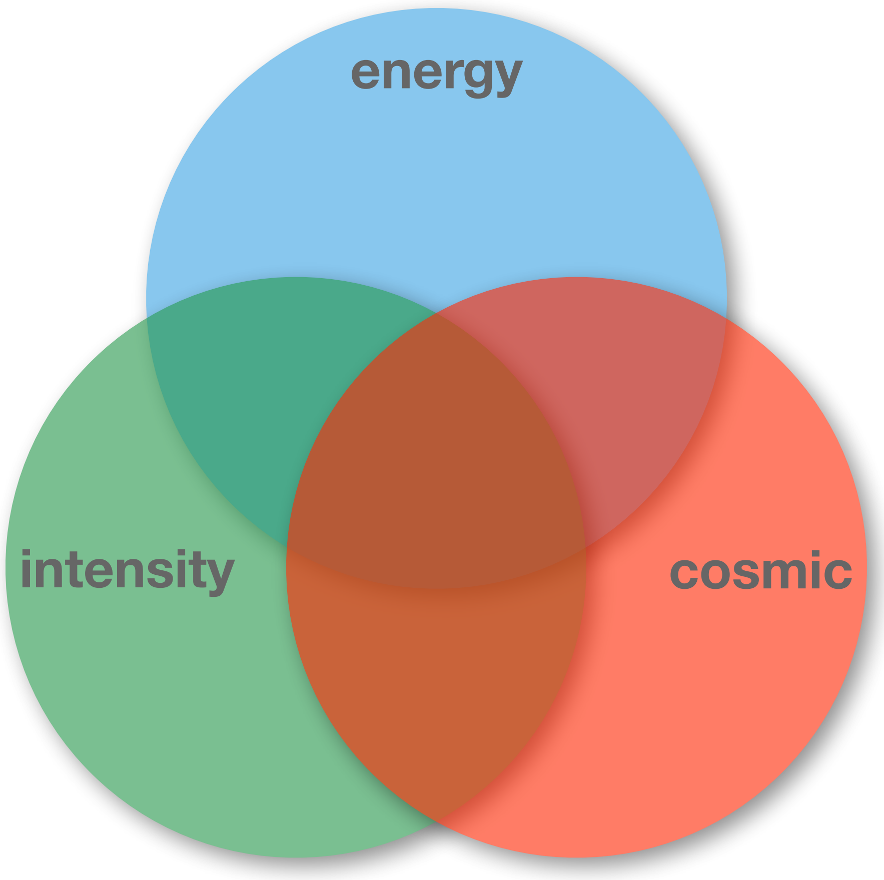
- As long as we know nothing about the neutral fermions or about 85% of the gravitating universe
- We don’t know the Mass story.

Understanding Mass is still
“all hands on deck”
– EF, IF, and CF

thing 2: the circles.

The Bumper Sticker Frontier

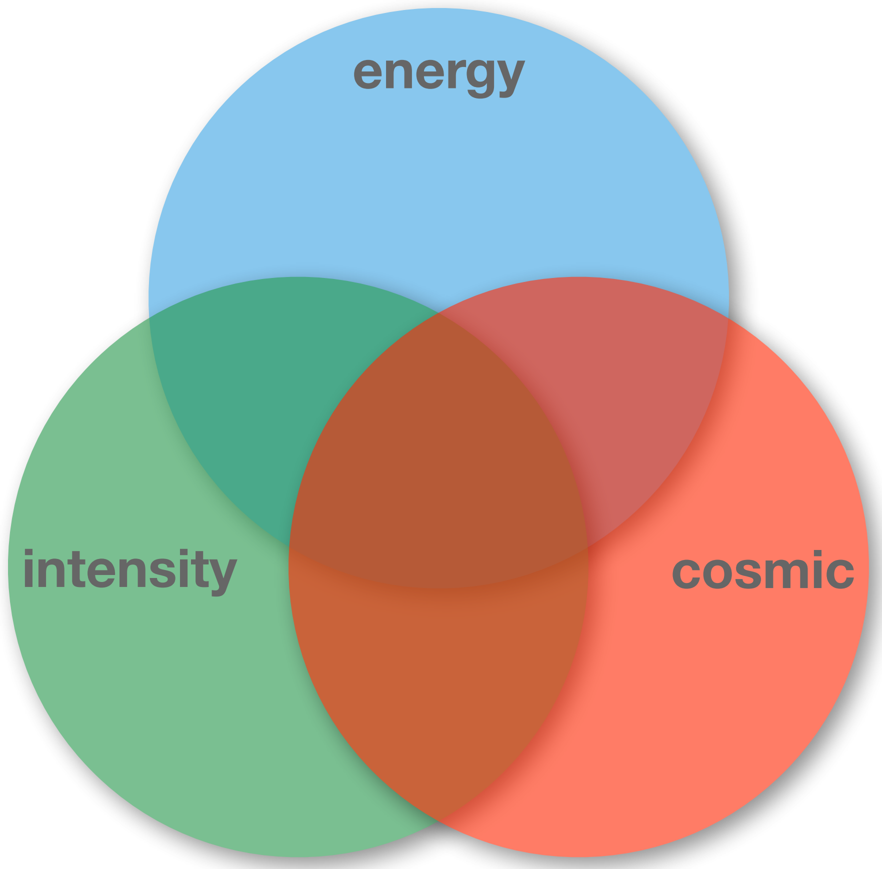
they’re pithy



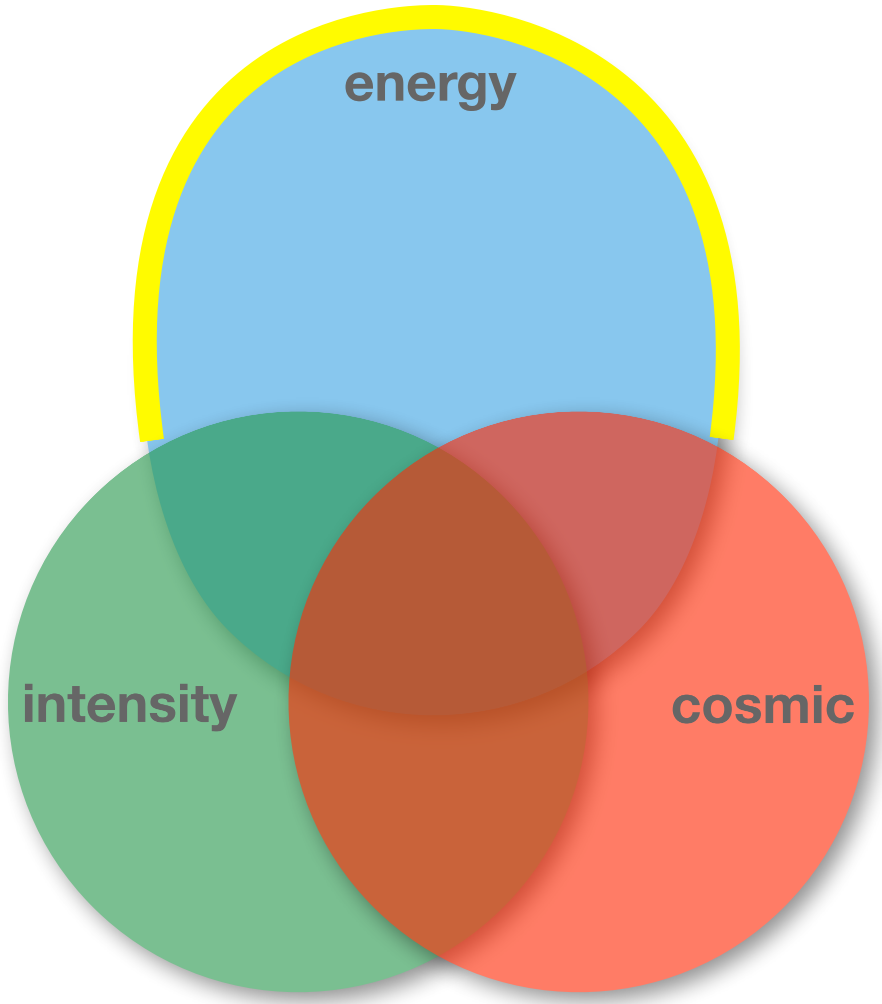
“Frontier”

I’m rethinking...

maybe an apt metaphor



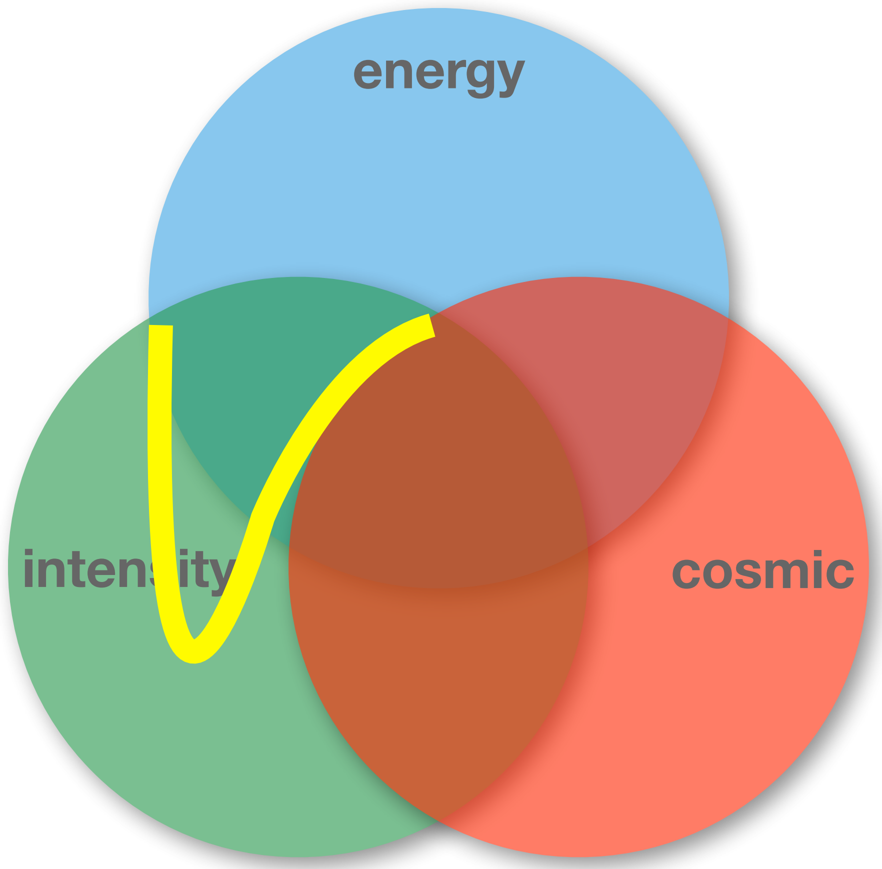
The new physics will bulge somewhere!



a unique “Frontier”

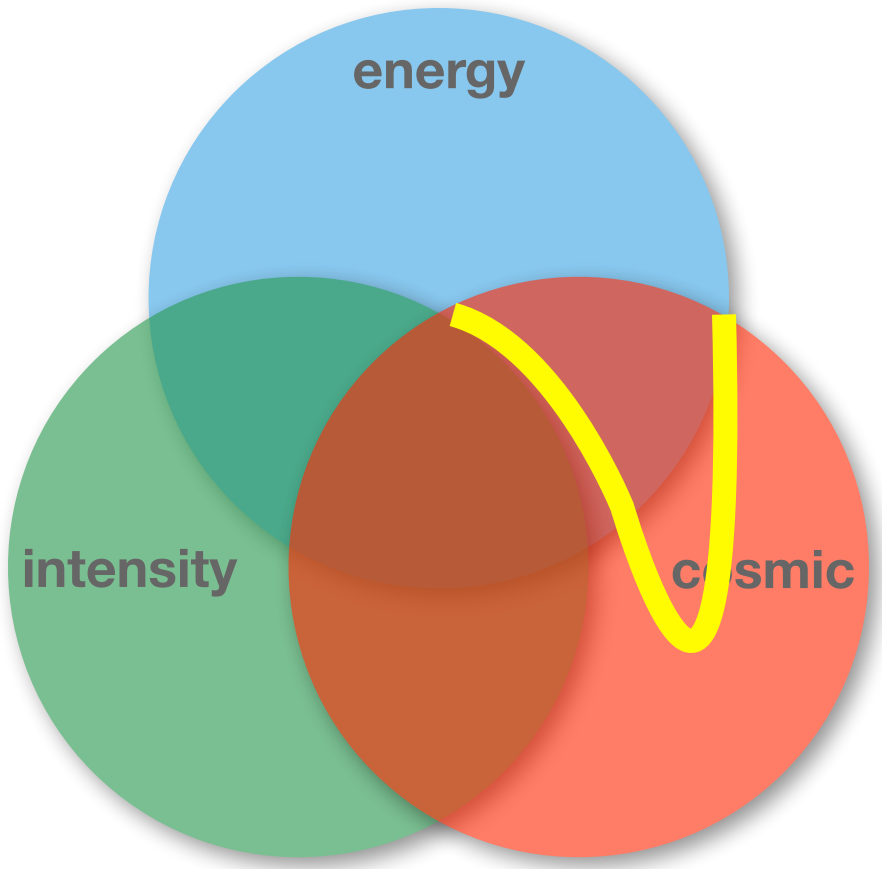
- The new physics will bulge somewhere!

a shared "Frontier"



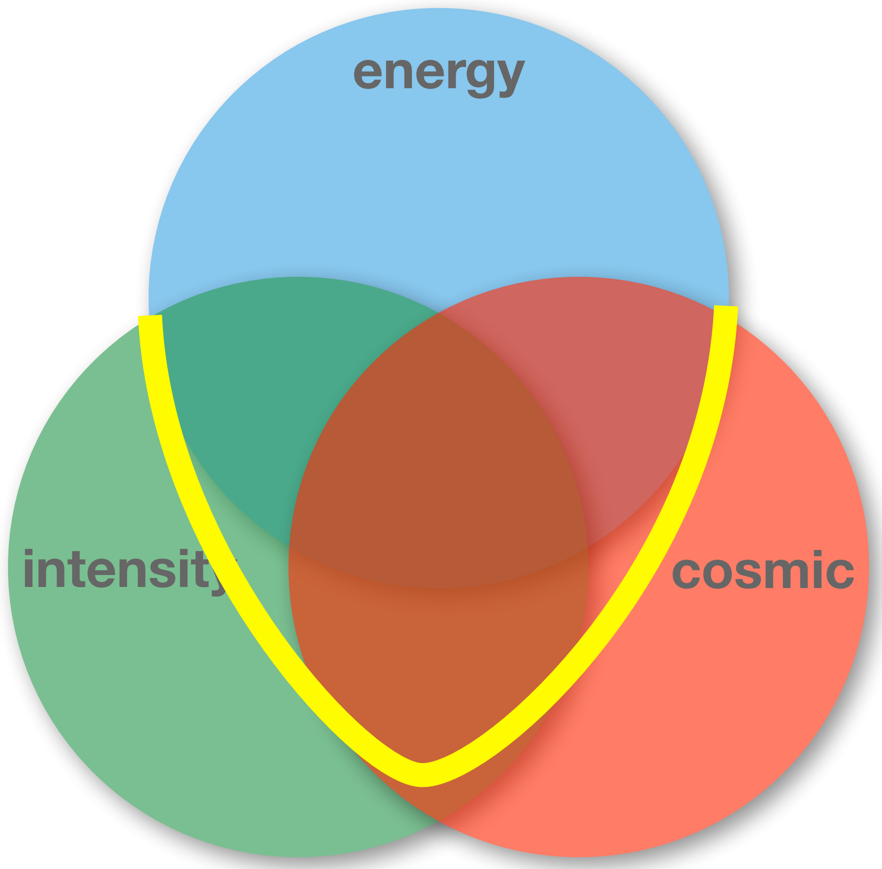
- The new physics will bulge somewhere!

a shared “Frontier”



but probably everywhere

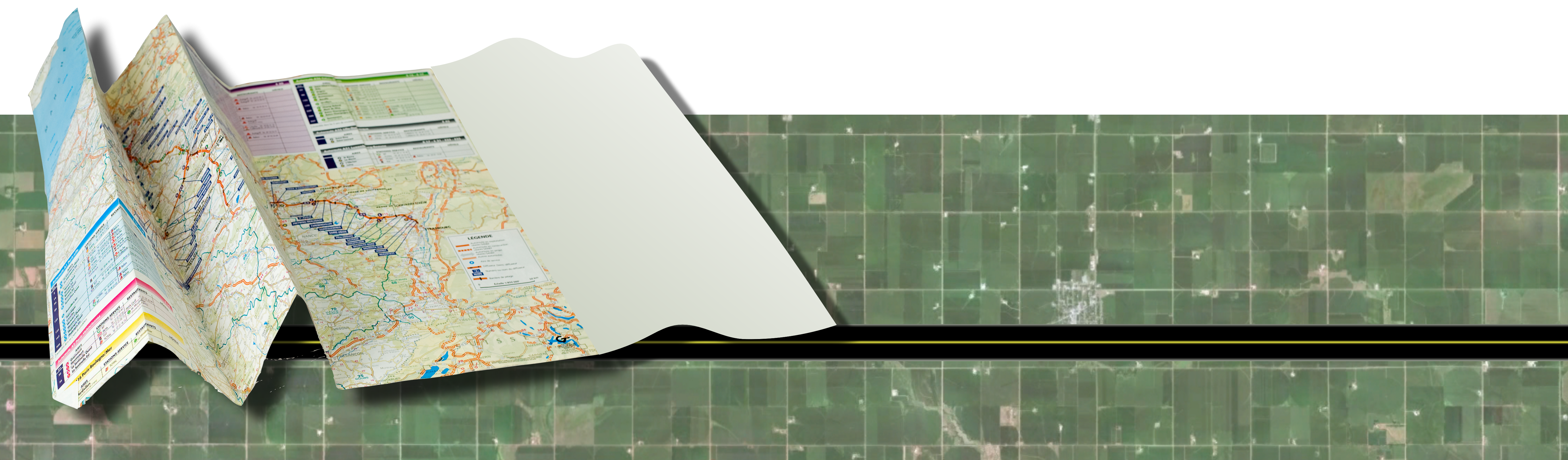
a shared “Frontier”



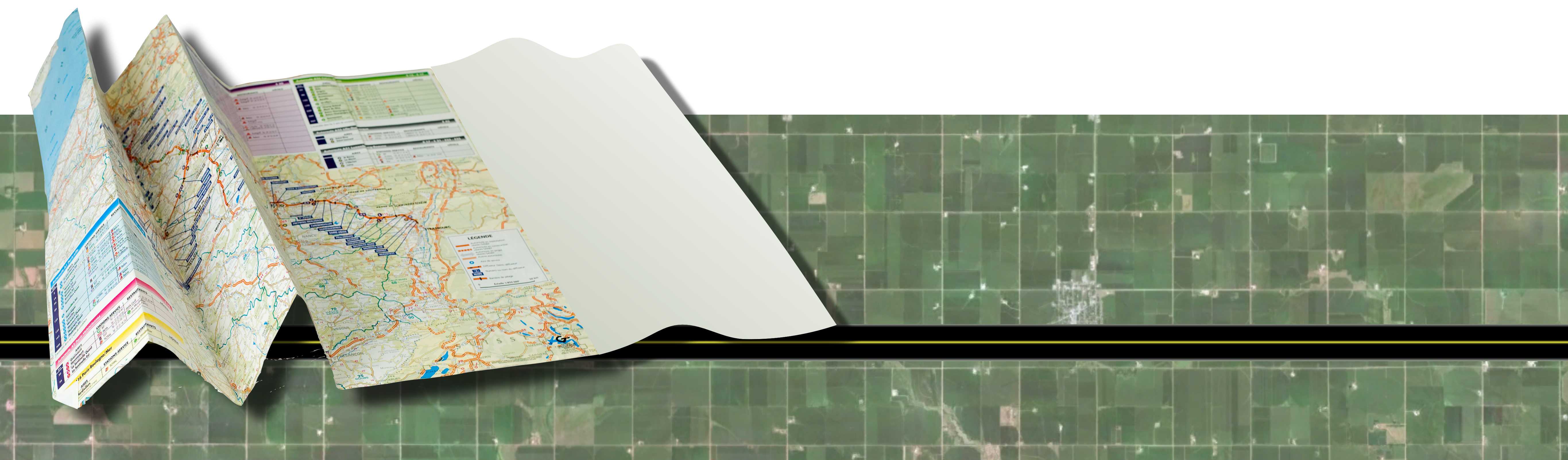
The Higgs particle changes everything.

SM guided research

un-guided research?



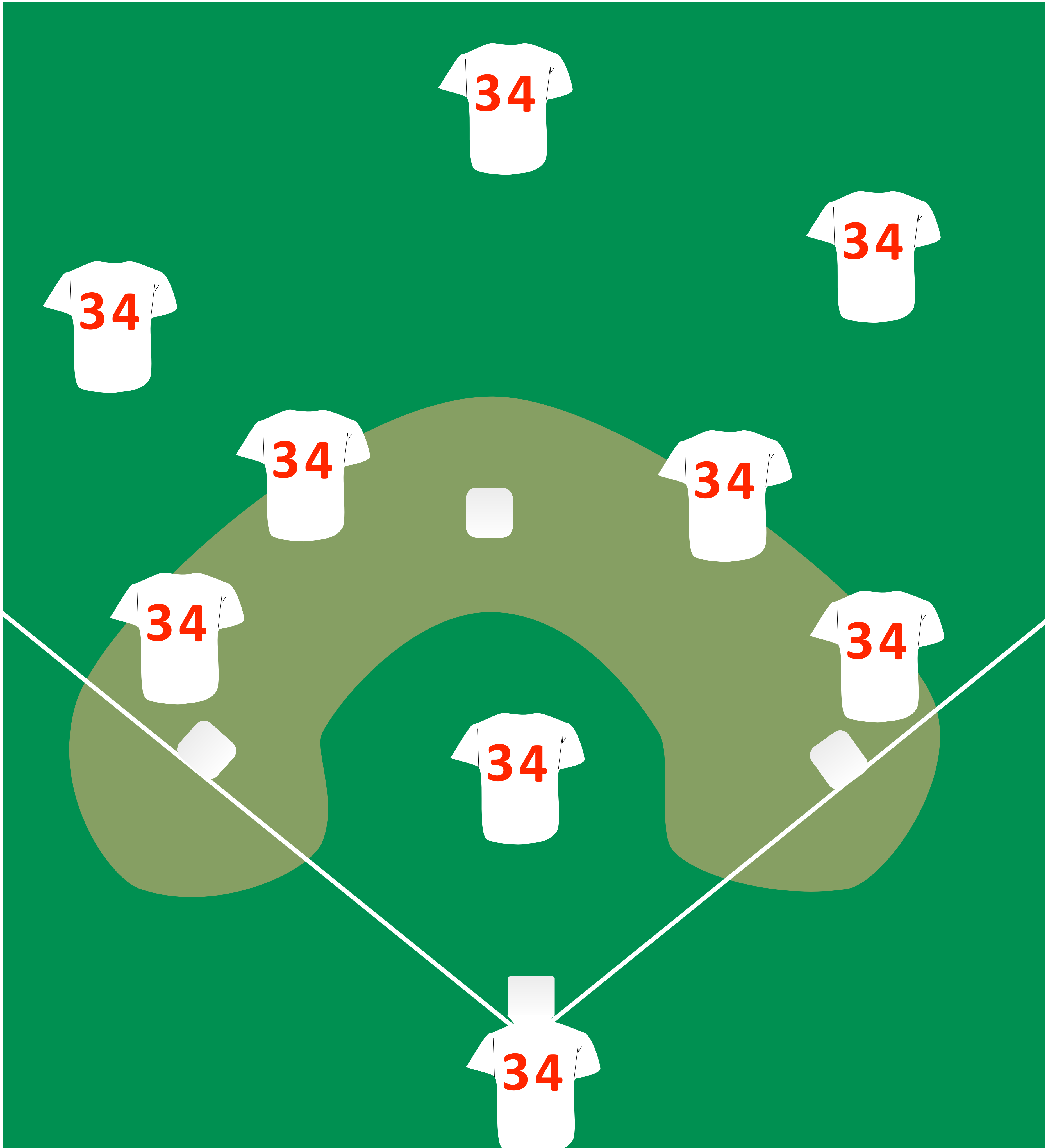
over-guided research?



over-guided research?

We're exploring.


"Frontier"


34
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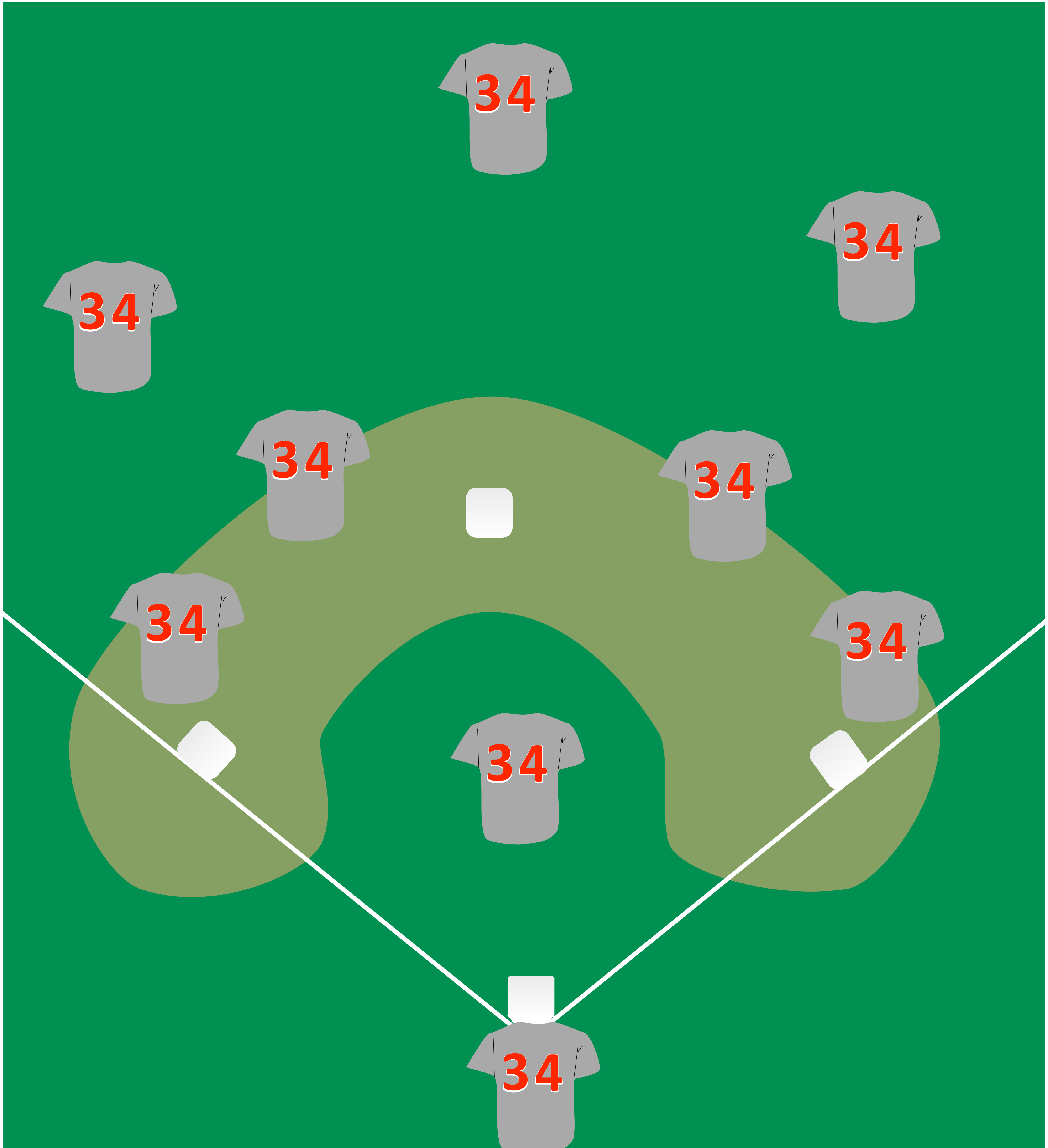
34


34
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34

every player
dresses himself:
locality

every player dresses himself: locality

athletic anarchy!

every player dresses himself: locality

athletic anarchy!

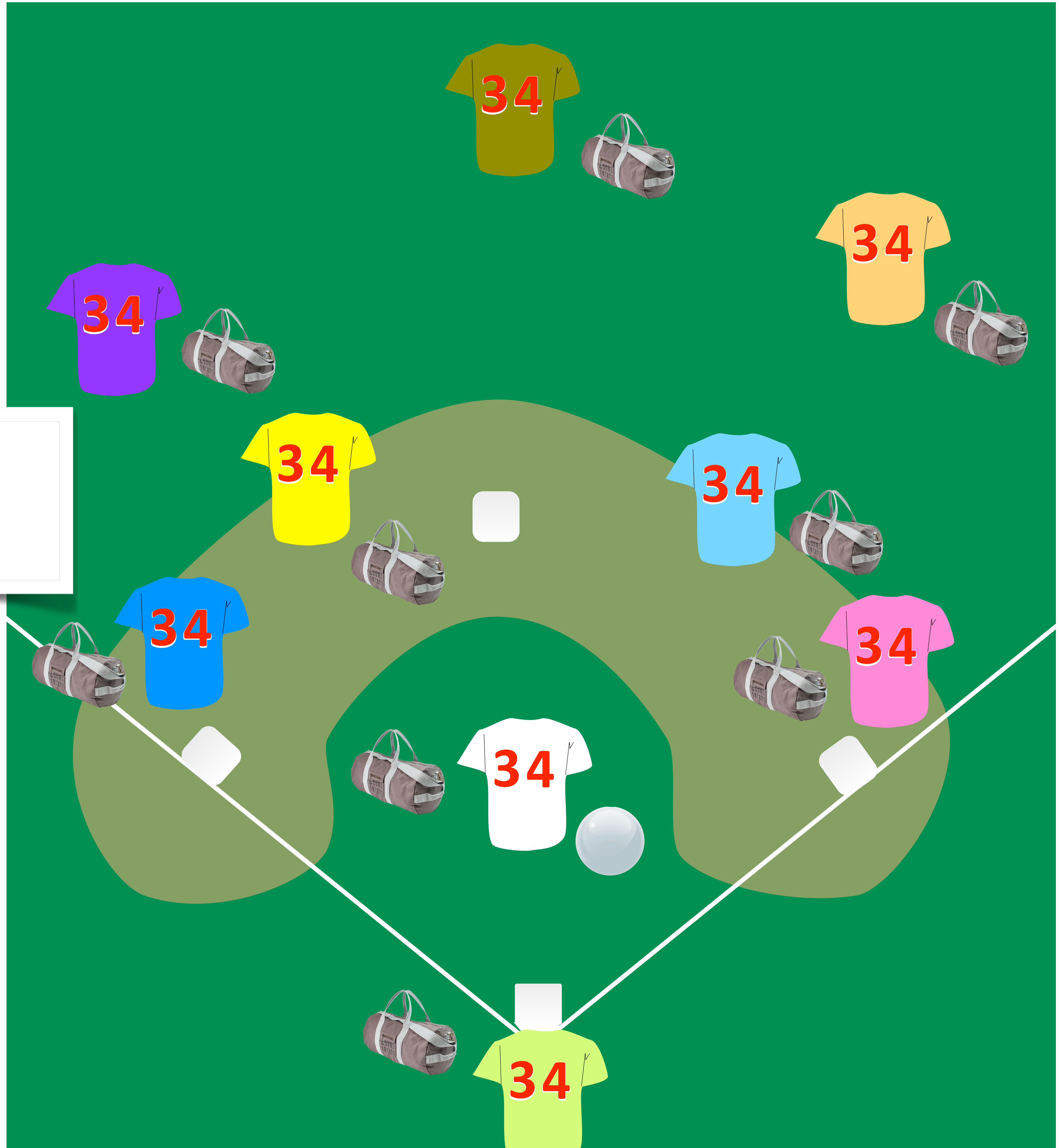
every player dresses himself: locality

athletic anarchy!

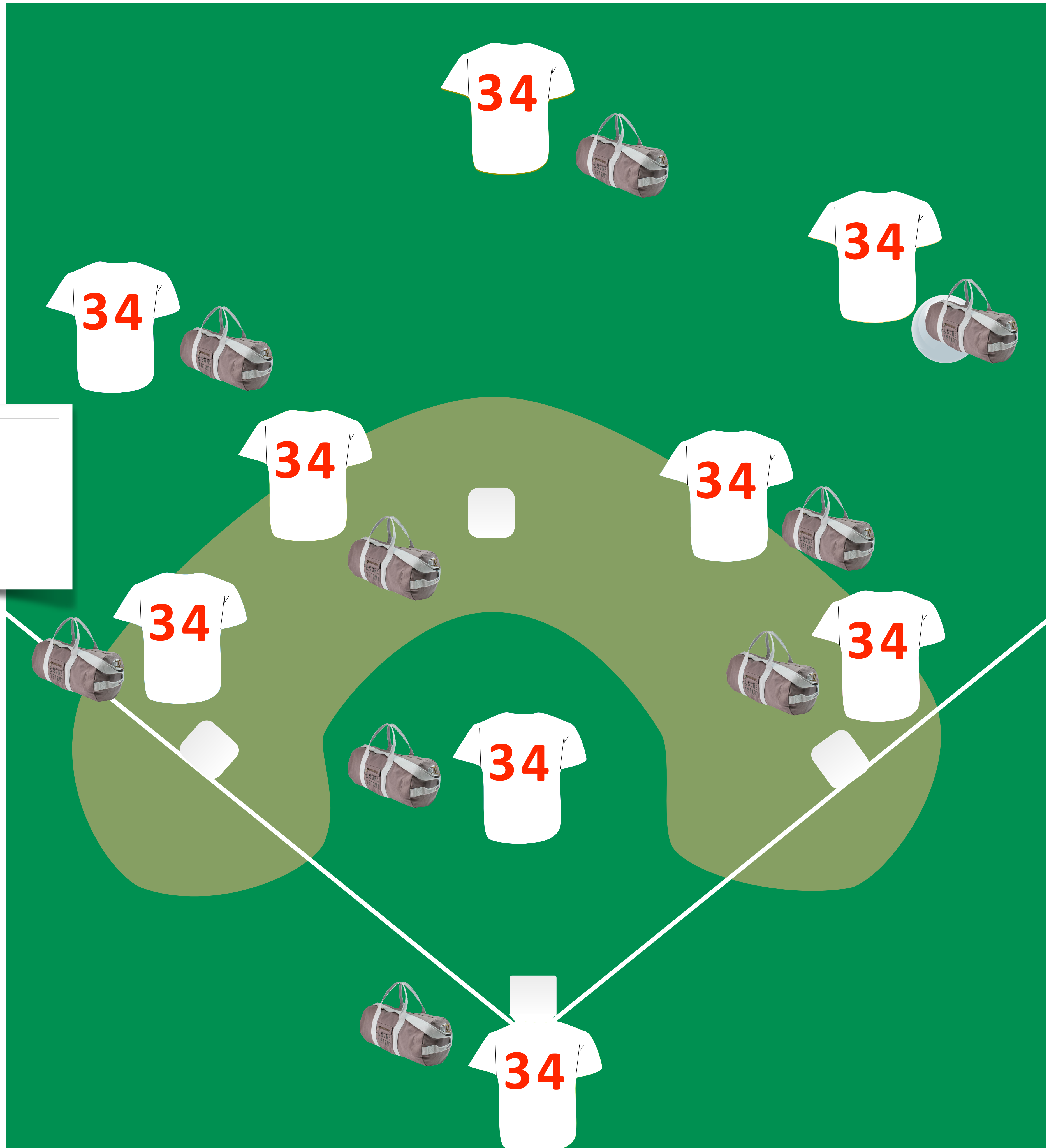
how to restore order?

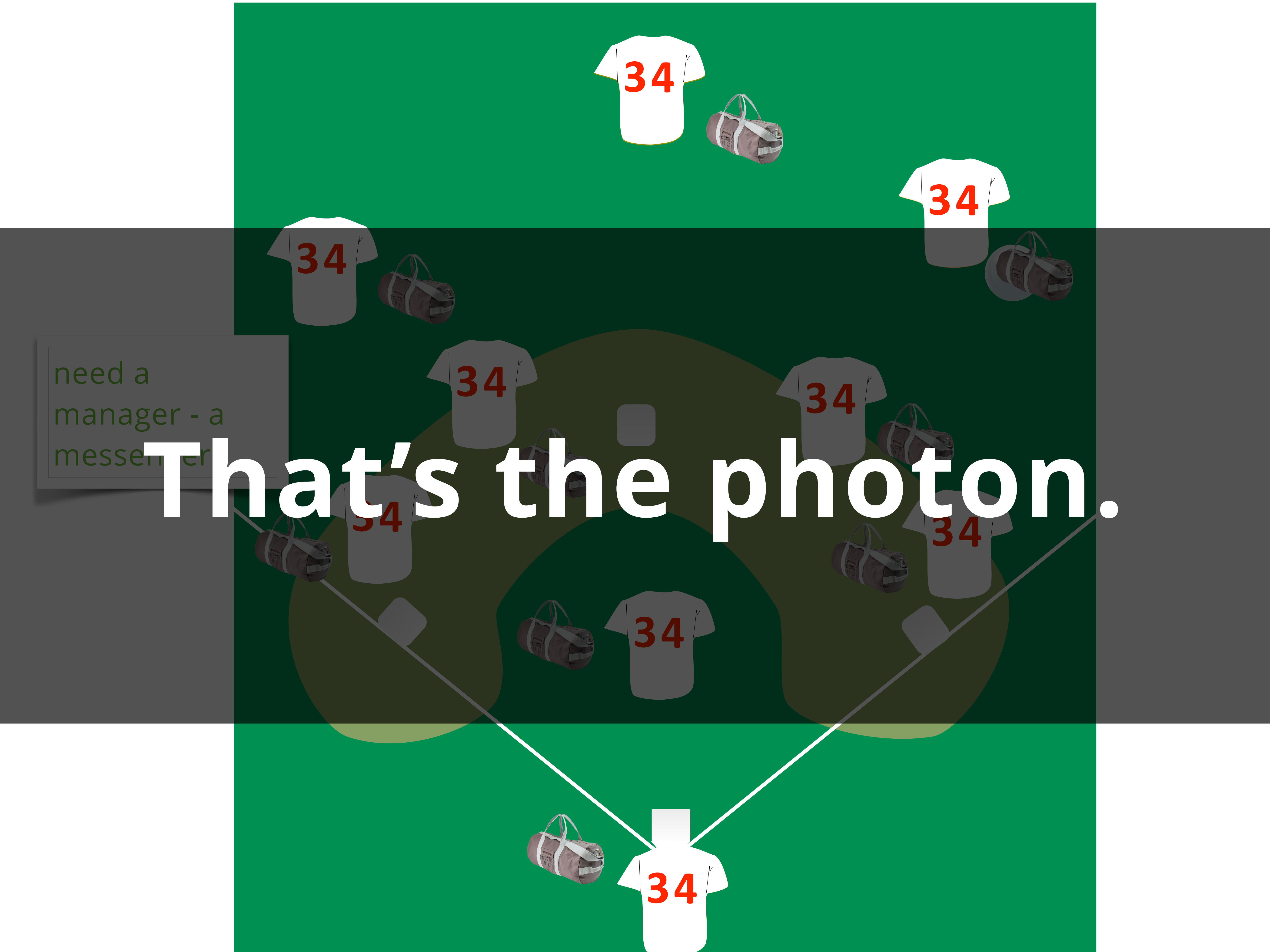
need a manager - a messenger

need a manager - a messenger

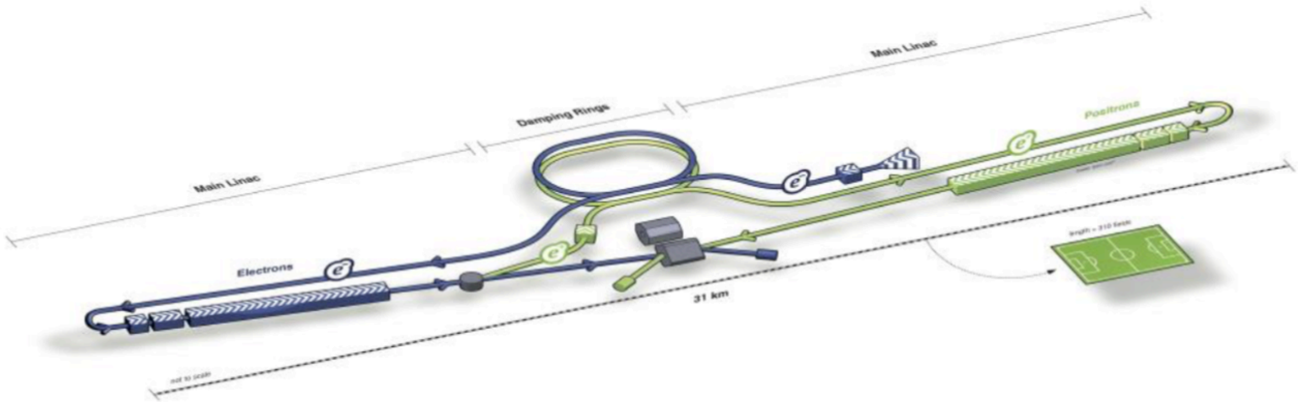


need a manager - a messenger




need a
manager - a
That’s the photon.

Electron-Positron Collider Proposals



Japan

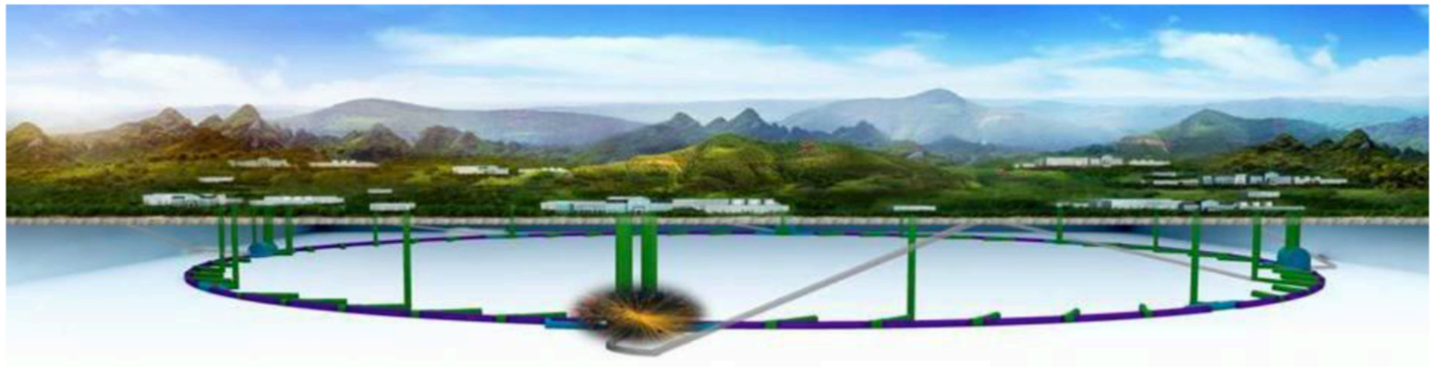
ILC 250: 2032

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

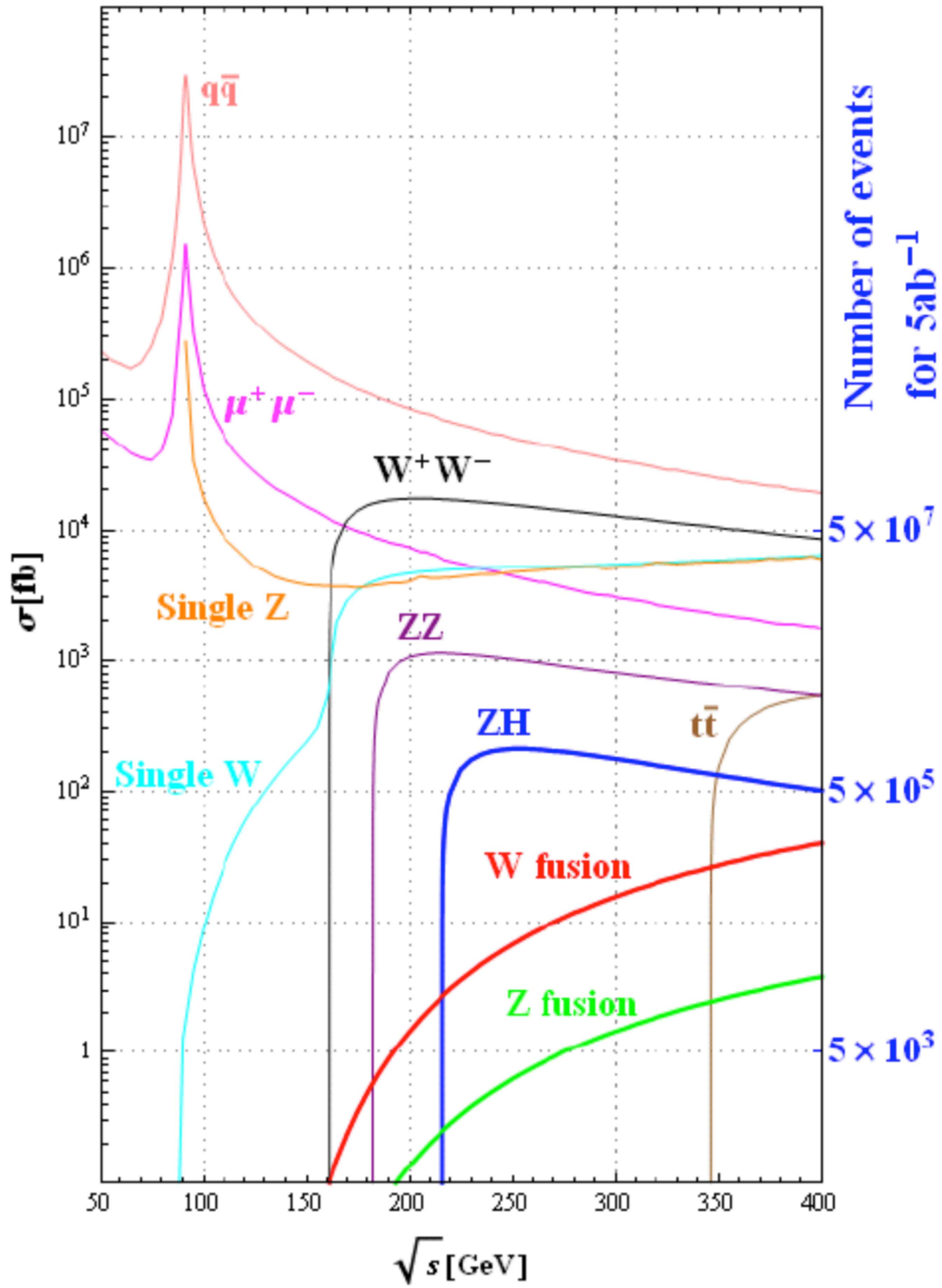
Well defined collision energy

allow for the “missing” mass reconstruction (*eg* recoiling mass)

Clean events, smaller background

small number of processes

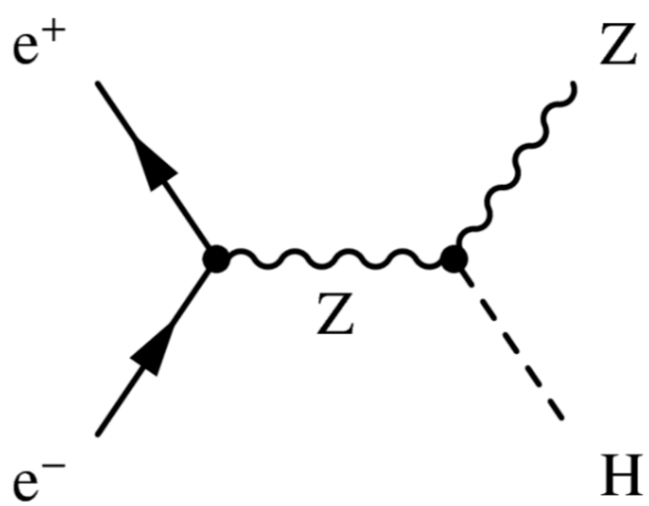
Ideal for precisions:
measurements or searches

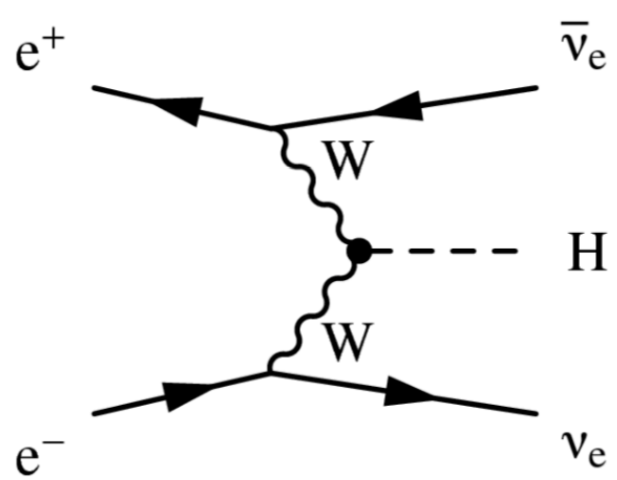


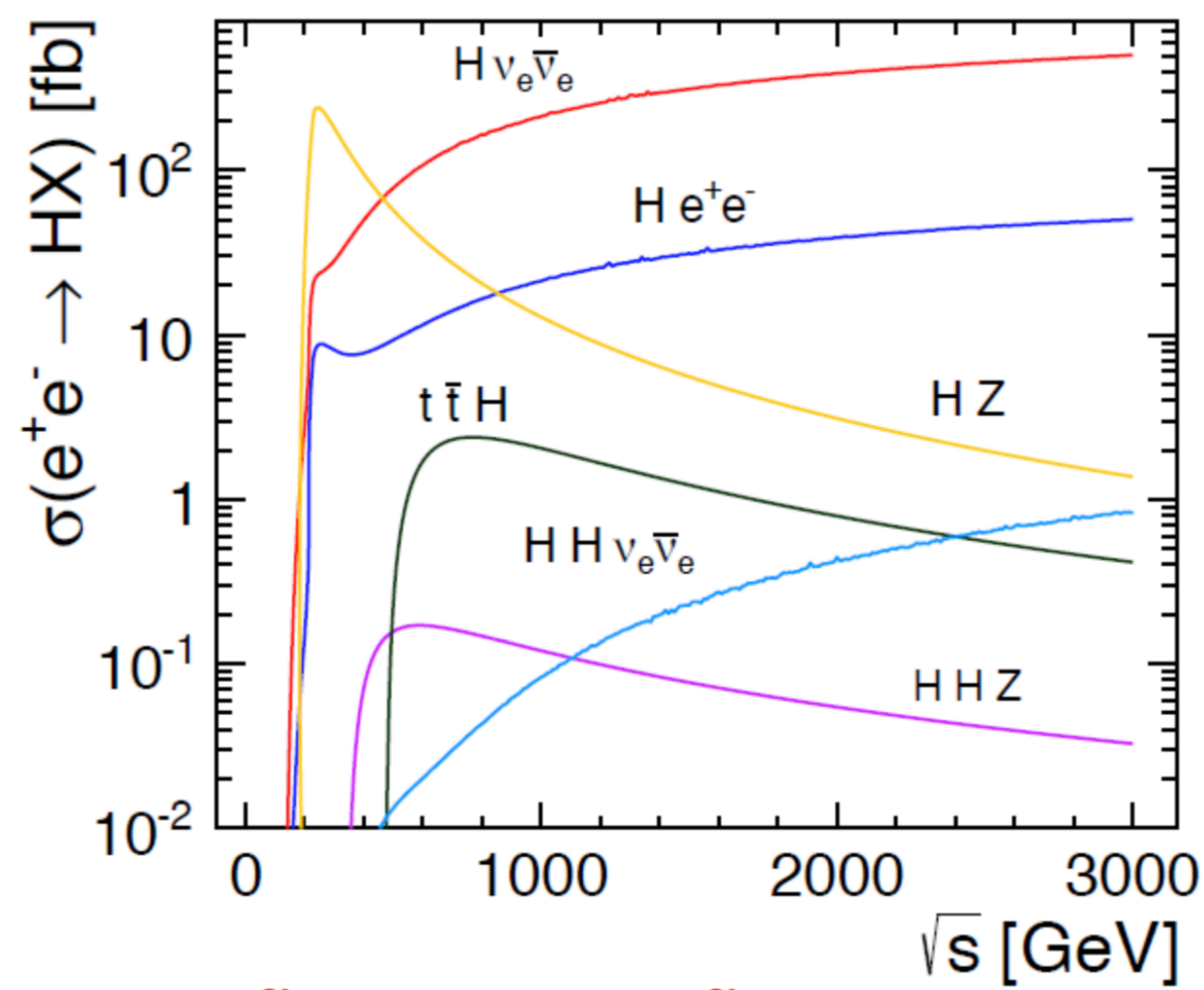
Higgs Boson Production in e^+e^- Collisions

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

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



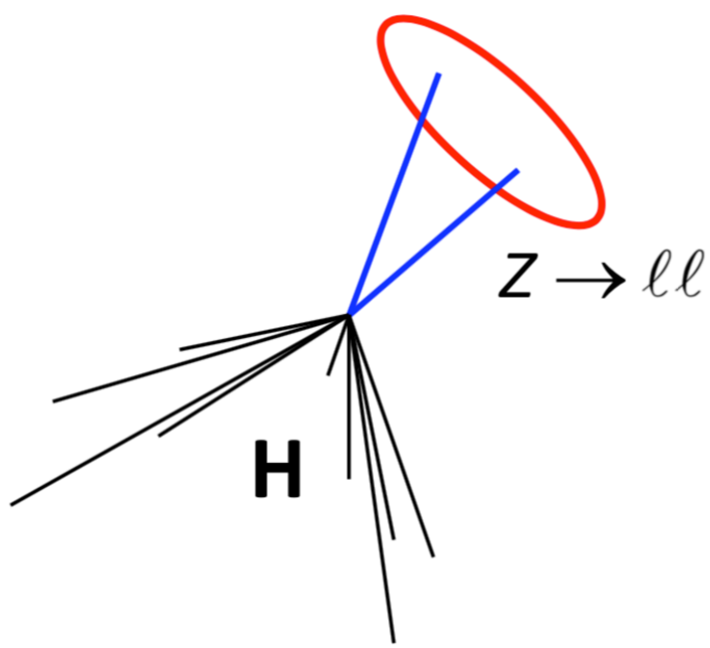


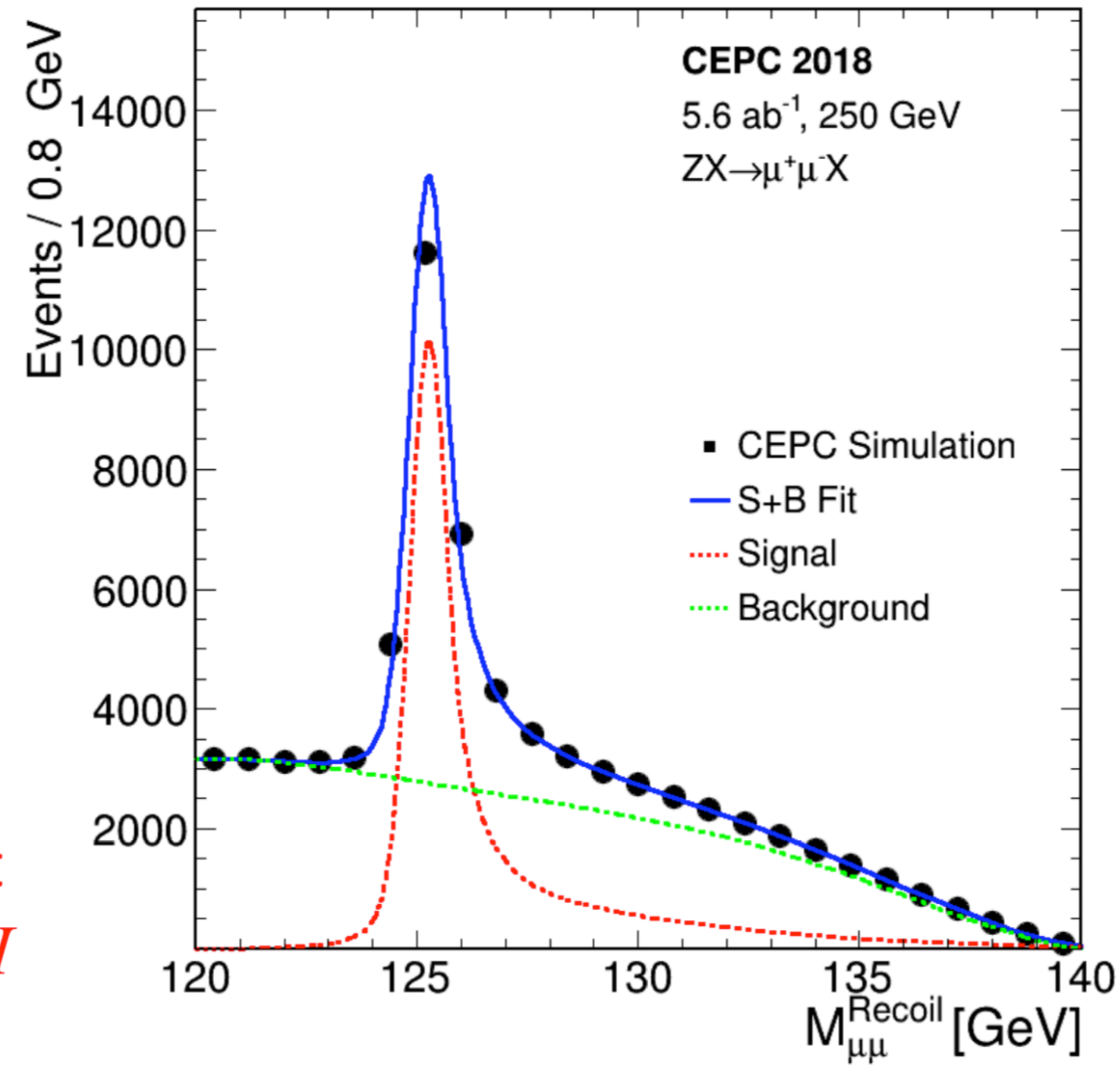


$\sqrt{s} = 250$ GeV: $\sigma_{ZH} \approx 200$ fb, $\sigma_{\nu\nu H} \approx 10$ fb

Higgs Boson Tagging

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





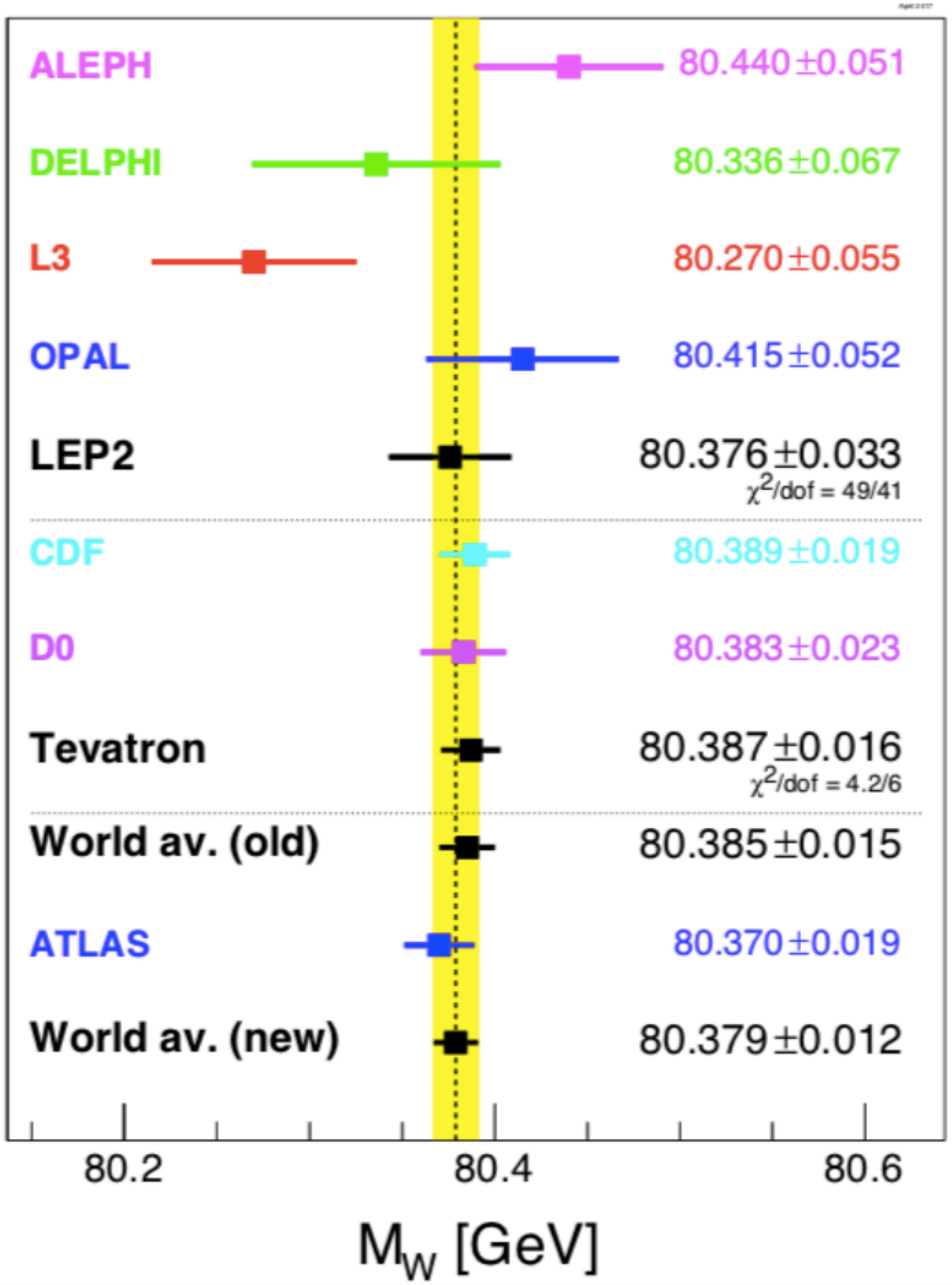
Recoil mass reconstruction:

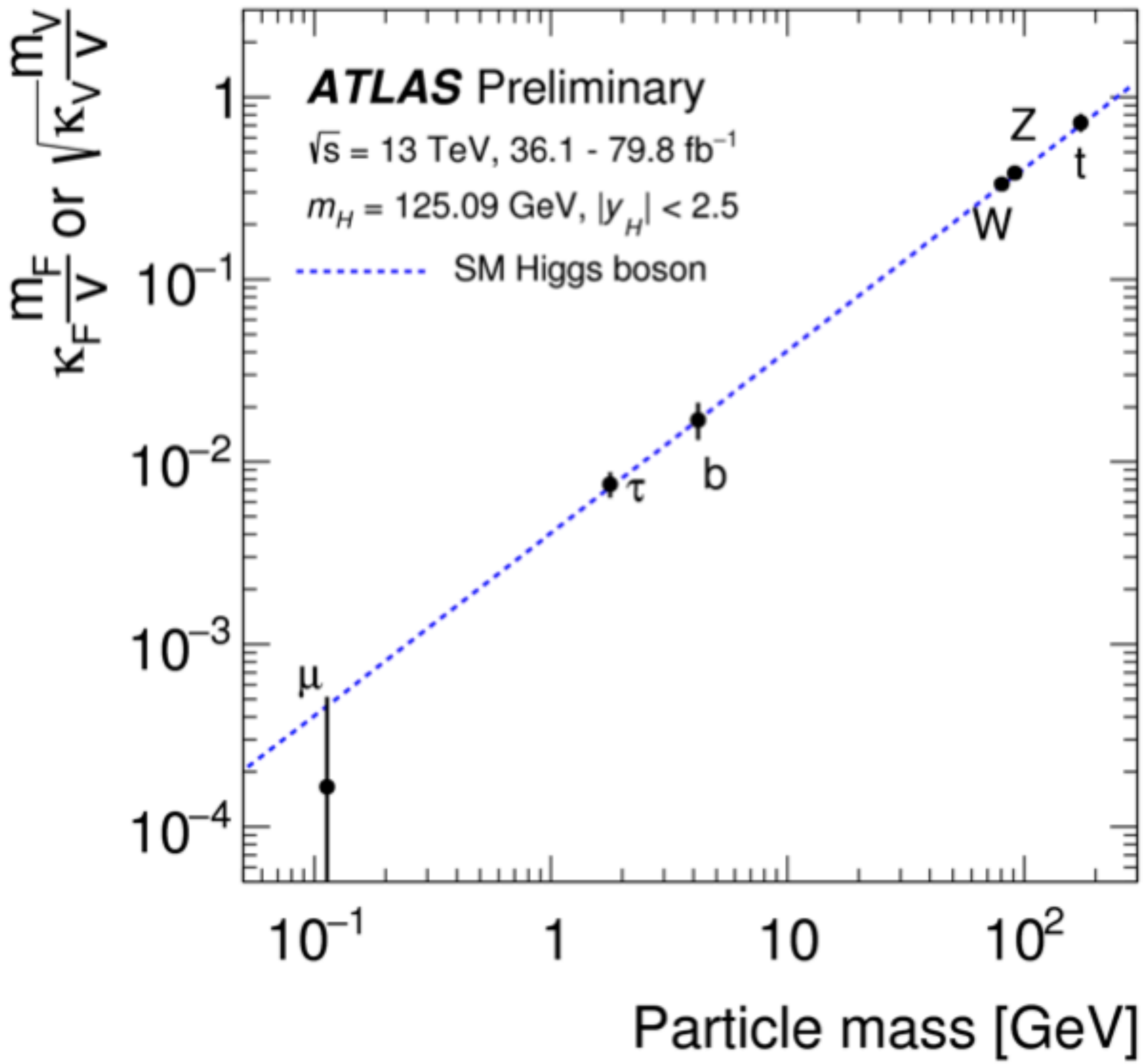
$$m^2_{\text{recoil}} = \left(\sqrt{s} - E_Z\right)^2 - \left|\vec{p}_Z\right|^2$$

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

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

[From PDG 2019]





ATLAS Preliminary
√s = 13 TeV, 36.1 - 79.8 fb⁻¹
m_H = 125.09 GeV, $|y_H|$ < 2.5
SM Higgs boson
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
Particle mass [GeV]
μ
τ
b
W
Z
t

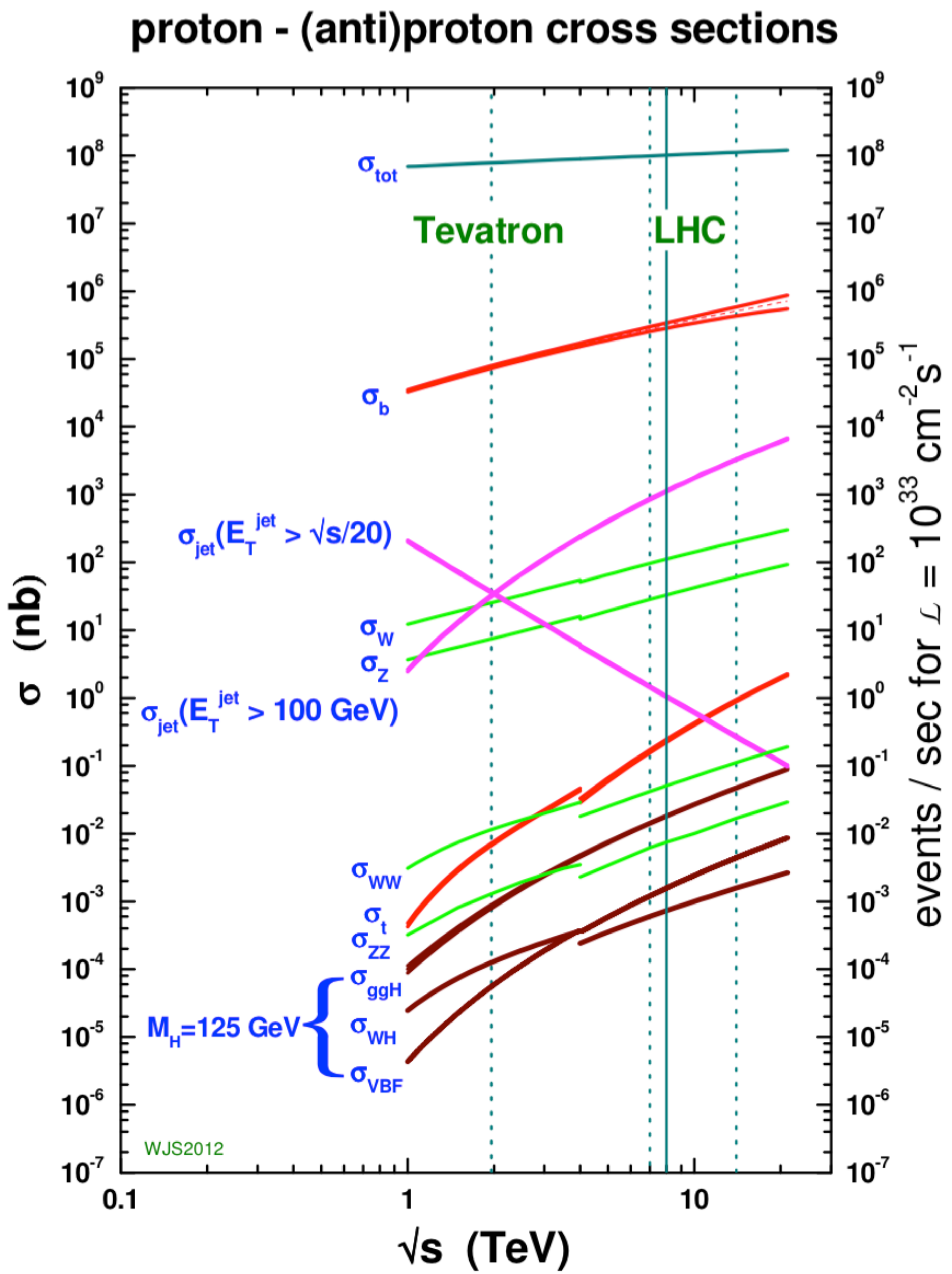
Run 2

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

Run 2

is a generational event

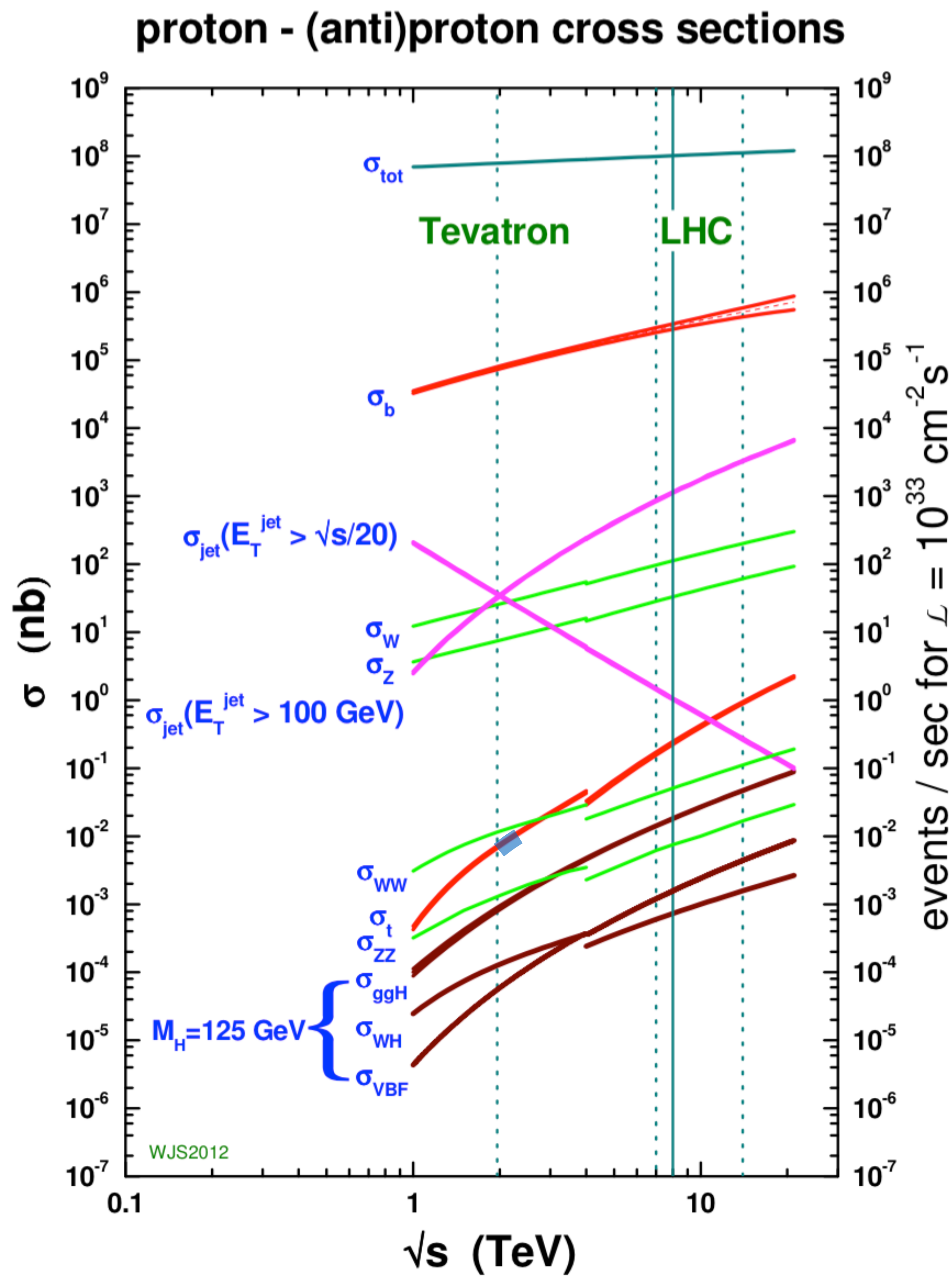
Run 1 to Run 2

bigger science increment than

Run 2 to Run 3

from:

< 1 tT event/s @ tevatron



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

Run 2

is a generational event

Run 1 to Run 2

bigger science increment than

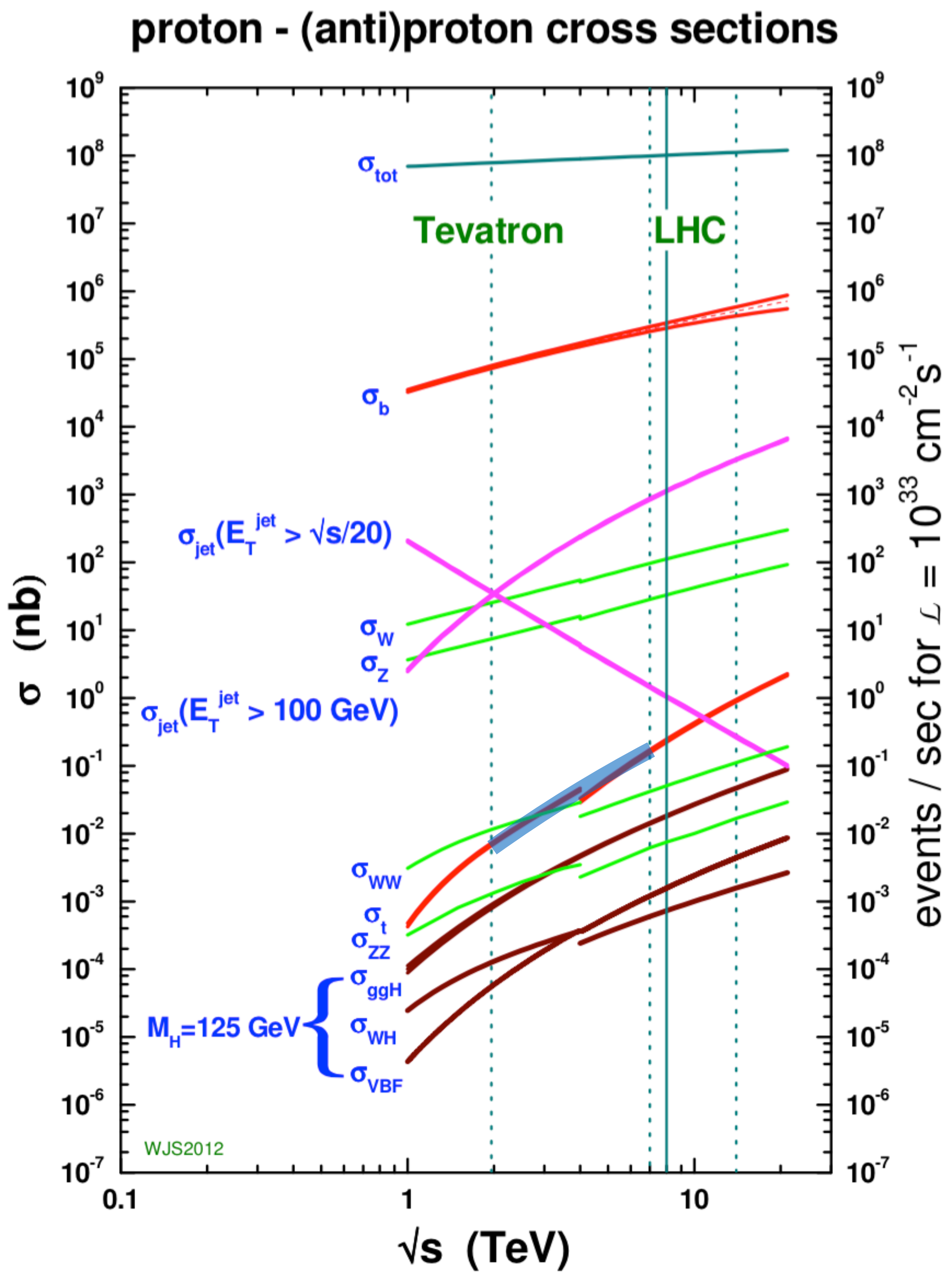
Run 2 to Run 3

from:

< 1 tT event/s @ tevatron

to:

2 tT events/s in Run 1



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

Run 2

is a generational event

Run 1 to Run 2

bigger science increment than

Run 2 to Run 3

from:

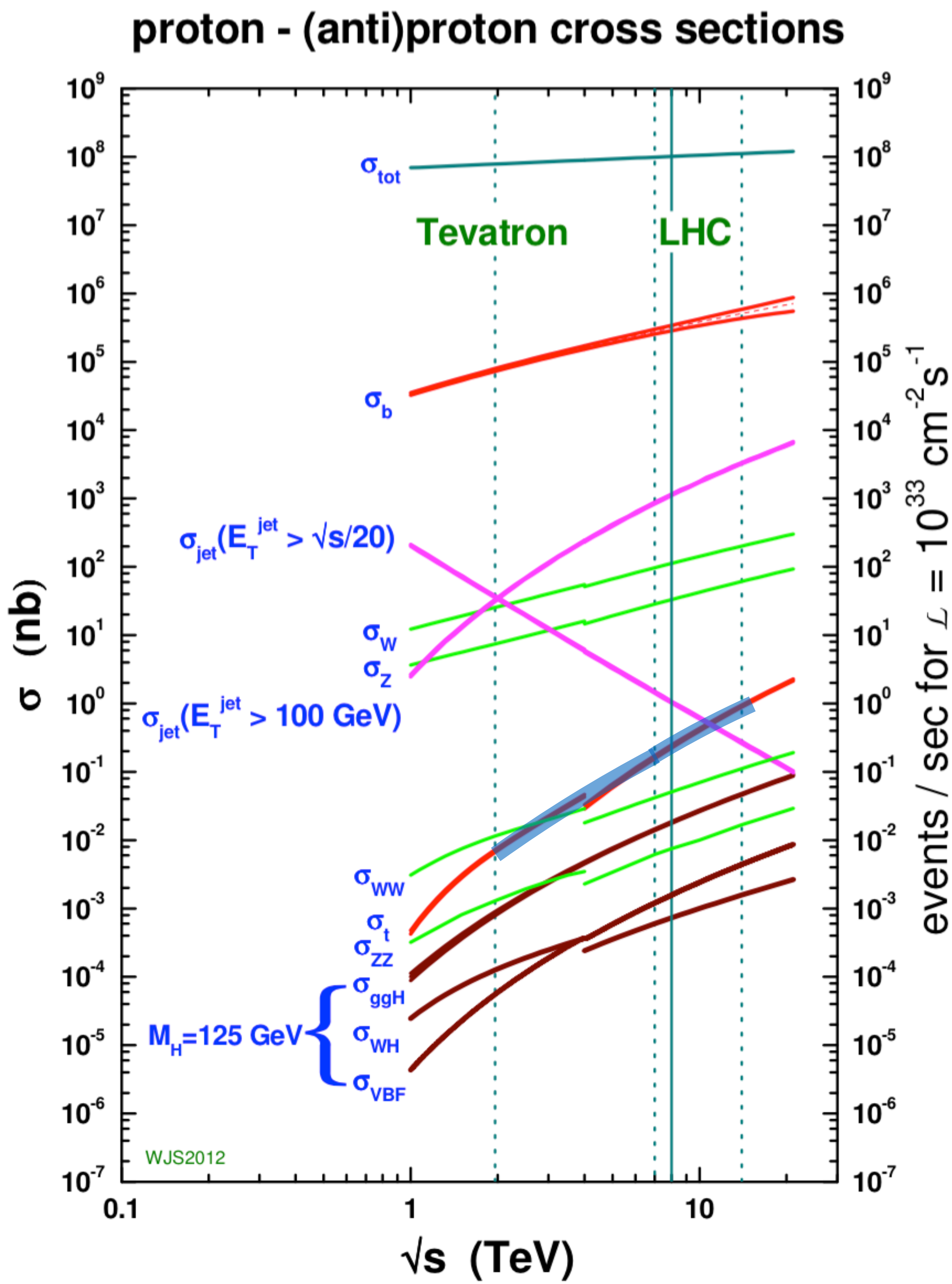
< 1 tT event/s @ tevatron

to:

2 tT events/s in Run 1

to:

13 tT events/s in Run 2



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

Run 2

is a generational event

Run 1 to Run 2

bigger science increment than

Run 2 to Run 3

from:

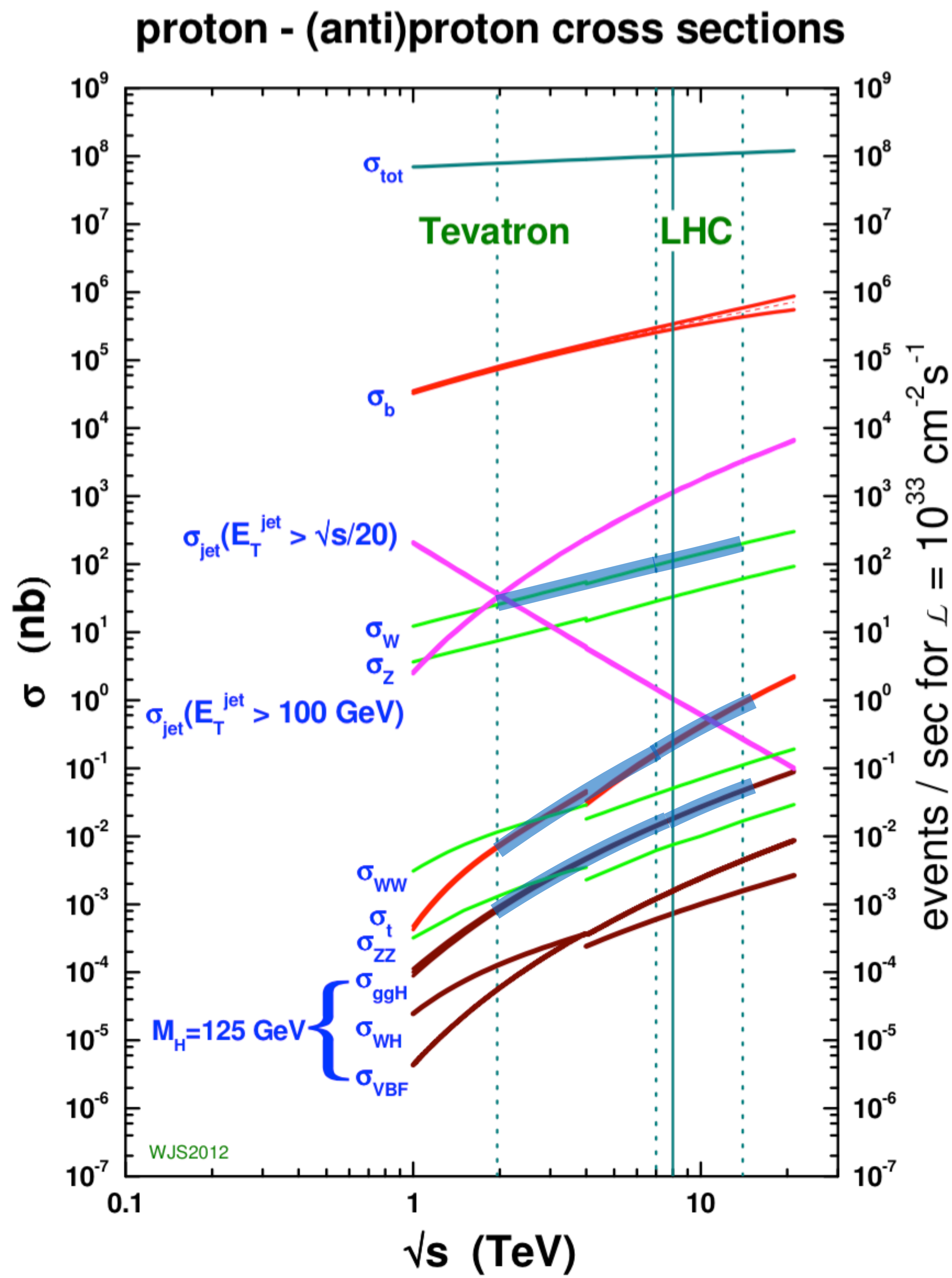
< 1 tT event/s @ tevatron

to:

2 tT events/s in Run 1

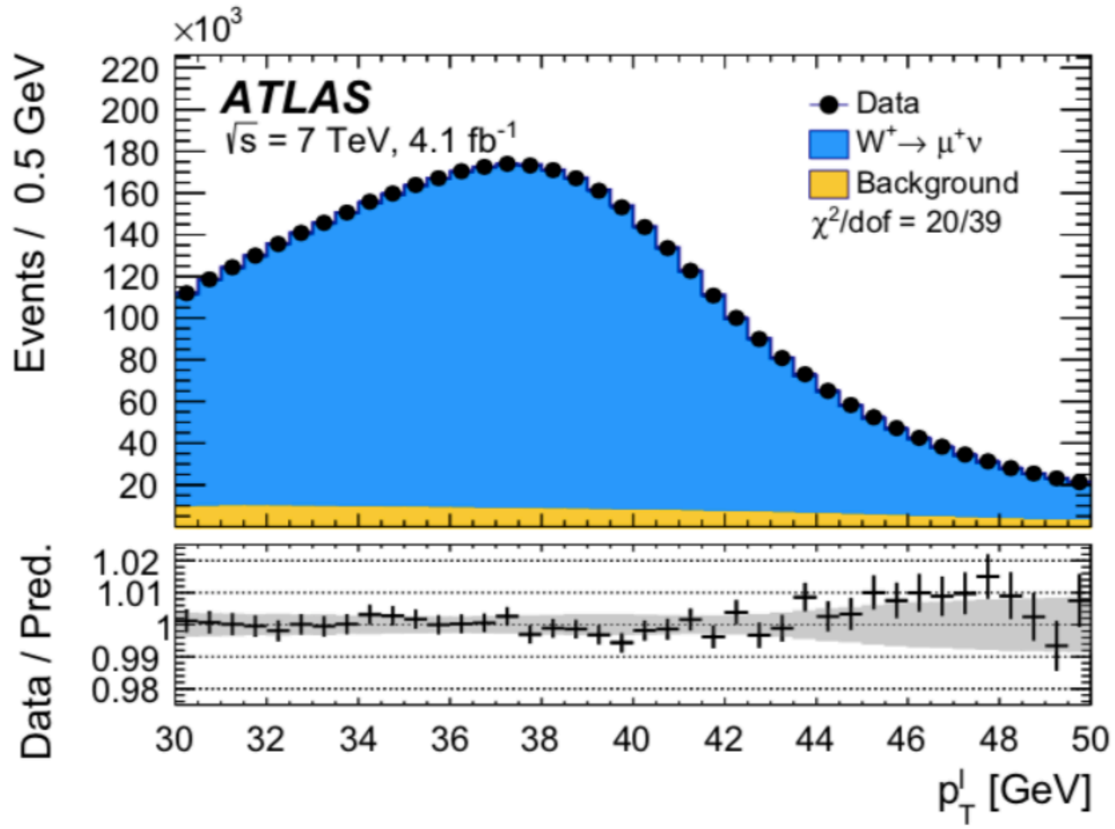
to:

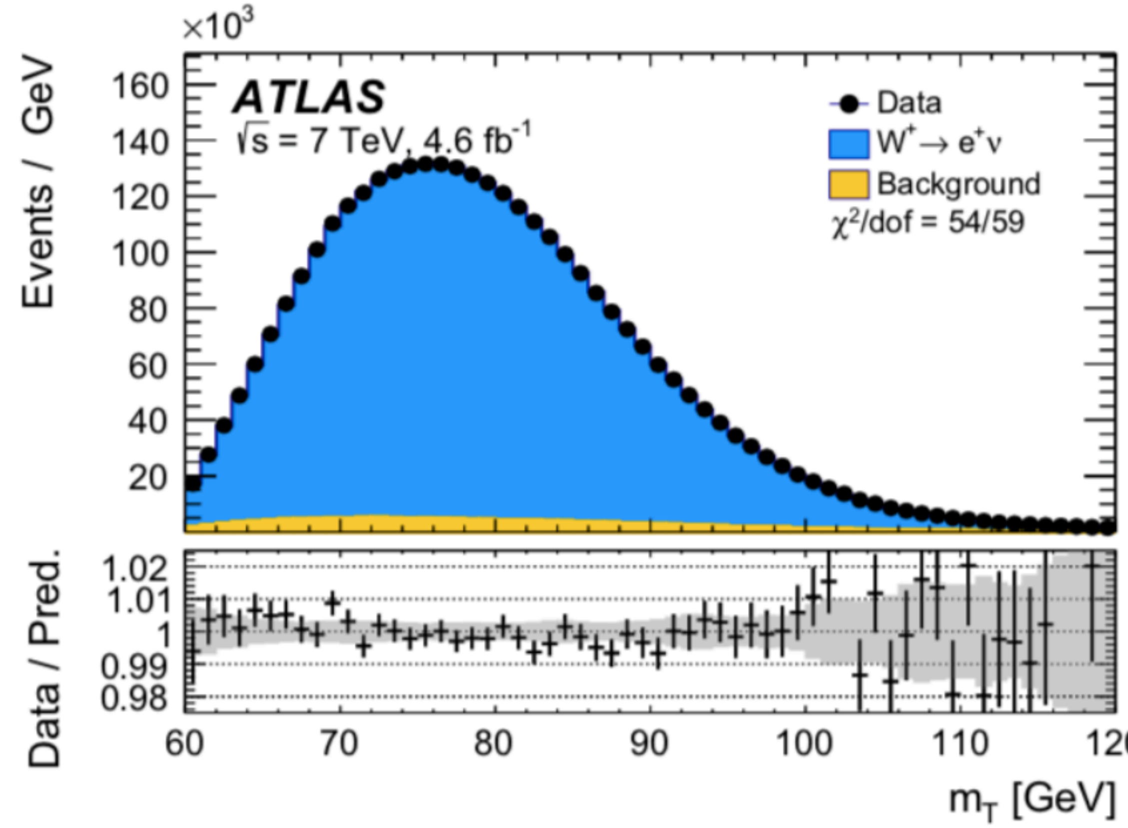
13 tT events/s in Run 2



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

- Fit from MC templates with different mass generated in steps of 1 - 10 MeV
- 28 χ^2 fits, separeted for lepton type (μ,e), W charge (+/-), rapidity interval (4 for μ, 3 for e) and fit variable (**m_T**, **p_T^l**).
- Many other fits were performed as consistency checks by varying fit range, etc …



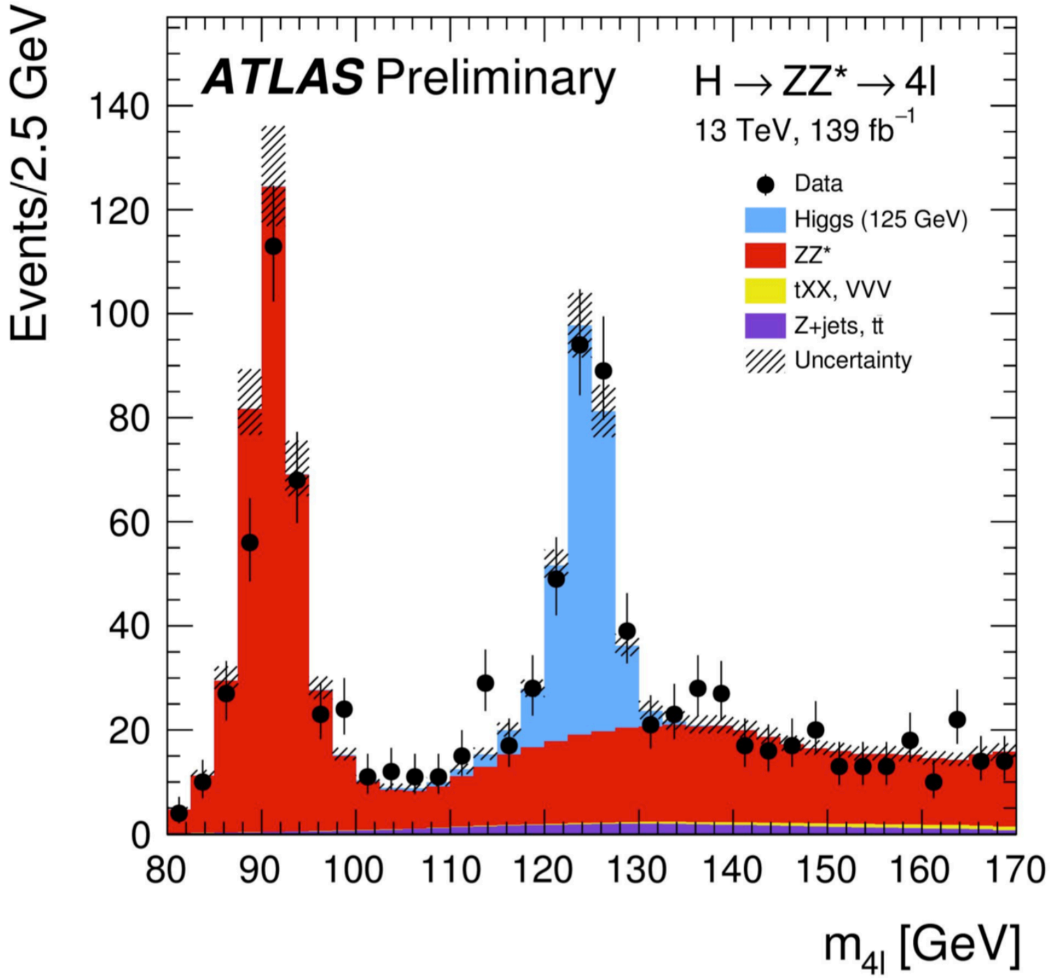


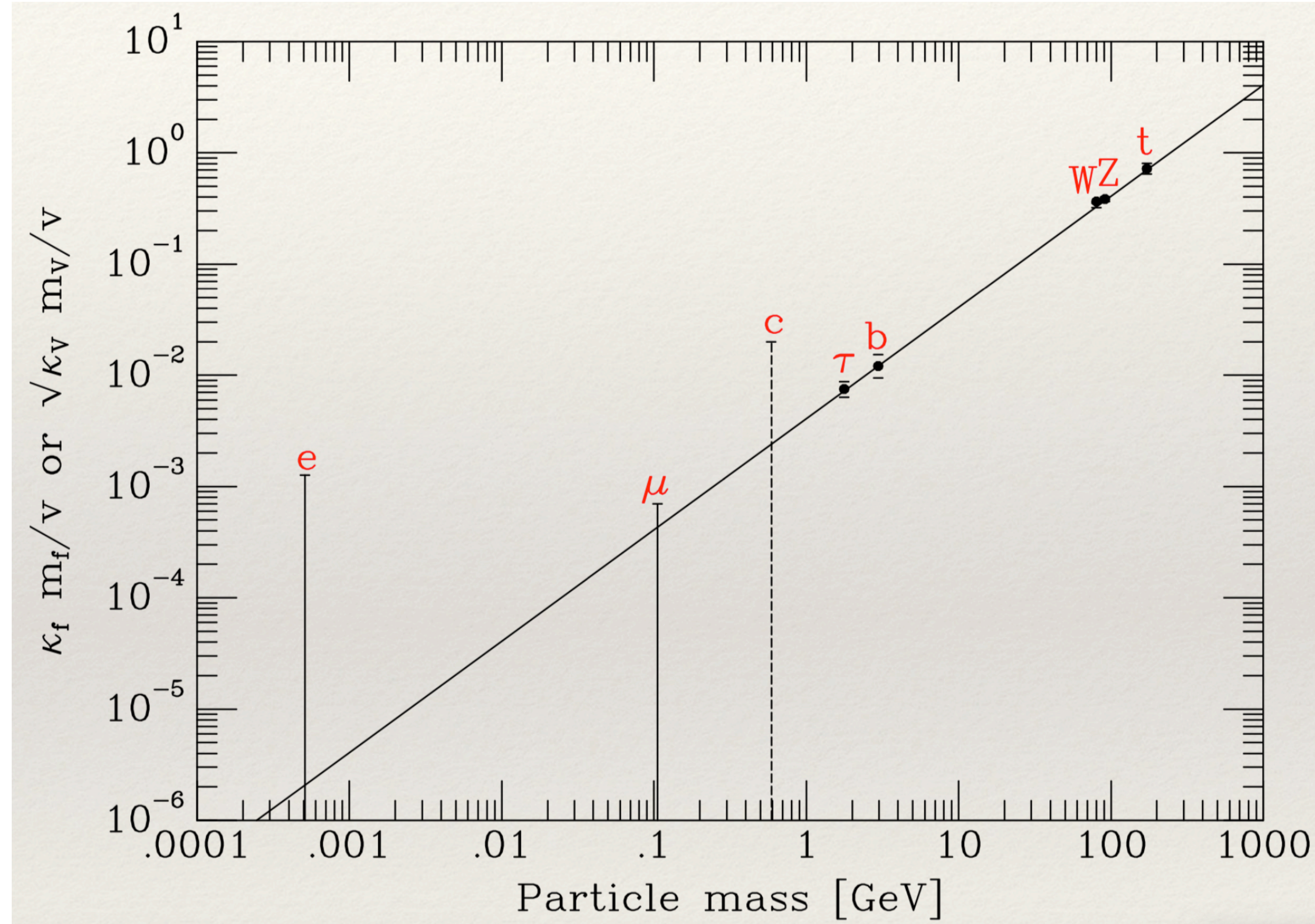
Combined result

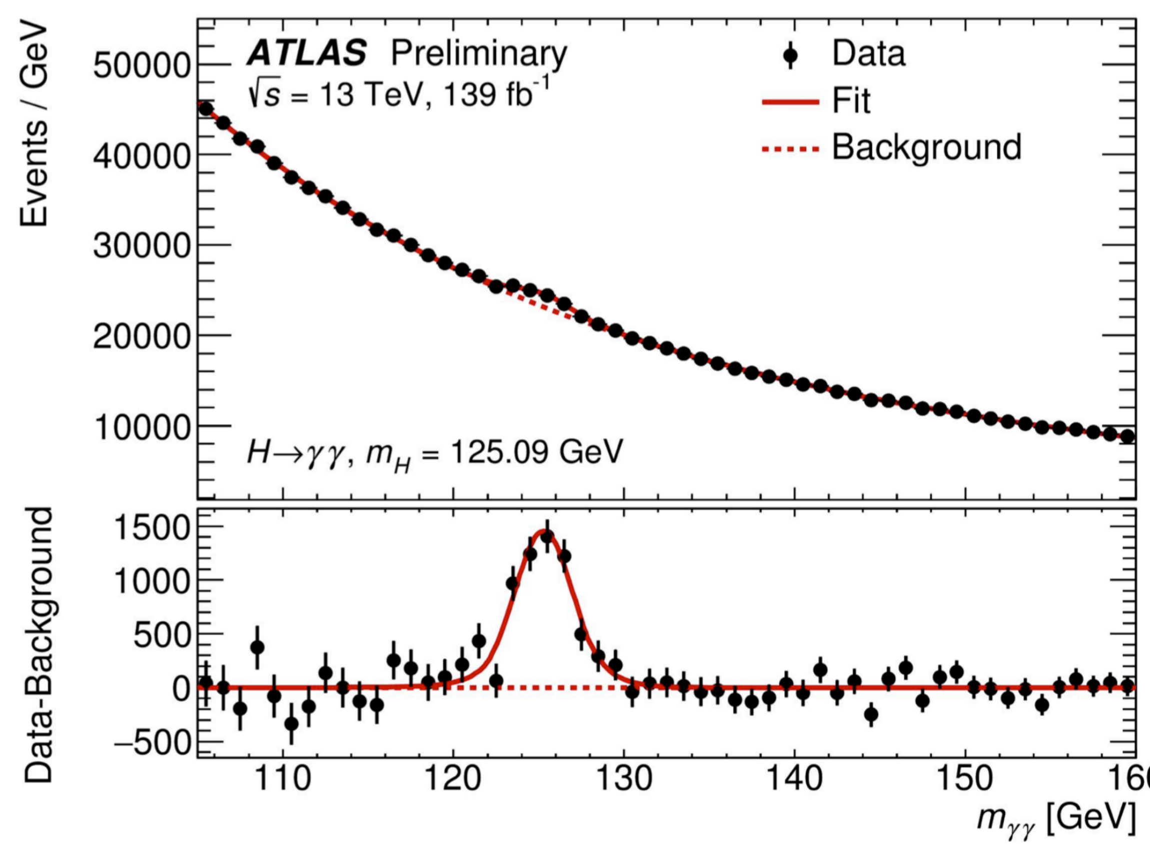
Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

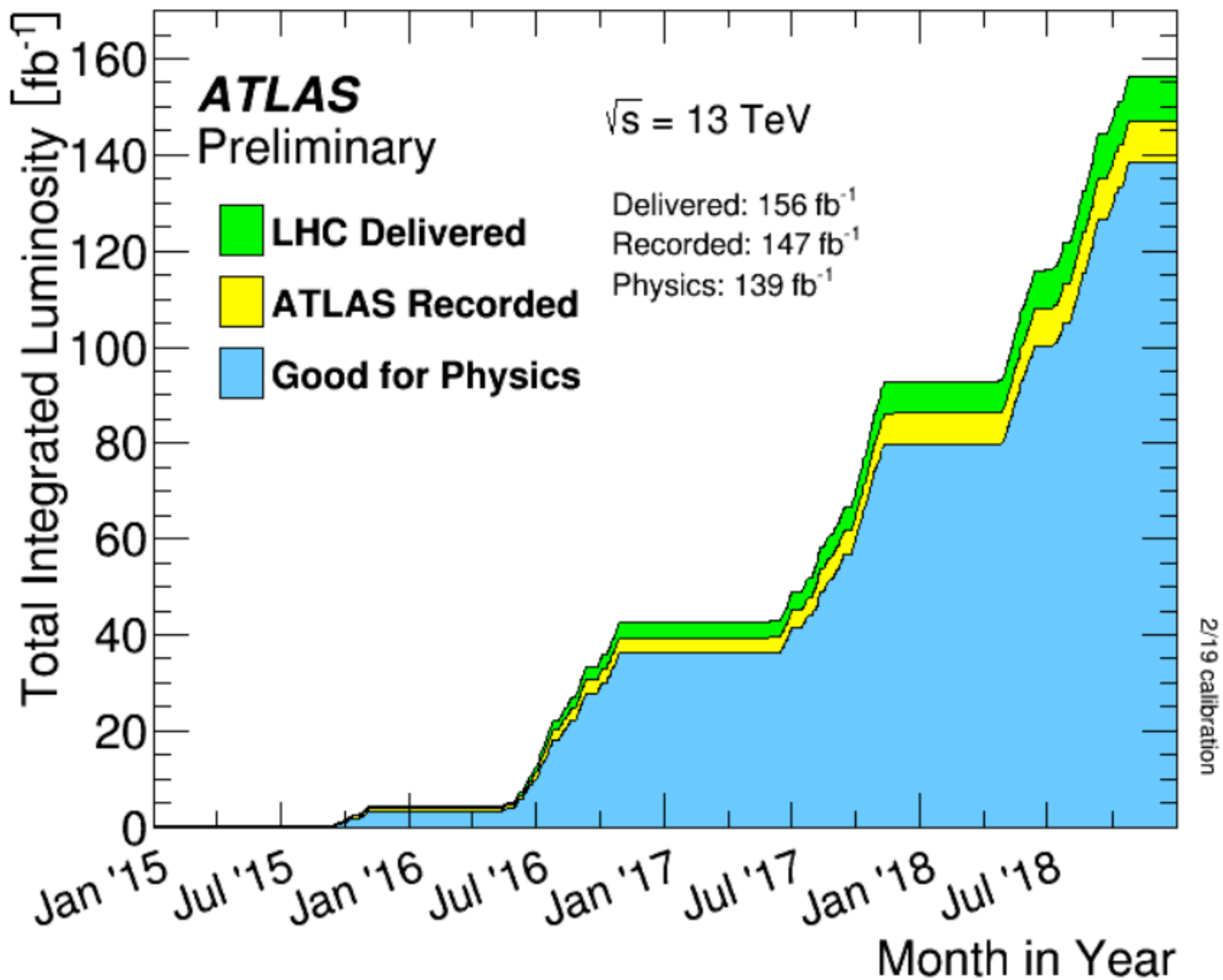
stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

M_W = 80370 ± 19 MeV


ATLAS Preliminary
H → ZZ* → 4l
13 TeV, 139 fb^{-1}
Data
Higgs (125 GeV)
ZZ*
tXX, VVV
Z+jets, tt
Uncertainty
Events/2.5 GeV
m_{4l} [GeV]


$\kappa_f\ m_f/v$ or $\sqrt{\kappa_V}\ m_V/v$
Particle mass [GeV]
e
μ
c
τ
b
WZ
t

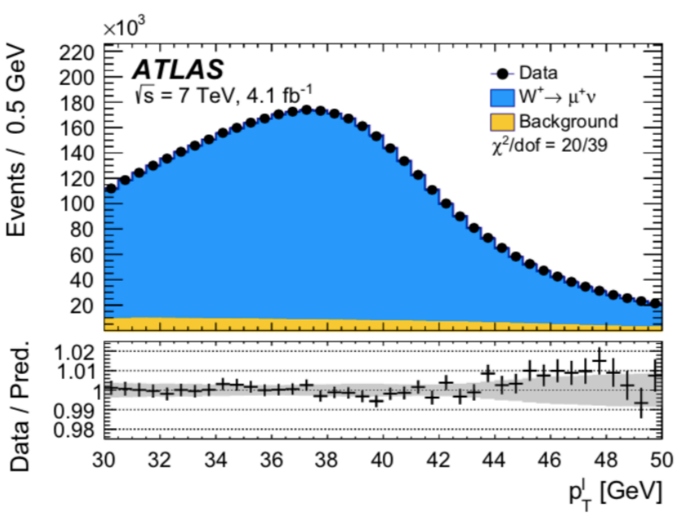

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Data
Fit
Background
$H\rightarrow\gamma\gamma$, m_H = 125.09 GeV
Events / GeV
Data-Background
$m_{\gamma\gamma}$ [GeV]

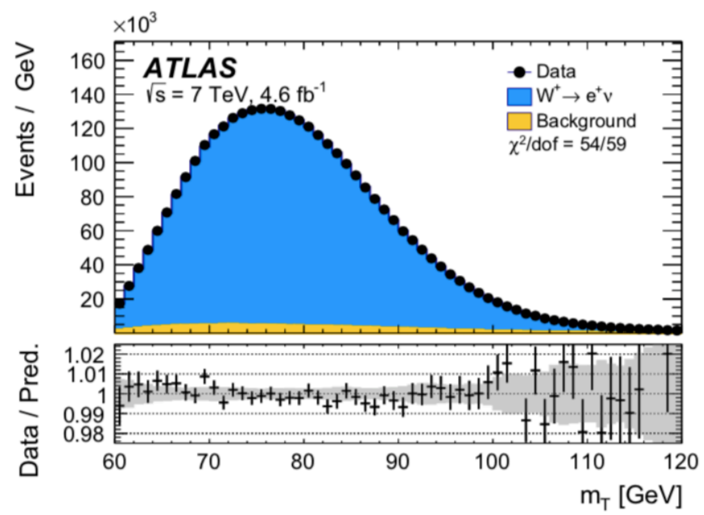


ATLAS
Preliminary
$\sqrt{s}$ = 13 TeV
LHC Delivered
ATLAS Recorded
Good for Physics
Delivered: 156 fb^{-1}
Recorded: 147 fb^{-1}
Physics: 139 fb^{-1}
Total Integrated Luminosity [fb^{-1}]
0
20
40
60
80
100
120
140
160
Jan '15
Jul '15
Jan '16
Jul '16
Jan '17
Jul '17
Jan '18
Jul '18
Month in Year
2/19 calibration

W mass

- Fit from MC templates with different mass generated in steps of 1 - 10 MeV
- 28 χ^2 fits, separeted for lepton type (μ,e), W charge (+/-), rapidity interval (4 for μ, 3 for e) and fit variable (**m_T**, **p_T^l**).
- Many other fits were performed as consistency checks by varying fit range, etc …





Combined result

Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
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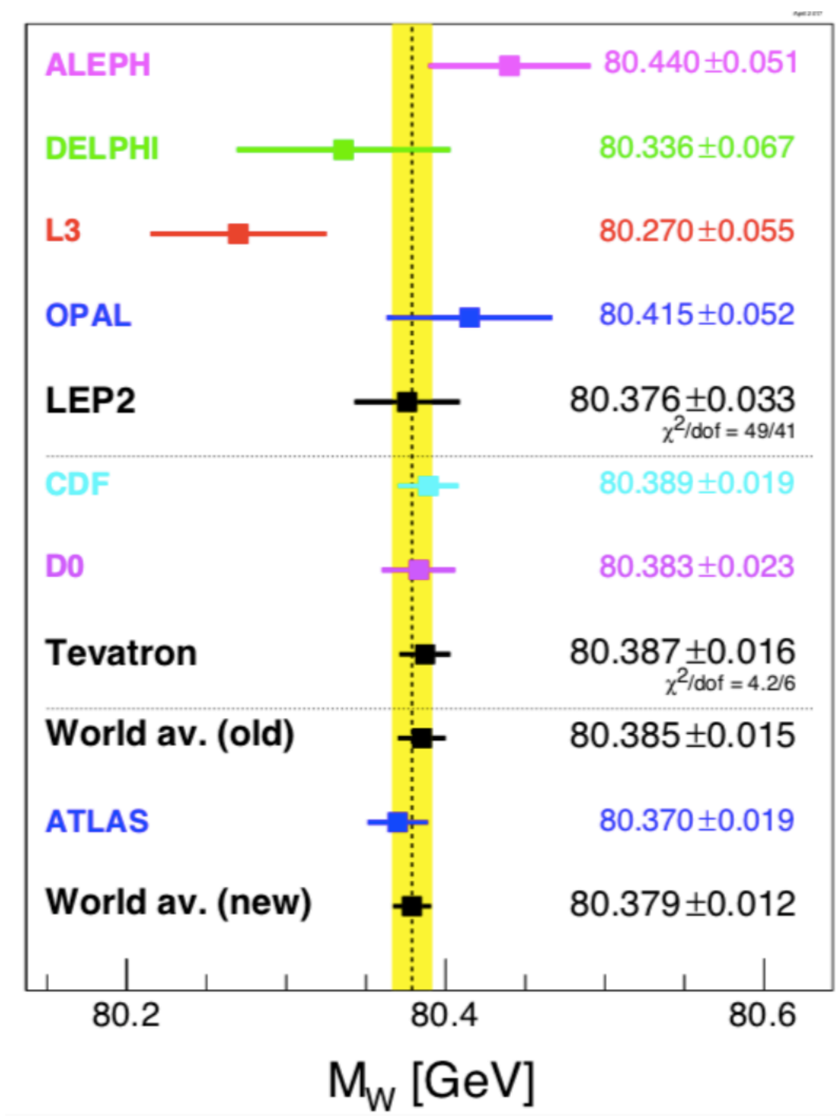
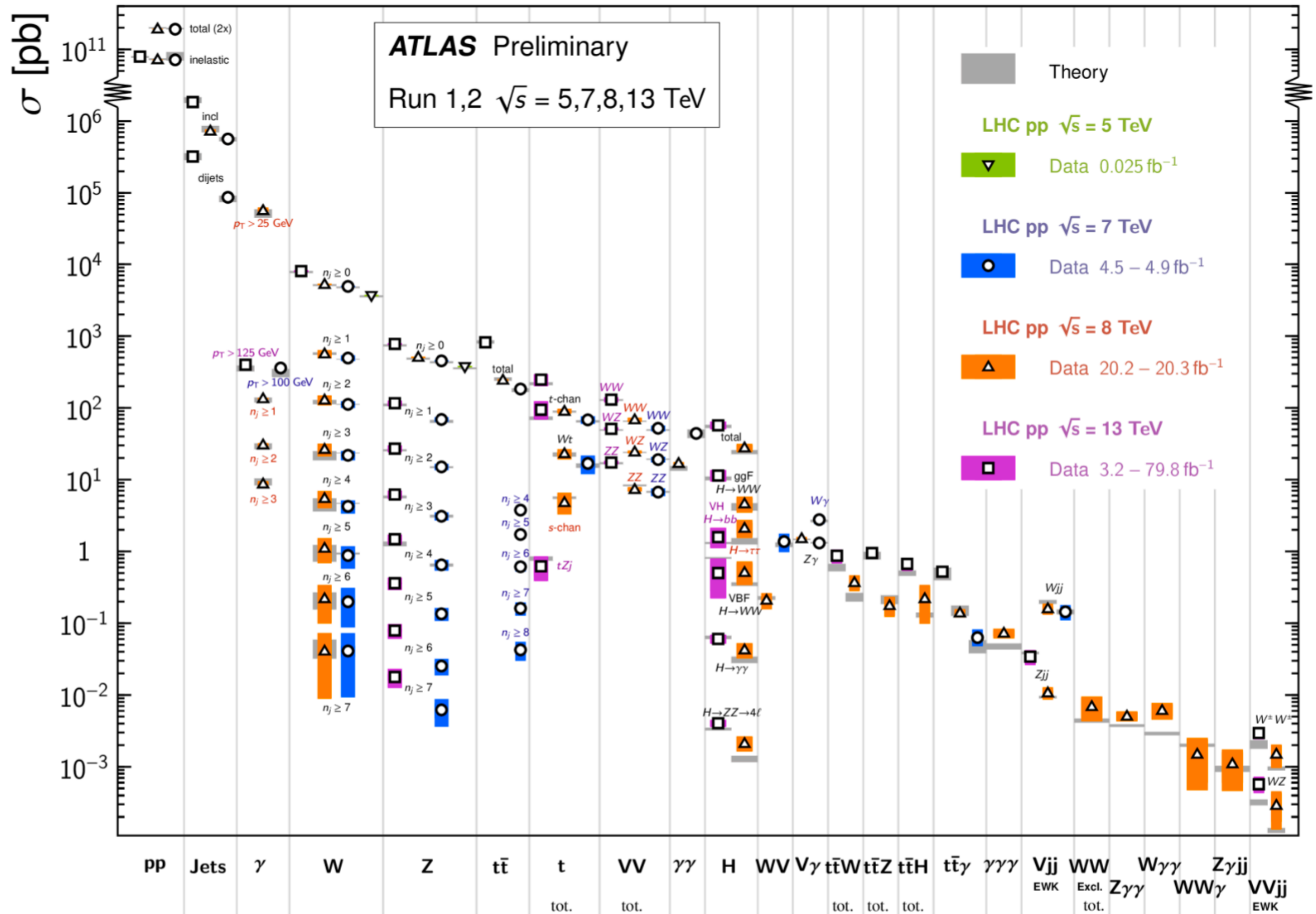
From PDG 2019



Standard Model Production Cross Section Measurements

Status: July 2019



100 km circular tunnel in China

Bejing

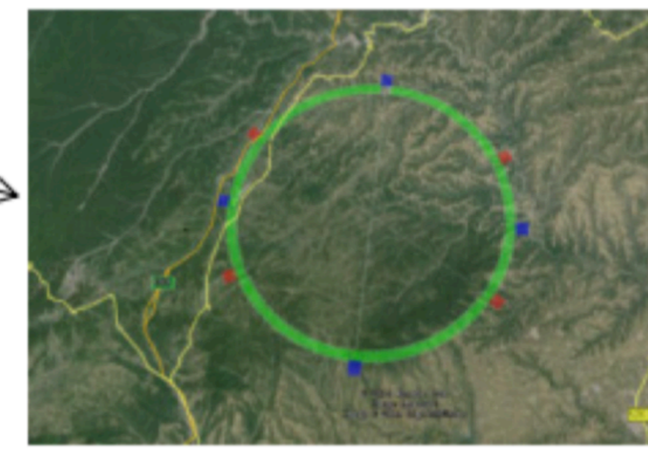
Baoding
(xiong an)

Tianjin

4

1

2



3

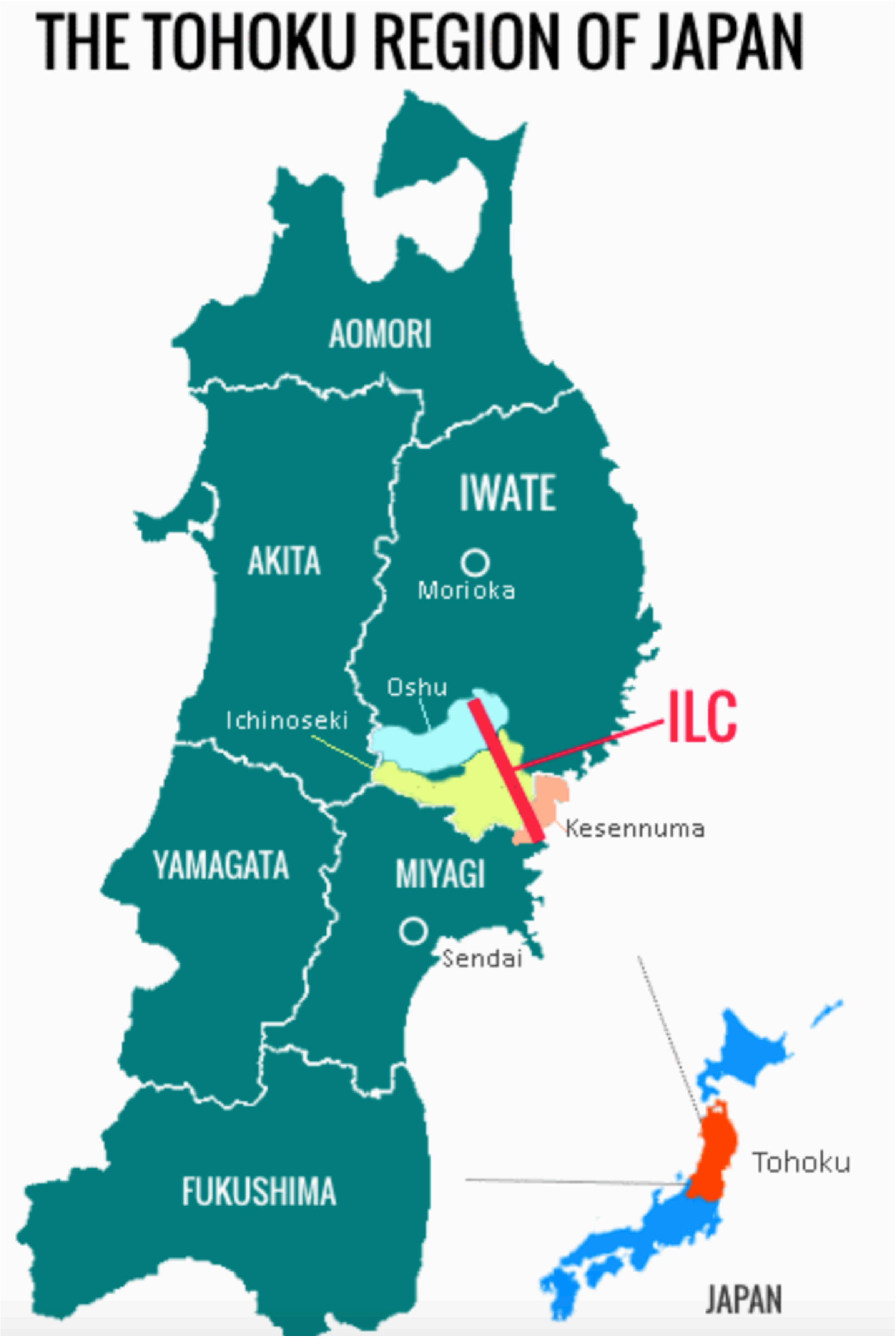
1) Qin huang dao，Heihe （Completed in 2014）

2) Huanging，Shanxi（Completed in 2017)

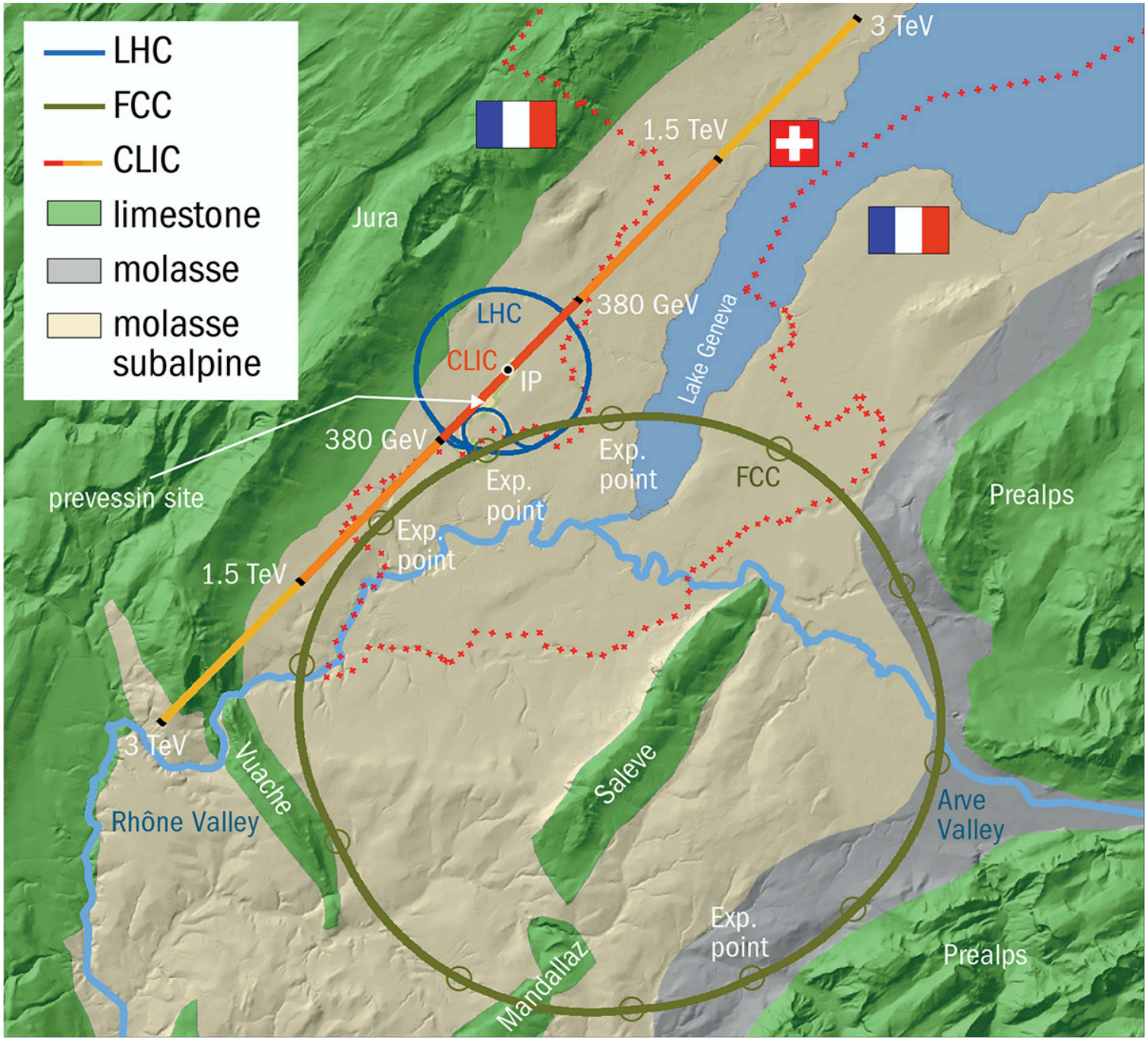
3)Shen shan，Guangdong (Completed in 2016)

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

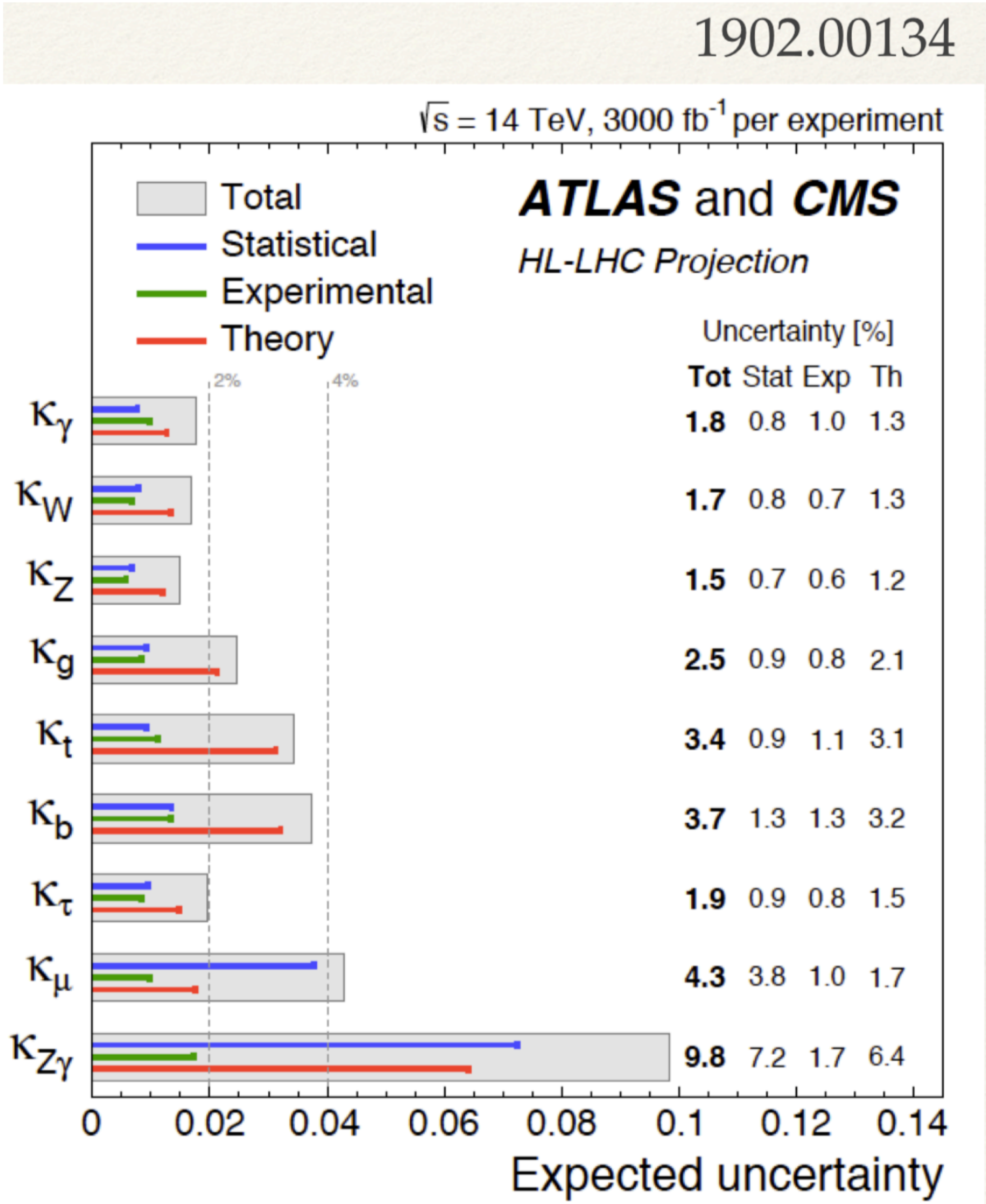
International Linear electron-positron Collider in Japan

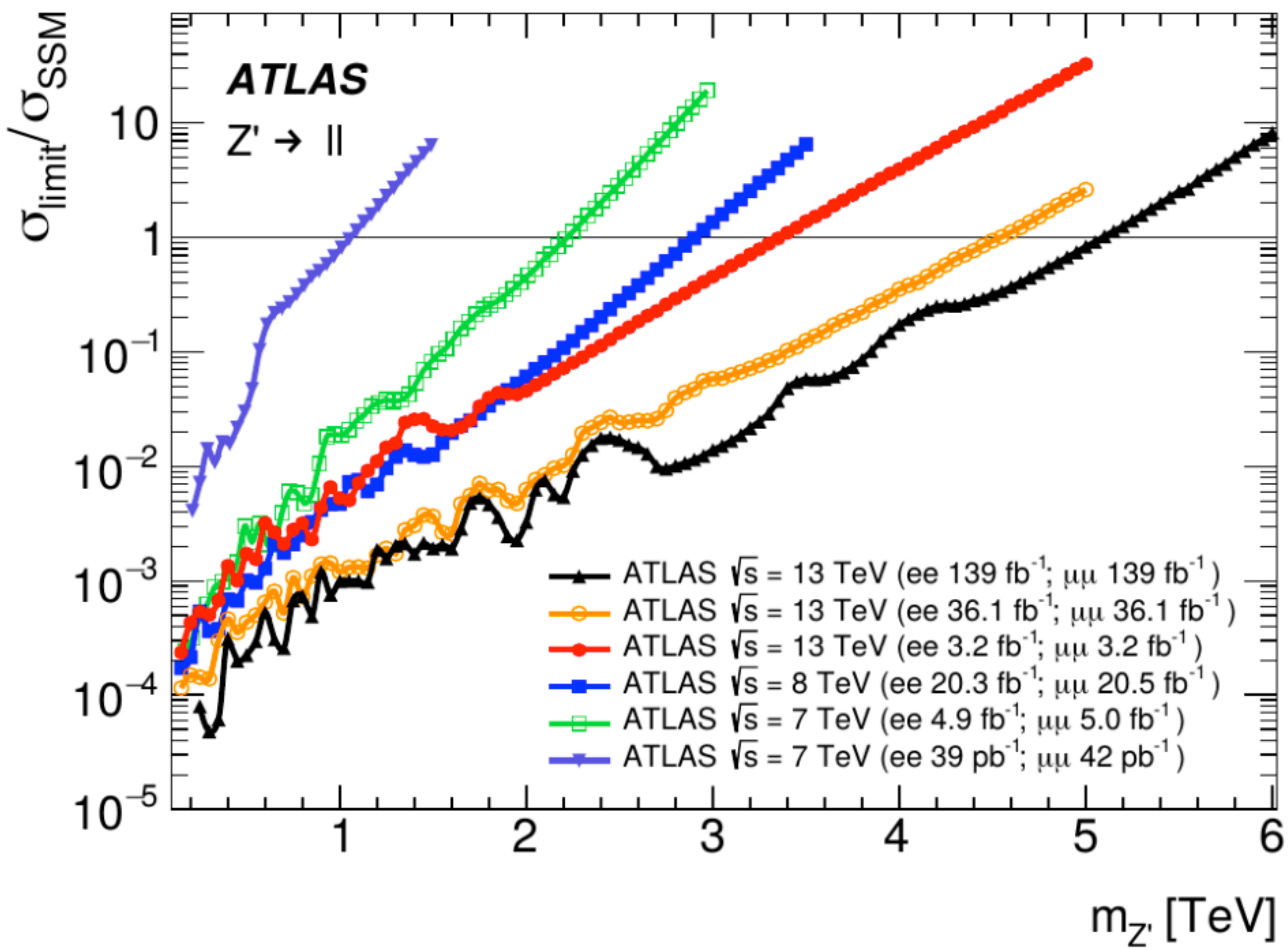


100 km Future Circular Collider or Compact Linear Collider at CERN



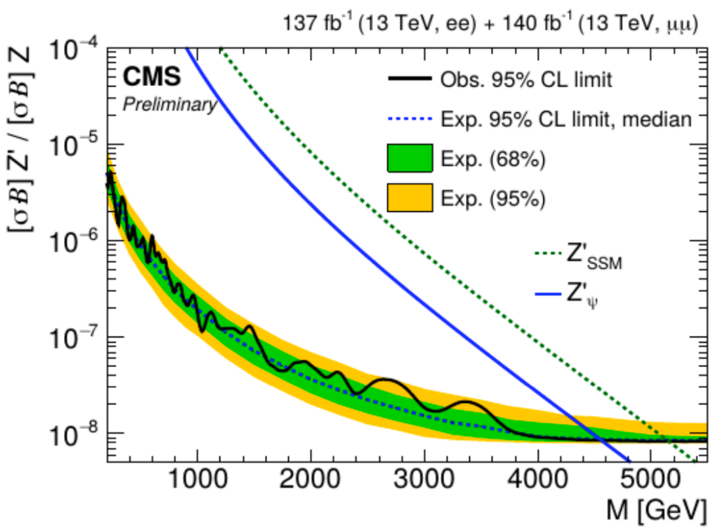
High-luminosity LHC 2026-2035

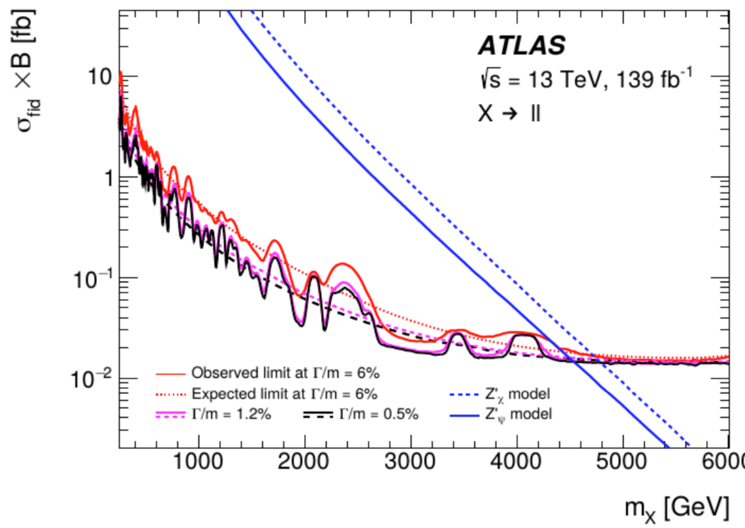


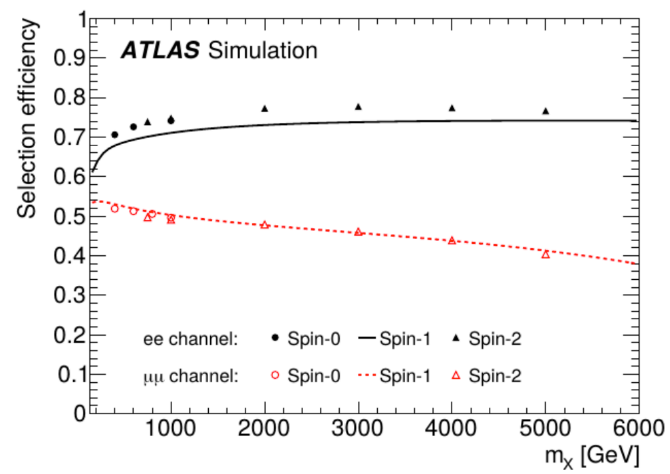


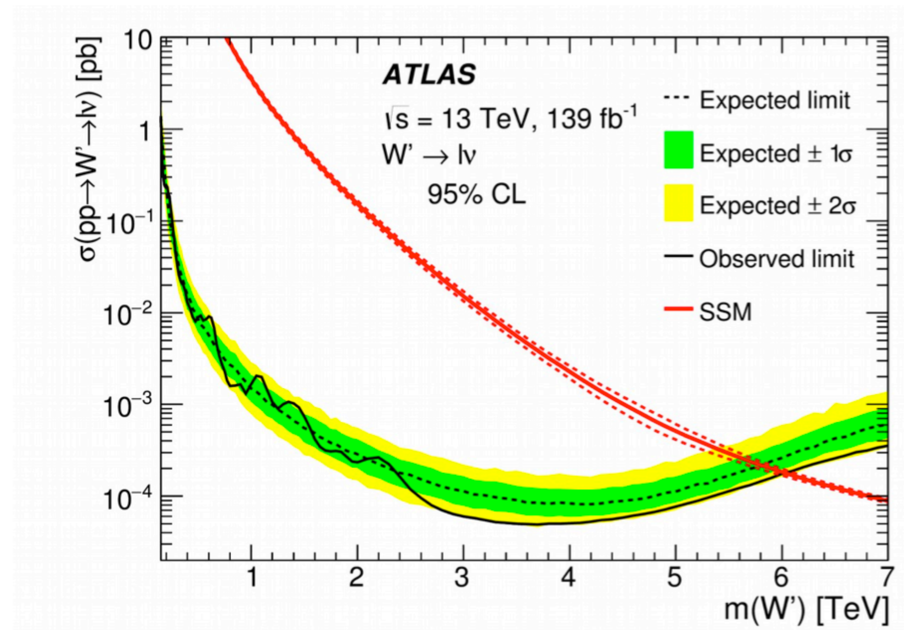
ATLAS
Z' → ll
$\sigma_{limit}/\sigma_{SSM}$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
2
3
4
5
6
$m_{Z'}$ [TeV]
ATLAS $\sqrt{s}$ = 13 TeV (ee 139 fb^{-1}; μμ 139 fb^{-1})
ATLAS $\sqrt{s}$ = 13 TeV (ee 36.1 fb^{-1}; μμ 36.1 fb^{-1})
ATLAS $\sqrt{s}$ = 13 TeV (ee 3.2 fb^{-1}; μμ 3.2 fb^{-1})
ATLAS $\sqrt{s}$ = 8 TeV (ee 20.3 fb^{-1}; μμ 20.5 fb^{-1})
ATLAS $\sqrt{s}$ = 7 TeV (ee 4.9 fb^{-1}; μμ 5.0 fb^{-1})
ATLAS $\sqrt{s}$ = 7 TeV (ee 39 pb^{-1}; μμ 42 pb^{-1})

Z′/W′





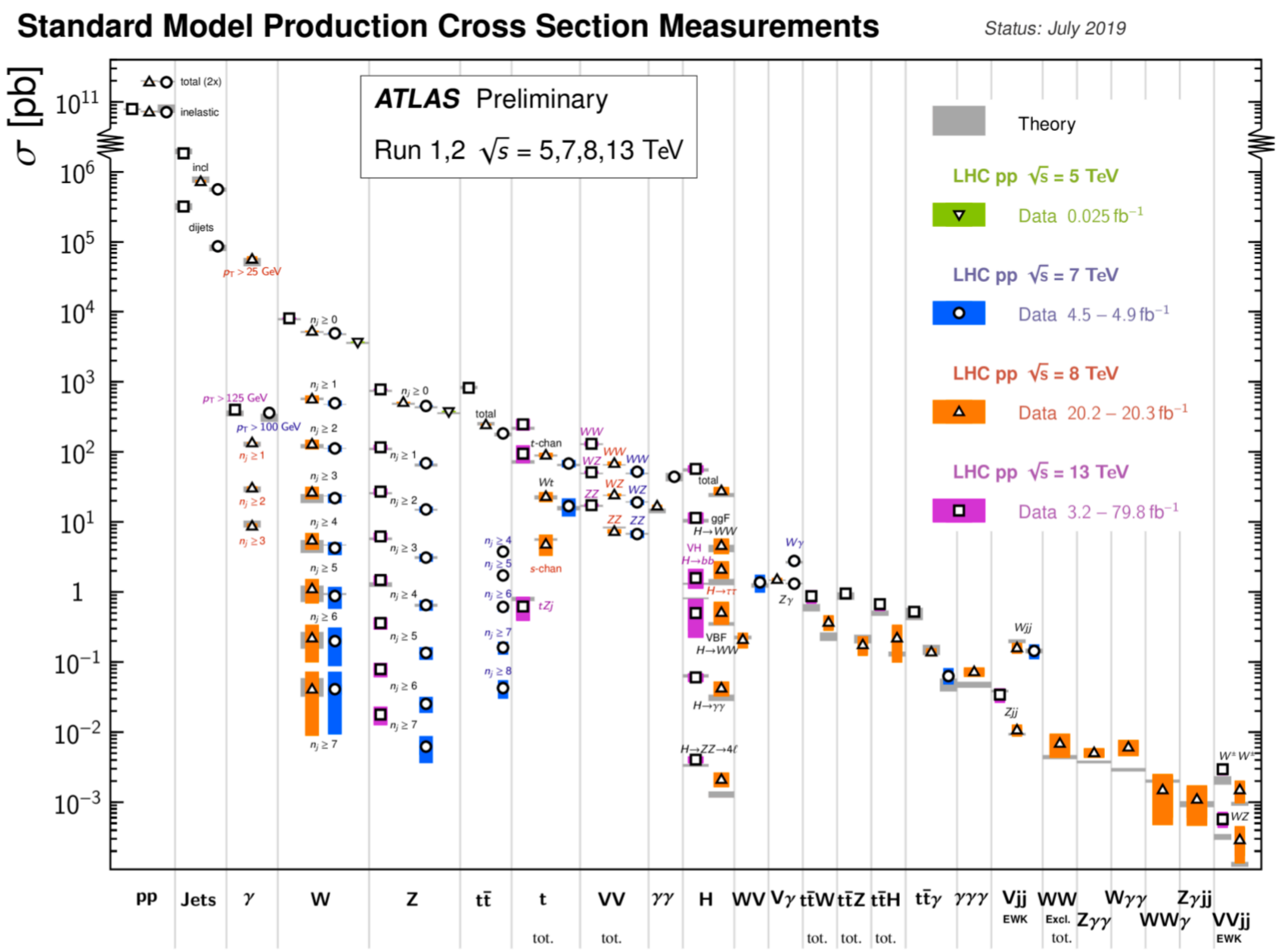




	$m(W')$ lower limit [TeV]	
Decay	Observed	Expected
$W' \to e\nu$	6.0	5.7
$W' \to \mu\nu$	5.1	5.1
$W' \to \ell\nu$	6.0	5.8

- Observed limits on $Z'_{\psi}\to ll$:
  - 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_{ll} available on HEPdata

SM


Standard Model Production Cross Section Measurements
Status: July 2019
ATLAS Preliminary
Run 1,2 √s = 5,7,8,13 TeV
Theory
LHC pp √s = 5 TeV
Data 0.025 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
σ [pb]
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Vjj EWK
WW Excl.
Zγγ
Wγγ
WWγ
Zγjj
VVjj EWK