

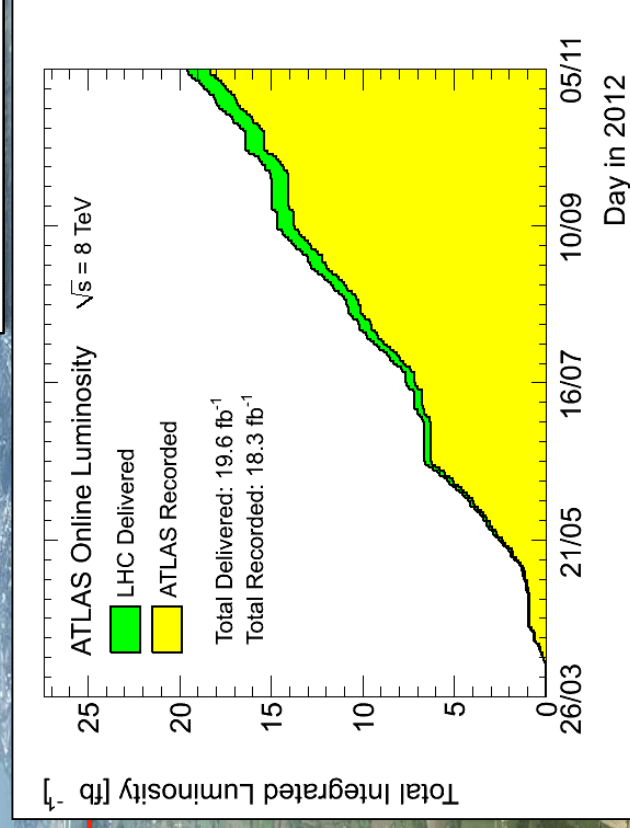


THE DISCOVERY OF THE HIGGS BOSON

Ivo van Vulpen

Large Hadron Collider

LHC Luminosity



ATLAS (2011): 4.8 fb^{-1} at $\sqrt{s}=7 \text{ TeV}$
ATLAS (2012): 19.6 fb^{-1} at $\sqrt{s}=8 \text{ TeV}$

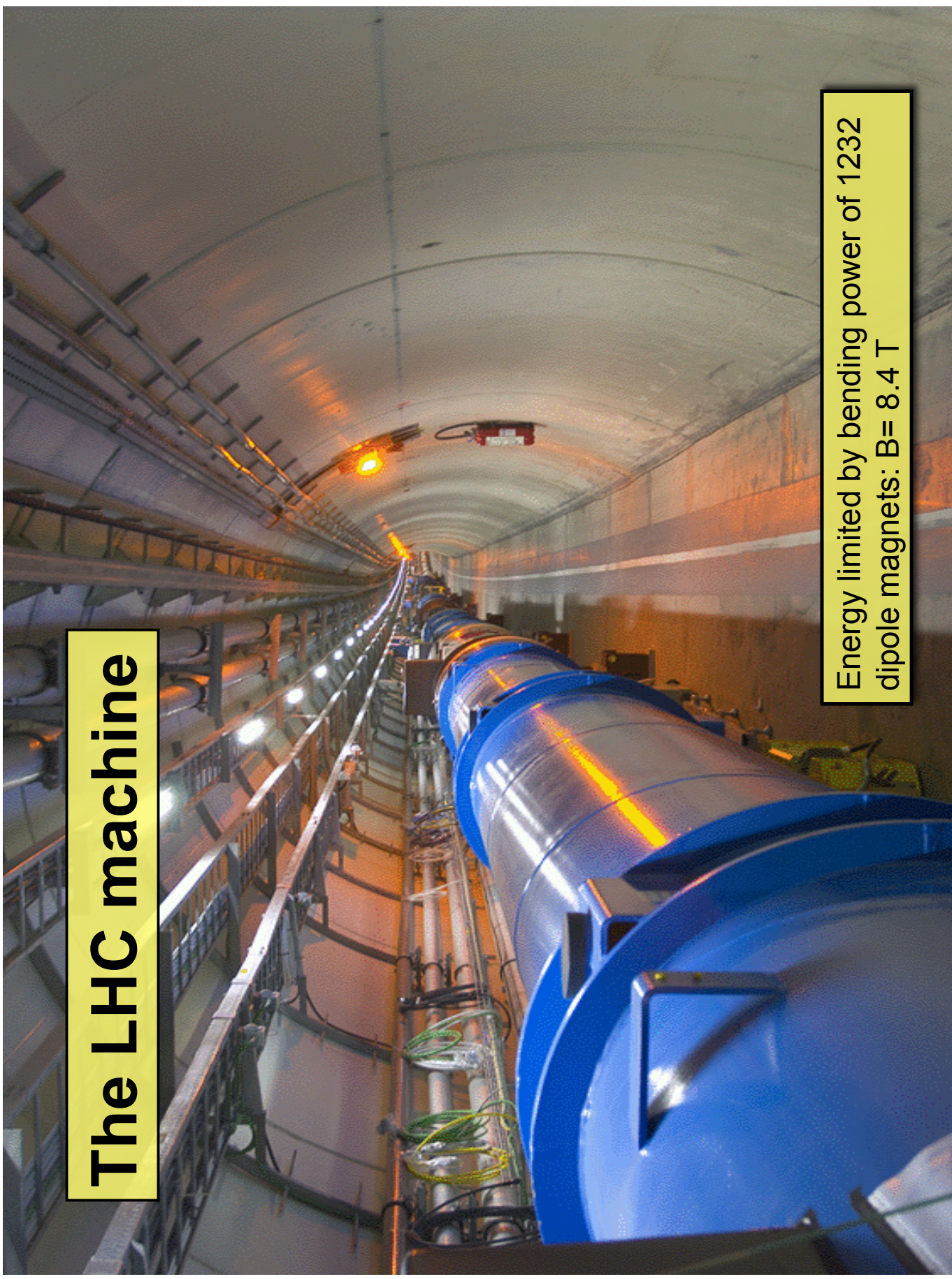
Limited Trigger rate: 200 Hz

An aerial photograph of the landscape near Geneva, Switzerland, showing a large red circular line representing the LHC tunnel. The line is marked with several small red circles. The background features a mix of green fields, urban areas, and distant mountains under a blue sky.

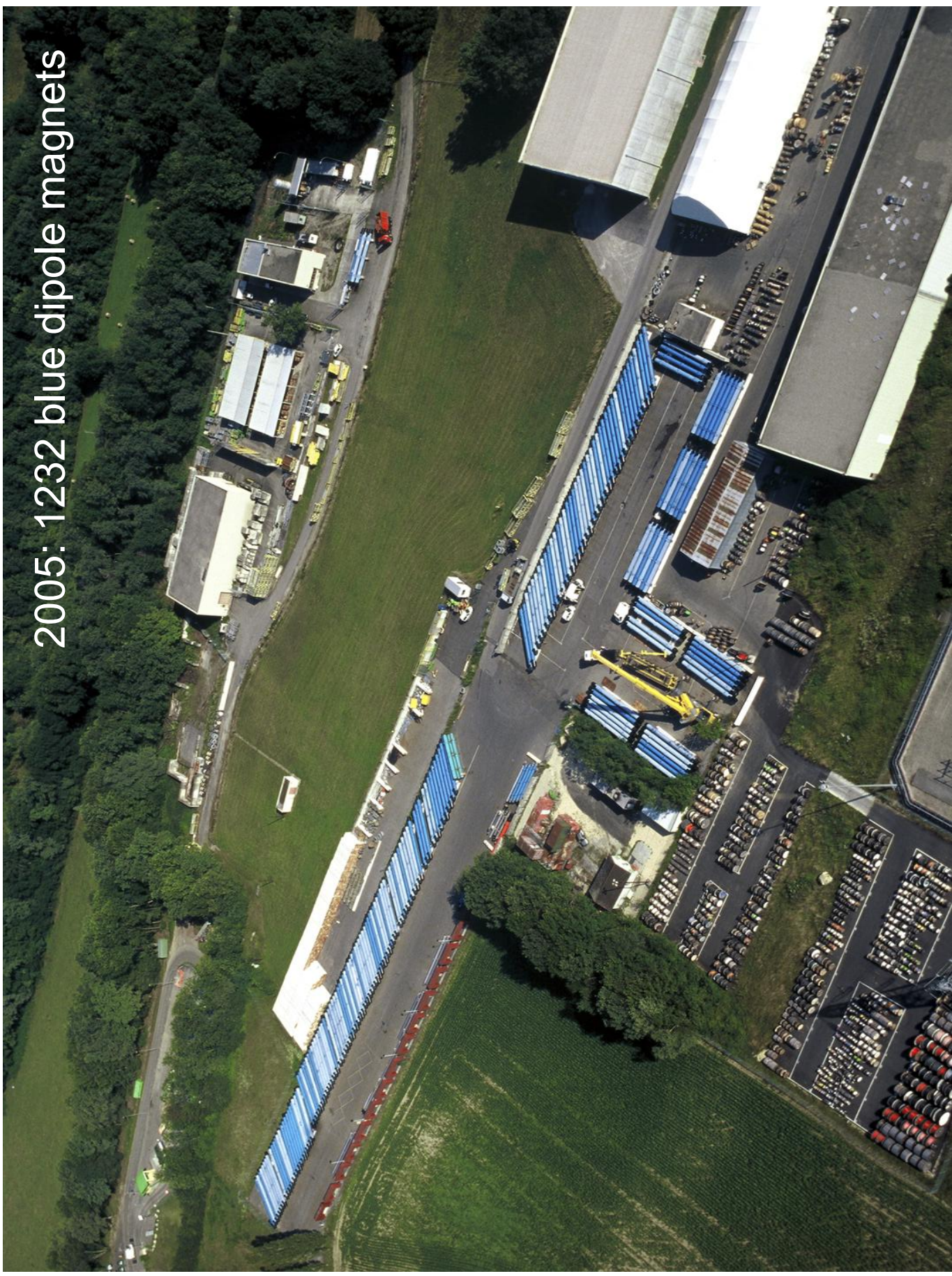
Largest microscope on earth
the Large Hadron Collider (LHC)
at CERN near Genève

The LHC machine

Energy limited by bending power of 1232
dipole magnets: $B = 8.4 \text{ T}$

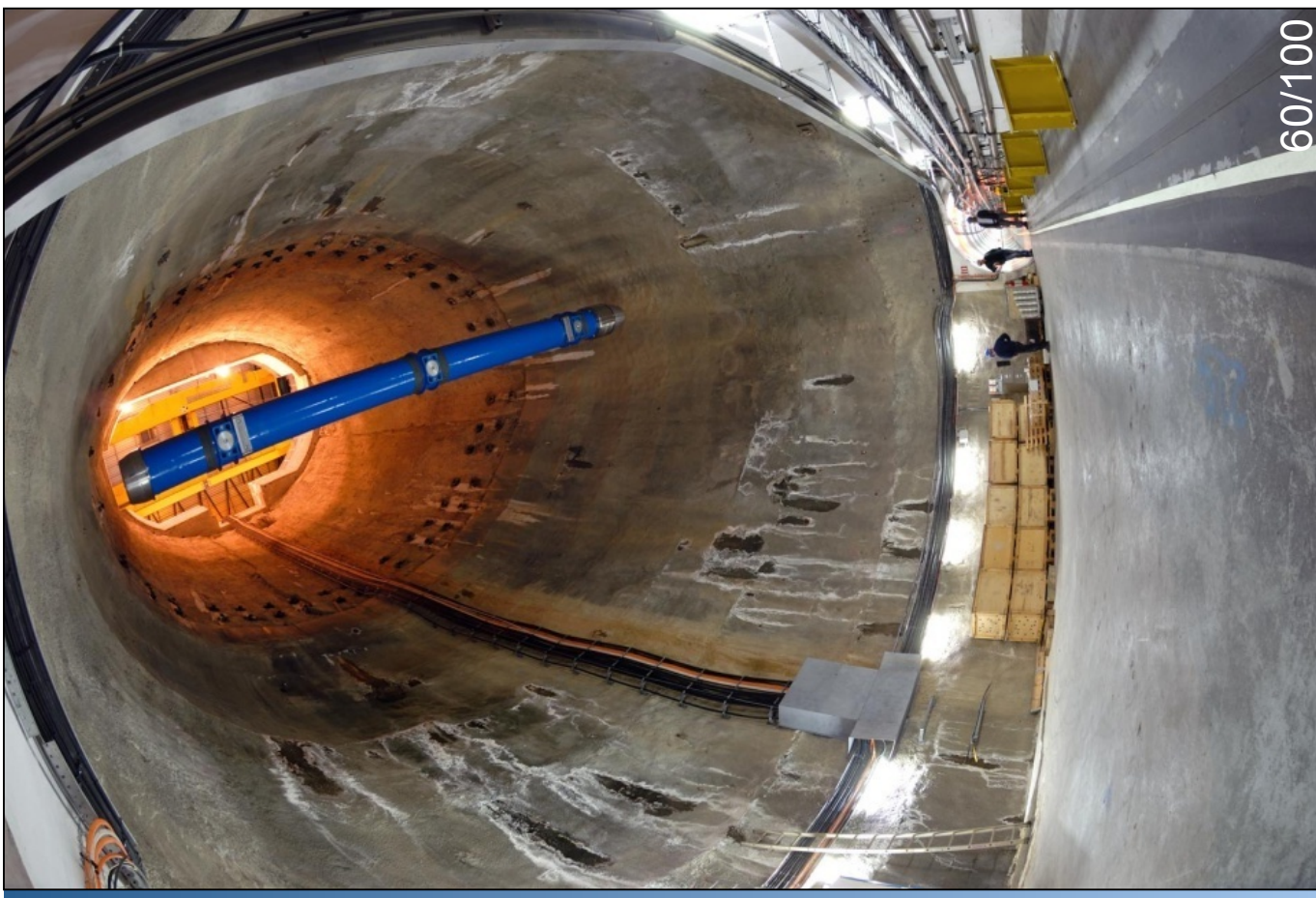


2005: 1232 blue dipole magnets

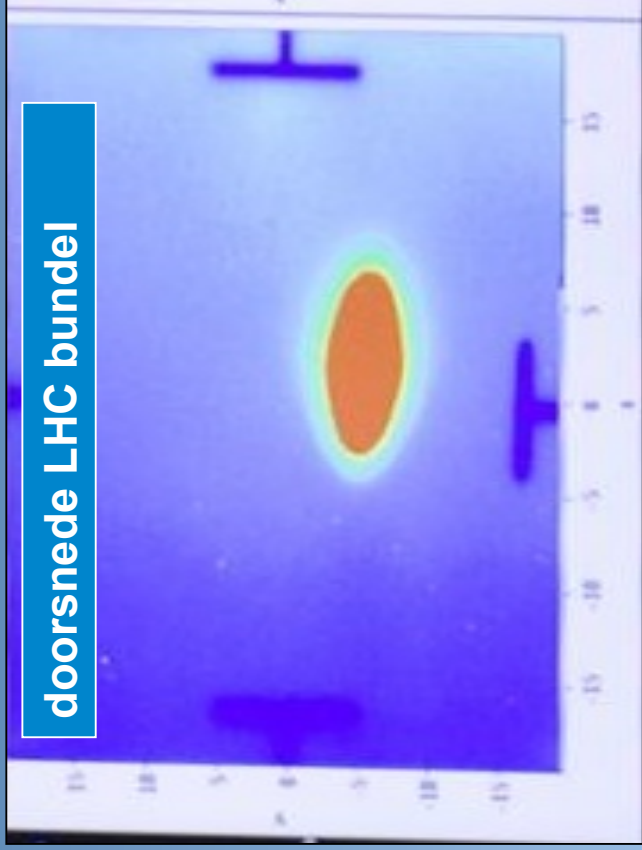


Logistic nightmare

But we (they) did it



Size LHC beam is size of Spain on a 2 Euro coin

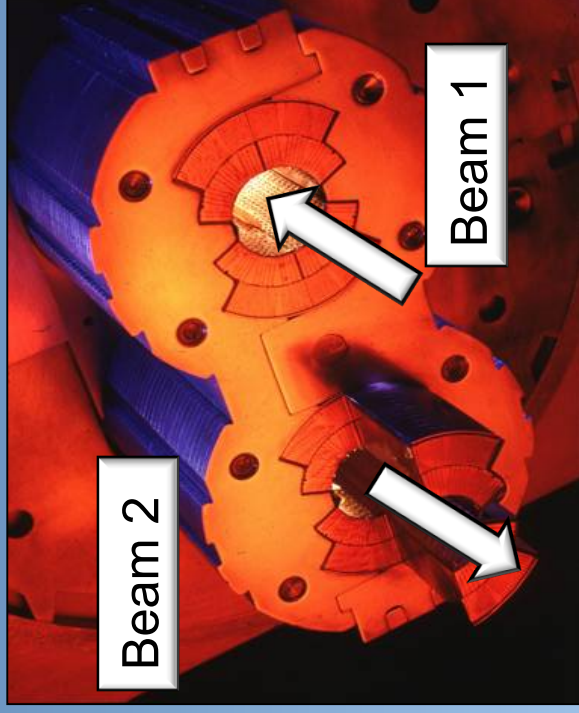


Energy 1 proton (LHC)



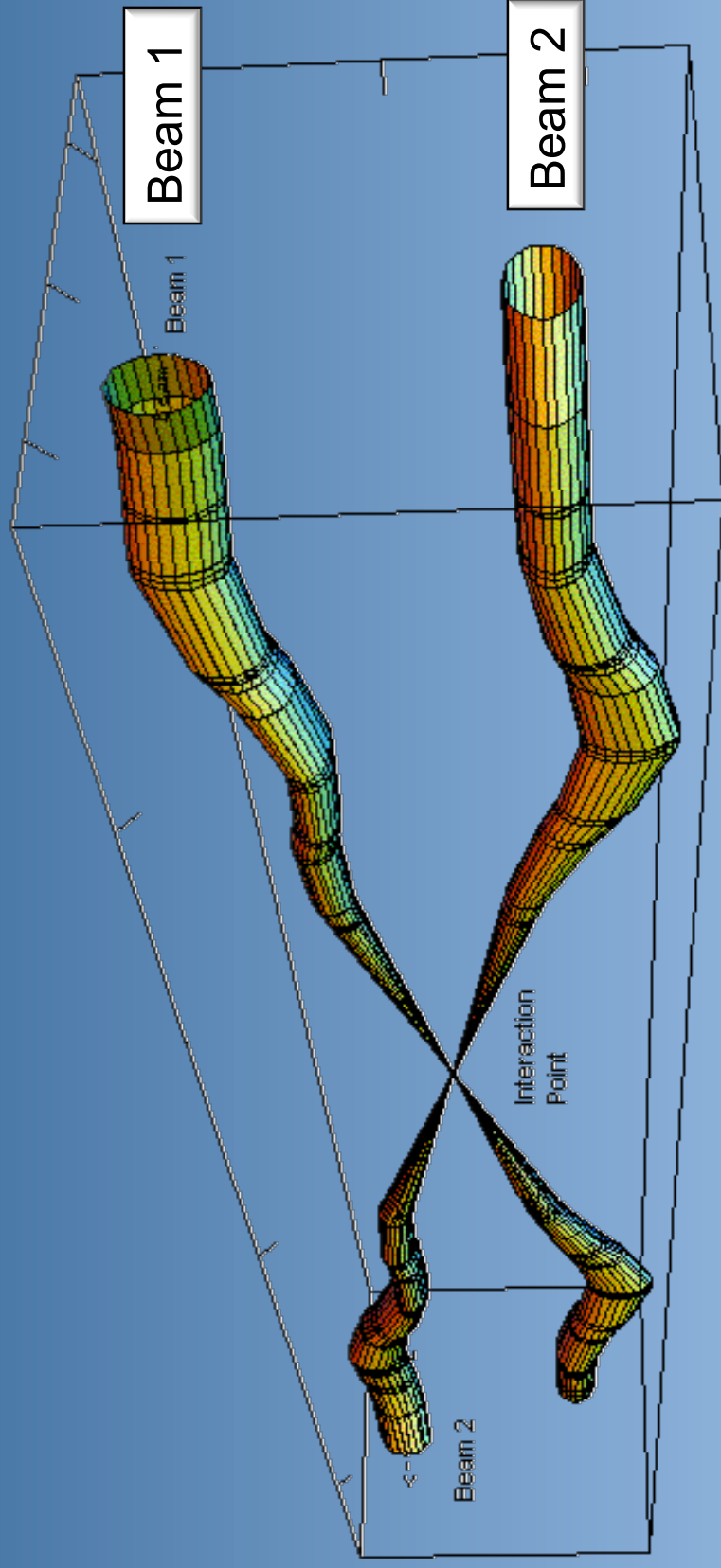
Energy LHC bundel

$3000 \times 100.000.000.000$ protons

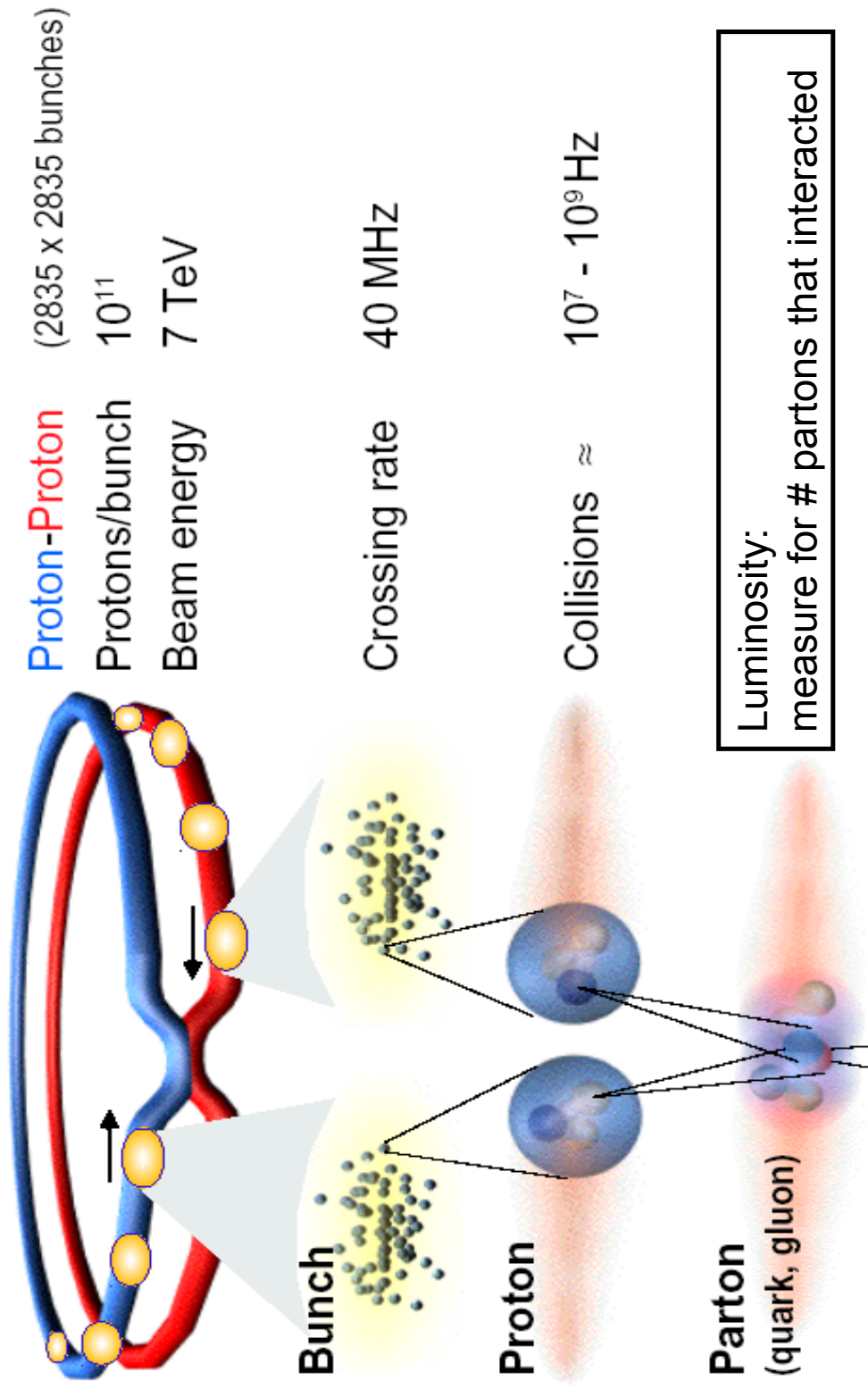


Slice LHC beampipe

40 million collisions per second



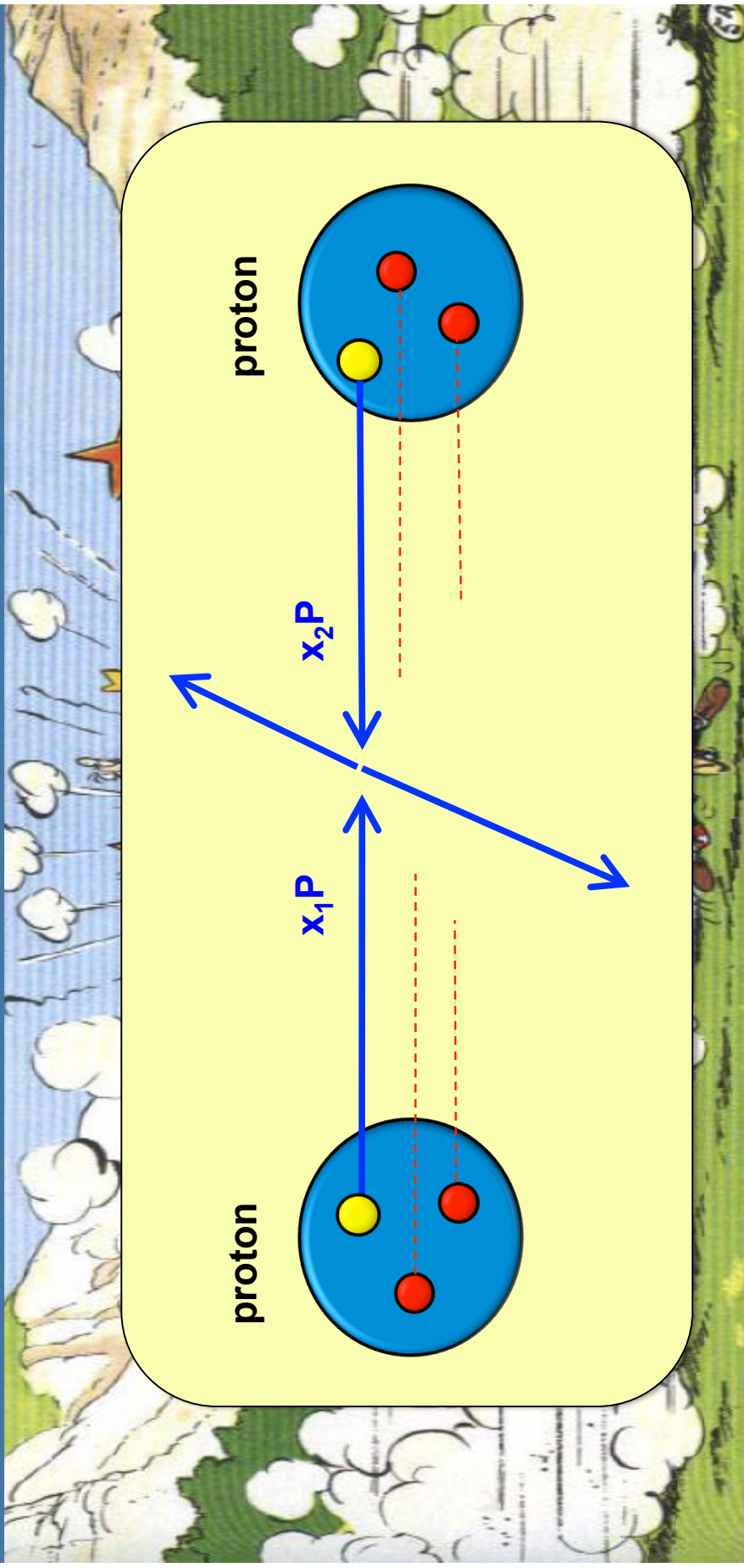
The Large Hadron Collider



Collides quarks and gluons: only a fraction of the total proton energy

Fenomenologie botsingen

“Proton is als een zak vol met (anti-)quarks en gluonen”



Maar klein deel van de energie beschikbaar voor de harde ('echte') botsing

What do we expect ?

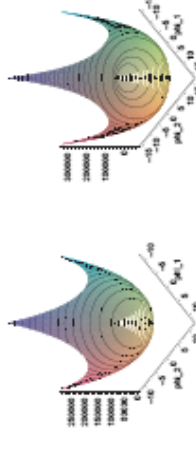


FIG. 1: The potential $V(\phi)$ ($\phi = \phi_1 + i\phi_2$) plotted for an arbitrary positive value of λ and for an arbitrary positive (right) or negative (left) value of μ^2 .

broken, and new interesting features emerge. To be more specific, let's pick the following ϕ_0 minimum (along the direction of the real part of ϕ as traditional) and shift the ϕ field accordingly:

$$\phi_0 = \left(-\frac{\mu^2}{2\lambda} \right)^{1/2} \longrightarrow \phi(x) = \phi_0 + \frac{1}{\sqrt{2}}(\phi_1(x) + i\phi_2(x)) . \quad (5)$$

The Lagrangian in Eq. (3) can then be rearranged as follows:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{massive vector field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_1)^2 + \frac{1}{2}(\partial^\mu\phi_2)^2}_{\text{massive scalar field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_2)^2 + \frac{1}{2}(\partial^\mu\phi_1)^2 + g v A_\mu \partial^\mu\phi_2 + \dots}_{\text{Goldstone boson}} \quad (6)$$

and now contains the correct terms to describe a massive vector field A^μ with mass $m_A^2 = g^2 v^2$ (originating from the kinetic term of $\mathcal{L}_\phi$), a massive real scalar field ϕ_1 with mass $m_{\phi_1} = -2\mu^2$, that will become a *Higgs boson*, and a massless scalar field ϕ_2 , a so called *Goldstone boson* which couples to the gauge vector boson A^μ . The terms omitted contain couplings between the ϕ_1 and ϕ_2 fields irrelevant to this discussion. The gauge symmetry of the theory allows us to make the particle content more transparent. Indeed, if we parameterize the complex scalar field ϕ as:

$$\phi(x) = \frac{e^{i\alpha(x)}}{\sqrt{2}}(v + H(x)) - \frac{1}{\sqrt{2}}(v + H(x)) , \quad (7)$$

the χ degree of freedom can be *rotated away*, as indicated in Eq. (7), by enforcing the $U(1)$ gauge invariance of the original Lagrangian. With this gauge choice, known as *unitary gauge* or *unitarity gauge*, the Lagrangian becomes:

$$\mathcal{L} = \mathcal{L}_A + \frac{g^2 v^2}{2} A^\mu A_\mu + \frac{1}{2} (\partial^\mu H \partial_\mu H + 2\mu^2 H^2) + \dots \quad (8)$$

a factor of two, making therefore almost a factor of four at the rate level. All other mass corrections, in the matrix element and phase space entering the calculation of the $H \rightarrow Q\bar{Q}$ decay rate, can in first approximation be safely neglected.

4. Loop induced Higgs boson decays: $H \rightarrow \gamma\gamma, \gamma Z, g g$

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son decays: $H \rightarrow \gamma\gamma, \gamma Z, g g$

the $H\gamma\gamma$ and $H\gamma Z$ couplings are induced at one loop via both a corrections, in the matrix element and phase space entering the calculation of the $H \rightarrow Q\bar{Q}$ decay rate, can in first approximation be safely neglected.

$$i) = \frac{G_F \alpha^2 M_H^2}{128\sqrt{2}\pi^2} \left| \sum_f N_f^2 Q_f^2 A_f^H(\tau_f) + A_W^H(\tau_W) \right|^2 , \quad (102)$$

i, q respectively), Q_f is the charge of the f fermion species, a $f(\tau)$ is defined as:

$$f(\tau) = \begin{cases} \arcsin^3 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4} \left[\ln \frac{1-\sqrt{1-\tau}}{1+\sqrt{1-\tau}} - i\pi \right]^2 & \tau < 1 , \end{cases} \quad (103)$$

and A_f^H are given by:

$$A_f^H = 2\tau [1 + (1-\tau)f(\tau)] , \quad (104)$$

$$A_W^H(\tau) = -[2 + 8\tau + 3\tau(2-\tau)f(\tau)] .$$

my rate for $H \rightarrow \gamma Z$ is given by:

$$\frac{\alpha M_H^2}{\pi^4} \left(1 - \frac{M_Z^2}{M_H^2} \right)^2 \left| \sum_f A_f^H(\tau_f, \lambda_f) + A_W^H(\tau_W, \lambda_W) \right|^2 , \quad (105)$$

$\lambda_i = 4M_i^2/M_Z^2$ ($i = f, W$), and the form factors $A_f^H(\tau, \lambda)$ and

$$2N_f^2 \frac{Q_f(I_f - 2Q_f \sin^2 \theta_W)}{\cos \theta_W} [I_1(\tau, \lambda) - I_2(\tau, \lambda)] , \quad (106)$$

$$\cos \theta_W \left\{ \left[\left(1 + \frac{2}{\tau} \right) \tan^2 \theta_W - \left(5 + \frac{2}{\tau} \right) \right] I_1(\tau, \lambda) + 4 \left(3 - \tan^2 \theta_W \right) I_2(\tau, \lambda) \right\} , \quad (107)$$

ed after Eq. (102), and I_f^2 is the weak isospin of the f fermion

$$\frac{\tau^2 \lambda^2}{\lambda} + \frac{\tau^2 \lambda^2}{2(\tau - \lambda)^2} [f(\tau) - f(\lambda)] + \frac{\tau^2 \lambda}{(\tau - \lambda)^2} [g(\tau) - g(\lambda)] ,$$

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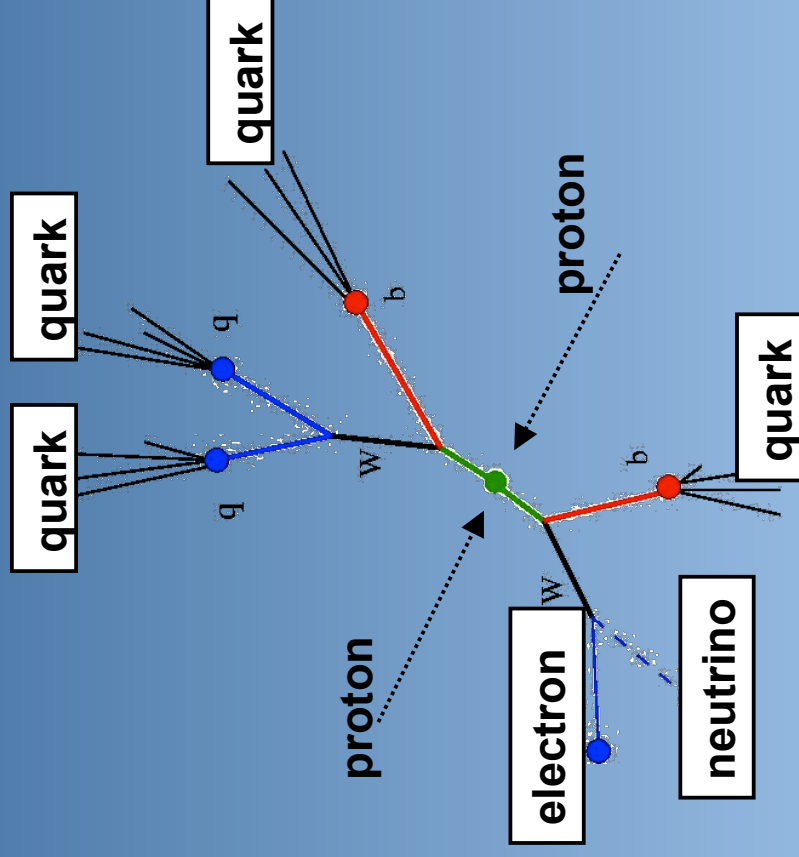
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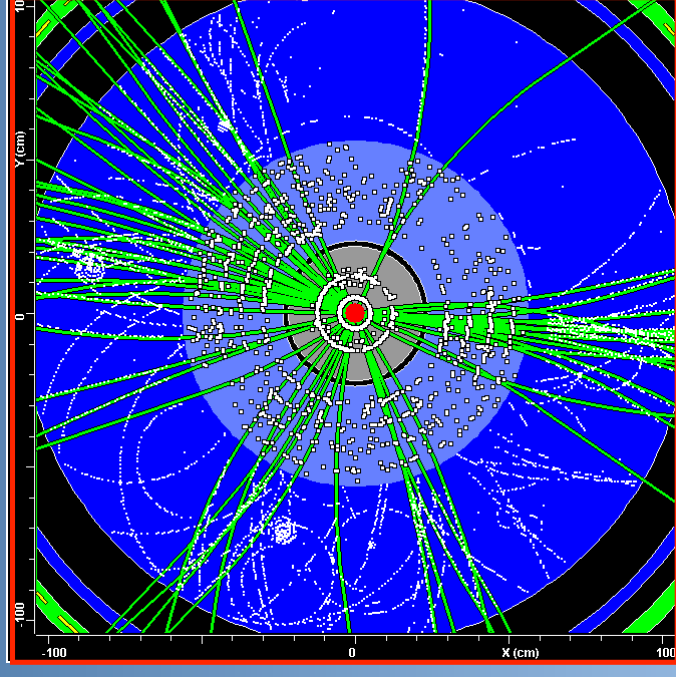
$$\frac{\tau^2 \lambda^2}{\lambda} + \frac{\tau^2 \lambda^2}{2(\tau - \lambda)^2} [f(\tau) - f(\lambda)] + \frac{\tau^2 \lambda}{(\tau - \lambda)^2} [g(\tau) - g(\lambda)] ,$$

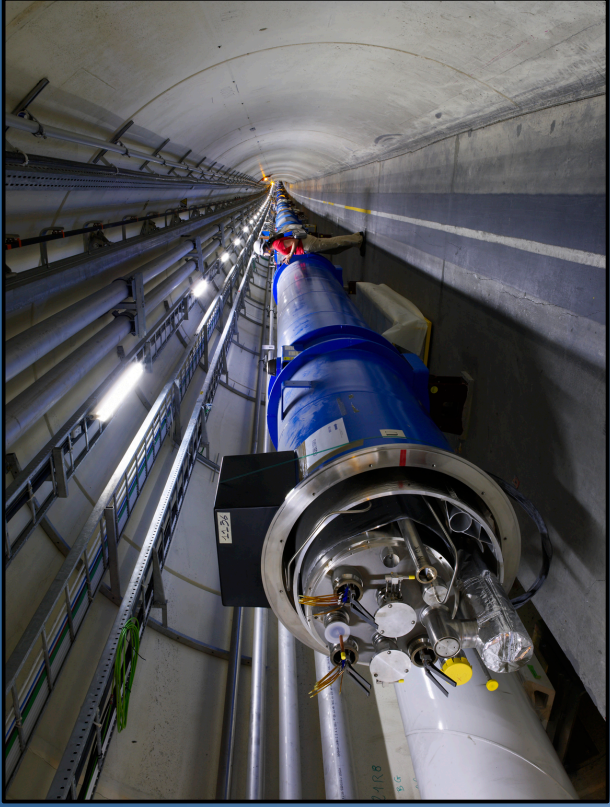
You can compute this now !

What do collisions look like ?

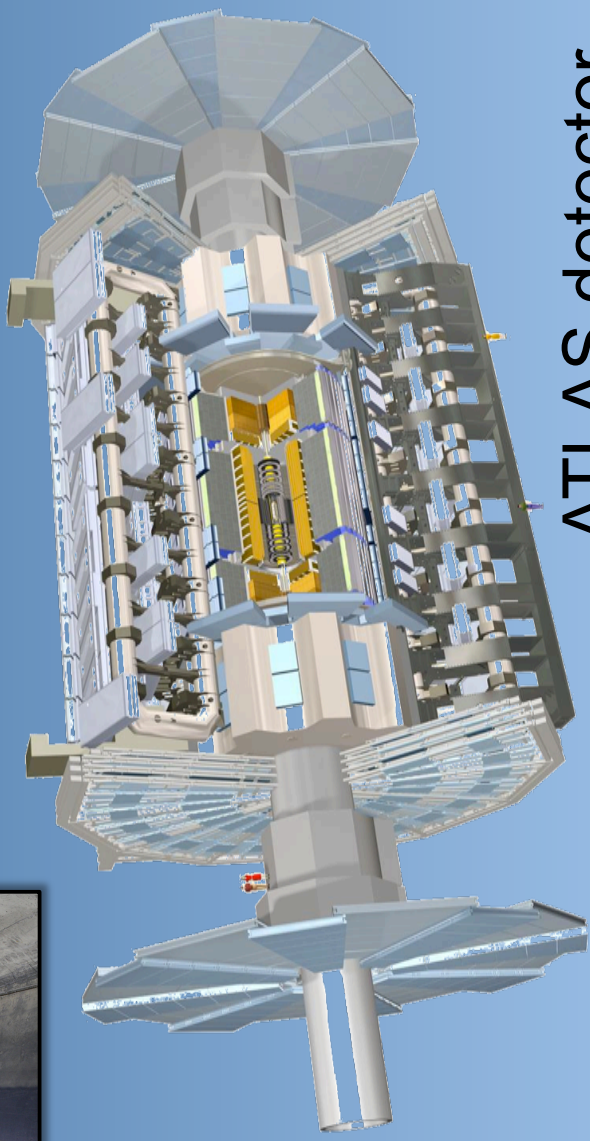


Simulation top quark production





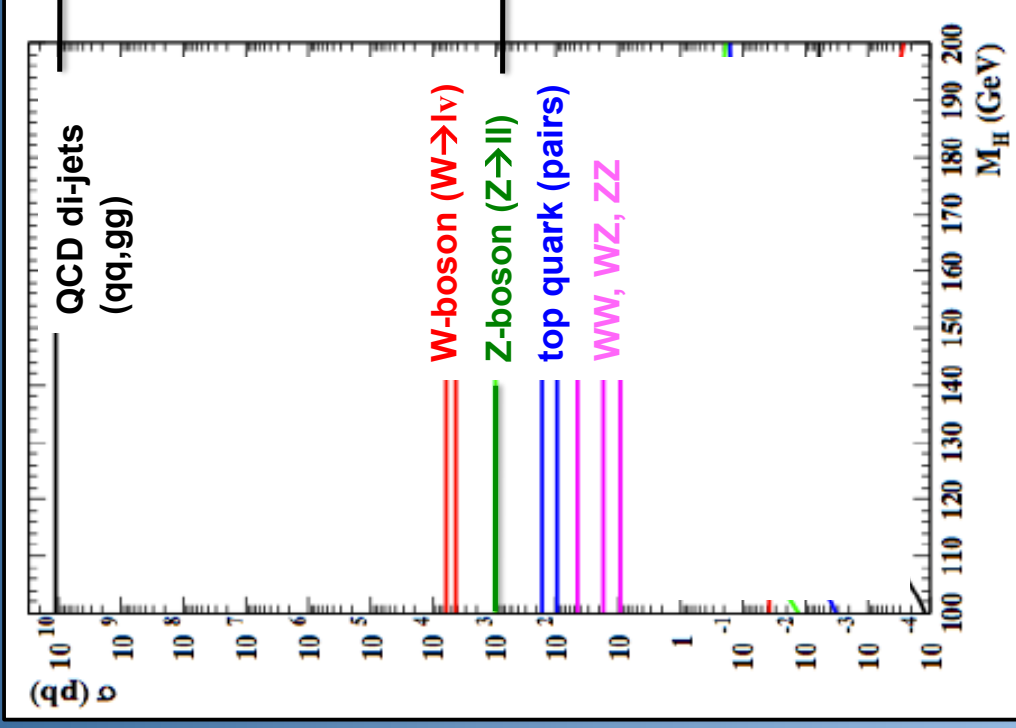
Large hadron collider



ATLAS detector

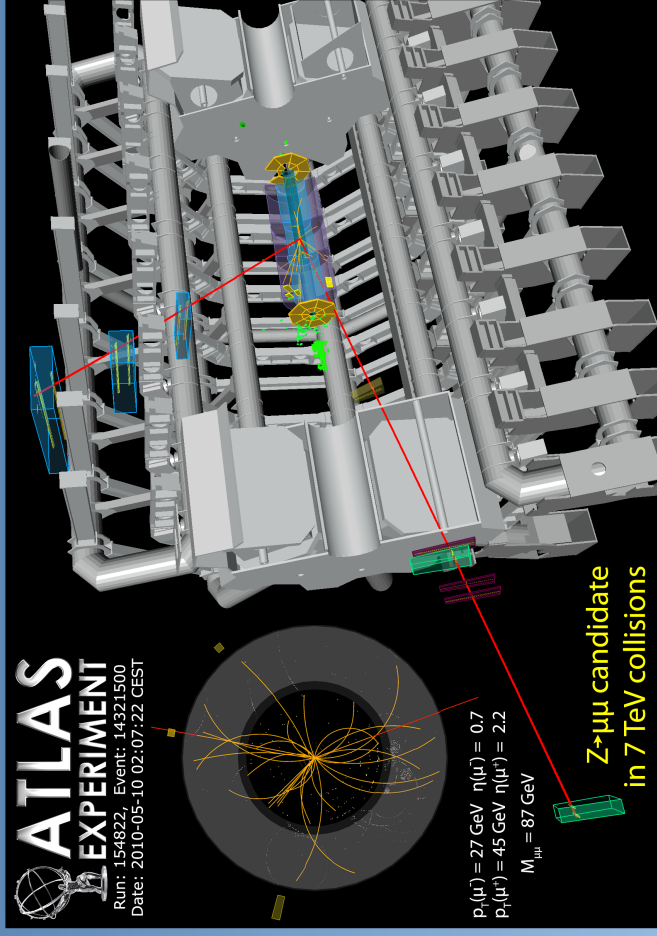
Standard Model processes at the LHC

predicted cross-sections



Jets, jets, jets: any signal without leptons is impossible to extract from di-jet background
 $\rightarrow$ high- P_T lepton triggers

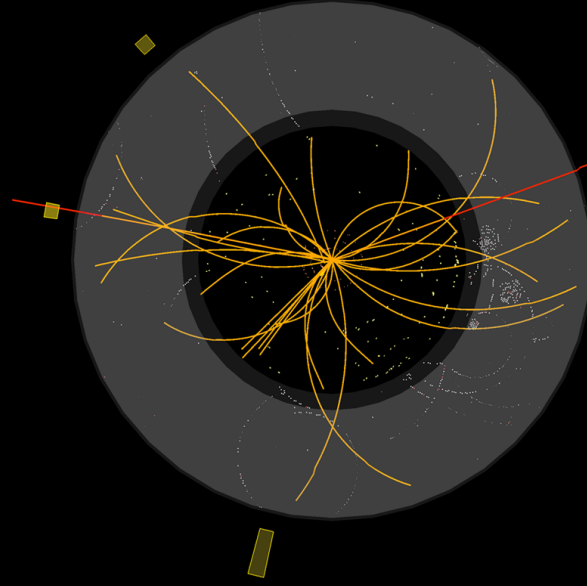
$Z \rightarrow \mu^+ \mu^-$ candidate (early data taking)



“LHC: strong machine for weak physics”

ATLAS EXPERIMENT

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST



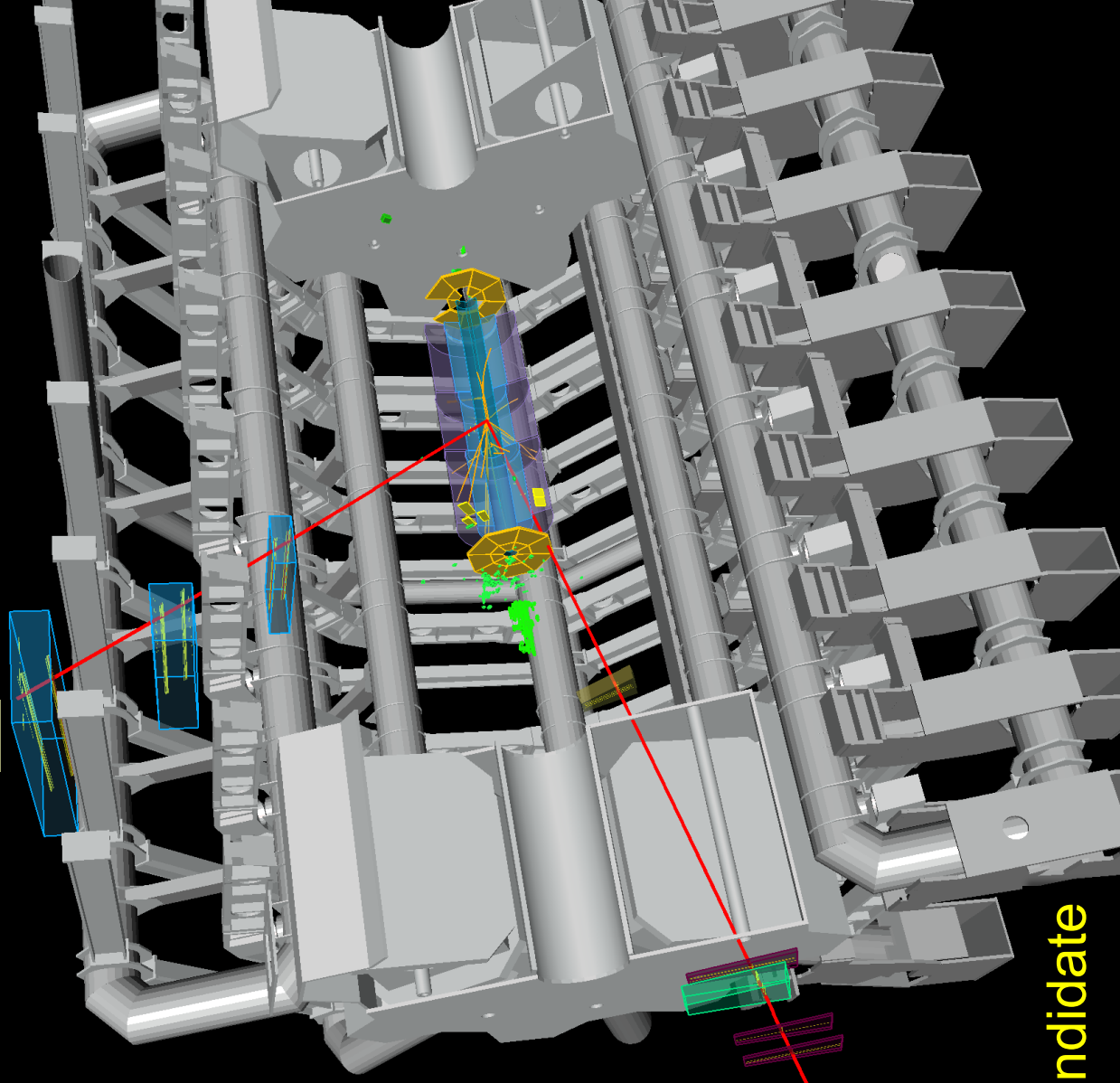
$p_T(\mu^-) = 27 \text{ GeV}$ $\eta(\mu^-) = 0.7$
 $p_T(\mu^+) = 45 \text{ GeV}$ $\eta(\mu^+) = 2.2$

$M_{\mu\mu} = 87 \text{ GeV}$

μ^+

$Z \rightarrow \mu^+\mu^-$ candidate

μ^-



Konijn, auto of mens ?



Quarks (jets)

Neutrino's

Geladen deeltjes

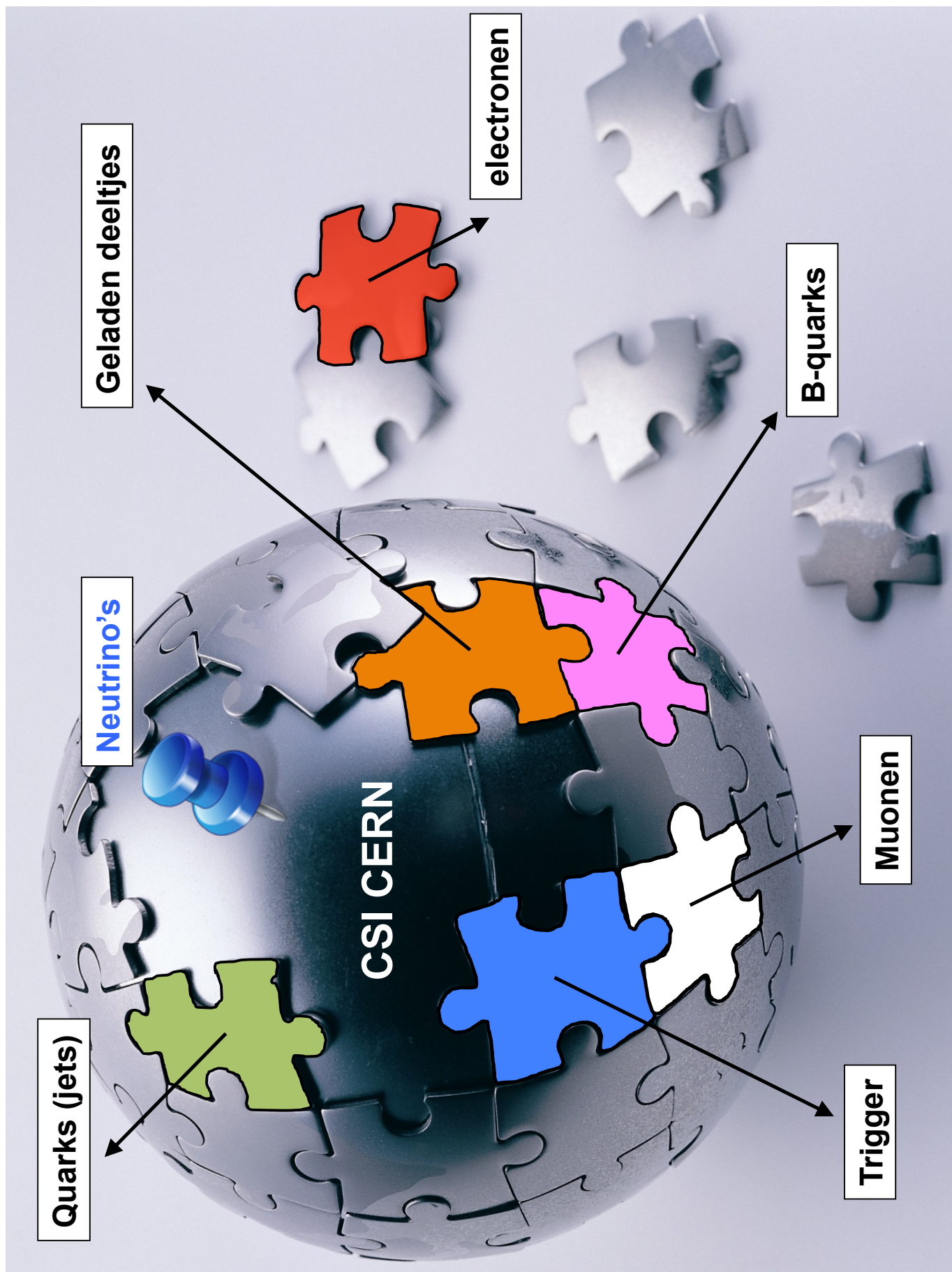
CSI CERN

electronen

B-quarks

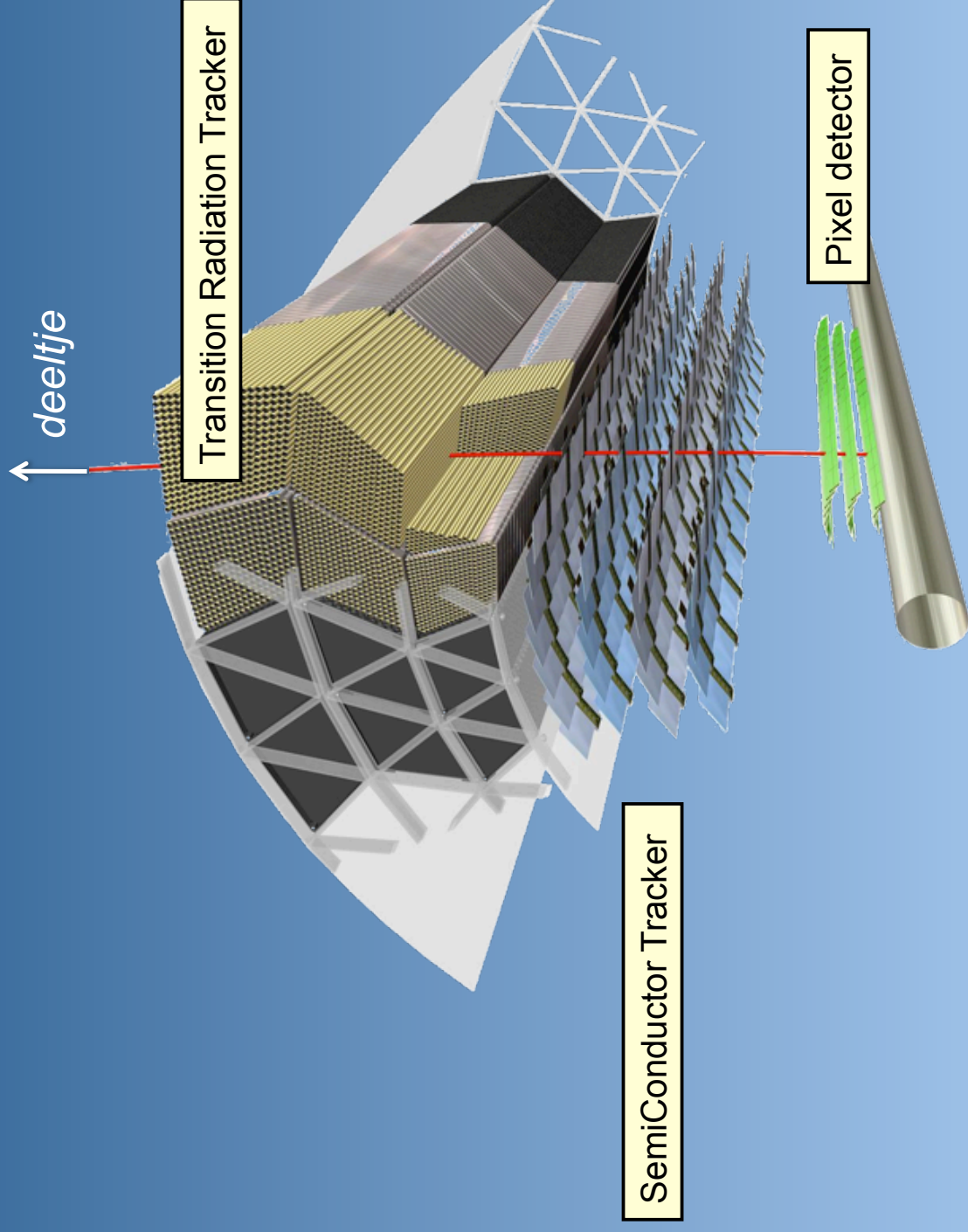
Muonen

Trigger



Waarom is die ATLAS detector nou zo complex ?

Het ene deeltje is het andere niet



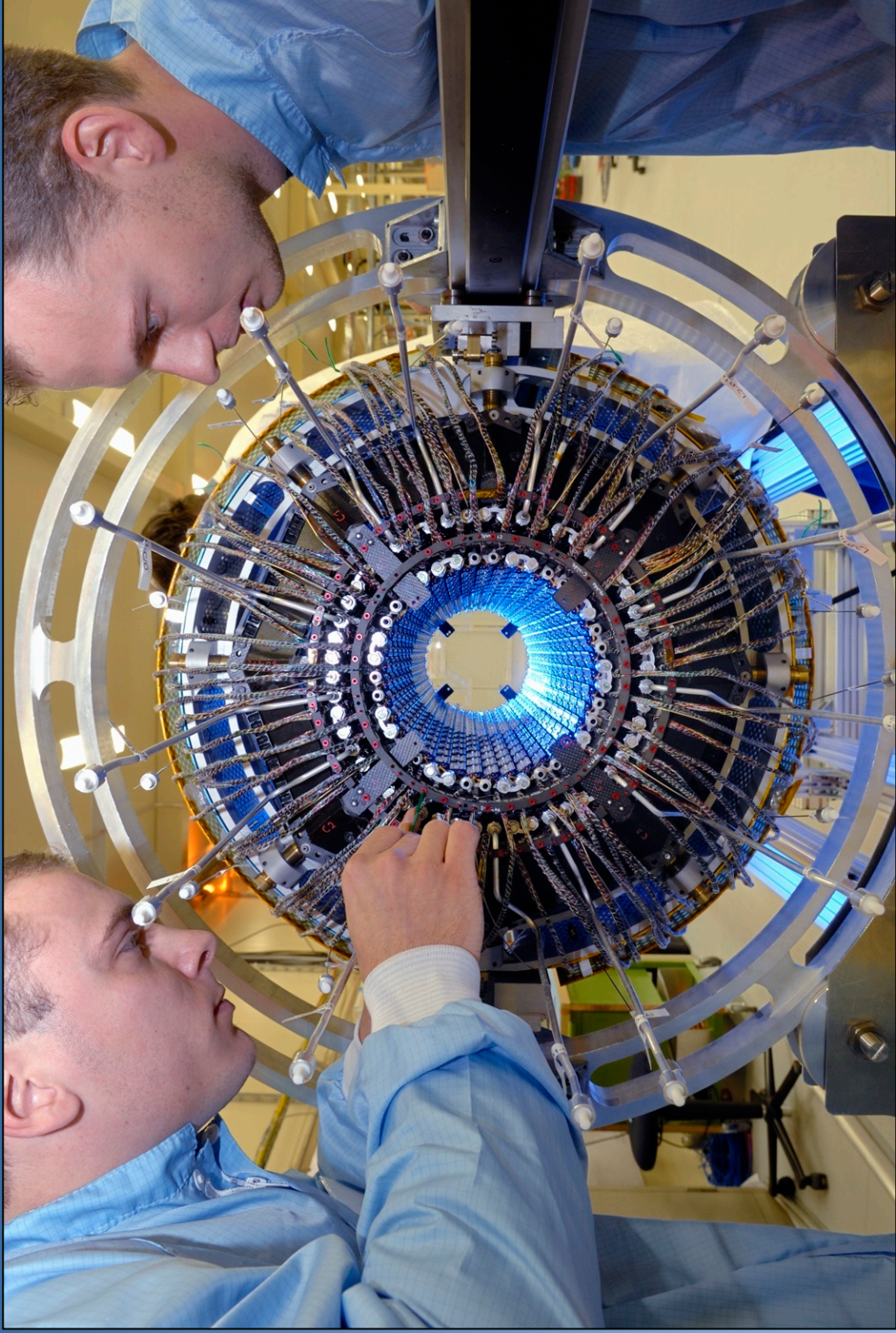
The Atlas detector really exists



old boss

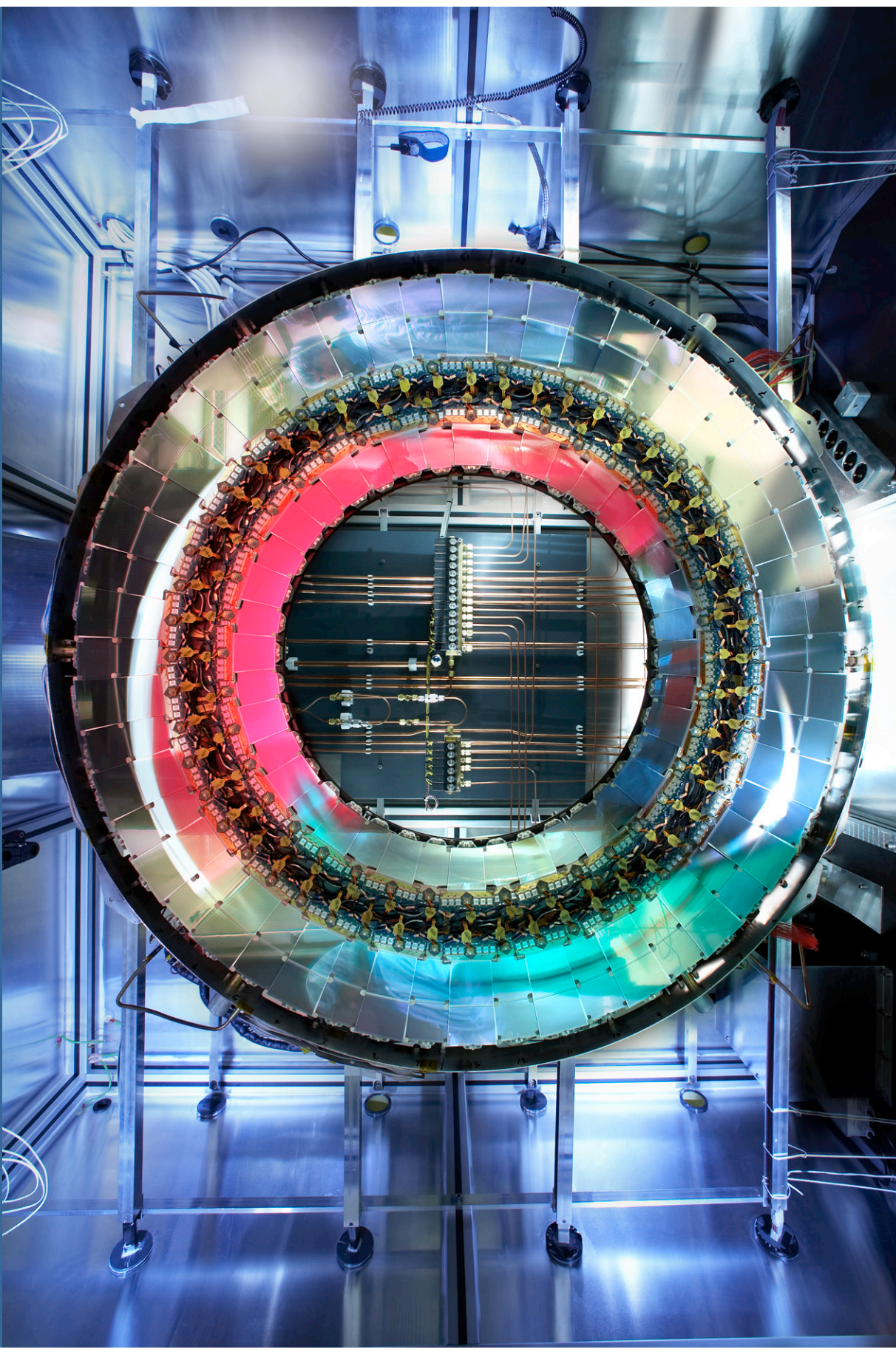
current boss

The Atlas pixel detector

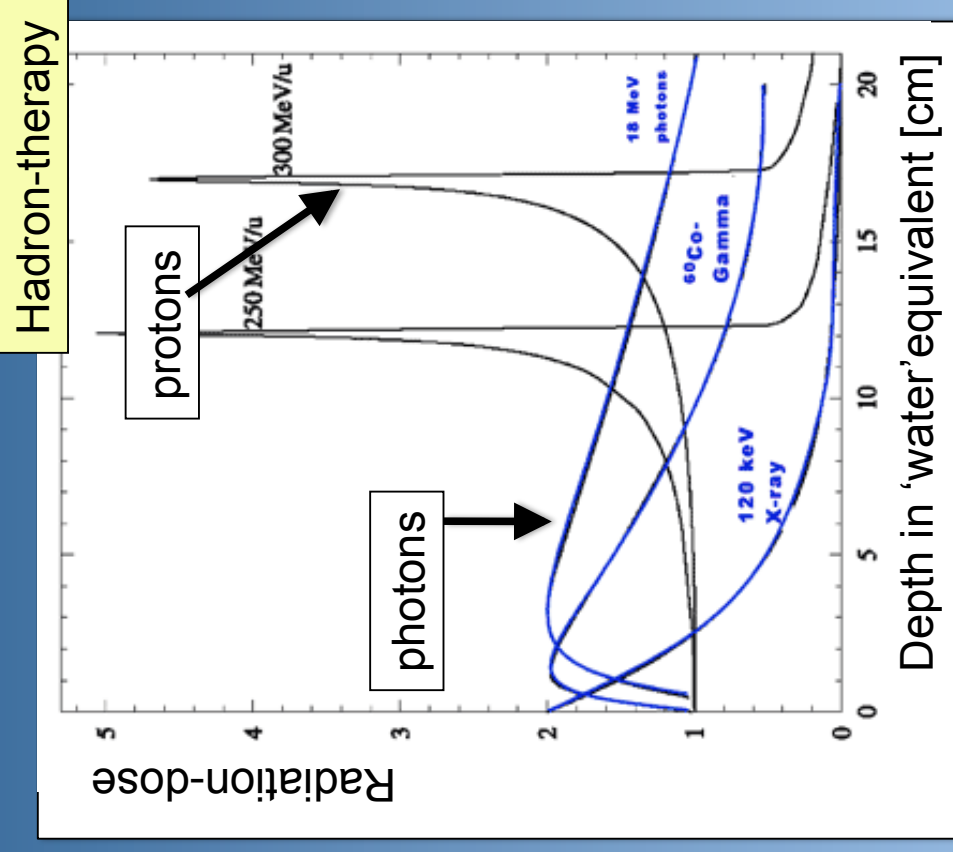
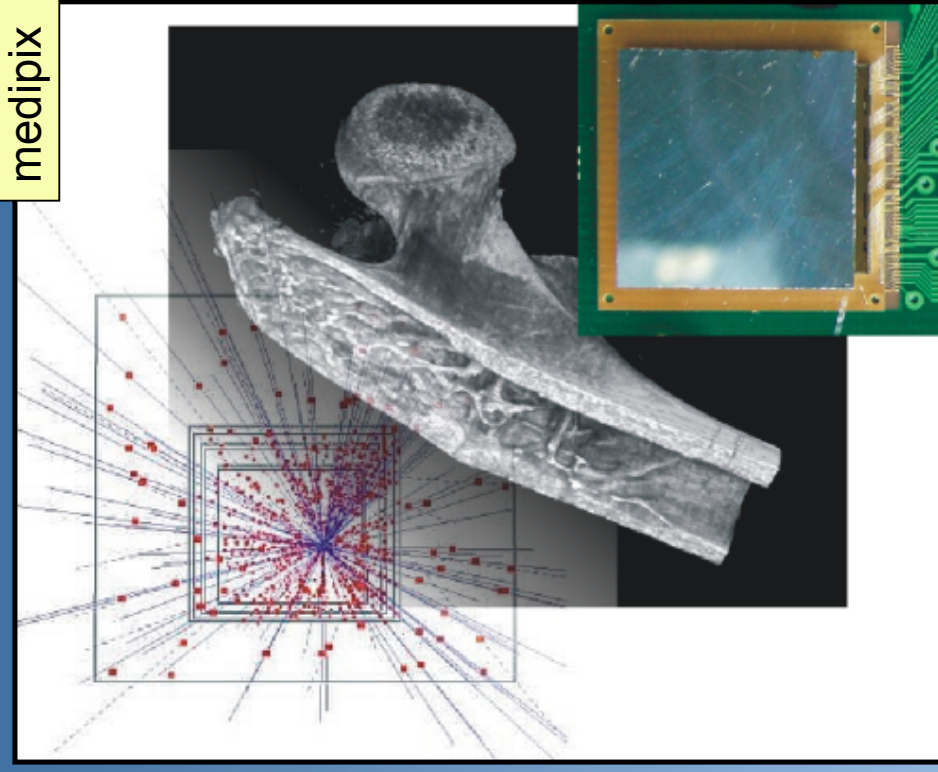


80 MegaPixel camera 40.000.000 pictures per second

Part of the ATLAS detector has been designed and built at Nikhef



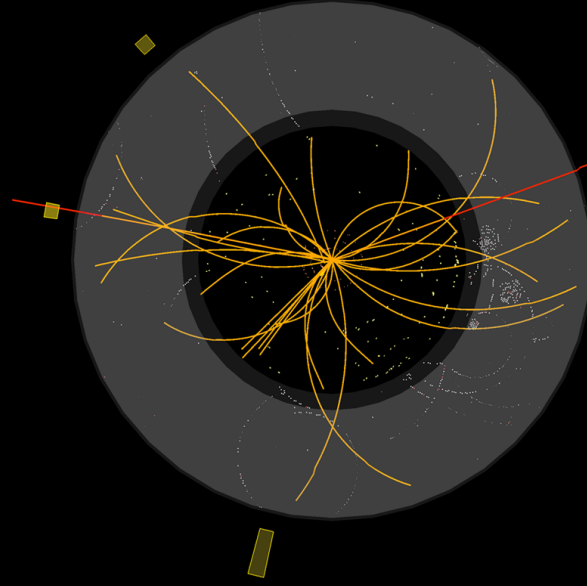
Medical applications



Many many more applications in industry:
electronics, seismology, data-processing/computing, seismology, ...

ATLAS EXPERIMENT

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST



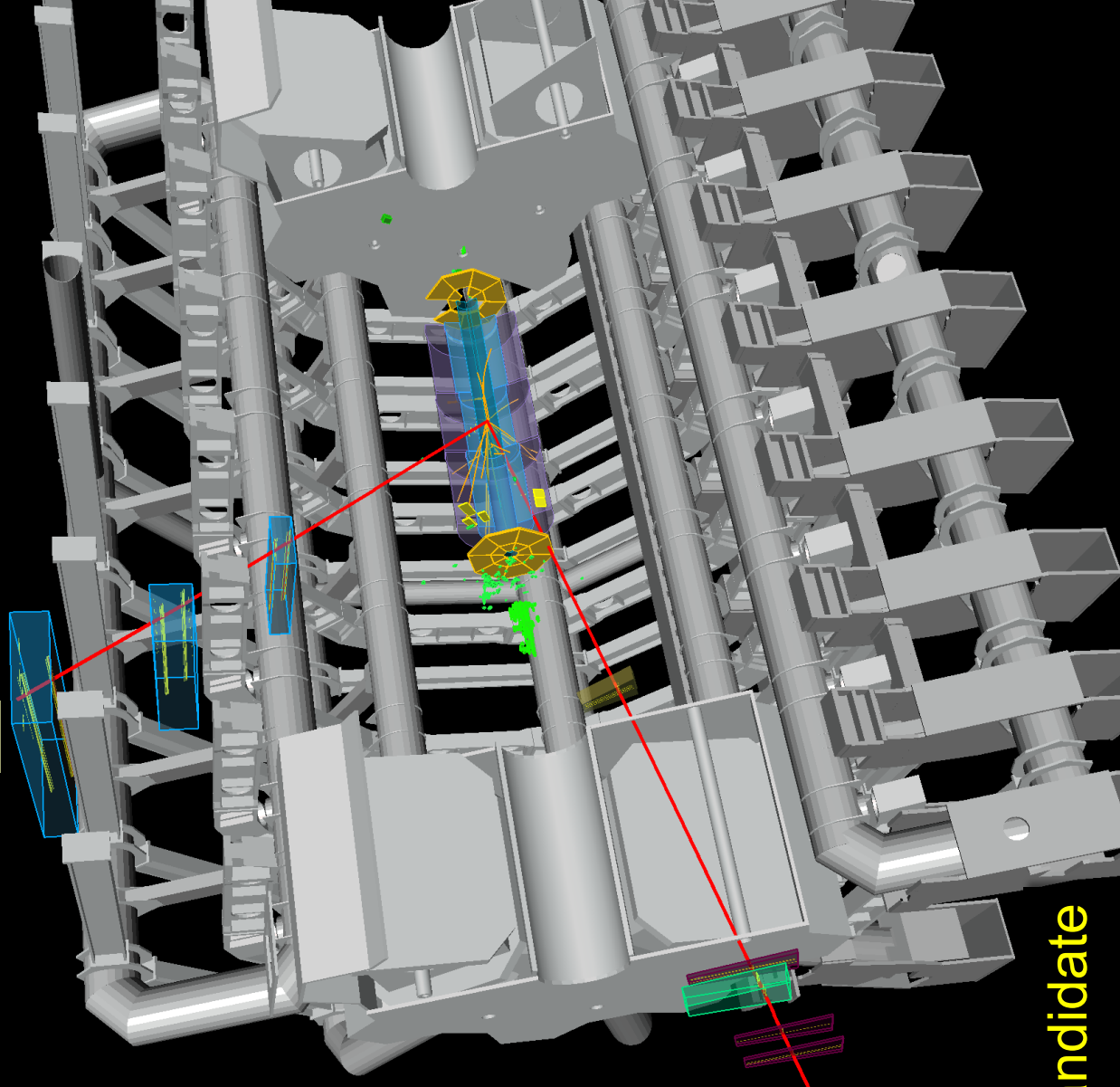
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μ^+

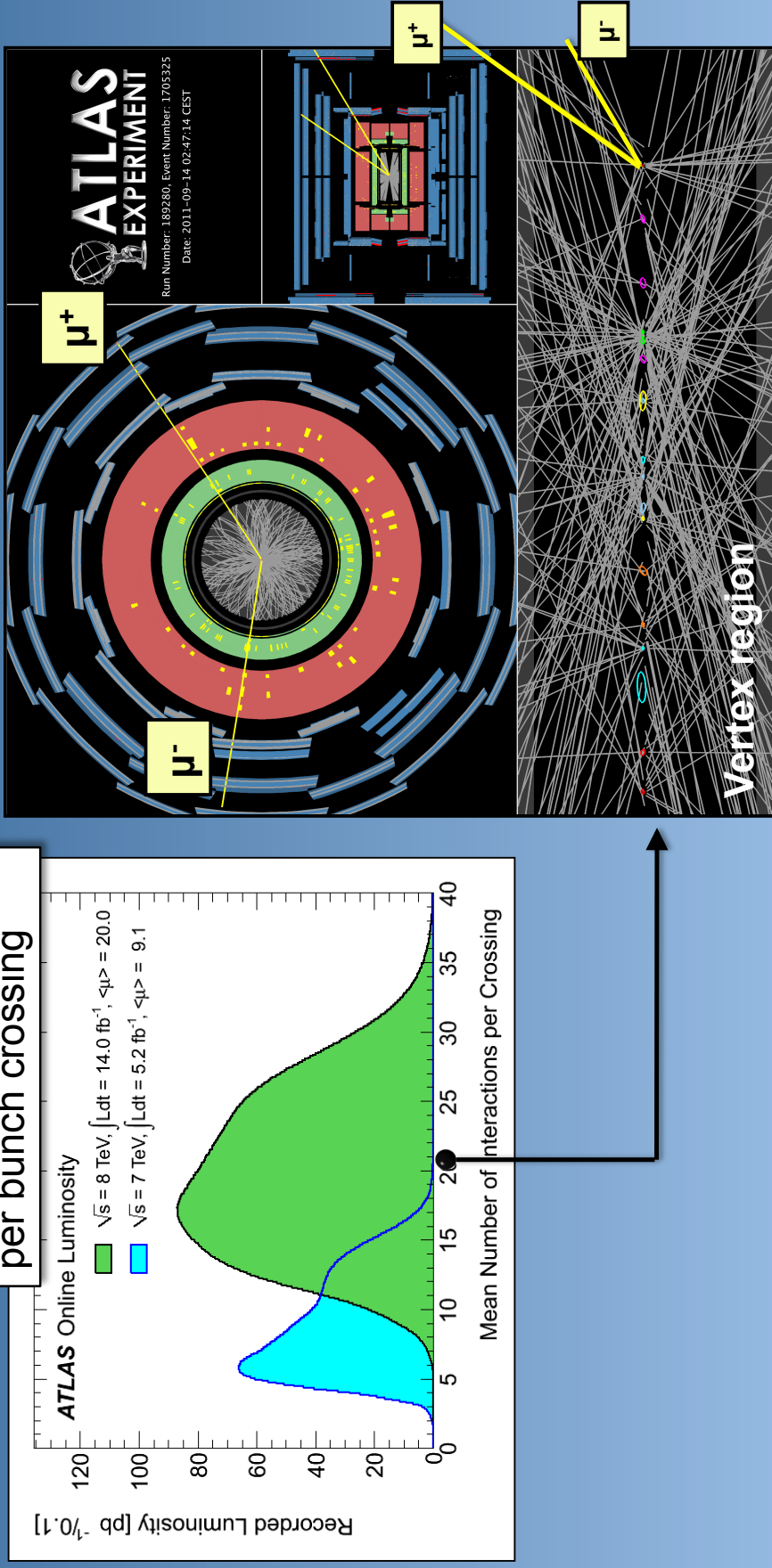
$Z \rightarrow \mu^+\mu^-$ candidate

μ^-

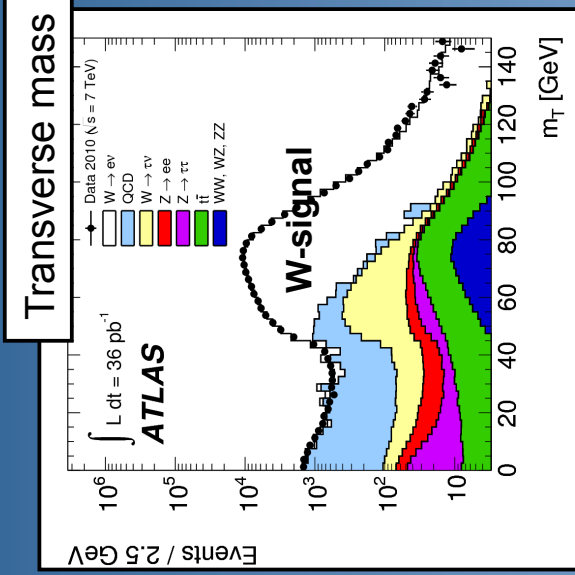


LHC is not a quiet environment

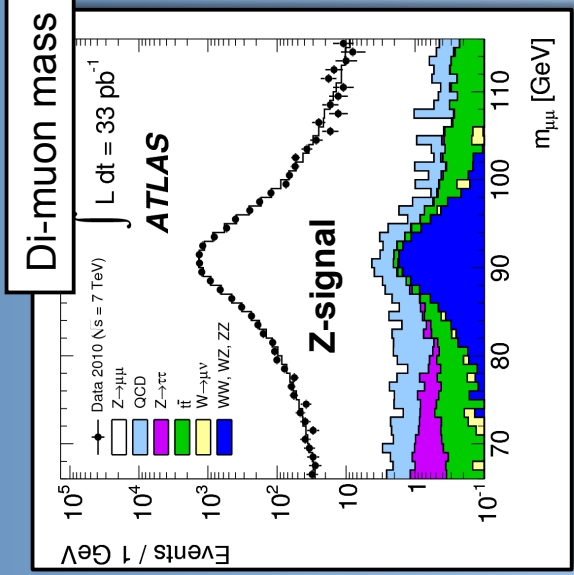
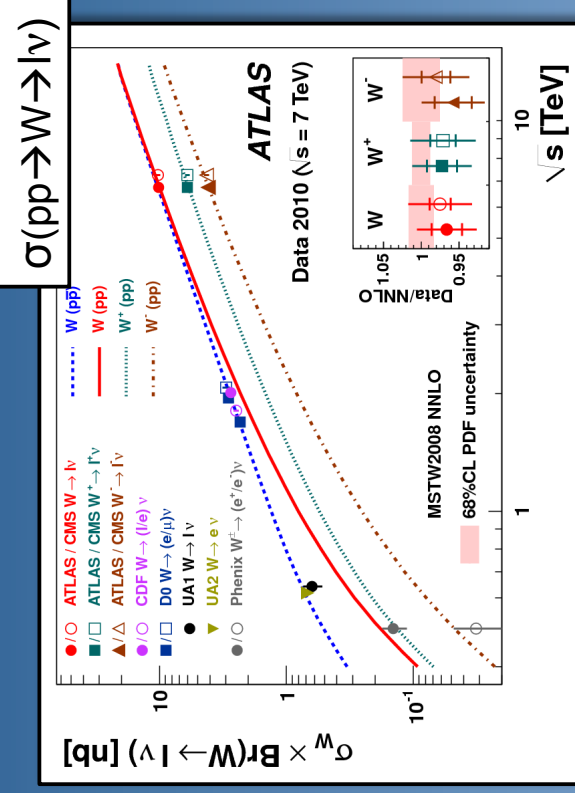
$Z \rightarrow \mu^+ \mu^-$ event with 20 vertices



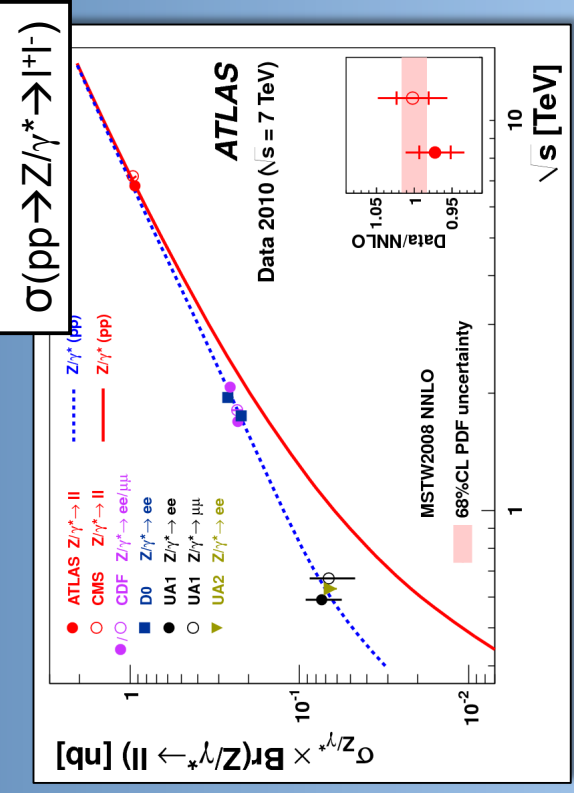
W and Z boson production at the LHC



W-boson

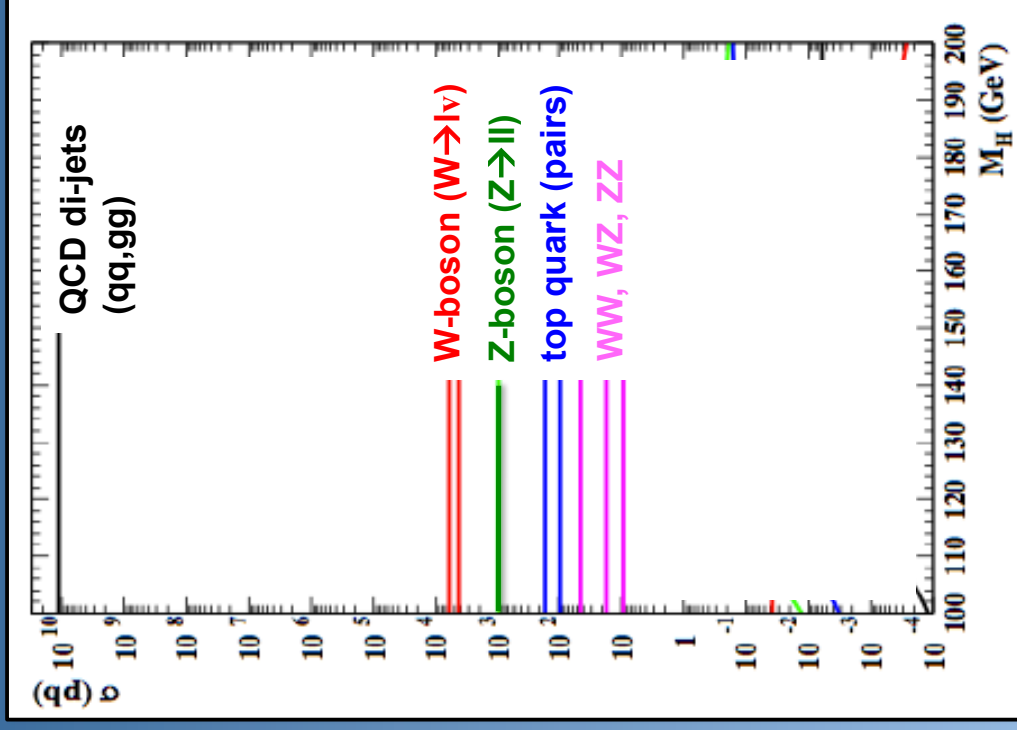


Z/ γ^* -boson



Standard Model processes at the LHC

predicted cross-sections



ATLAS measurements



Enormous data-set to understand and calibrate the ATLAS detector

What is missing in our Standard Model ?

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

Local gauge invariance

$$D_\mu = \partial_\mu + \frac{1}{2} g \vec{\tau} \cdot \vec{W}_\mu + \frac{1}{2} g' Y B_\mu + \dots$$

GOOD THINGS:

- ‘understand’ origin of forces
- Excellent agreement data
- Connection EM / Weak force



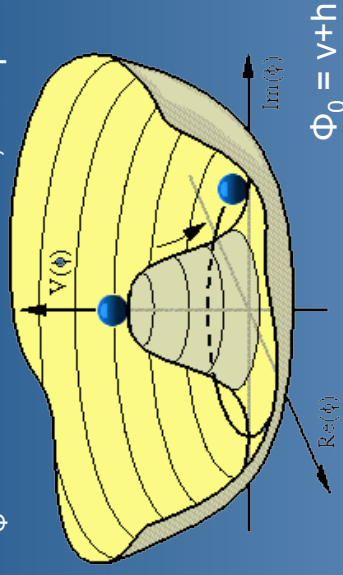
NOT-SO-GOOD THINGS:

- No massive gauge bosons ($W^\pm, Z$)
- No massive fermions (all particles)
- Vector boson scattering diverges

Add iso-spin doublet
 Φ , with $Y_\Phi = +1$

$$V(\Phi) = \mu^2 \Phi^2 + \lambda \Phi^4$$

, with $\mu^2 < 0$



Gauge bosons

$$(V = W^+, W^-, Z, \gamma)$$

$$L(\phi) = (D_\mu \phi)(D^\mu \phi) - V(\phi)$$



$$\propto \vec{V}^2 \quad \text{mass } V$$

$$\propto h \vec{V}^2$$



$$\propto h^2 \vec{V}^2$$

Fermions:

$$(\psi = e, \mu, \dots)$$

$$L(\psi) = \bar{\psi} \phi \psi + \dots$$



$$m_\psi \bar{\psi} \psi$$

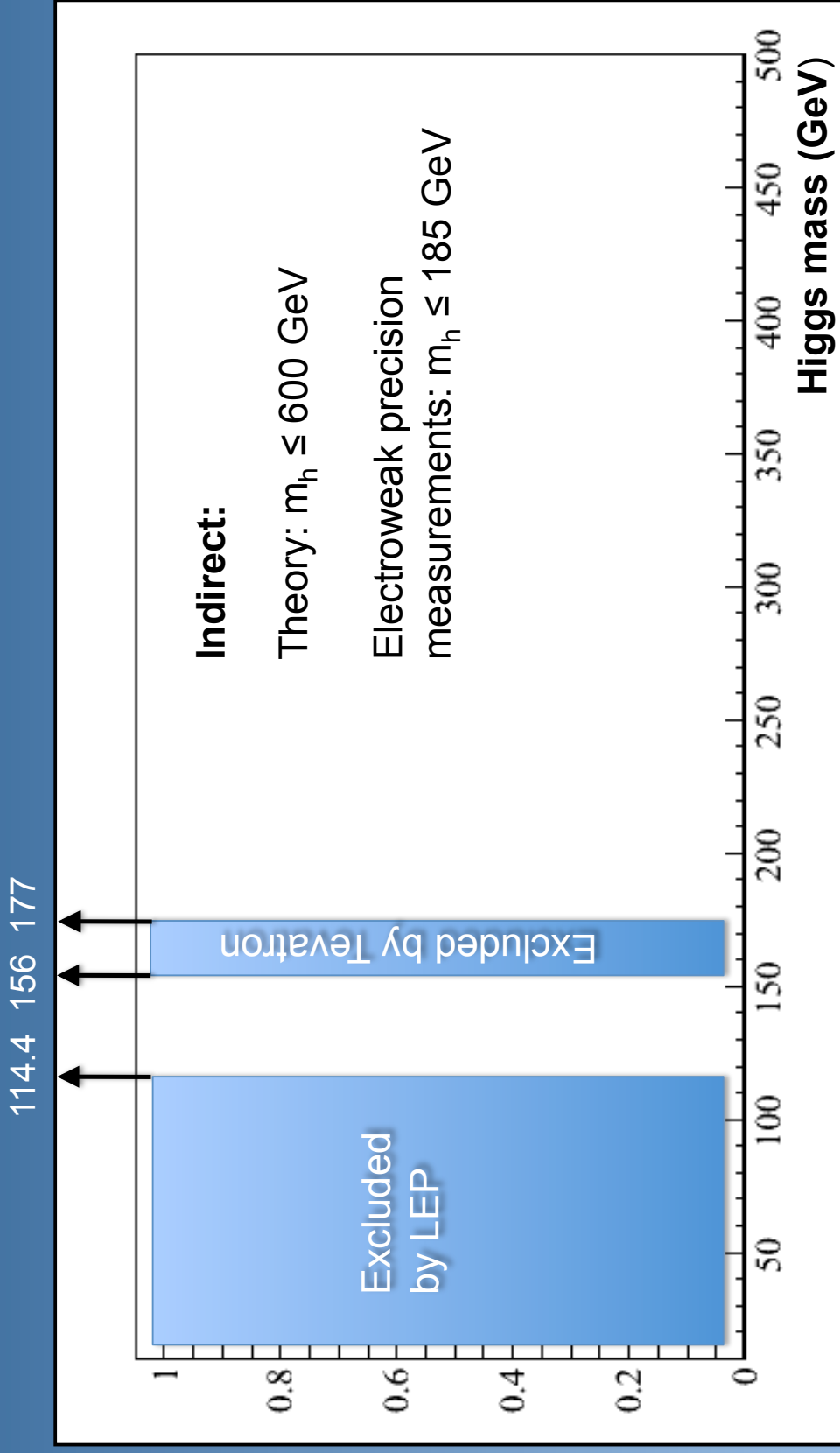
$$\text{mass } \psi$$

$$\frac{m_\psi}{v} \bar{\psi} h \psi$$



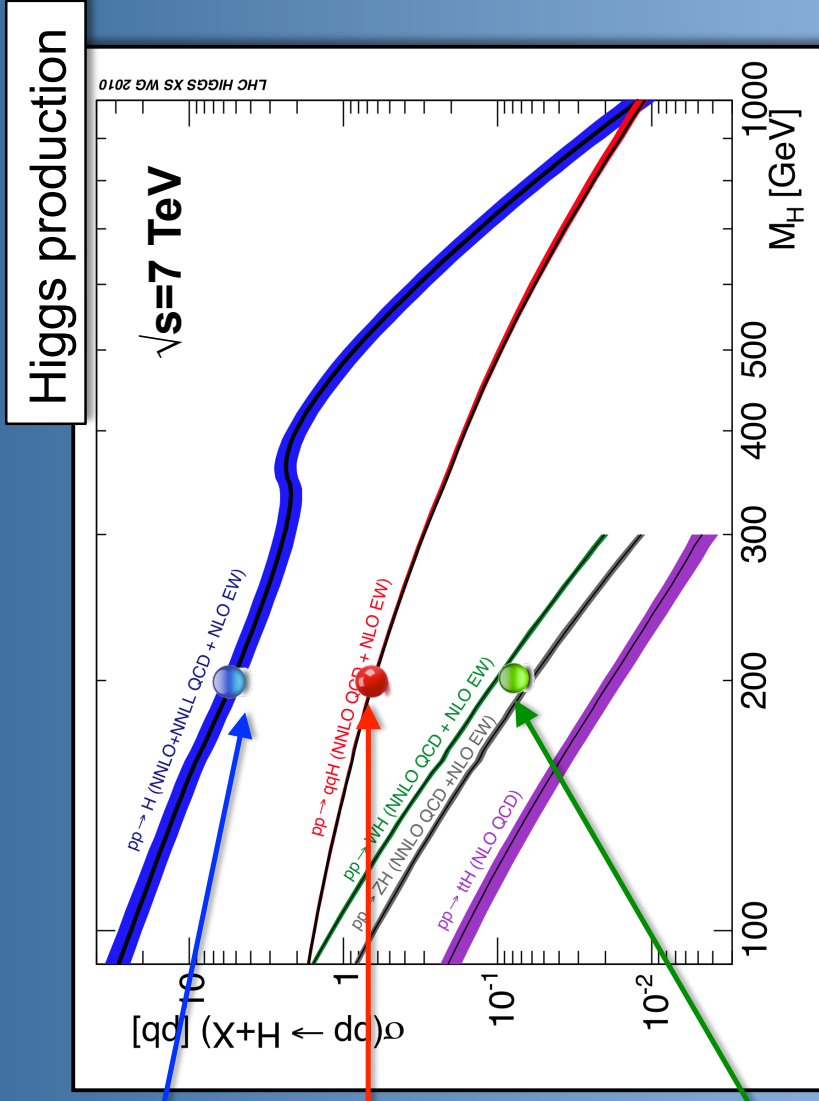
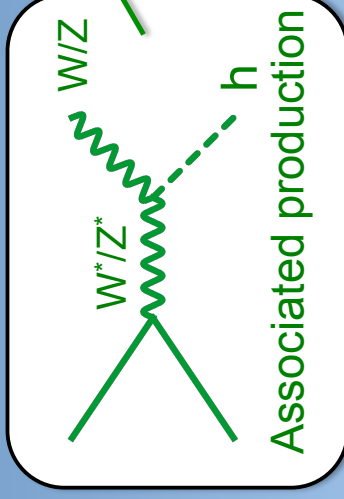
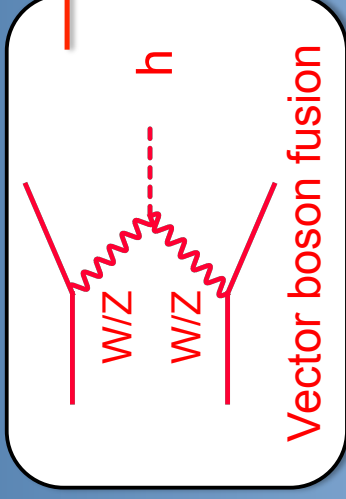
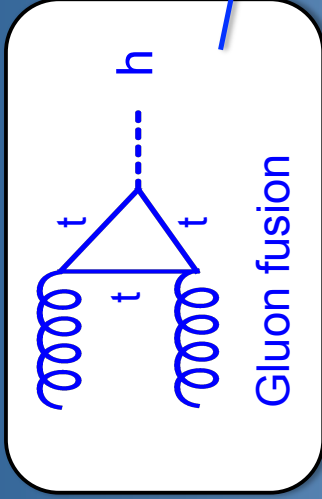
“the Higgs couples to mass”

Search for the Higgs boson at the LHC



LHC can cover full mass region from 114-1000 GeV

Production of the Higgs boson



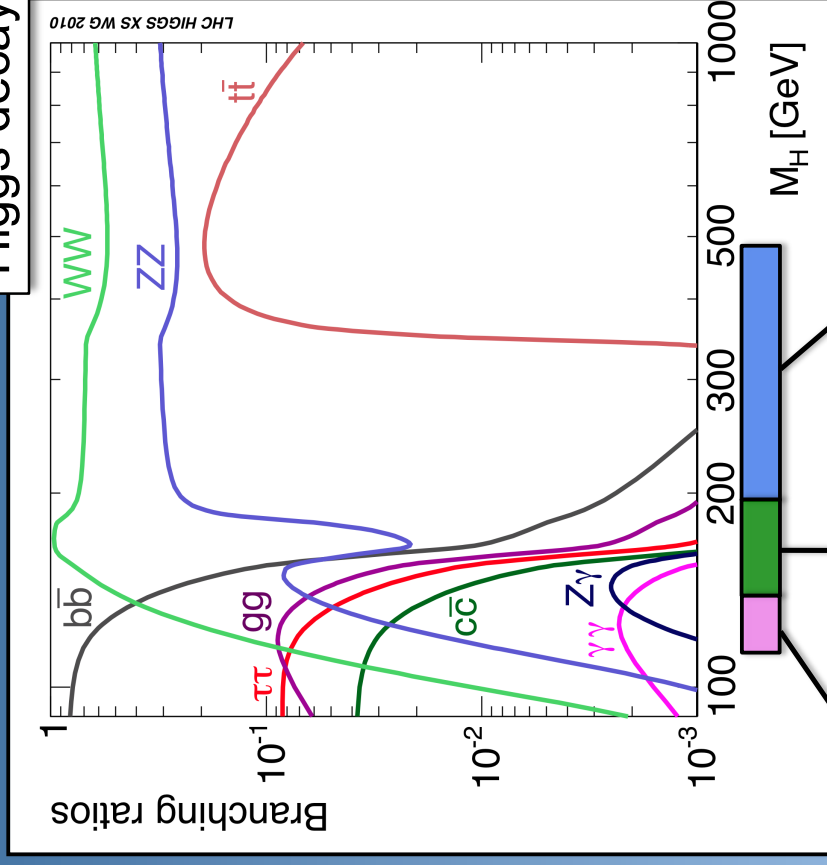
$$\sigma_{pp \rightarrow \text{Higgs}}(m_h=125\text{ GeV}, \sqrt{s}=7/8\text{ TeV}) \sim 16.54 / 21.10\text{ pb}$$

$$\text{Luminosity } (\sqrt{s}=7/8\text{ TeV}) = 4.8 / 19.6\text{ fb}^{-1}$$

Already 493,000 Higgs bosons produced at the LHC

Decay of the Higgs boson

Higgs decay



Most sensitive channels:
(leptons or photons)

Low mass ($m_h < 130$)

$h \rightarrow \gamma\gamma$

Intermediate ($130 < m_h < 200$)

$h \rightarrow WW^{(*)} \rightarrow \ell\ell\nu\bar{\nu}$

High mass: ($m_h > 200$)

$h \rightarrow ZZ \rightarrow 4 \text{ leptons}$

$h \rightarrow \gamma\gamma$

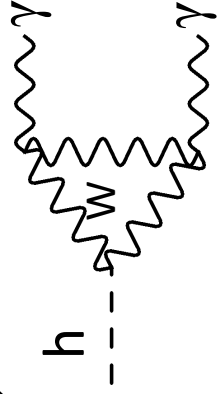
$h \rightarrow WW^{(*)} \rightarrow \ell\ell\nu\bar{\nu}$

$h \rightarrow ZZ \rightarrow 4 \text{ leptons}$

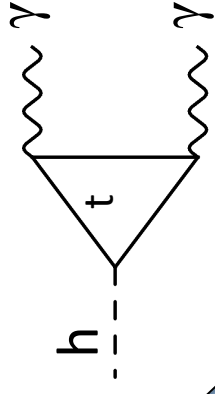
Low Mass Range ($m_h < 130 \text{ GeV}$)

$higgs \rightarrow \gamma\gamma$

Small branching fraction: $\Gamma(h \rightarrow \gamma\gamma) \sim 0.2\%$

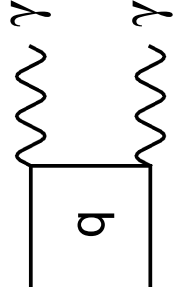


W-loop



top-loop

signal



1) di-photon

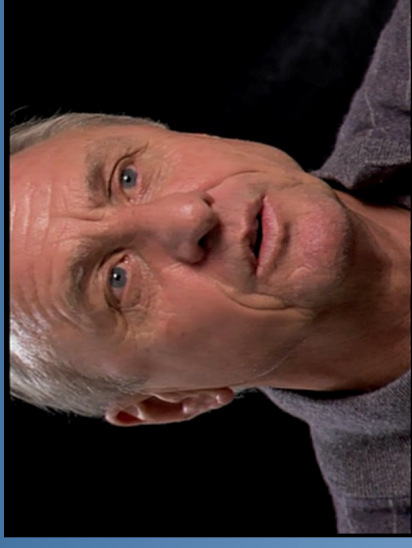
2) Mis-identified jets/electrons

backgrounds

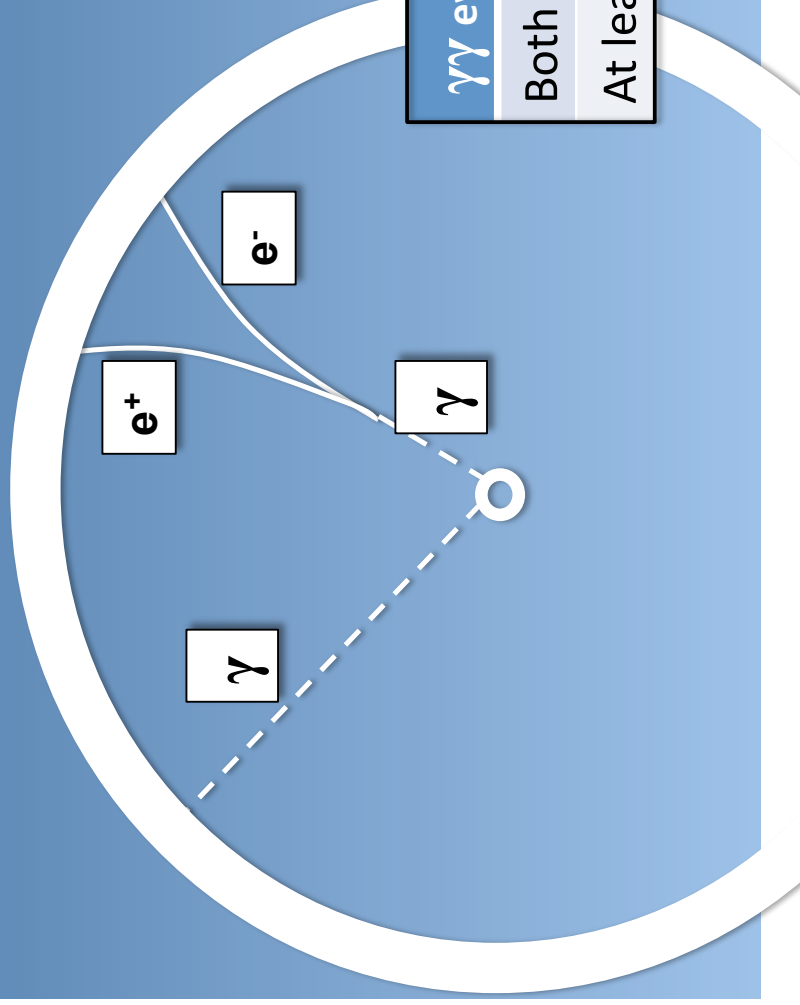
Photon identification and event selection

Selection: 2 isolated photons: $P_T > 40$ (25 GeV)

39% selection efficiency

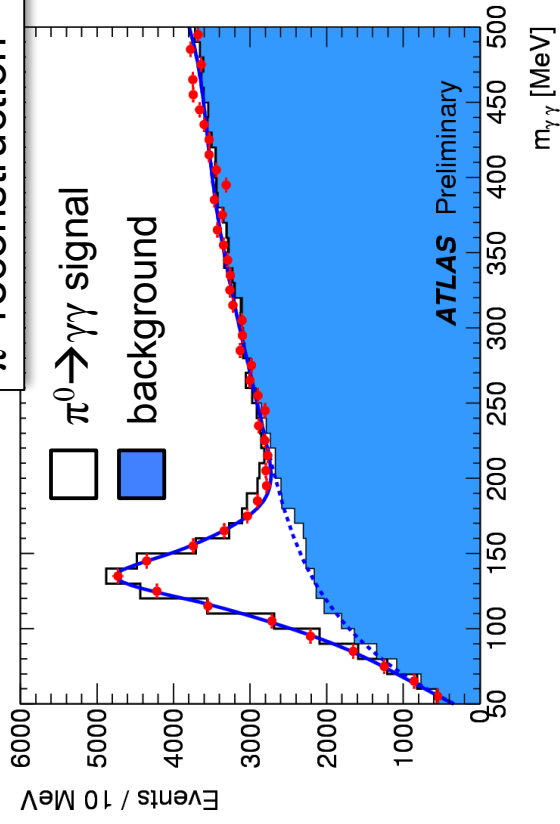


“Elk nadeel hep z’n voordeel”

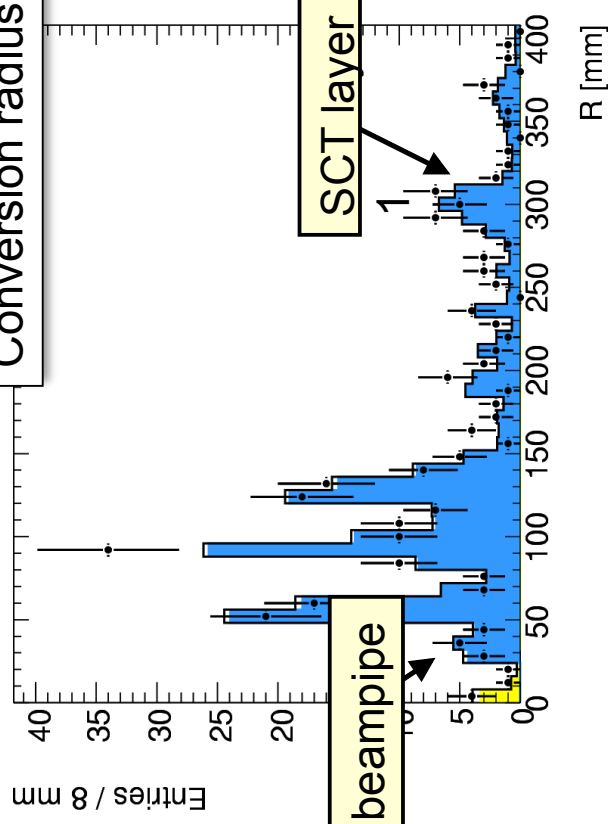


$\gamma\gamma$ event classification	Fraction
Both unconverted	36%
At least 1 converted	64%

π^0 reconstruction

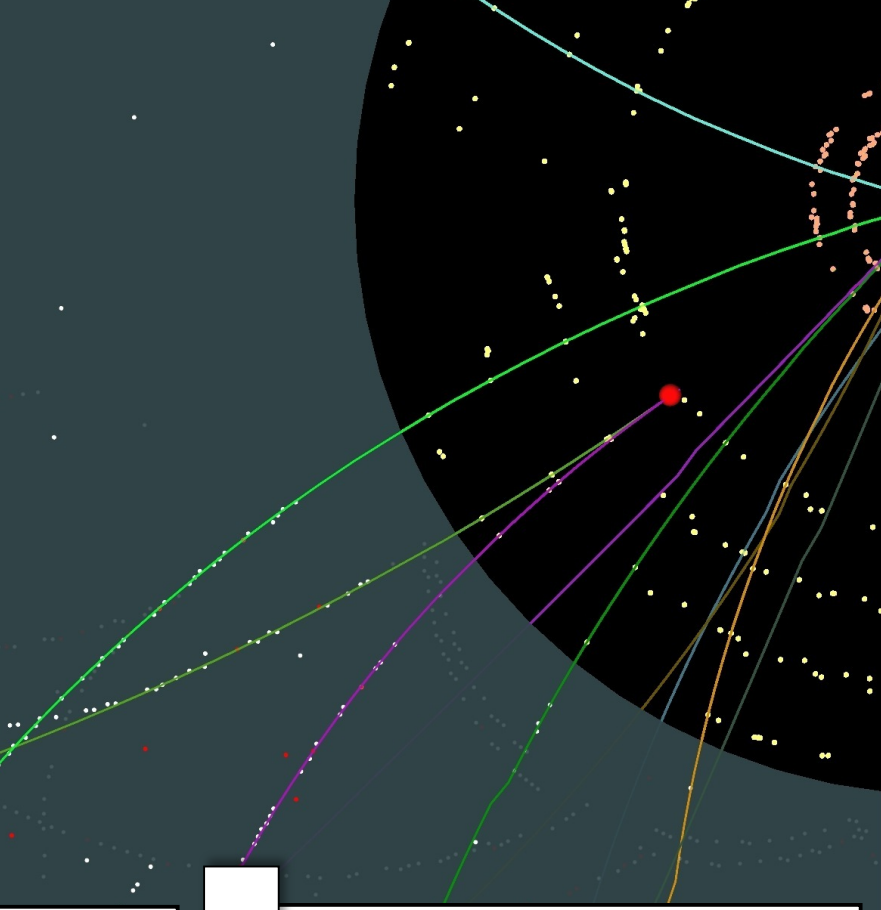


Conversion radius



Photon conversions

Clean electron sample
Good material description in MC



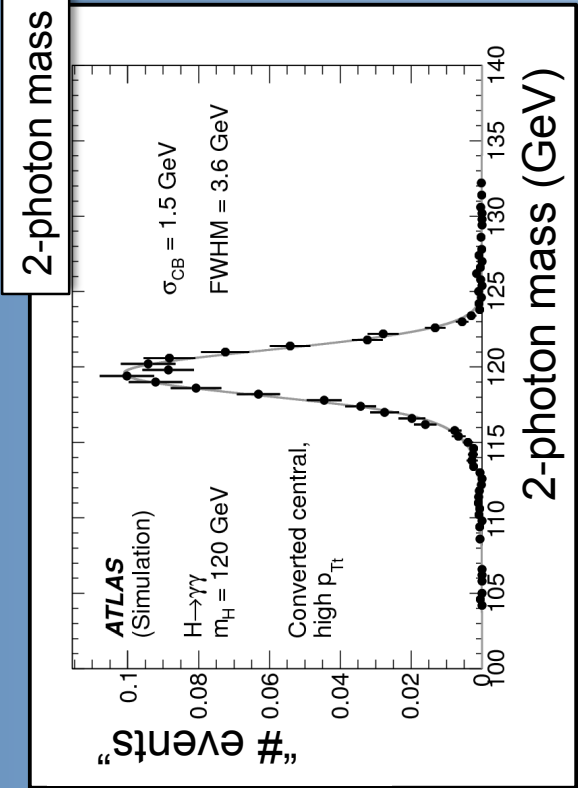
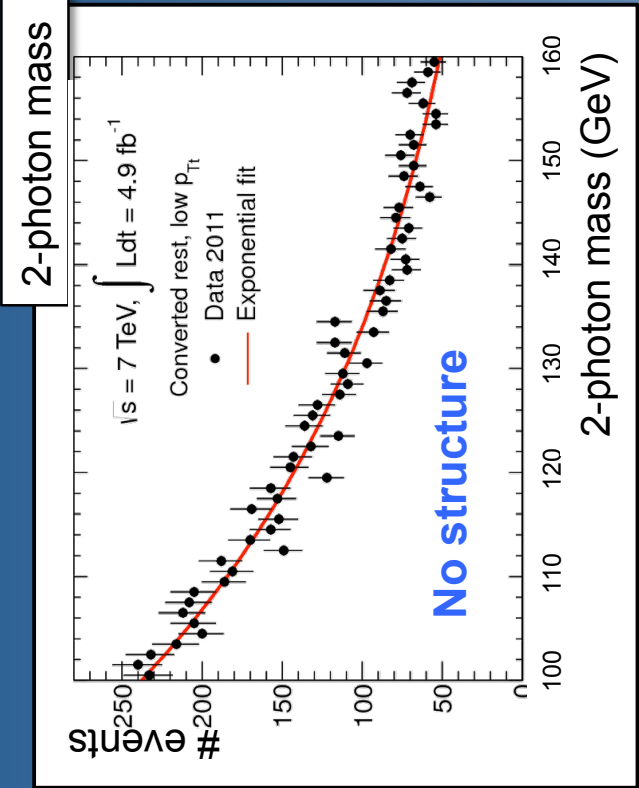
Event-type	Number of events
------------	------------------

Other origin

$\gamma\gamma$	3650 ± 100 ± 290
γ + jet	1110 ± 60 ± 270
Di-jet	220 ± 20 ± 130
Drell-Yan	86 ± 1 ± 14
‘normal’	5066

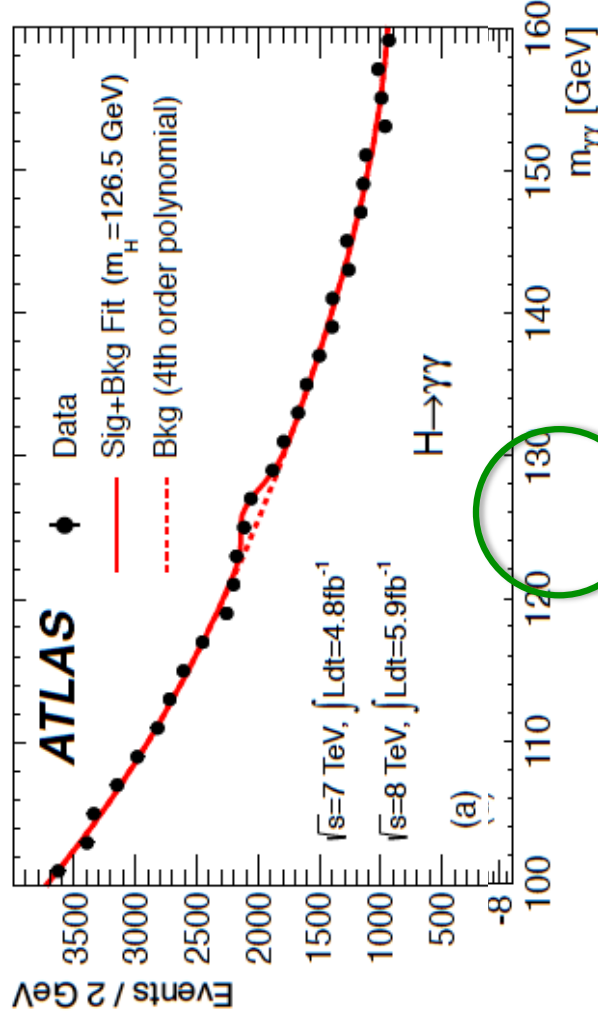
Higgs

Higgs signal	17.6
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The results of the ATLAS experiment - july 2012 -

Higgs $\rightarrow$ 2 photons



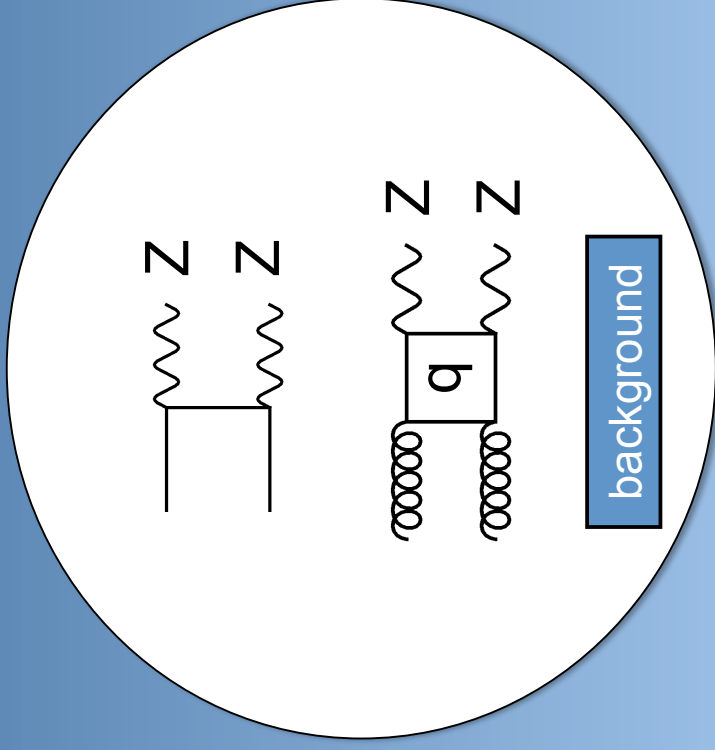
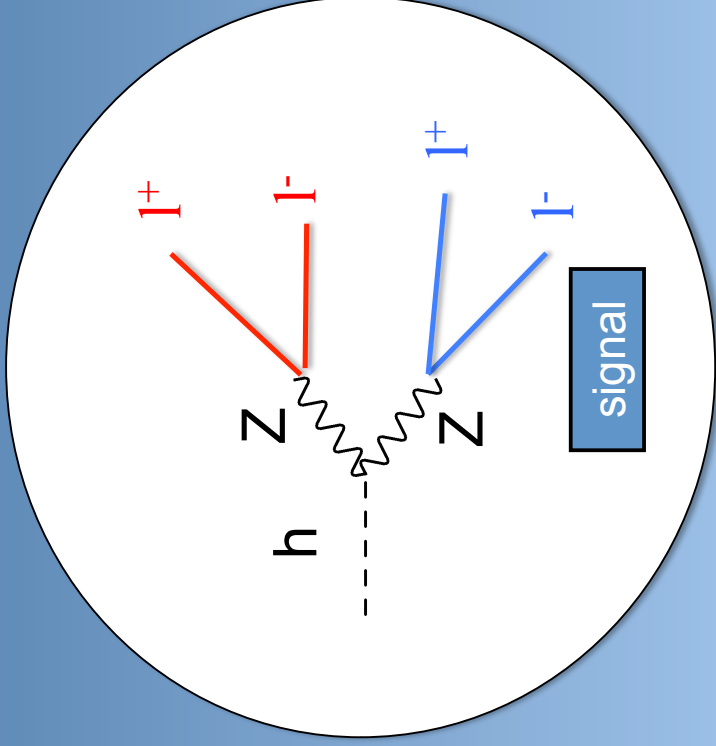
Yes, a peak !!! Or not ?

Do we also see a hint
(excess) at this mass in
4-muon events ?

High Mass Range ($m_h > 200 \text{ GeV}$)

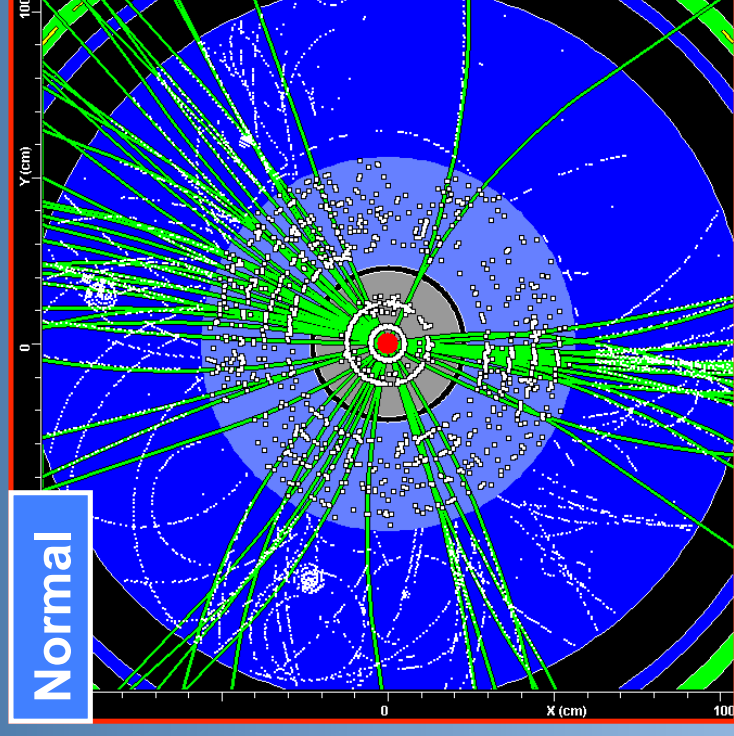
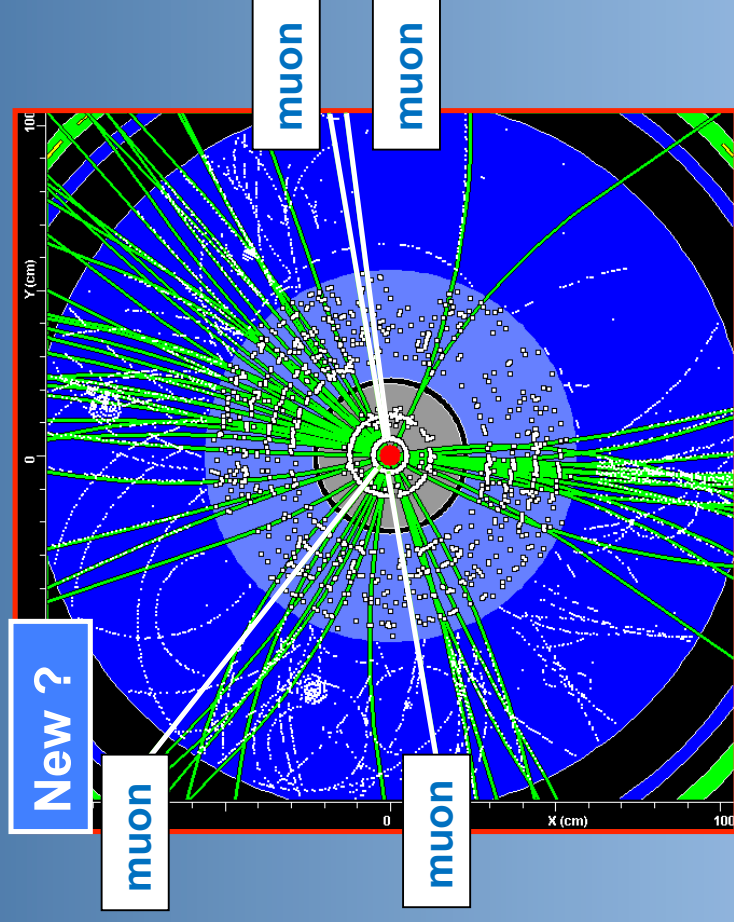
$higgs \rightarrow ZZ$

Analysed: $llll$, $ll\nu\nu$, $llqq$, $llbb$

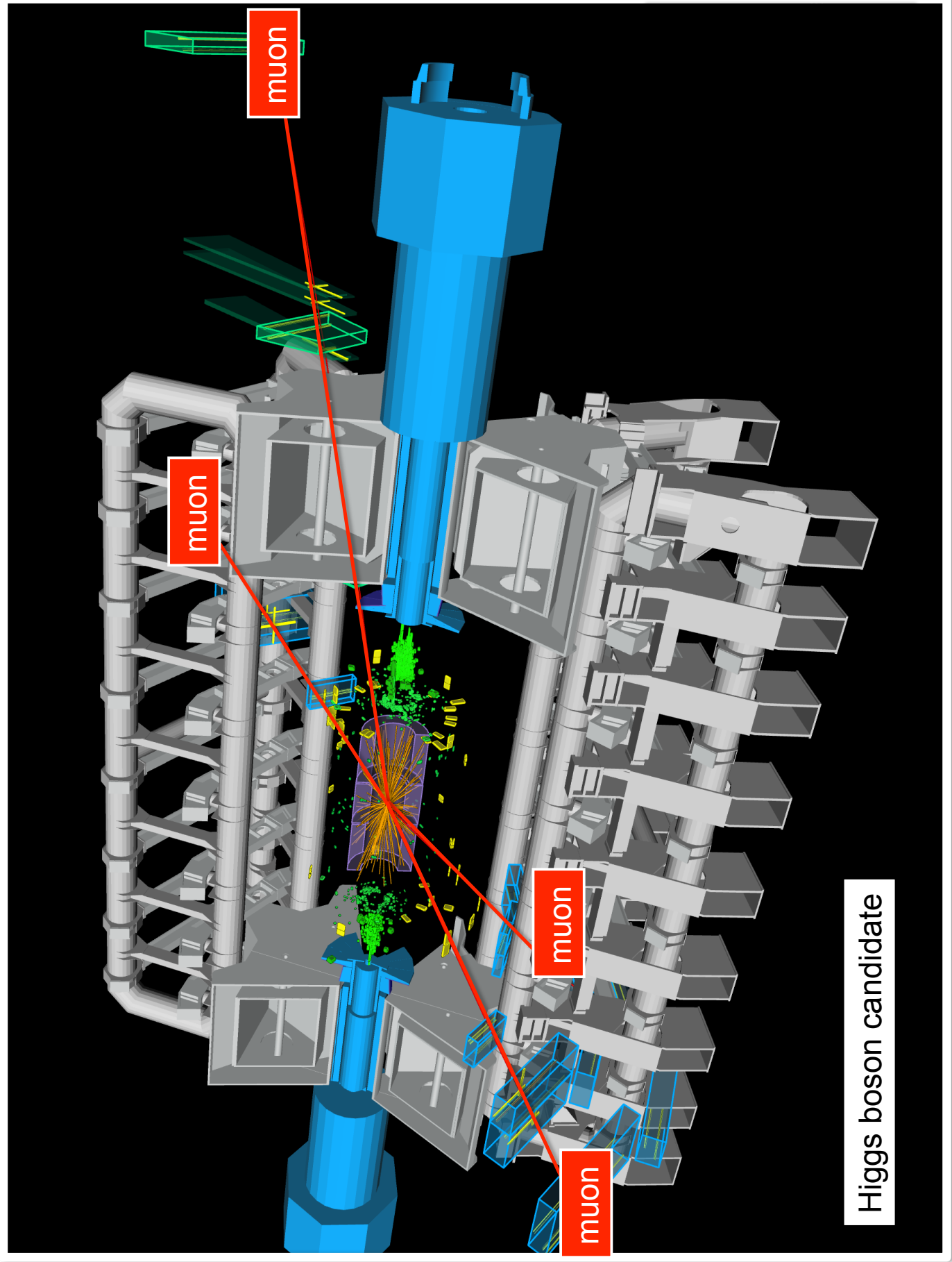


How do you discover new things ?

New distance scale AND a new detector



Yes .Higgs probably is



Higgs boson candidate

Higgs $\rightarrow ZZ \rightarrow 4$ leptons: small sample of beautiful events

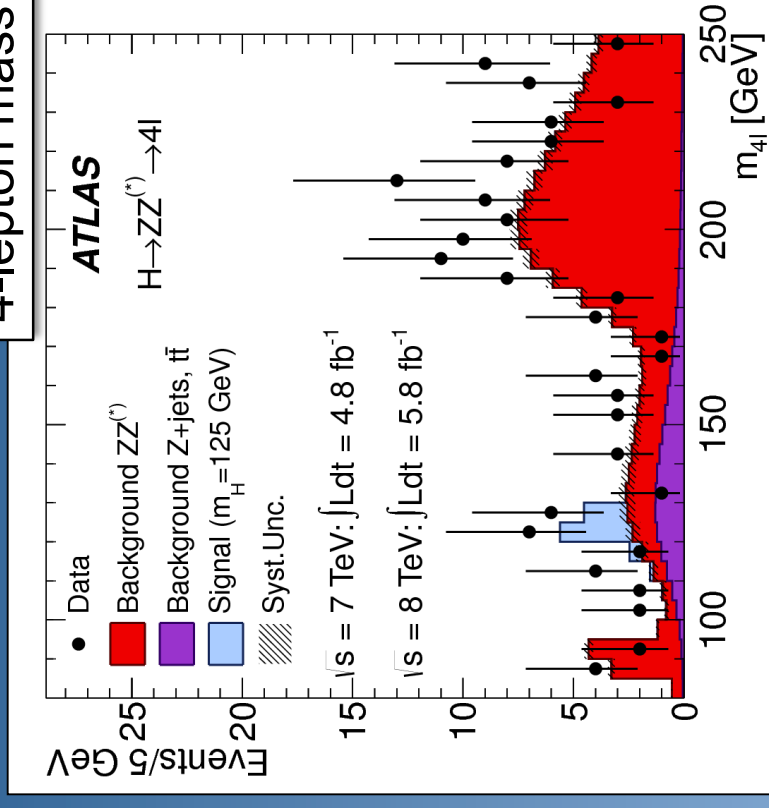
Example: 125 GeV Higgs

1) Theory: $H \rightarrow ZZ \rightarrow 4l$ ($l=e, \mu$):

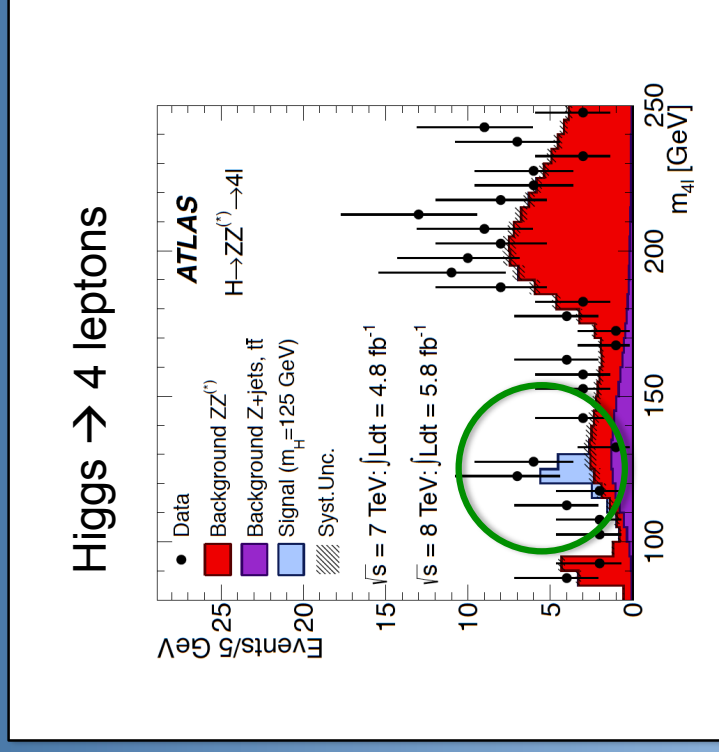
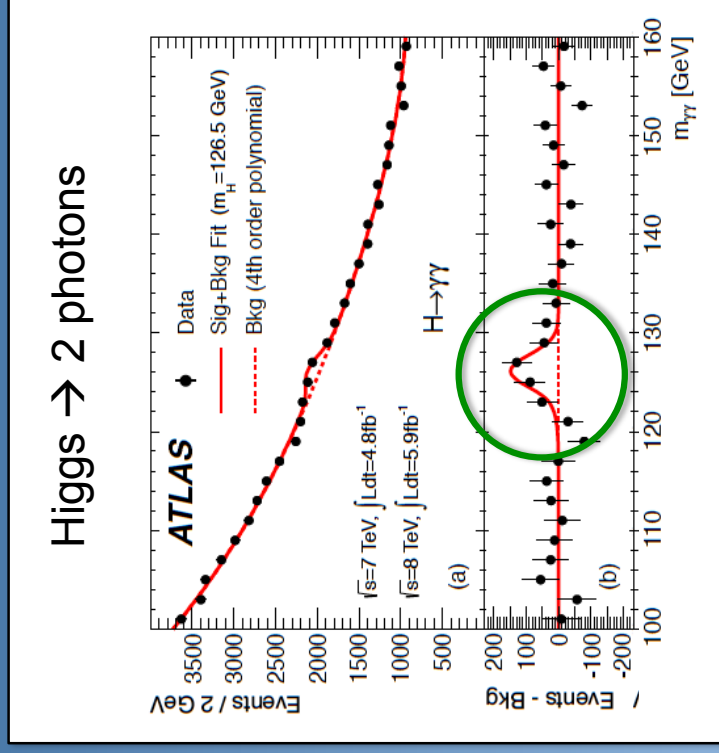
$$\left. \begin{aligned} \Gamma(h \rightarrow ZZ) &= 25.6\% \\ \Gamma(ZZ \rightarrow 4l) &= 5.2 \cdot 10^{-3} \end{aligned} \right\} 1/1000$$

2) ATLAS detector: reconstruct 4μ
detector acceptance, Atlas muon
reconstruction and selection criteria

4-lepton mass

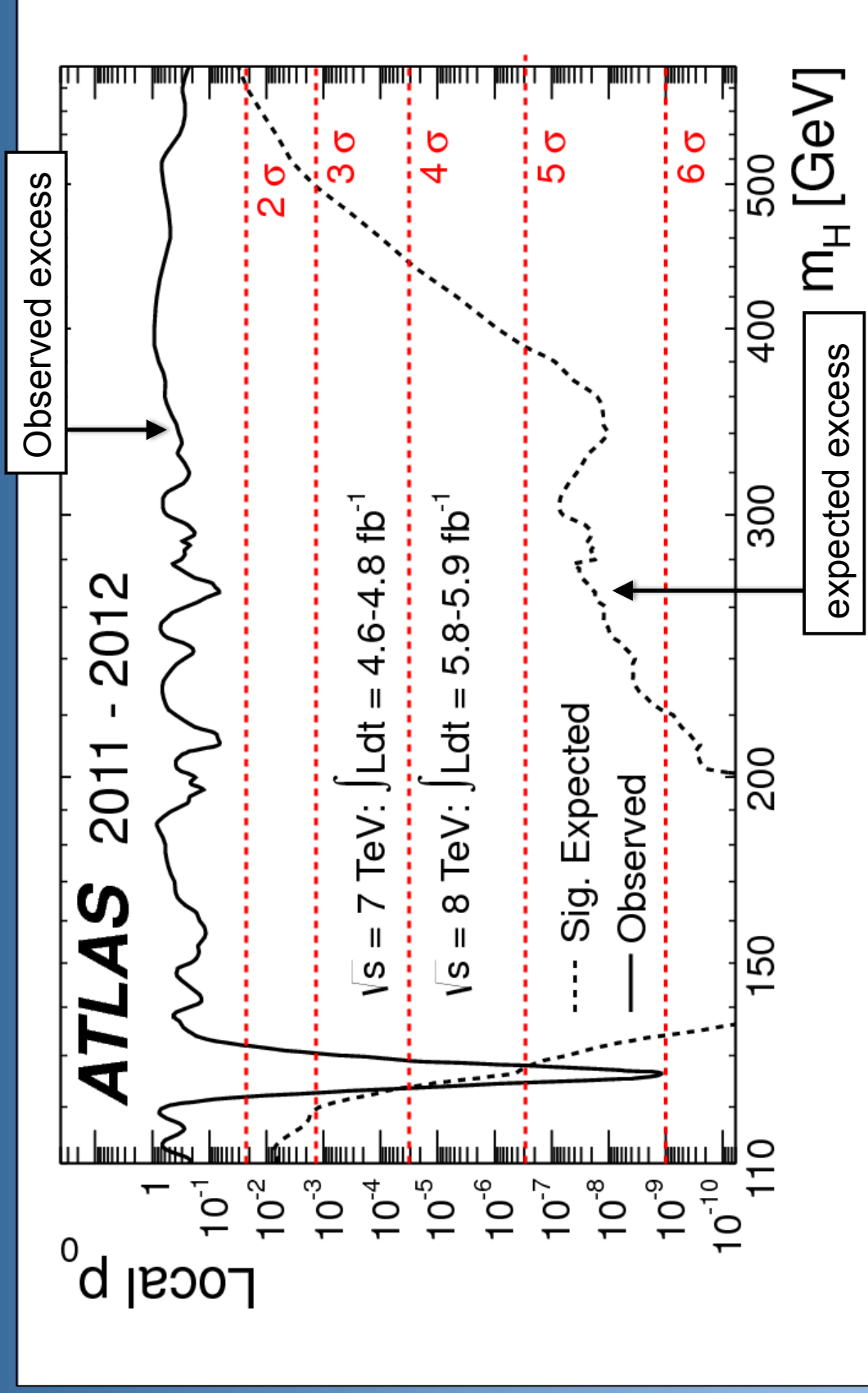


The results of the ATLAS experiment - july 2012 -



Probability that you would observe such an excess in both distributions if there would be no Higgs boson is 1 in a billion $\rightarrow$ we discovered something new !

Incompatibility excess with the SM hypothesis



Presentation CMS en ATLAS experiment: Higgs boson discovery



Peter Higgs

Jos Engelen (director NWO)



Higgs boson cross-section and mass

Cross-section

$$\mu = 1.43 \pm 0.16 \text{ (stat)} \pm 0.14 \text{ (sys)} \text{ GeV} \quad m_h = 125.5 \pm 0.5(stat)^{+0.6}_{-0.5}(sys) \text{ GeV}$$

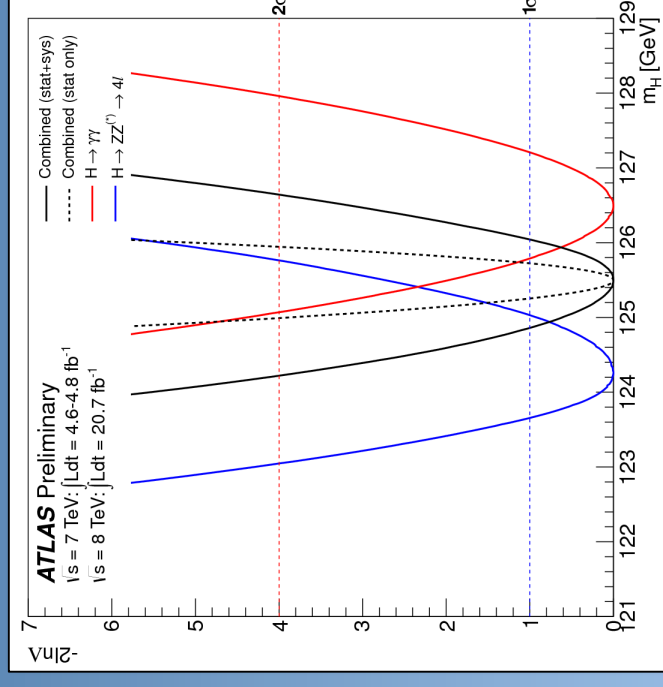
$$h \rightarrow ZZ \rightarrow 4l$$

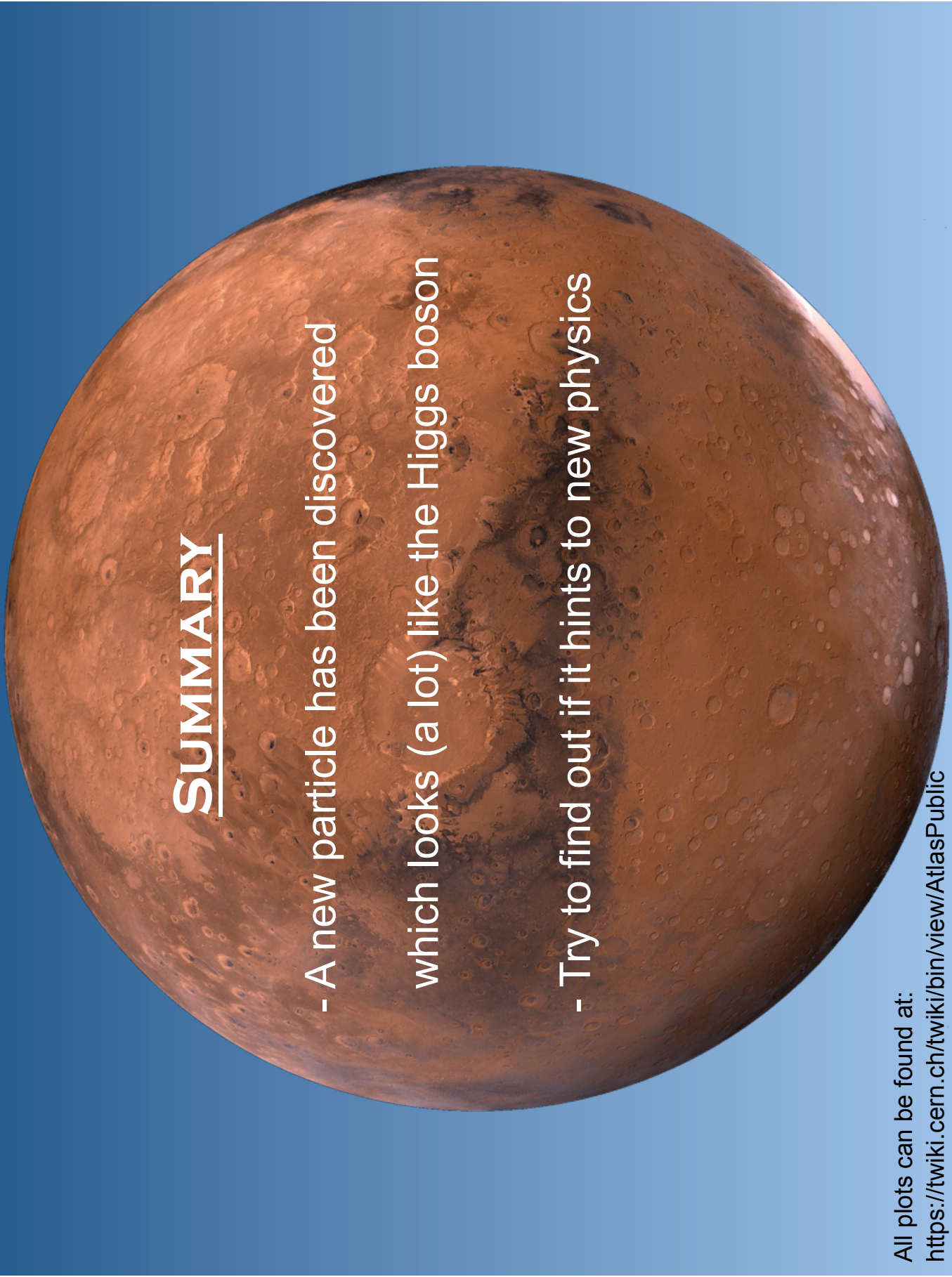
$$m_h = 126.8 \pm 0.2(stat) \pm 0.7(sys) \text{ GeV}$$

$$h \rightarrow \gamma\gamma$$

$$m_h = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(sys) \text{ GeV}$$

Mass





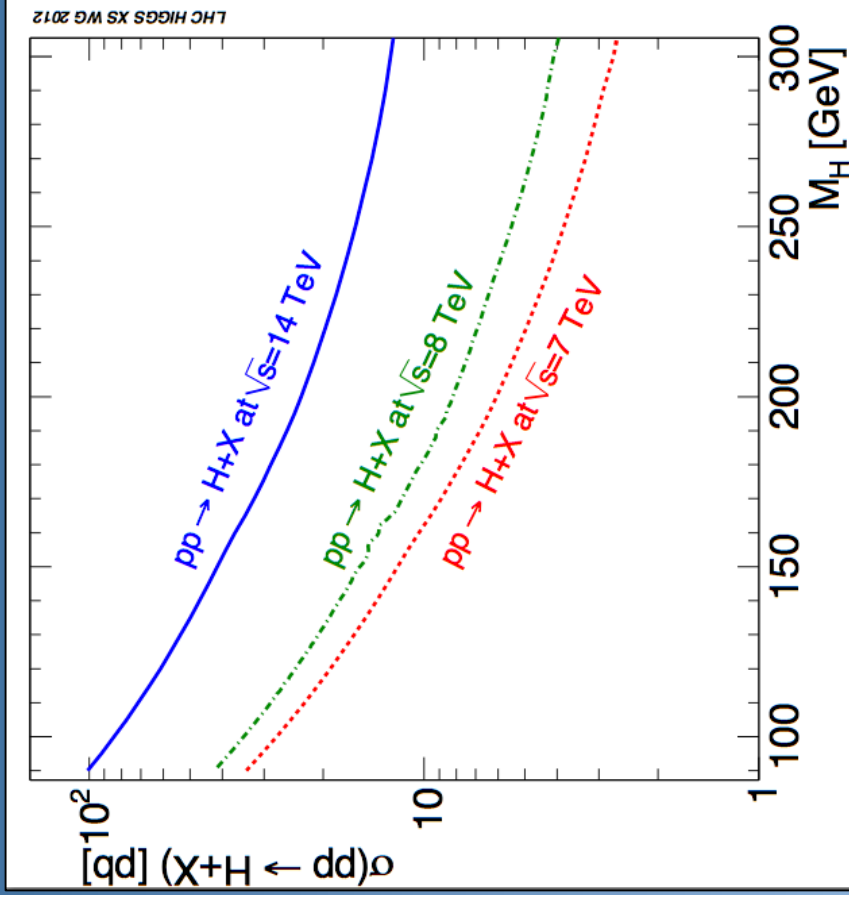
SUMMARY

- A new particle has been discovered which looks (a lot) like the Higgs boson
- Try to find out if it hints to new physics

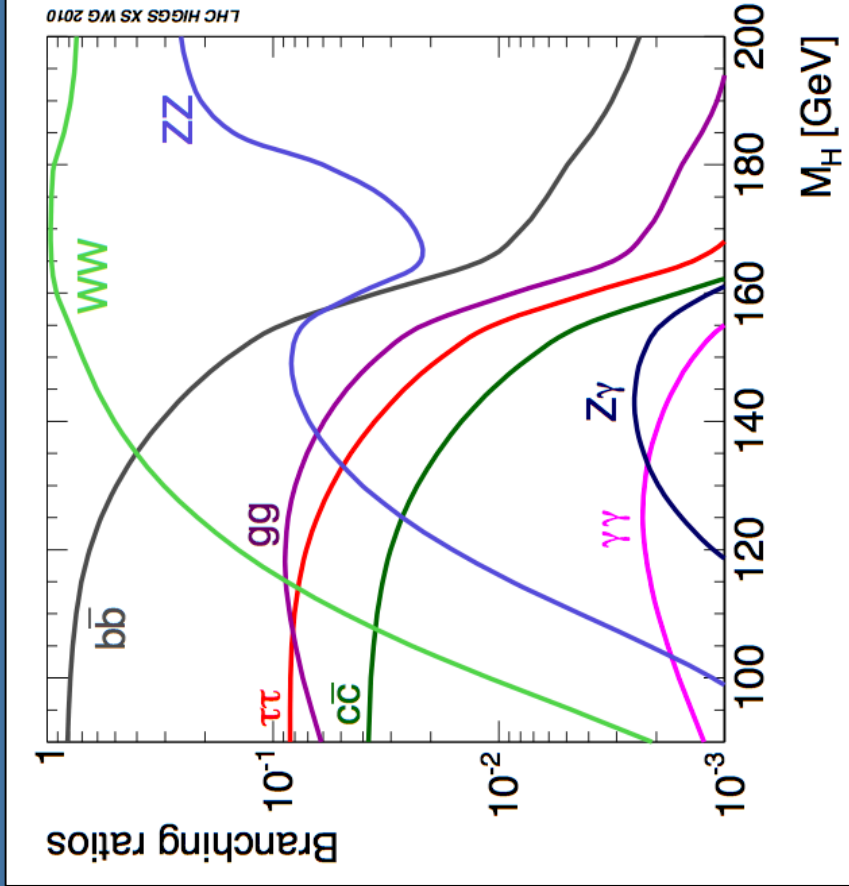
All plots can be found at:
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

Backup for exercises

Higgs boson production



Higgs boson decay



<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections>

ATLAS results

$pp \rightarrow h \rightarrow ZZ^{*} \rightarrow 4 \text{ leptons}$



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



CERN-PH-EP-2012-218
Accepted by: Physics Letters B

arXiv:1207.7214v2 [hep-ex] 31 Aug 2012

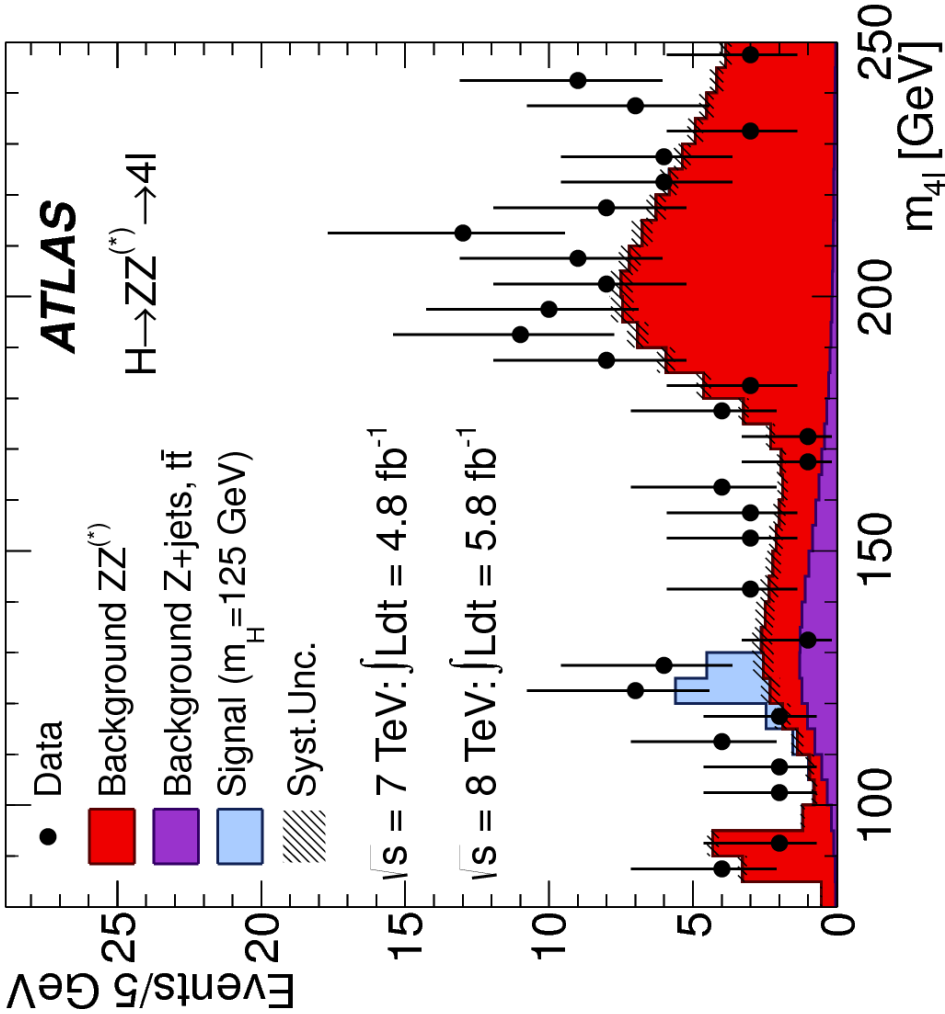
Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$ in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ in 2012. Individual searches in the channels $H \rightarrow ZZ^{0,0} \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^{0,0} \rightarrow e\nu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \rightarrow ZZ^{0,0}$, $WW^{0,0}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \rightarrow ZZ^{0,0} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (sys)} \text{ GeV}$ is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9} , is compatible with the production and decay of the Standard Model Higgs boson.



Exercise 4:

a) Why is there a 'dip' in the fraction of Higgs bosons that decay to 2 Z bosons for Higgs masses between 160 and 180 GeV ?

b) How many $h \rightarrow ZZ \rightarrow \mu\mu\mu\mu$ ($e^+e^-e^+e^- + e^+e^-\mu^+\mu^- + \mu^+\mu^-\mu^+\mu^-$) do you expect to be produced at the LHC for 4.8 fb⁻¹ at $\sqrt{s}=7$ TeV and 5.8 fb⁻¹ at $\sqrt{s}=8$ TeV ?

Note: Number of events = cross-section * Luminosity

On the previous slide you see expectation/measurement of the ATLAS experiment: background histogram in red/purple, signal ($m_h=125$ GeV) in blue and the data.

c) What is the fraction of events that all leptons have all been well reconstructed ?
Name reasons why leptons are not detected

We do a counting experiments in the most populated 2 bins around each signal.

d) Did ATLAS make a discovery using this result ? Did it expect to be able to do so ?

e) Could the ATLAS experiment exclude a Higgs boson at $m_h=200$ GeV ?

Statistics: rules for discovery and rejection

Observe x events when λ are expected:

$$P(x | \lambda) = \frac{\lambda^x e^{-\lambda}}{x!}$$

Poisson distribution

discovery

$$\int_0^{x_{\text{obs}}} P(x | \lambda_{\text{SM}}) dx < 5.7 \cdot 10^{-7}$$

“5 sigma effect”

exclusion

$$\int_0^{x_{\text{obs}}} P(x | \lambda_{\text{SM}} + \lambda_{\text{H}}) dx < 0.05$$

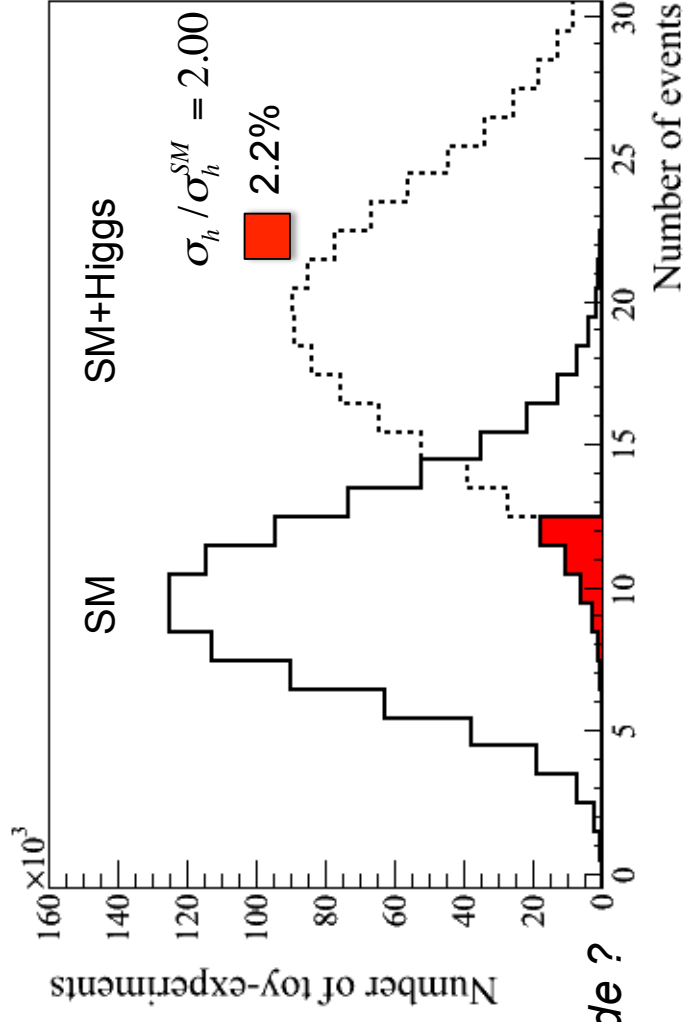
When / how do you exclude a signal

Standard Model

SM	10
Higgs	5
Data	12

Can we exclude the SM+Higgs hypothesis ?

What σ_h / σ_h^{SM} can we exclude ?



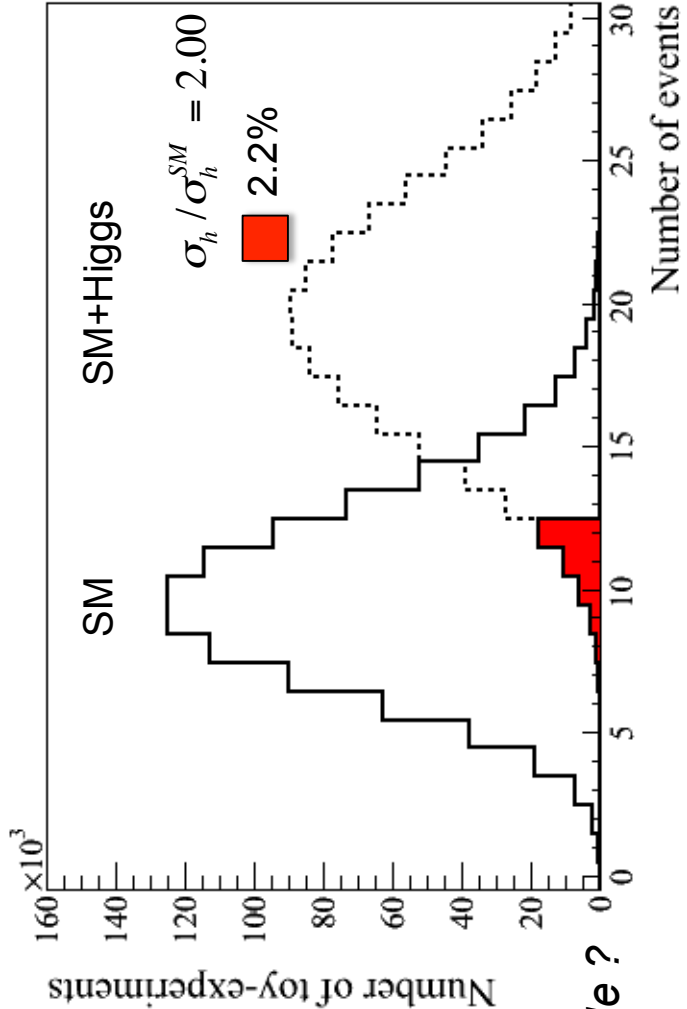
When / how do you exclude a signal

Standard Model

SM	10
Higgs	5
Data	12

Can we exclude the SM+Higgs hypothesis ?

What σ_H/σ_h^{SM} can we exclude ?



σ/σ_{SM}	SM	# data	SM+Higgs	
1.0	10	12	15.0	18.5 %
1.5	10	12	17.5	6.8 %
2.0	10	12	20.0	2.2 %

excluded

Expected exclusion ? Use mean SM instead of Ndata

Observed excluded cross-section, σ_H/σ_h^{SM} , = 1.64