



THE SEARCH FOR THE HIGGS BOSON

Ivo van Vulpen (Uva/Nikhef)

(In)famous Higgs boson



The Higgs boson

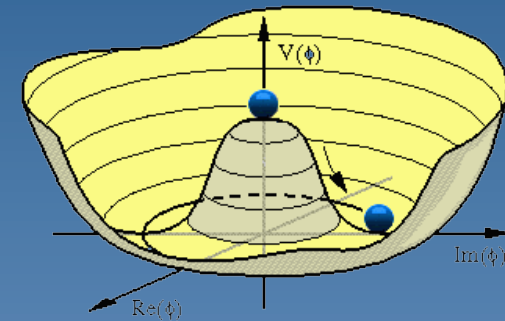


Paris Hilton

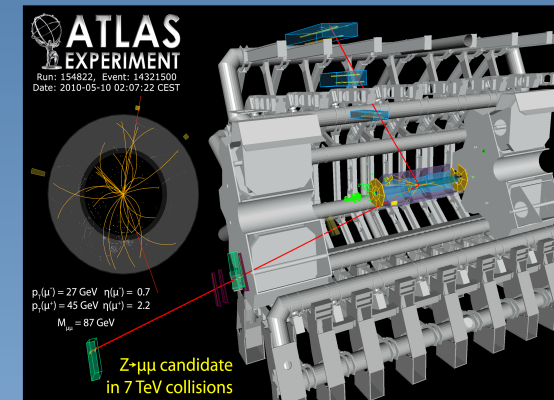
Famous and constantly in the news
... but are they important ?

Things to remember

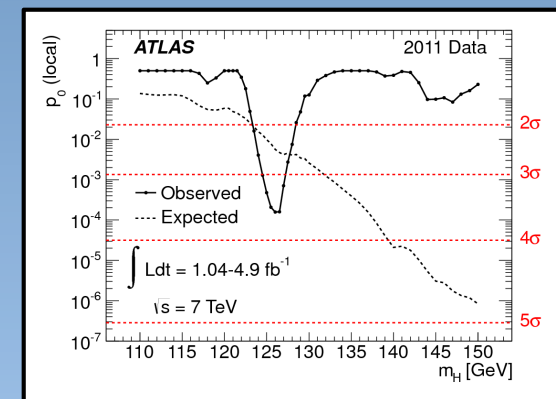
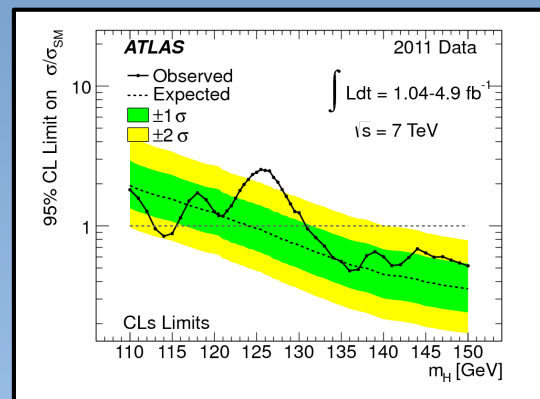
1) The Higgs mechanism is at the heart of the Standard Model



2) LHC and ATLAS detector operating fine!

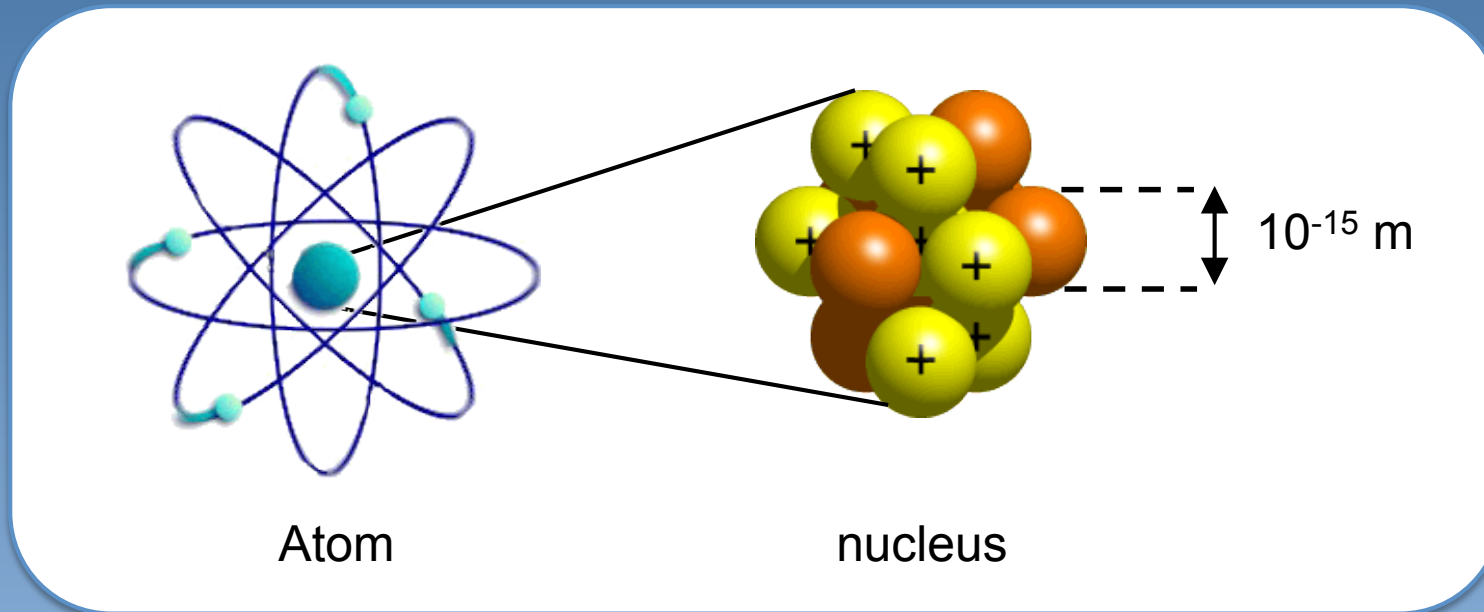


3) How to interpret the Higgs summary plots from LHC experiments



Particle Physics

Studies nature at distance scales $< 10^{-15}$ m

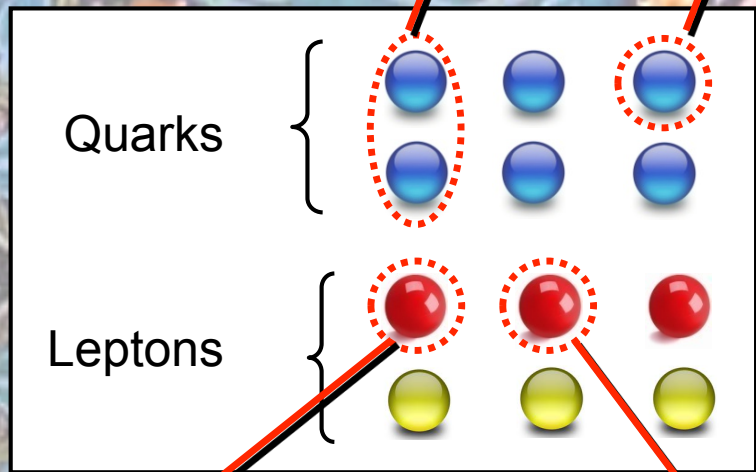


Standard Model:

Quantum theory that describes phenomena down to 10^{-18} m

Particles

Forces



- 1) Electromagnetism (photon)
- 2) Weak force (W^+ , W^- , Z)
- 3) Strong force (8 gluons)

electron

Fermions

muon

Bosons

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

Standard Model is based on symmetries

Free electron

$$\mathcal{L}_e = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi$$

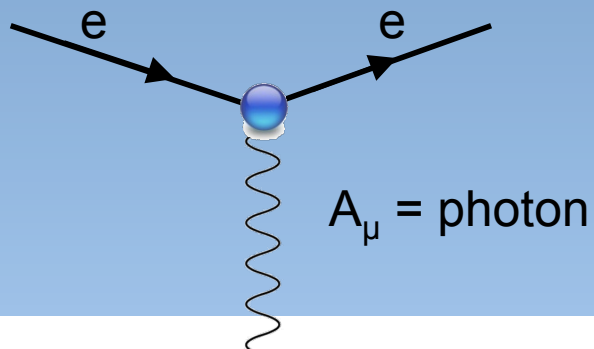
Extra symmetry requirement

Local gauge invariance

$$\psi(x) \rightarrow e^{i\alpha(x)}\psi(x)$$

Introduce covariant derivative
(with vector-field)

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - ieA_\mu$$



In the Standard Model

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

Electroweak:
 W^+, W^-, Z, γ

QCD:
8 gluons

What is missing in our Standard Model ?

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



Solved by the Higgs mechanism



Dark matter
Dark energy
Matter/anti-matter
Nature of gravity
Beginning of time

The Higgs mechanism

Massive gauge bosons in a local gauge invariant theory

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

There has to be a Higgs boson

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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Math Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 17 July 1964

Recently a number of people have discussed the Goldstone theorem^{1,2,3}; this says that in a Lorentz-invariant theory which contains an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee⁴ showed that this theorem does not necessarily apply in non-relativistic theories and implied that their considerations would apply equally well to Lorentz-invariant field theories. Gilbert^{5,6}, however,

gave a proof that the failure of the Goldstone theorem in the non-relativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the conserved currents are coupled to gauge fields.

Following the procedure used by Gilbert⁵, let us consider a theory of two Hermitian scalar fields

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$\phi_1(x)$, $\phi_2(x)$ which is invariant under the phase transformation

$$\phi_1 \rightarrow \phi_1 \cos \theta + \phi_2 \sin \theta, \quad (1)$$

$$\phi_2 \rightarrow -\phi_1 \sin \theta + \phi_2 \cos \theta.$$

Then there is a conserved current j_μ such that

$$[j_\mu, \phi_1^2(x)] = 0, \quad [j_\mu, \phi_2^2(x)] = 0. \quad (2)$$

We assume that the Lagrangian is such that symmetry is broken by the nonvanishing of the vacuum expectation value of ϕ_2 . Goldstone's theorem is proved by showing that the Fourier transform of $\langle j_\mu(x), \phi_1^2(x) \rangle$ contains a term $2\pi \delta(k) \langle j_\mu(x), \phi_1^2(x) \rangle$, where $\delta(k)$ is the delta function, as a consequence of Lorentz invariance, the conservation law and eq. (2).

Klein and Lee⁴ avoided this result in the non-relativistic case by showing that the most general form of this Fourier transform is now, in Gilbert's notation,

$$F(k) = \langle j_\mu(x), \phi_1^2(x) \rangle + \langle j_\mu(x), \phi_2^2(x) \rangle + C \delta(k) \langle j_\mu(x), \phi_1^2(x) \rangle \quad (3)$$

where $\delta(k)$ which may be taken as $\delta(k_0)$, $\delta(k)$ gives rise to a special Lorentz frame. The conservation law then reduces eq. (3) to the less general form

$$F(k) = \langle j_\mu(x), \phi_1^2(x) \rangle + \langle j_\mu(x), \phi_2^2(x) \rangle + C \delta(k) \langle j_\mu(x), \phi_1^2(x) \rangle. \quad (4)$$

It turns out, on applying eq. (4), that all three terms in eq. (4) can contribute to $\langle j_\mu(x), \phi_1^2(x) \rangle$. Thus the Goldstone theorem fails if $\delta(k) \neq 0$, which is possible only if the other terms exist. Gilbert's remark that no special theorem vector ϕ_2 is available in a Lorentz-invariant theory appears to rule out this possibility in such a theory.

There is however a class of relativistic field theories in which a vector ϕ_2 does indeed play a part. This is the class of gauge theories, where an auxiliary well known vector ϕ_2 must be introduced in order to define a radiation gauge in which the vector gauge fields are well defined operators. Such theories are nevertheless Lorentz-invariant, as has been shown by Schwinger^{7,8}. (This has, of course, long been known of the simplest such theory, quantum electrodynamics.) There seems to be no reason why the vector ϕ_2 should not appear in the Fourier transform under consideration.

It is characteristic of gauge theories that the conservation laws hold in the strong sense, as a consequence of field equations of the form

$$\partial_\mu \phi_2 = \partial_\mu \phi_1 + \partial_\mu \phi_2. \quad (5)$$

Except in the case of Abelian gauge theories, the fields ϕ_1, ϕ_2 are not simply the gauge field variables $A_\mu, F_{\mu\nu}$, but contain additional terms with combinations of the structure constants of the group as coefficients. Now the structure of the Fourier transform of $\langle j_\mu(x), \phi_1^2(x) \rangle$ must be given by eq. (4). Applying eq. (5) to this commutator gives us as the Fourier transform of $\langle j_\mu(x), \phi_1^2(x) \rangle$ the single term $\langle j_\mu(x), \phi_1^2(x) \rangle + \langle j_\mu(x), \phi_2^2(x) \rangle$. We have thus excluded both Goldstone's zero-mass bosons and the "spurious" state ($\delta(k) \neq 0$) proposed by Klein and Lee.

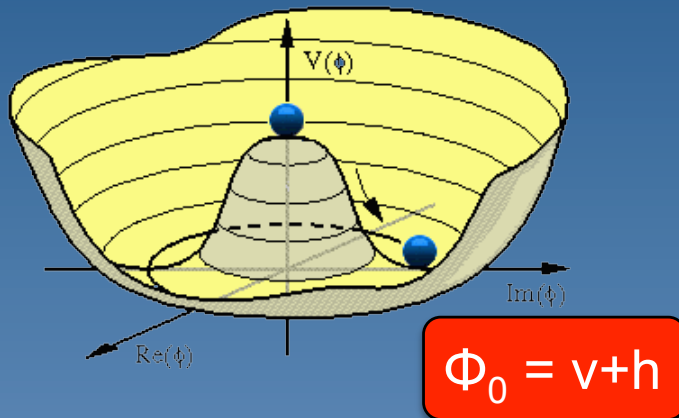
In a subsequent note it will be shown, by considering some classical field theories which display broken symmetries, that the introduction of gauge fields may be expected to produce qualitative changes in the nature of the particles described by such theories after quantization.

References

1. J. Goldstone, Nuovo Cimento **13** (1962), 164.
2. J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. **127** (1962), 965.
3. A. Klein and B. W. Lee, Phys. Rev. Letters **12** (1964), 462.
4. B. Gilbert, Phys. Rev. Letters **13** (1964), 115.
5. J. Schwinger, Phys. Rev. **127** (1962), 235.

- September 1964 -

The Higgs mechanism



- 1) Add iso-spin doublet Φ (4 d.o.f.), with $Y_\Phi = +1$
- 2) Potential: $V(\Phi) = \mu^2\Phi^2 + \lambda\Phi^4$, with $\mu^2 < 0$

Gauge bosons

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

$$L(\phi) = \underbrace{(D_\mu \phi)(D^\mu \phi)}_{\propto \vec{V}^2} - V(\phi)$$

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

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

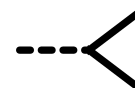

$$\propto h^2 \vec{V}^2$$


Fermions:

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

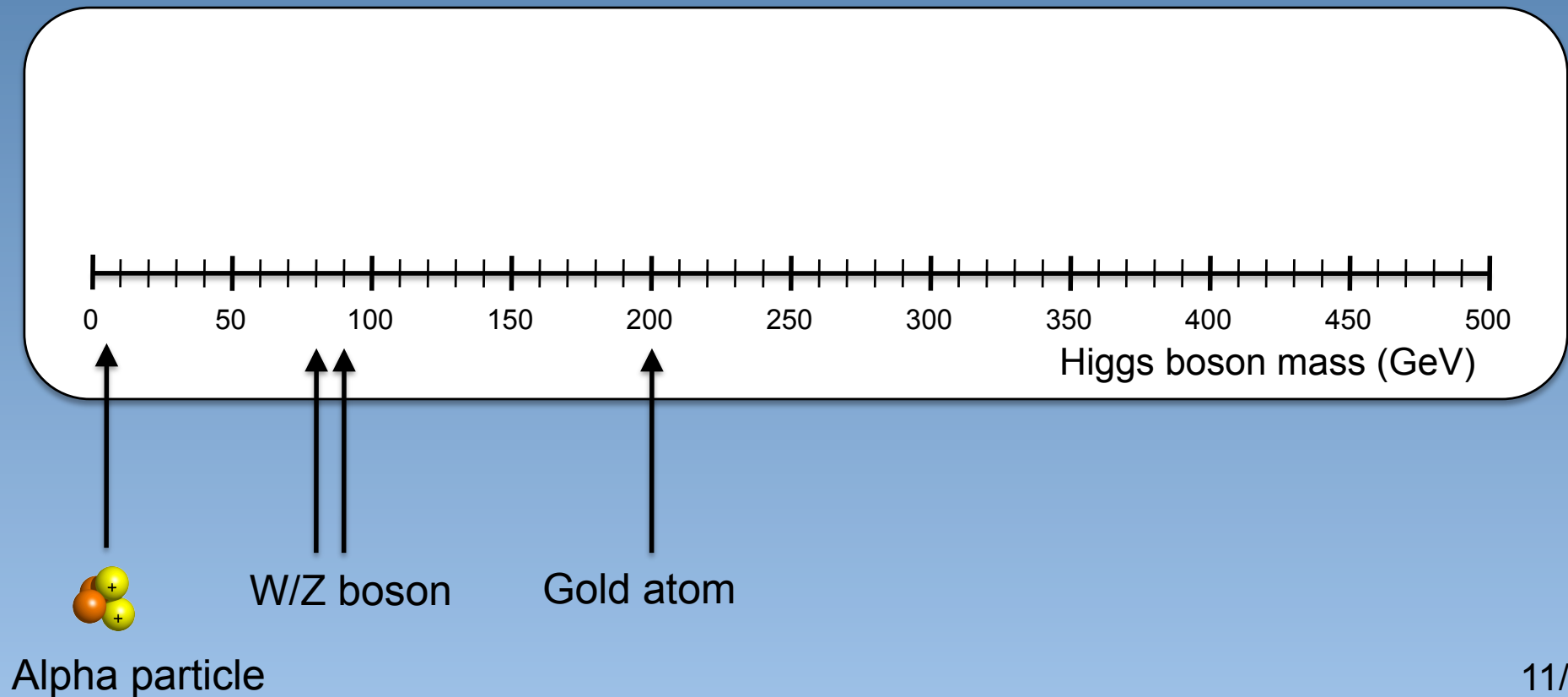
$$L(\psi) = \underbrace{\bar{\psi} \phi \psi}_{m_\psi \bar{\psi} \psi} + \dots$$

$$m_\psi \bar{\psi} \psi \quad \text{mass } \psi$$

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


“the Higgs couples to mass”

The mass of the Higgs boson



If the Higgs boson is discovered
it will go straight into our history books

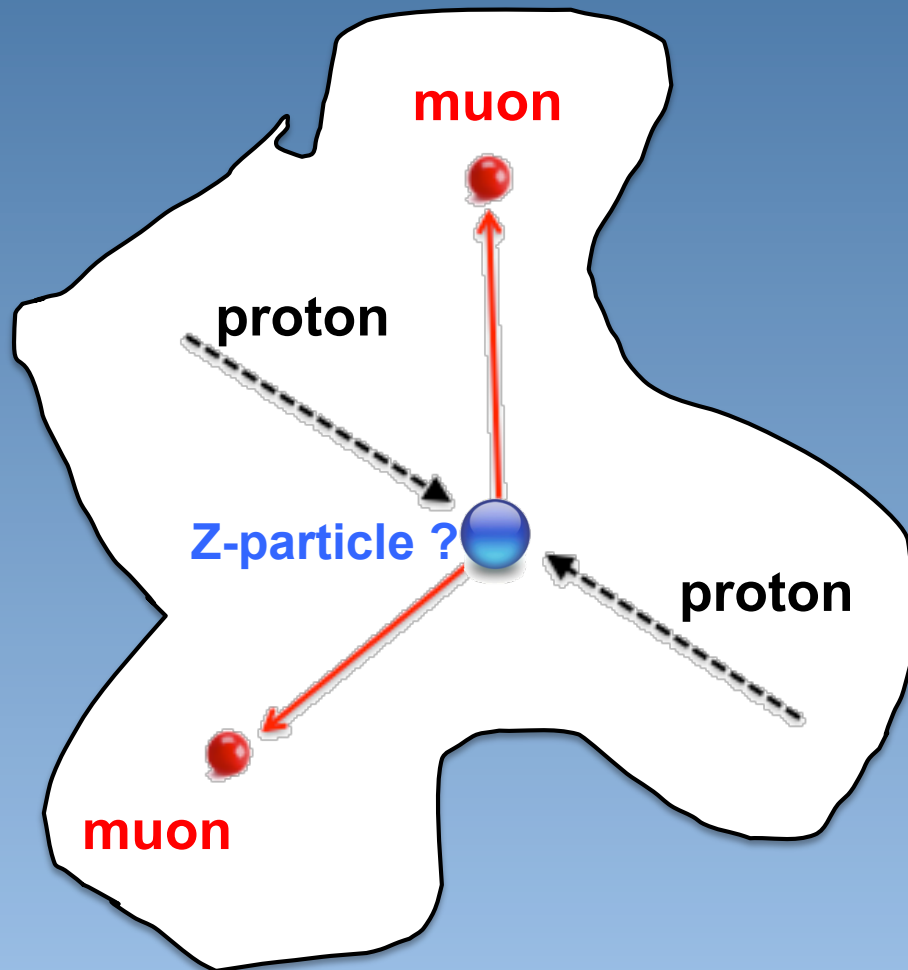


If the Higgs boson is **not** discovered
it will **also** go straight into our history books

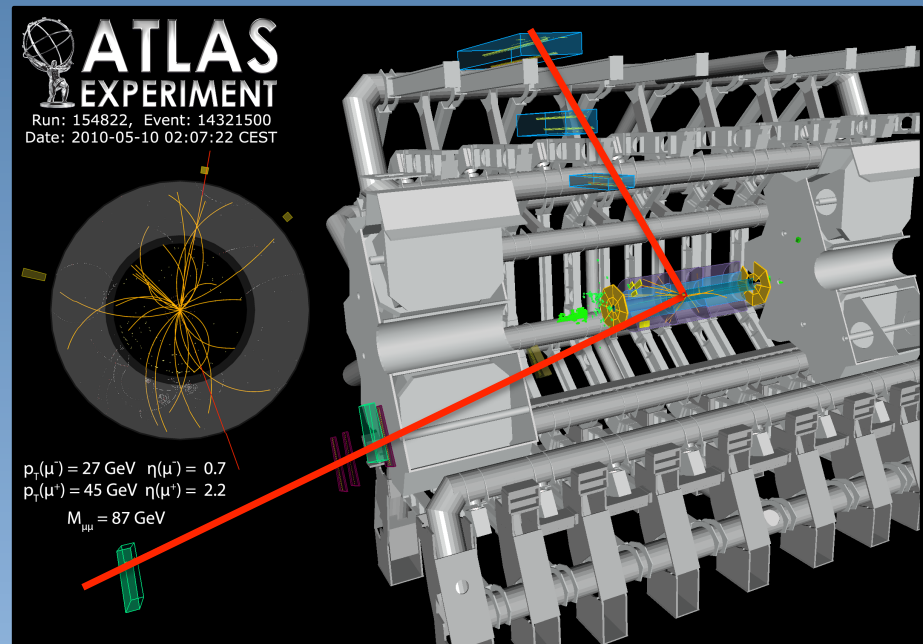


How do you discover a Z particle ?

Deviations from the prediction without a Z boson



2-muons as seen in the ATLAS detector



What is the fingerprint of the Z particle:
→ the di-muon mass

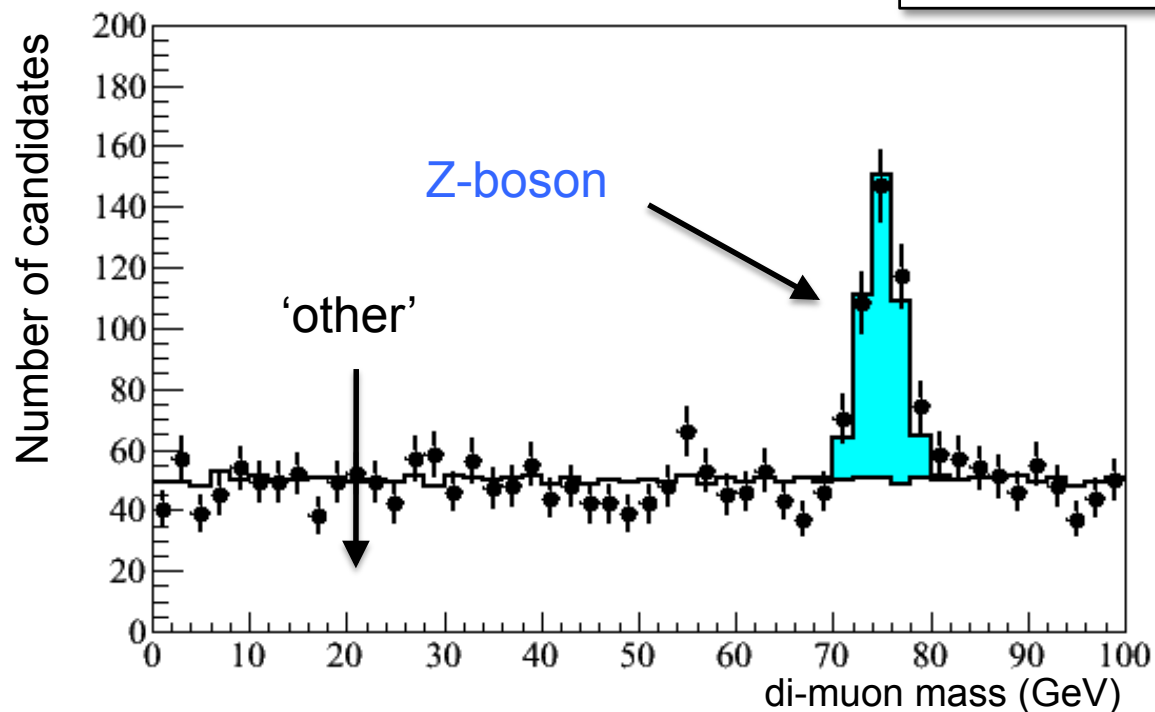
di-muon mass



'other': no preference/structure

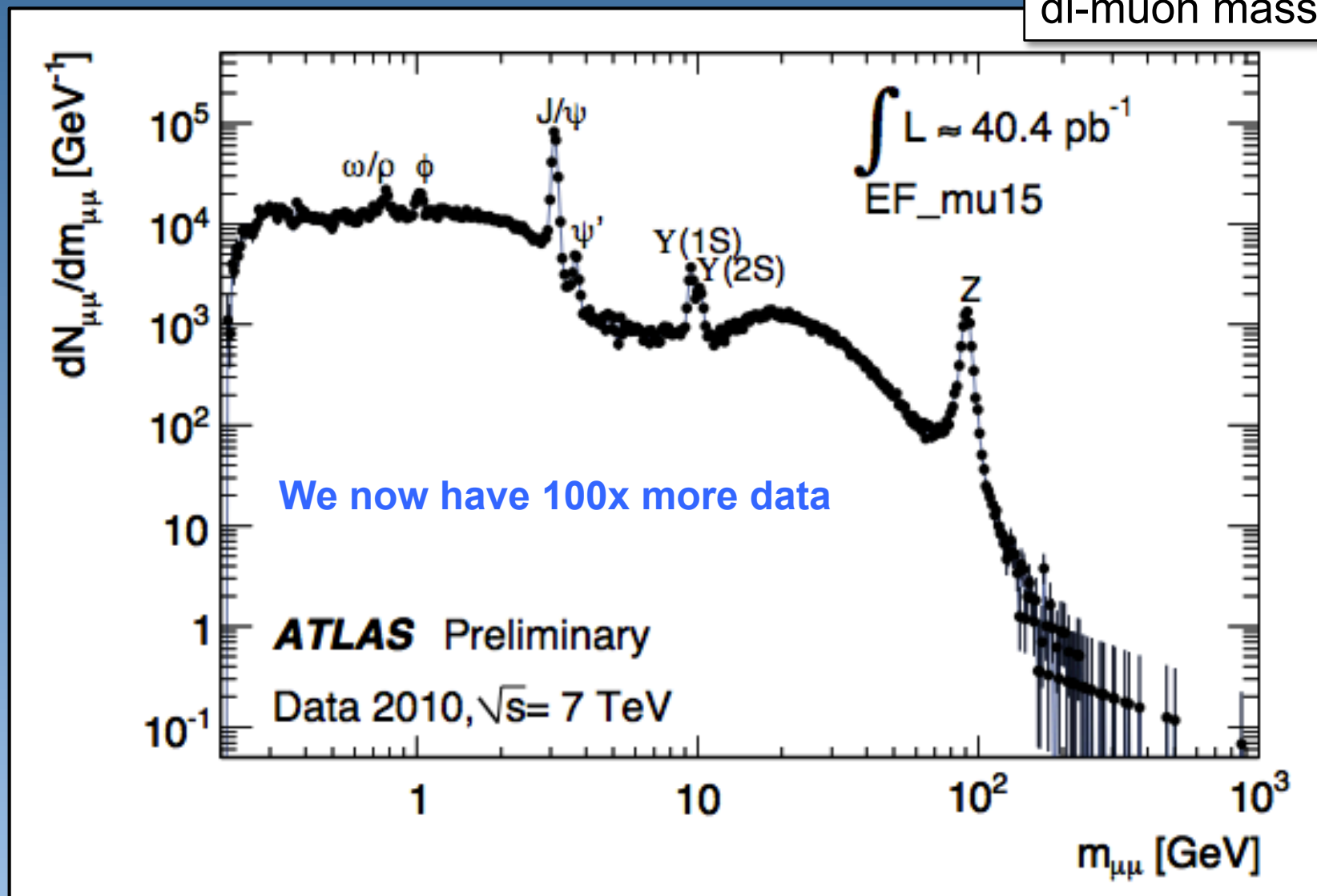
Z-boson: Breit-Wigner $\otimes$ resolution

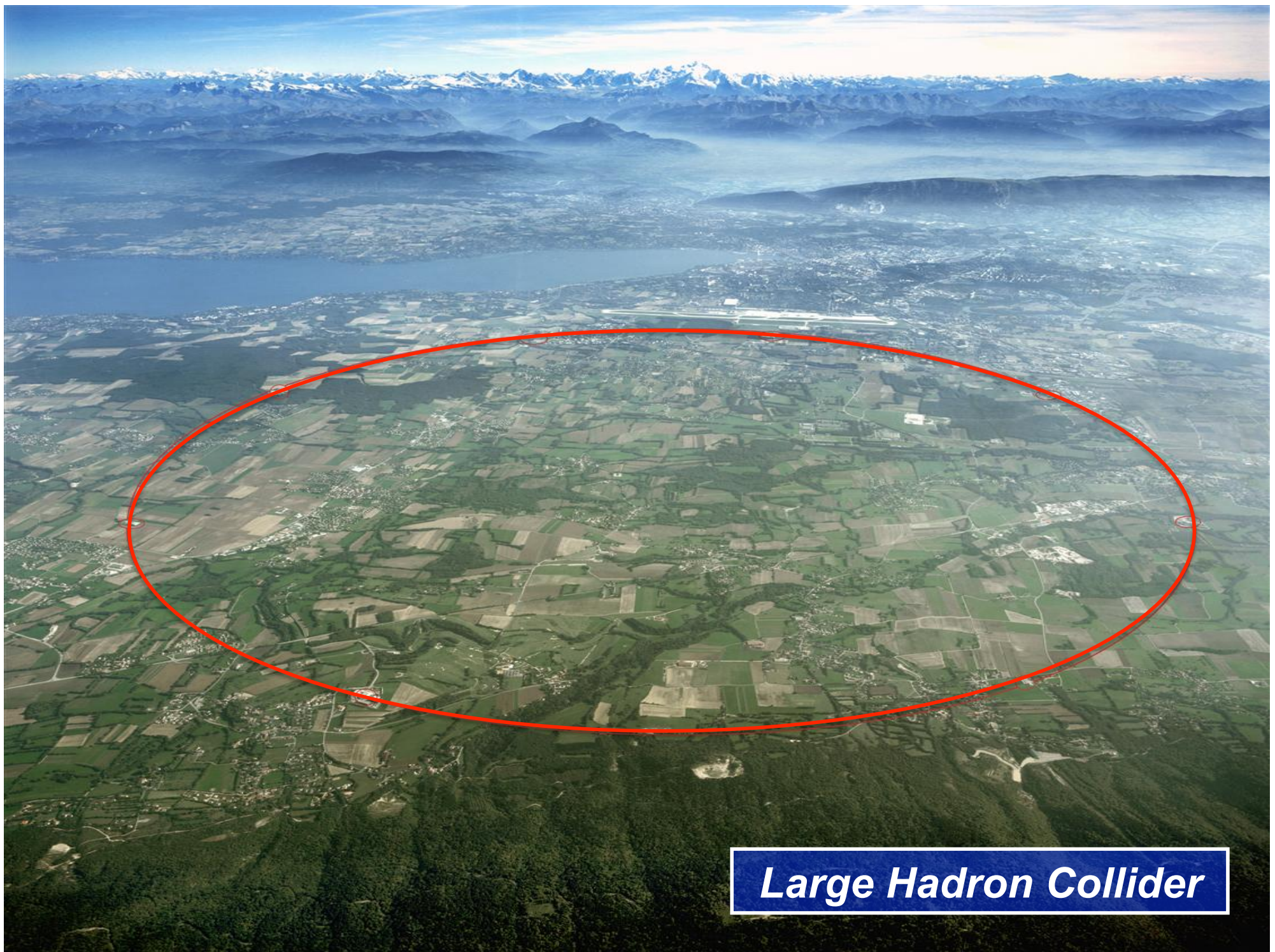
di-muon mass



Di-muon resonances in proton-proton

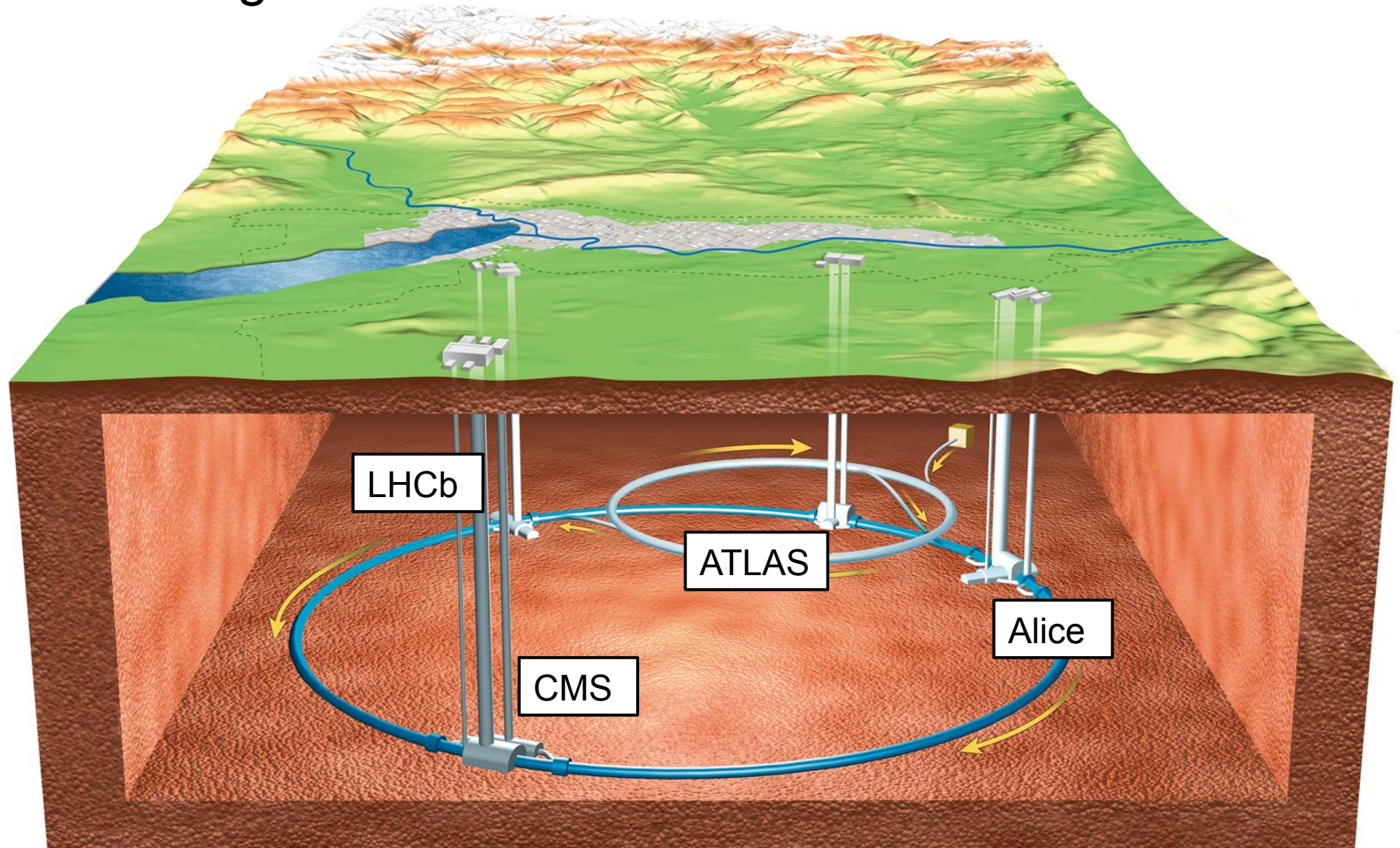
di-muon mass





Large Hadron Collider

The Large hadron collider



Acceleration is 'easy'



High energy: 14 TeV

Energy limited by strength of 1234 dipole magnets, with $B = 8.4 \text{ T}$ at 1.9 K

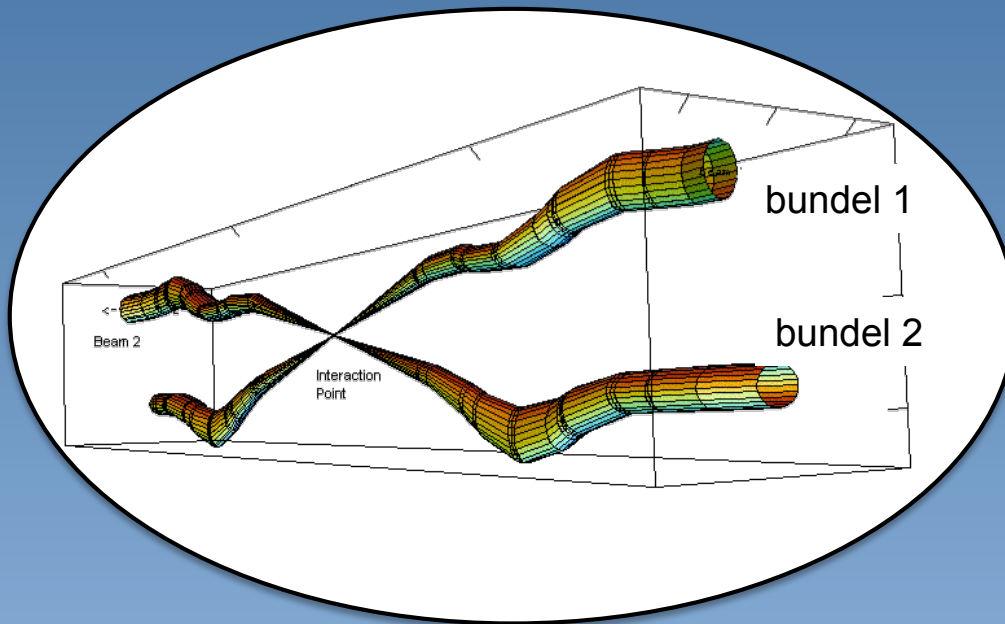
→ *Production of heavy particles (few TeV)*

High intensity: $10^{33/34} \text{ cm}^{-2}\text{s}^{-1}$

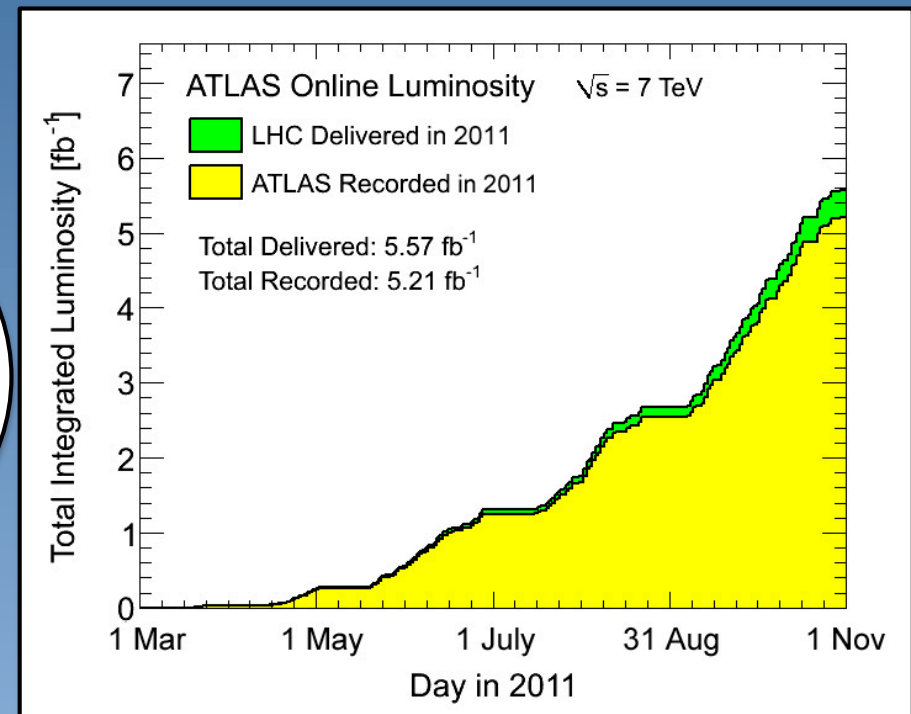
40 million collisions per second

→ *Look for rare processes*

LHC 2012 data-set



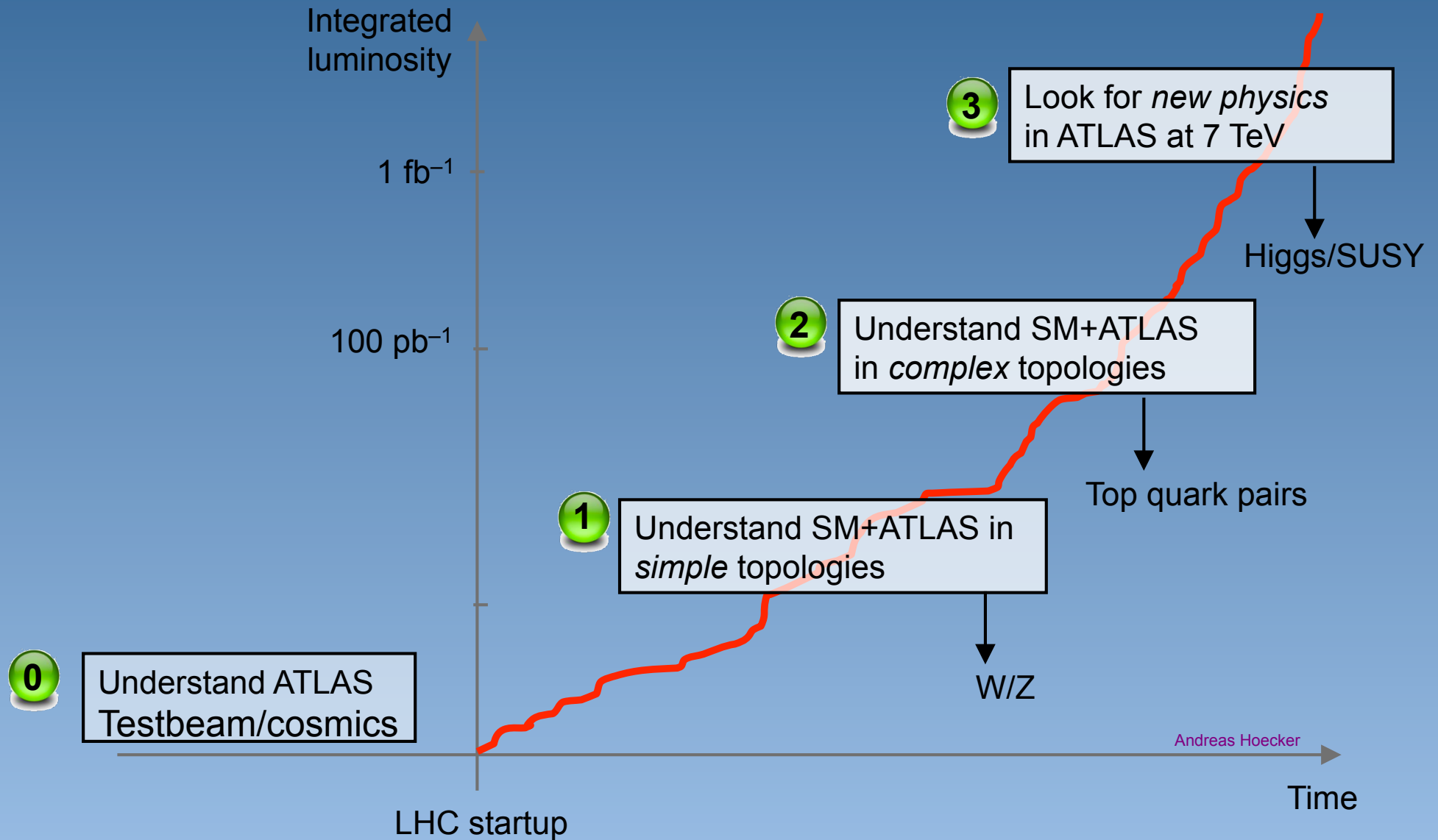
➤ 40 million collisions per second
Only 200 Hz to tape



Peak Luminosity = $3.65 \cdot 10^{33} \text{ cm}^2 \text{ s}^{-1}$
Limited Trigger rate: 200 Hz

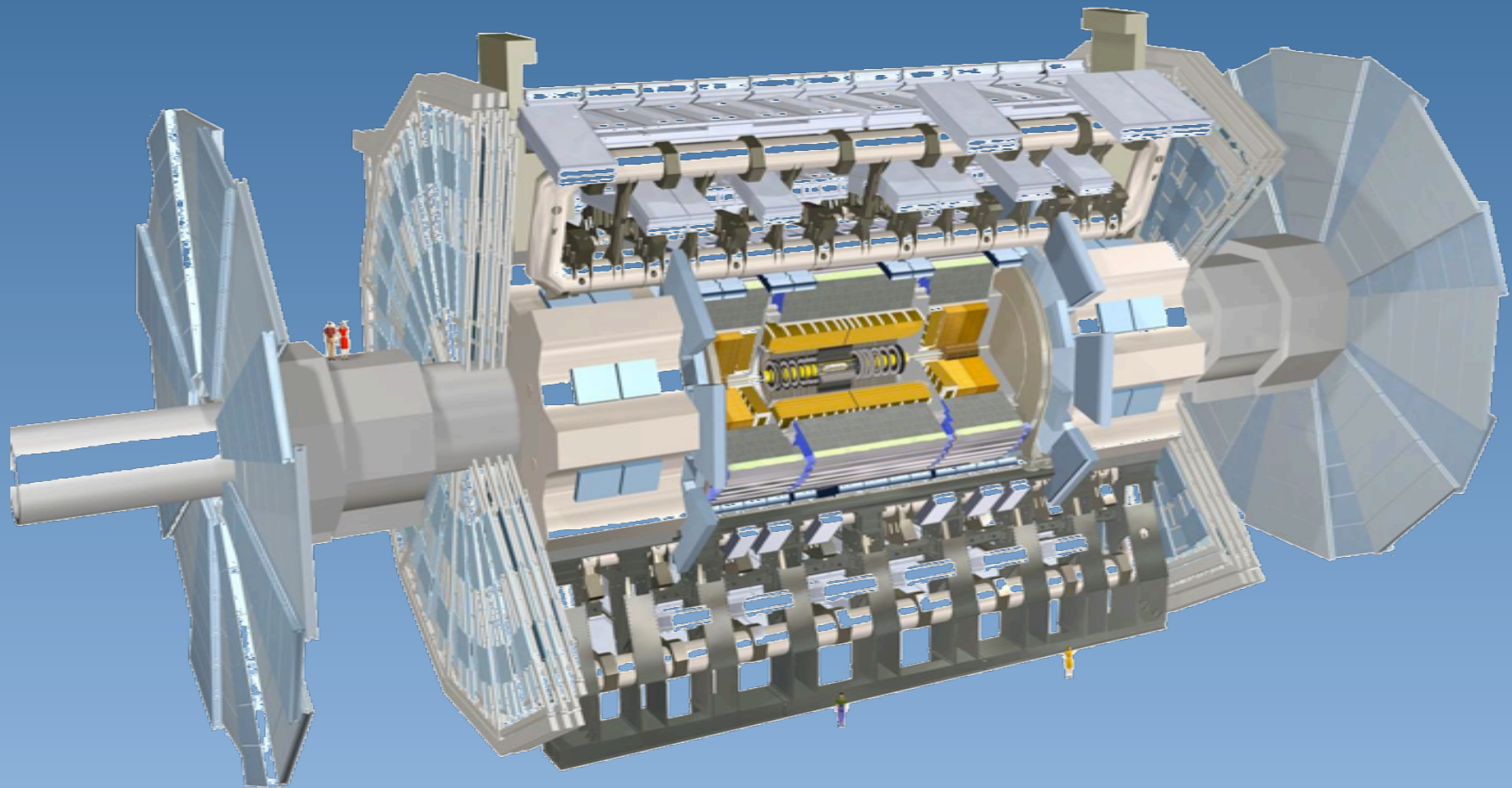
LHC start-up programme

New detector and new energy scale



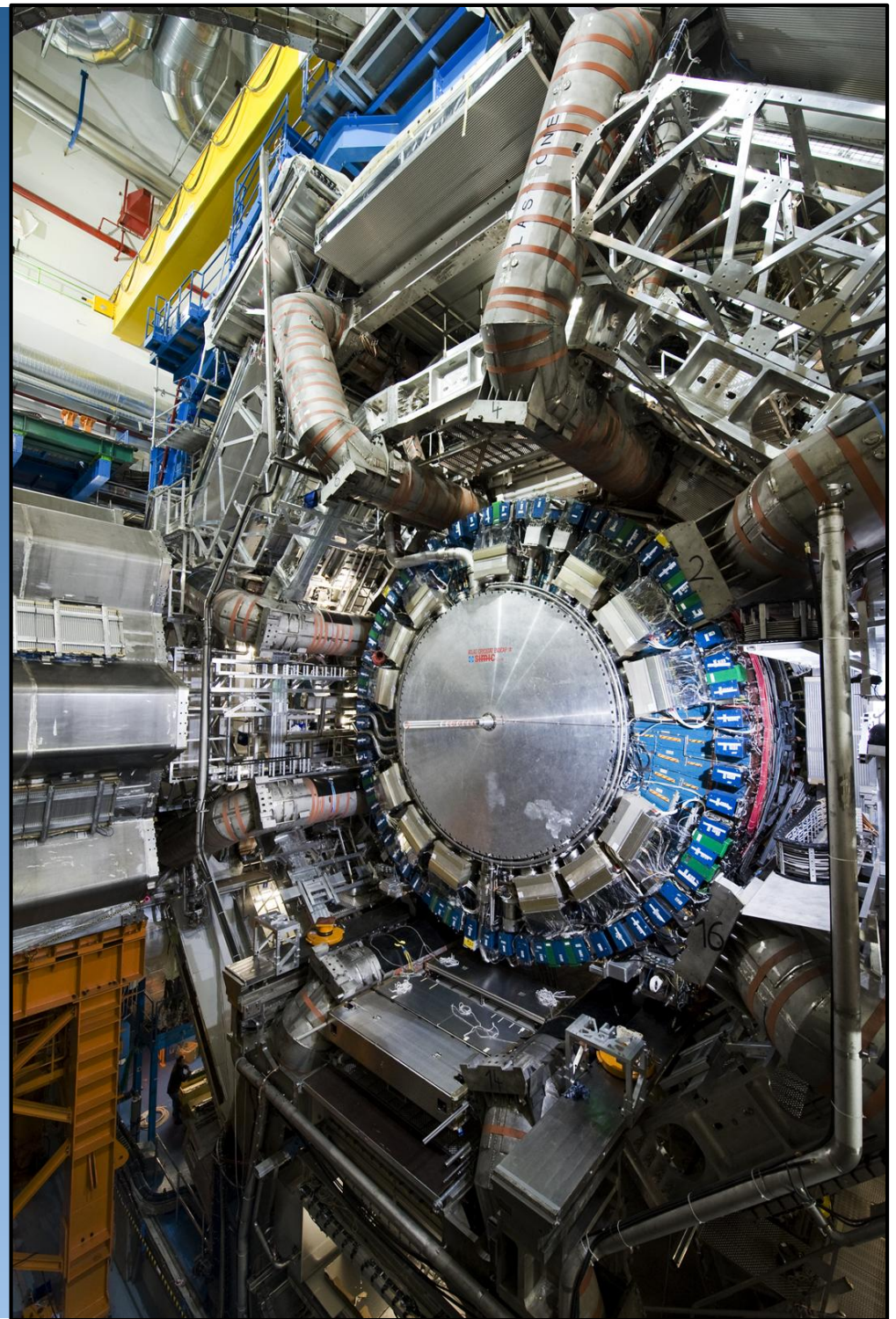
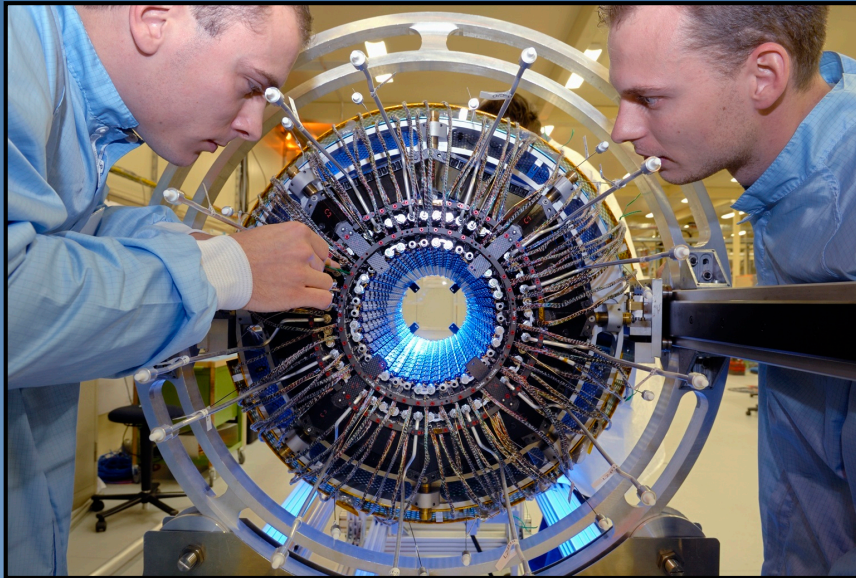
The ATLAS detector

(as a computer model)



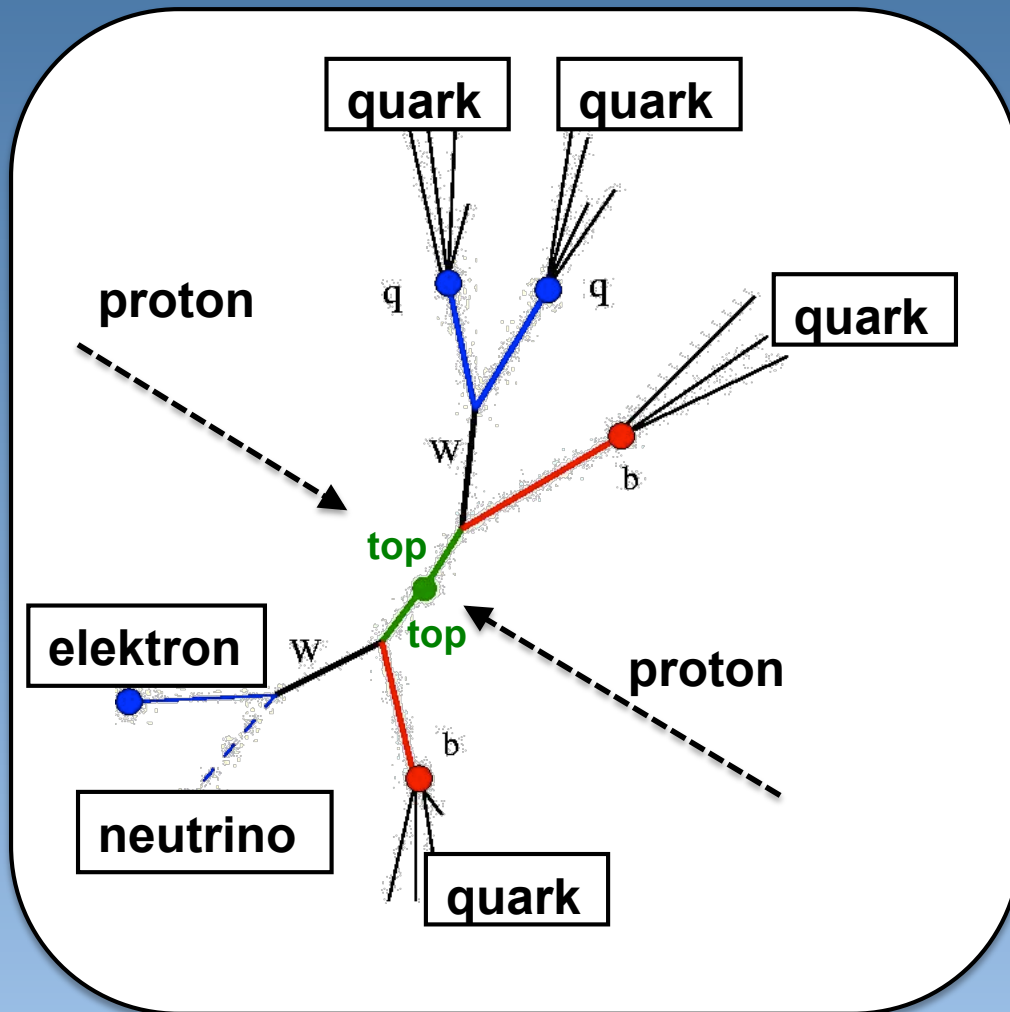
The ATLAS detector

(in real life)

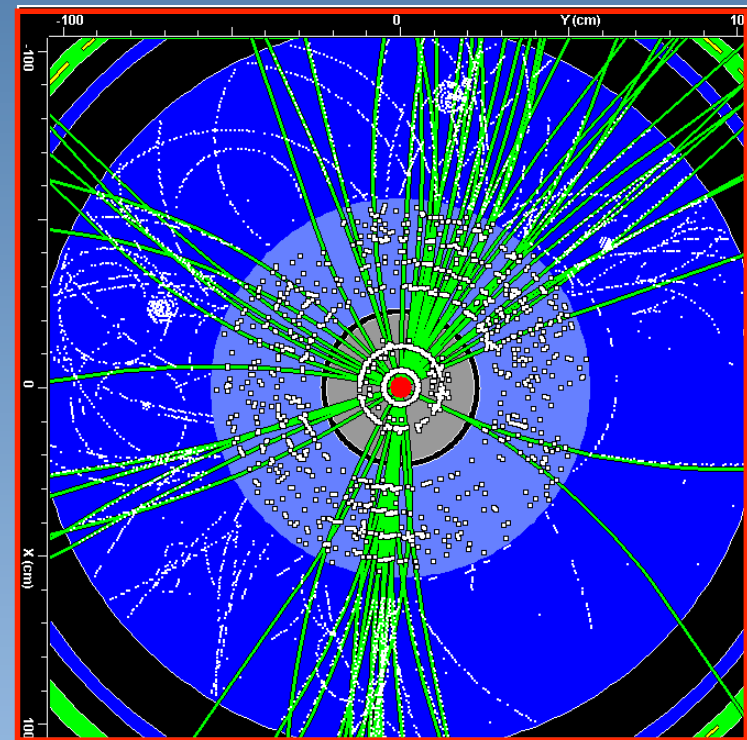


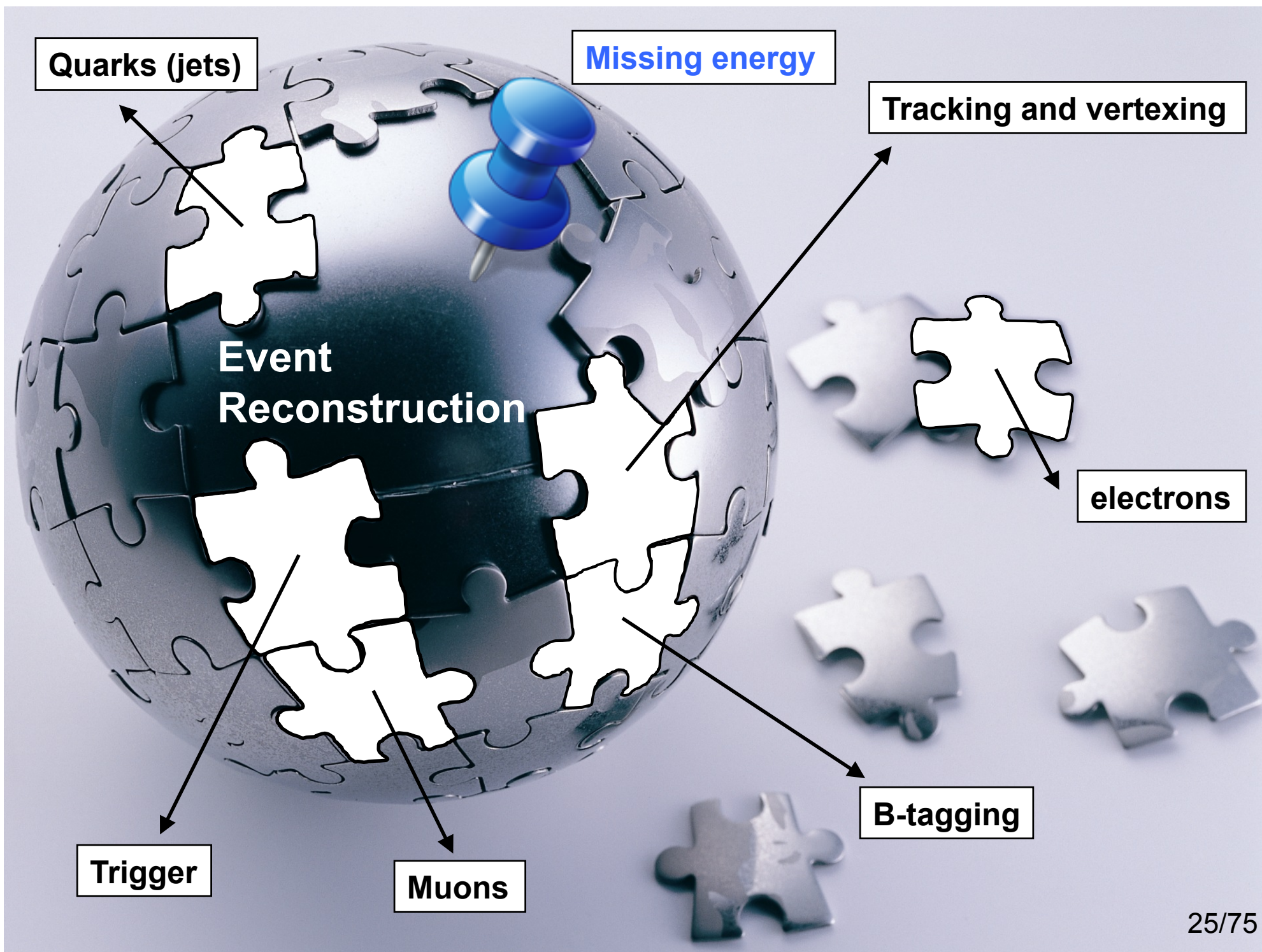
Interpreting LHC events

top quark pair-production

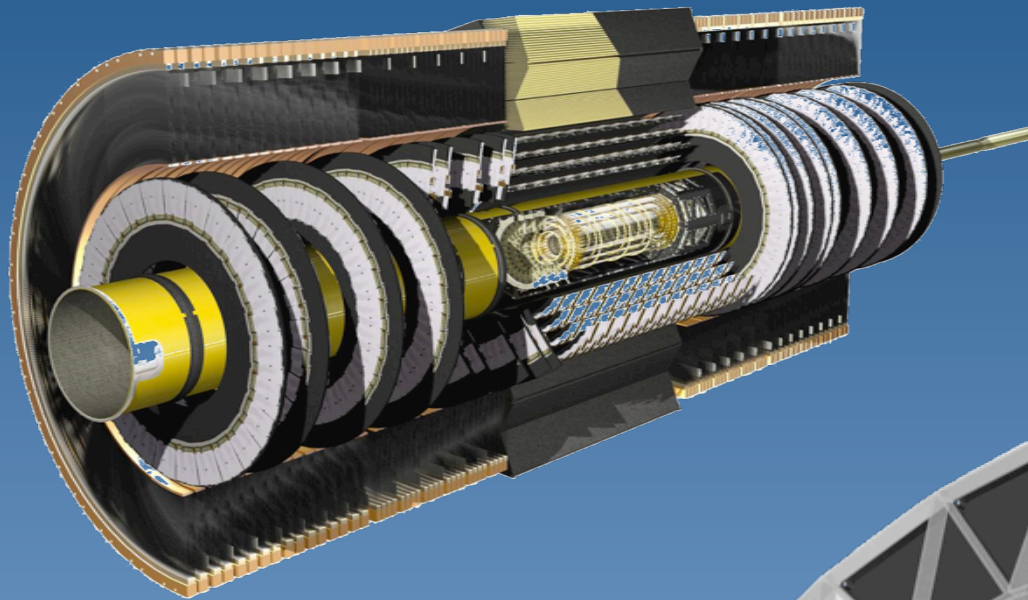


Simulation top quark production





Inner detector



ATLAS inner detector

Transition Radiation Tracker

barrel: ≥ 30 straws

SemiConductor Tracker

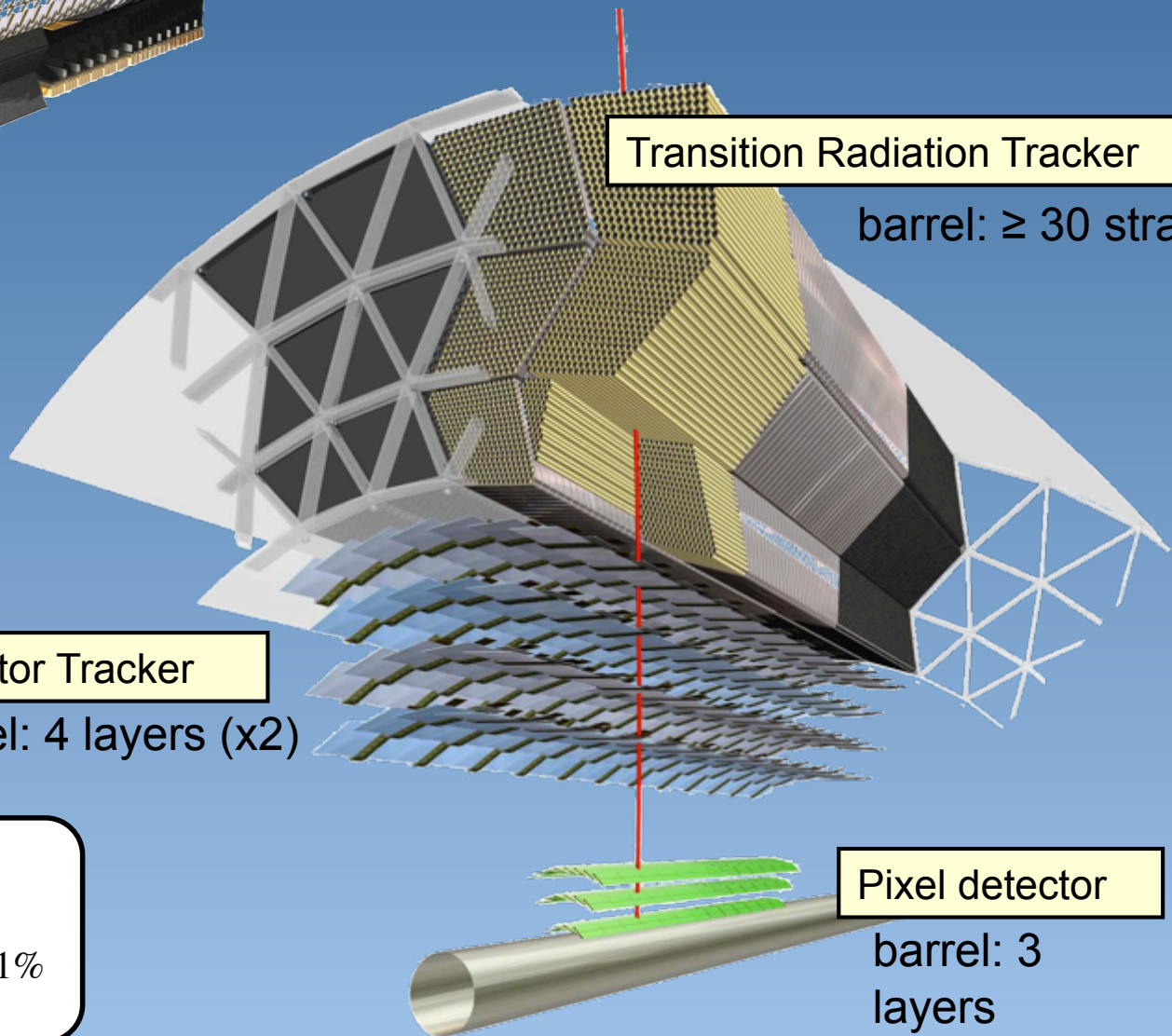
barrel: 4 layers (x2)

3 systems in 2 T solenoid

$$|\eta| < 2.5 \quad \frac{\sigma_{p_T}}{p_T} = 0.05\% p_T \oplus 1\%$$

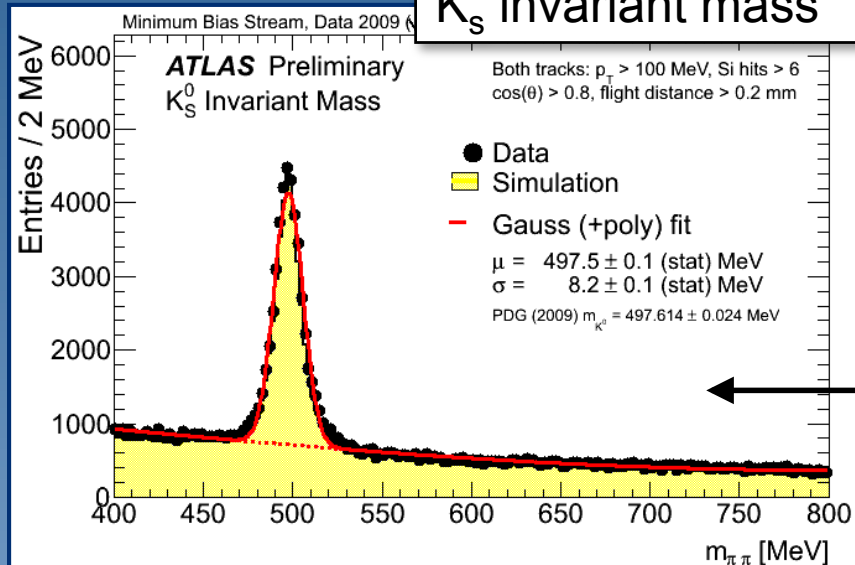
Pixel detector

barrel: 3
layers

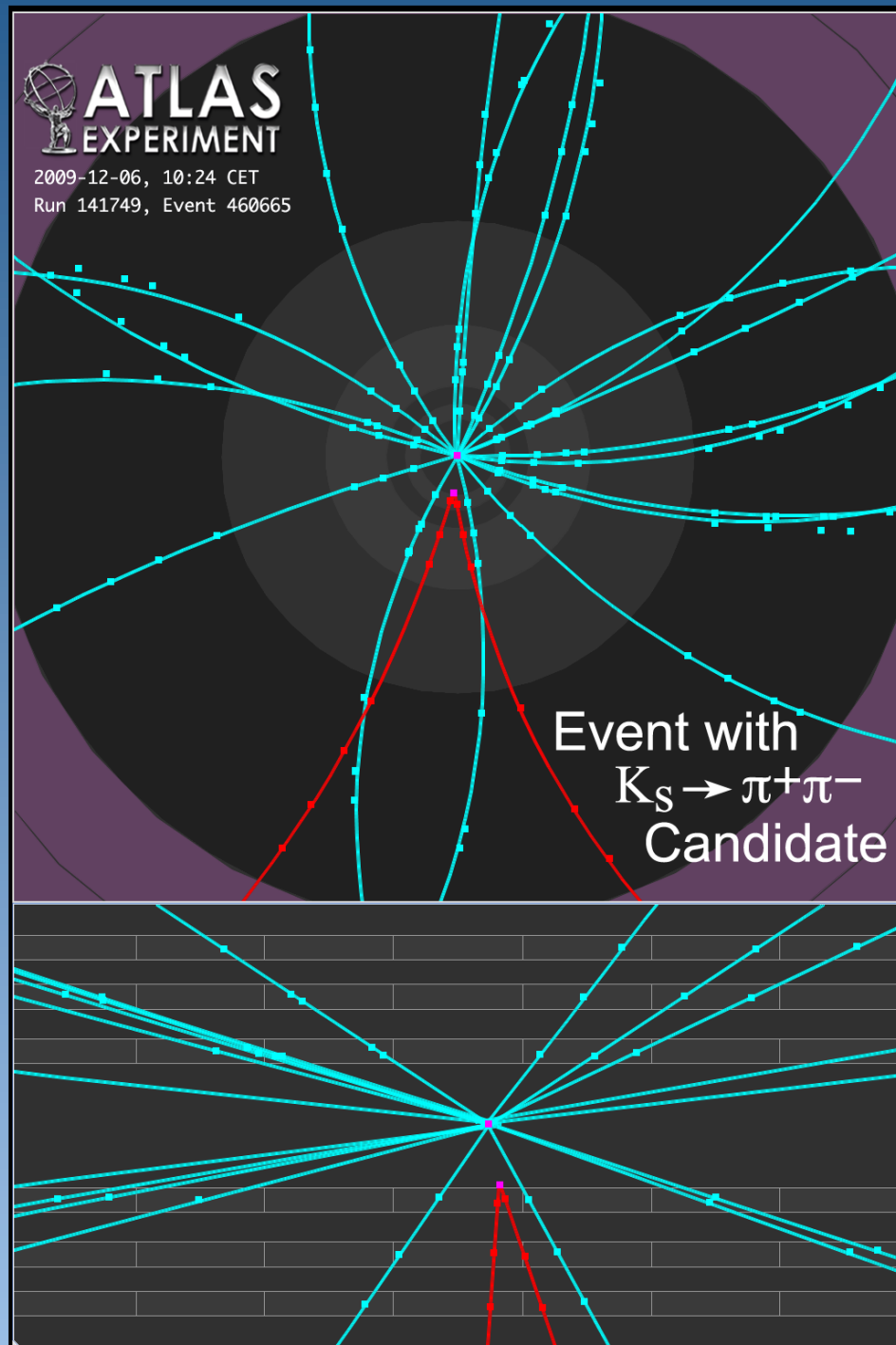
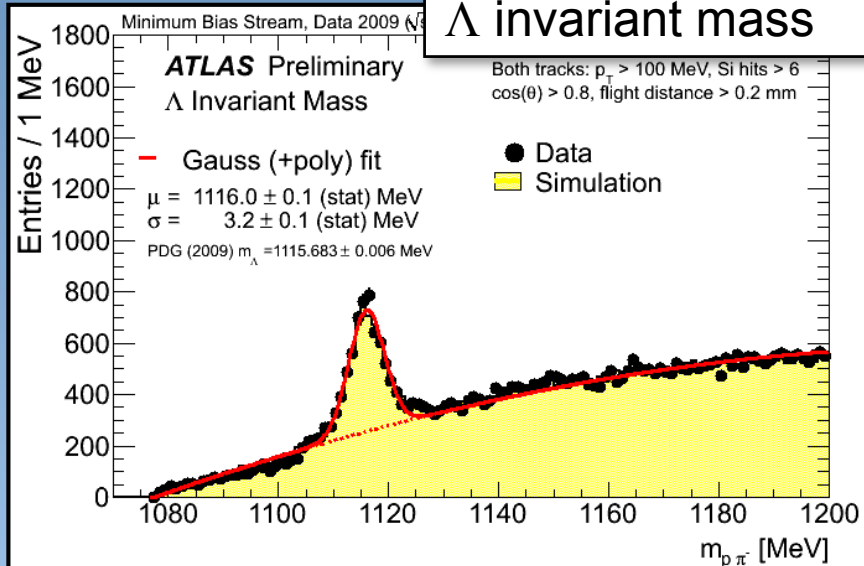


Secondary vertices

K_S invariant mass

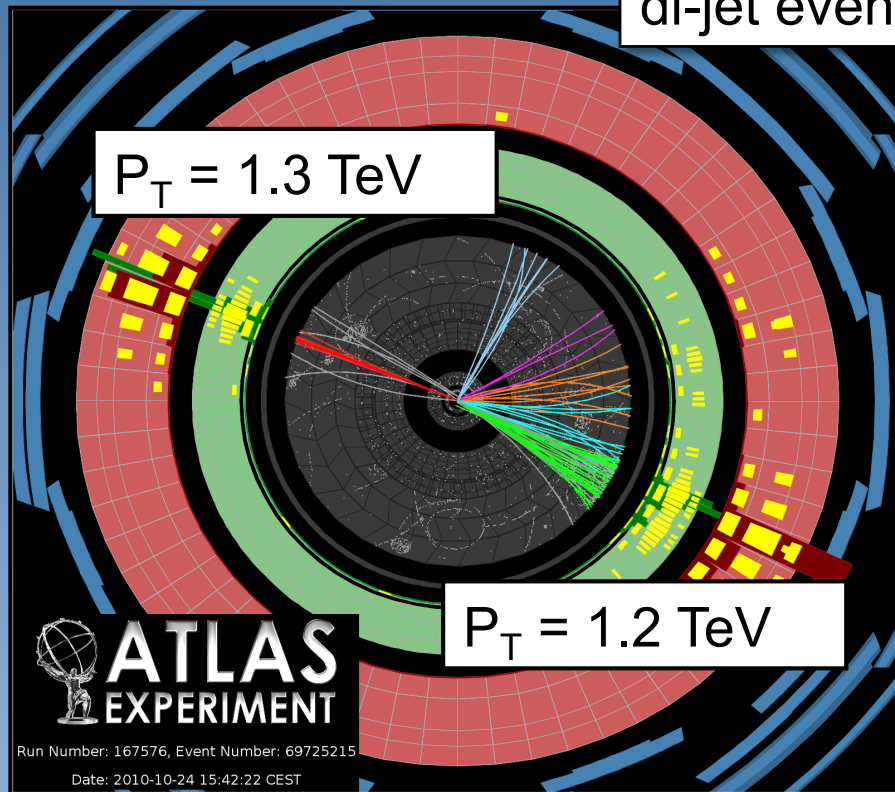


Λ invariant mass



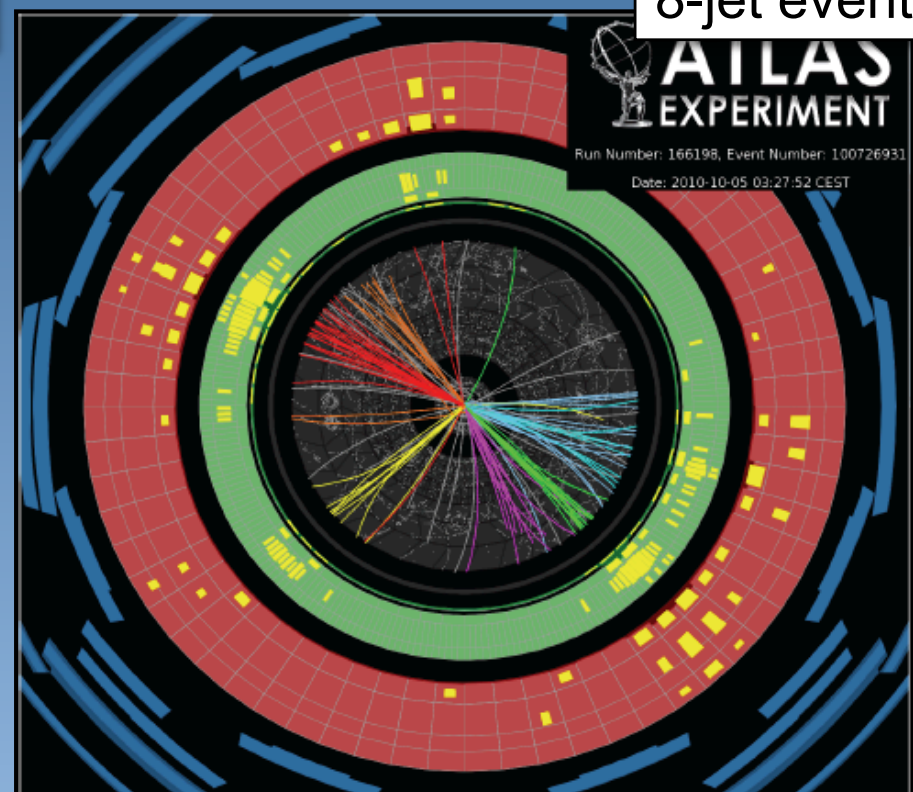
Quark (jet) reconstruction

di-jet event



High transverse momentum

8-jet event

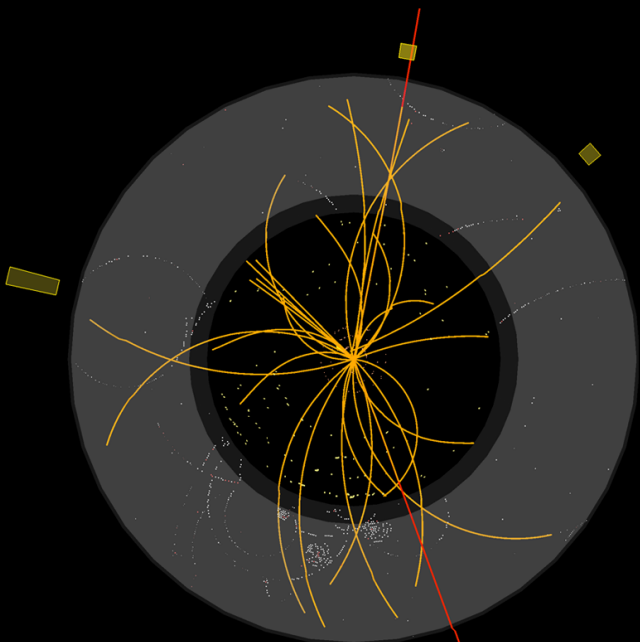


Multi-jet: 8 jets with $P_T > 60 \text{ GeV}$



ATLAS EXPERIMENT

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



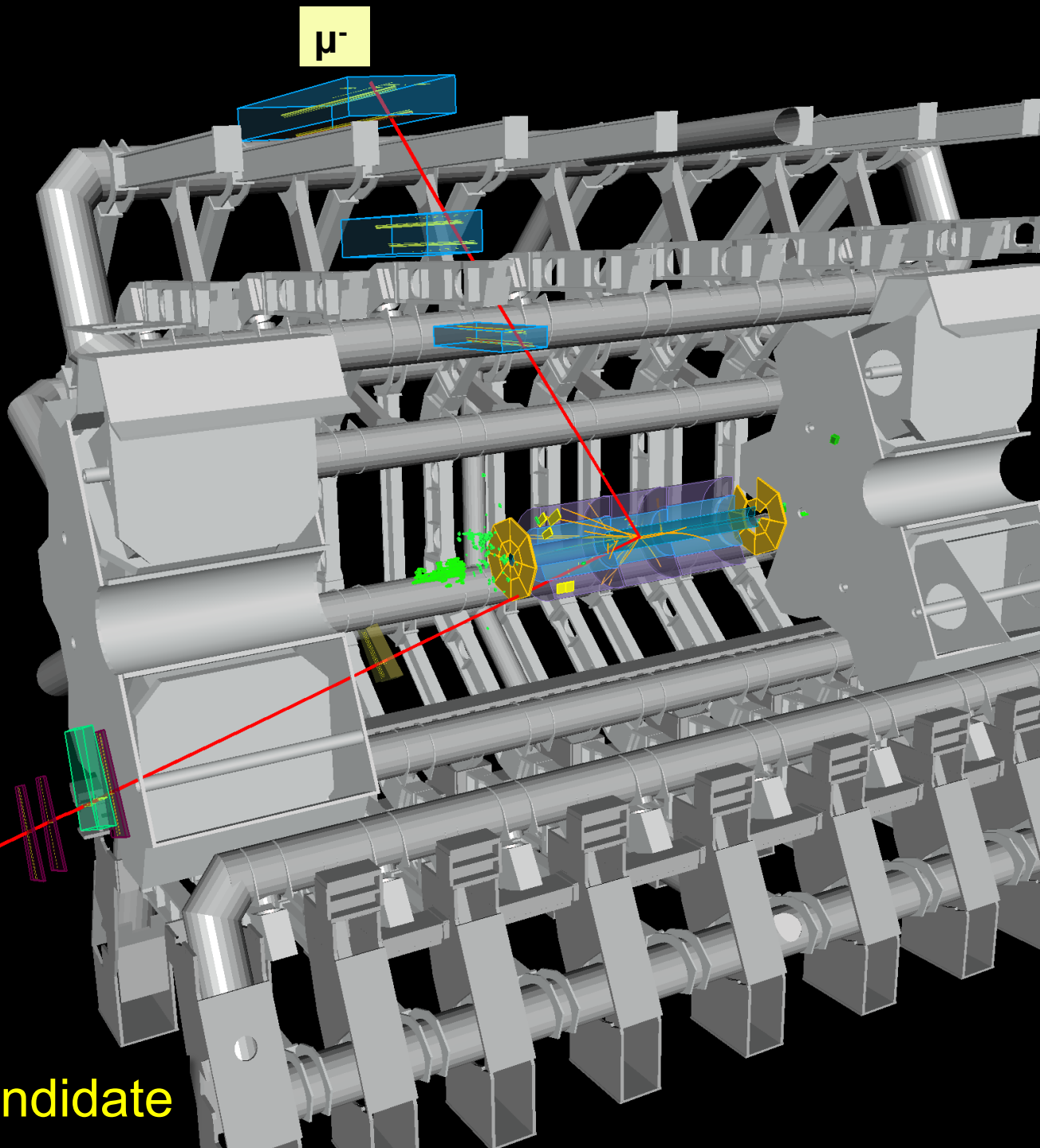
$p_T(\mu^-) = 27 \text{ GeV}$ $\eta(\mu^-) = 0.7$
 $p_T(\mu^+) = 45 \text{ GeV}$ $\eta(\mu^+) = 2.2$

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

μ^+



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





Trigger:
From 40 MHz (LHC) to a few hundred Hz

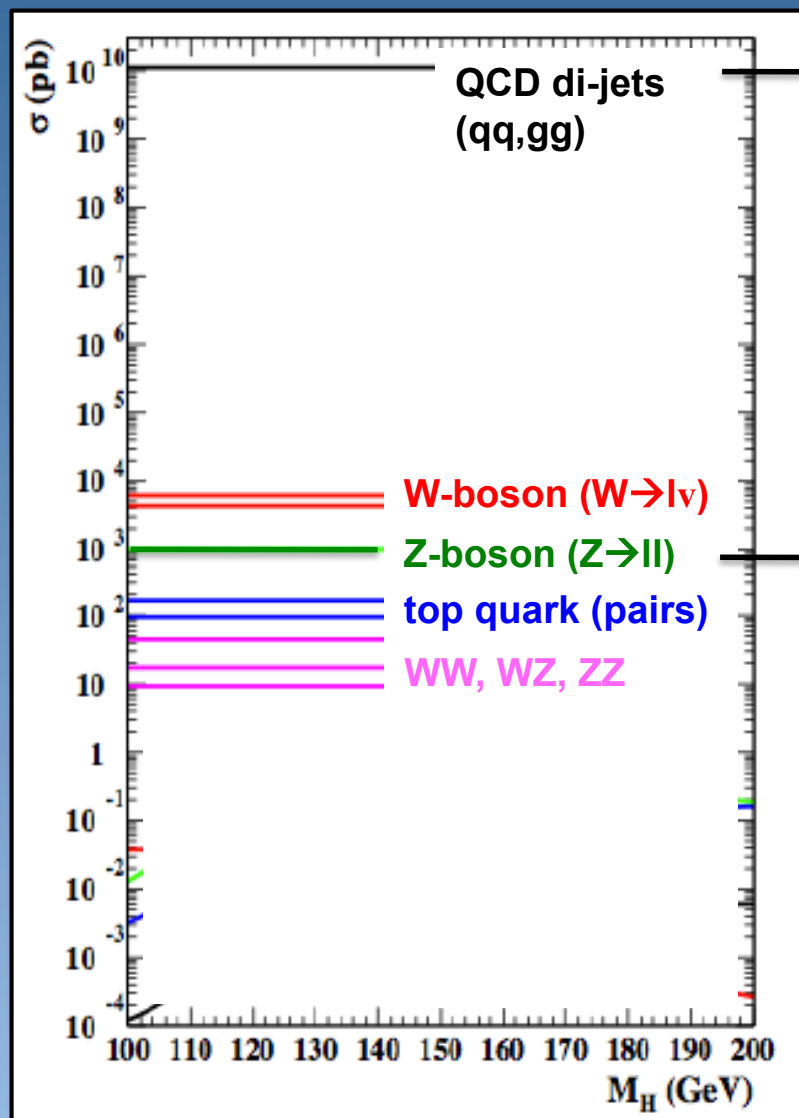


Bottleneck: disk space

Selecting interesting physics from a background of 10^{13} events

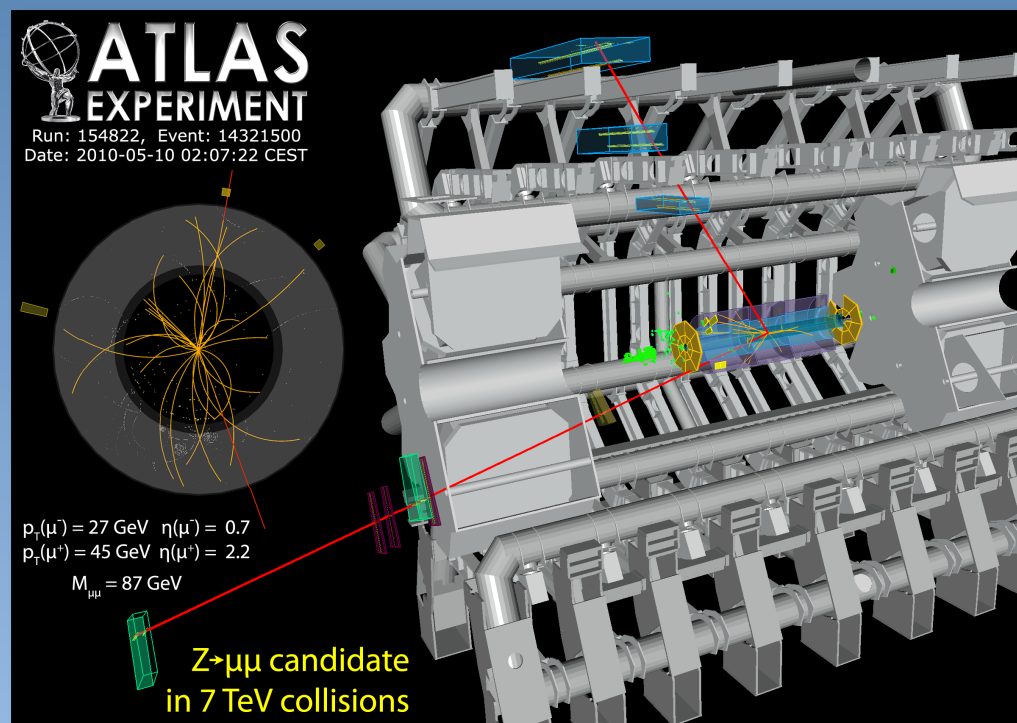
Standard Model processes at the LHC

predicted cross-sections



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

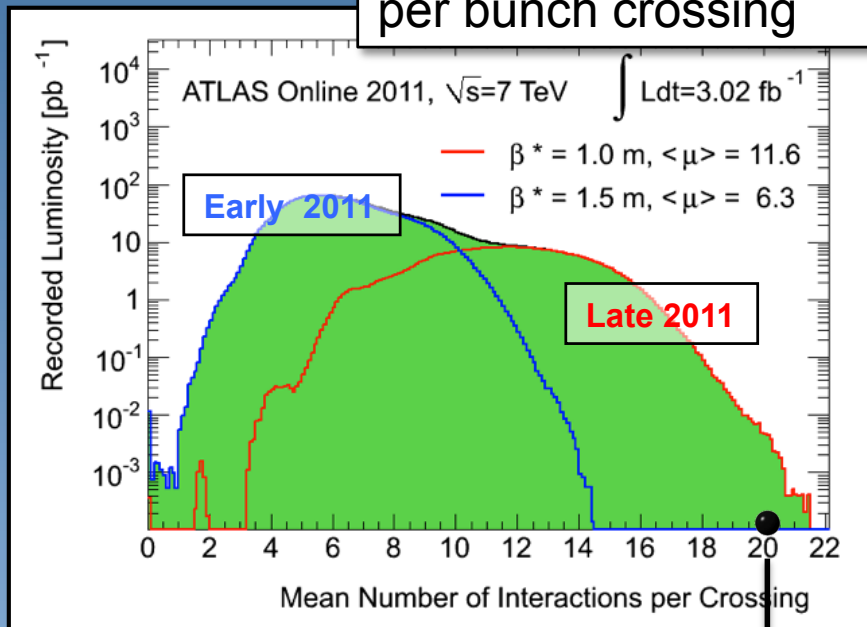
$Z \rightarrow \mu^+\mu^-$ candidate (early data taking)



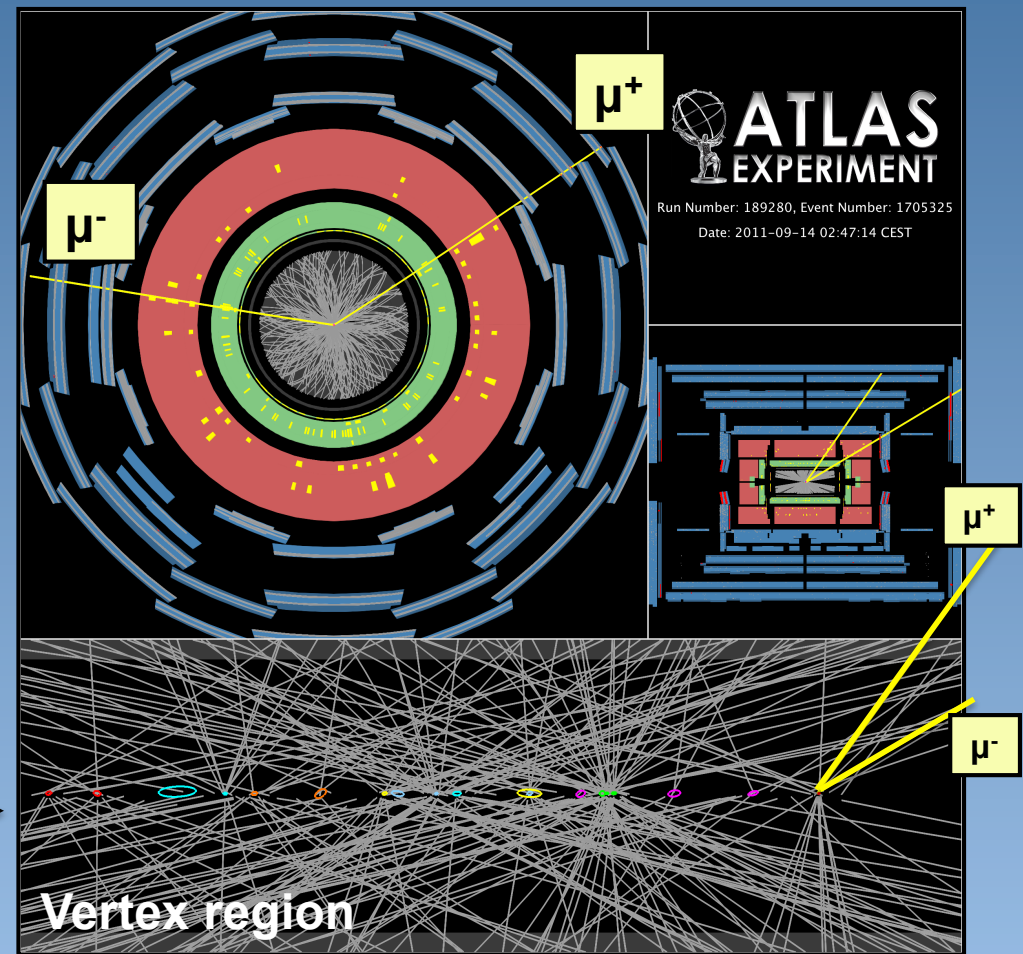
“LHC: strong machine for weak physics”

LHC is not a quiet environment

Number of interactions
per bunch crossing

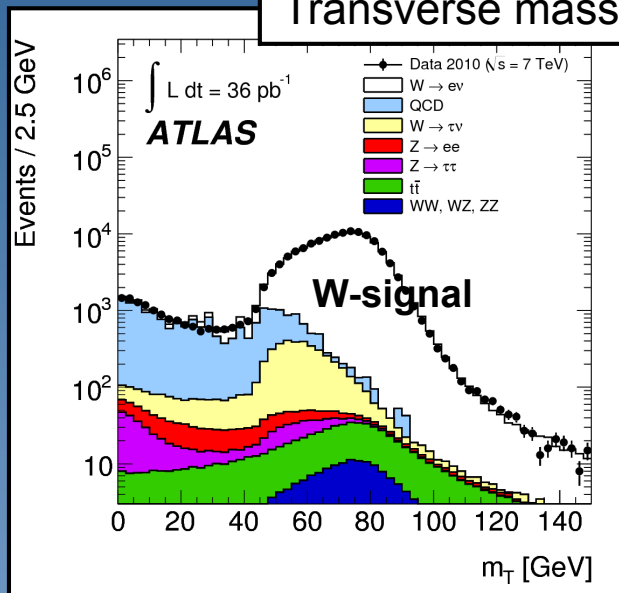


$Z \rightarrow \mu^+ \mu^-$ event with 20 vertices



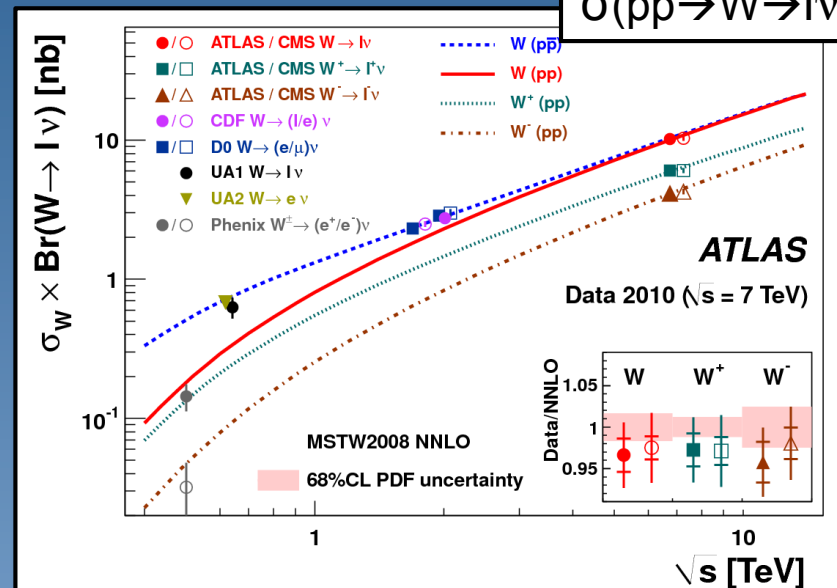
W and Z boson production at the LHC

Transverse mass

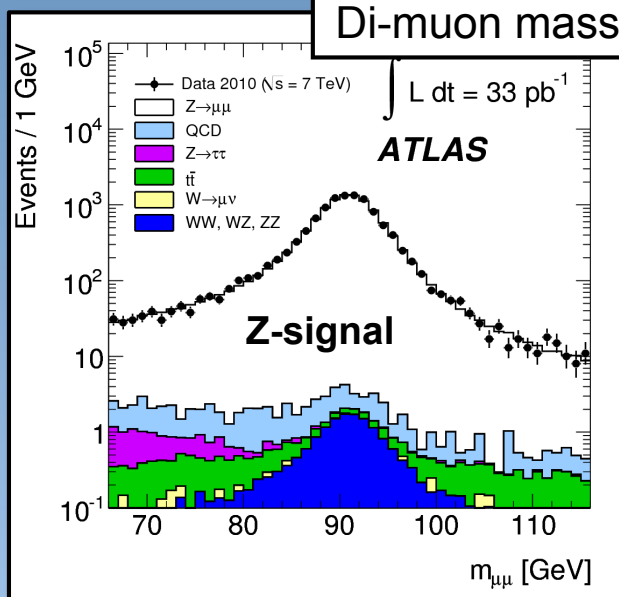


W-boson

$\sigma(pp \rightarrow W \rightarrow l\nu)$

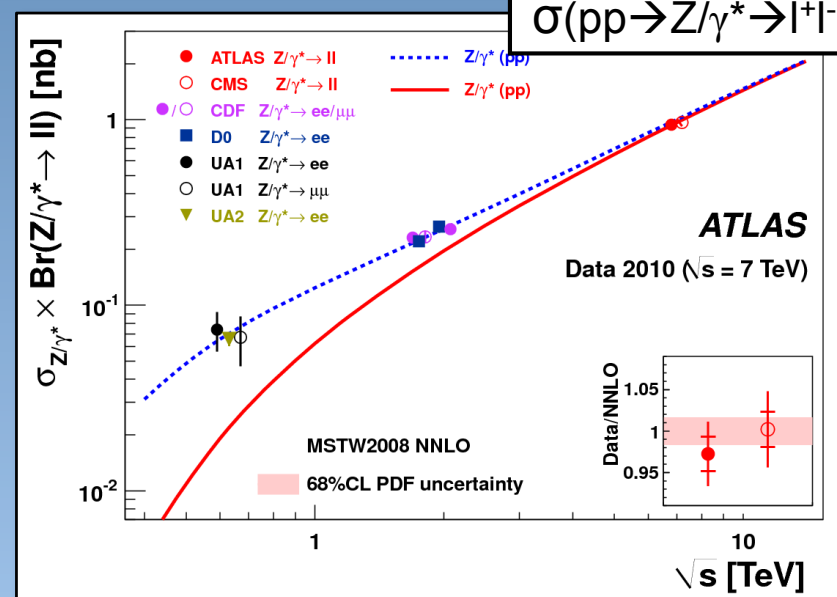


Di-muon mass



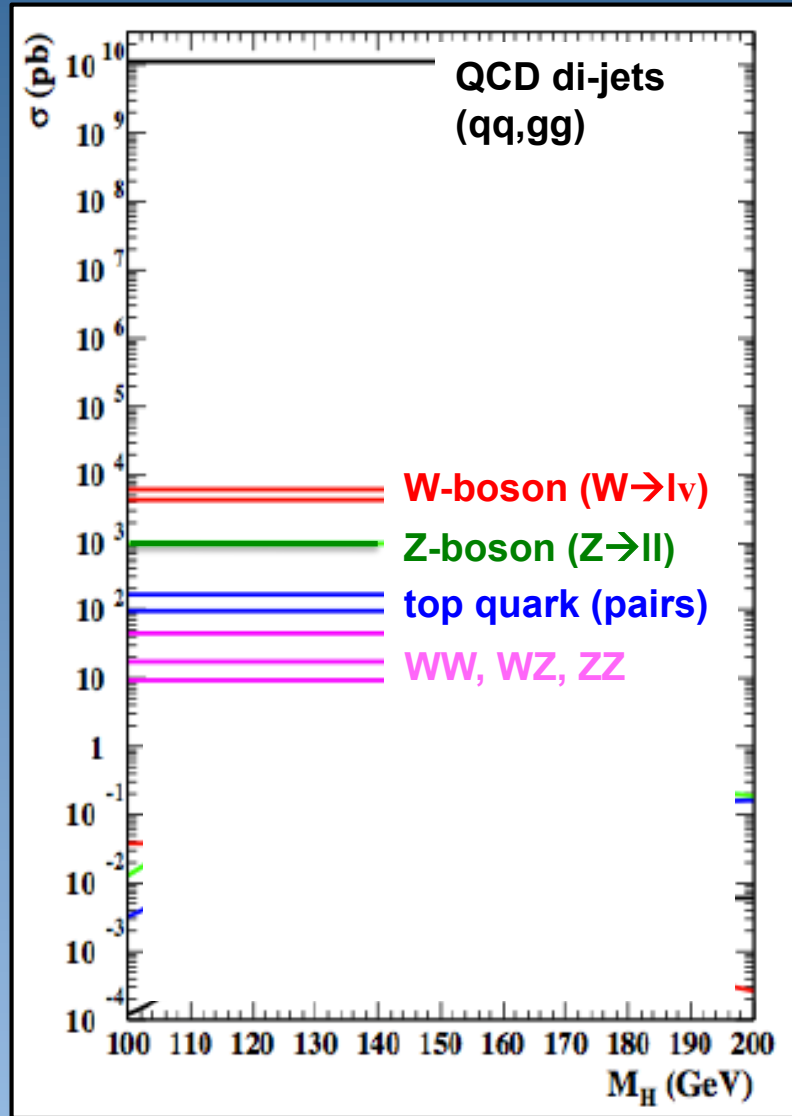
Z/ γ^* -boson

$\sigma(pp \rightarrow Z/\gamma^* \rightarrow l^+l^-)$

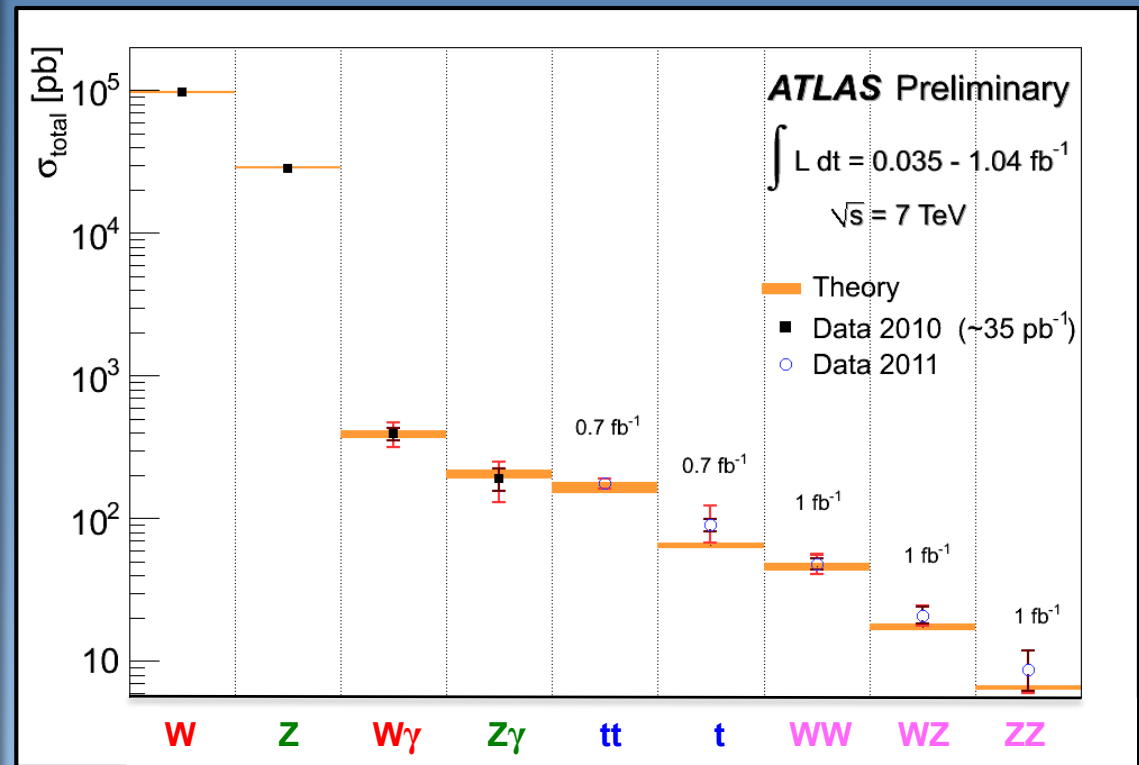


Standard Model processes at the LHC

predicted cross-sections

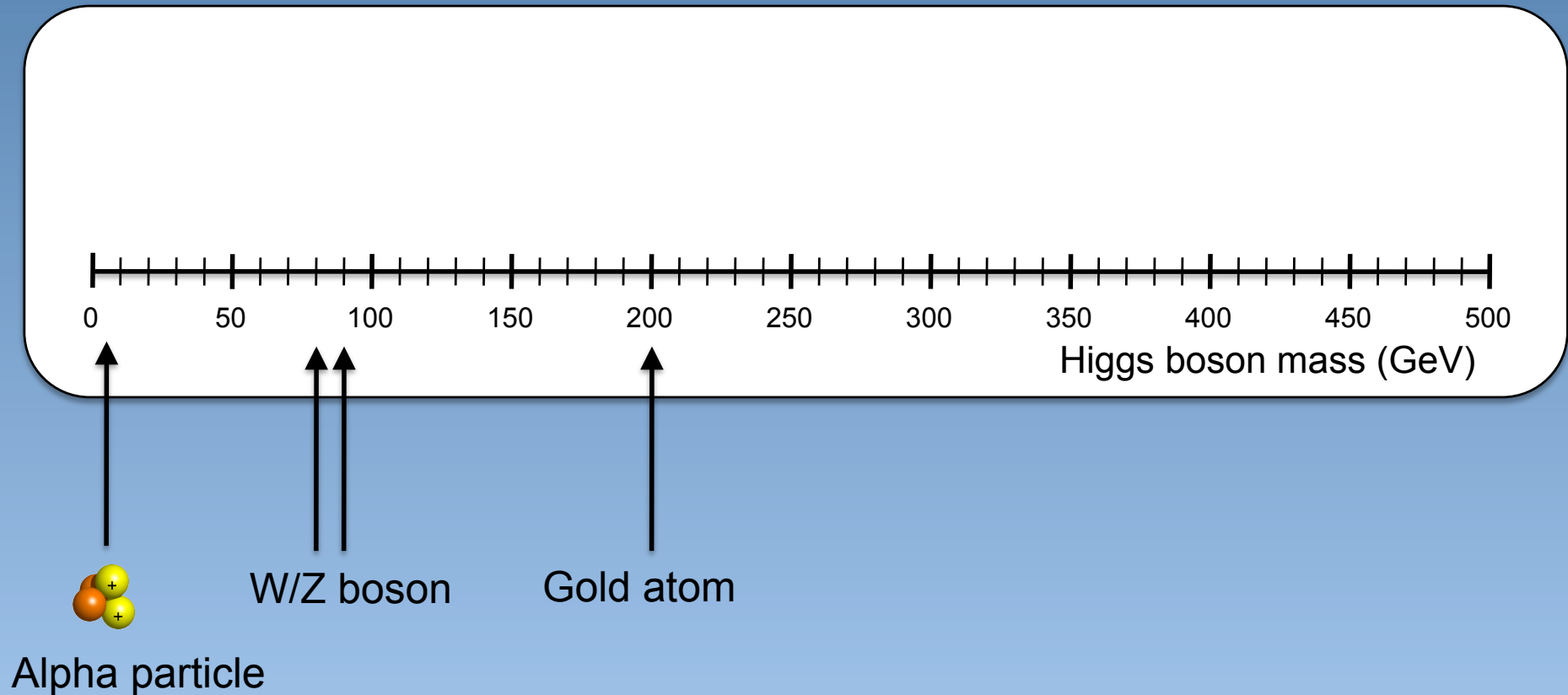


ATLAS measurements



Enormous data-set to understand and calibrate the ATLAS detector

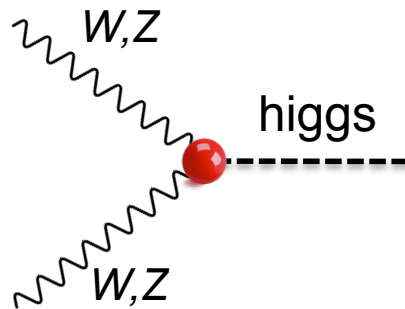
The mass of the Higgs boson



How do you produce a Higgs particle ?

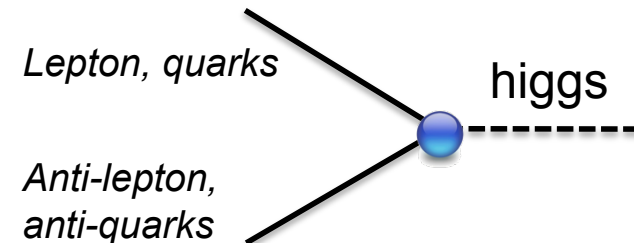
Gauge bosons

*Massive gauge boson ?
... then it coupling to the Higgs!*



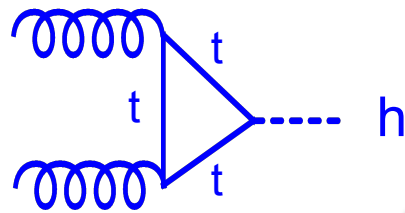
Fermions

*Massive fermion ?
... then it couples to the Higgs!*

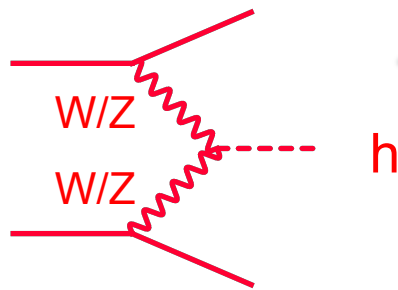


Higgs boson production

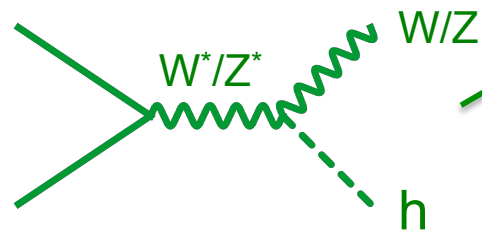
Production of the Higgs boson



Gluon fusion

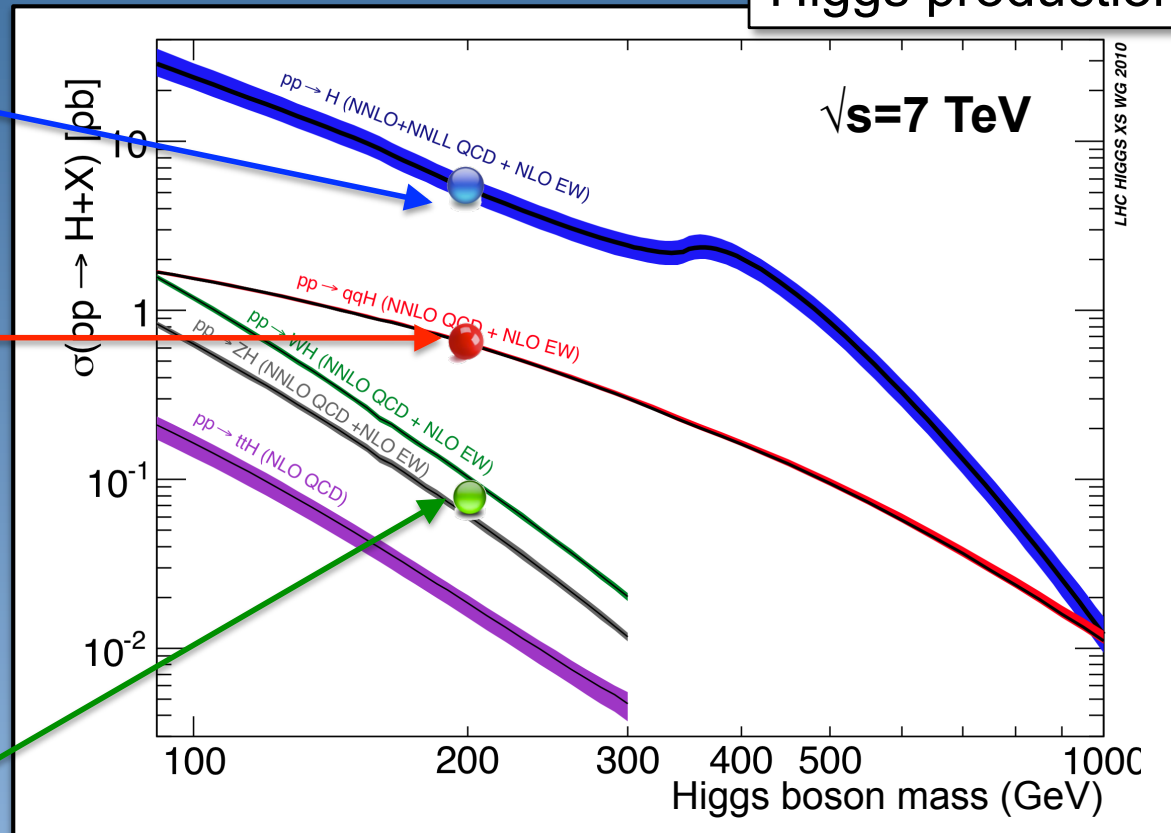


Vector boson fusion



Associated production

Higgs production



How many Higgs bosons have been produced at the LHC in 2011?



If the Higgs boson exists:

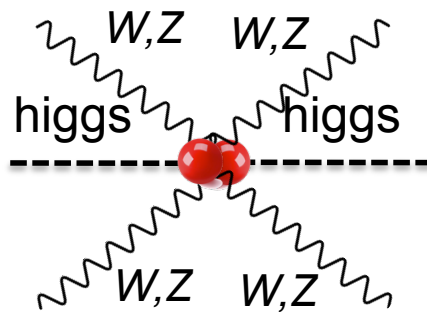
$m_h = 120 \text{ GeV: } 60.000$

$m_h = 200 \text{ GeV: } 30.000$

How does the Higgs boson decay ?

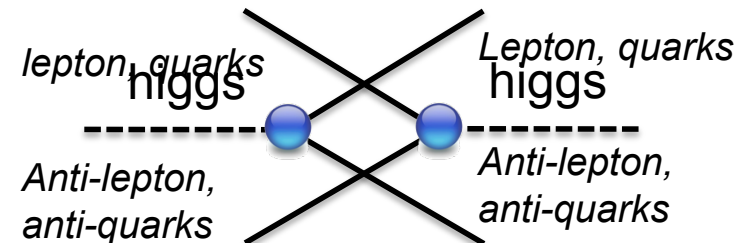
Gauge bosons

*Massive gauge boson ?
... then it coupling to the Higgs!*



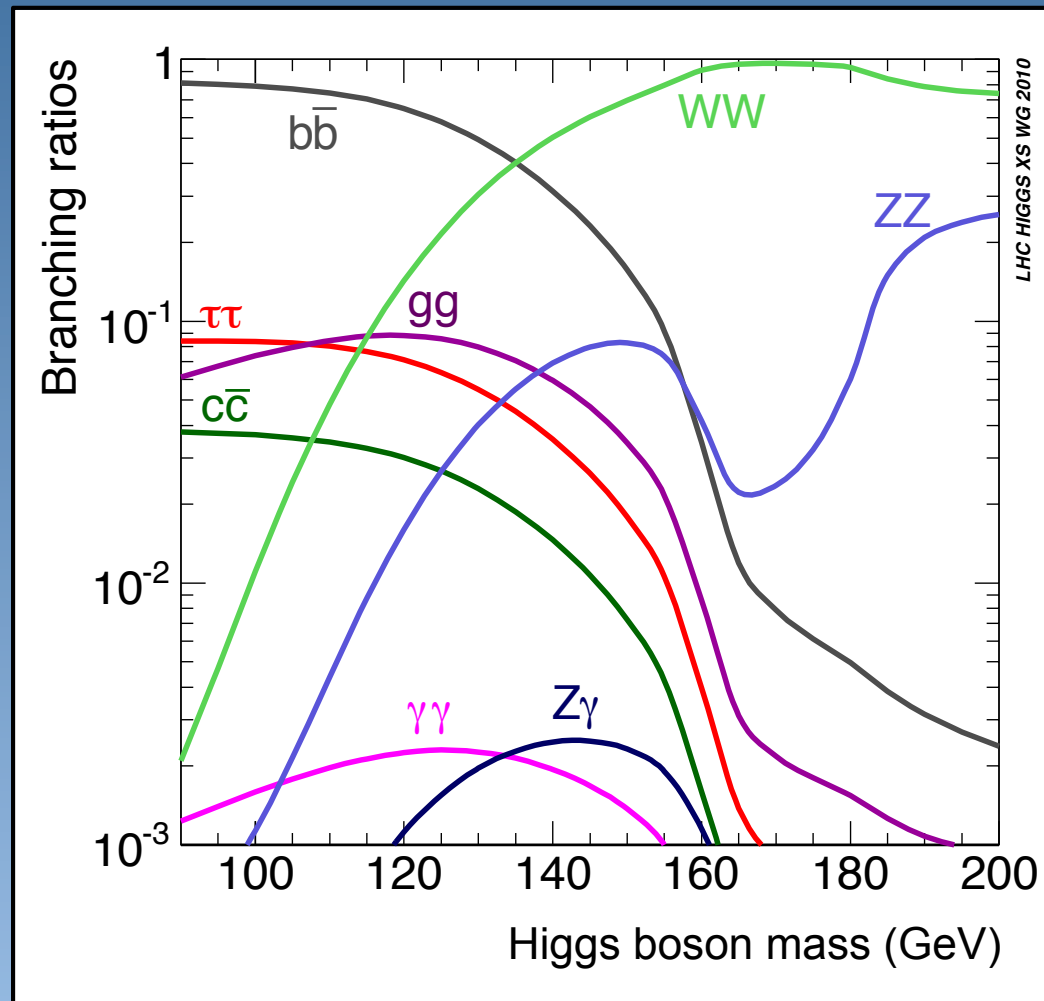
Fermions

*Massive fermion ?
... then it couples to the Higgs!*



Higgs boson production

Decay of the Higgs boson



Subsequent gauge boson decay

$W \rightarrow qq$	67%
$W \rightarrow l\nu$	33%

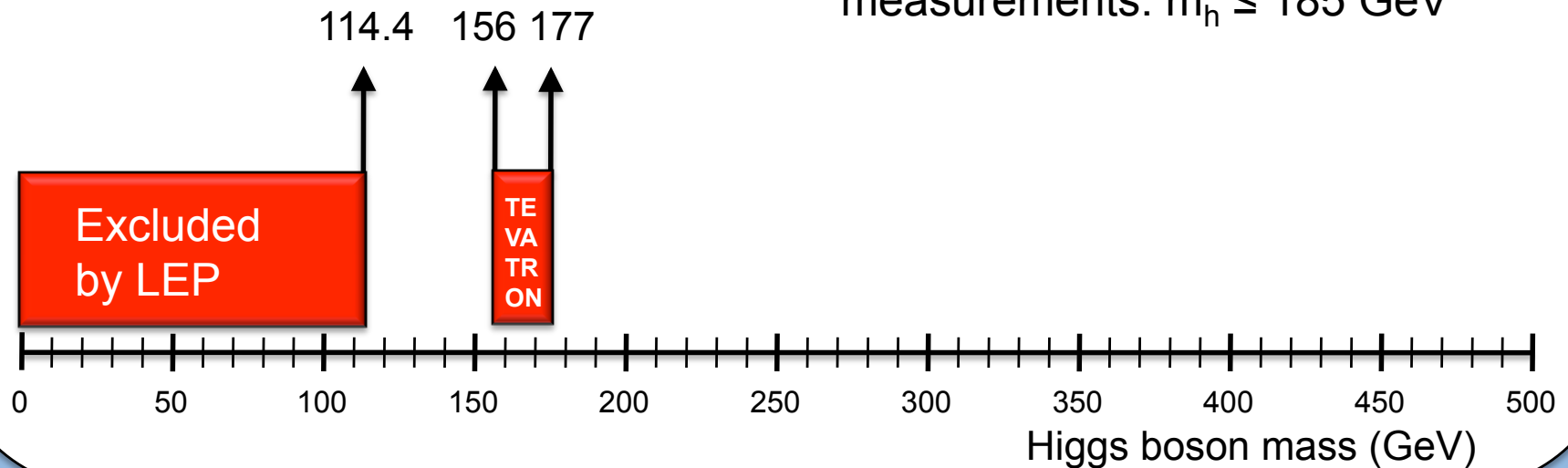
$Z \rightarrow qq$	70%
$Z \rightarrow \nu\nu$	20%
$Z \rightarrow ll$	10%

Status on February 8, 2011

Indirect:

Theory: $m_h \leq 600$ GeV

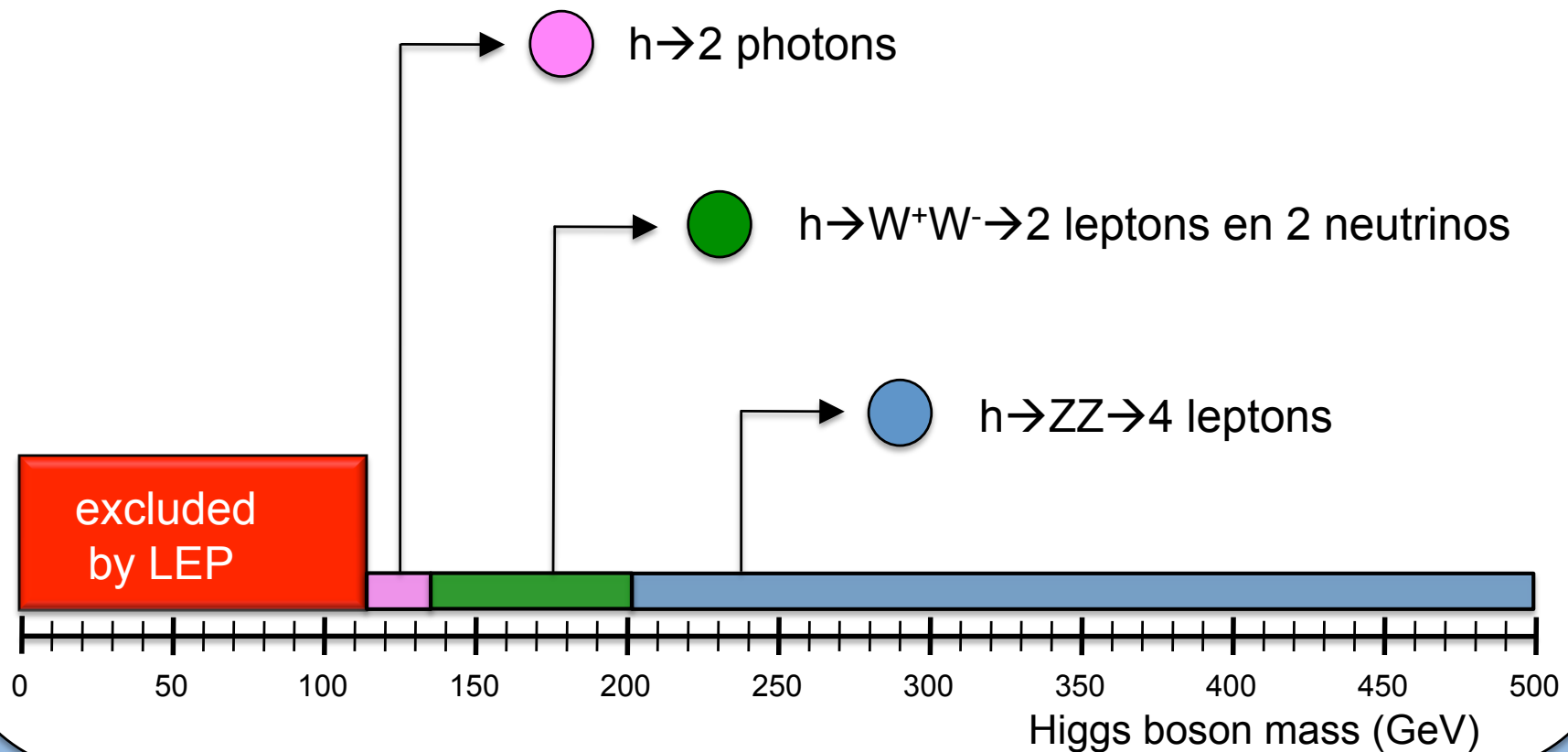
Electroweak precision-
measurements: $m_h \leq 185$ GeV



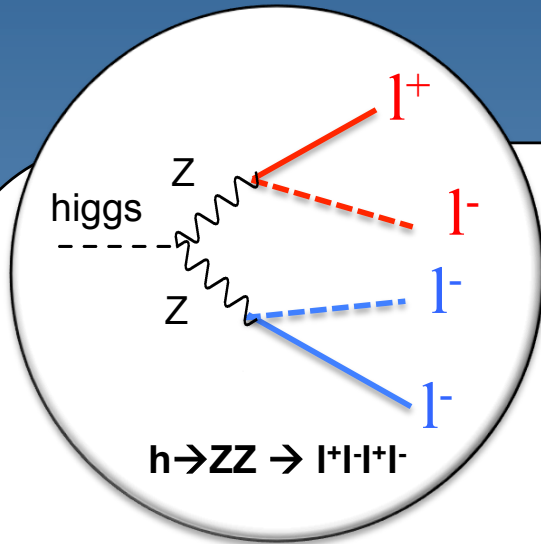
Experiments at the LHC Sensitive for mass range: 114-1000 GeV

The clearest fingerprint of the Higgs boson

For every mass here are multiple channels: these are most sensitive ones



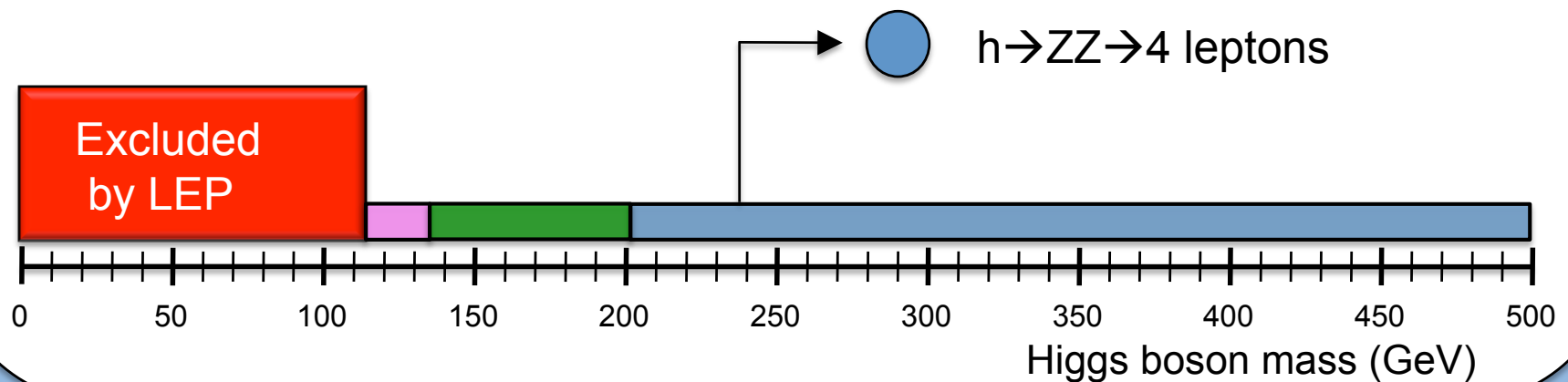
High mass's: $m_H > 200$ GeV

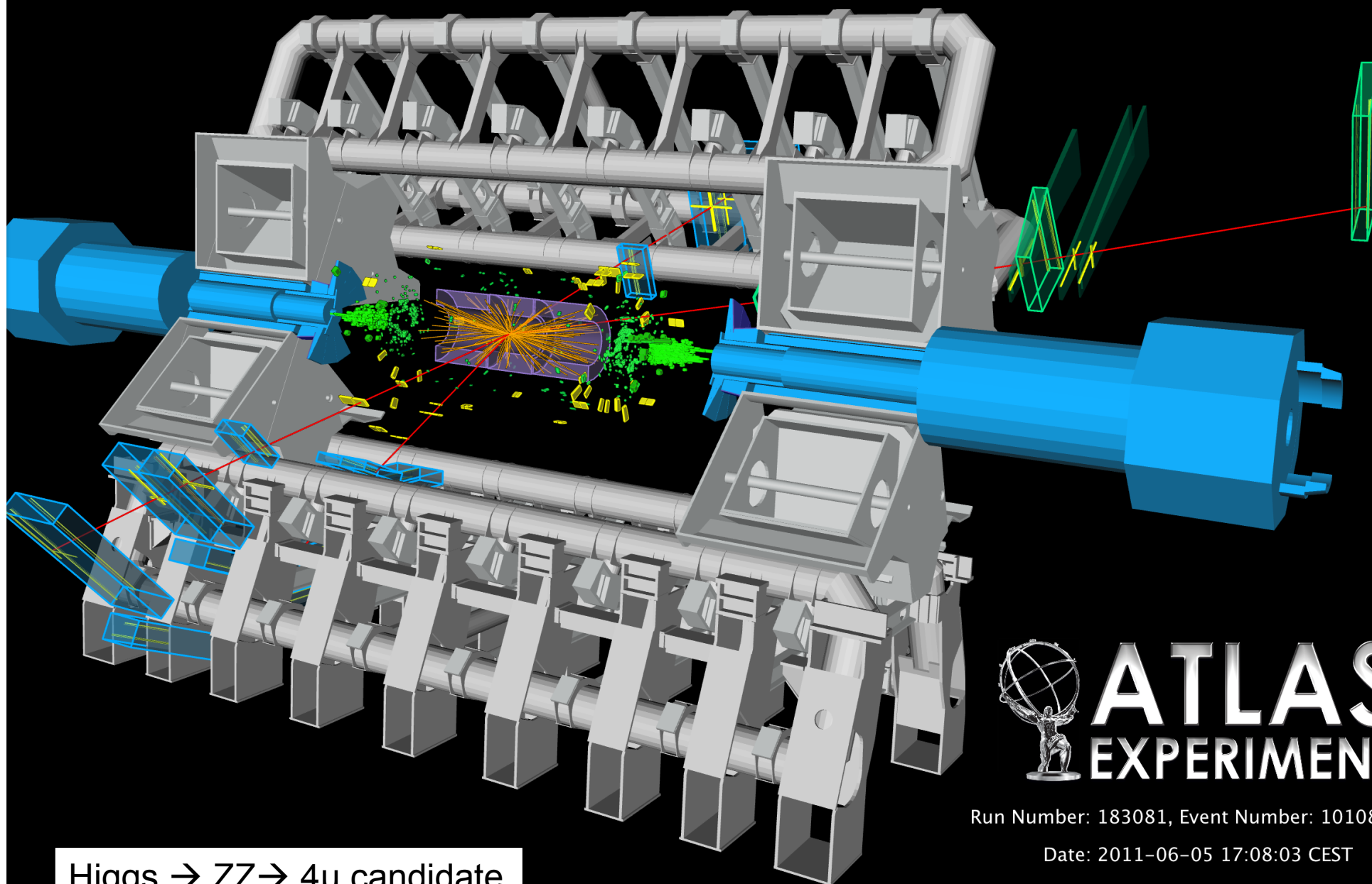


The golden channel

- 4 leptons (e/μ)
- very rare: Higgs of ZZ

Fingerprint: 4-lepton mass





Higgs $\rightarrow$ ZZ $\rightarrow$ 4 μ candidate



ATLAS
EXPERIMENT

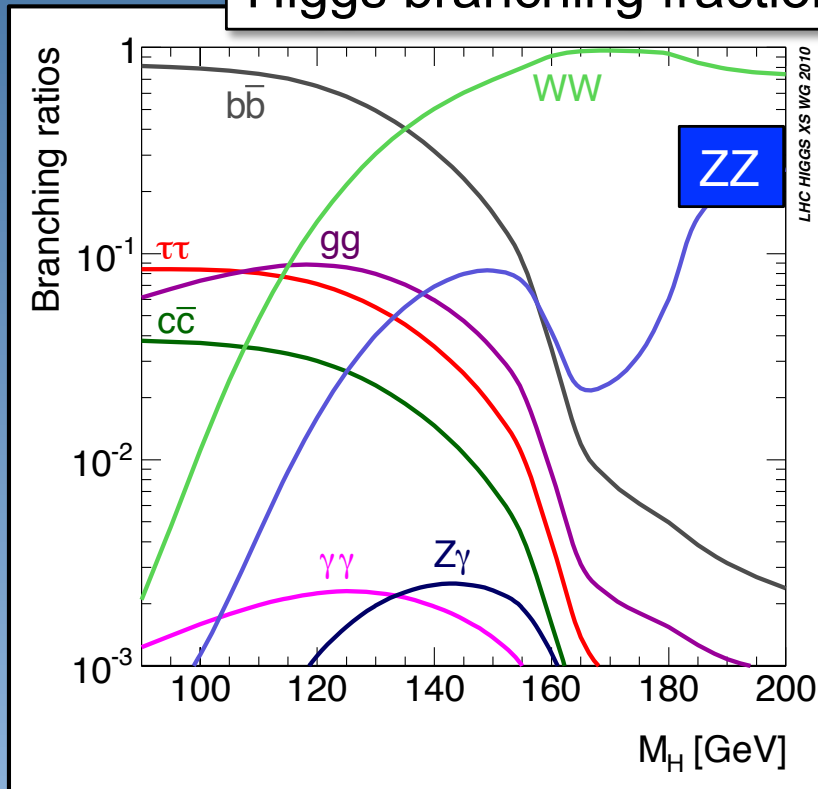
Run Number: 183081, Event Number: 10108572

Date: 2011-06-05 17:08:03 CEST

Higgs $\rightarrow$ ZZ $\rightarrow$ 4 leptons

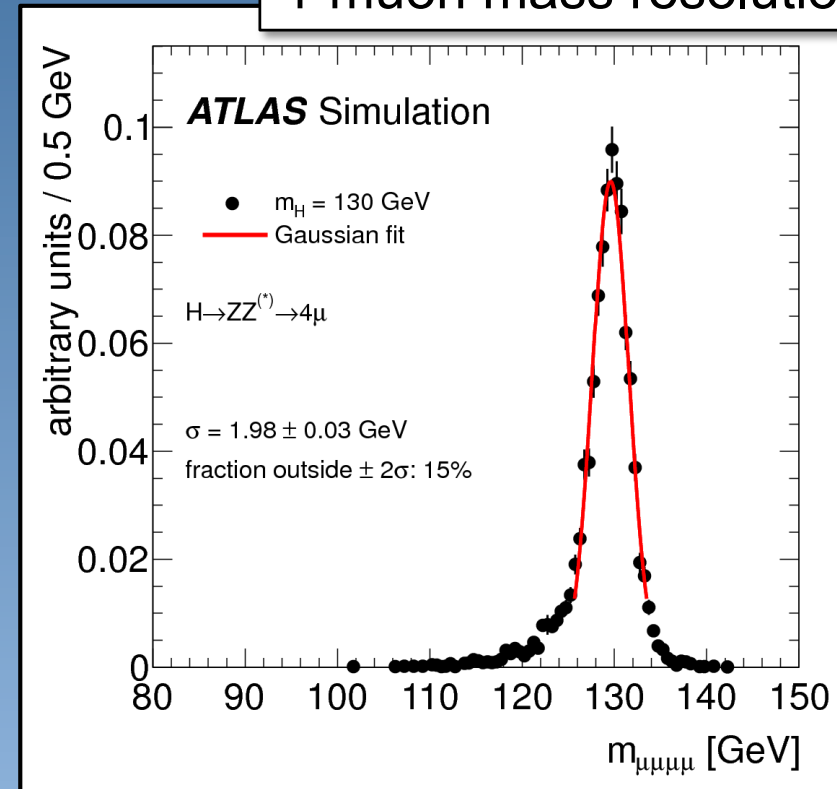
Small number of beautiful collisions

Higgs branching fraction



$$\Gamma(Z \rightarrow ee) = \Gamma(Z \rightarrow \mu\mu) = 3.36\%$$

4-muon mass resolution



Mass resolution ~ 2 GeV

Higgs $\rightarrow$ ZZ $\rightarrow$ 4 leptons

Small number of beautiful collisions

30.000 Higgs bosons

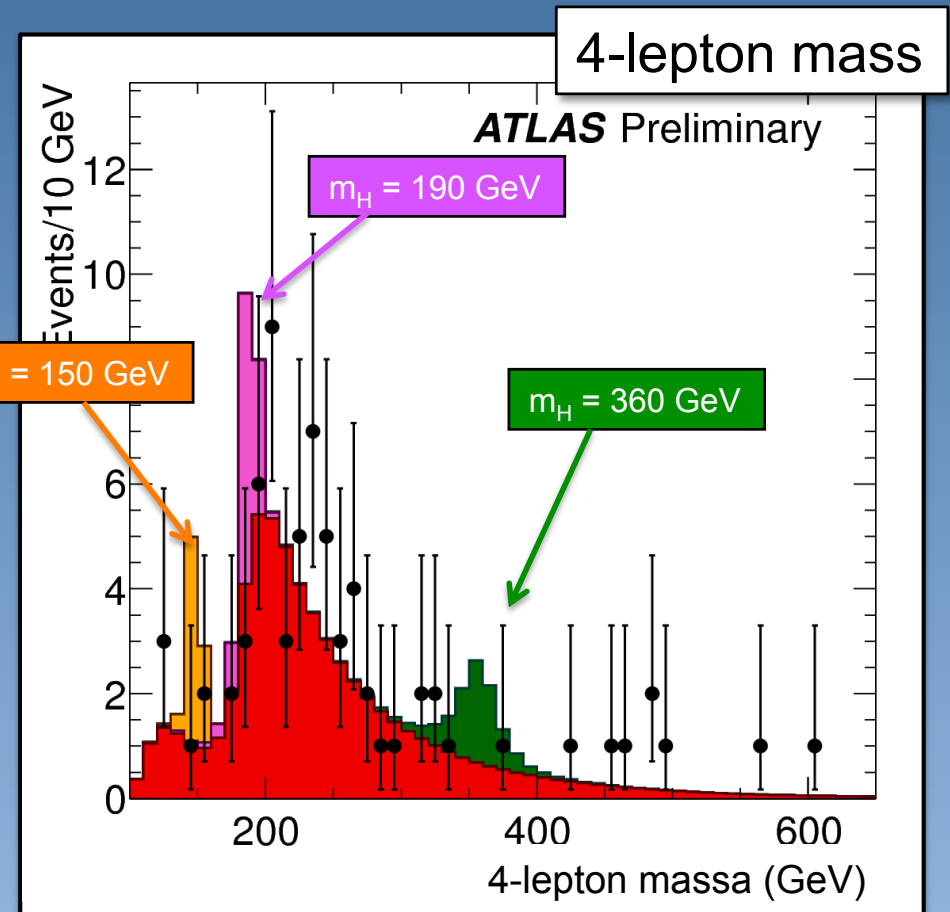


- Only 1 in 1000 Higgs bosons decays to 4 leptons (e/ μ).
- 50% of them are all correctly reconstructed by the ATLAS detector



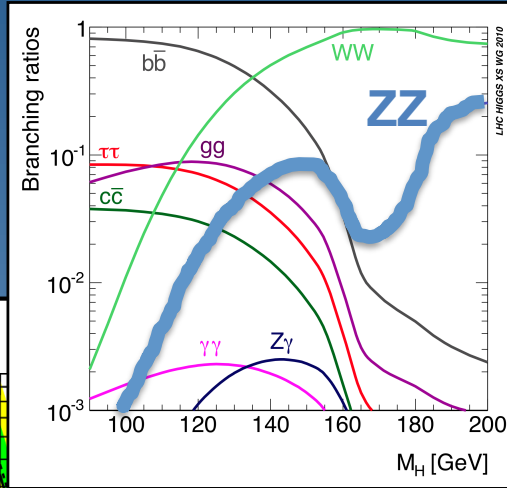
16 Higgs decays to 4 leptons

'overig'	52 events
with Higgs	68 events



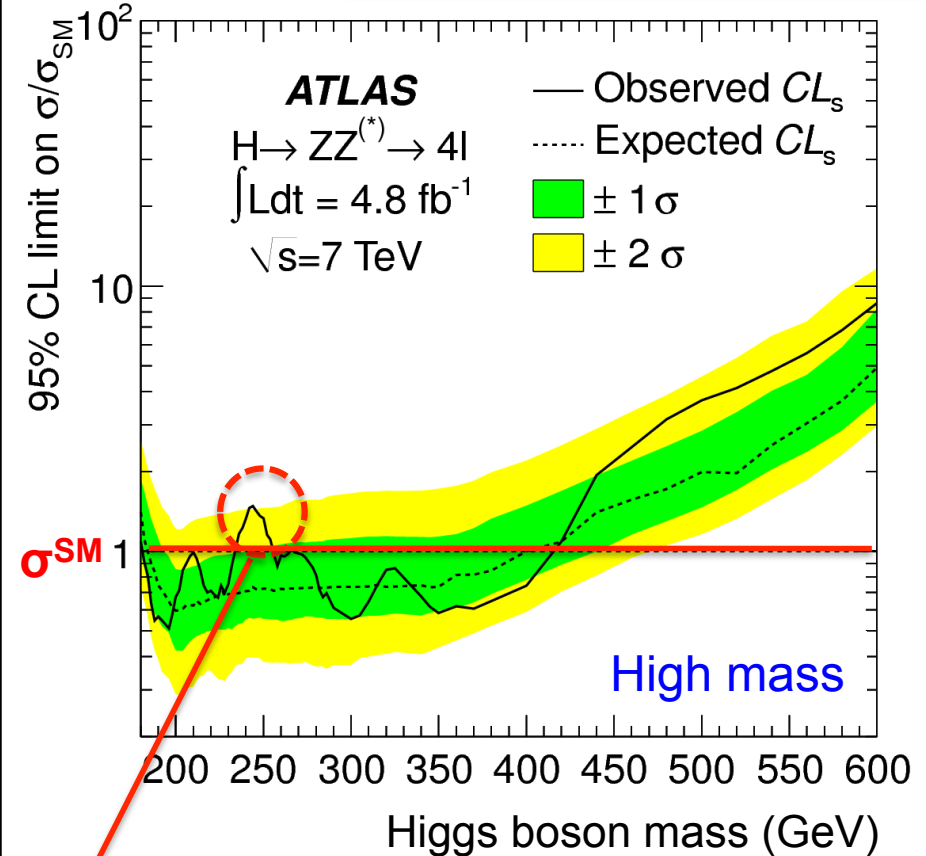
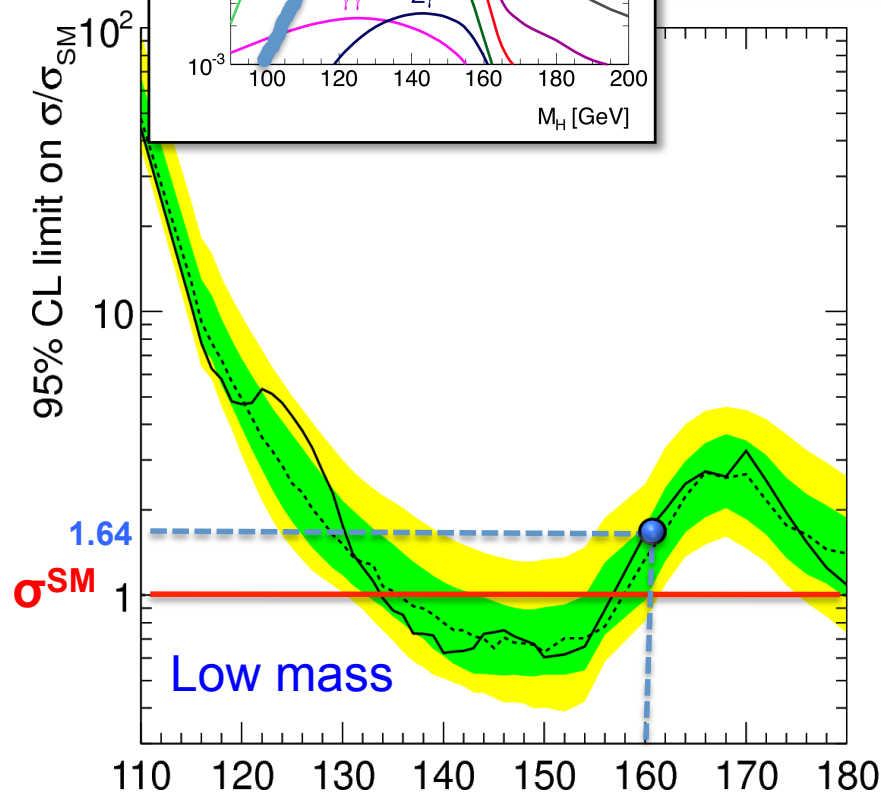
No clear peak unfortunately
 $\rightarrow m_h < 200$ GeV

Higgs $\rightarrow ZZ \rightarrow 4l$: excluded cross-section



Cross-section

Excluded cross-section



No clear excess, ... but has made a Nikhef PhD student lose quite some sleep

When / how do you exclude a signal

Measurement

SM	10
Higgs	5
Data	12

We exclude a Higgs hypothesis at 95% CL if:

“The probability to observe as little events as observed (or even less) is smaller than 5%, under the assumption that the Higgs exists”

1) Can we exclude the SM+Higgs hypothesis ?

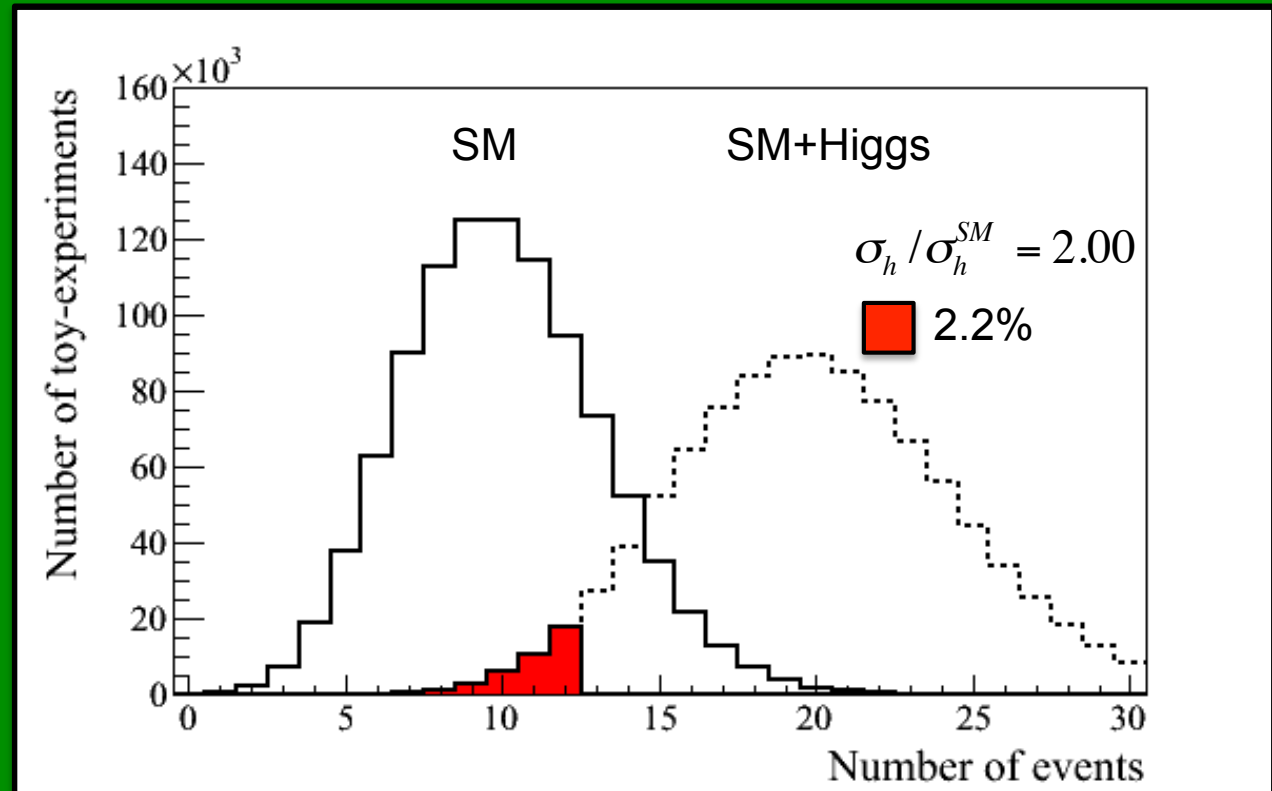
When / how do you exclude a signal

Measurement

SM	10
Higgs	5
Data	12

1) Can we exclude the SM+Higgs hypothesis ?

2) If not, what σ_h/σ_h^{SM} can we exclude ?



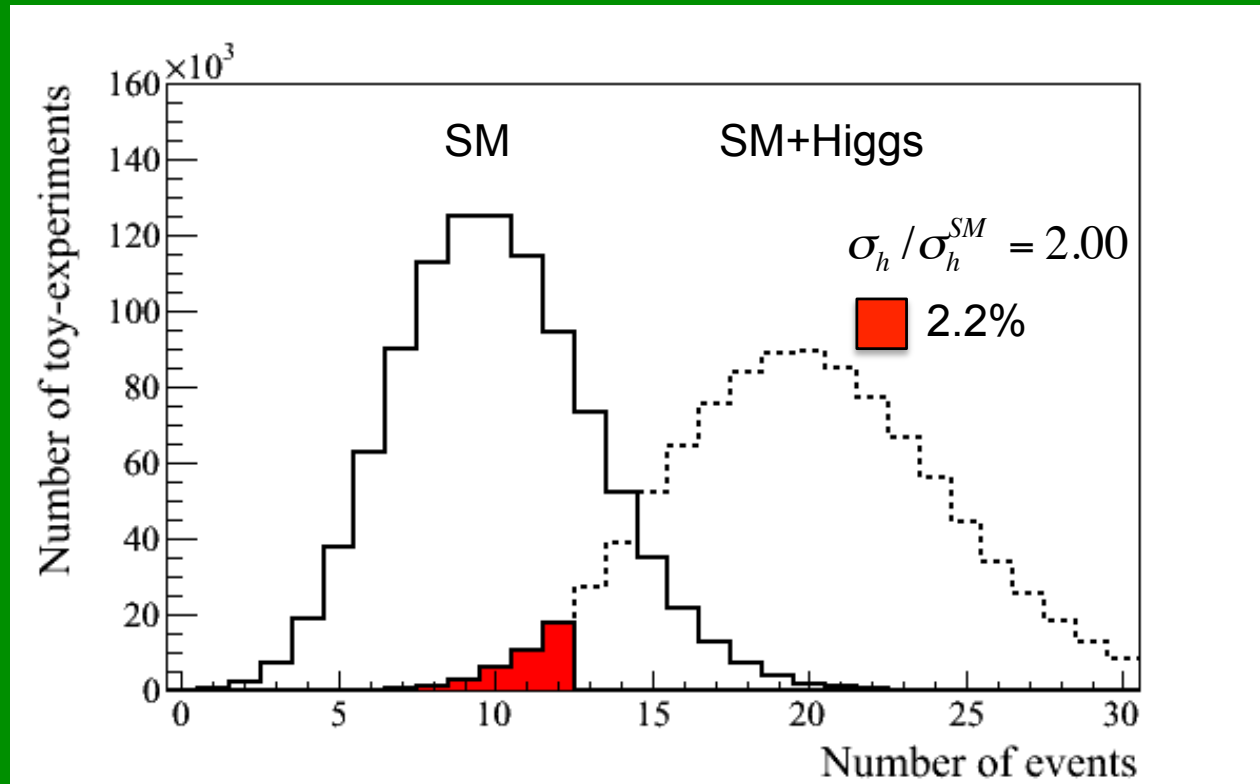
When / how do you exclude a signal

Standard Model

SM	10
Higgs	5
Data	12

1) Can we exclude the SM+Higgs hypothesis ?

2) If not, 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%

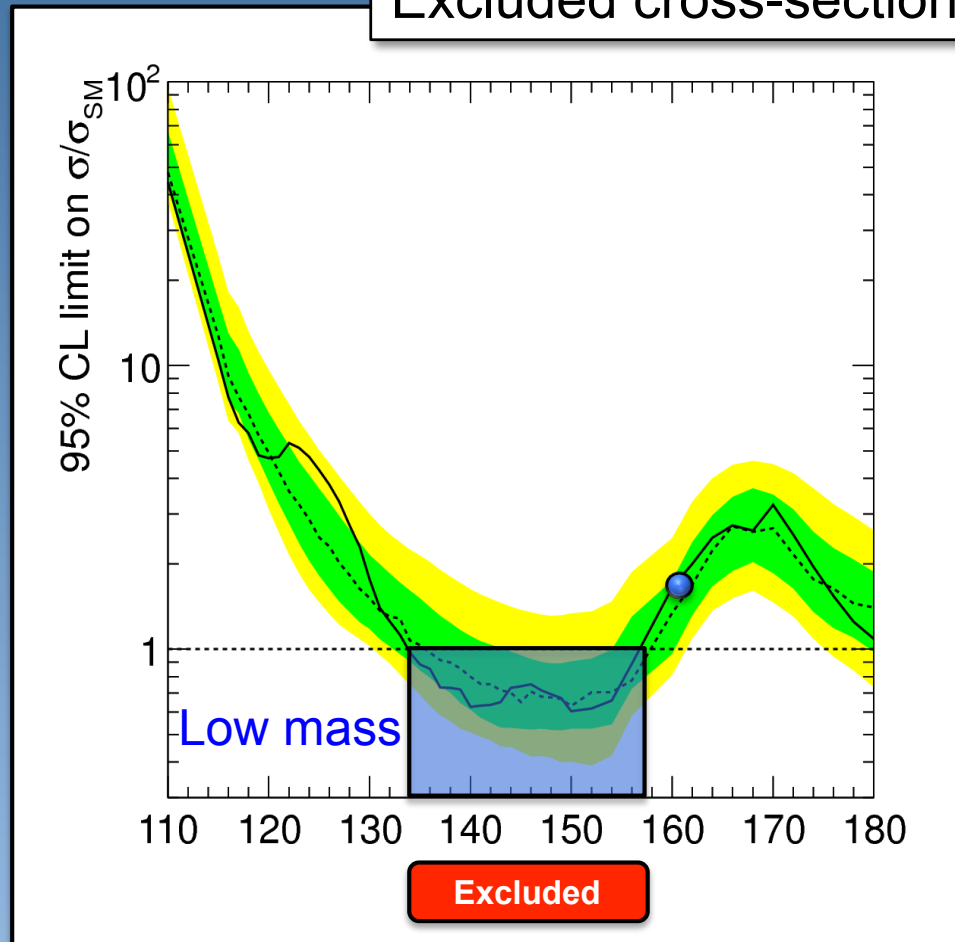
< 5%? Exclude at 95% CL

Expected exclusion ? Use mean SM instead of Ndata

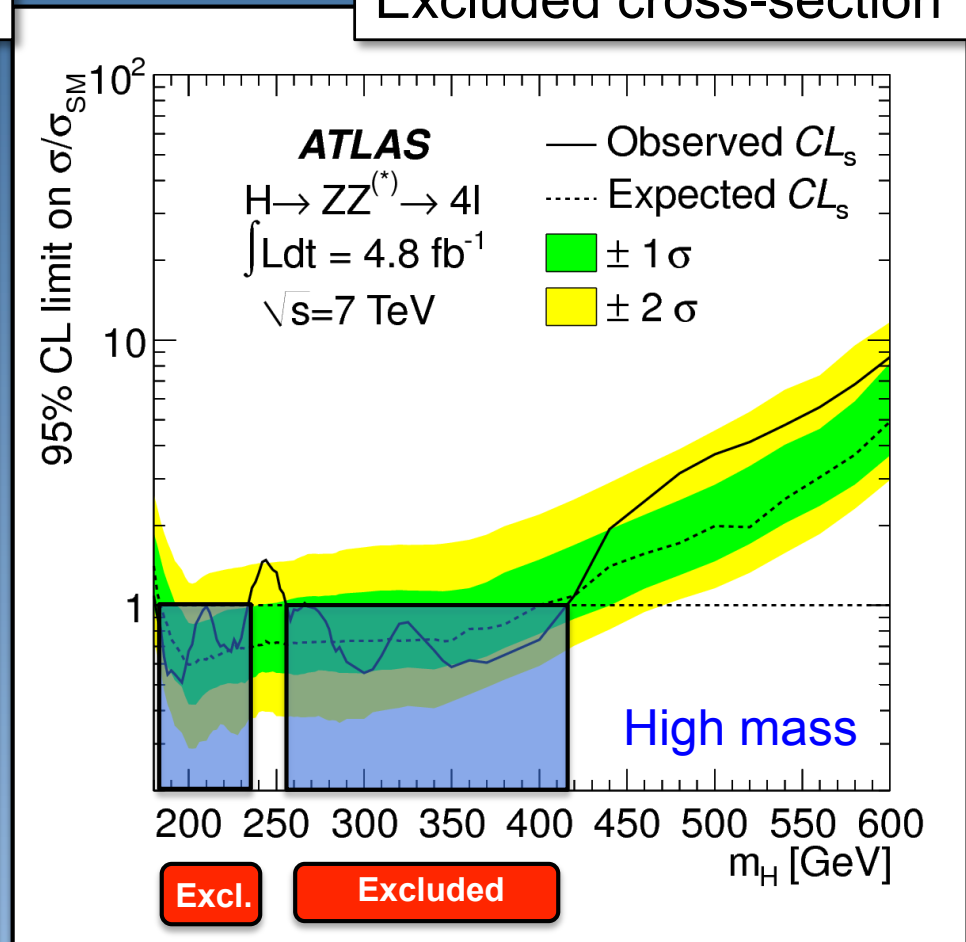
Observed excluded cross-section, $\sigma_h/\sigma_h^{SM} = 1.64$

Higgs $\rightarrow ZZ \rightarrow 4l$: from excluded cross-section to excluded mass

Excluded cross-section

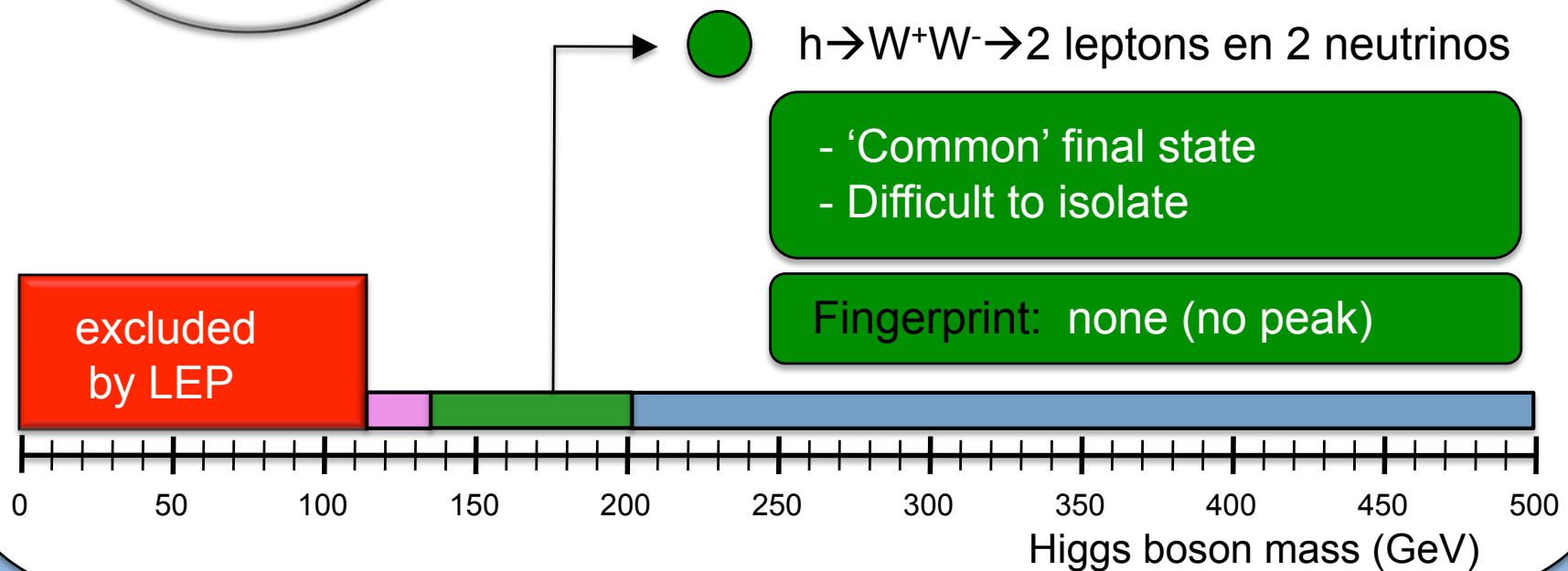
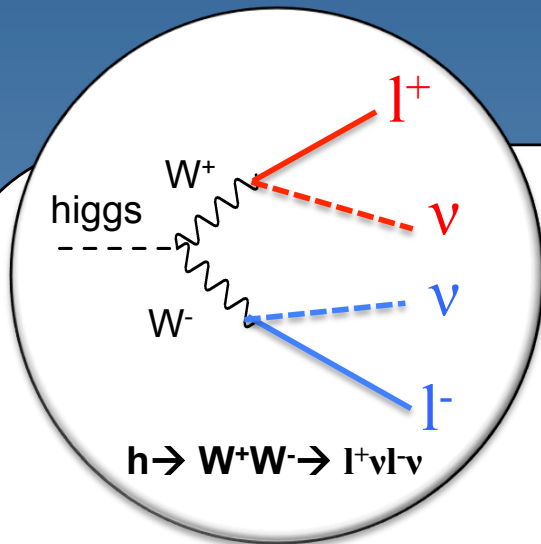


Excluded cross-section

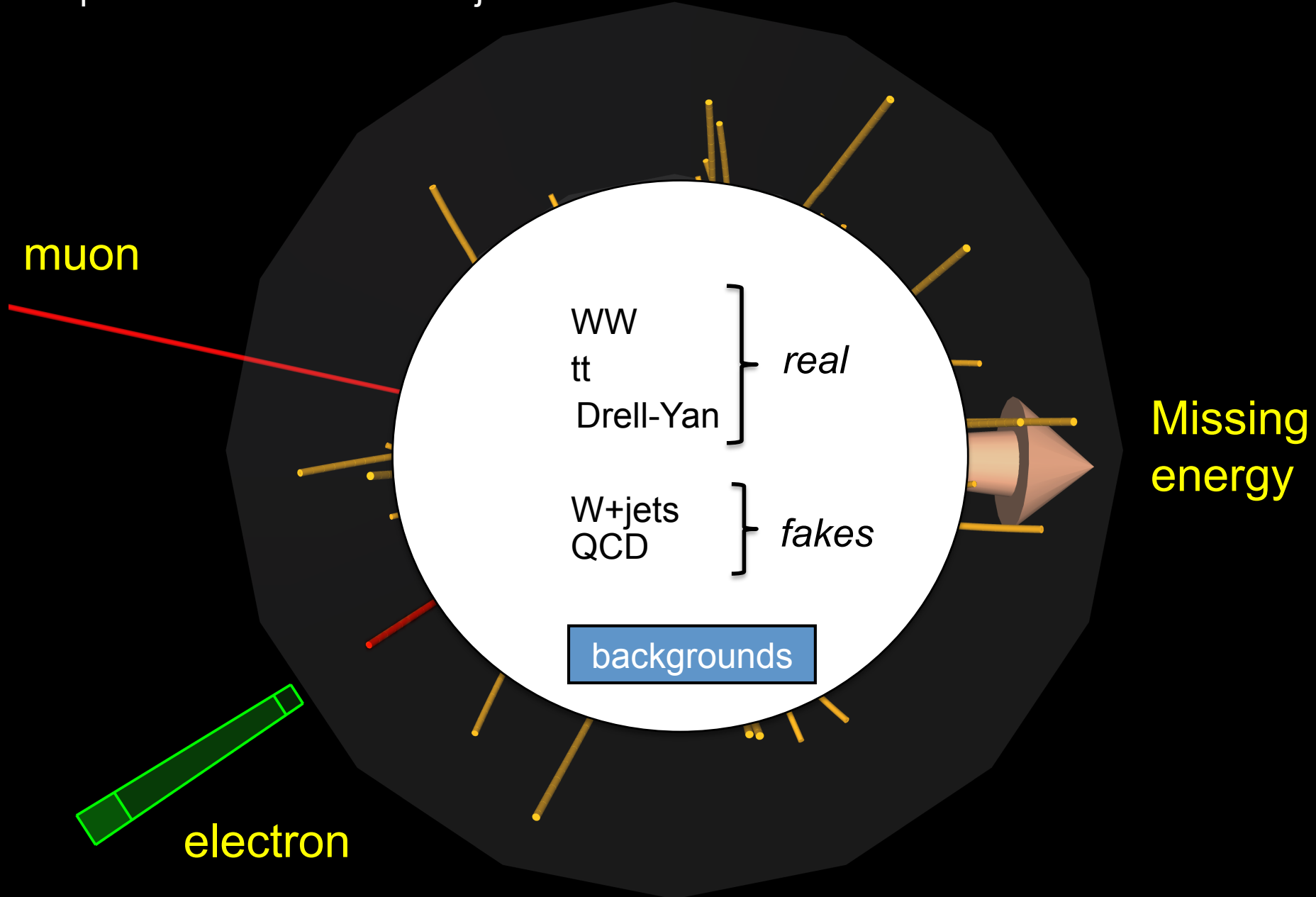


If Standard Model cross-section is excluded, the Higgs mass can be excluded

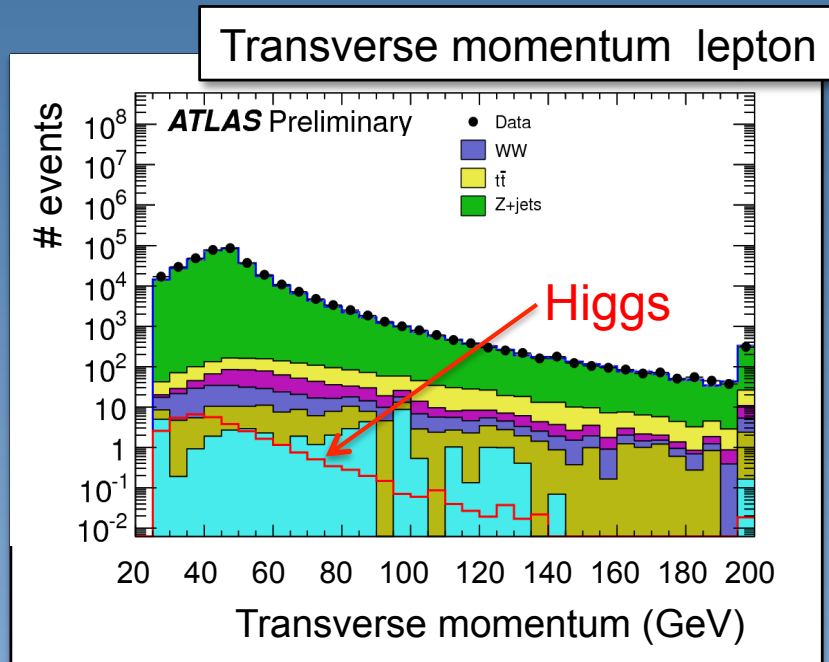
Mid-range: $130 < m_H < 200$ GeV



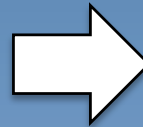
2 leptons and 2 neutrino's + jets



The possible Higgs signal is well hidden



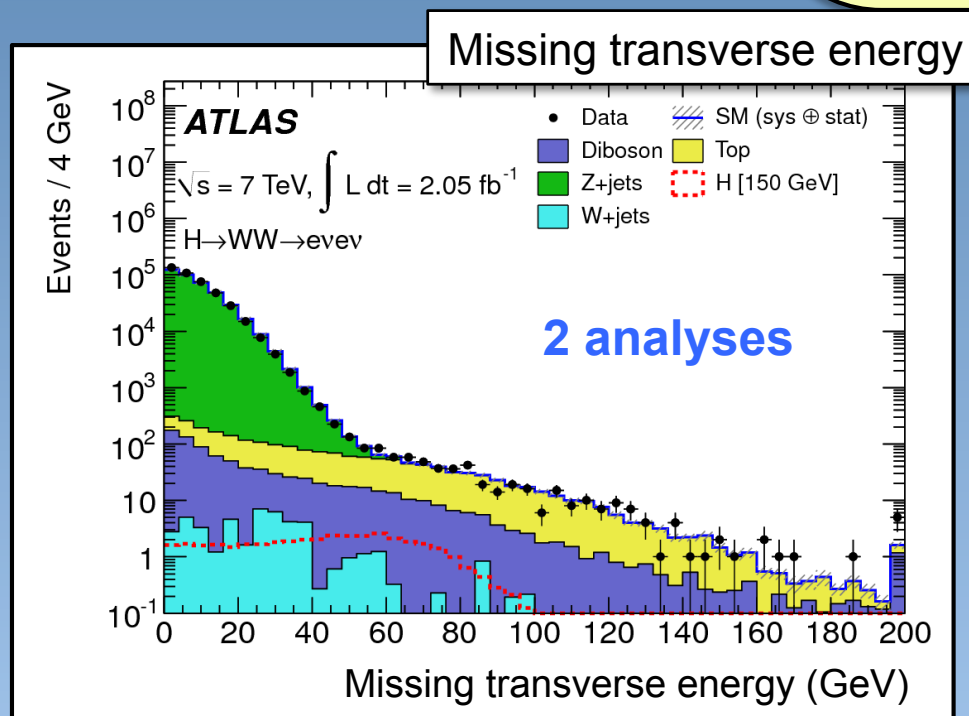
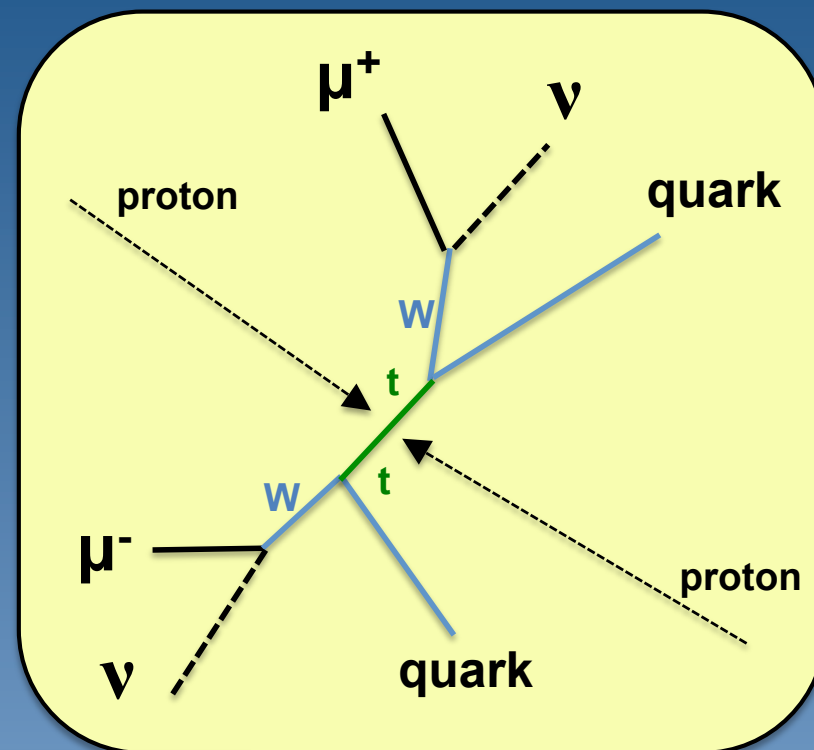
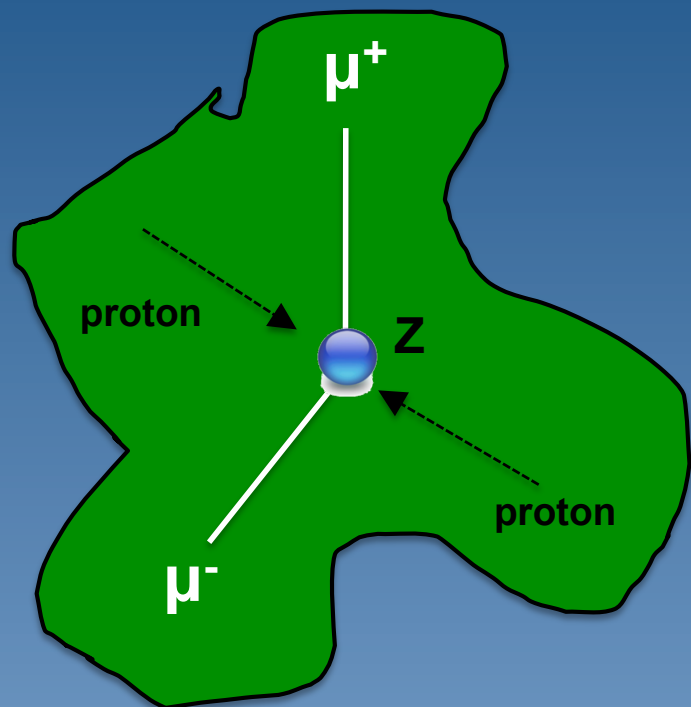
signal < 1/10.000 of background



Delicate multi-dimensional selection

How well do you understand your detector and simulation in this multi-dimensional phase space ?

Control regions → extrapolate to signal region

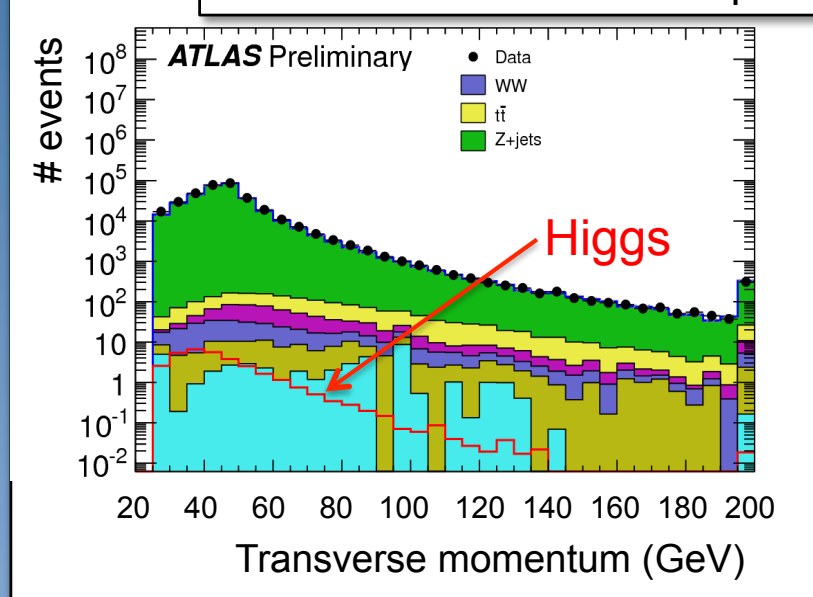


Looking for diamonds

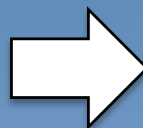


The possible Higgs signal is well hidden

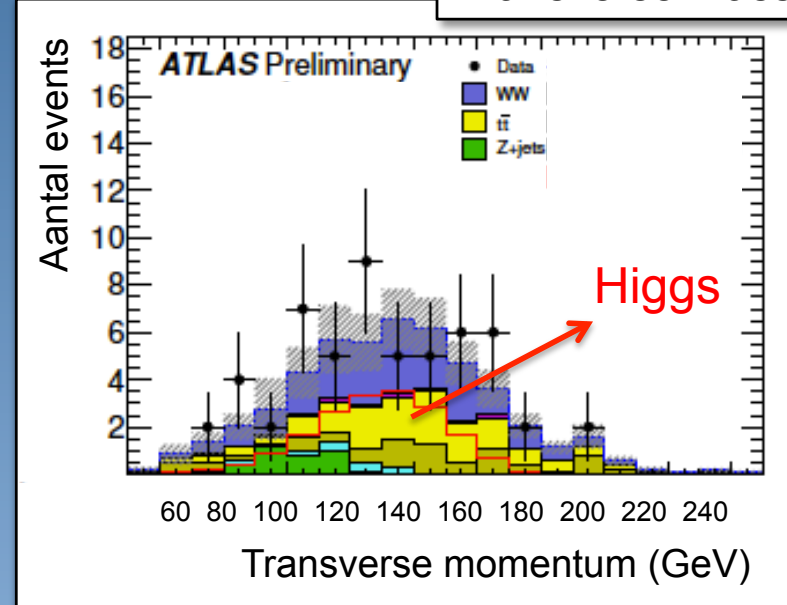
Transverse momentum lepton



signal < 1/10.000 of background



Transverse mass



signal = 1/2 of background

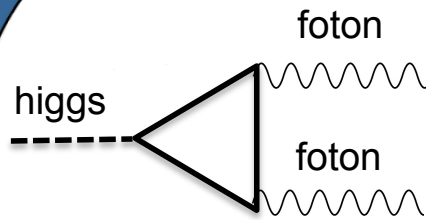
Overig	23
Met Higgs	35

LHC data:

23 (aargh!)

The low-mass region

0.2%



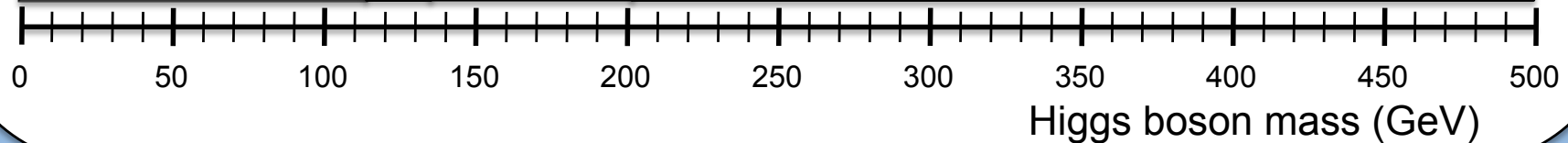
$h \rightarrow \gamma\gamma$ decay

 $h \rightarrow 2$ photons

- 2 energetic isolated photons
- detector sensitive for 'fake' signals

Fingerprint: 2-photon mass

excluded
by LEP



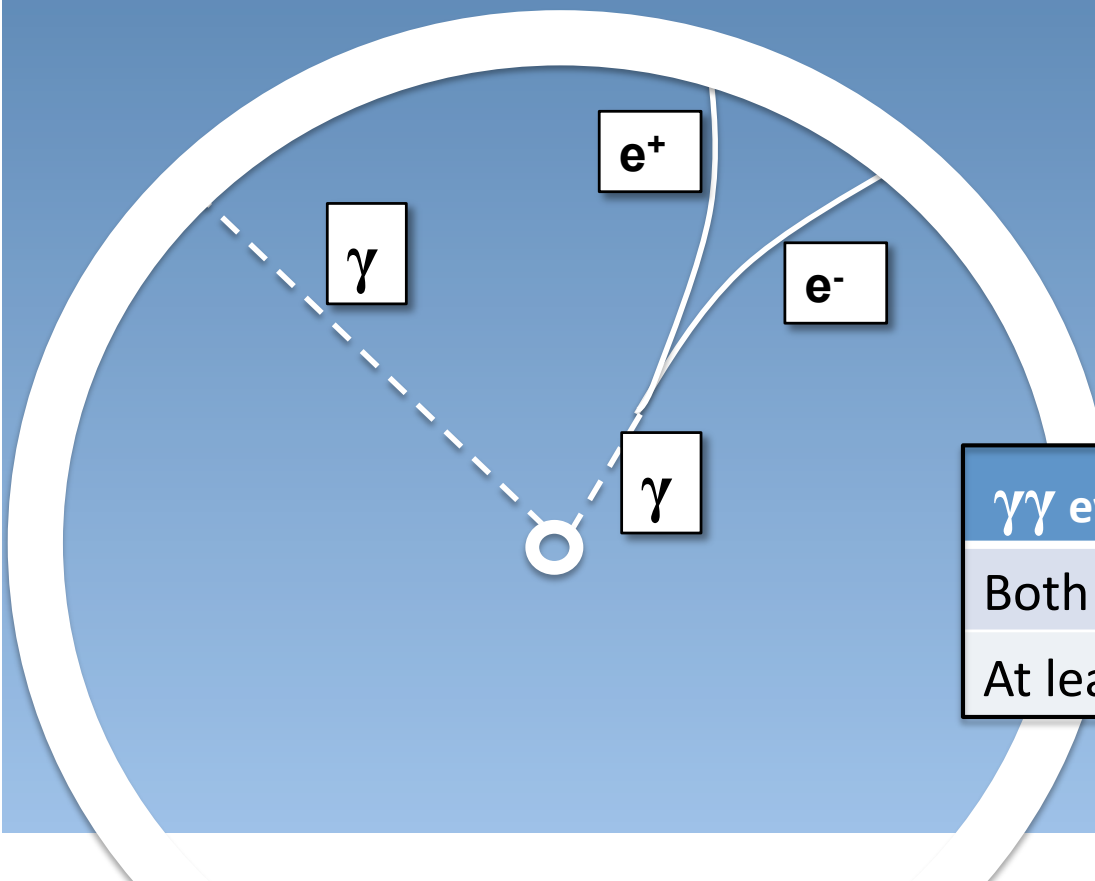
Photon identification and event selection

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

39% selection efficiency



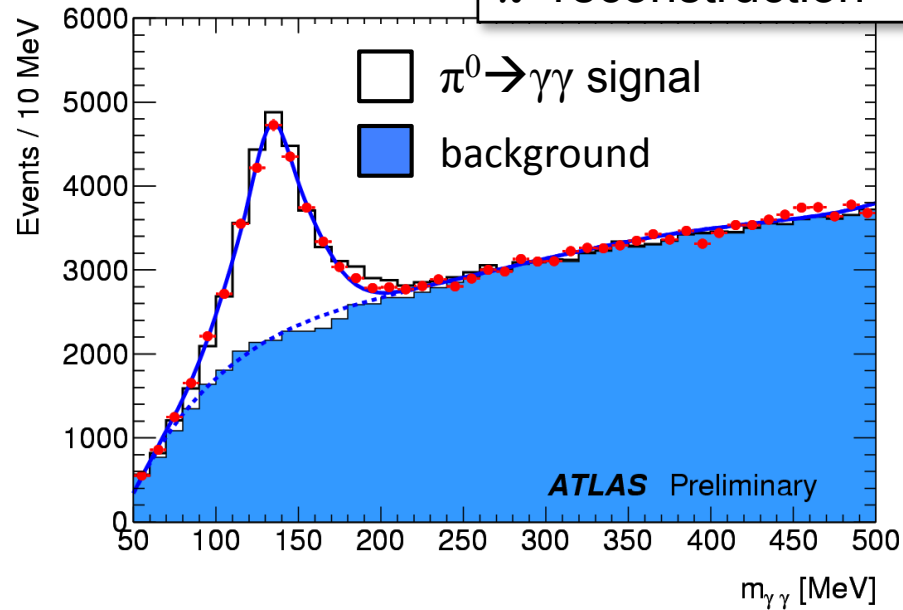
“Elk nadeel hep z'n voordeel”



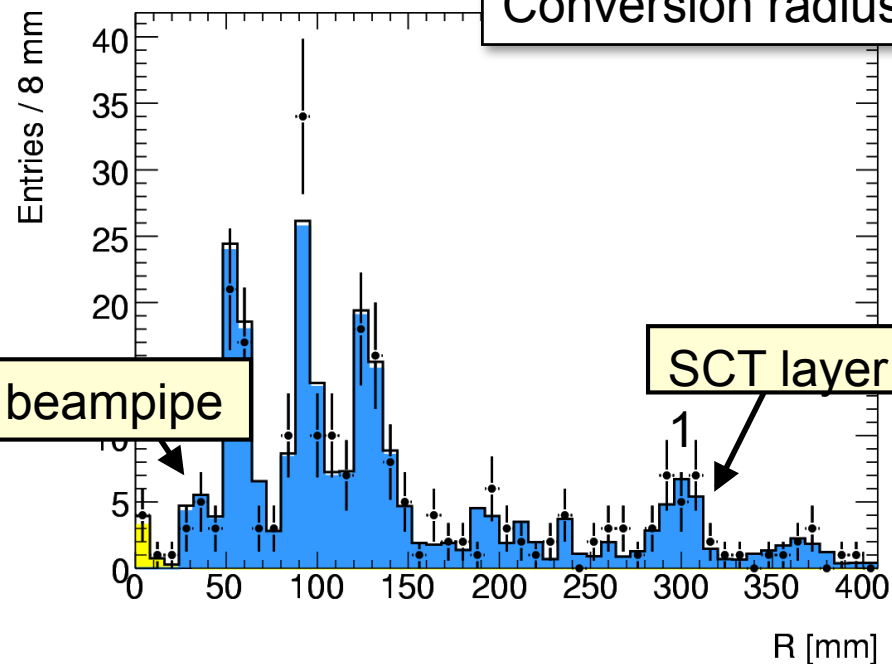
$\gamma\gamma$ event classification	Fraction
Both unconverted	36%
At least 1 converted	64%

Photon conversions

π^0 reconstruction



Conversion radius



Clean electron sample
Good material description in MC

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

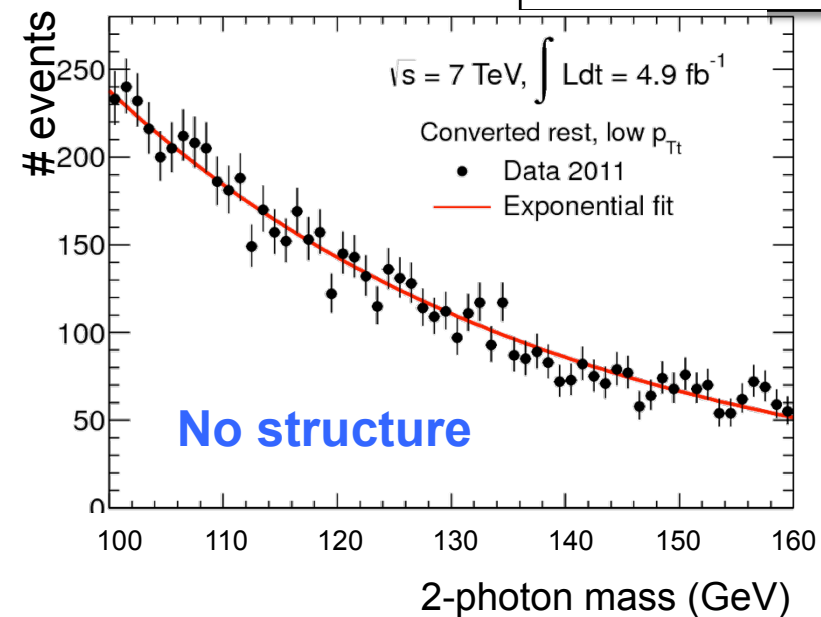
Other origin

$\gamma\gamma$	3650 ± 100 ± 290
$\gamma + \text{jet}$	1110 ± 60 ± 270
Di-jet	220 ± 20 ± 130
Drell-Yan	86 ± 1 ± 14
'normal'	5066

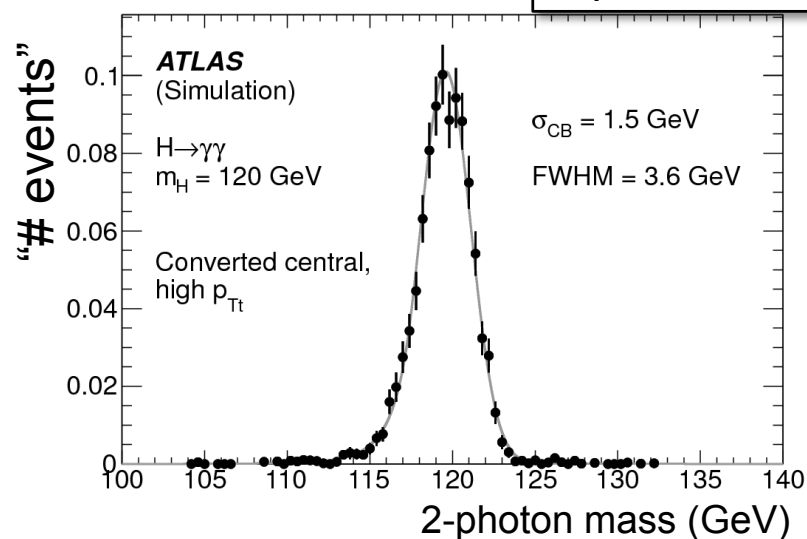
Higgs

Higgs signal	17.6
---------------------	-------------

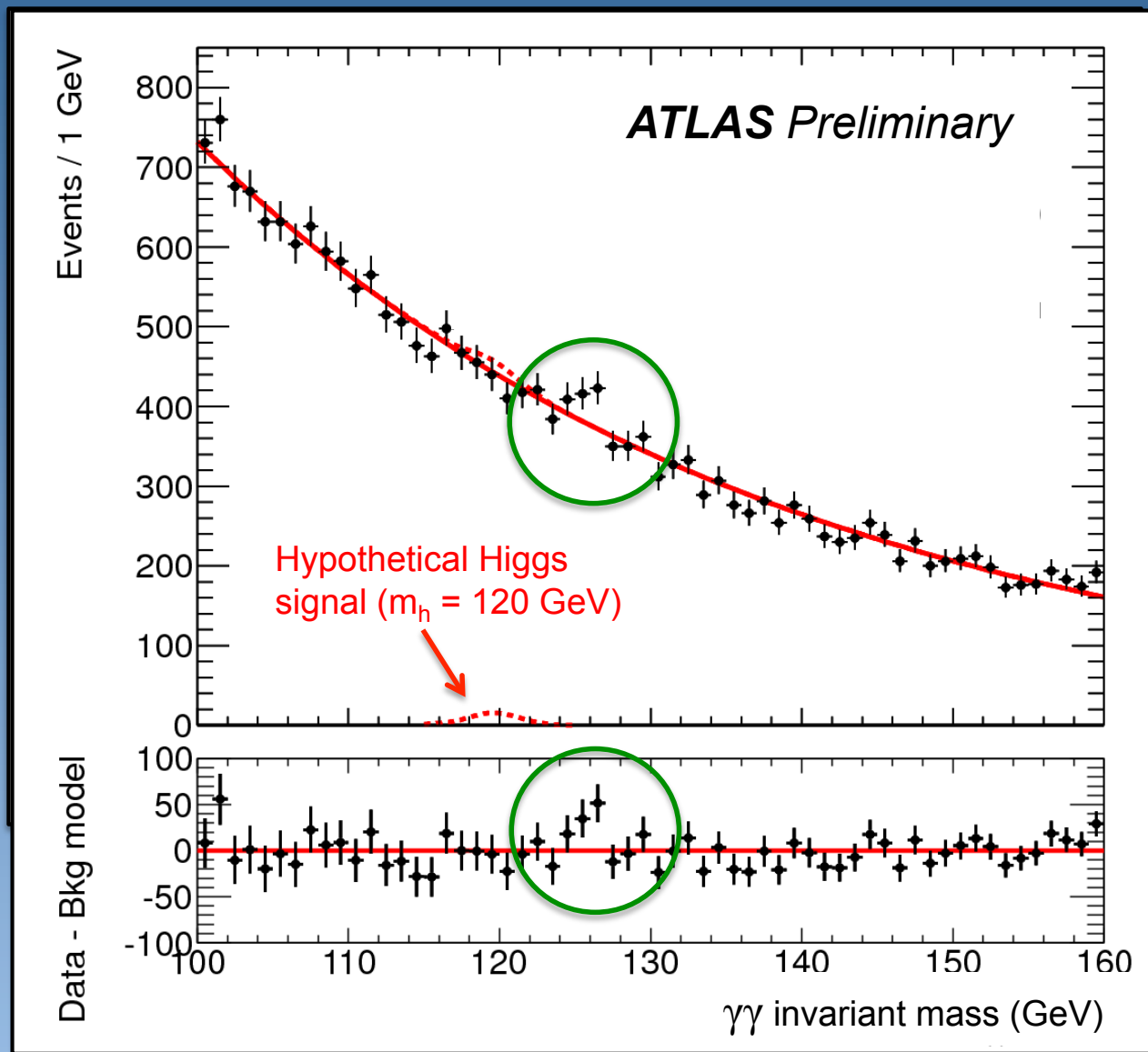
2-photon mass



2-photon mass



The ATLAS data



peak ?

Quantifying an excess: p-value

Measurement

SM	10
Higgs	5
Data	12

For a given number of events, the p-value is:

*“The probability to observe as many events as this number (or even more) under the assumption that the Higgs does **not** exists”*

→ Can be translated into a (gaussian) significance

Quantifying an excess: p-value

Measurement

SM	10
Higgs	5
Data	12

For a given number of events, the p-value is:

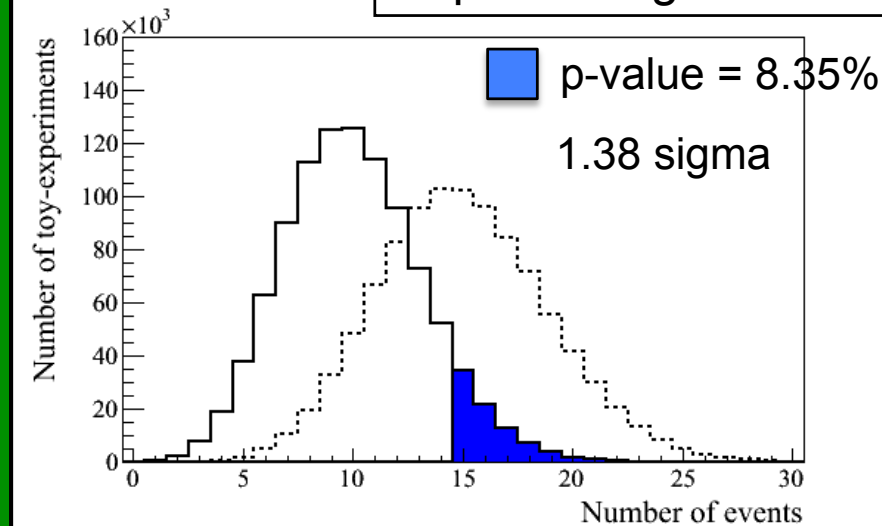
*“The probability to observe as many events as this number (or even more) under the assumption that the Higgs does **not** exist”*

→ Can be translated into a (gaussian) significance

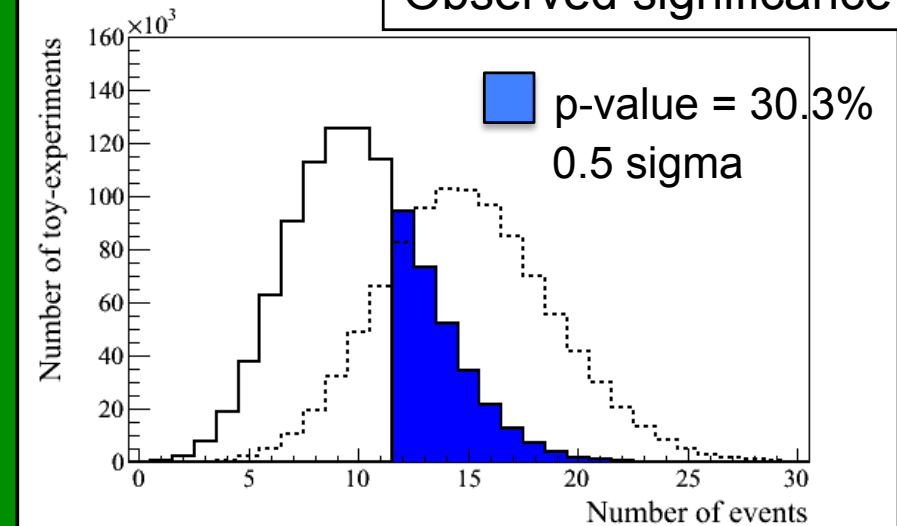
1) What is the expected significance ?

2) What is the observed significance ?

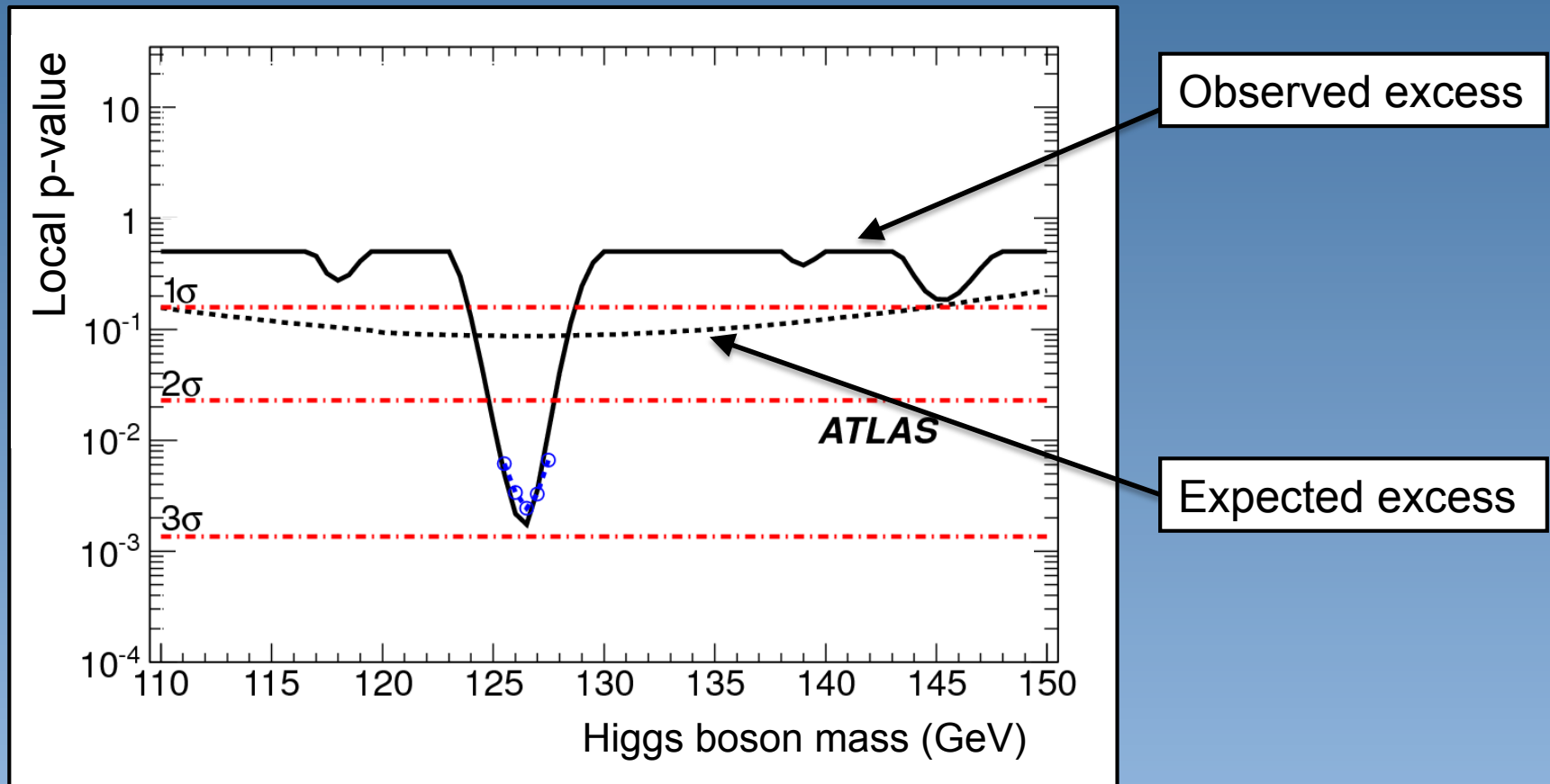
Expected significance



Observed significance

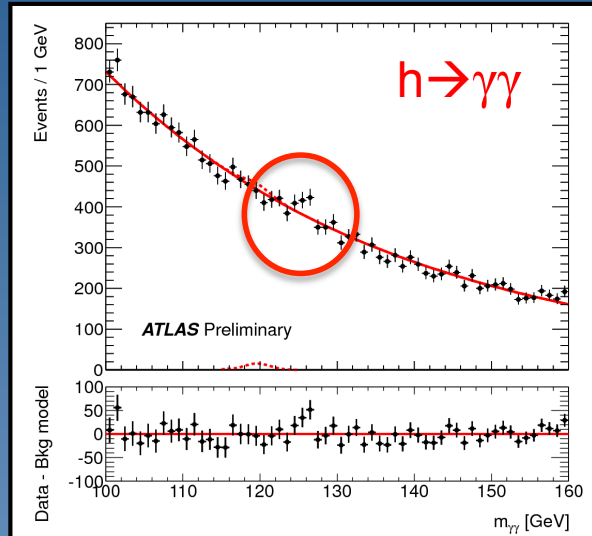


The excess in a single channel: $h \rightarrow \gamma\gamma$



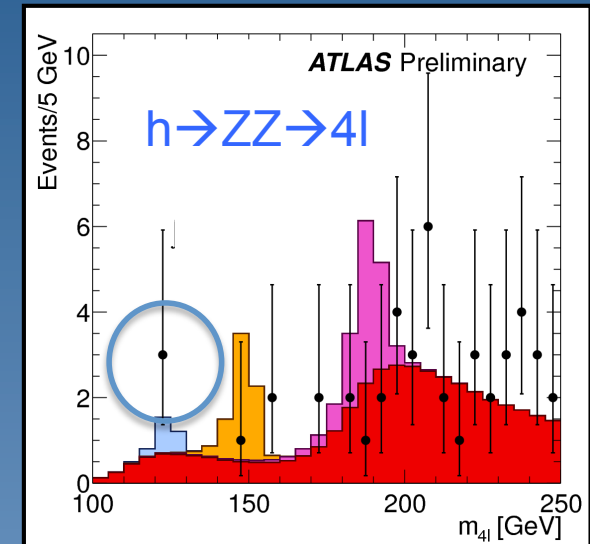
P-value ~ 0.002

Higgs $\rightarrow$ 2 photons

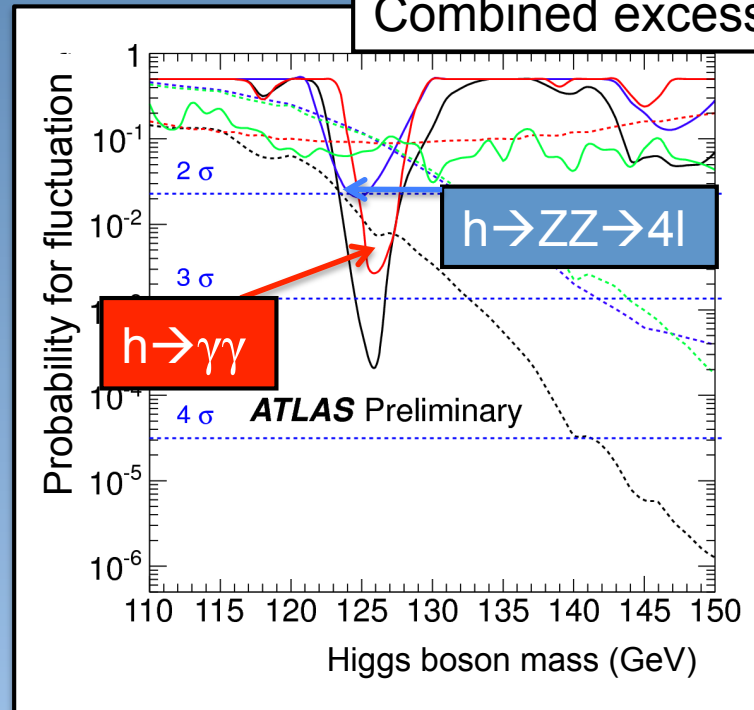


Excess visible in
in two channels

Higgs $\rightarrow$ 4 leptons



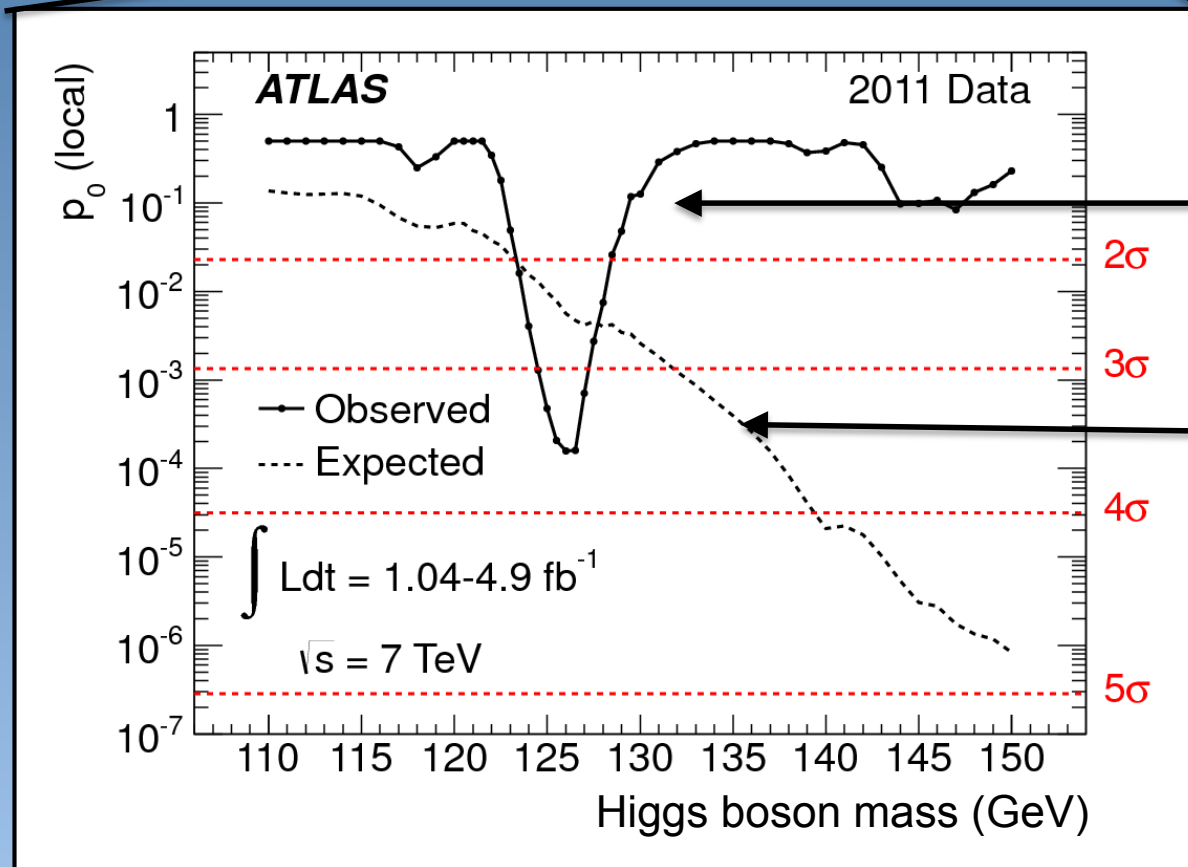
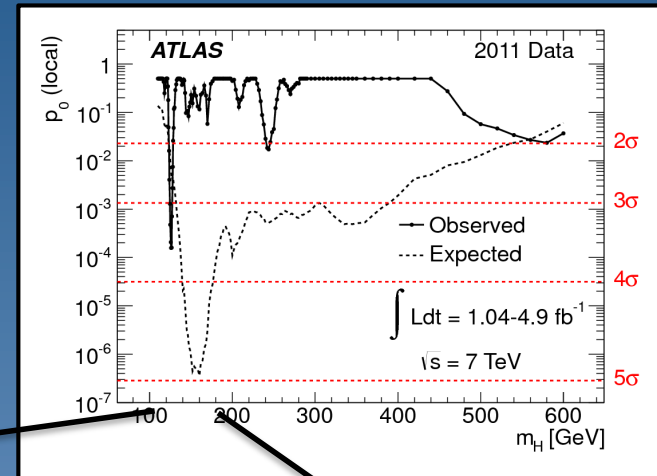
Combined excess



Corrected for look-
elsewhere effect:

Probability
 $\sim 1/100$ (2.3 σ)

Looking at the Excess: *p*-value



Observed excess

Expected excess

Corrected for look-elsewhere effect:

Probab. ~1%

Interpretation excess in ATLAS

Probability to fluctuate as much as observed or even higher: ~ 1 op 100

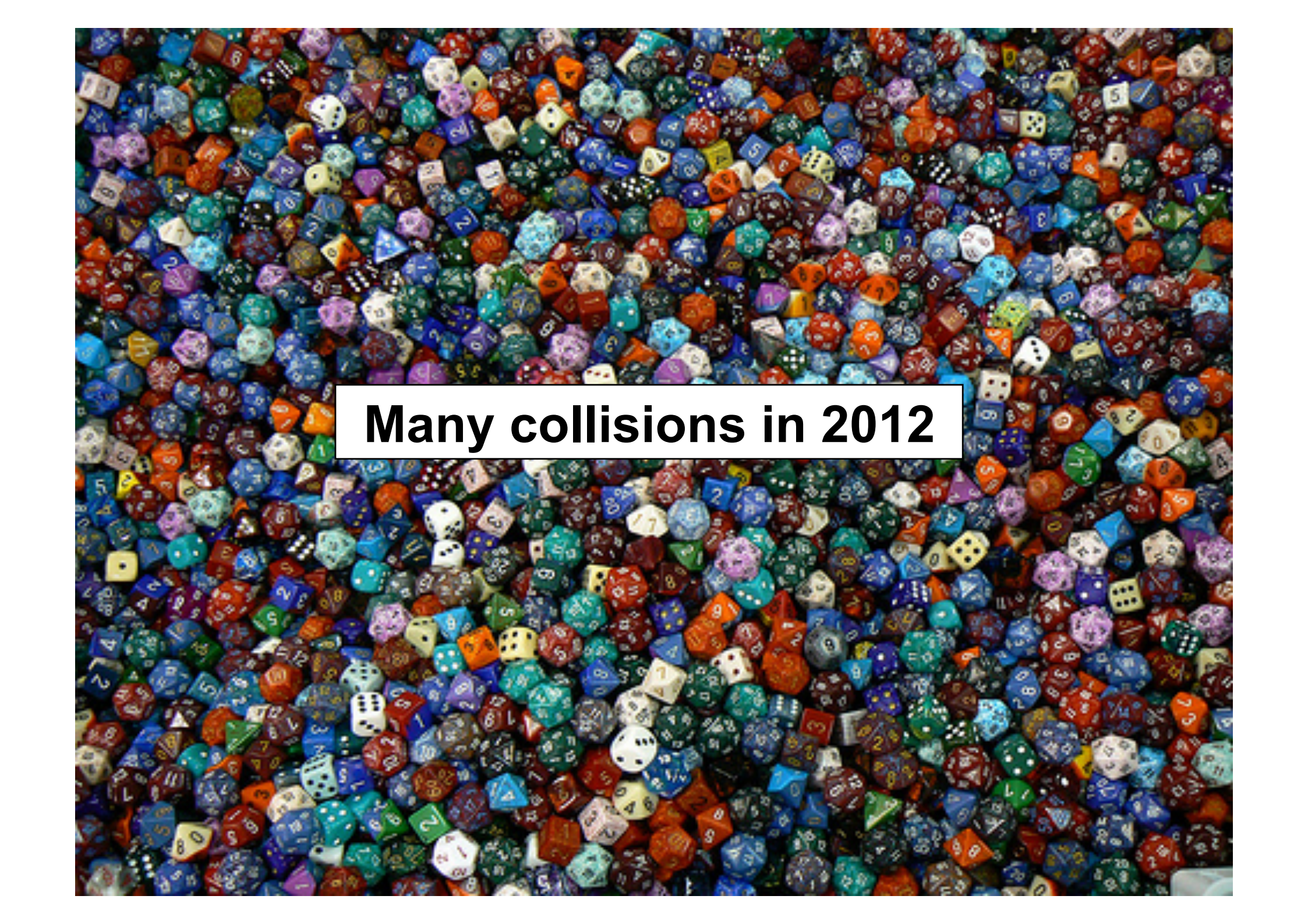
Pure chance of fake dice ?



Claim discovery if:

Probability on such a fluctuation from other processes < 1 on 1,000,000

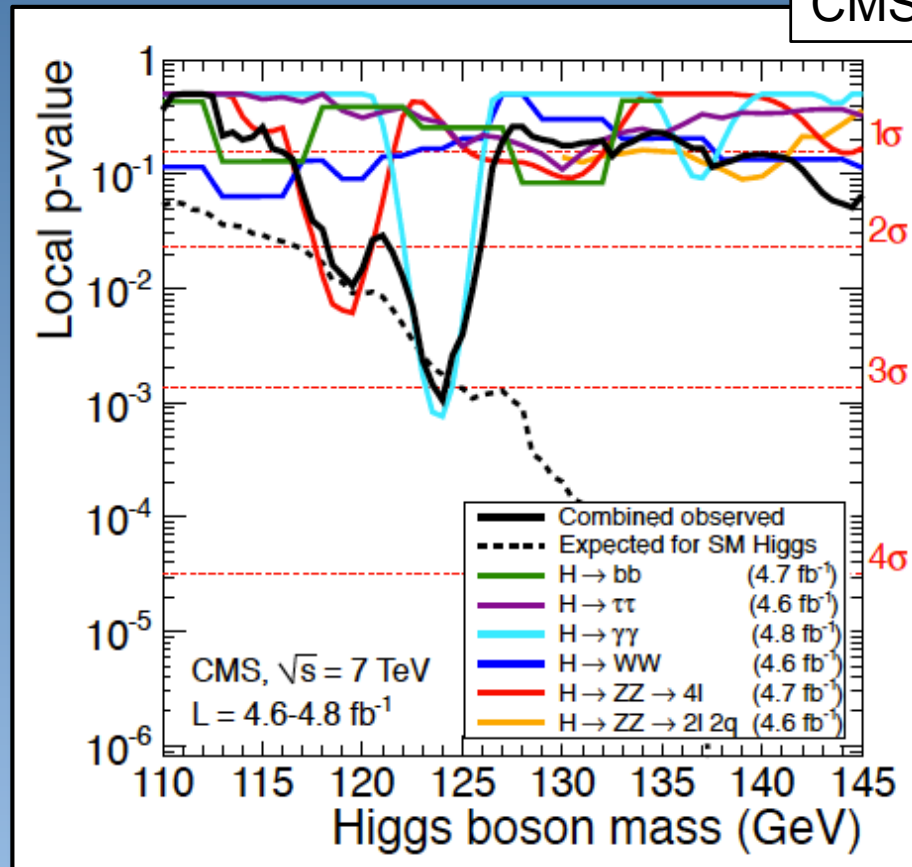
Throw 8 times 6 in a row
(need ~ 3 times more data)



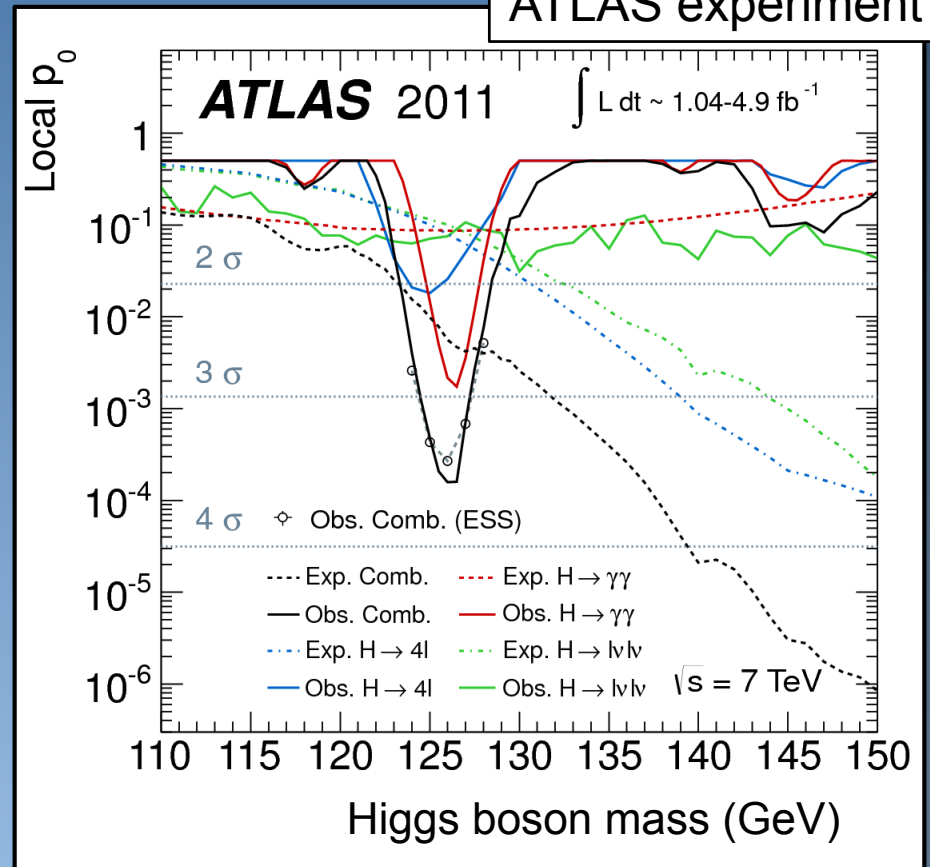
Many collisions in 2012

Comparison results from ATLAS and CMS experiments

CMS

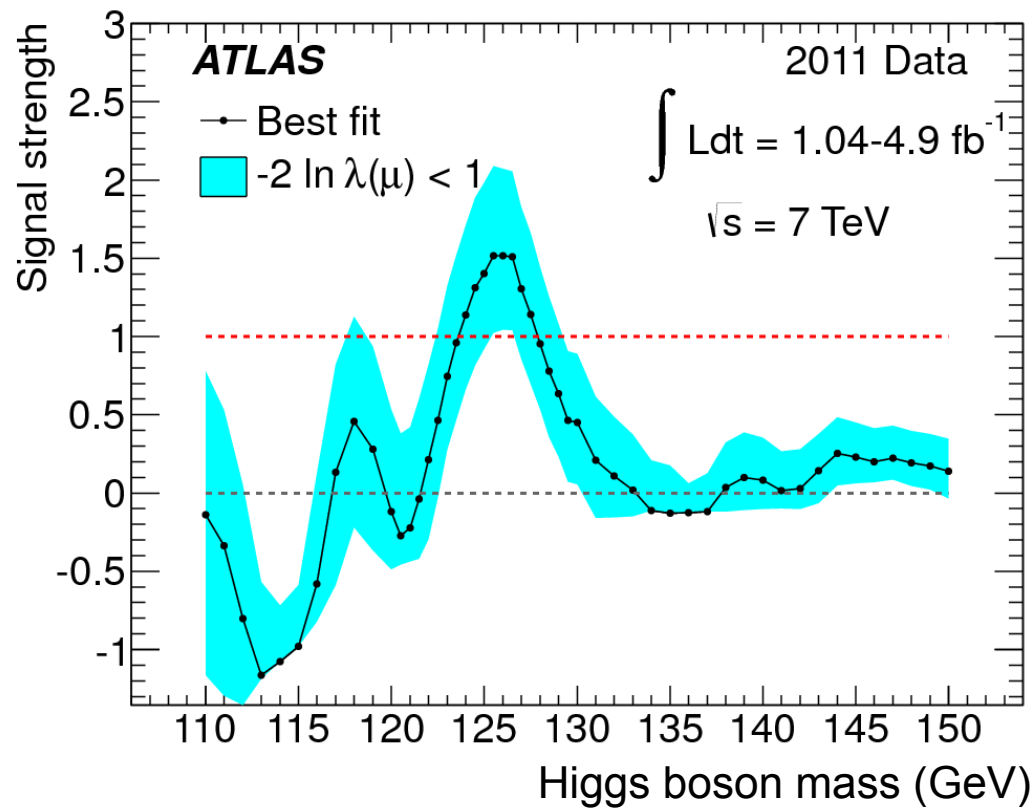
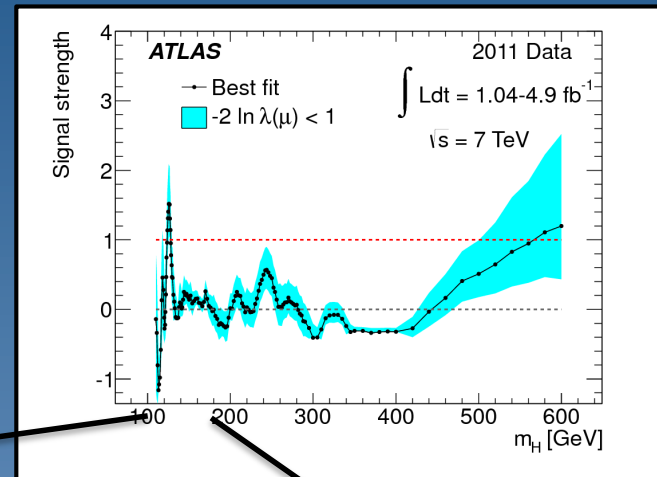


ATLAS experiment



Looking at the Excess: *signal strength*

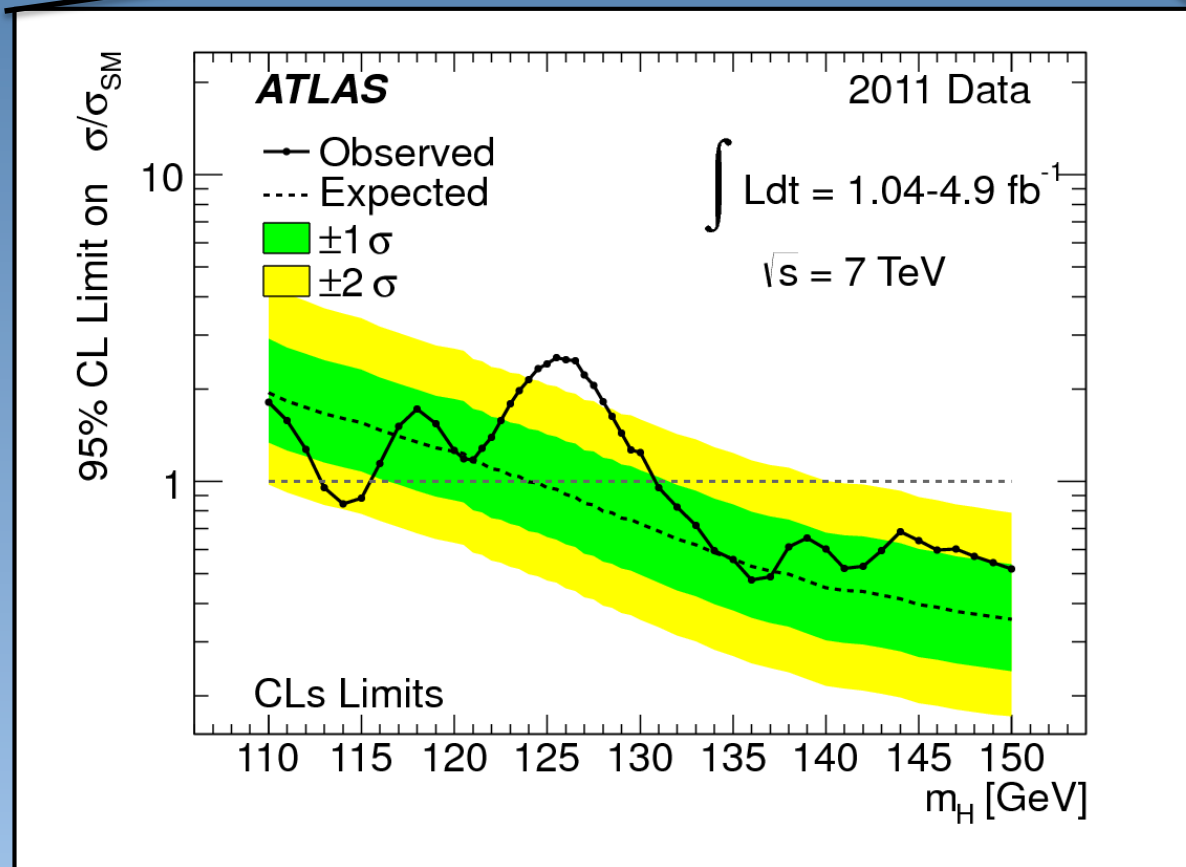
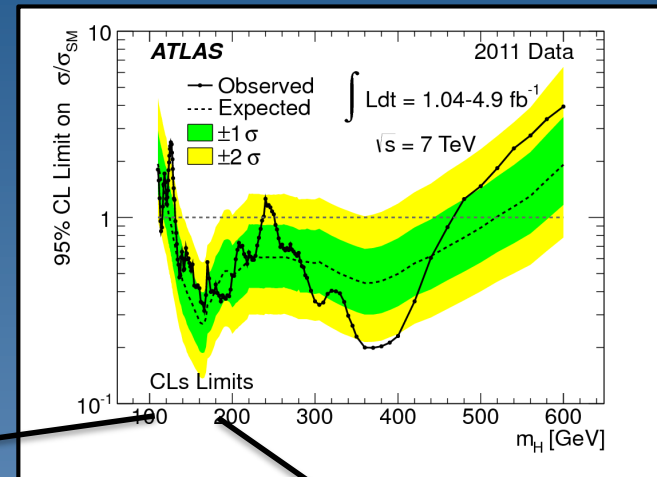
Fit: SM + *signal strength* * Higgs



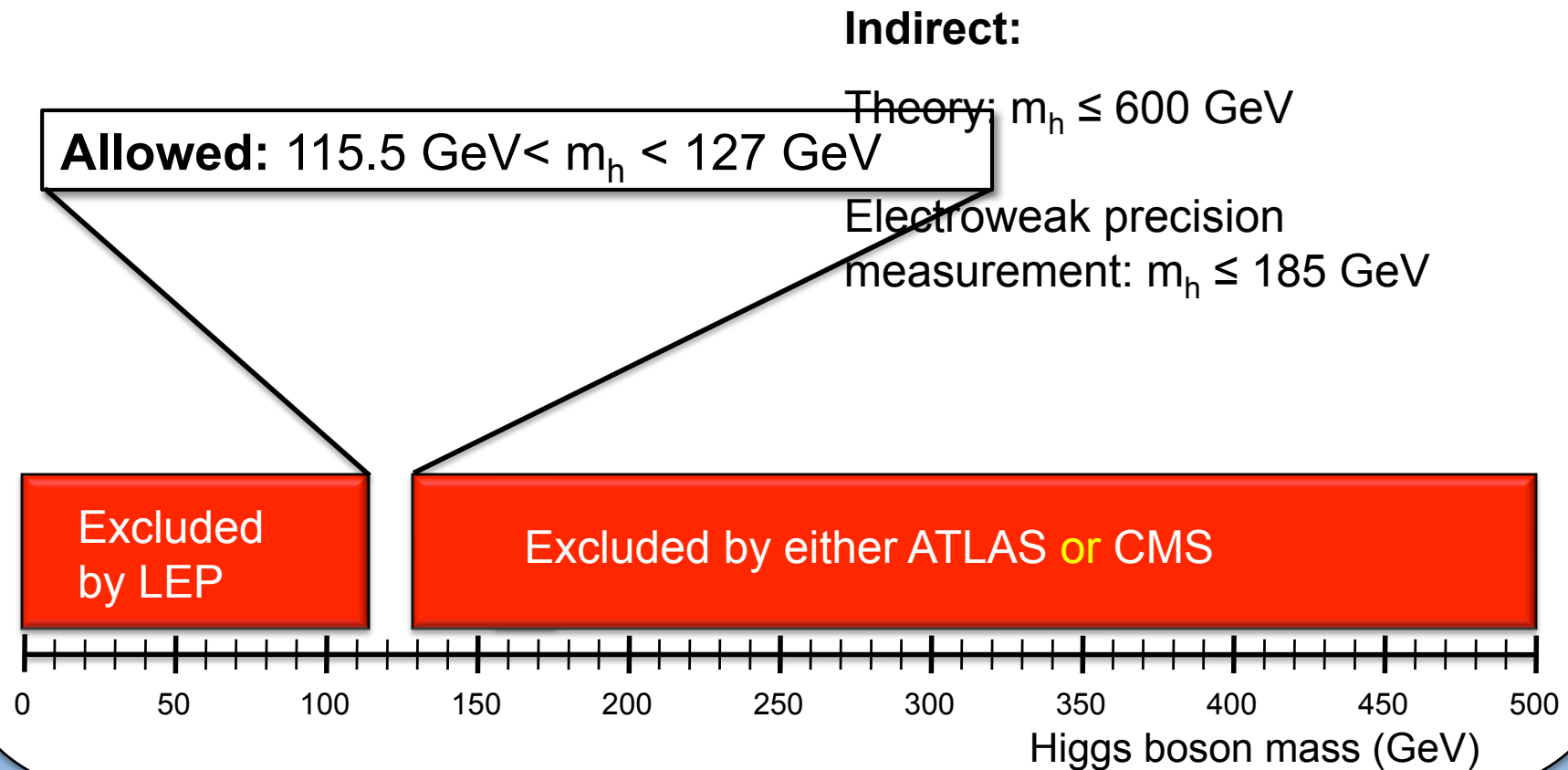
← SM Higgs
signal strength

← No Higgs

Looking at the Excess: *excluded cross-section*



Status on February 8, 2012



Some thoughts about the Higgs boson (discovery):

We need to prove that it is the SM Higgs boson:

- Verify coupling to fermions and gauge bosons
 - o SUSY model predict different couplings
 - o Fermiophobic Higgses might be a possibility
 - o Higgs potential and self-coupling
- Spin zero ?
- ...

To be honest ... there are some 'tiny' issues that remain:

- Radiative corrections (from top) to Higgs mass are huge $\propto \Lambda^2$. Extreme fine-tuning to get light Higgs.
- Higgs does not give any hint to particle masses or dark matter
- Contribution to $\rho_{Higgs}^{vac} (\Omega_\Lambda)$ factor 10^{54} off

... but maybe we have already seen it

It giet oan! Summary

- 0) Large Hadron Collider and experiments are simply fan-tas-tic!
- 1) Search for the Higgs in 2011
Excluded a large mass region
Excess at low mass (~ 125 GeV) $\rightarrow$ no discovery yet
- 2) Search for the Higgs in 2012
If the Higgs boson exists, CMS and ATLAS will discover it
... together

backup

REFERENCES

ATLAS experiment

All ATLAS public resultats: publications, numbers and plots

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

ATLAS and CMS papers

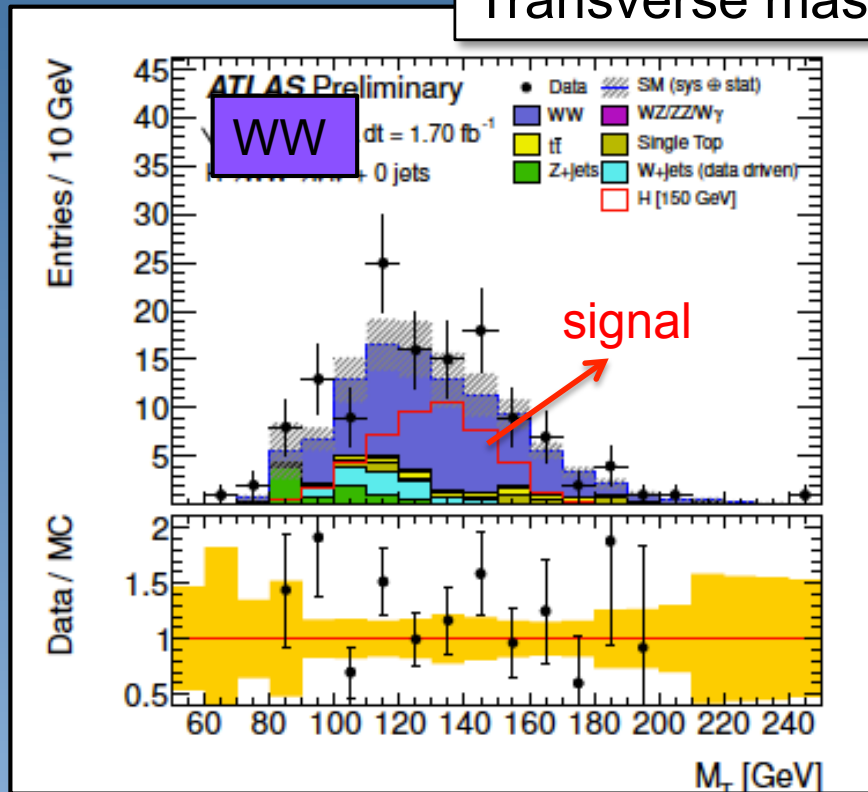
ATLAS <http://arxiv.org/abs/1202.1408>

CMS <http://cdsweb.cern.ch/record/1422382/files/HIG-11-032-arXiv-gen.pdf>

Example: $m_h = 150$ GeV

Topology: Higgs + 0 jets

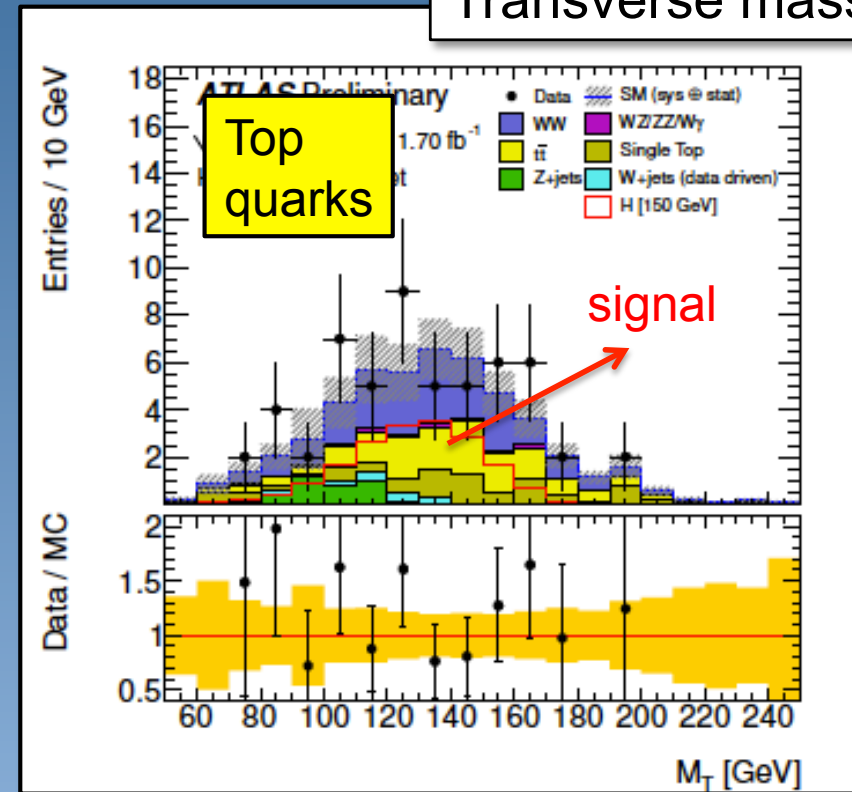
Transverse mass



background	53 ± 9
observation	70
signal	34 ± 7

Topology: Higgs + 1 jet

Transverse mass



background	23 ± 4
observation	23
signal	12 ± 3