The search for the Higgs boson

Ivo van Vulpen (Uva/Nikhef)

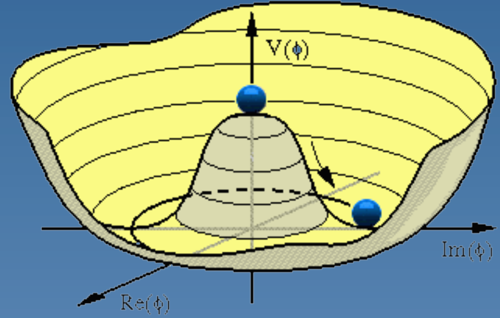
(In)famous Higgs boson

The Higgs boson

Paris Hilton

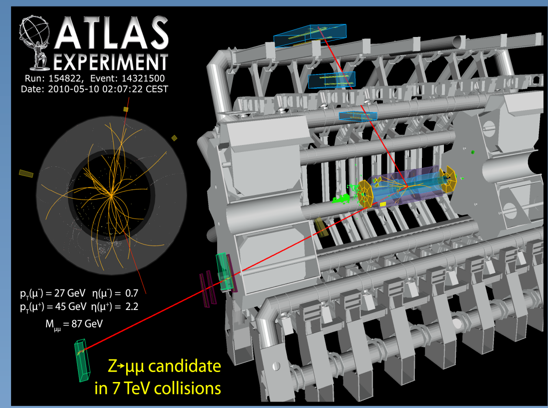
Famous and constantly in the news
… but are they important ?

Things to remember

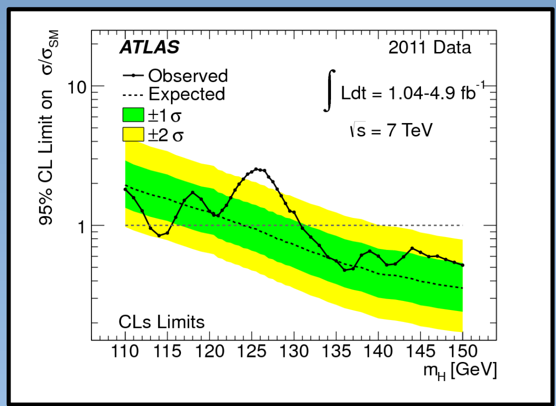


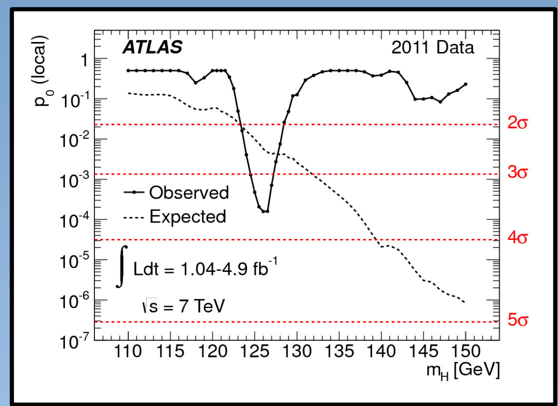
1) The Higgs mechanism is at the heart of the Standard Model

2) LHC and ATLAS detector operating fine!



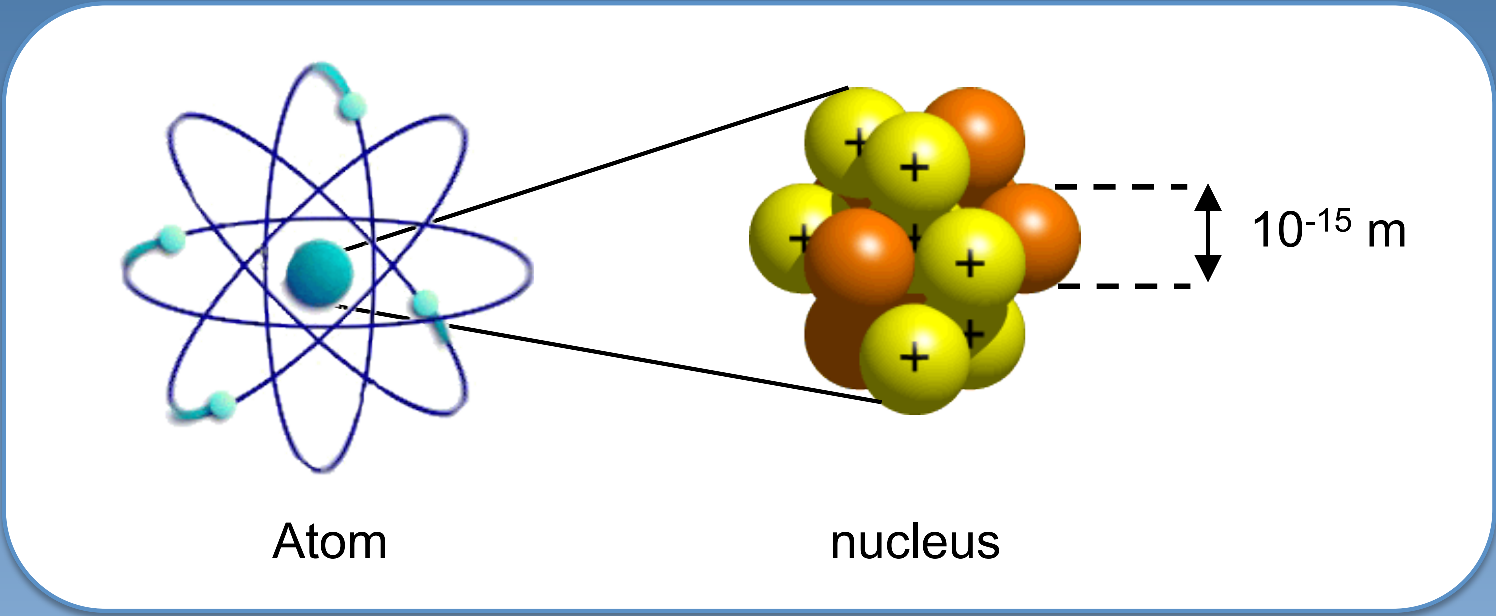
3) How to interpret the Higgs summary plots from LHC experiments



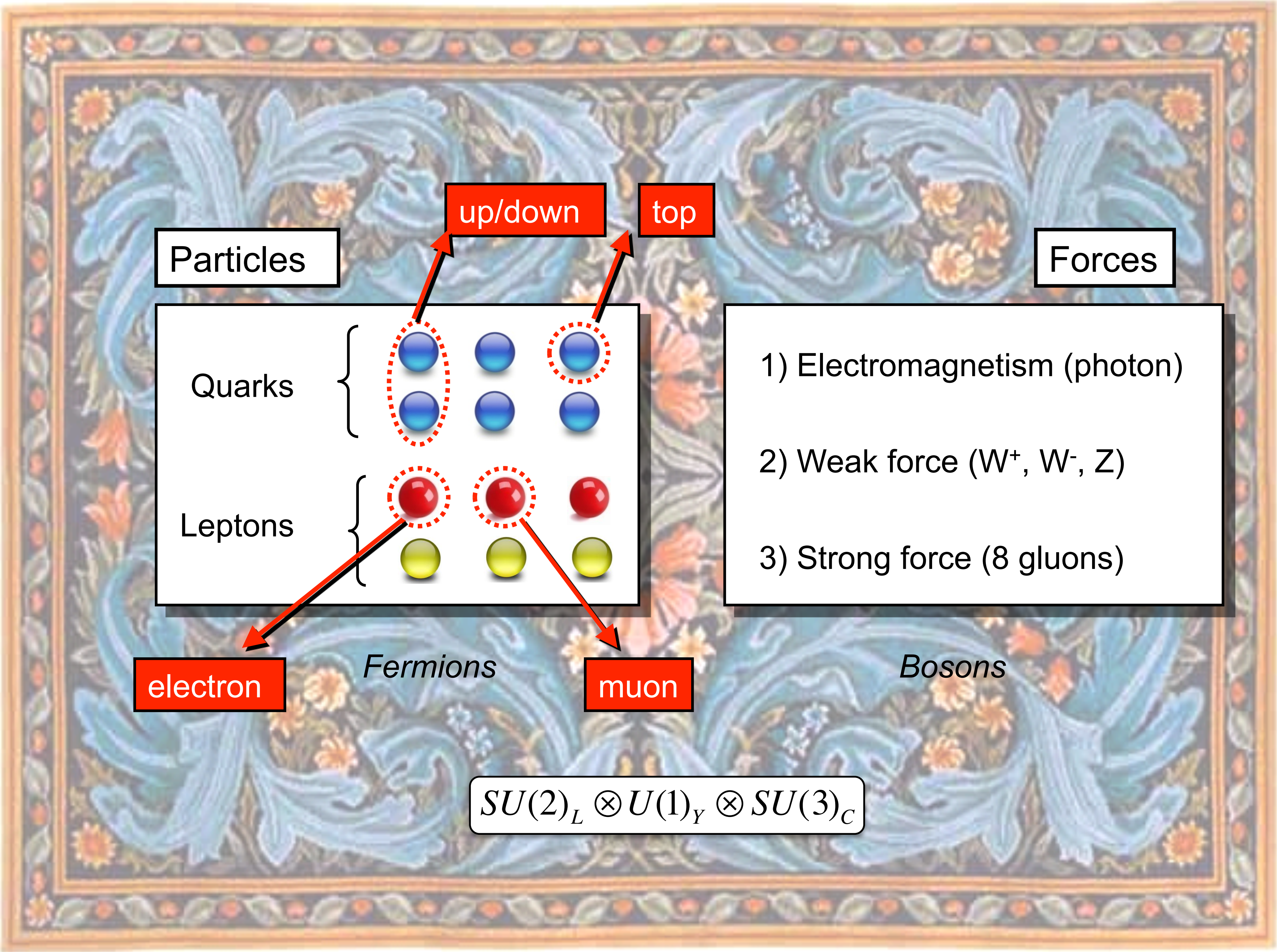


Particle Physics

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



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



Particles
up/down
top
Quarks
Leptons
electron
Fermions
muon
Forces
1) Electromagnetism (photon)
2) Weak force (W^+, W^-, Z)
3) Strong force (8 gluons)
Bosons
$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$

Standard Model is based on symmetries

Free electron

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

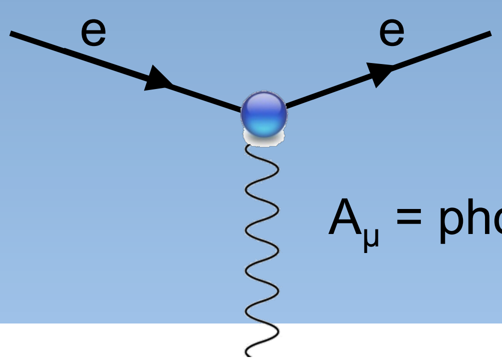
Extra symmetry requirement

Local gauge invariance

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

Introduce covariant derivative
(with vector-field)

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



A_μ = photon

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

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

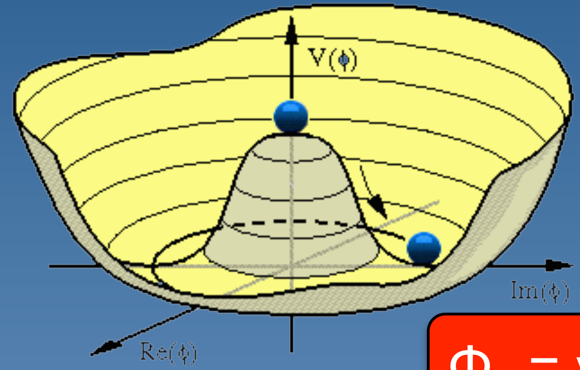
There has to be a **Higgs boson**


BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

- September 1964 -

The Higgs mechanism



Φ_0 = v+h

1) Add iso-spin doublet Φ (4 d.o.f.), with $Y_\Phi = +1$

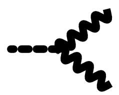
2) Potential: $V(\Phi) = \mu^2\Phi^2 + \lambda\Phi^4$, with $\mu^2<0$

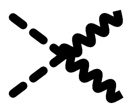
Gauge bosons

(V = W^+,W^-,Z,γ)

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

$\propto \vec{V}^2$ mass *V*

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

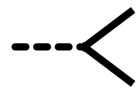
$\propto h^2\vec{V}^2$ 

Fermions:

(ψ =e,μ,…)

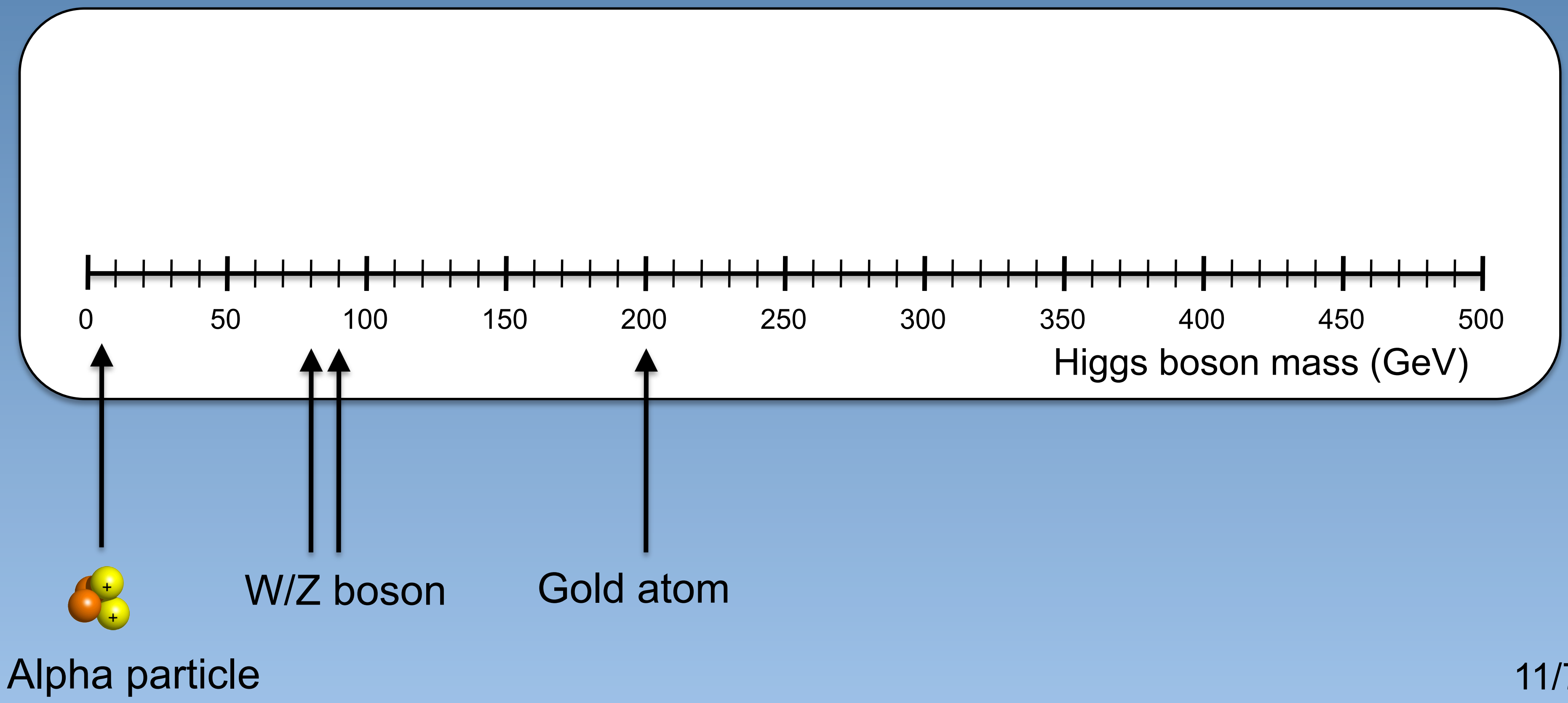
$$L(\psi) = \overline{\psi}\phi\psi + \ldots$$

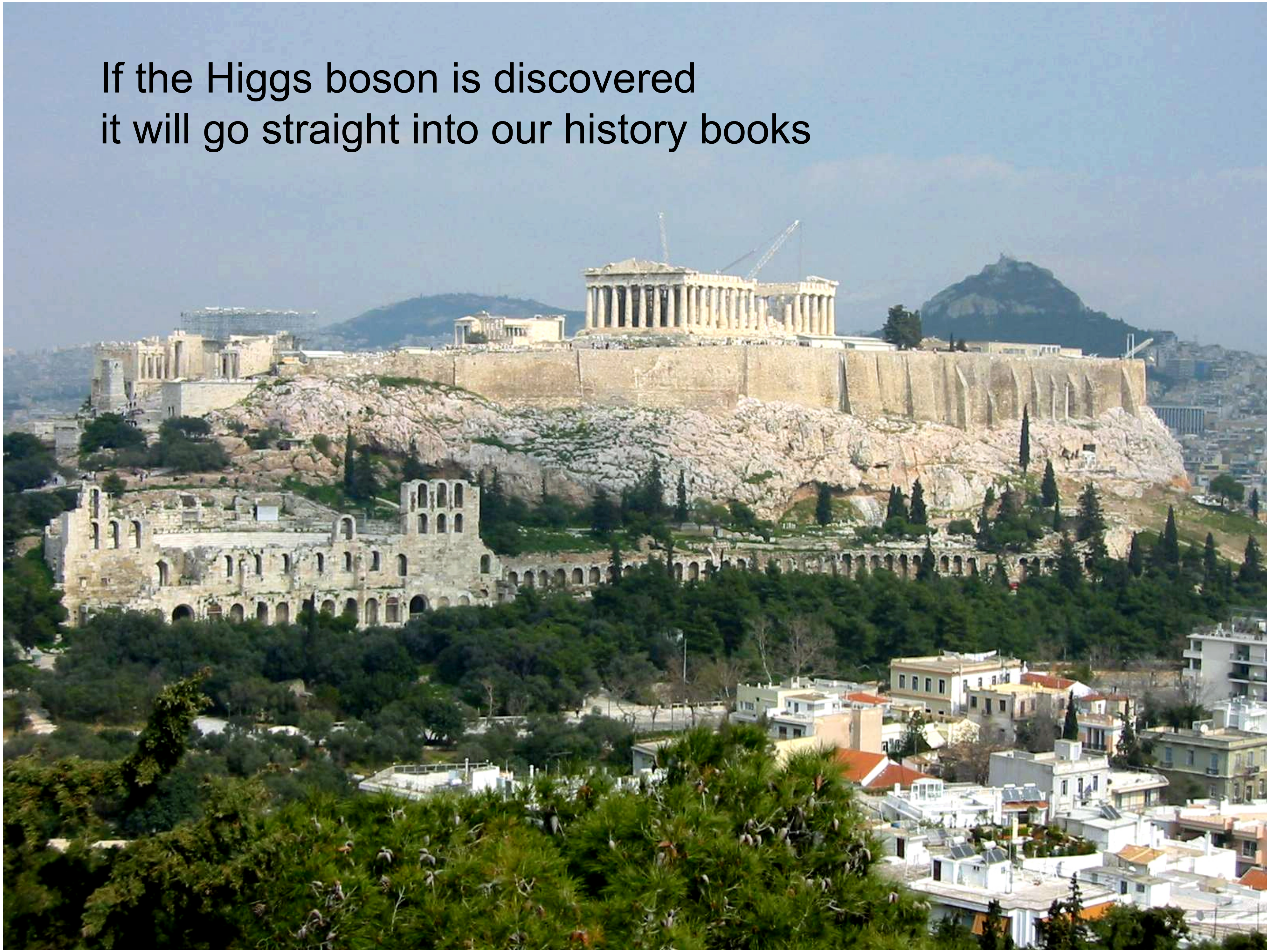
$m_\psi\overline{\psi}\psi$ mass ψ

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

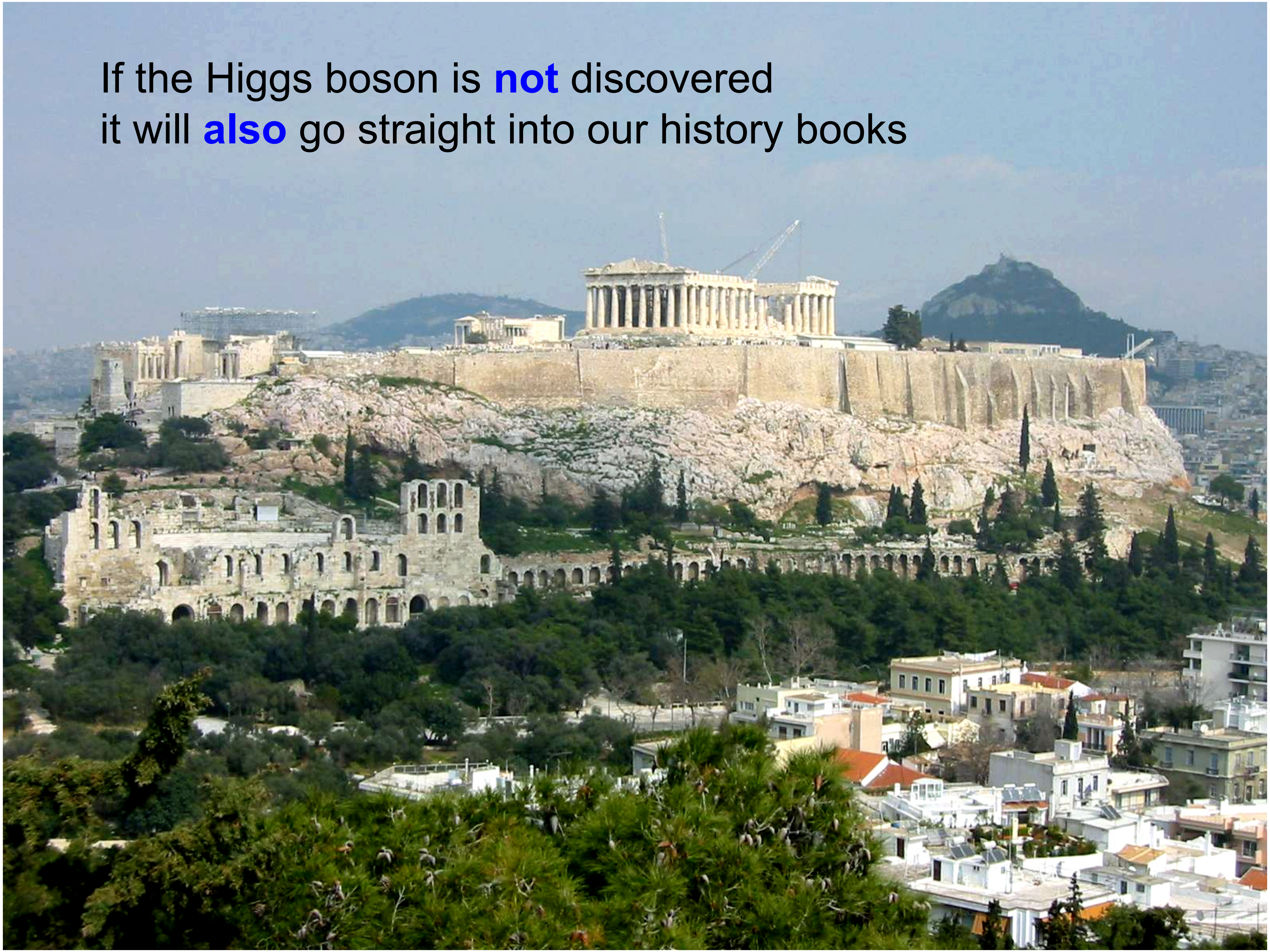
"the Higgs couples to mass"

The mass of the Higgs boson



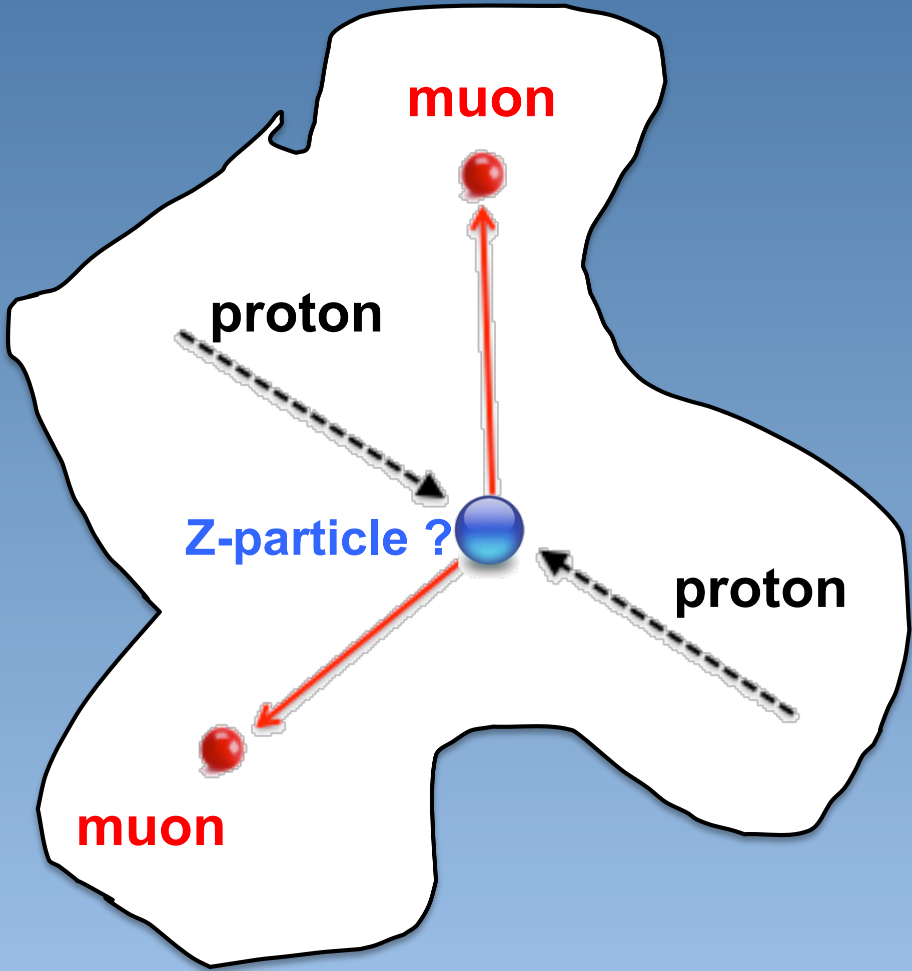

If the Higgs boson is discovered
it will go straight into our history books

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

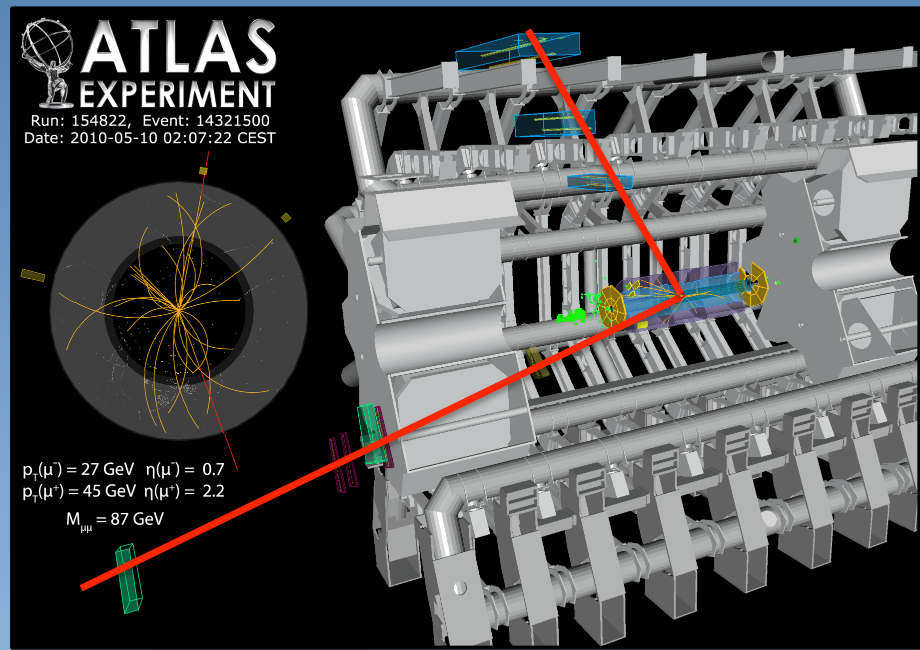


How do you discover a Z particle ?

Deviations from the prediction without a Z boson



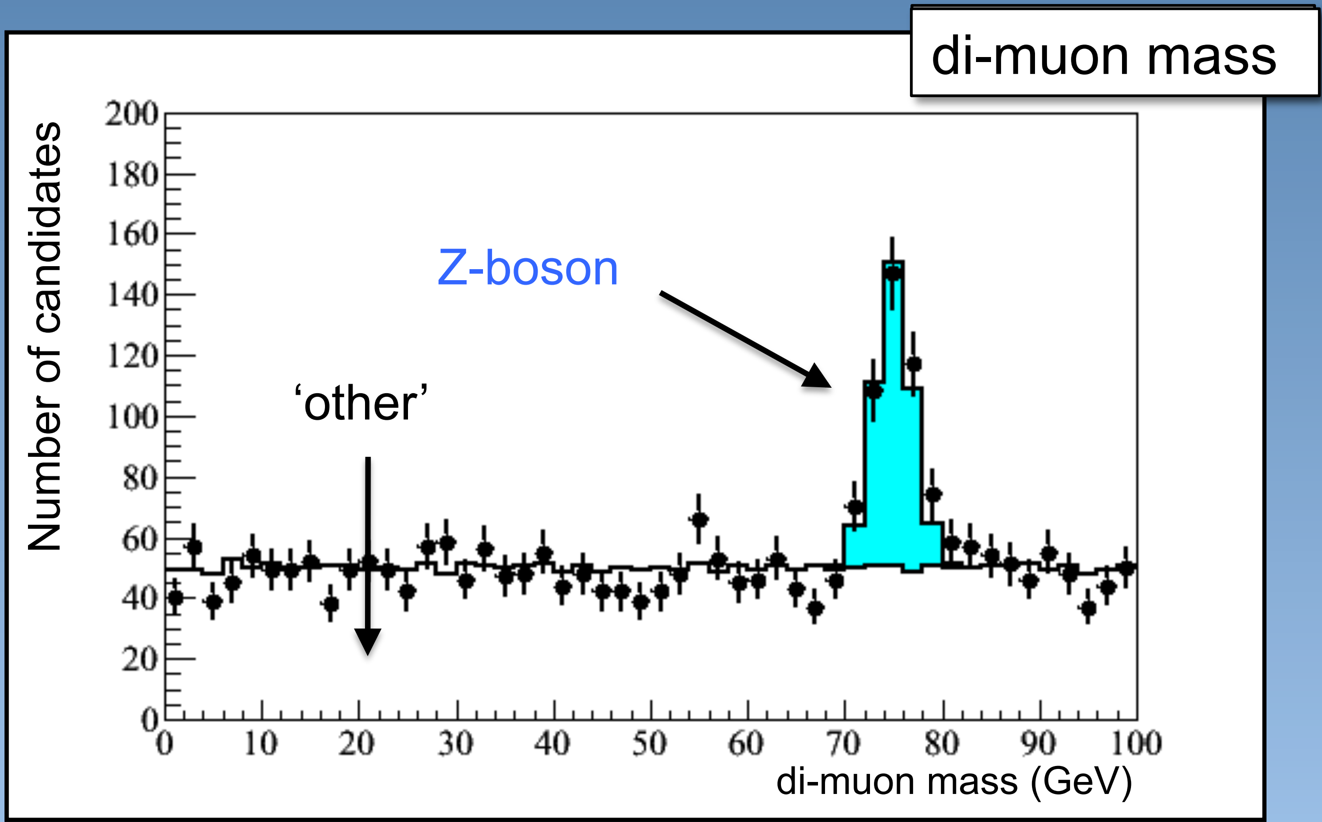
2-muons as seen in the ATLAS detector



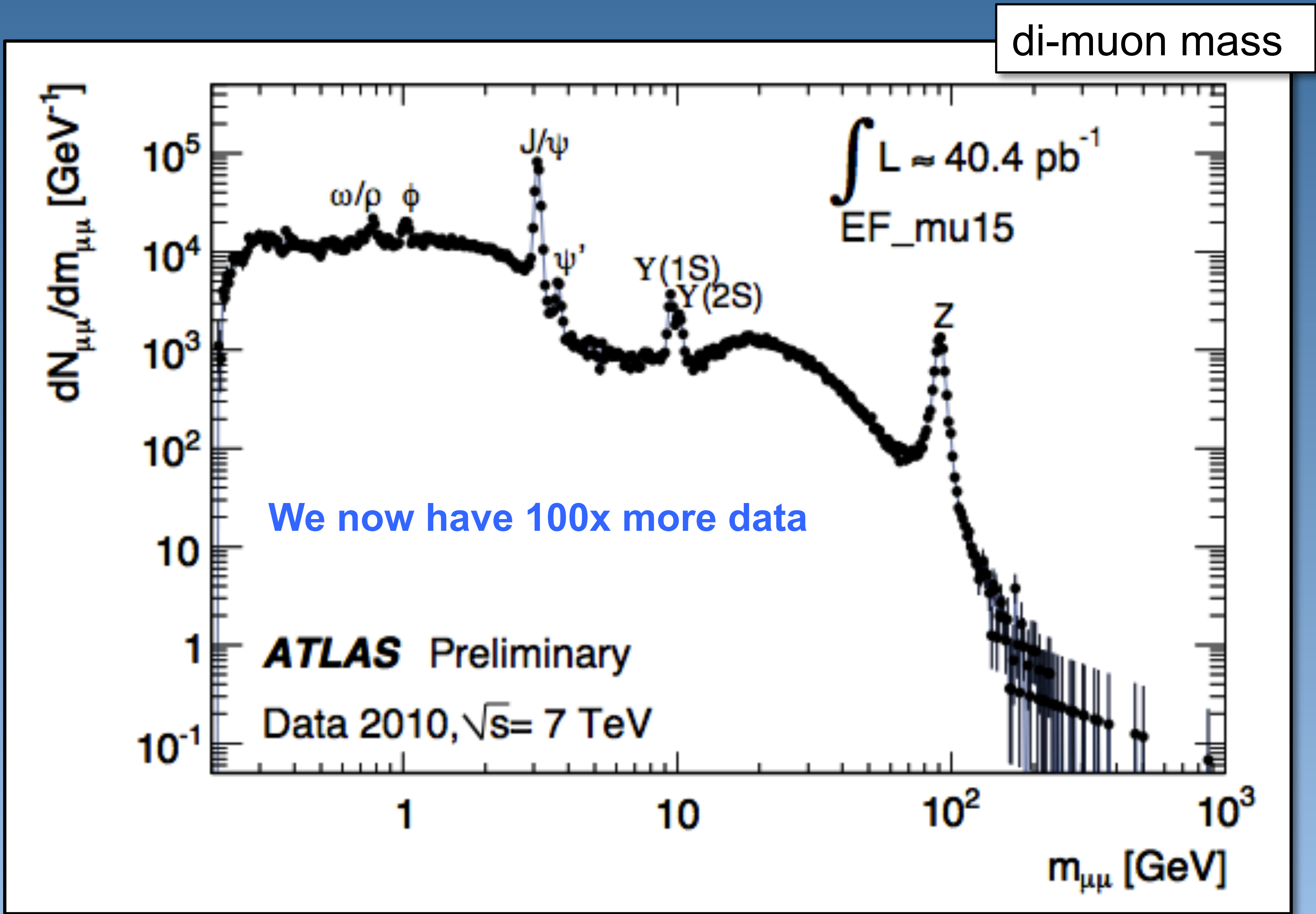
What is the fingerprint of the Z particle:
→ the di-muon mass

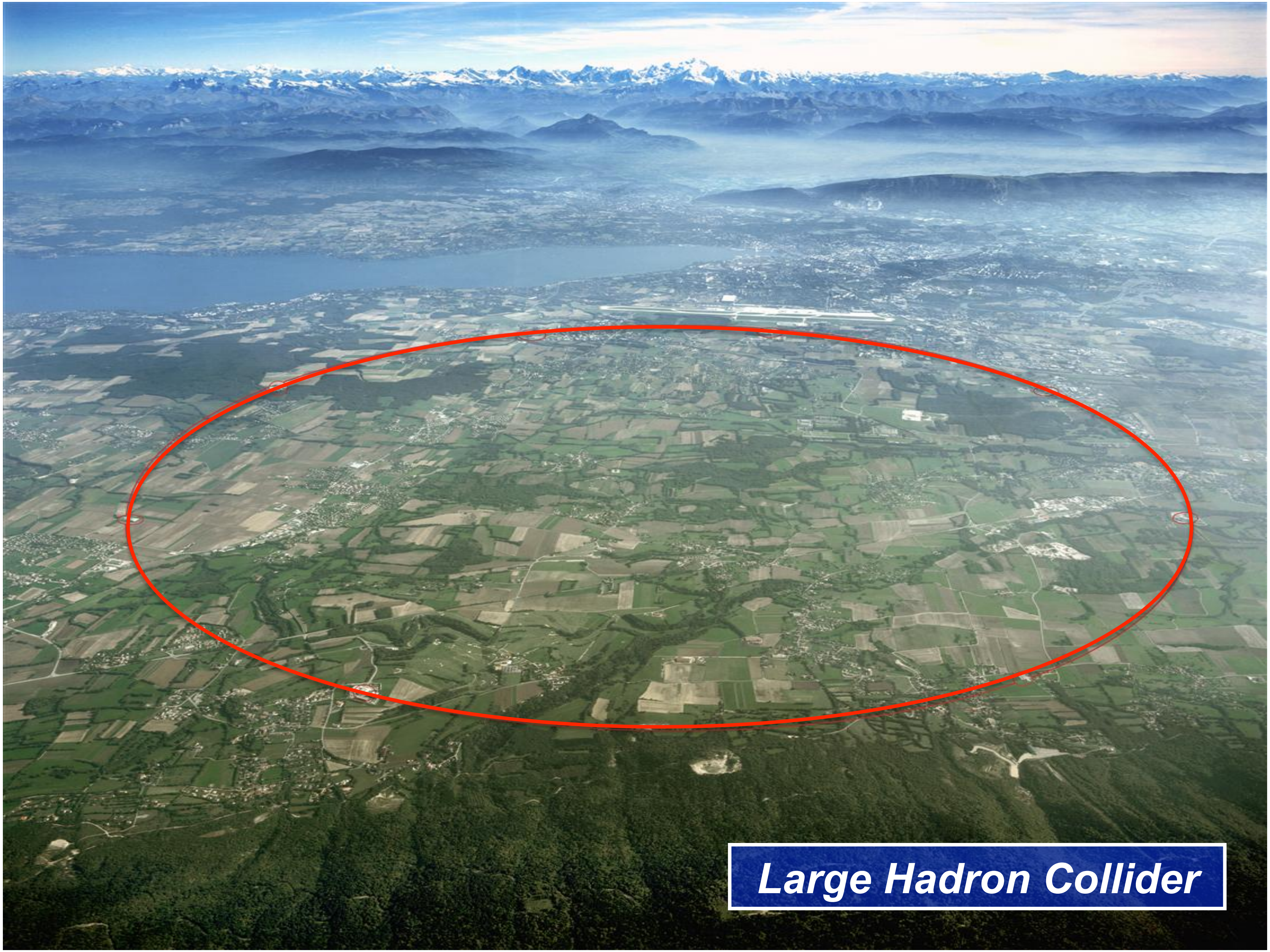
‘other’: no preference/structure

Z-boson: Breit-Wigner ⊗ resolution

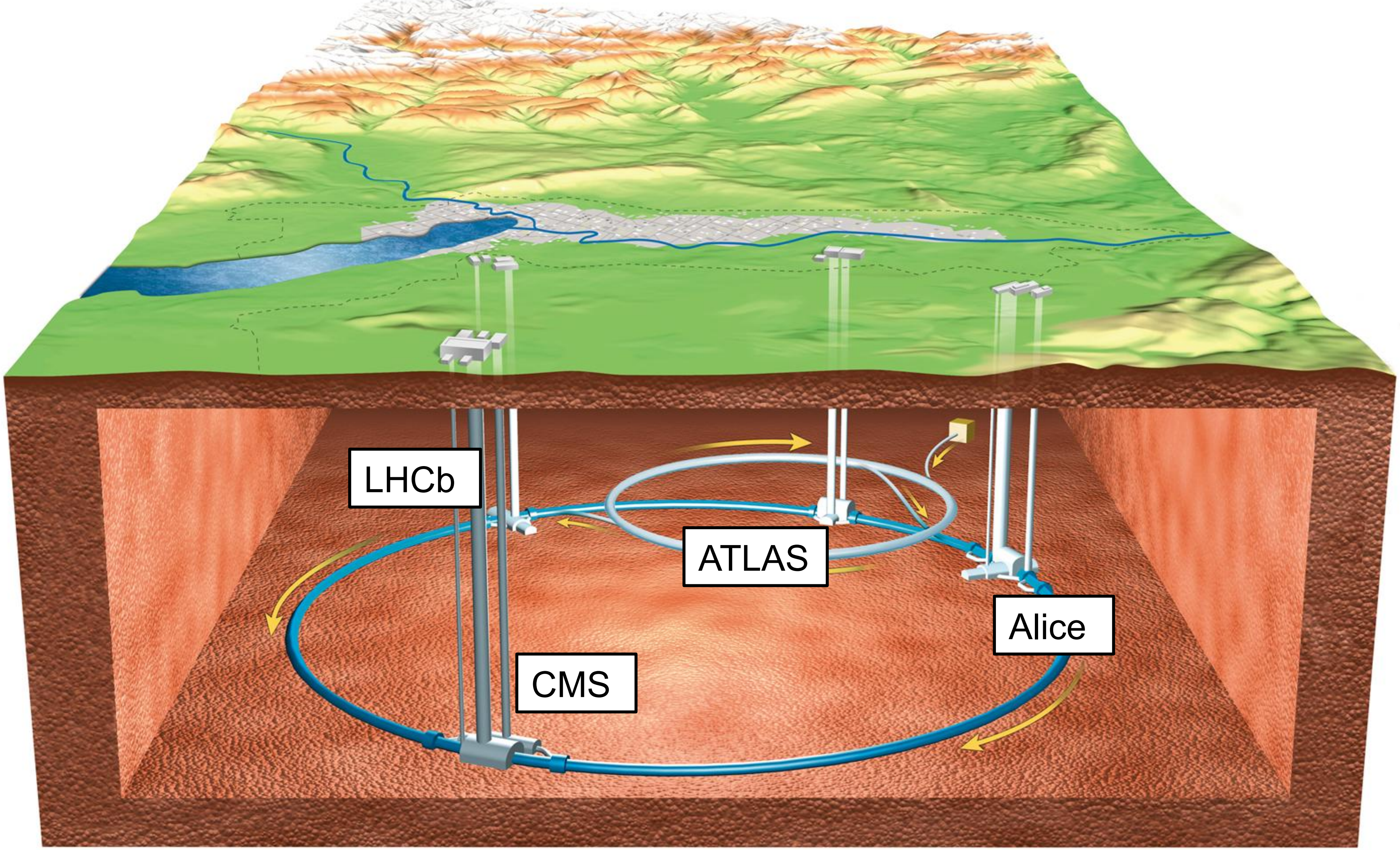


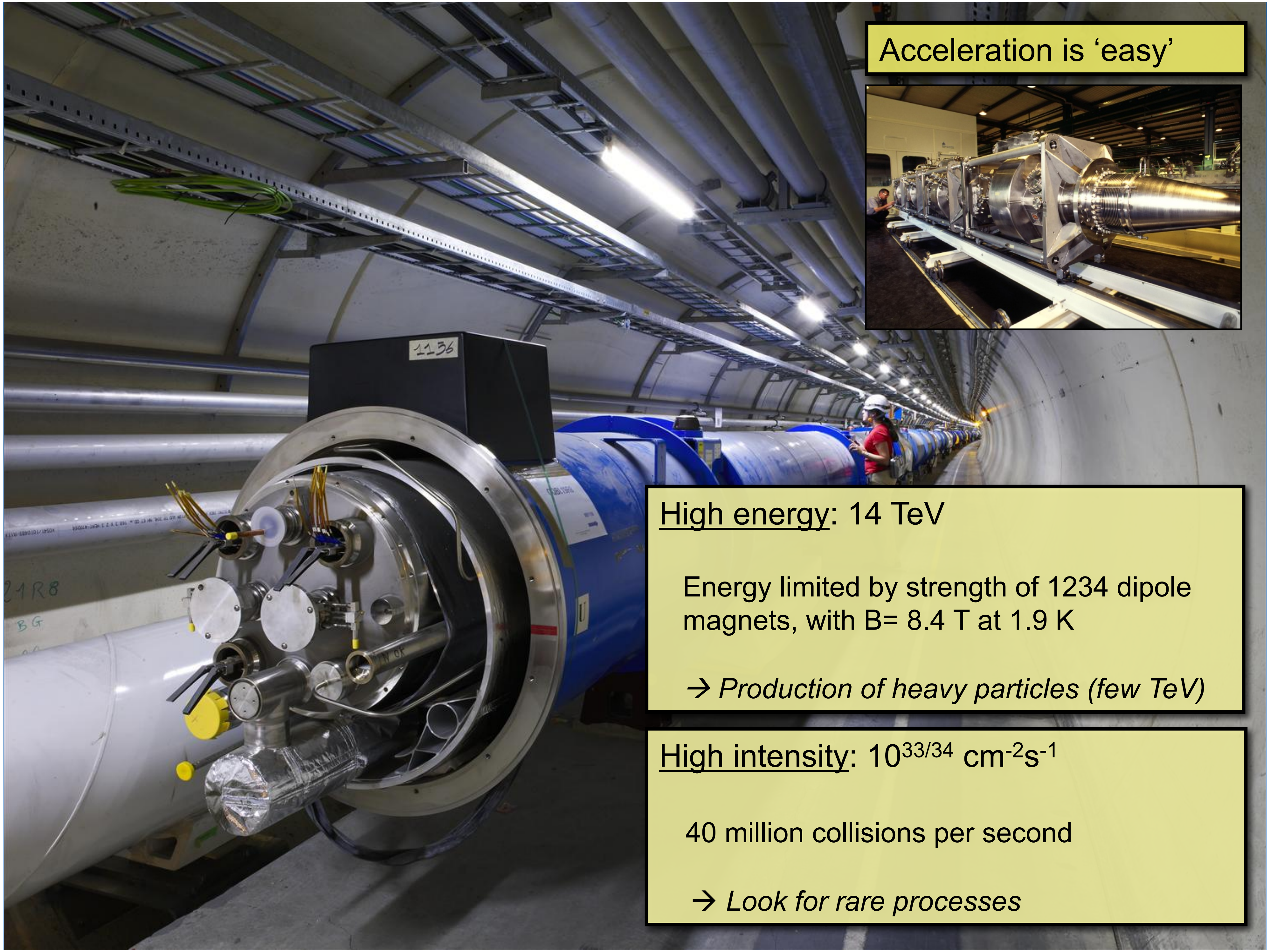
Di-muon resonances in proton-proton




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 T at 1.9 K

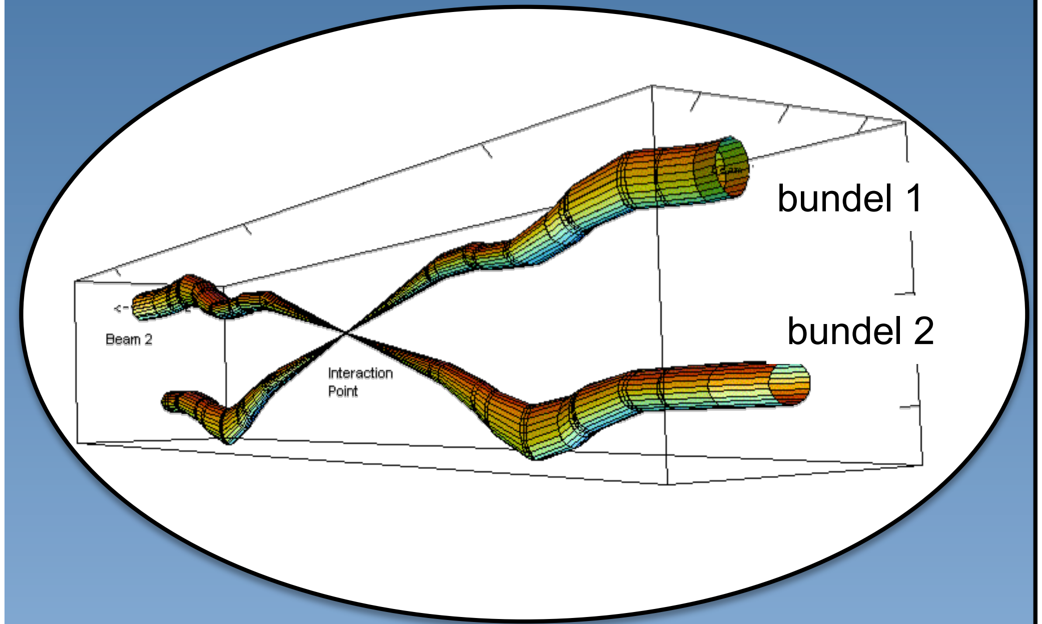
→ *Production of heavy particles (few TeV)*

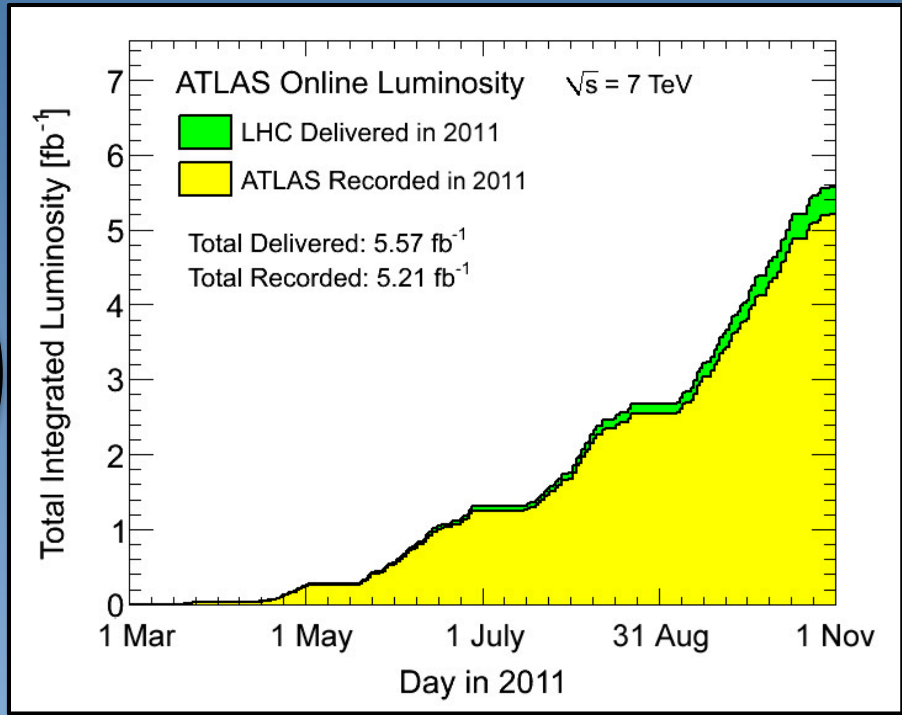
High intensity: $10^{33/34}$ $cm^{-2}s^{-1}$

40 million collisions per second

→ *Look for rare processes*

LHC 2012 data-set





- 40 million collisions per second

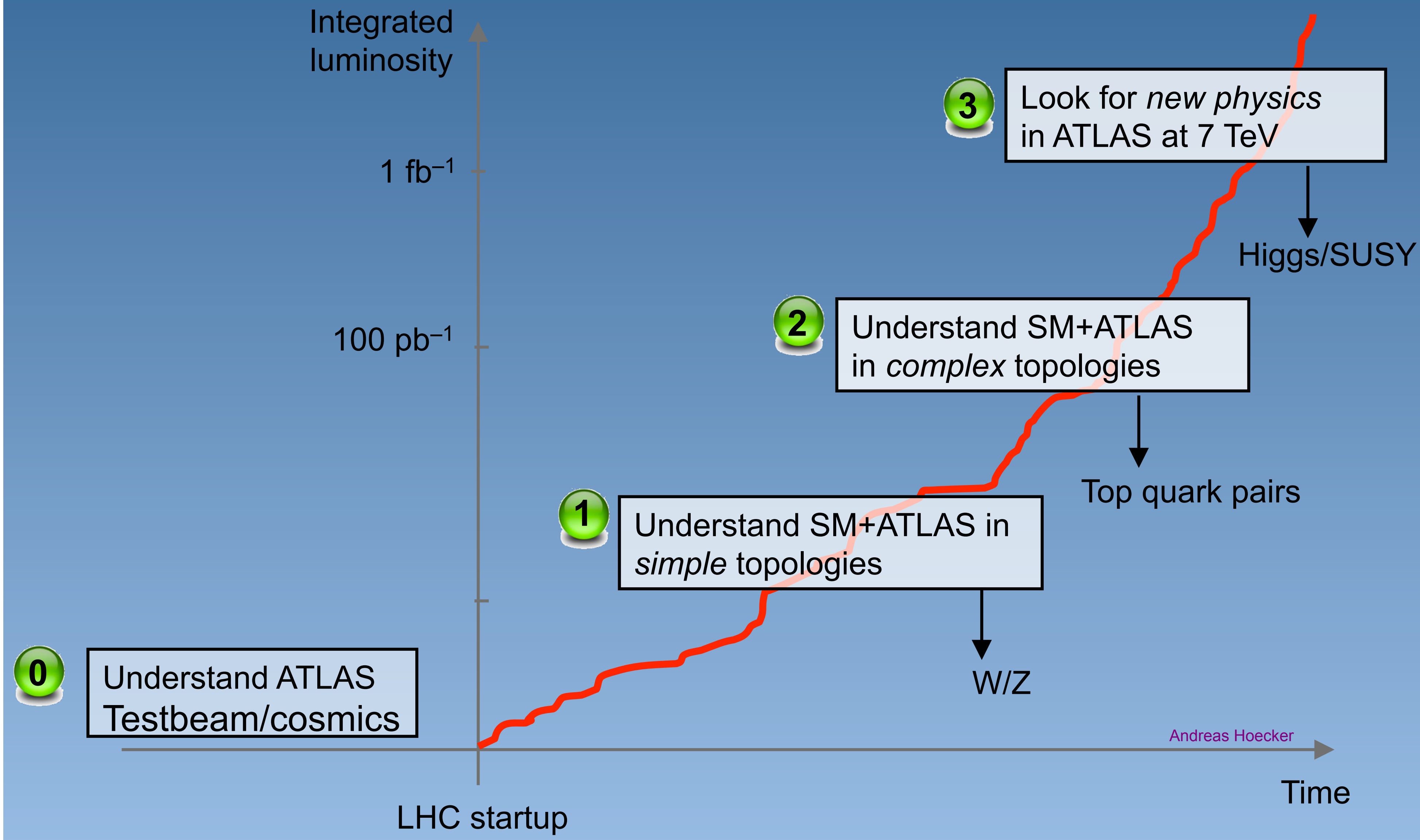
Only 200 Hz to tape

Peak Luminosity = $3.65*10^{33}$ cm^2 s^{-1}

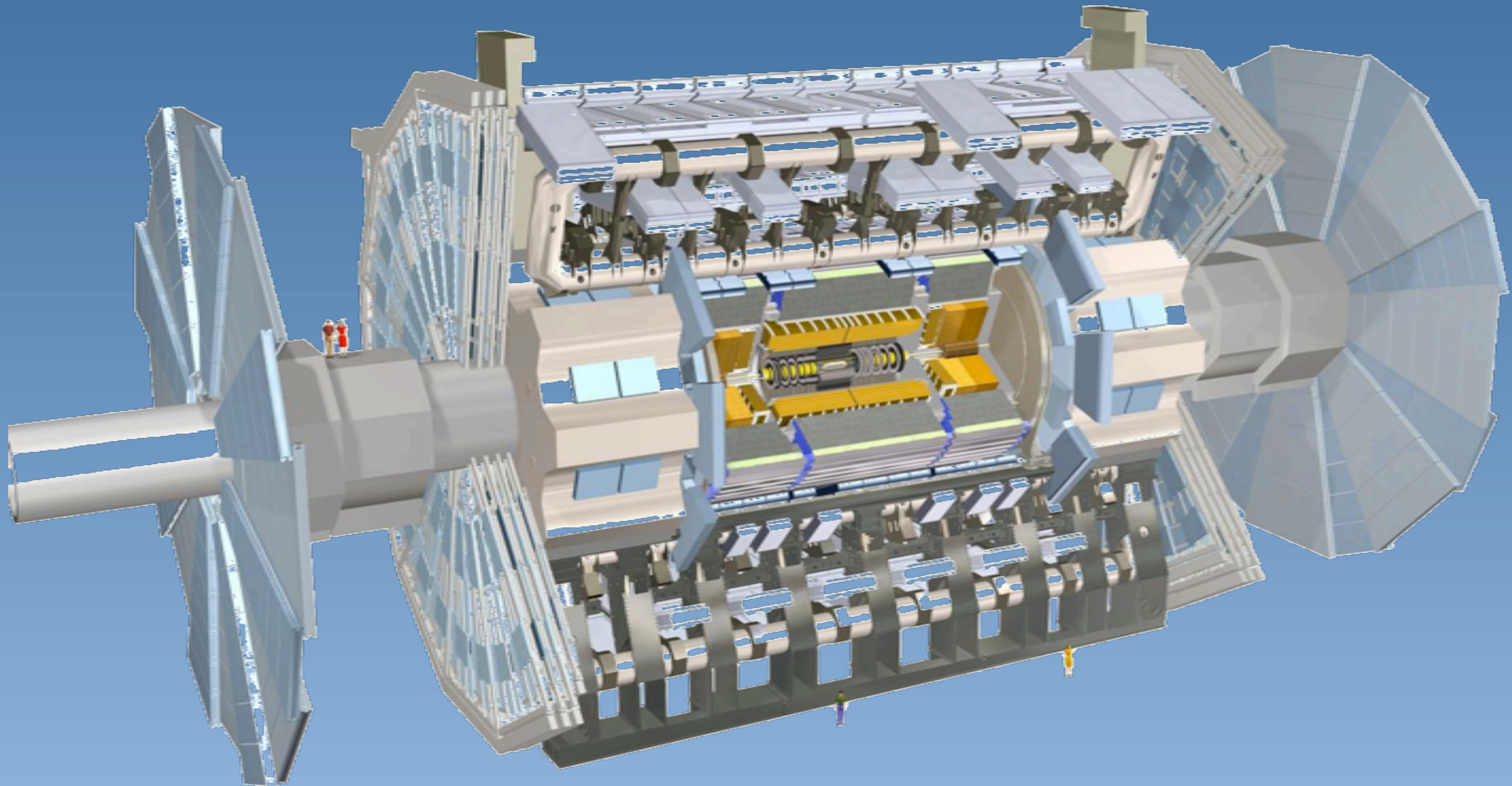
Limited Trigger rate: 200 Hz

LHC start-up programme

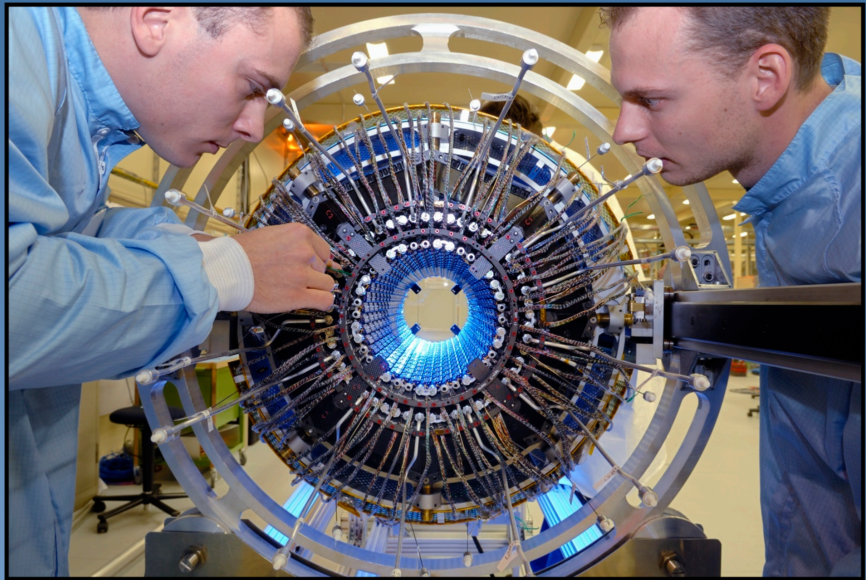
New detector **and** new energy scale

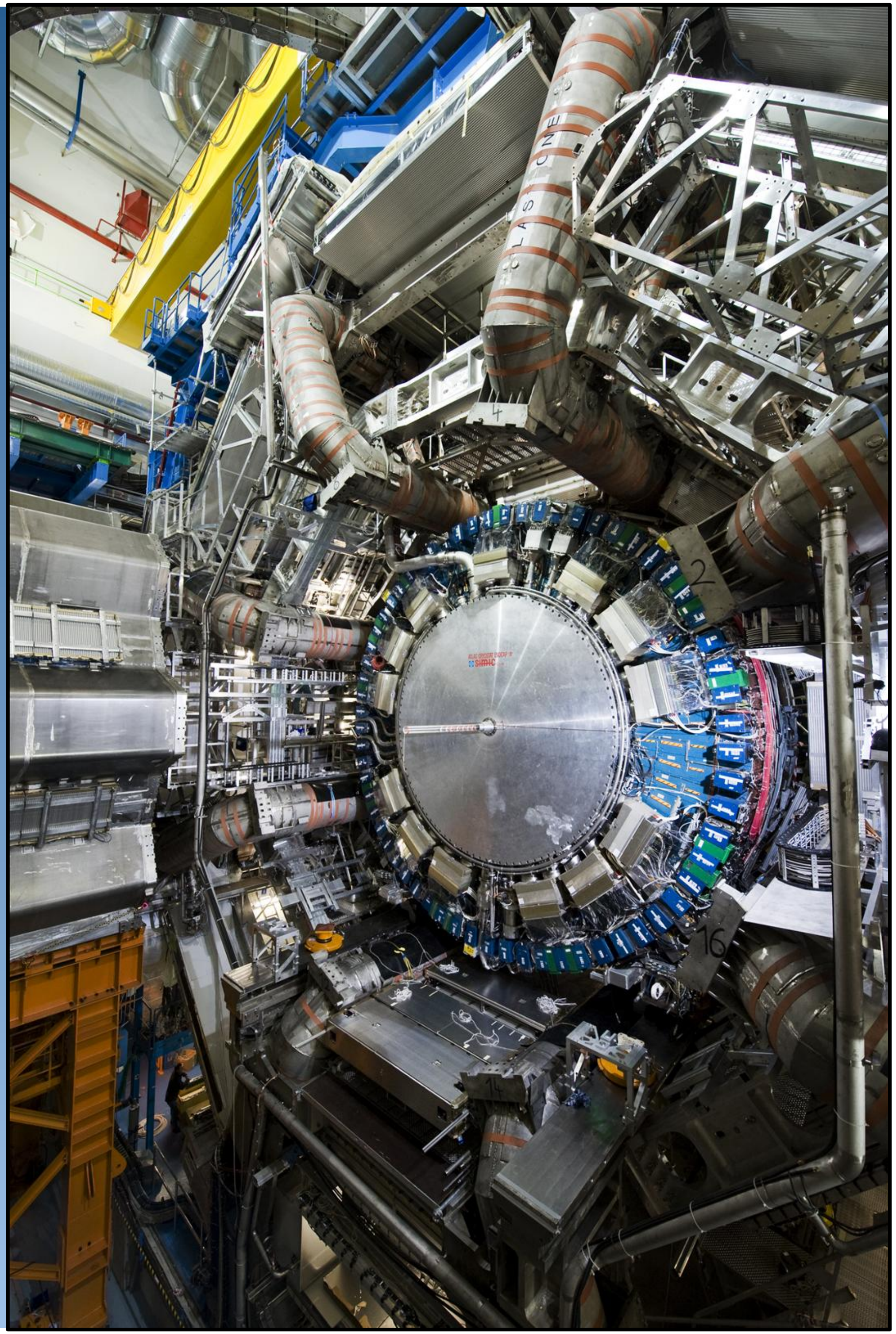


The ATLAS detector
(as a computer model)



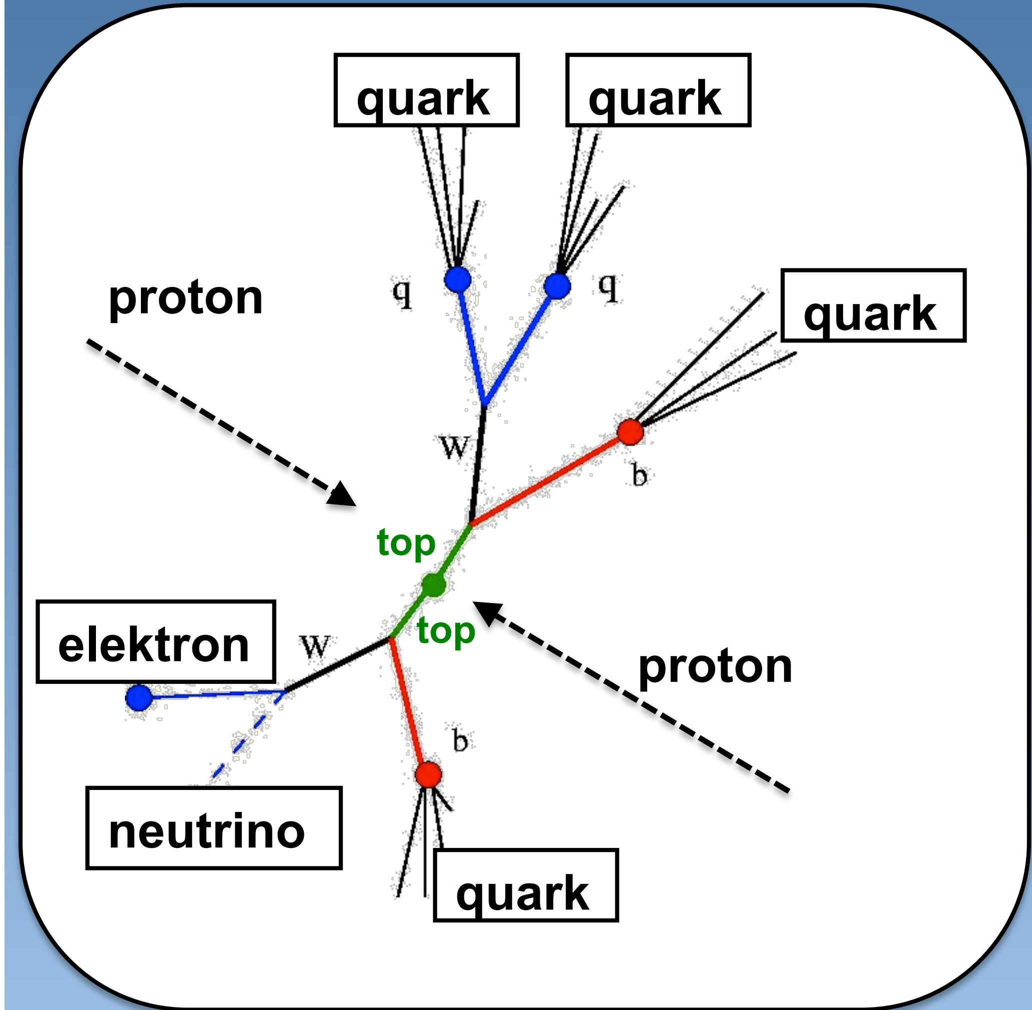
The ATLAS detector
(in real life)



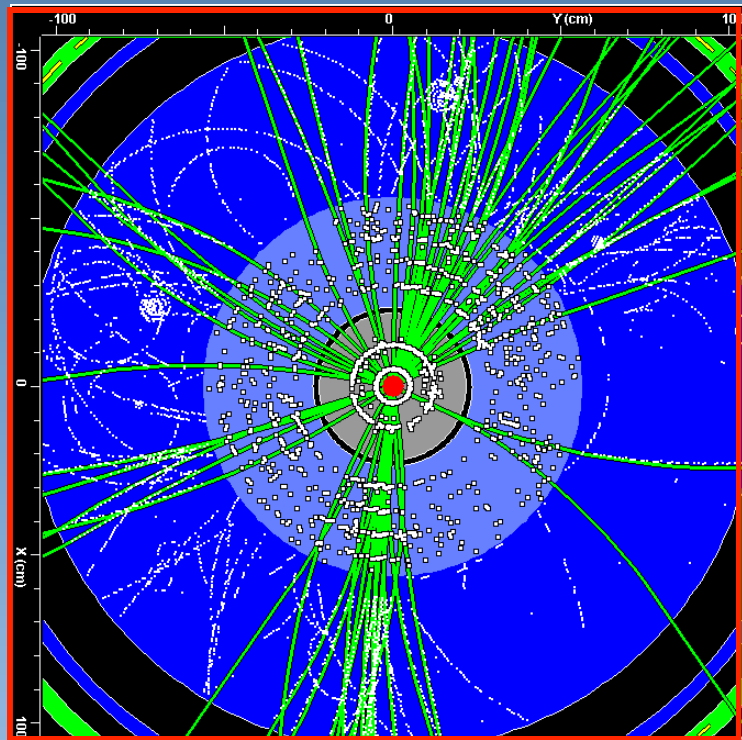


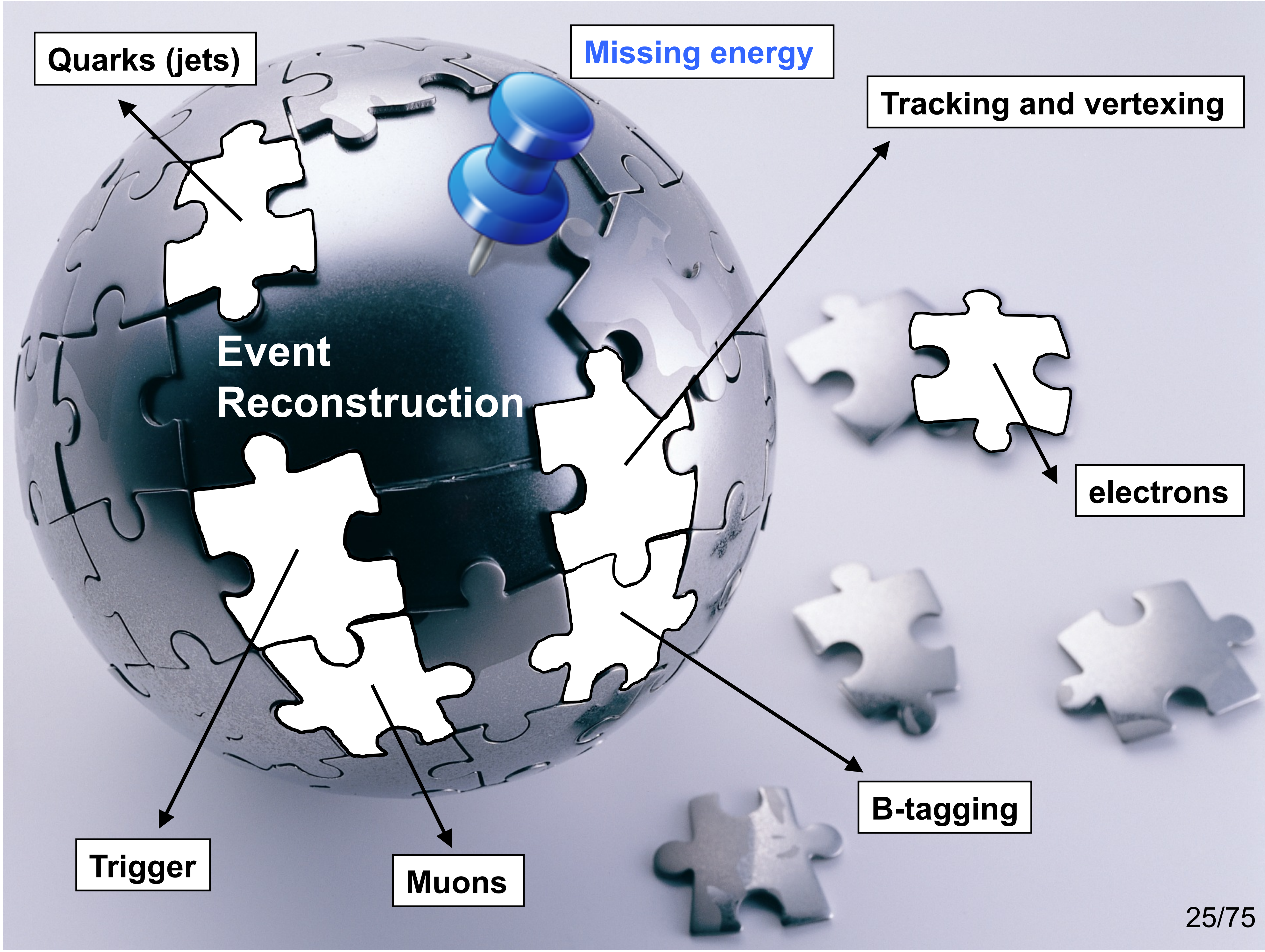
Interpreting LHC events

top quark pair-production



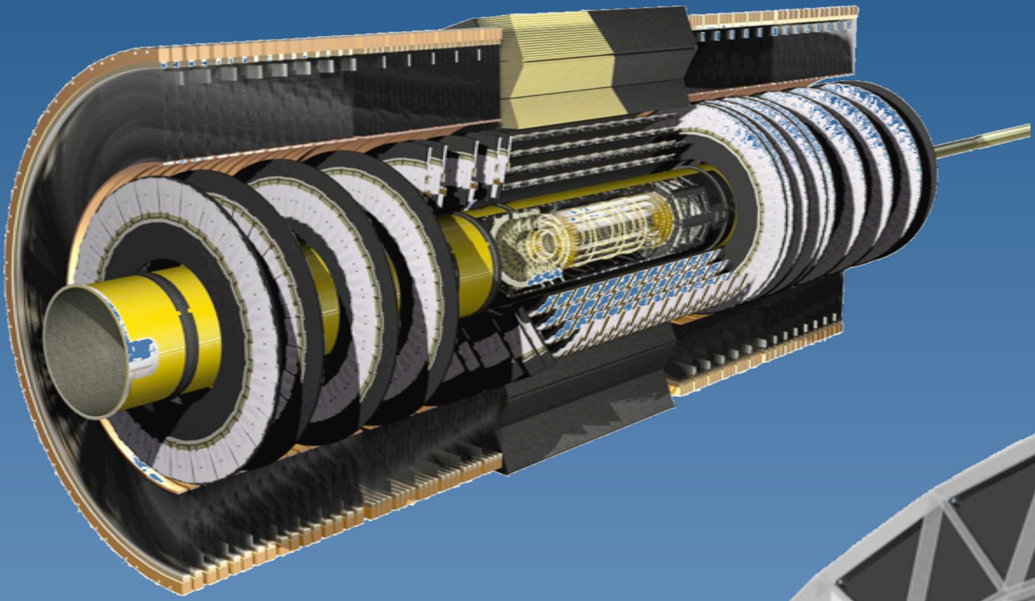
Simulation top quark production



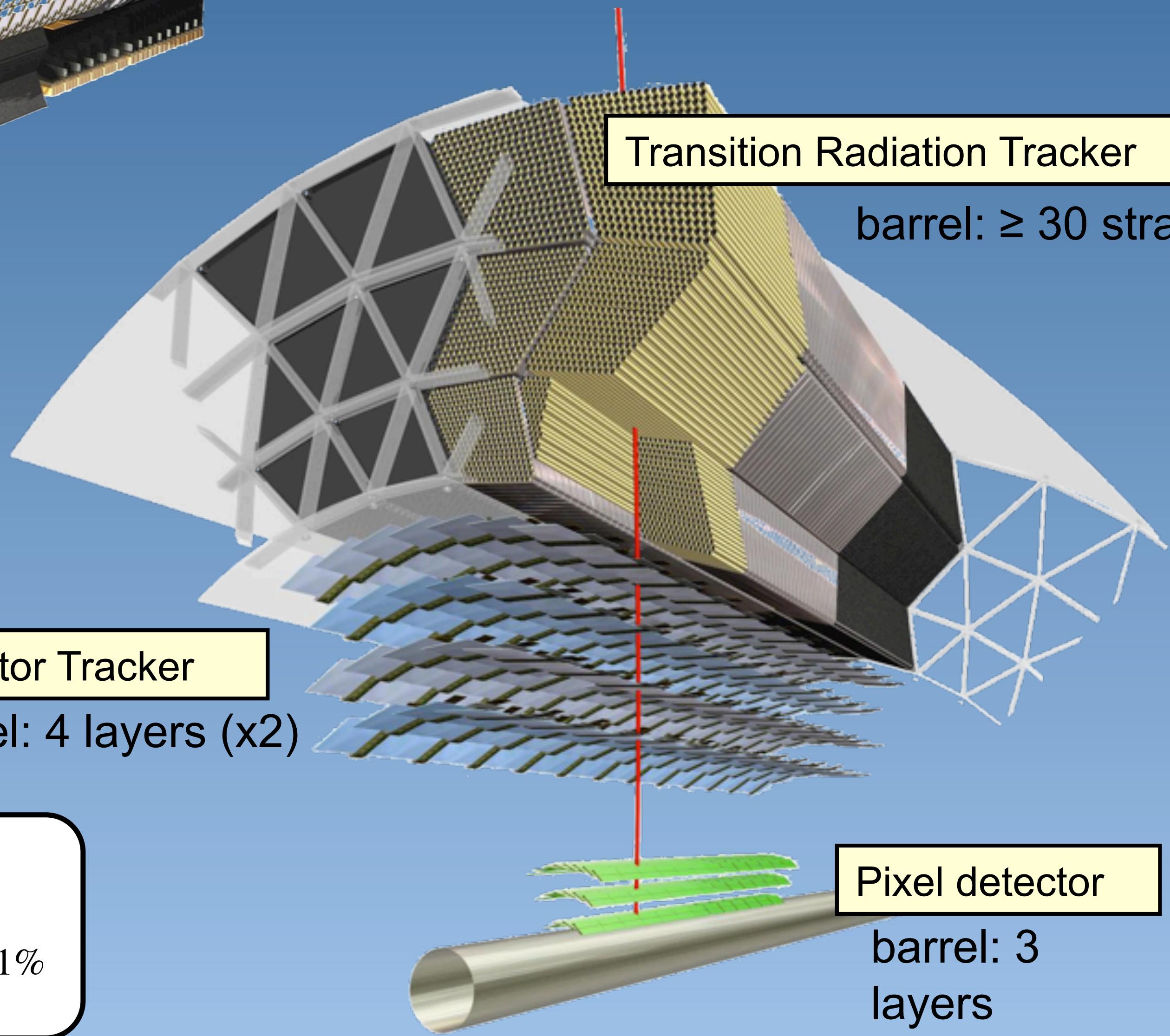


Quarks (jets)
Missing energy
Tracking and vertexing
Event Reconstruction
electrons
B-tagging
Trigger
Muons

Inner detector



ATLAS inner detector

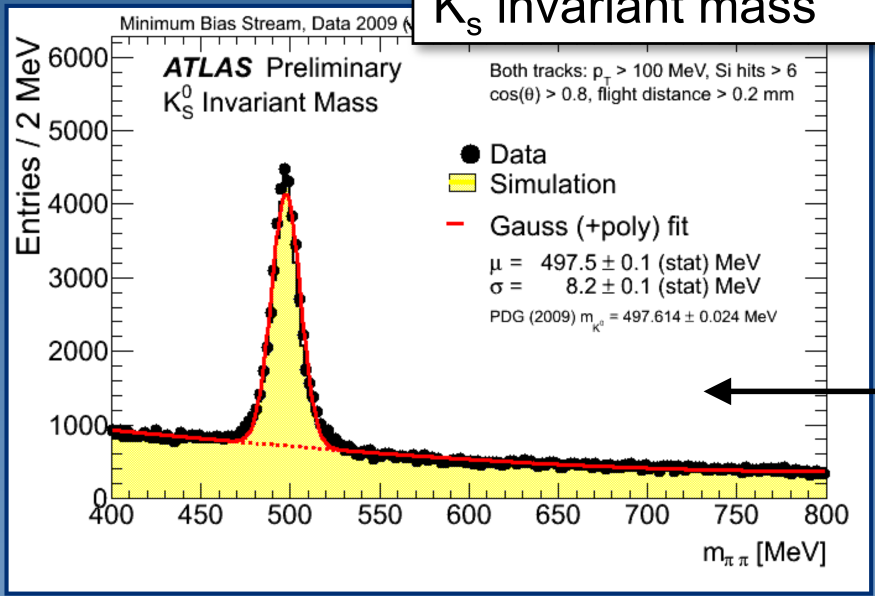


3 systems in 2 T solenoid

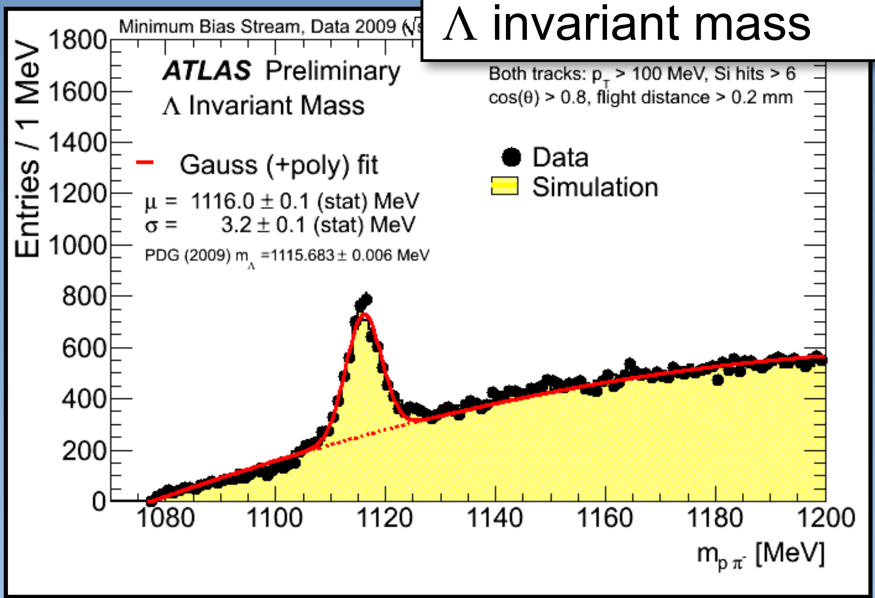
$|\eta| < 2.5$ $$\frac{\sigma_{p_T}}{p_T} = 0.05\%\ p_T \oplus 1\%$$

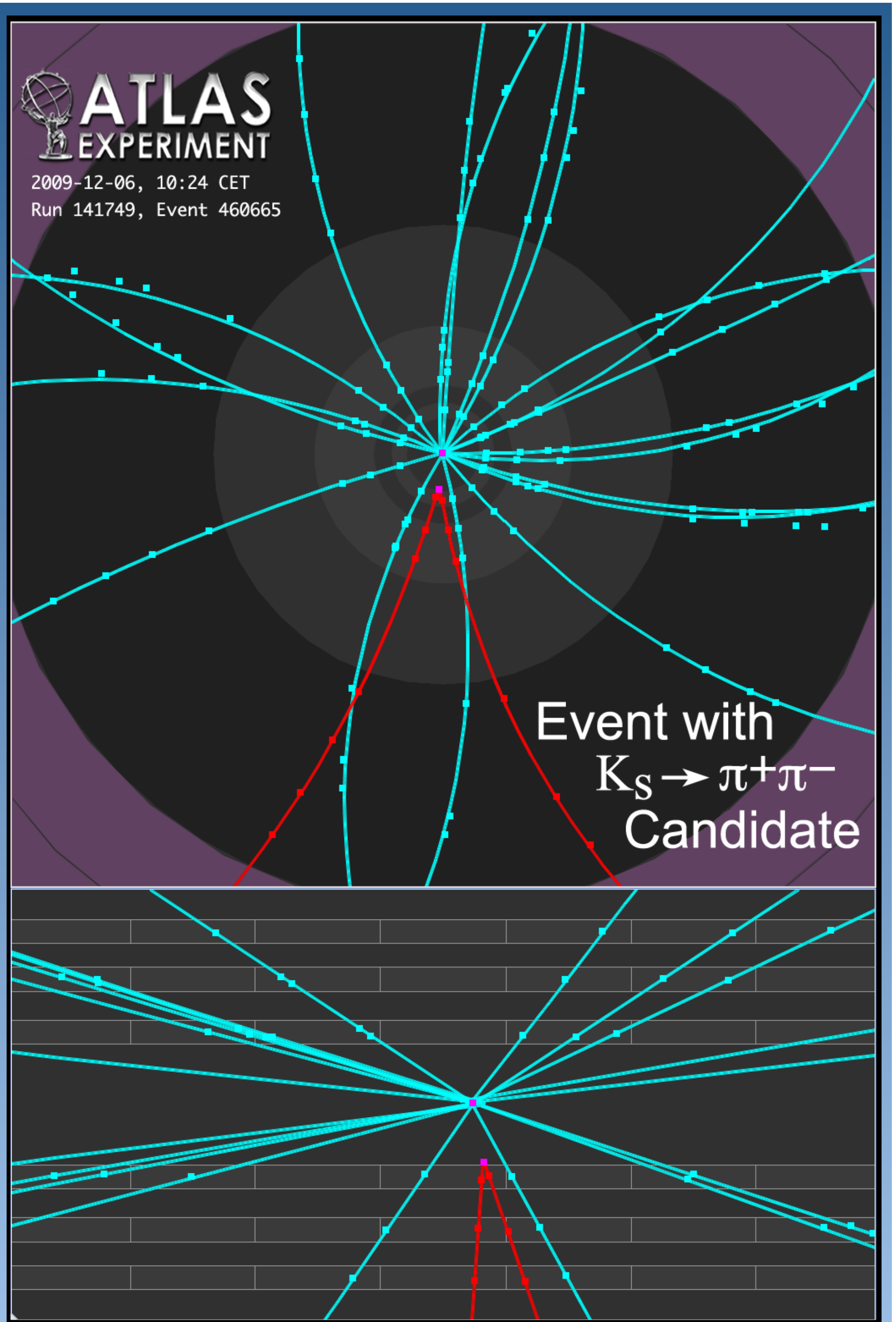
Secondary vertices

K_s invariant mass

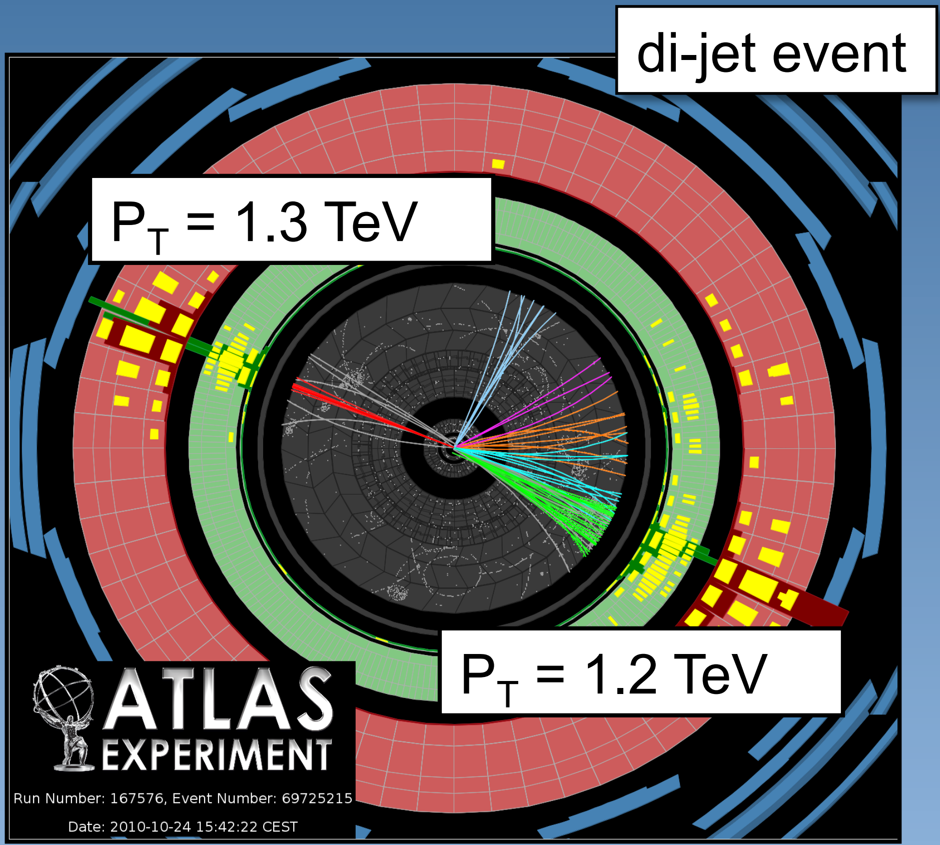


Λ invariant mass

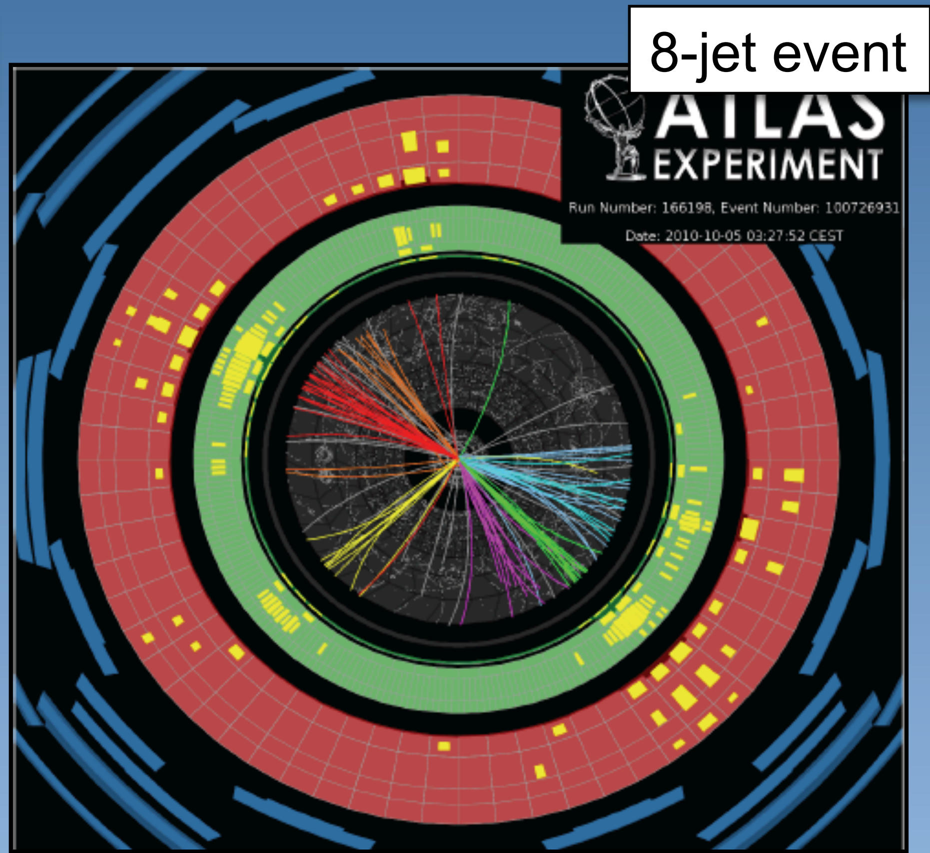




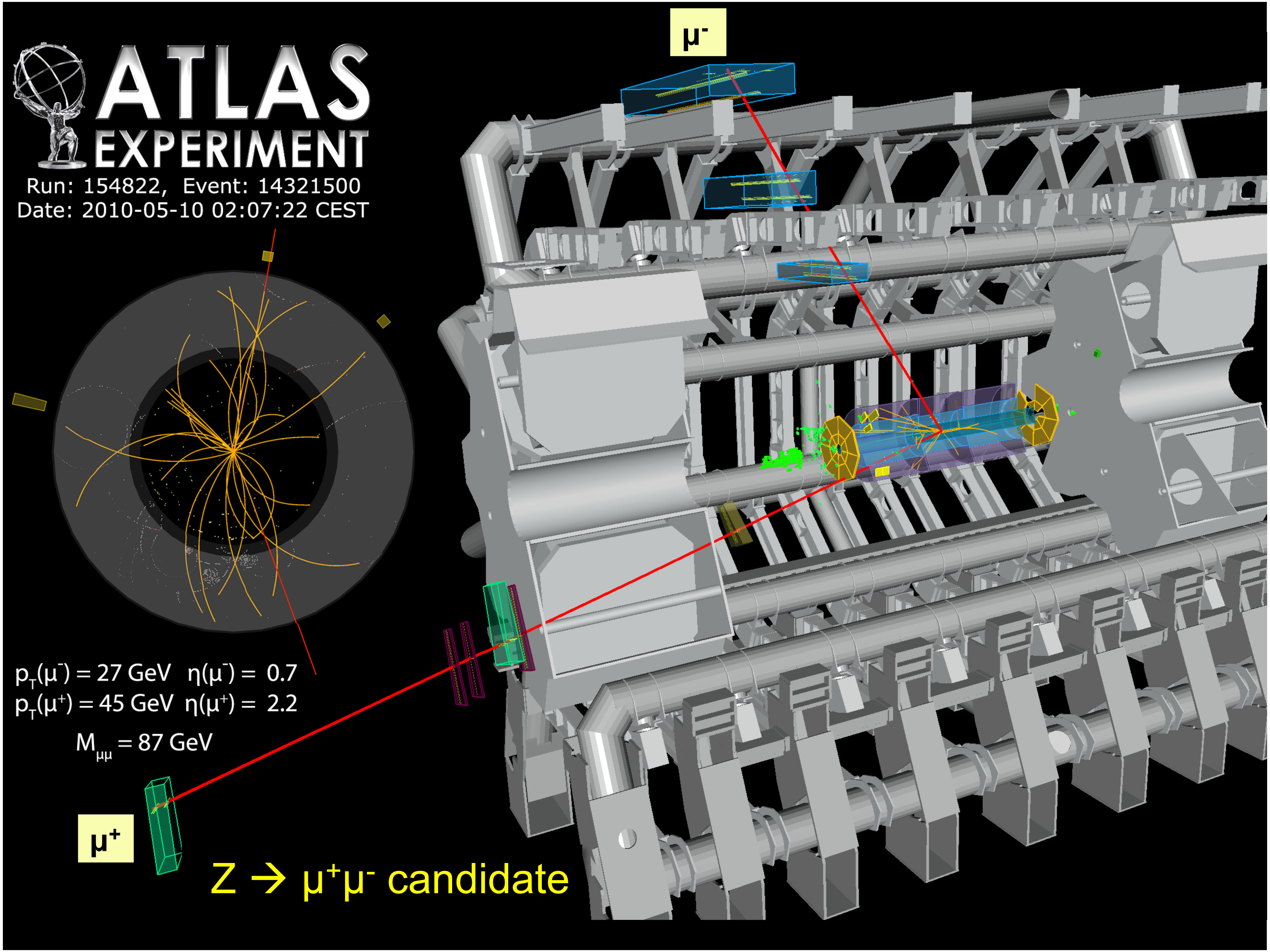
Quark (jet) reconstruction

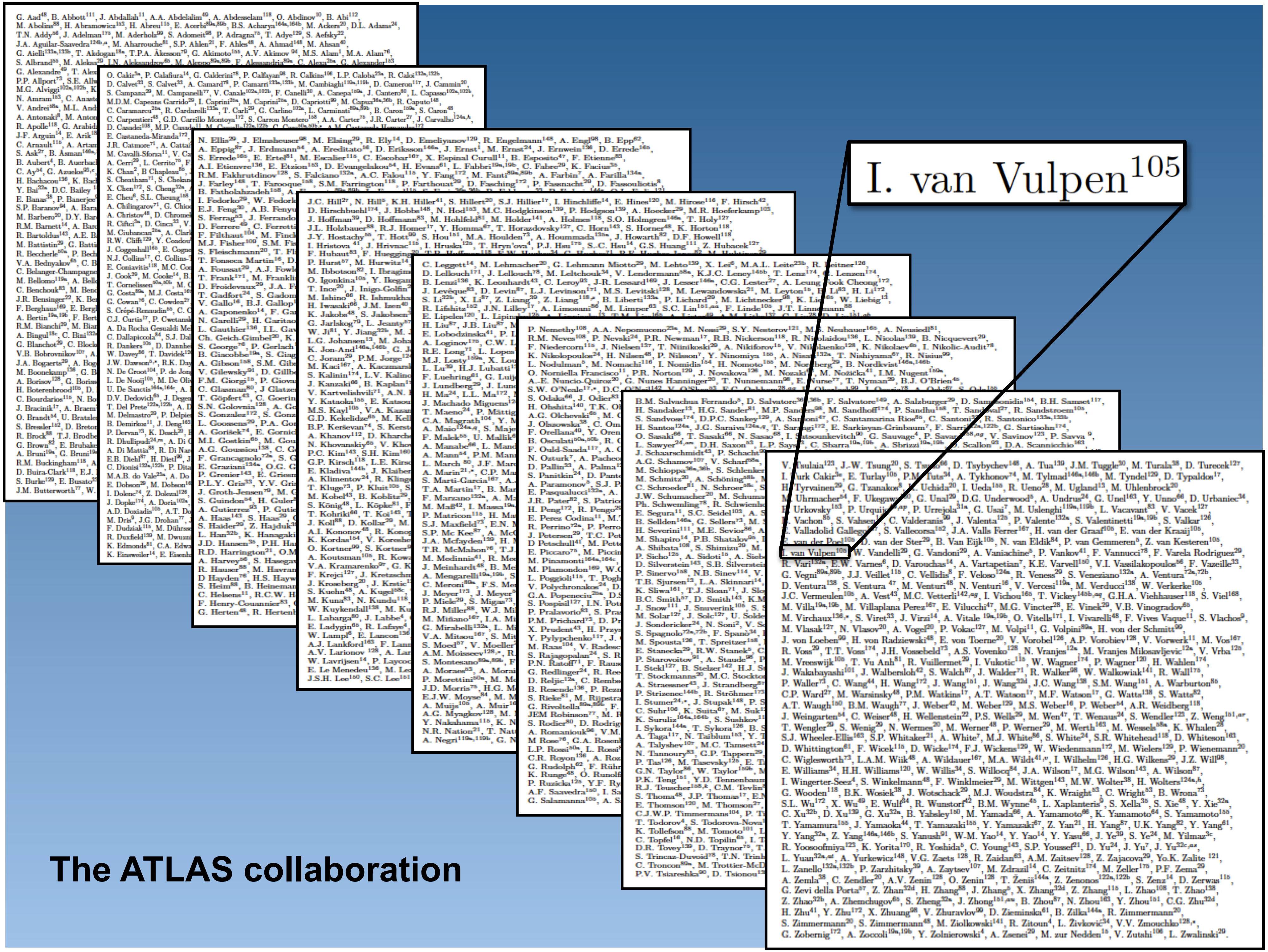


High transverse momentum



Multi-jet: 8 jets with P_T > 60 GeV


ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
μ-
μ+
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z → $\mu^+\mu^-$ candidate

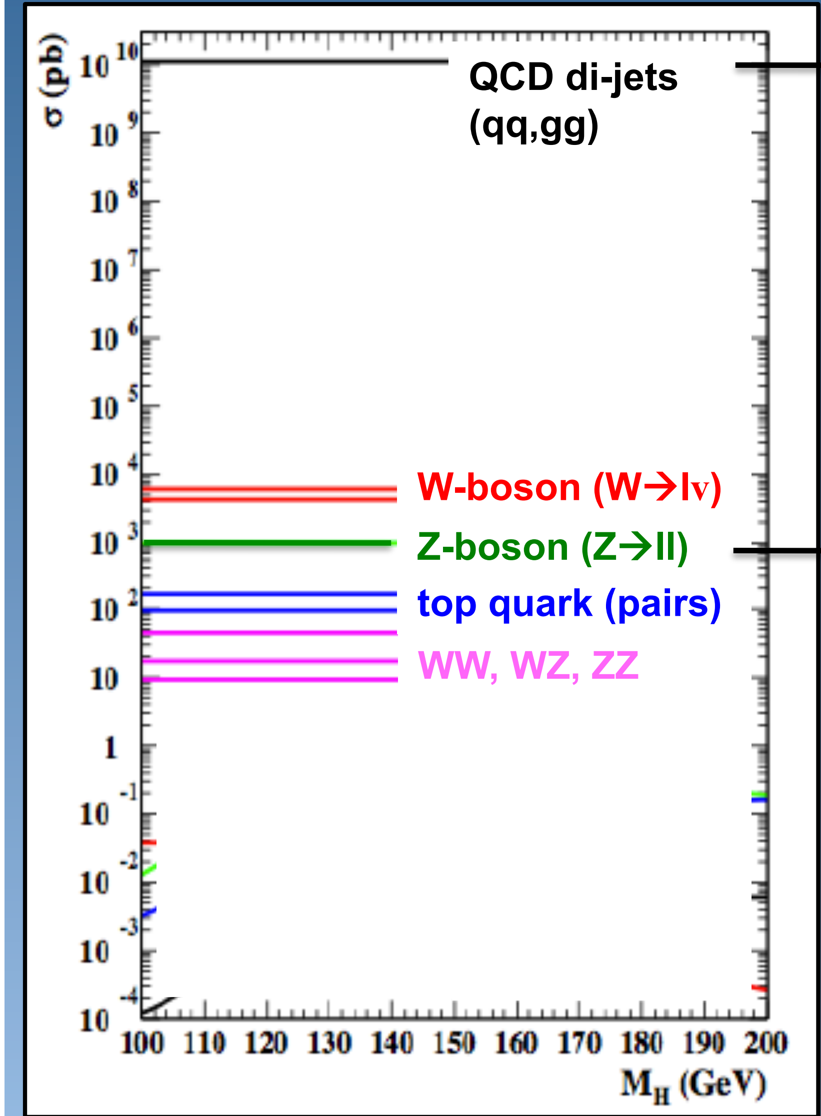


The ATLAS collaboration


Trigger:
From 40 MHz (LHC) to a few hundred Hz
Bottleneck: disk space
Selecting interesting physics from a background of 10^13 events

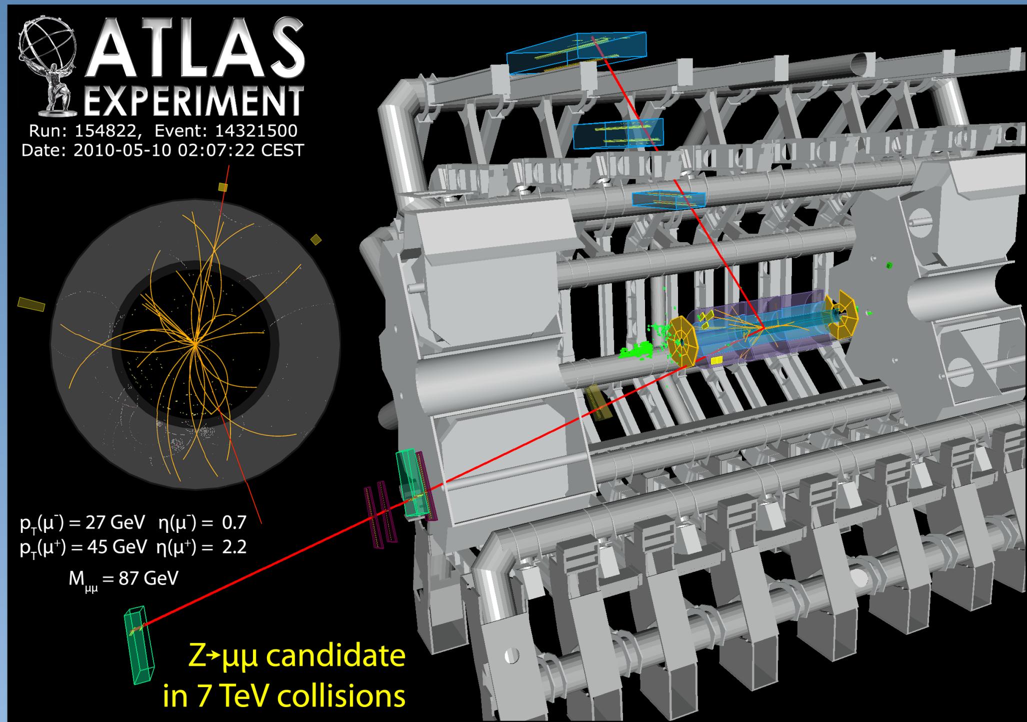
Standard Model processes at the LHC

predicted cross-sections



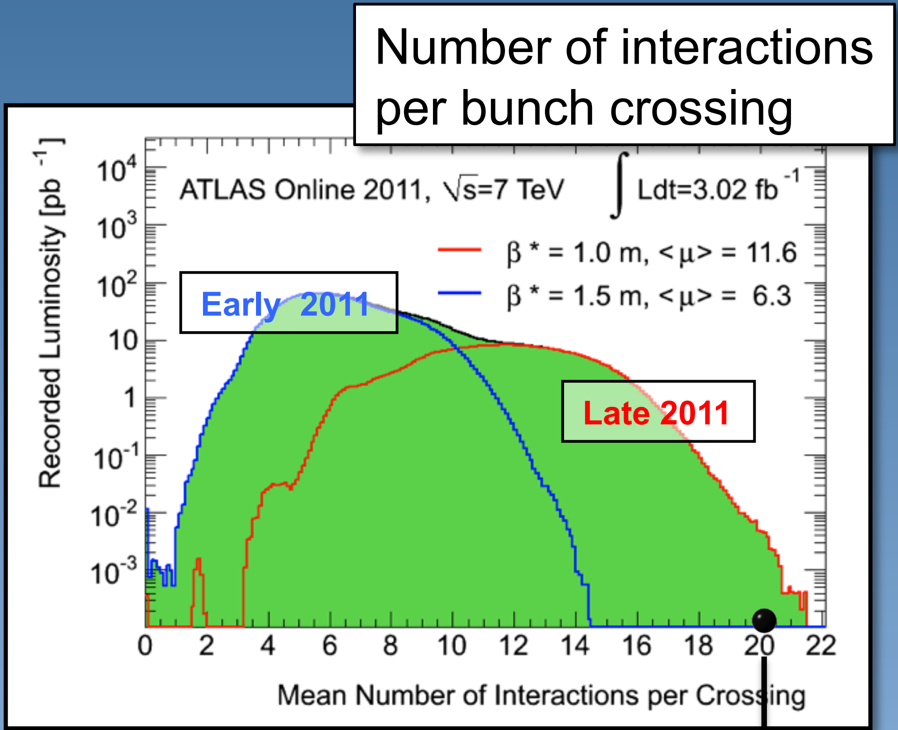
Jets, jets, jets: any signal without leptons is impossible to extract from di-jet background → high-P_T lepton triggers

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

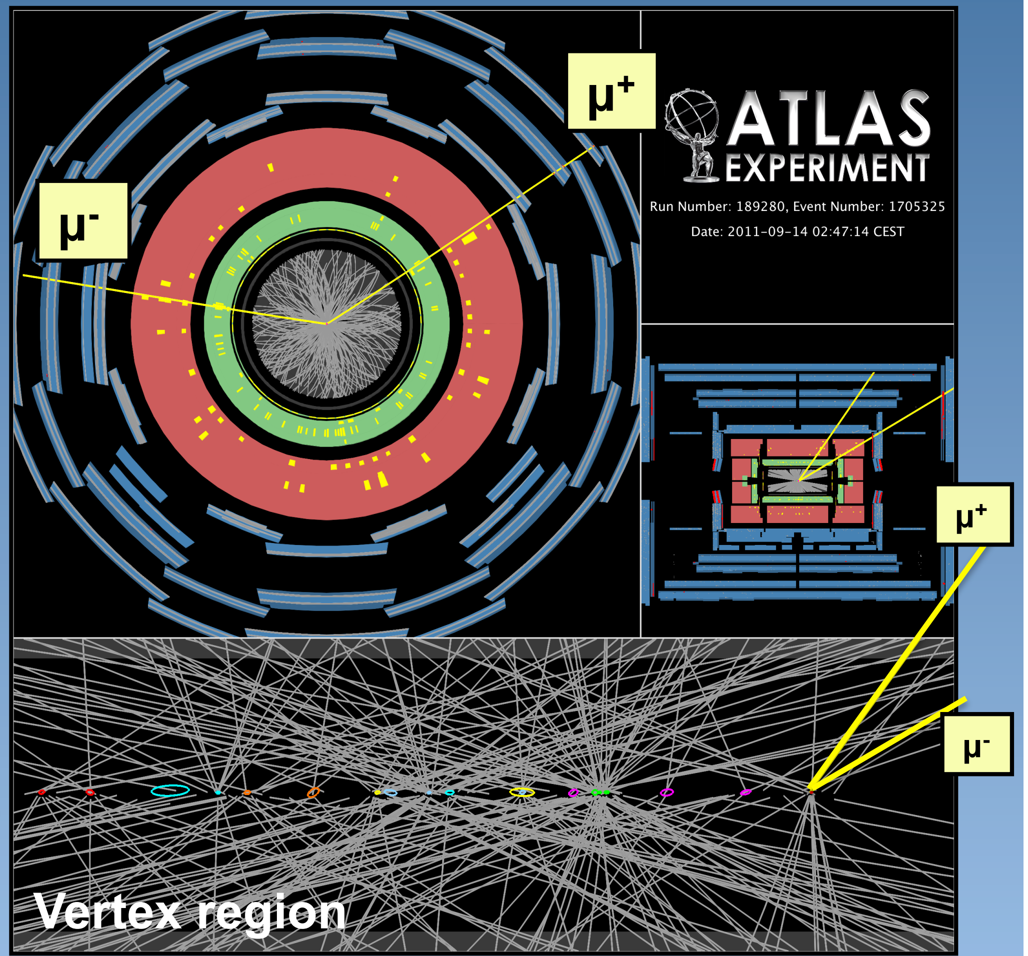


"LHC: strong machine for weak physics"

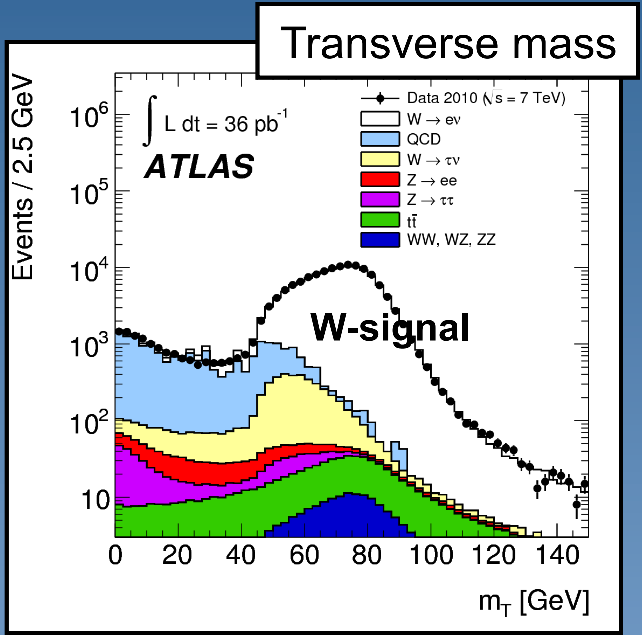
LHC is not a quiet environment

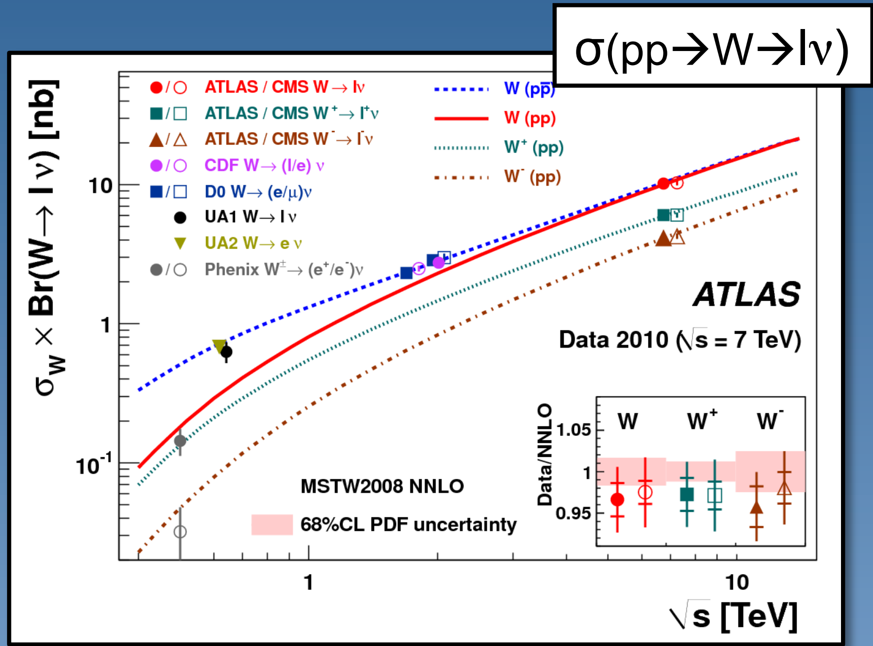


Z →μ⁺μ⁻ event with 20 vertices

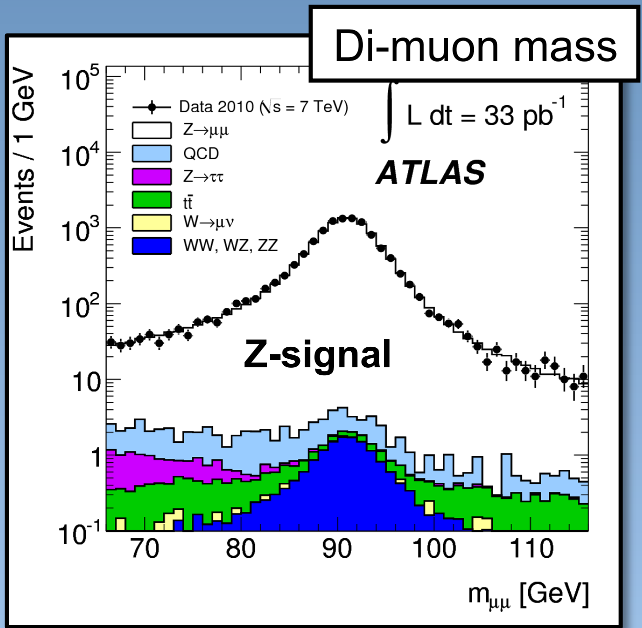


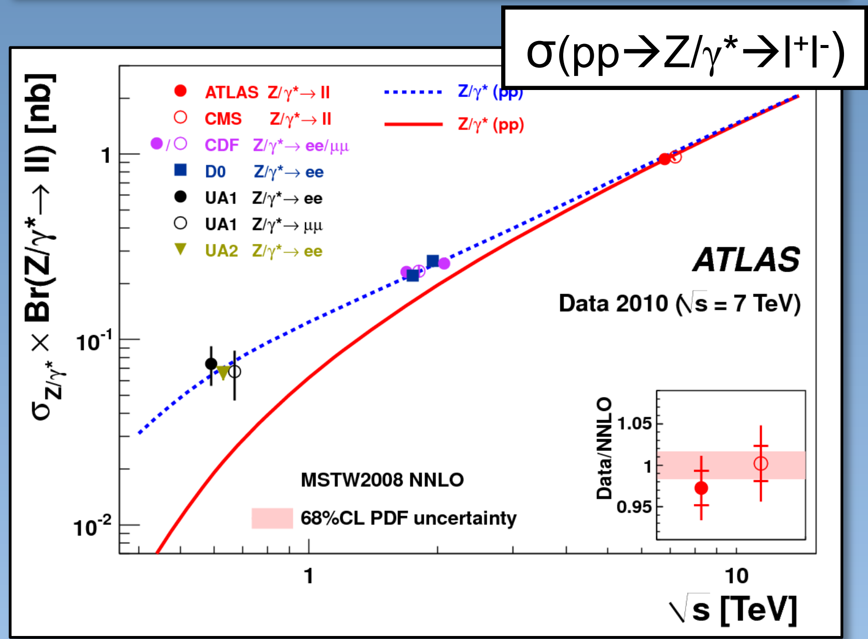
W and Z boson production at the LHC





W-boson

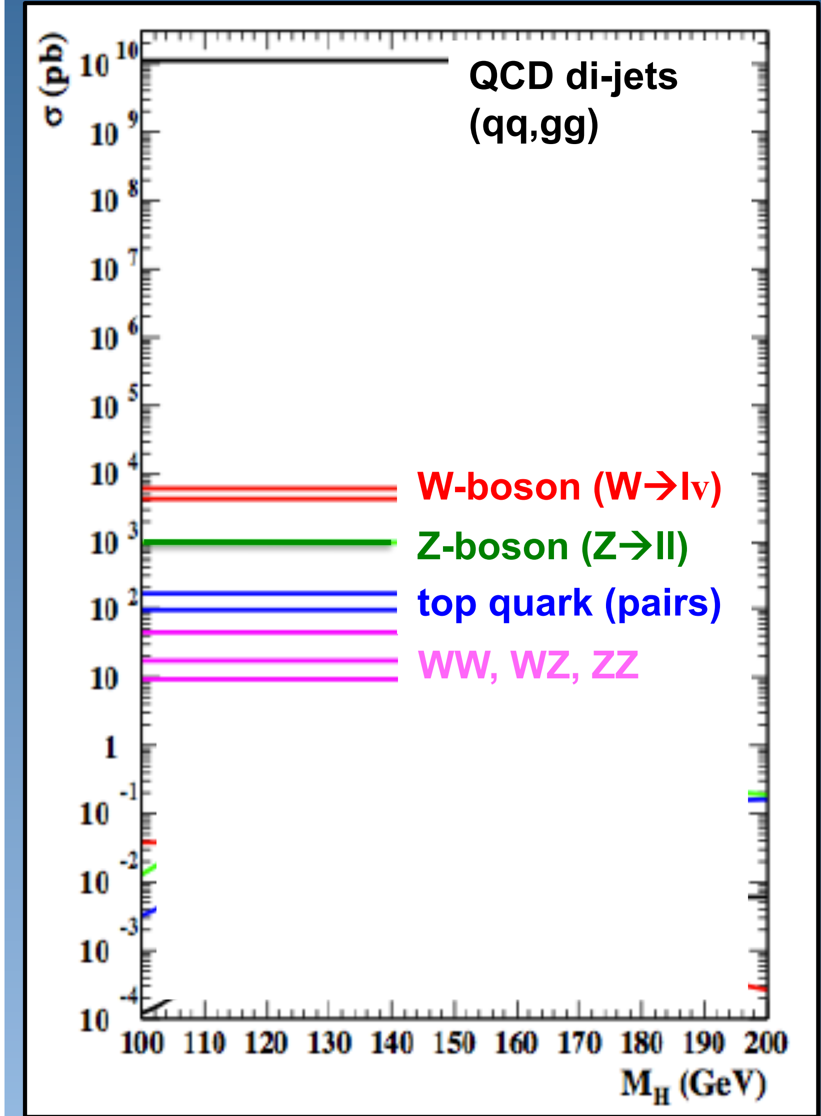




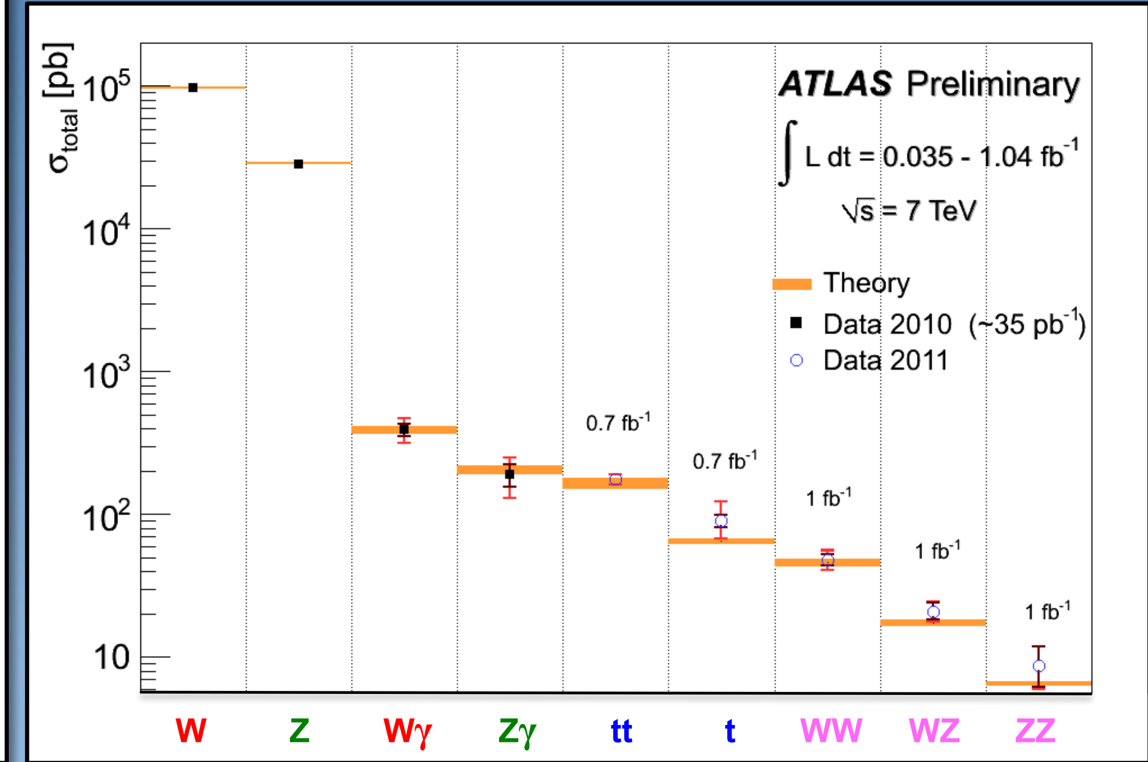
Z/γ*-boson

Standard Model processes at the LHC

predicted cross-sections

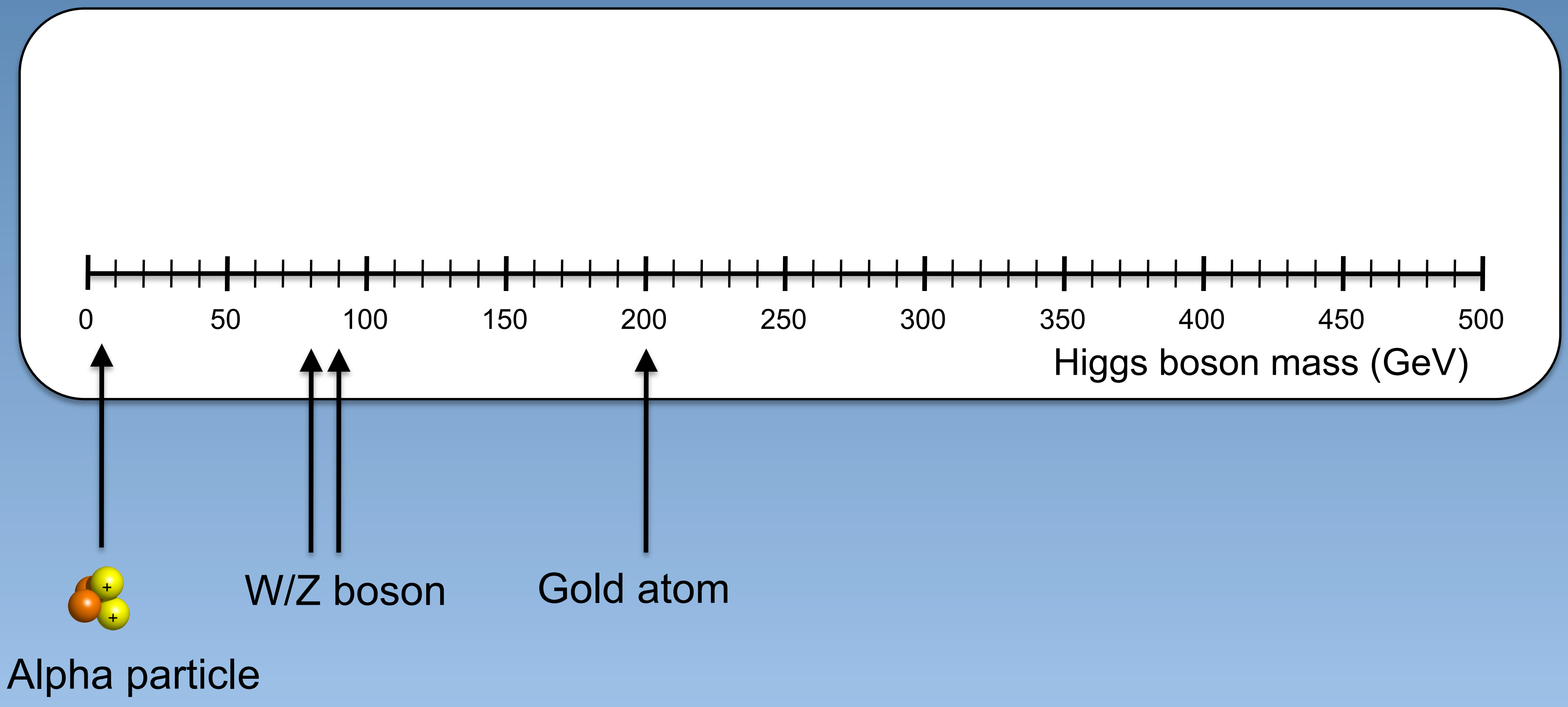


ATLAS measurements



Enormous data-set to understand and calibrate the ATLAS detector

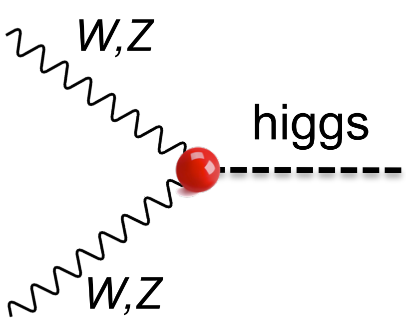
The mass of the Higgs boson



How do you produce a Higgs particle ?

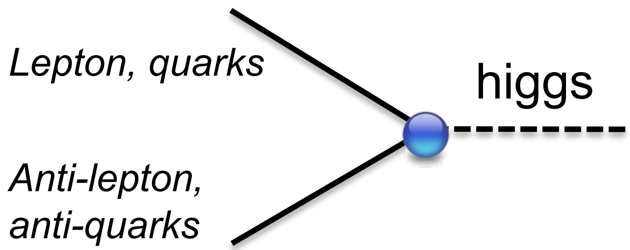
Gauge bosons

Massive gauge boson ?
… then it coupling to the Higgs!



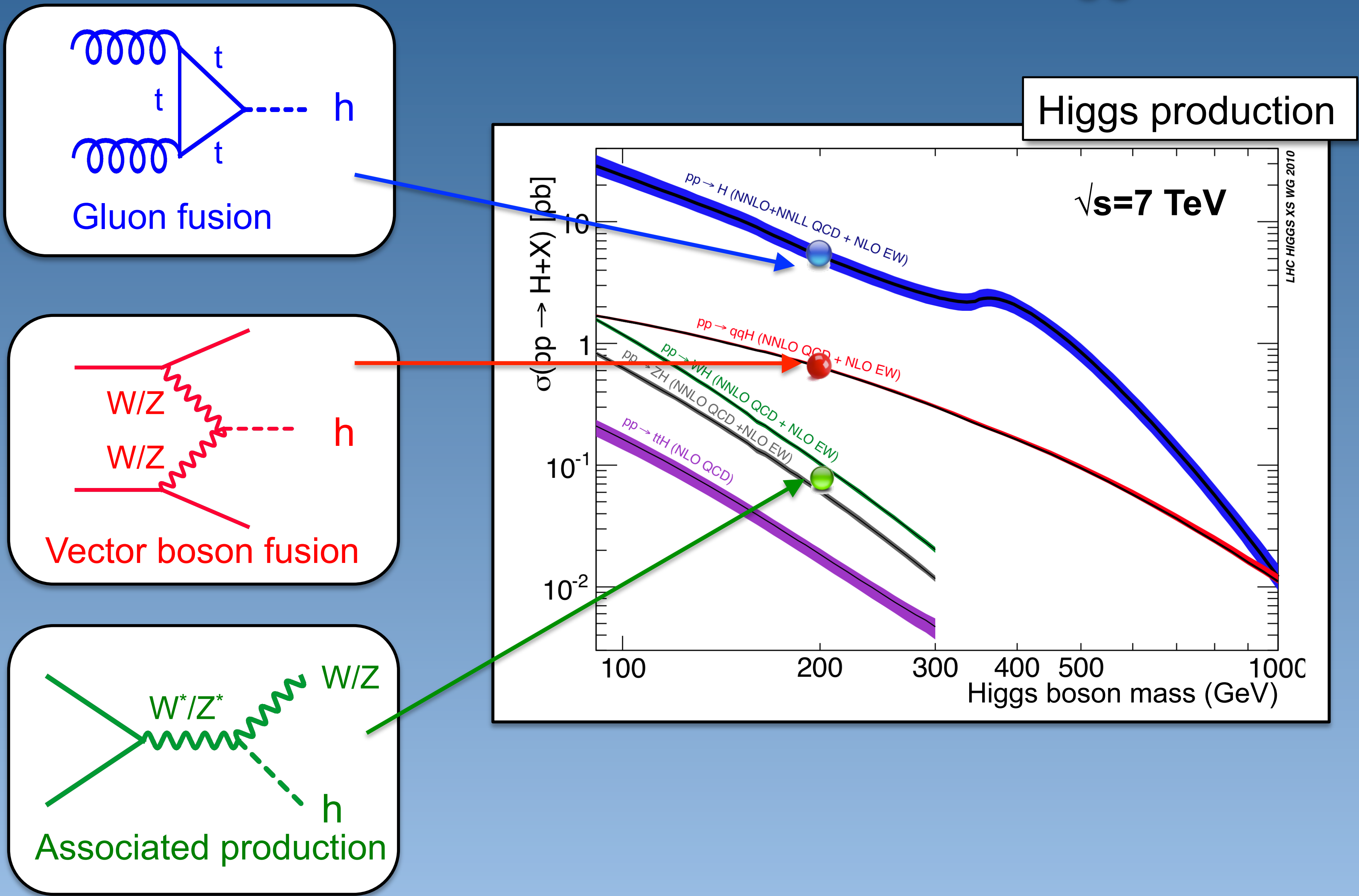
Fermions

Massief fermion ?
… then it couples to the Higgs!



Higgs boson production

Production of the Higgs boson



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

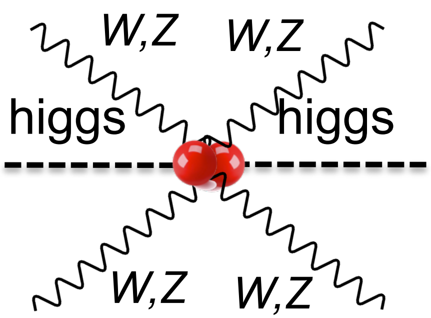
If the Higgs boson exists:

m_h = 120 GeV:	60.000
m_h = 200 GeV:	30.000

How does the Higgs boson decay ?

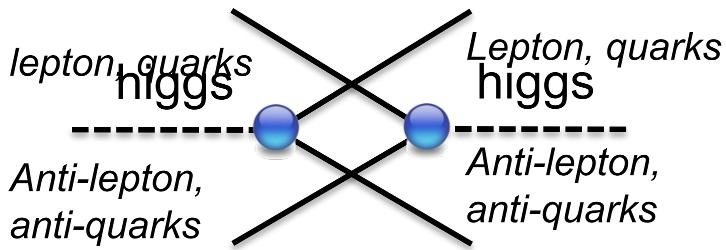
Gauge bosons

Massive gauge boson ?
… then it coupling to the Higgs!



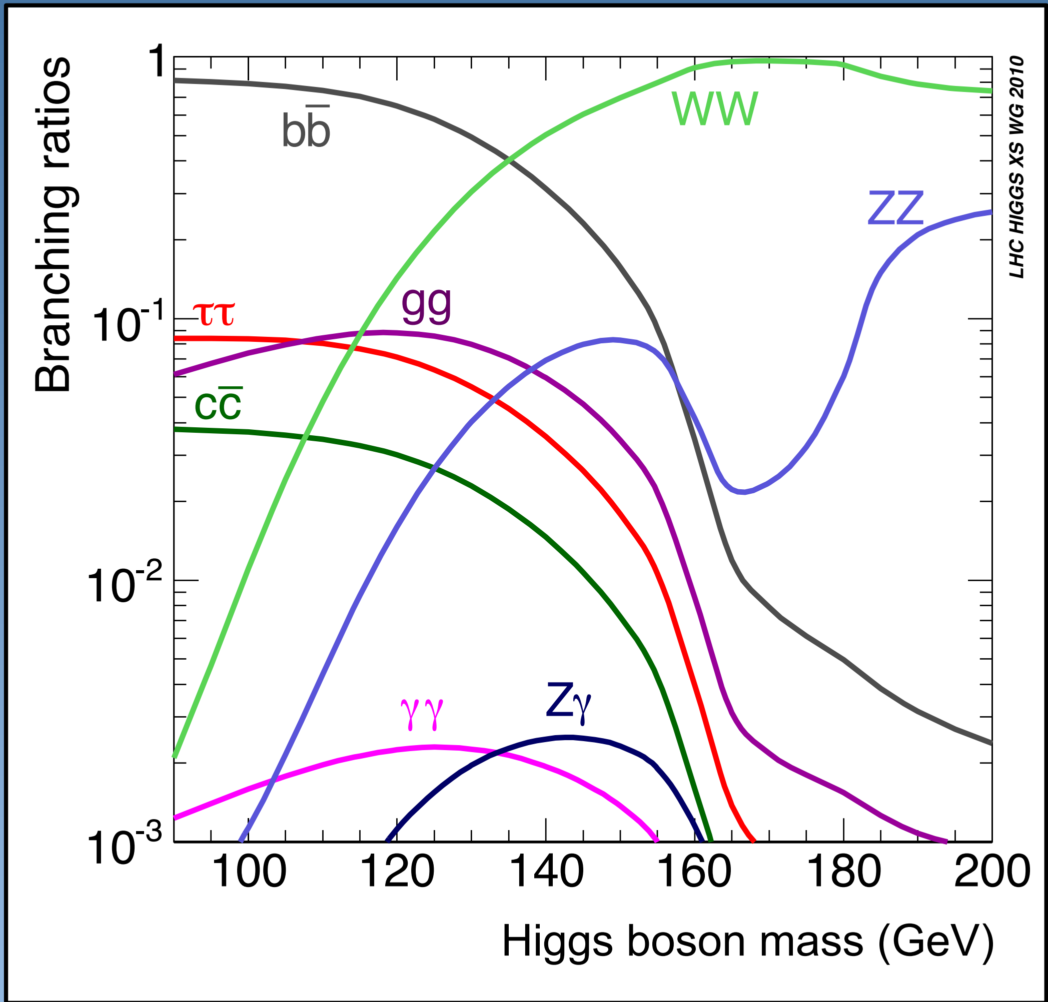
Fermions

Massief fermion ?
… then it couples to the Higgs!



Higgs boson decay production

Decay of the Higgs boson



Subsequent gauge boson decay

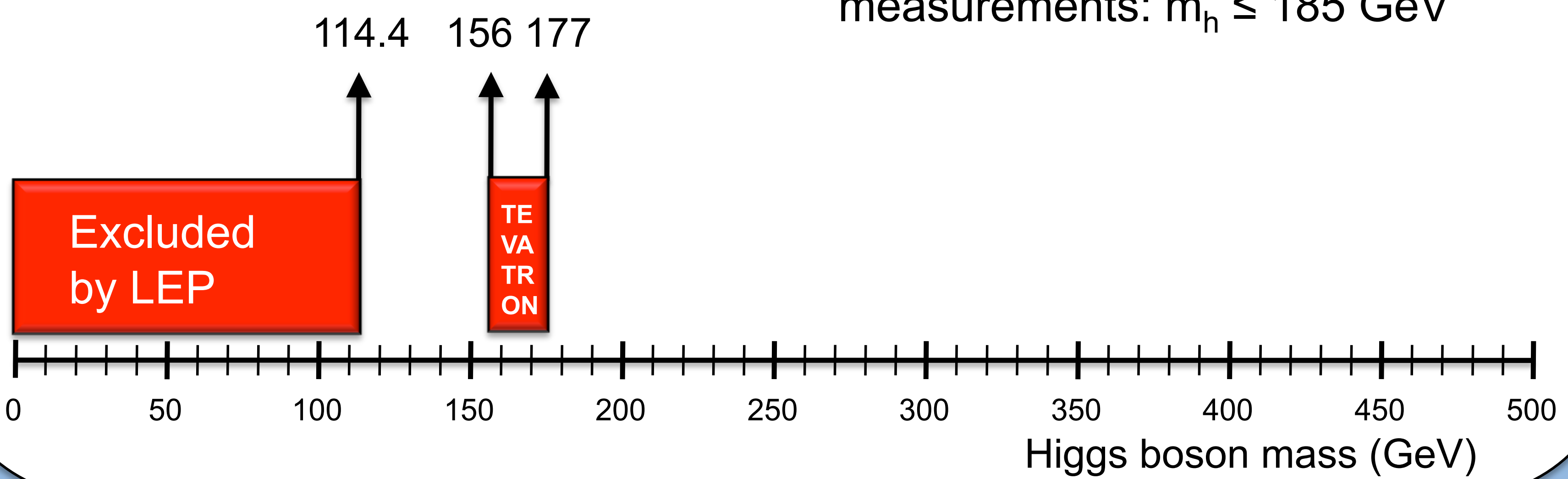
W→	qq	67%
	lν	33%
Z→	qq	70%
	νν	20%
	ll	10%

Status on February 8, 2011

Indirect:

Theory: $m_h \leq 600$ GeV

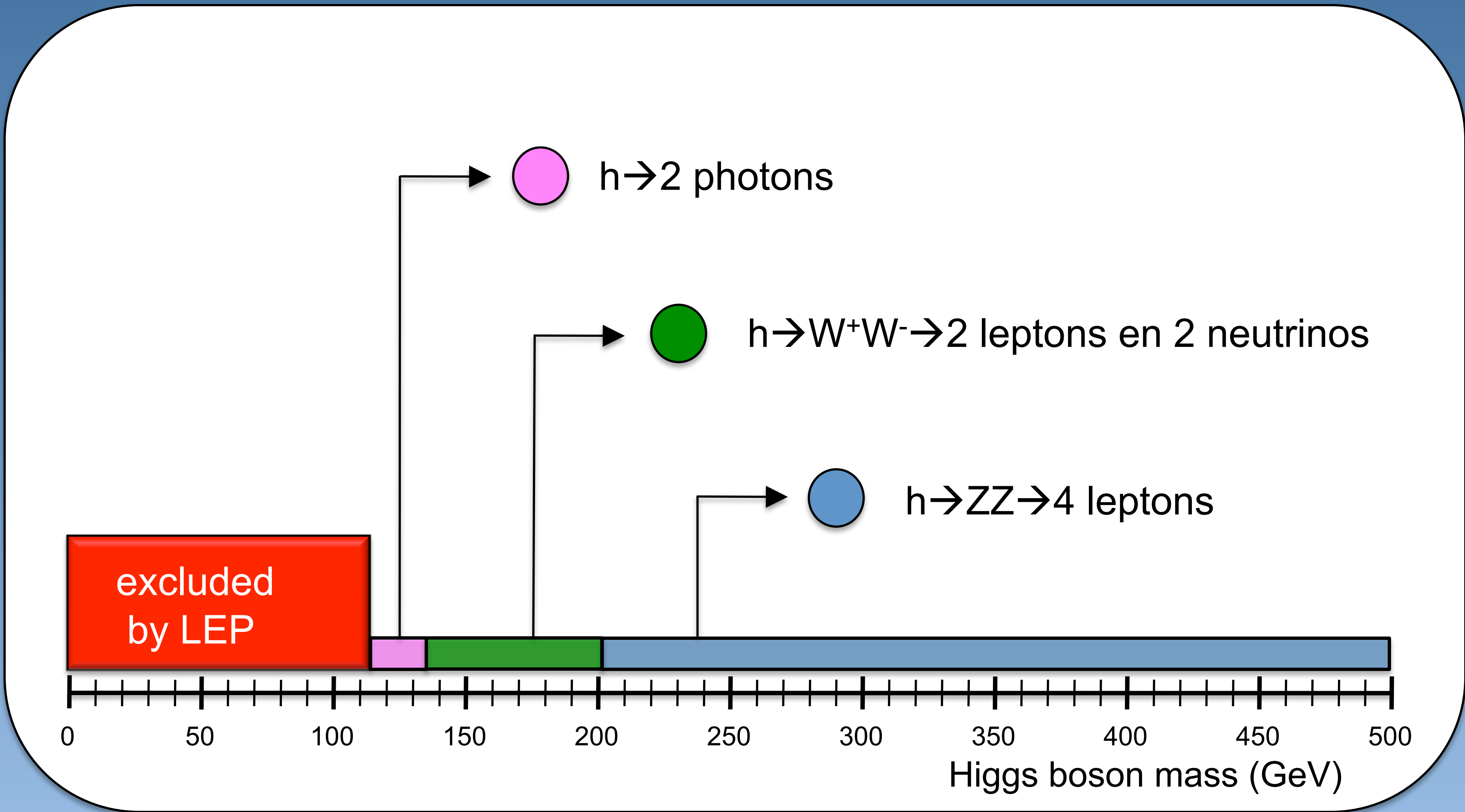
Electroweak precision-measurements: $m_h \leq 185$ GeV



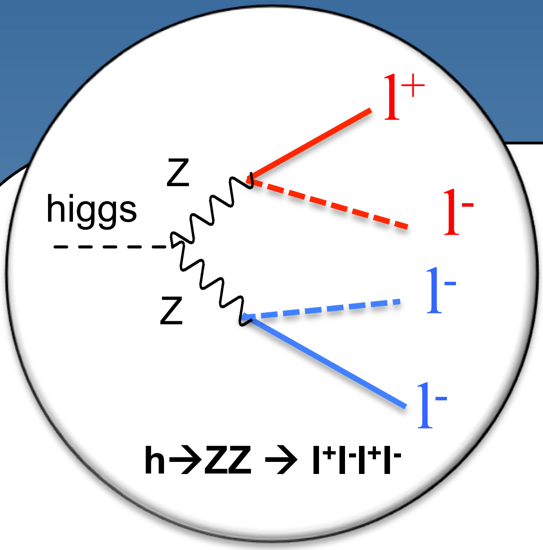
Experiments at the LHC Sensitive for mass range: 114-1000 GeV

The clearest fingerprint of the Higgs boson

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



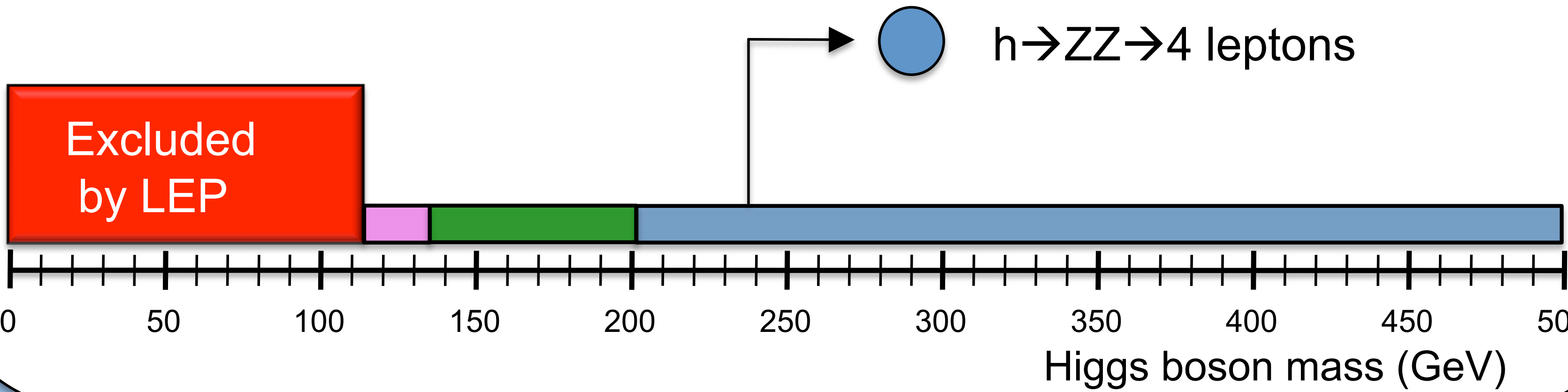
High massa's: m_H > 200 GeV

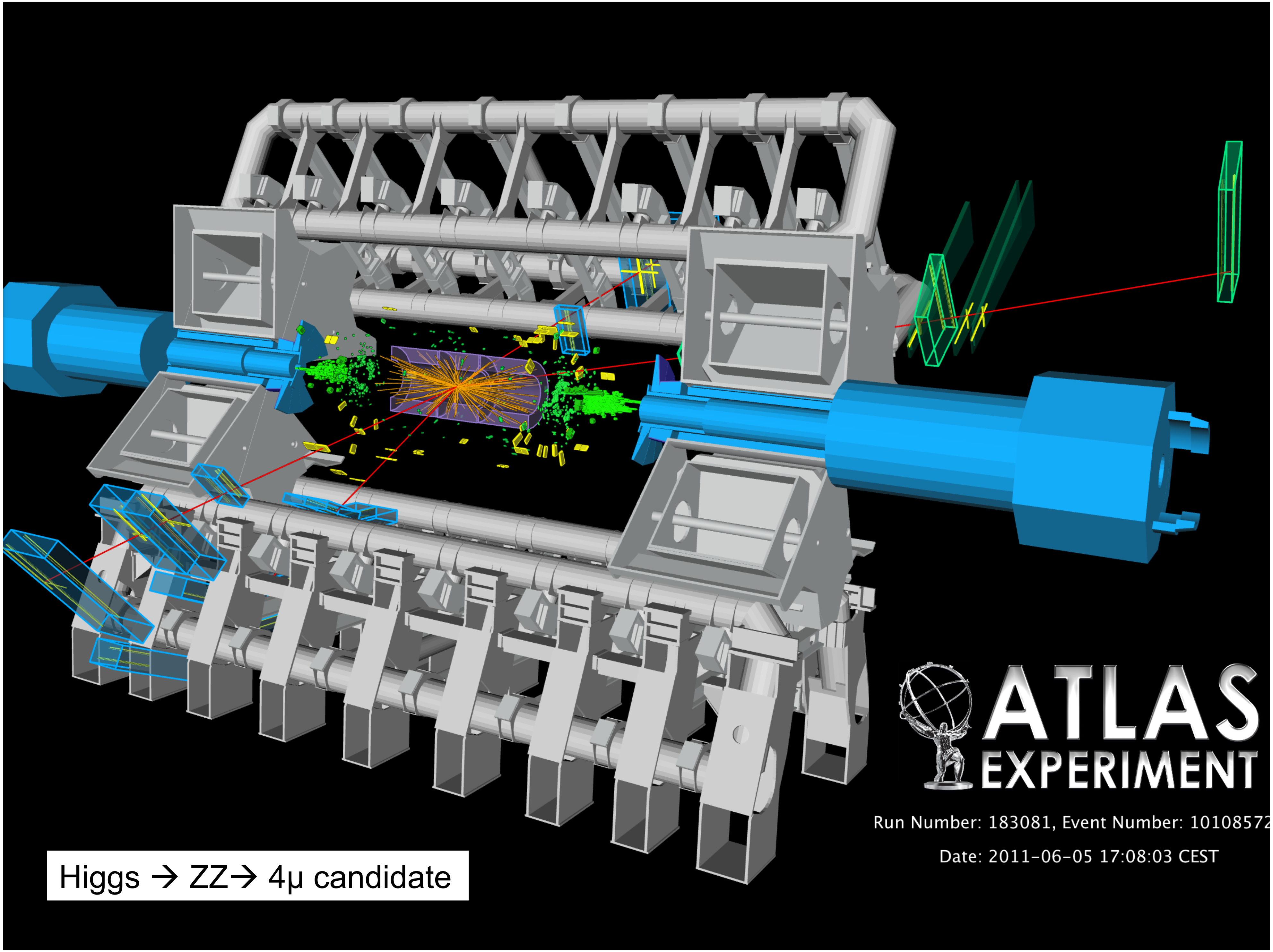


The golden channel

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

Fingerprint: 4-lepton mass

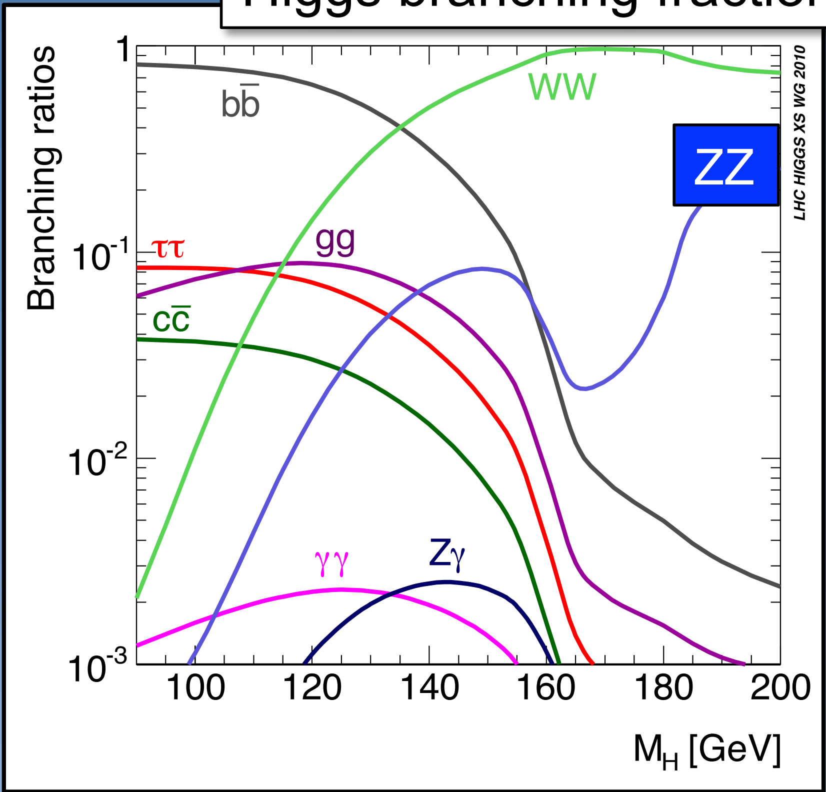



ATLAS
EXPERIMENT
Run Number: 183081, Event Number: 10108572
Date: 2011-06-05 17:08:03 CEST
Higgs → ZZ→ 4μ candidate

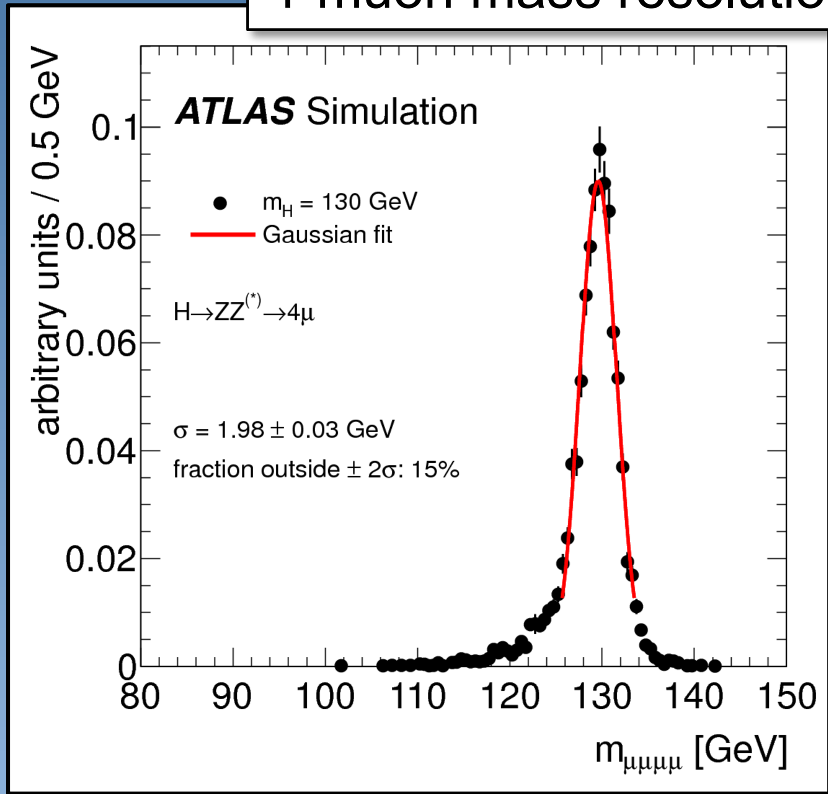
Higgs → ZZ → 4 leptons

Small number of beautiful collissions

Higgs branching fraction



4-muon mass resolution



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

Mass resolution ~ 2 GeV

Higgs → ZZ → 4 leptons

Small number of beautiful collissions

30.000 Higgs bosons

⇩

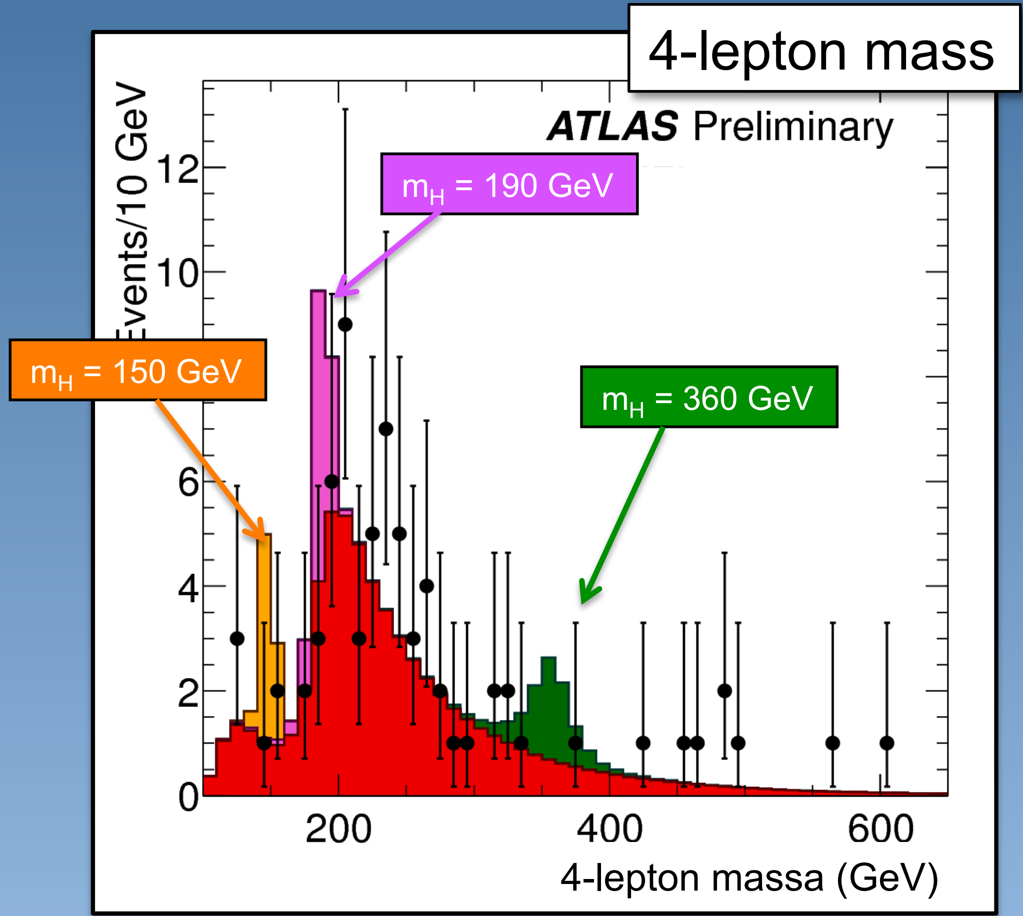
- Only 1 in 1000 Higgs bosons decays to 4 leptons (e/μ).

- 50% of them are all correctly reconstructed by the ATLAS detector

⇩

16 Higgs decays to 4 leptons

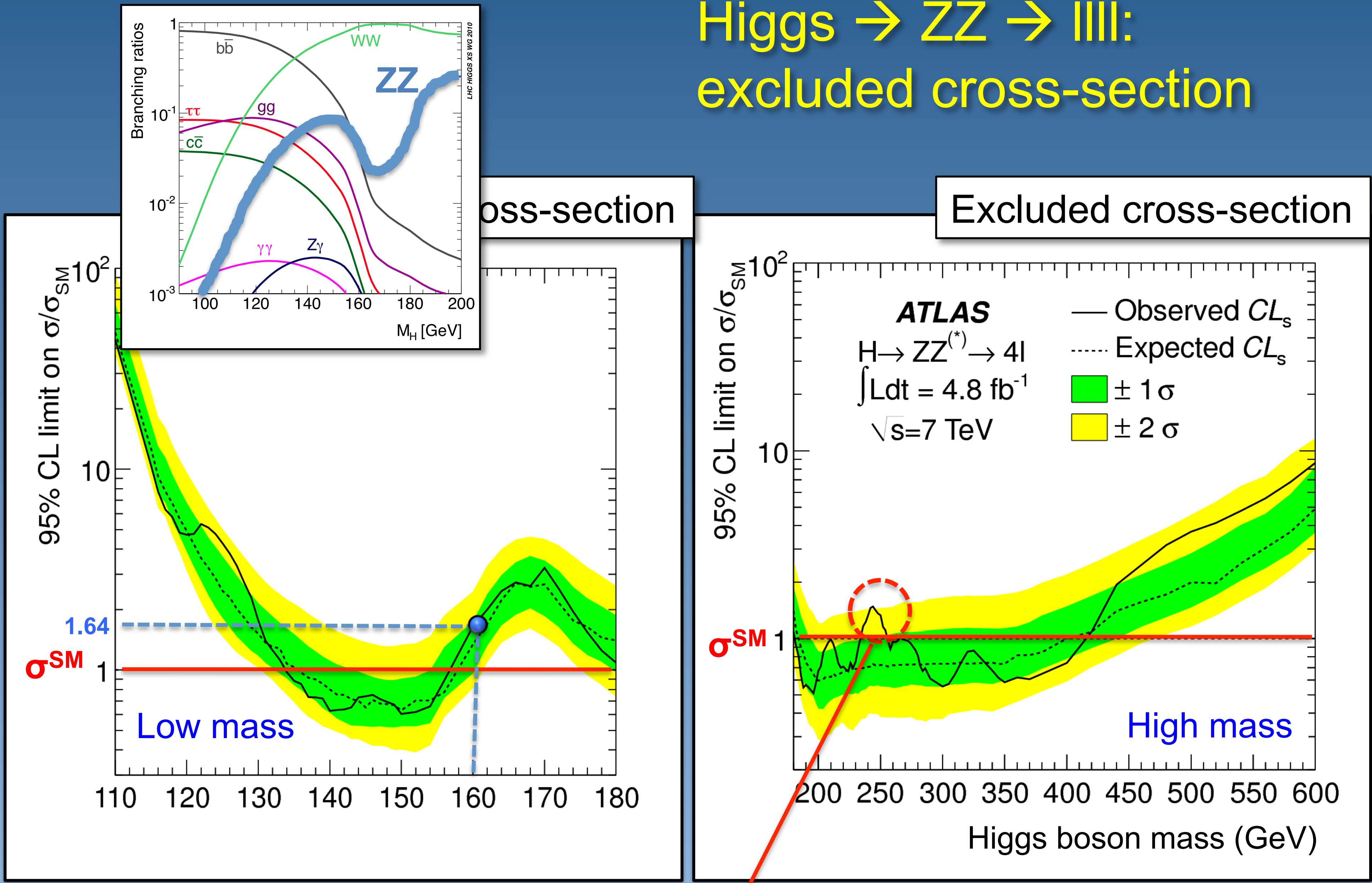
'overig'	52 events
with Higgs	68 events



No clear peak unfortunately

→ m_h < 200 GeV

Higgs → ZZ → llll: 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

1) Can we exclude the SM+Higgs hypothesis ?

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"

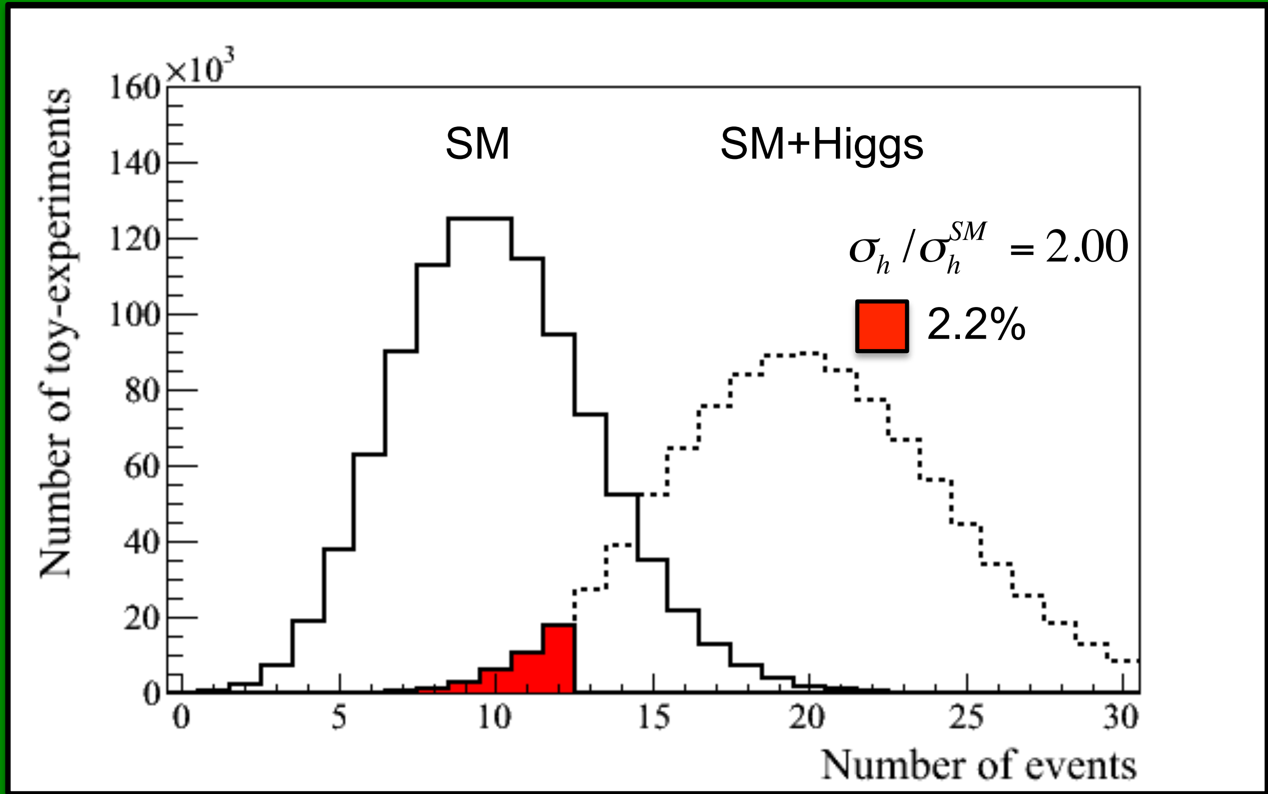
When / how do you exclude a signal

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 ?*



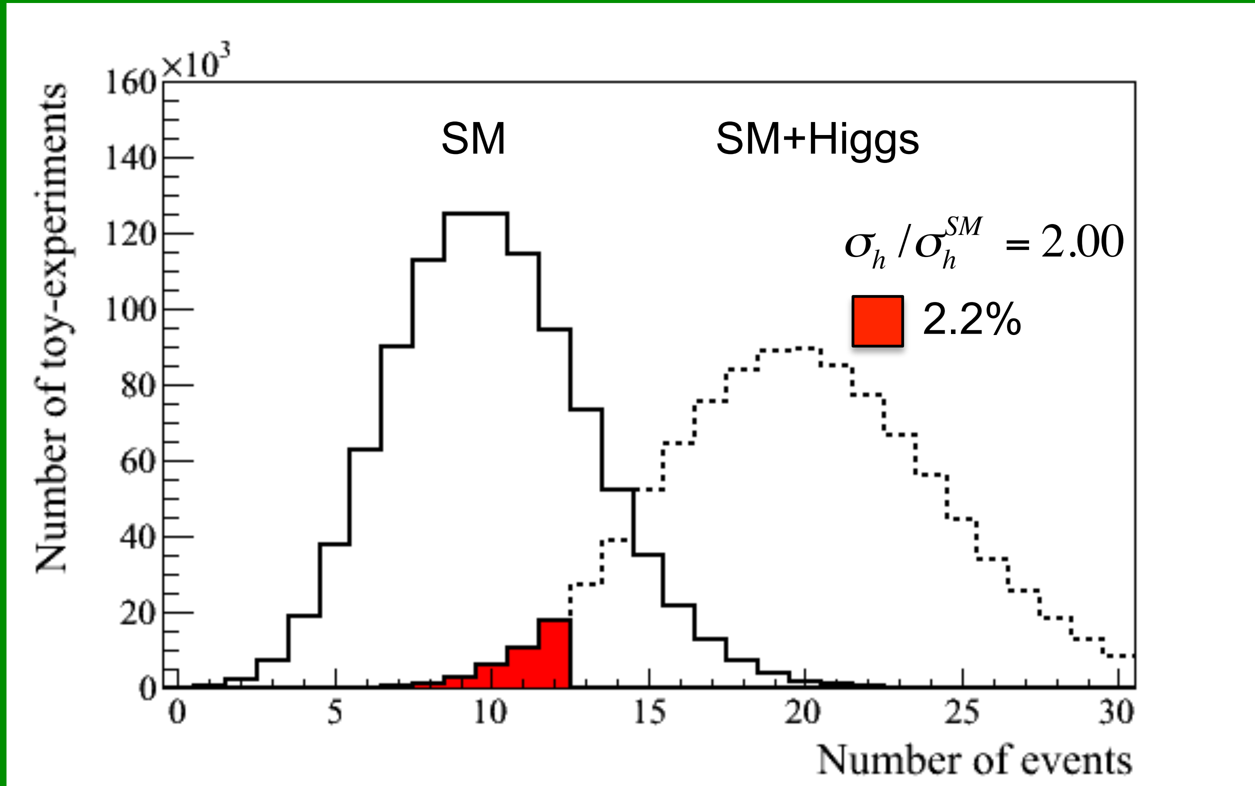
When / how do you exclude a signal

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 ?*



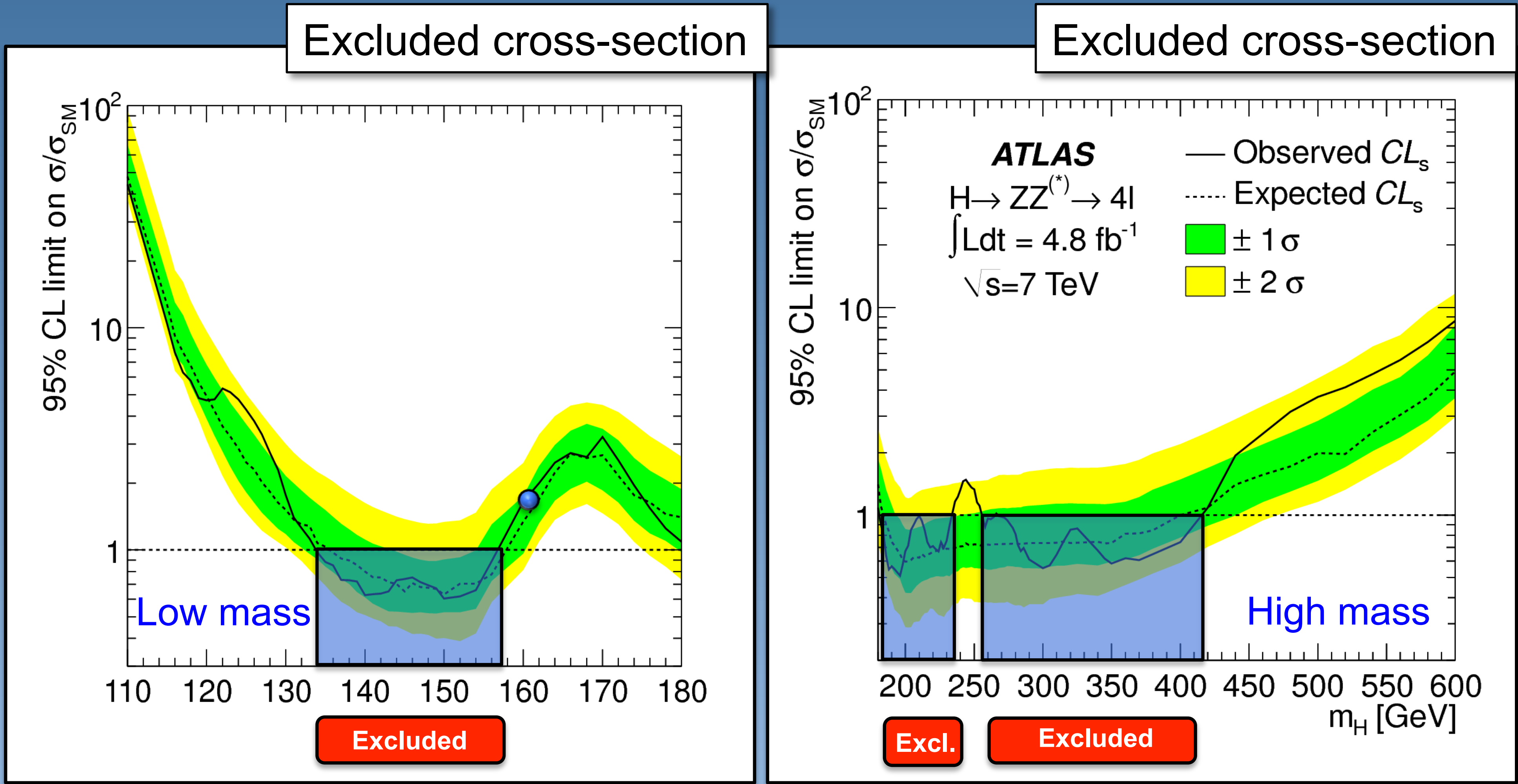
σ/σ_{SM}	SM	# data	SM+Higgs	
1.0	10	12	15.0	18.5 %
1.5	10	12	17.5	6.8%
2.0	10	12	20.0	2.2%

< 5%? Exclude at 95% CL

Expected exclusion ? Use mean SM instead of Ndata

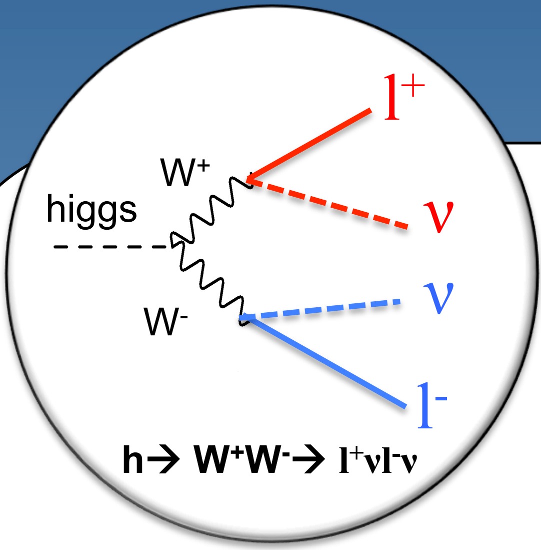
Observed excluded cross-section, σ_h/σ_h^{SM} = 1.64

Higgs → ZZ → llll:
from excluded cross-section to excluded mass



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

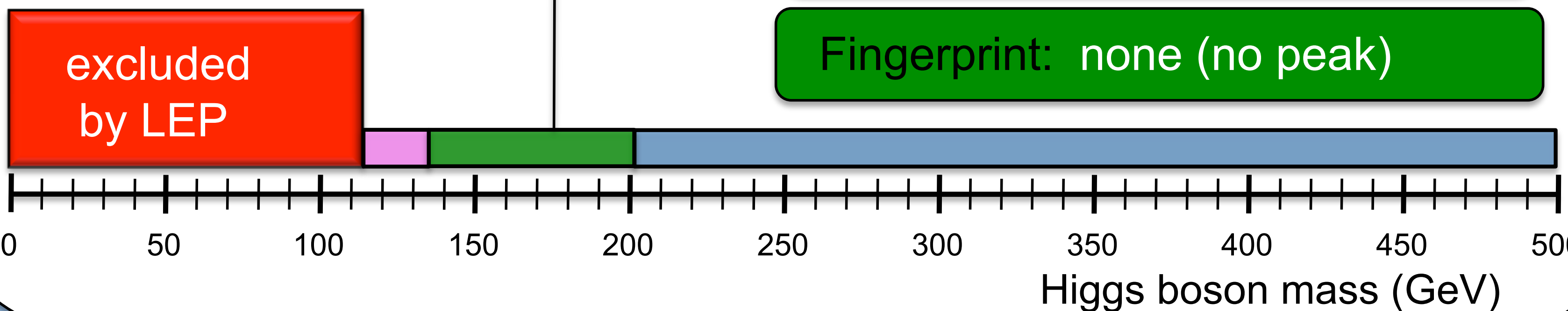
Mid-range: $130 < m_H < 200$ GeV

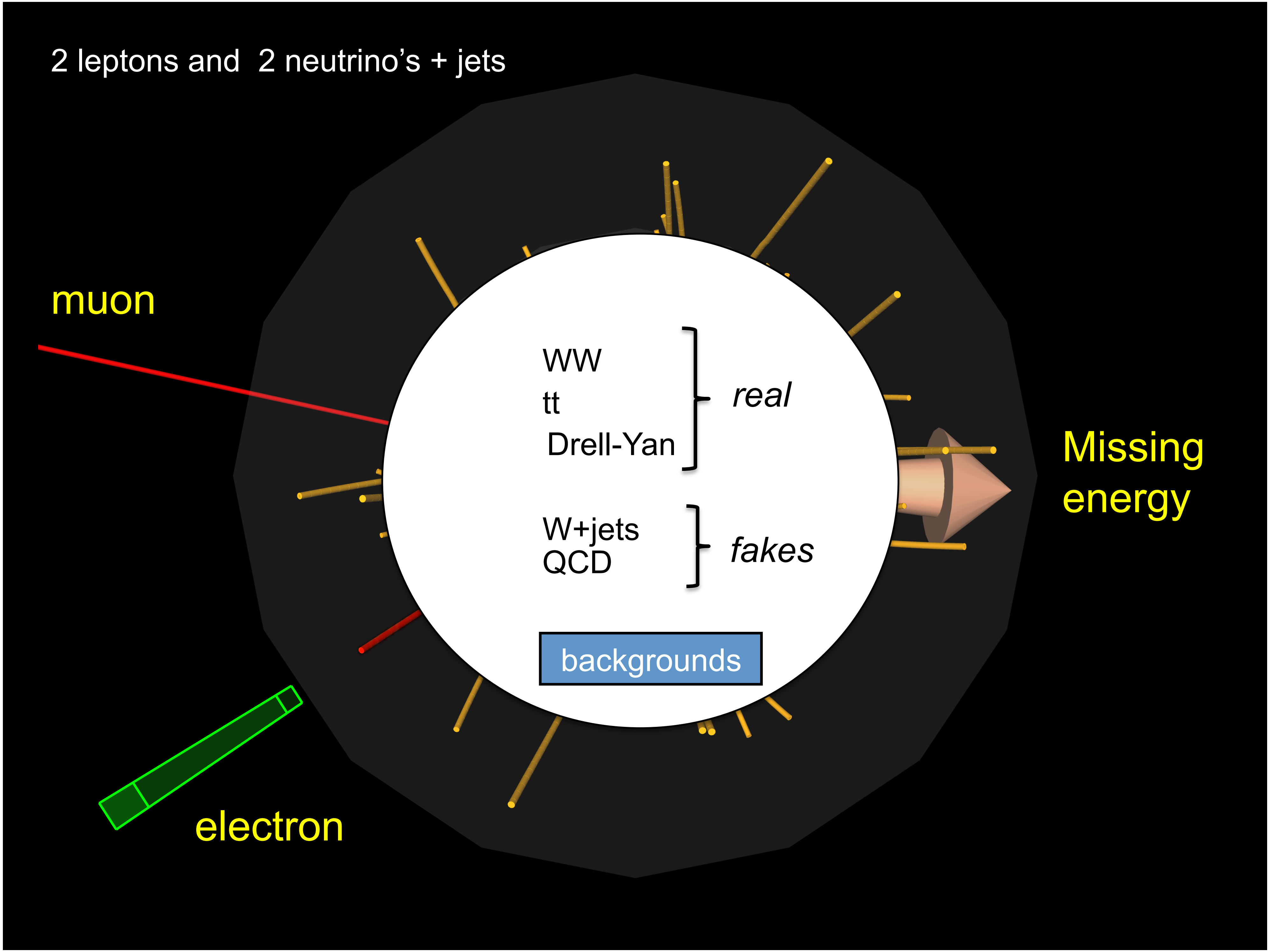


h→W+W-→2 leptons en 2 neutrinos

- 'Common' final state
- Difficult to isolate

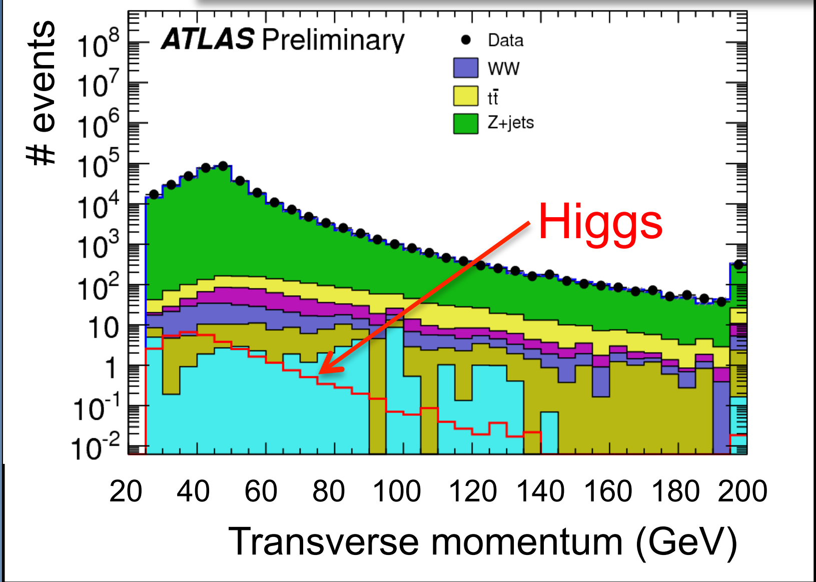
Fingerprint: none (no peak)




2 leptons and 2 neutrino's + jets
muon
WW
tt
Drell-Yan
real
W+jets
QCD
fakes
backgrounds
Missing energy
electron

The possible Higgs signal is well hidden

Transverse momentum lepton

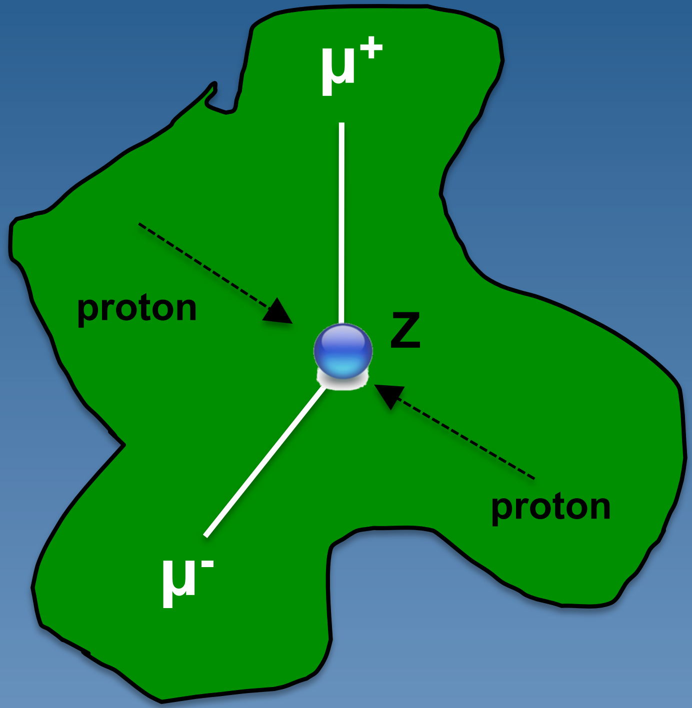


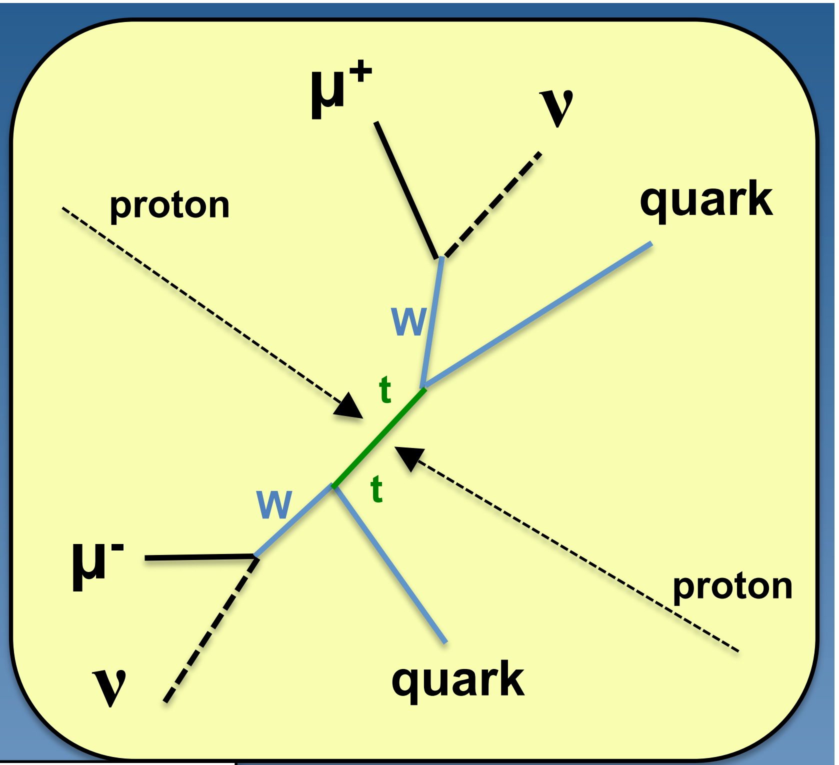
signal < 1/10.000 of background

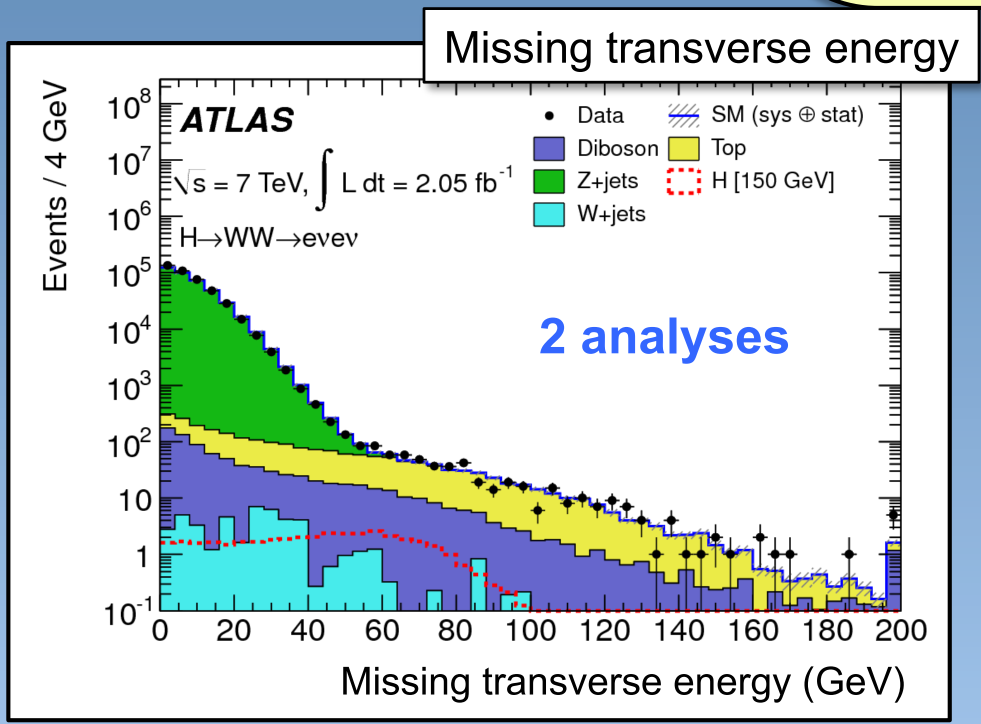
Delicate multi-dimensional selection

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

Control regions → extrapolate to signal region


μ+
proton
Z
proton
μ-

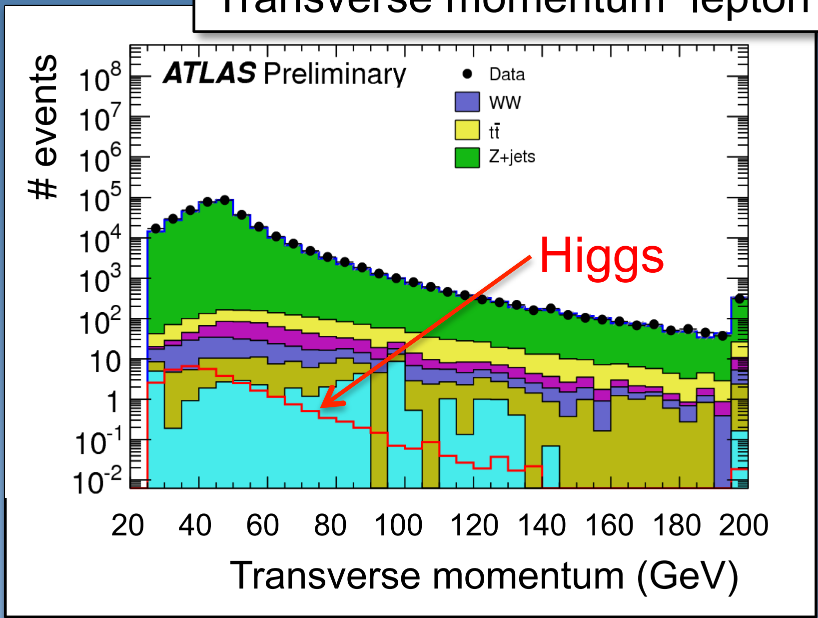

μ+
ν
proton
quark
W
t
t
W
μ-
proton
ν
quark


Missing transverse energy
ATLAS
√s = 7 TeV, ∫ L dt = 2.05 fb-1
H→WW→eνeν
Data
SM (sys ⊕ stat)
Diboson
Top
Z+jets
H [150 GeV]
W+jets
2 analyses
Events / 4 GeV
Missing transverse energy (GeV)

Looking for diamonds

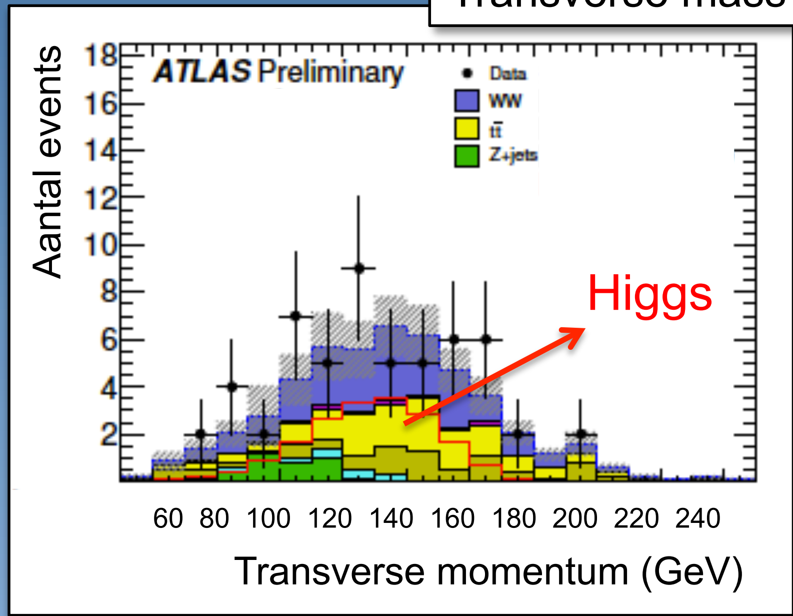
The possible Higgs signal is well hidden

Transverse momentum lepton



signal < 1/10.000 of background

Transverse mass

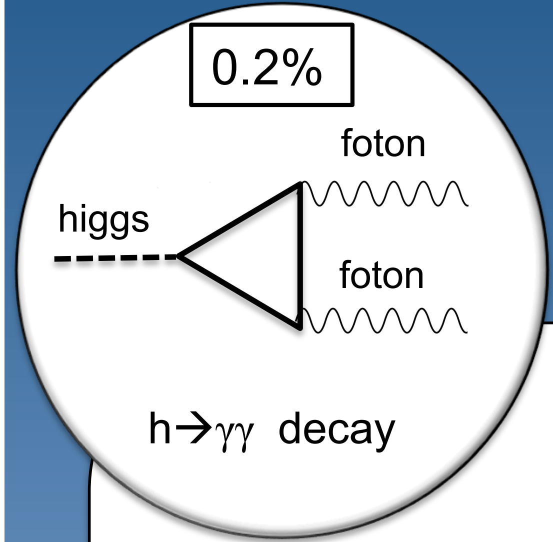


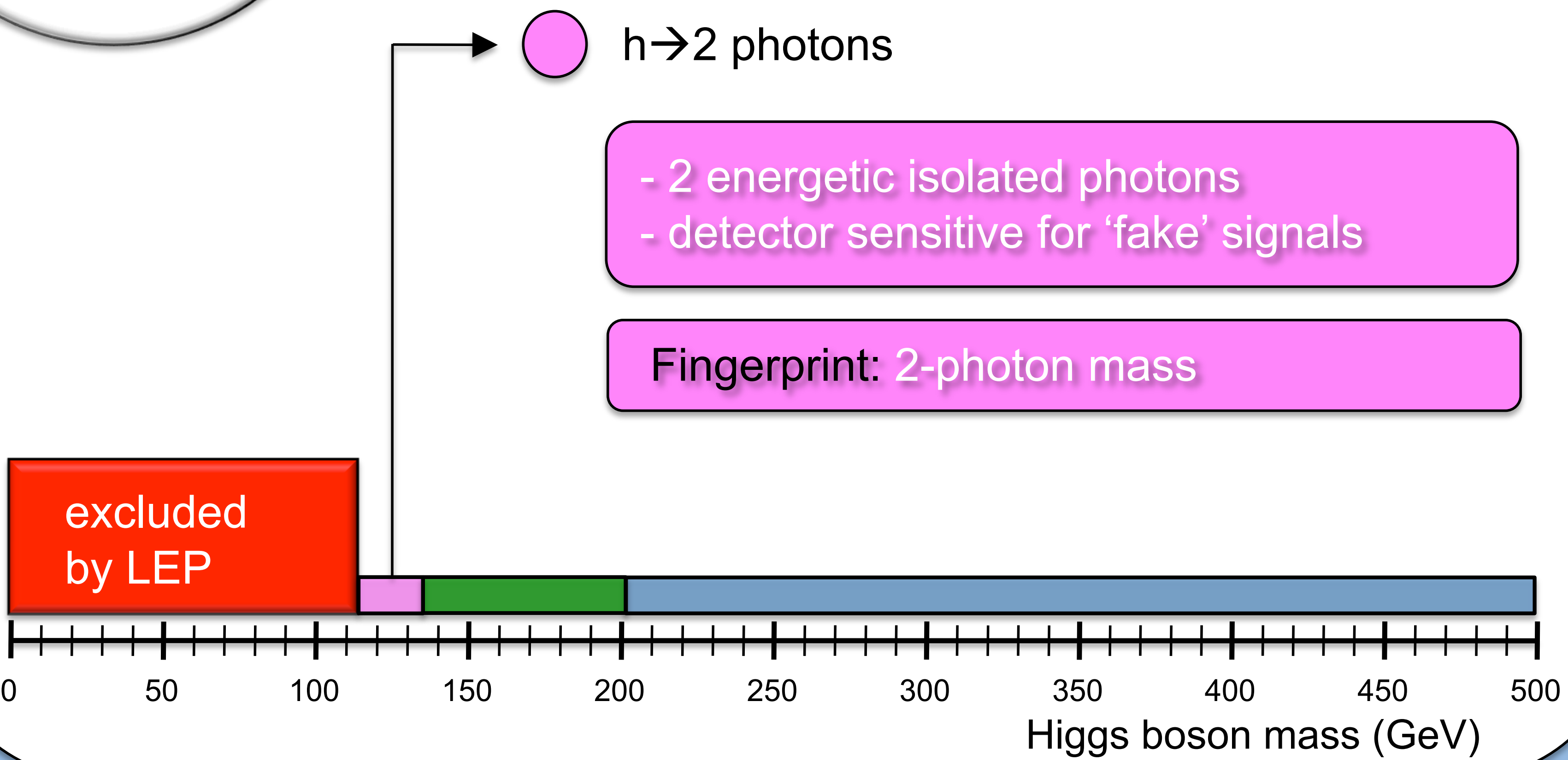
signal = 1/2 of background

Overig	**23**
Met Higgs	35

LHC data: **23** **(aargh!)**

The low-mass region





- 2 energetic isolated photons
- detector sensitive for ‘fake’ signals

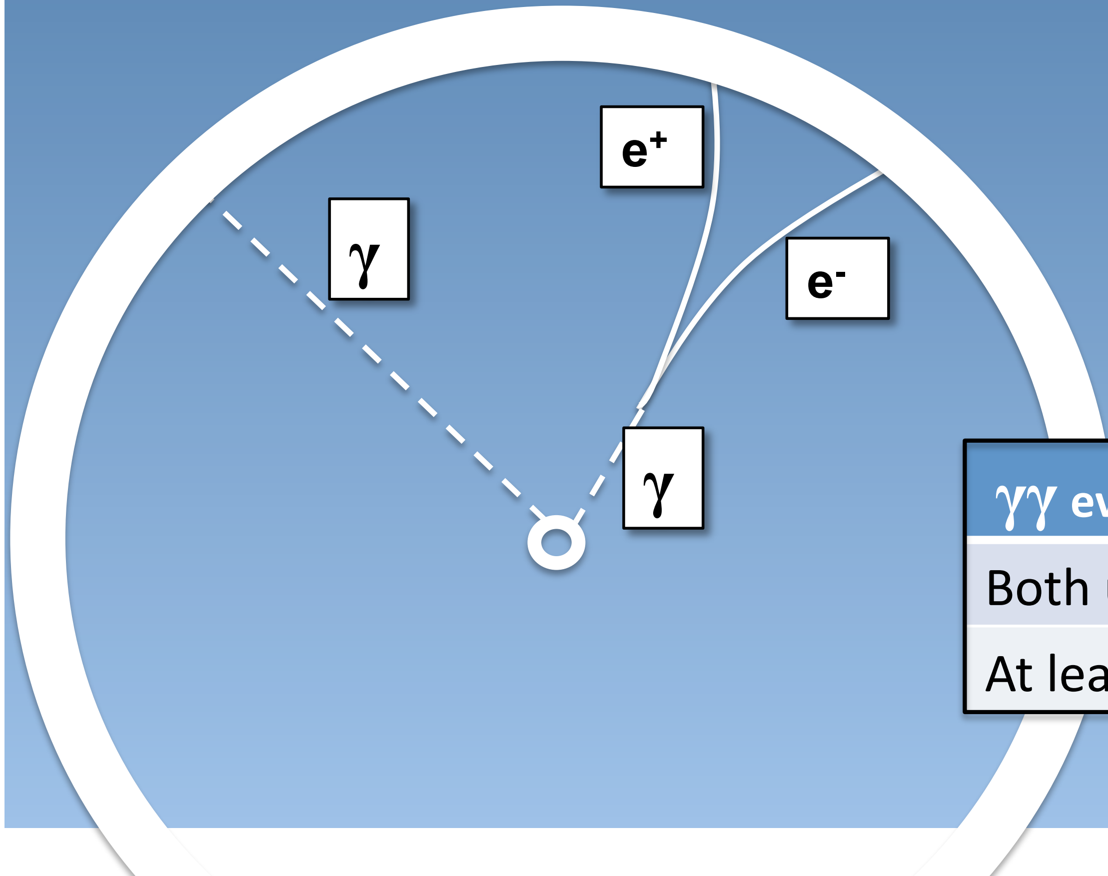
Fingerprint: 2-photon mass

Photon identification and event selection

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

39% selection efficieny

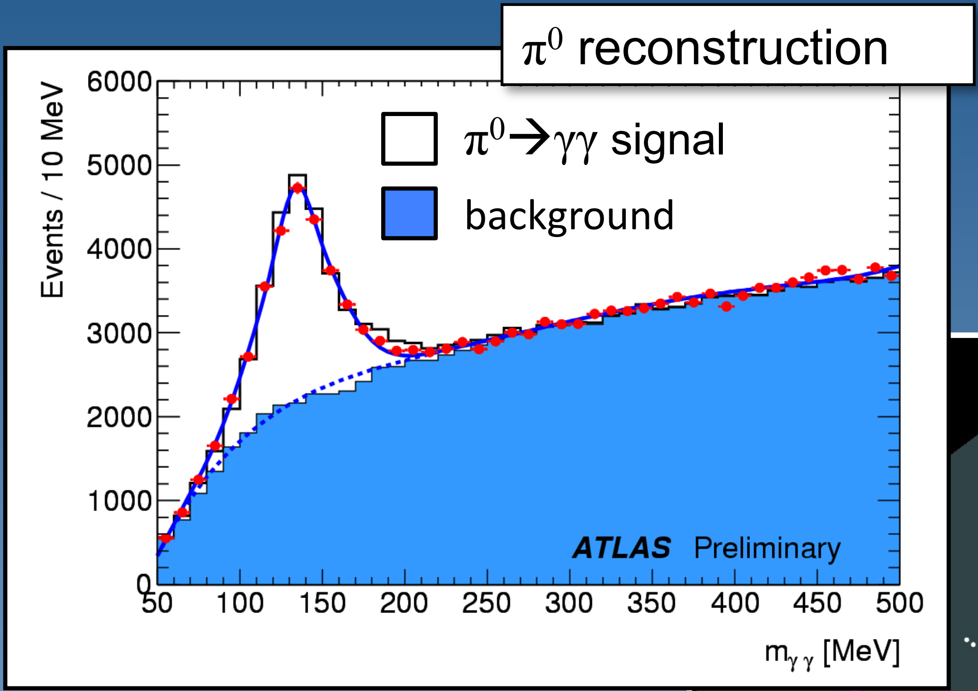
"Elk nadeel hep z'n voordeel"

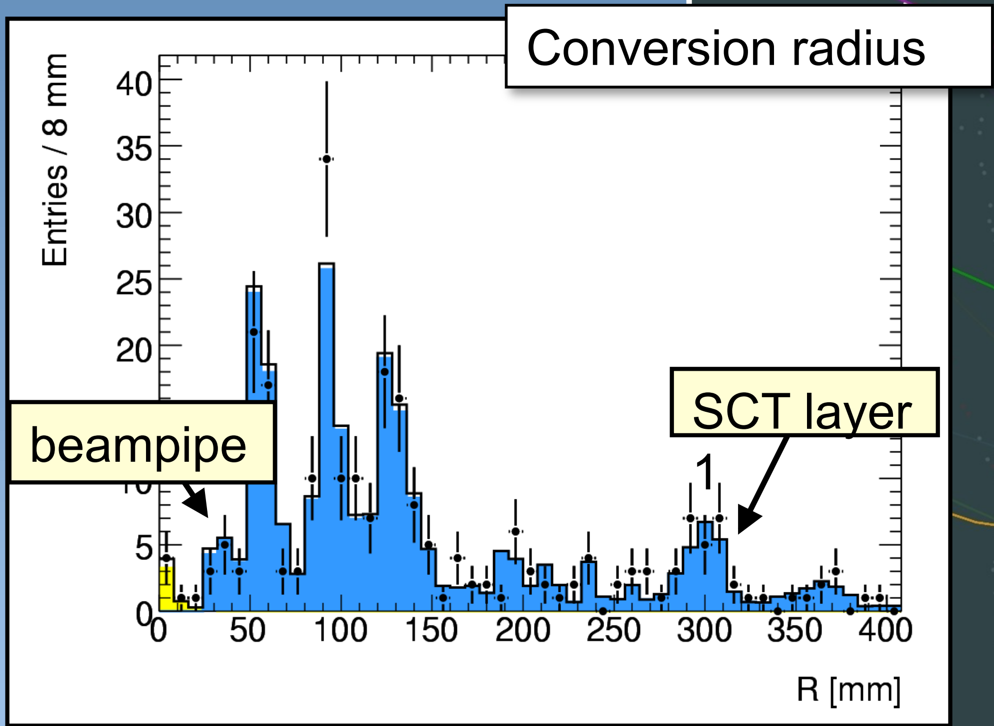


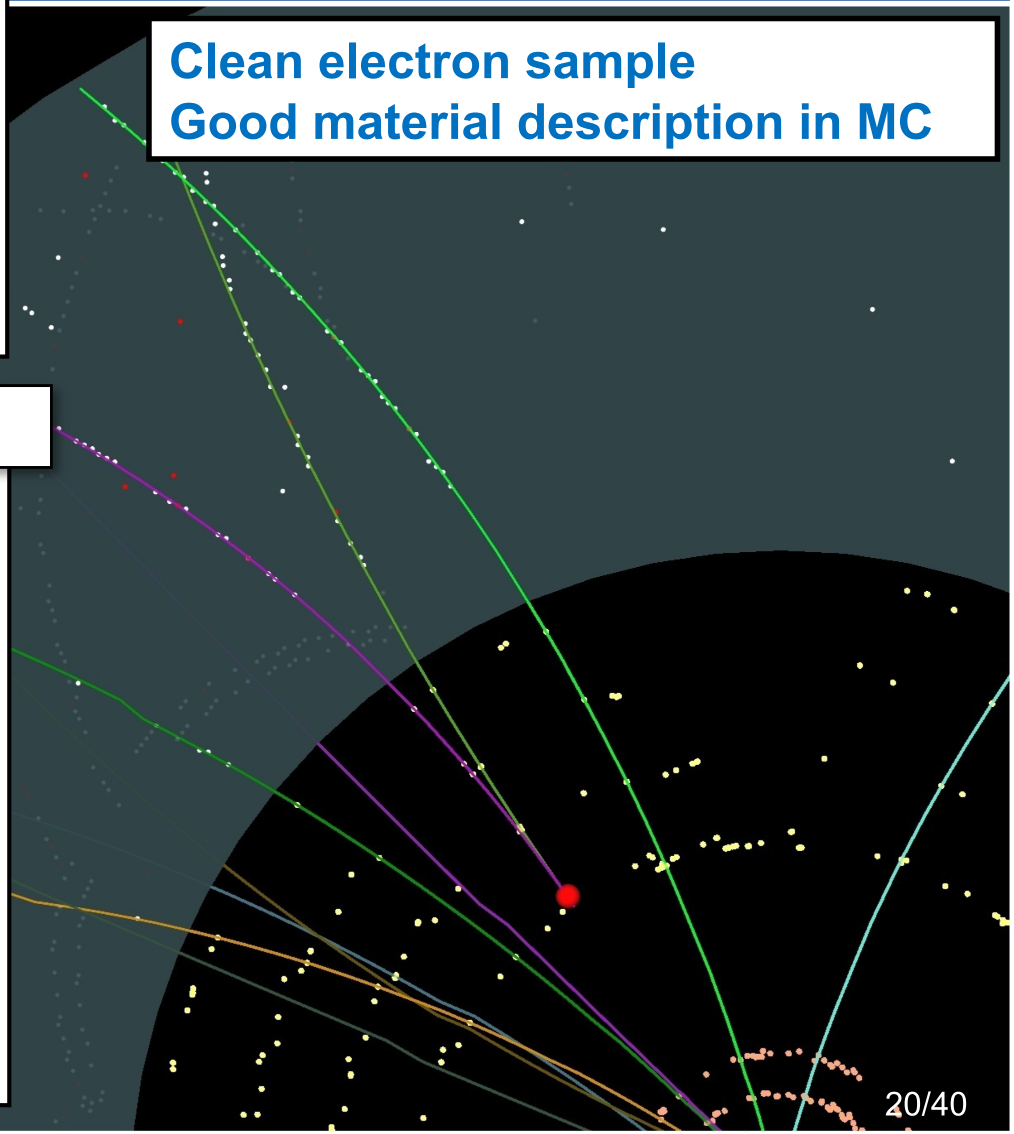
γγ event classification	Fraction
Both unconverted	36%
At least 1 converted	64%

Photon conversions

Clean electron sample
Good material description in MC







Event-type	Number of events

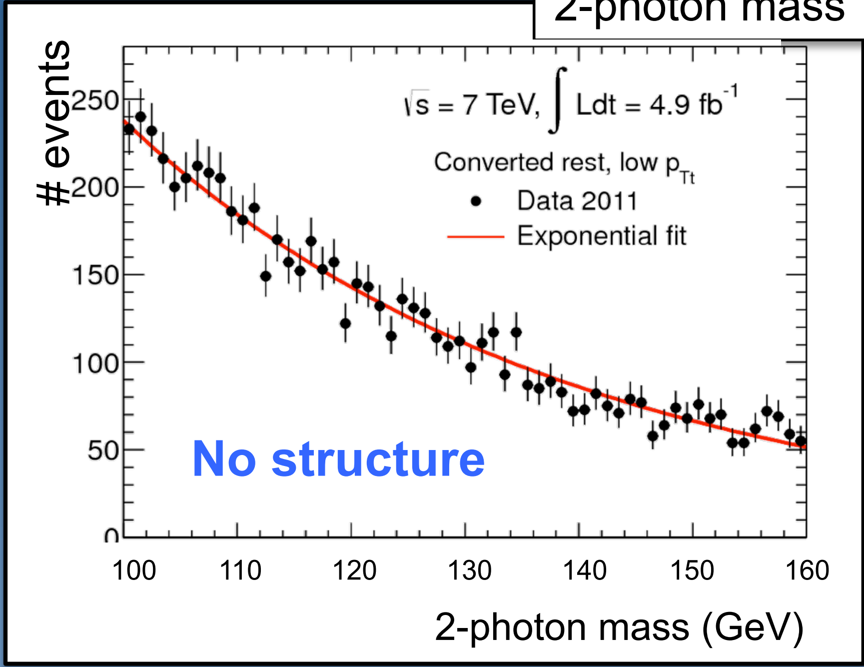
Other origin

γγ	3650 ±100 ±290
γ + jet	1110 ± 60 ±270
Di-jet	220 ± 20 ±130
Drell-Yan	86 ± 1 ± 14
'normal'	**5066**

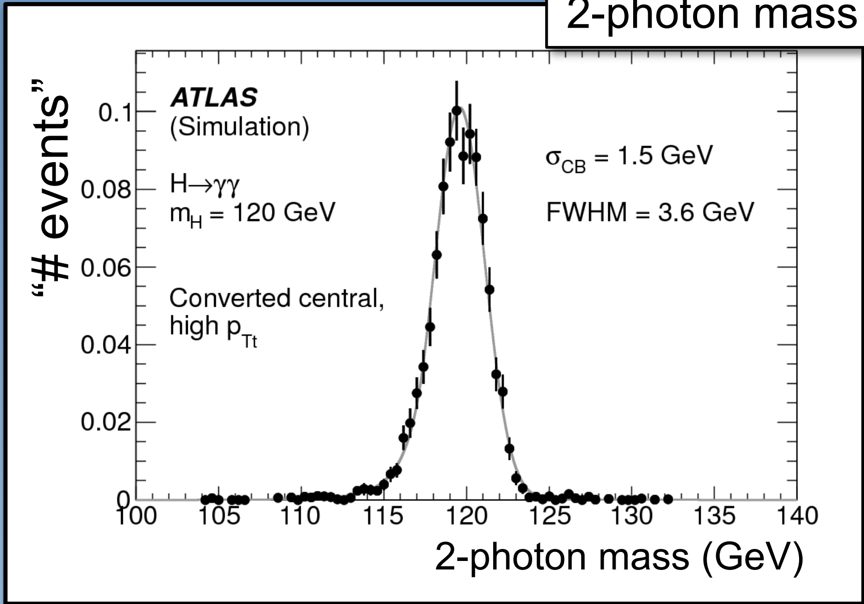
Higgs

Higgs signal	**17.6**

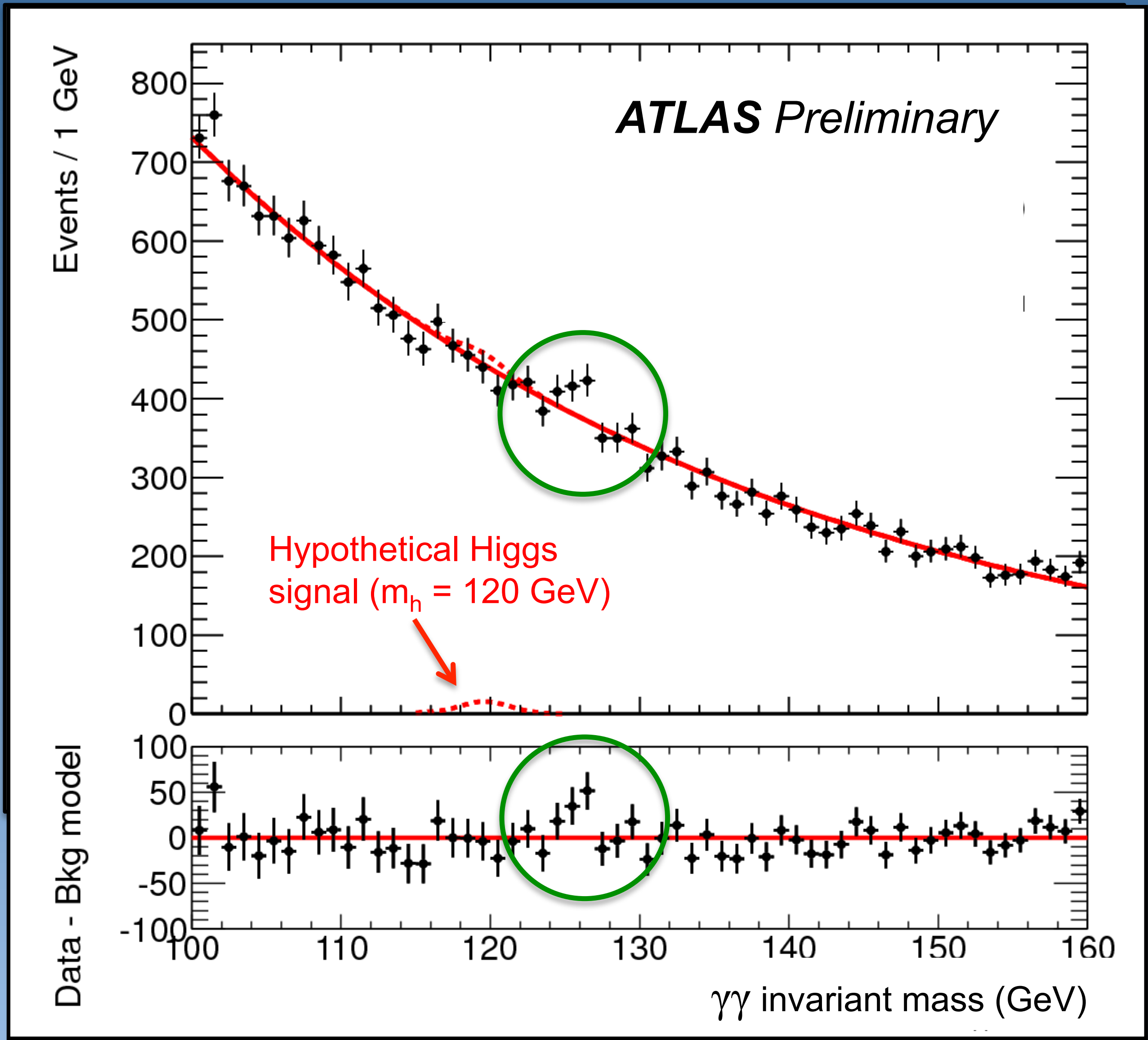
2-photon mass



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

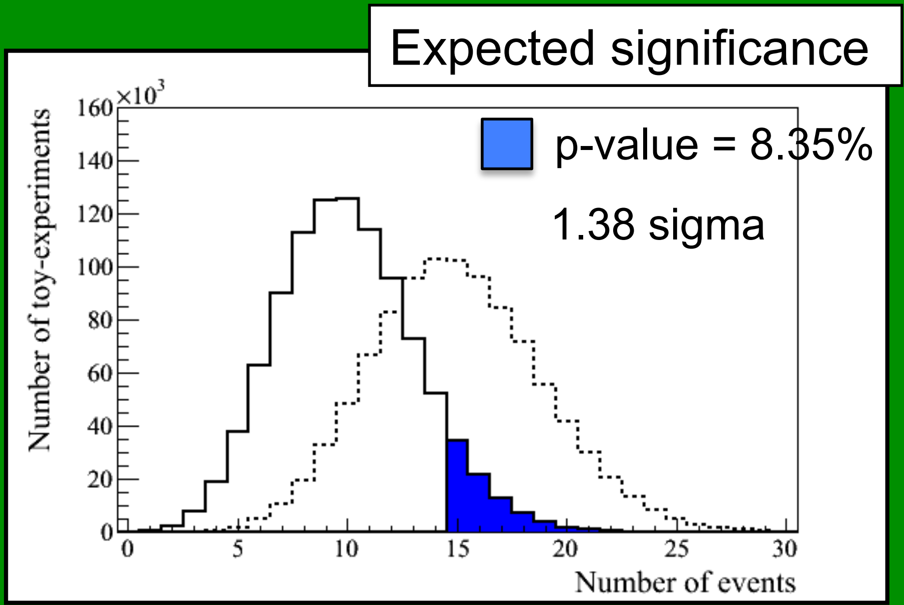
For a given number of events, the p-value is:

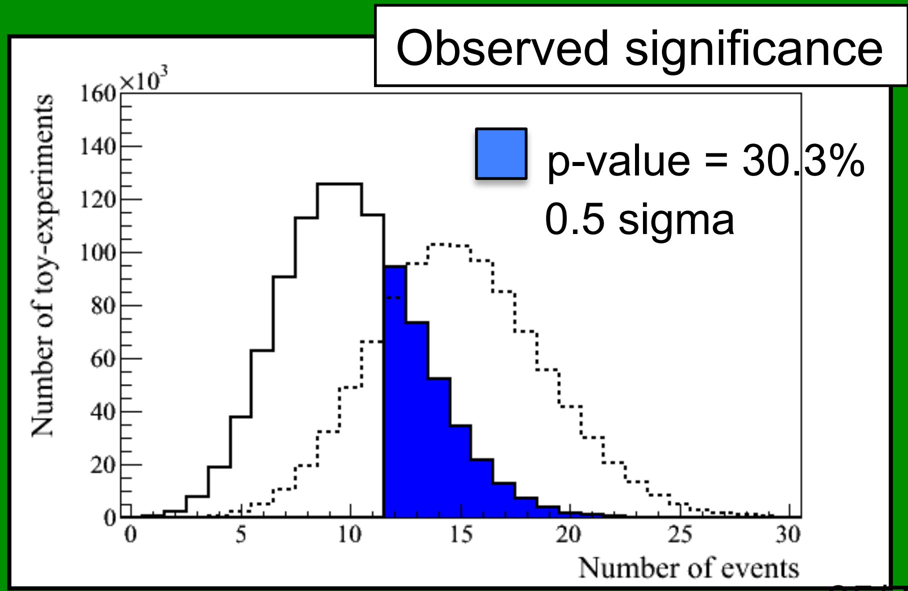
*"The probability to observe as many events as this number (or even more) under the assumption that the Higgs does **not** exists"*

→ *Can be translated into a (gaussian) significance*

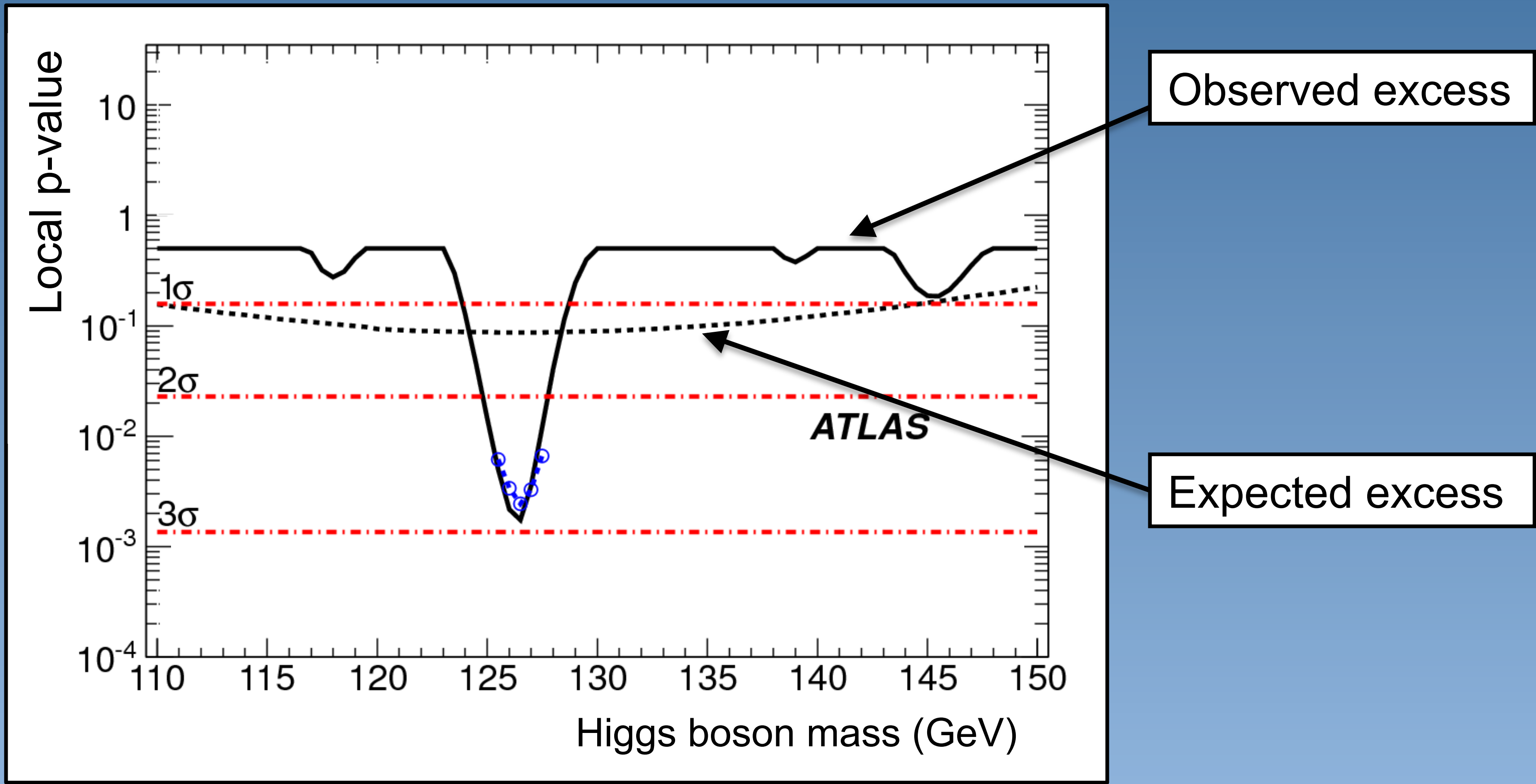
1) What is the expected significance ?

2) What is the observed significance ?



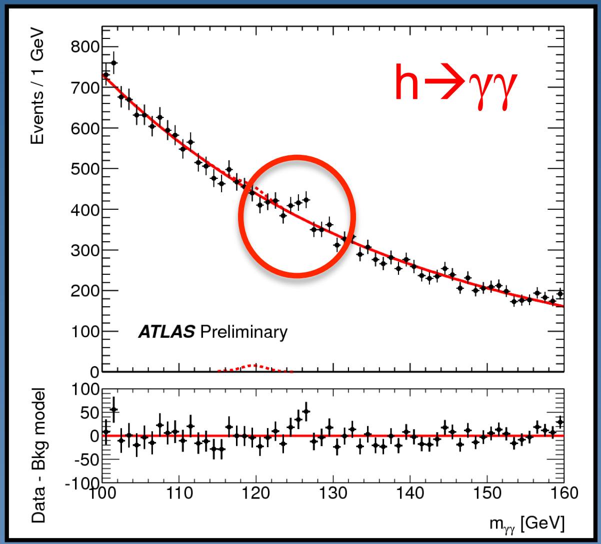


The excess in a single channel: h→γγ

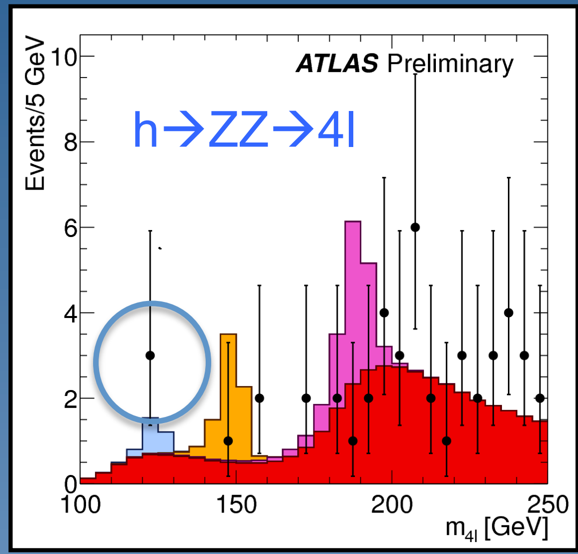


P-value ~ 0.002

Higgs → 2 photons

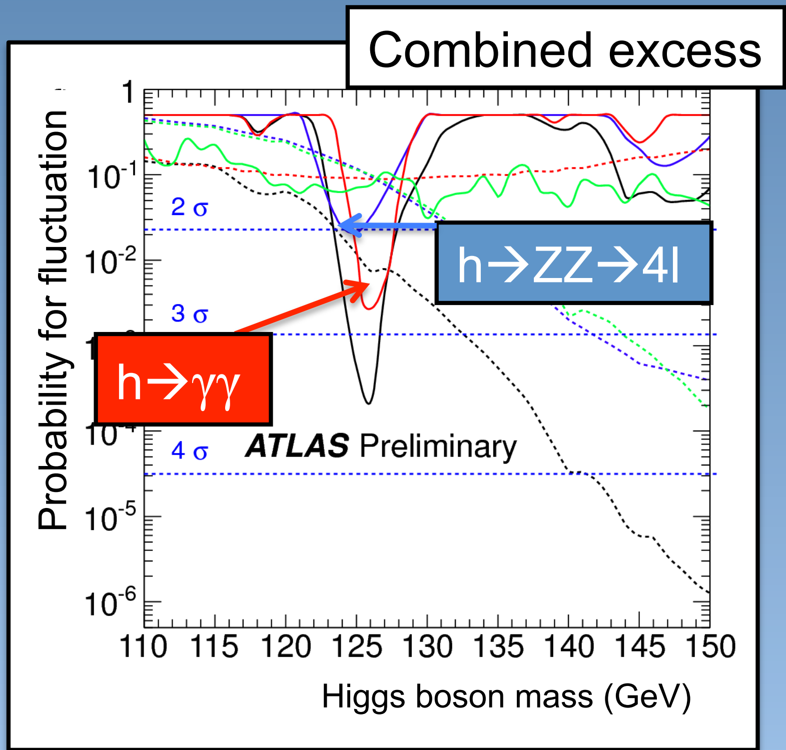


Higgs → 4 leptons



Excess visible in
in two channels

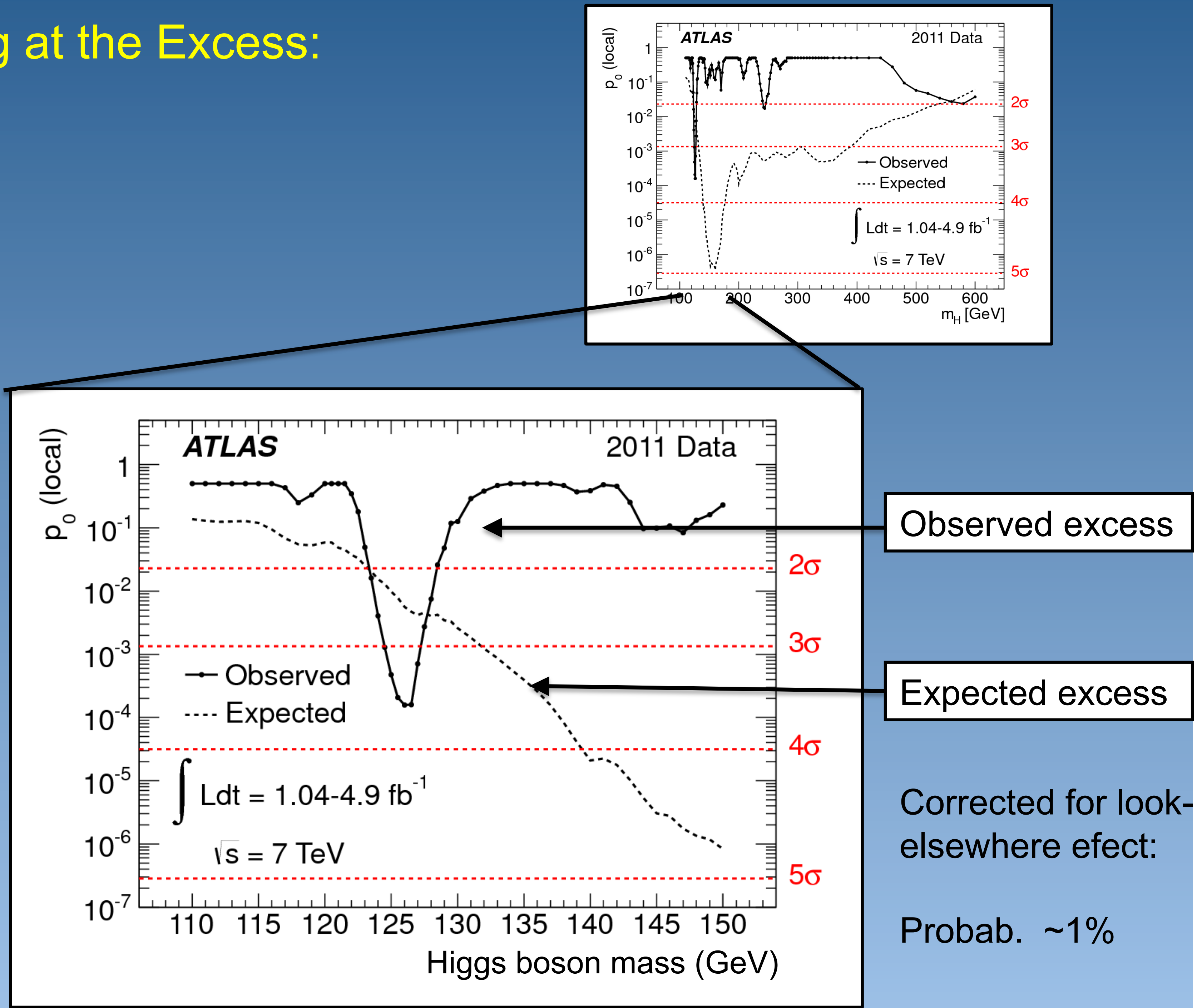
Combined excess



Corrected for look-elsewhere efect:

Probability
~ 1/100 (2.3 σ)

Looking at the Excess:
p-value



Corrected for look-elsewhere efect:

Probab. ~1%

Interpretation excess in ATLAS

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

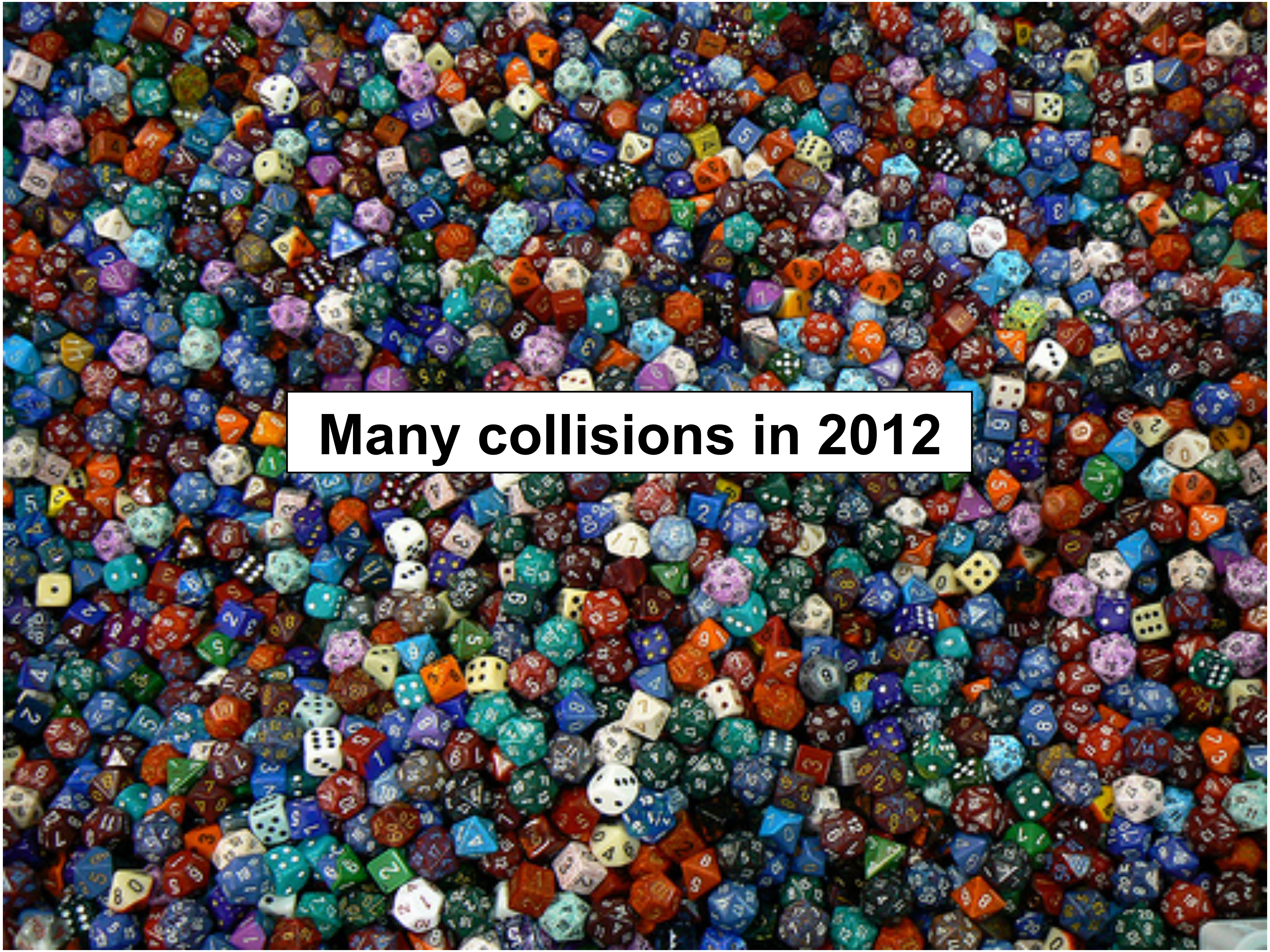
Pure chance of fake dice ?

Claim discovery if:

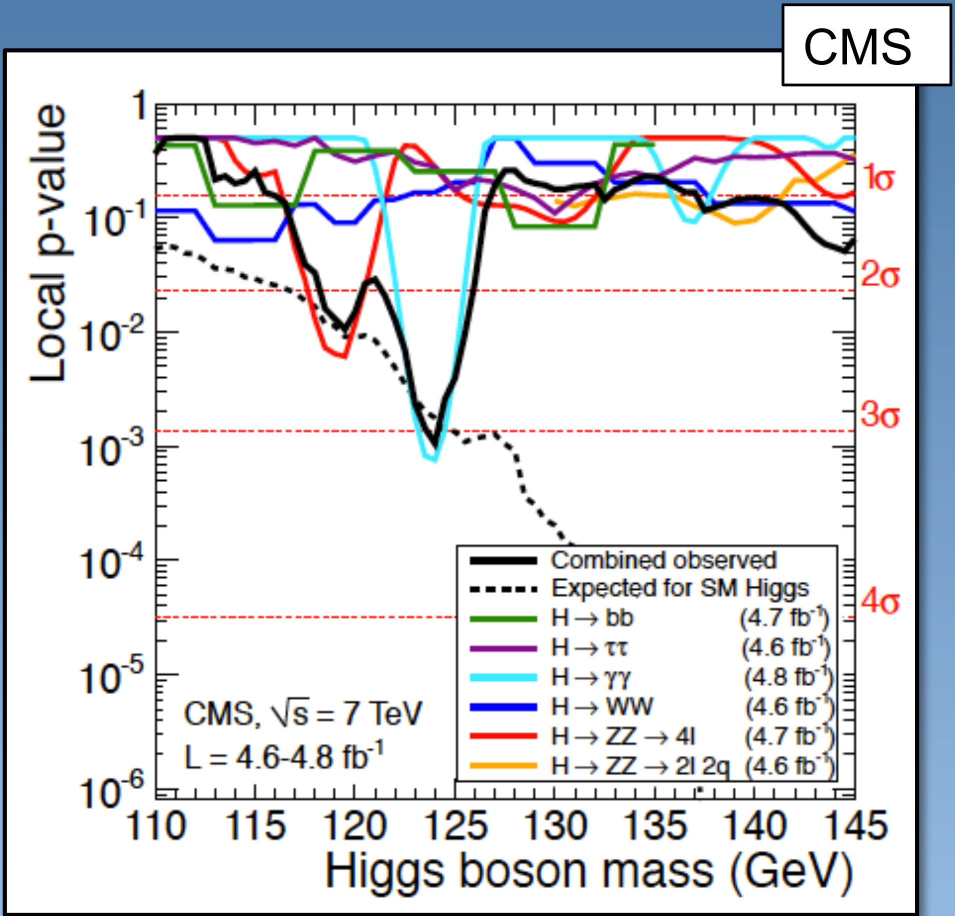
Probability on such a fluctuation from other processes < 1 on 1,000,000

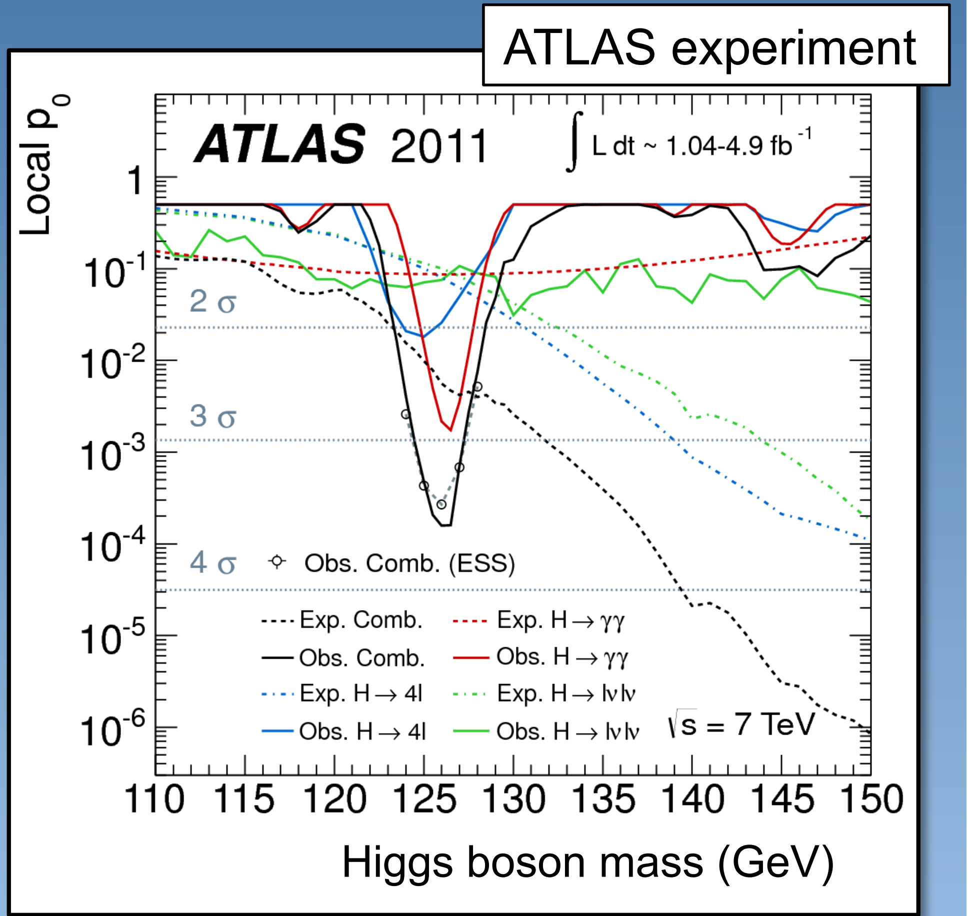
Throw 8 times 6 in a row
(need ~3 times more data)

Many collisions in 2012



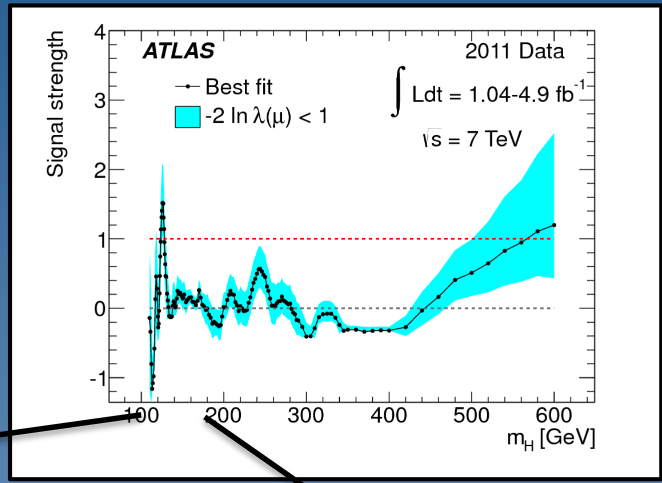
Comparison results from ATLAS and CMS experiments

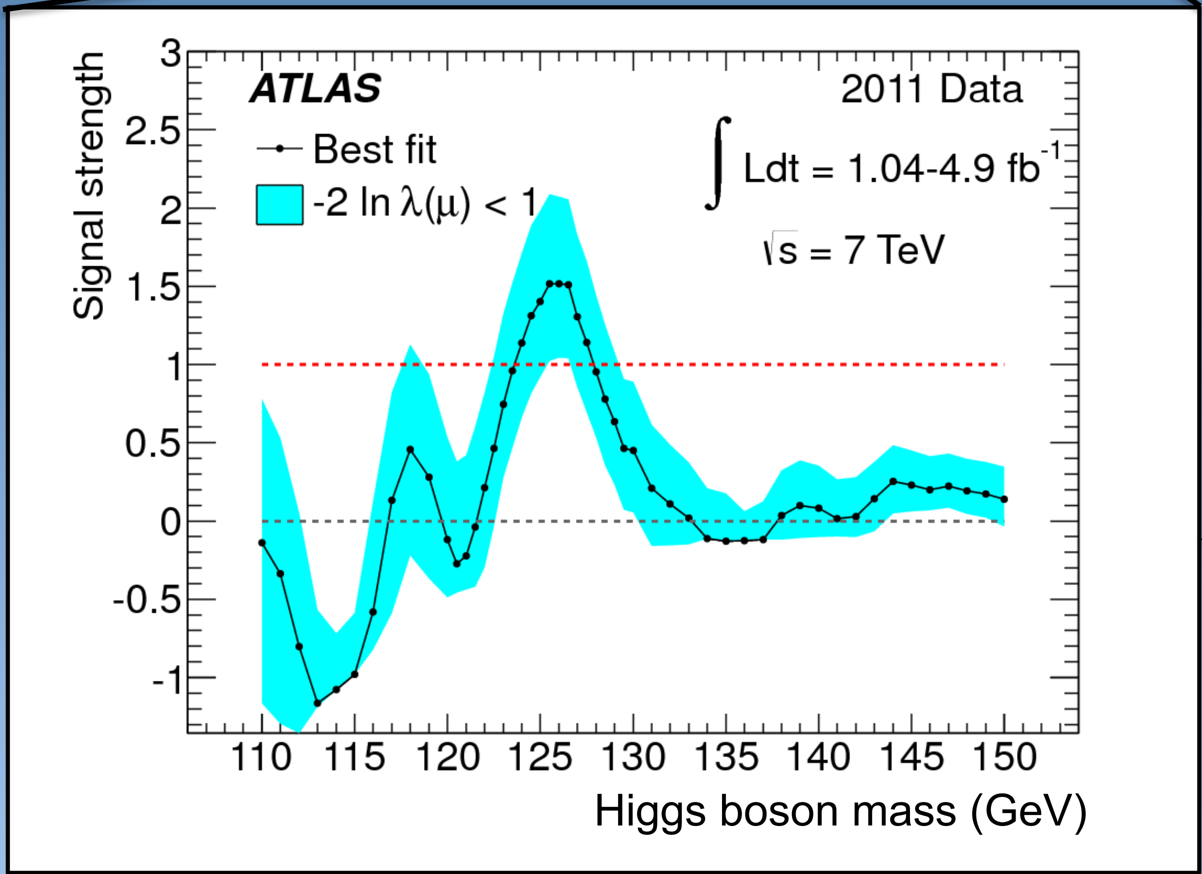




Looking at the Excess:
signal strength

Fit: SM + *signal strength* * Higgs

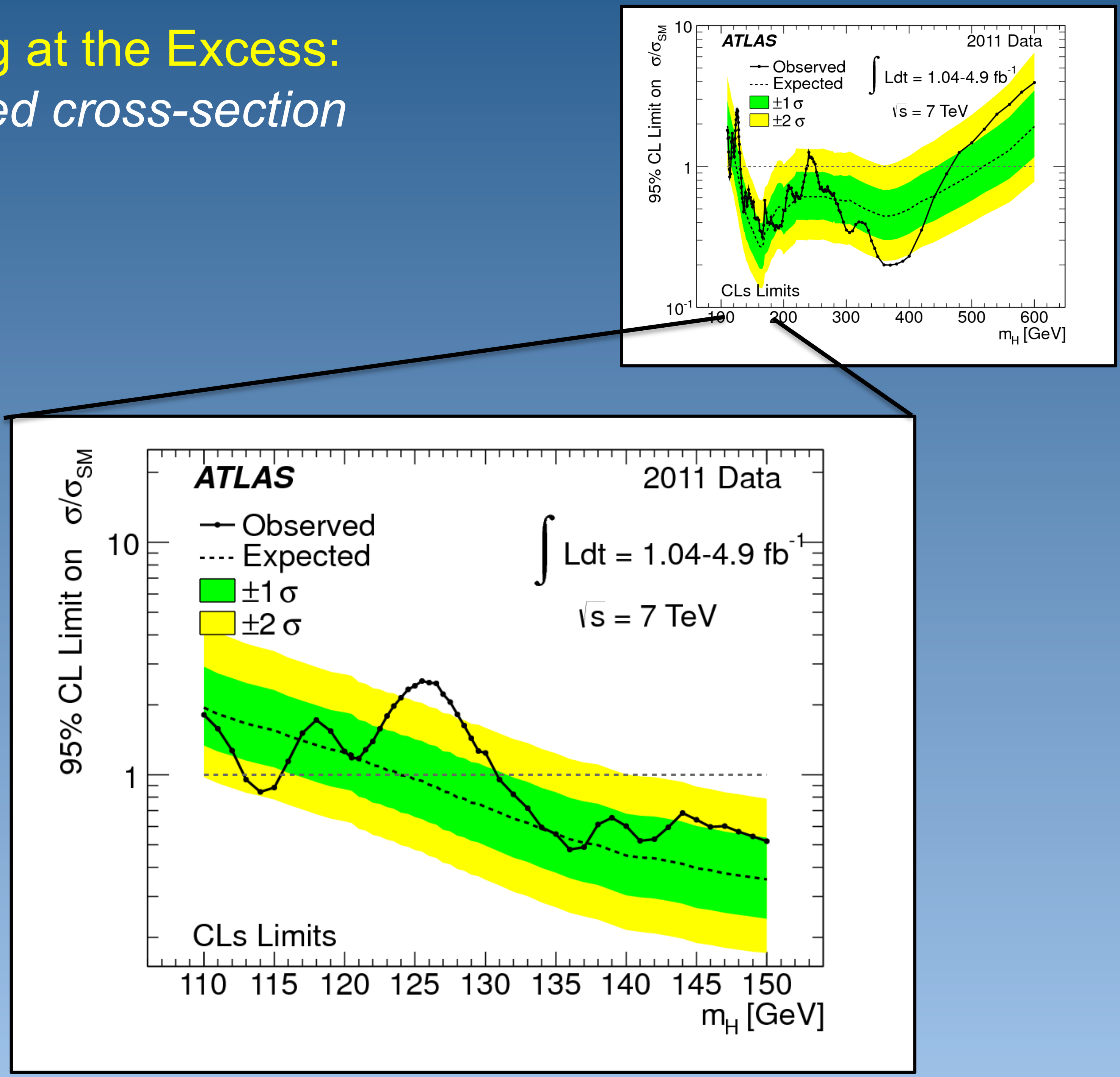




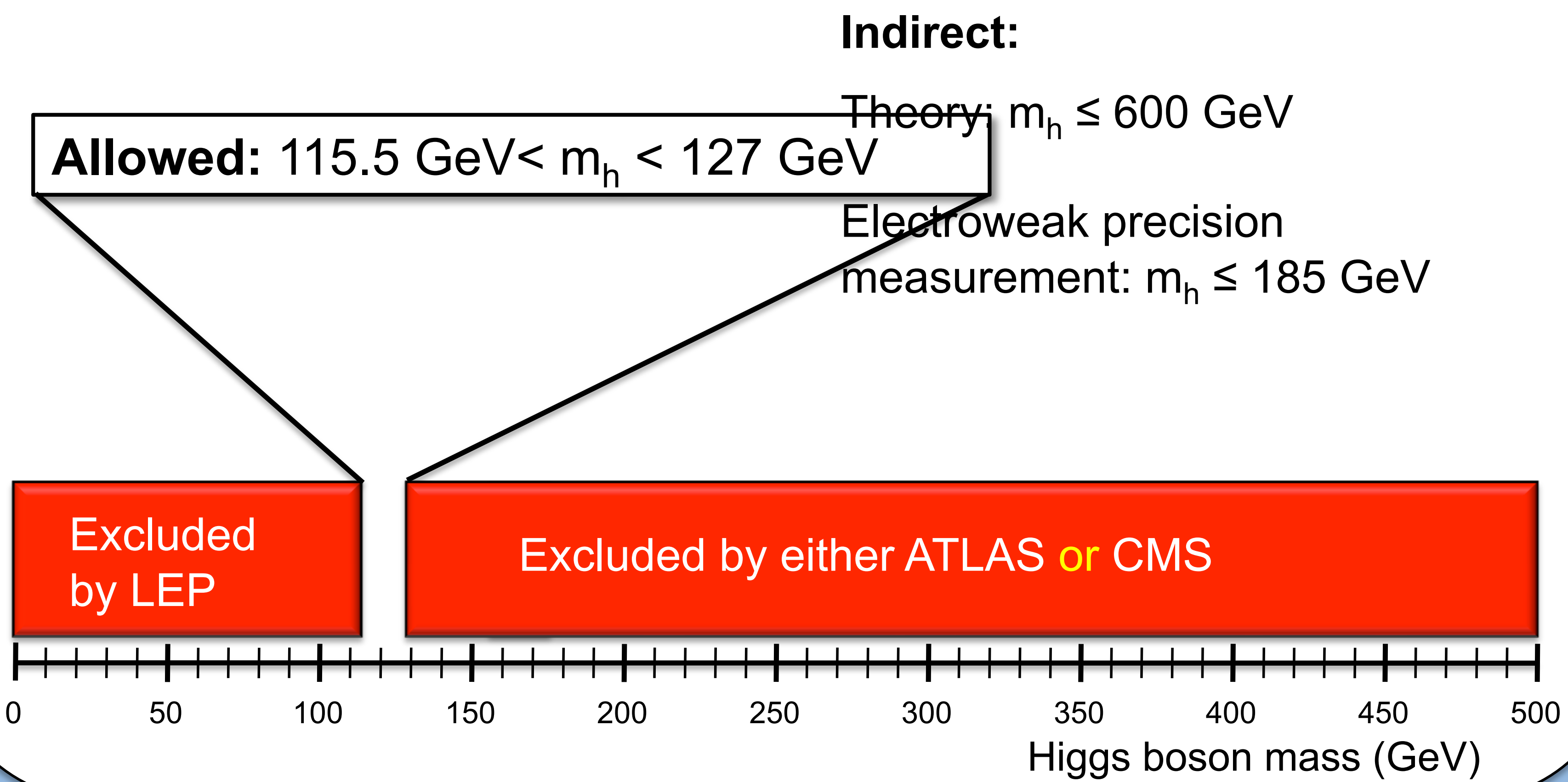
SM Higgs signal strength

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 ρ^{vac}_{Higgs} (Ω_Λ) 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 ow mass (~ 125 GeV) → no discovery yet

2) Search for the Higgs in 2012
   If the Higgs boson exists, CMS and ATLAS will discover it
   … together

Ivo.van.Vulpen@nikhef.nl

backup

References

ATLAS experiment

All ATLAS public resultats: publications, numbers and plots
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

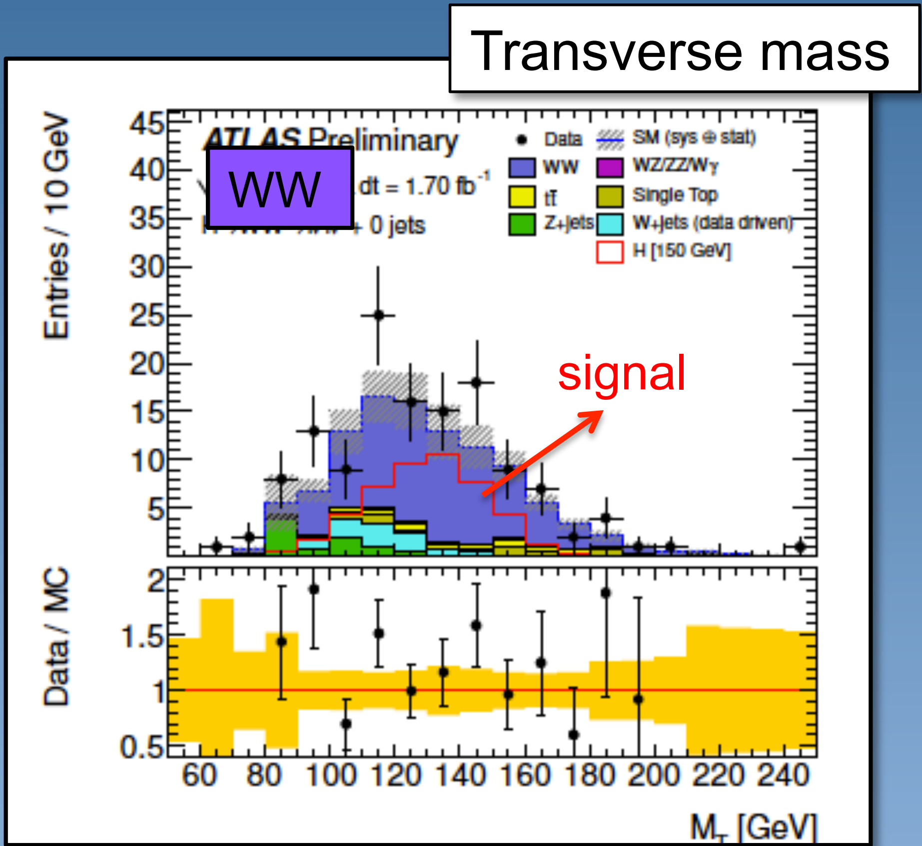
ATLAS and CMS papers

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

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

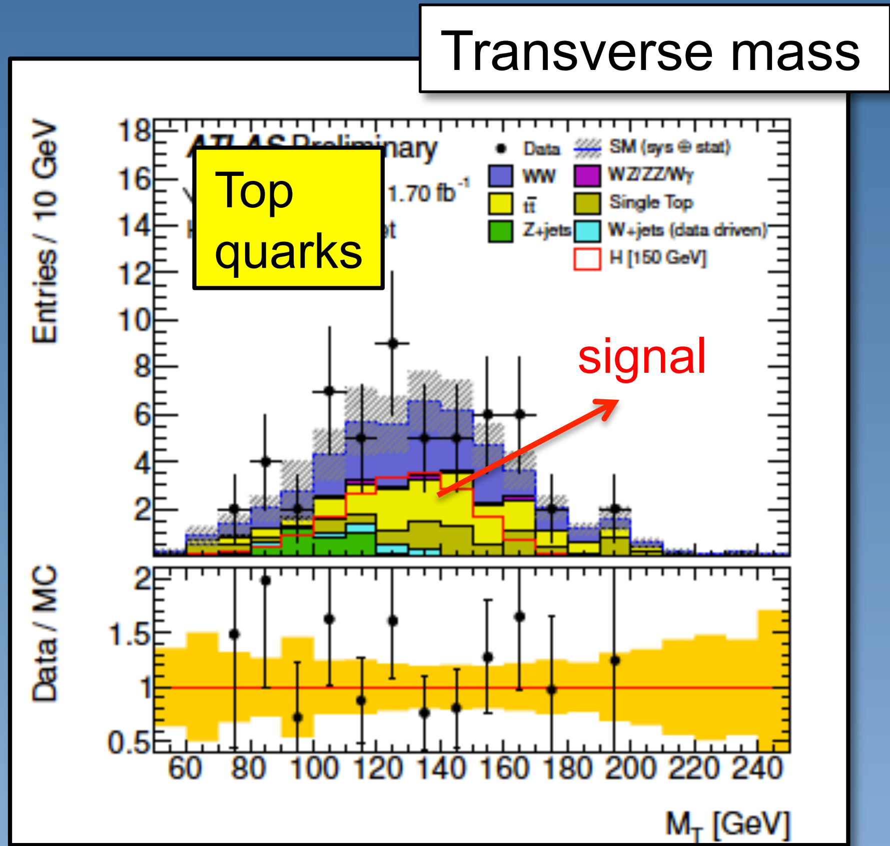
Example: m_h = 150 GeV

Topology: Higgs + 0 jets



background	53 ± 9
observation	70
signal	34 ± 7

Topology: Higgs + 1 jet



background	23 ± 4
observation	23
signal	12 ± 3