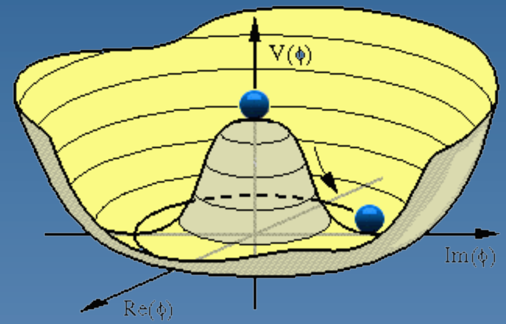
The discovery of the Higgs boson

Ivo van Vulpen (Uva/Nikhef)

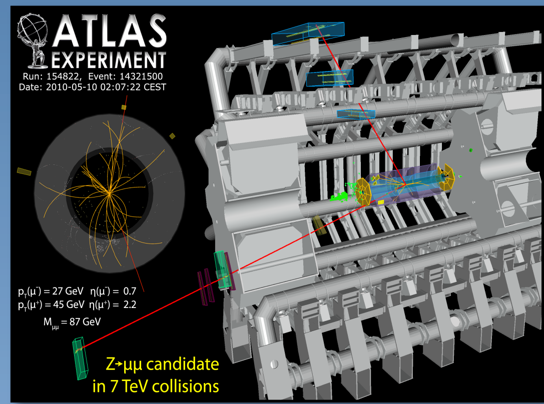
CERN in Geneva, Switzerland

Things to remember

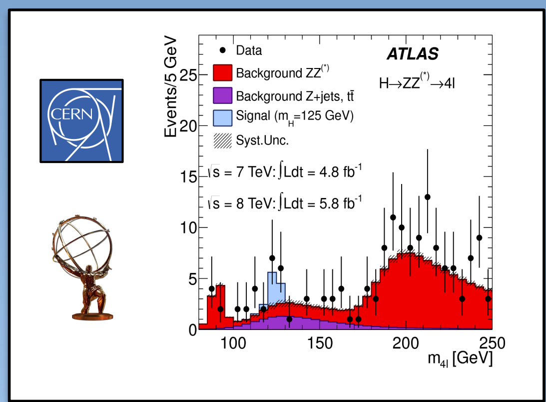
1) Higgs mechanism is at the heart of the Standard Model

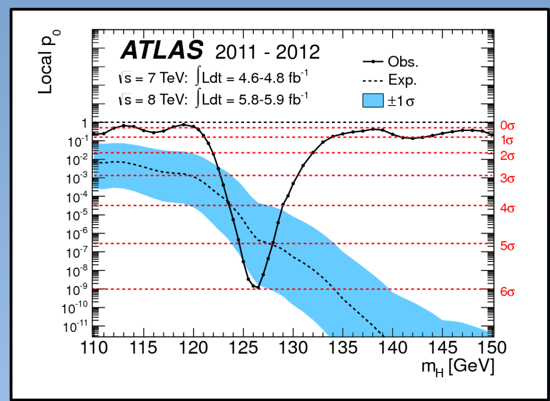


2) LHC and ATLAS detector operating fine!



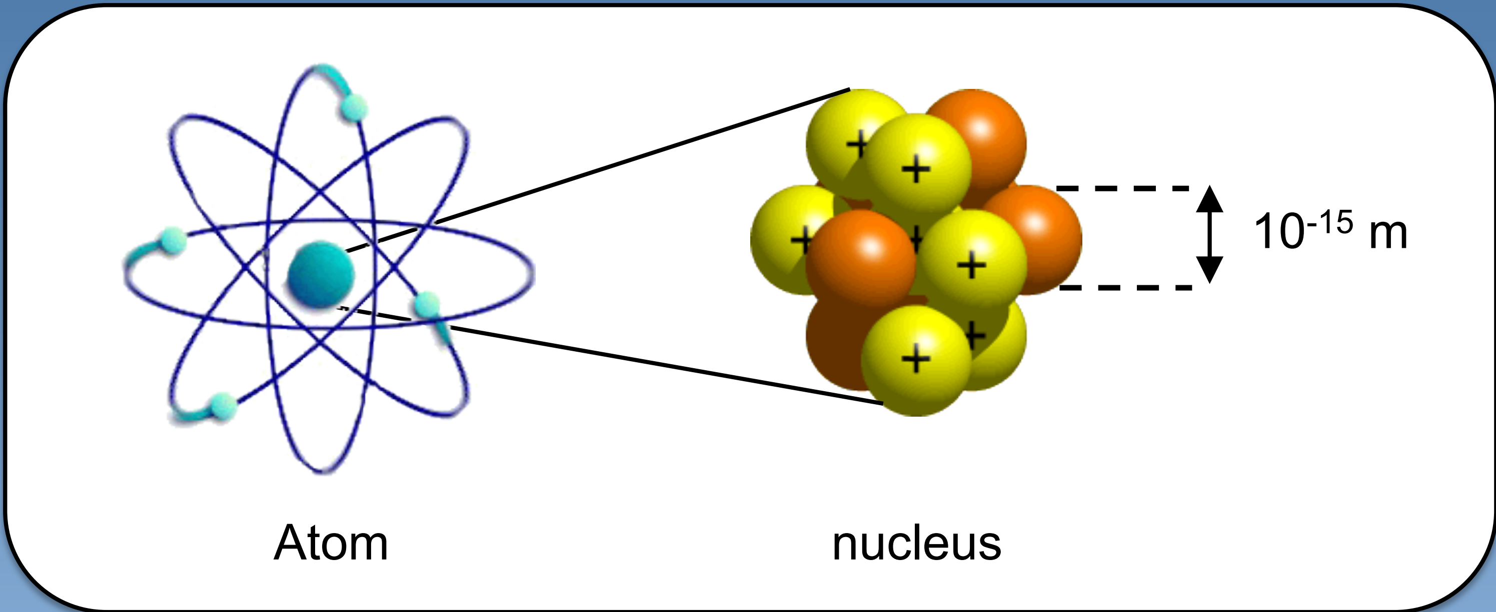
3) Discovery of the Higgs boson (interpretation)





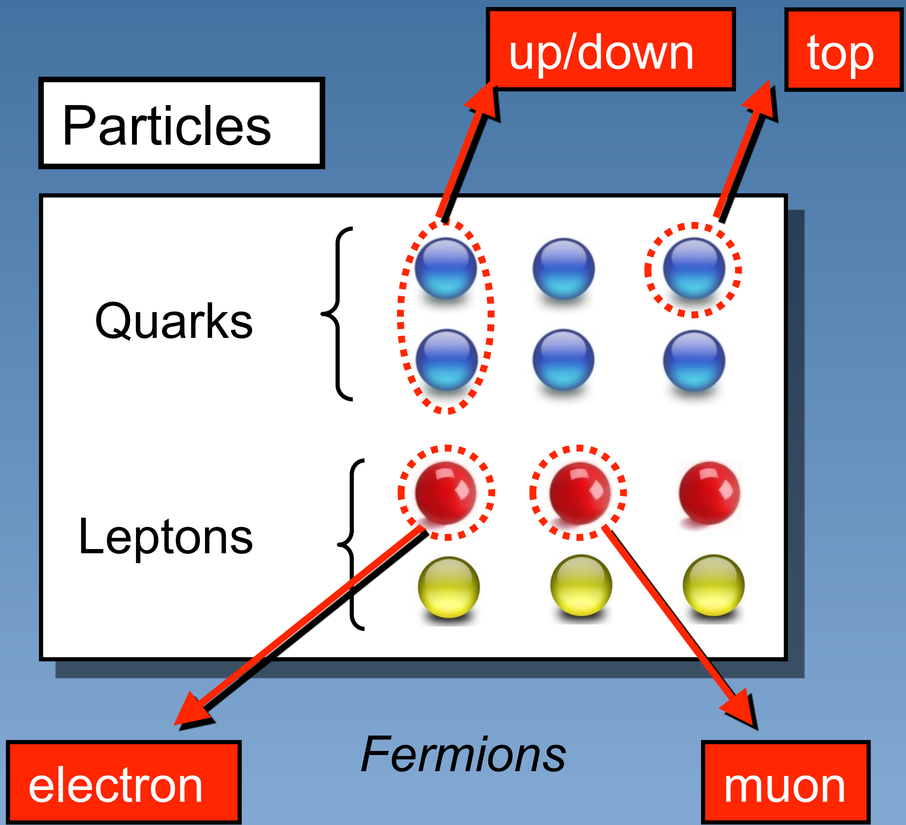
Particle Physics

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



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

The Standard Model



Forces

1) Electromagnetism (photon)

2) Weak force (W^+, W^-, Z)

3) Strong force (8 gluons)

Bosons

The Standard Model

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

Weak iso-spin, hypercharge, colour

Standard Model based on local gauge invariance (symmetries)

Free electron

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

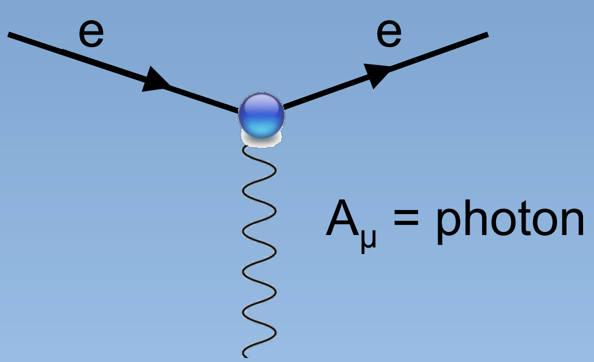
Extra symmetry requirement

Local gauge invariance

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

Introduce covariant derivative (vector-field)

$$\partial_\mu \rightarrow D_\mu \equiv \partial_\mu - iqA_\mu$$



'automatic' force carriers and interactions'

In the Standard Model

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

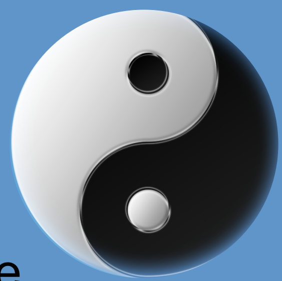
Electroweak:
W^+, W^-, Z, γ

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:

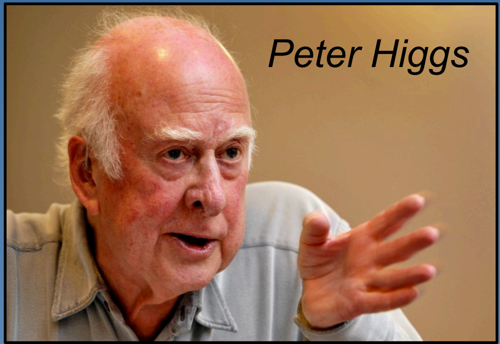
- No massive gauge bosons ($W^{\pm}$,Z)
- No massive fermions (all particles)
- Vector boson scattering diverges

↓

Higgs mechanism


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

The Higgs mechanism




BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Received 27 July 1964

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**

- September 1964 -

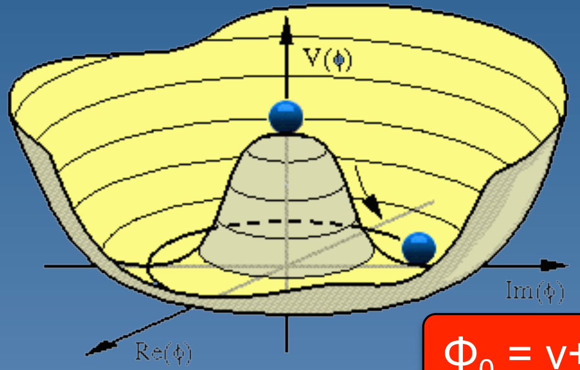
(In)famous Higgs boson

The Higgs boson

Paris Hilton

Being famous is not the same as being important

The Higgs mechanism



Φ_0 = v+h

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

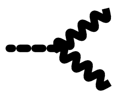
2) Potential: $V(\Phi) = \mu^2\Phi^2 + \lambda\Phi^4$, with $\mu^2<0$

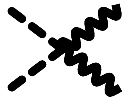
Gauge bosons

(V = W^+,W^-,Z,γ)

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

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

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

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

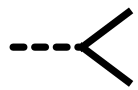
+ scalar particle

Fermions

(ψ =e,μ,…)

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

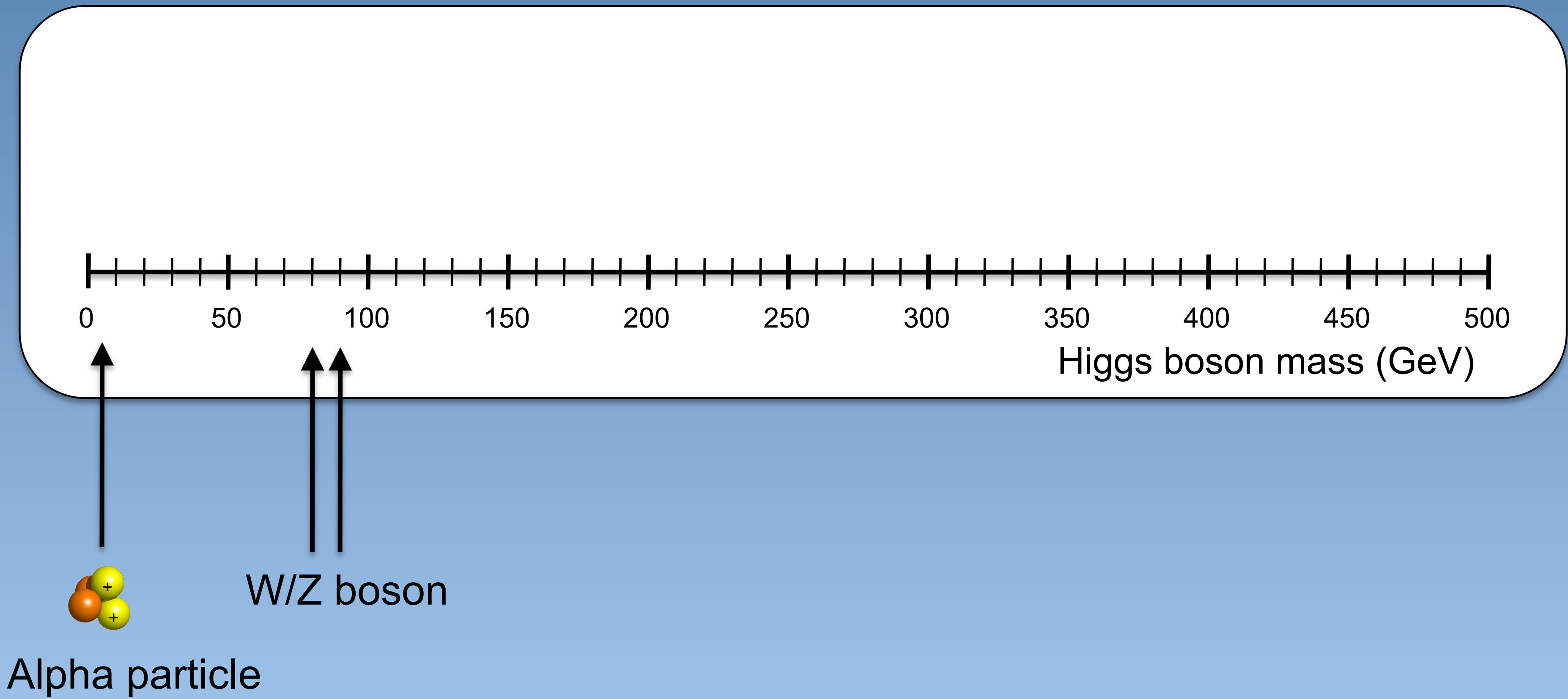
$\propto m_\psi\overline{\psi}\psi$ mass ψ

$\propto \left(\frac{m_\psi}{\mathrm{v}}\right)\overline{\psi}h\psi$ 

"the Higgs couples to mass"

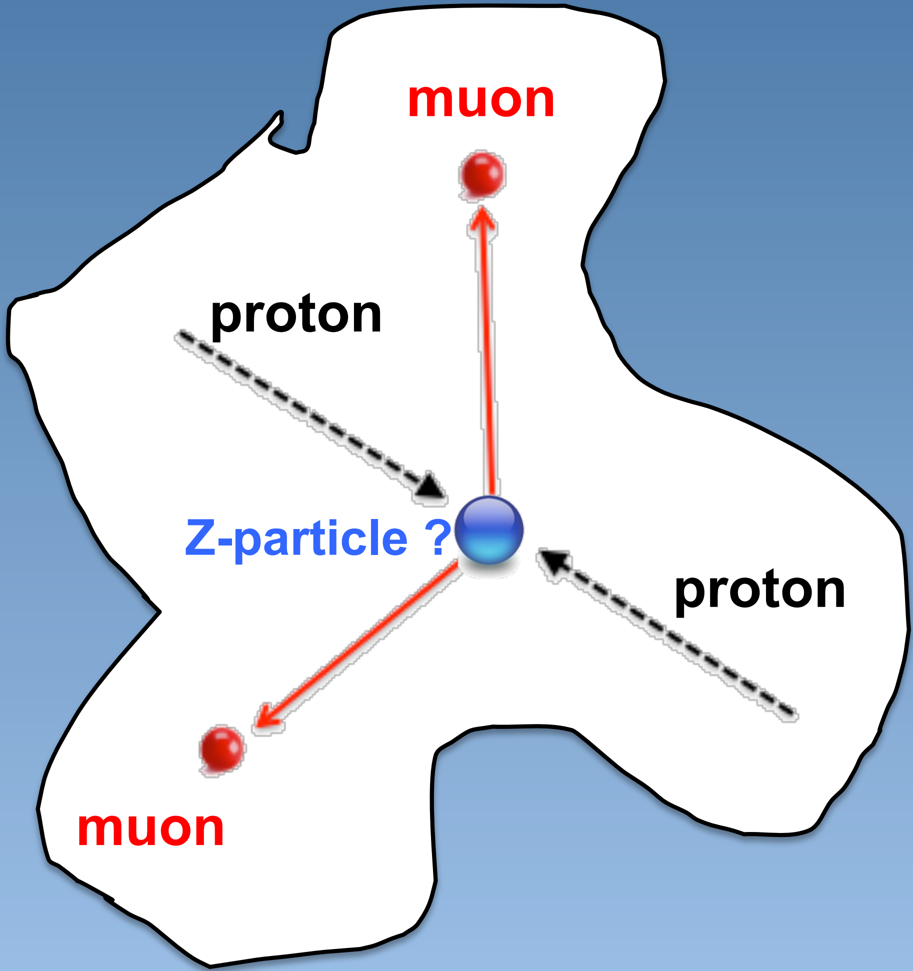
The mass of the Higgs boson

Properties of the Higgs boson are known … as a function of it's ***unknown*** *mass*

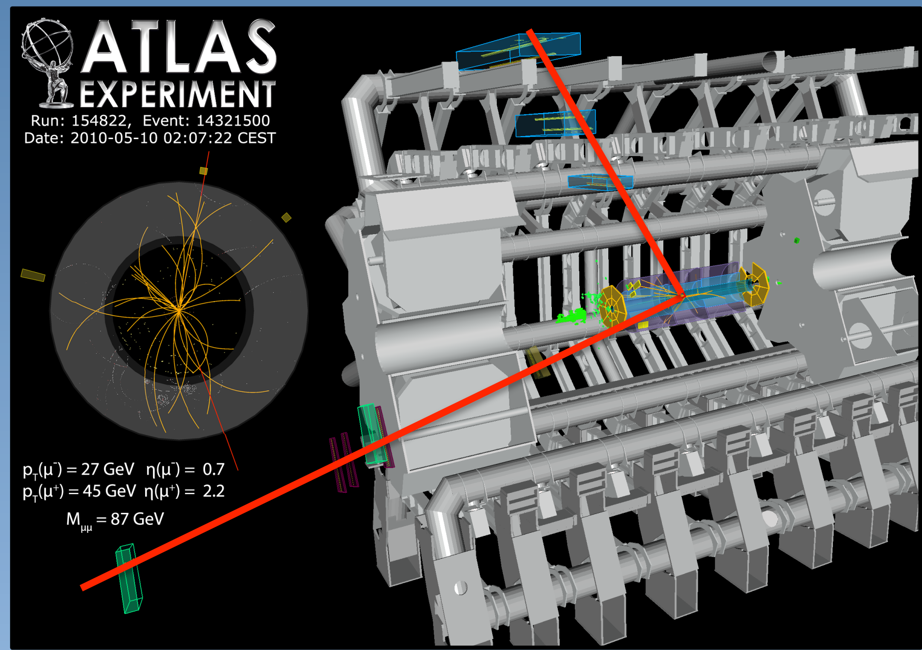


How do you discover a Z particle ?

Deviations from the prediction without a Z boson



2-muons as seen in the ATLAS detector



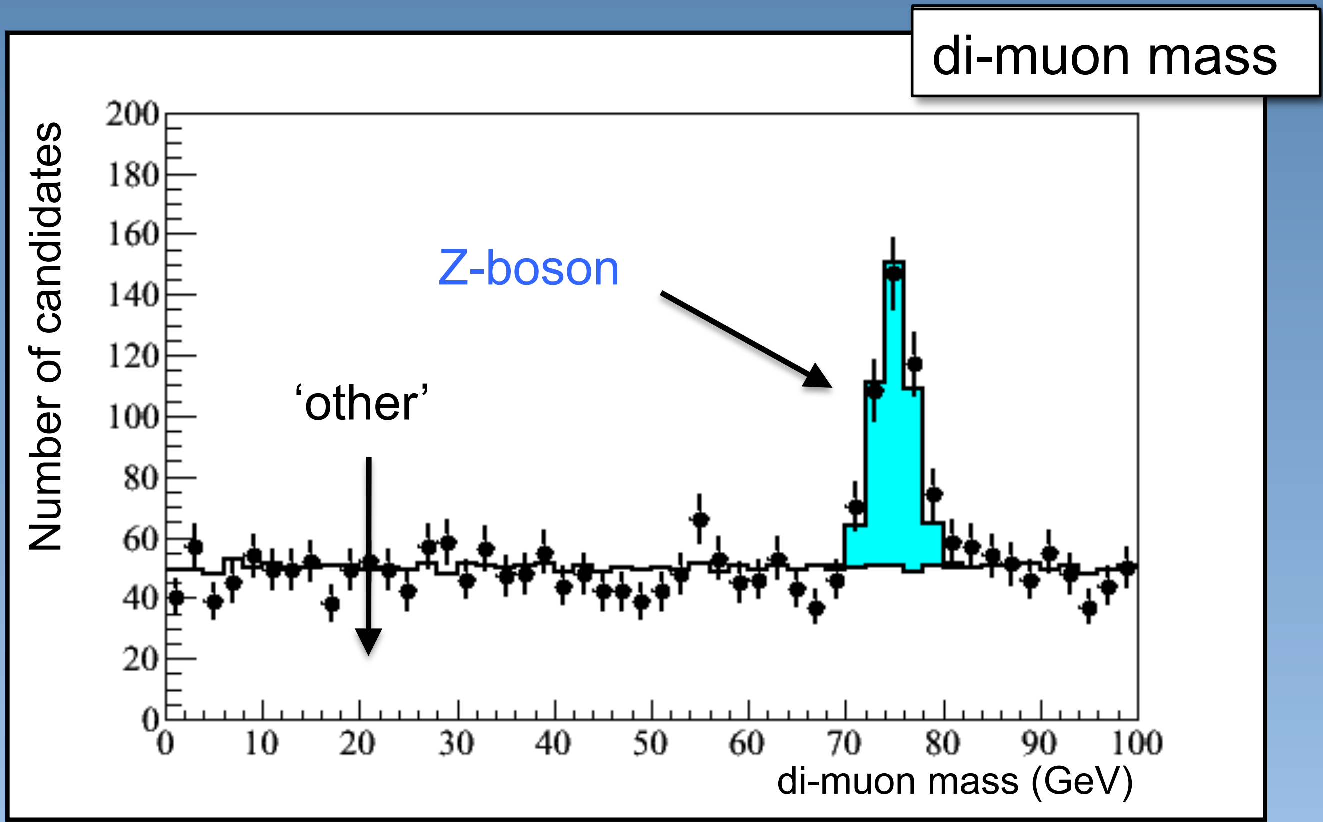
What is the fingerprint of the Z particle:

→ the di-muon mass

di-muon mass

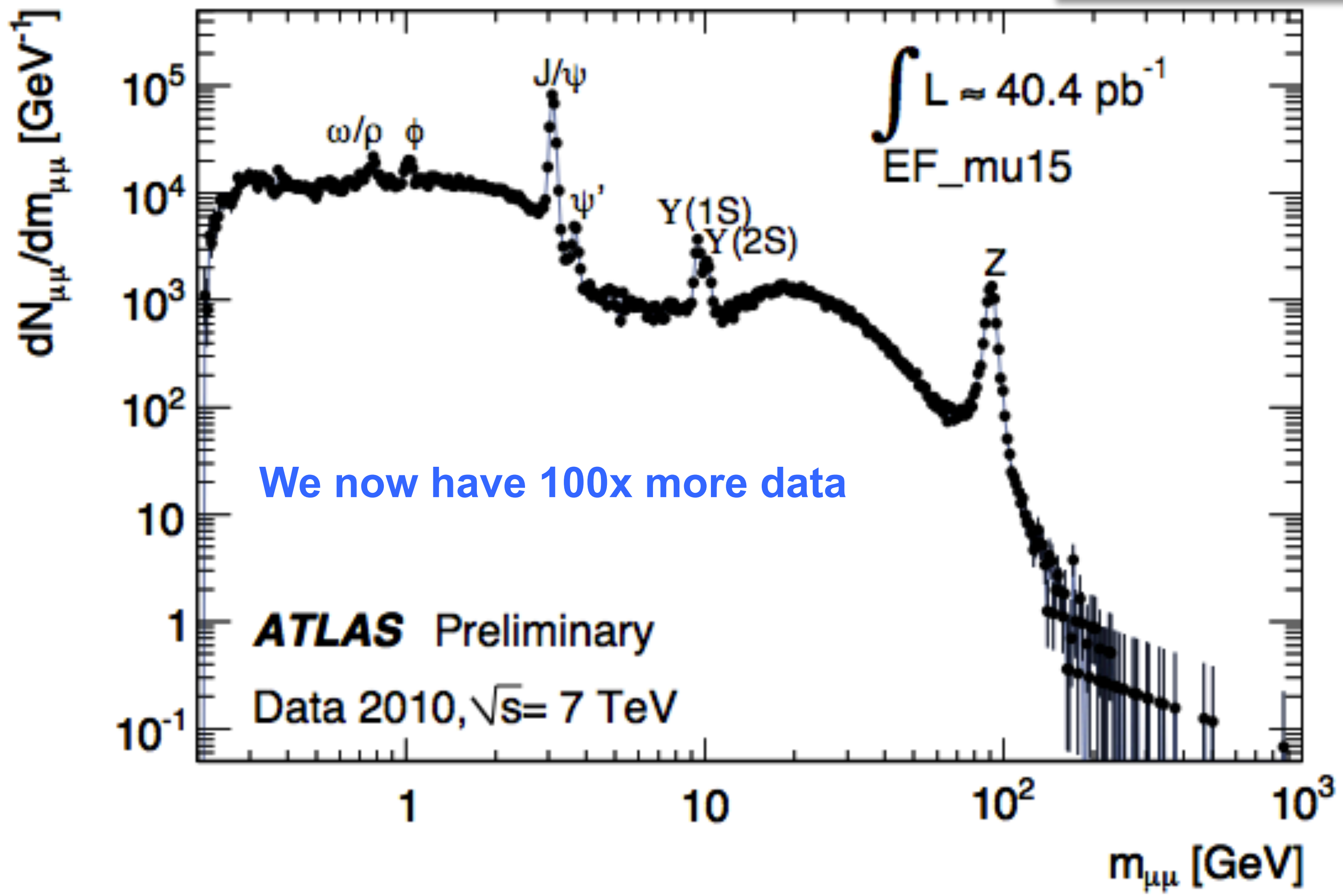
‘other’: no preference/structure

Z-boson: Breit-Wigner ⊗ resolution

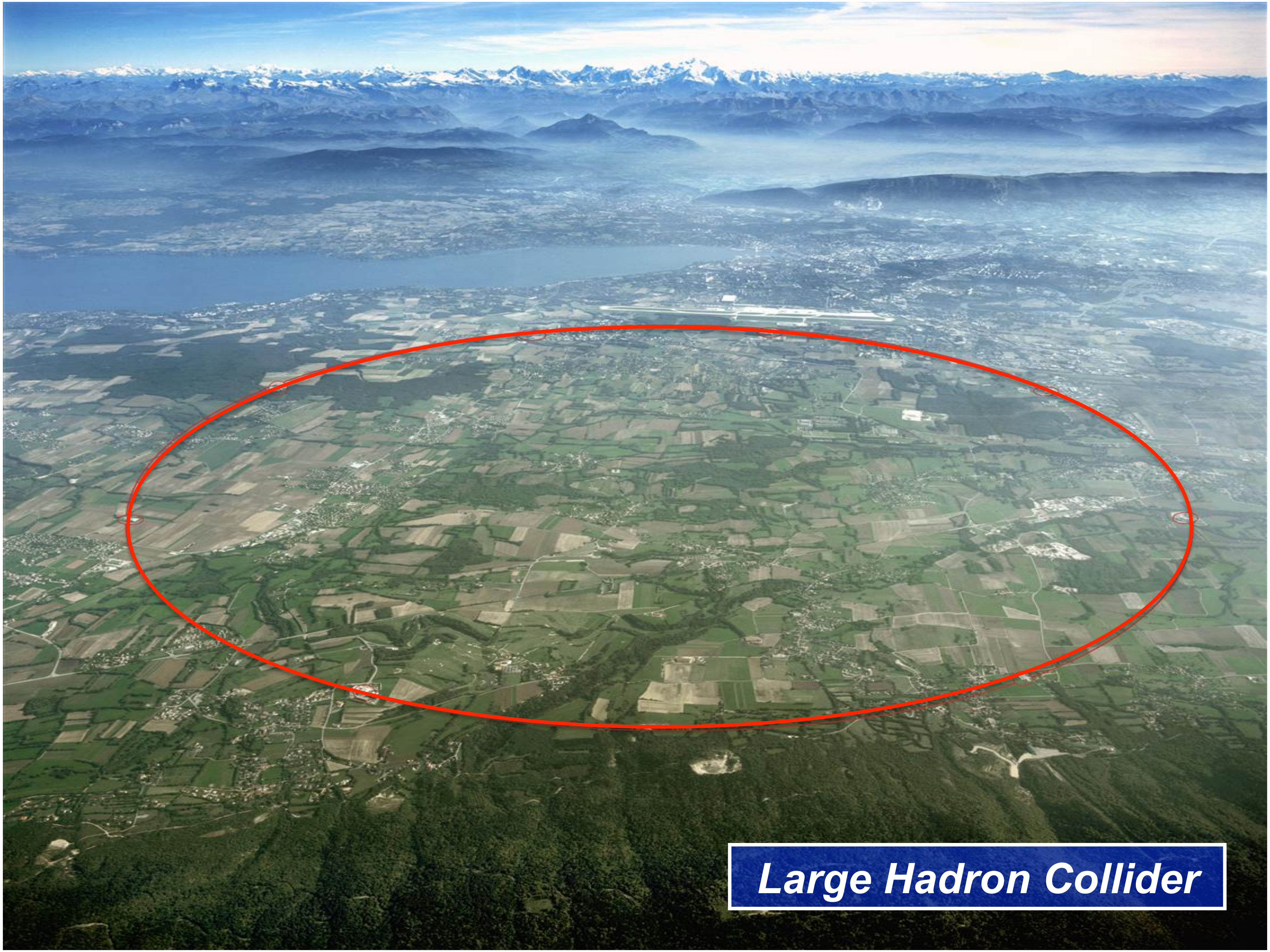


Di-muon resonances seen at the LHC

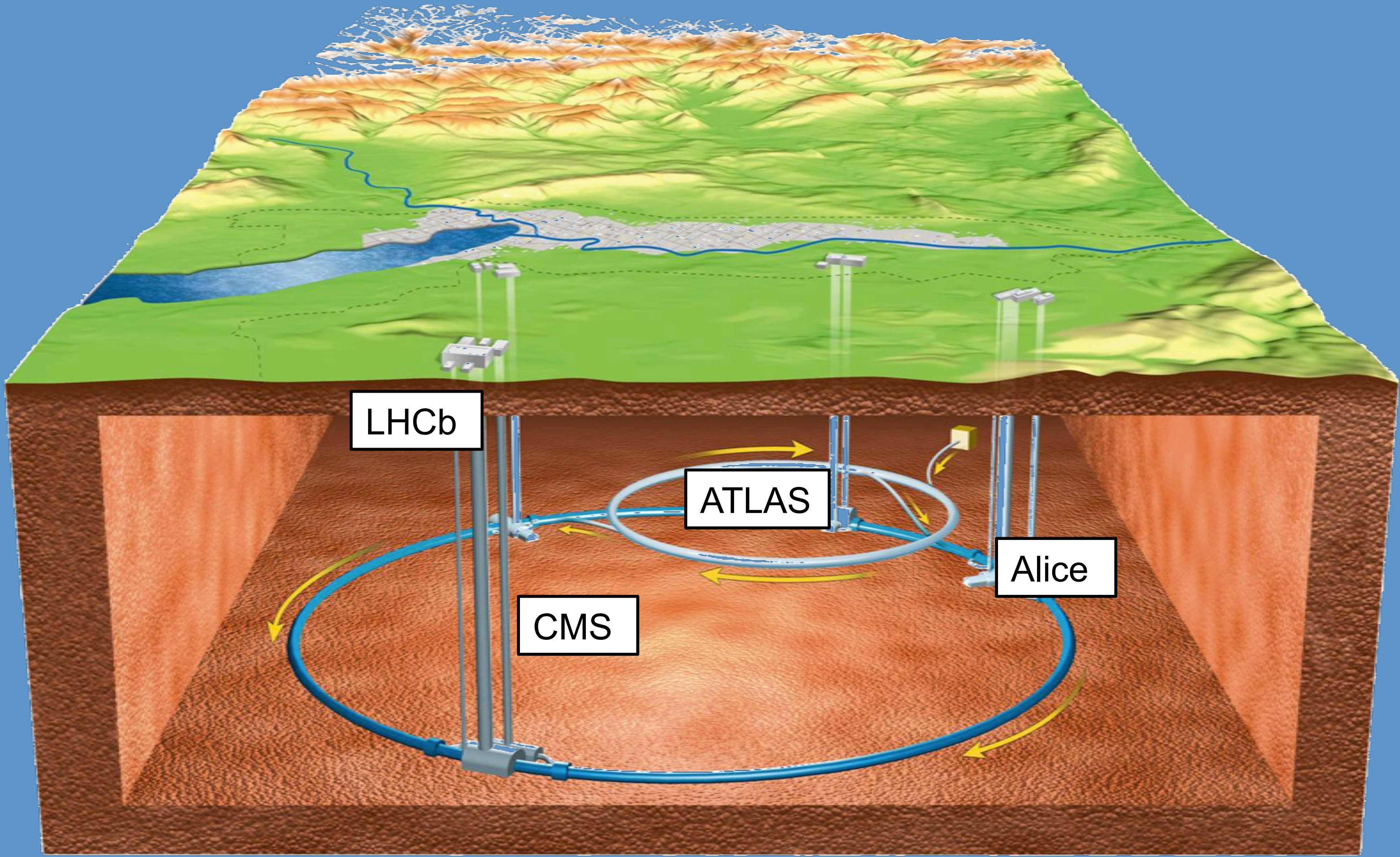
di-muon mass

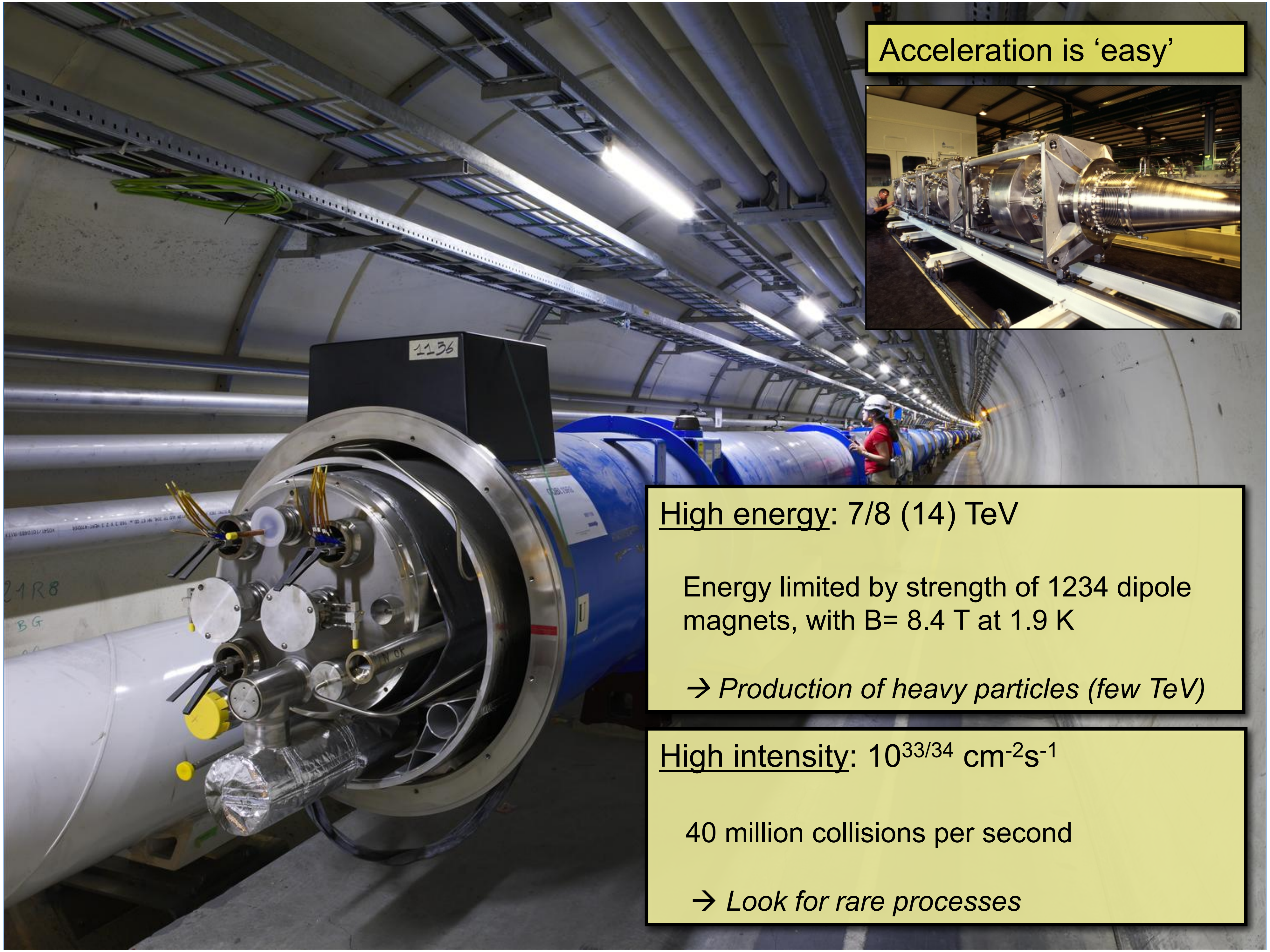


We now have 100x more data


Large Hadron Collider

The Large hadron collider





Acceleration is ‘easy’

High energy: 7/8 (14) TeV

Energy limited by strength of 1234 dipole magnets, with B= 8.4 T at 1.9 K

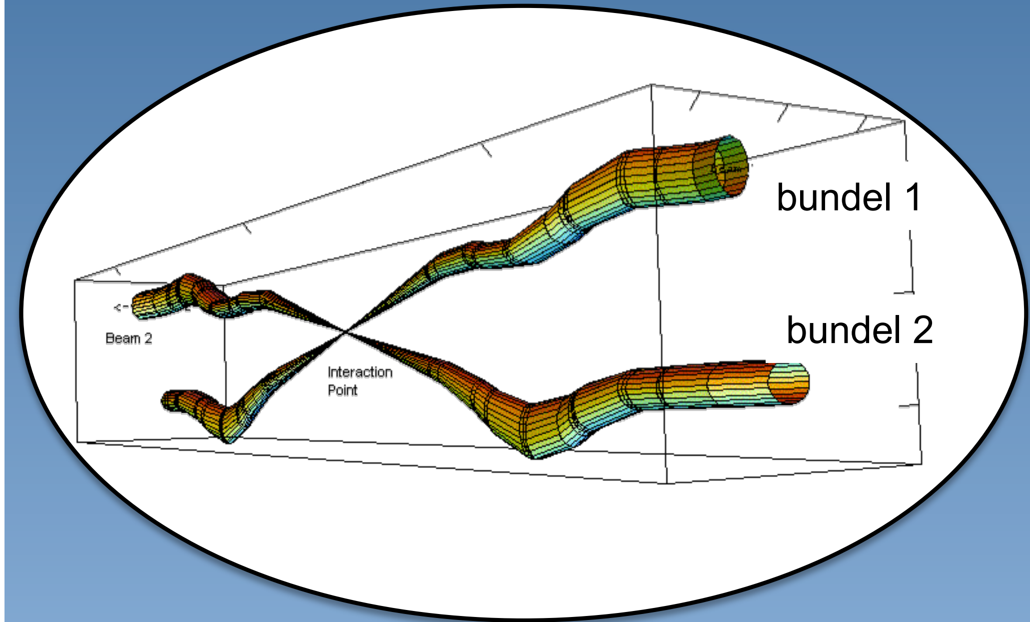
→ *Production of heavy particles (few TeV)*

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

40 million collisions per second

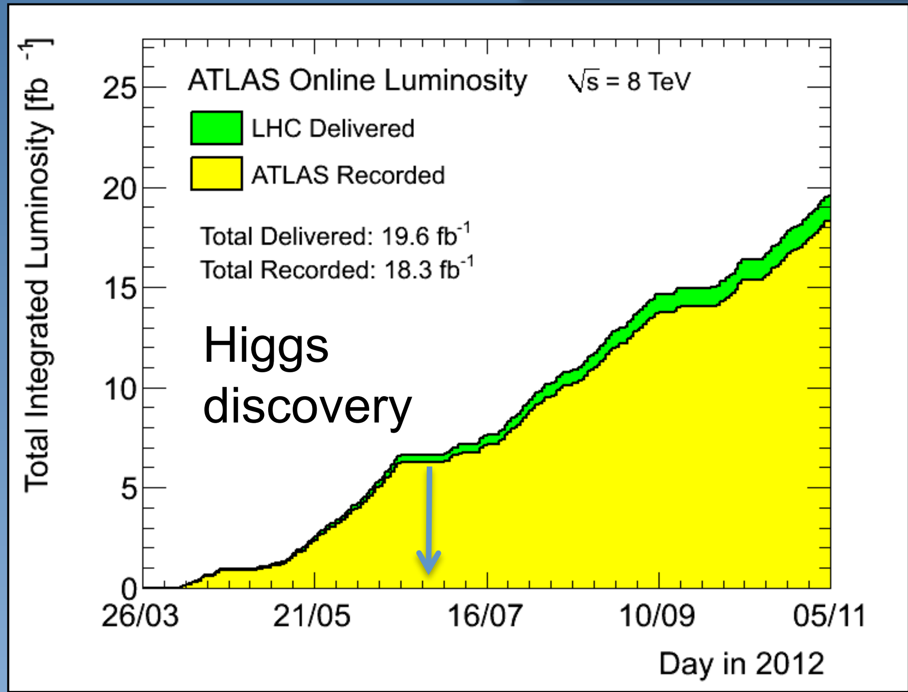
→ *Look for rare processes*

LHC data-set 2011+ 2012



40 million collisions per second
Only 200 Hz to tape

LHC Luminosity

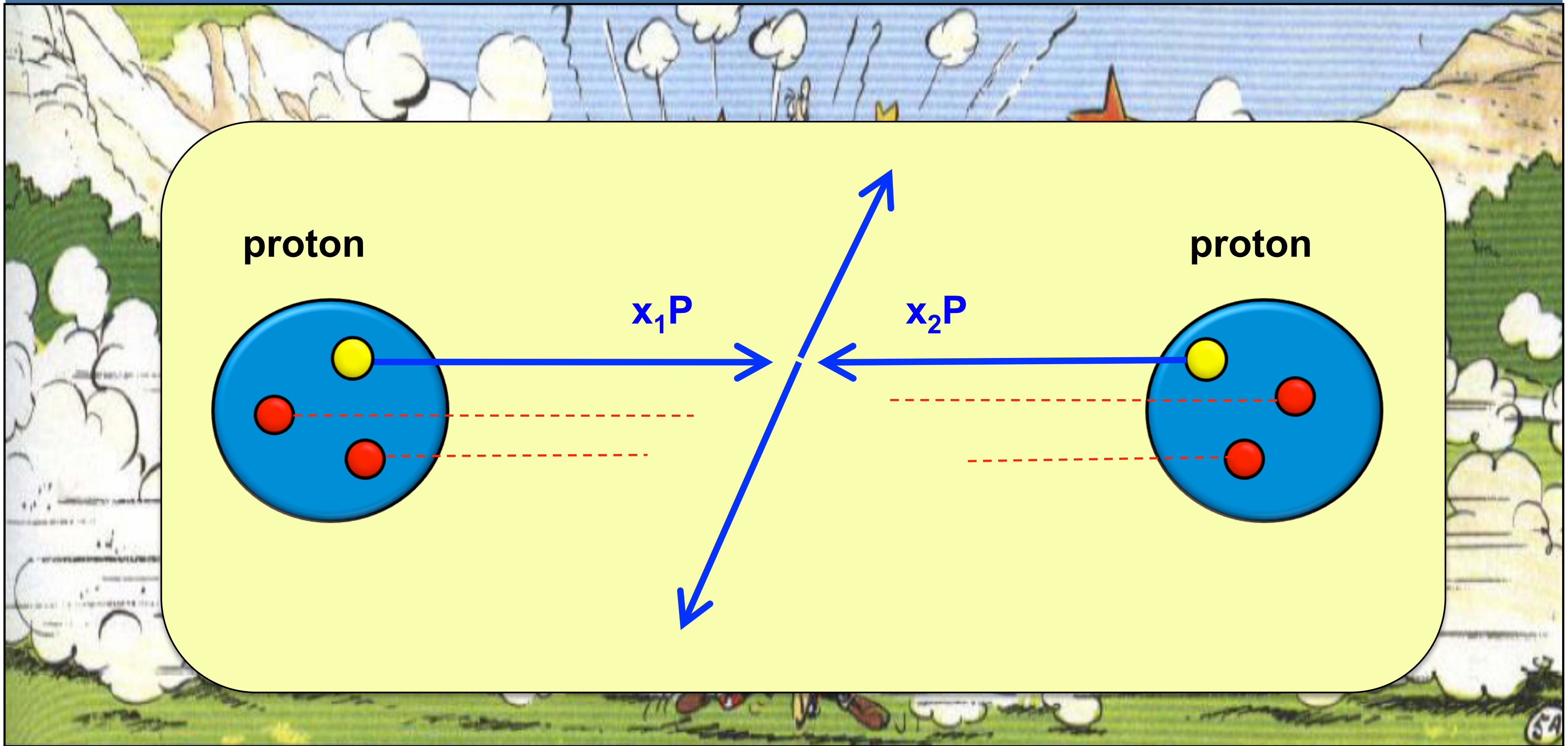


ATLAS (2011): 4.8 fb^{-1} at $\sqrt{s}$=7 TeV
ATLAS (2012): 19.6 fb^{-1} at $\sqrt{s}$=8 TeV

Note: almost all results in this talk are from data up to discovery

Phenomenology of proton-proton collisions

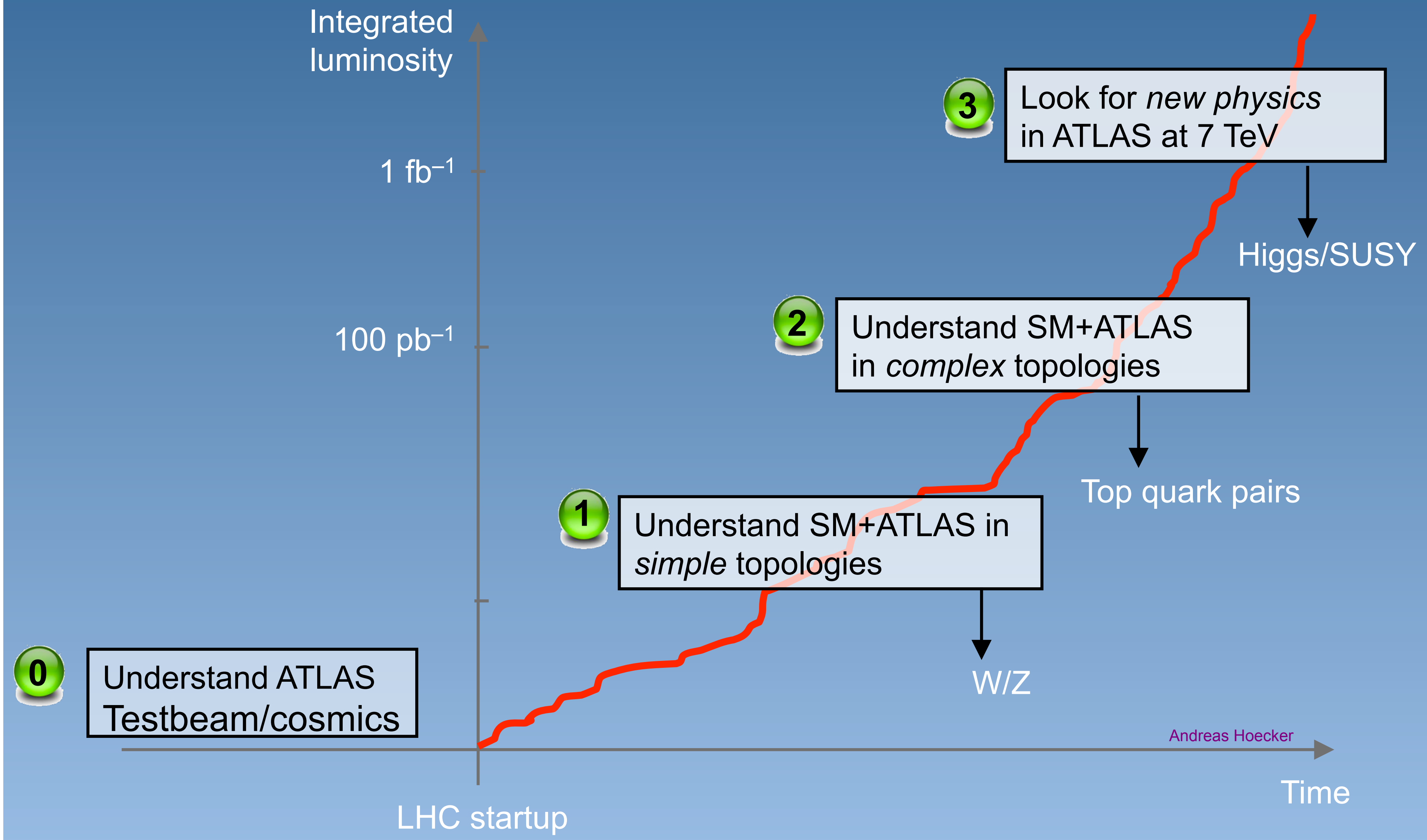
"Proton is a bag full of (anti-)quarks and gluons"



Only a fraction of the collision energy available for 'hard' interaction

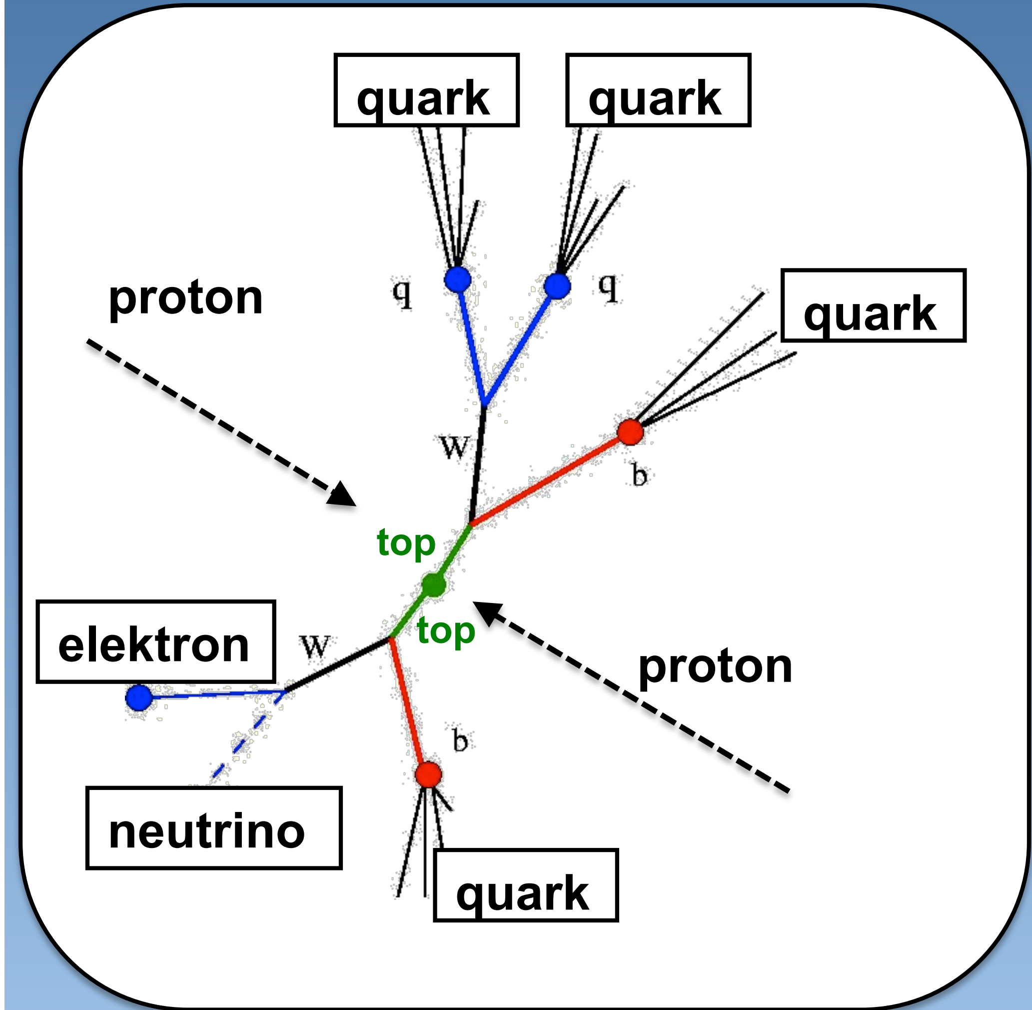
LHC start-up programme

New detector **and** new energy scale

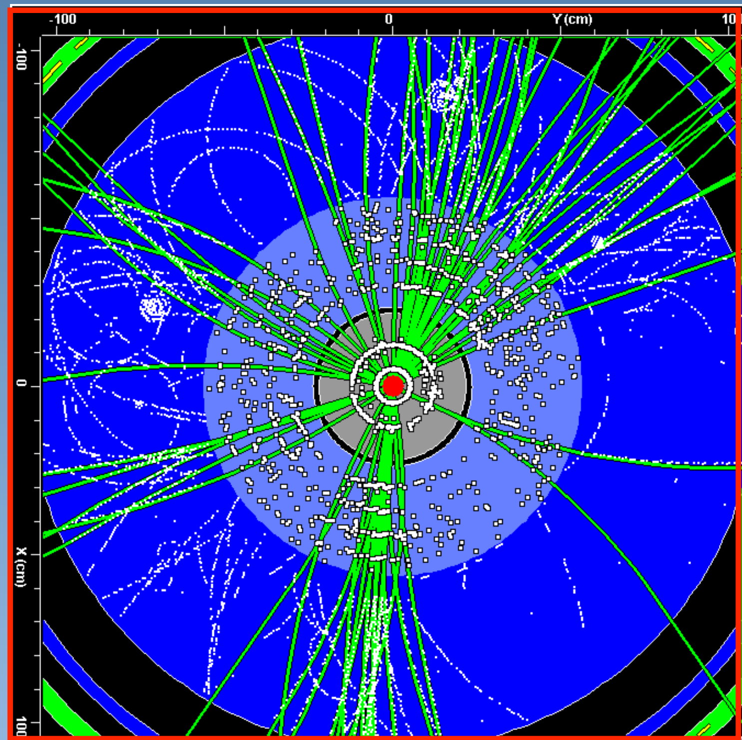


Interpreting LHC events

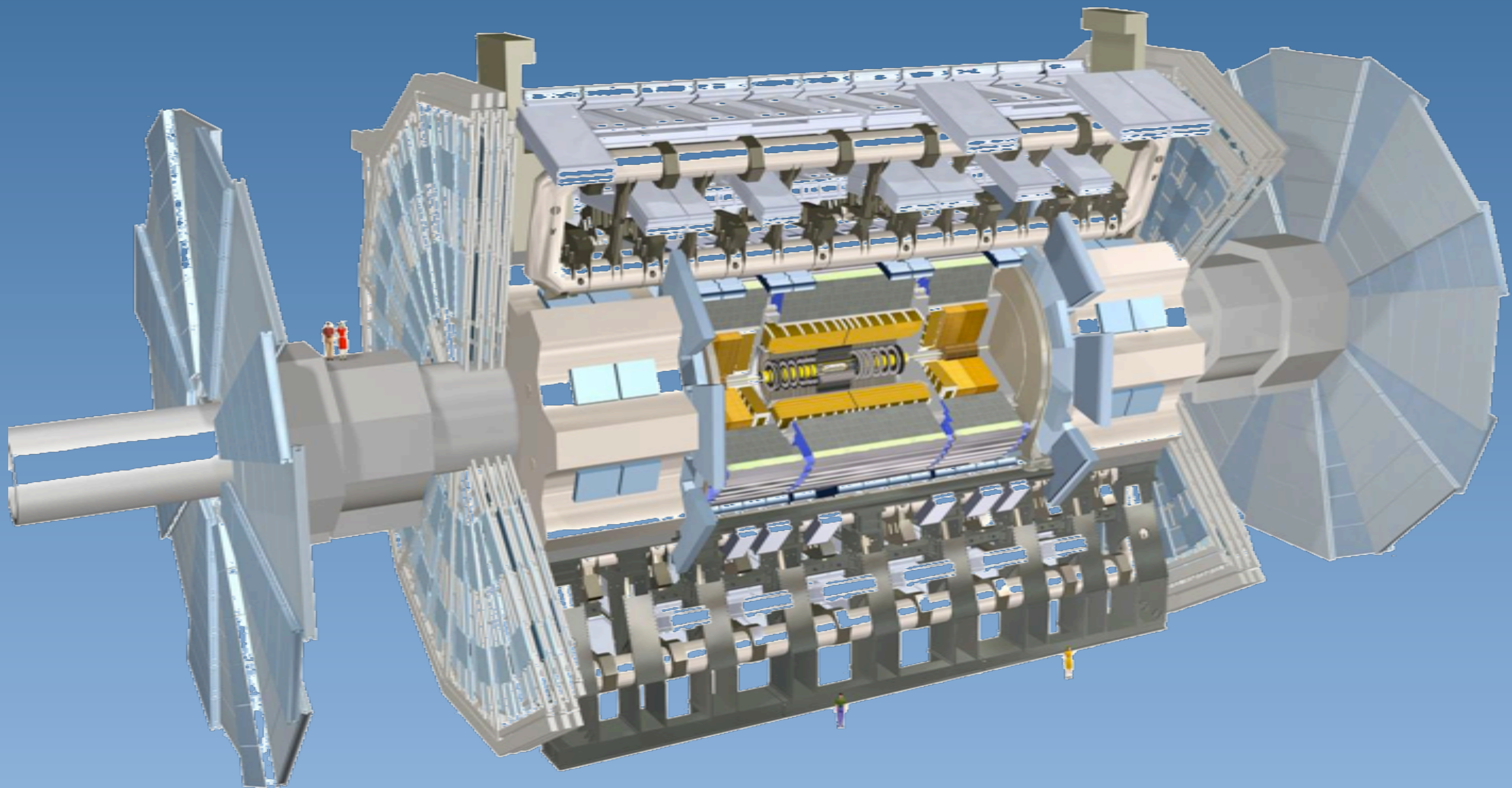
top quark pair-production



Simulation top quark production

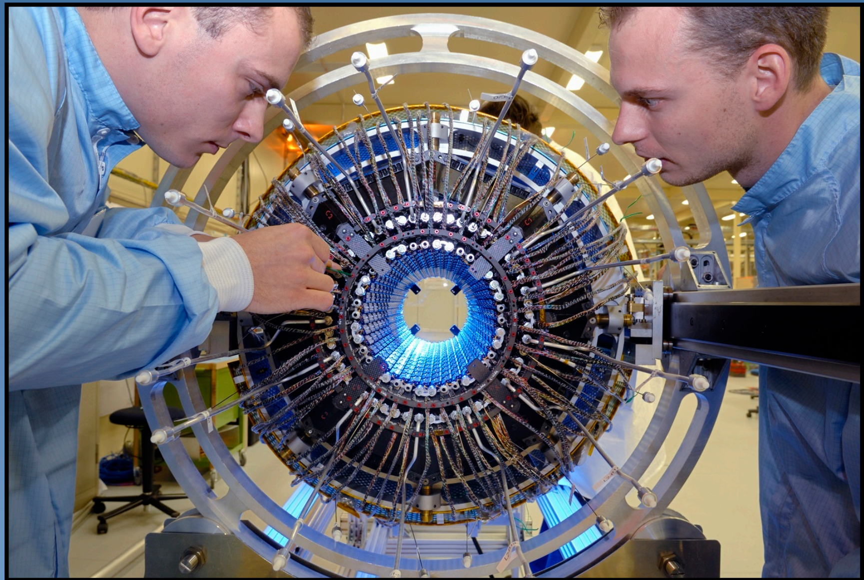


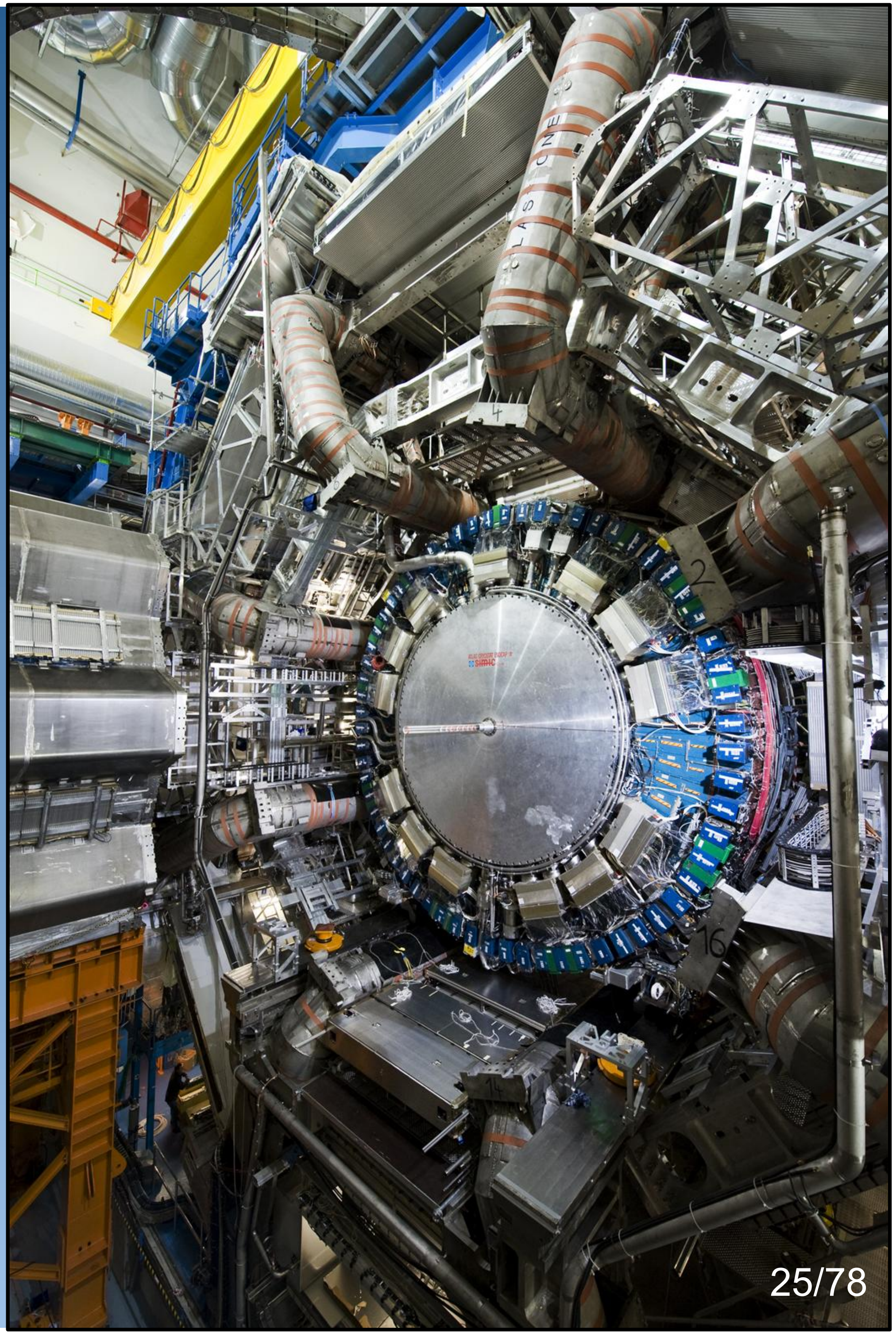
The ATLAS detector
(as a computer model)



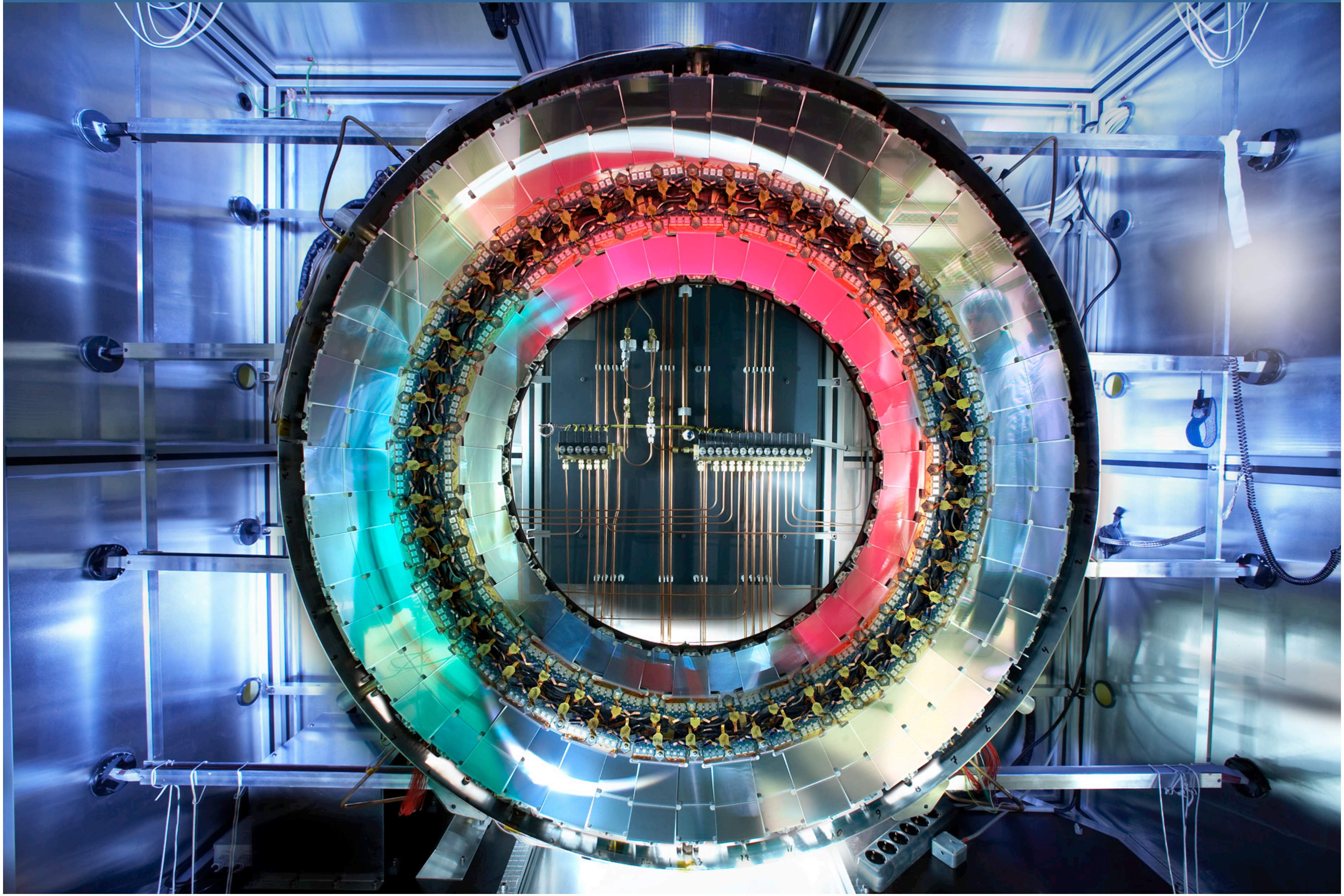
The Atlas detector really exists

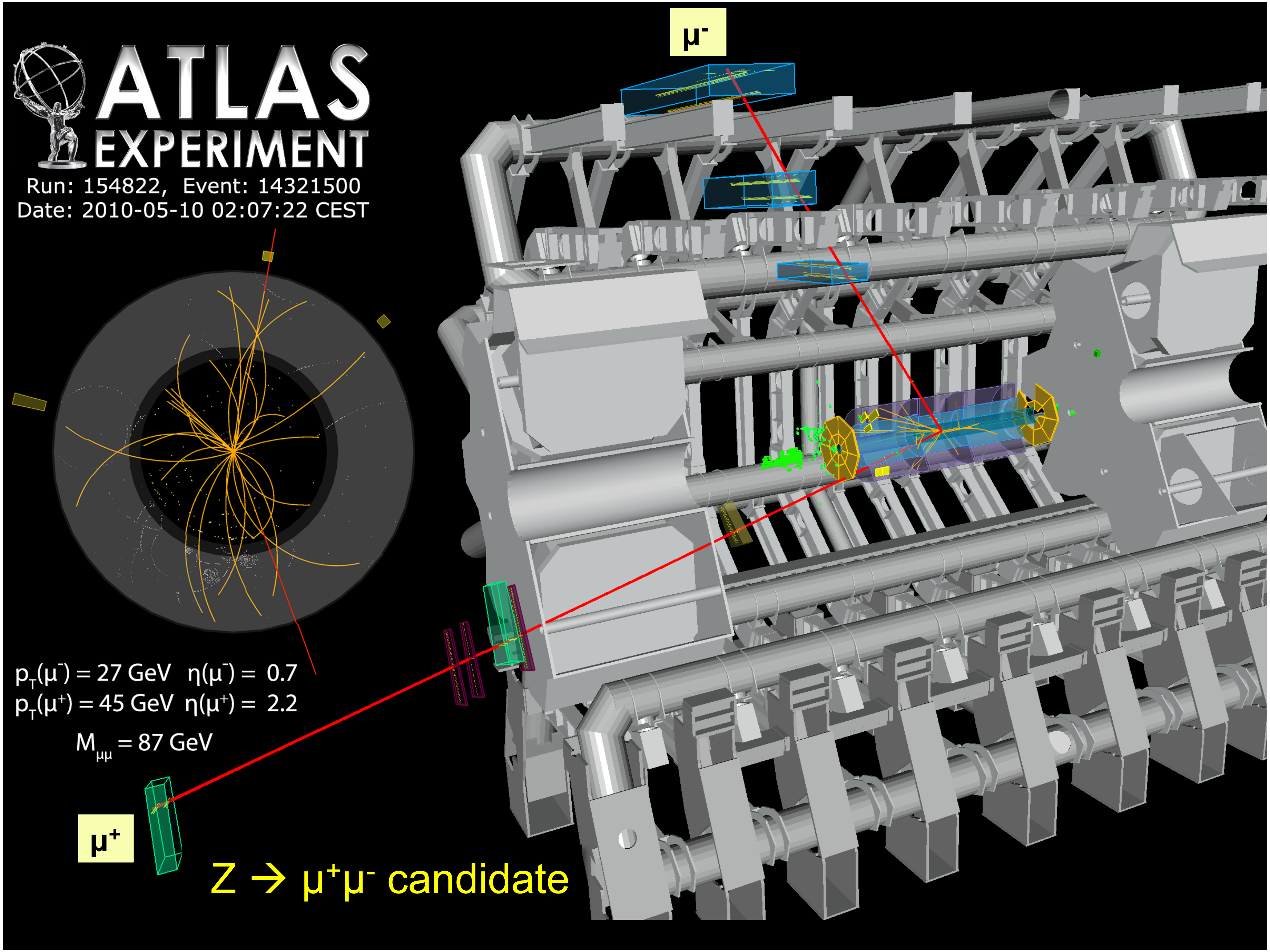
The ATLAS detector
(in real life)



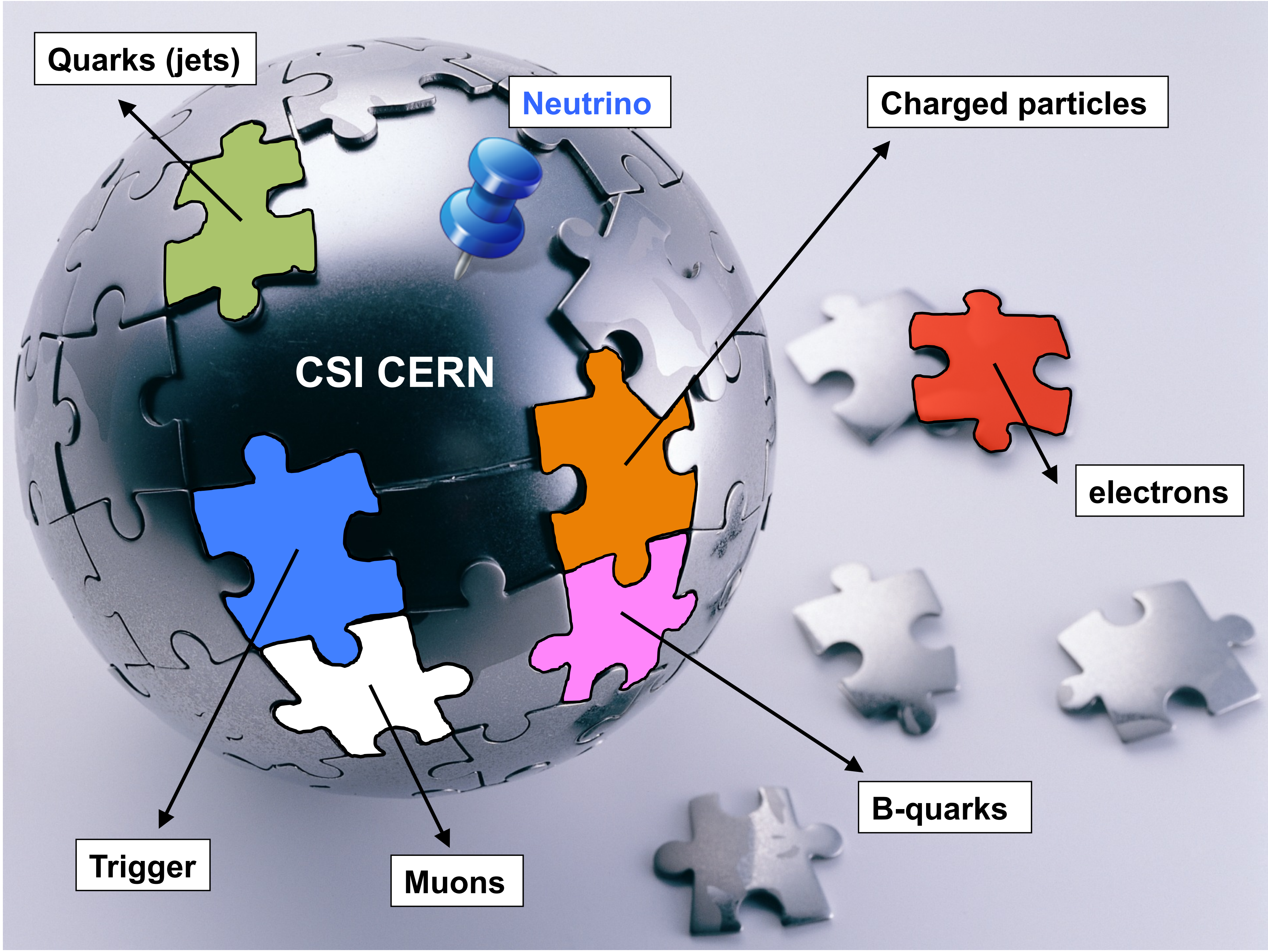


Part of the ATLAS detector has been designed and built at Nikhef



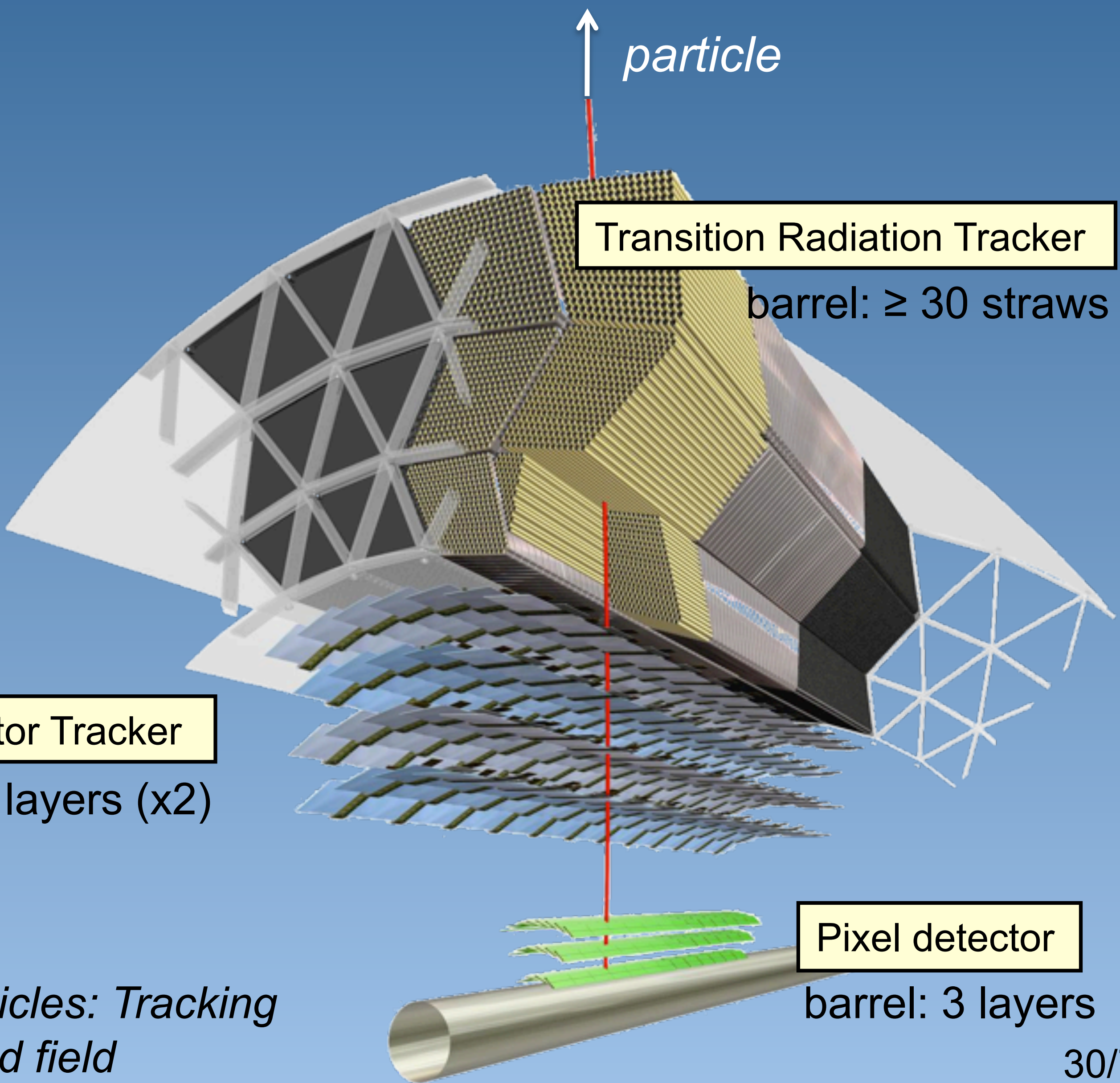

μ-
ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
p_T(μ-) = 27 GeV η(μ-) = 0.7
p_T(μ+) = 45 GeV η(μ+) = 2.2
M_μμ = 87 GeV
μ+
Z → μ+μ- candidate

Rabbit, car or human ?


Quarks (jets)
Neutrino
Charged particles
CSI CERN
electrons
B-quarks
Trigger
Muons

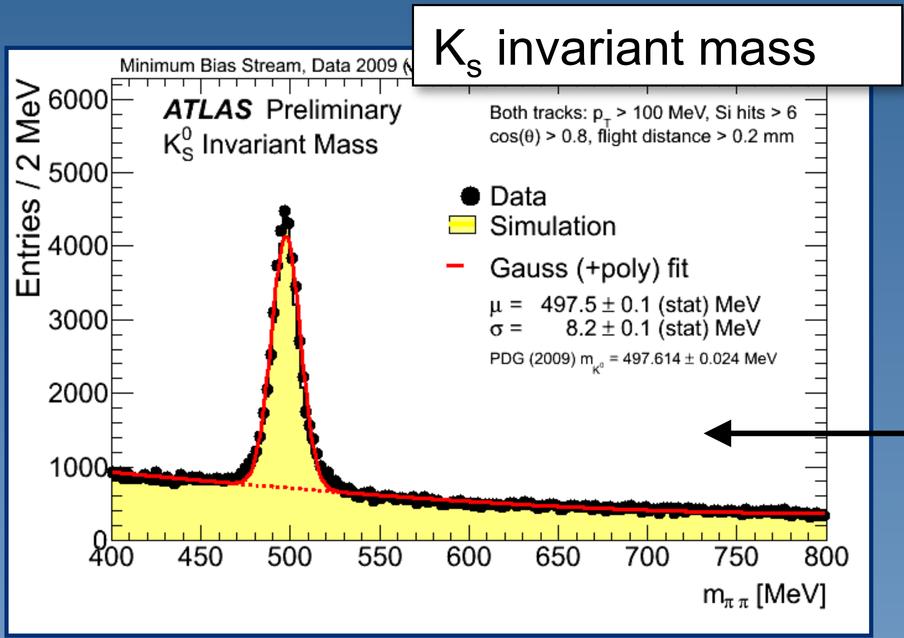
Complex structure ATLAS detector ?

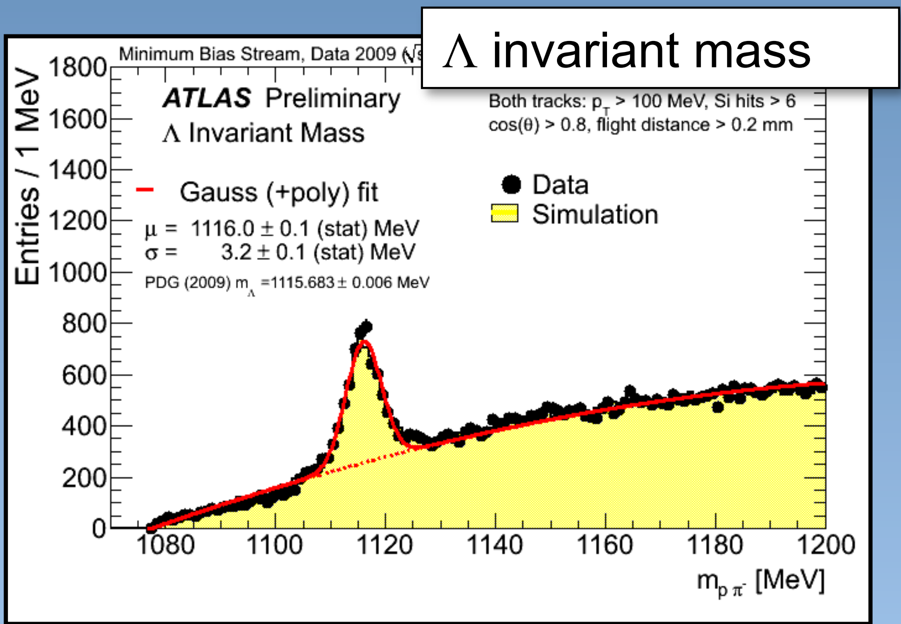
Wide range of particle types / characteristics

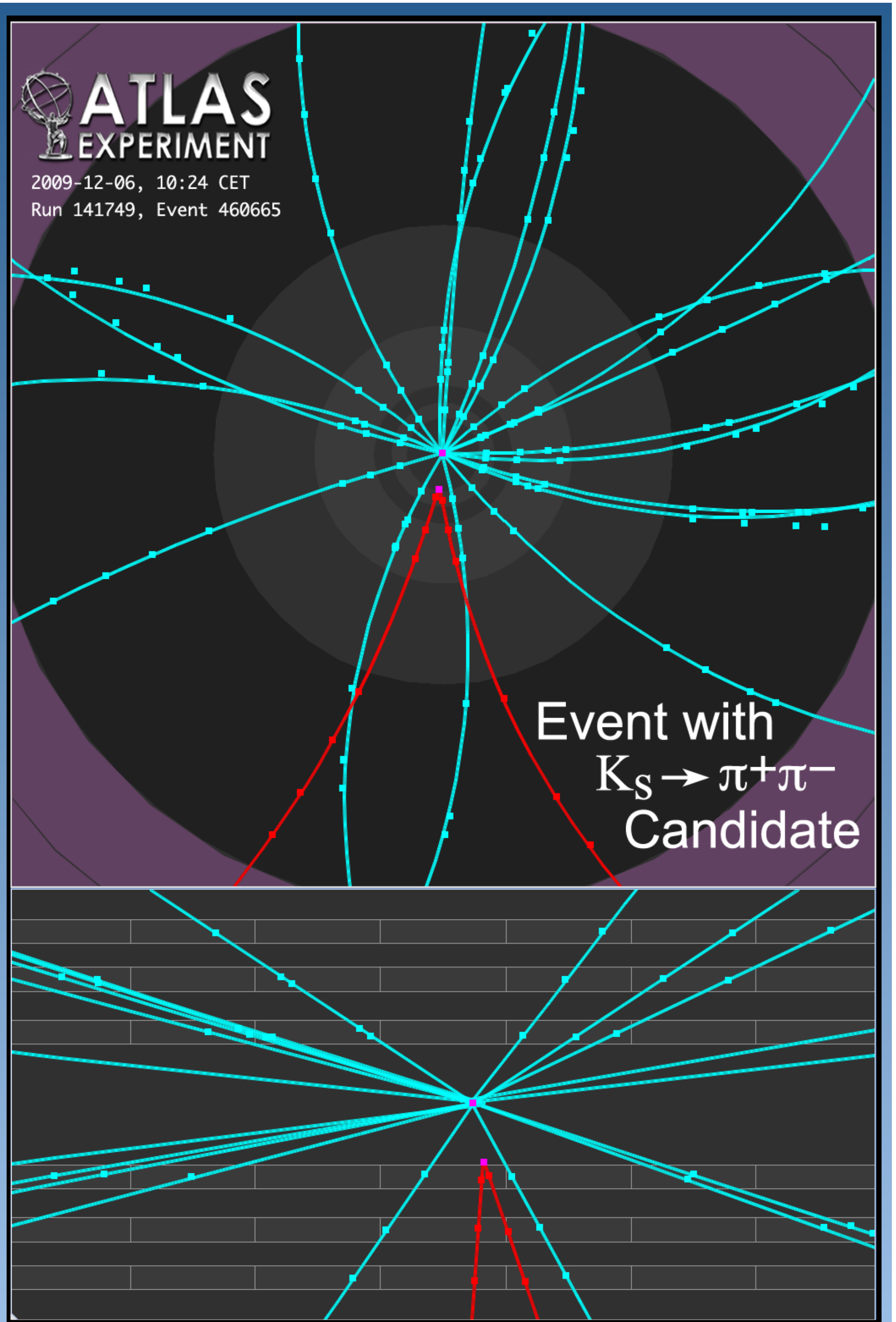


Momentum charged particles: Tracking detectors in a 2T solenoid field

Secondary vertices

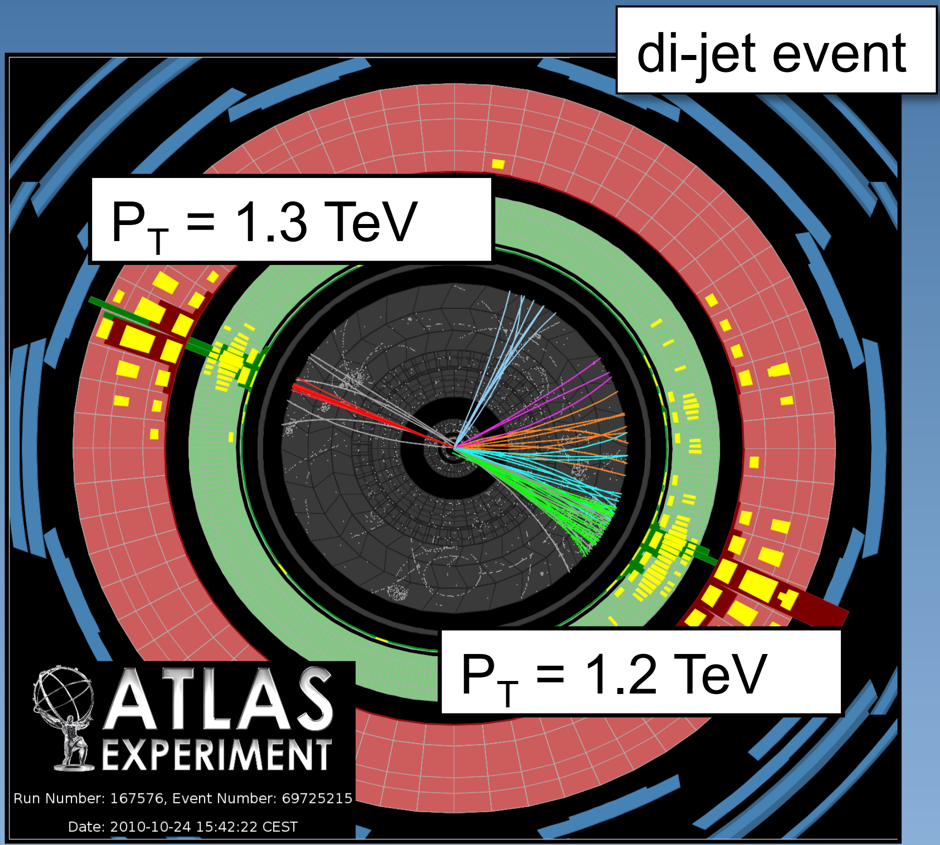


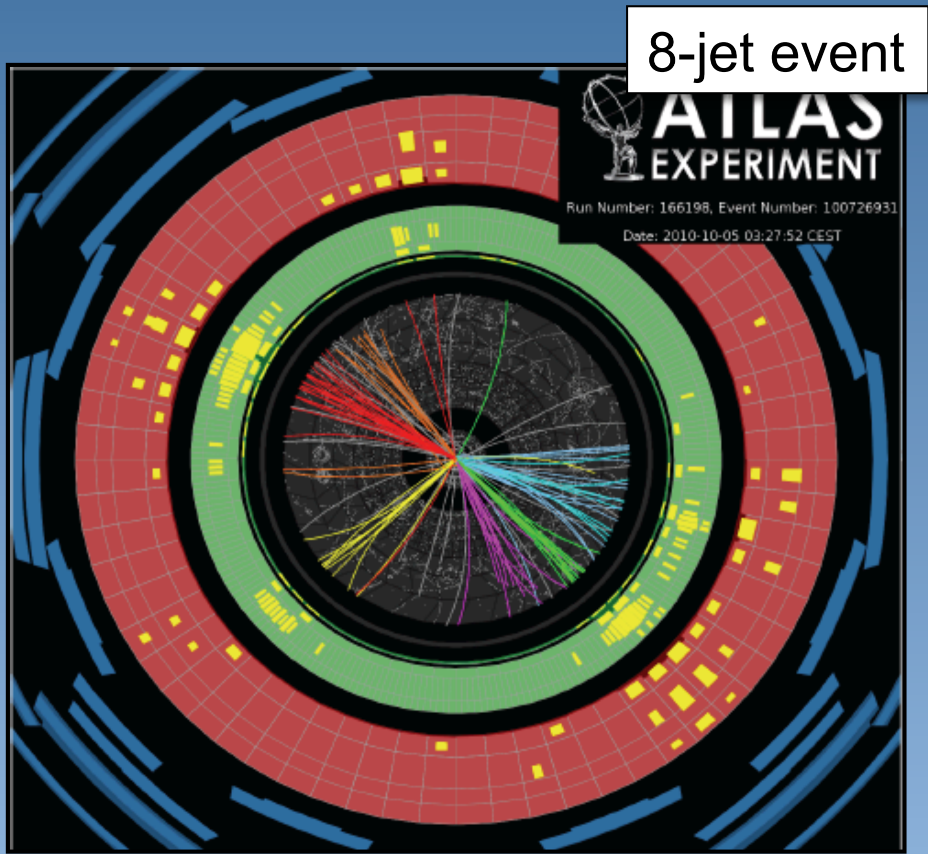




Quark (jet) reconstruction

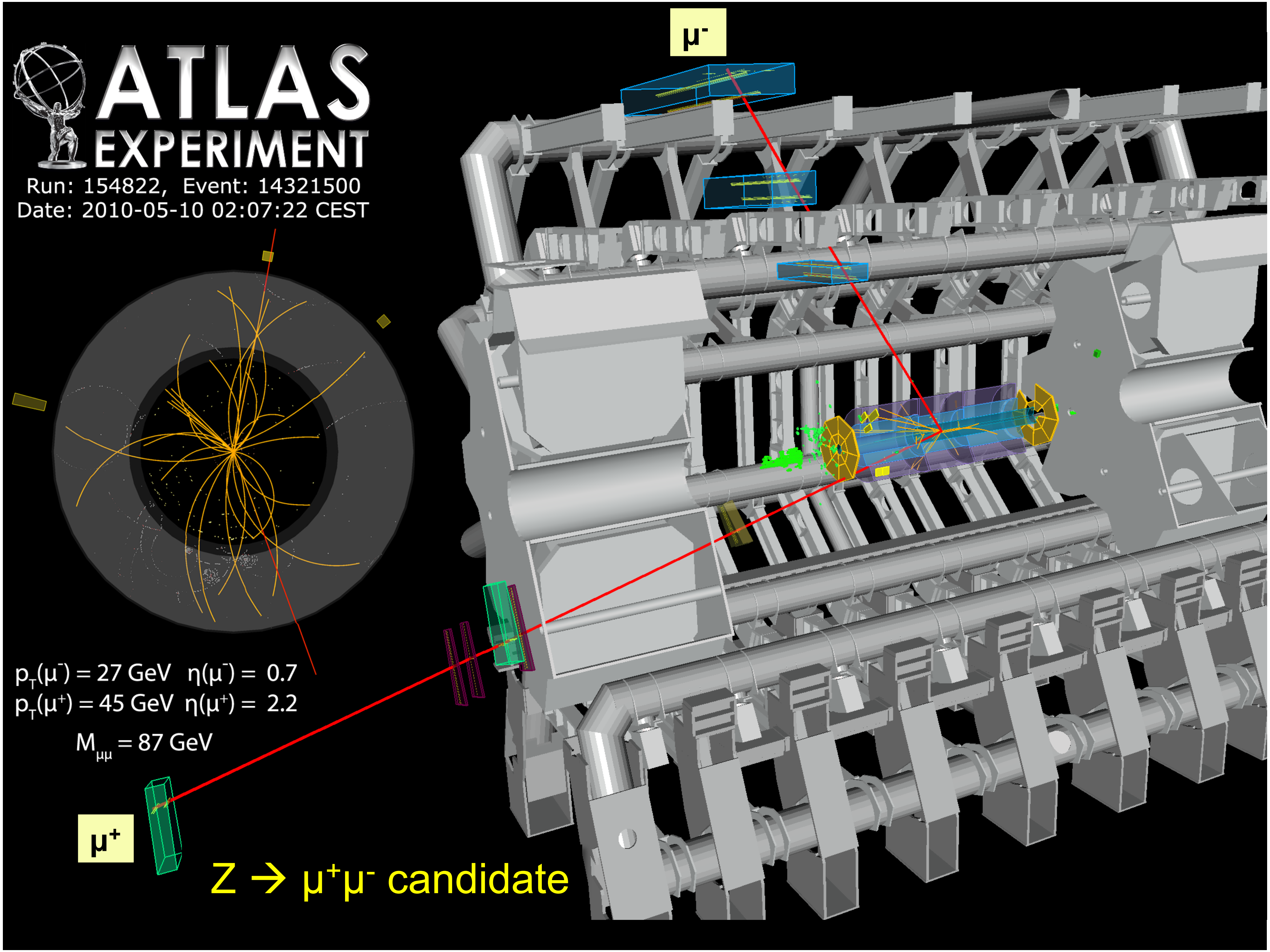
Tracker and calorimeters





High transverse momentum

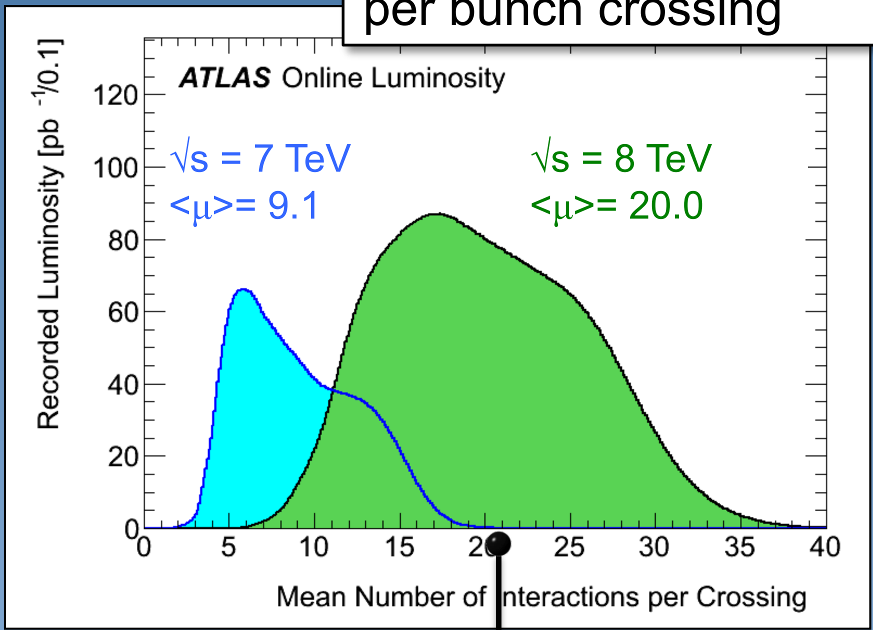
Multi-jet: 8 jets with P_T > 60 GeV



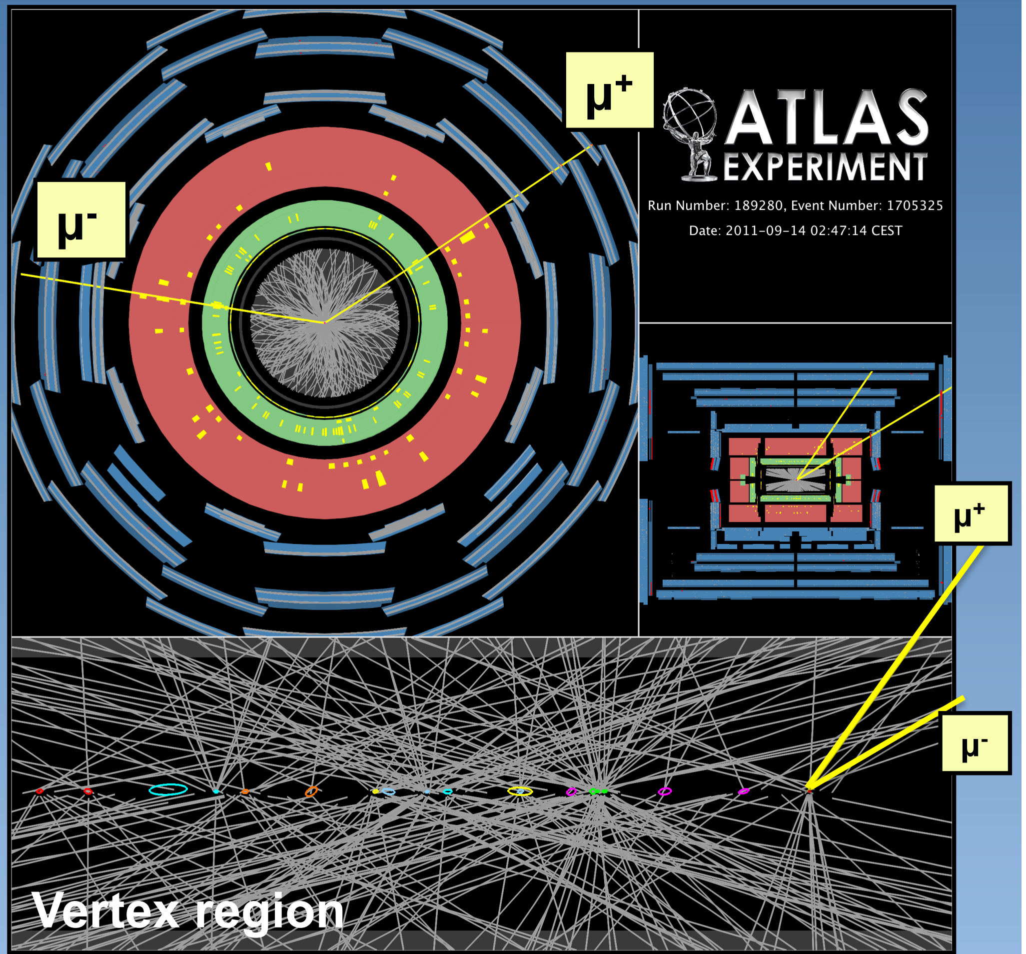
ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
μ-
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
μ+
$Z \rightarrow \mu^+\mu^-$ candidate

LHC is not a quiet environment

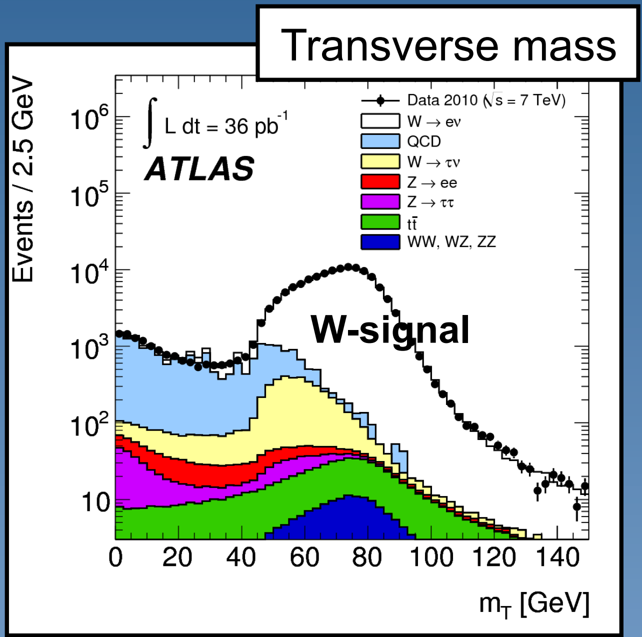
Number of interactions per bunch crossing



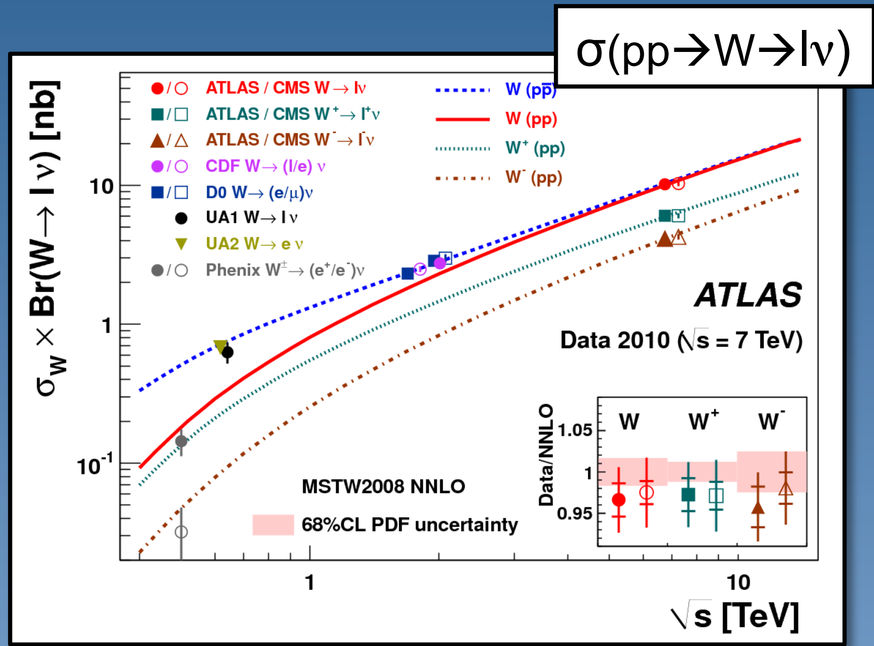
$Z \rightarrow \mu^+\mu^-$ event with 20 vertices

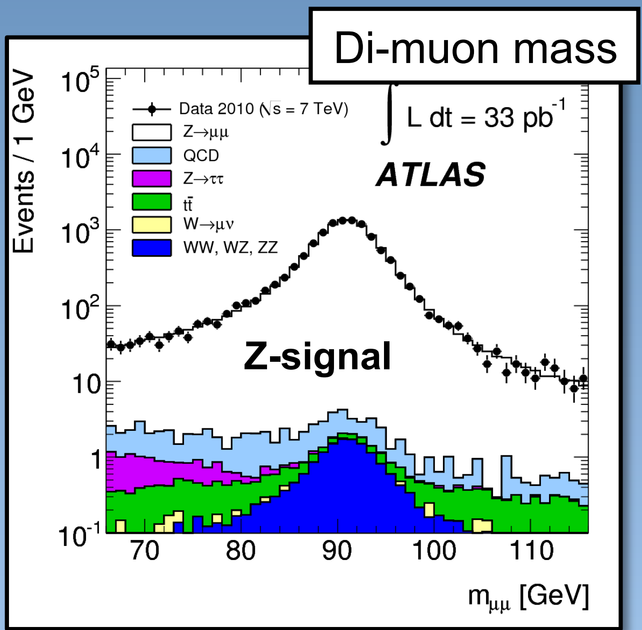


W and Z boson production at the LHC

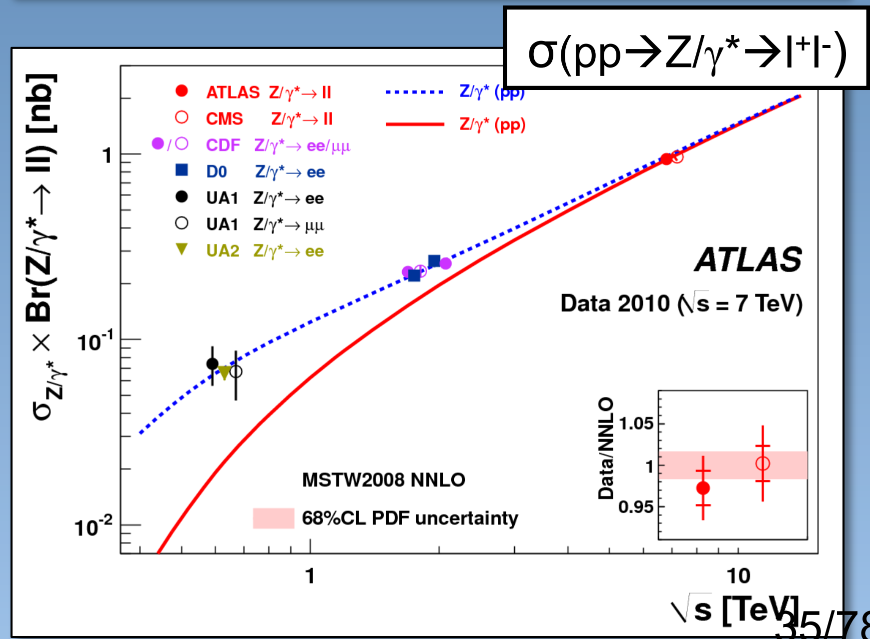


W-boson



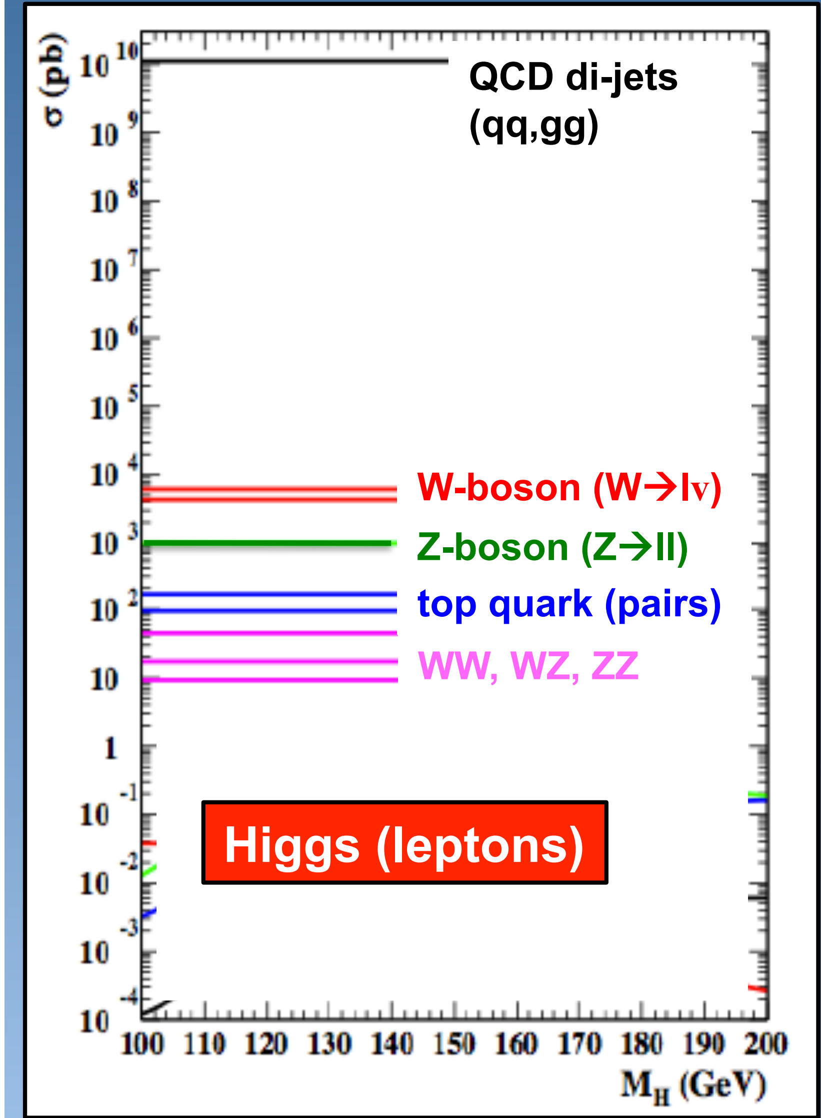


Z/γ*-boson



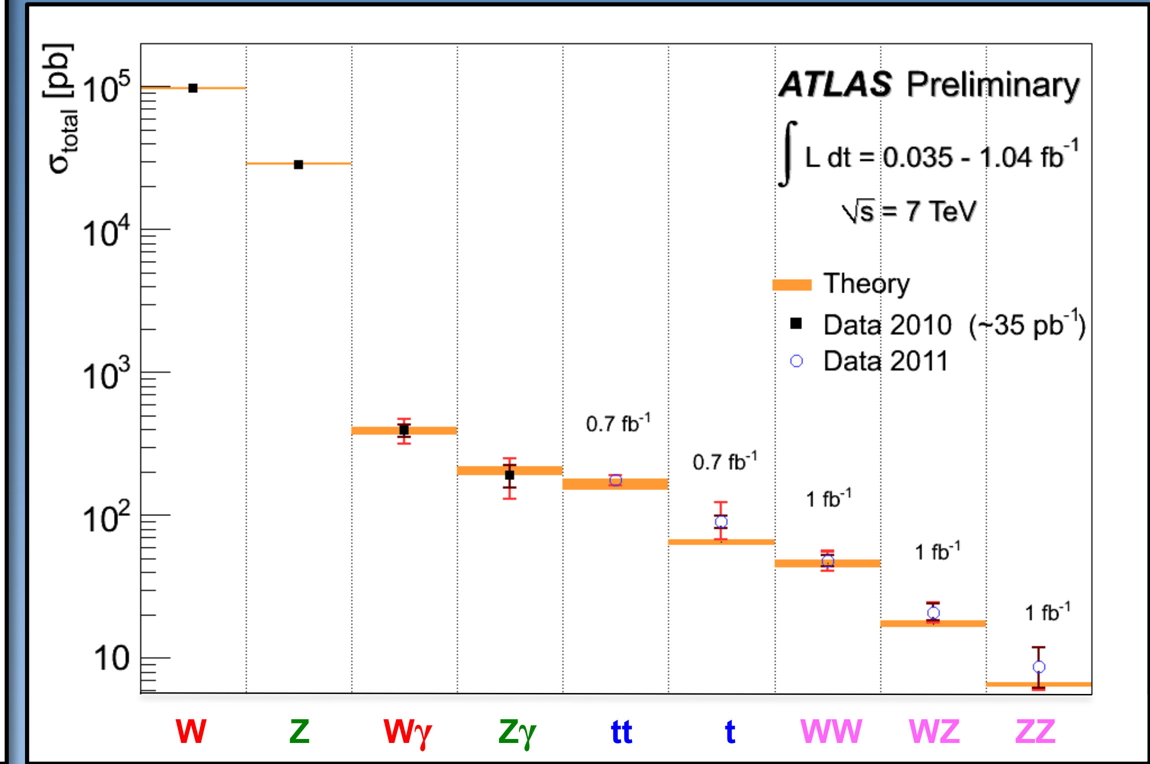
Standard Model processes at the LHC

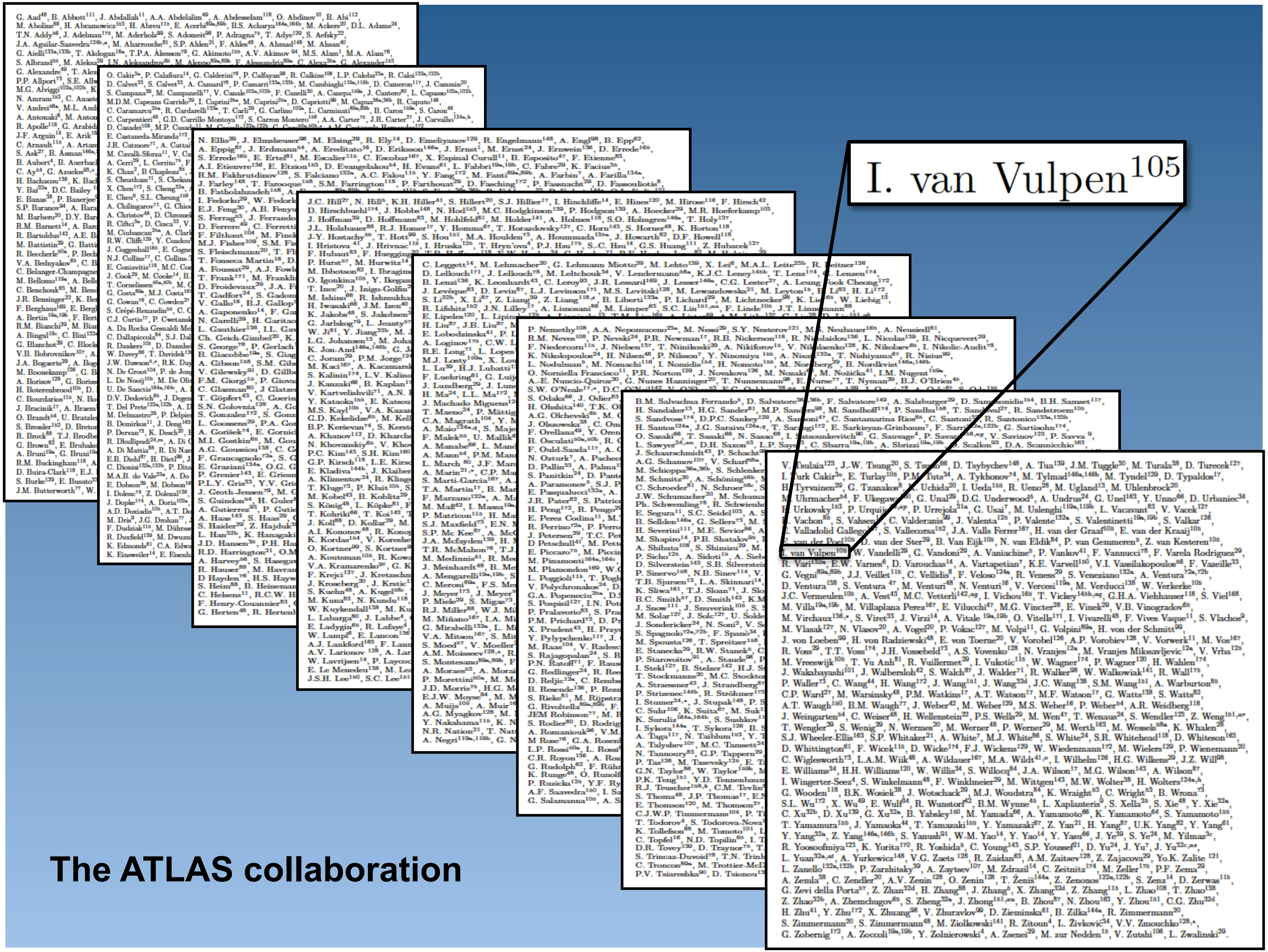
predicted cross-sections



Note: many many many jets (quarks/gluons):
→ look for leptons (electrons/ muons)

ATLAS measurements





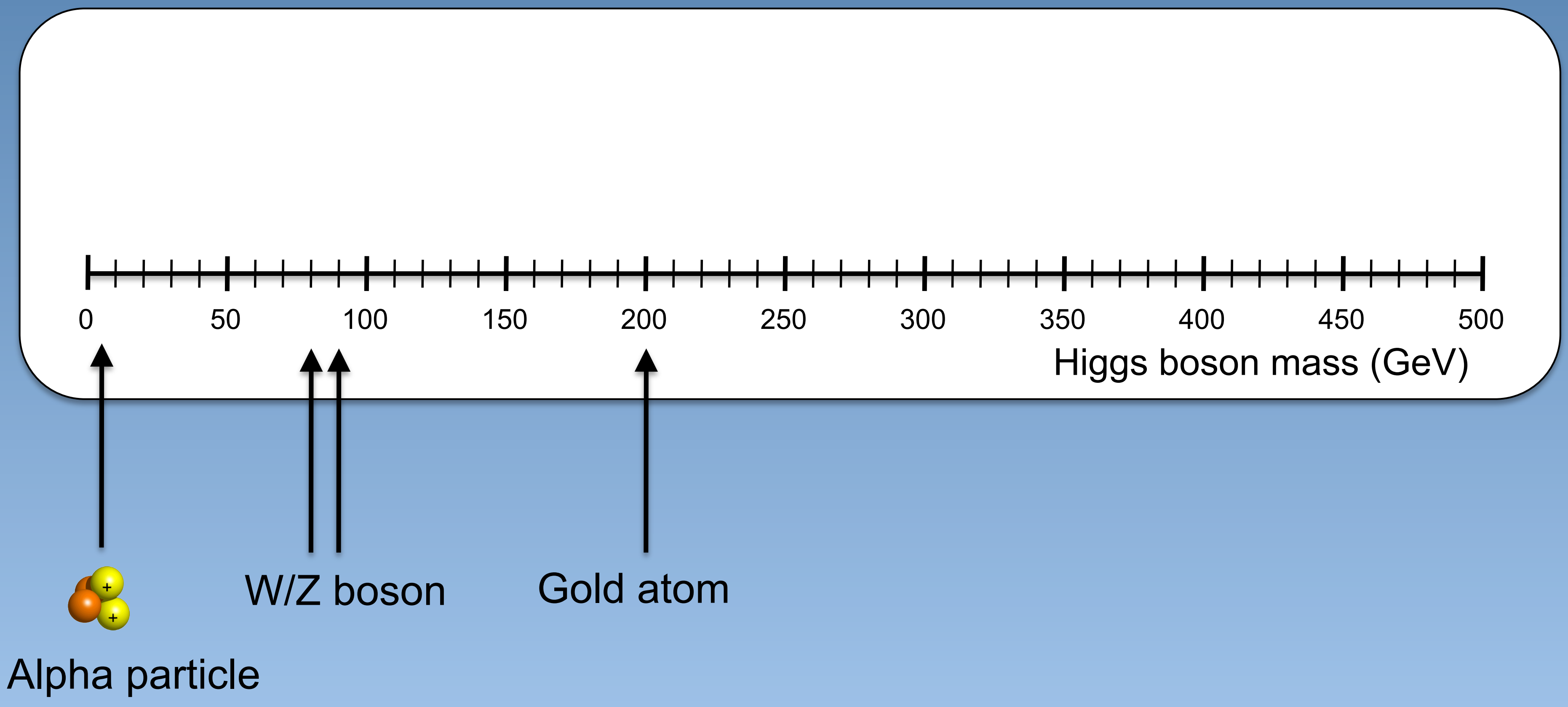
The ATLAS collaboration

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

Bottleneck: disk space

Selecting interesting physics from an e-nor-mous background

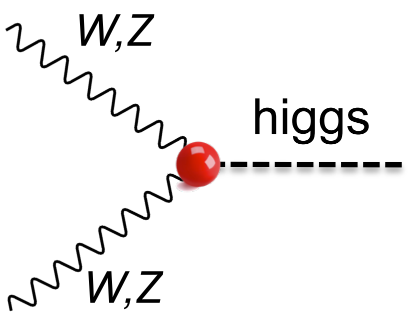
The mass of the Higgs boson



How can you produce a Higgs particle ?

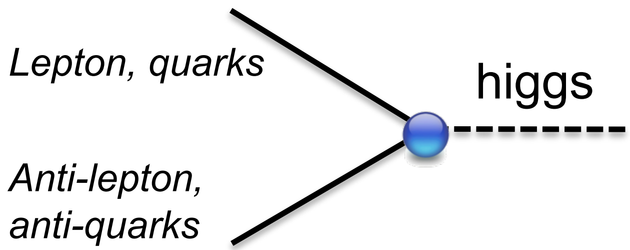
Gauge bosons

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



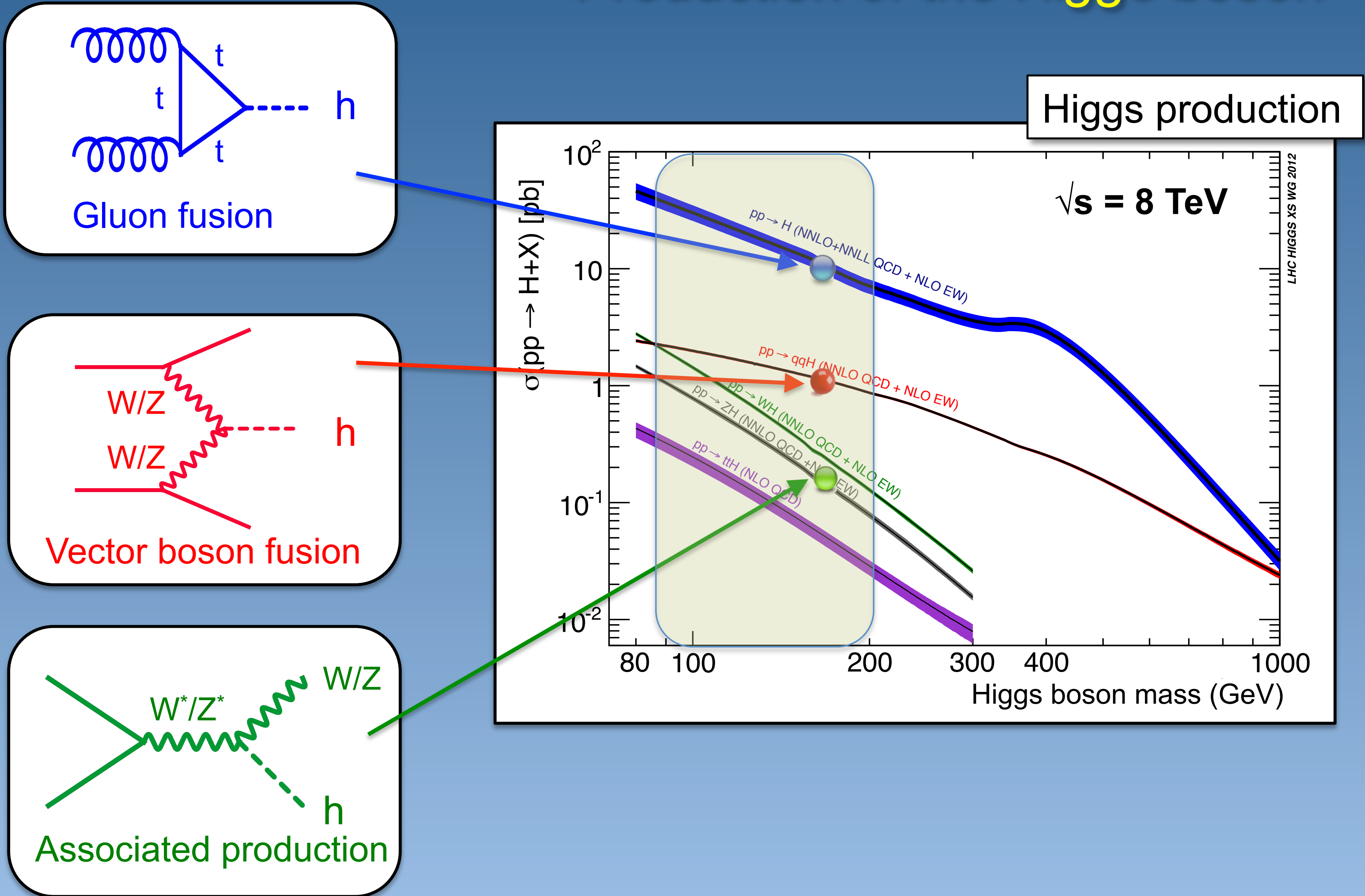
Fermions

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 (until July 4th) ?

If the Higgs boson exists:

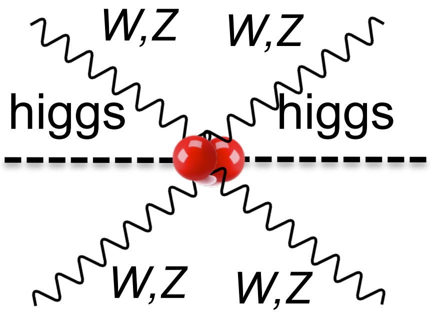
m_h = 125 GeV: 212.000

m_h = 200 GeV: 77.000

How does the Higgs boson decay ?

Gauge bosons

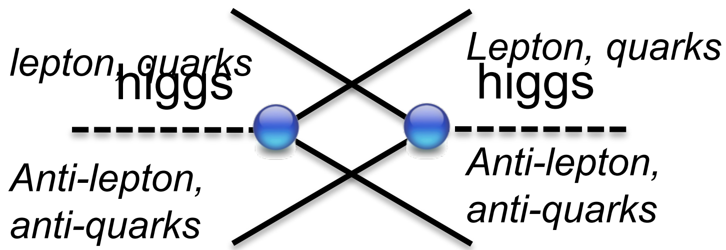
Massive gauge boson ?
… then it coupling to the Higgs!



$$\Gamma(h \rightarrow VV^*) \propto m_V^4$$

Fermions

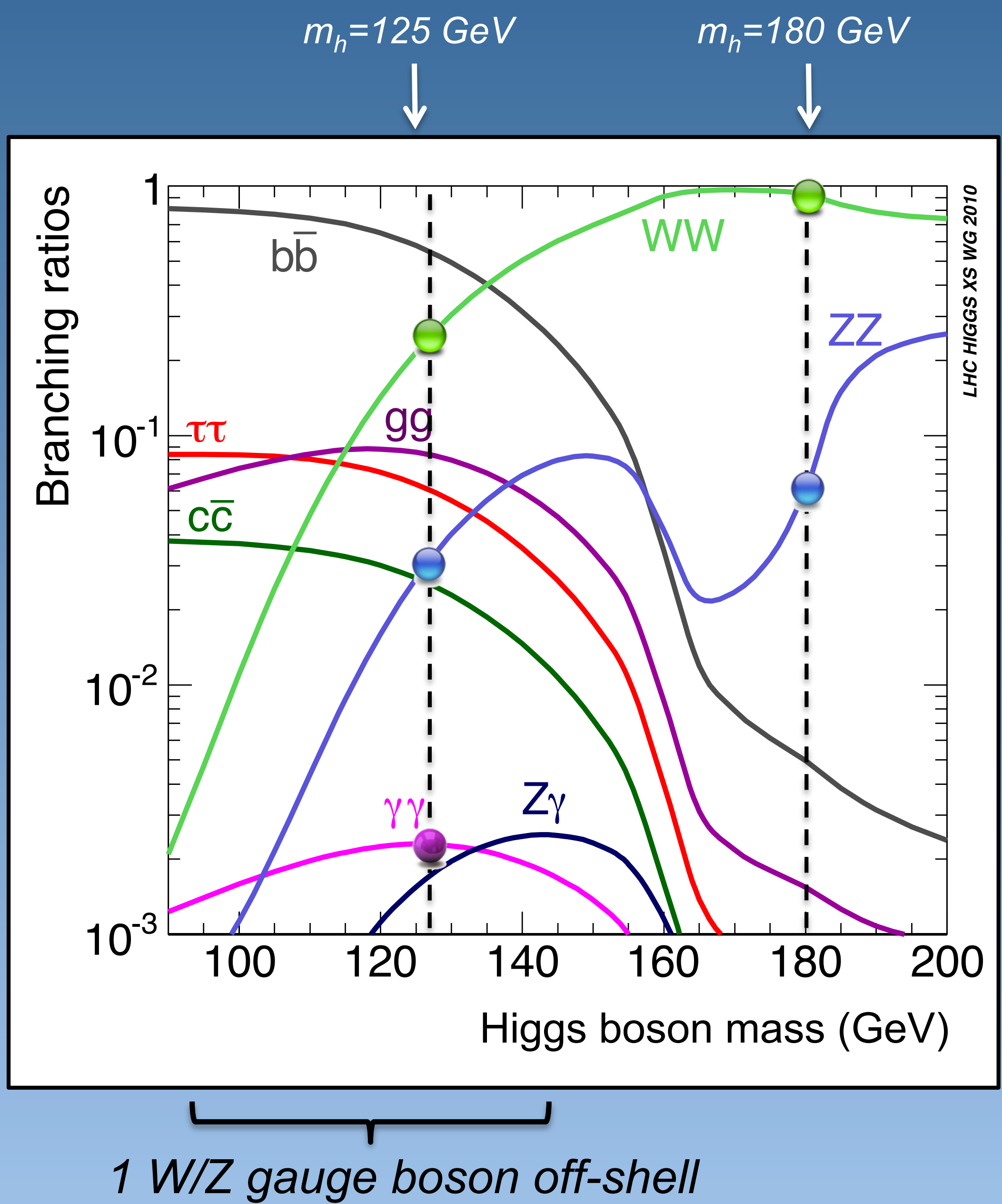
Massief fermion ?
… then it couples to the Higgs!



$$\Gamma(h \rightarrow f\bar{f}) \propto m_f^2$$

Higgs boson decay production

Decay of the Higgs boson



Subsequent gauge boson decay

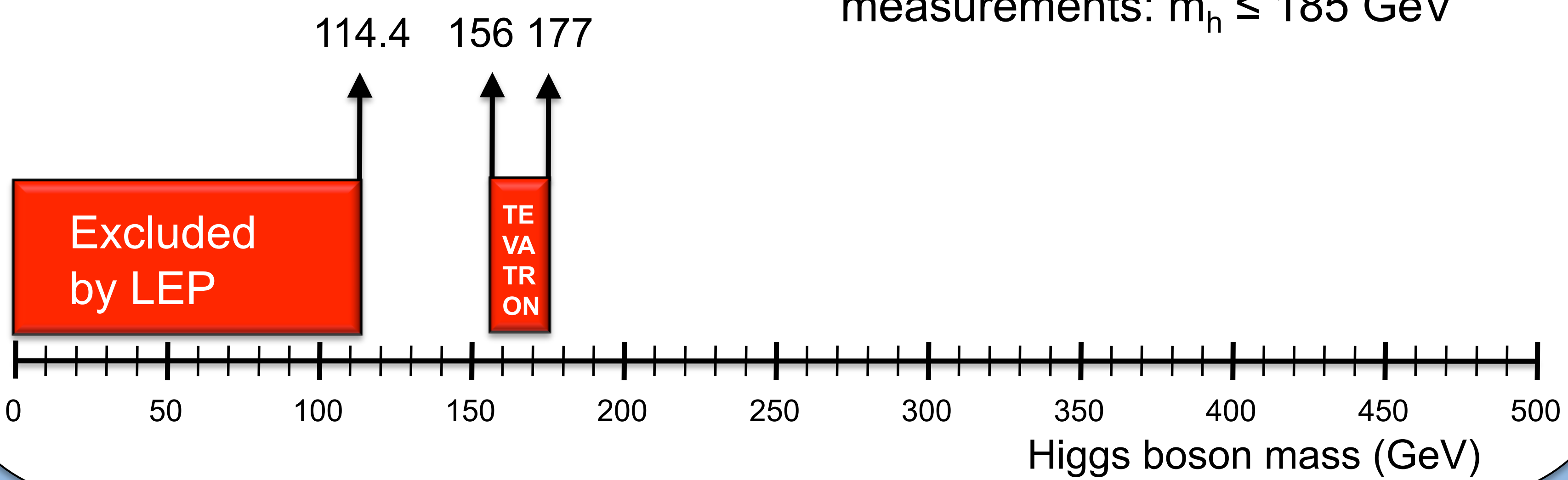
$W \rightarrow$	qq	67%
	$l\nu$	33%
$Z \rightarrow$	qq	70%
	$\nu\nu$	20%
	ll	10%

Status beginning of last year

Indirect:

Theory: $m_h \leq 600$ GeV

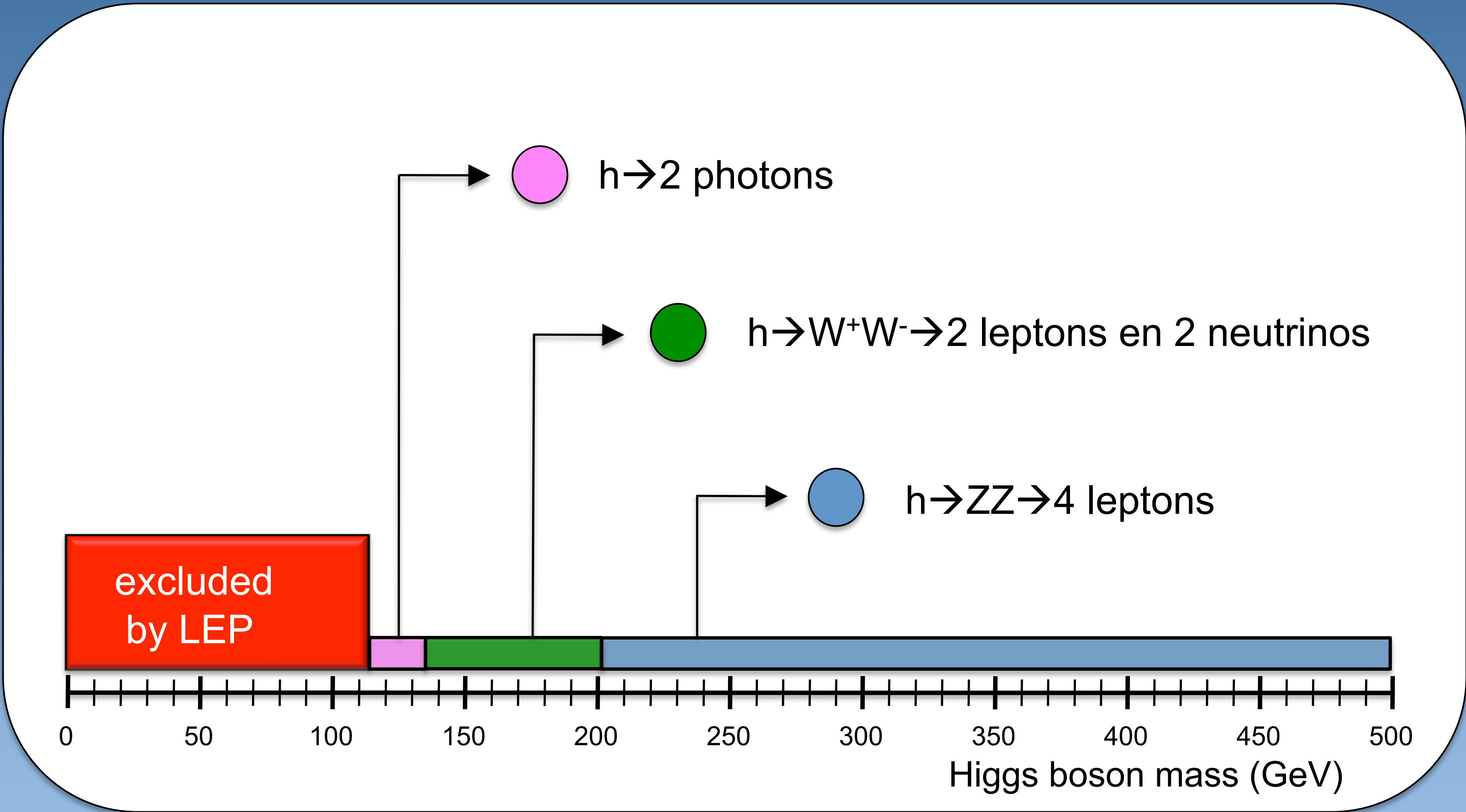
Electroweak precision-measurements: $m_h \leq 185$ GeV



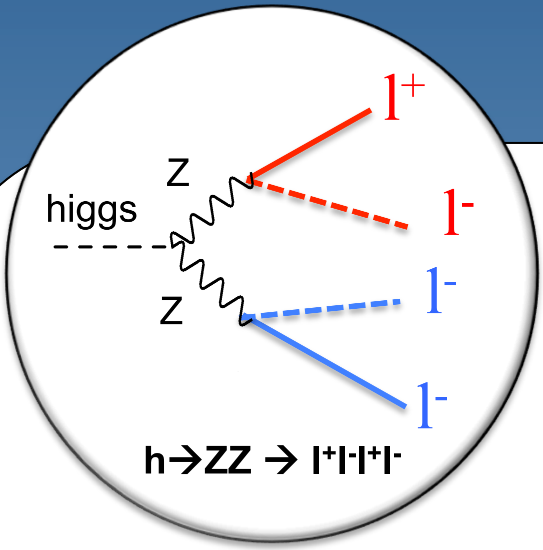
Experiments at the LHC Sensitive for mass range: 114-1000 GeV

The clearest fingerprint of the Higgs boson

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



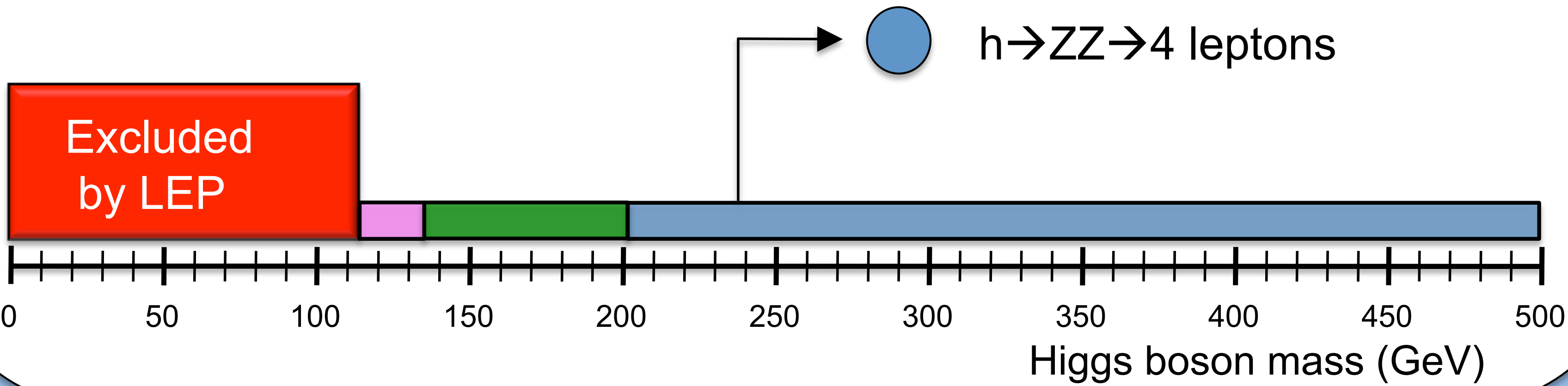
High massa's: m_H > 200 GeV



The golden channel

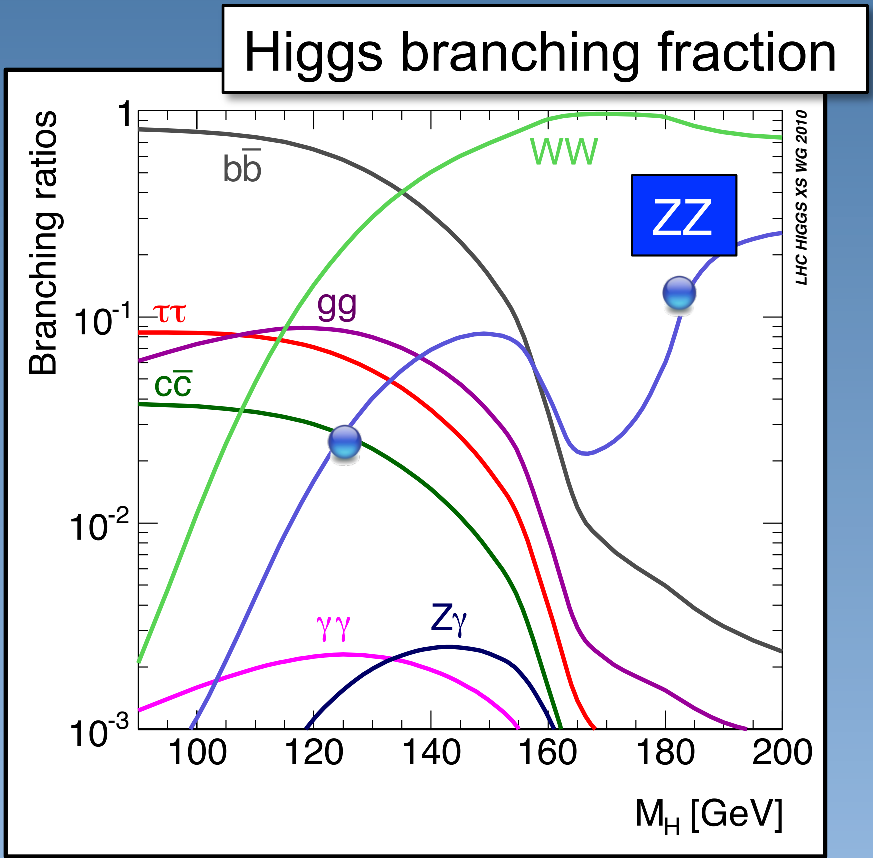
- 4 leptons (e/μ)
- very rare: Higgs of ZZ

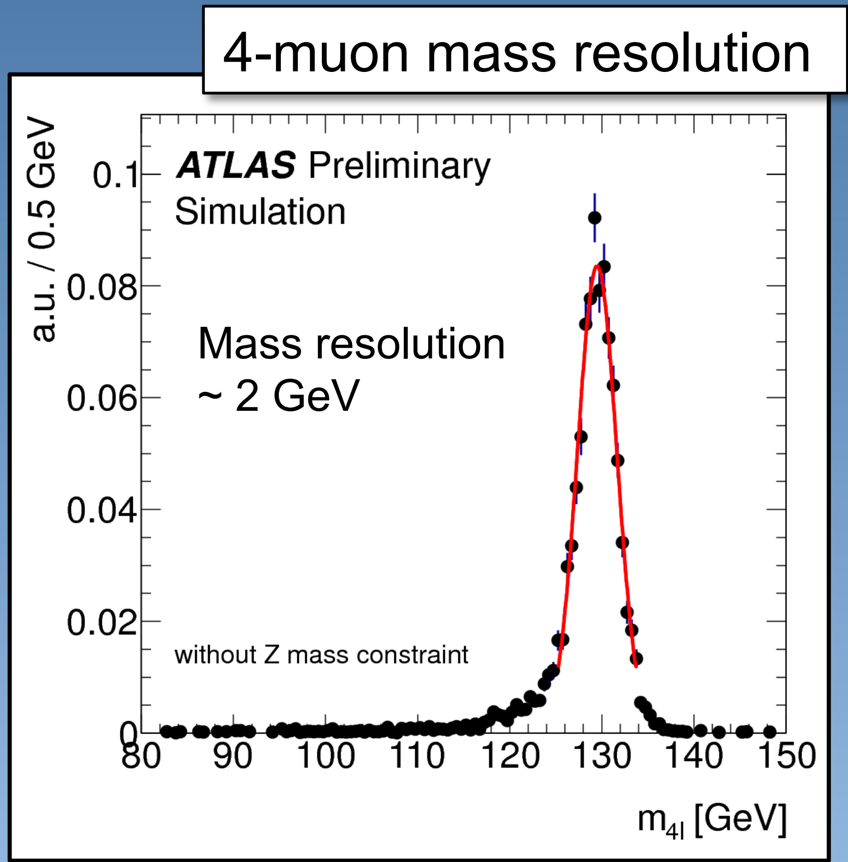
Fingerprint: 4-lepton mass



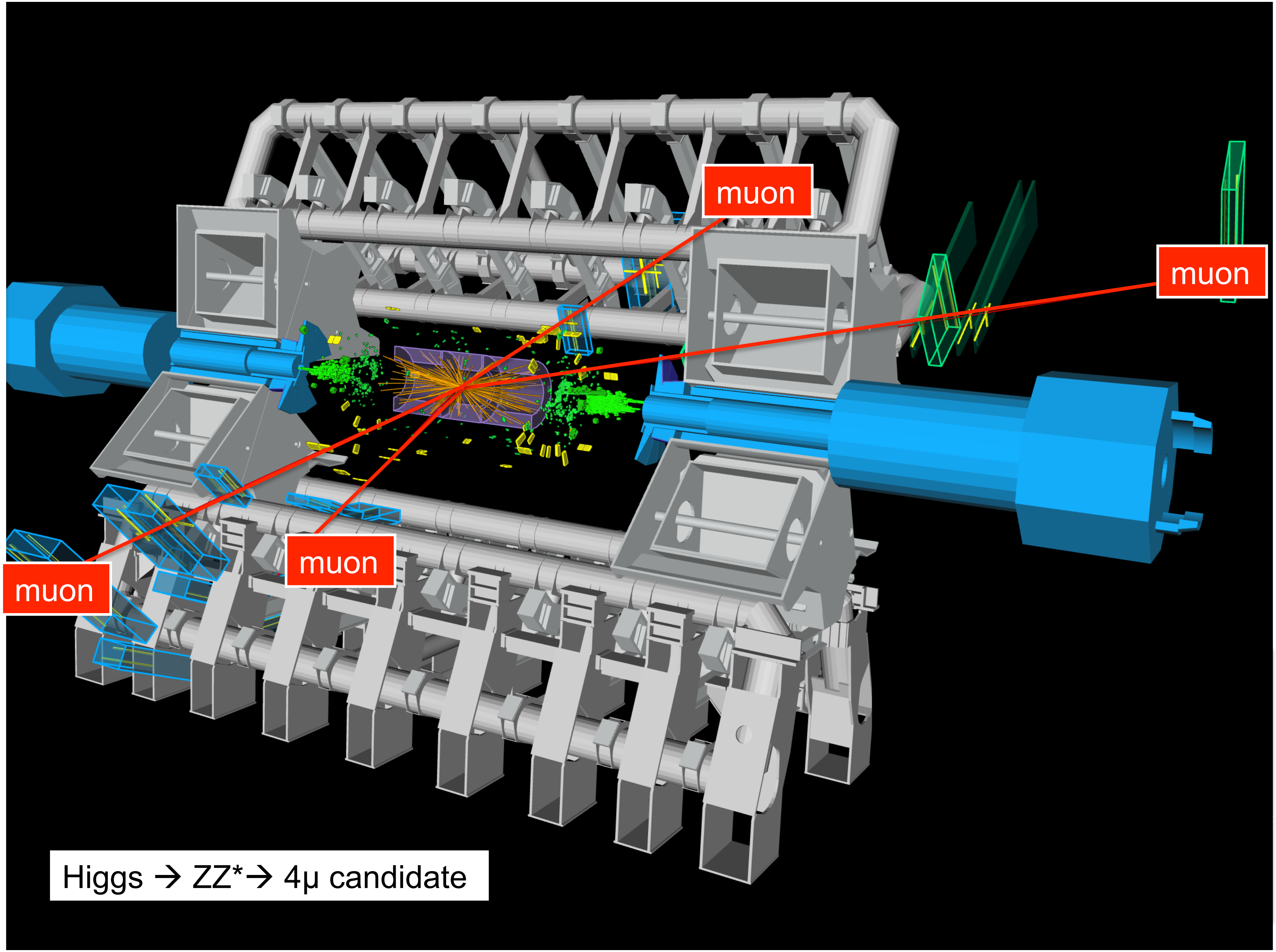
Higgs → ZZ → 4 leptons

Small number of beautiful collissions





Note: if m_h = 125 GeV: only 1 in 8,000 Higgs bosons results in a 4 lepton (lepton = electron or muon) final state



Higgs → ZZ*→ 4μ candidate

Higgs → ZZ → 4 leptons:
small sample of beautiful events

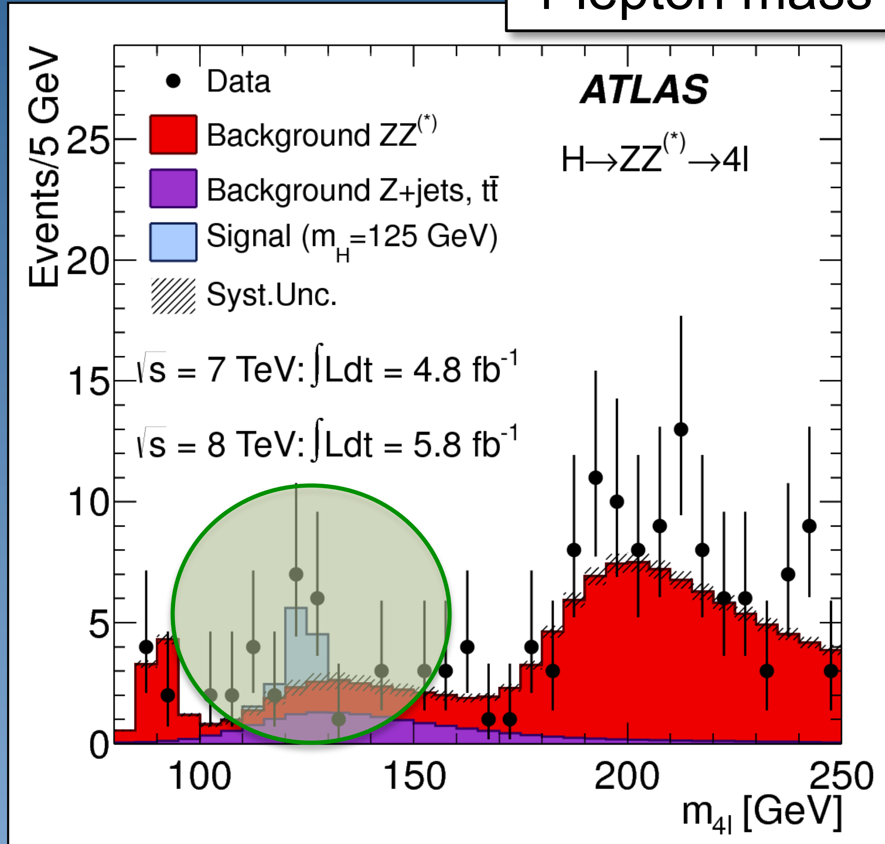
Example: 125 GeV Higgs

1) Theory: H→ ZZ → 4l (l=e, μ):

$\Gamma(h \to ZZ) = 2.64\ \%$
$\Gamma(Z \to ll) = 3.37\ \%$
} $1.25 \cdot 10^{-4}$

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

4-lepton mass



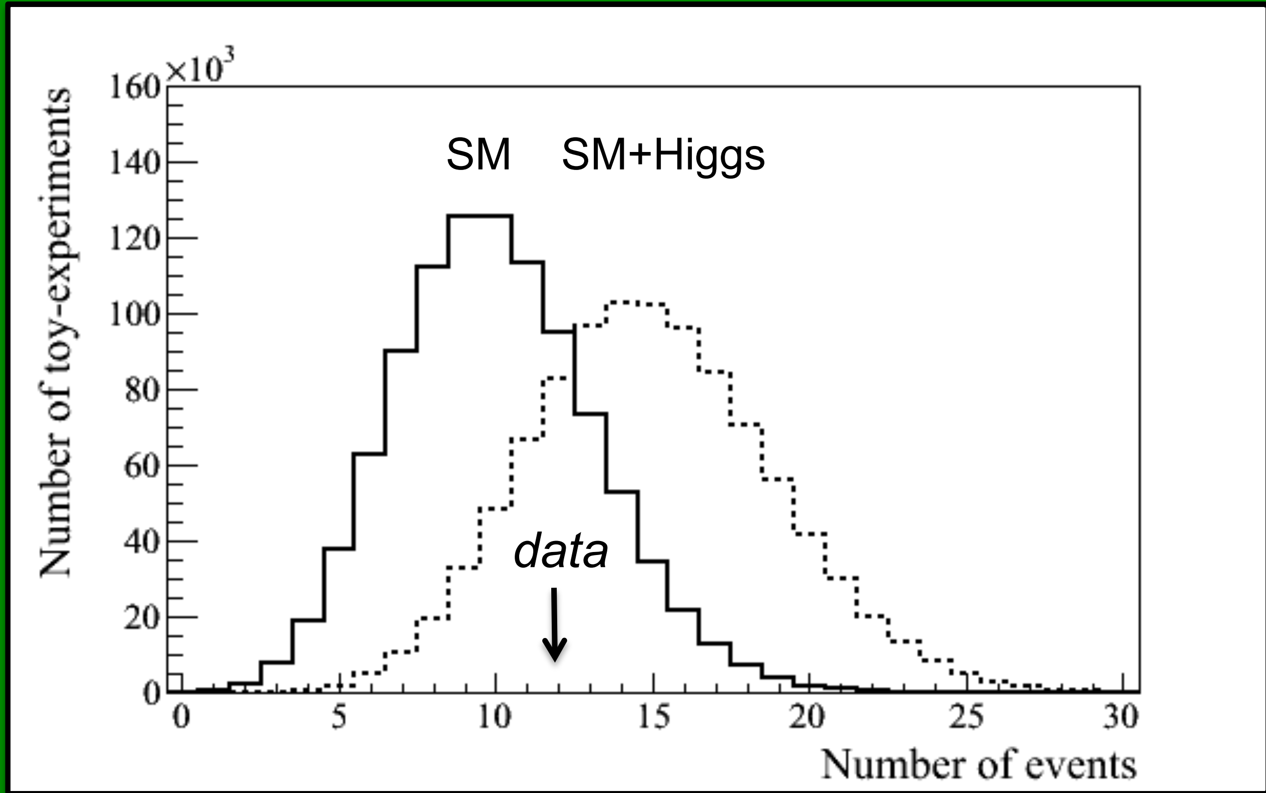
m_{4l} = 125±5 GeV

Expectation:	SM (+Higgs)	4.8 (10.1)
Observation:	Data	13

EXAMPLE: Quantifying compatibity with SM hypothesis

Measurement

SM	10
Higgs	5
Data	12



1) Expected excess (p-value)

2) Observed excess (p-value)

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*

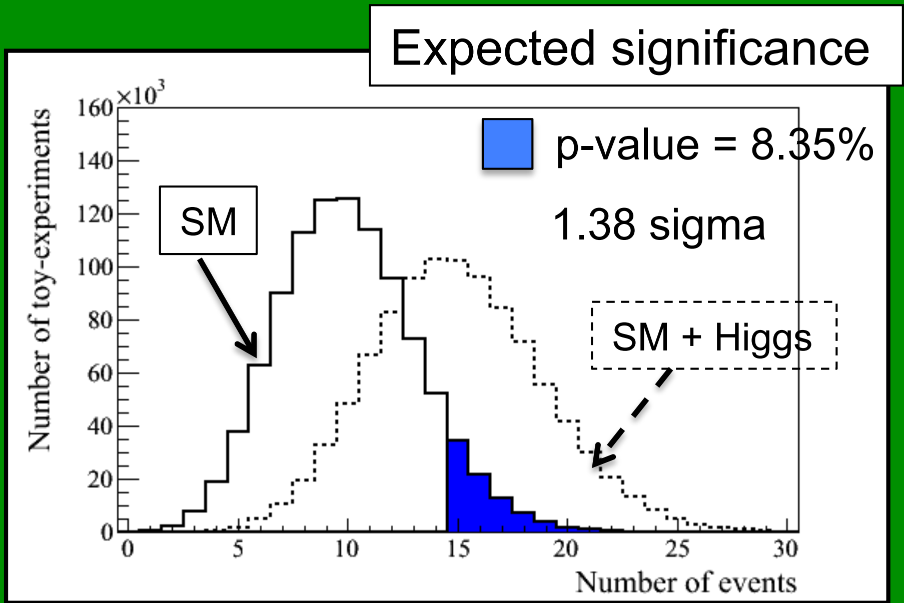
Quantifying an excess: p-value

Measurement

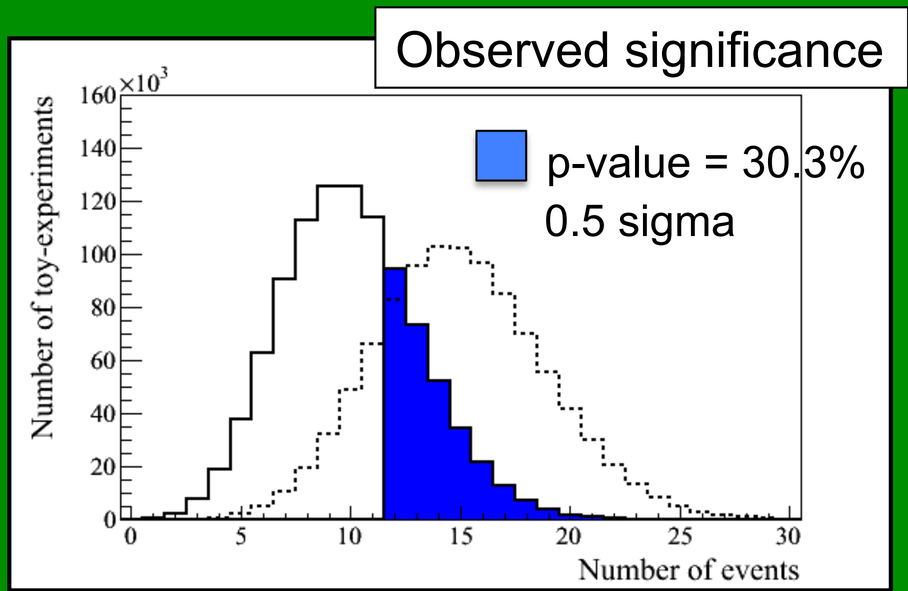
SM	10
Higgs	5
Data	12

p-value < 2•10^{-7} →discovery!

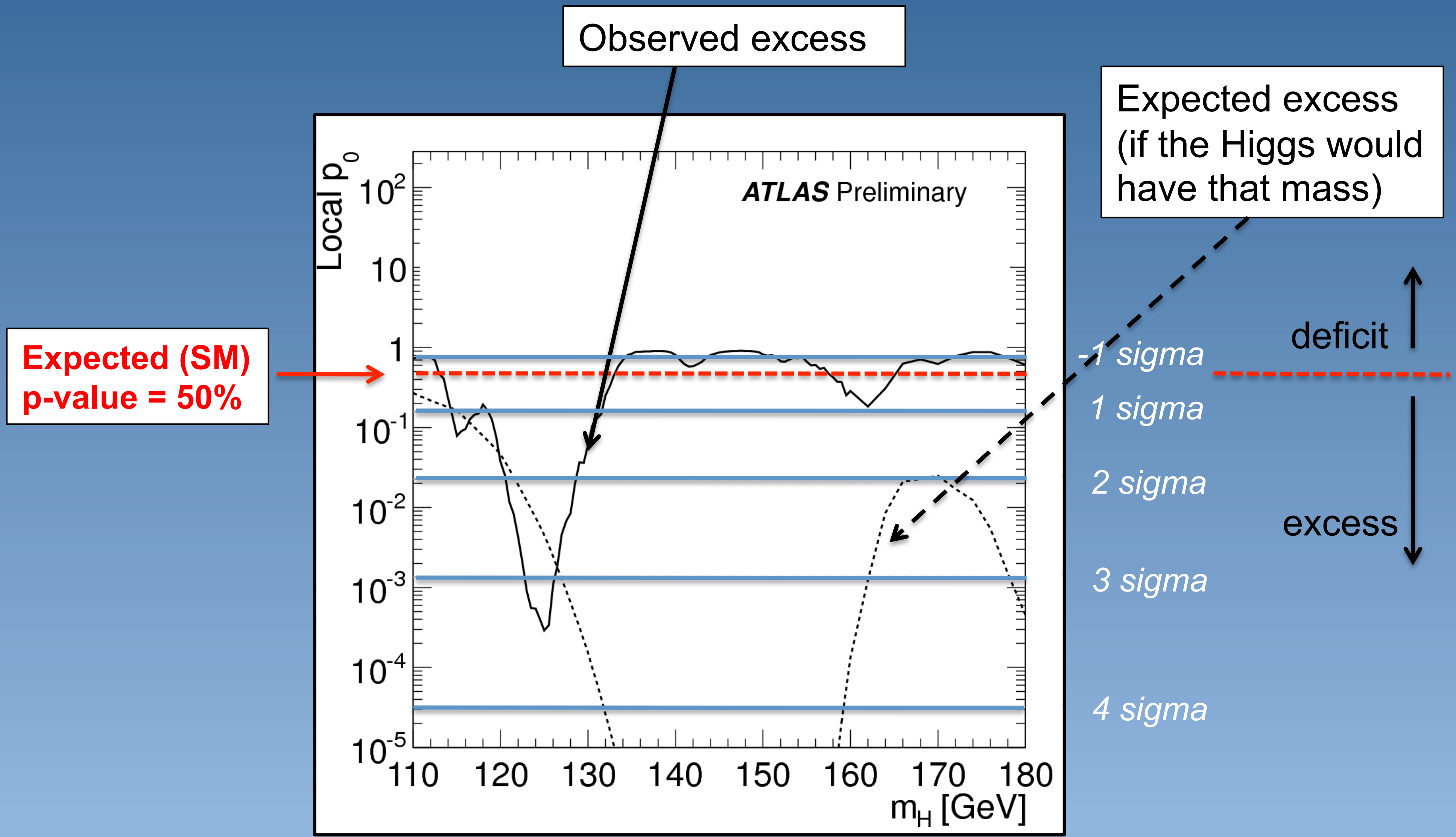
1) What is the expected significance ?



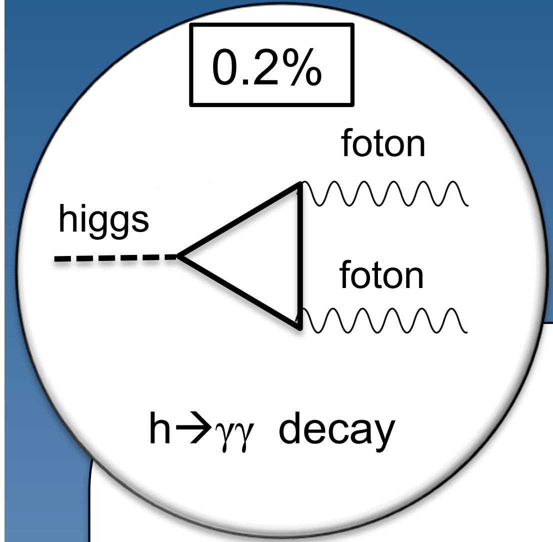
2) What is the observed significance ?



Quantifying the excess:



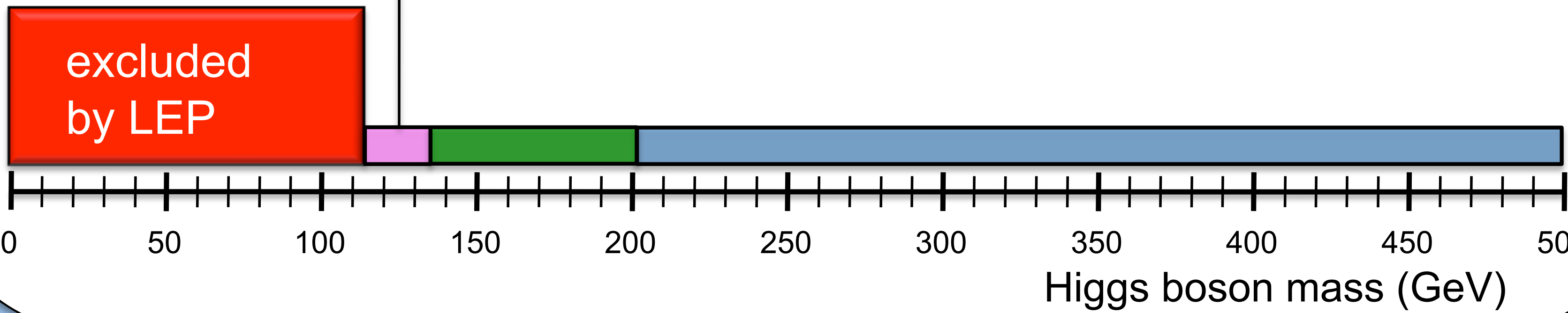
The low-mass region



h→2 photons

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

Fingerprint: 2-photon mass

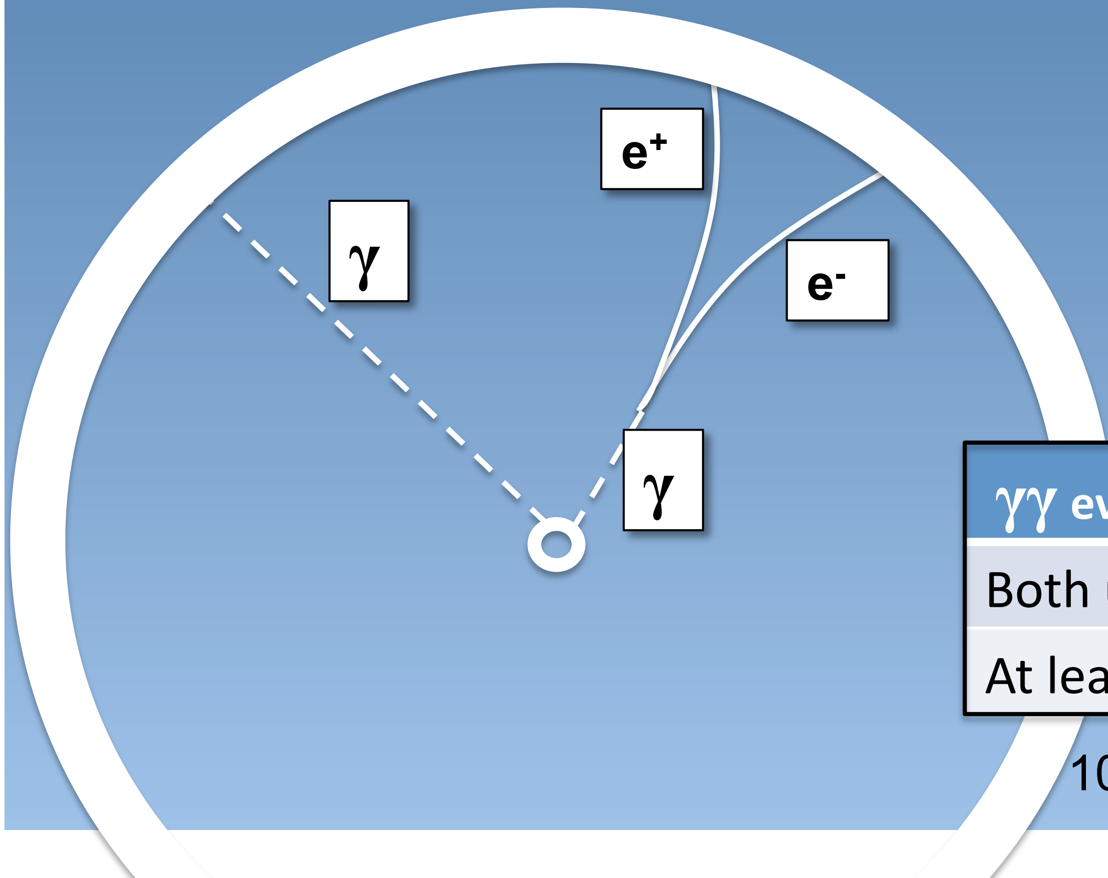


Photon identification and event selection

Selection: 2 isolated photons: $P_T > 40$ (30 GeV)

40% selection efficieny

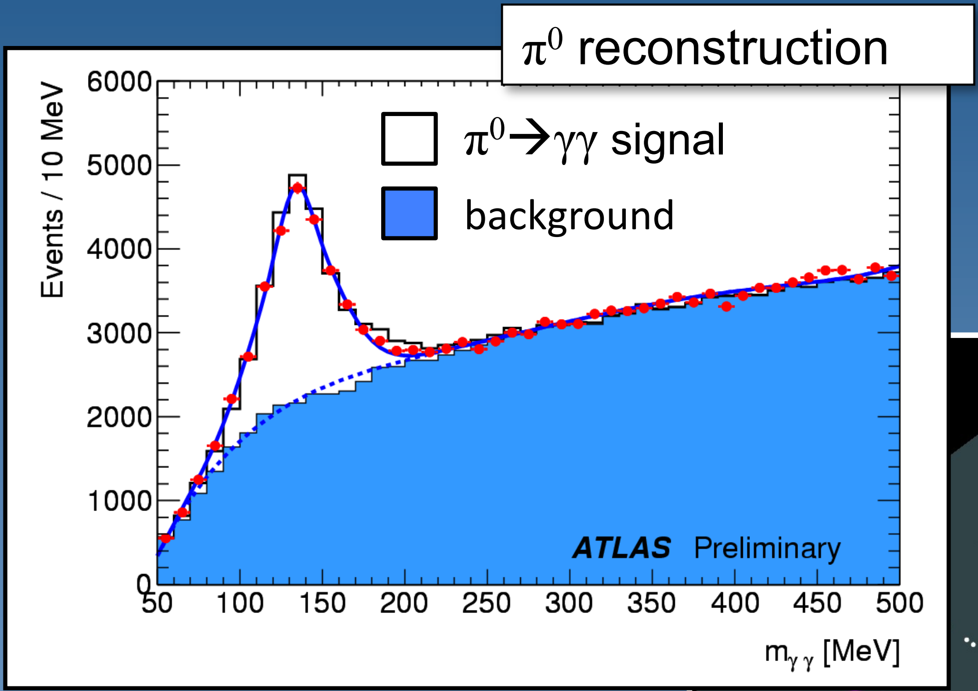
"Elk nadeel hep z'n voordeel"

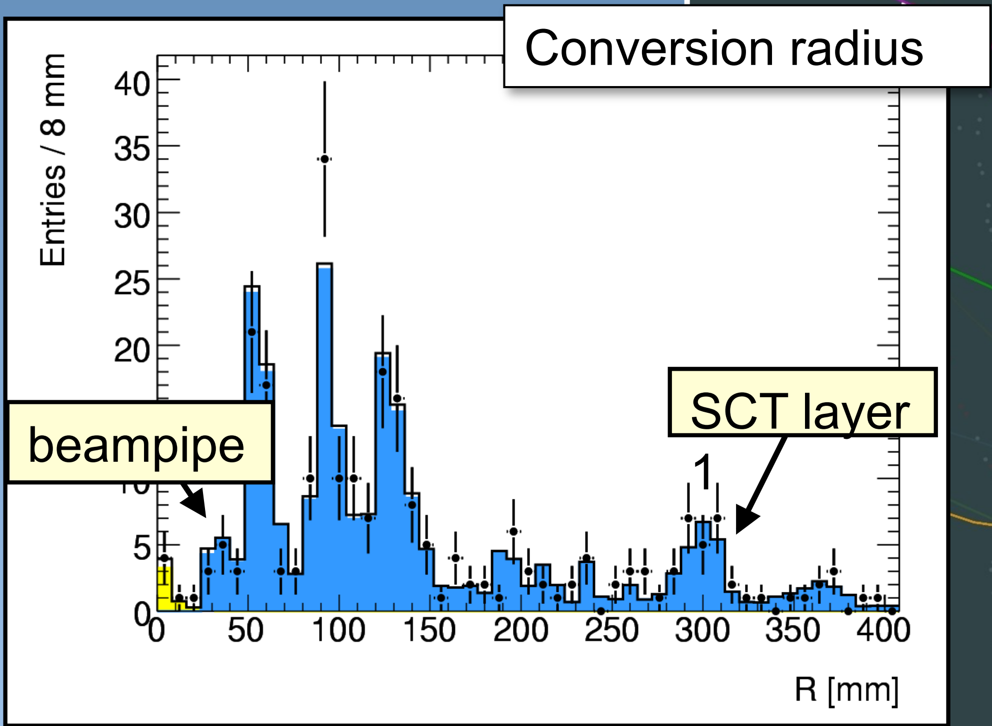


γγ event classification	Fraction
Both unconverted	41%
At least 1 converted	59%

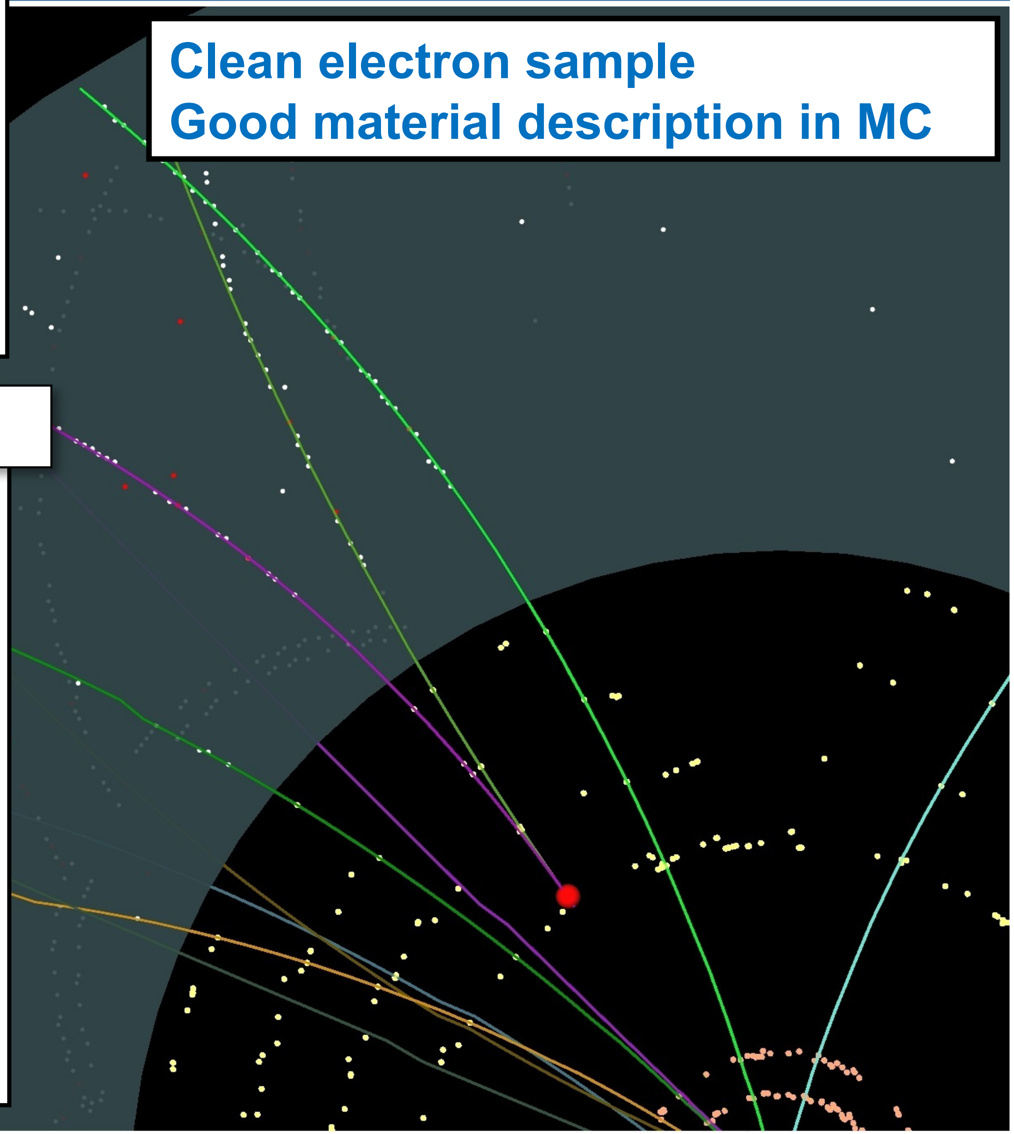
10 separate topology-categories

Photon conversions





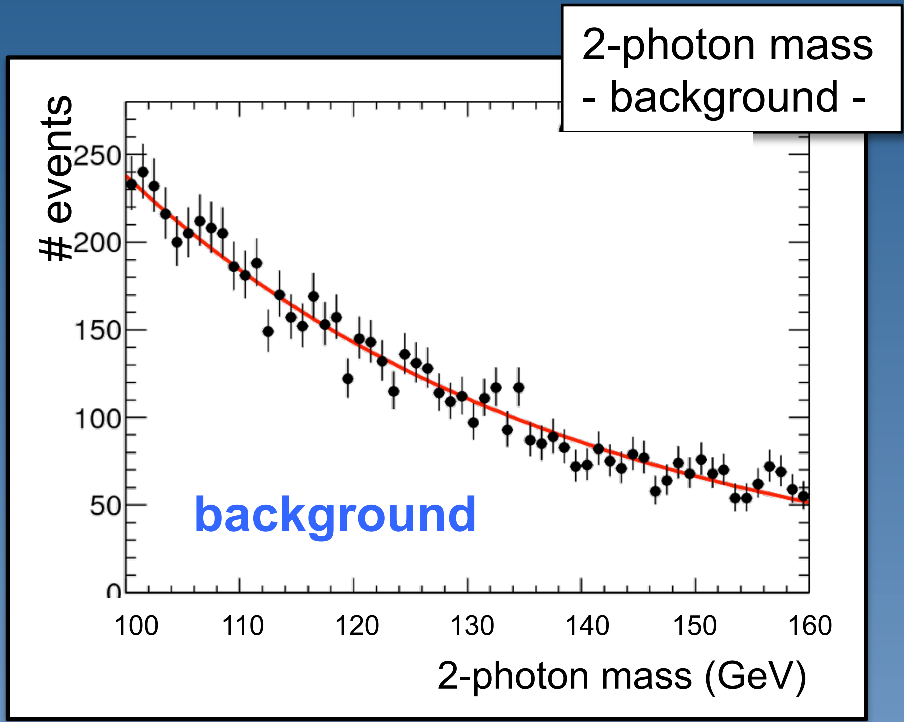
Clean electron sample
Good material description in MC

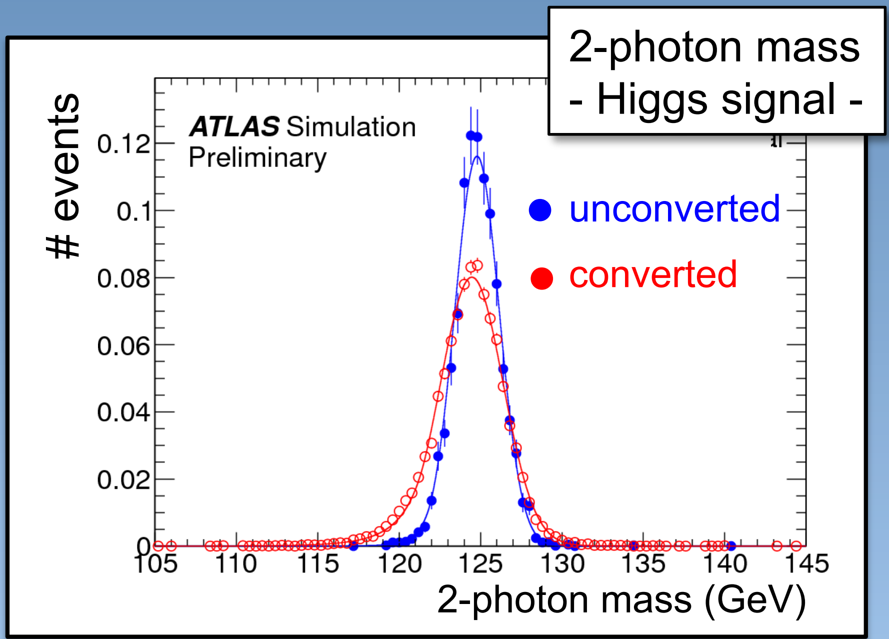


Di-photon events

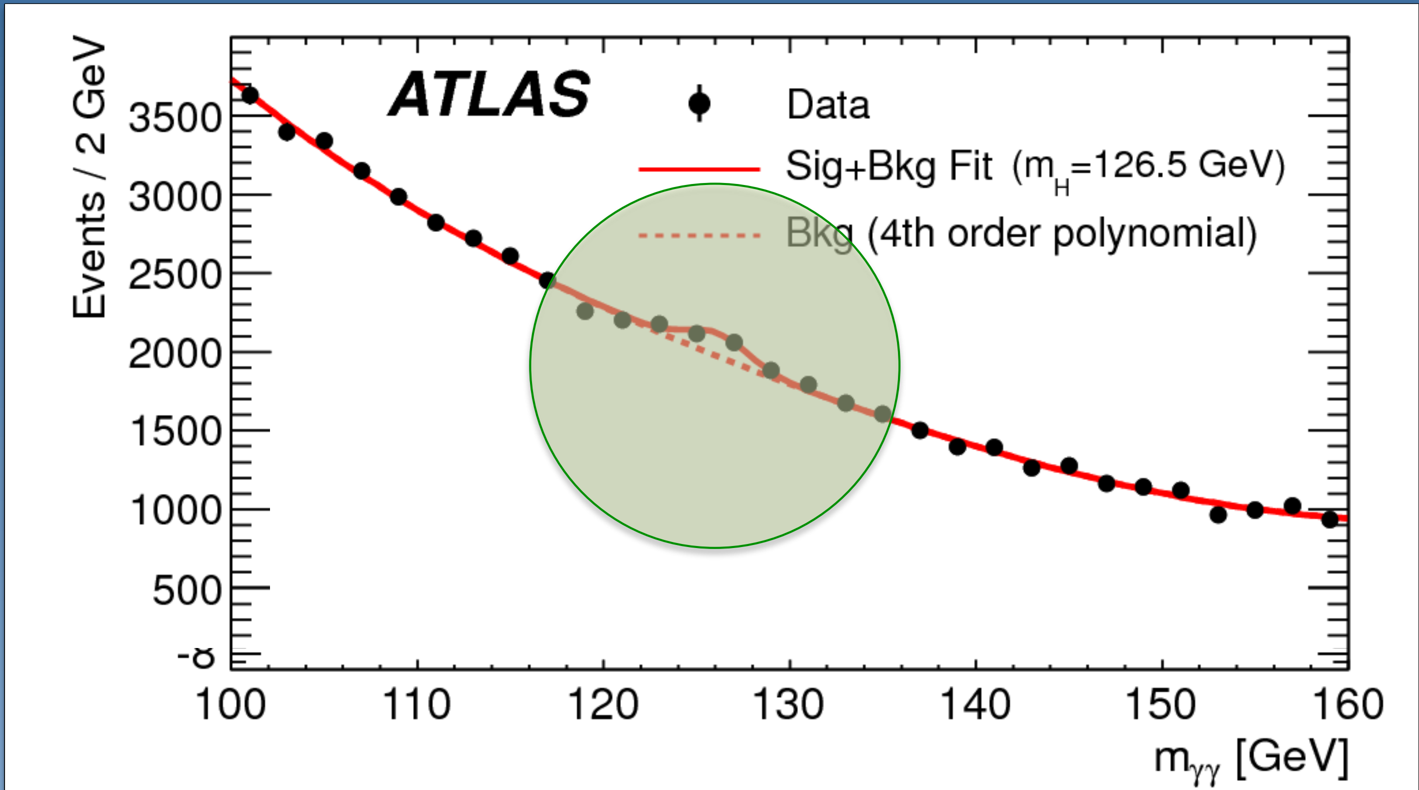
Other origin
59,000 events

Higgs
190 events

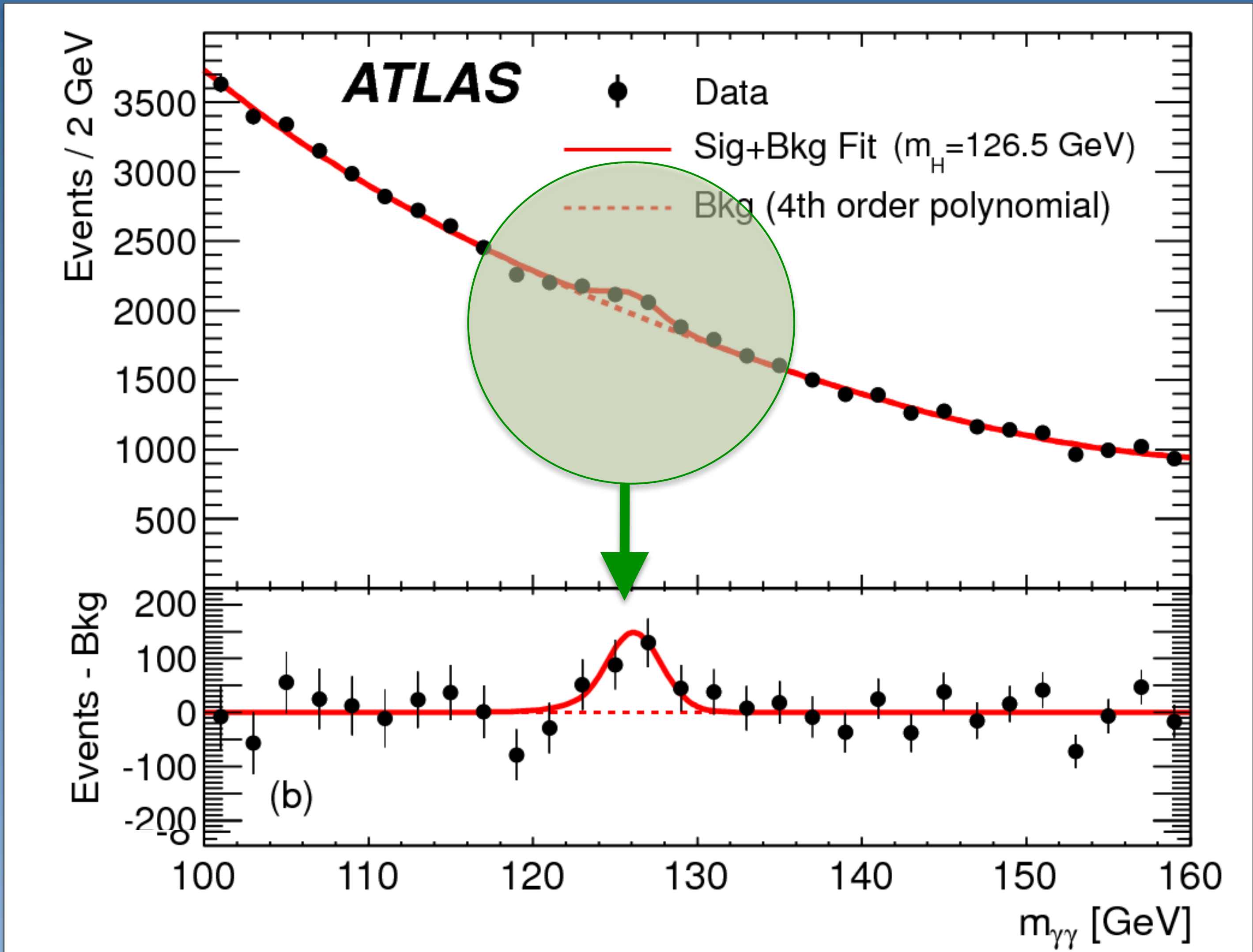




The ATLAS data

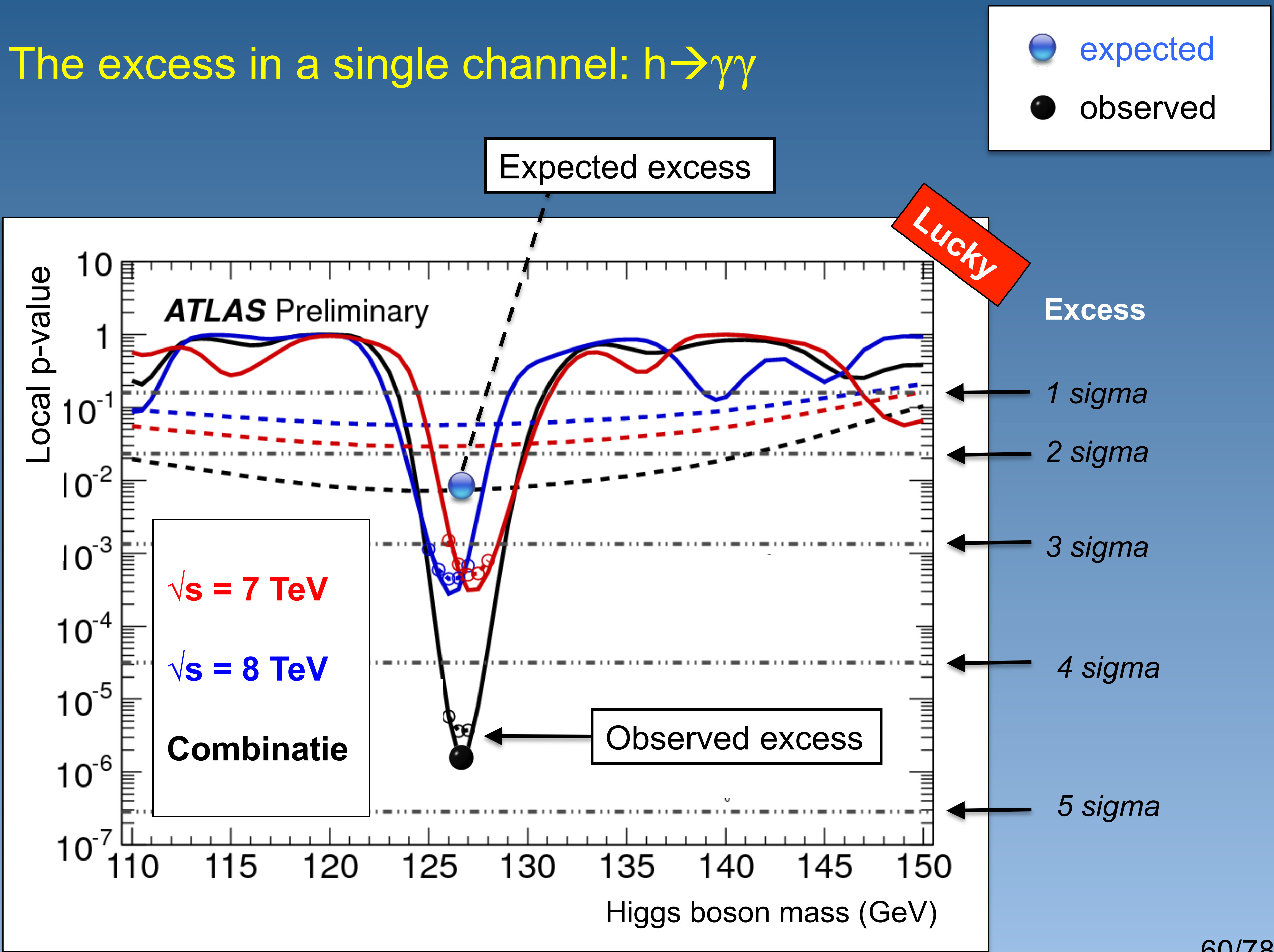


The ATLAS data

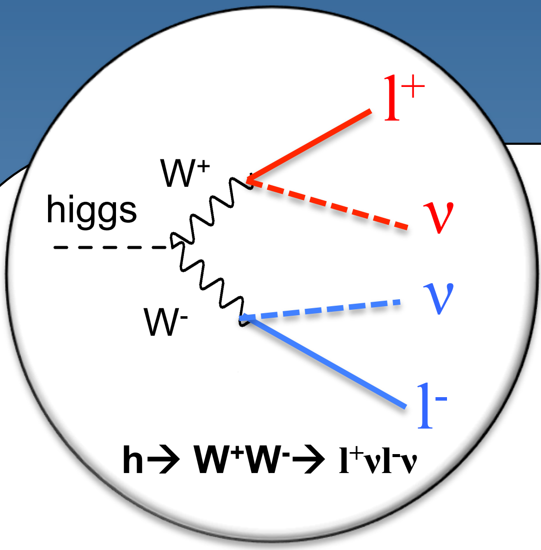


Quantify the significance ?

The excess in a single channel: h→γγ



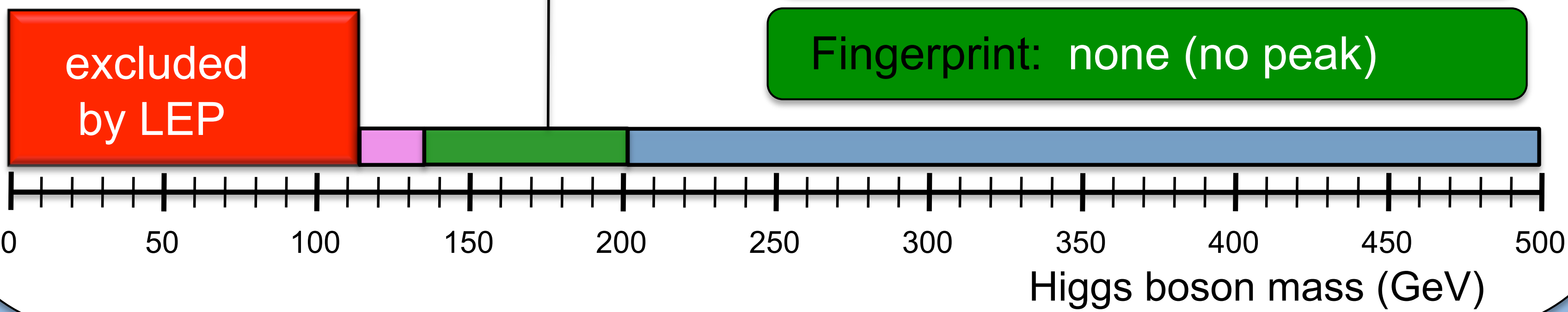
Mid-range: 130 < m_H < 200 GeV

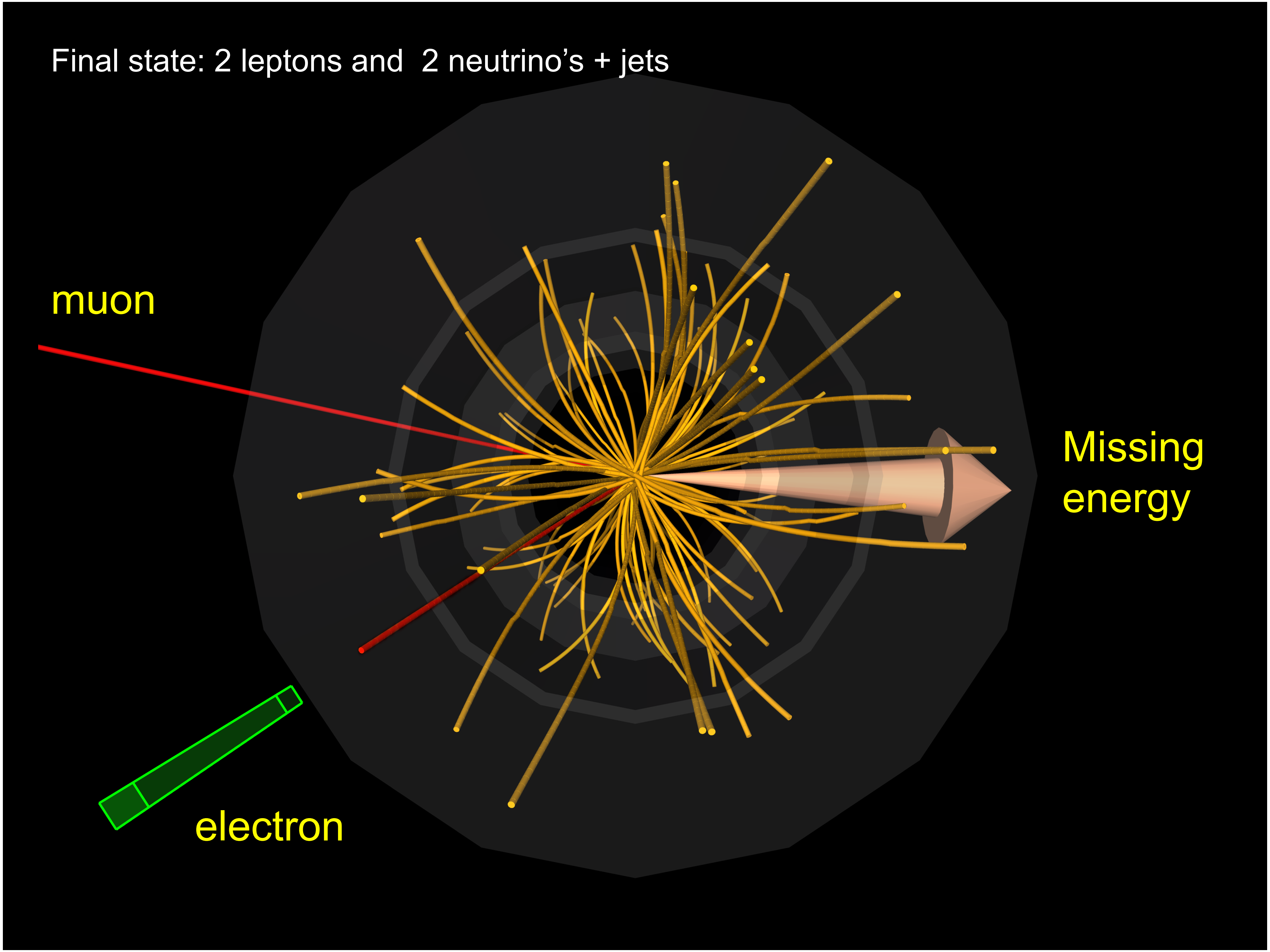


h→W^+W^-→2 leptons en 2 neutrinos

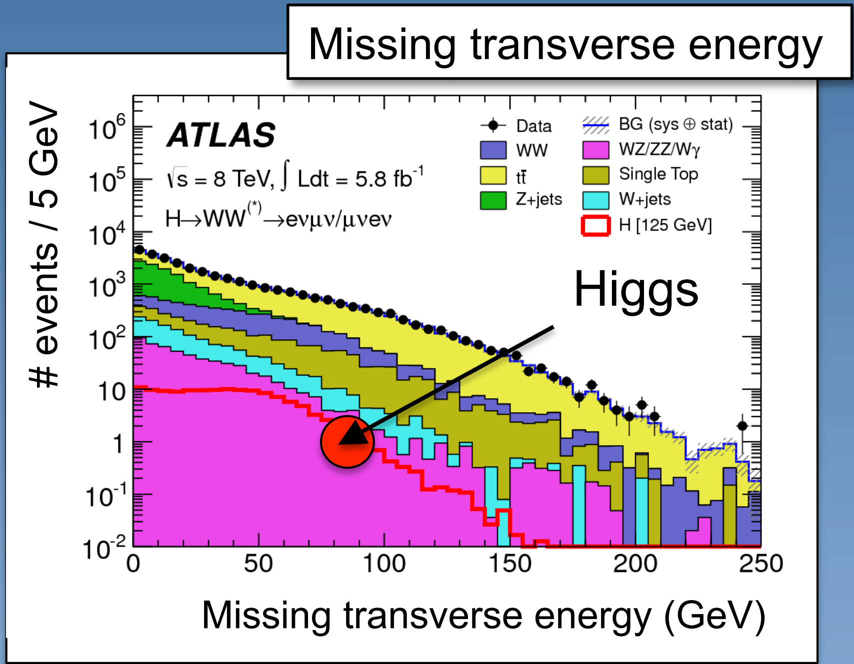
- ‘Common’ final state
- Difficult to isolate

Fingerprint: none (no peak)




Final state: 2 leptons and 2 neutrino's + jets
muon
Missing
energy
electron

The possible Higgs signal is well hidden



Delicate multi-dimensional selection

signal < 1/1,000 of background


Looking for diamonds
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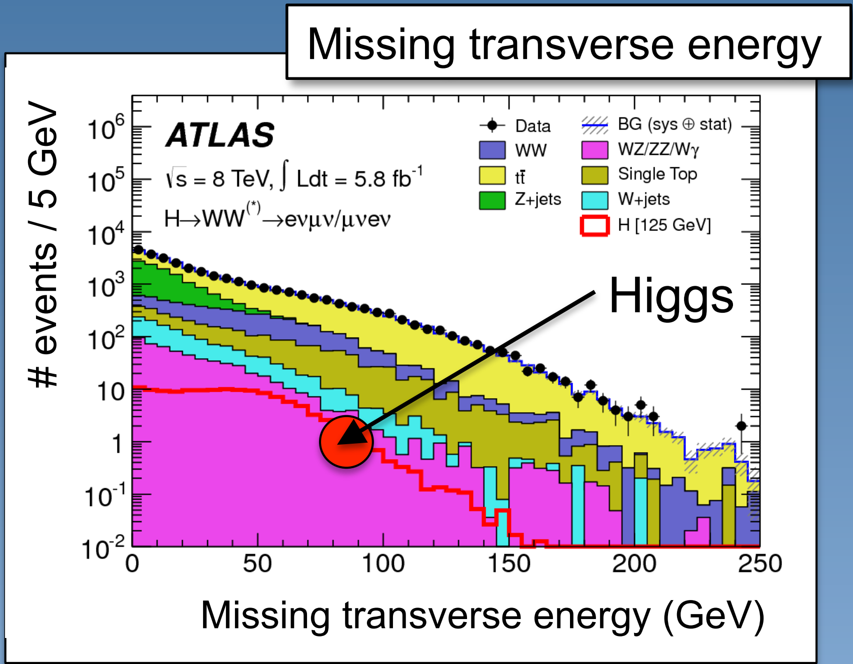
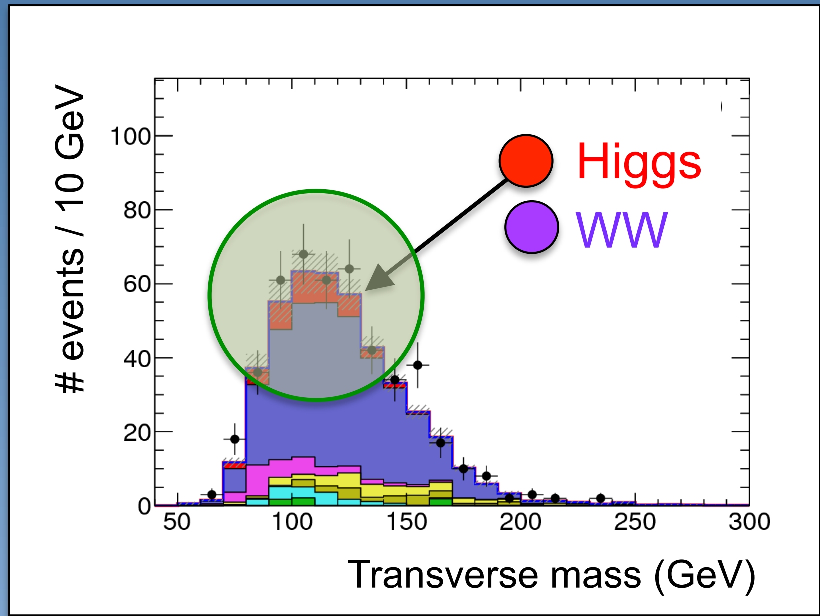
The possible Higgs signal is well hidden





S/B ~ 1/1,000

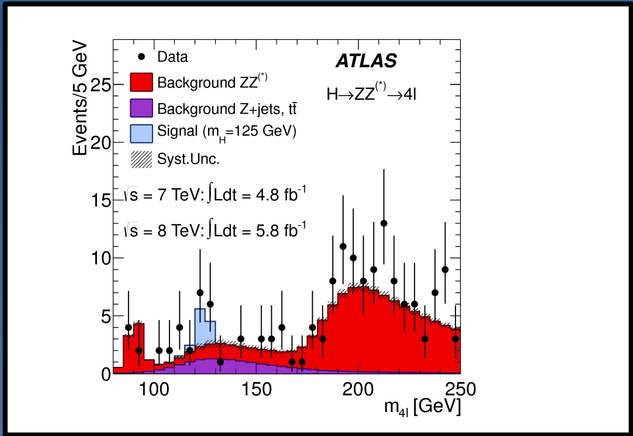
S/B ~ 1/10

Expectation: SM (+Higgs) 774 (850)

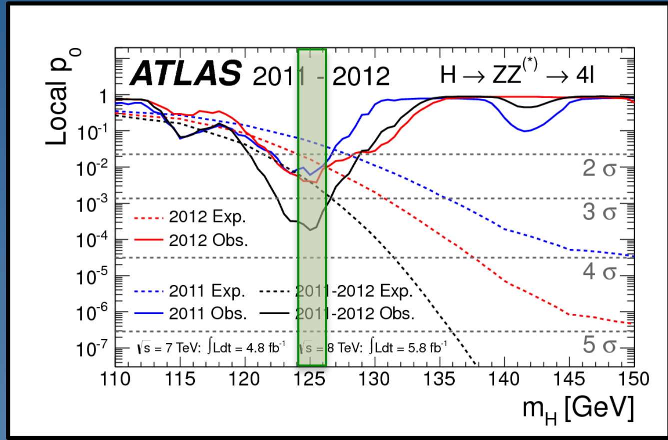
Observation: Data 917

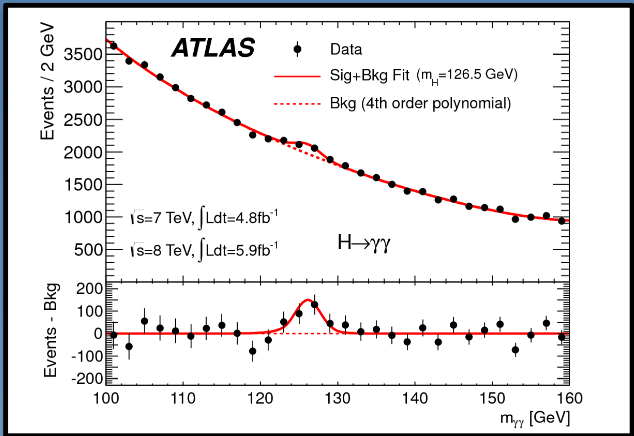
Combine the evidence

$h \rightarrow \gamma\gamma$, $h \rightarrow ZZ^*$ and $h \rightarrow WW^*$

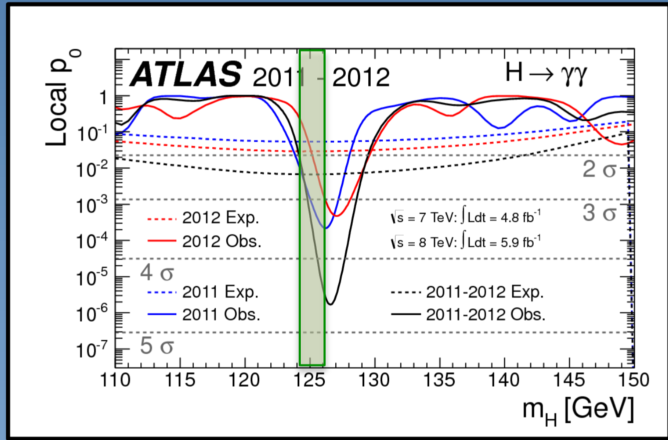

ATLAS
H→ZZ(*)→4l
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
m4l [GeV]

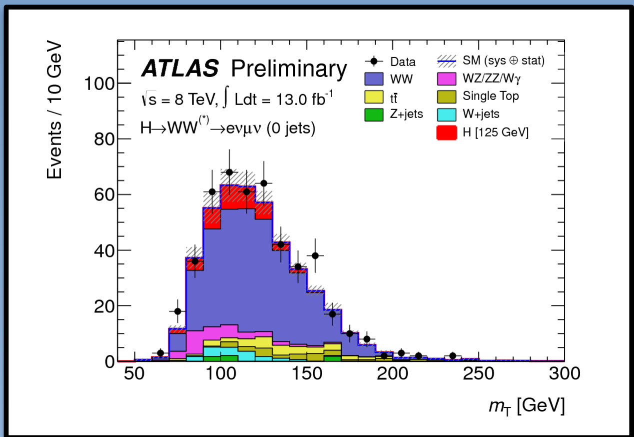
H→ ZZ


ATLAS 2011 - 2012
H → ZZ(*) → 4l
Local p0
2012 Exp.
2012 Obs.
2011 Exp.
2011 Obs.
2011-2012 Exp.
2011-2012 Obs.
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
mH [GeV]

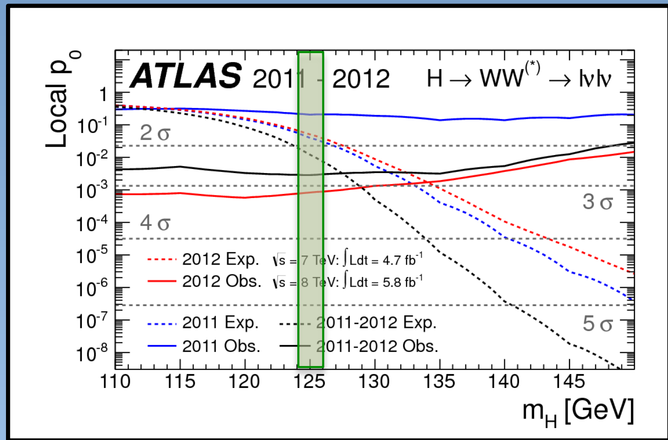

ATLAS
Data
Sig+Bkg Fit (mH=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb-1
√s=8 TeV, ∫Ldt=5.9fb-1
H→γγ
Events / 2 GeV
Events - Bkg
mγγ [GeV]

H→ γγ


ATLAS 2011 - 2012
H → γγ
Local p0
2012 Exp.
2012 Obs.
2011 Exp.
2011 Obs.
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.9 fb-1
2011-2012 Exp.
2011-2012 Obs.
mH [GeV]

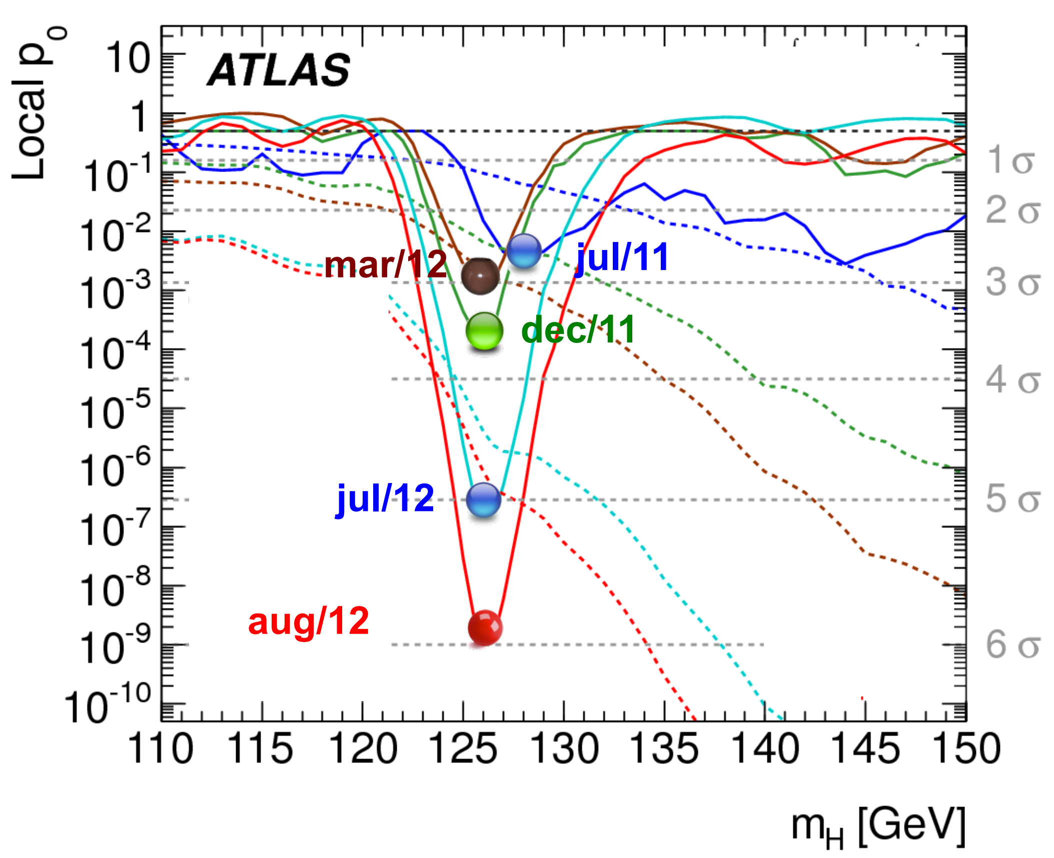

ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 13.0 fb-1
H→WW(*)→eνμν (0 jets)
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 10 GeV
mT [GeV]

H→ WW


ATLAS 2011 - 2012
H → WW(*) → lνlν
Local p0
2012 Exp.
2012 Obs.
√s = 7 TeV: ∫Ldt = 4.7 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
2011 Exp.
2011 Obs.
2011-2012 Exp.
2011-2012 Obs.
mH [GeV]

A discovery in slow-motion

Time-line higgs discovery



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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 $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,(\text{stat}) \pm 0.4\,(\text{sys})$ 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.

$m_h = 126.0 \pm 0.4\ (\text{stat}) \pm 0.4\ (\text{syst})$ GeV

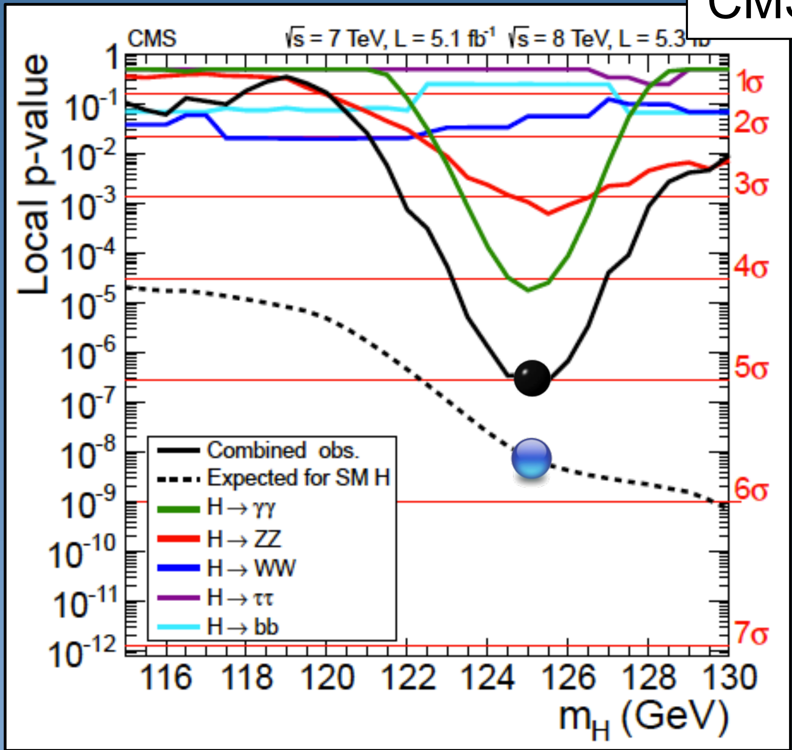
‘Are you sure Ivo ?’

‘Yes Diederik, we’re pretty sure’

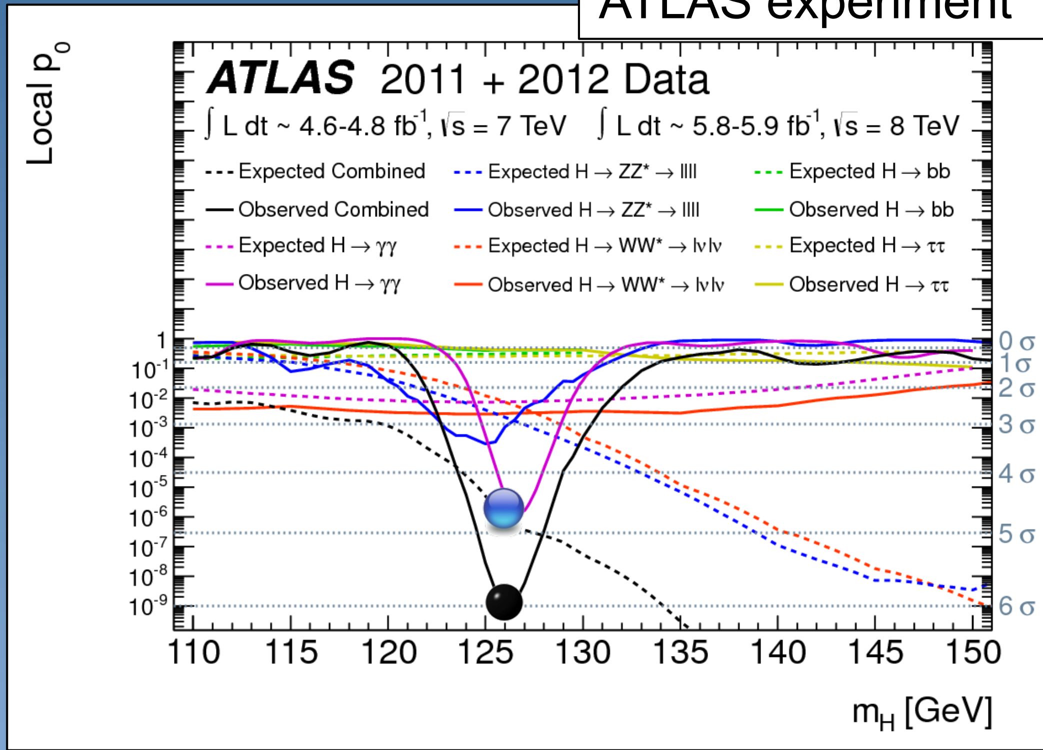
‘Independent cross-check ?’ ‘ Yep!’

Comparison results from ATLAS and CMS experiments

CMS



ATLAS experiment



expected

observed

Conclusion (in July):

- 2 experiments observe new particle
- CMS more sensitive than ATLAS
  … but ATLAS was lucky
  ATLAS had highest observed significance

Presentation CMS en ATLAS experiment: Higgs boson discovery

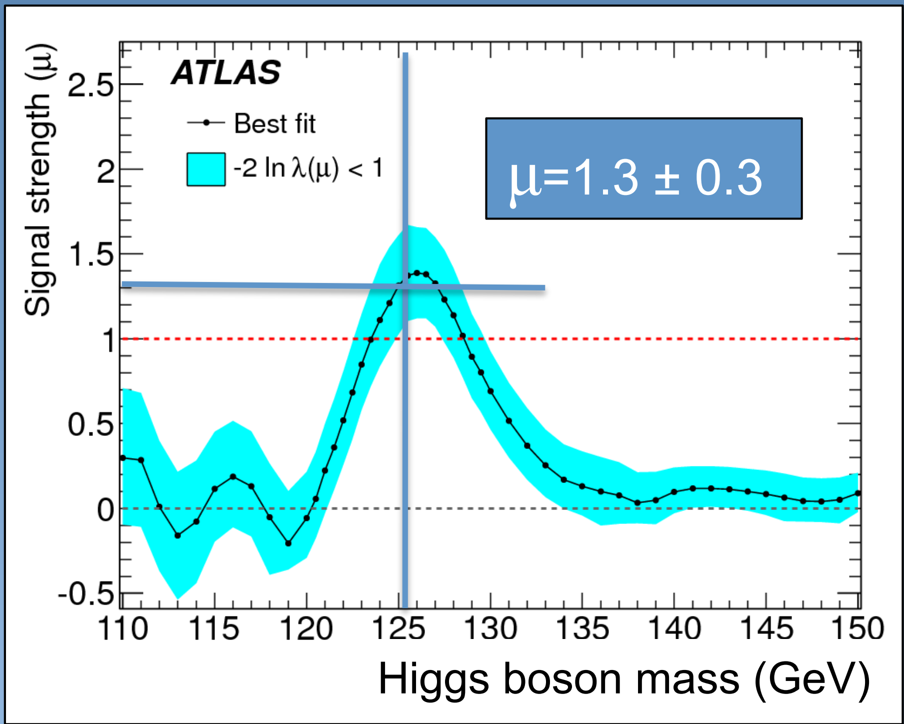
Is it the SM Higgs boson ?

SM: all properties are well predicted … as a function of it’s mass

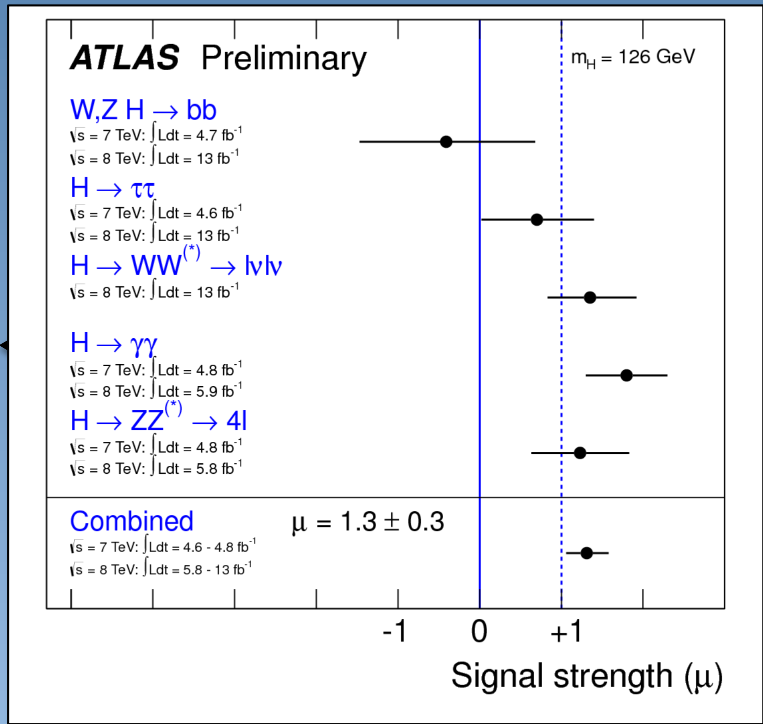
SuSy: 5 Higgs bosons, lightest one is like the SM Higgs boson,
… but slightly different

Looking at the Excess:
signal strength (μ) compared to SM

Overall production cross-section scaling

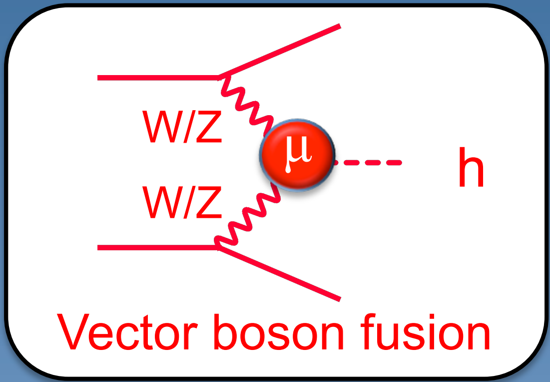


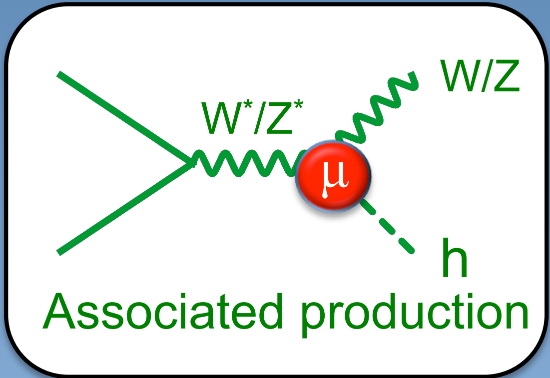
Coupling to gauge bosons and fermions

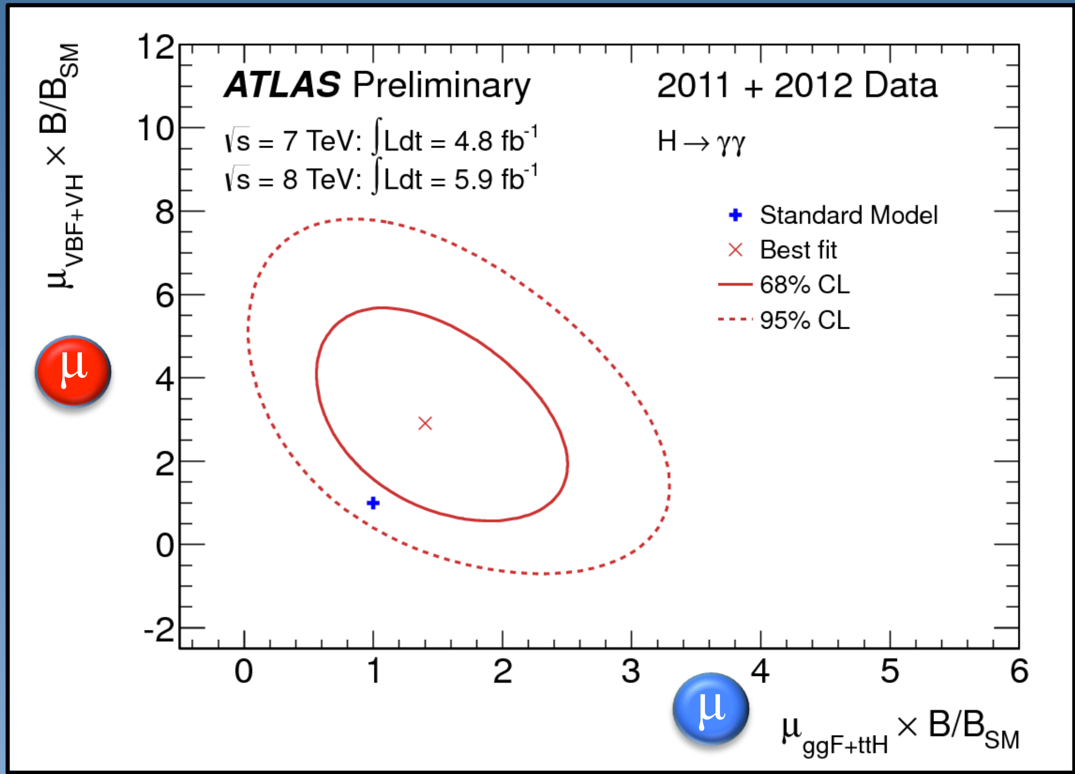


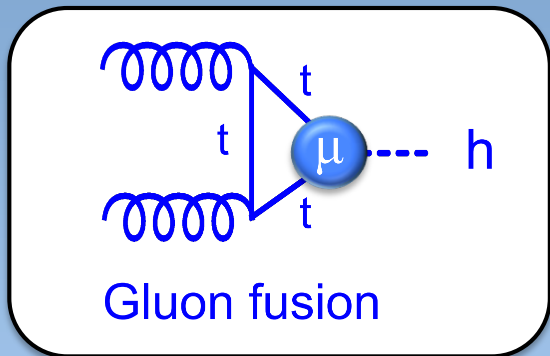
Properties: [couplings]

coupling to gauge bosons and fermions (Yukawa)









Properties: [spin/CP]

Prediction: the Higgs boson is a scalar particle

Spin 1 ? No!
- produced through gluon-gluon fusion (2x spin-1)
- decays to 2 photons (2x spin-1)

Spin-0 ? Spin-2

Spin/CP parameters: look at decay angles in gg→H→ZZ→4 leptons

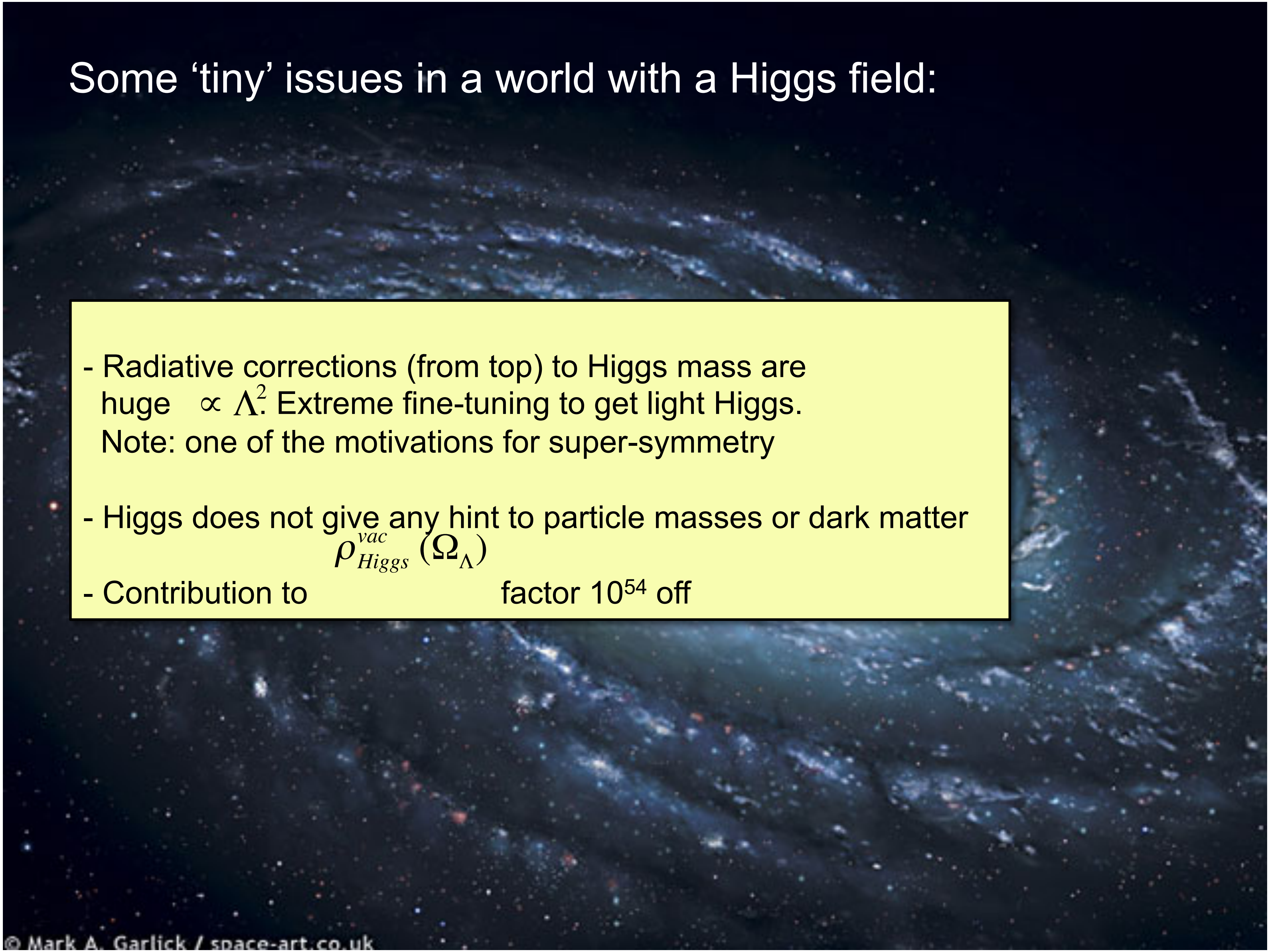
Not many plots/numbers public yet ….

Some 'tiny' issues in a world with a Higgs field:

- Radiative corrections (from top) to Higgs mass are huge $\propto \Lambda^2$. Extreme fine-tuning to get light Higgs. Note: one of the motivations for super-symmetry

- Higgs does not give any hint to particle masses or dark matter

- Contribution to $\rho^{vac}_{Higgs}\ (\Omega_\Lambda)$ factor 10^{54} off

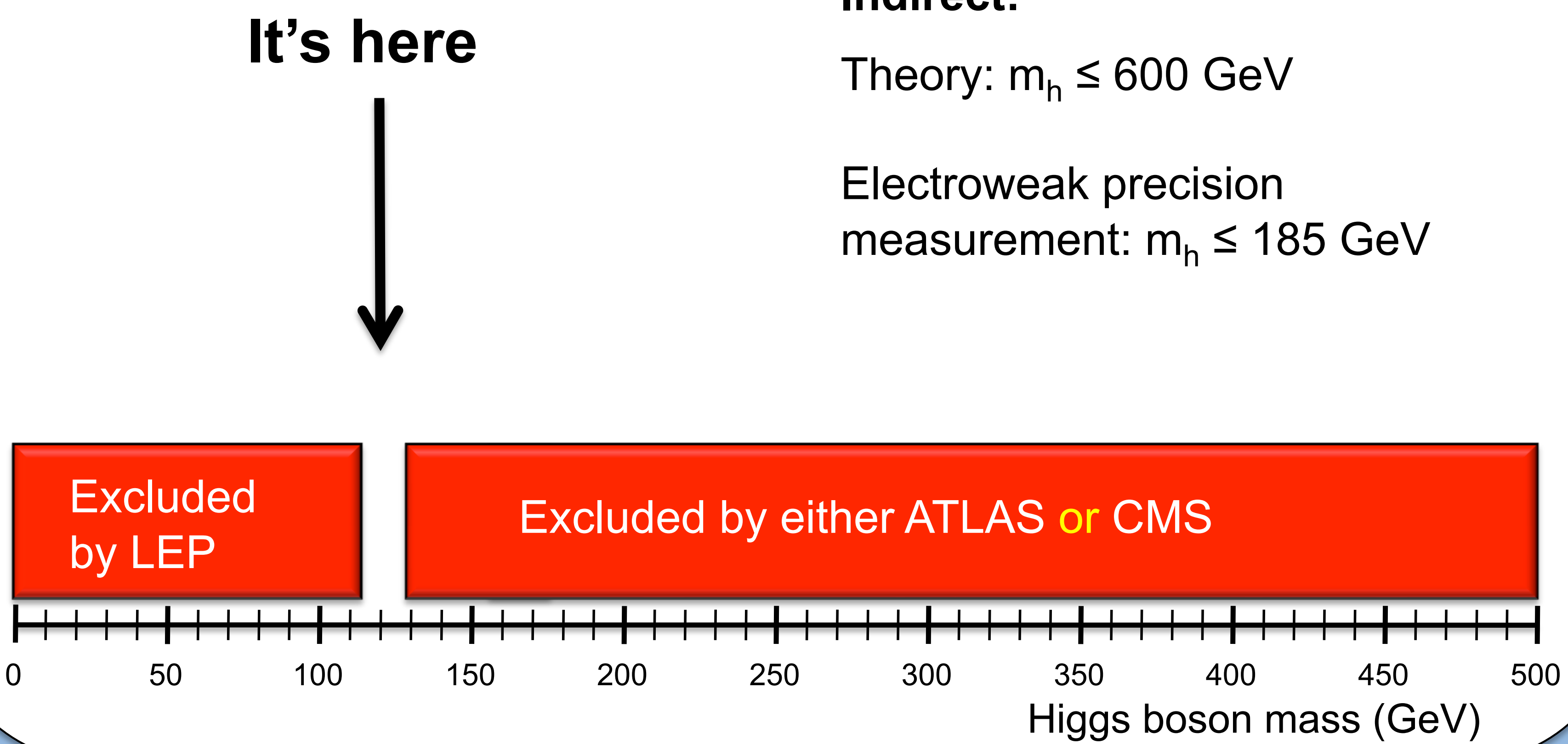


Knowledge on mass Higgs boson

Indirect:

Theory: $m_h \leq 600$ GeV

Electroweak precision measurement: $m_h \leq 185$ GeV



Summary

1) Large Hadron Collider and experiments
   are working fan-tas-tic!

2) Search for the Higgs boson in 2011+2012
   Discovery !!

3) Standard Model has serious shortcomings
   Looking forward to new physics (SuSy, extra dimensions, …)

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

Ivo.van.Vulpen@nikhef.nl

backup

References

ATLAS experiment

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

Higgs paper: *"Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC",* Phys. Lett. B716 (2012) or http://arxiv.org/abs/1207.7214

CMS experiment

All CMS public results: publications, numbers and plots
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Higgs paper: *"Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC",* Phys. Lett. B716 (2012) or http://arxiv.org/abs/1207.7235