Finding a new (Higgs?) boson at the Large Hadron Collider

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UT Physics Colloquium, 31 Oct 2012

THE UNIVERSITY OF TEXAS AT AUSTIN

ATLAS EXPERIMENT
http://atlas.ch

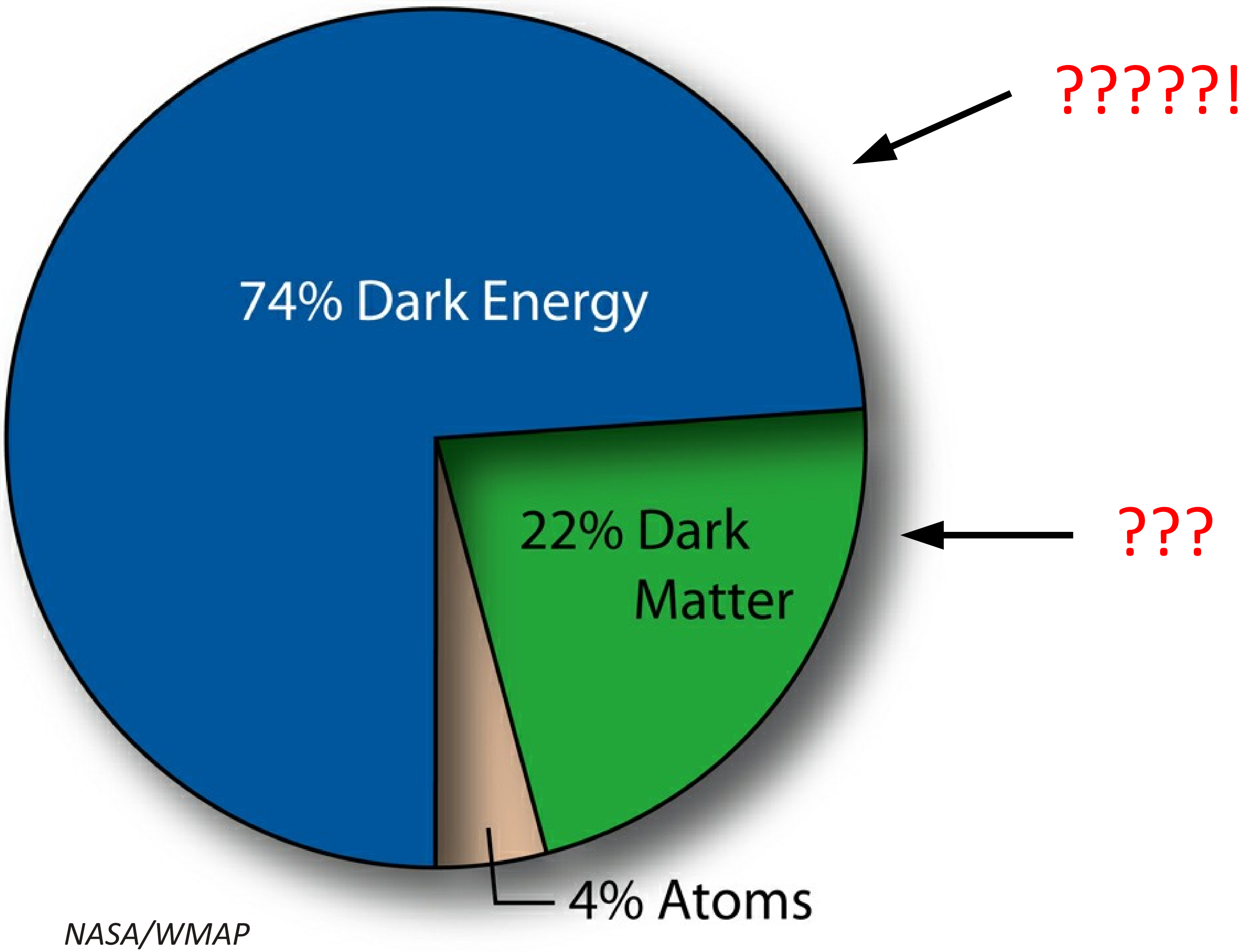

HIGGS BOSON
H
The HIGGS BOSON is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland, which collides particles at 99.99% the speed of light, will detect the elusive Higgs Boson
Higgs boson
$10.49 PLUS SHIPPING
LIGHT
HEAVY
Wool felt, fleece with gravel fill for maximum mass. MADE IN CHINA.
GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP
NEUTRON DOWN QUARK TAU GLUON HIGGS BOSON NEUTRINO TACHYON ELECTRON UP QUARK DOWN
NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO
The PARTICLE ZOO

The big picture

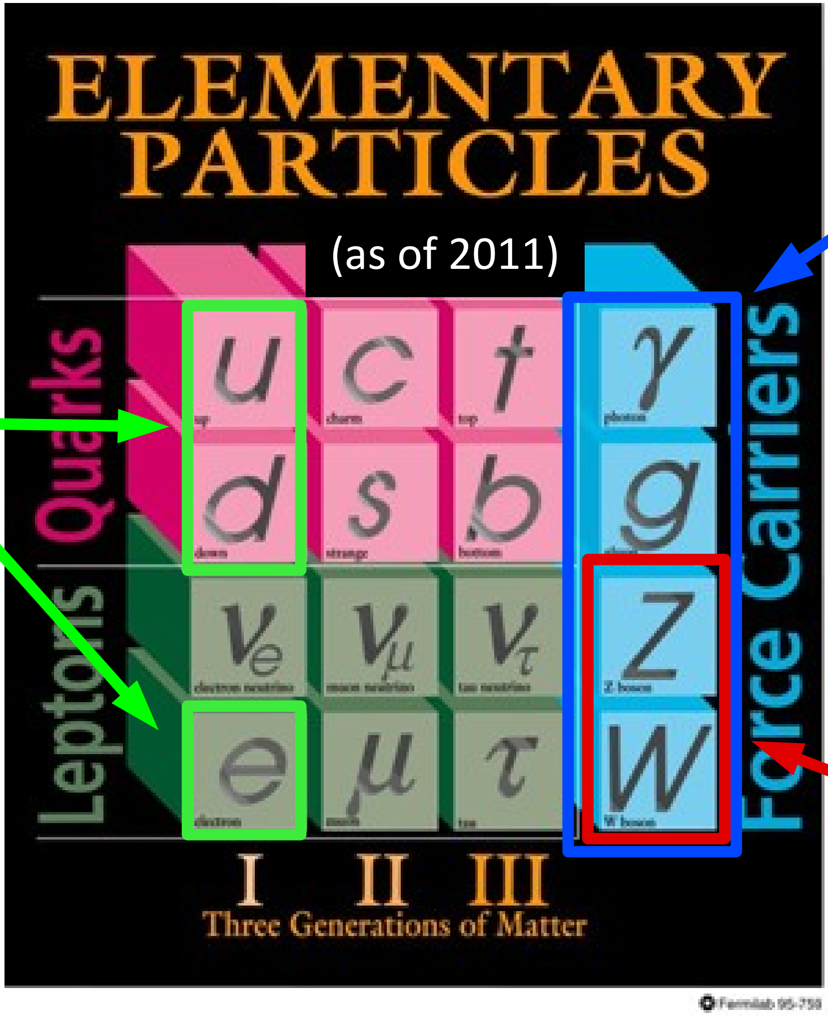
What is particle physics about?

- What is the Lagrangian of the universe?
  - What are the matter and force particles? How big are the coefficients of the terms?
- What principles guide the terms that are present?
  - Symmetries and conserved charges: not everything goes
- How do we go from the small to the large?
  - Protons and neutrons (e.g.) are not fundamental particles, but we had best be able to explain them!
  - Physics at the smallest and largest scales is intimately related

The Modern Universe



NASA/WMAP



What you're made of

Gauge bosons:
carriers of fundamental forces
electromagnetism, *strong* and *weak* nuclear forces

Interactions determined by *gauge symmetries*

Massive carriers of the weak force

Still very mysterious:
Gravity?
Dark matter?
Dark energy?
Baryon asymmetry?
…

1 GeV = 1.07 protons
125 GeV ≈ 1 Cs atom

Gauge Theory

- Forces in the particle physics Standard Model are specified by *symmetries*
  - Particles that feel a force are affected by its symmetry transformations
  - Constrains possible interactions very strongly
- If a particle interacts with a force, it has a charge for that force. *Charge conservation applies!*

Classical electrodynamics has a gauge symmetry:

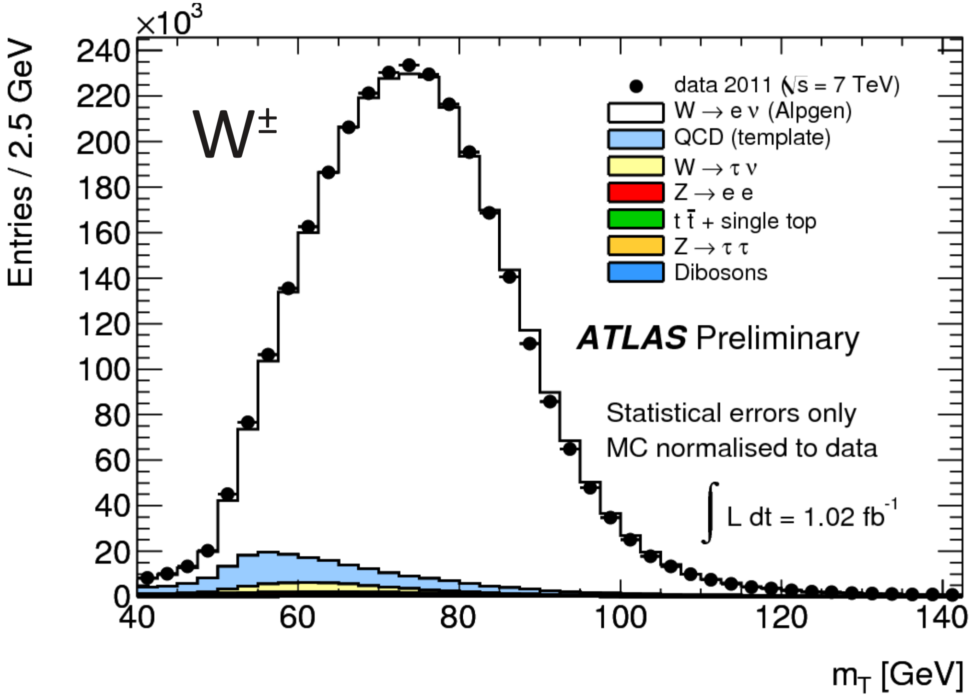
$$A^\mu = (\phi, \vec{A}) \to A^\mu + \partial^\mu \chi$$

Leaves **E** and **B** unchanged

The Weak Force is Weird

- The weak force carriers are massive.
- The weak force carriers form a triplet W^+, Z^o, W^- (as expected from their symmetry), but they do not all have the same mass, and they do not all have the same interactions.
- The weak force distinguishes left- and right-handed particles.

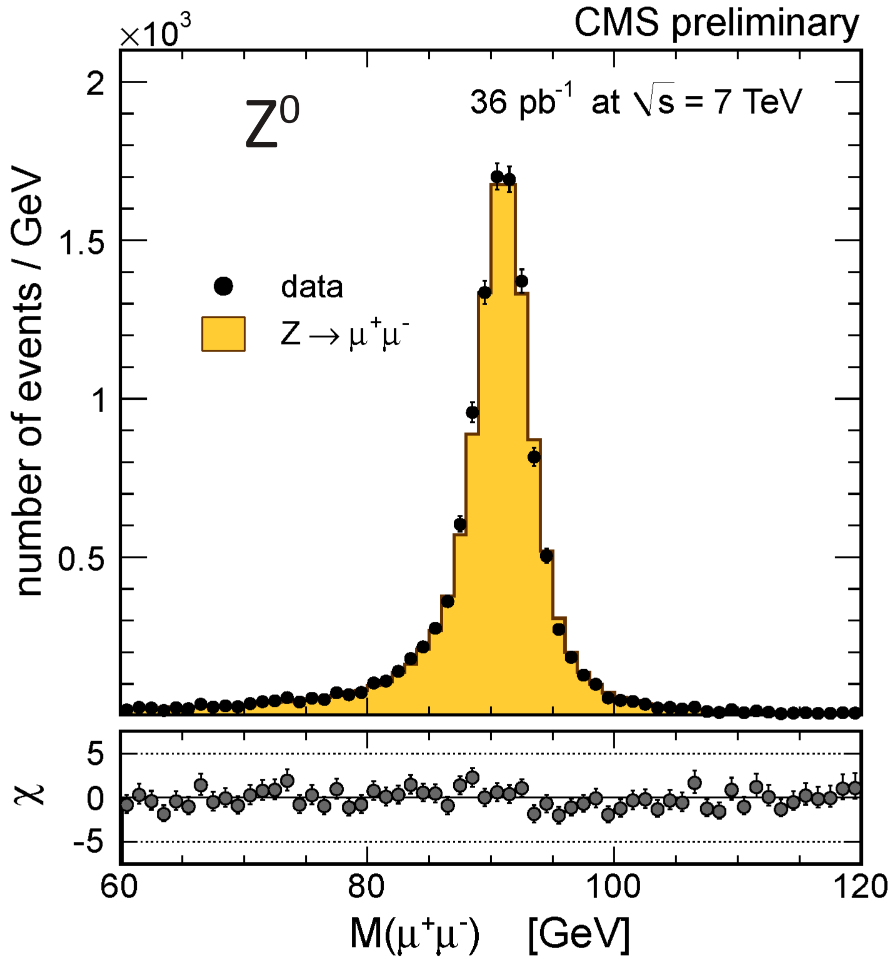
The Weak Force Carriers



Detection mode:

W decays to a charged lepton + neutrino

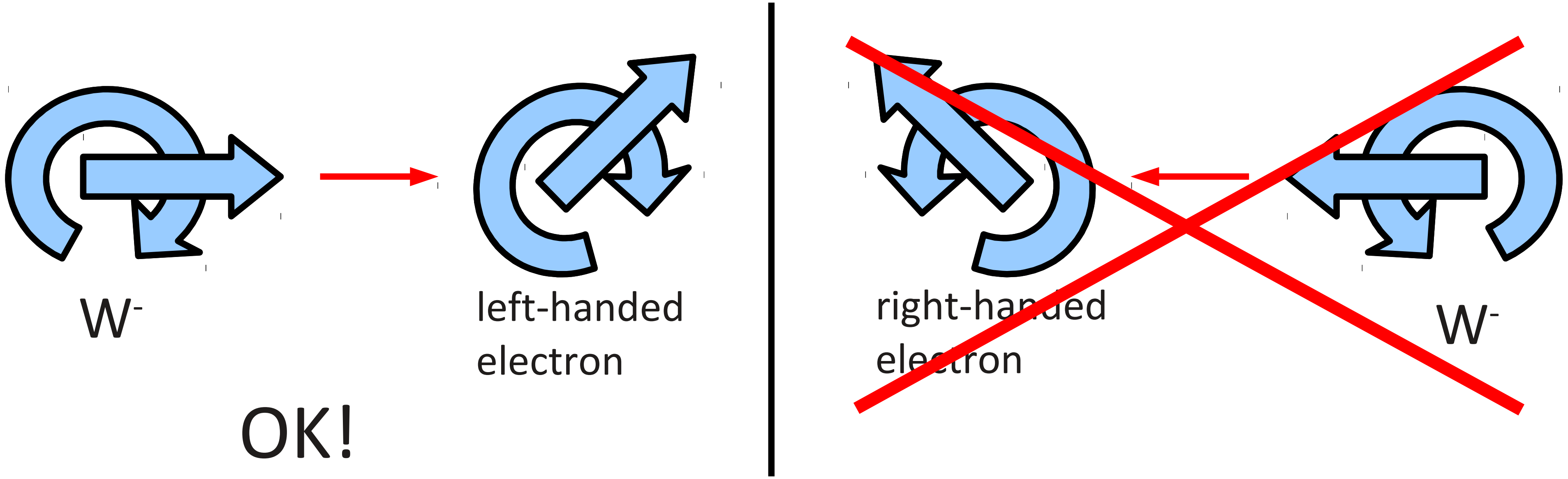
Z decays to charged lepton + antilepton



We even use the W and Z masses for experimental calibration

Parity and Chirality

- The weak force treats left and right handed electrons (and all fermions) differently
  - left handed fermions and right handed antifermions have weak interactions. Their antiparticles don't.
- Left and right handed fermions are **different particles**.



So, the Problems…

- Gauge invariance forbids the Standard Model from having explicit masses for the W and Z

$$\frac{1}{2}m_Z^2 Z_\mu Z^\mu$$

- Gauge invariance forbids explicit (Dirac) fermion mass terms, as these would create/destroy weak charge.

$$-me_R^\dagger e_L$$

How do we get a realistic model of the weak force without abandoning gauge theory?

Enter the Vacuum

Add a weak-charged scalar field $\phi = (v+h)/\sqrt{2}$, where $v \neq 0$ in the vacuum state. Then the *required* interaction

$$\frac{g^2}{4}(W^+\phi)^\dagger(W^+\phi)$$

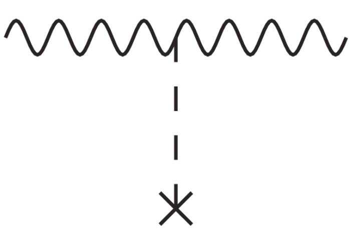
Englert and Brout; Higgs;
Guralnik, Hagen, and Kibble (1964)

Weinberg; Salam (1967-8)

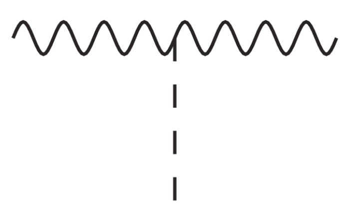
becomes

$$\frac{1}{2}\frac{g^2v^2}{4}W^-W^+\left(1+2\frac{h}{v}+\frac{h^2}{v^2}\right)$$

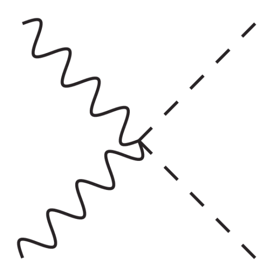
W mass
$m_W = gv/2$



WWh
coupling $\propto g m_W$



WWhh
coupling $\propto g^2$



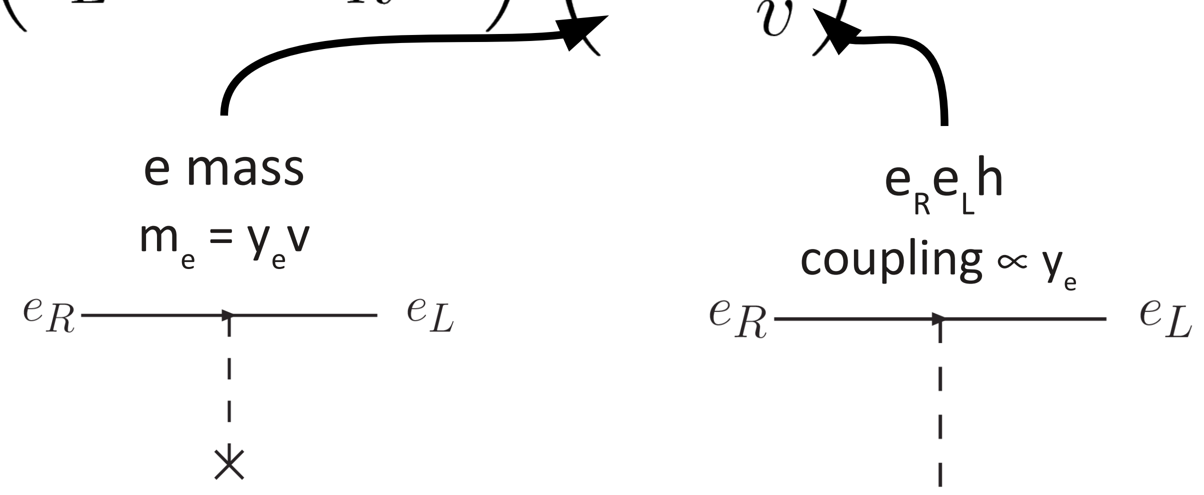
Fermion Masses

Since ϕ field has weak charge the following is ok:

$$-y_e \left(e_L^\dagger e_R \phi + e_R^\dagger e_L \phi^* \right)$$

which becomes

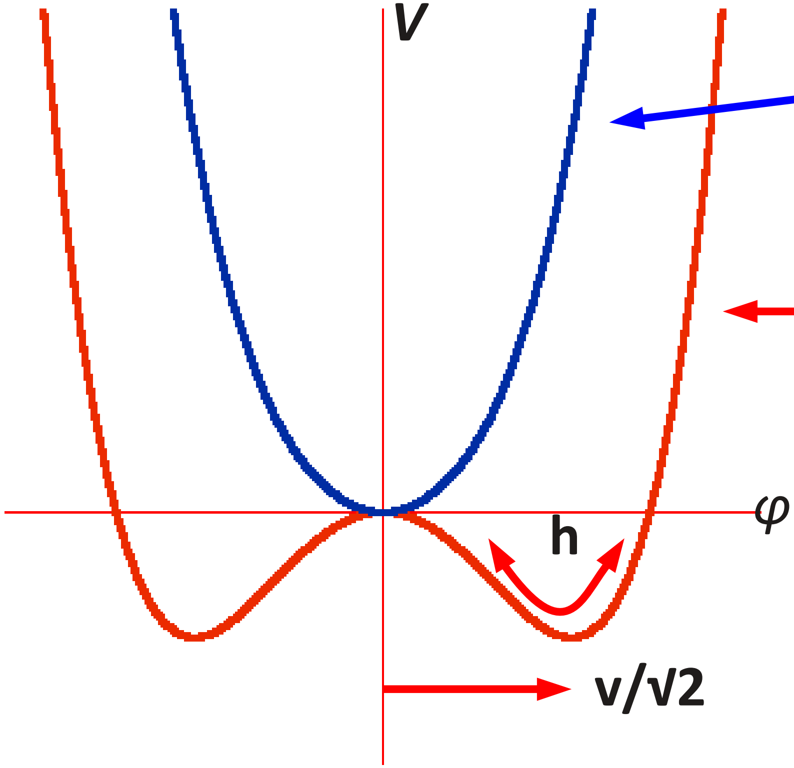
$$-y_e v \left(e_L^\dagger e_R + e_R^\dagger e_L \right) \left(1 + \frac{h}{v} \right)$$



y_e (the "Yukawa coupling") is not predicted from theory but determined from observed masses.

Getting v ≠ 0

Arrange so it is energetically favorable for the ground state to break a symmetry of the potential (pretty standard!)



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

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

Fluctuations of ϕ around the minimum correspond to a massive particle ("the Higgs boson") with

$$m_h = v\sqrt{2\lambda}$$

quartic term → *h* self-interaction

From known m_W and g, v = 246 GeV.

Higgs Boson Characteristics

- It is a neutral scalar.
- It has a specific pattern of interactions with the W, Z, and fermions, which depends on their masses.
  - For a given Higgs boson mass, its behavior is predicted.
- It interacts with itself.

(True for the minimal SM Higgs mechanism)

Q: why do the W and Z have different masses?

A: there are two broken symmetries –
the Z gets two mass terms, and the W only gets one

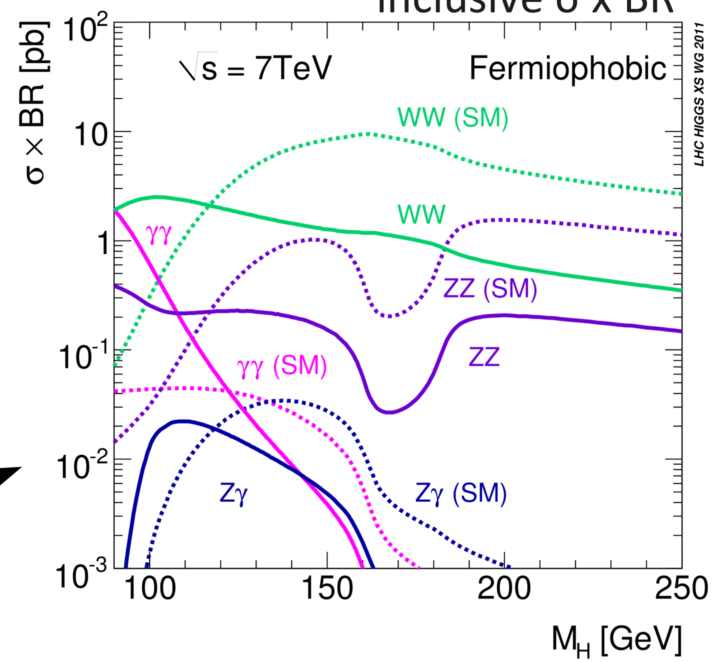
More Complicated Models

- Can add more fields (e.g. two-Higgs doublet models [2HDM], supersymmetry)
- Higgs potential can be fixed by other physics
- The "Higgs field" could be a composite, not a fundamental scalar (e.g. technicolor)

2HDM would give more particles:
light and heavy neutral scalars h and H,
neutral pseudoscalar A,
charged scalars H^+ and H^-

Fermiophobic models turn off the fermion couplings

inclusive σ x BR



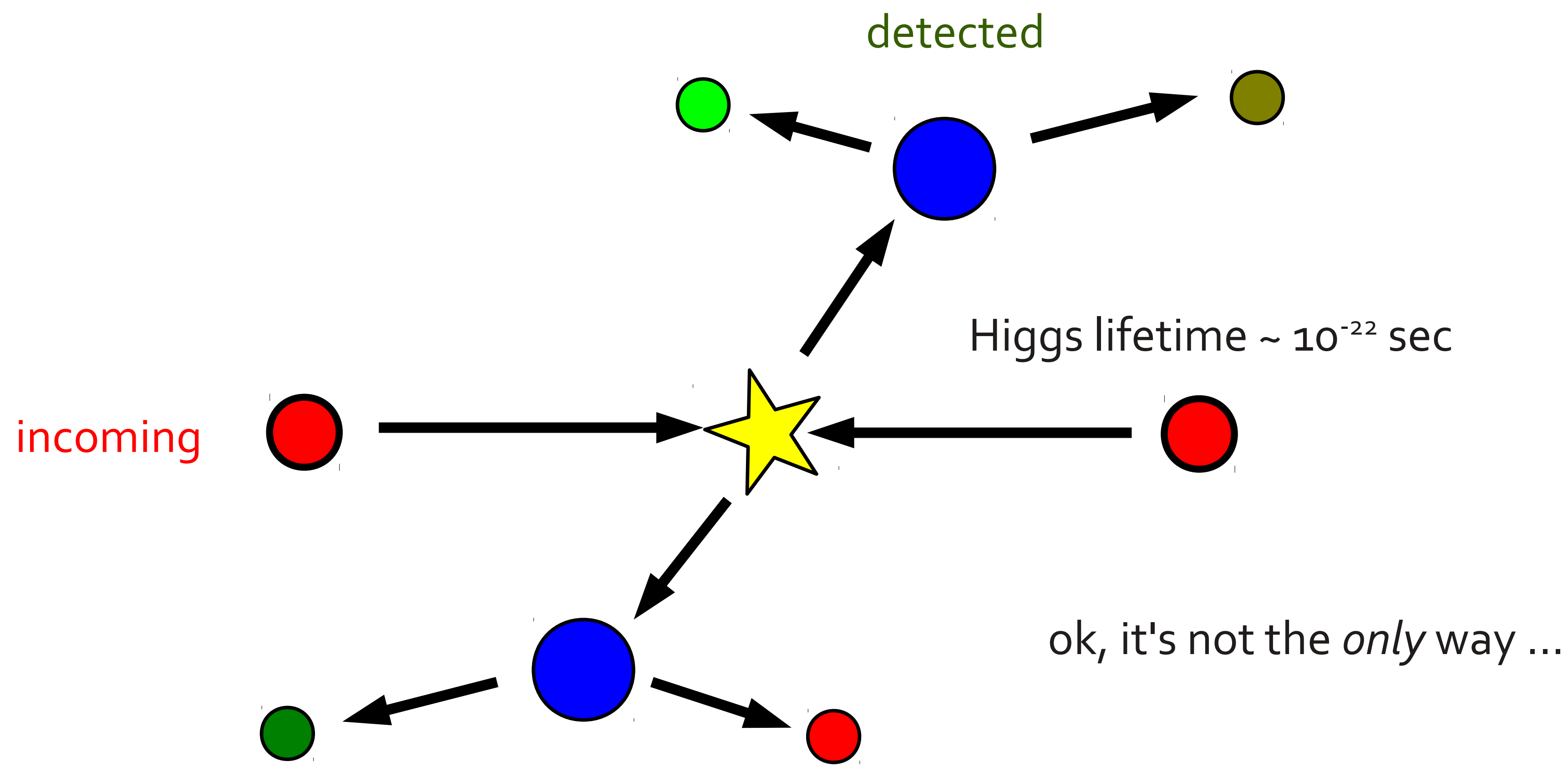
Exotica

- The Higgs could interact with particles outside the Standard Model
  - portal to dark matter or other hidden sectors
  - fourth SM-like generation would strongly affect Higgs production
- These scenarios can modify Higgs production rates or decay patterns

Example "**Higgs portal**" to dark matter:
Add a SM singlet S with interaction

$$k|\phi|^2|S|^2$$

How do we look for new particles?

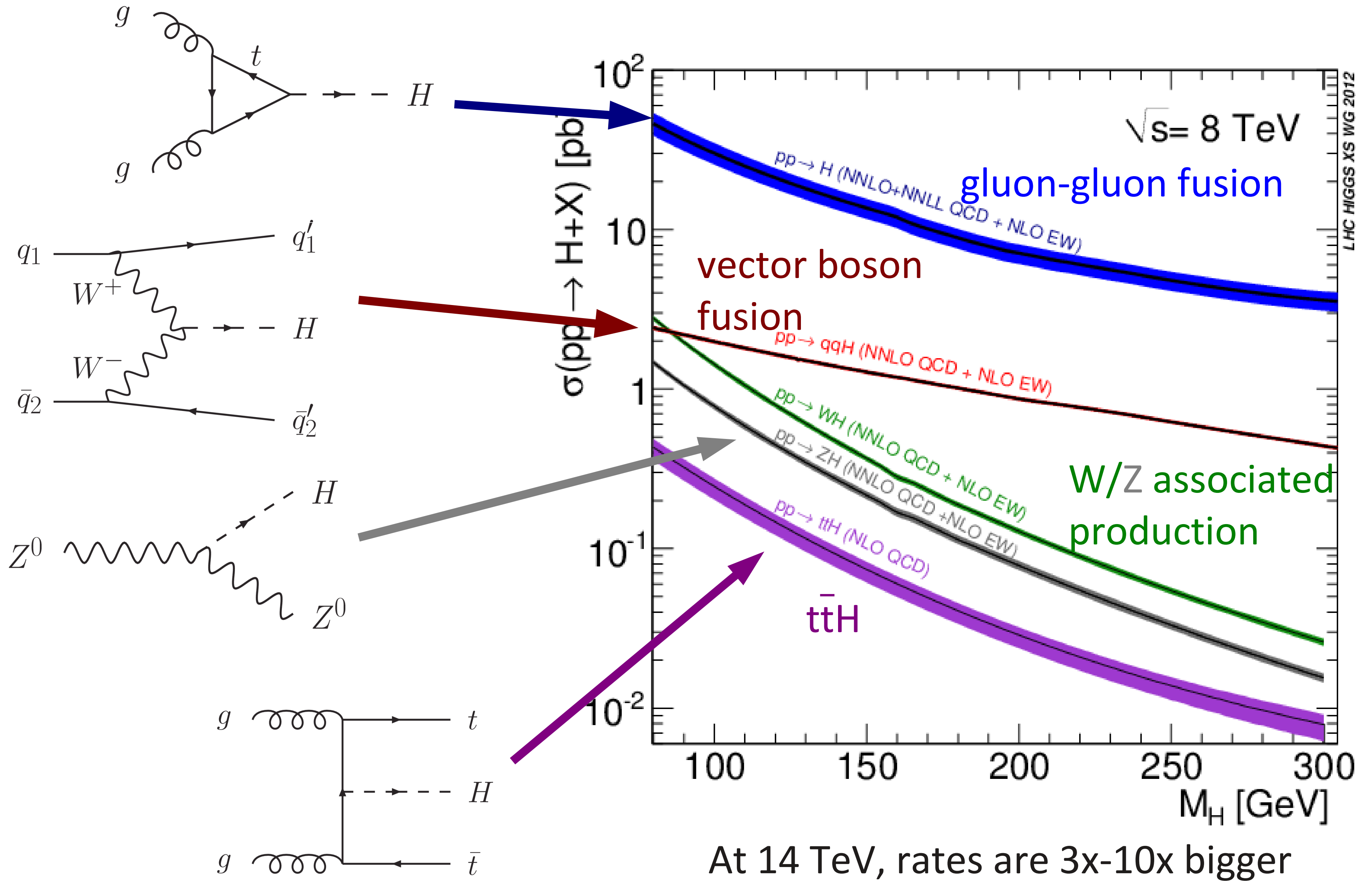


convert kinetic energy to mass energy of new particles

Proton kinetic energy > 4000 times proton mass

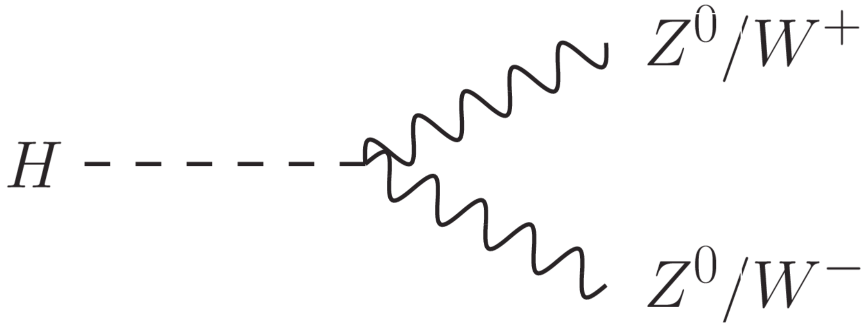
Detect “stable” remnants of collisions in detectors, look for patterns

LHC Higgs Production

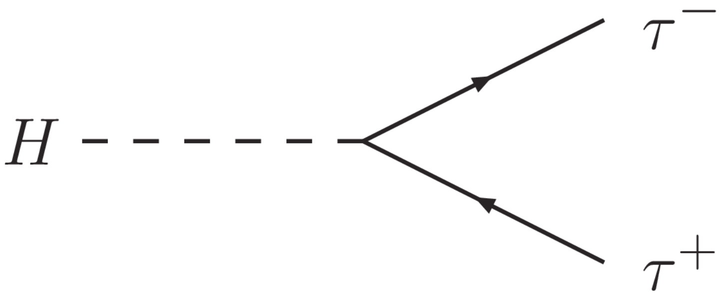


At 14 TeV, rates are 3x-10x bigger

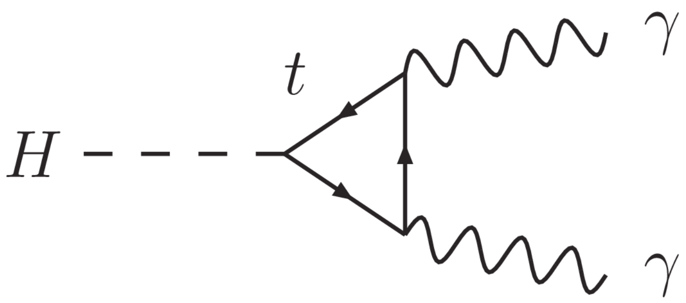
Directions to See a Higgs



Gauge boson decays: direct probe of EWSB
Rate reduced for Higgs mass below $2M_W$, $2M_z$



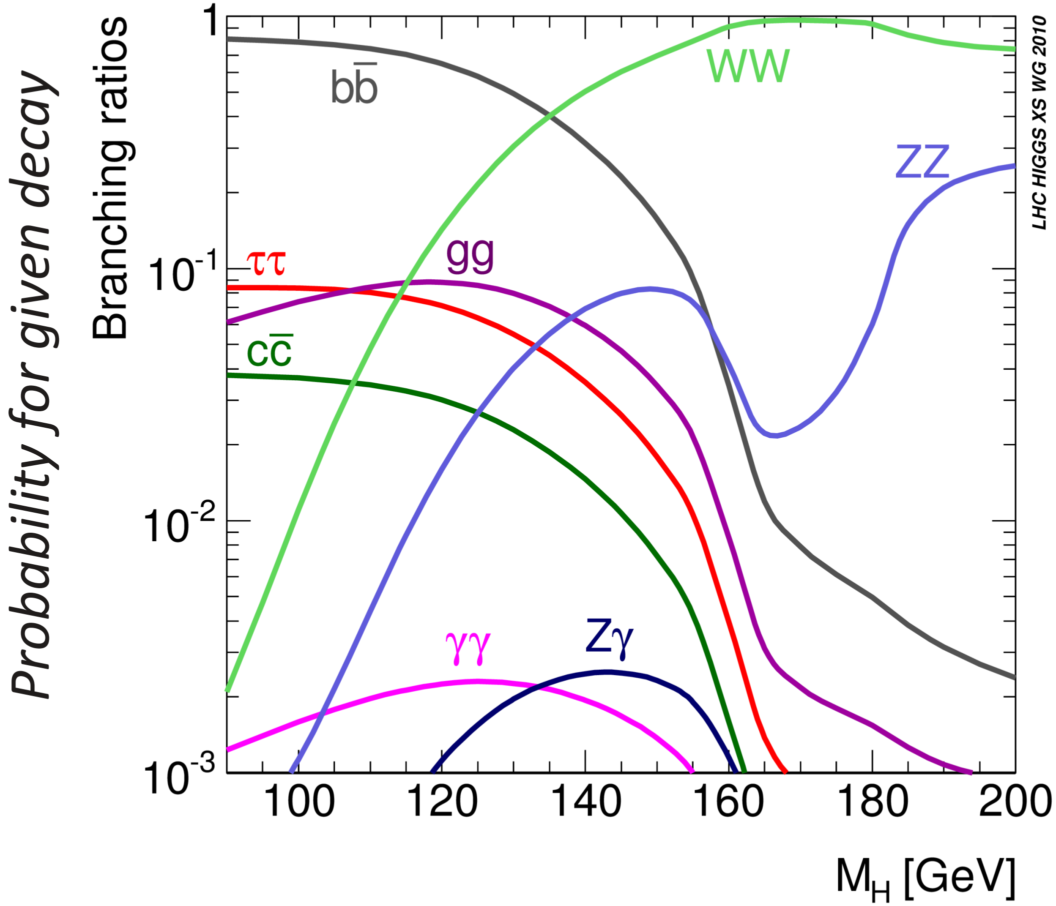
Tests Yukawa couplings
ττ and $b\bar{b}$ accessible at LHC, but are tricky experimentally



γγ is cleanest mode for low mass Higgs
Rate is sensitive to particles in loop

Higgs Branching Fractions

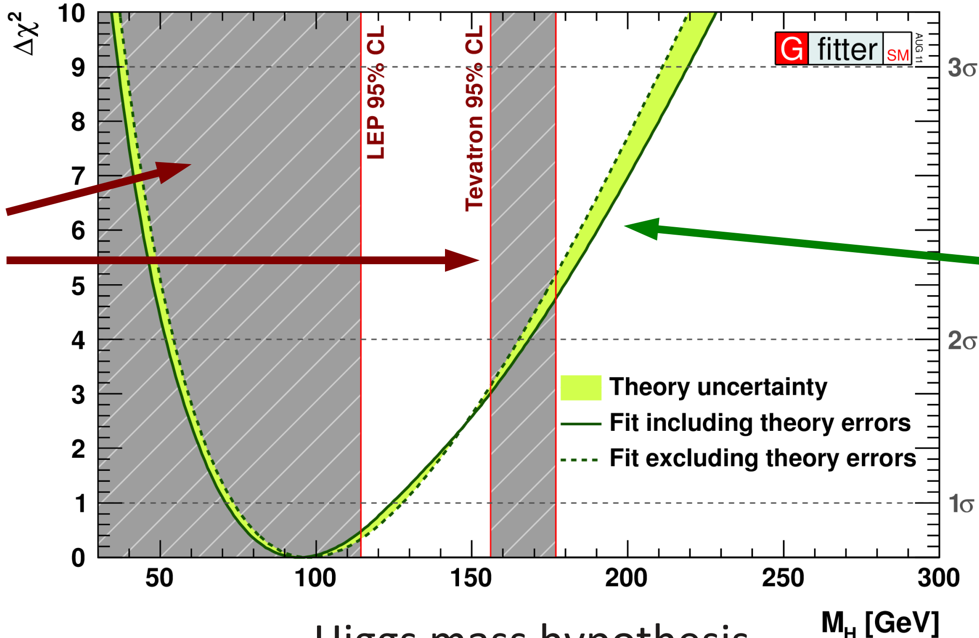
LHC Higgs WG



Behavior varies a lot with m_H – but all very well predicted in the SM!

Knowledge before the LHC

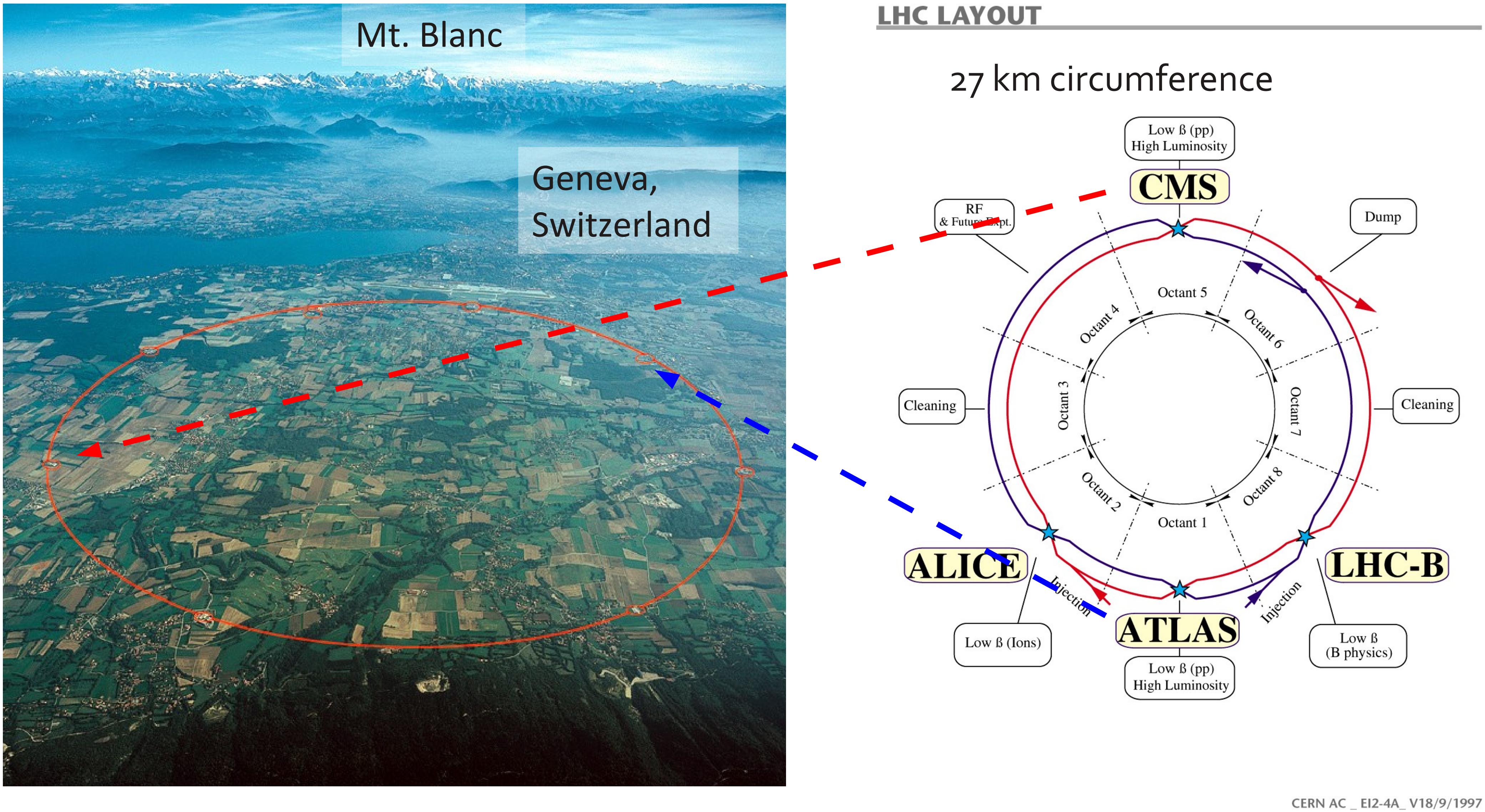
Direct exclusion from experimental searches



Higgs mass hypothesis

$\Delta\chi^2$ of global electroweak fit

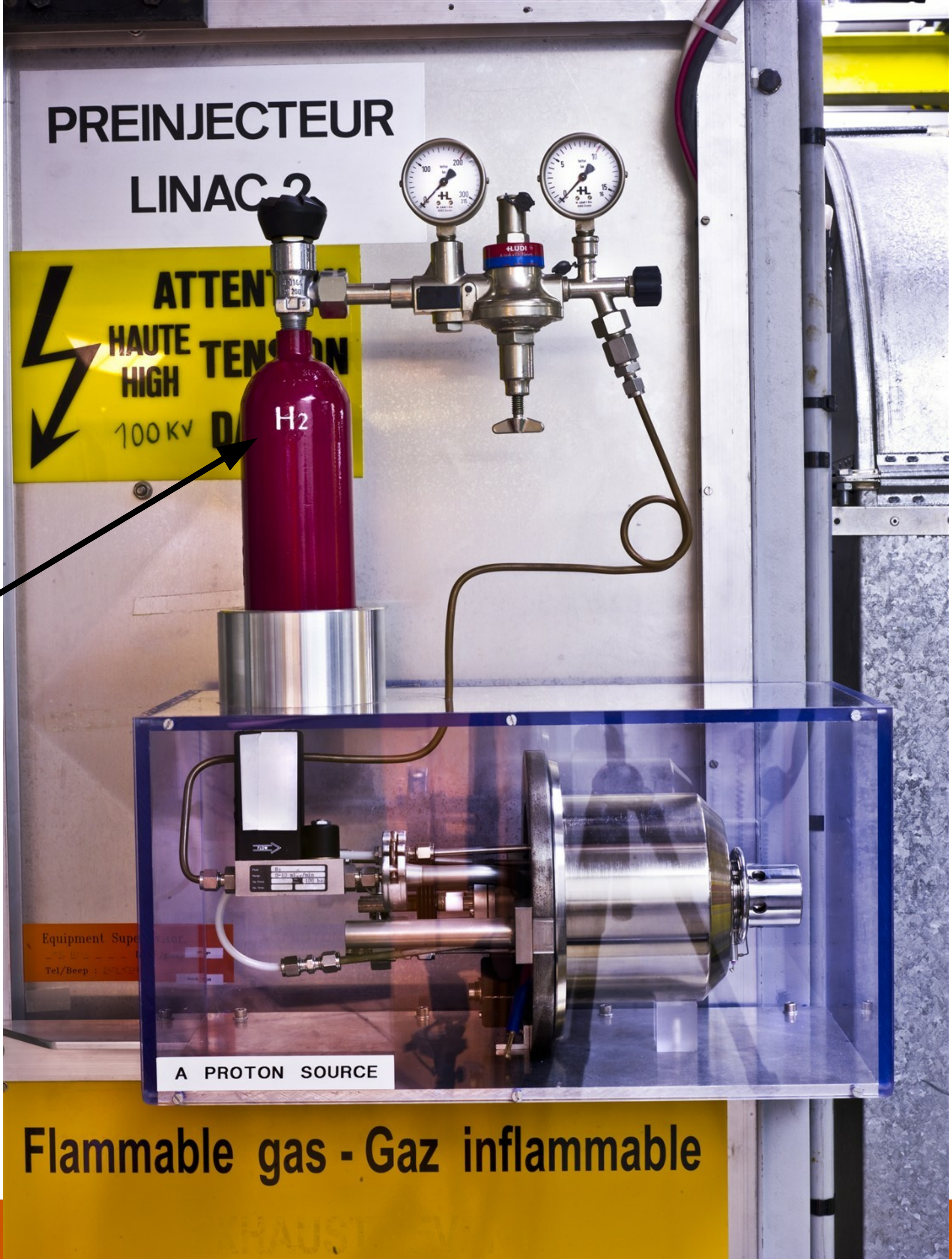
- LEP and Tevatron experiments excluded some mass ranges with direct searches
- Higher-order calculations in the SM relate the Higgs mass to other observables (e.g. m_W and m_t) for an indirect prediction of m_H



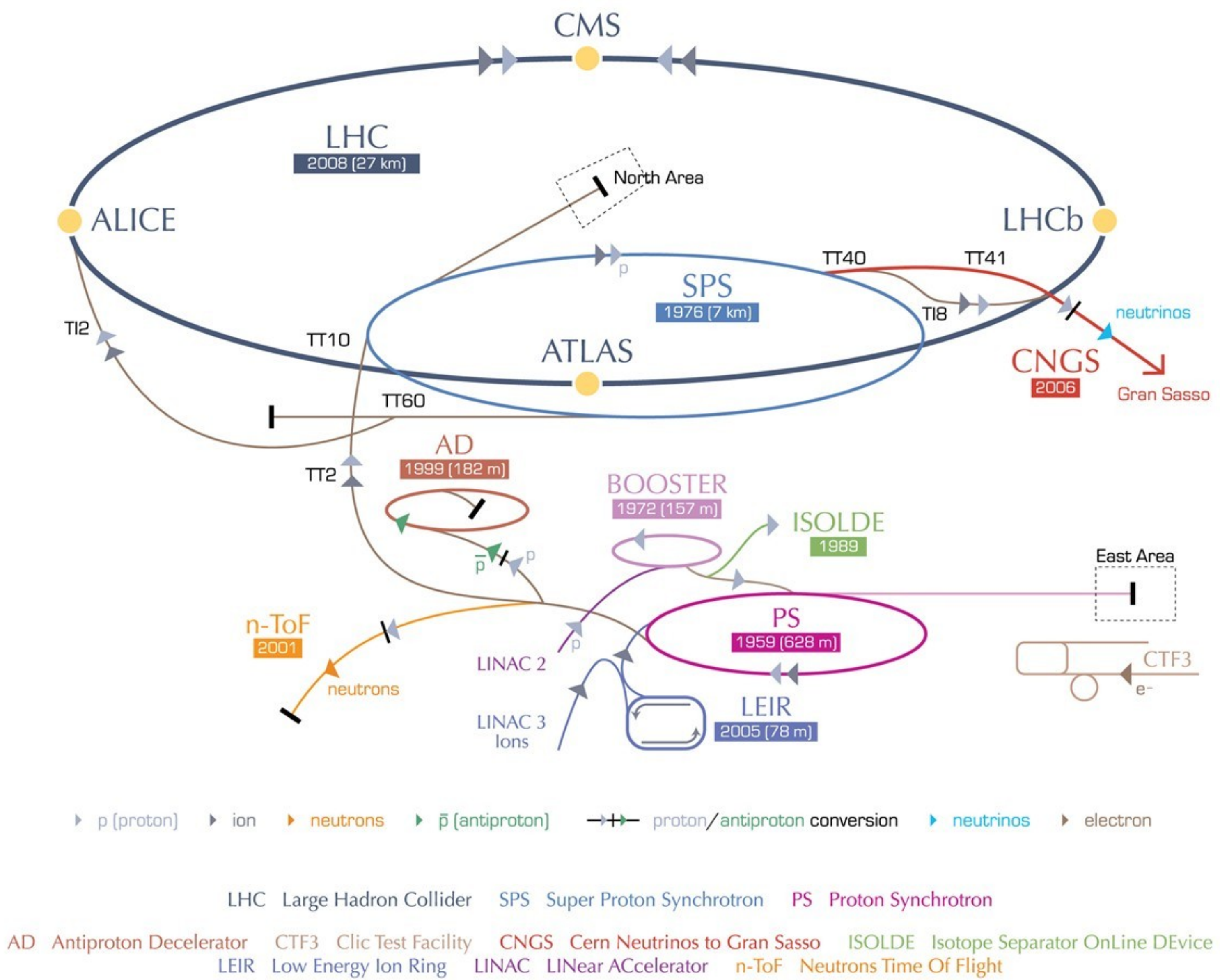
CERN: the European laboratory for particle physics

LHC: collides protons with kinetic energy > 4000 times their rest mass where it all begins

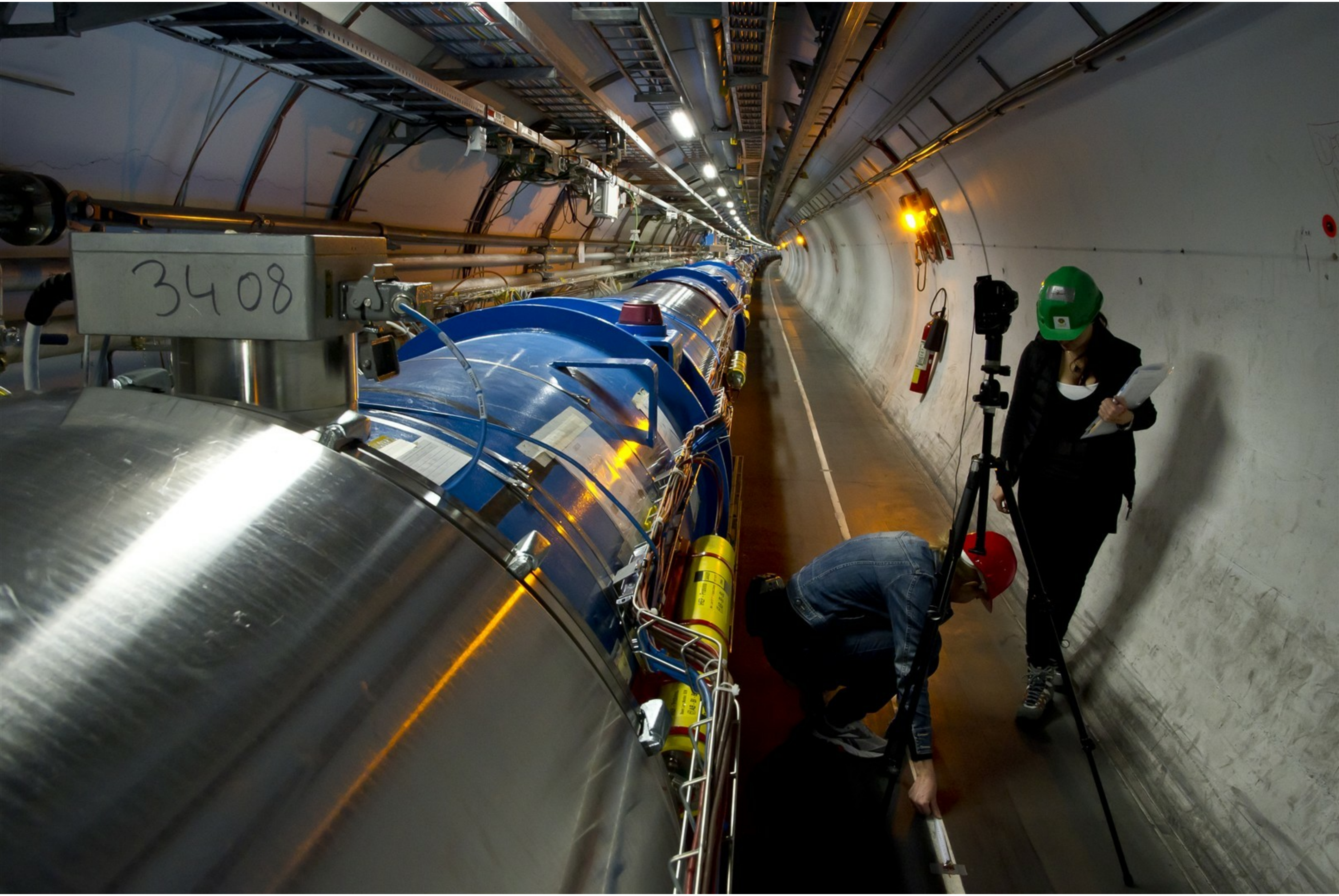
consumption per day
≈ 2 nanograms



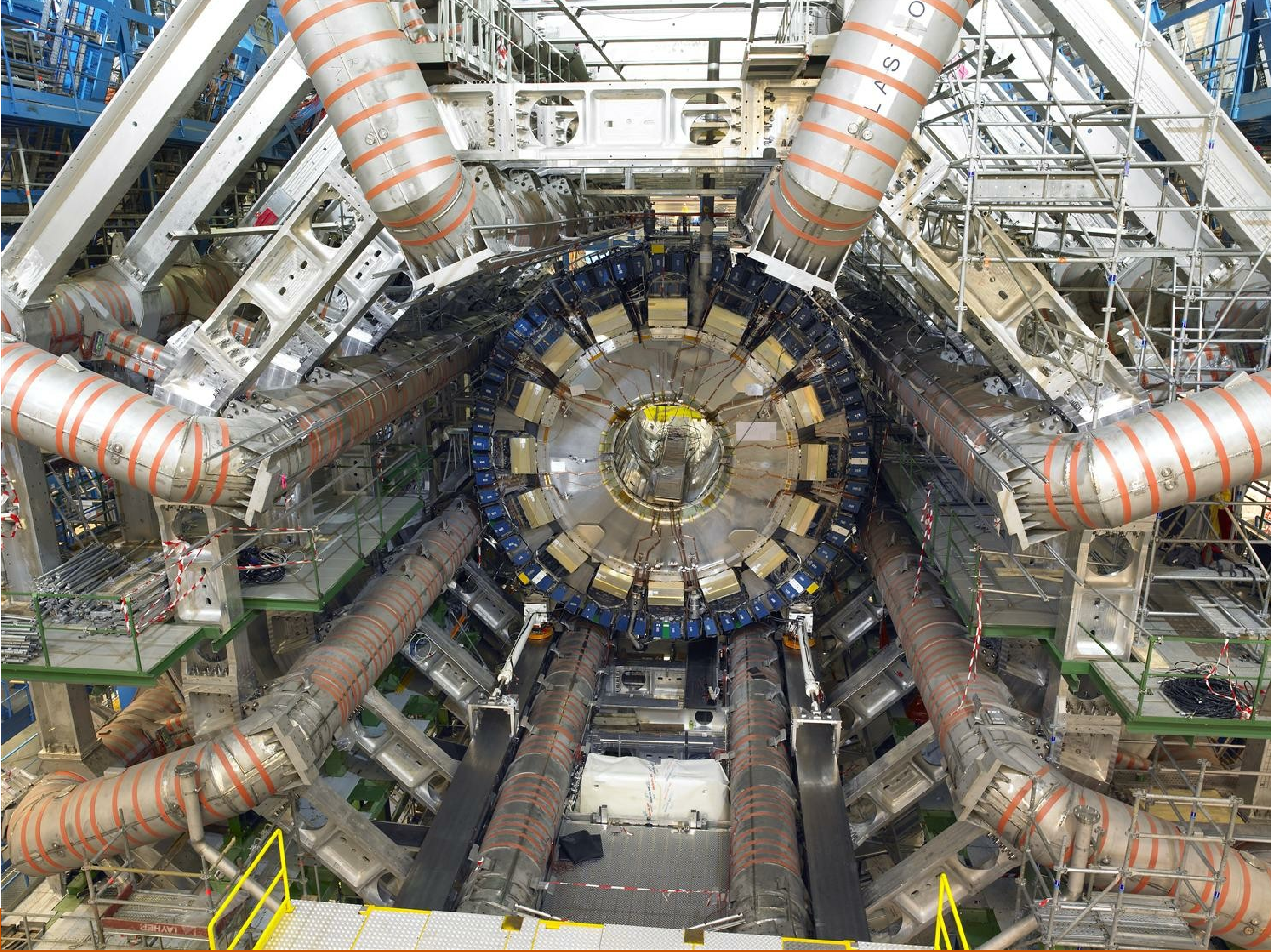
CERN's accelerator complex

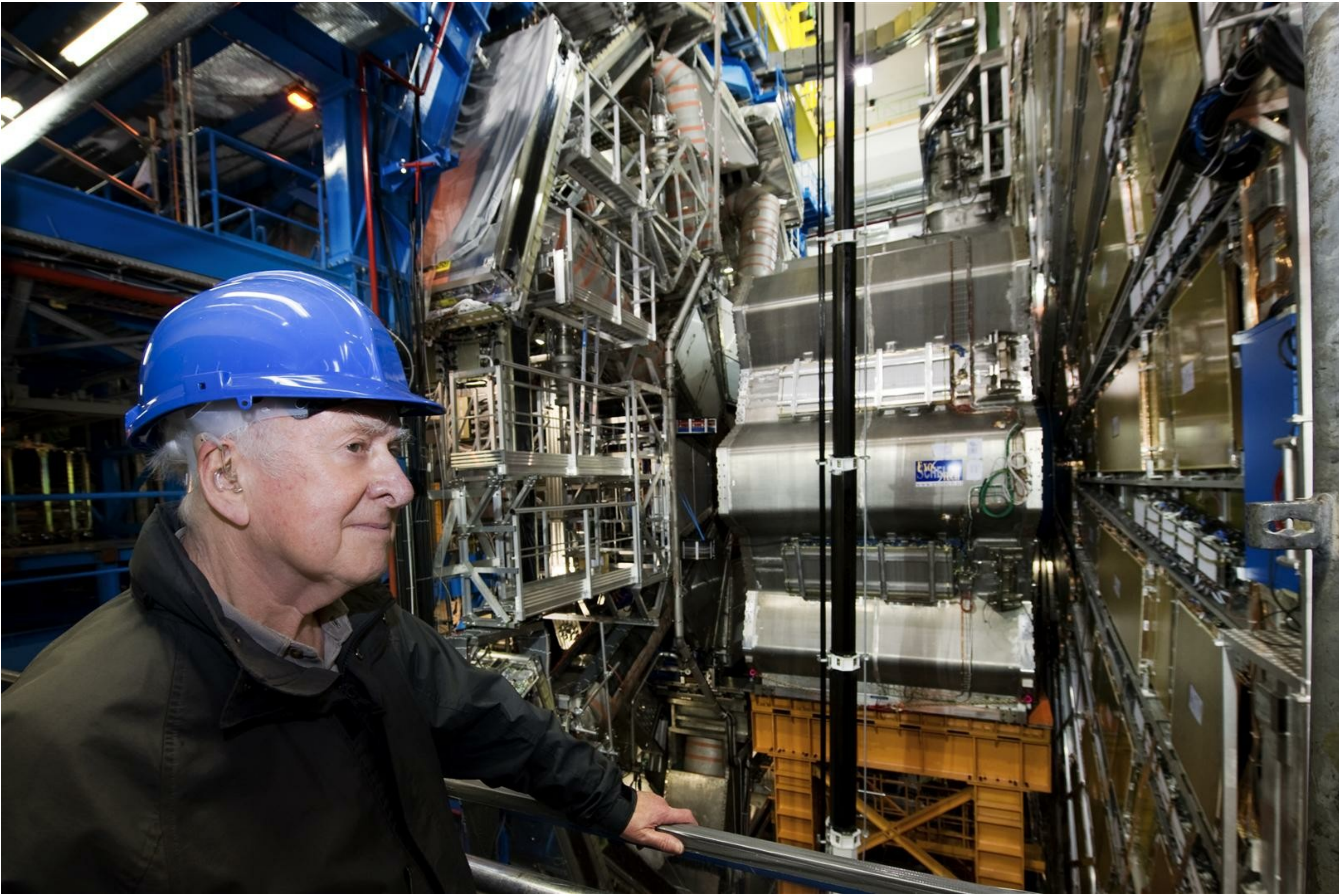


European Organization for Nuclear Research | Organisation européenne pour la recherche nucléaire

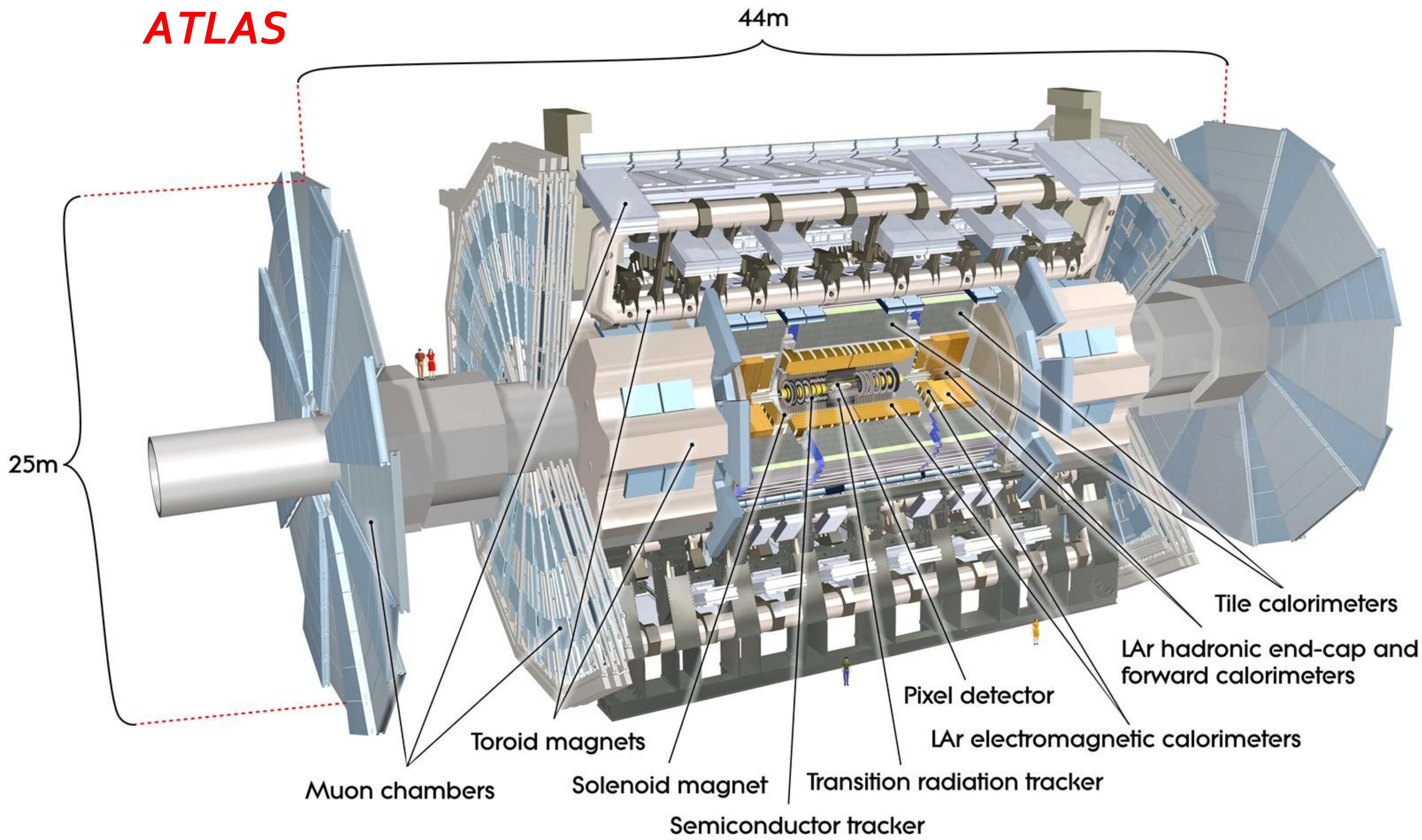


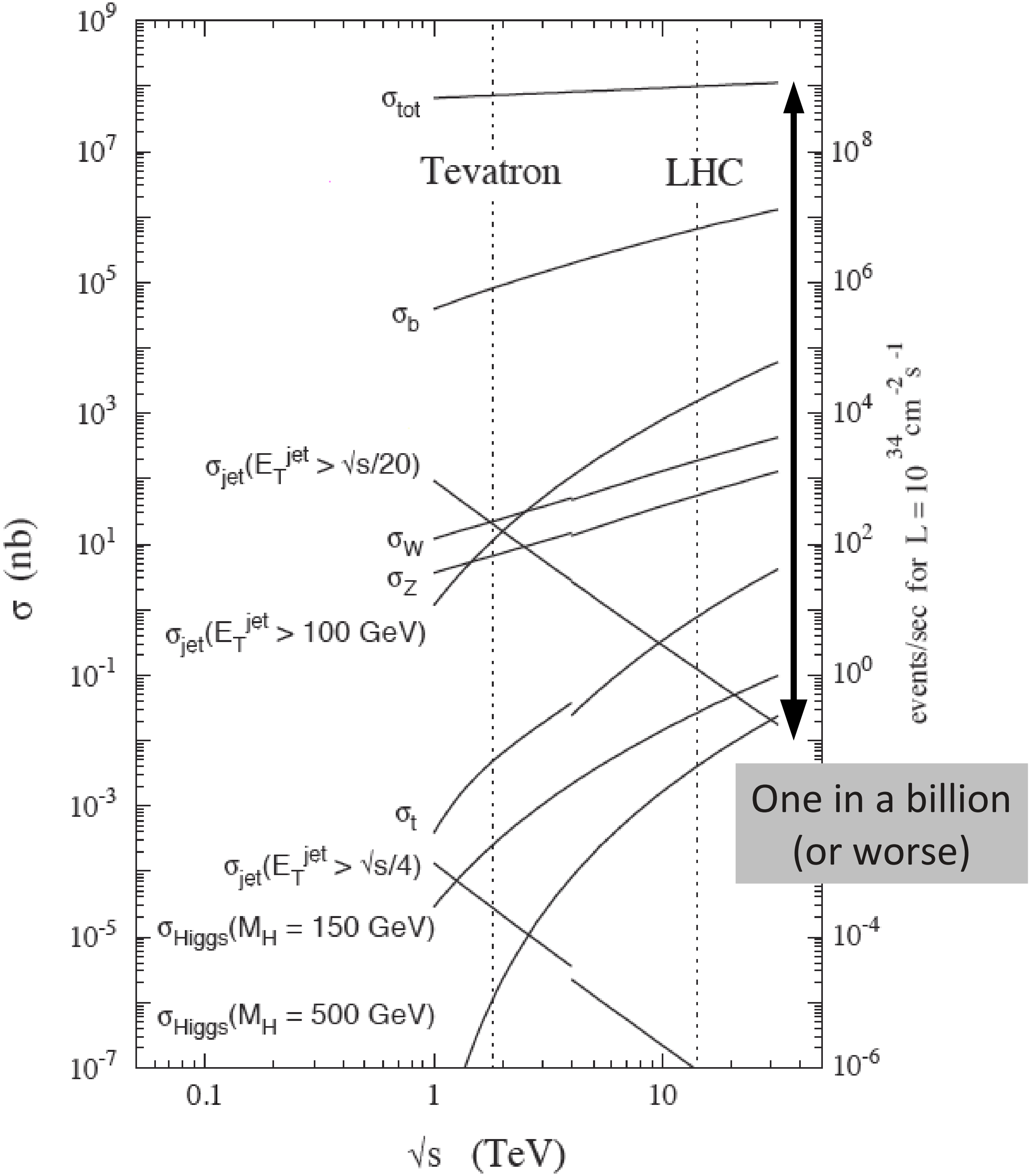
Inside the LHC tunnel





ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker



Quantum mechanics:
We only have *probabilities*

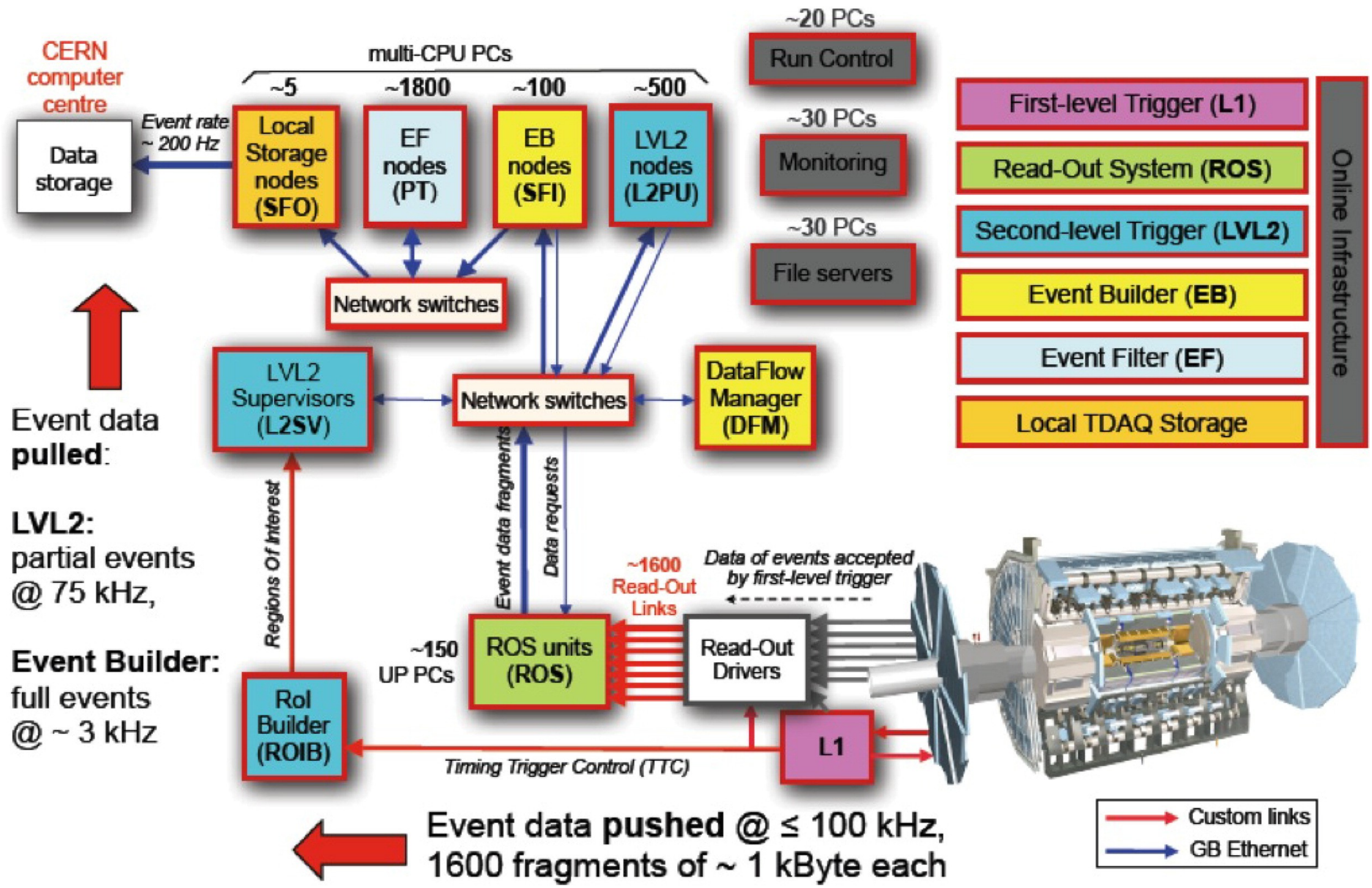
Every collision is a *random occurrence*

We're looking for things happening less often than once in a trillion collisions

ATLAS Readout

~ 1 MB/event

100 million channels



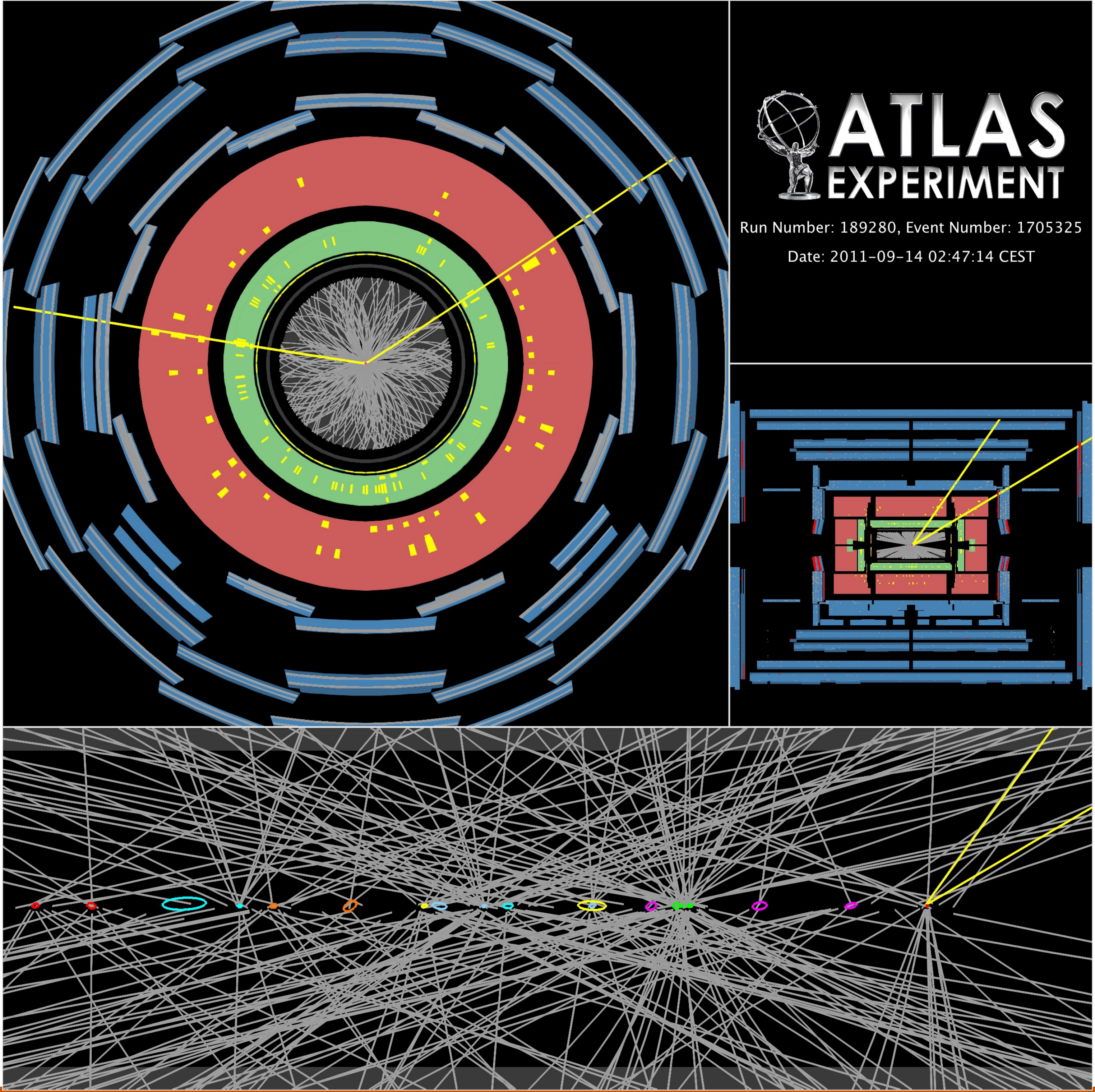
Can't read out all 40 MHz of collisions

Reduce to 300-500 Hz via hardware and software “trigger system”

"Pileup": many collisions at once

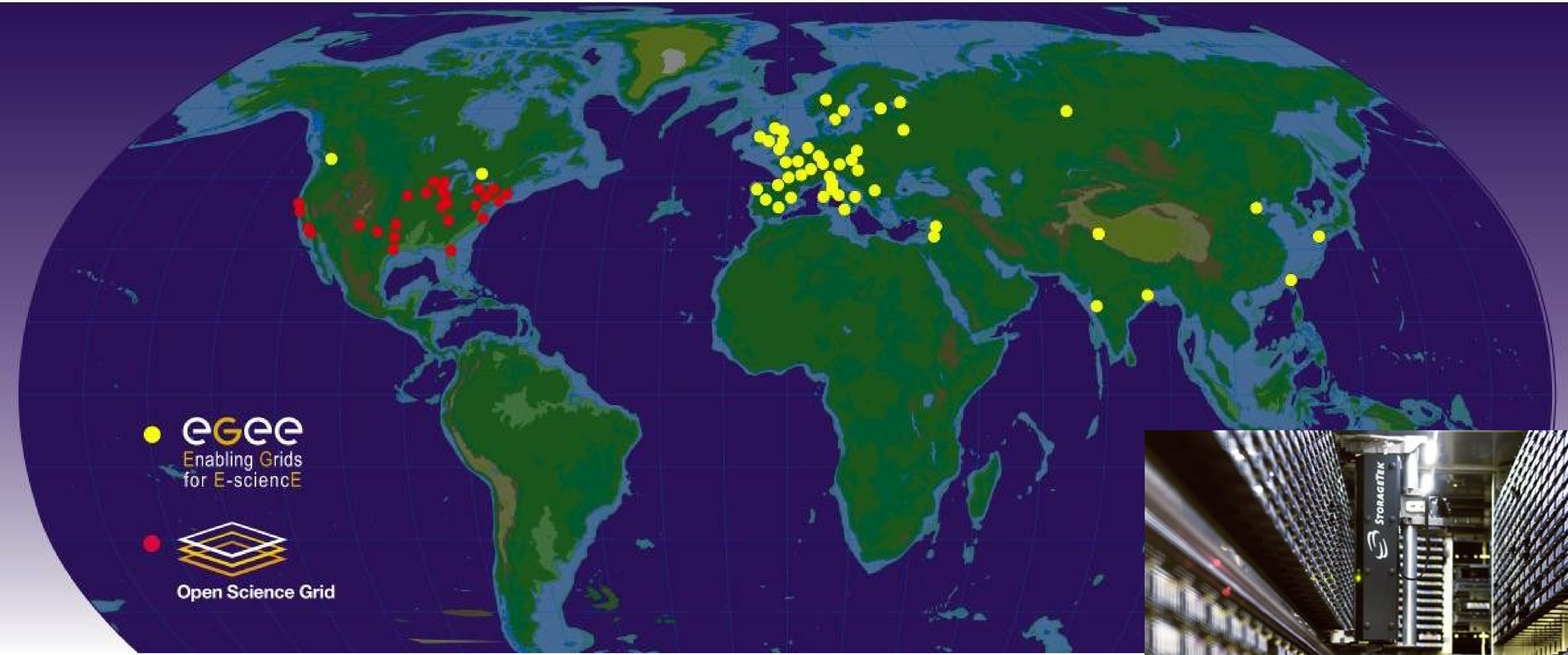
Needed to get enough collisions

Very tricky to handle!



Over 3000 people work on ATLAS… here are a few (at the Higgs party!)

First Collisions Day



LHC experiments record billions of collisions, tens of petabytes of data per year

Need to search through them with computers throughout the globe

How do we take advantage of new computing technologies in HEP? Area of interest here at UT

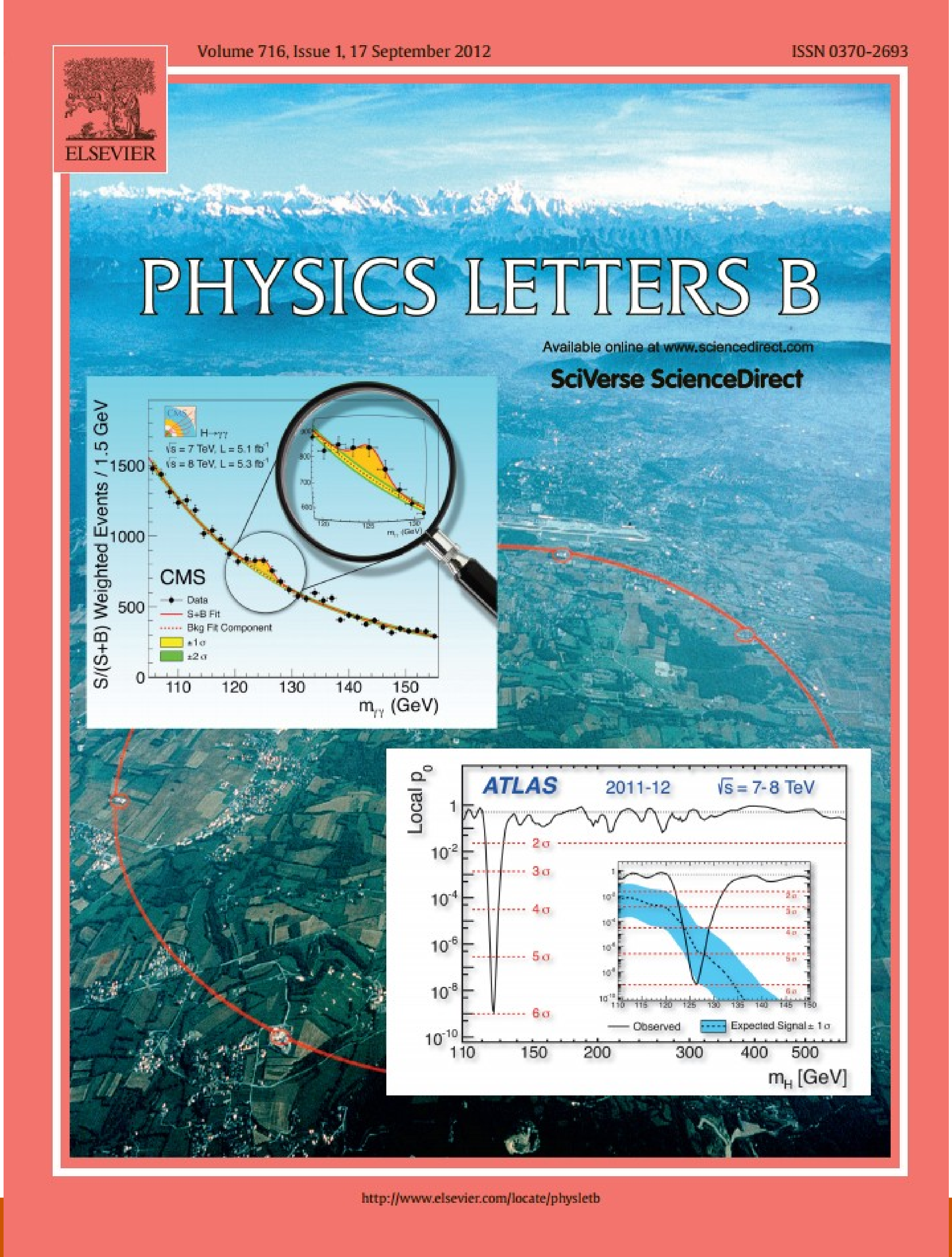
The Pace of Higgses

At the absolute best collision rate we have had so far, we get

- a $H \to WW \to \ell\nu\ell\nu$ event every 20 minutes
- a $H \to \gamma\gamma$ event every 45 minutes
- a $H \to ZZ \to 4\ell$ event every 13 hours

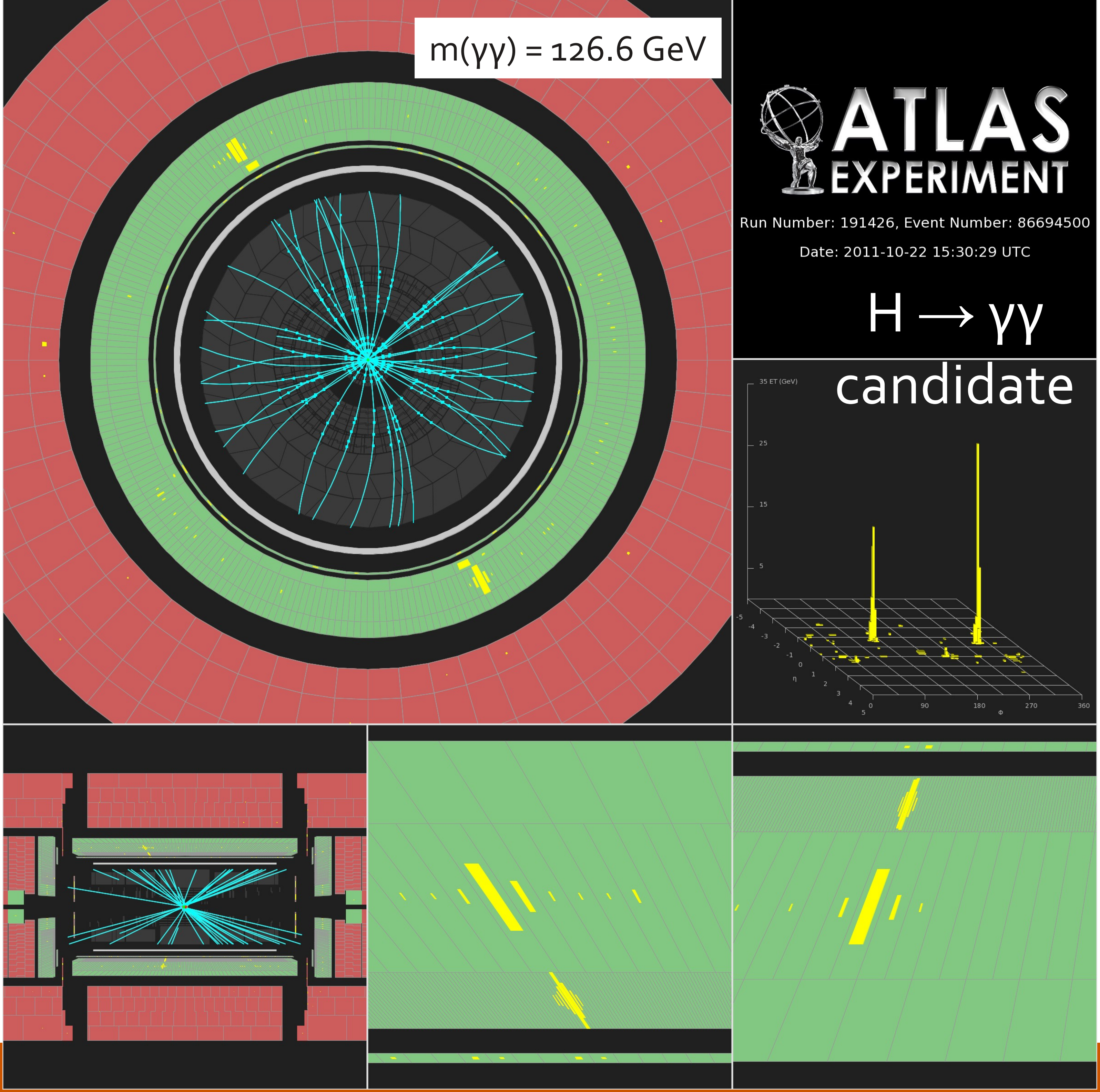
We're not 100% efficient at catching them, and we need a lot to separate them from other processes

In short, it takes a long time.

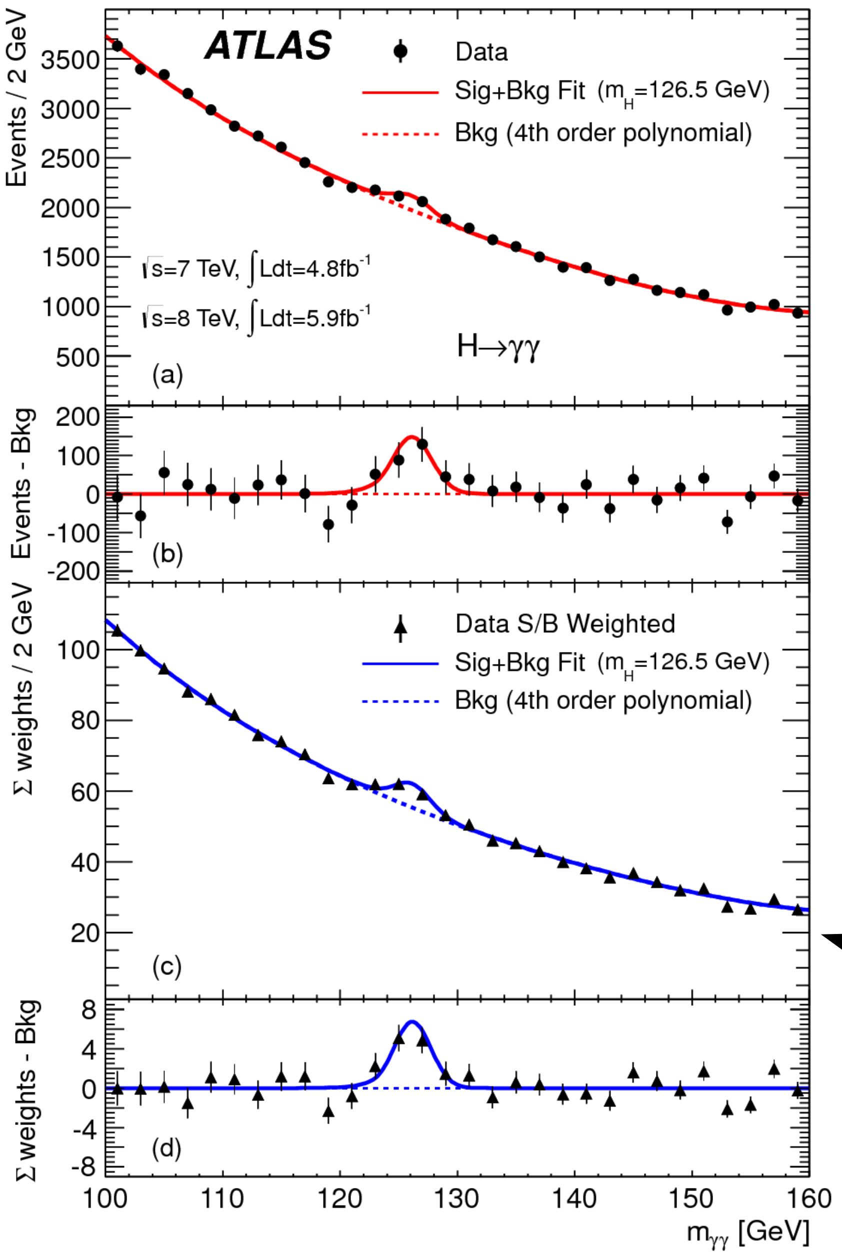


Simultaneous ATLAS and CMS papers

PL B716, 1


m(γγ) = 126.6 GeV
ATLAS EXPERIMENT
Run Number: 191426, Event Number: 86694500
Date: 2011-10-22 15:30:29 UTC
H ⟶ γγ
candidate

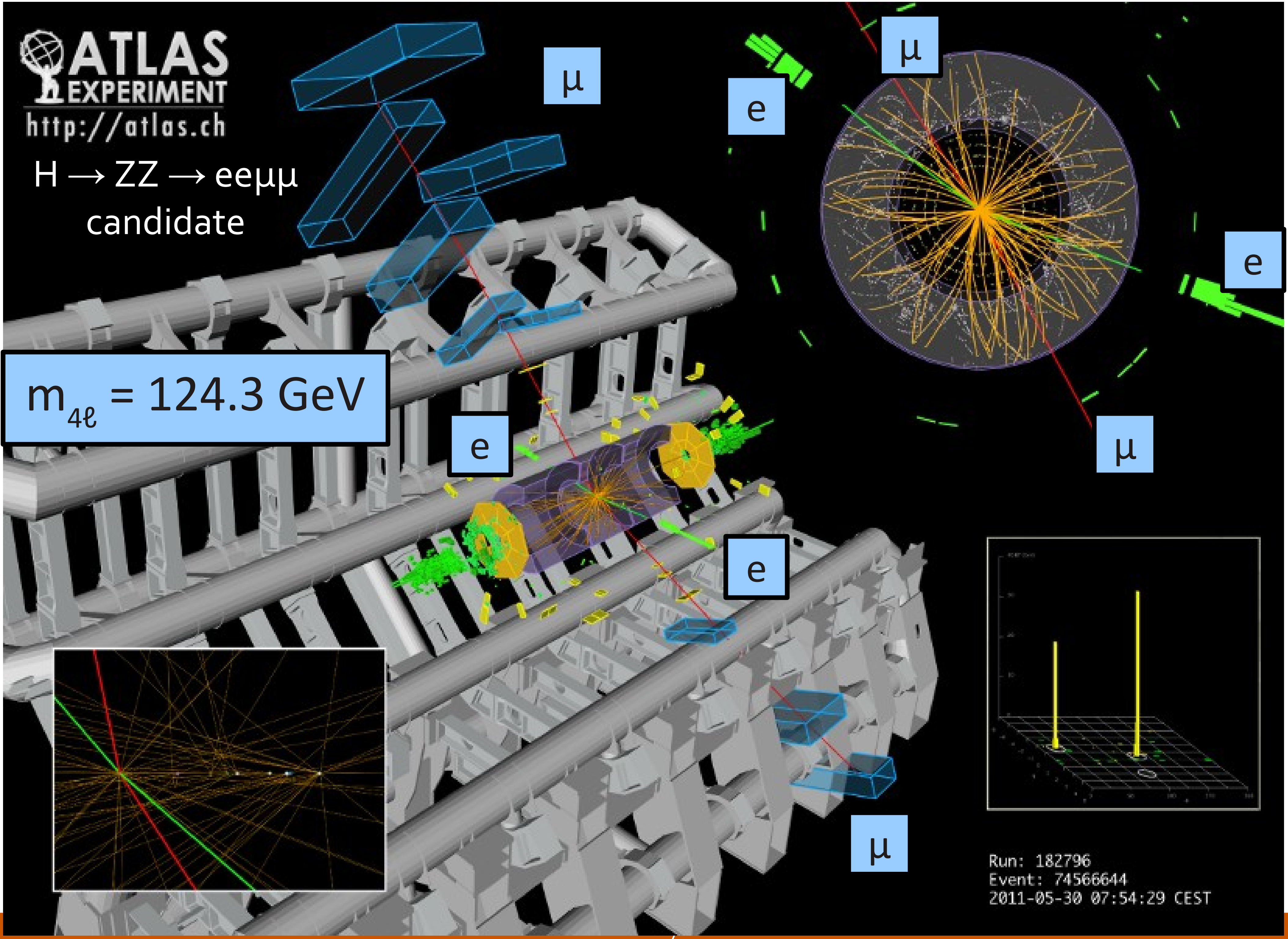
The Discovery Plots: H ⟶ 2γ



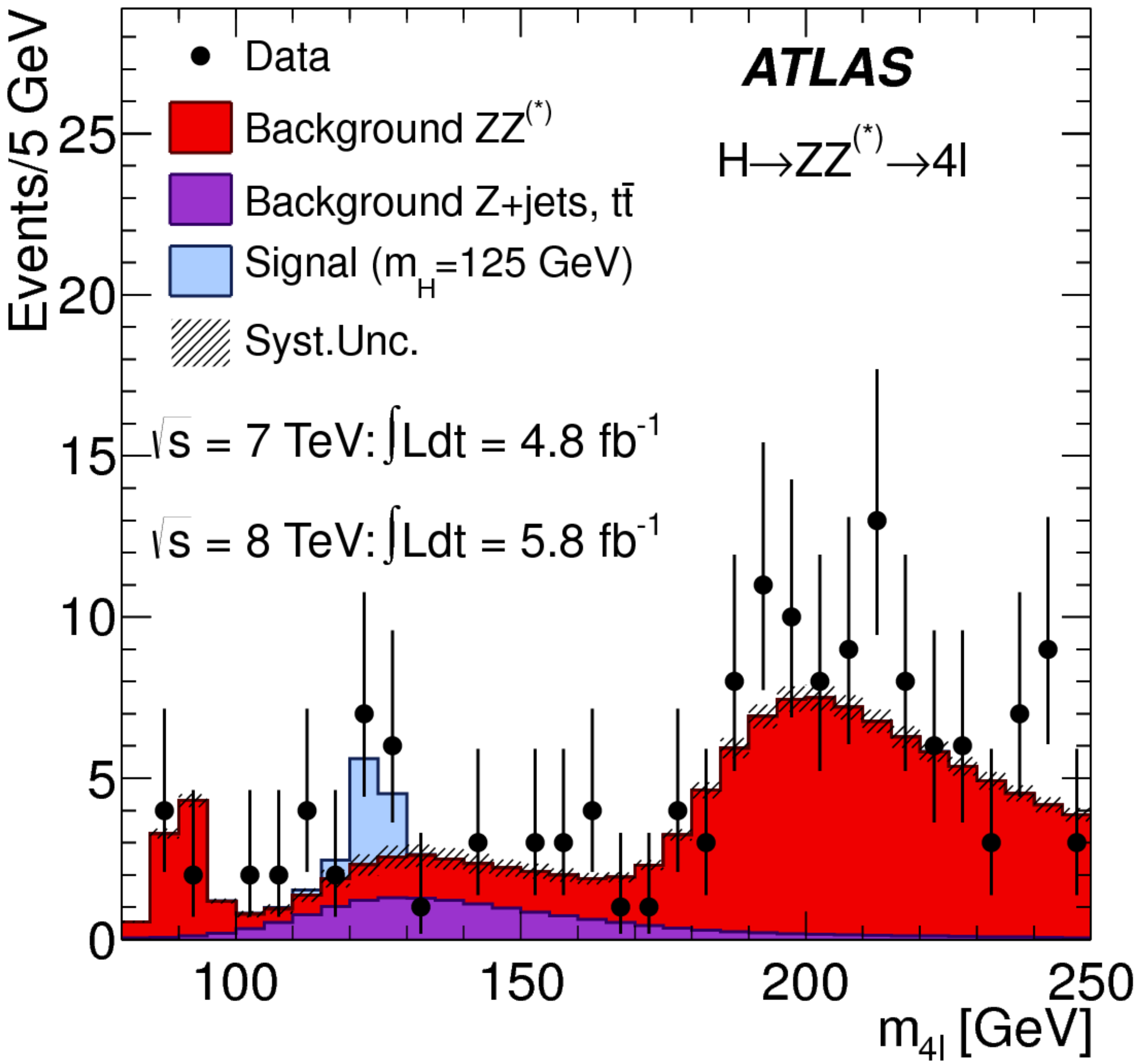
x axis is invariant mass of γγ system: bump is a signature of a particle

Impossible to tell if any given event is from Higgs decay: use smoothness of non-Higgs contributions

"Weighted" plot: events weighted by expected purity of event category. Enhances events that are (a priori) more likely to be signal.


ATLAS EXPERIMENT
http://atlas.ch
H → ZZ → eeμμ candidate
m4ℓ = 124.3 GeV
μ
e
μ
e
e
μ
e
μ
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

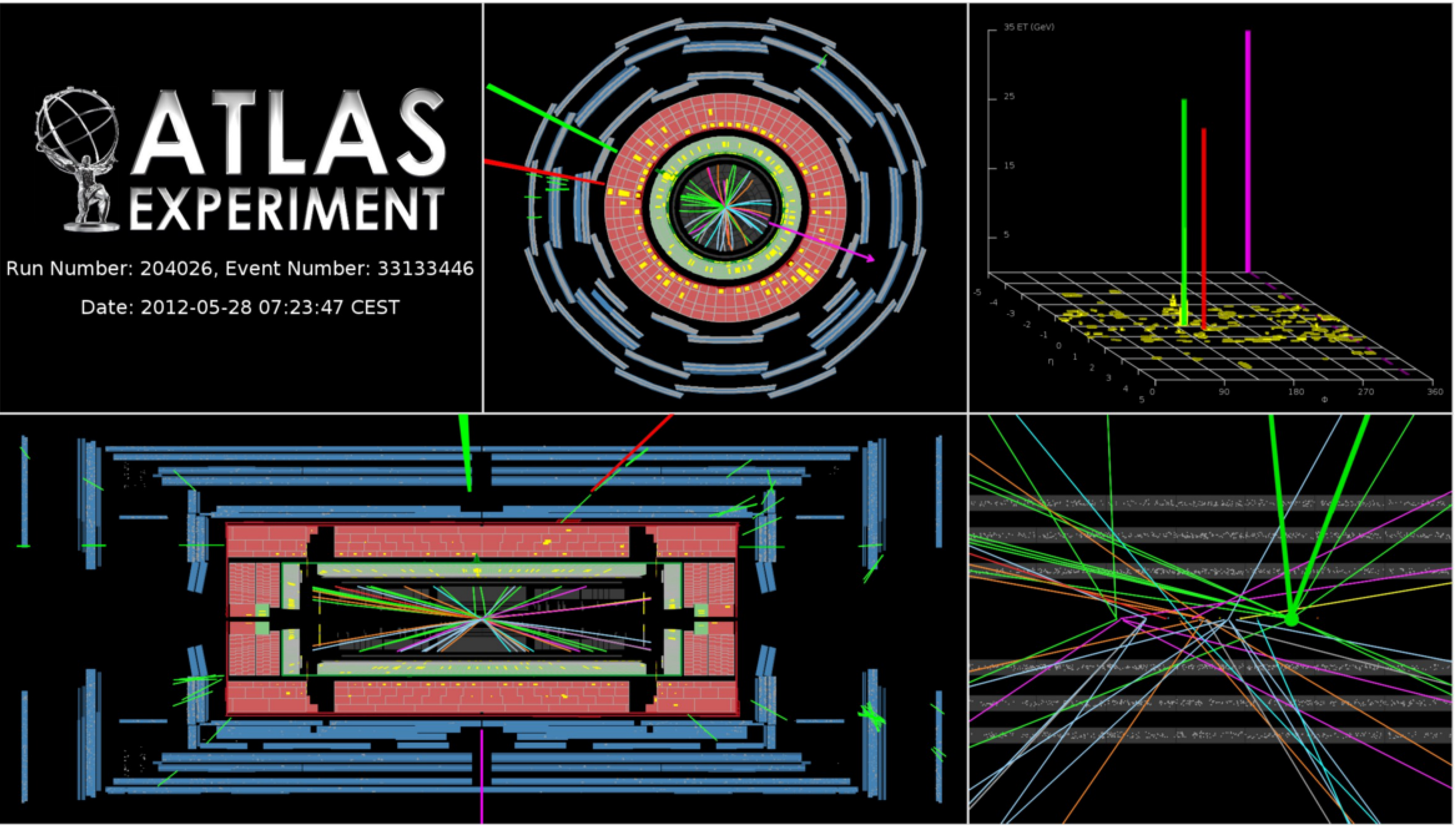
The Discovery Plots: $H \to ZZ \to 4\ell$



ℓ = electron or muon

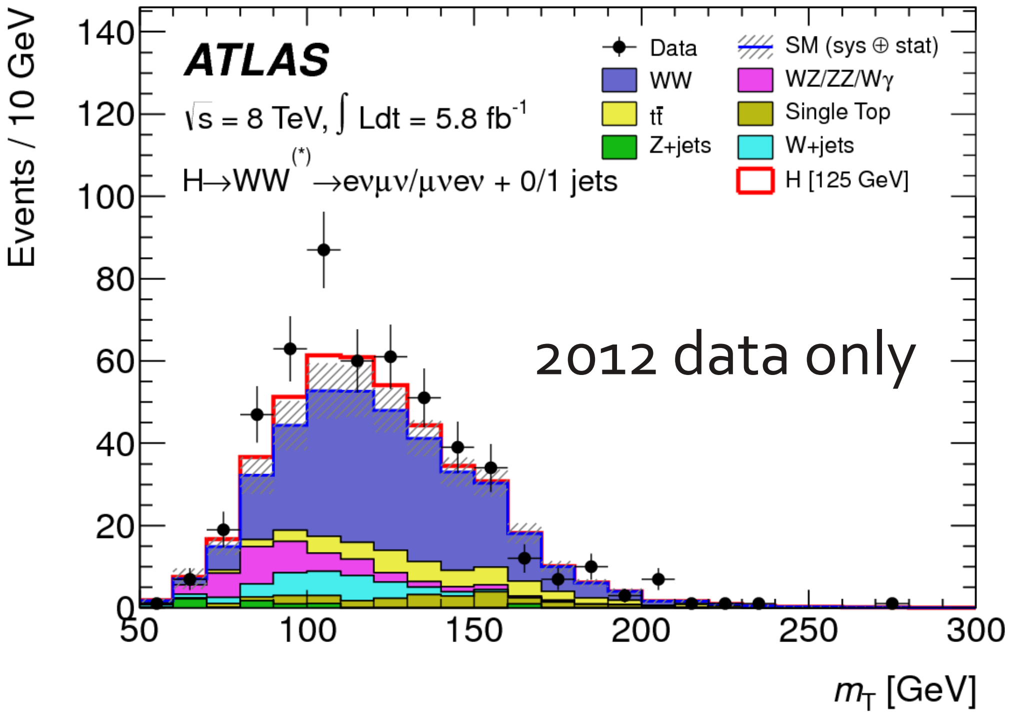
Very clean channel: signal/background ≈ 1/1

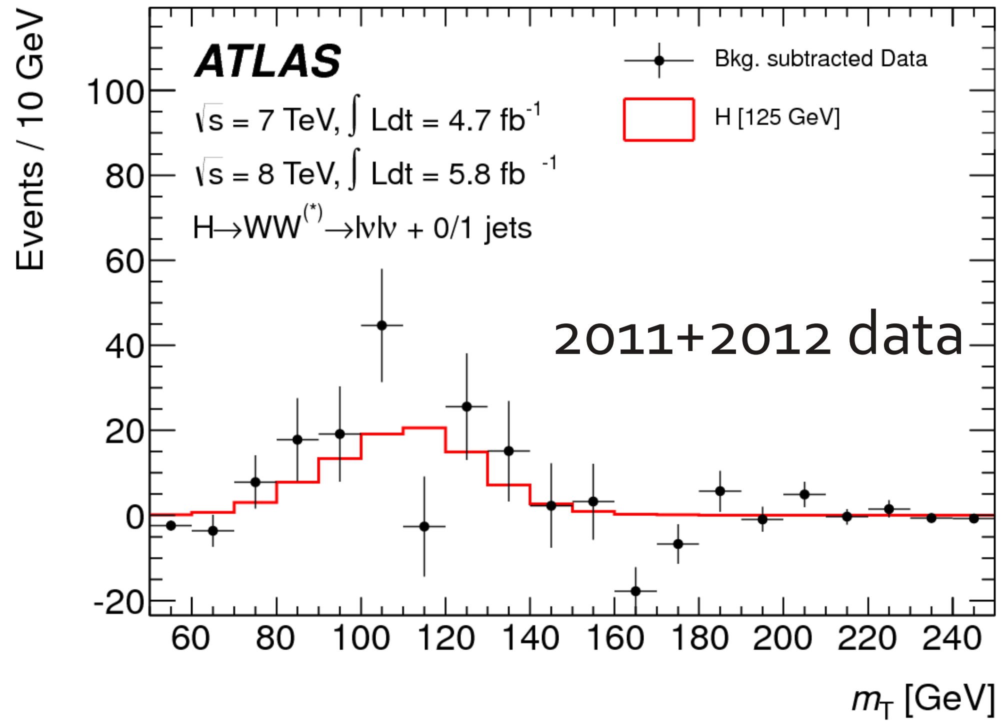
Low rate though



$H \to WW \to e\nu\mu\nu$ candidate

The Discovery Plots: H → WW → ℓνℓν

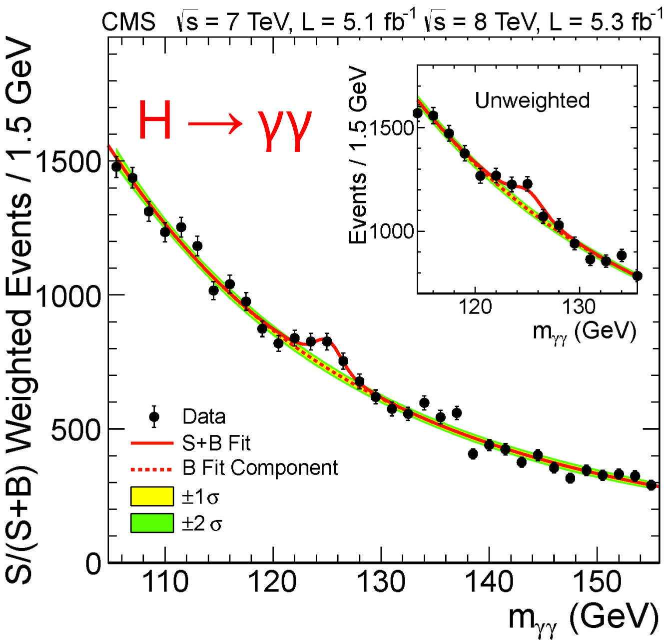




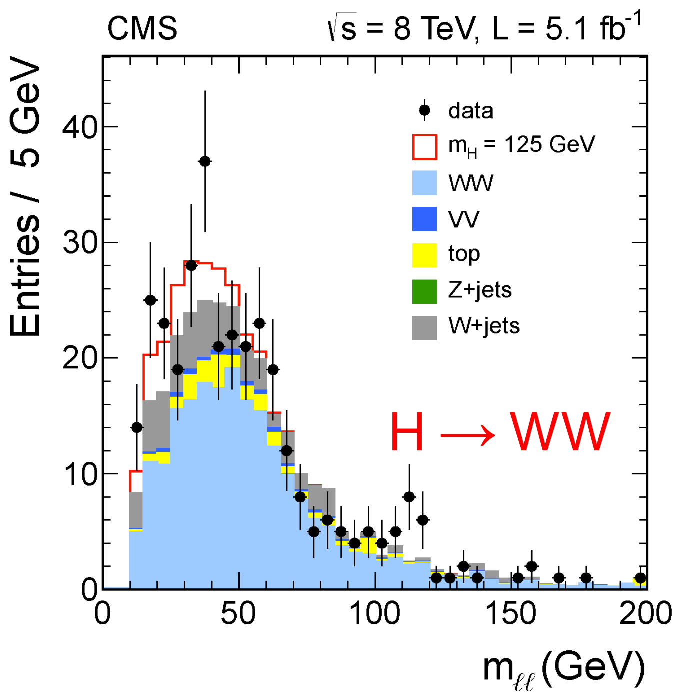
Neutrinos make this channel harder: signal is a broad lump, background has shape

Use a measurable proxy variable ("transverse mass") instead of Higgs candidate mass

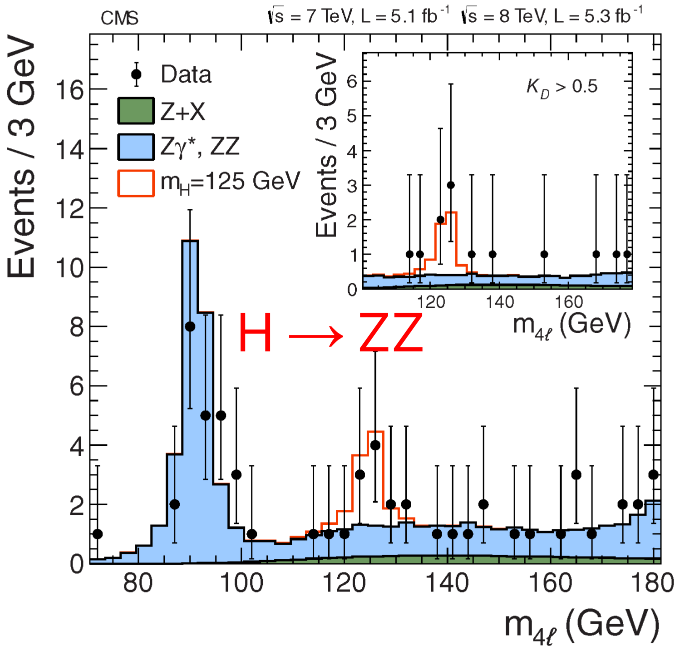
CMS plots



CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
H → γγ
Unweighted
Events / 1.5 GeV
S/(S+B) Weighted Events / 1.5 GeV
Data
S+B Fit
B Fit Component
±1σ
±2 σ
mγγ (GeV)

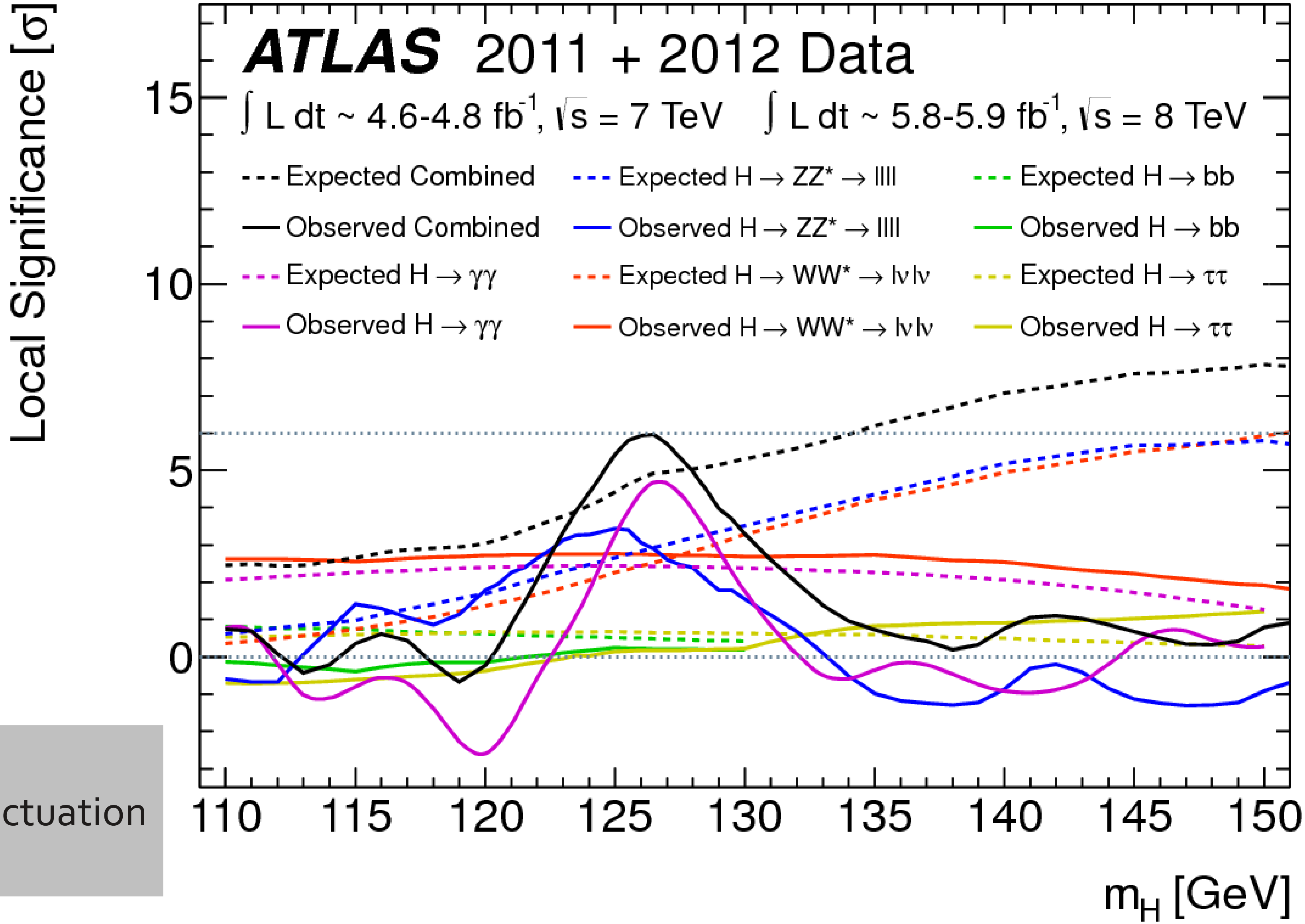


CMS √s = 8 TeV, L = 5.1 fb-1
H → WW
data
mH = 125 GeV
WW
VV
top
Z+jets
W+jets
Entries / 5 GeV
mℓℓ (GeV)



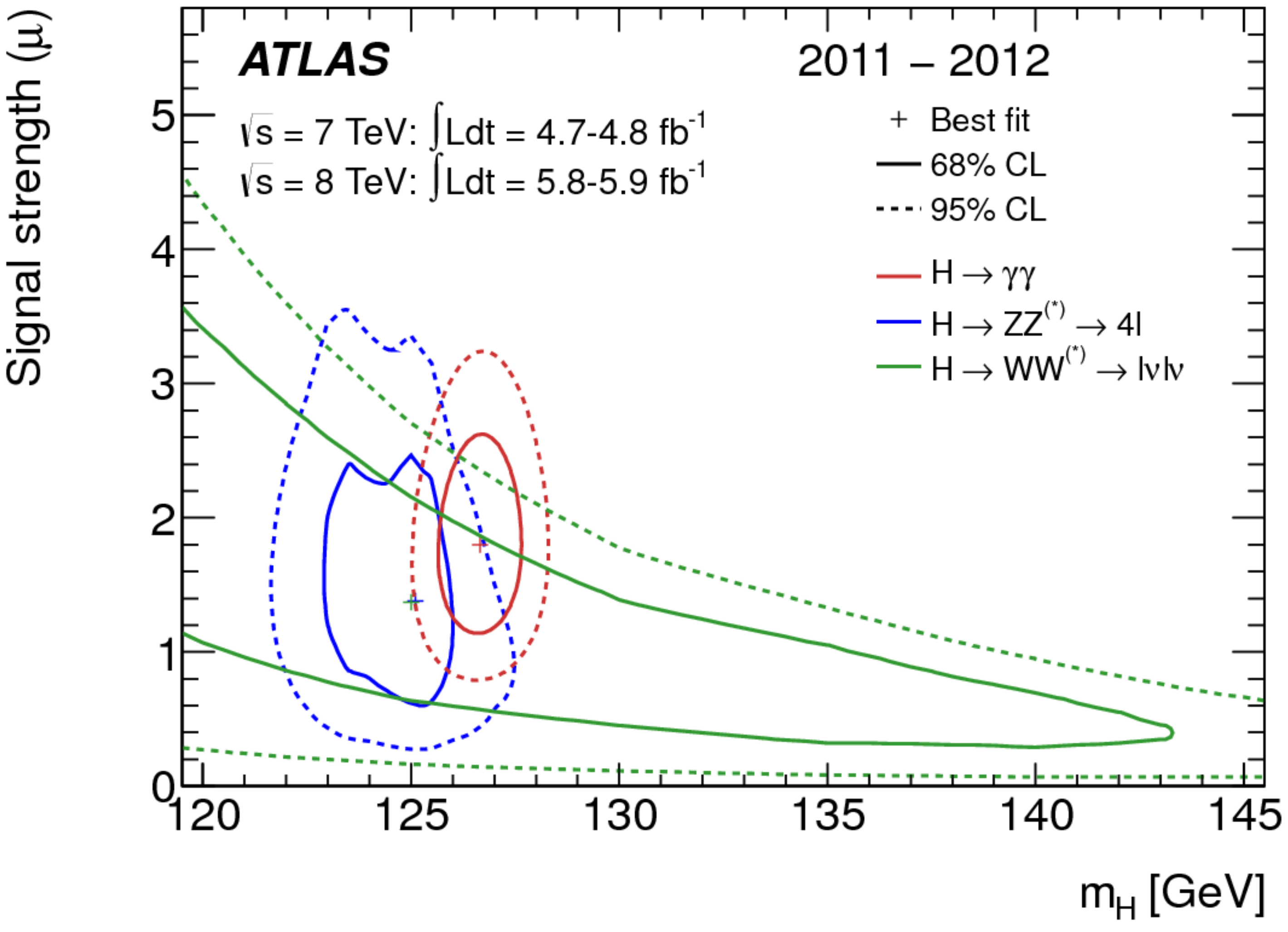
CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
H → ZZ
Data
Z+X
Zγ*, ZZ
mH=125 GeV
KD > 0.5
Events / 3 GeV
m4ℓ (GeV)

Discovery?



"5.9σ":
probability of fluctuation is 1.7×10^{-9}

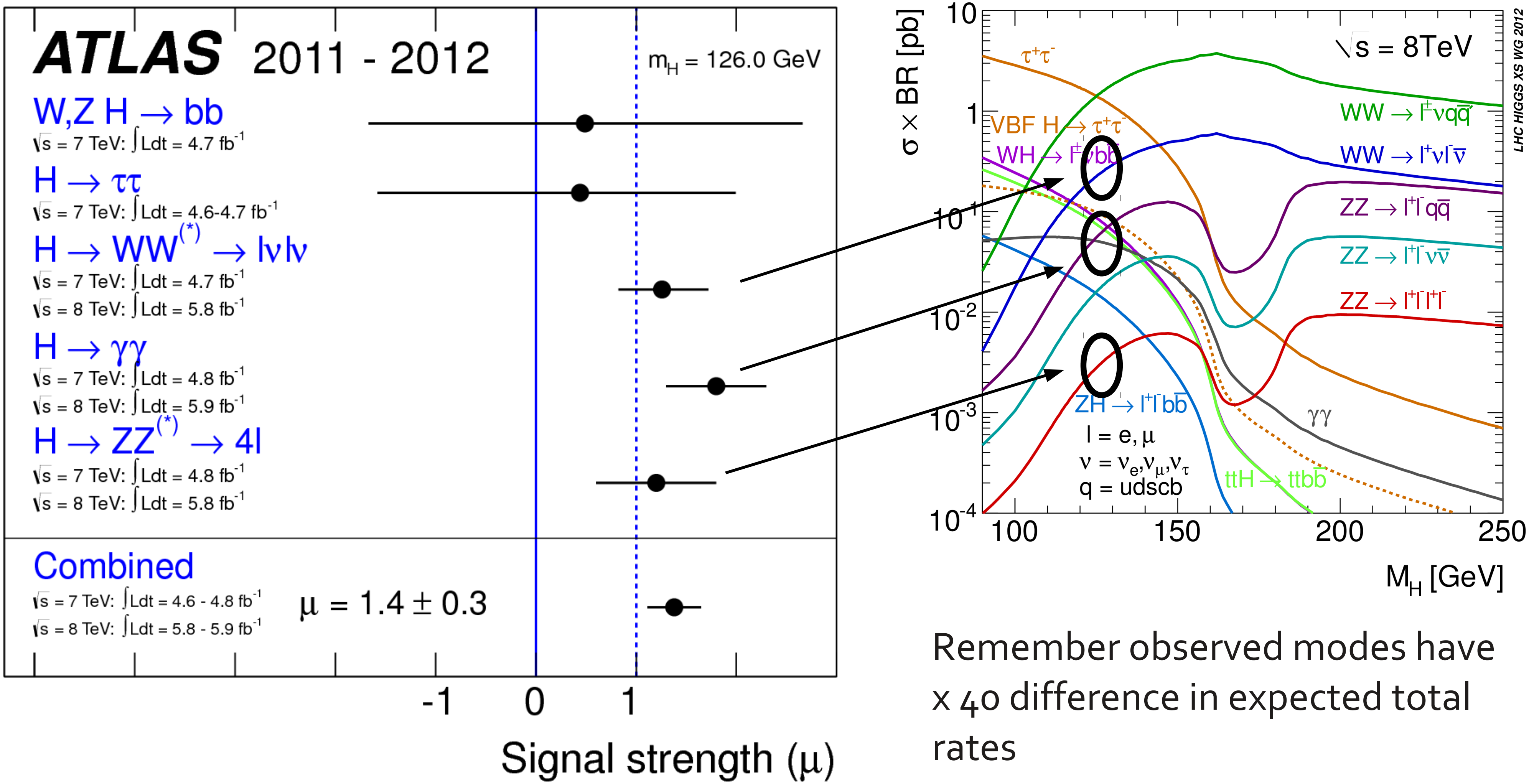
What have we seen?



Decays to γγ:
has integral spin (≠ 1)

Mass compatible between all channels

Compatible with Standard Model?

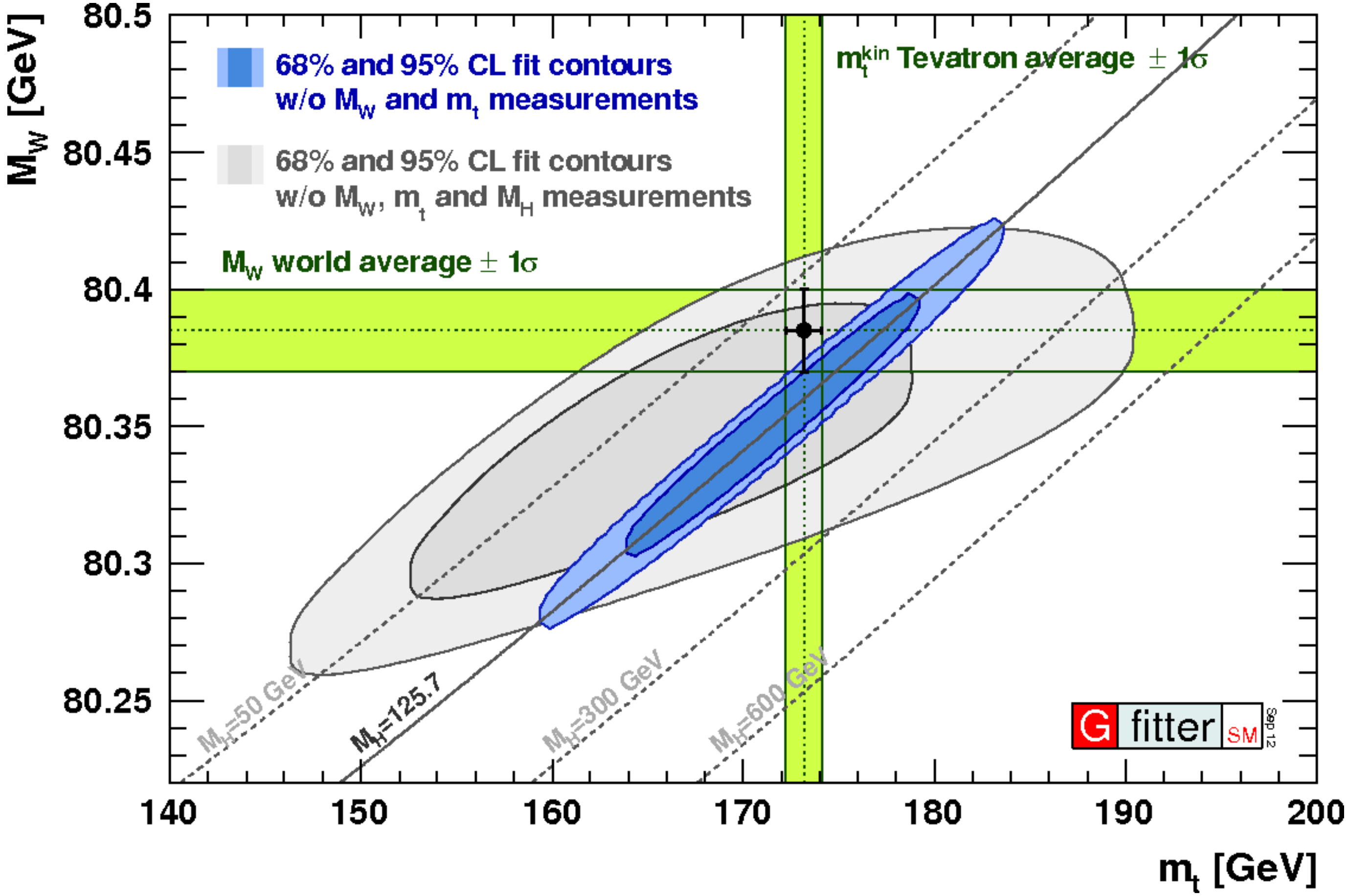


Signal strength = observed/SM rate

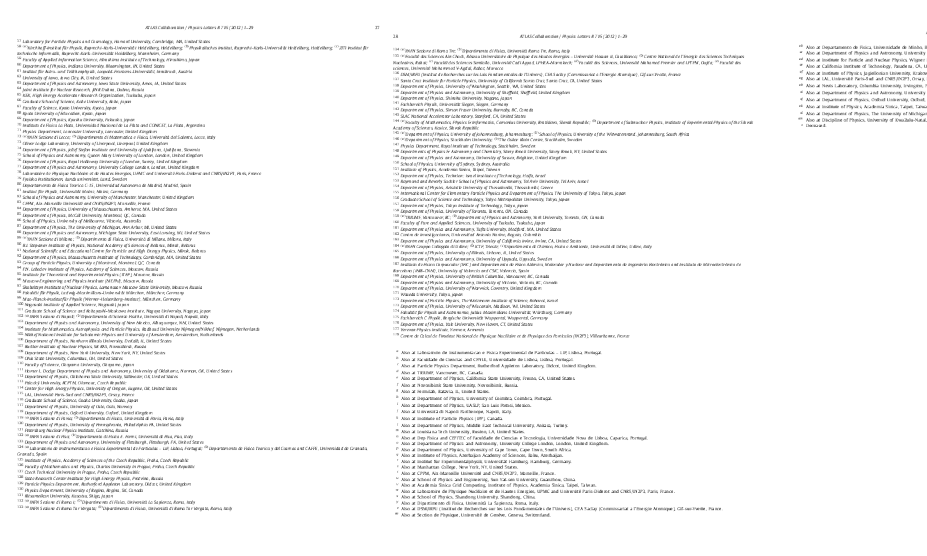
Remember observed modes have x 40 difference in expected total rates

Agreement with SM is not trivial!

Compatible with Standard Model?



Observed Higgs mass consistent with indirect predictions



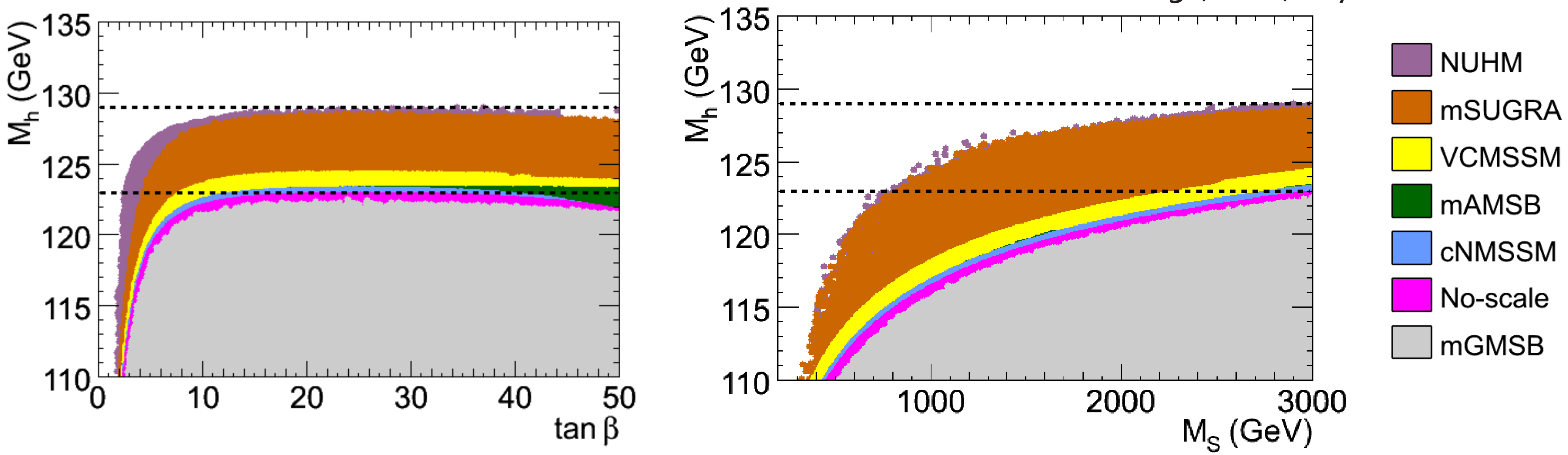
The Higgs discovery paper author list

Constraints on New Physics

Discovery of a SM Higgs-like particle at 125 GeV already limits "new physics" models

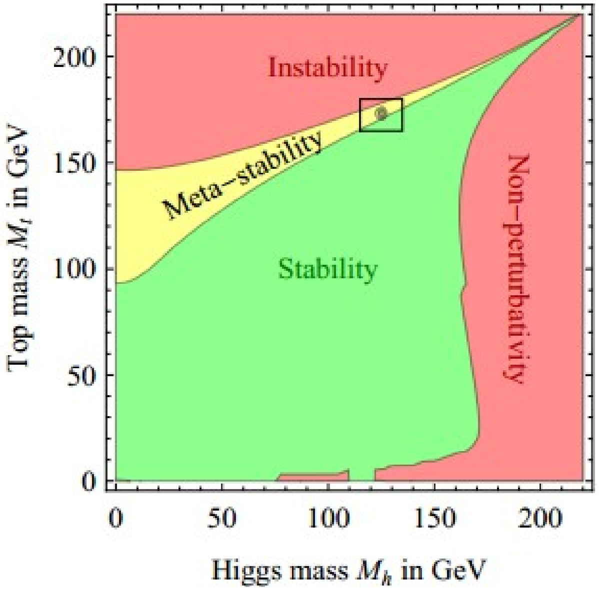
- Technicolor: gone
- Supersymmetry: strongly constrained (prefers lower m_H if "natural")

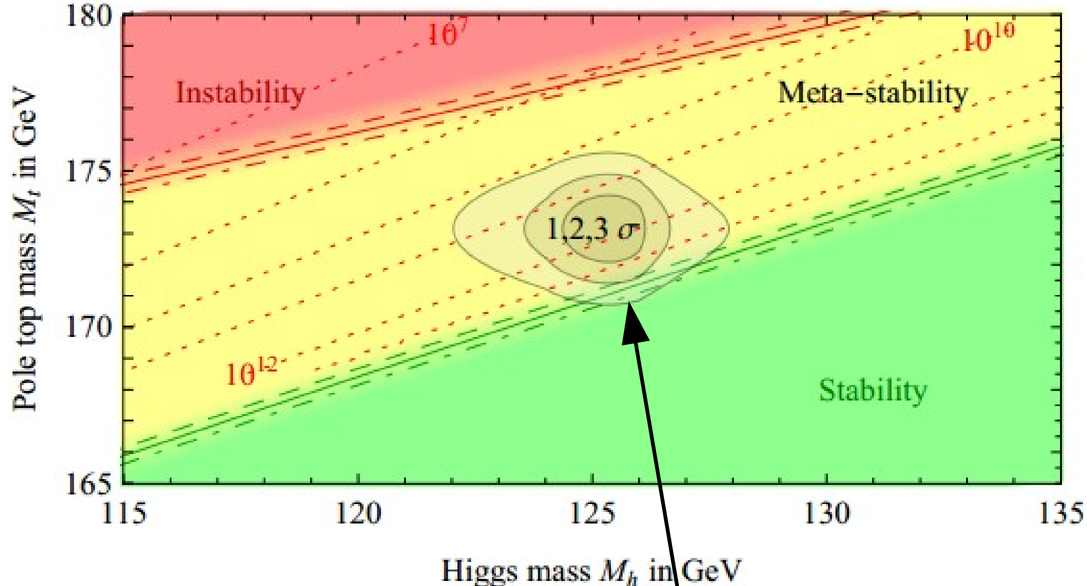
Arbey, Battaglia, Djouadi, Mahmoudi
JHEP 1209 (2012) 107

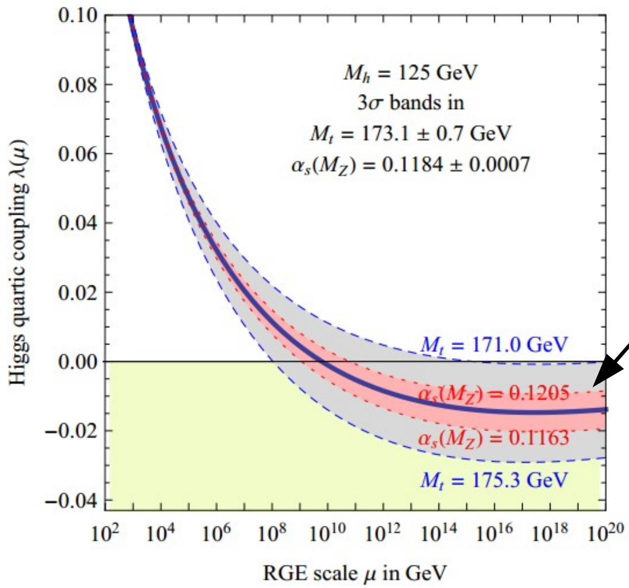


$$= \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Is our vacuum stable?







Renormalization drives quartic term negative at high energy

Perhaps we are not in the true minimum of the Higgs potential?

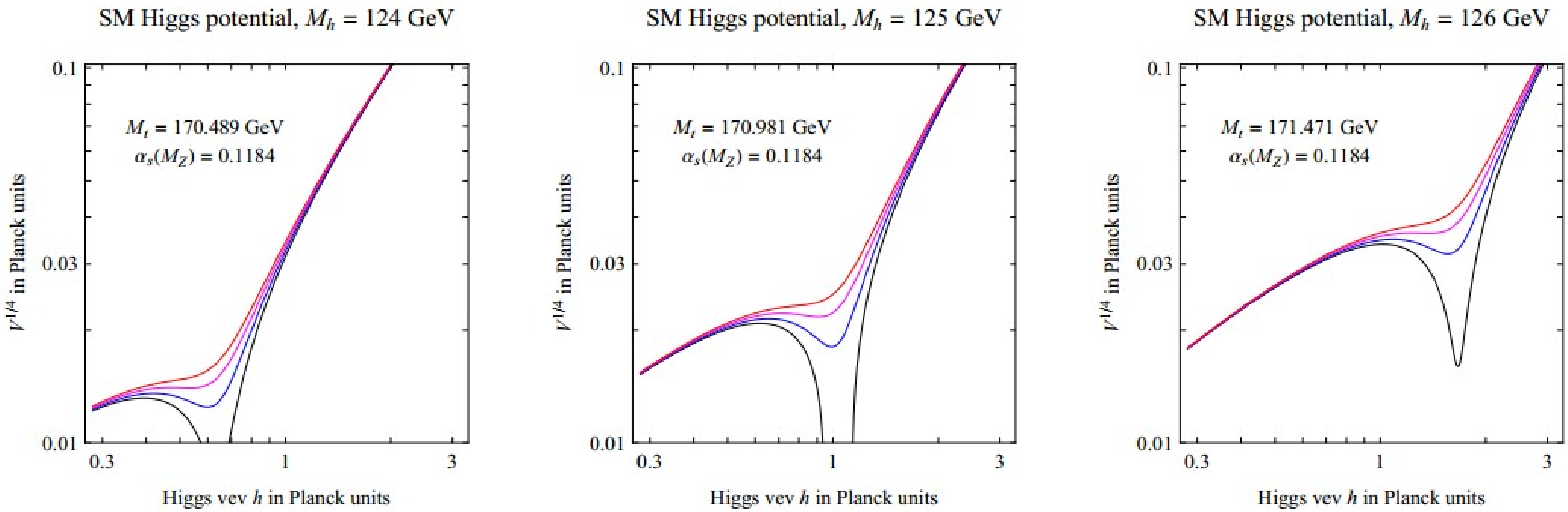
λ = 0 boundary condition?

New physics at 10^{10} GeV?

Degrassi et al, arxiv:1205.6497
Higgs effective potential @ NNLO

Higgs and Inflation?

- For (very) special choices of the Higgs and top quark masses, a second minimum develops in the potential at high vev
- Could this drive primordial inflation ("false vacuum")?



Degrassi et al, arxiv:1205.6497

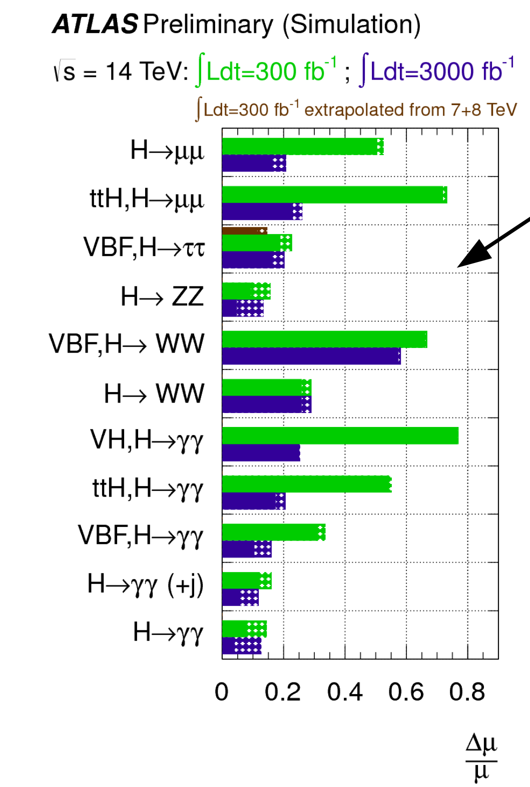
Towards the Future

What else do we need to study about the Higgs?

- Detect it in as many decay channels as possible
  - e.g. we do not know yet if it couples to leptons
- Show that the couplings are those of the Standard Model (or not)
  - Huge uncertainties right now
  - Lots of theoretical excitement over "high" $H \to \gamma\gamma$ rate...
- Show it couples to itself
  - Necessary for electroweak symmetry breaking mechanism to work
- Non-SM decays? (Dark matter?)
- Precision mass

(and then there's the hierarchy problem ...)

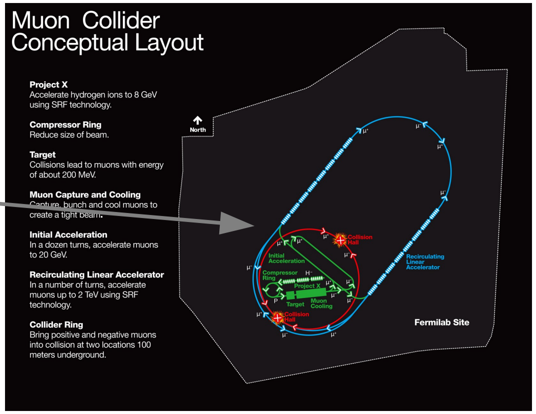
Potential Futures



Wring more collisions out of the LHC?

$300\ fb^{-1}$ ~ 2020

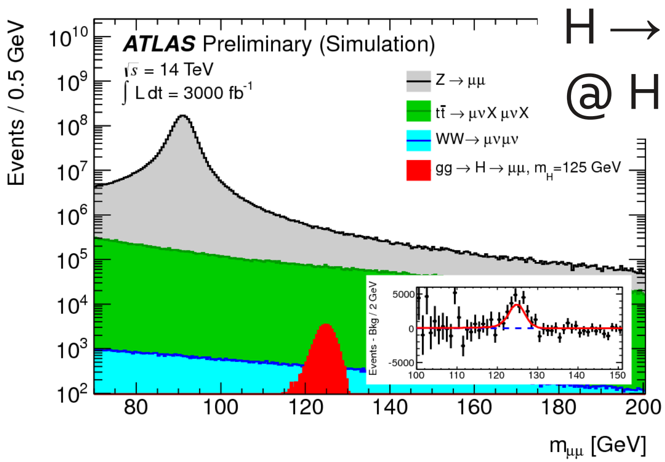
$3000\ fb^{-1}$ ~ 2030 ("HL-LHC")



New lepton "Higgs Factory"?

e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$ collider?

Circular or linear?



$H \rightarrow \mu\mu$ @ HL-LHC

Very Large Hadron Collider?

Something totally new, like plasma acceleration?

Summary

- ATLAS and CMS have found a new particle, mass ~ 125 GeV, with properties consistent with the minimal Standard Model Higgs boson.
- This already strongly constrains the parameter space for physics beyond the Standard Model, and has implications for physics at very high energies.
- With more data we will improve the measurements of production and decay parameters of the particle, and see if it is embedded in a larger symmetry breaking sector.