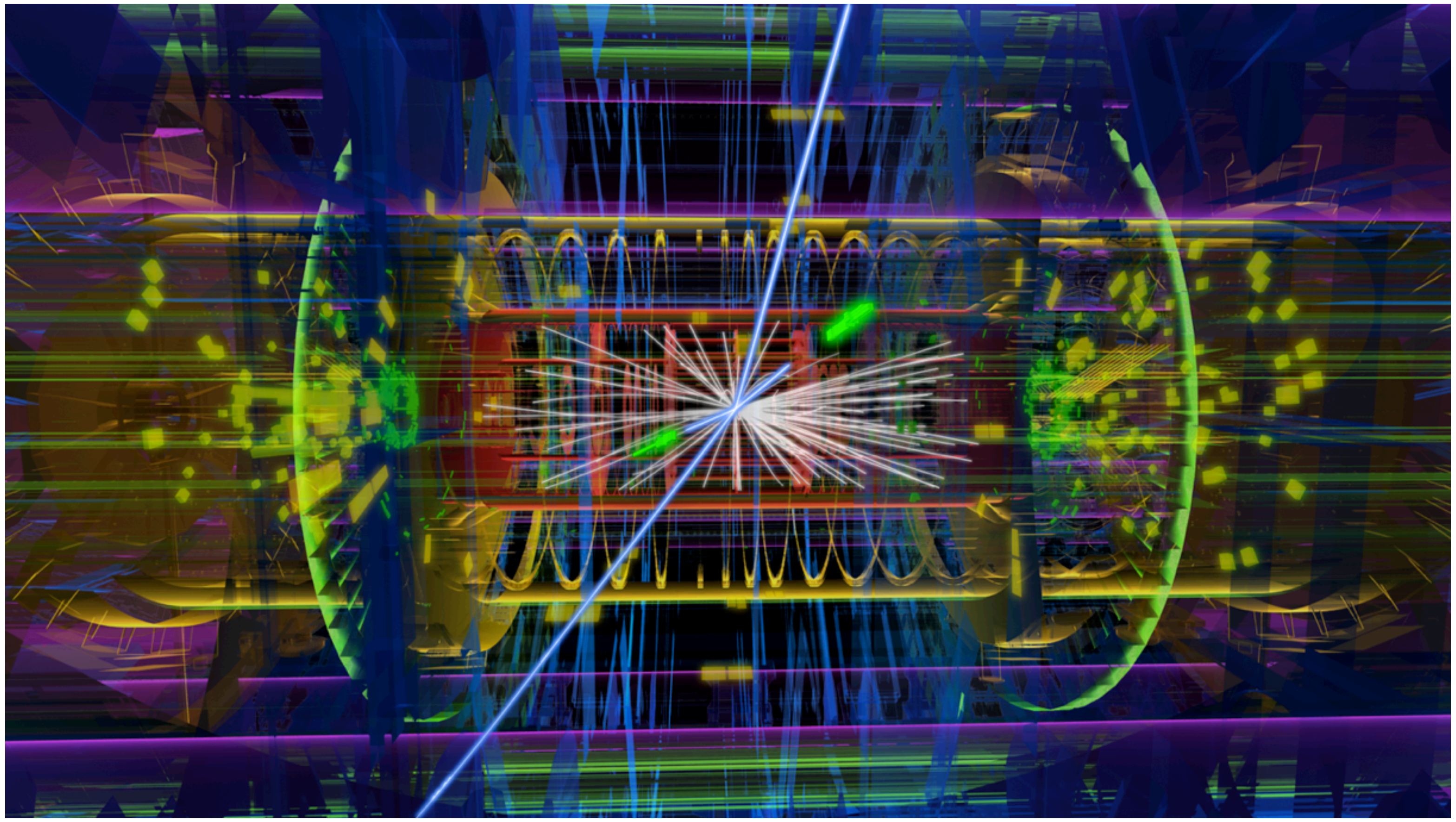
Exploring the energy frontier with the ATLAS experiment at the Large Hadron Collider

Michel Lefebvre
University of Victoria



- Matter and forces
- The LHC and ATLAS
- pp collisions
- Search for the Higgs
- More searches
- What's next

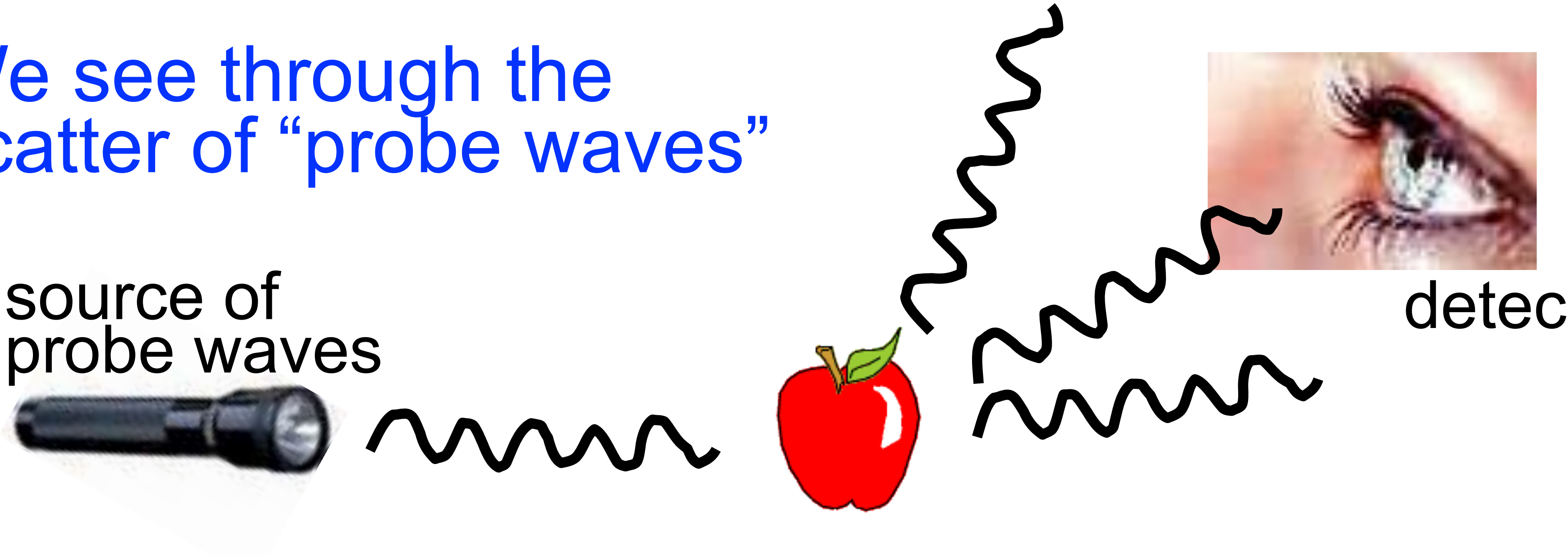
Bell Lecture
McGill University
23 November 2012

abstract

The recent discovery of a new particle opens up a new window in our exploration of the fundamental constituents of matter and the interactions between them. To date, the Standard Model of particle physics is extremely successful and accounts for all measured subatomic phenomena. However the postulated Higgs mechanism, from which all particles acquire mass, remains to be verified experimentally. Is the new particle the predicted Standard Model Higgs boson? Many other questions are so far left unanswered. Research at the energy frontier is being carried out at the Large Hadron Collider (LHC), operating at CERN near Geneva since 2010. The LHC currently provides proton-proton collisions at a centre of mass energy of 8 TeV, allowing the exploration of distance scales smaller than 10^{-19} m. The ATLAS detector is successfully recording the products of these collisions; it will be introduced with an emphasis on Canadian contributions. The ATLAS experiment has collected a large data set in 2012, and features Standard Model physics measurements and a rich programme of searches for new physics phenomena. The discovery of a new particle and other important results will be presented. The future increase in energy and intensity at the LHC, and the associated ATLAS plans, will also be discussed. These are exciting times indeed for particle physics!

Scattering experiment

We see through the scatter of “probe waves”



source of probe waves

detector

Matter waves:

particle aspect

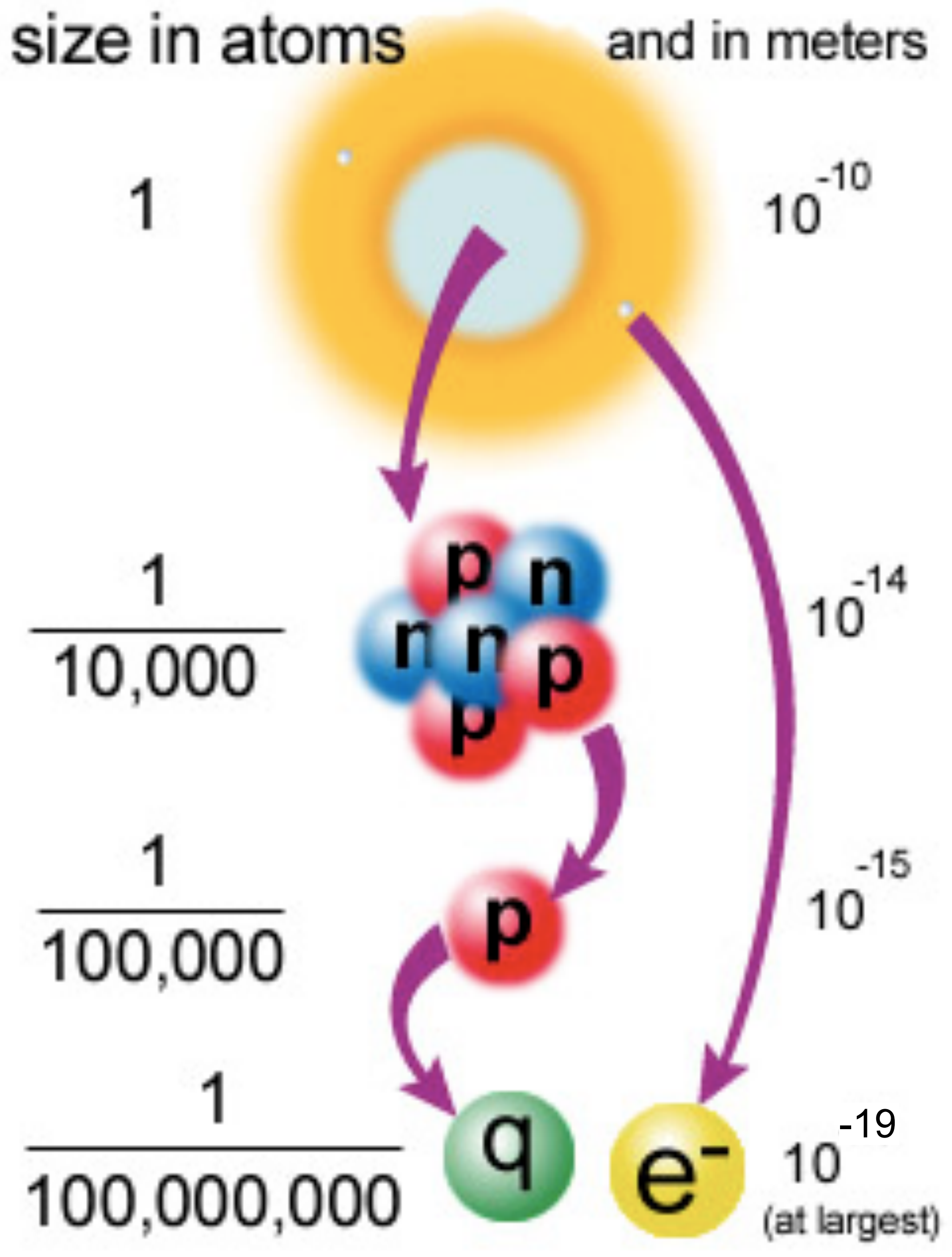
$$\left\{ \begin{array}{ccc} p & = & \dfrac{h}{\lambda} \\ E & = & h\nu \end{array} \right\}$$

wave aspect

The matter wave can resolve features about the size of its wavelength, given sufficient luminosity

Inside the atom

> “Nothing exists except atoms and empty space; everything else is opinion.”
>
> Democritus (ca. 460 BC - ca. 370 BC)



atom

nucleus

nucleon (here a proton)

quark and electron

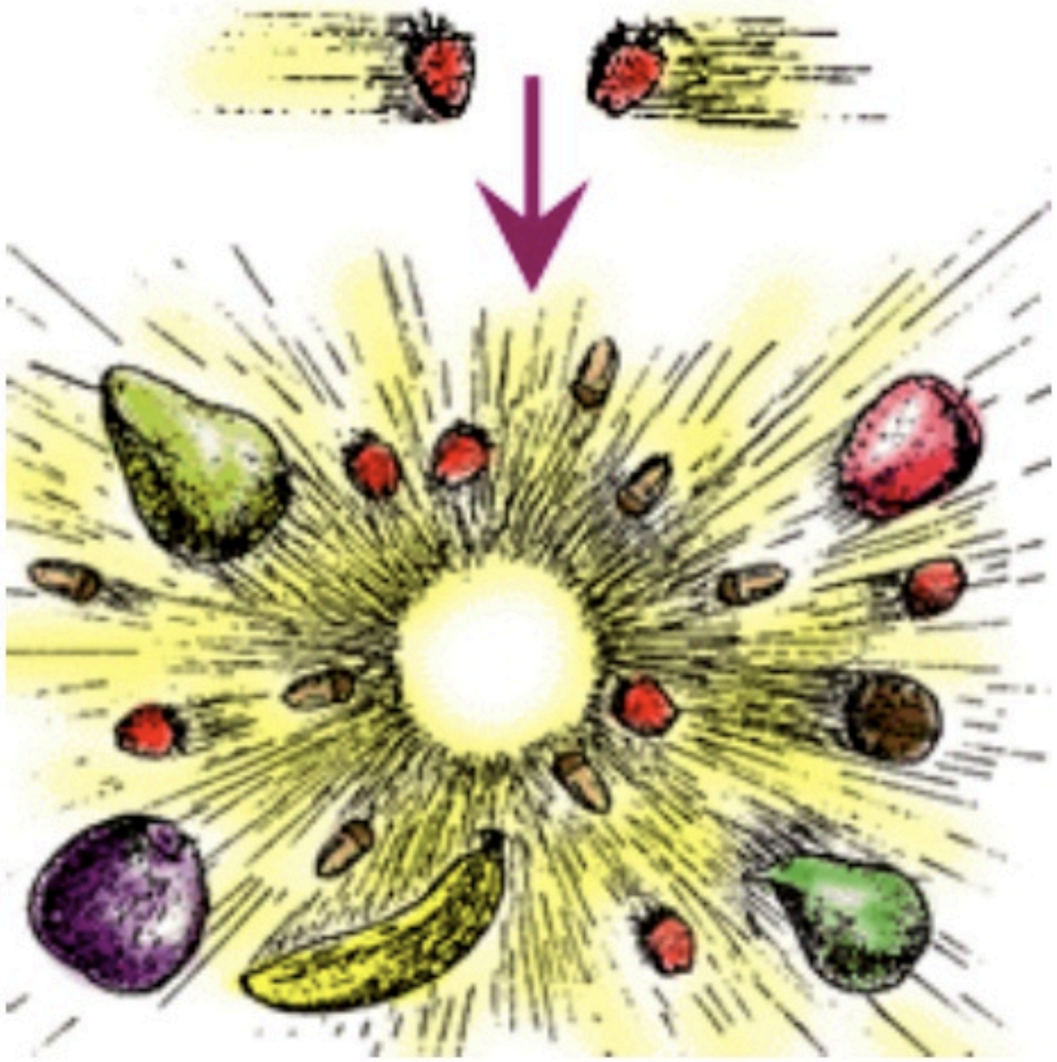
Rutherford’s scattering experiments:

$$K_\alpha = 7.7\ \mathrm{MeV} \quad {}^{214}\mathrm{Po}$$

$$\lambda = 5.2\ \mathrm{fm}$$

Now looking smaller still!

Colliding particles

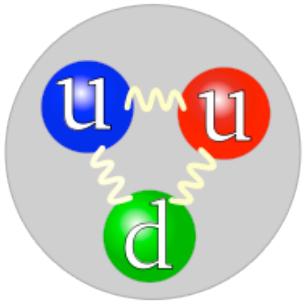


Particles and antiparticles, perhaps new and unknown ones, can be produced from the pure energy available after the collision

$$E = mc^2$$

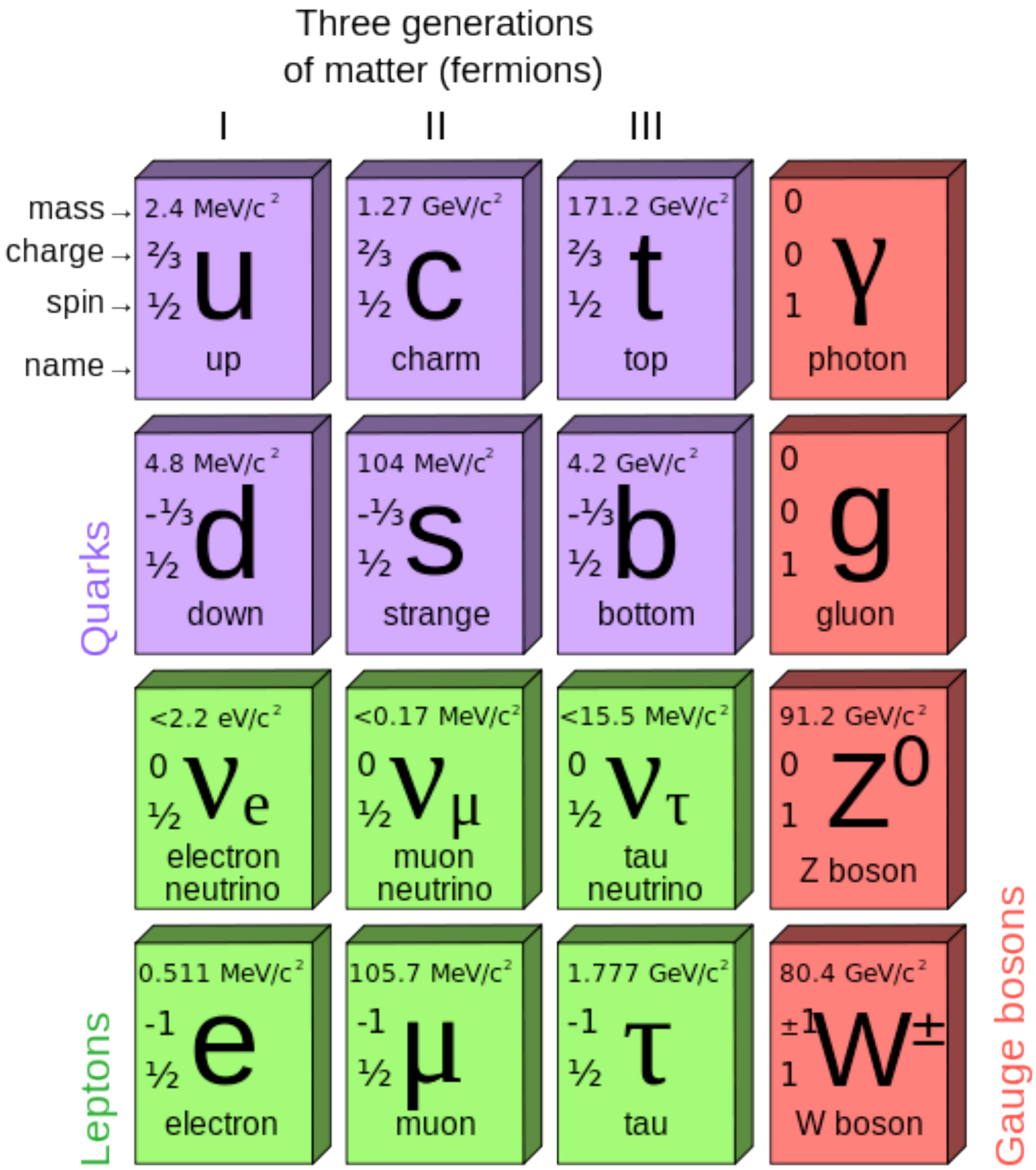
New particles signal new physical laws!

Matter and Forces



the **proton**: three bound quarks

Matter: spin 1/2 fermions



Three generations of matter (fermions)

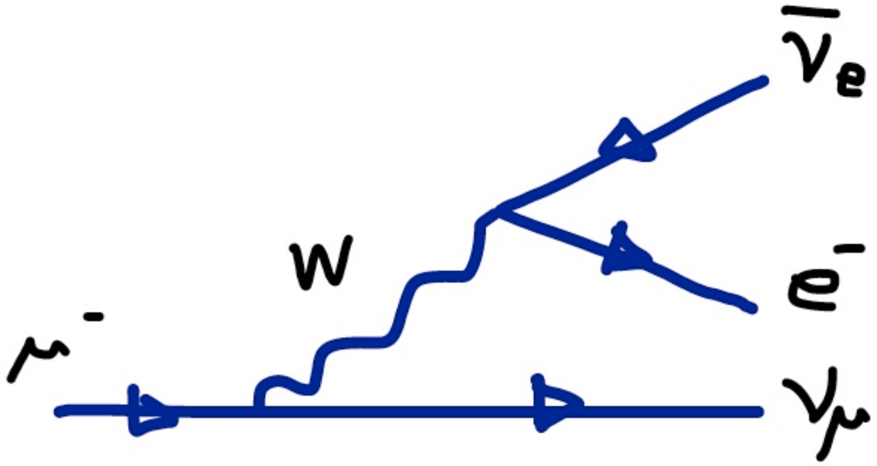
	I	II	III	
mass → charge → spin → name →	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon
	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson
Leptons	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson

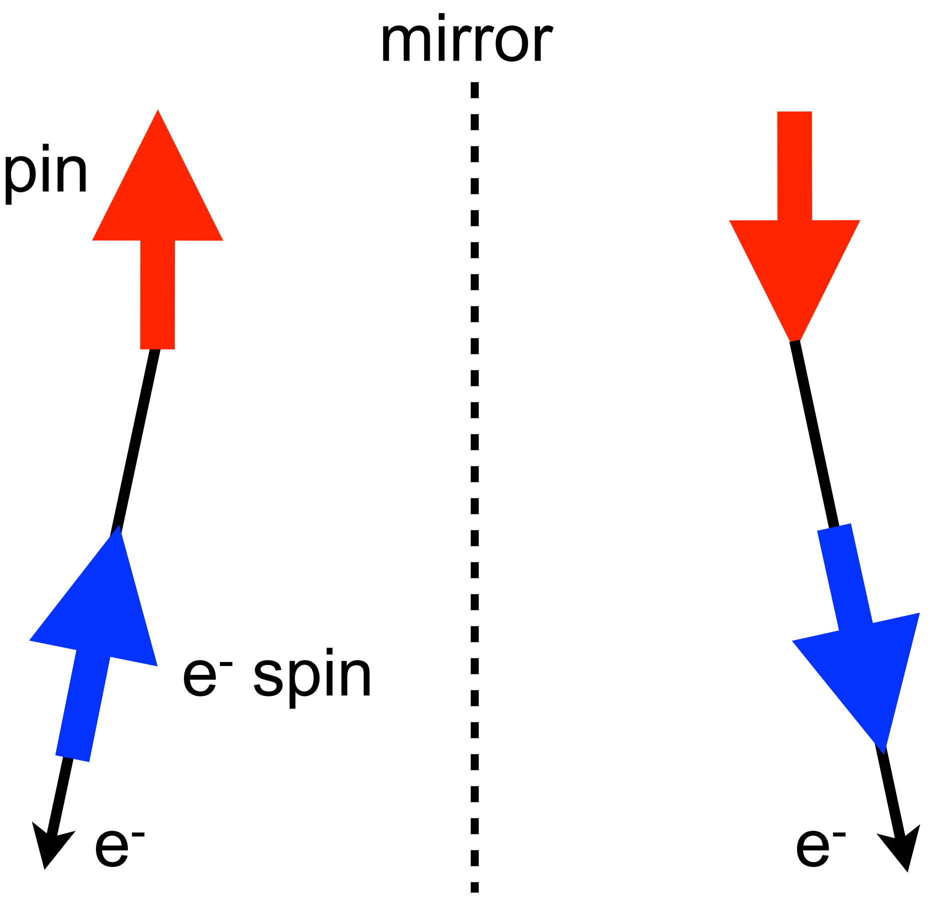
Gauge bosons

Forces: mediated by spin 1 bosons

Weak interaction and parity

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$





The weak interaction violates parity!

This is very odd, and crucial to the understanding of the mystery of the origin of mass

Global symmetries

global symmetry ⇒ conservation law

homogeneity of space ⇒ momentum

homogeneity of time ⇒ energy

isotropy of space ⇒ angular momentum

isotropy of some abstract space ⇒ some “charge”

invariance under ⇒ **conservation of electric charge**

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

Dirac spinor

global phase transformation

Local symmetries

local symmetry = gauge symmetry

Gauge principle:

the laws of nature are required to be invariant under a local symmetry

All known fundamental interactions are formulated as gauge theories!

invariance under

$$\underbrace{\psi(x)}_{\text{Dirac spinor}} \to e^{i\underbrace{\epsilon(x)}_{\text{arbitrary local phase transformation}}}\psi(x) \quad \Rightarrow$$

- **require a vector boson (photon)**
- **predicts the electron-photon coupling!**

Gauge invariance

- We wish to generate the EM, weak, and strong forces from a gauge invariance of the type

$$\mathrm{U(1)_Y \times SU(2)_L \times SU(3)_C}$$

Standard Model gauge

$$\begin{pmatrix} \nu_\mathrm{e} \\ \mathrm{e}^- \end{pmatrix} \qquad \begin{pmatrix} \mathbf{u} \\ \mathbf{u} \\ \mathbf{u} \end{pmatrix}$$

- But **ALL masses** violate this assumption!

gauge boson mass terms

$$M Z^\mu Z_\mu$$

fermion mass terms because of SU(2)$_\mathrm{L}$

$$m\bar{\psi}\psi = m\left(\bar{\psi}_\mathrm{L}\psi_\mathrm{R} + \bar{\psi}_\mathrm{R}\psi_\mathrm{L}\right)$$

We need a gauge invariant mechanism to generate mass

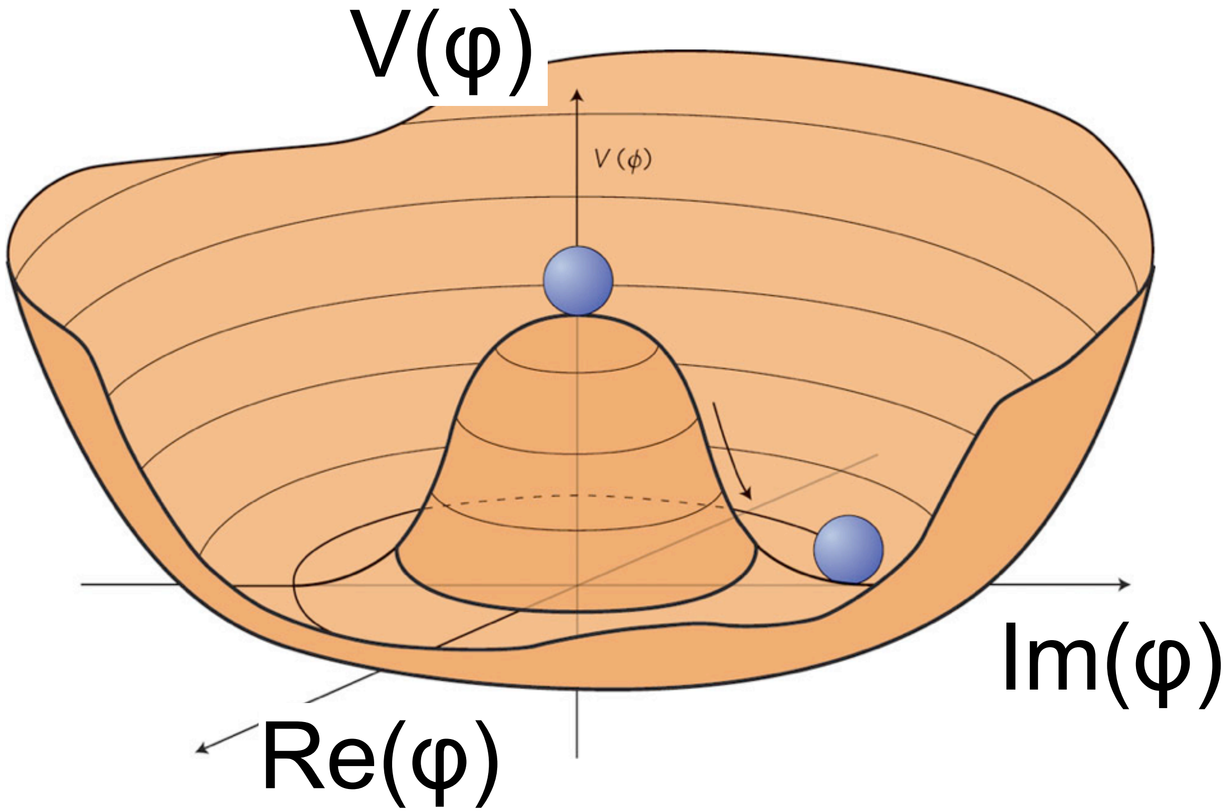
Higgs mechanism!

R. Brout, F. Englert, P. Higgs, G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble

Higgs mechanism

- The Higgs mechanism postulates the existence of a Higgs field φ
  - with its potential, and couplings to fermions

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2 \quad \lambda > 0$$



- The equilibrium state is φ ≠ 0 and not unique!
  - nature make a choice, partially **hiding the gauge invariance**
  - gauge bosons W^+,W^-, Z **acquire mass**
  - all fermions **acquire mass**
  - **prediction of one neutral scalar Higgs boson particle:**

H^0

F. Englert and P. Higgs at CERN July 4th 2012

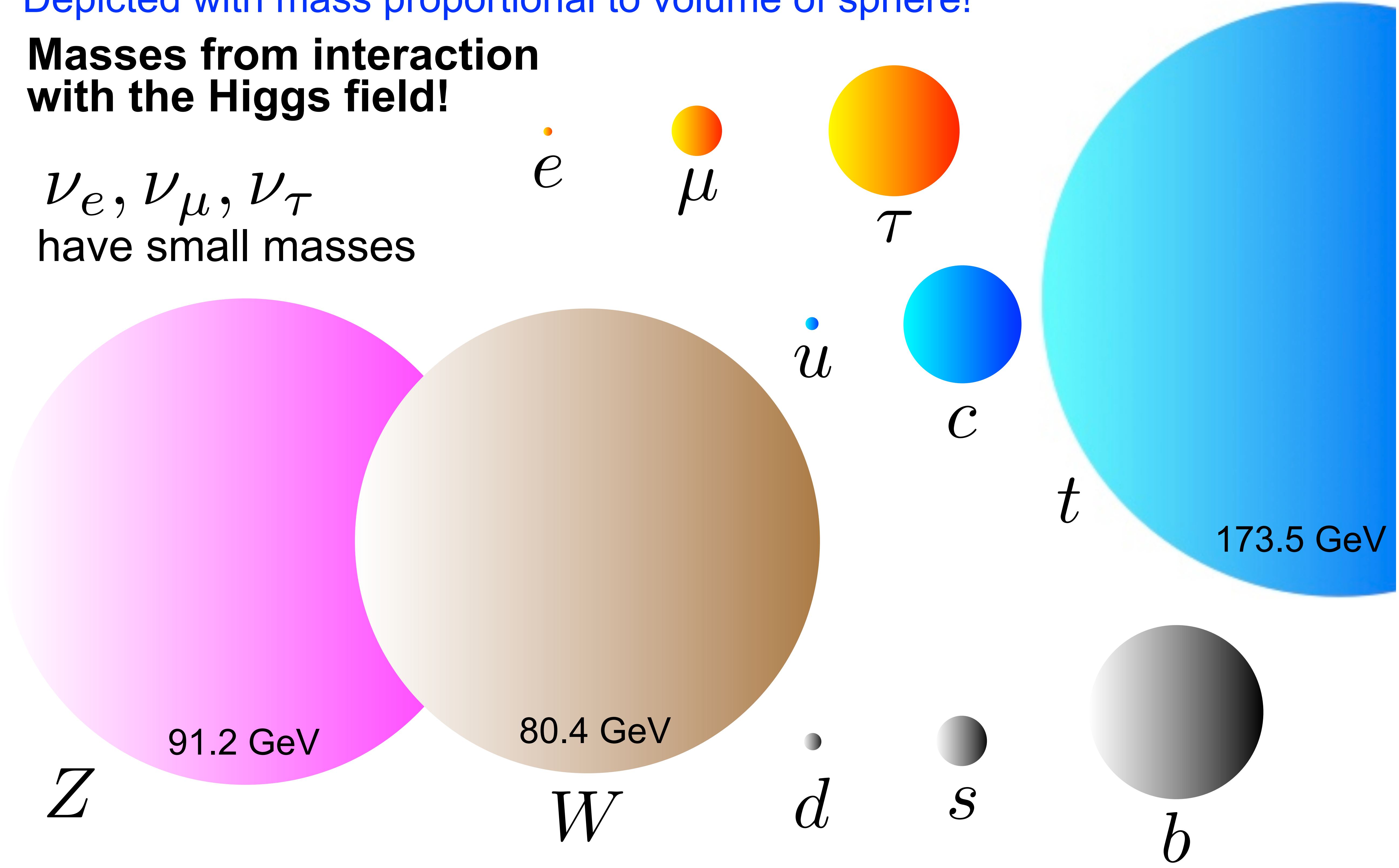
Fundamental Masses

γ, g
massless

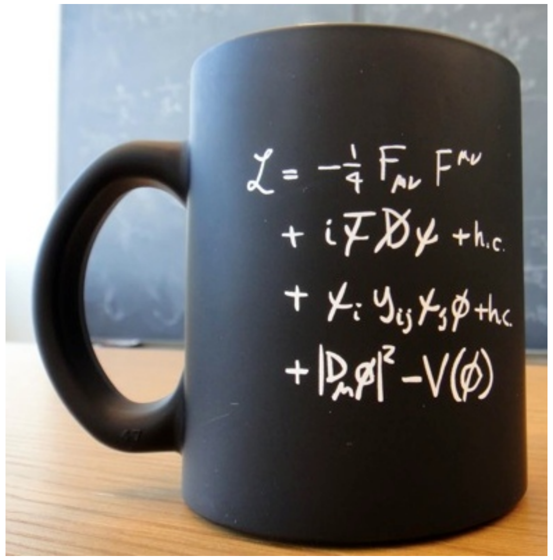
Depicted with mass proportional to volume of sphere!

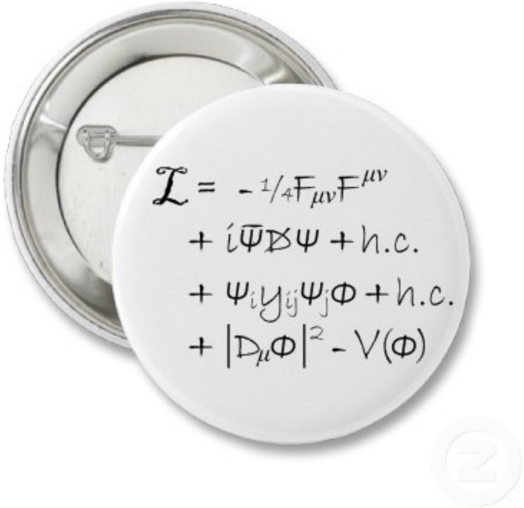
Masses from interaction with the Higgs field!

ν_e, ν_μ, ν_τ
have small masses



The Standard Model





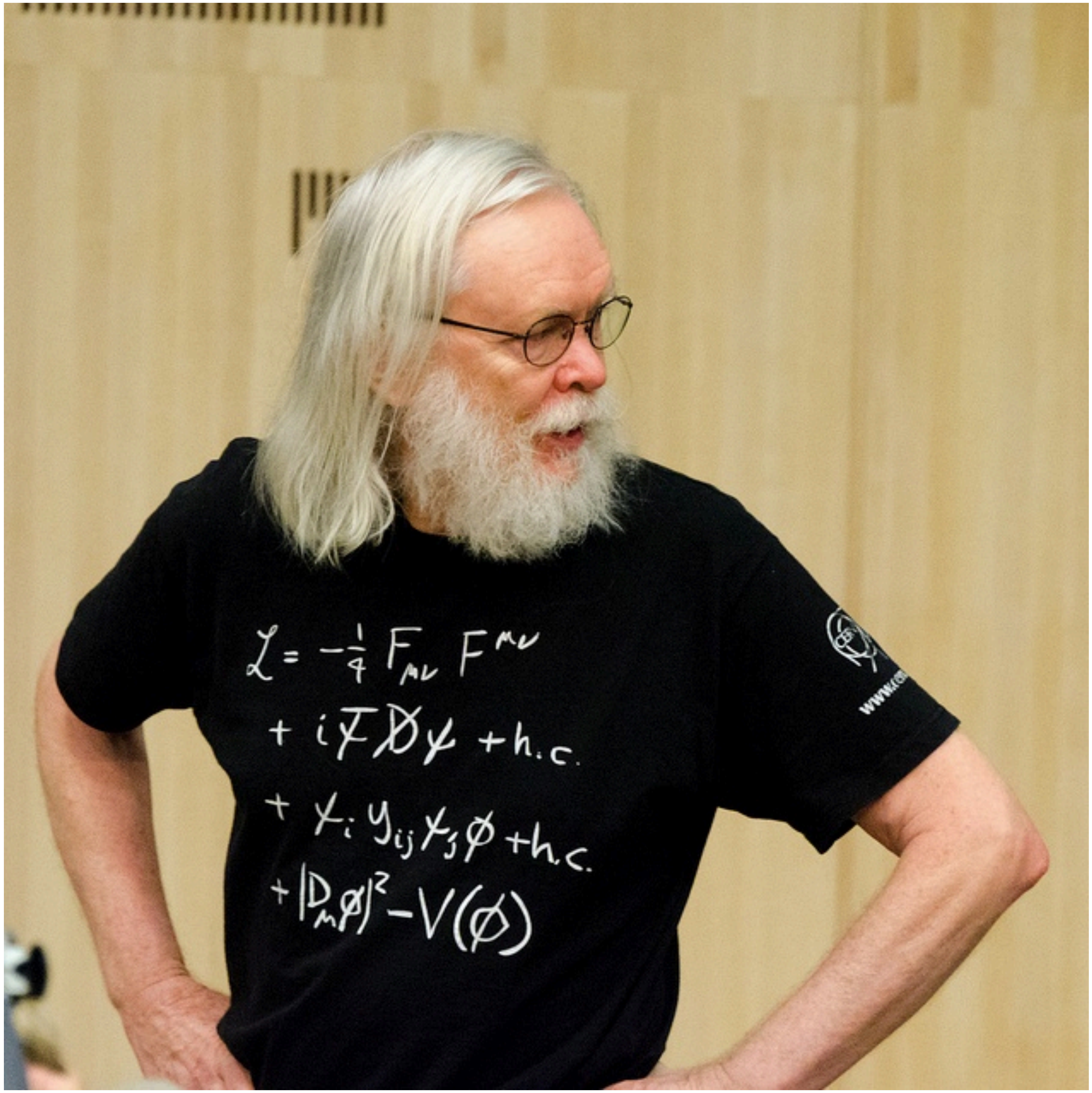
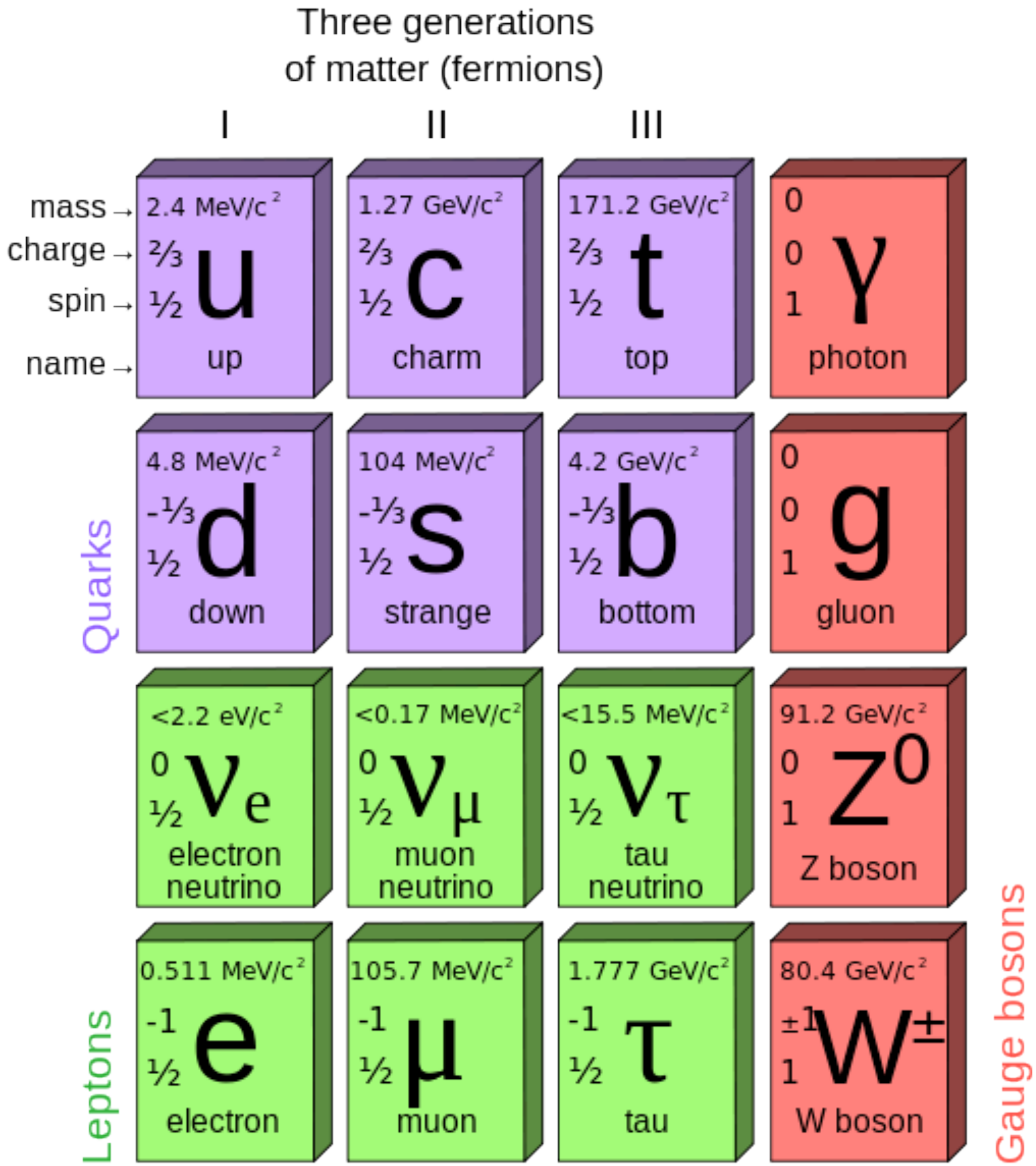


Photo: Josh Thompson

The Standard Model

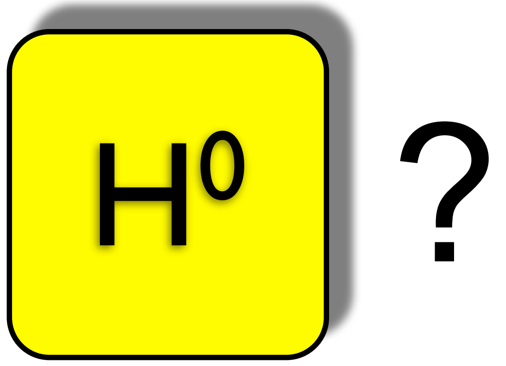


Three generations of matter (fermions)

		I	II	III	
Quarks	mass → charge → spin → name →	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon
Quarks		4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon
Leptons		<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson
Leptons		0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson

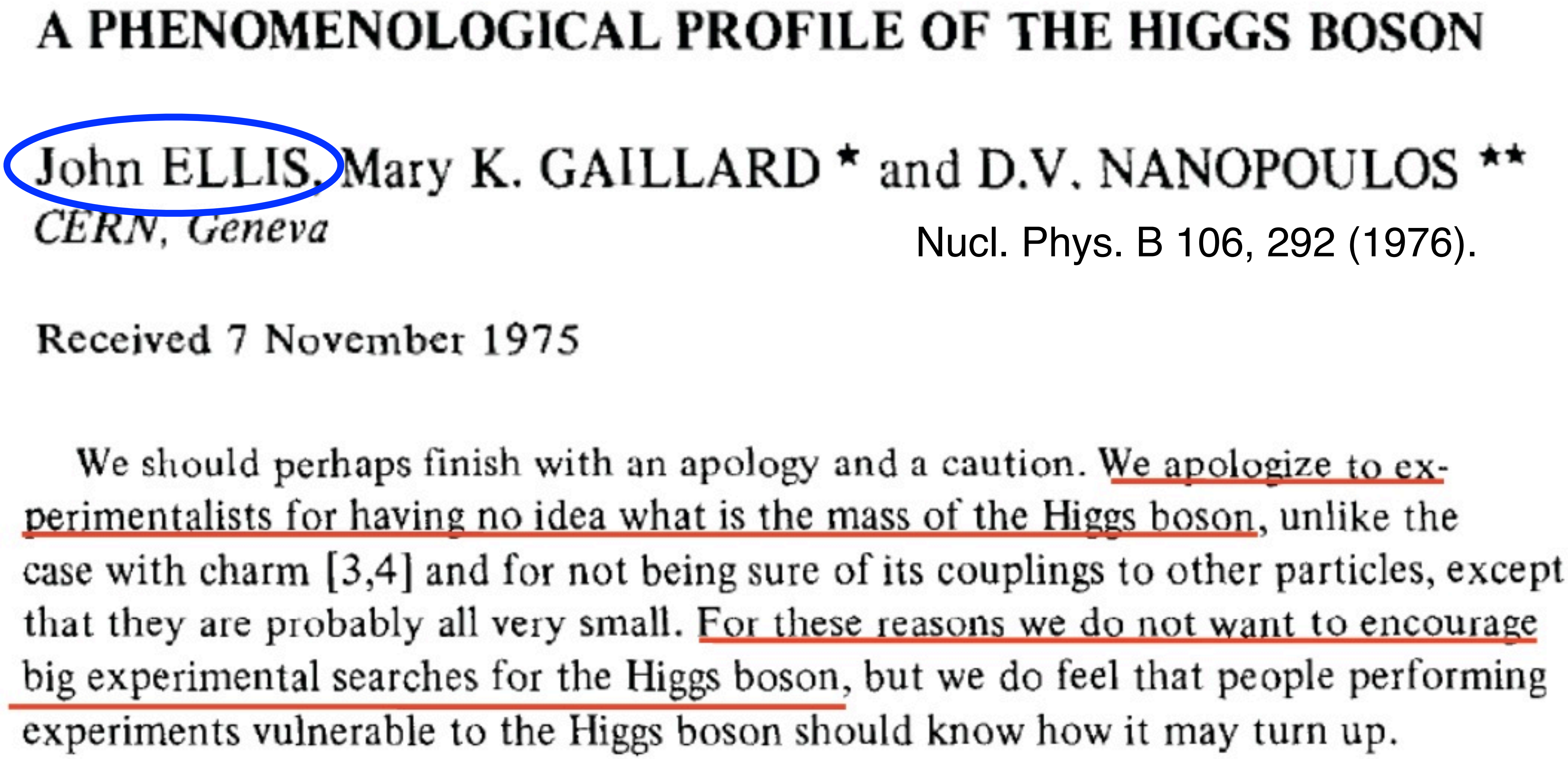
Gauge bosons

Higgs boson:
the missing piece



- The SM is a very successful theory
  - relativistic quantum fields
- All experimental measurements at the subatomic level agree with the SM to date!
- But it does not predict the mass of the Higgs boson!

Higgs boson mass??



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Nucl. Phys. B 106, 292 (1976).

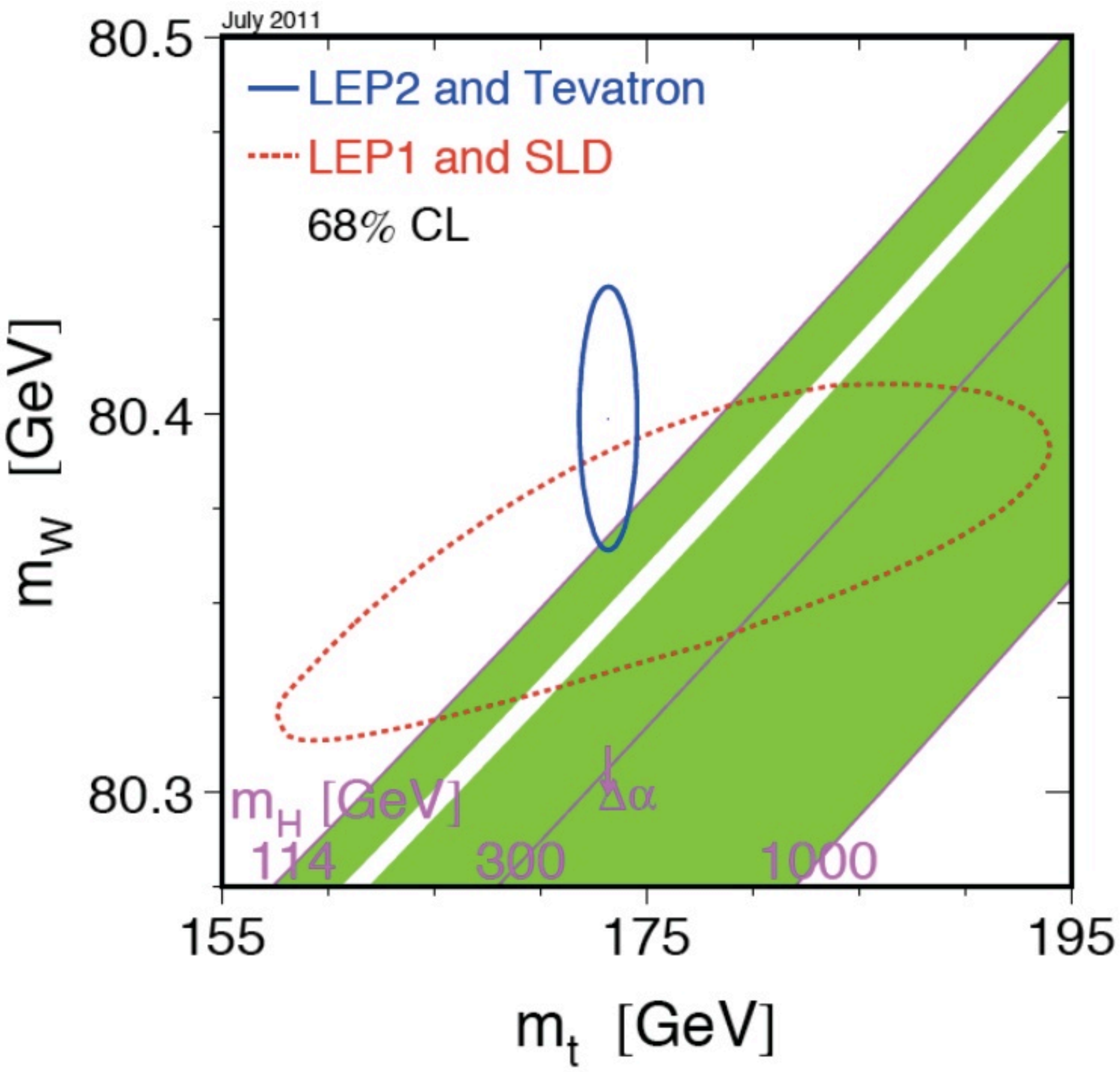
Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Many thanks to J.-F. Arguin (UdeM) for pointing out this anecdote!

Precision measurements

- Precise Standard Model measurements put constraints on the Higgs mass
  - Higgs couples to mass... look at heavy particles!



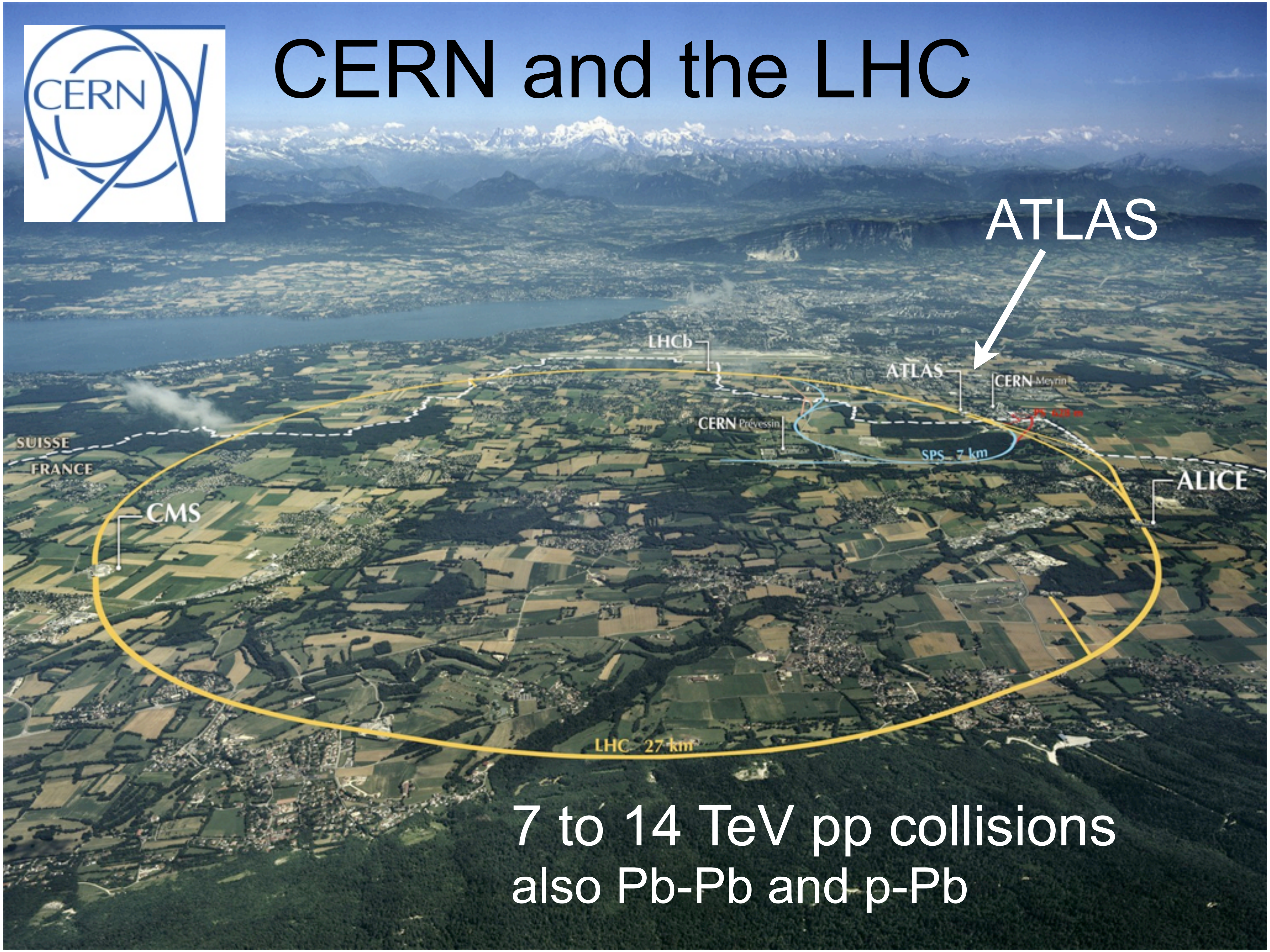
Higgs mass constraints

$114 < M_H < 161$ GeV 95%CL

Direct searches

Indirect: precision measurements. Assumes SM

CERN and the LHC



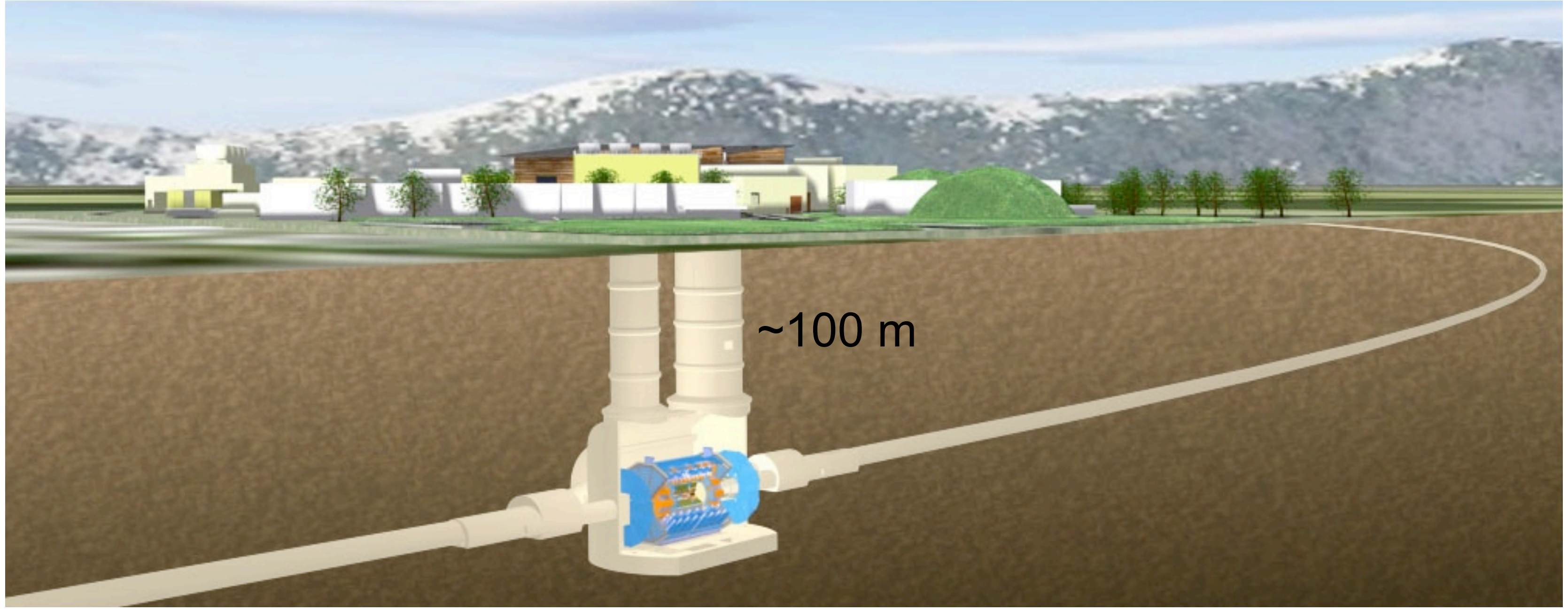
ATLAS

7 to 14 TeV pp collisions

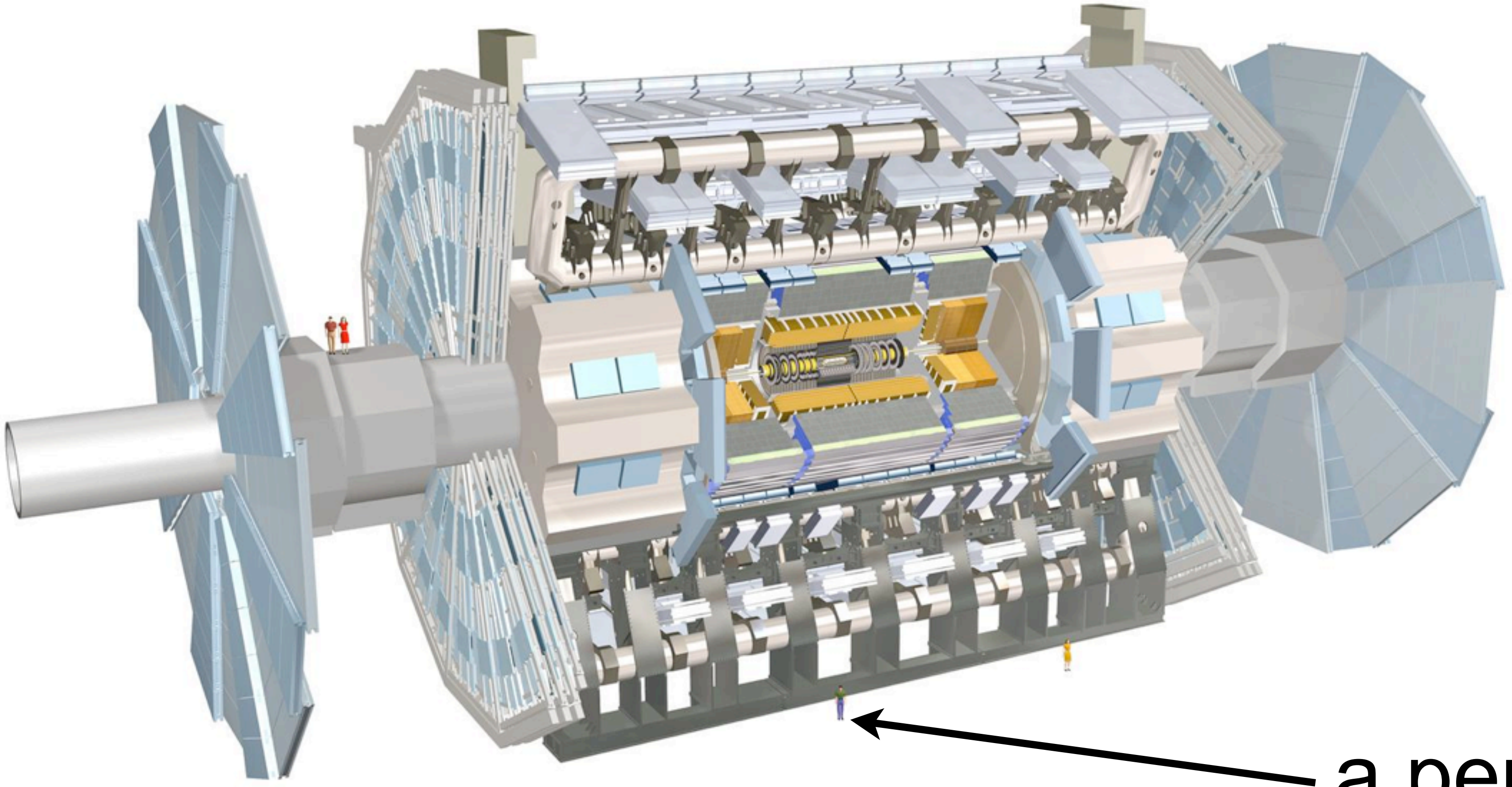
also Pb-Pb and p-Pb

CERN PhotoLab CERN-MI-0807031

The ATLAS detector at the LHC



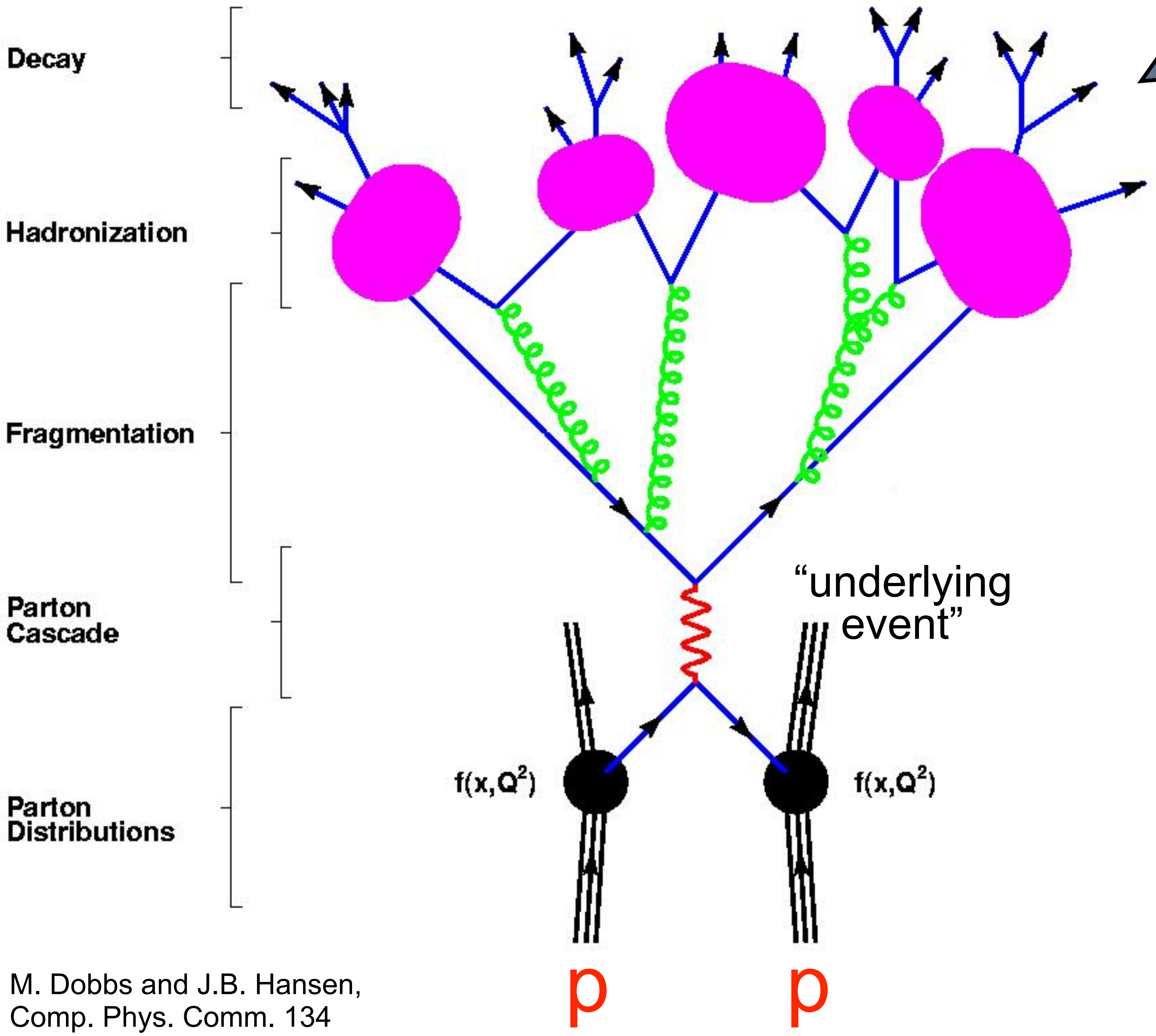
The ATLAS Experiment at CERN, http://atlas.ch



a person!

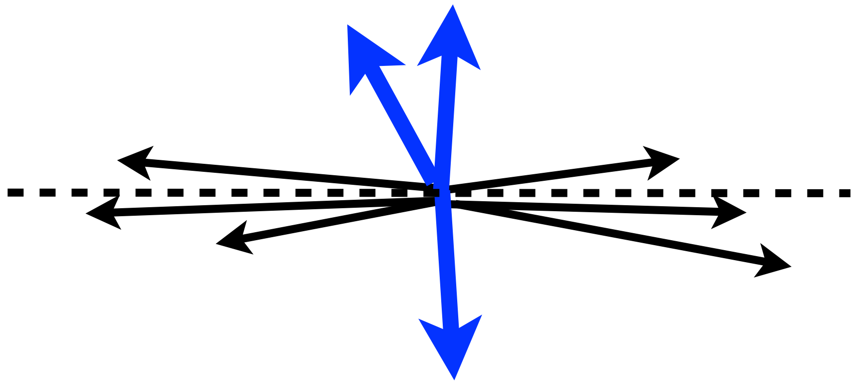
LHC magnets operate at 1.9 K
1232 dipoles (8.4 T, 34 t)
392 quadrupoles

Proton-proton collisions

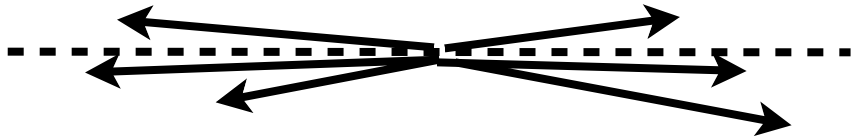


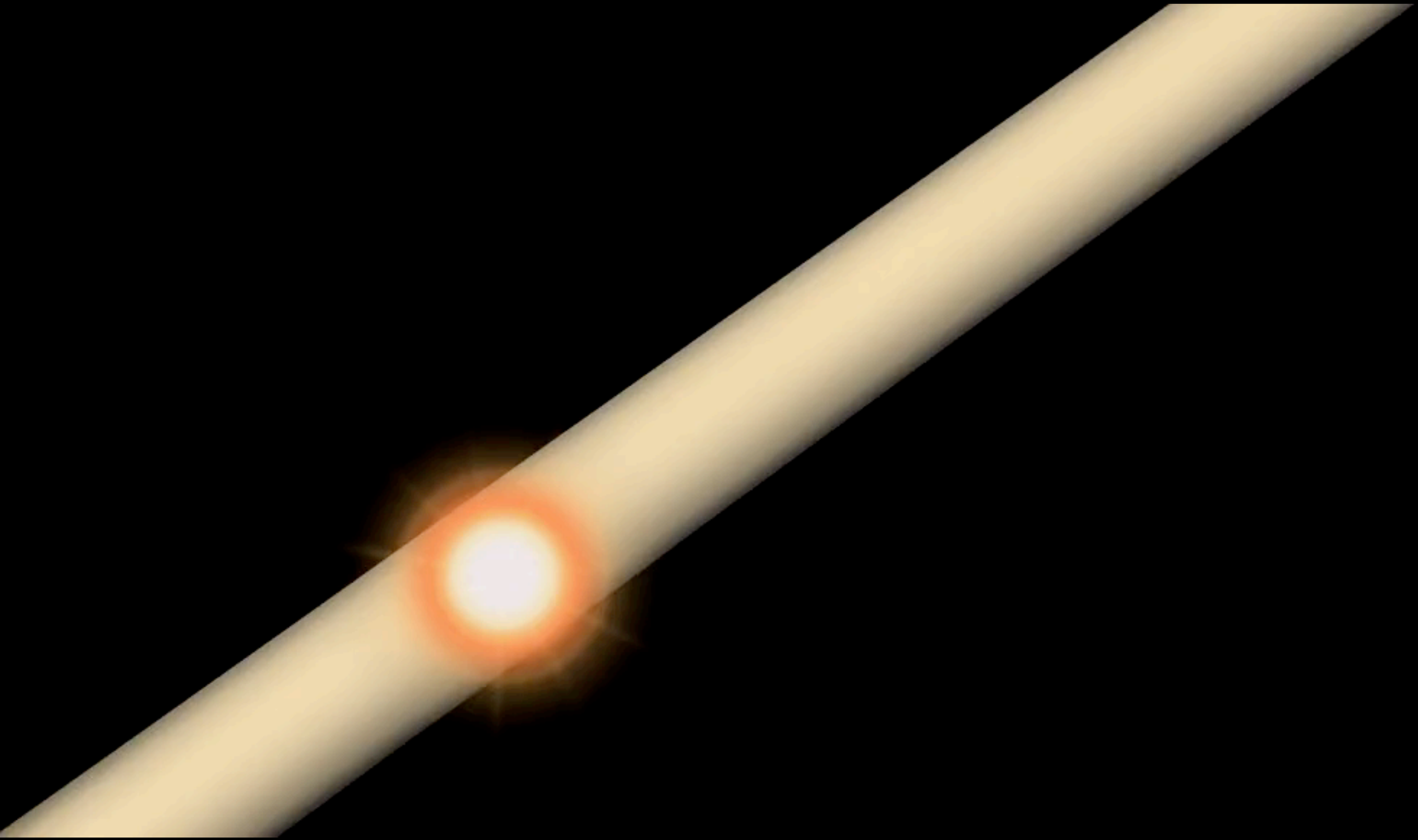
M. Dobbs and J.B. Hansen, Comp. Phys. Comm. 134 (2001) 41-46.

Hard scatter

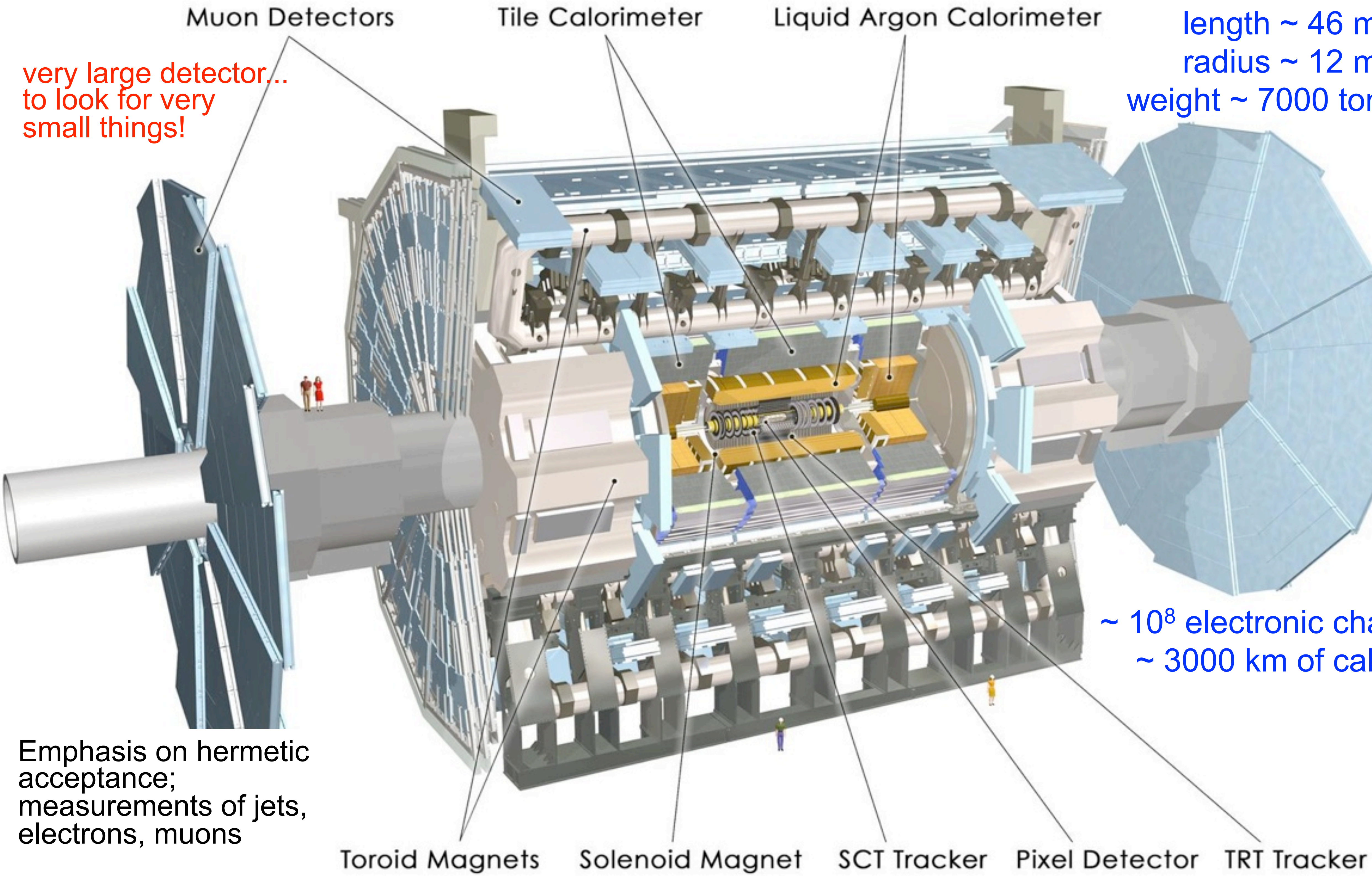


soft scatter





The ATLAS detector



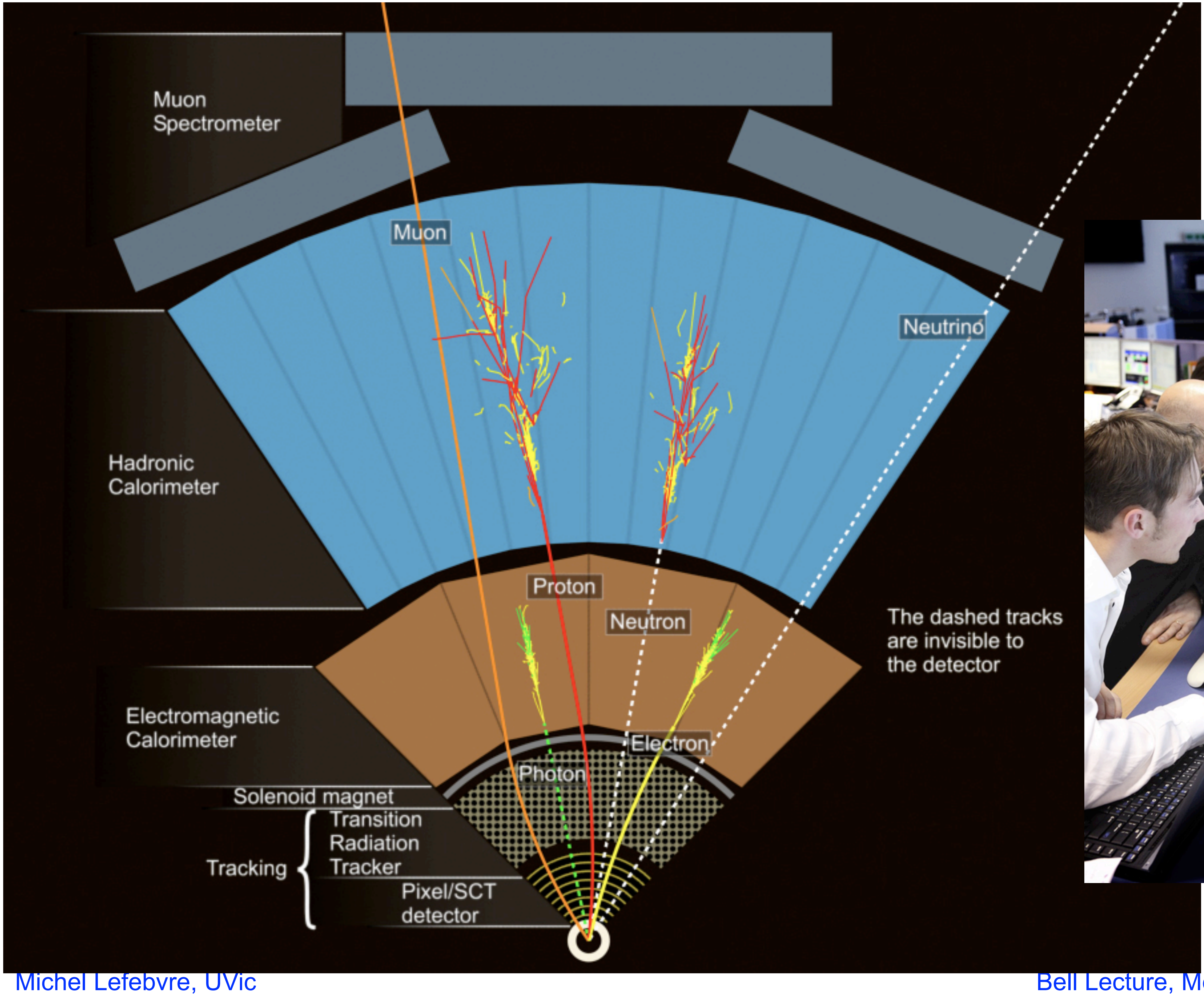
very large detector... to look for very small things!

length ~ 46 m
radius ~ 12 m
weight ~ 7000 tonnes

~ 10^8 electronic channels
~ 3000 km of cables

Emphasis on hermetic acceptance; measurements of jets, electrons, muons

Particle identification in ATLAS



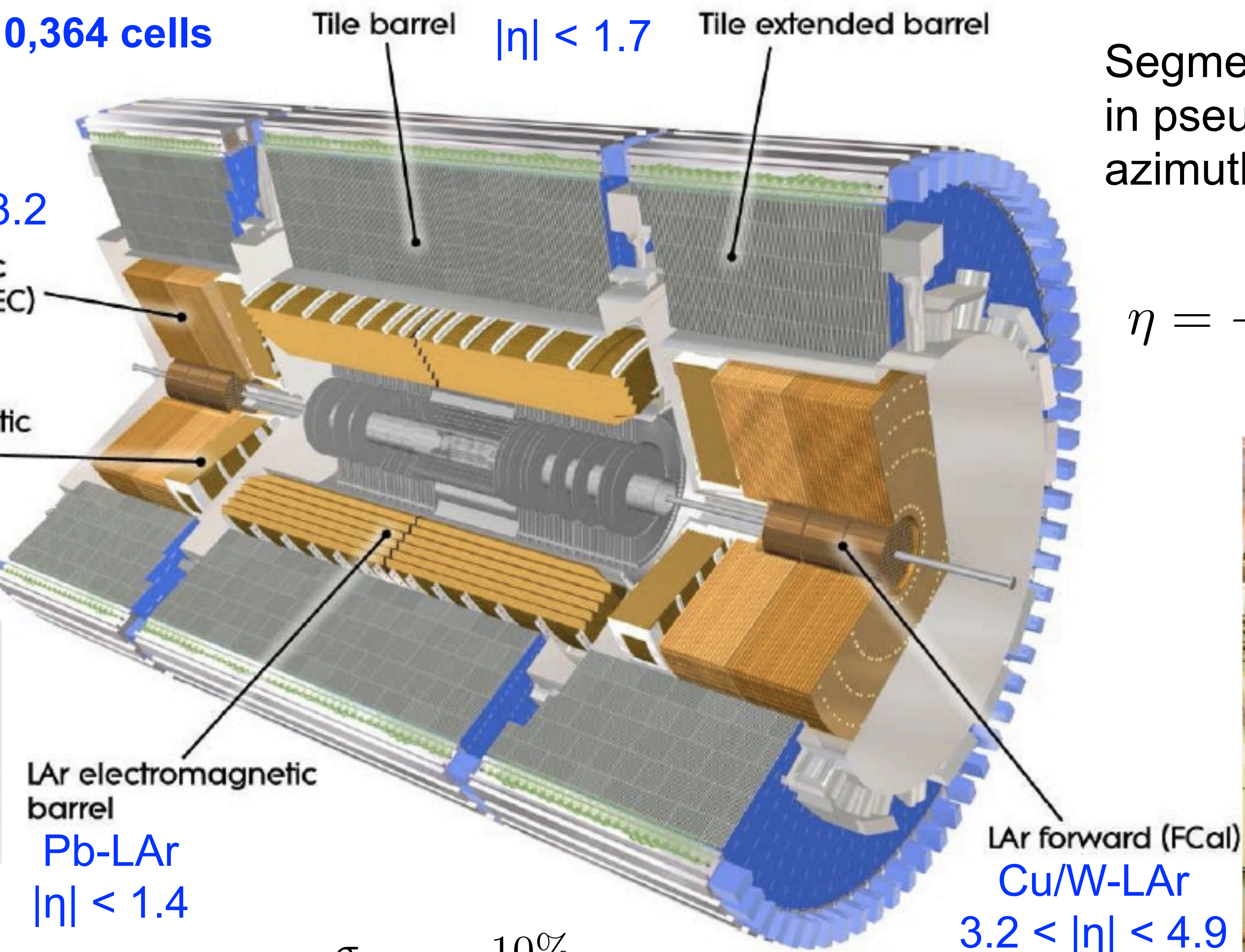
The dashed tracks are invisible to the detector

ATLAS calorimetry

- **LAr system: 182,468 cells**
- **Tile system: 10,364 cells**

Segmented in depth and in pseudorapidity η and azimuthal angle ϕ

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



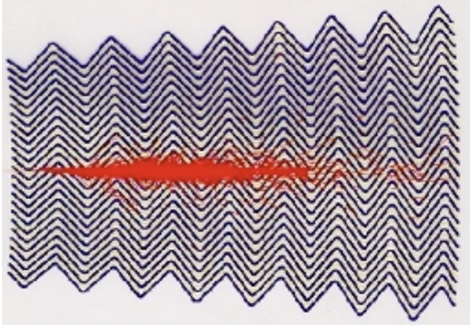
Fe-Scintillator
|η| < 1.7

Cu-LAr
1.5 < |η| < 3.2

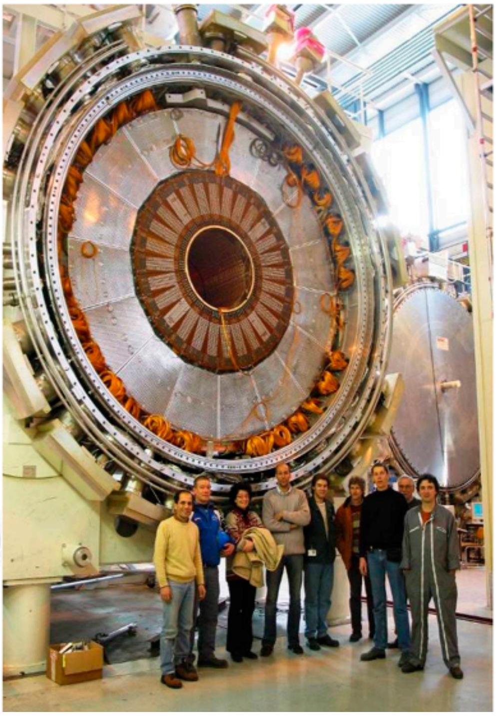
Pb-LAr
1.375 < |η| < 3.2

Pb-LAr
|η| < 1.4

Cu/W-LAr
3.2 < |η| < 4.9



and γ pointing!

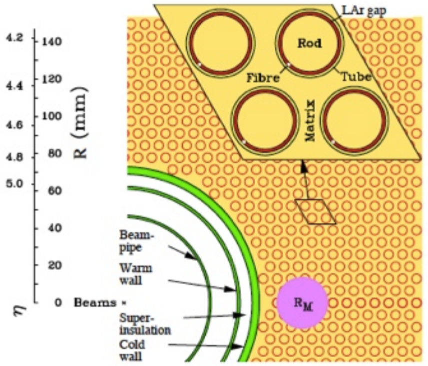


ATLAS Experiment © 2012 CERN

e/γ/jet trigger, identification, *E* measurement

EM: $\frac{\sigma}{E} = \frac{10\%}{\sqrt{E[\mathrm{GeV}]}} \oplus 0.7\%$

Had: $\frac{\sigma}{E} = \frac{50\%}{\sqrt{E[\mathrm{GeV}]}} \oplus 3\%$



ATLAS and Canada

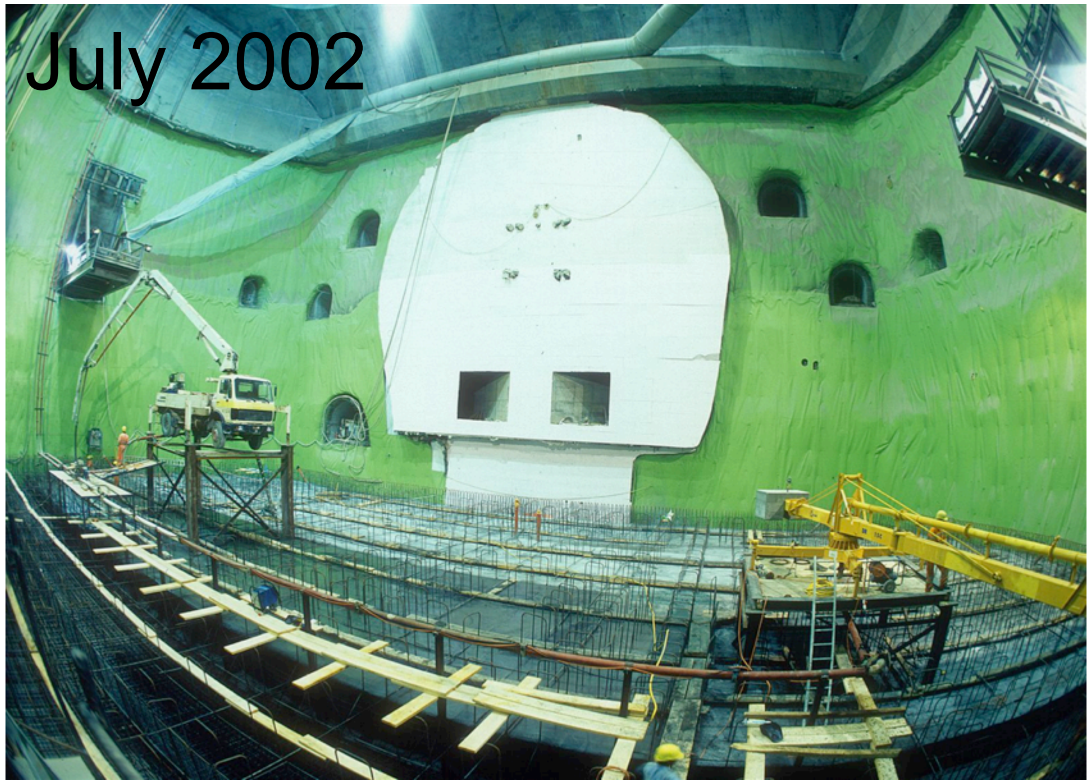
Alberta
Carleton
McGill
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

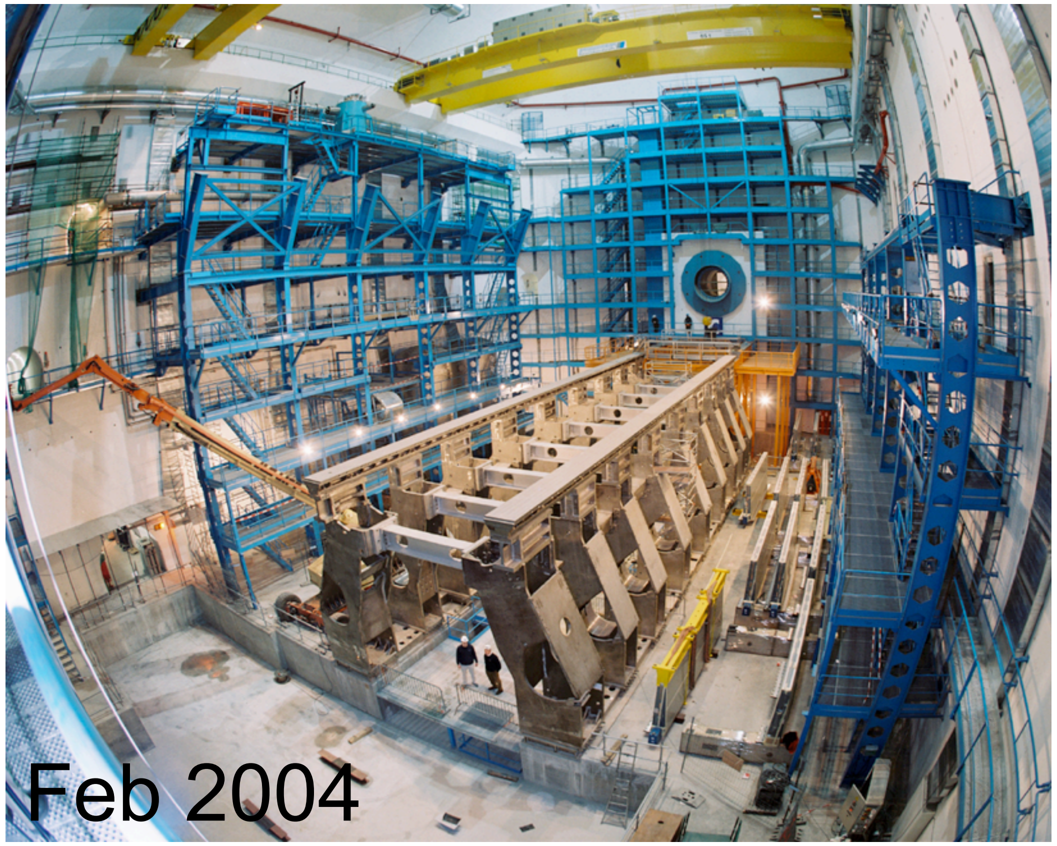
- ATLAS celebrated its 20th anniversary on Oct 1st
- Over 150 Canadian scientists participate in the ATLAS experiment
- ATLAS Canada Collaboration

Founded in 1992	ML, UVic
Spokesperson (07-)	Rob McPherson, UVic/IPP
Deputy	Dugan O’Neil, SFU
Physics Coordination	Pierre Savard, UofT/TRIUMF
Computing Coordination	Reda Tafirout, TRIUMF

- Contributions to the ATLAS detector construction
  - Calorimetry, cryogenics, electronics, trigger, ...
- Contributions to the LHC construction (TRIUMF)
- TRIUMF, Canada’s nuclear and particle physics laboratory located in Vancouver
  - http://www.triumf.ca/

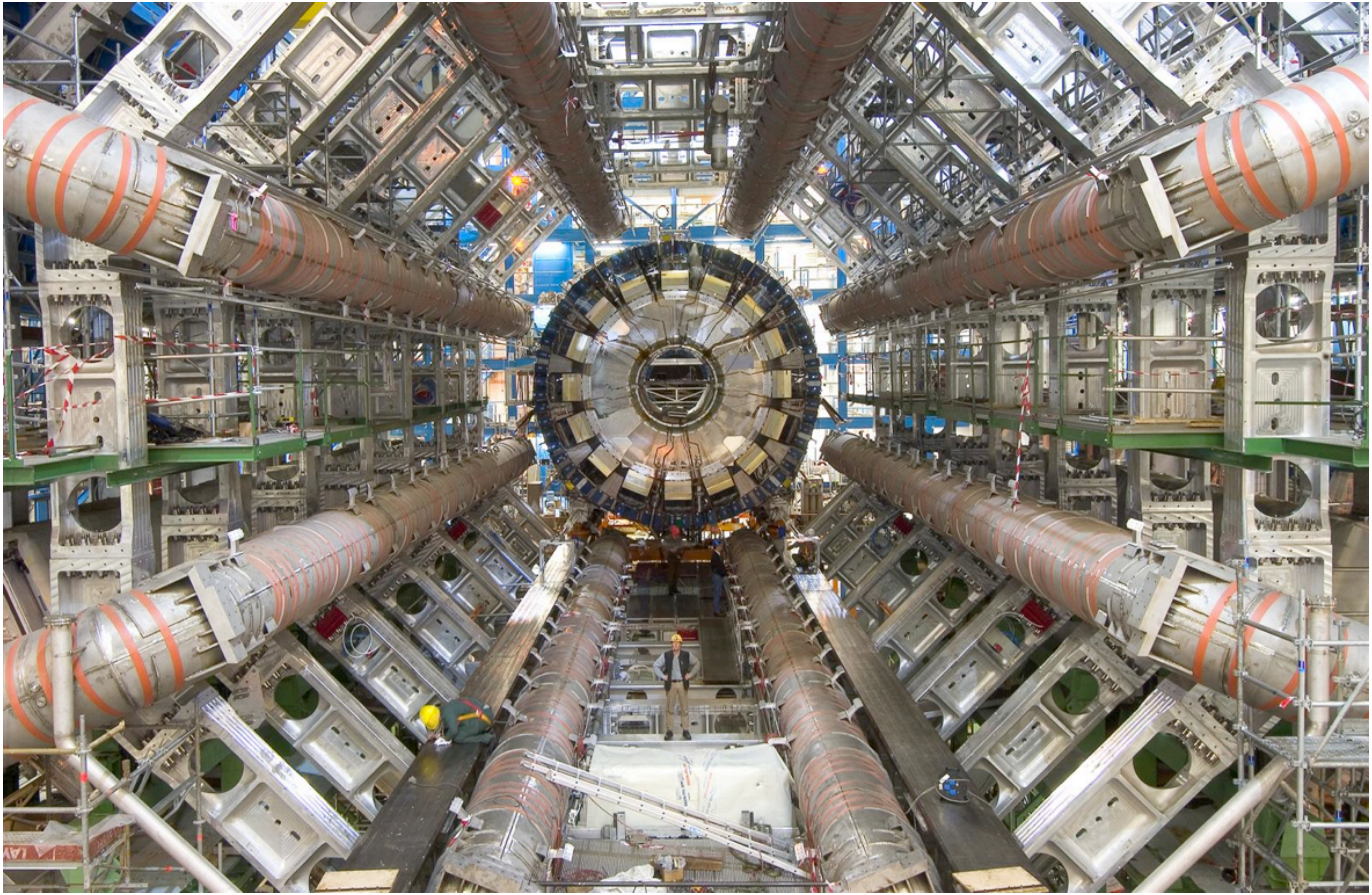
ATLAS cavern





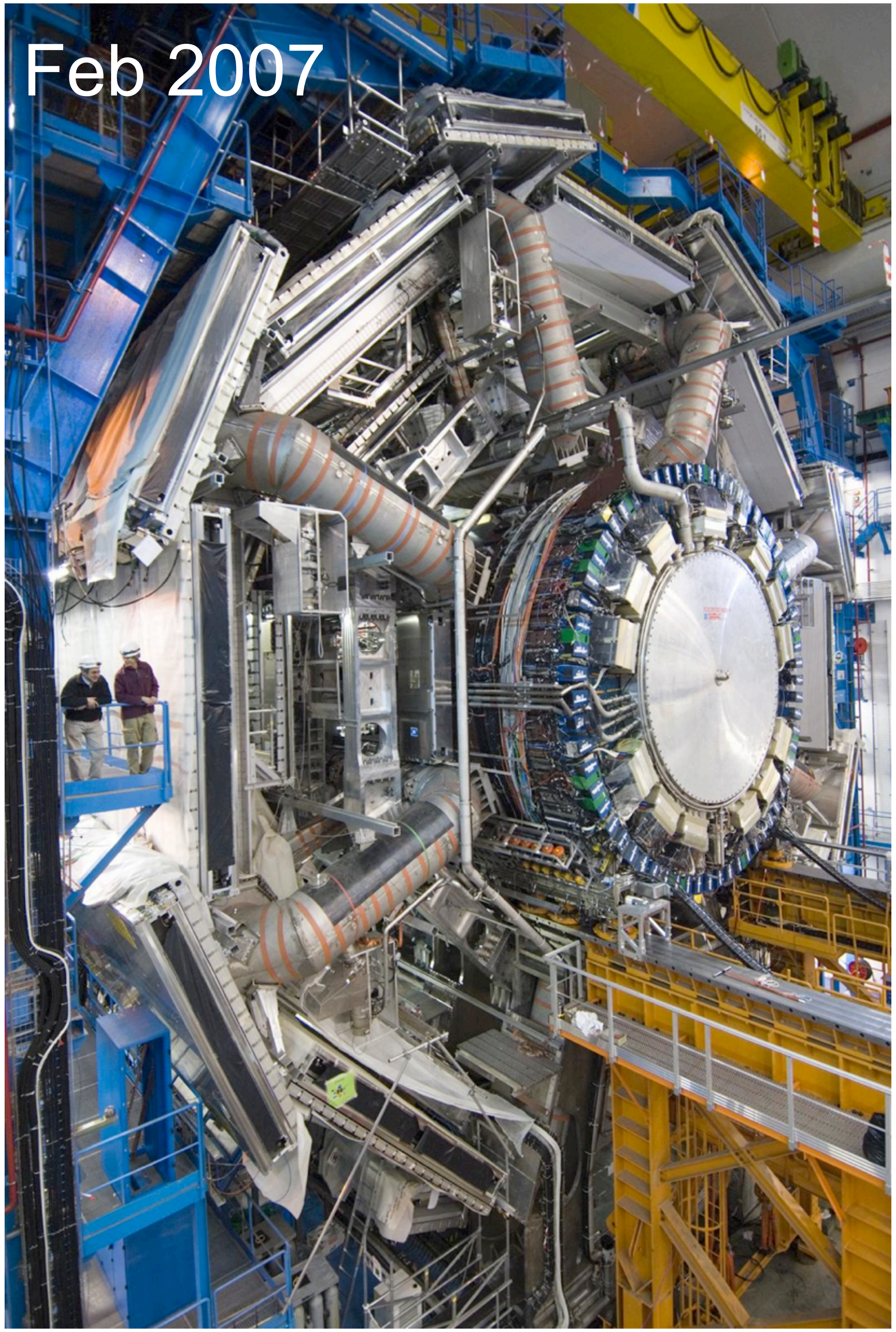
The ATLAS Experiment at CERN, http://atlas.ch

Barrel Toroids all installed (Nov 2005)



The ATLAS Experiment at CERN, http://atlas.ch

Moving the calorimeters in place


Feb 2007


May 2008, side A

Closing of LHC beam pipe (16 June 2008)

The ATLAS Experiment at CERN, http://atlas.ch

Luminosity and cross section

event production rate in Hz

instantaneous luminosity in cm^{-2} s^{-1}

$$R = L\sigma$$

cross section for the relevant process, in nb, pb, fb

$$1\ \mathrm{pb} = 10^{-36}\ \mathrm{cm}^2$$

number of events produced

integrated luminosity in fb^{-1}

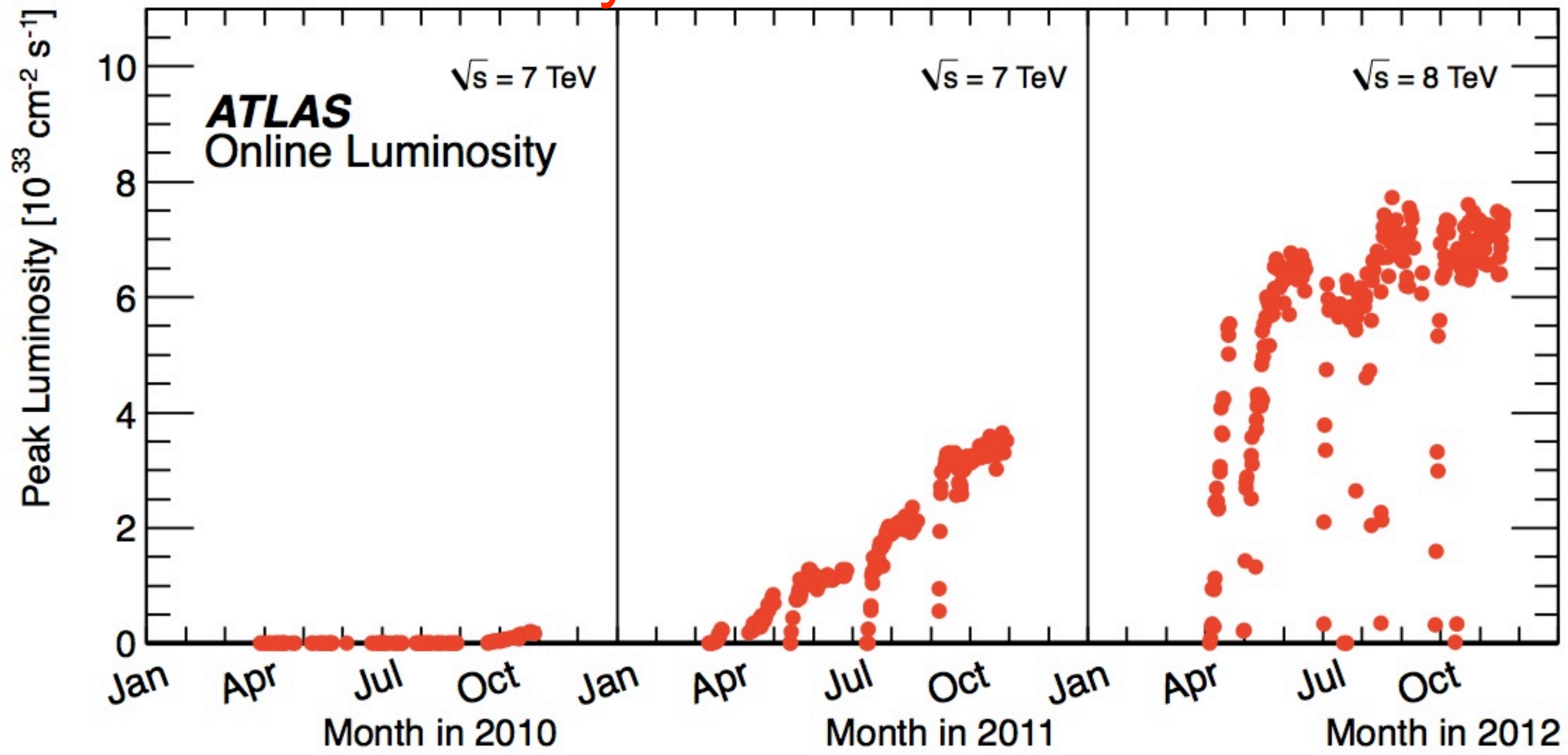
$$N = \left(\int L\,dt\right)\sigma$$

- if you want to make a measurement of a rare process (low cross section) with any significance, you need a large integrated luminosity. If you want to achieve this in a reasonable time, you need a large luminosity!

LHC luminosity, pp collisions

Superb LHC performance!!

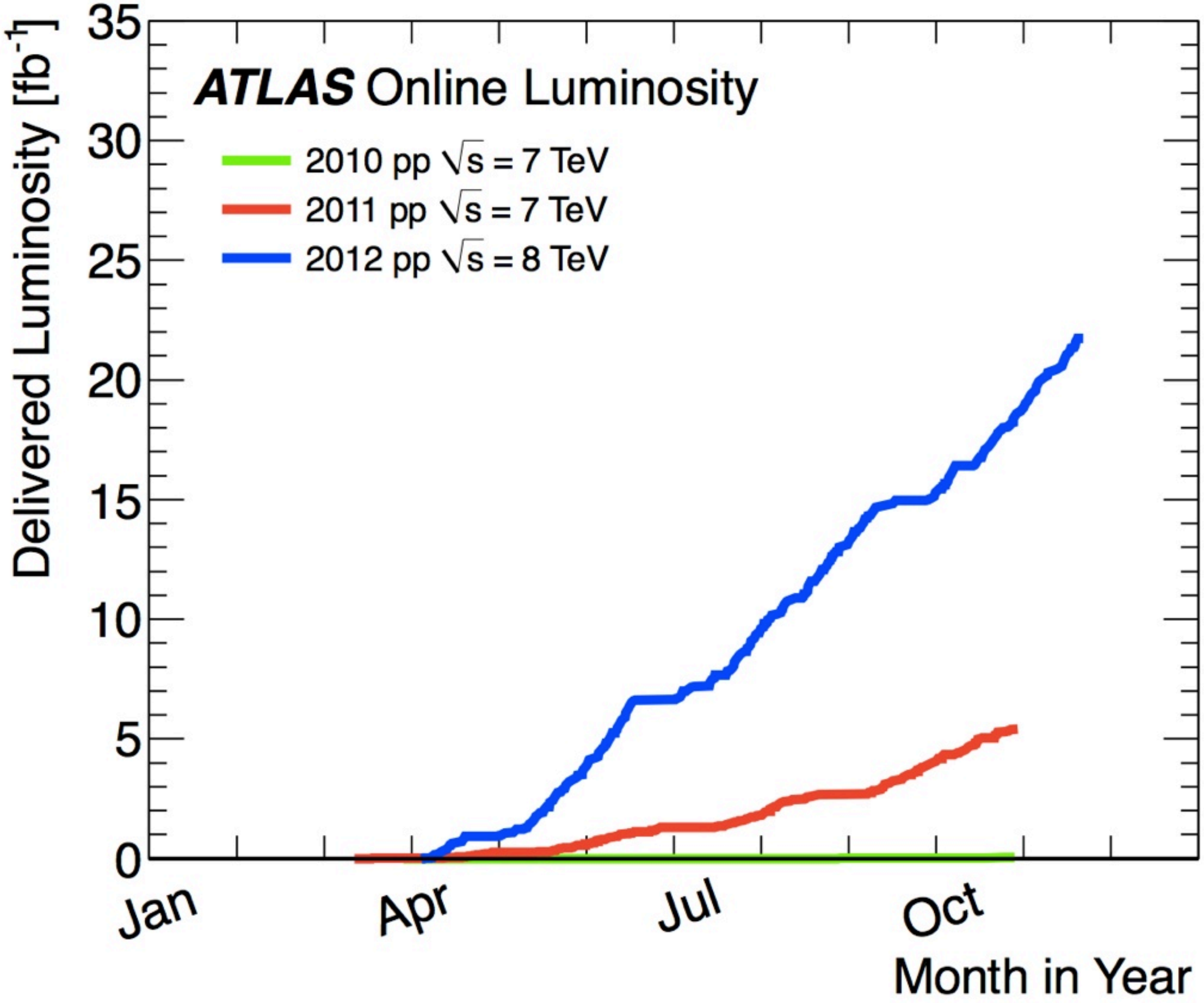
Peak luminosity: $7.73 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



A challenge for the experiments to keep up!

LHC integrated luminosity

Superb LHC performance!!



$$\int L\,dt$$

> 21 fb^{-1} 8 TeV

5.6 fb^{-1} 7 TeV

0.05 fb^{-1} 7 TeV

Cross sections and event rates

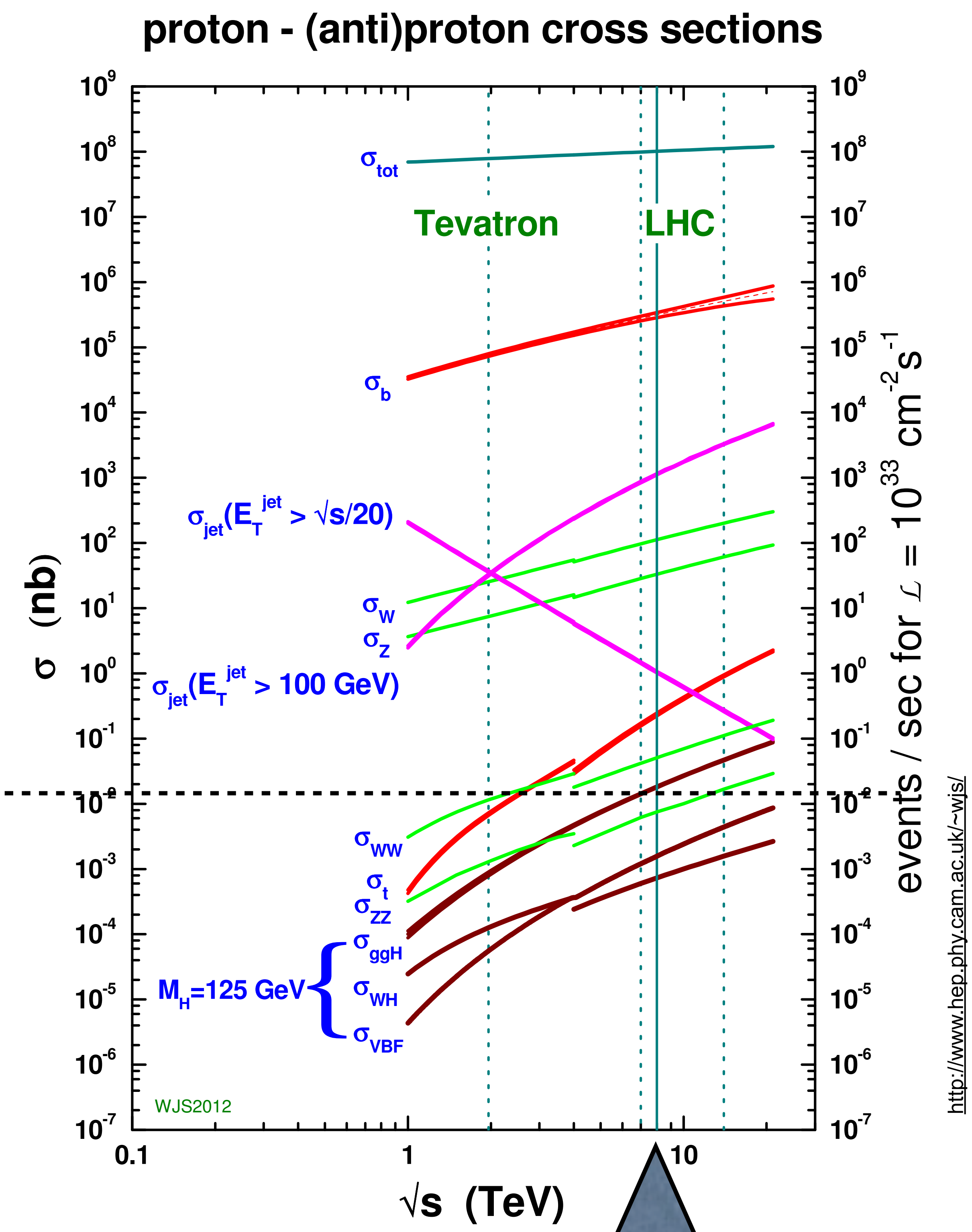
$$\sigma_{\mathrm{tot}} \sim 115\ \mathrm{mb} \sim \left(3.4 \times 10^{-15}\ \mathrm{m}\right)^2$$

@ 7 × 10^{33} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

process	σ(nb)	R(Hz)
inelastic	~7.5x10^7	0.53x10^9
Z	~35	250
ttbar	~0.24	1.7
$H_{(125\mathrm{GeV})}$	~0.022	0.15

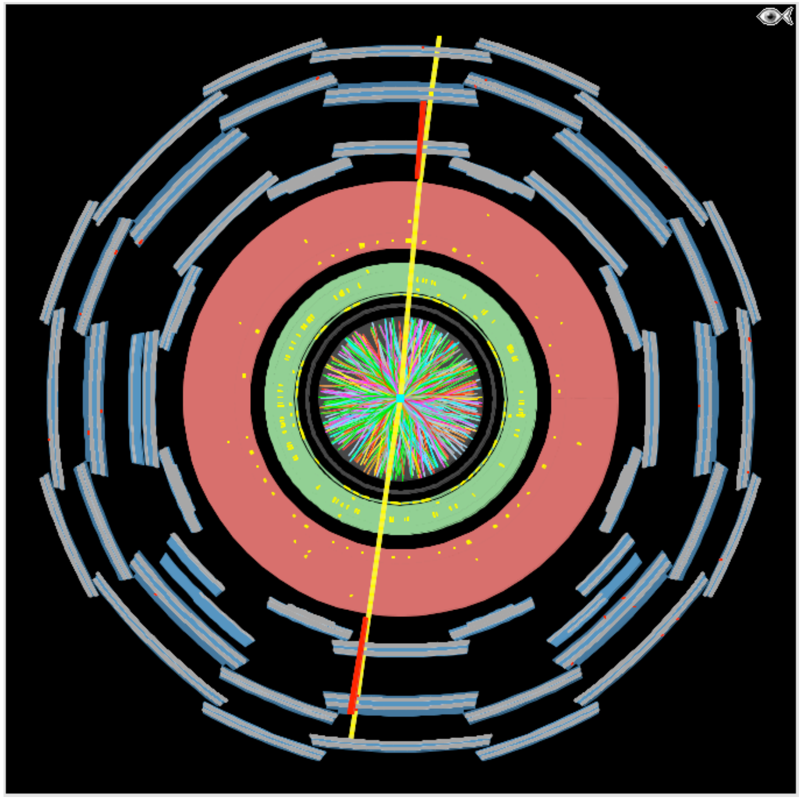
~0.5 M in 2012!

Higgs production is nearly **10 orders of magnitude** less than the total cross section!

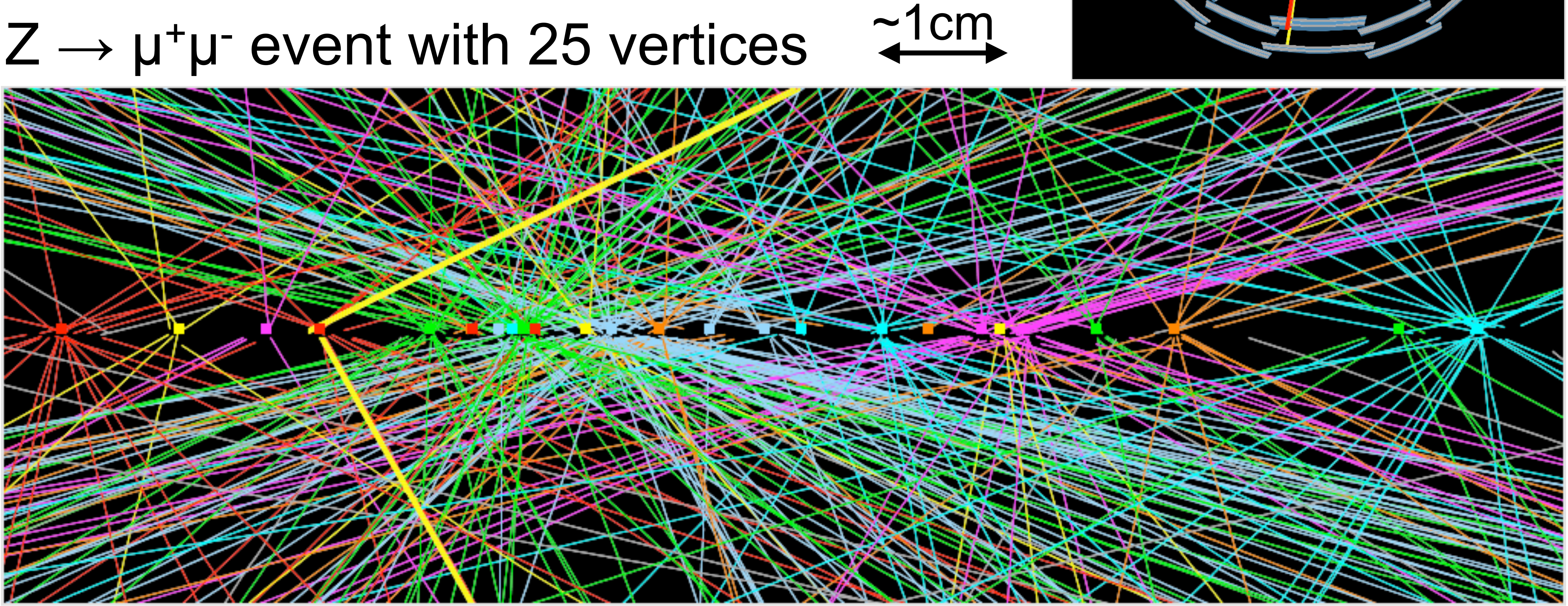


Experimental challenge: Pile-up

- In-time pile-up
  - due to multiple collisions per bunch crossing
  - **in 2012, ~20 events per bunch crossing!!**
- Out-of-time pile-up
  - superposition of signal from preceding (and following) bunch crossing



$Z \rightarrow \mu^+\mu^-$ event with 25 vertices



SM production cross sections

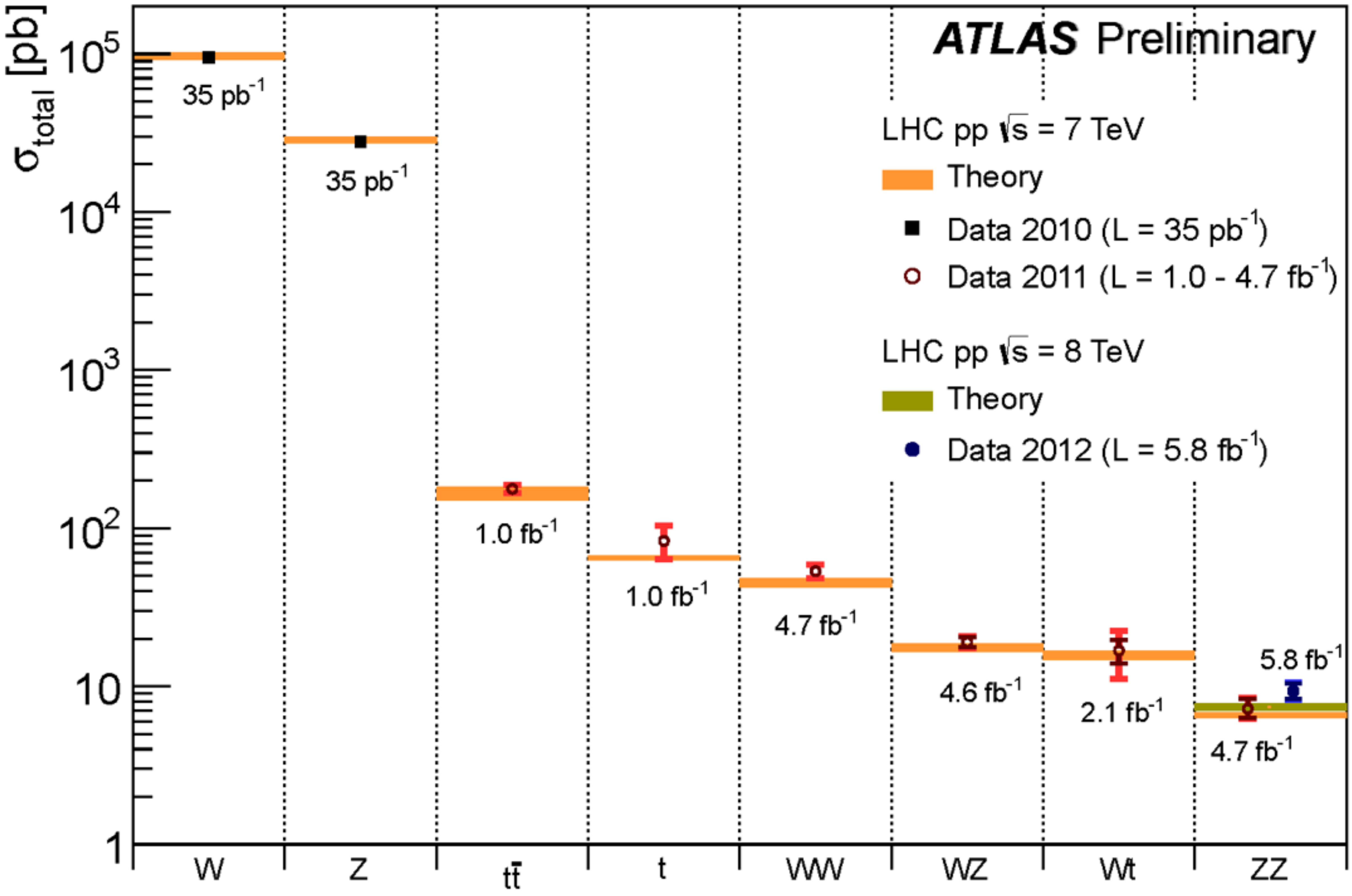


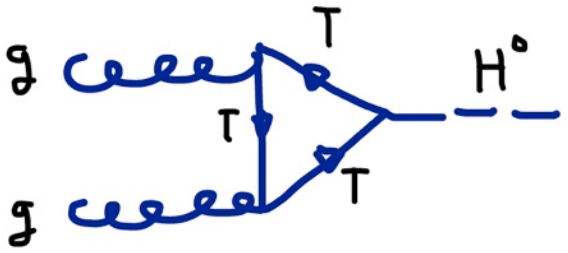
figure as of 2012/06/30

the **Higgs boson**: the missing piece

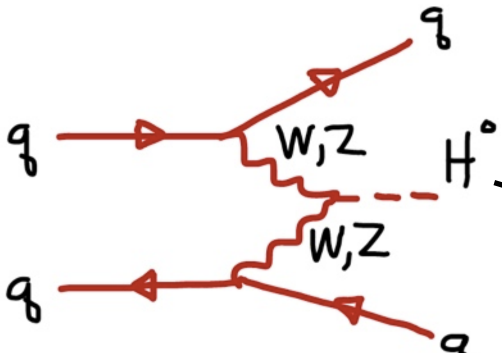
H^0

neither matter nor force

SM Higgs production

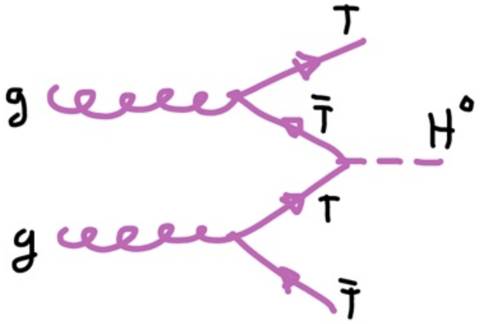


gg fusion



W,Z fusion

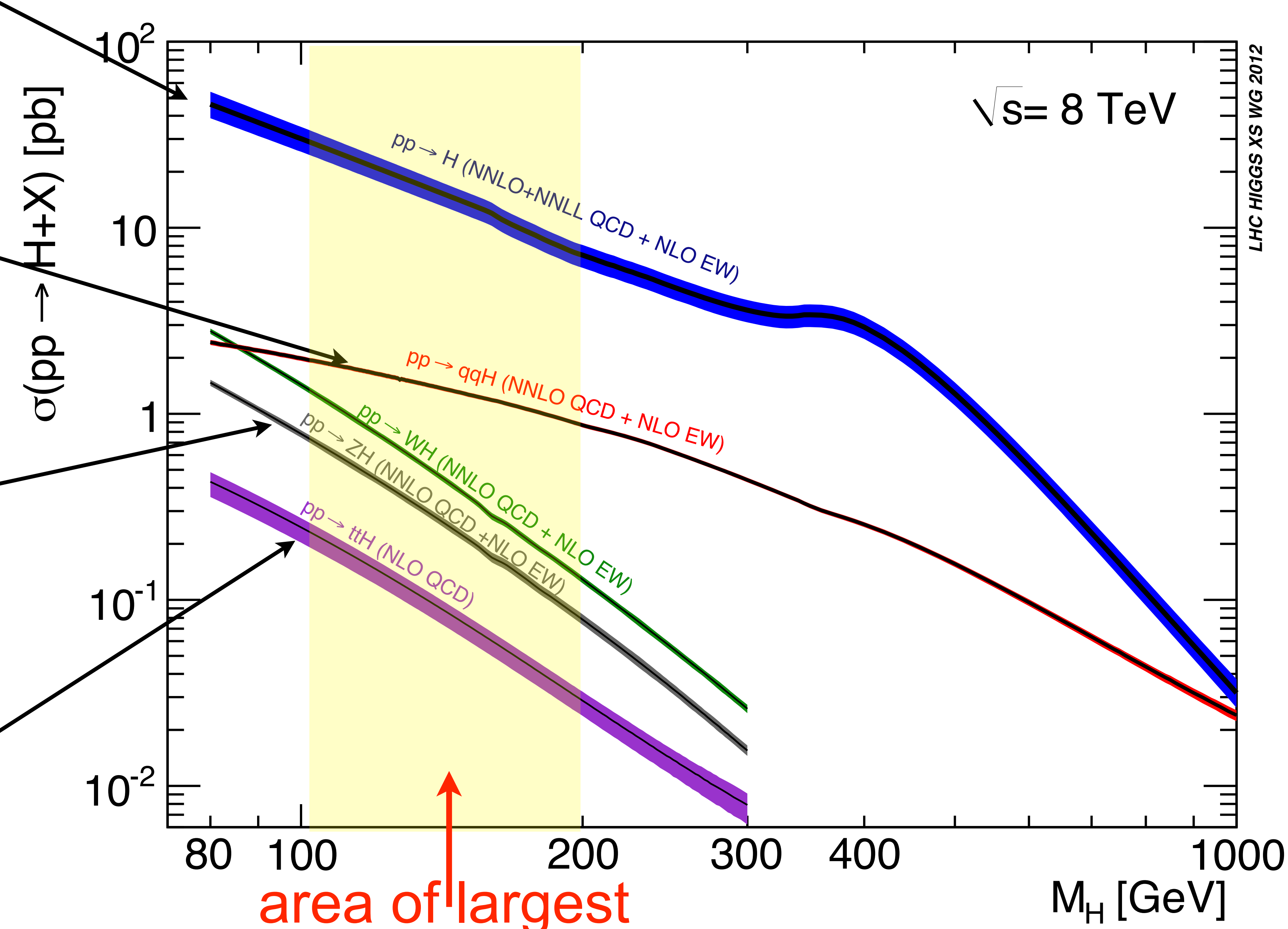
W,Z bremsstrahlung



top-antitop fusion

Predicted cross sections for

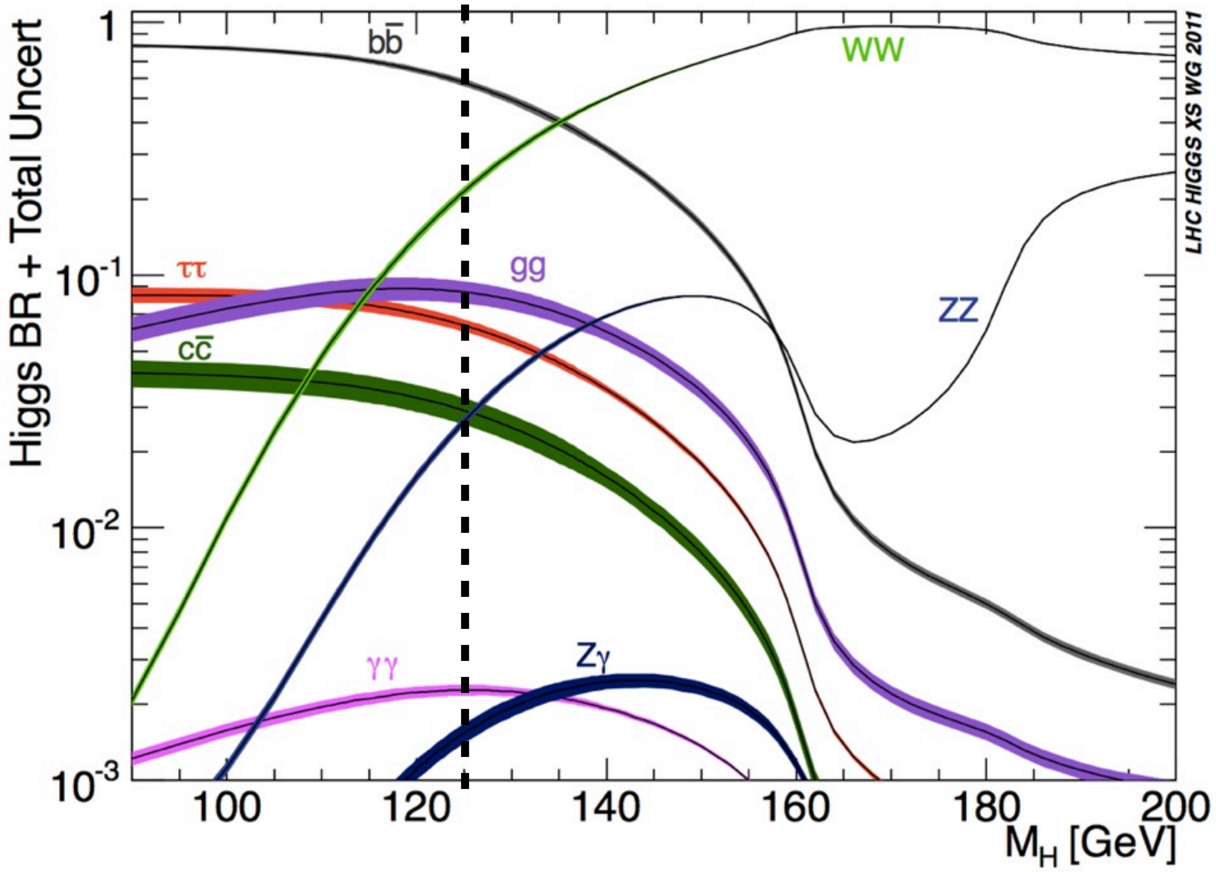
M_H = 125 GeV @ 8 TeV : **22.3 pb**



area of largest interest

SM Higgs decays

Many possible decay channels of the Higgs boson



The most important decays for searches, with fractions for M_H = 125 GeV:

~58% $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$

~0.5% $\mathrm{H} \to \mathrm{W}\,\mathrm{W}^{(*)} \to e\,\nu\,\mu\,\nu$

~6.3% $\mathrm{H} \to \tau\,\tau$

~0.23% $\mathrm{H} \to \gamma\,\gamma$

e or μ pairs

~0.02% $\mathrm{H} \to \mathrm{Z}\,\mathrm{Z}^{(*)} \to 4\ell$

The cleanest channels are also the rarest...

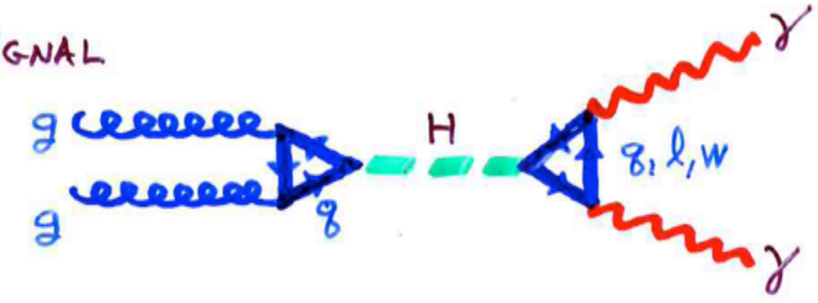
CAP June 1996

$H \rightarrow \gamma\gamma$

- BEST CHANNEL FOR 80 GeV $< M_H <$ 120 GeV

  PRESENT DIRECT LIMIT FOR SM H : $M_H > 65.2$ 95%
  EXPECT LEP (192 GeV) : $M_H > 95$ GeV

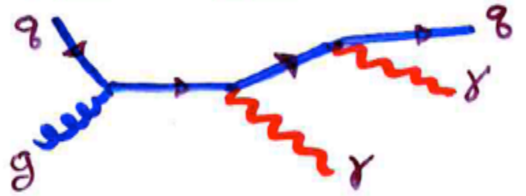
- SIGNAL



g FUSION

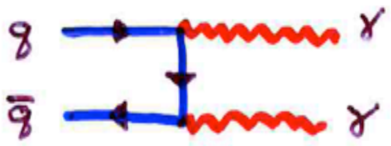
- BACKGROUND

  IRREDUCIBLE : QCD PRODUCTION



q BREM

$gg \rightarrow \gamma\gamma$ (BOX)



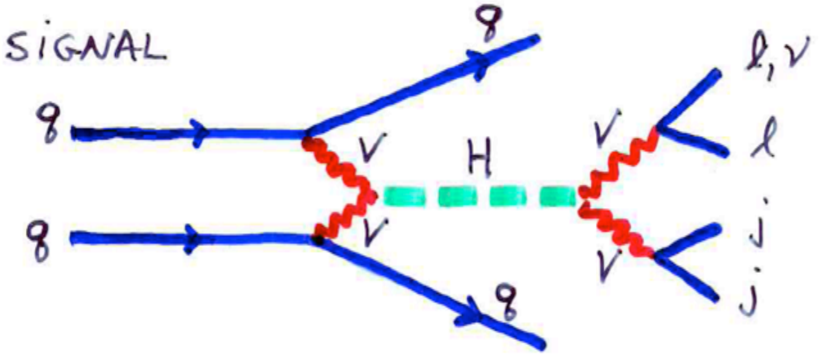
$q\bar{q} \rightarrow \gamma\gamma$ (BORN)

  REDUCIBLE : QCD JETS } WITH FAKE γ
  $Z \rightarrow ee$

- CHALLENGING CHANNEL

$H \rightarrow WW \rightarrow l\nu jj$
$ZZ \rightarrow lljj$

- INTERESTING BECAUSE 150× BRANCHING RATIO OF γγ CHANNEL
- SIGNAL



V FUSION

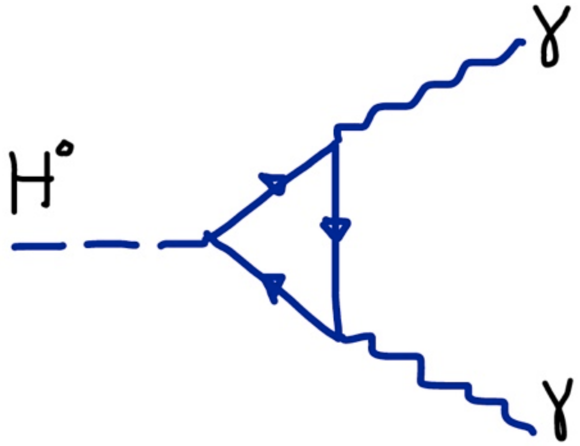
- BACKGROUND

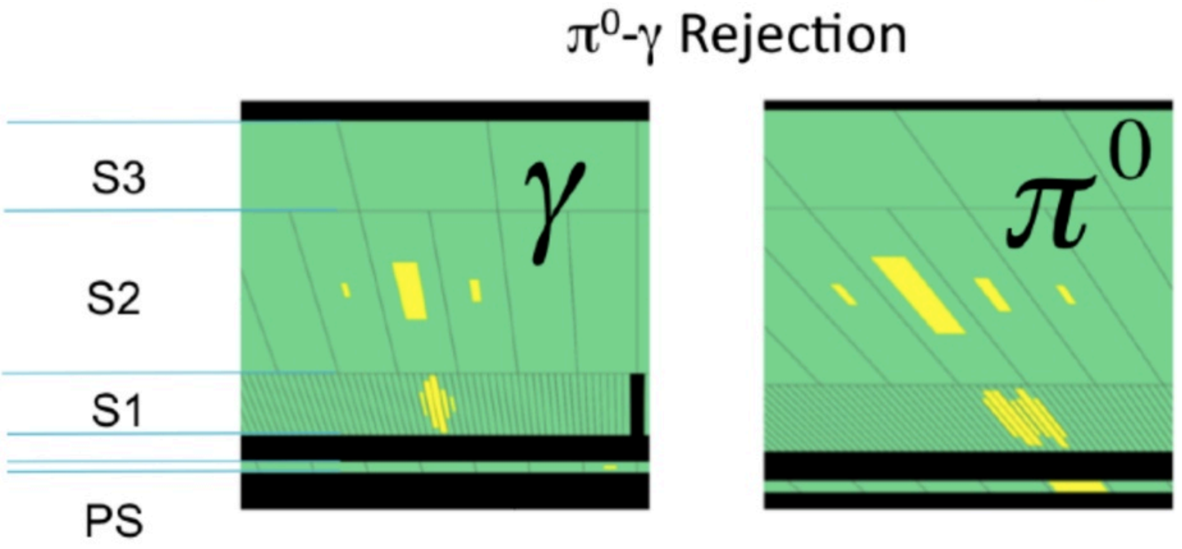
  $T\bar{T}$, W + JETS

- TO CONTROL BACKGROUND
  - NEED A GOOD $\sigma_{M_{jj}}$ FOR M_W, M_Z RECONSTRUCTION
    - → CALORIMETER GRANULARITY
    - → PILEUP CONTROL
  - FORWARD JET TAGGING $2 < |\eta| < 5$
  - CENTRAL JET VETO

H → $\gamma\ \gamma$

- Look for two isolated high energy photons
  - need good photon identification
- Large background
  - irreducible SM 2-photon production
  - fake photons (neutral pions)
    - use shower shape in LAr calorimeter segmented readout





- Reconstruct the 2-photon invariant mass
  - look for a signal mass bump over a large background

$$M_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\alpha)$$

need good photon energy reconstruction

need good photon direction

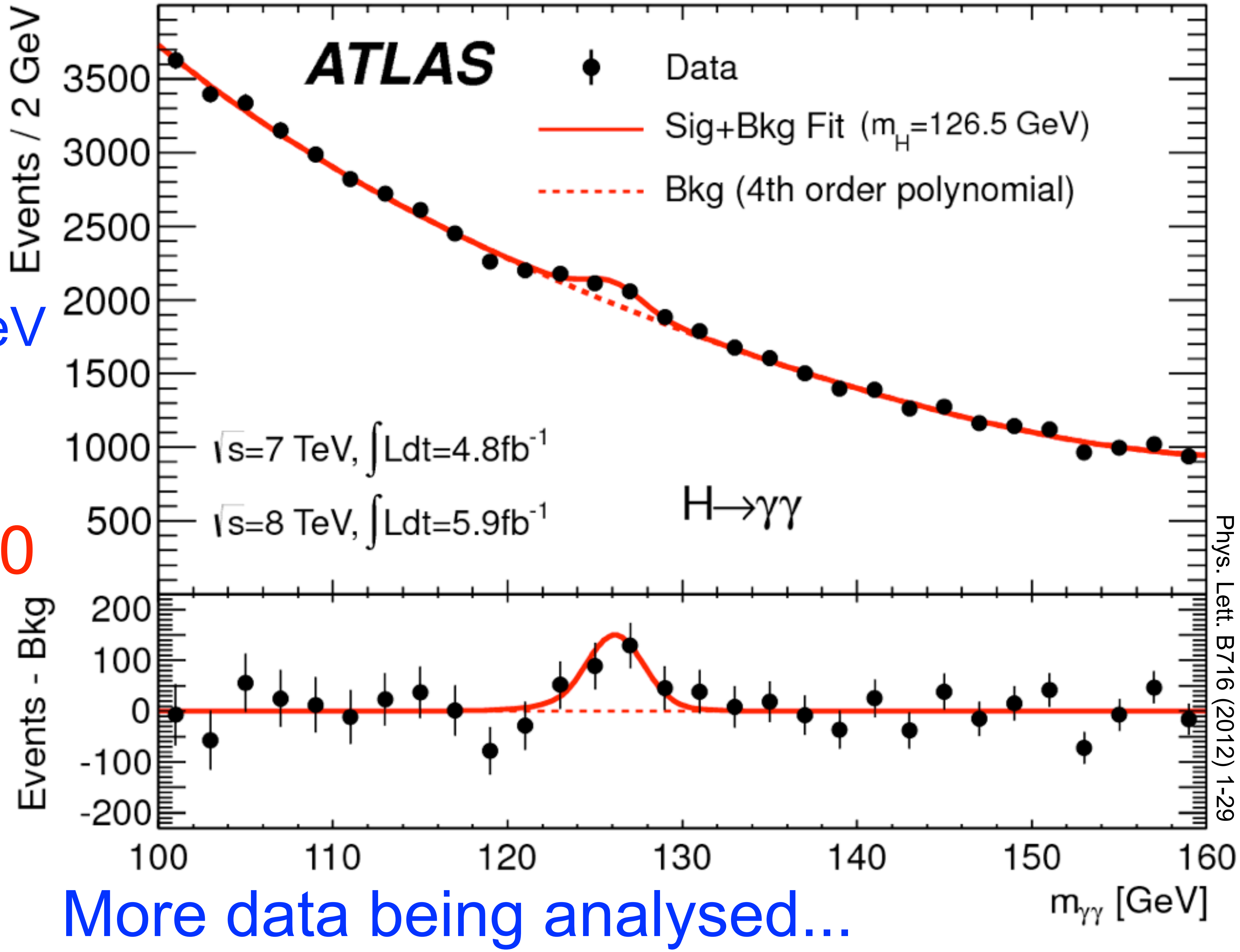
H → γ γ

Excess of events!

M ~ 126.5 GeV

4.5 σ

~1 / 300000 chance of being a statistical fluctuation



Phys. Lett. B716 (2012) 1-29

More data being analysed...

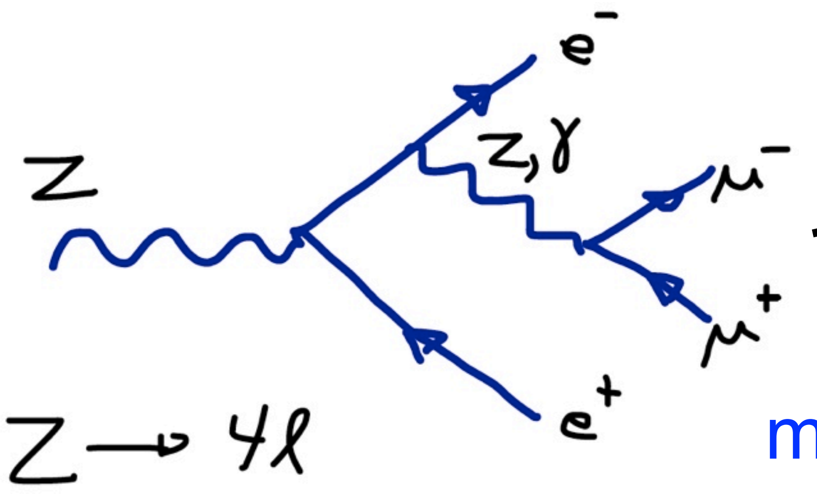
$H \rightarrow ZZ^{(*)} \rightarrow$ 4 leptons

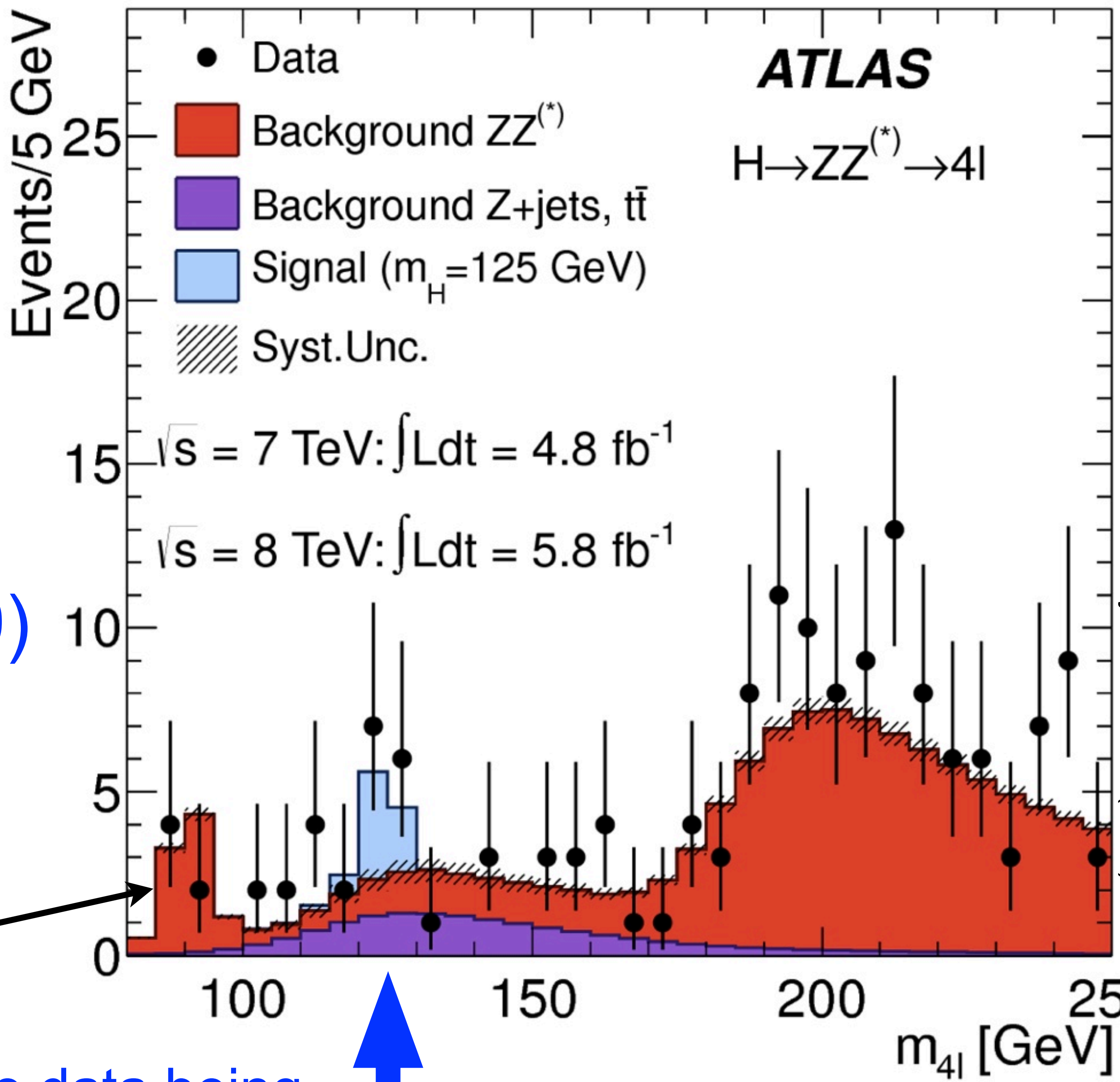
- Look for four isolated high energy leptons
  - very clean, but rare!
- Reconstruct invariant mass of system
  - excellent mass resolution

Excess of events!

3.6 σ (~1 / 6300)

M ~ 125.0 GeV

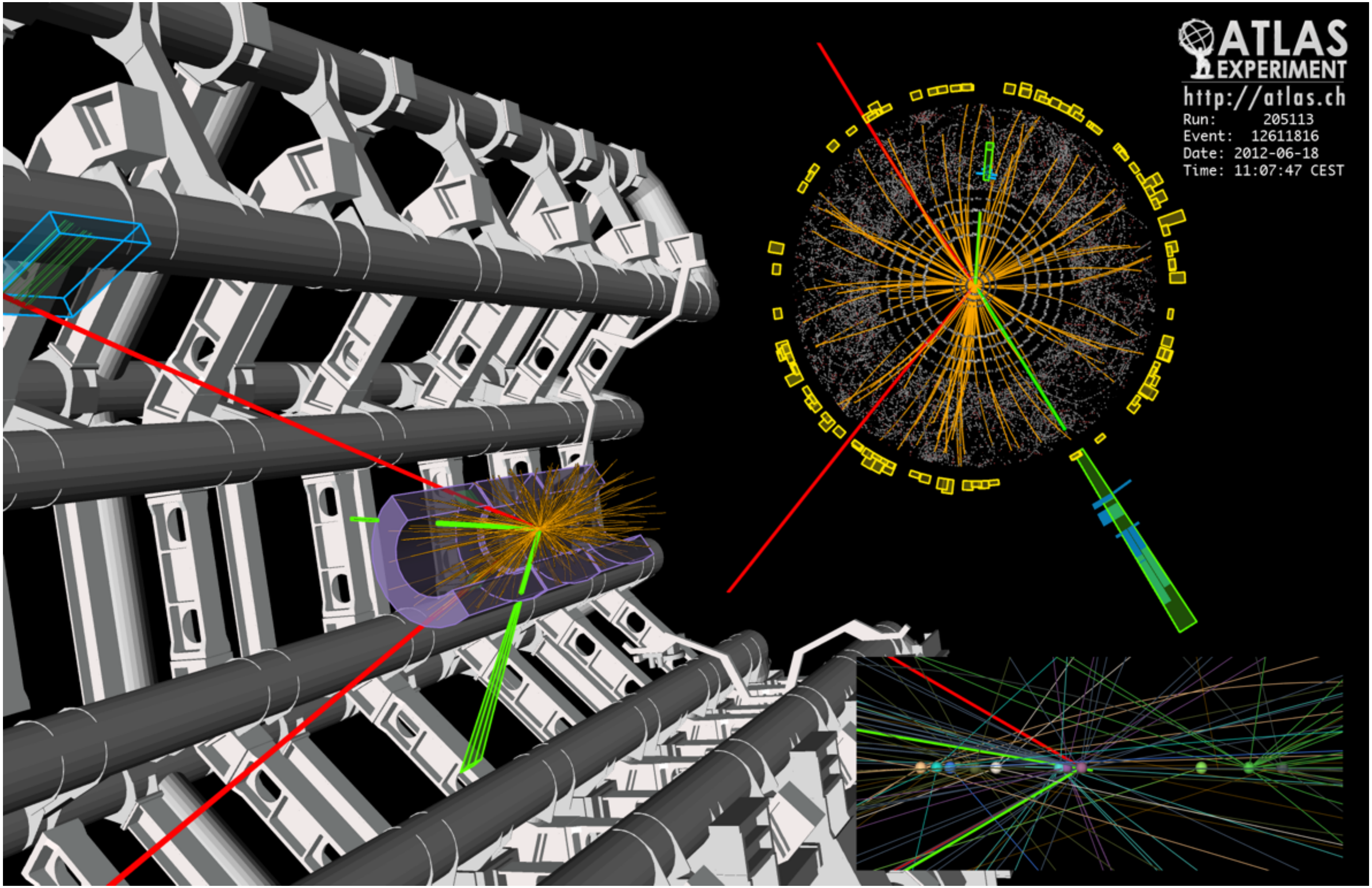




Phys. Lett. B716 (2012) 1-29

more data being analysed...

$H \rightarrow ZZ^{(*)} \rightarrow 4\ e$?



$H \to WW^{(*)} \to 2$ leptons + 2 neutrinos

- Look for two isolated high energy leptons and missing transverse momentum
  - good rate, but lots of background
- Cannot fully reconstruct the invariant mass of system
  - neutrinos escape detection
  - use a discriminant variable related to the Higgs candidate mass

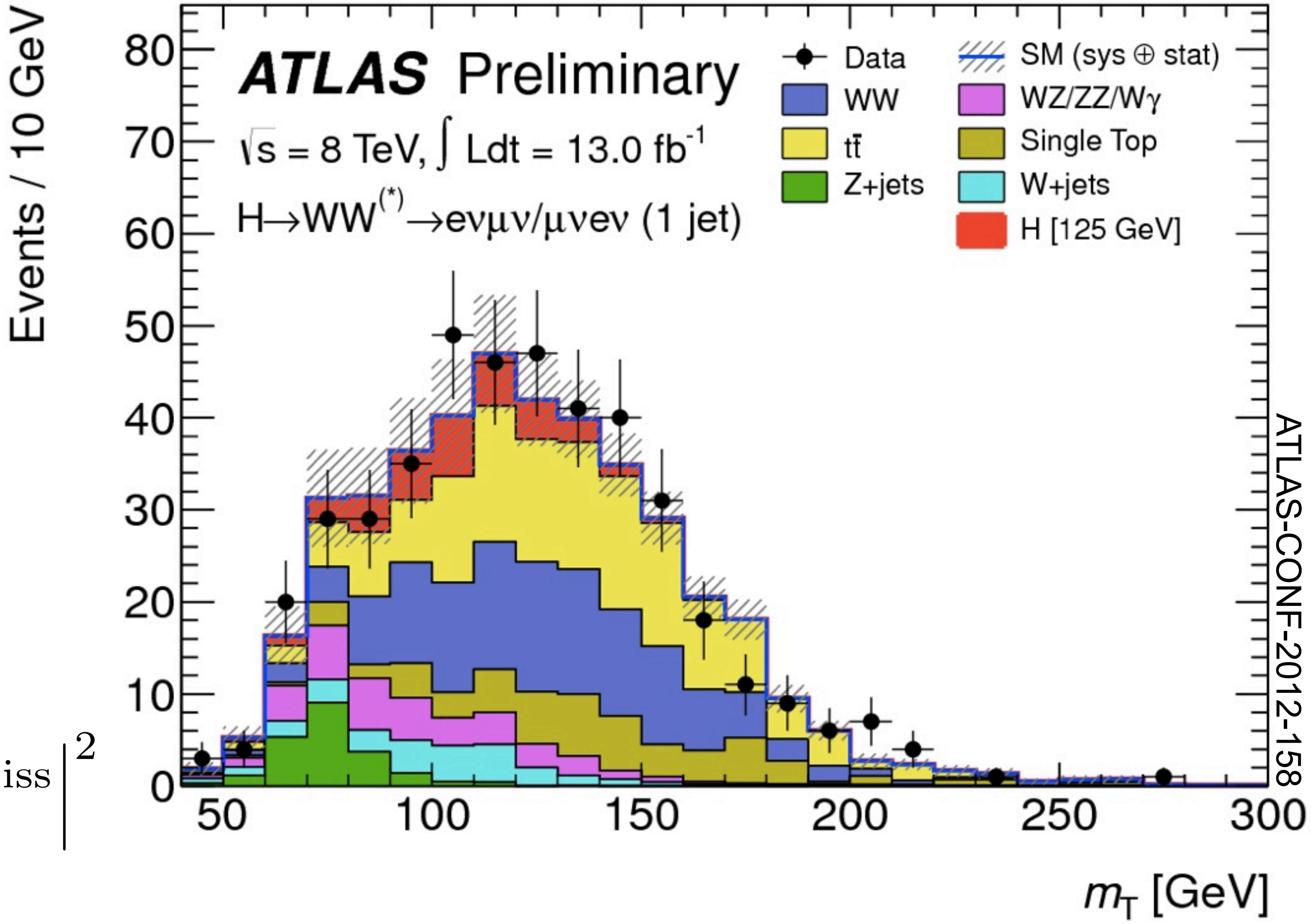
Excess of events!

2.8 σ (~1 / 400)

M ~ 125.0 GeV

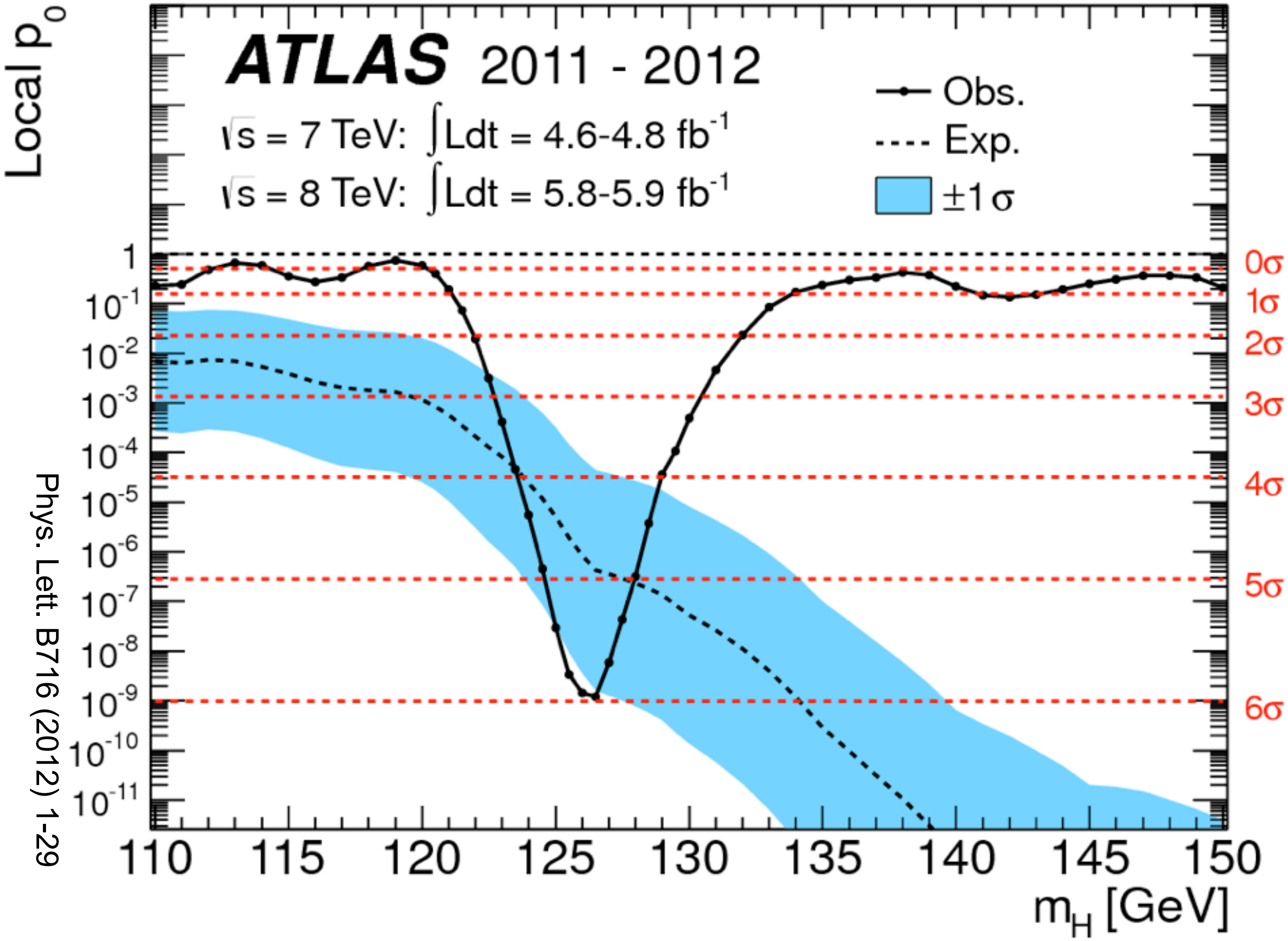
$$m_T^2 = \left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2$$

$$(E_{\ell\ell})^2 = \left|\vec{p}_T^{\,\ell\ell}\right|^2 + m_{\ell\ell}^2$$



Observation of a new particle

- The five best channels are statistically combined
  - sophisticated treatment, including all systematic errors



Phys. Lett. B716 (2012) 1-29

p_0: test of background only hypothesis

$p_0 = 1.8 \times 10^{-9}$

local: 5.9 σ

~1 / 550,000,000 chance of being a statistical fluctuation of the background!

global: 5.1σ

for 100-600 GeV

1.7×10^{-7}

~1 / 5,900,000

$$M = 126.0 \pm 0.4\ (\text{stat}) \pm 0.4\ (\text{sys})\ \text{GeV}$$

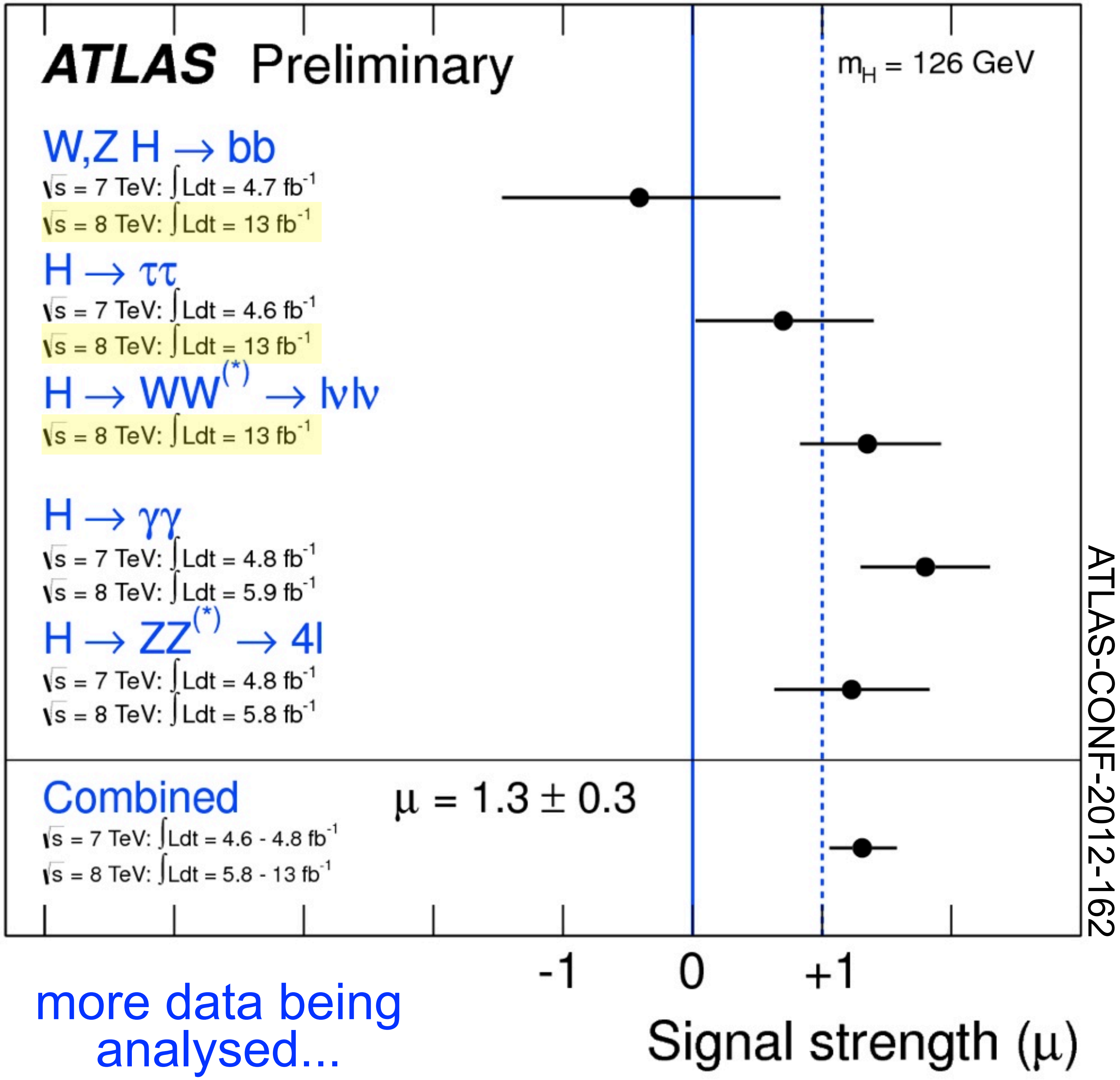
4 July 2012 CERN and Melbourne

CERN, 09:00

ICHEP 2012, Melbourne, 19:00

00:00 in Victoria!

Higgs-like particle signal strength



13 Nov 2012 update

$$\mu = \frac{\sigma}{\sigma_{\rm SM}} \frac{B}{B_{\rm SM}}$$

$$1.3 \pm 0.3$$

Assuming a common μ for all measurements, compatibility is 36%

Compatibility with SM μ=1 with observed measurement is 23%

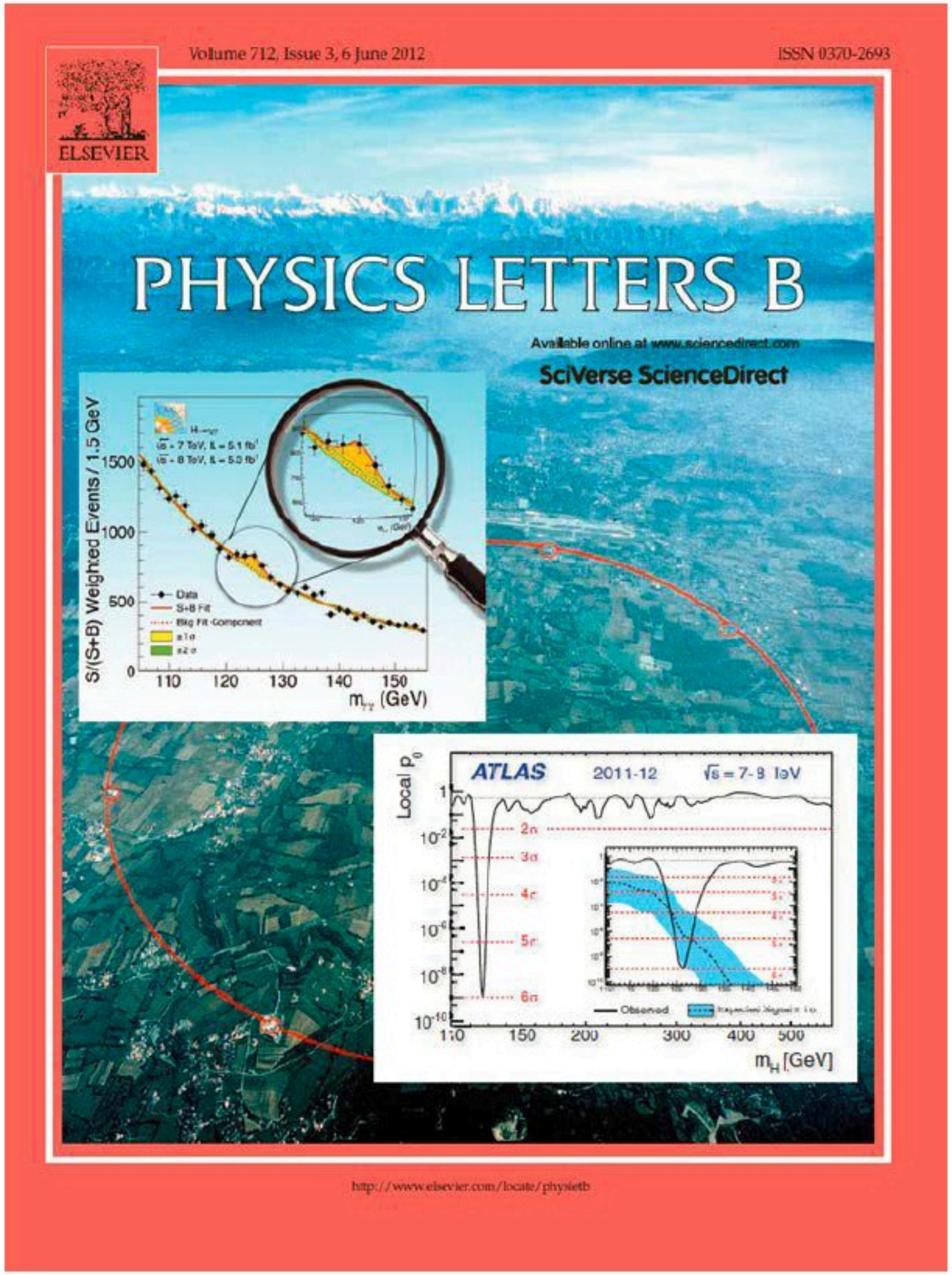
CMS obtains

$$0.88 \pm 0.21$$

more data being analysed...

Is it the Higgs boson?

- We have discovered a new particle!
  - savour this privileged and historical moment
- Spin 0?
  - naturalness issue: M_H small only if protected by some symmetry
  - so far: **boson, not of spin 1**
- Couplings as predicted by the SM gauge symmetry?
  - otherwise at odds with gauge principle that rules all forces!
  - so far: 20-25% error on measured couplings, **agreement with SM**



Volume 712, Issue 3, 6 June 2012

ISSN 0370-2693

ELSEVIER

PHYSICS LETTERS B

Available online at www.sciencedirect.com

SciVerse ScienceDirect

http://www.elsevier.com/locate/physletb

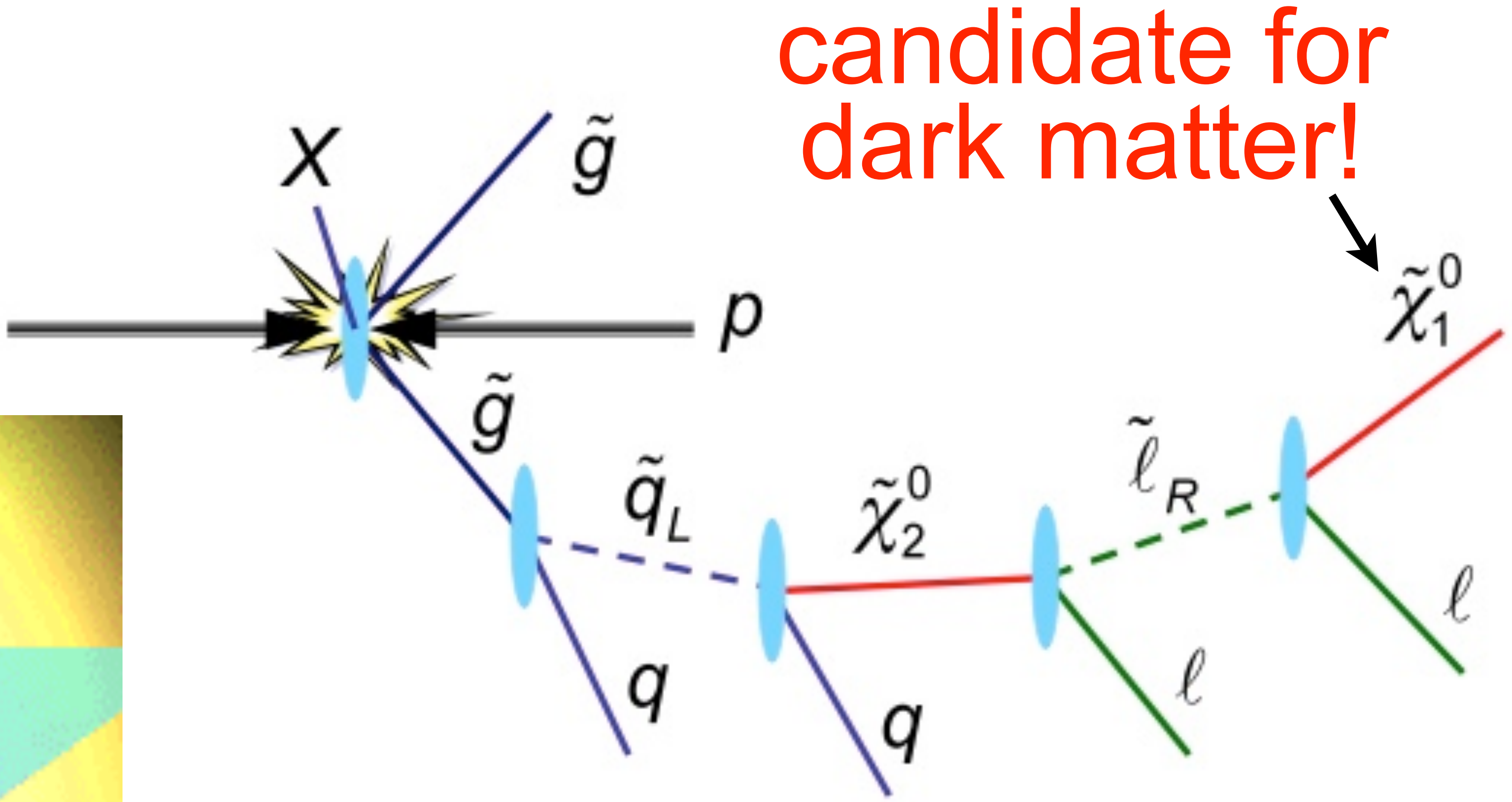
Phys. Lett. B 716 (2012) 1-29 (ATLAS)

Many more questions

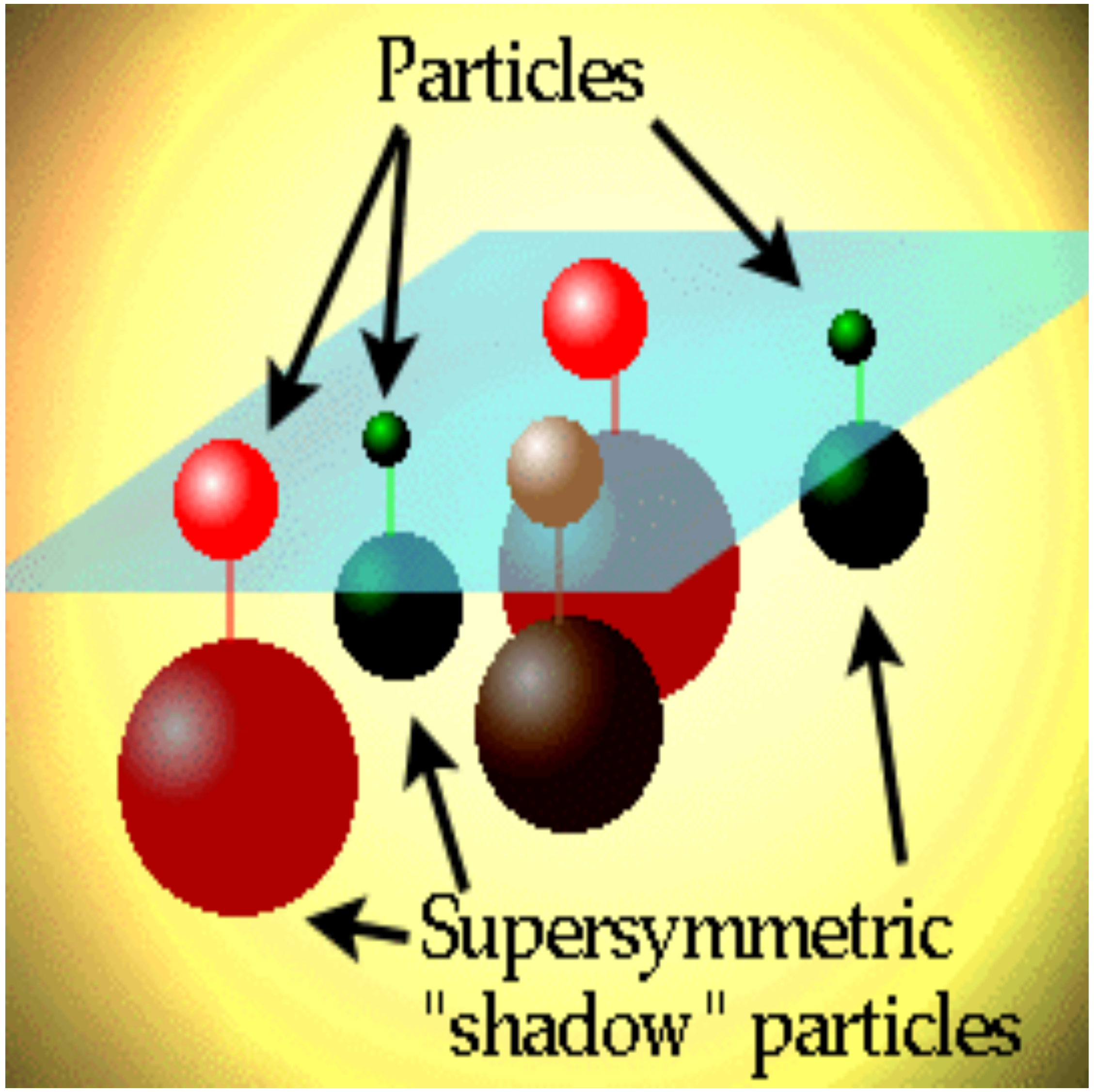
- What is the nature of Dark Matter?
- Why is there more matter than antimatter?
- Can all forces be unified?
- Is SuperSymmetry realized in Nature?
- Are fundamental particles fundamental?
- Are the extra dimensions of space?
- Why three families of quarks and leptons?
- Why are neutrinos so light?
- What is Dark Energy?

Supersymmetry

- Theoretical idea: extended symmetry of Nature
  - Wess and Zumino, 1974
  - establishes a symmetry between fermions (matter) and bosons (forces)



candidate for dark matter!



- Required in most theories of new physics
- Predicts super-partners of all particles!
  - “sparticles”,not yet found: broken symmetry
- Many possible signatures sought for at the LHC!

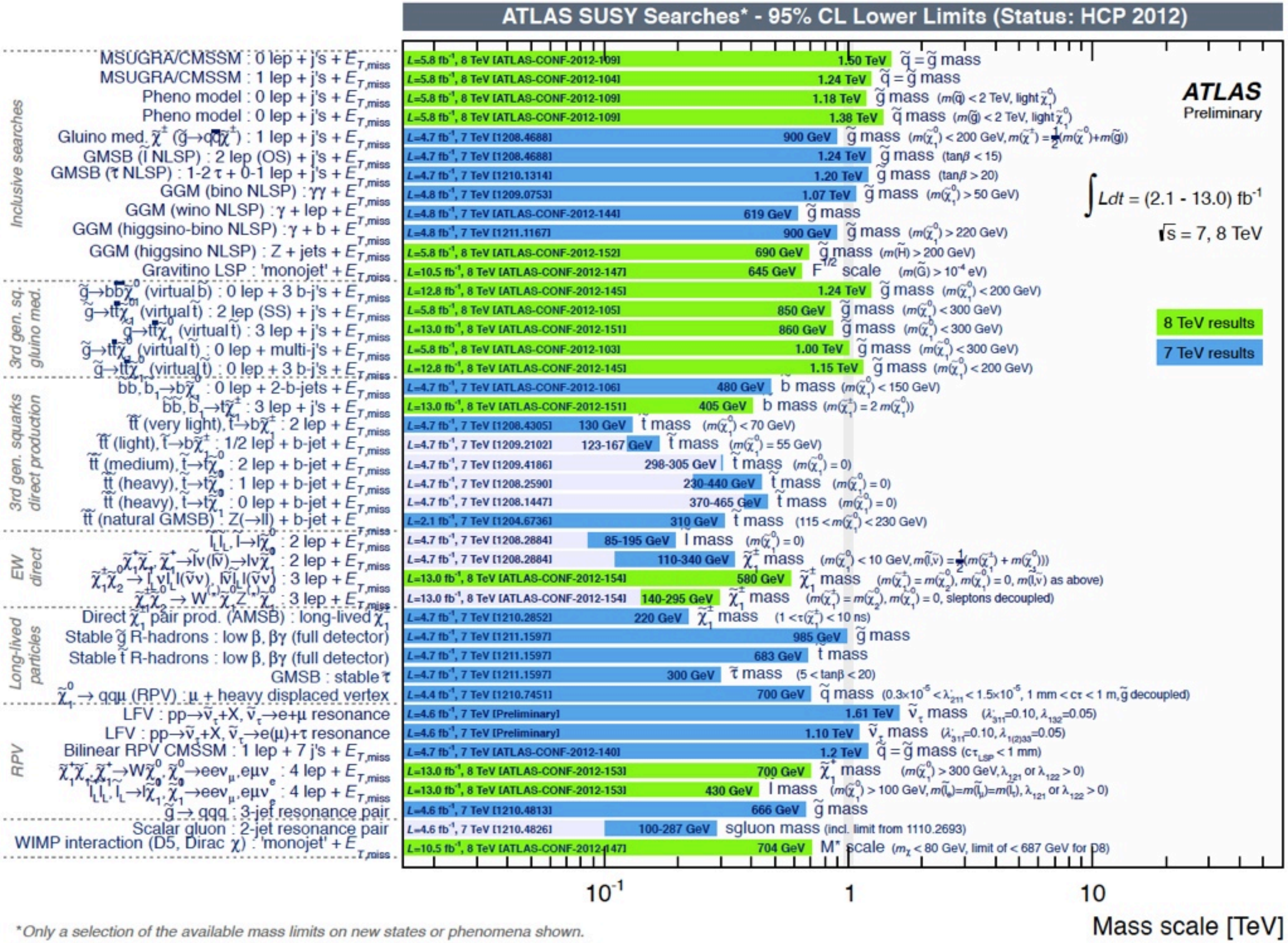
Supersymmetry searches

- Aggressively probing weak scale SUSY between 100 GeV and 1 TeV

inclusive searches

natural SUSY

long lived particles



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Exotic searches

- Many searches... no evidence for new physics so far

extra dimensions

substructure

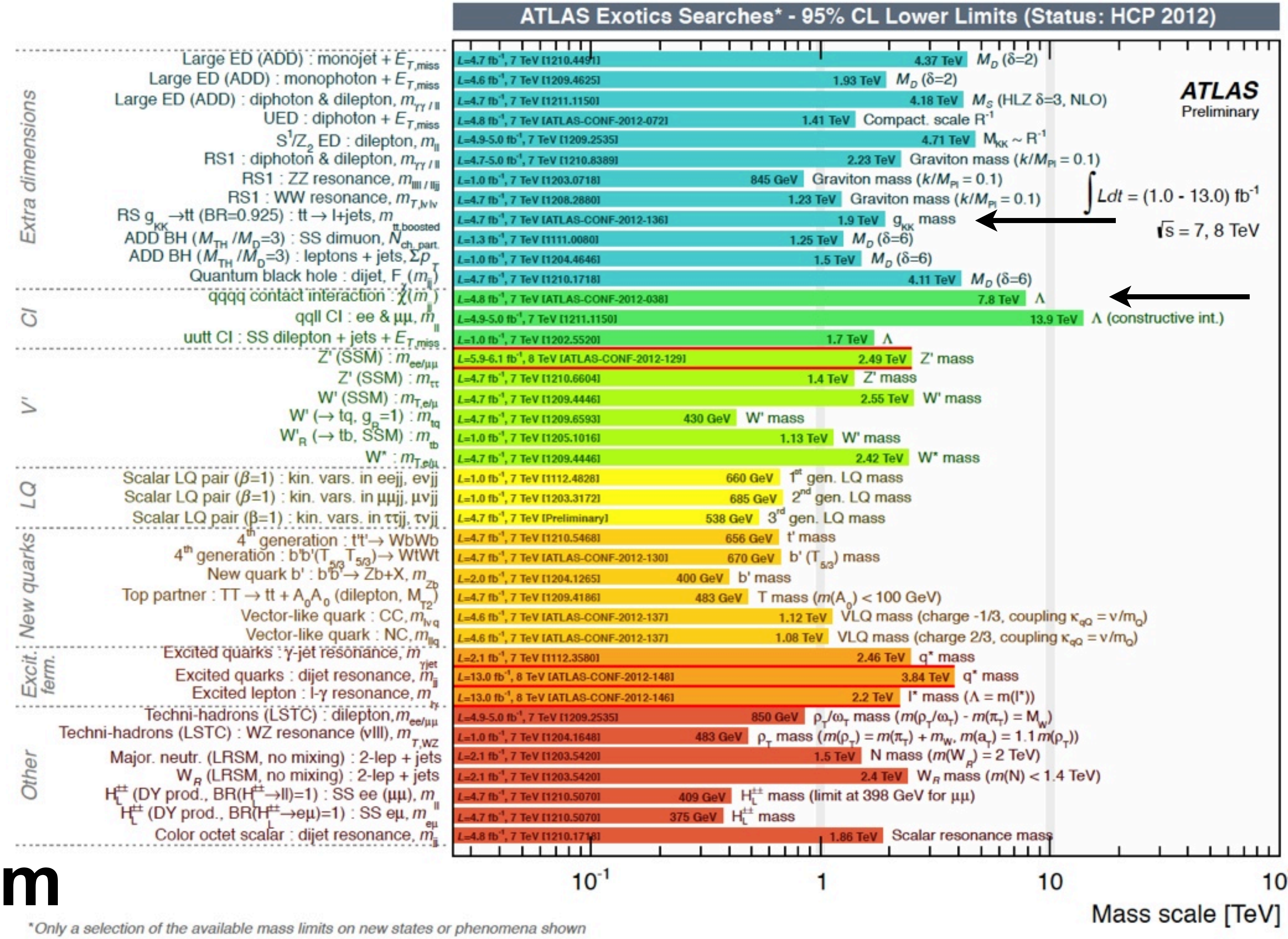
W’, Z’

leptoquarks

new quarks

substructure

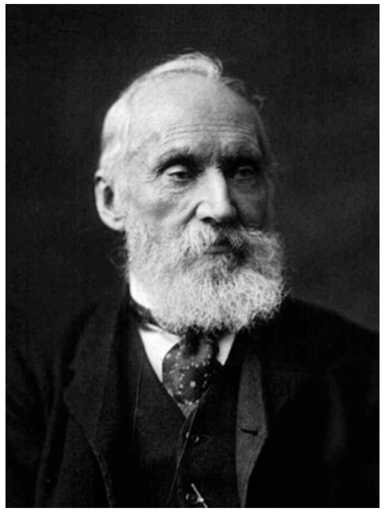
10 TeV → ~ 2 x 10^{-20} m



If it's the Higgs, is that it?

"Our future discoveries must be looked for in the 6th place of decimals."

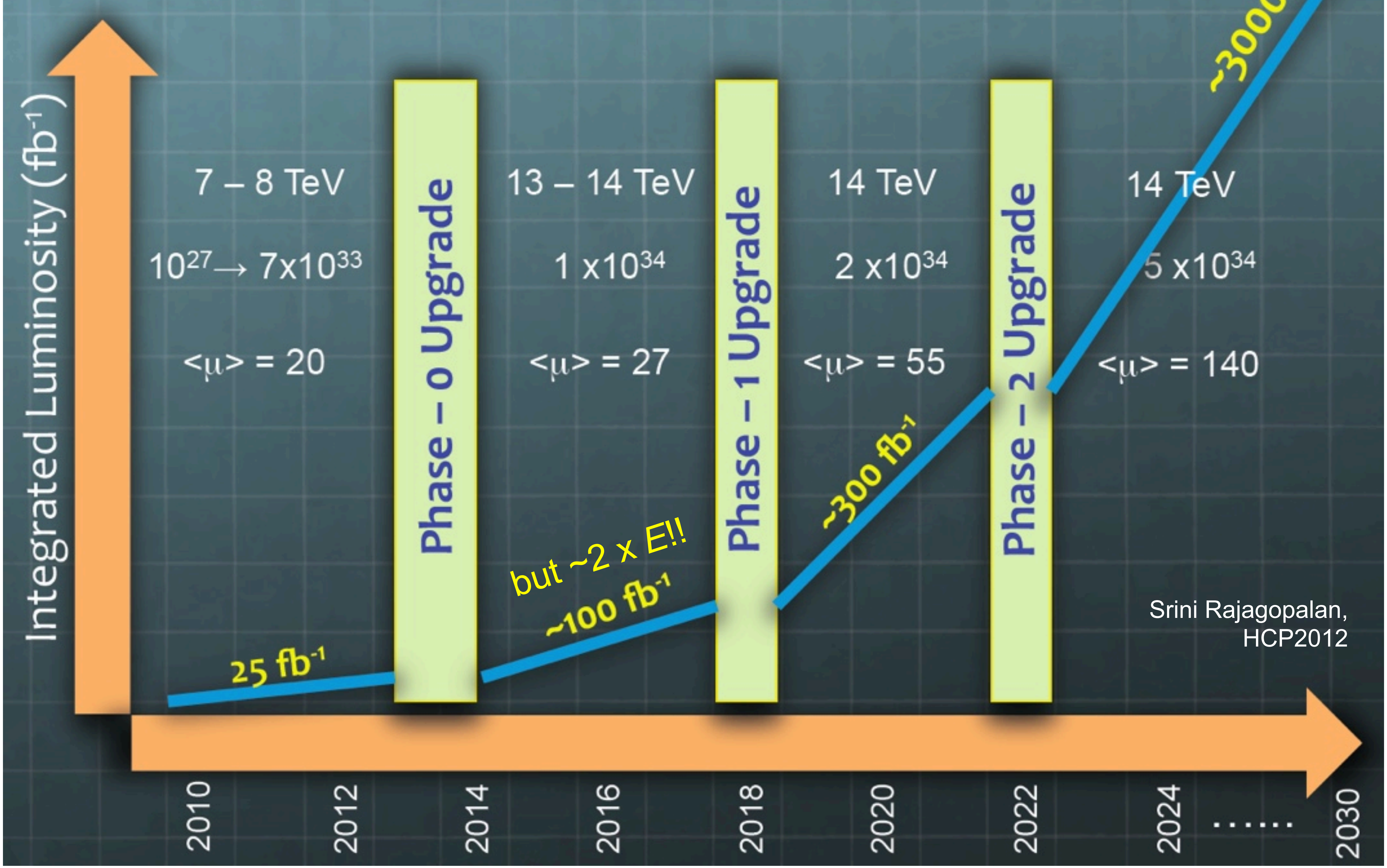
Albert A. Michelson, 1894



"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

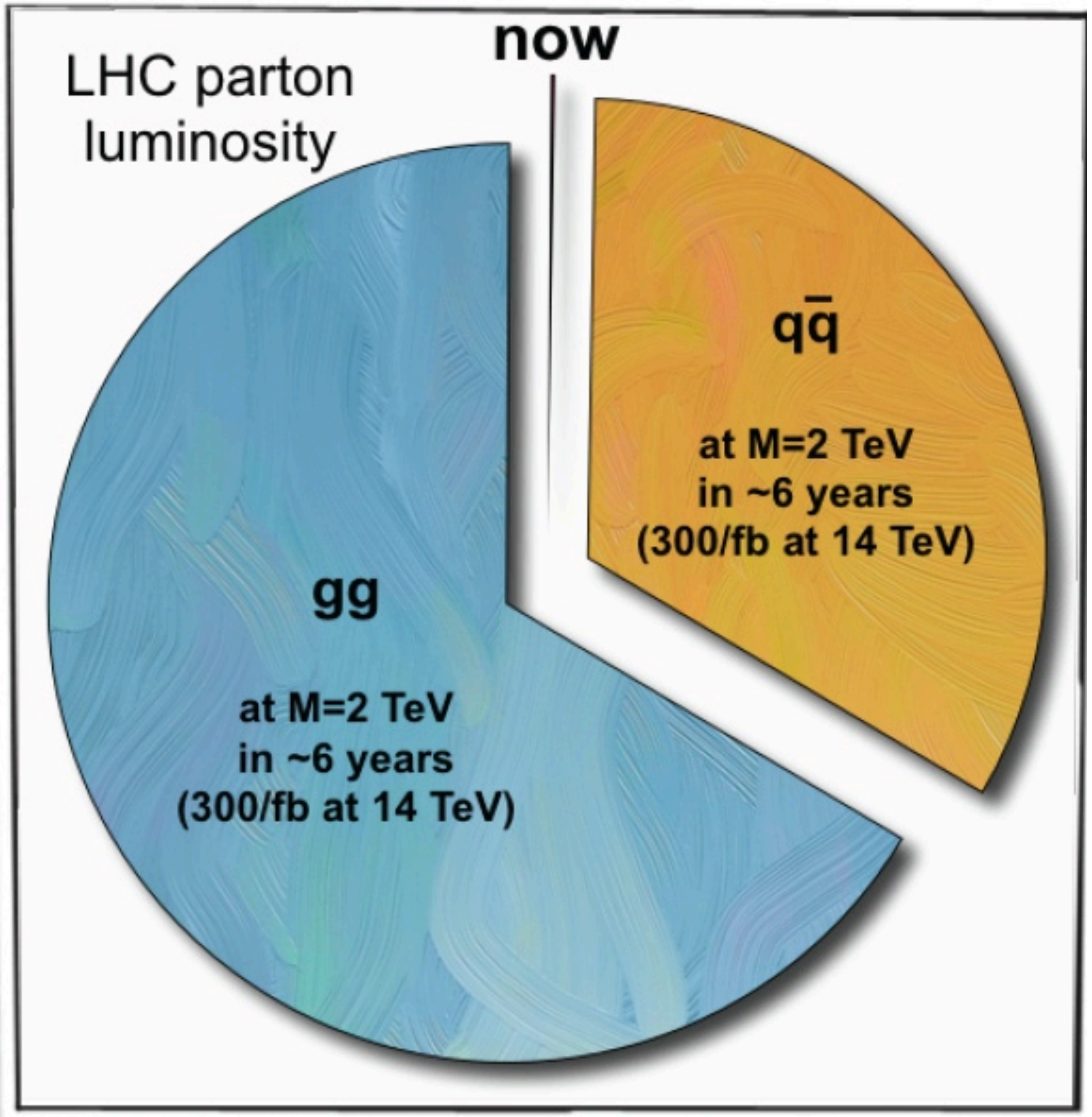
William Thomson (Lord Kelvin), 1900

LHC forecast



Srini Rajagopalan,
HCP2012

More explorations

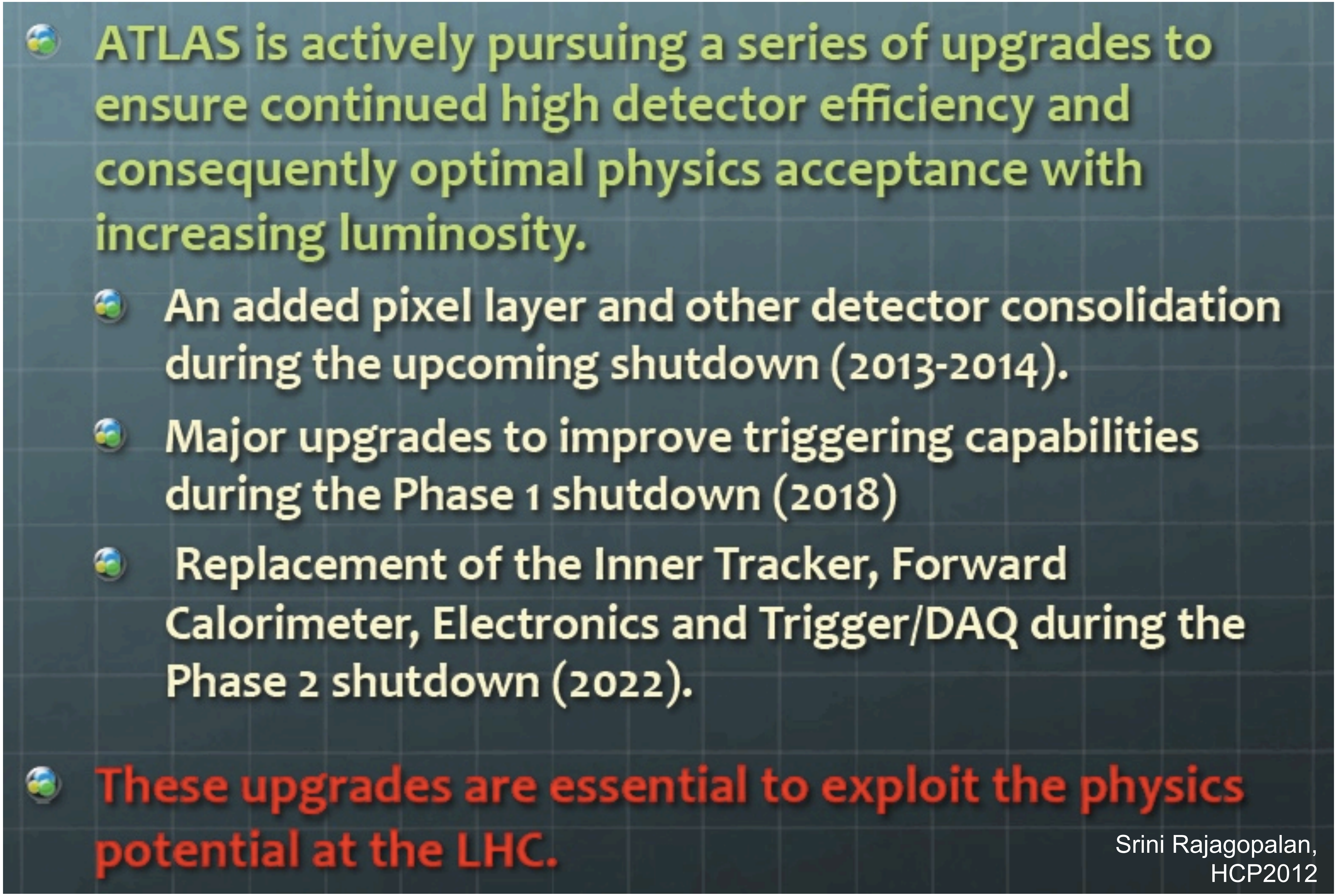


G. Dissertori, quoted by C. Grojean, HCP2012

...and the unexpected!

- We are only starting the exploration of the TeV scale at the LHC!
- 300 fb^{-1} → 3000 fb^{-1}
  - precision measurement of Higgs couplings (in particular measure coupling with top and μ)
  - direct measurements of the Higgs tri-linear self-couplings via HH pair production: ~30% precision with ATLAS+CMS with 3000 fb^{-1}
  - extend the reach of searches for physics beyond the Standard Model, eg top-antitop resonances up to 7 TeV

ATLAS Upgrades



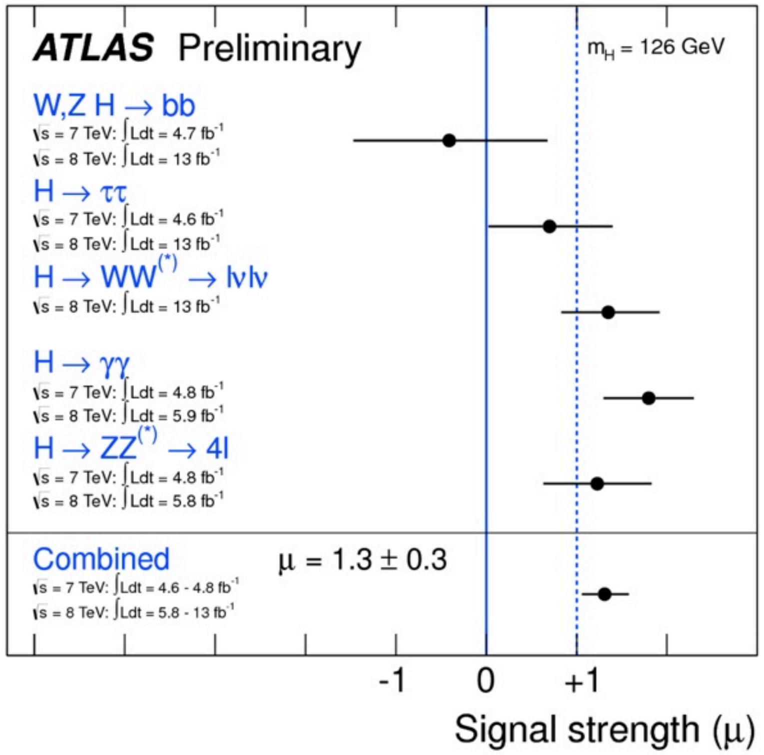
- ATLAS is actively pursuing a series of upgrades to ensure continued high detector efficiency and consequently optimal physics acceptance with increasing luminosity.
  - An added pixel layer and other detector consolidation during the upcoming shutdown (2013-2014).
  - Major upgrades to improve triggering capabilities during the Phase 1 shutdown (2018)
  - Replacement of the Inner Tracker, Forward Calorimeter, Electronics and Trigger/DAQ during the Phase 2 shutdown (2022).
- These upgrades are essential to exploit the physics potential at the LHC.

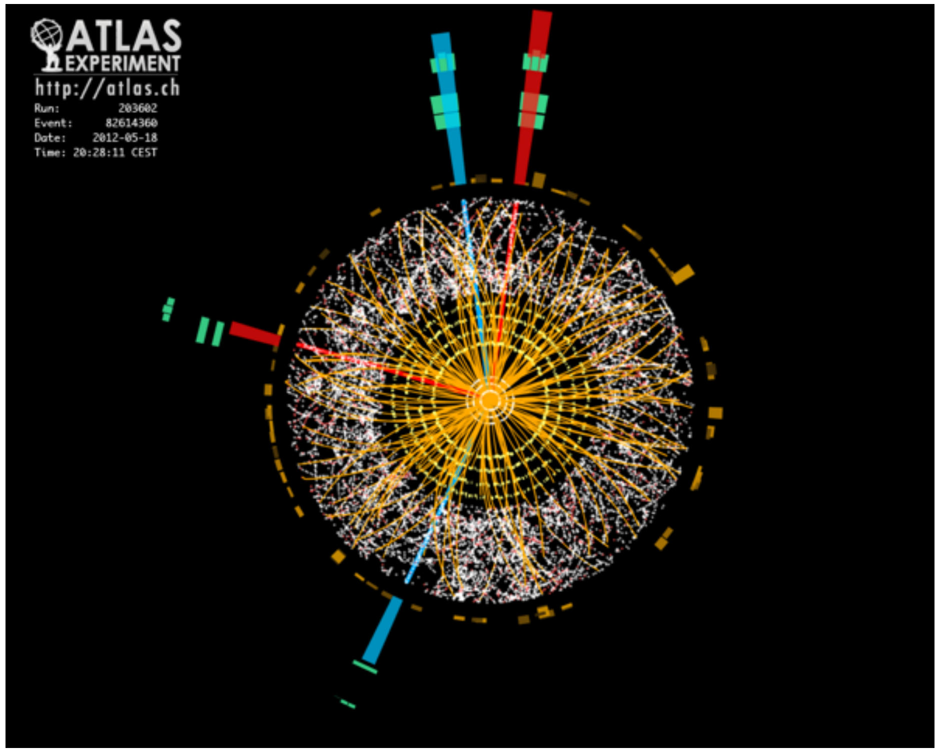
Srini Rajagopalan,
HCP2012

Busy in the ATLAS control room...

Conclusions

- Discovery of a new particle
  - a ~126 GeV neutral boson
  - historical event of great significance
    - is it the Standard Model Higgs boson?
    - decay into two photons rules out spin 1
    - so far compatible with the SM Higgs

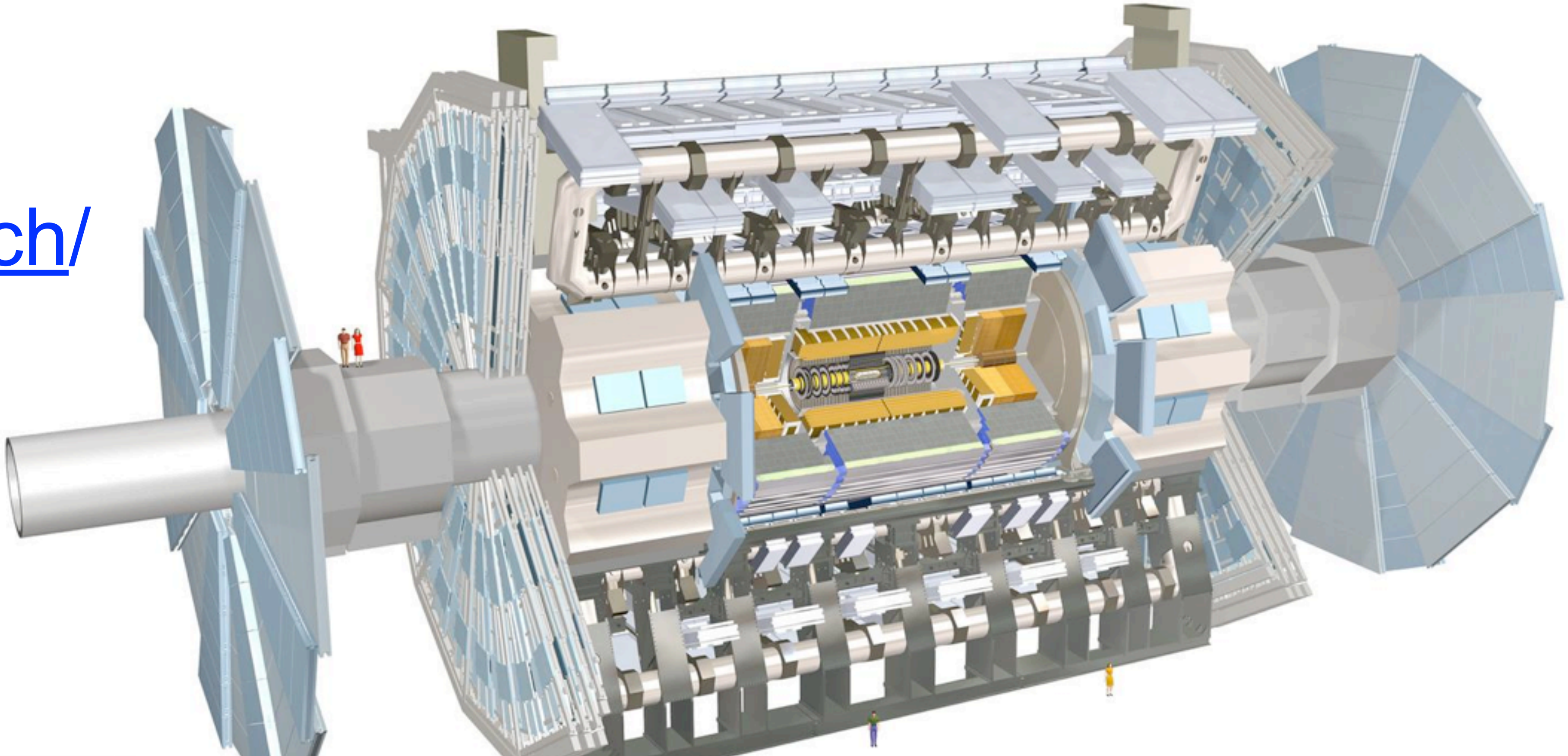


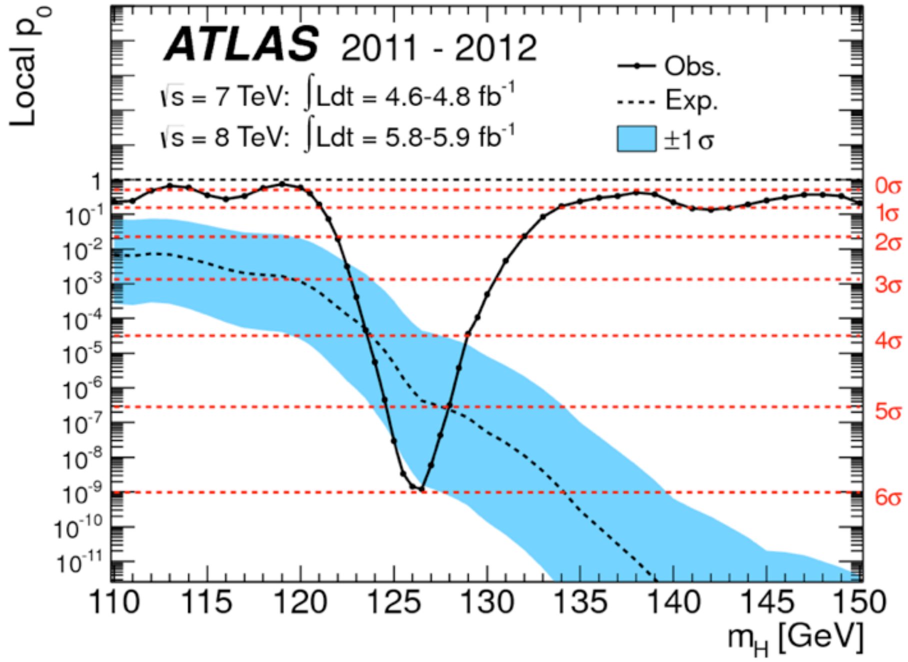


- Exploration at the energy frontier
  - Excellent LHC performance
  - Excellent ATLAS performance
  - this is just the beginning
- Expect more exciting results from the LHC!!

Stay tuned!

- ATLAS
  - http://atlas.ch/
- Opportunities for graduate studies!





Funding support for ATLAS-Canada is gratefully acknowledged: NSERC, NRC and CFI.