Discovery at the Large Hadron Collider

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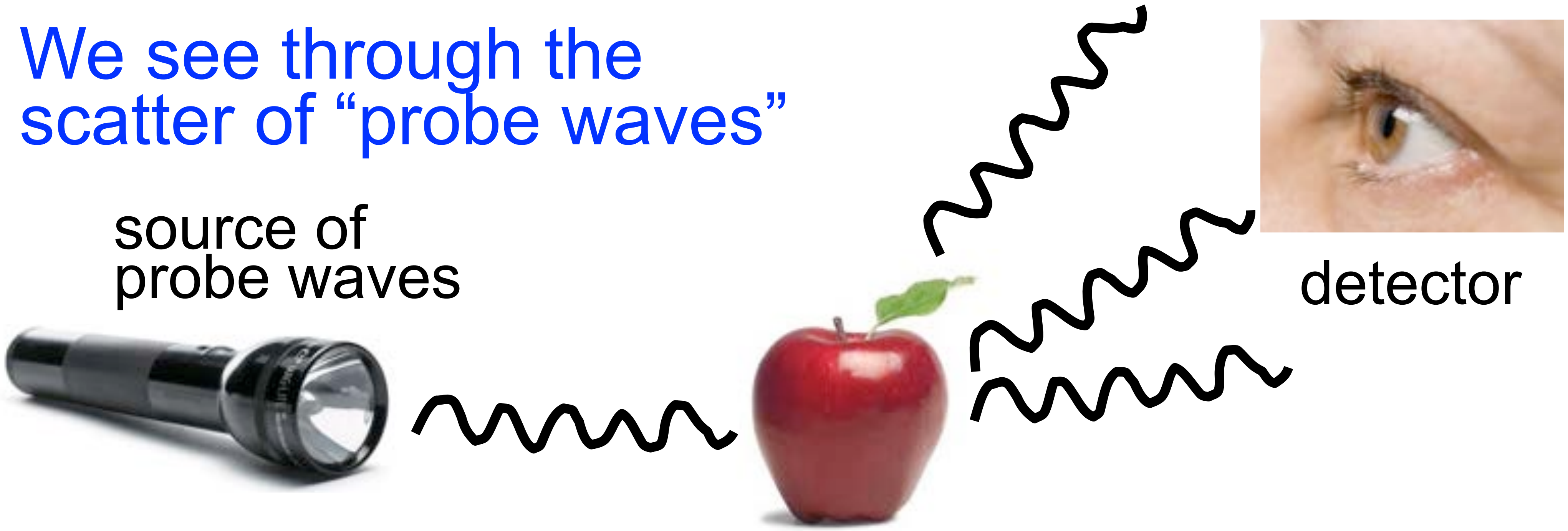
Abstract

Discovery at the Large Hadron Collider

The recent discovery of a new particle is a historic event 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 fundamental particles acquire mass, remains to be verified experimentally. Research at the energy frontier is being carried out at the Large Hadron Collider (LHC), operating at CERN near Geneva since 2010. From 2010 to 2012, the LHC provided proton-proton collisions at a centre of mass energy of 7 to 8 TeV, allowing the exploration of distance scales smaller than a tenth of an attometer. The products of these collisions were successfully recorded by the ATLAS detector, which will be introduced in this lecture, with emphasis on Canadian contributions. The ATLAS physics programme features Standard Model measurements and a rich array of searches for new physics phenomena. The discovery of a new Higgs-like 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”



Matter waves:

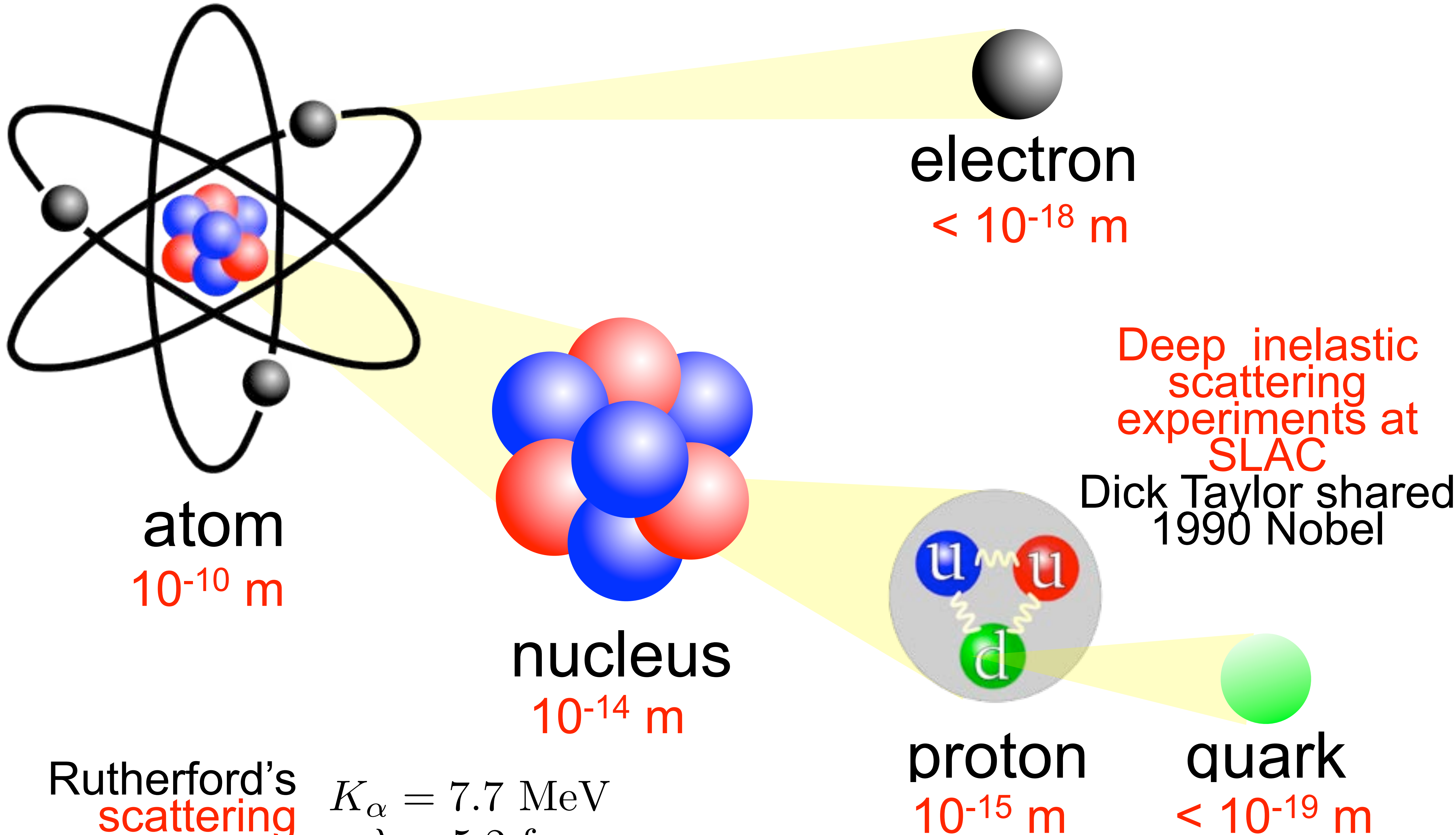
particle aspect

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

wave aspect

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

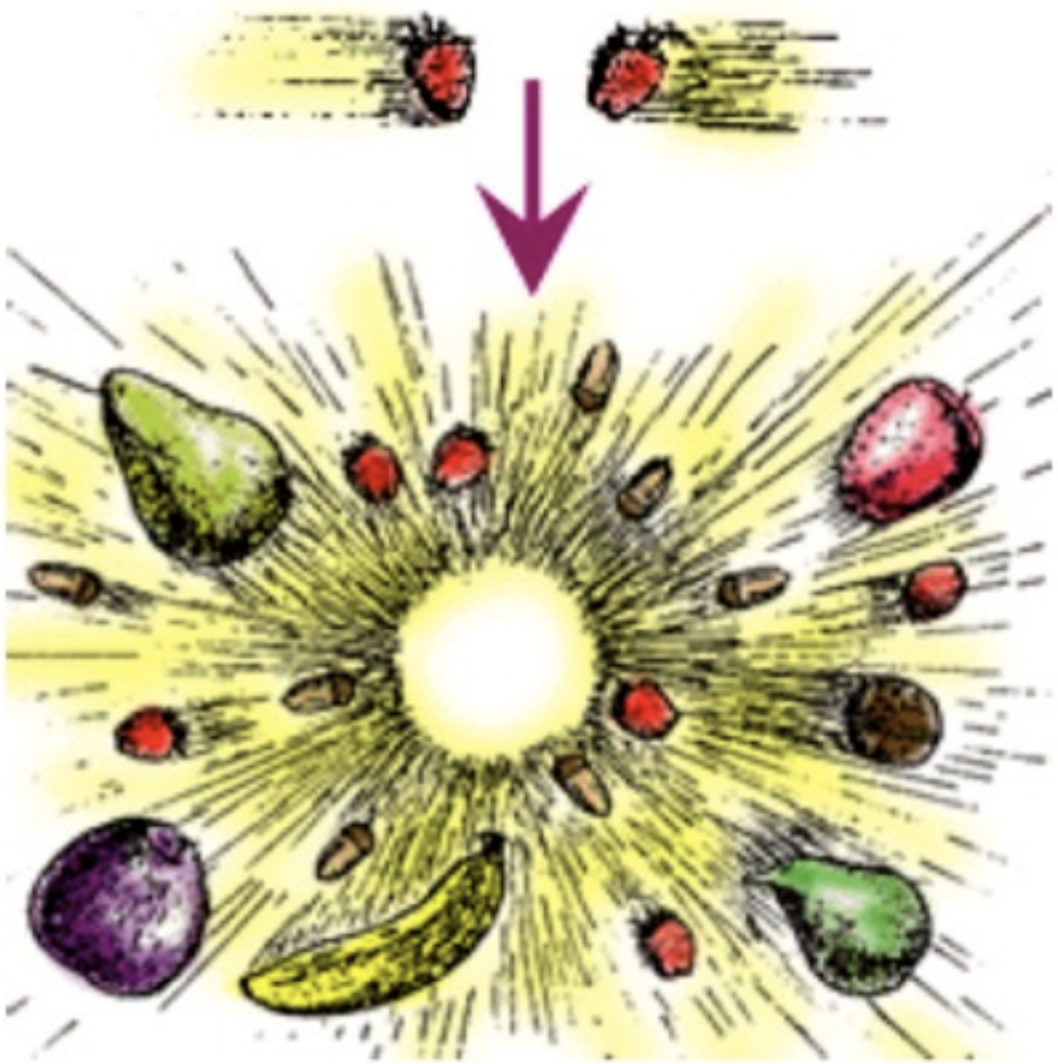
Inside the atom



Rutherford's scattering experiments

$$K_\alpha = 7.7 \text{ MeV}$$
$$\lambda = 5.2 \text{ fm}$$

Colliding particles



http://www.particleadventure.org/collision.html

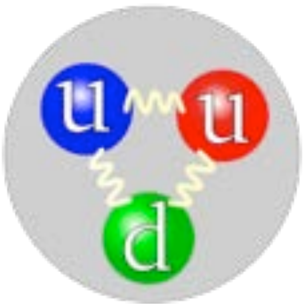
Particles and antiparticles, perhaps new and unknown ones, can be produced from the pure energy available after the collision

$$E = mc^2$$

New particles signal new physical laws!

Convenient mass units: GeV/c^2 or GeV

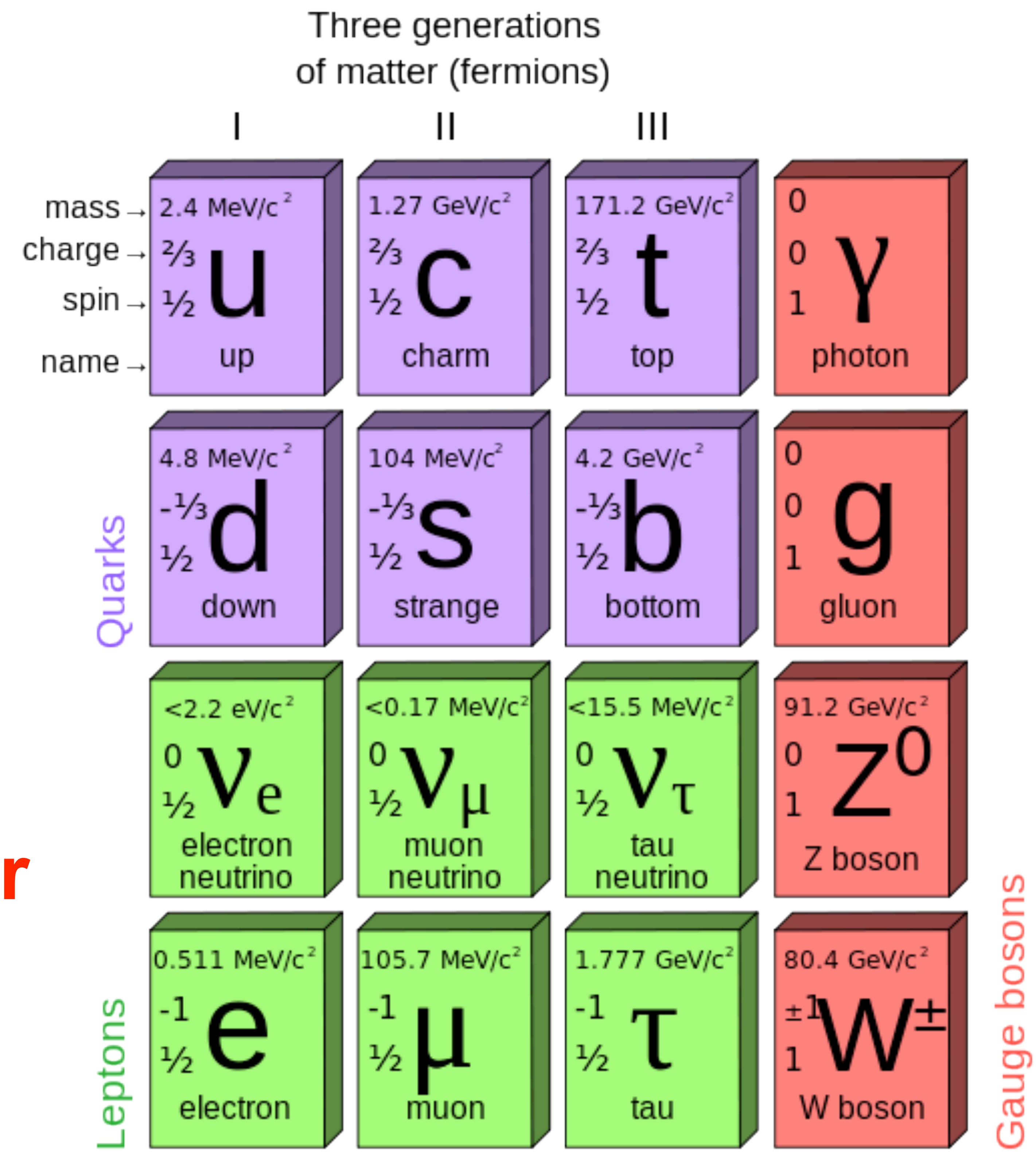
Matter and forces



the **proton**: three bound quarks

Matter: spin 1/2 fermions

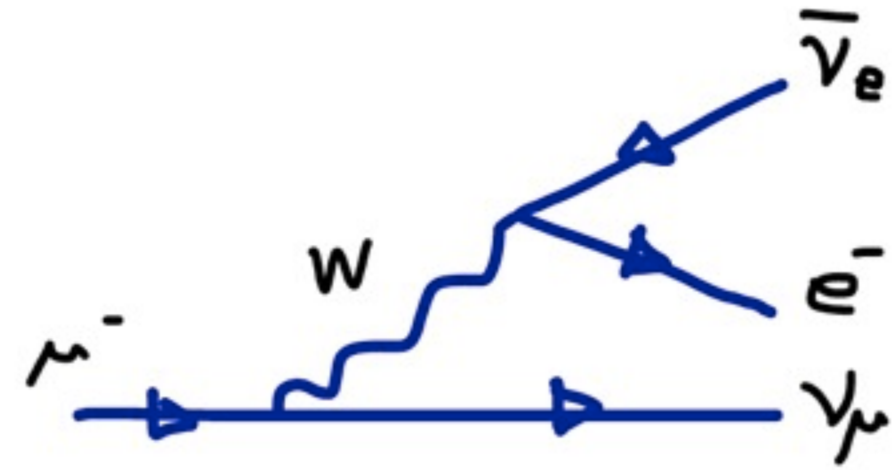
and Antimatter



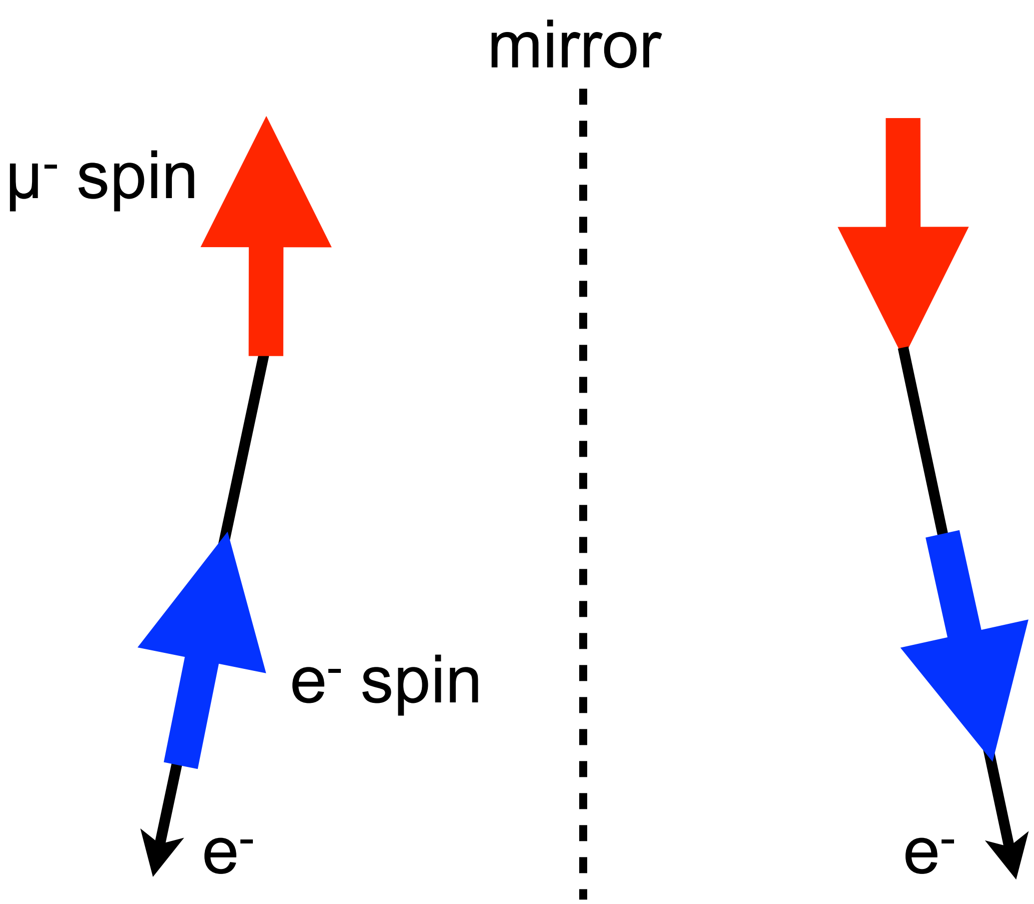
Forces: mediated by spin 1 bosons

Weak interaction and parity

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



favoured



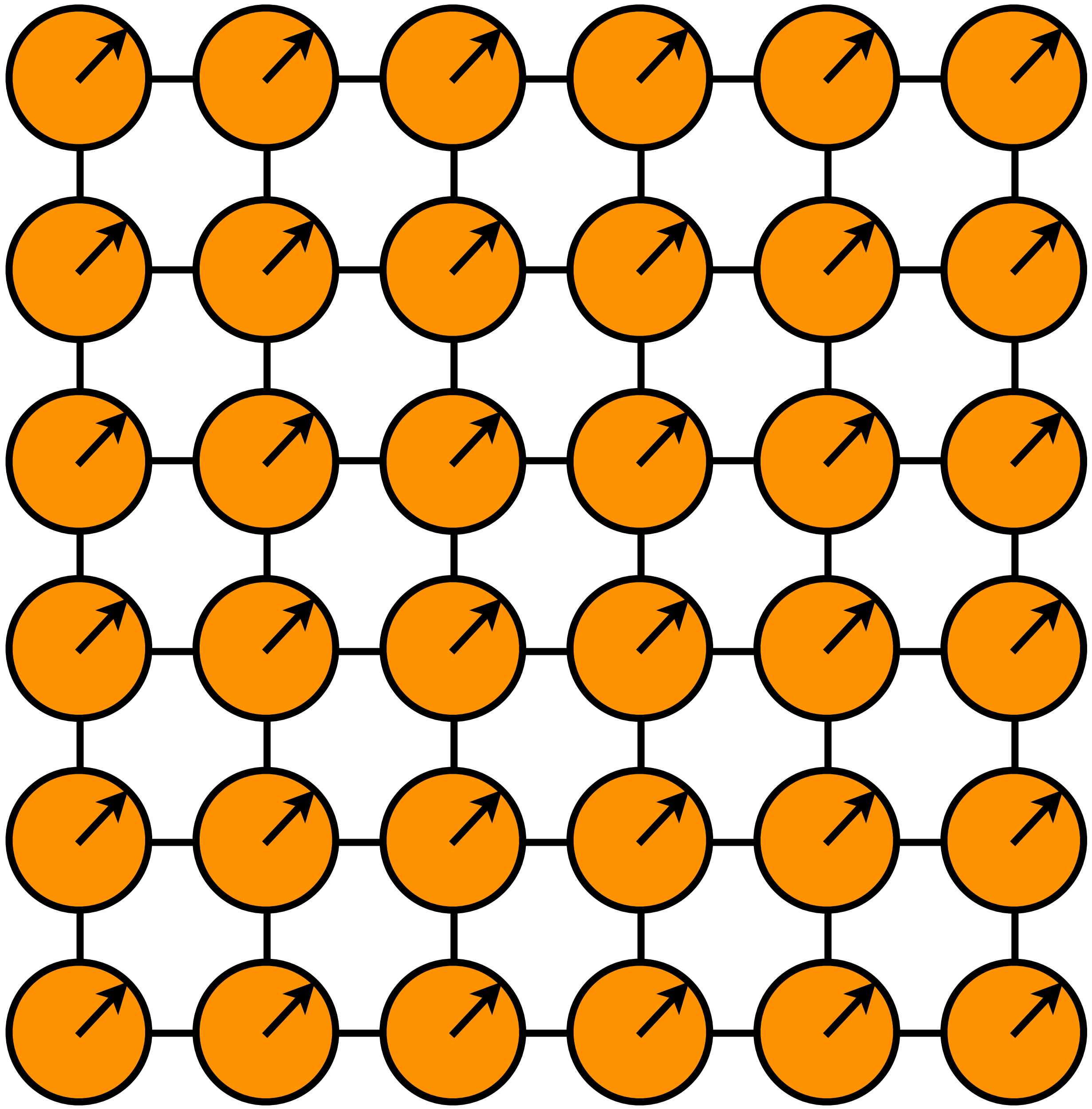
not favoured

not favoured!

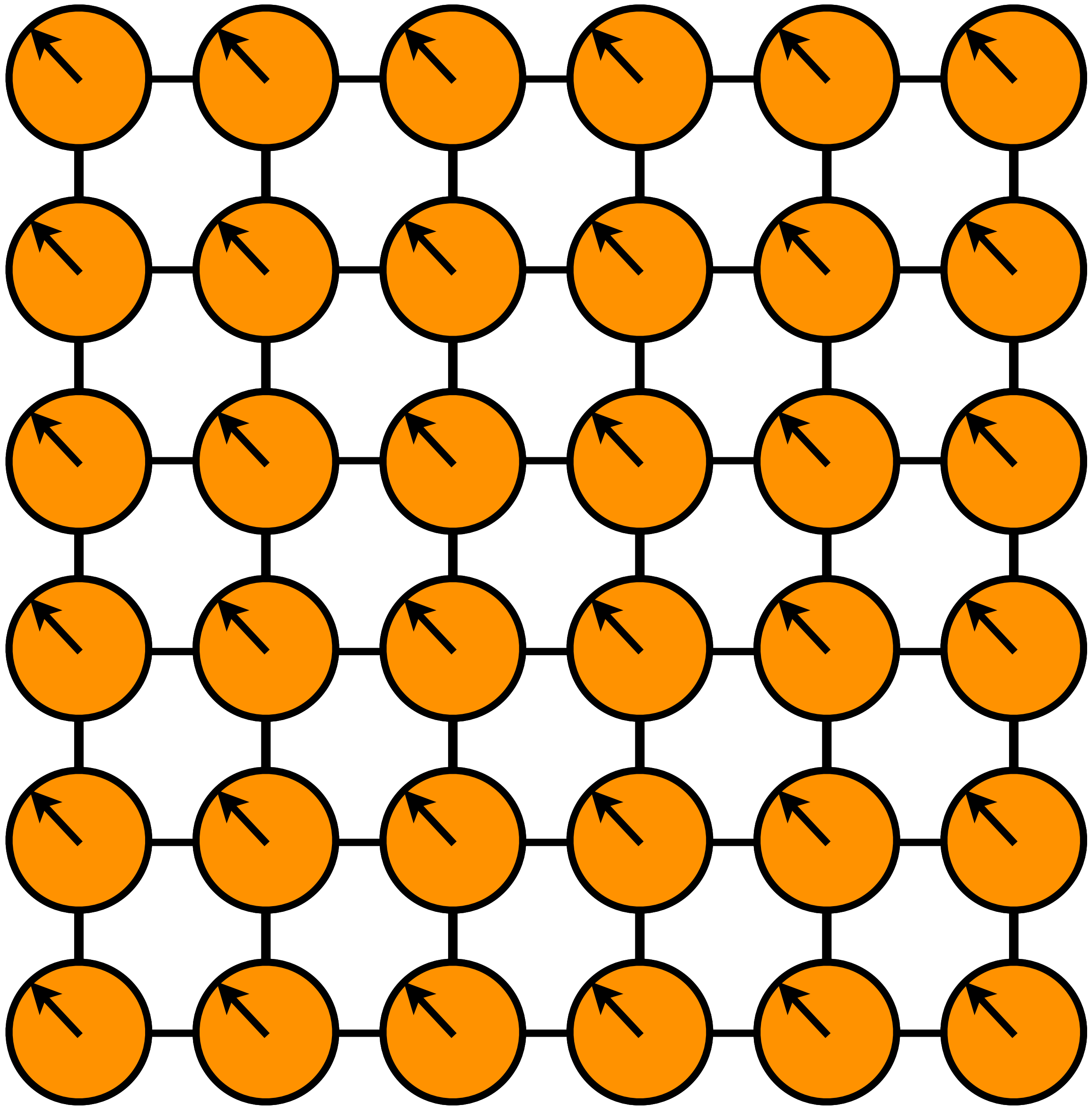
The weak interaction violates parity!

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

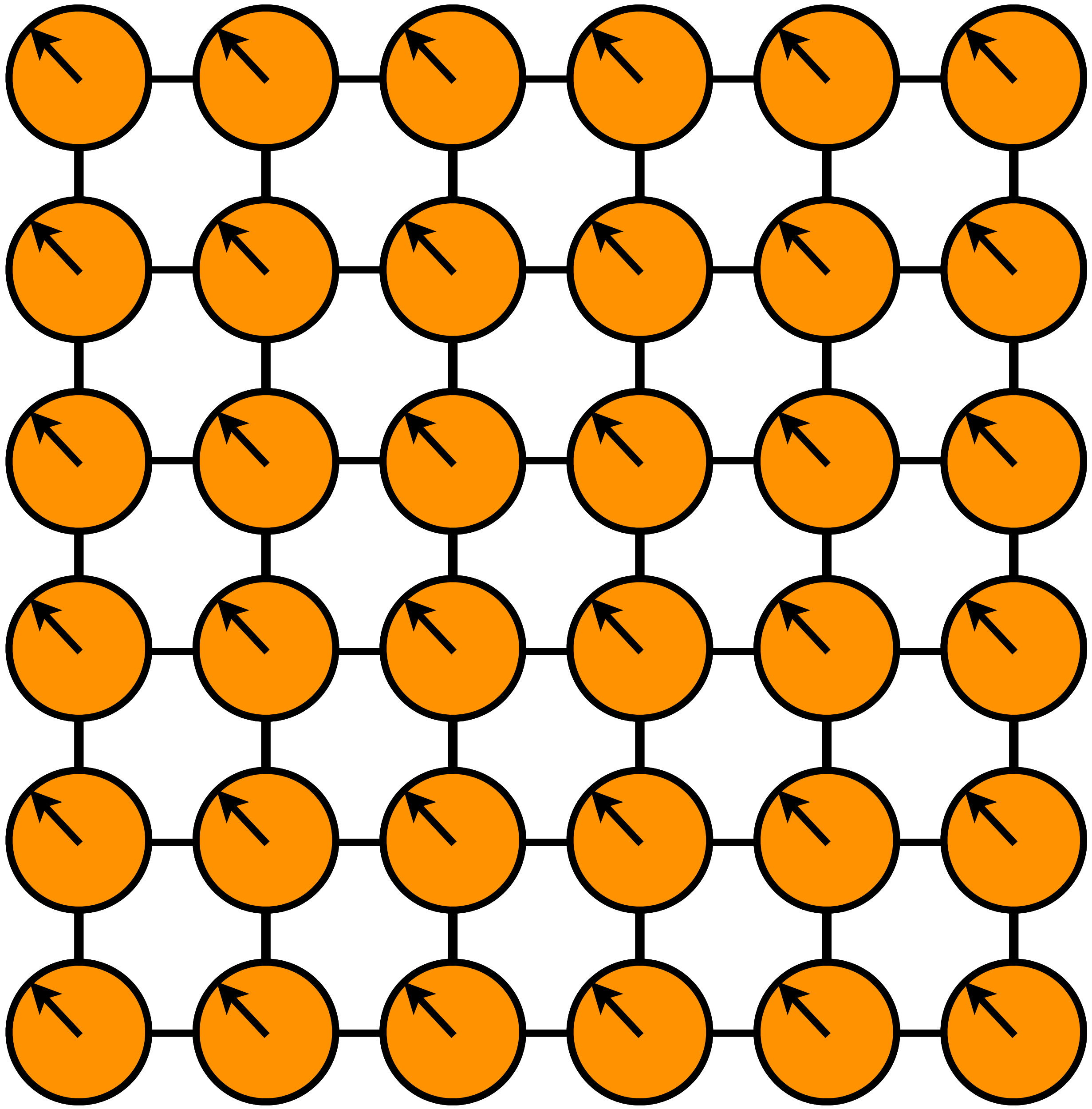
Global symmetries



Global symmetries



Global symmetries



Global symmetry

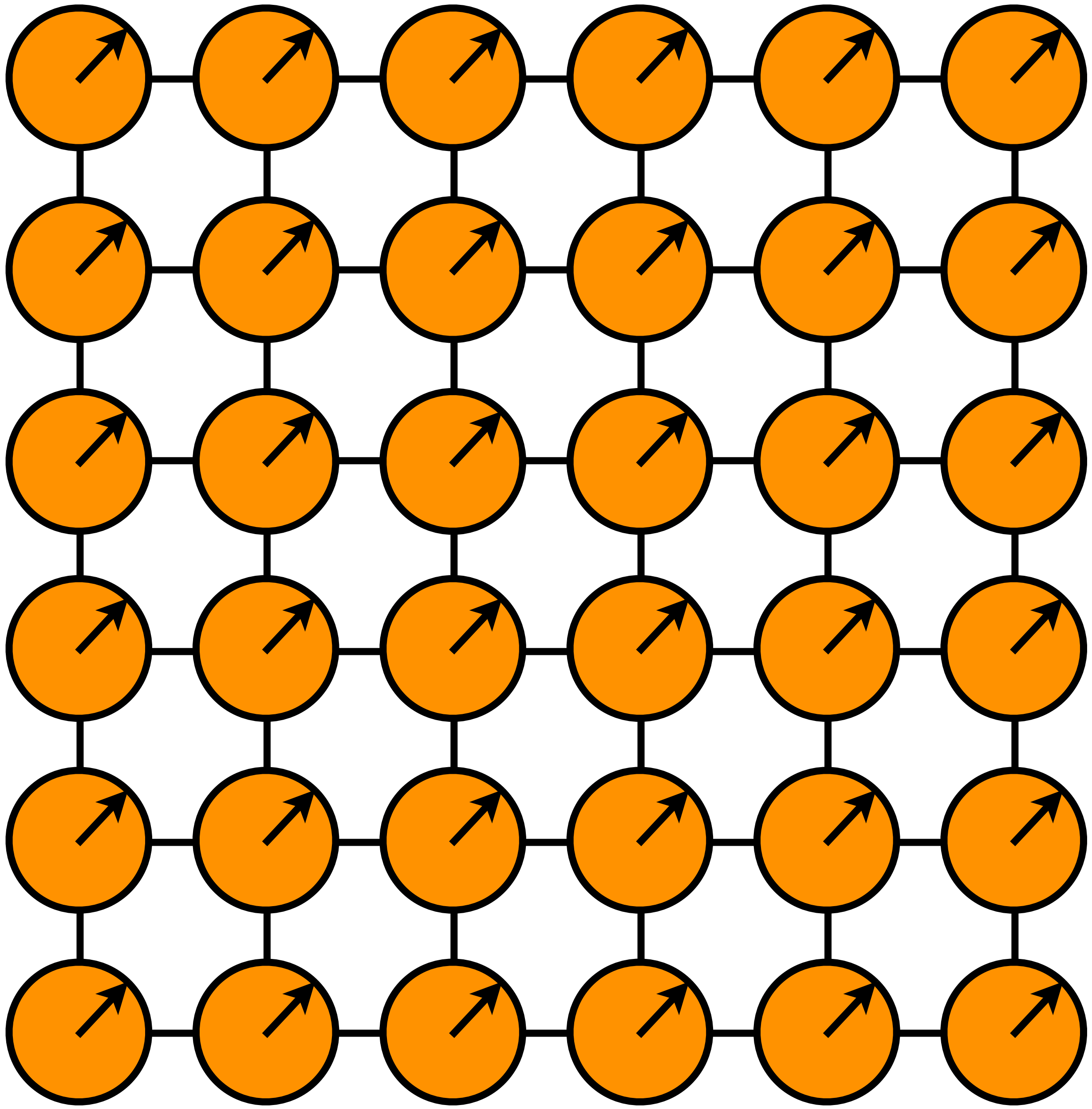
↓

Conservation Law!

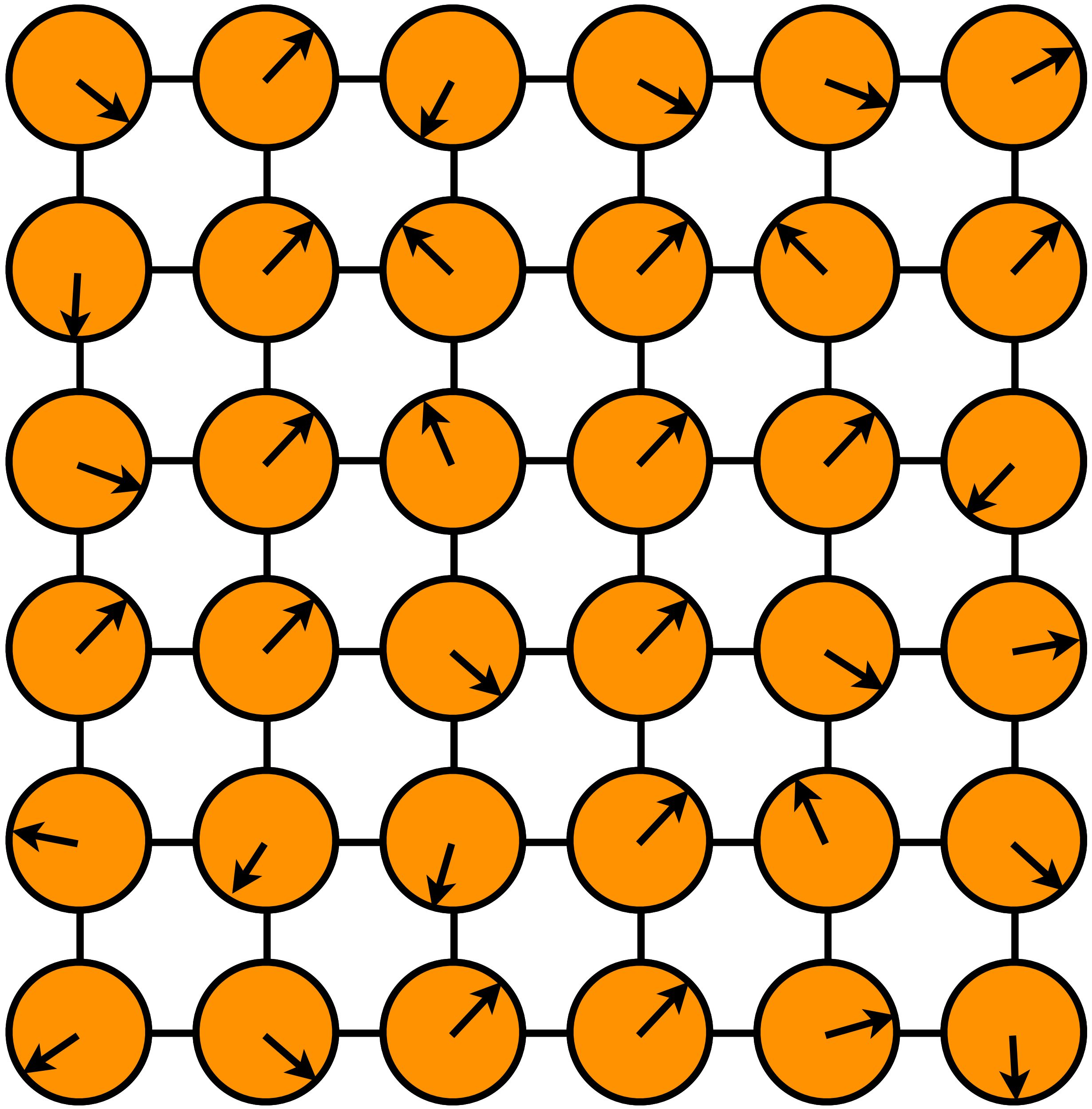
$$\psi(x) \to e^{i\epsilon}\psi(x)$$

→ Conservation of electric charge

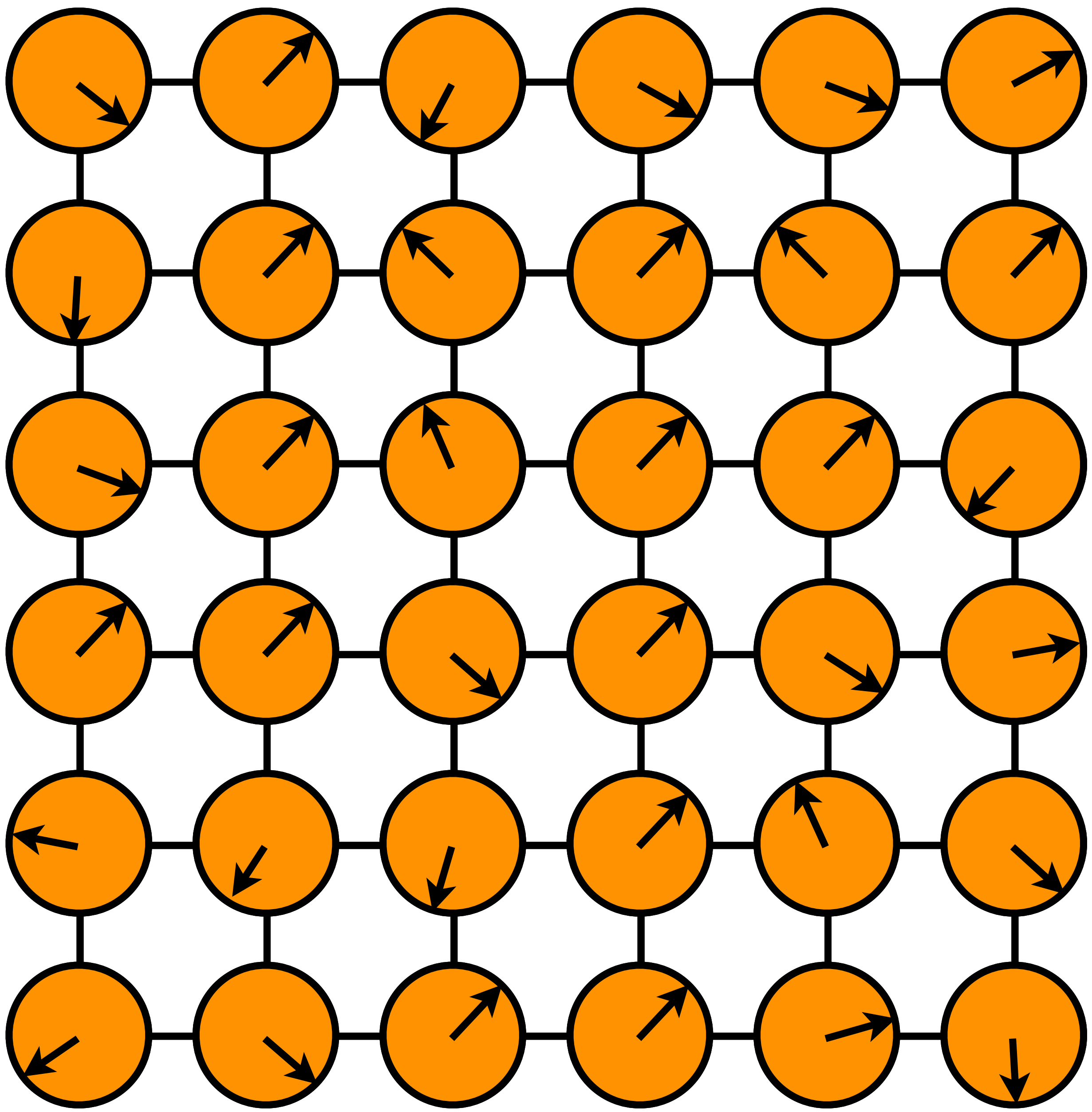
Local symmetries and forces



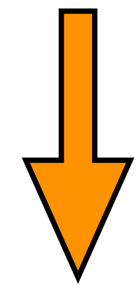
Local symmetries and forces



Local symmetries and forces



Local symmetry



Forces!

All known forces are consequences of local symmetries...
but this only works for massless particles!!

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

Gauge invariance

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

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

Standard Model gauge

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \qquad \begin{pmatrix} u \\ u \\ u \end{pmatrix}$$

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

gauge boson mass terms

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

fermion mass terms because of $SU(2)_L$

$$m\bar{\psi}\psi = m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right)$$

We need a gauge invariant mechanism to generate mass

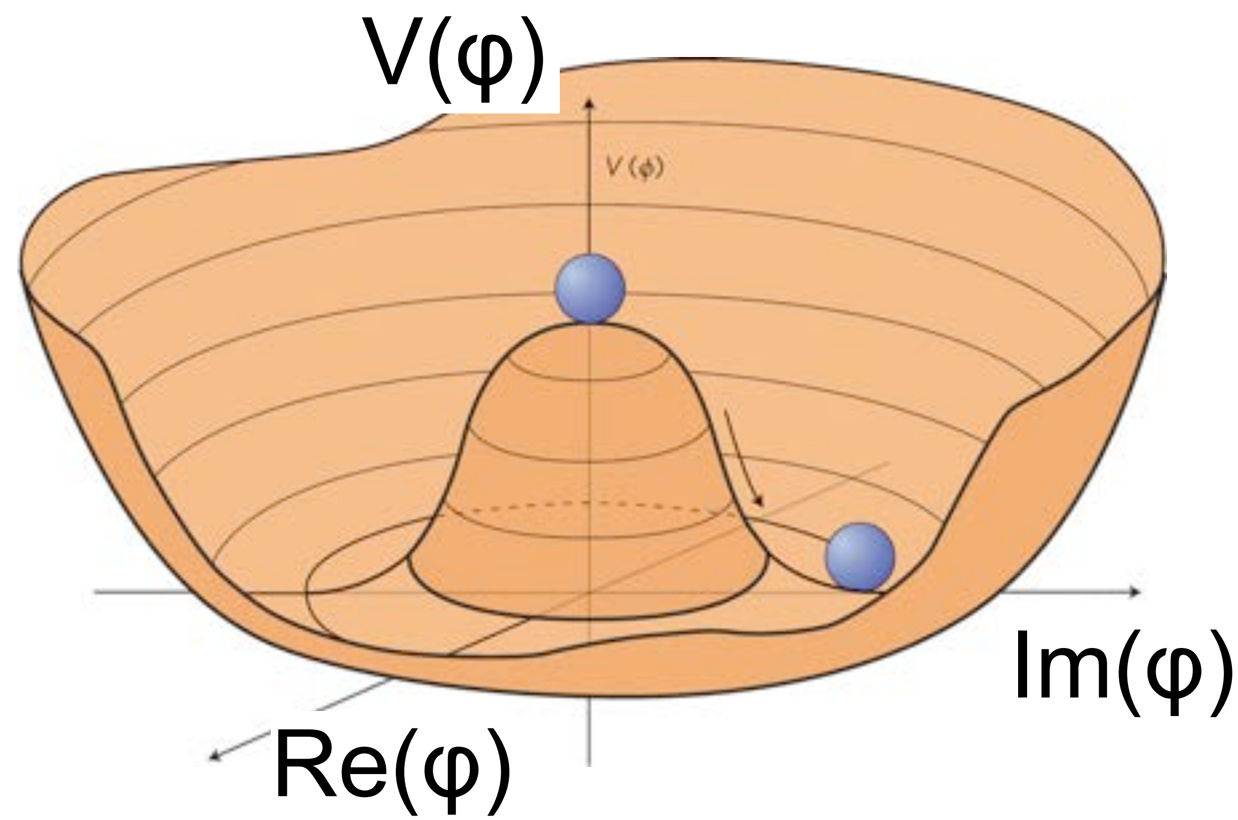
Higgs mechanism!

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

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



- The equilibrium state is φ ≠ 0 and not unique!
  - nature makes 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

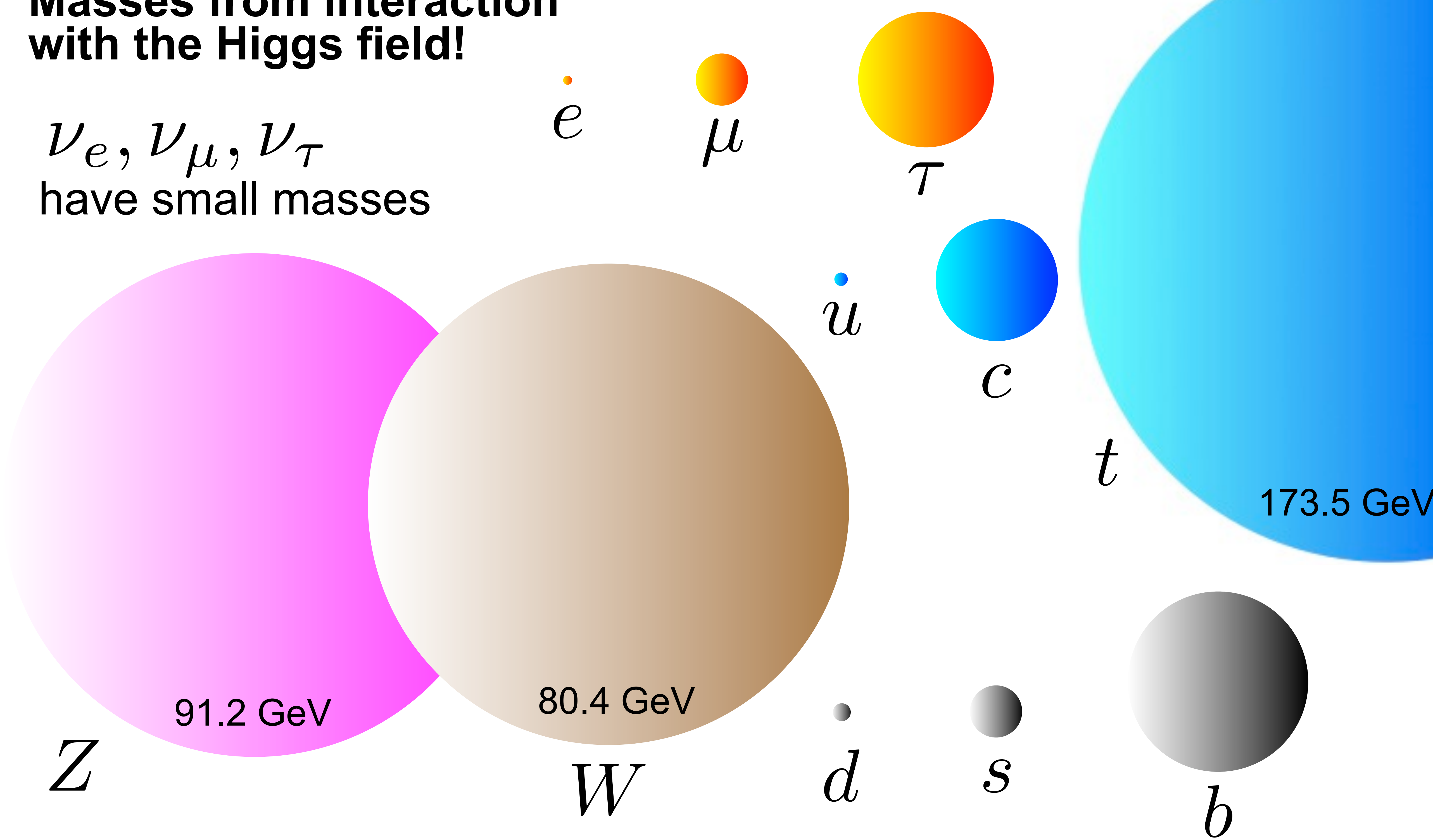
Fundamental masses

γ, g massless

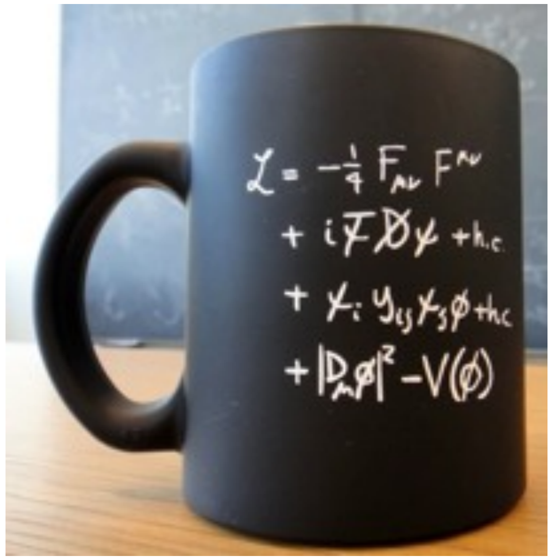
Depicted with mass proportional to volume of sphere!

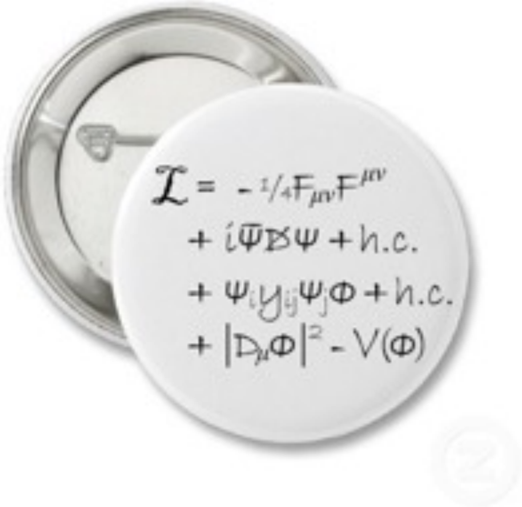
Masses from interaction with the Higgs field!

ν_e, ν_μ, ν_τ have small masses



The Standard Model





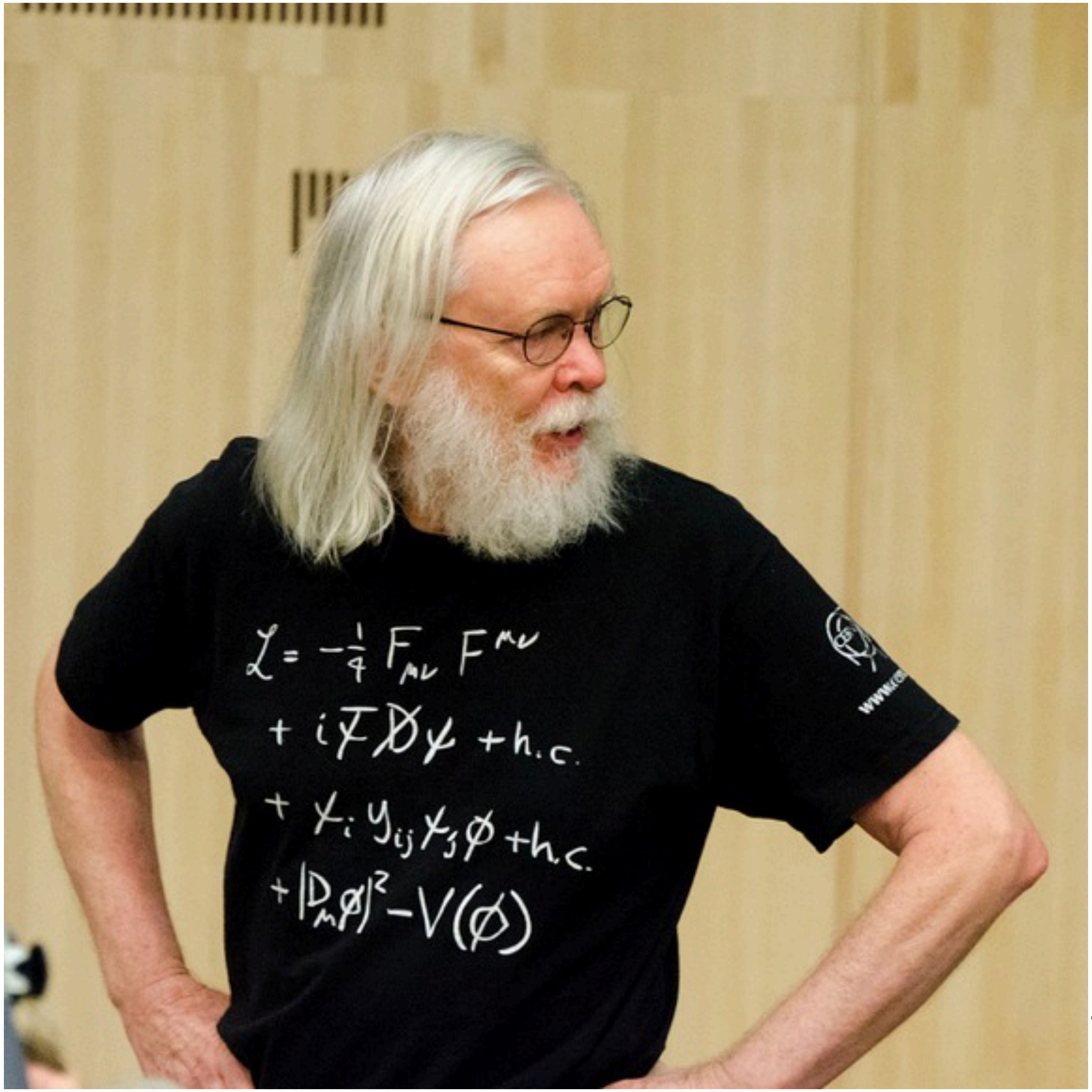
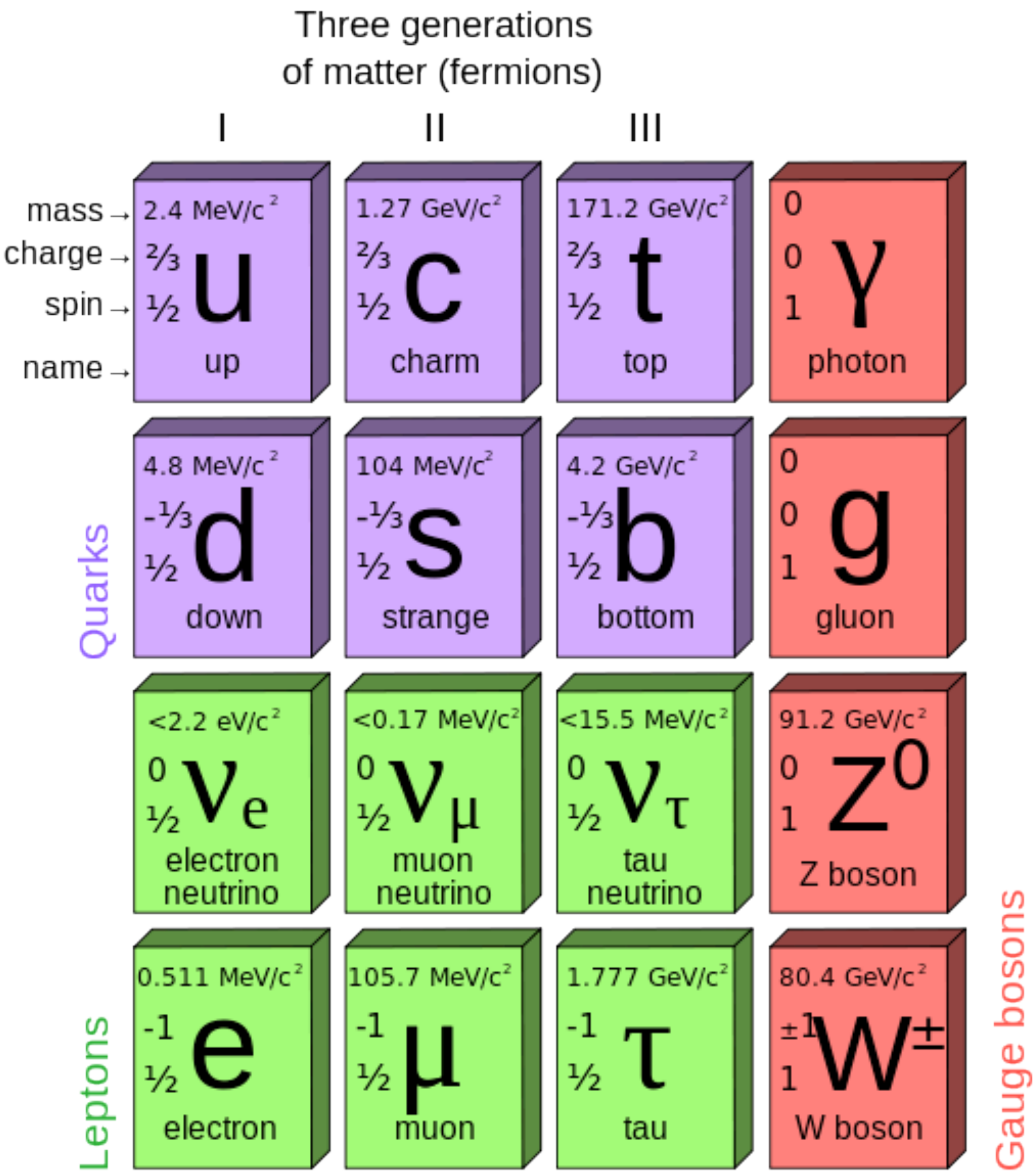


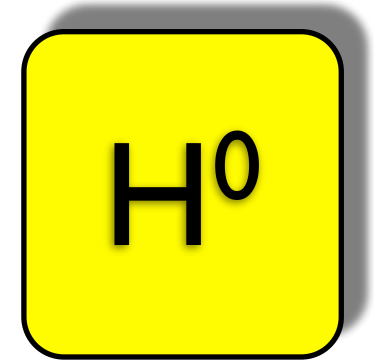
Photo: Josh Thompson

"The LSP = The Ellis Particle"

The Standard Model



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).

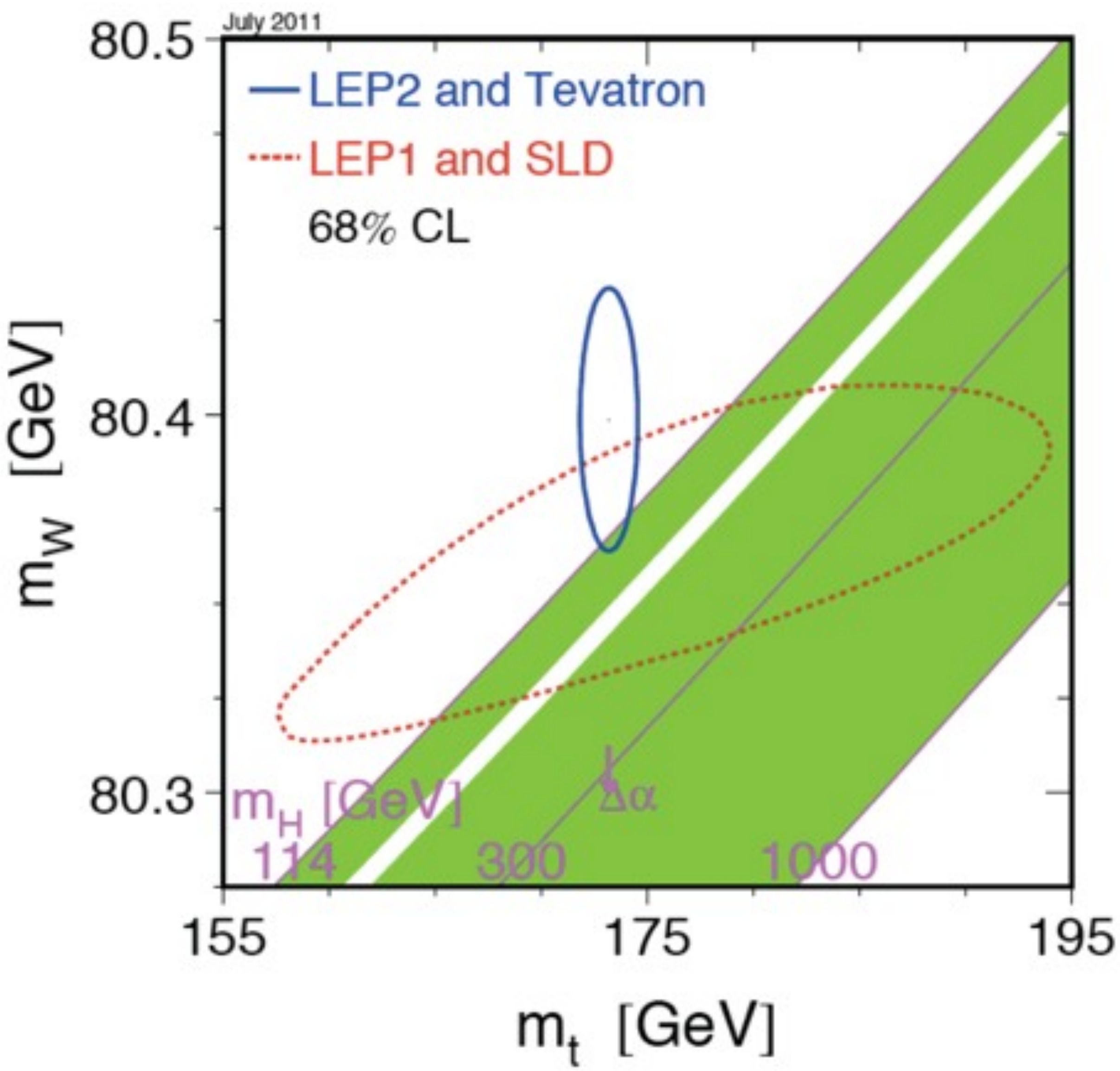
Received 7 November 1975

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!



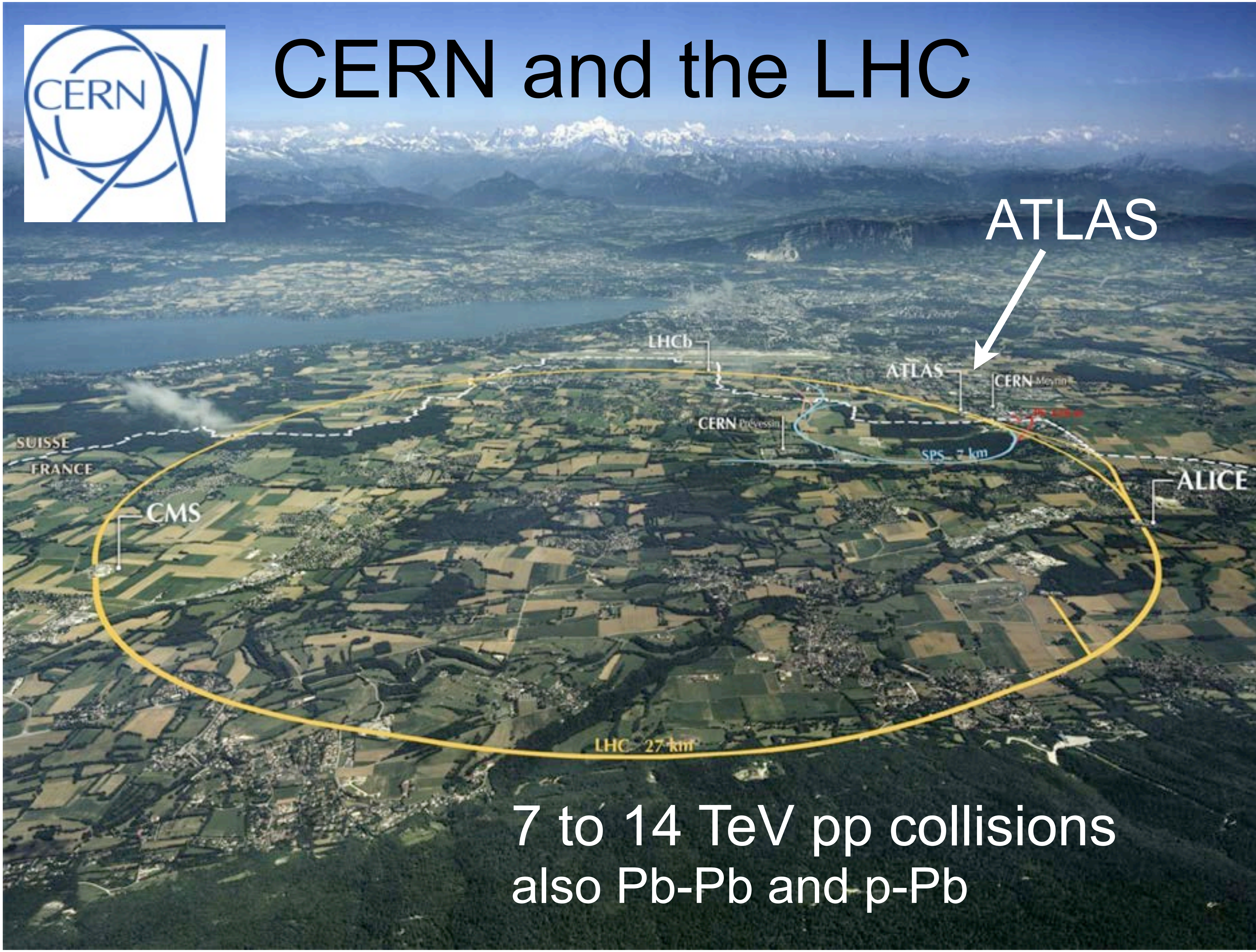
Higgs mass constraints

$114 < M_H < 161$ GeV 95%CL

Direct searches

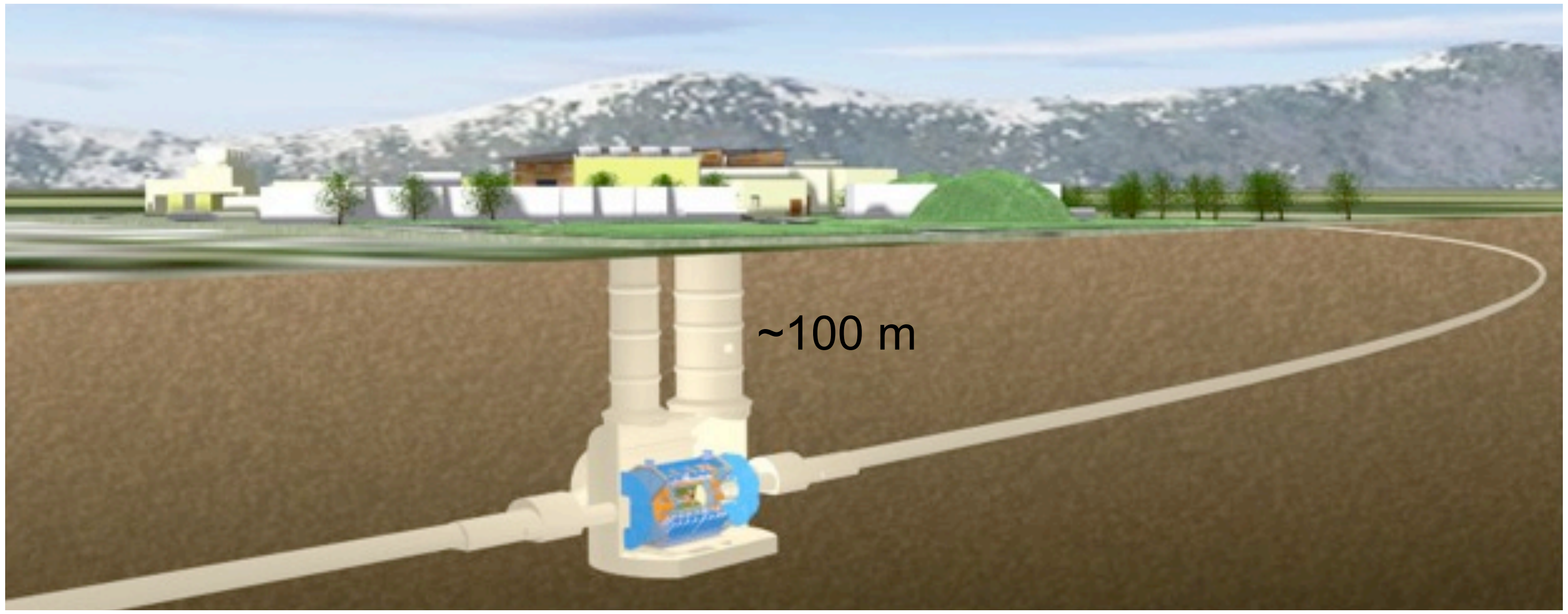
Indirect: precision measurements. Assumes SM

CERN and the LHC

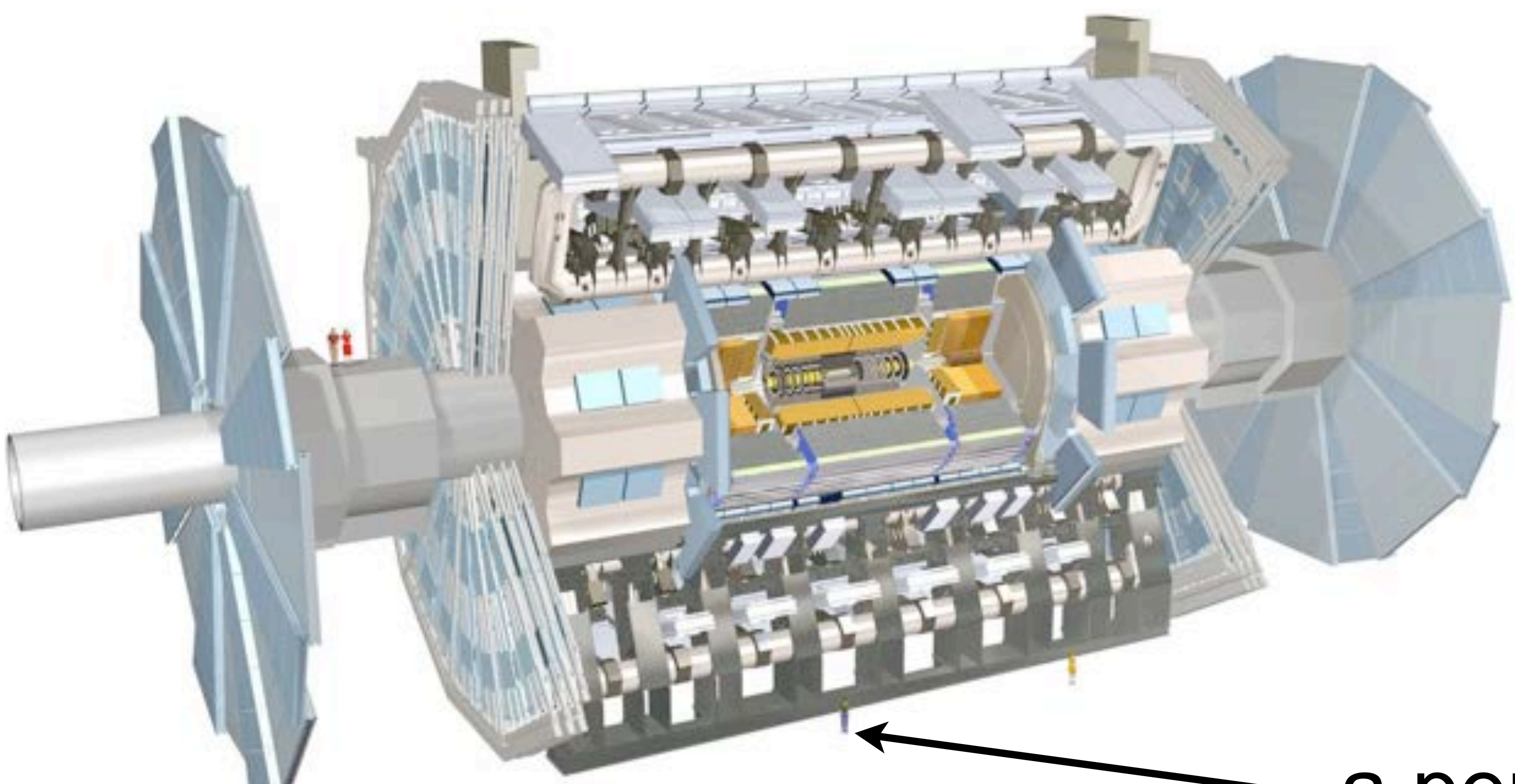


CERN PhotoLab CERN-MI-0807031

The ATLAS detector at the LHC



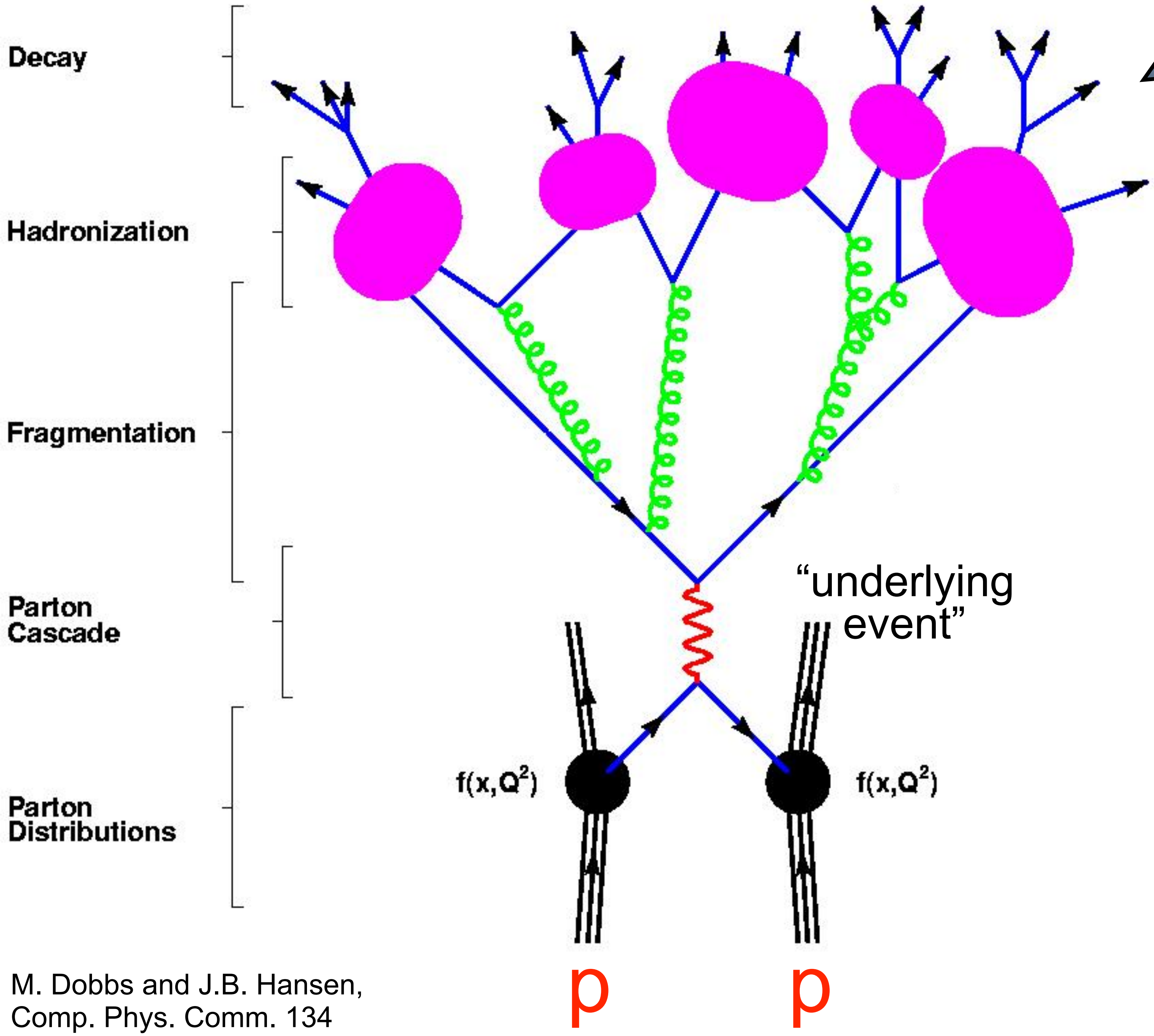
The ATLAS Experiment at CERN, http://atlas.ch



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

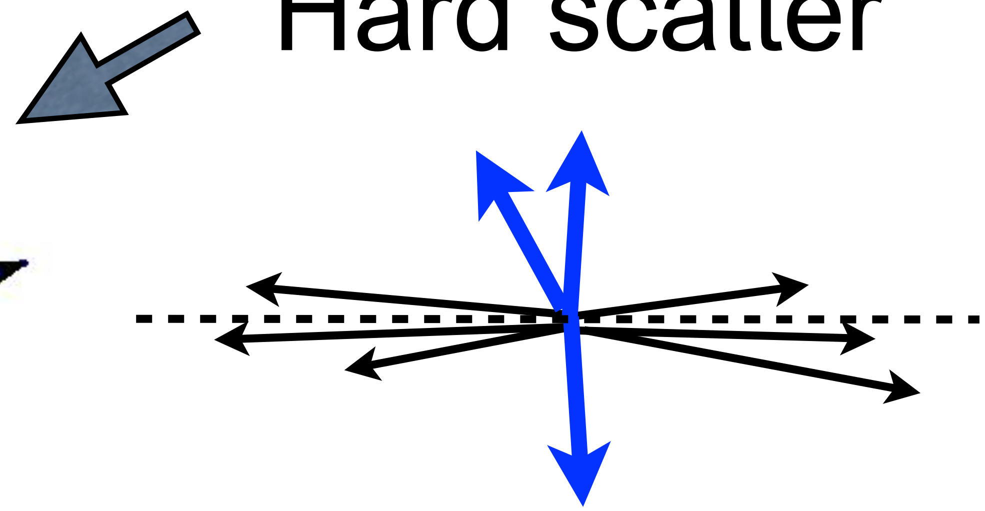
a person!

Proton-proton collisions

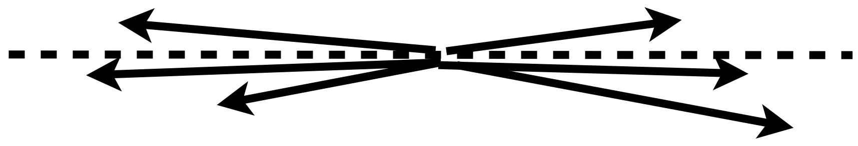


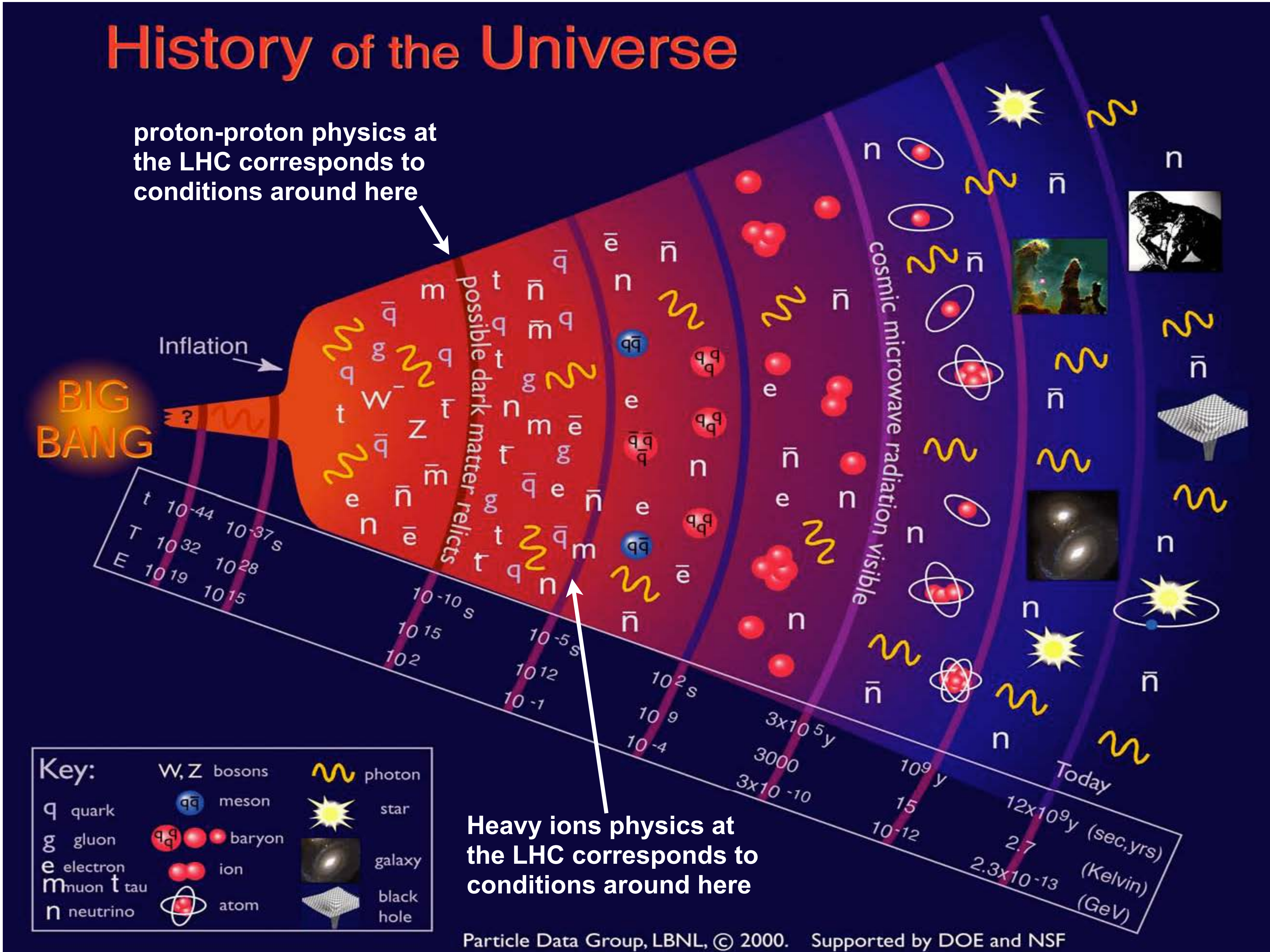
M. Dobbs and J.B. Hansen, Comp. Phys. Comm. 134 (2001) 41-46.

Hard scatter



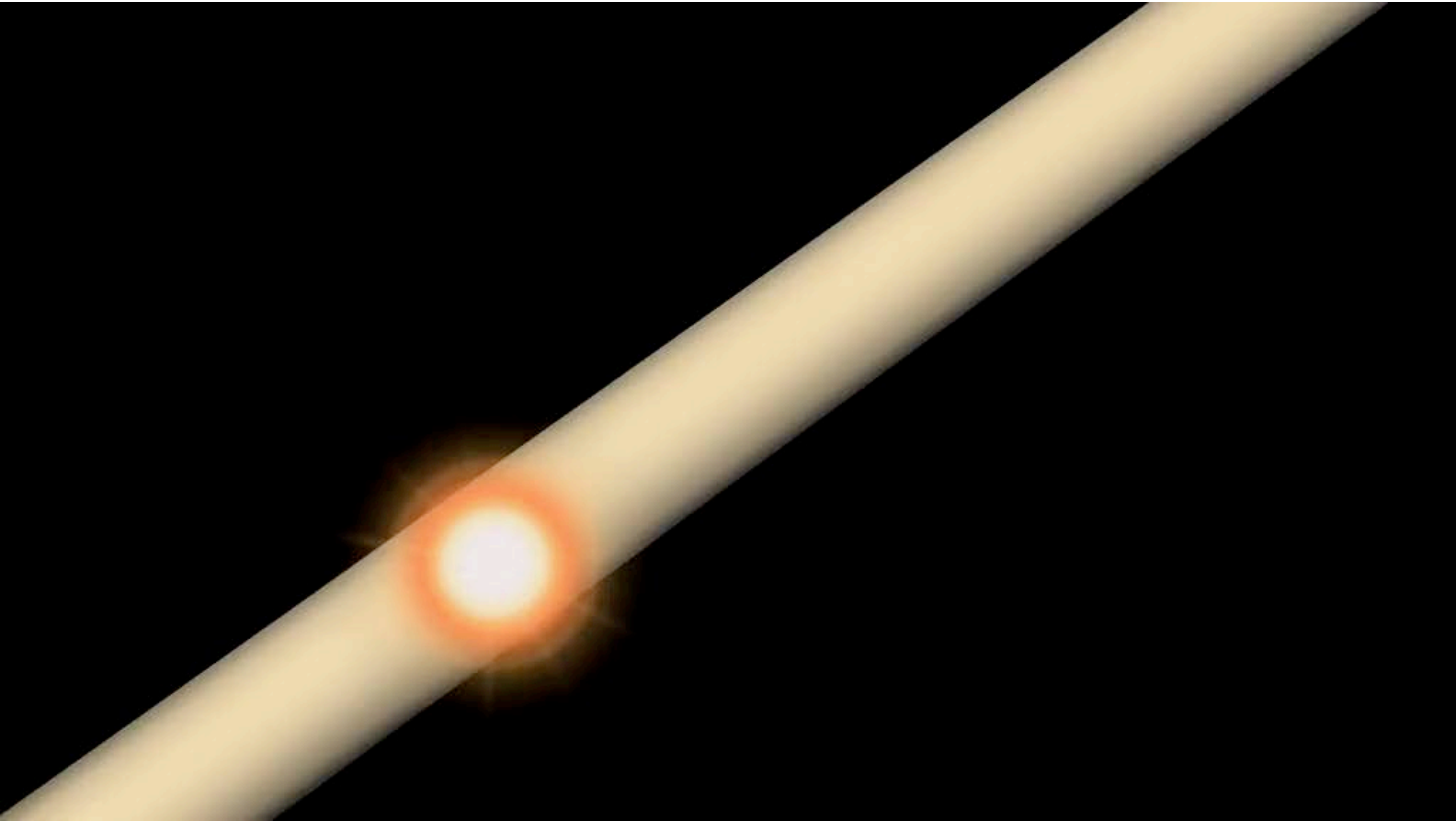
soft scatter





http://www.particleadventure.org/

Proton-proton collisions



http://www.atlas.ch/multimedia

Canada and the LHC

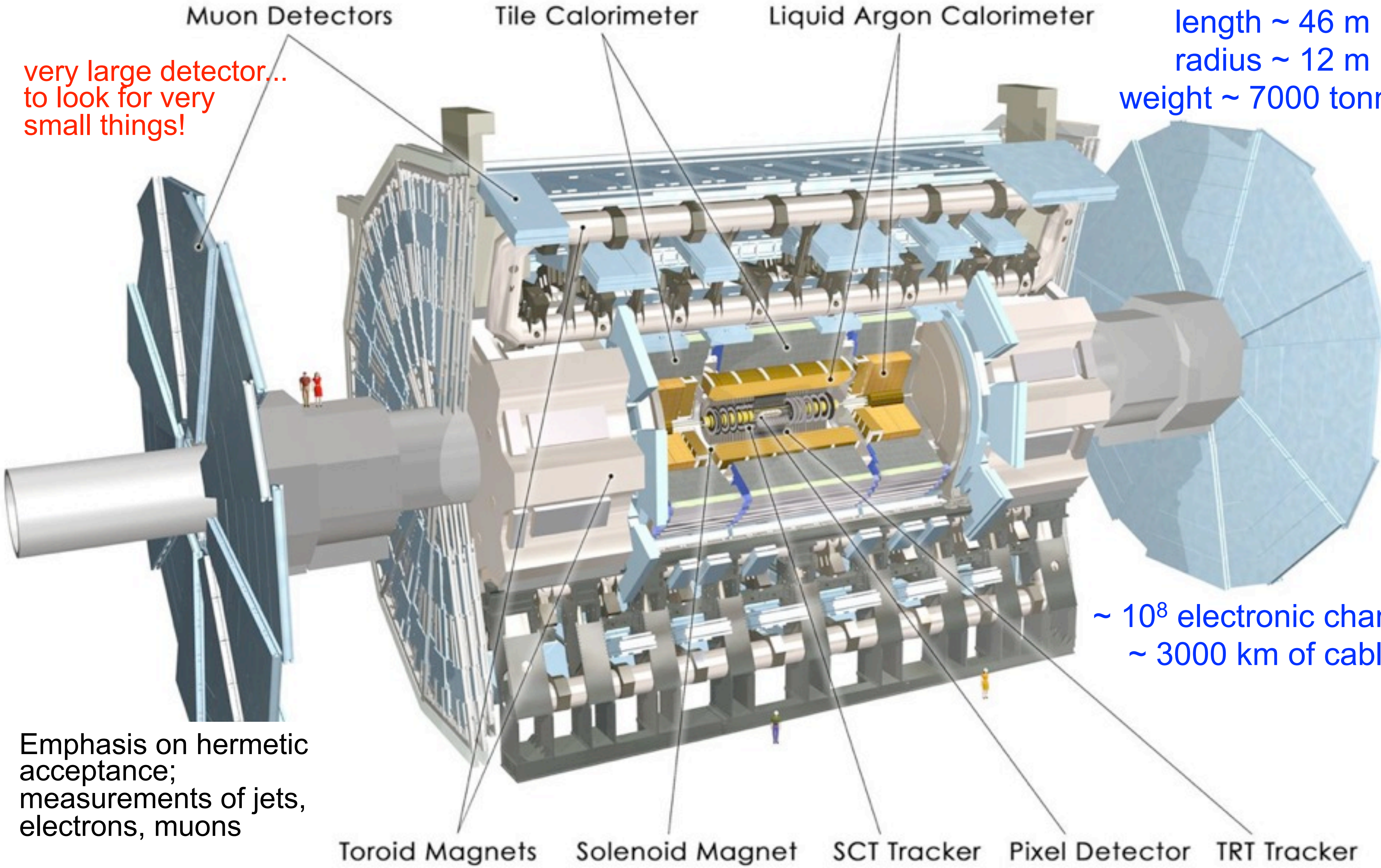
Canada made important contributions to the LHC machine: warm insertions and injector upgrades, with TRIUMF engineering

48 + 4 warm twin-aperture quadrupoles for cleaning insertions

The ATLAS detector

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

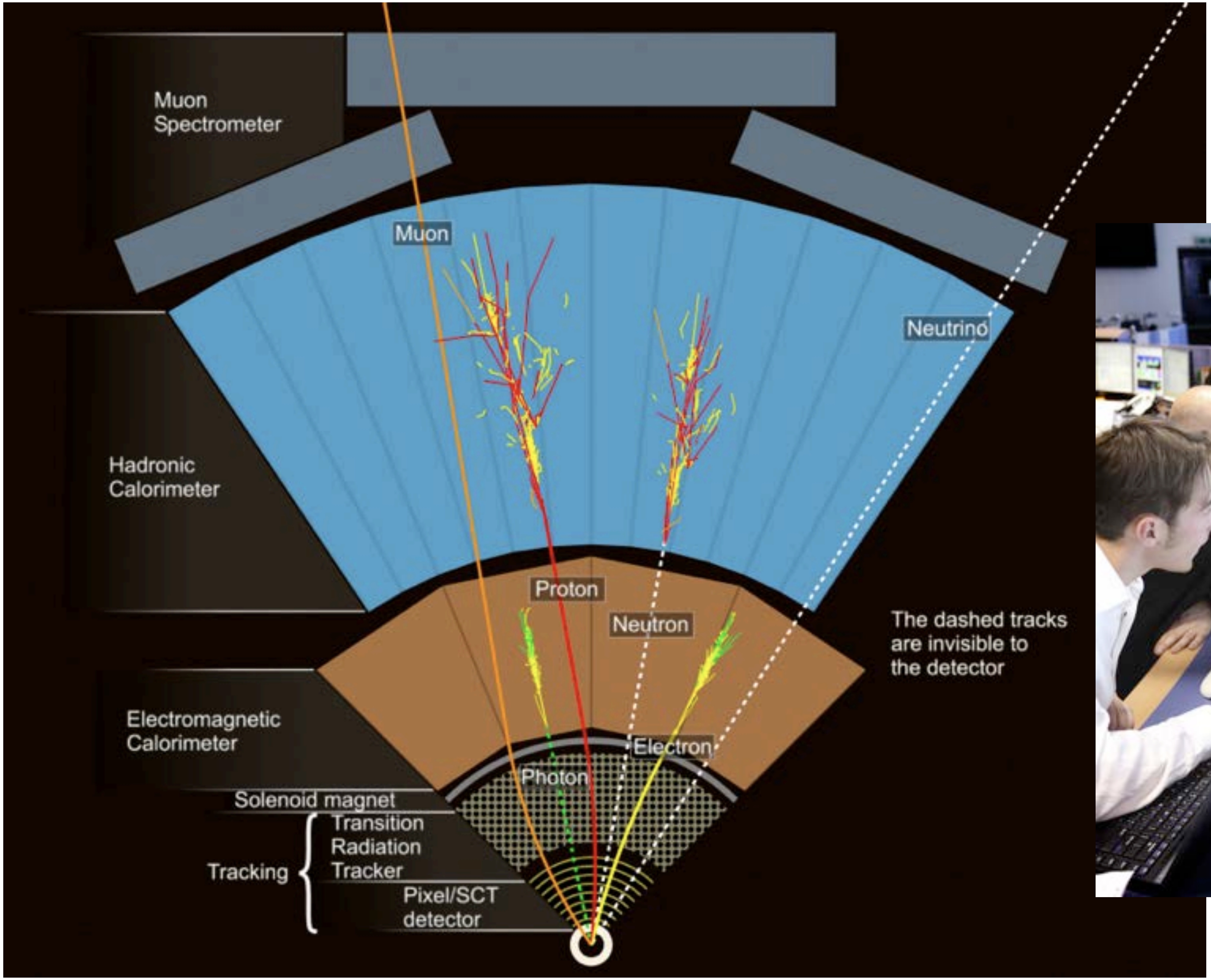
length ~ 46 m
radius ~ 12 m
weight ~ 7000 tonnes

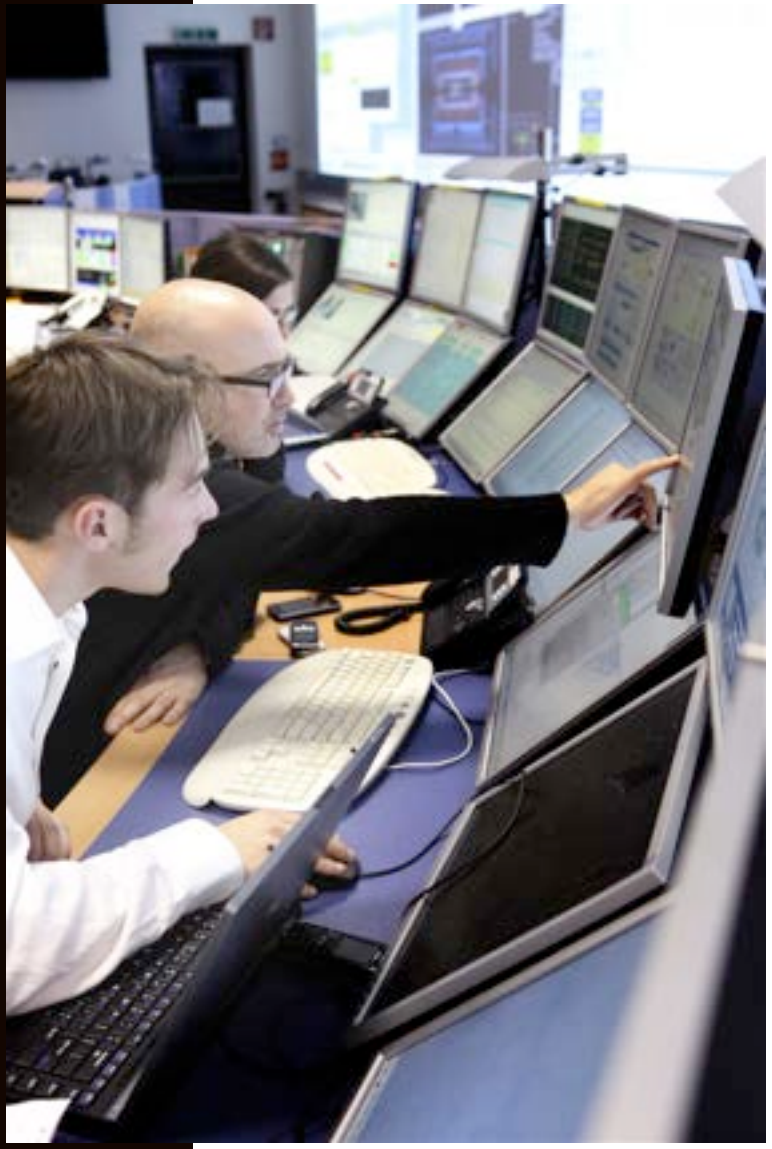


~ 10^8 electronic channels
~ 3000 km of cables

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

Particle identification in ATLAS





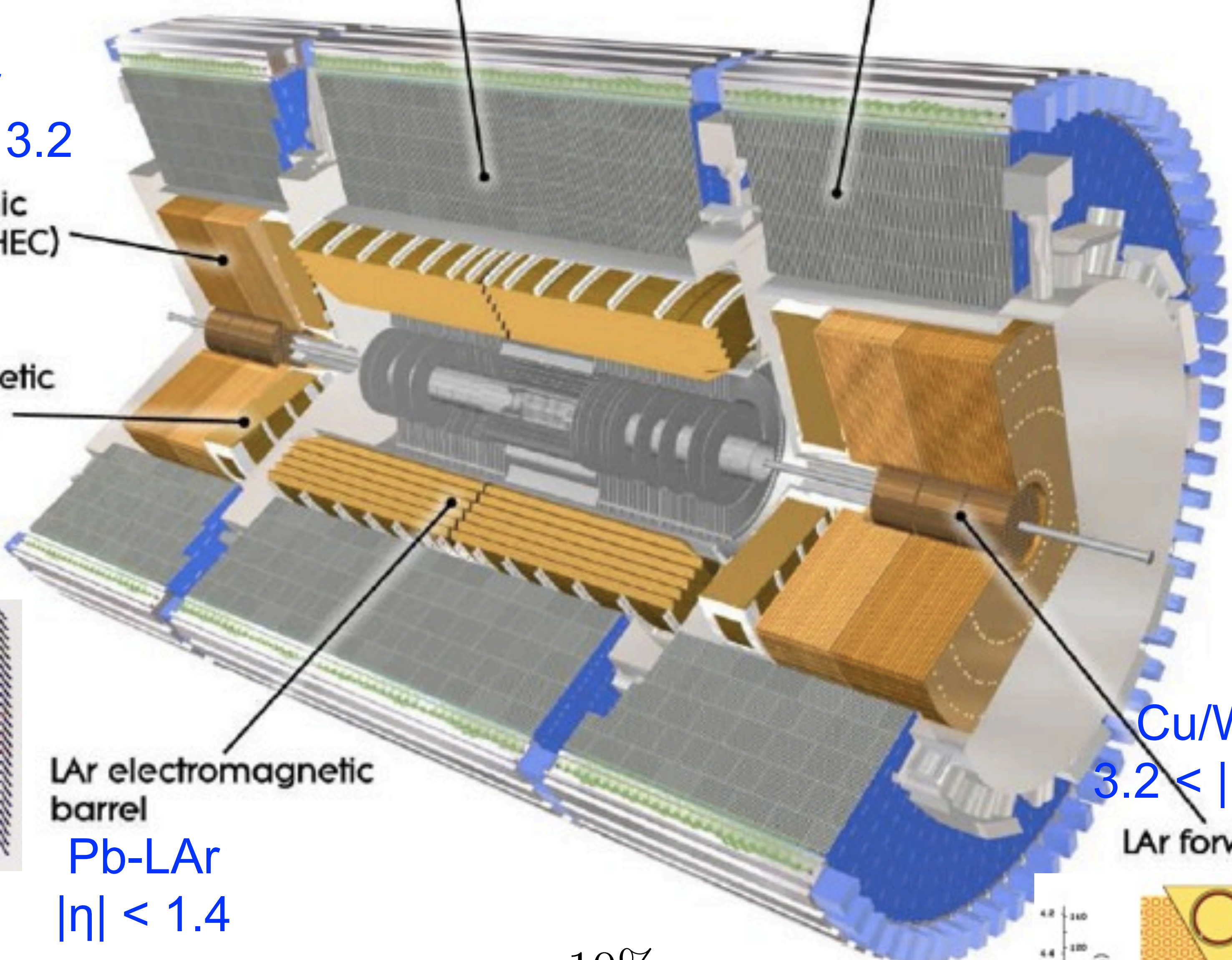
ATLAS calorimetry

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

Fe-Scintillator
|η| < 1.7

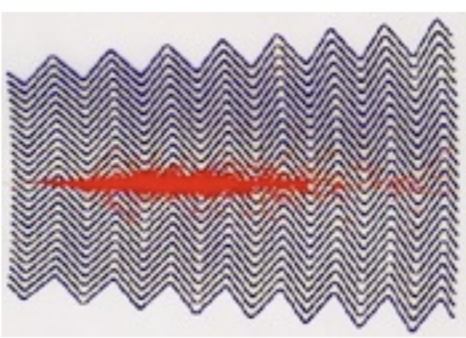
Cu-LAr
1.5 < |η| < 3.2

Pb-LAr
1.375 < |η| < 3.2



Segmented in depth and in pseudorapidity η and azimuthal angle ϕ

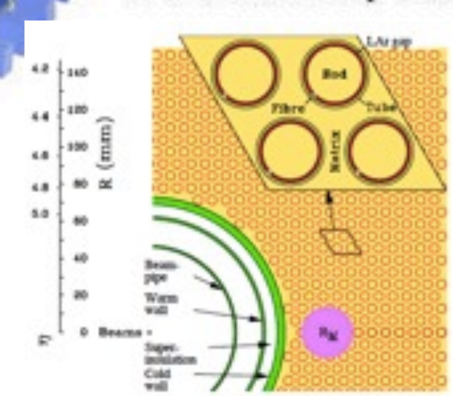
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

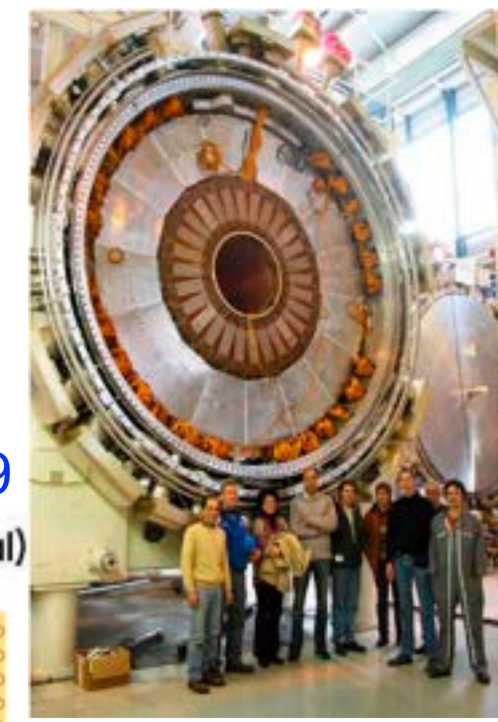


photon pointing!

Pb-LAr
|η| < 1.4

Cu/W-LAr
3.2 < |η| < 4.9





ATLAS Experiment © 2012 CERN

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

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

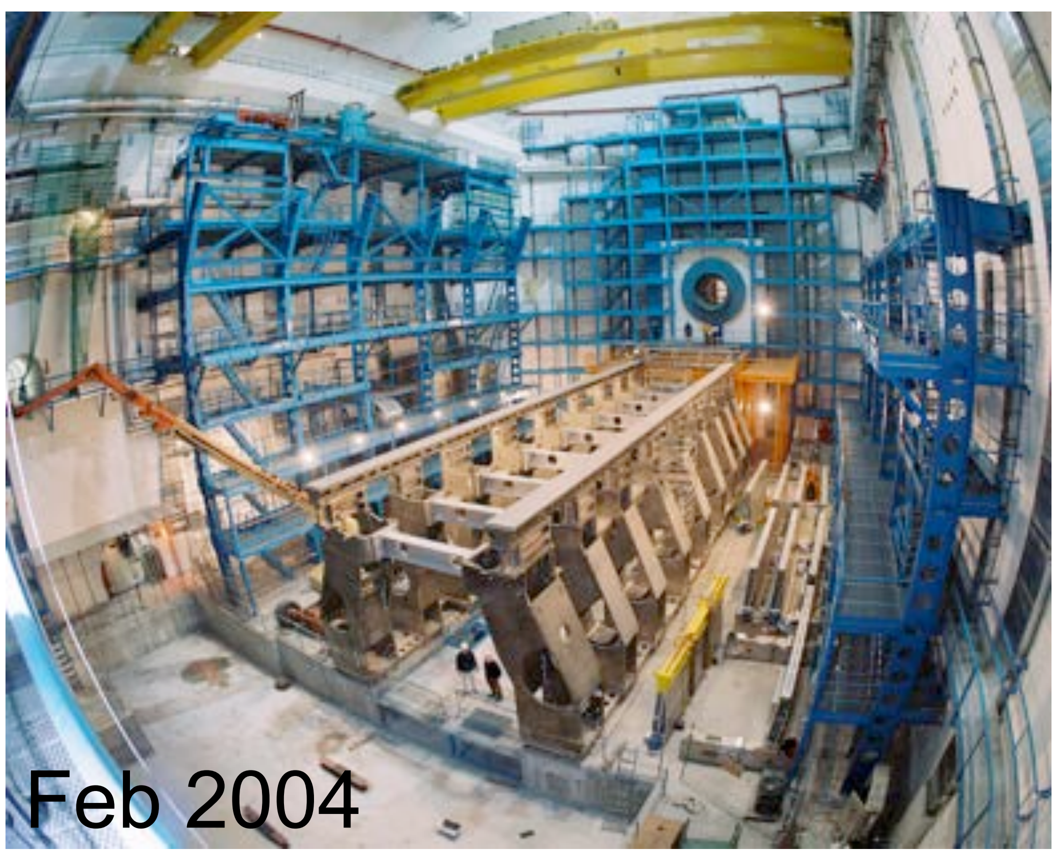
Had: $$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E[\text{GeV}]}} \oplus 3\%$$

ATLAS and Canada

Alberta
Carleton
McGill
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

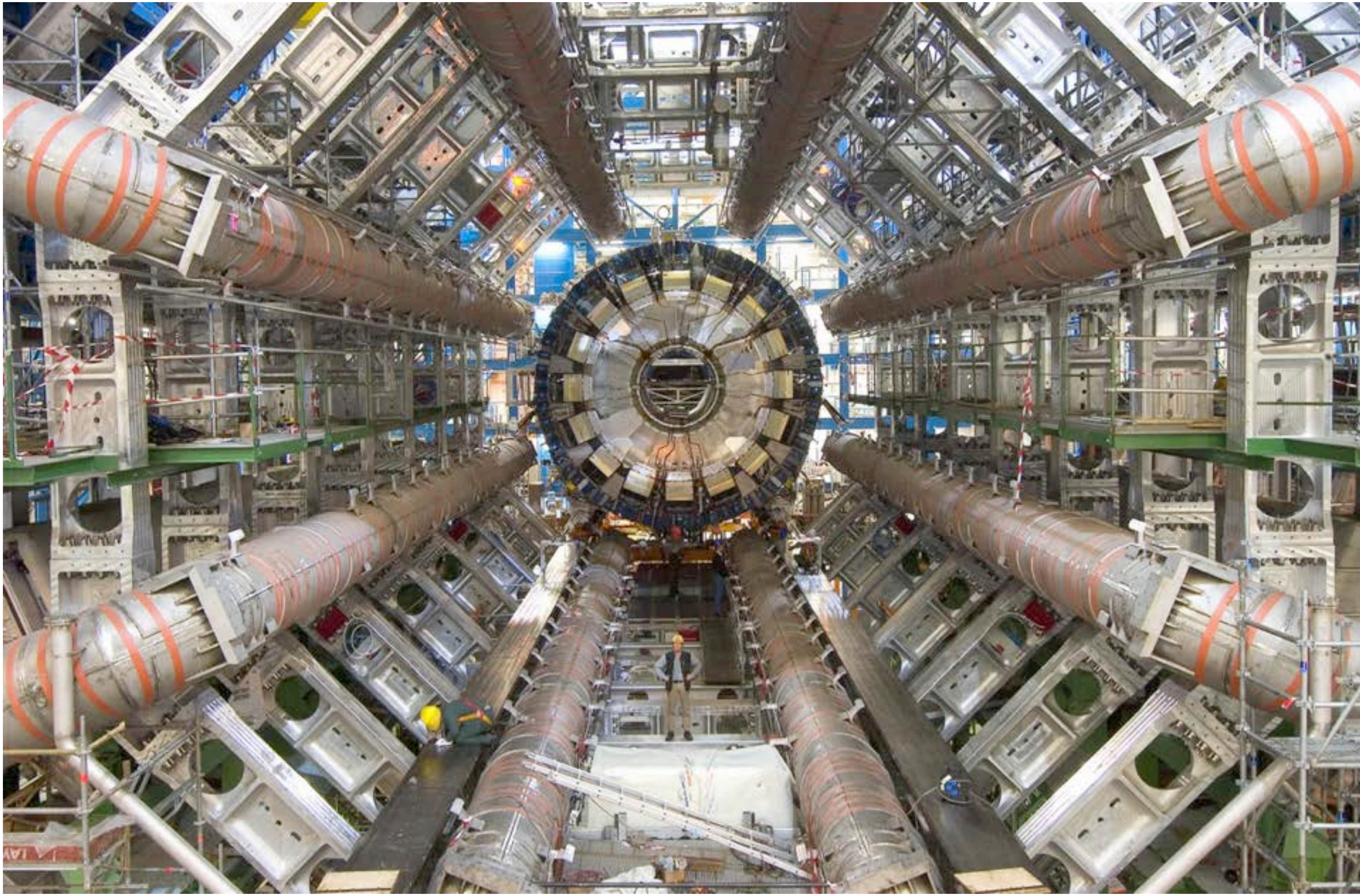
- ATLAS celebrated its 20th anniversary on 1 Oct 2012
- Over 150 Canadian scientists participate in the ATLAS experiment
- ATLAS Canada Collaboration
  - Founded in 1992 — ML Spokesperson, UVic
  - Spokesperson (07-) — Rob McPherson, UVic/IPP
  - Deputy — Richard Teuscher, UofT/IPP
  - Physics Coordination — Bernd Stelzer, SFU
  - Computing Coordination — Reda Tafirout, TRIUMF
- Contributions to the ATLAS detector construction
  - Calorimetry, cryogenics, electronics, trigger, radiation
  - Now much more: trigger, tracking, muon, beam monitor...
- Contributions to the LHC construction (TRIUMF)
- TRIUMF, Canada's nuclear and particle physics laboratory located in Vancouver
  - http://www.triumf.ca/

ATLAS cavern



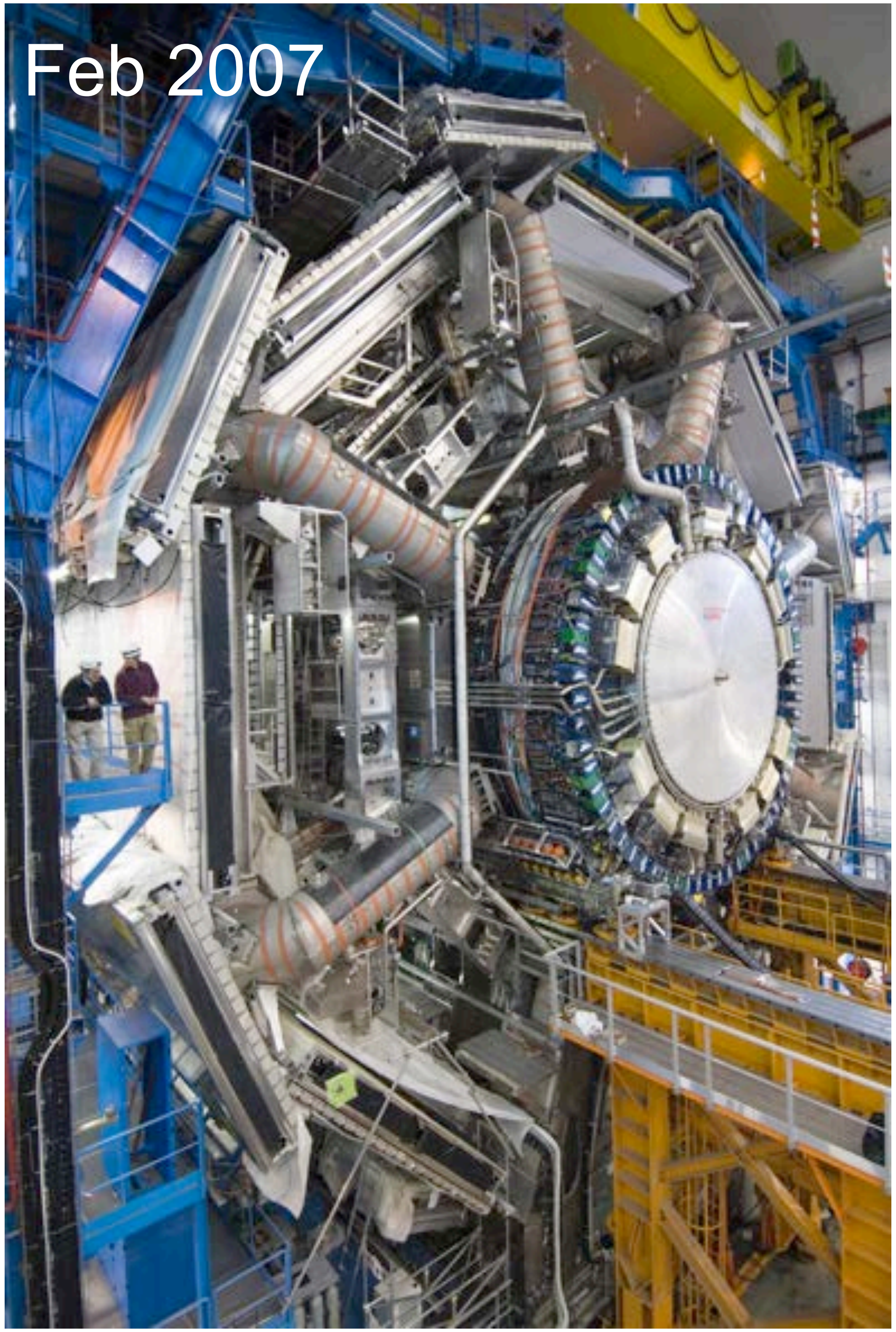
The ATLAS Experiment at CERN, http://atlas.ch

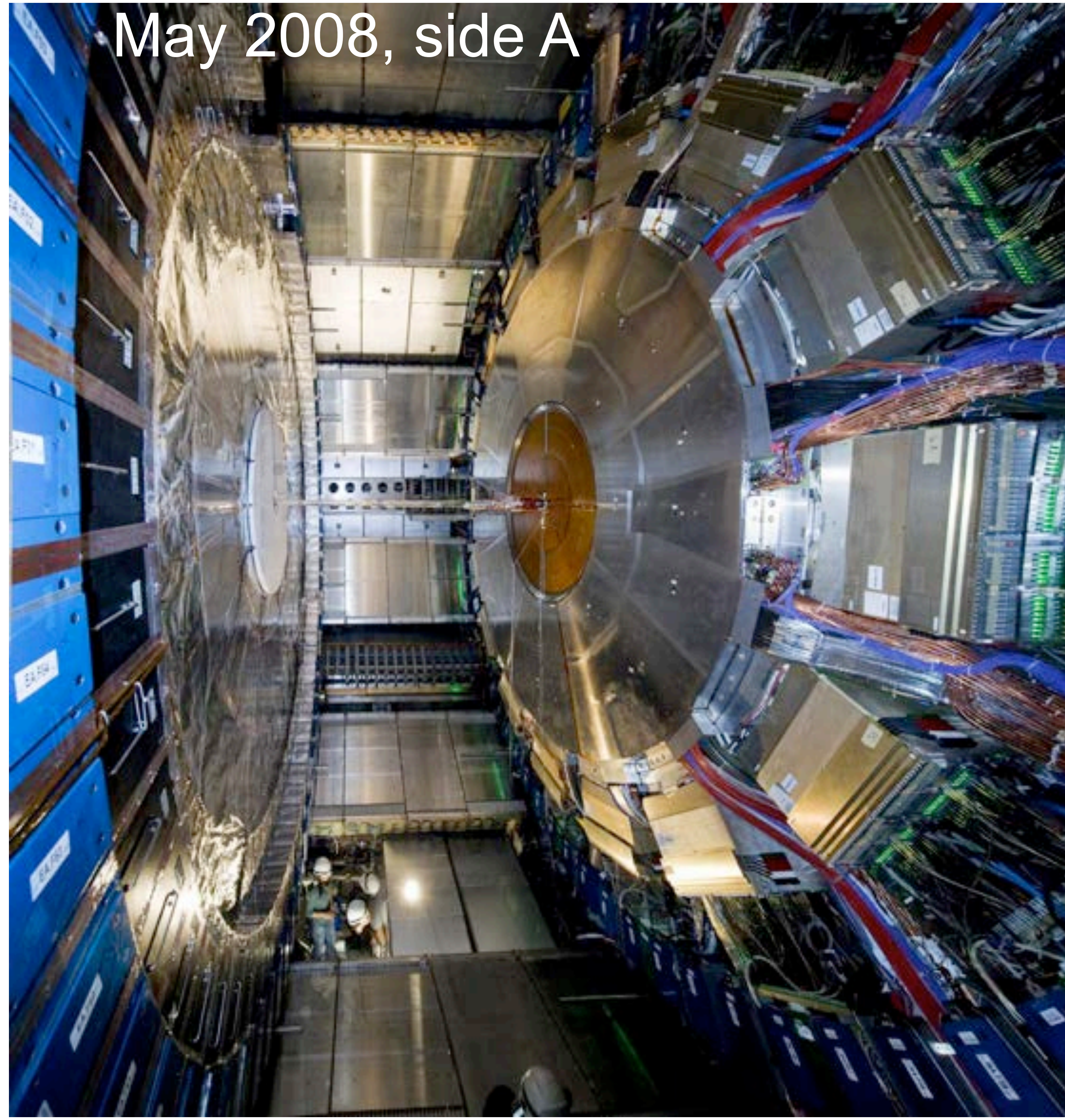
Barrel Toroids all installed (Nov 2005)



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

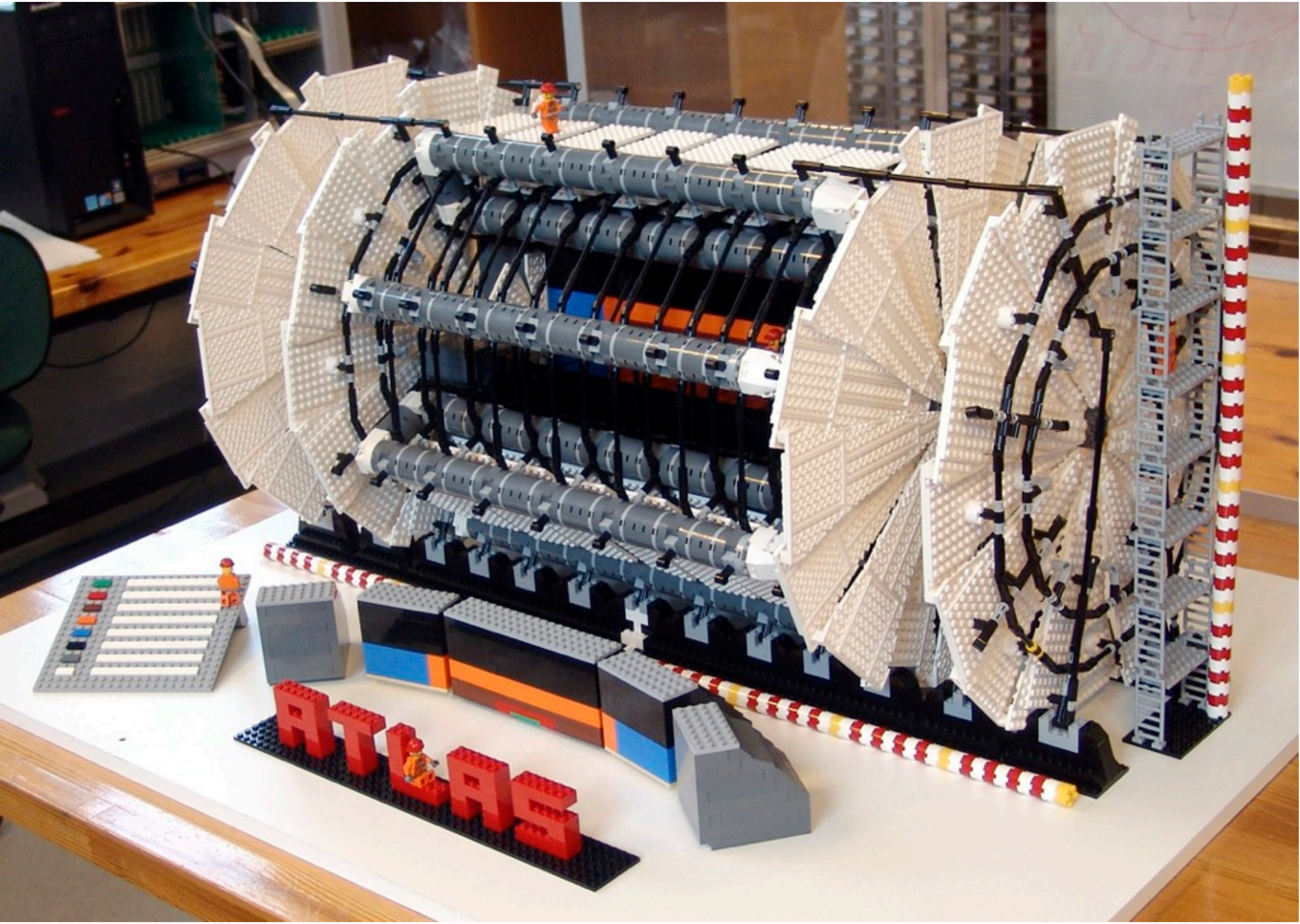
Moving the calorimeters in place





Closing of LHC beam pipe (16 June 2008)

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


ATLAS

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}

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

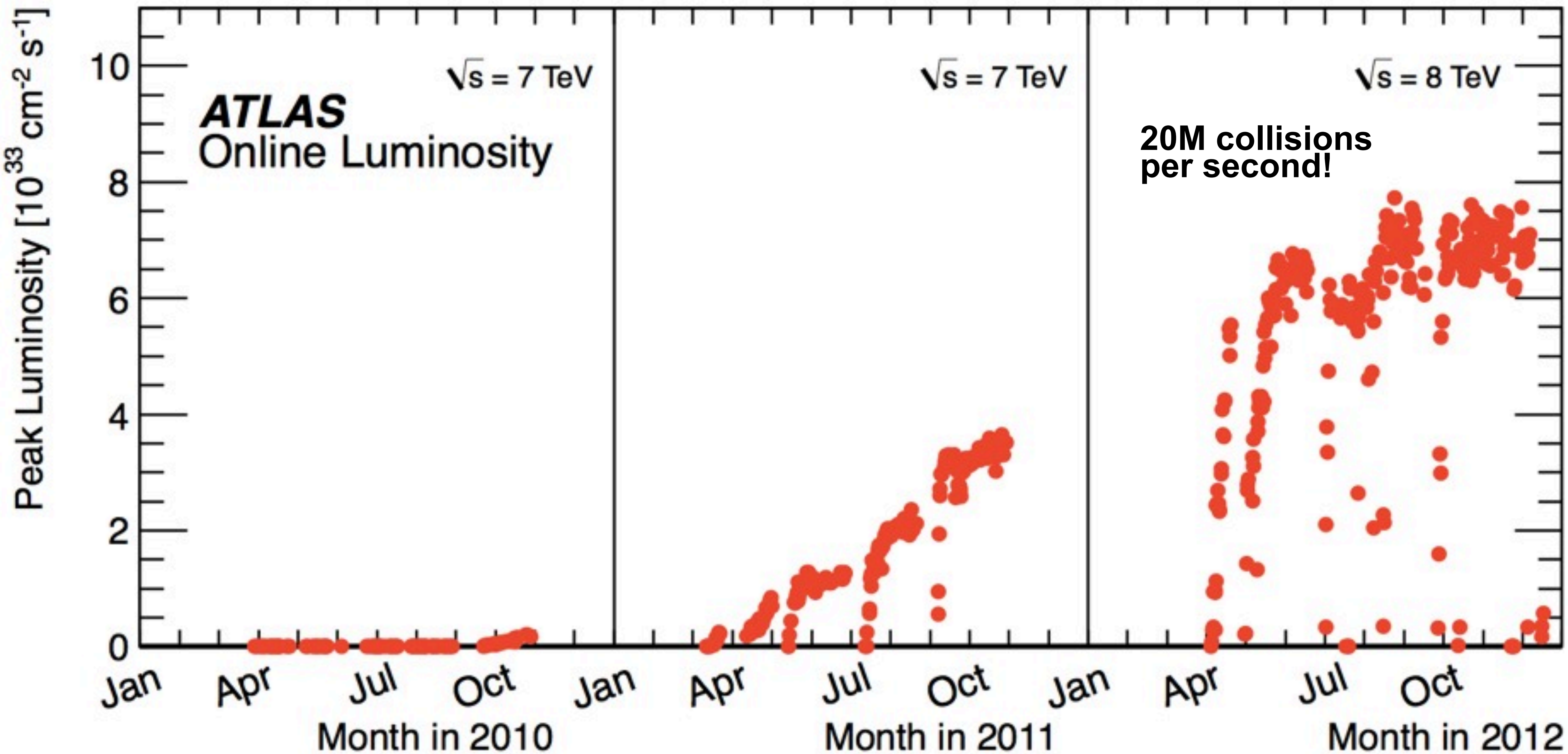
- if you want to make a measurement of a rare process (low cross section) with any significance, you need a large integrated luminosity. If you want to achieve this in a reasonable time, you need a large luminosity!

LHC luminosity, pp collisions

Superb LHC performance!!

Peak luminosity: 7.73×10^{33} cm^{-2} s^{-1}

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults

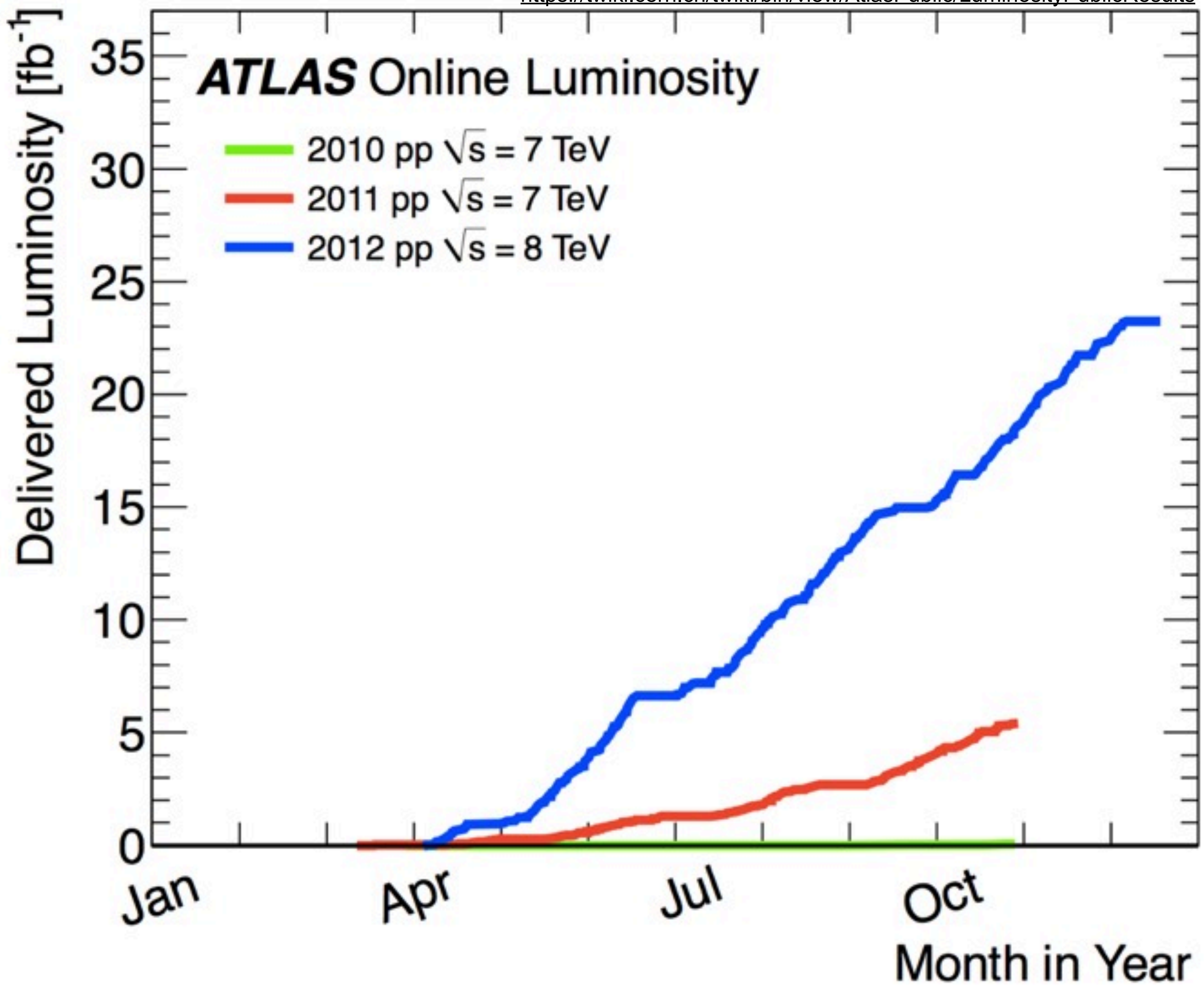


A challenge for the experiments to keep up!

LHC integrated luminosity, pp

Superb LHC performance!!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults



$$\int L\,dt$$

23.3 fb^{-1} 8 TeV

5.6 fb^{-1} 7 TeV

48.9 pb^{-1} 7 TeV

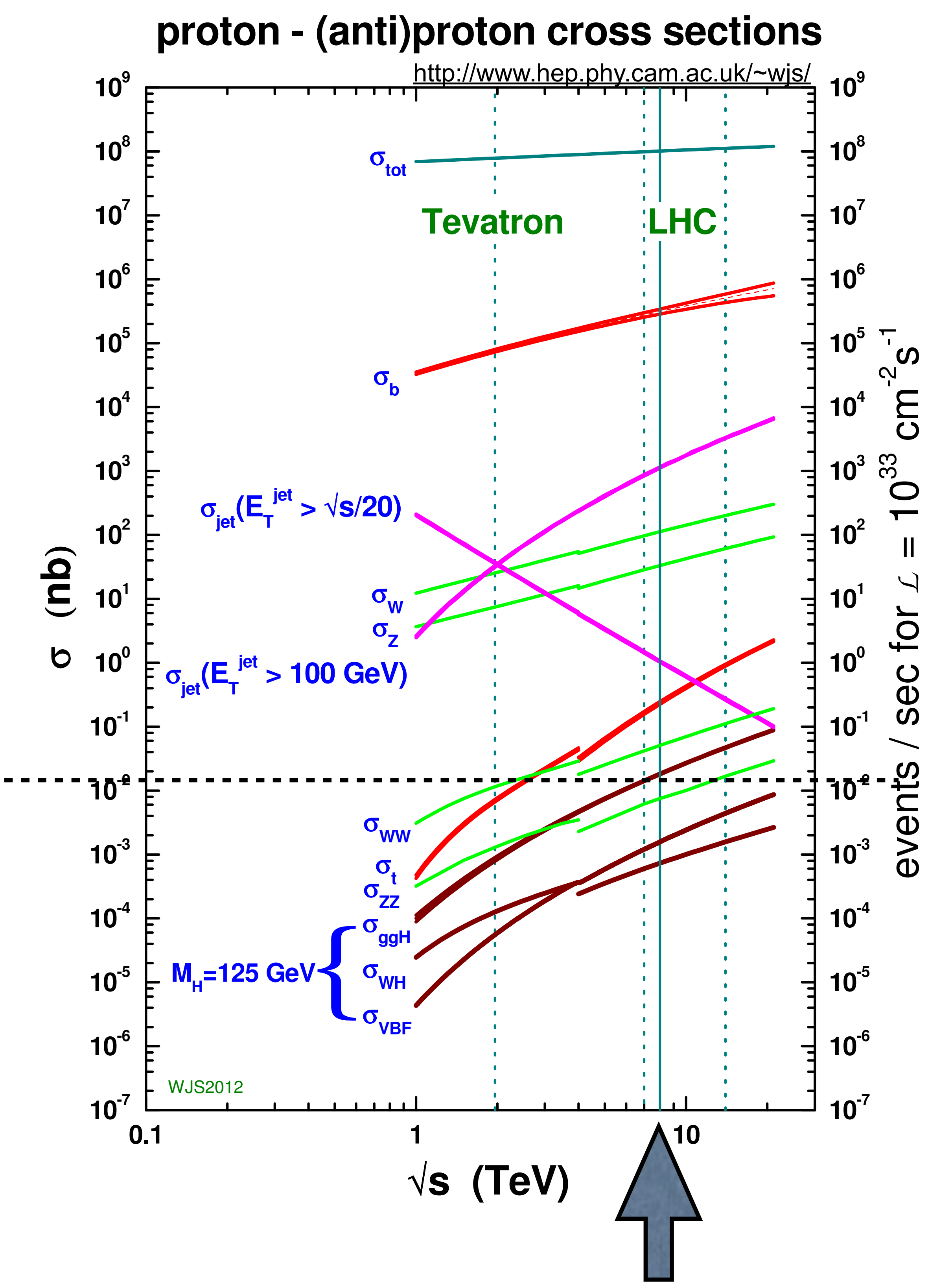
Cross sections and event rates

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

@ 7×10^{33} cm^{-2} s^{-1}

process	σ(nb)	R(Hz)
inelastic	~7.5×10^7	0.53×10^9
Z	~35	250
ttbar	~0.24	1.7
$H_{(125 GeV)}$	~0.022	0.15

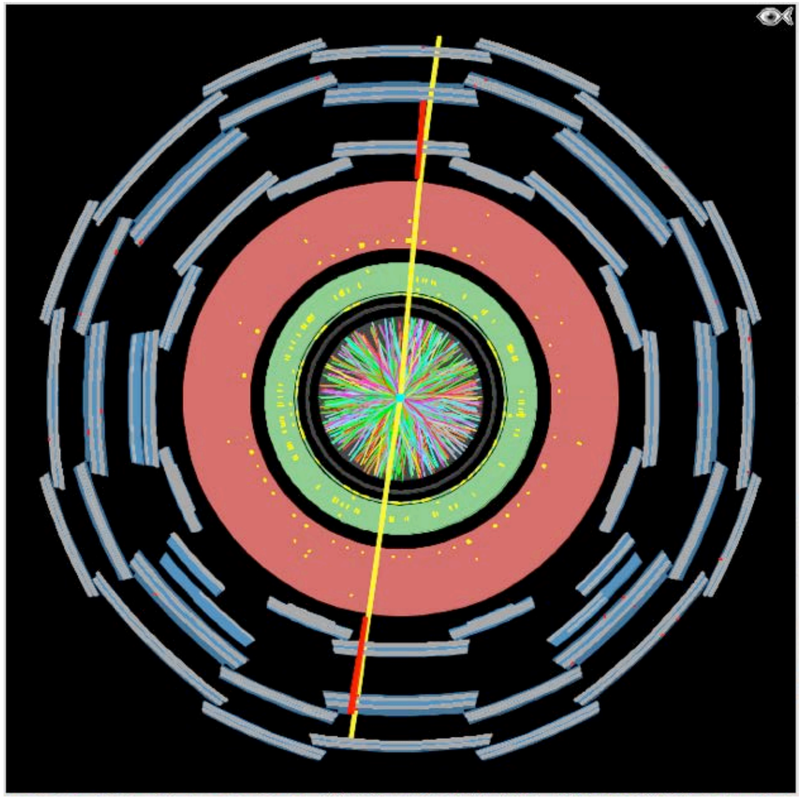
~0.5 M in 2012!



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

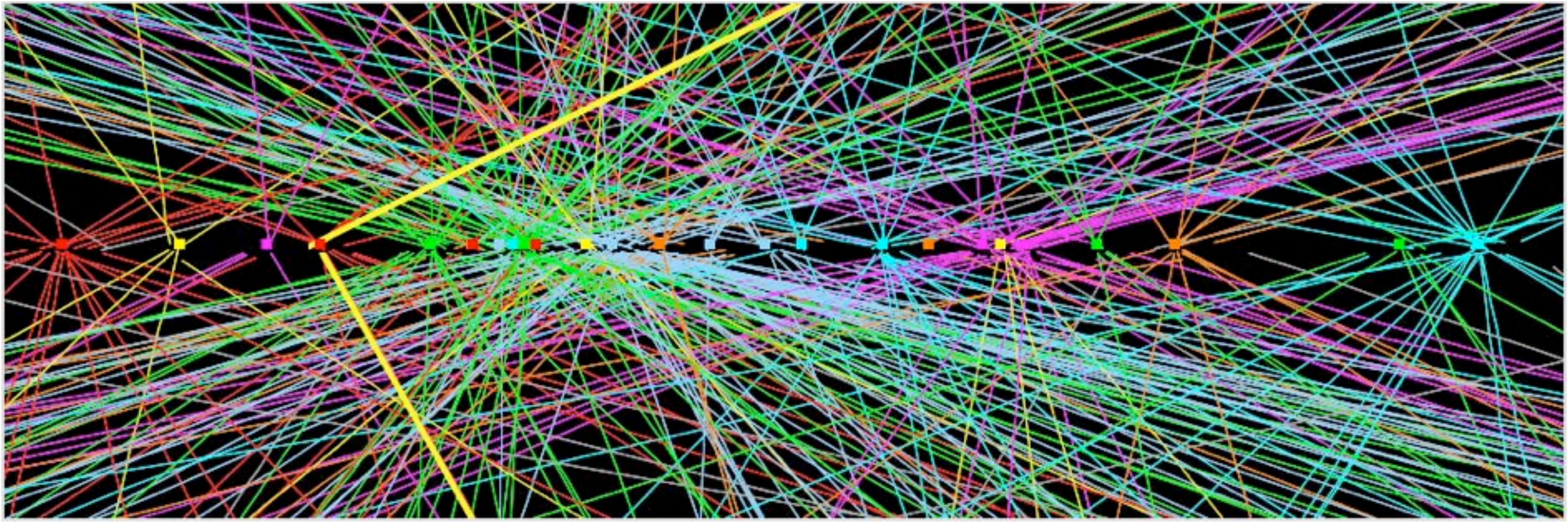
Experimental challenge: Pile-up

- In-time pile-up
  - due to multiple collisions per bunch crossing
  - **in 2012, ~20 events per bunch crossing!!**
    - near value of 23 at design instantaneous luminosity!
- Out-of-time pile-up
  - superposition of signal from preceding (and following) bunch crossing



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

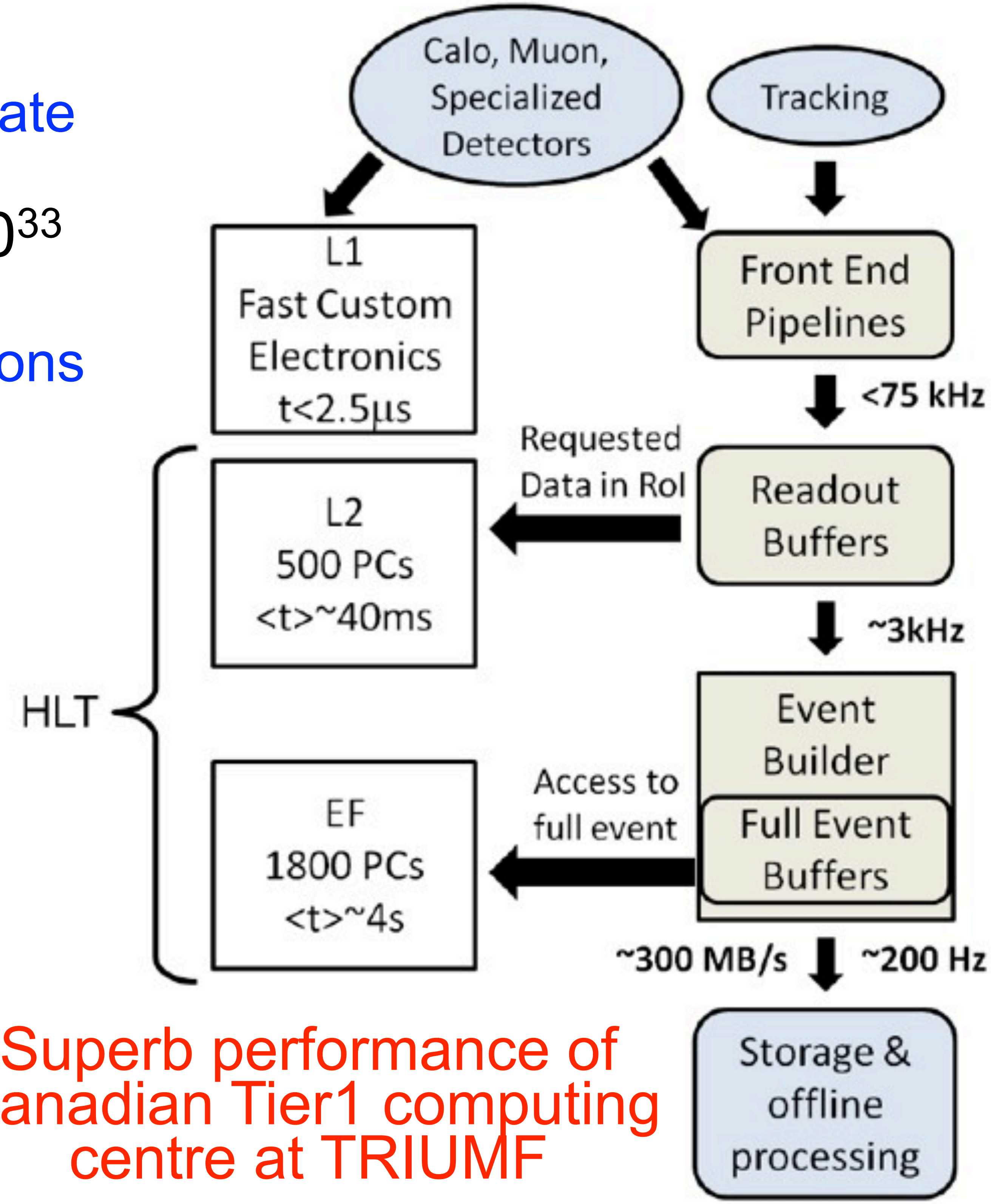
~1cm



Trigger system

- Three-level trigger system
  - designed to reduce the data rate from 40 MHz to ~200 Hz
- Menu now optimized for 7×10^{33} cm^{-2} s^{-1}
  - improvement of object selections and trigger algorithms
- Good performance in 2012!

Main triggers at 7×10^{33} $cm^{-2}s^{-1}$				
Offline (GeV)	L1 thr (GeV)	L1 rate (kHz)	EF thr (GeV)	EF rate (Hz) @5 10^{33}
e > 25	18	17	24	70
μ > 25	15	8	24	45
dilepton	10-15	15	8-18	21
2γ 25-40	10-16	12	20-35	17
2τ 30-45	11-15	12	20-29	12
Jet > 360	75	2	2	5
MET 120	40	2	80	17



Superb performance of Canadian Tier1 computing centre at TRIUMF

Eur.Phys.J. C72 (2012) 1849

SM production cross sections

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots

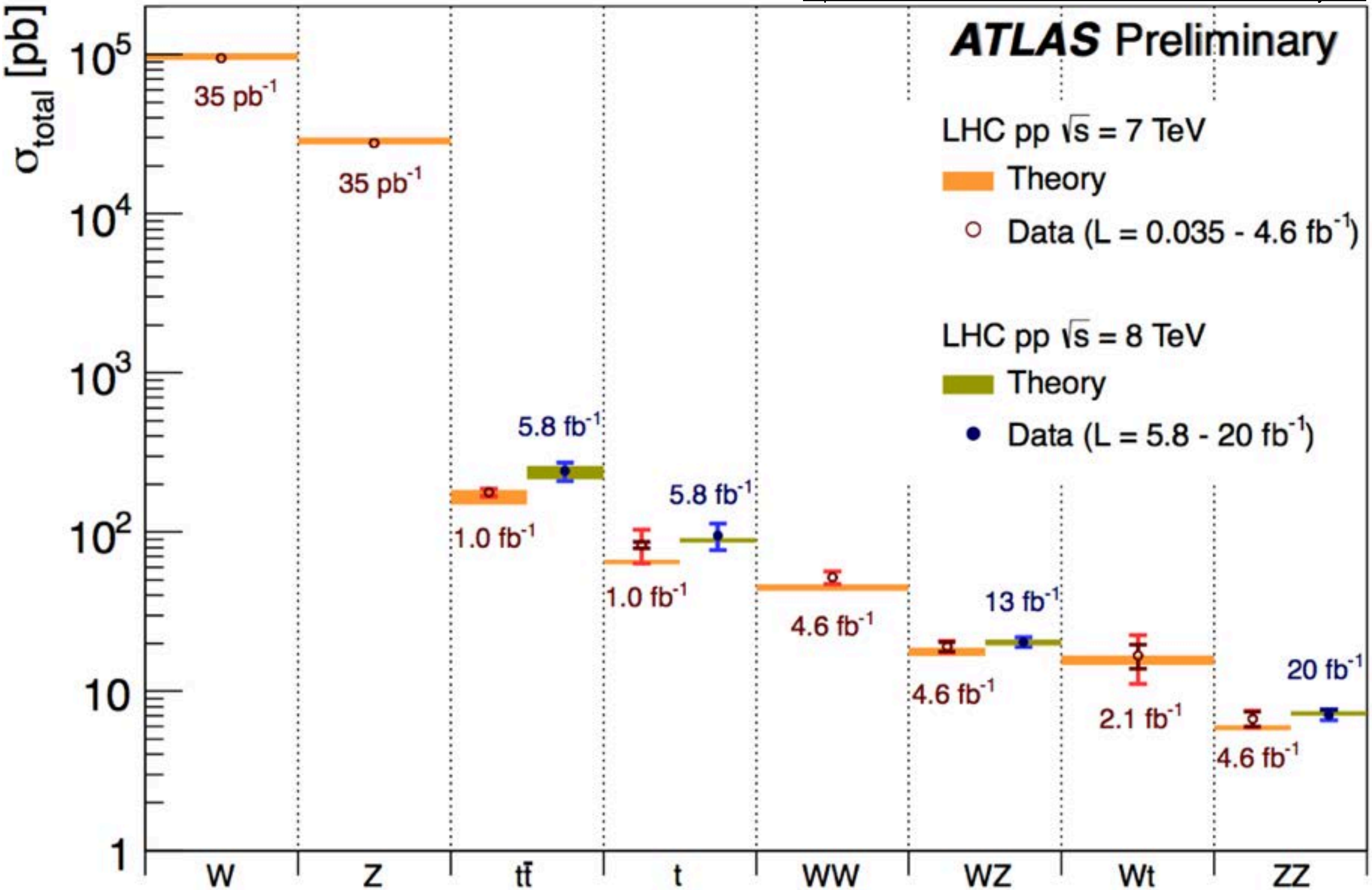


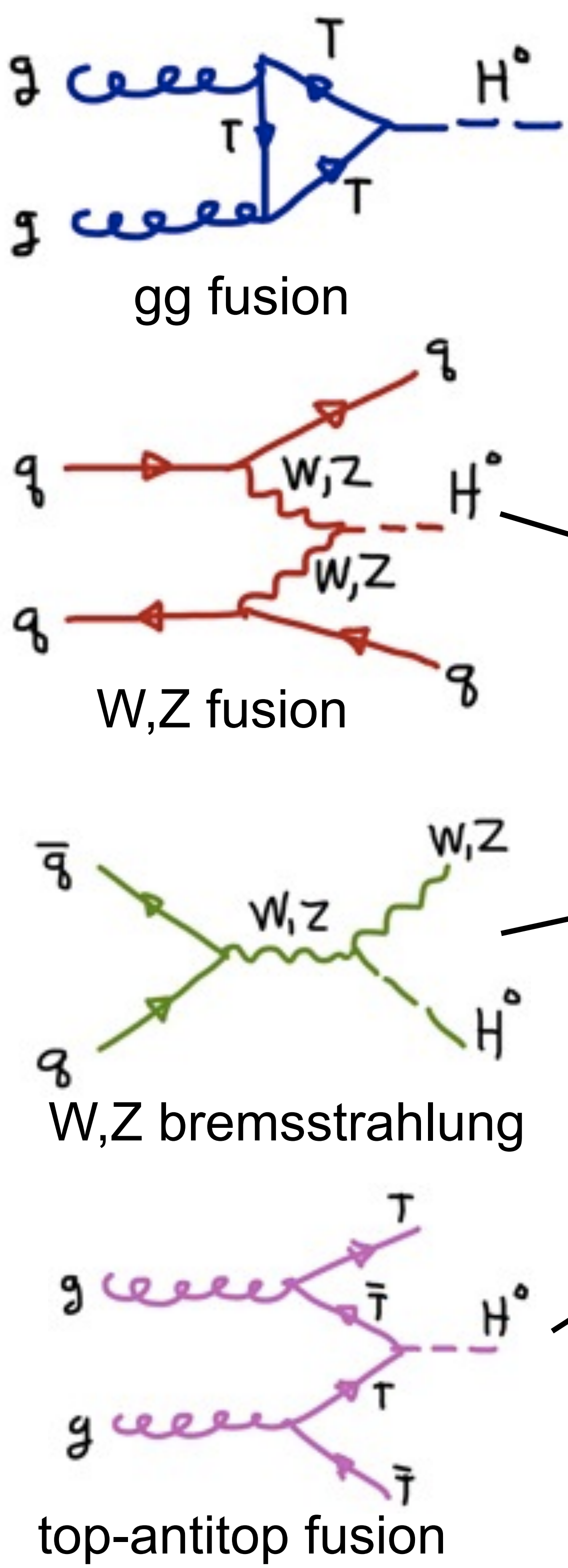
figure as of 2013/03/08

the **Higgs boson**: the missing piece

H^0

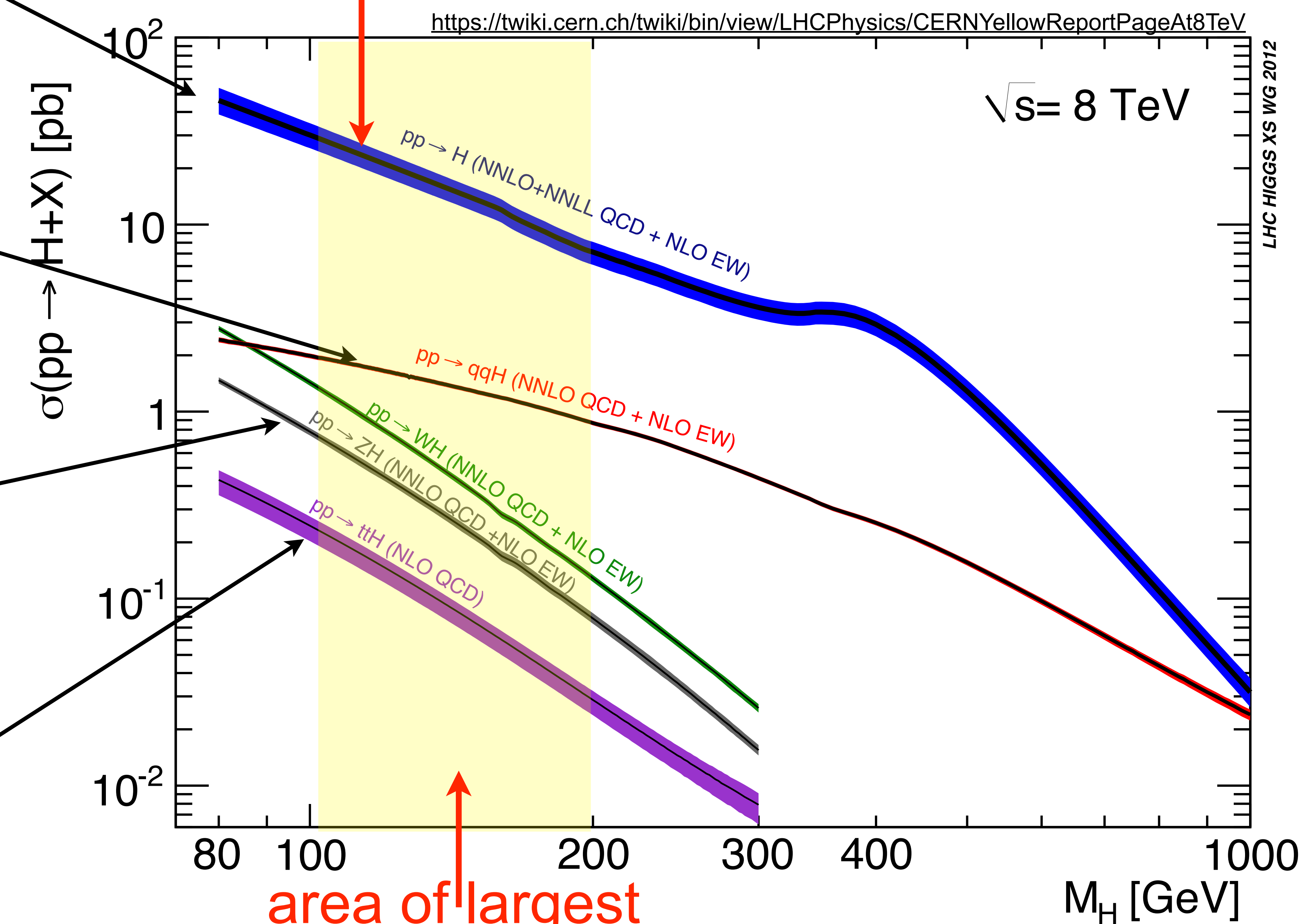
a spin 0 boson!

SM Higgs production



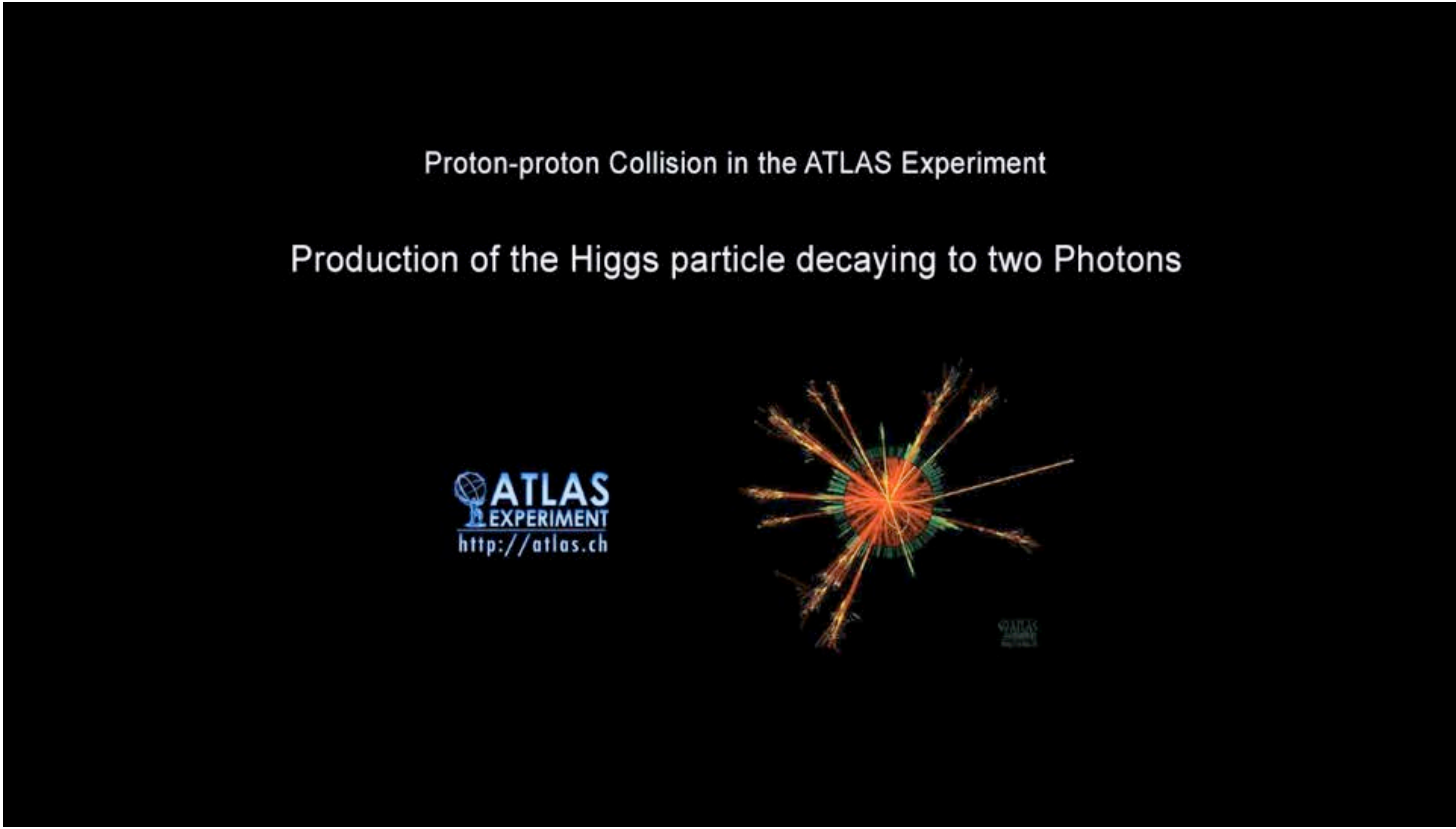
Predicted cross sections for

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



area of largest interest

Higgs production



http://www.atlas.ch/multimedia

Most important Higgs decays

Here the most important decays for searches, with fractions for M_H = 125 GeV

~58% $$H \rightarrow b\bar{b}$$

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

~6.3% $$H \rightarrow \tau\,\tau$$

~0.23% $$H \rightarrow \gamma\,\gamma$$

~0.02% $$H \rightarrow Z\,Z^{(*)} \rightarrow 4\ell$$ e or μ pairs

The cleanest channels are also the rarest...

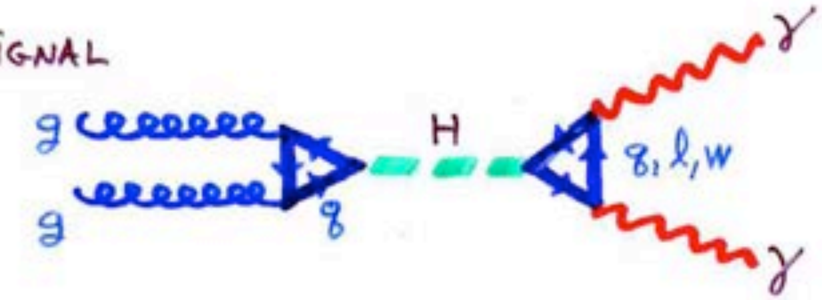
CAP Congress June 1996

$H \rightarrow \gamma\gamma$

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

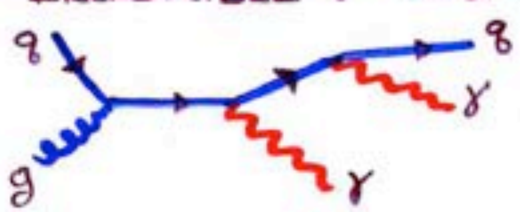
  PRESENT DIRECT LIMIT FOR SM H : $M_H > 652$
  EXPECT LEP (192 GeV) : $M_H > 95$ GeV 95%

- SIGNAL

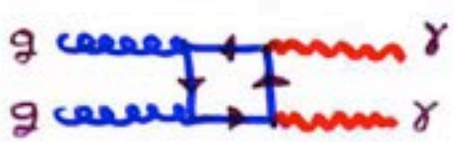


g FUSION

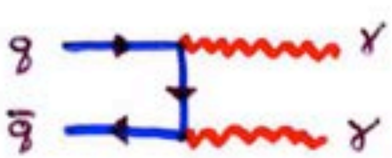
- BACKGROUND
  IRREDUCIBLE : QCD PRODUCTION



q BREM



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



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

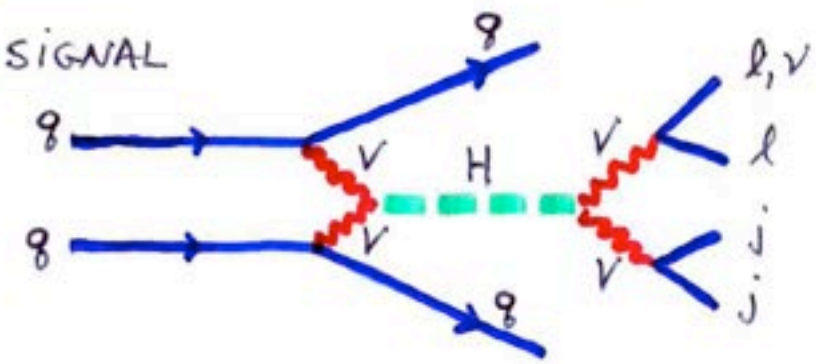
REDUCIBLE : QCD JETS, $Z \rightarrow ee$ } WITH FAKE γ

- CHALLENGING CHANNEL

$H \rightarrow WW \rightarrow \ell\nu jj$
$ZZ \rightarrow \ell\ell jj$

- INTERESTING BECAUSE 150× BRANCHING RATIO OF 4ℓ CHANNEL

- SIGNAL



V FUSION

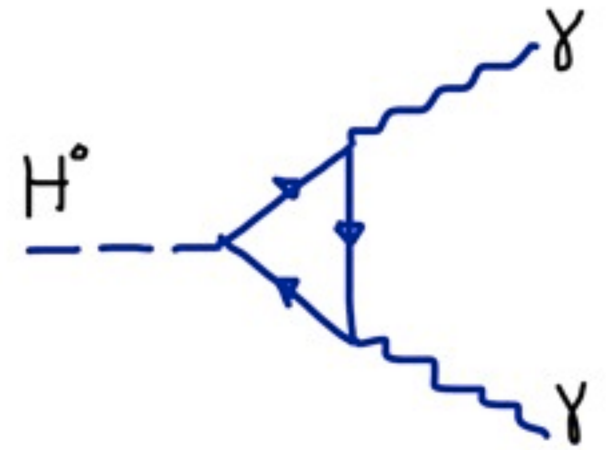
- BACKGROUND

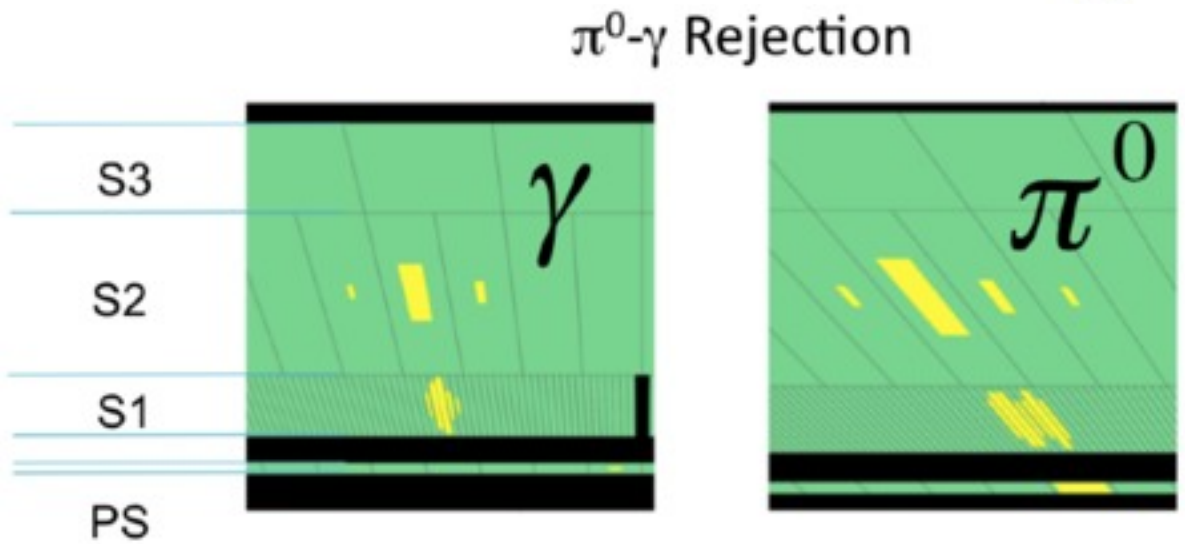
  $t\bar{t}$, W + JETS

- 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

$H \to \gamma\ \gamma$

- 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





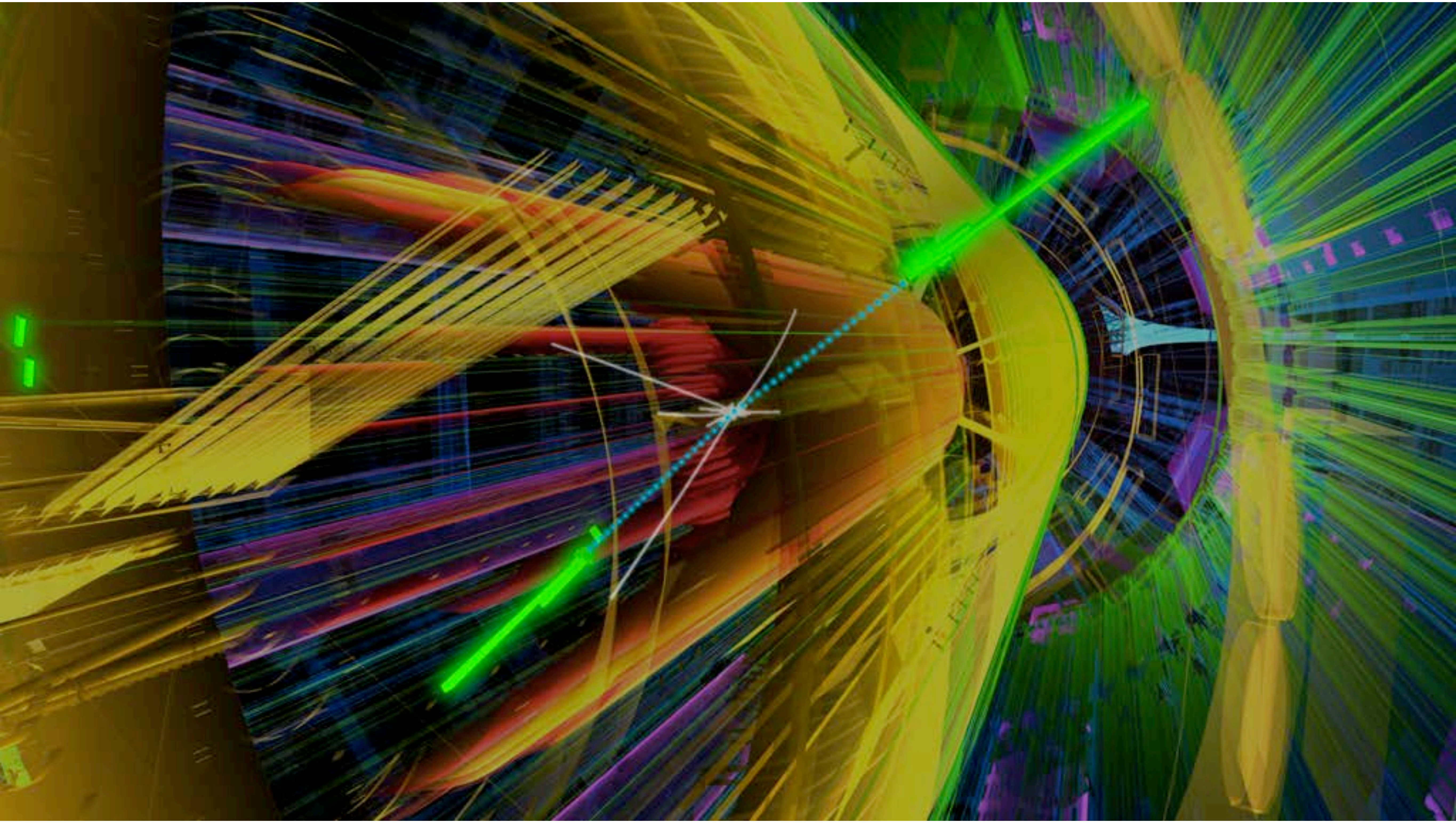
- Reconstruct the 2-photon invariant mass
  - look for a signal mass bump over a large background

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

need good photon energy reconstruction

need good photon direction

$H \rightarrow \gamma\ \gamma$?



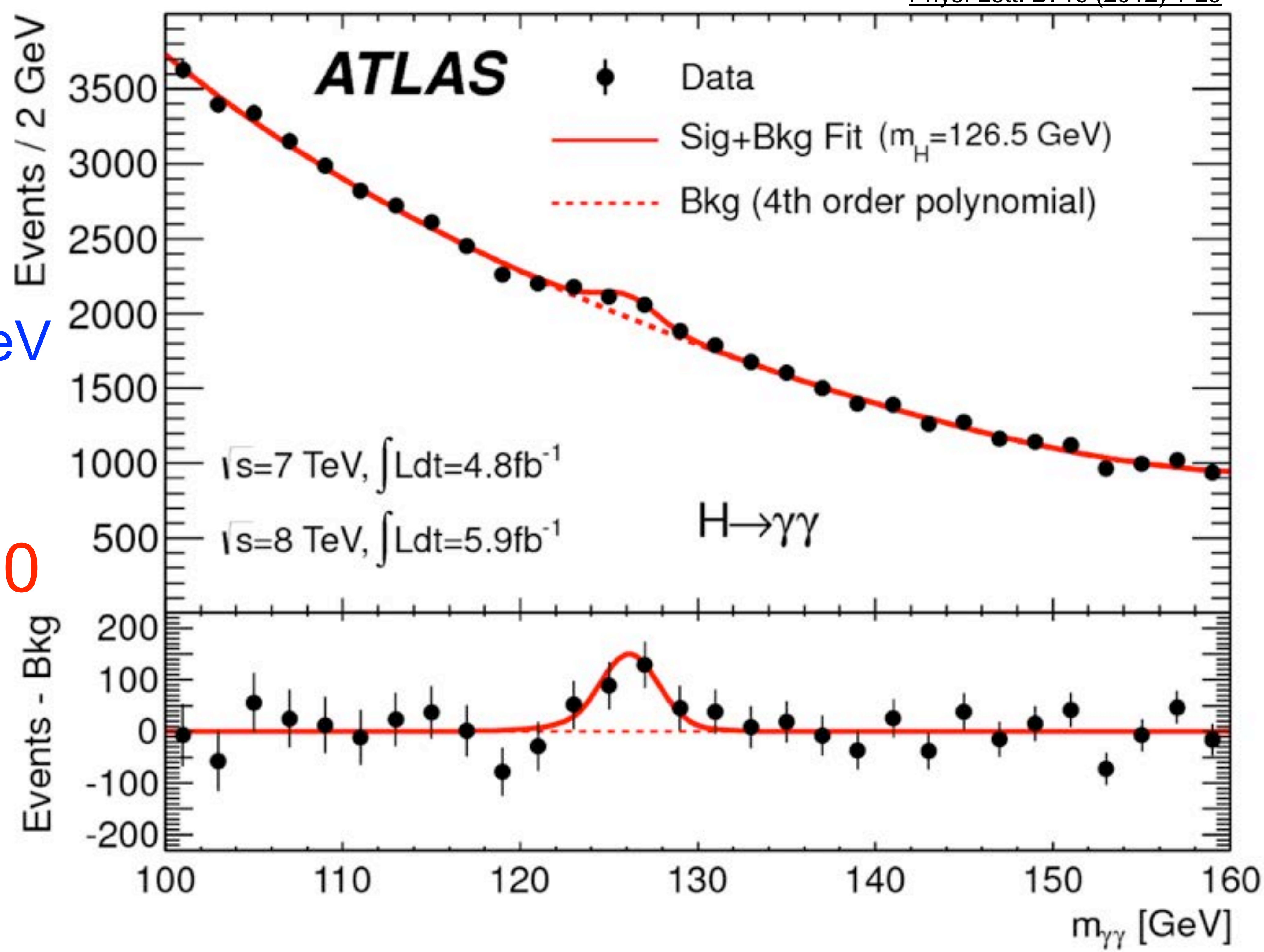
$H \rightarrow \gamma\ \gamma$ (July 2012)

Phys. Lett. B716 (2012) 1-29

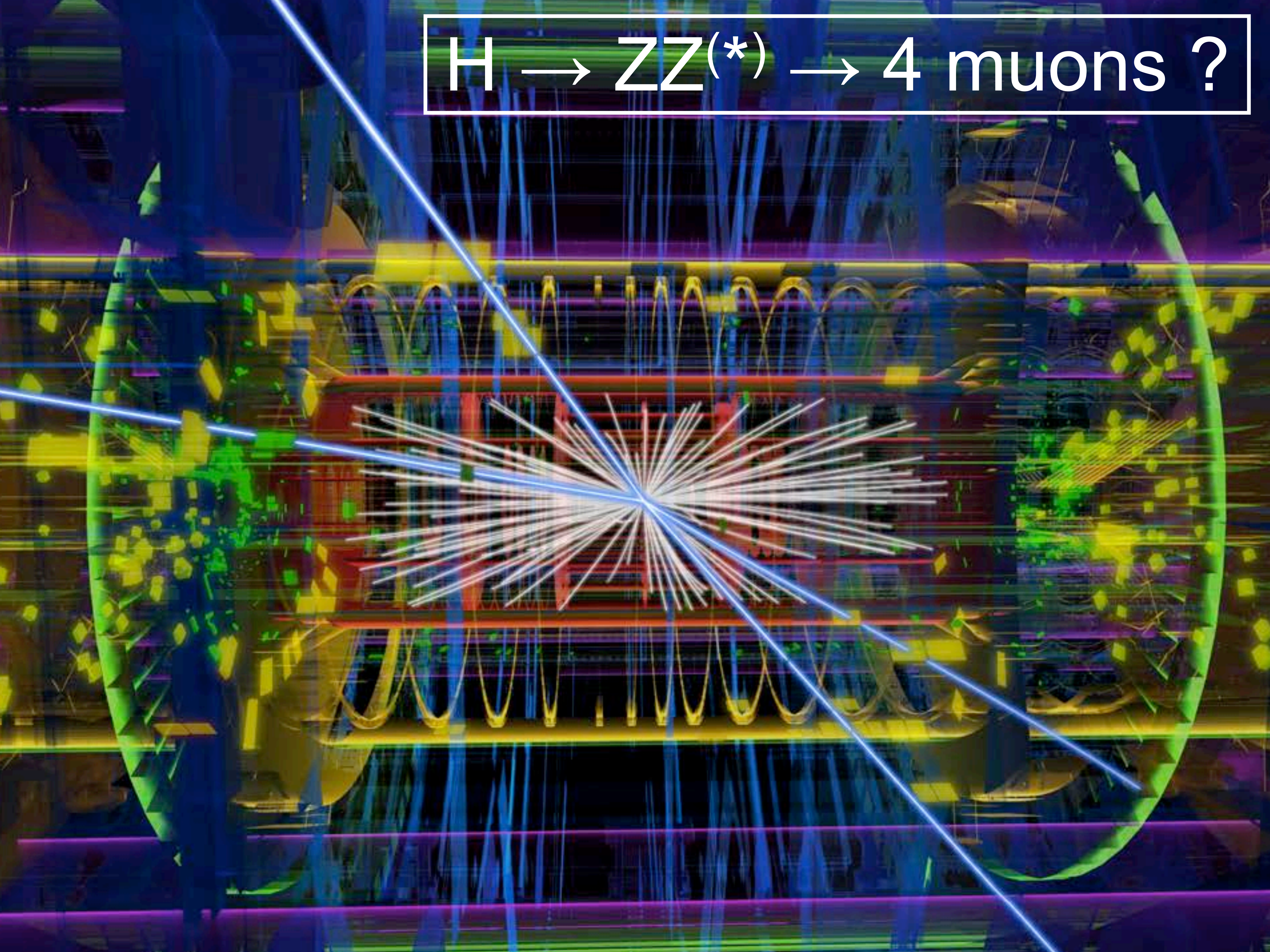
Excess of events!

M ~ 126.5 GeV
4.5 σ

~1 / 300000 chance of being a statistical fluctuation



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



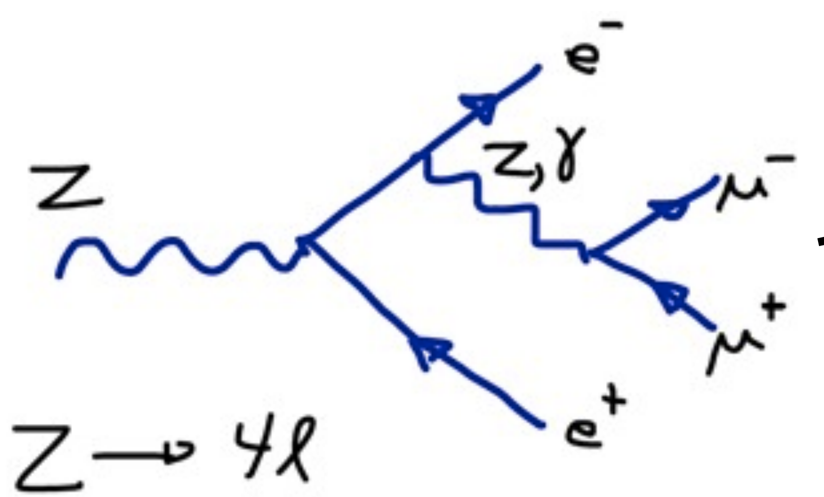
$H \rightarrow ZZ^{(*)} \rightarrow$ 4 leptons (July 2012)

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

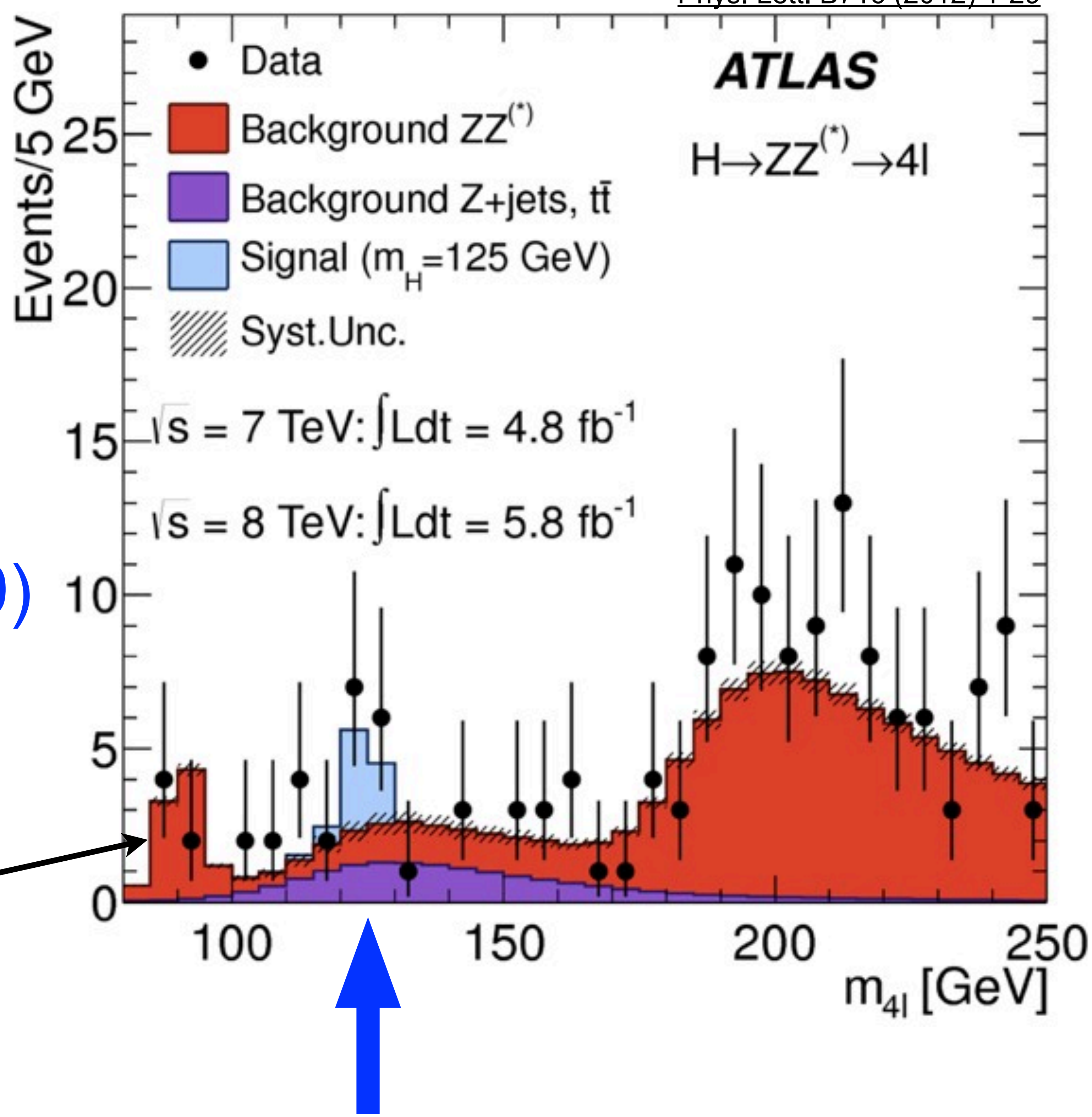
Excess of events!

3.6 σ (~1 / 6300)

M ~ 125.0 GeV



Phys. Lett. B716 (2012) 1-29



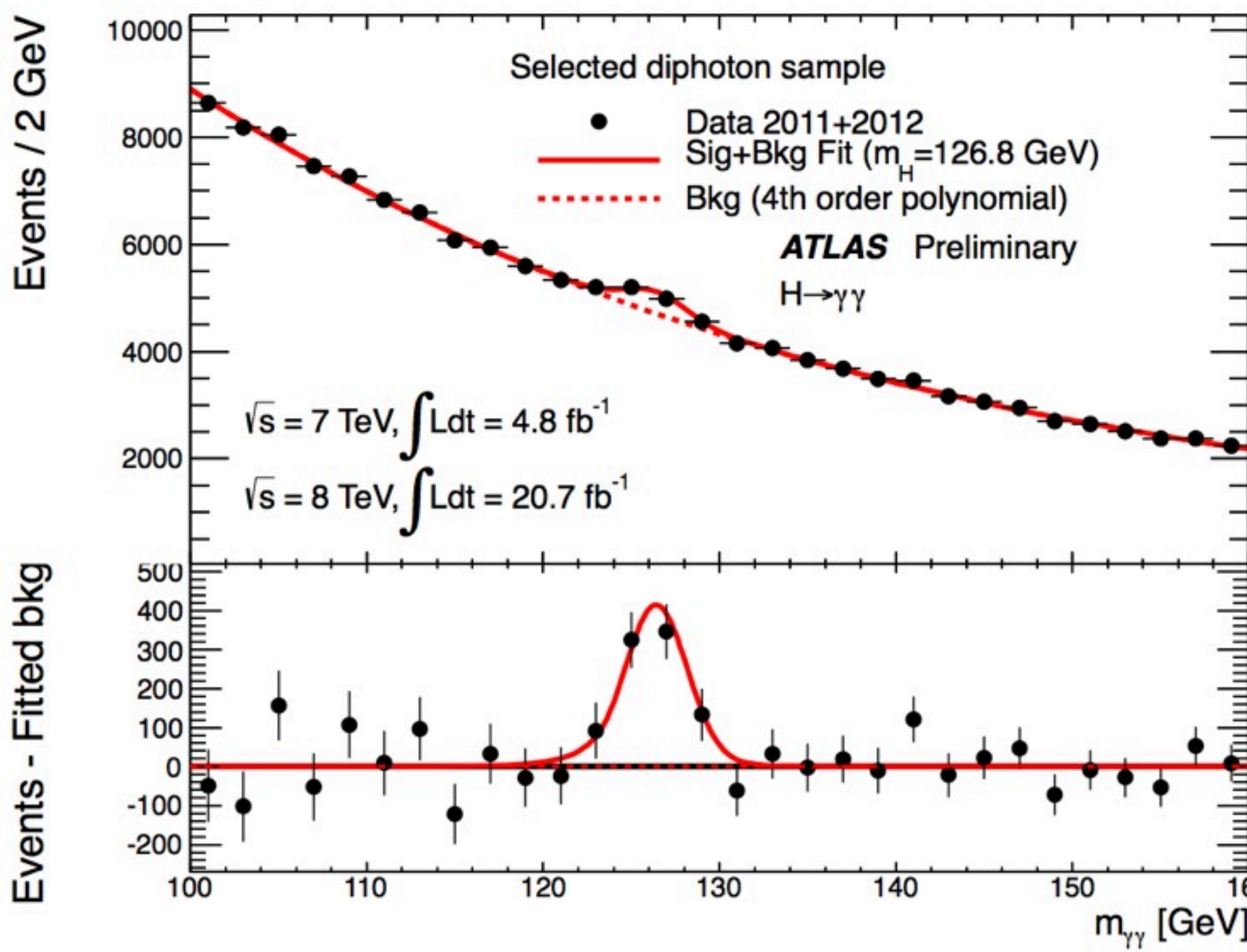
4 July 2012 CERN and Melbourne

CERN, 09:00

ICHEP 2012, Melbourne, 19:00

00:00 in Victoria!

H → γ γ

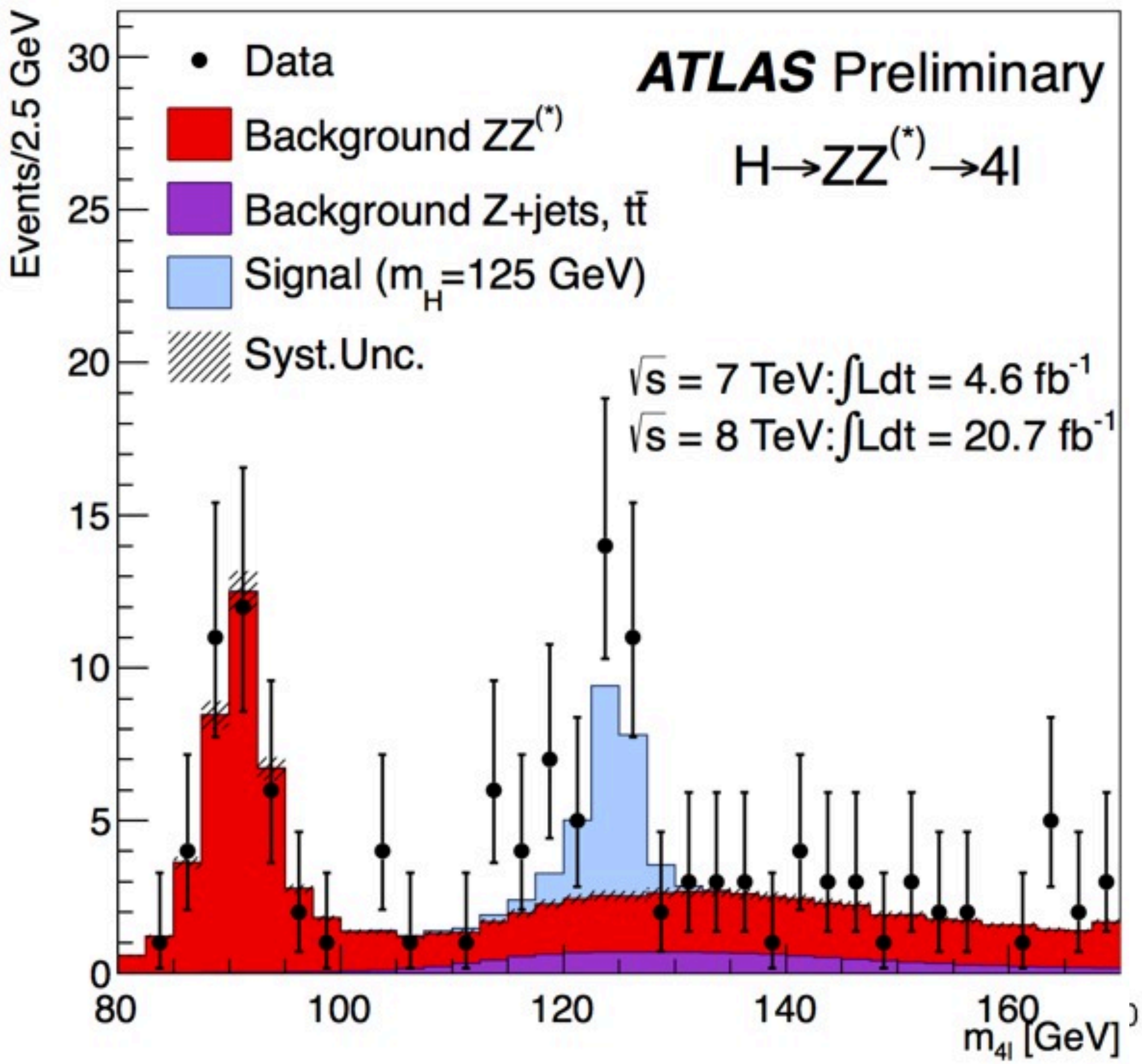


ATLAS-CONF-2013-012

7.4 σ
(6.8×10^{-14})

$$M_{\gamma\gamma} = 126.8 \pm 0.2\ (\mathrm{stat}) \pm 0.7\ (\mathrm{sys})\ \mathrm{GeV}$$

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



6.6 σ (2.7×10^{-11})
Latest results:
ATLAS-CONF-2013-013
In [120, 130 GeV], expect
Signal: 16 events
Background: 11 events
Observed: 32 events

The difference between the measured masses
is found to have a significance of
2.4 σ (or 1.5%).

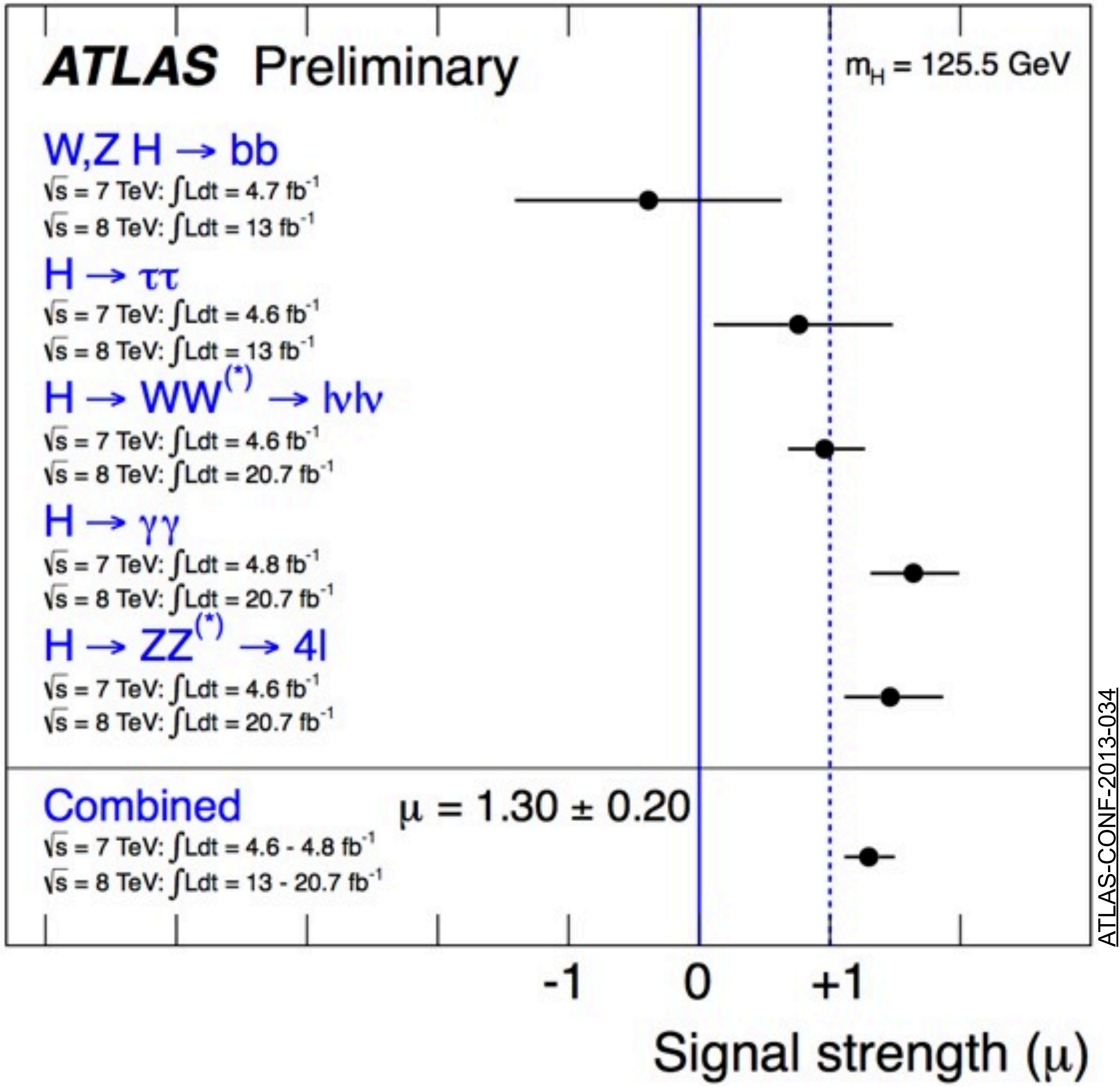
$$2.3^{+0.6}_{-0.7}\ (\text{stat})\ \pm 0.6\ (\text{sys})\ \text{GeV}$$

Latest mass combination:
ATLAS-CONF-2013-014

$$M_{4\ell} = 124.3^{+0.6}_{-0.5}\ (\text{stat})\ ^{+0.5}_{-0.3}\ (\text{sys})\ \text{GeV}$$

Higgs particle signal strength

$$M_{\mathrm{H}} = 125.5 \pm 0.2\ (\mathrm{stat})\ ^{+0.5}_{-0.6}\ (\mathrm{sys})\ \mathrm{GeV}$$



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

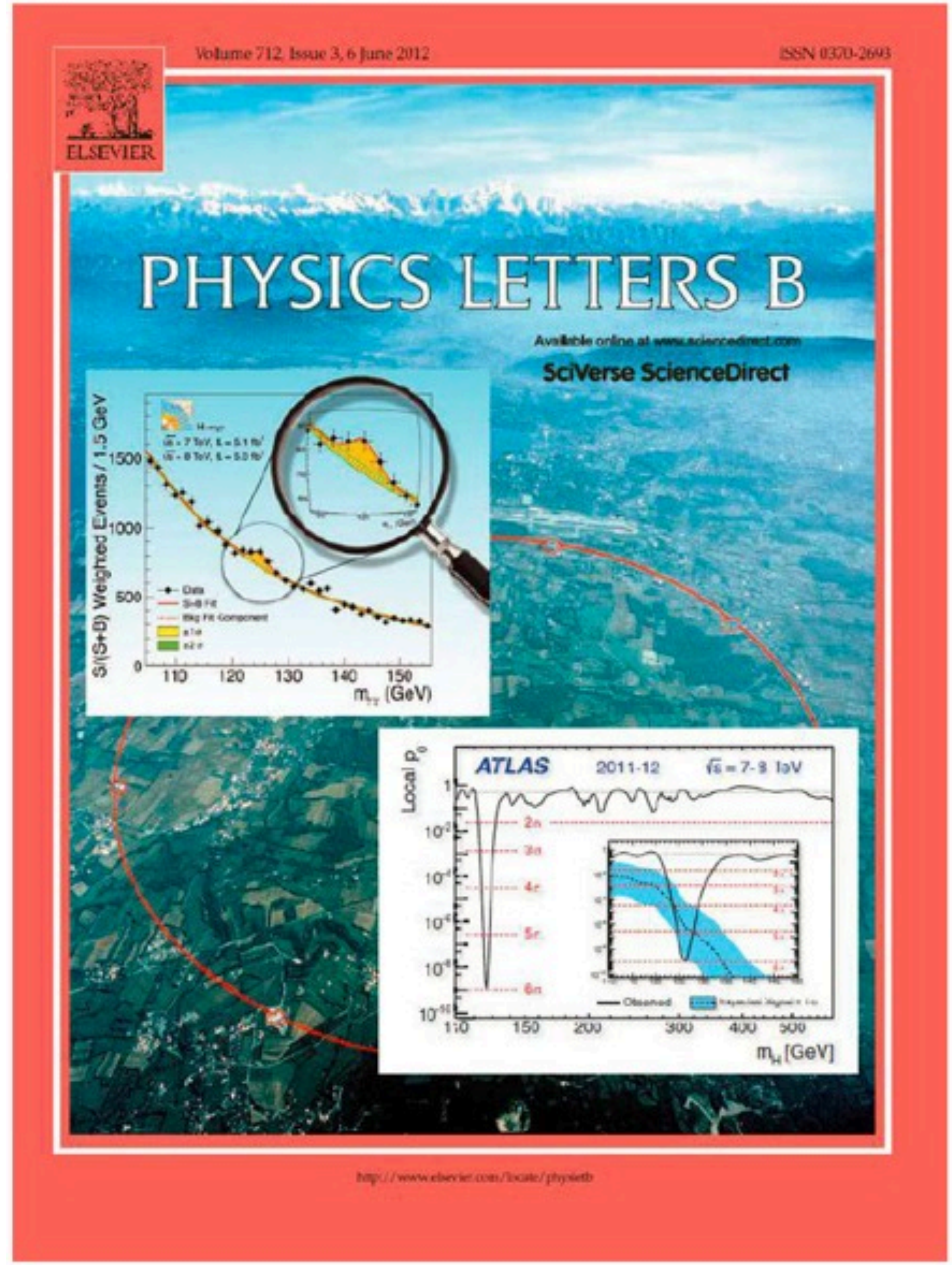
$$= 1.30 \pm 0.20$$

Compatibility with SM μ = 1 with observed measurement is ~9%

Latest Higgs combination:
ATLAS-CONF-2013-034

Is it the SM Higgs boson?

- We have discovered a new particle!
  - savour this privileged and historic moment
  - a Higgs boson
    - naturalness issue: M_H small only if protected by some symmetry
- Spin and parity
  - boson, not of spin 1
  - compatible with SM prediction of 0^+
- Couplings as predicted by the SM gauge symmetry?
  - otherwise at odds with gauge principle that rules all forces!
  - so far: agreement with SM



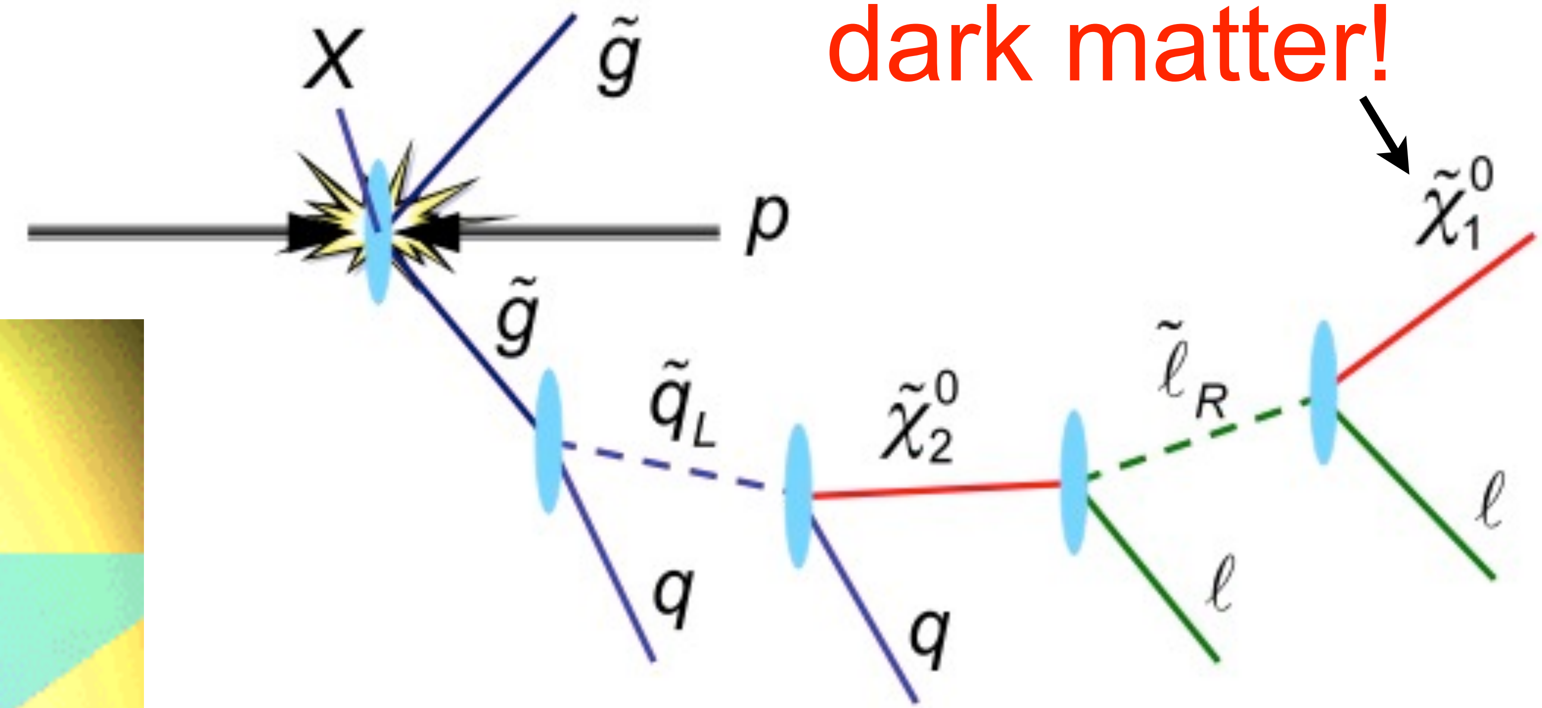
Phys. Lett. B 716 (2012) 1-29 (ATLAS)

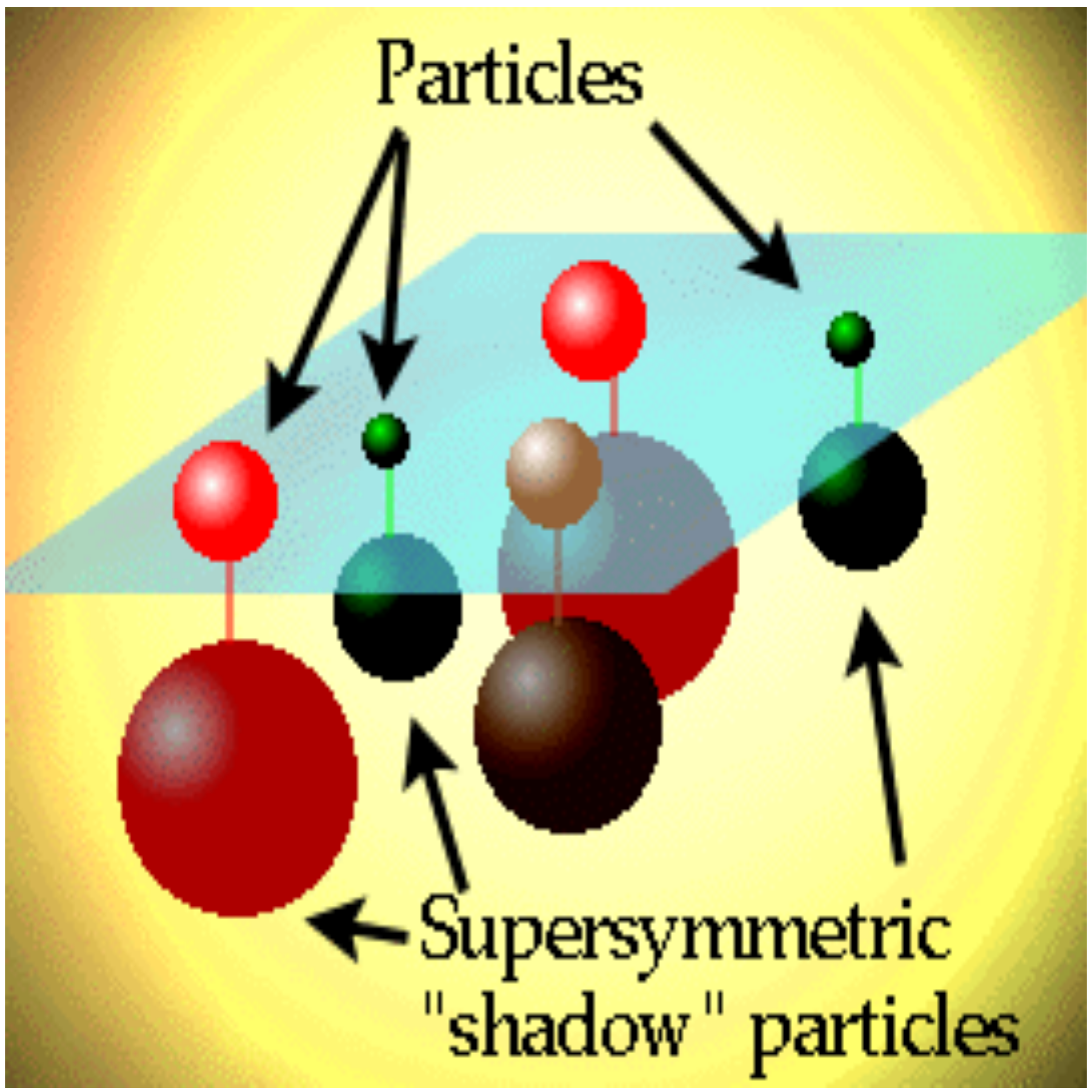
Many more questions

- 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 and bosons





- 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

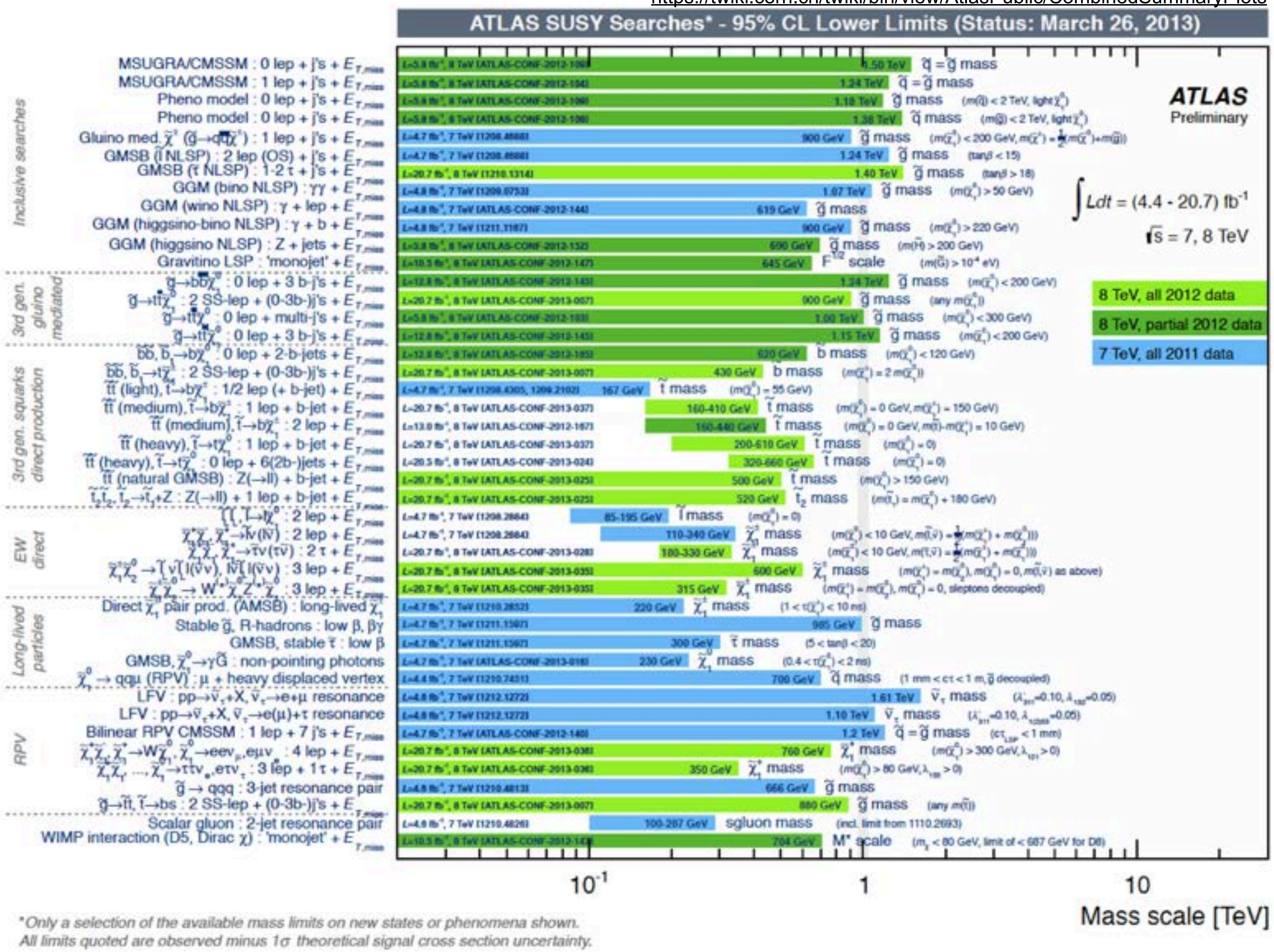
- Aggressively probing weak scale SUSY between 100 GeV and 1 TeV

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots

inclusive searches

natural SUSY

long lived particles



Exotic searches

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

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots

extra dimensions

substructure

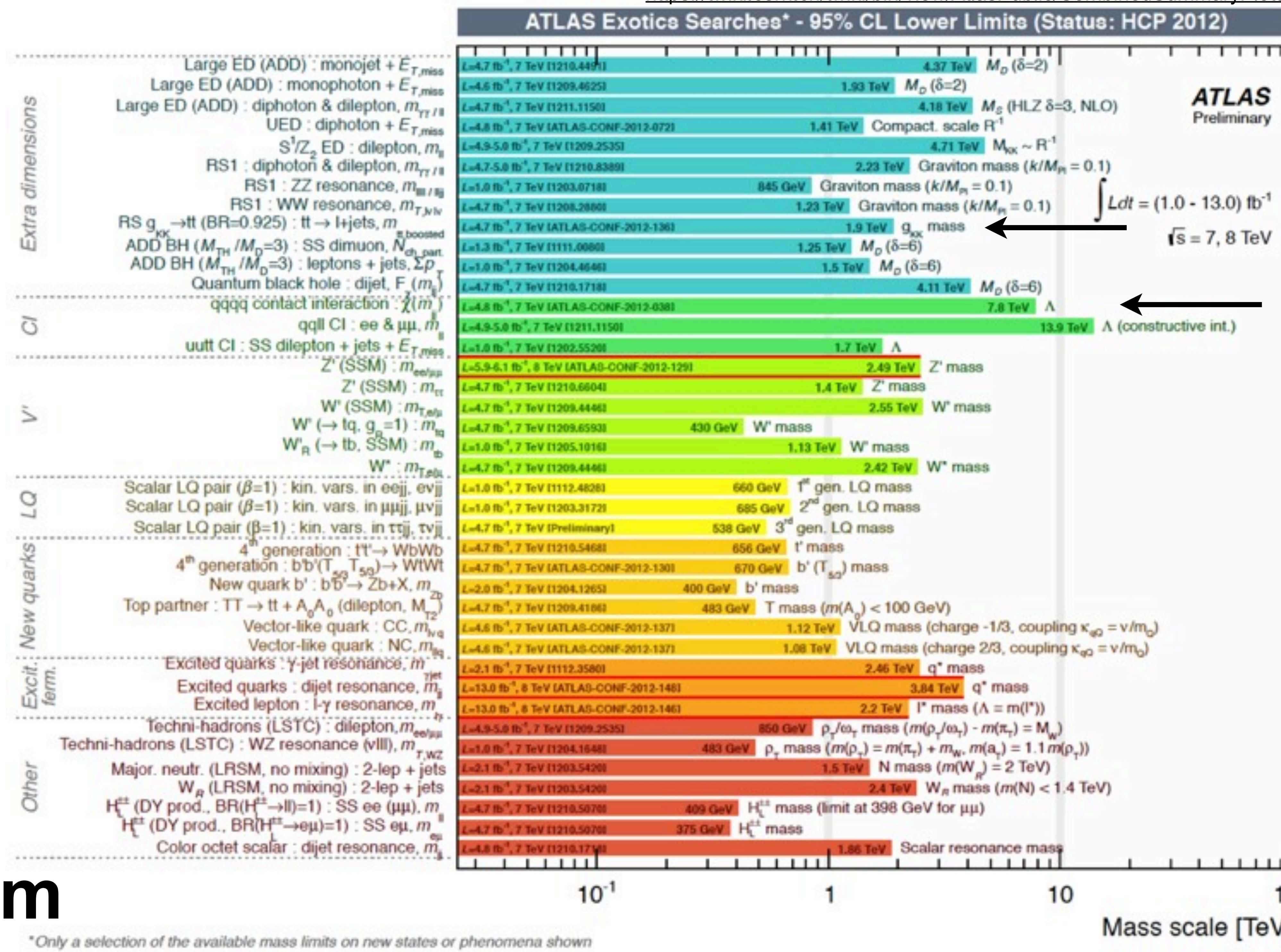
W', Z'

leptoquarks

new quarks

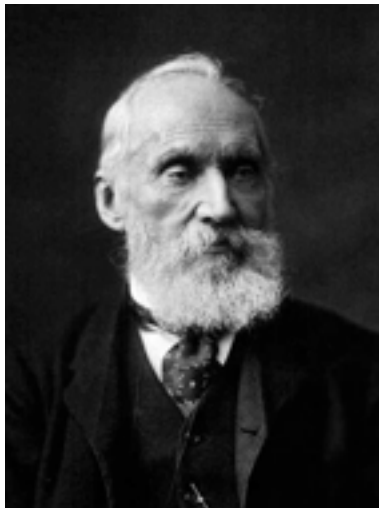
substructure

10 TeV → ~ 2 x 10^{-20} m



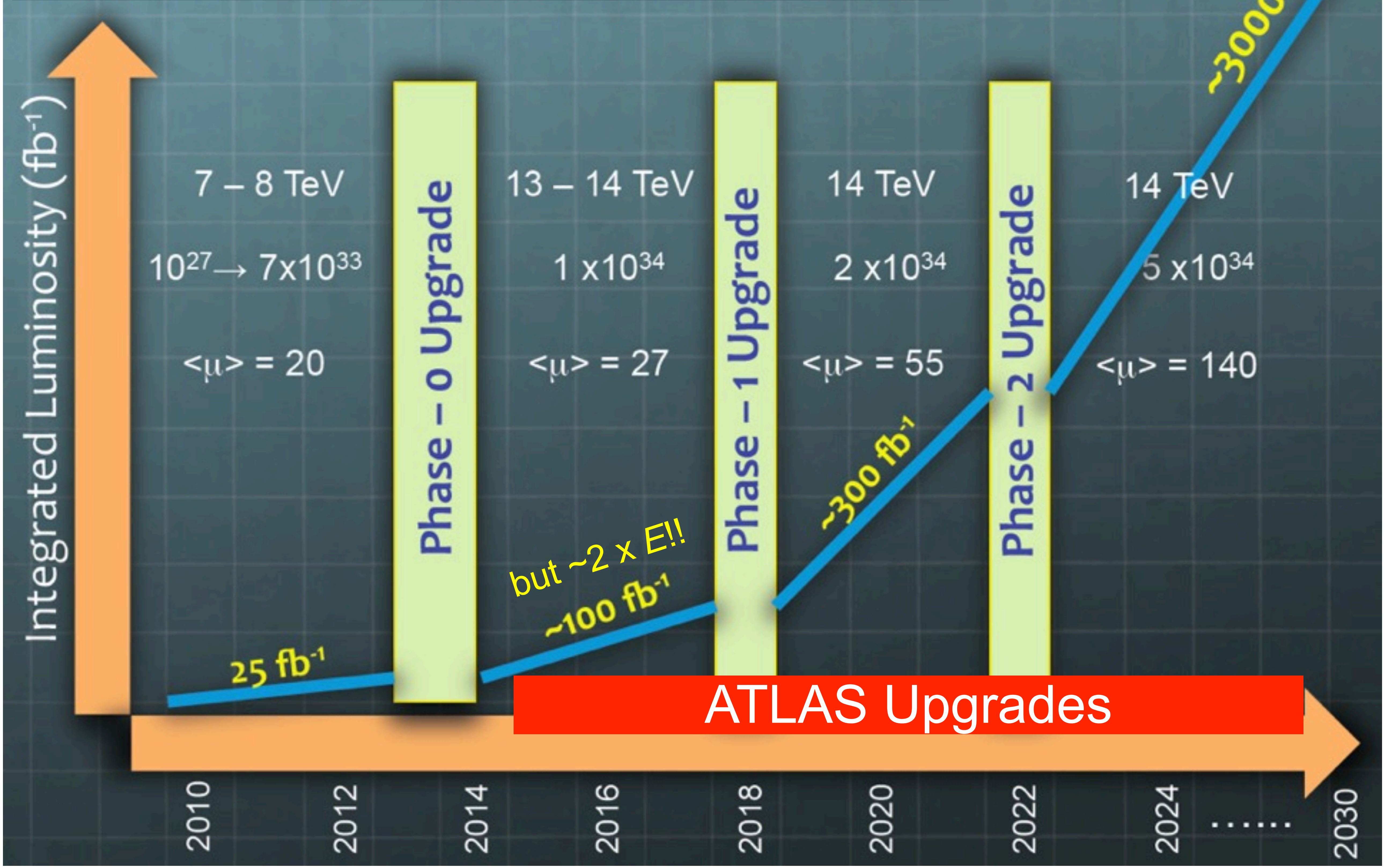
If it's the SM Higgs, is that it?

"Our future discoveries must be looked for in the 6th place of decimals."
Albert A. Michelson, 1894

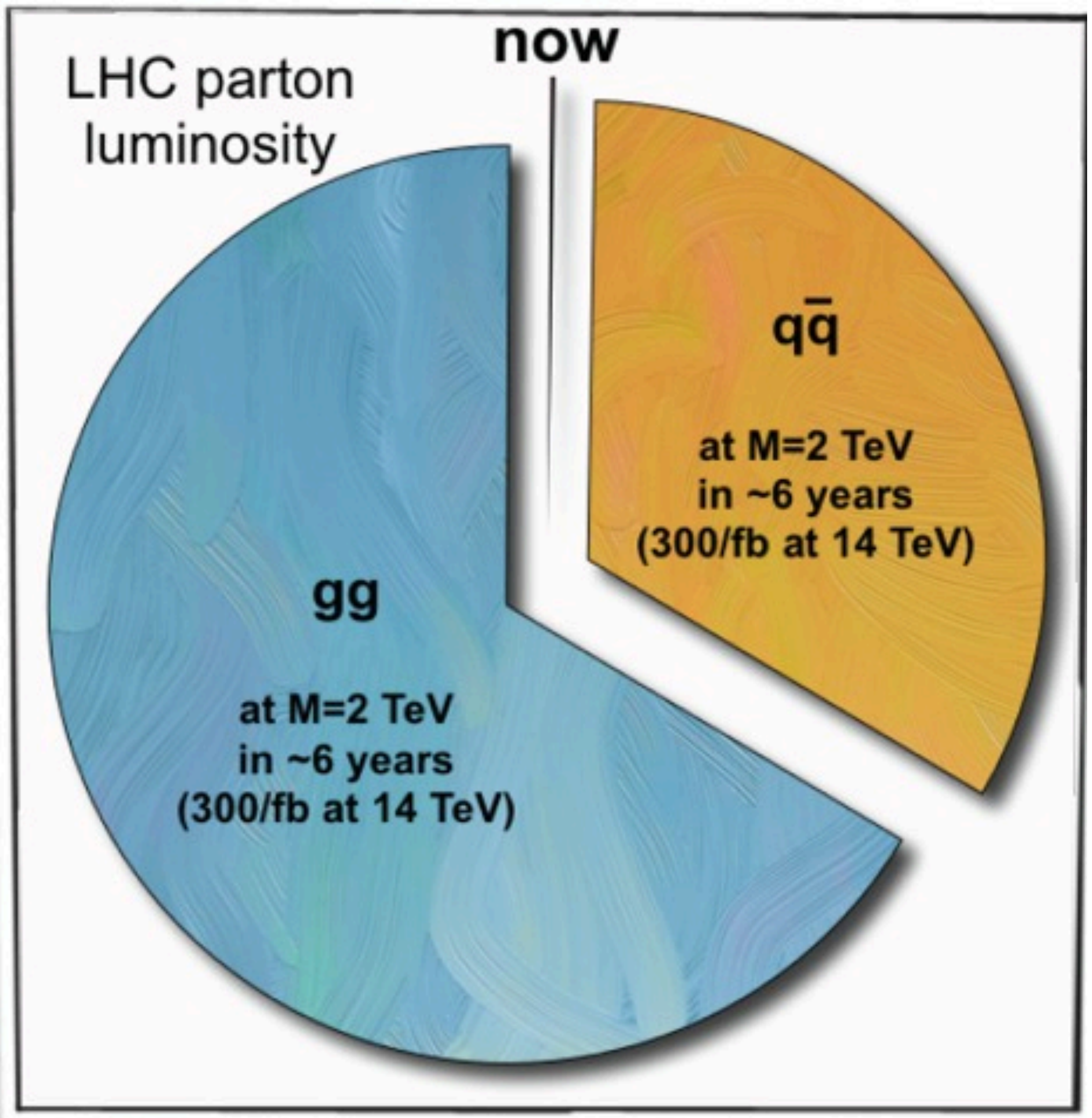


"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."
William Thomson (Lord Kelvin), 1900

LHC forecast



More explorations



G. Dissertori, quoted by C. Grojean, HCP2012

- 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

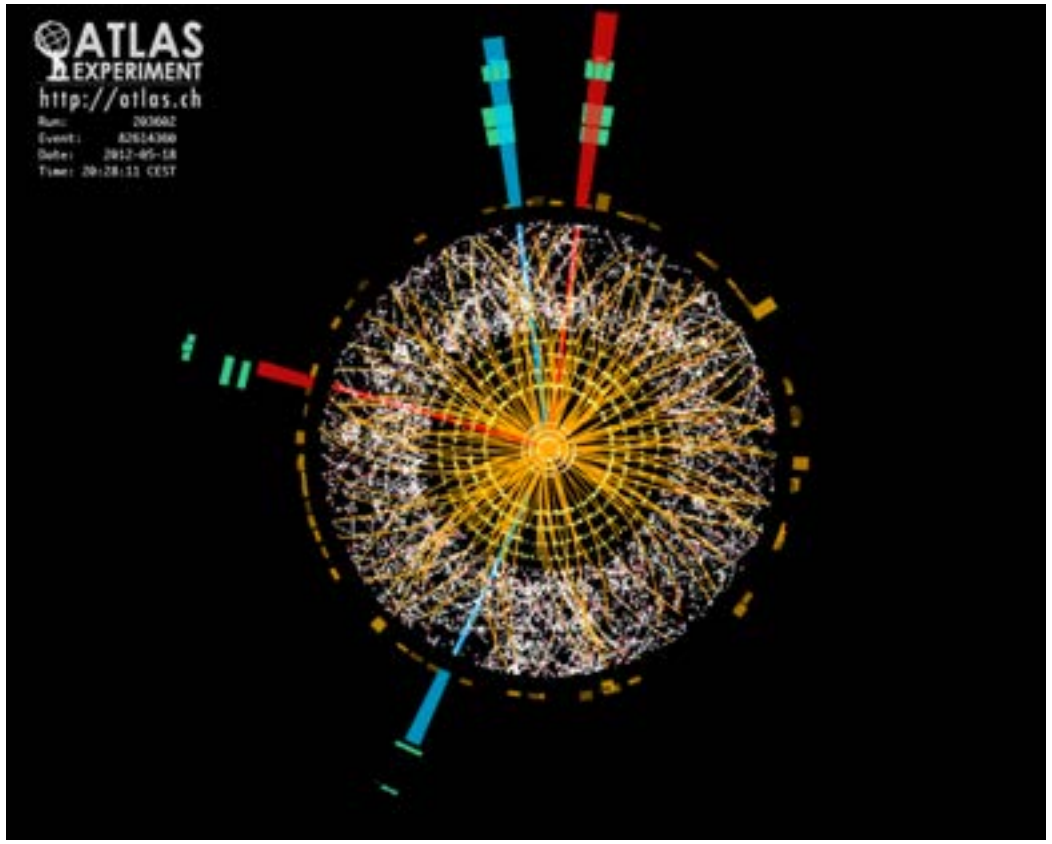
...and the unexpected!

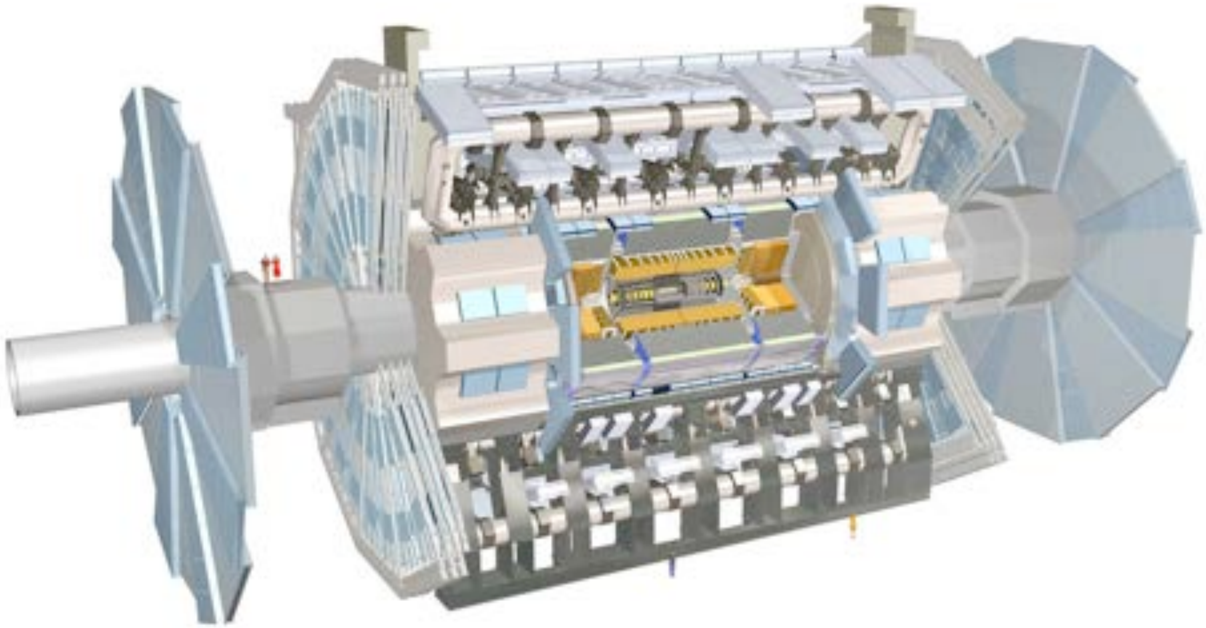
ATLAS Upgrades and Canada

- Liquid Argon Calorimeter Electronics
  - maintain ~20 GeV electron trigger p_T thresholds at highest luminosities
  - critical for a huge range of ATLAS physics programmes
  - make all calorimeter cells available to a fully digital level 1 trigger
- Muon Small Wheel
  - replace muon small wheels with improved trigger capability
  - increase granularity
  - new chamber technologies capable of higher rates and increased precision
- Forward Calorimetry
  - current forward calorimeter performance will degrade at high luminosity
  - two solutions are envisaged
    - install new forward calorimeters with smaller LAr gaps
    - shield the forward calorimeters with high-rate “Mini-FCal”
      - pCVD Diamonds, LAr, or high pressure Xe gas.

CAP Congress ATLAS contributions

- M1-1-1 Session
  - Dr. Thomas Koffas, Higgs
  - Dr. Mark Stockton, SM
  - Dr. Bernd Stelzer, Searches
- ~25 contributions
  - T1-1
  - T3-1
  - W1-1
  - W2-3
  - W2-8
  - Posters

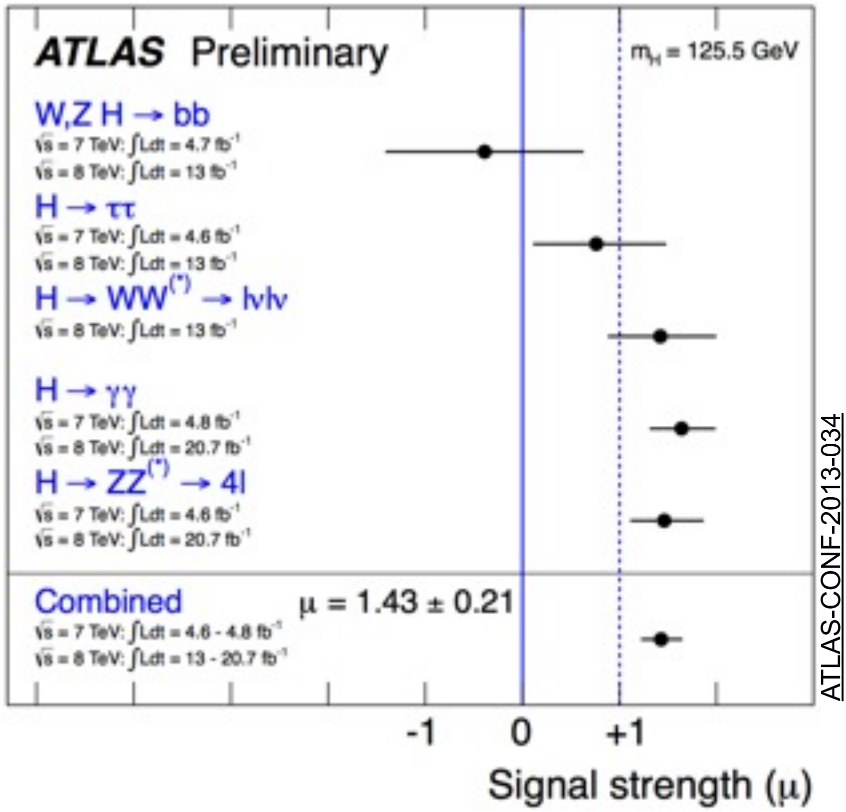





15/5/

Conclusions

- Discovery of a new particle
  - a ~125.5 GeV neutral Higgs boson
  - historic event of great significance
    - 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!!

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

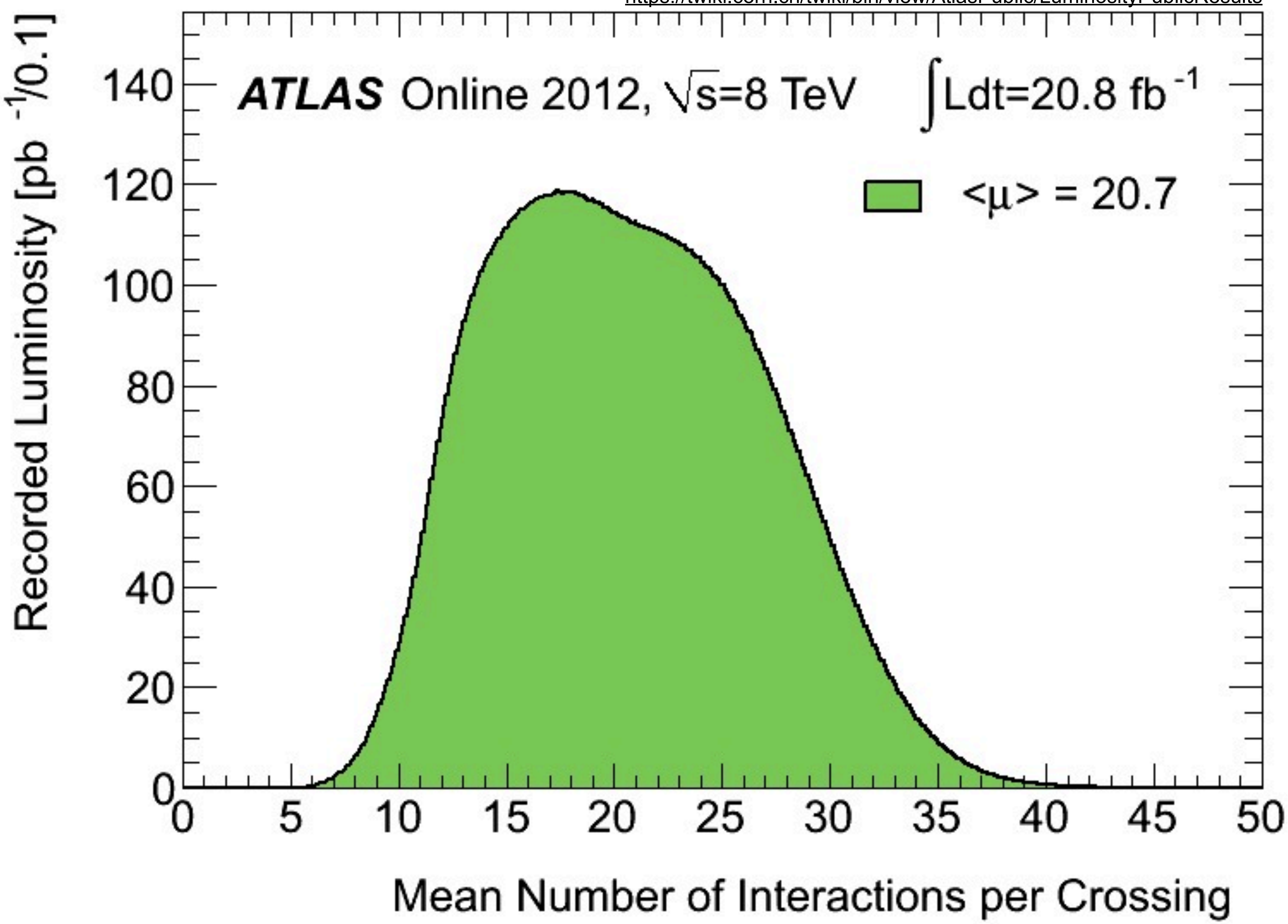
ATLAS papers:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Publications

Extra slides

Interactions per beam crossing

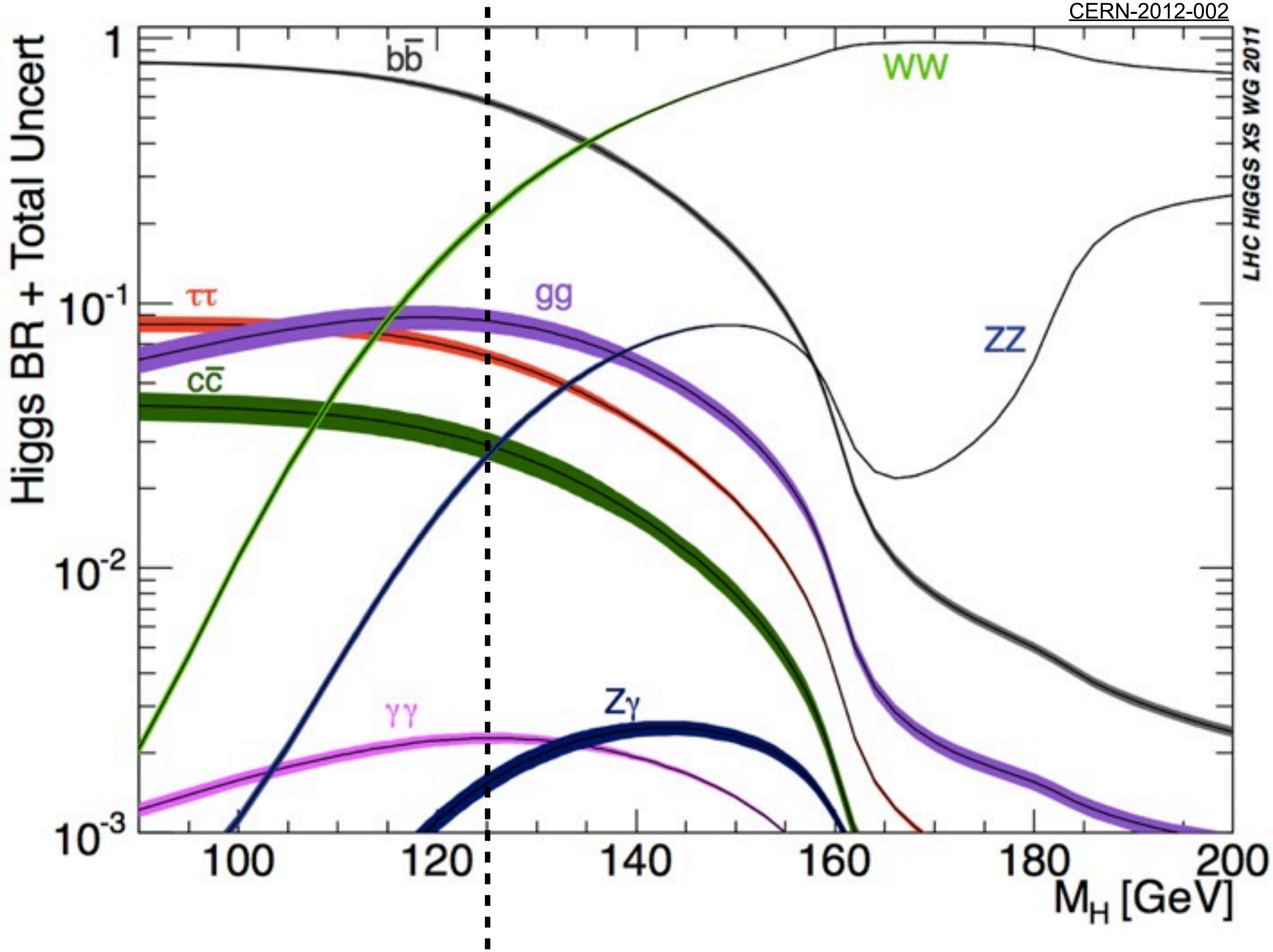
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults



Standard Model Higgs decays

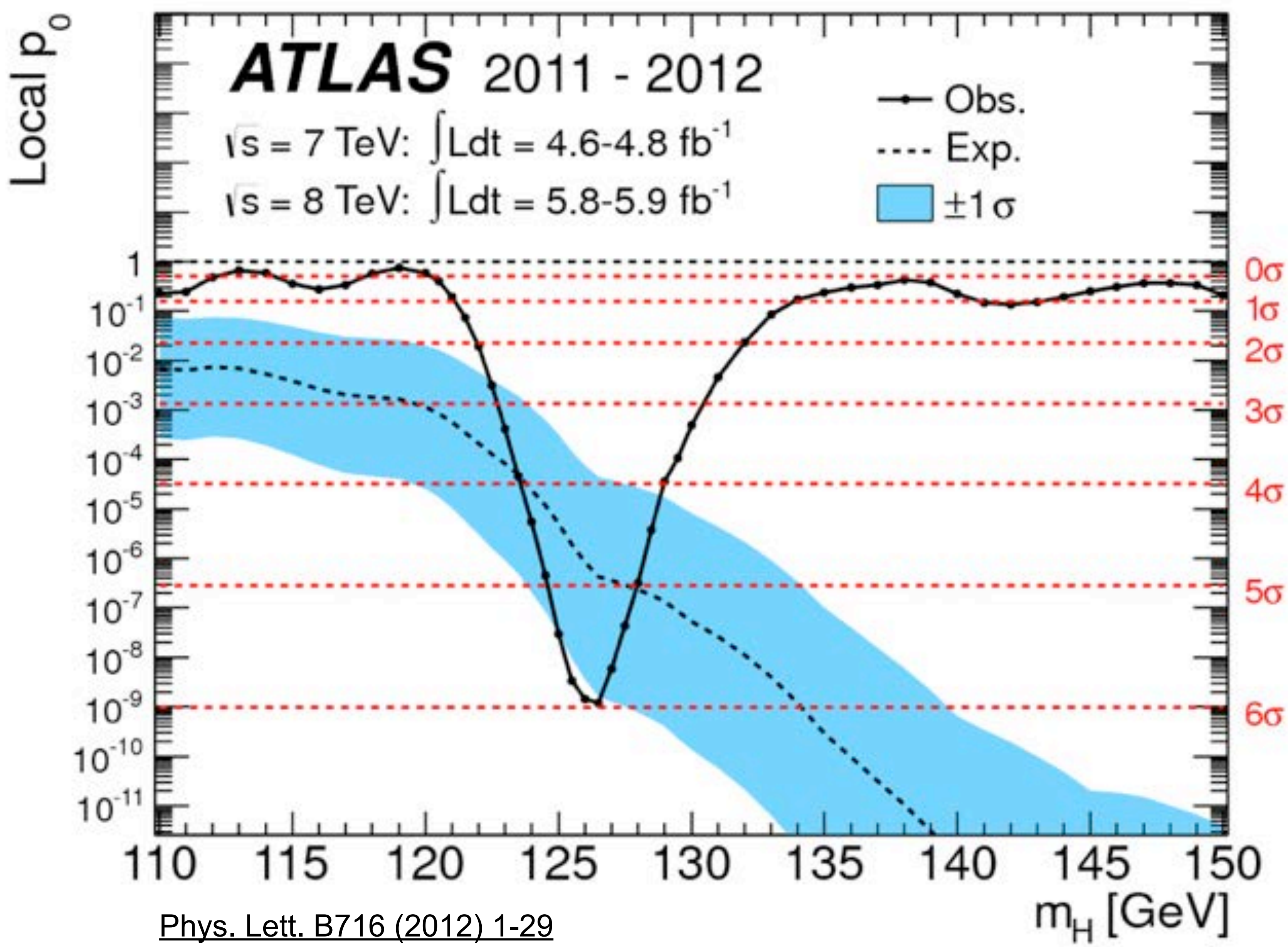
Many possible decay channels of the Higgs boson

CERN-2012-002



Observation of a new particle

- The five best channels are statistically combined (July 2012)
  - sophisticated treatment, including all systematic errors



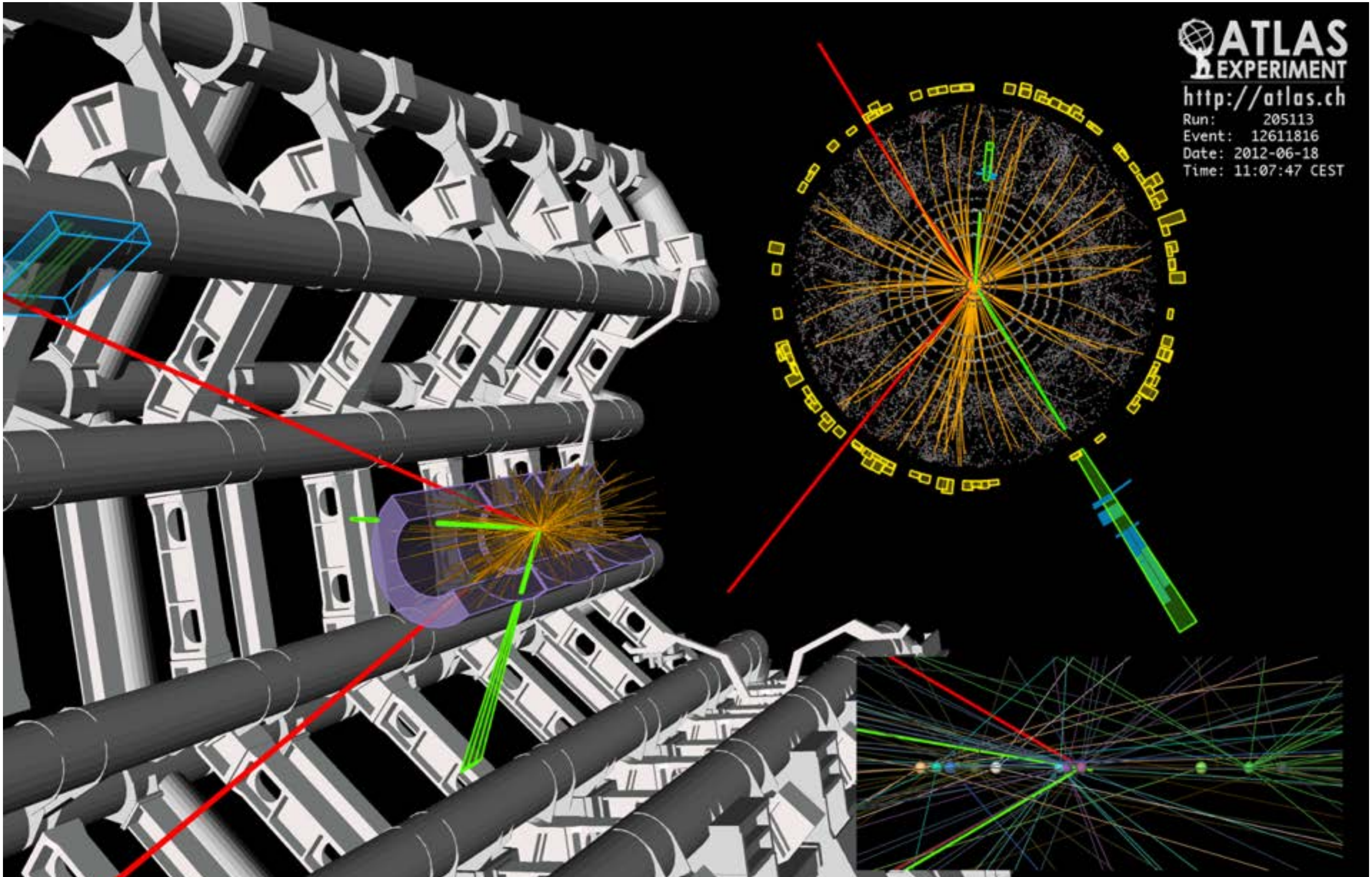
Phys. Lett. B716 (2012) 1-29

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!

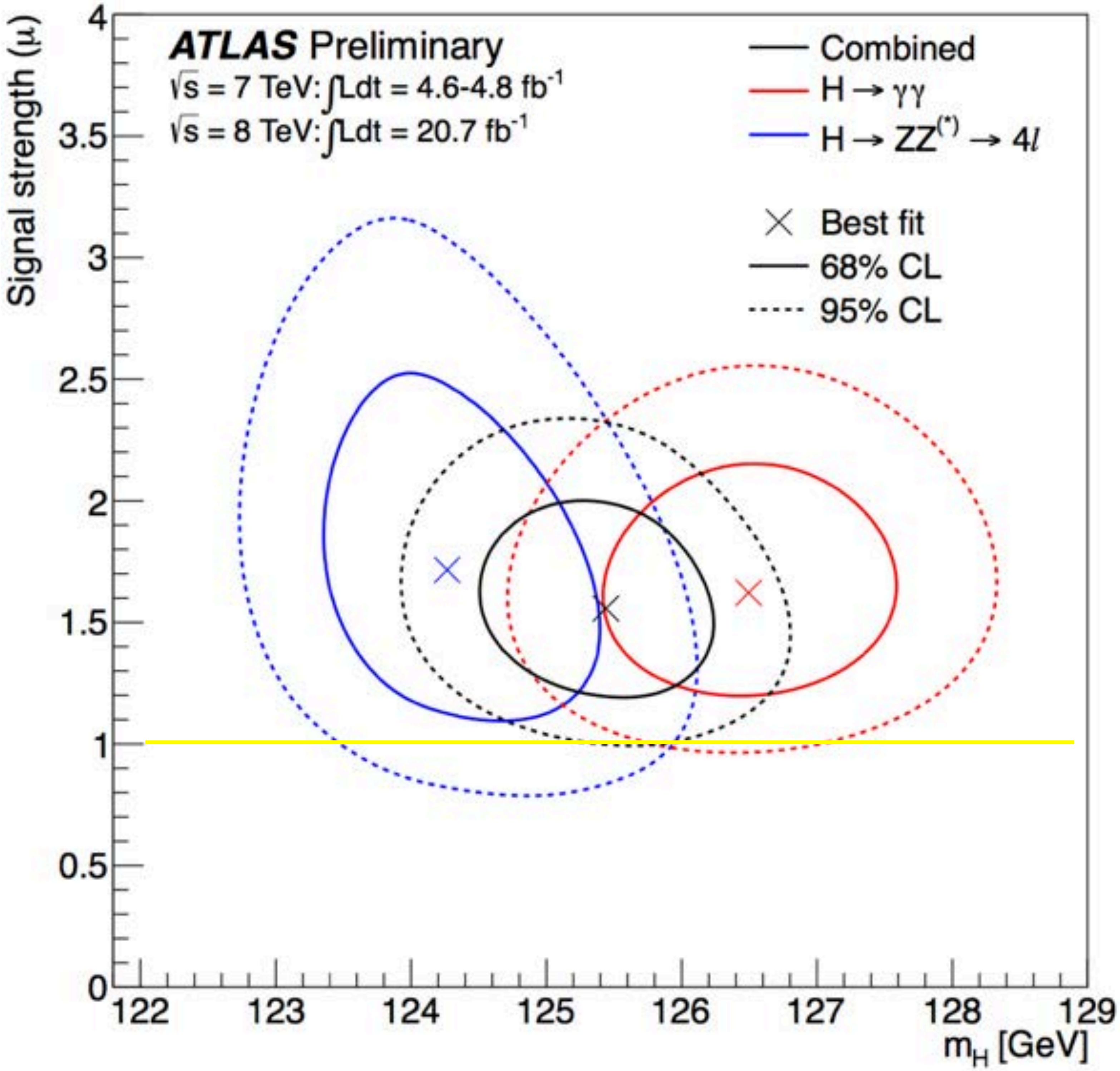
global: 5.1σ
for 100-600 GeV
1.7×10^{-7}
~1 / 5,900,000

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



Mass Combination

$$M_H = 125.5 \pm 0.2\ (\text{stat})\ ^{+0.5}_{-0.6}\ (\text{sys})\ \text{GeV}$$

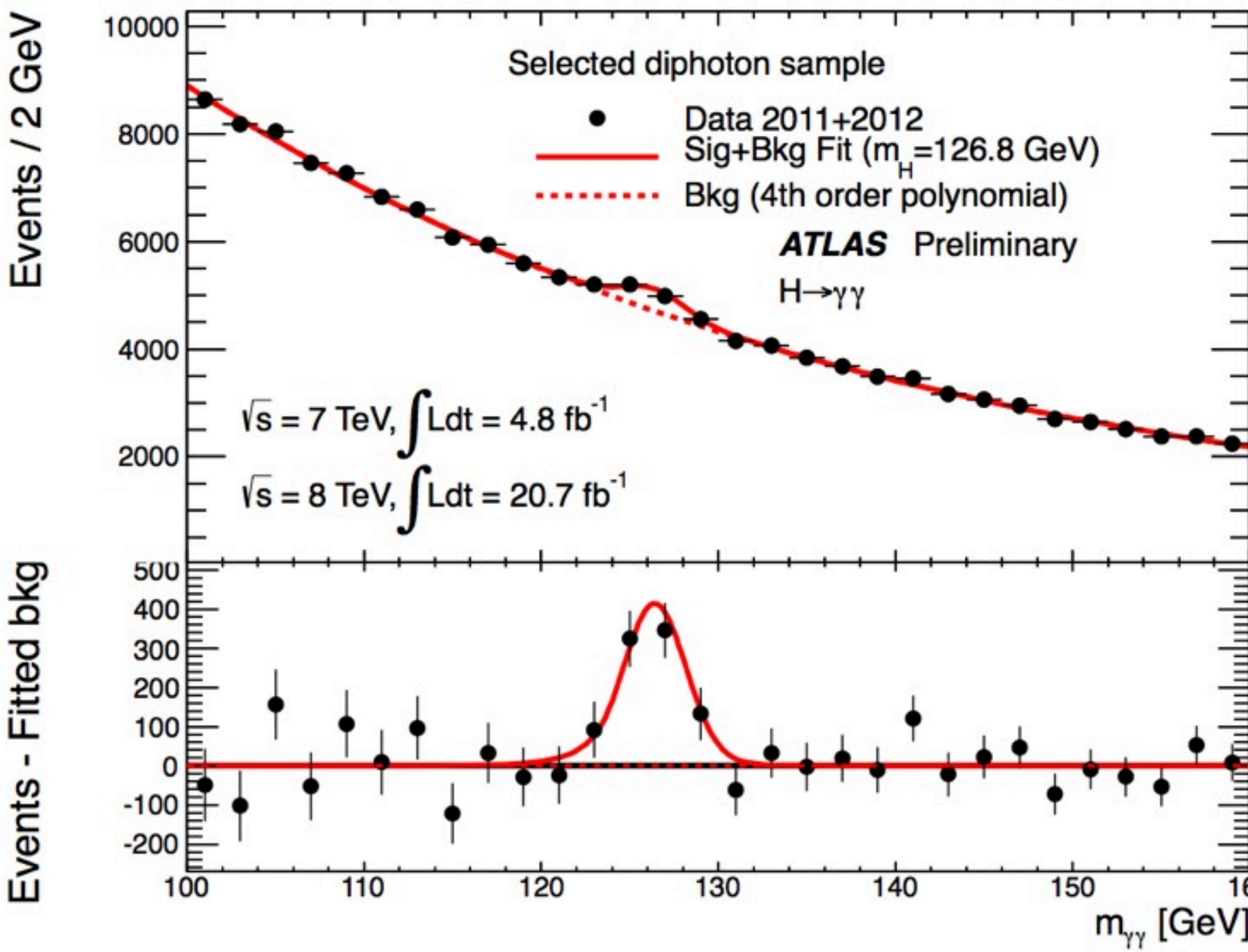


The difference between the measured masses is found to have a significance of 2.5 σ (or 1.2%).

$$2.3^{+0.6}_{-0.7}\ (\text{stat})\ \pm 0.6\ (\text{sys})\ \text{GeV}$$

Latest mass combination: ATLAS-CONF-2013-014

H → γ γ



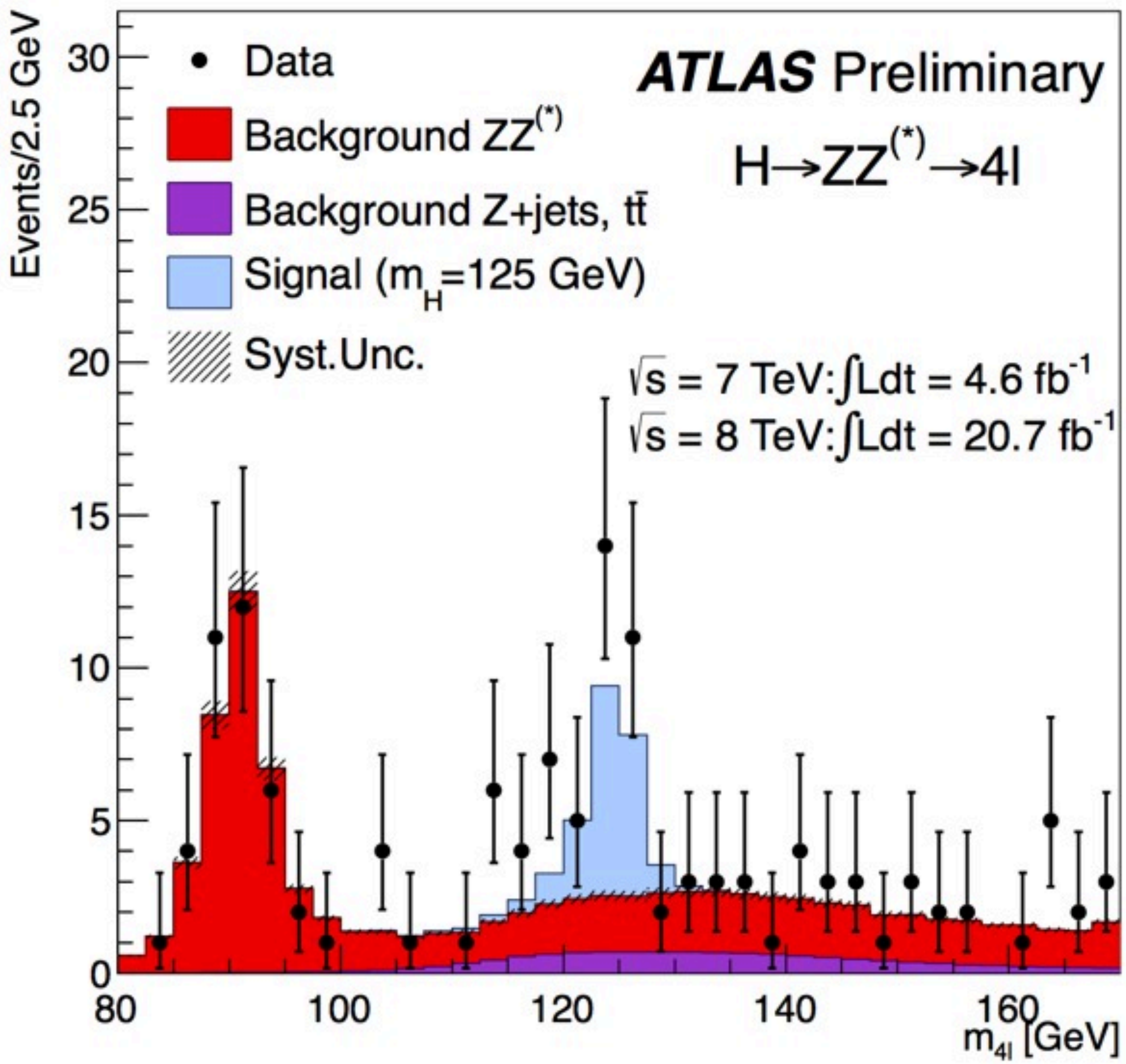
ATLAS-CONF-2013-012

7.4 σ

($6.8{\times}10^{-14}$)

$$M_{\gamma\gamma} = 126.8 \pm 0.2\ (\text{stat}) \pm 0.7\ (\text{sys})\ \text{GeV}$$

H → ZZ(*) → 4 leptons



6.6 σ (2.7×10^-11)

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In [120, 130 GeV], expect

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