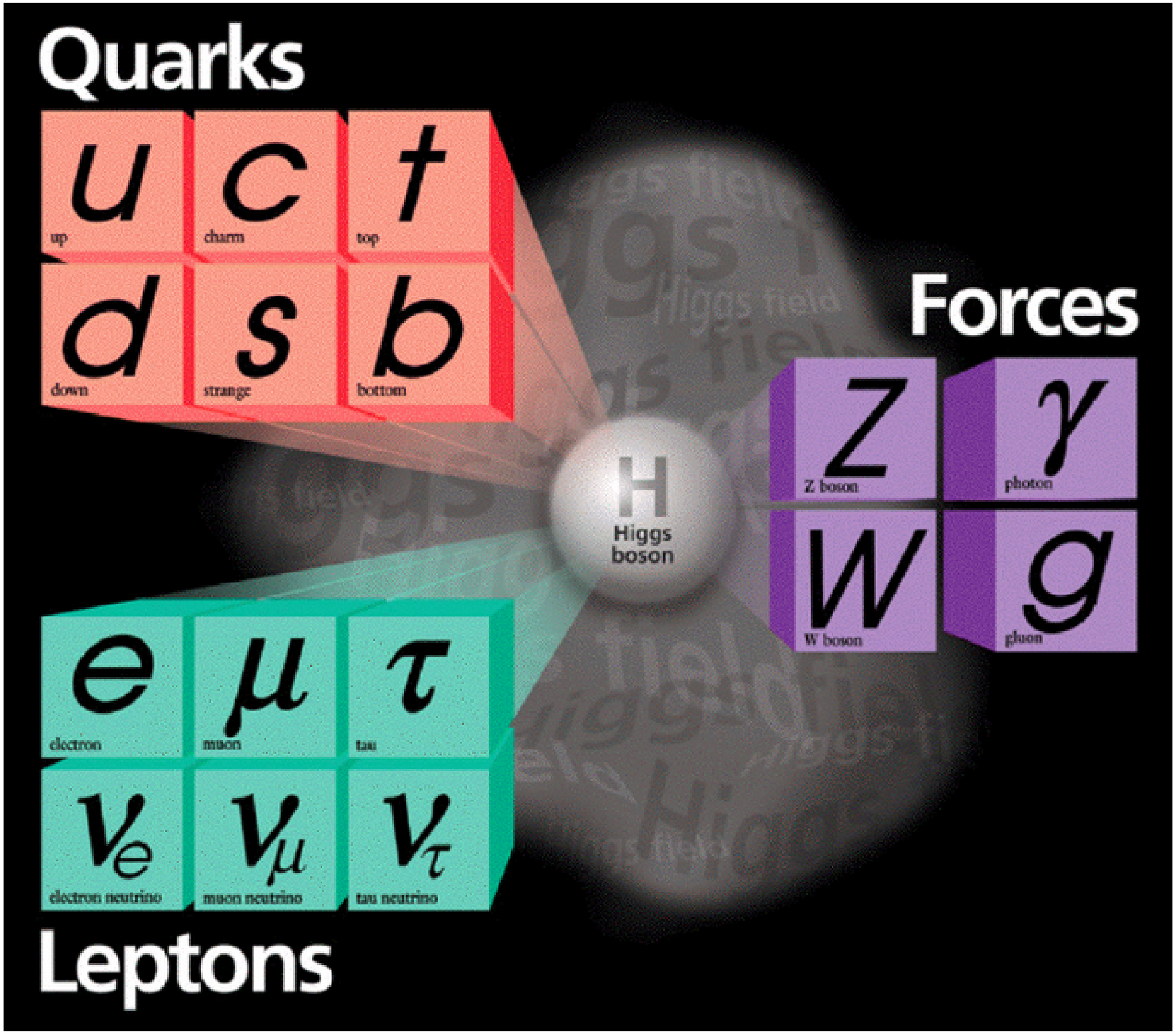
Standard Model and Higgs Physics

A brief review of selected results from the ATLAS and CMS experiments at the CERN Large Hadron Collider

Dave Charlton (University of Birmingham, UK)
Dave.Charlton@cern.ch
ACP 2018, Windhoek

The Standard Model of particle physics

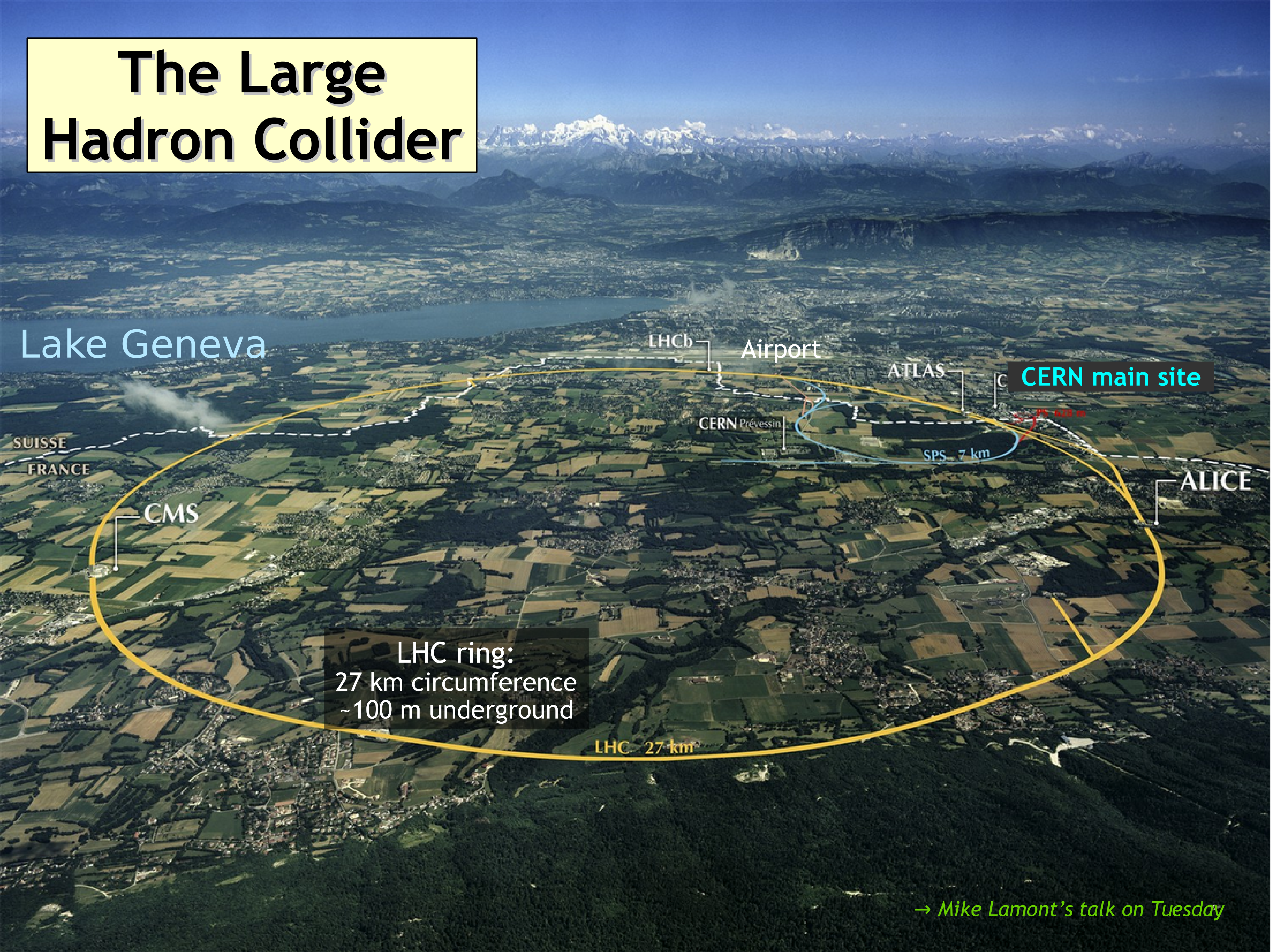
Matter Particles



Force-carriers

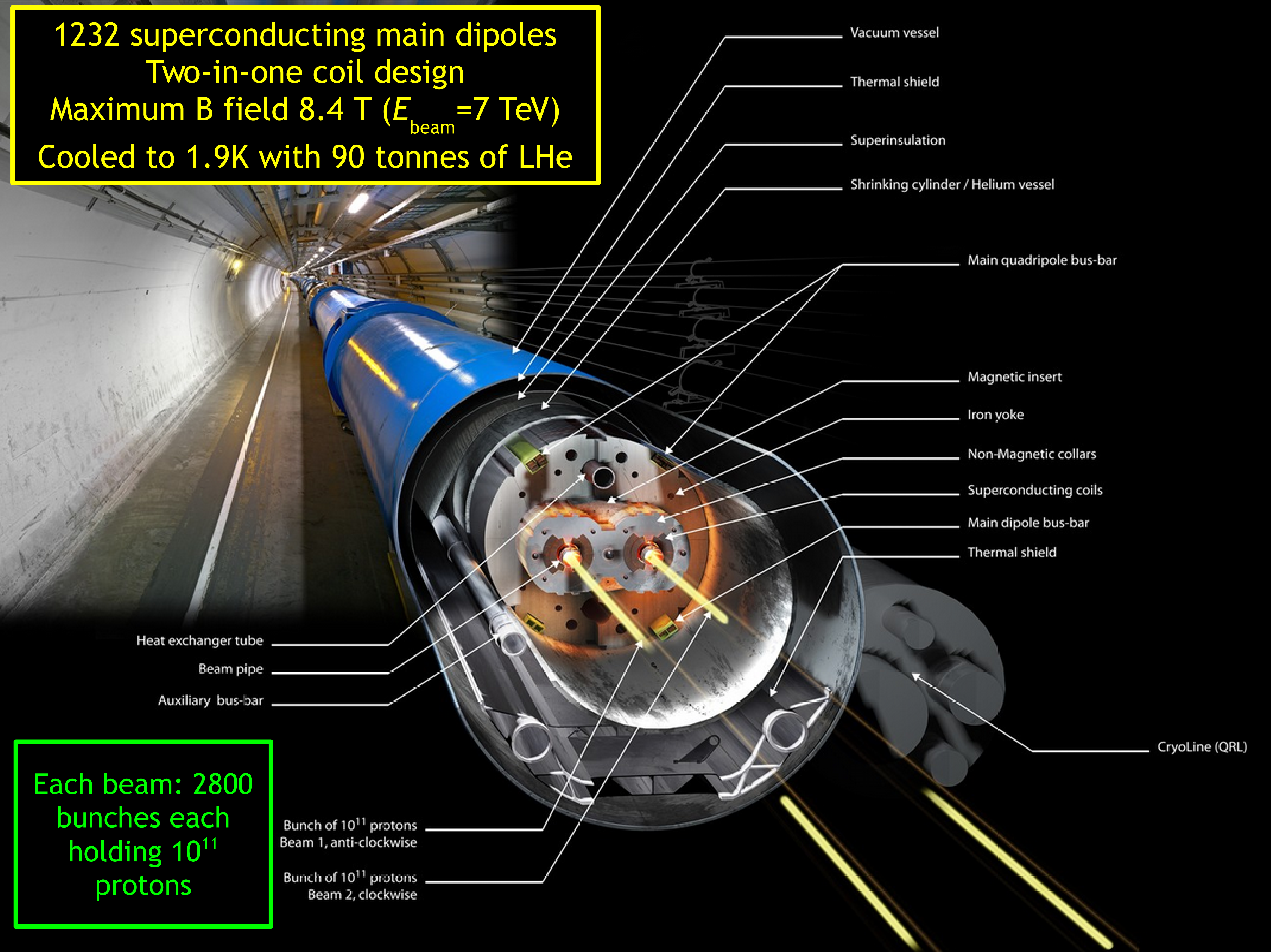
Fermions Bosons

The Large Hadron Collider



→ *Mike Lamont's talk on Tuesday*

1232 superconducting main dipoles
Two-in-one coil design
Maximum B field 8.4 T (E_{beam}=7 TeV)
Cooled to 1.9K with 90 tonnes of LHe

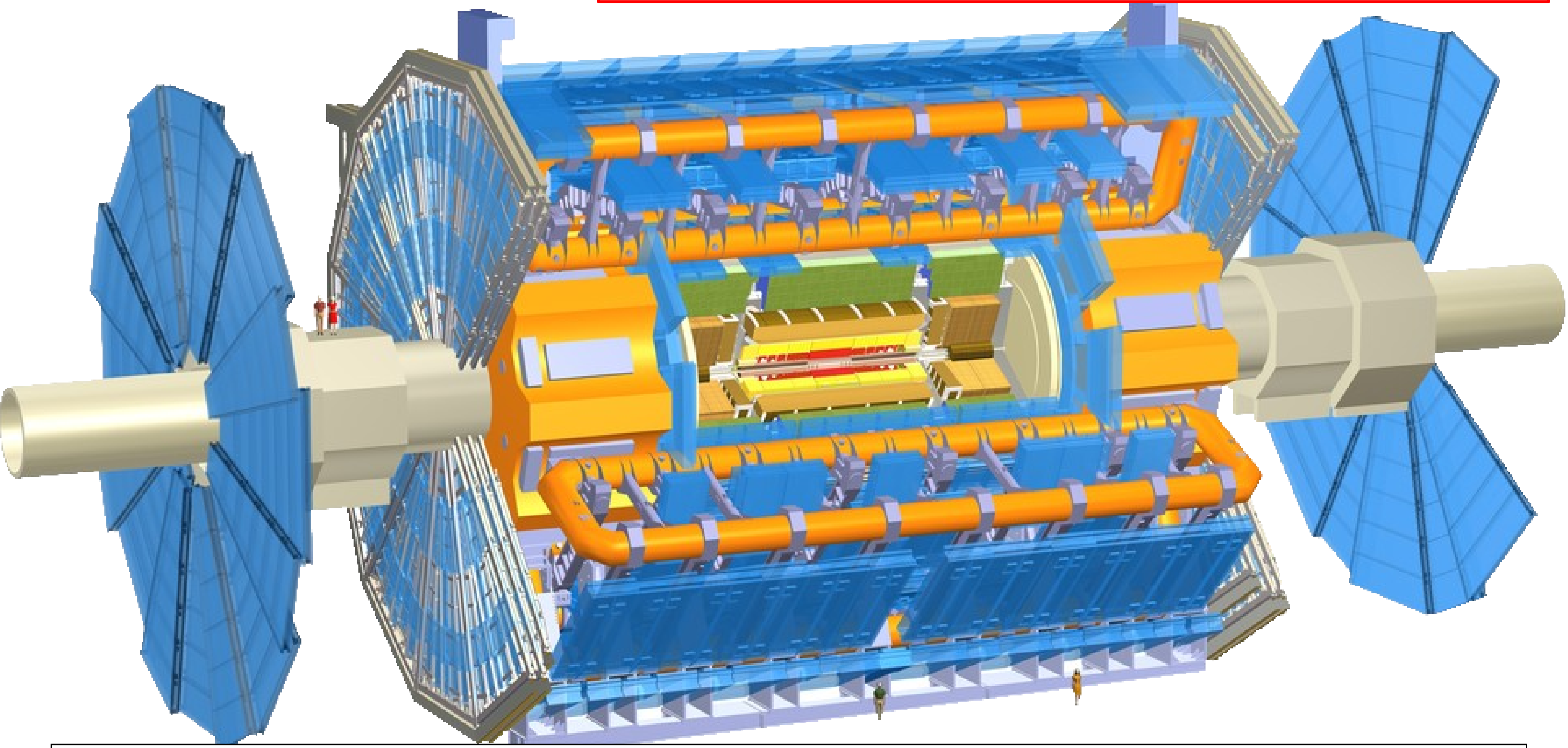


Each beam: 2800 bunches each holding 10^{11} protons

The ATLAS and CMS detectors

ATLAS detector

7000 t, 45m long x 25m diameter
Silicon+gas (transition radiation) tracker, 2T solenoid, LAr + scintillator tile sampling calorimetry, large air-core toroid muon spectrometer, peak field ~4 T



~100 M channels, with timing capable of separating particles from adjacent proton-proton bunch-crossings (25ns spacing)

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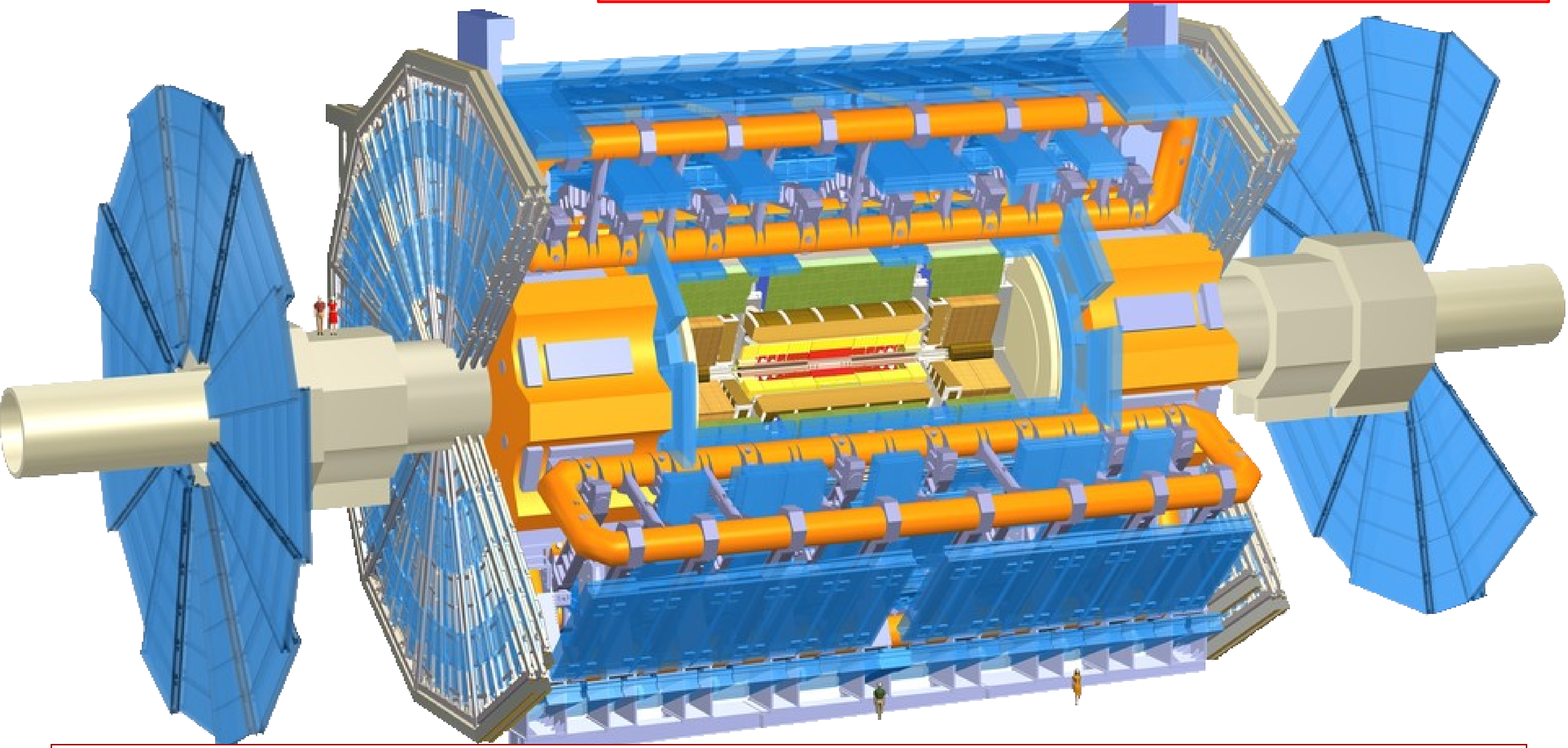
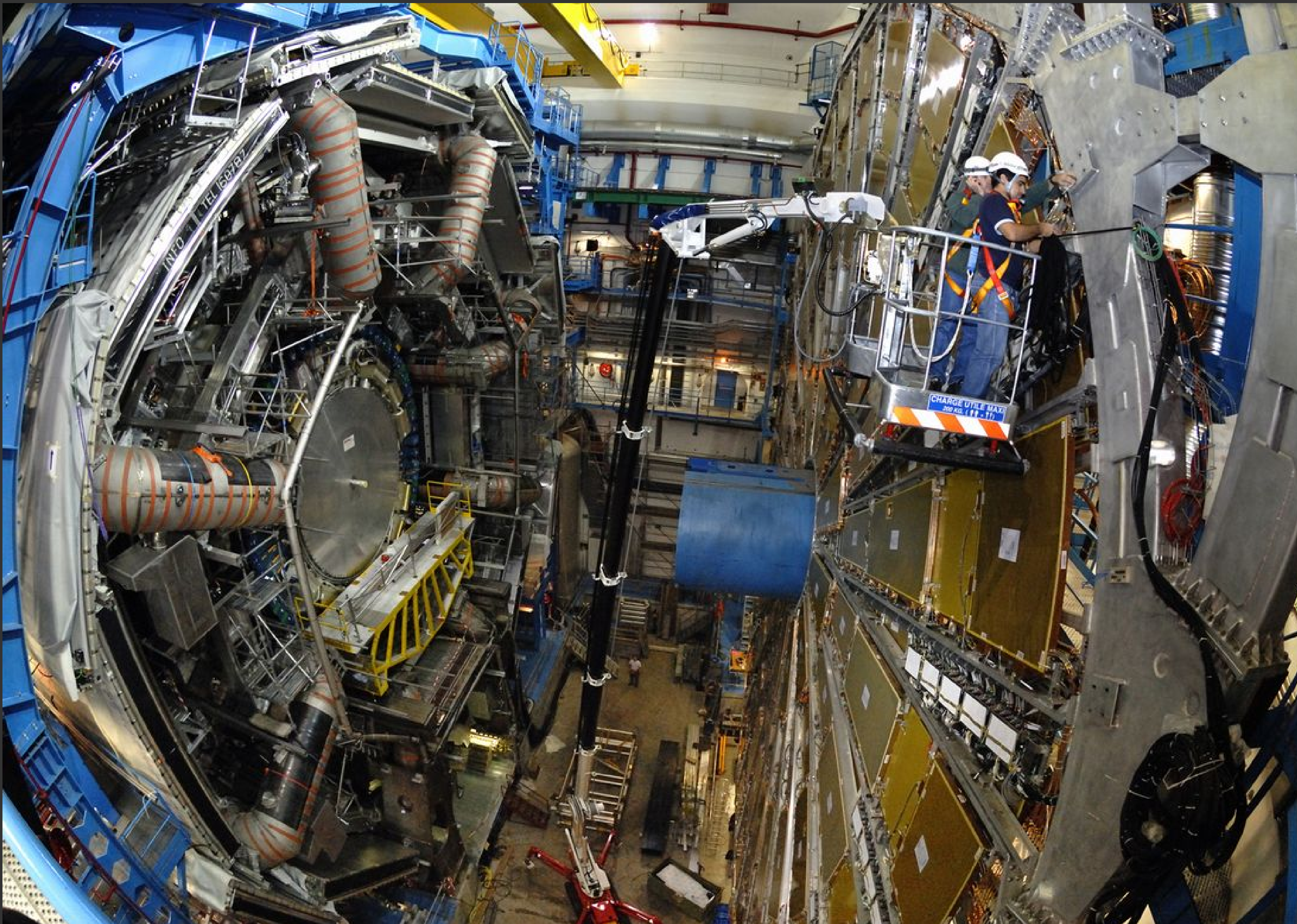


Construction was a ten-year enterprise with also several years of R&D – component production in the member institutions and in industry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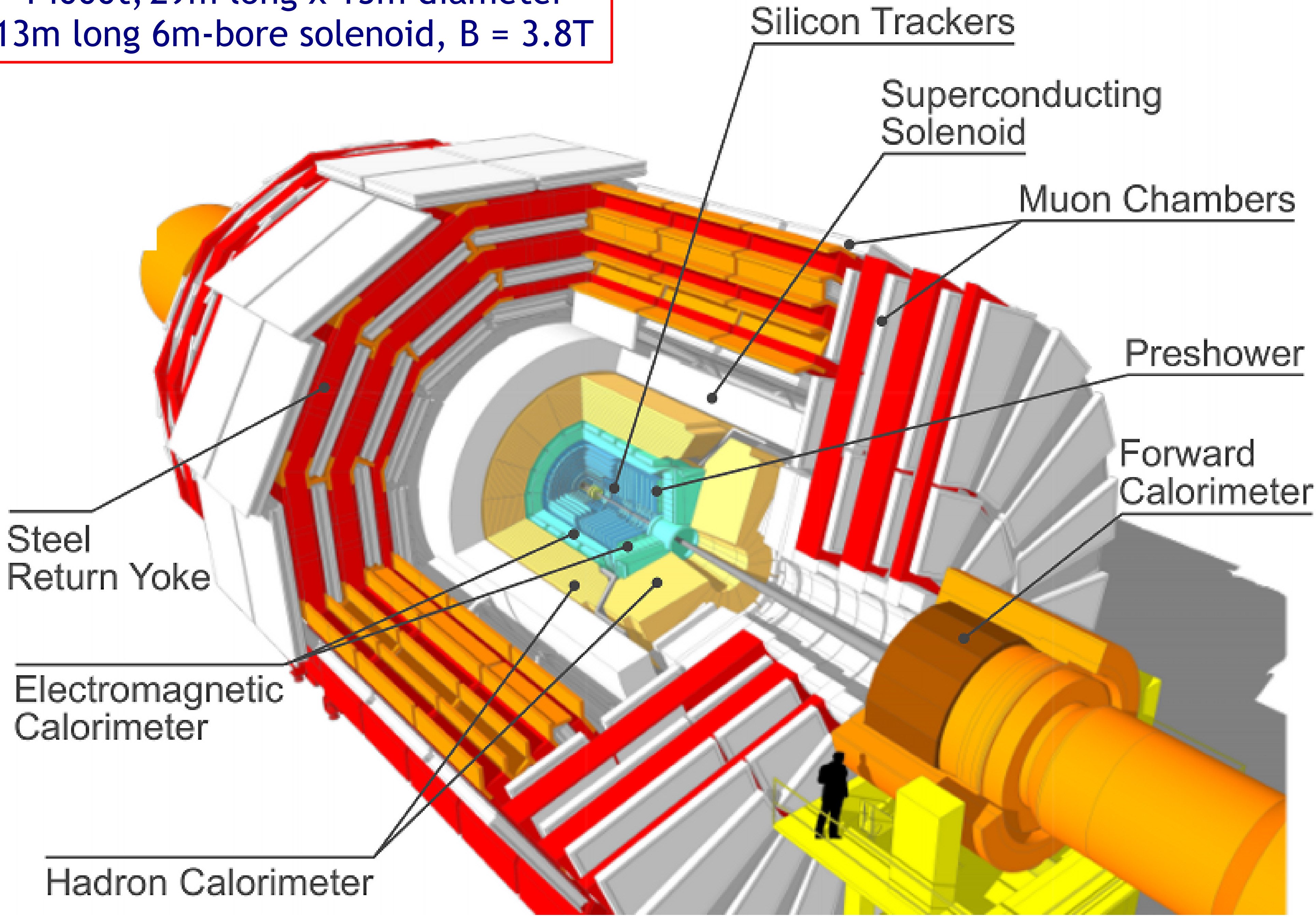
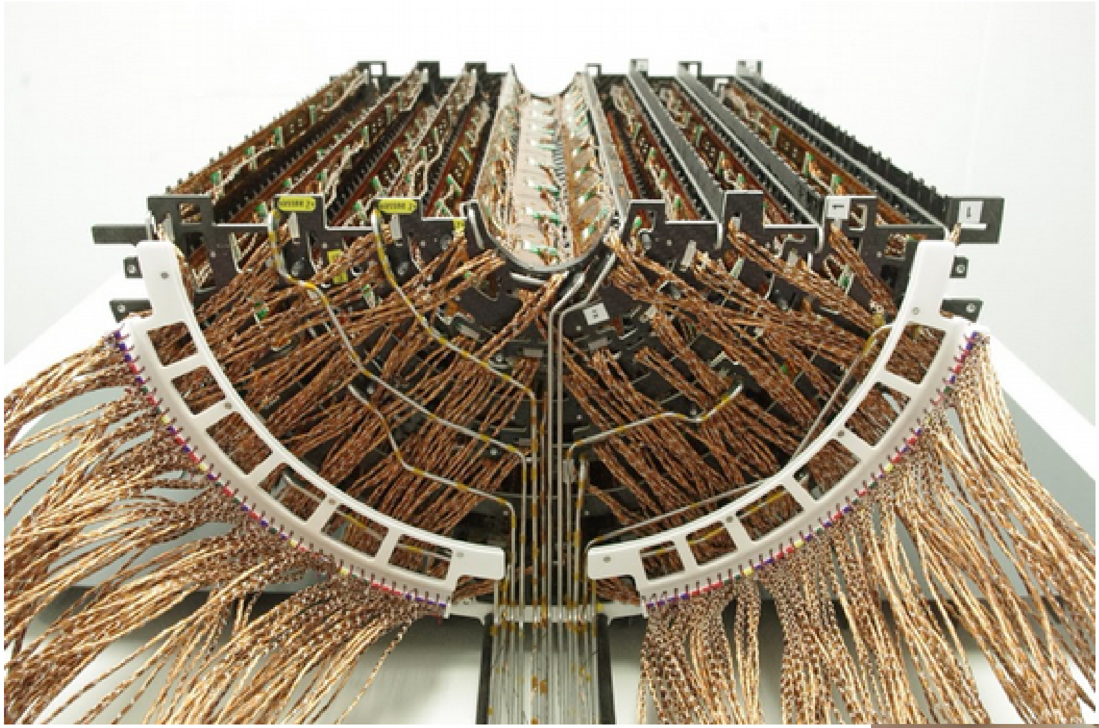
CMS detector

14000t, 29m long x 15m diameter
13m long 6m-bore solenoid, B = 3.8T



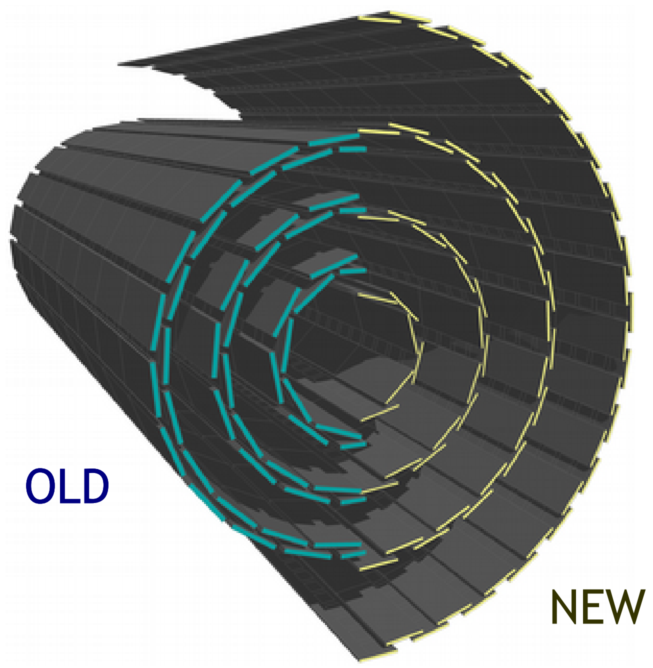
Detector upgrades



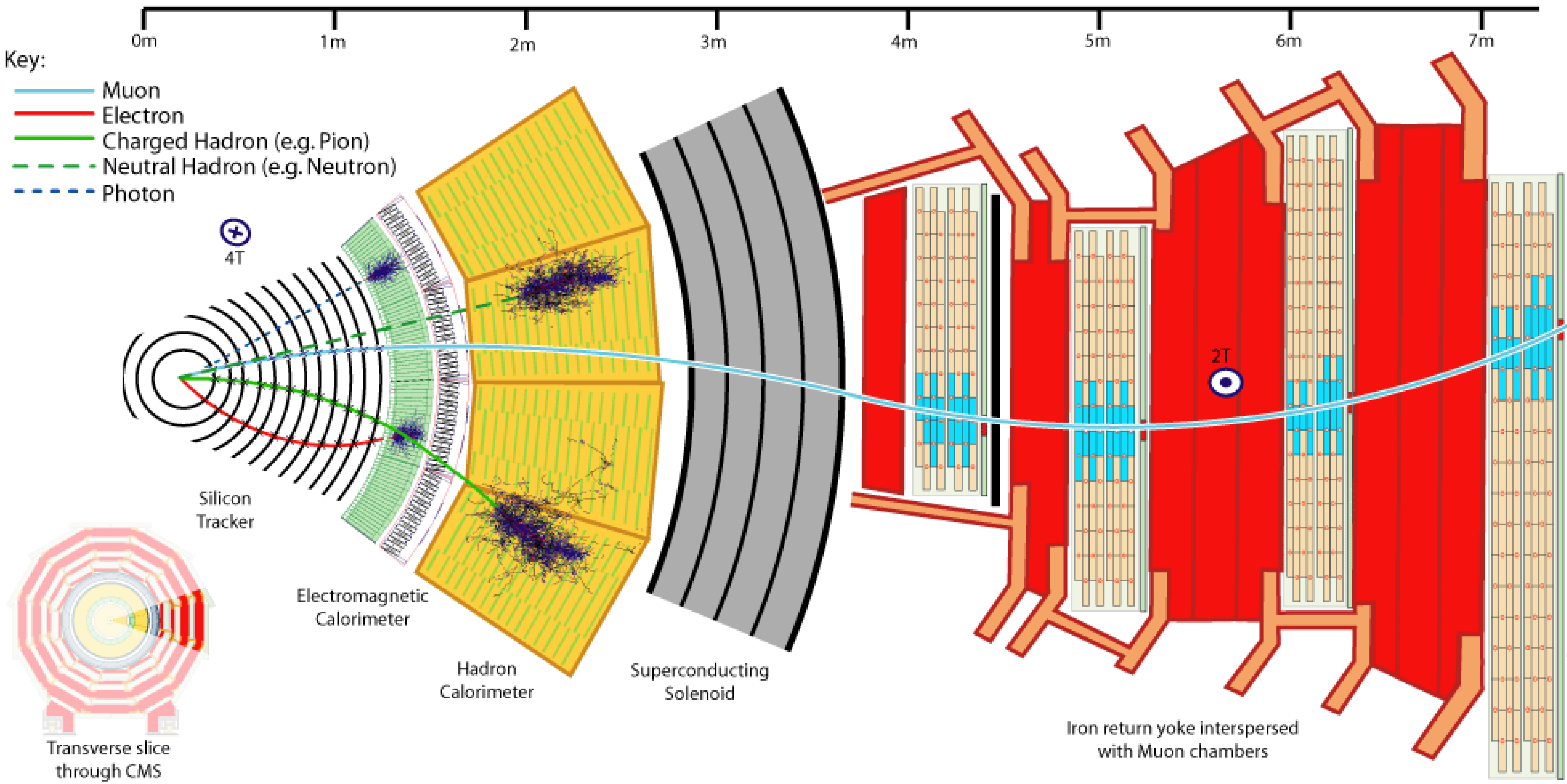
The LHC experiments have staged upgrade programmes

ATLAS and CMS will take data for about 20 more years

Illustrated here: CMS replacement pixel detector installed in 2017



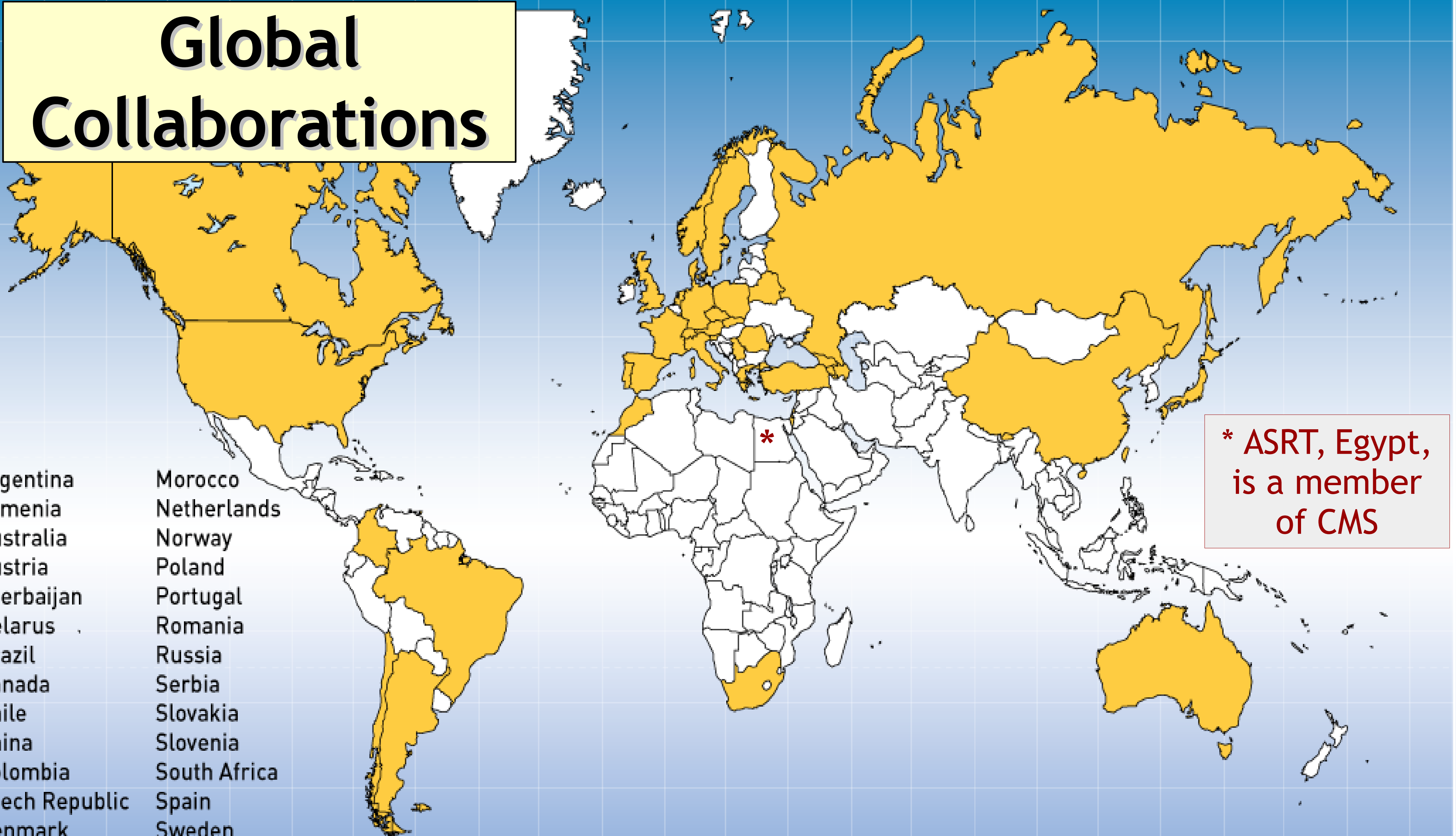
Detector principles



Multiple layers: measure charged particle momenta (tracks), EM and hadronic energies (calorimetry), and provide particle identification from different signatures

Full event: transverse momentum balance → sensitive to invisible particles (ν, …?)

Global Collaborations



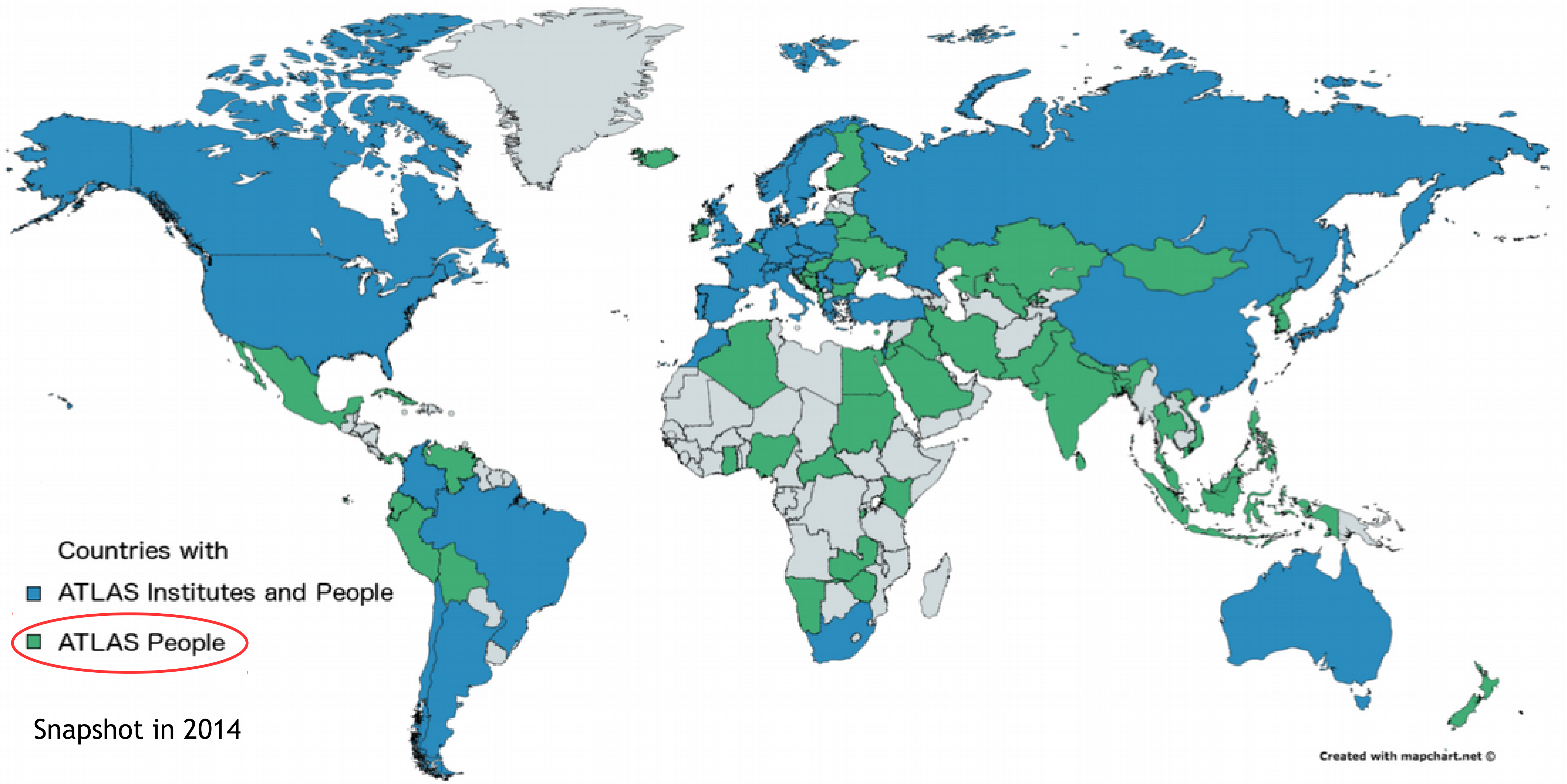
* ASRT, Egypt, is a member of CMS

Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR

ATLAS: 220 member institutes across 38 countries
~3000 scientific authors, including ~1000 students

July 2010

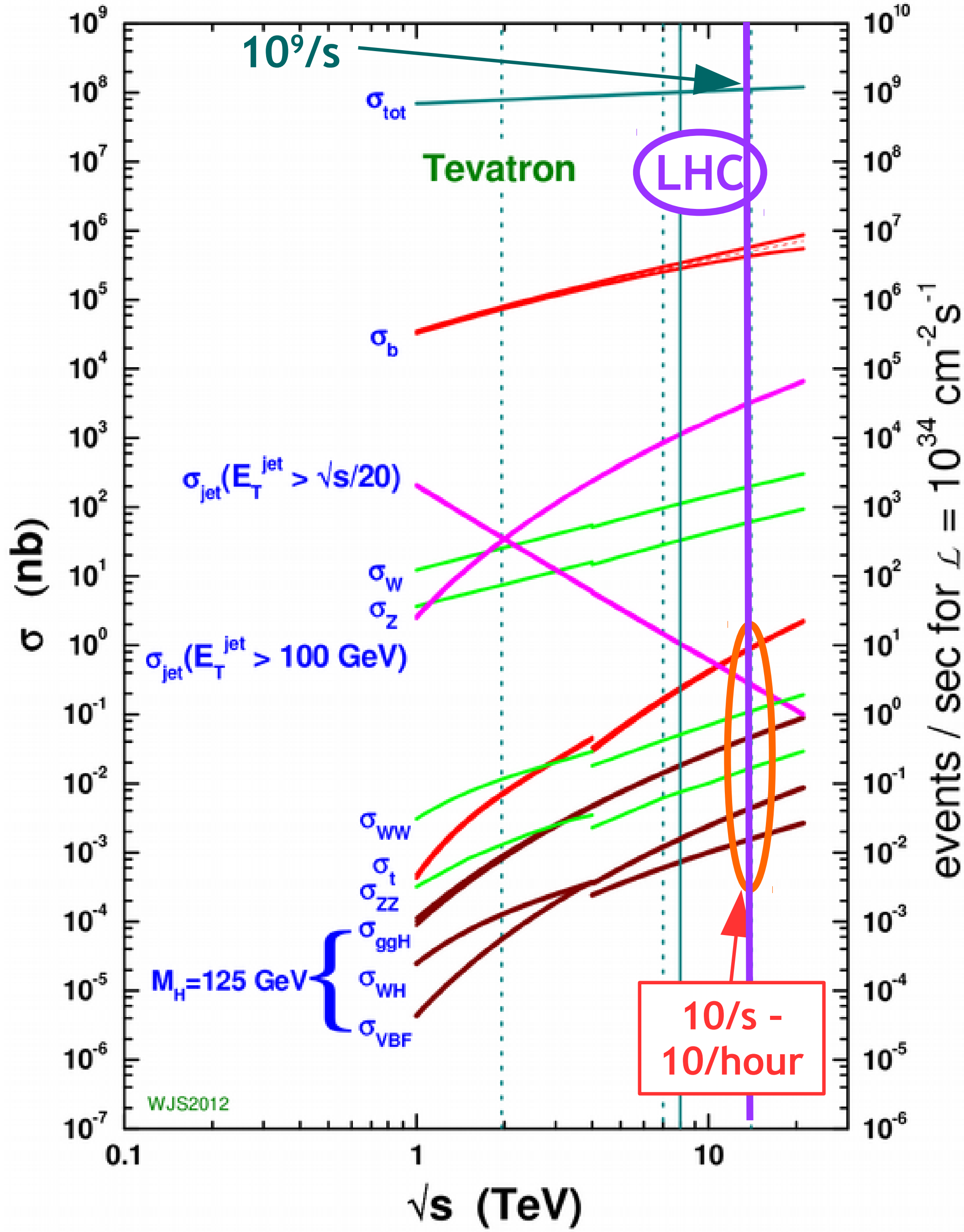
Global Collaborations



Snapshot in 2014

Breadth of LHC physics

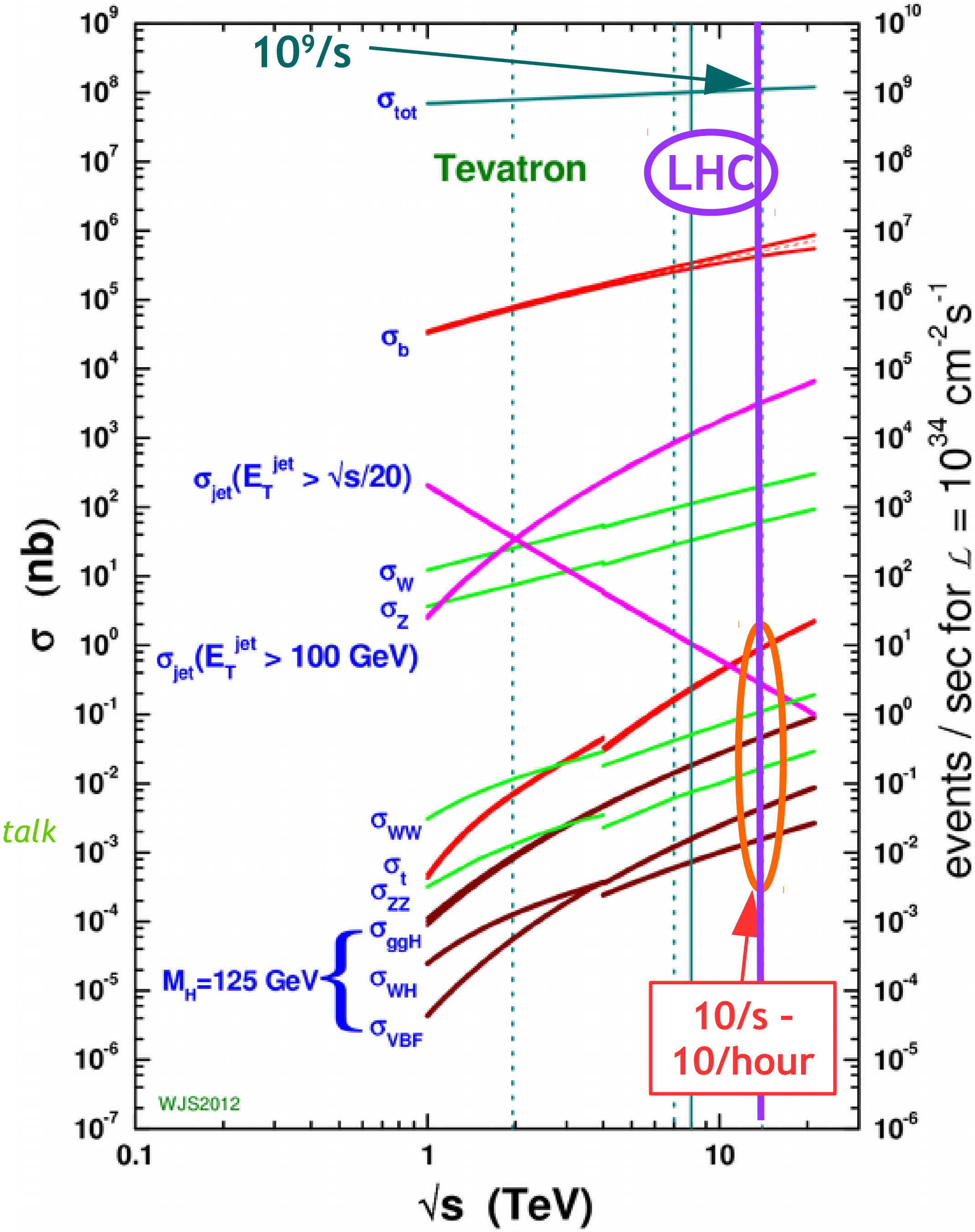
While it is best known for the Higgs boson, there is a huge range of physics studied at the LHC



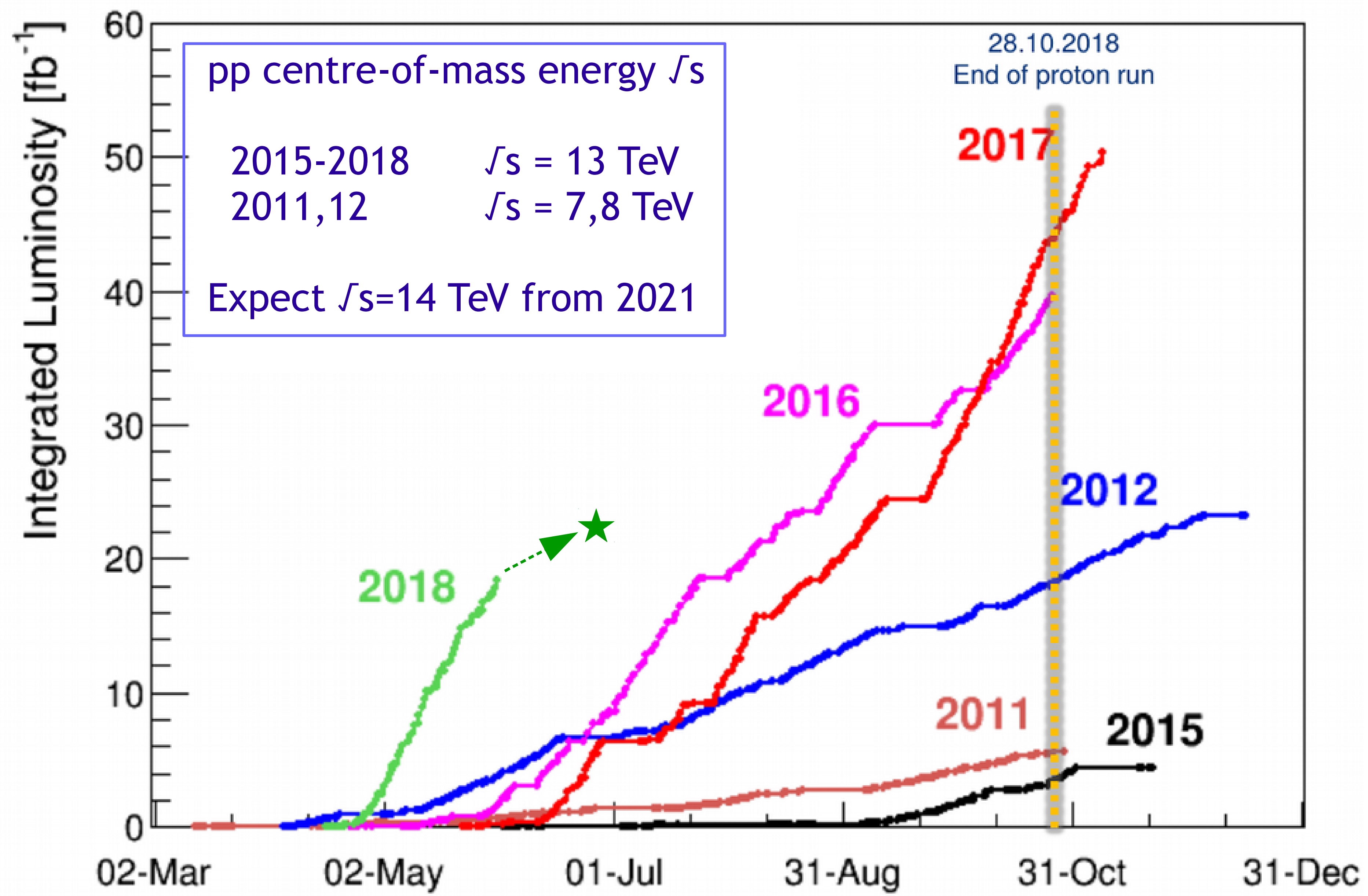
Breadth of LHC physics

While it is best known for the Higgs boson, there is a huge range of physics studied at the LHC

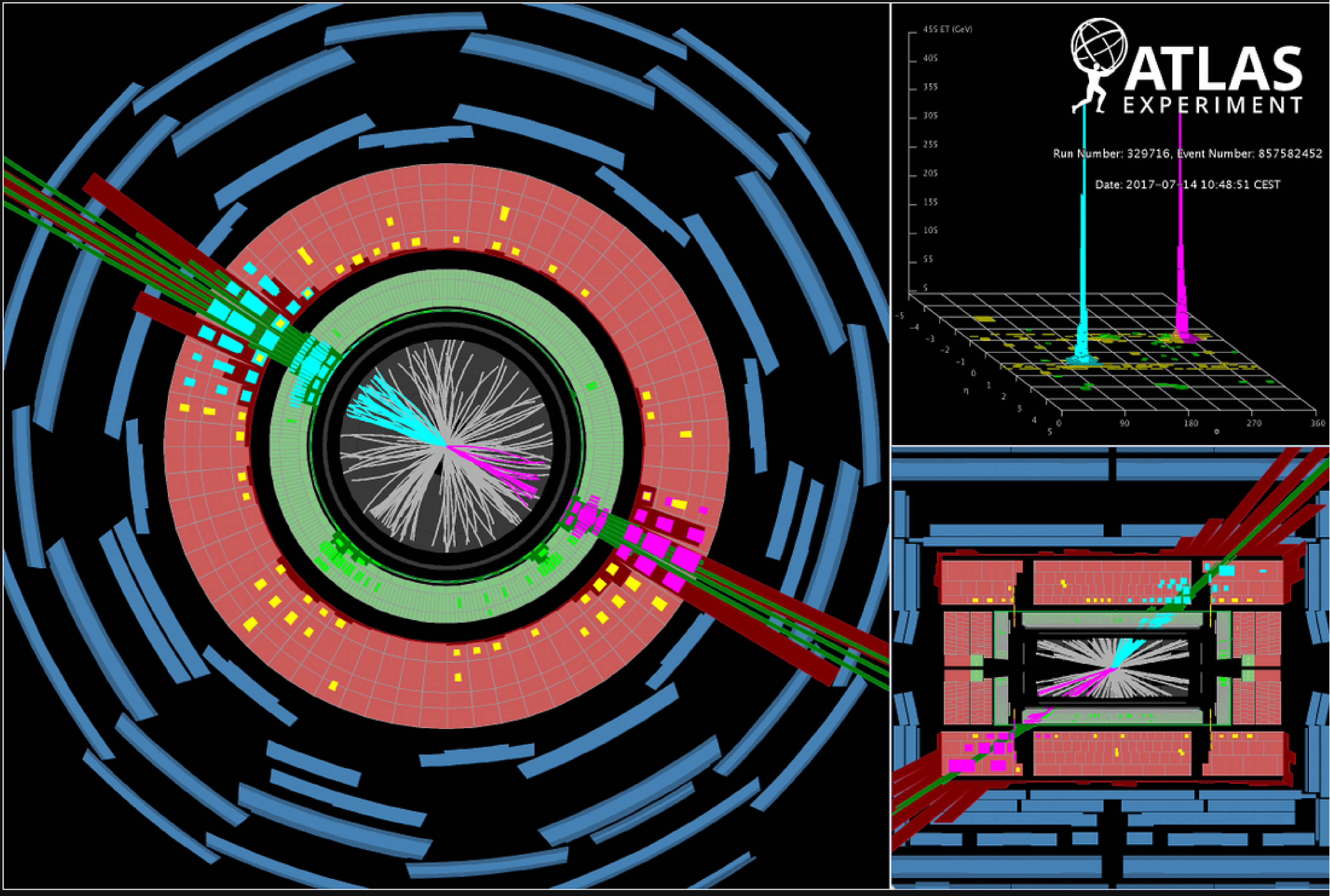
- Higgs boson properties and physics *This talk*
- Othe fundamental SM parameters – masses, couplings
- Electroweak gauge bosons *This talk*
- Top quarks
- b quarks
- Measuring the CKM quark mixing matrix, and CP violation
- Strong interaction, QCD, at the high and low energies
- Study of hot dense hadronic matter (heavy ion collisions) *→ Zihnle Buthelezi's talk tomorrow*
- Huge range of searches for physics beyond the Standard Model *→ Jory Sonneveld's talk, next*



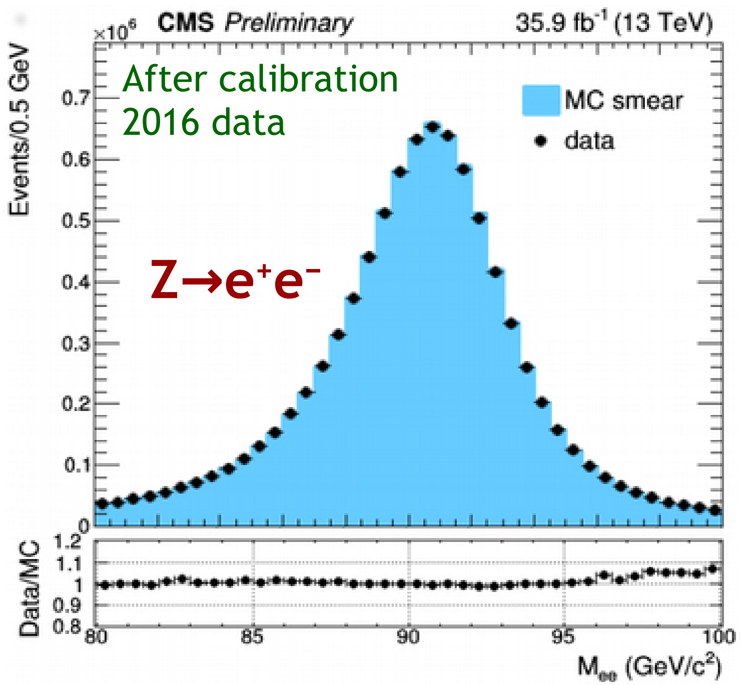
LHC pp data samples



A high-mass dijet event, m(jj)=9.3 TeV



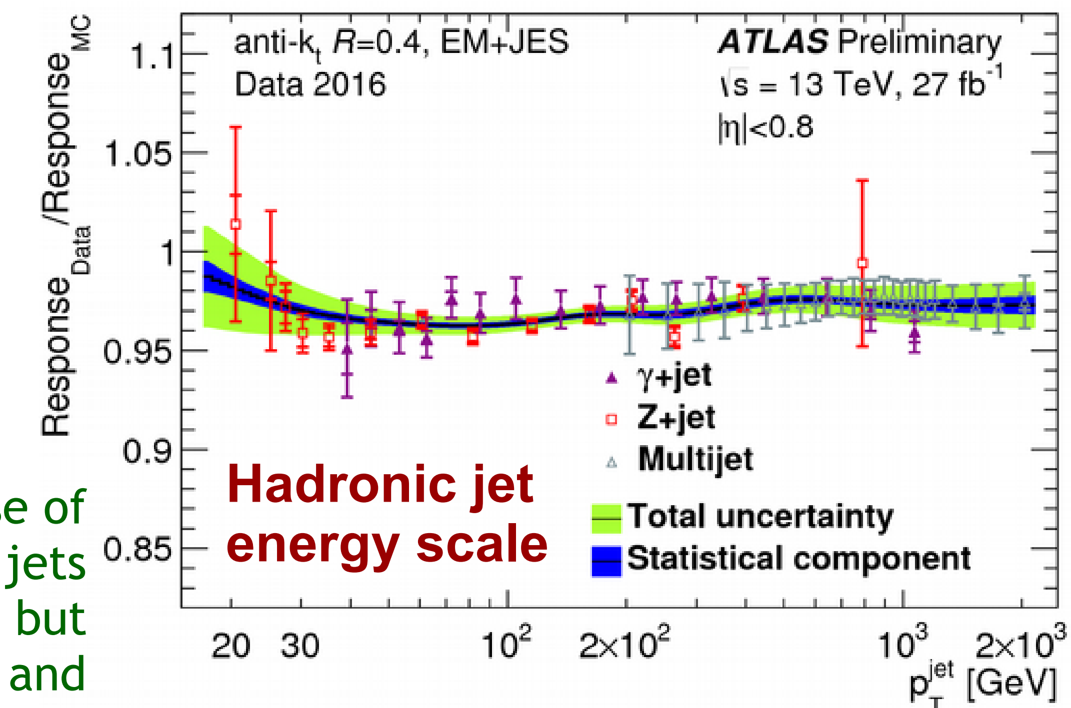
Detector performance examples



To compare theoretical predictions with real data, we must map from the primary particles we study through the response of the detector, using Monte Carlo (MC) simulations

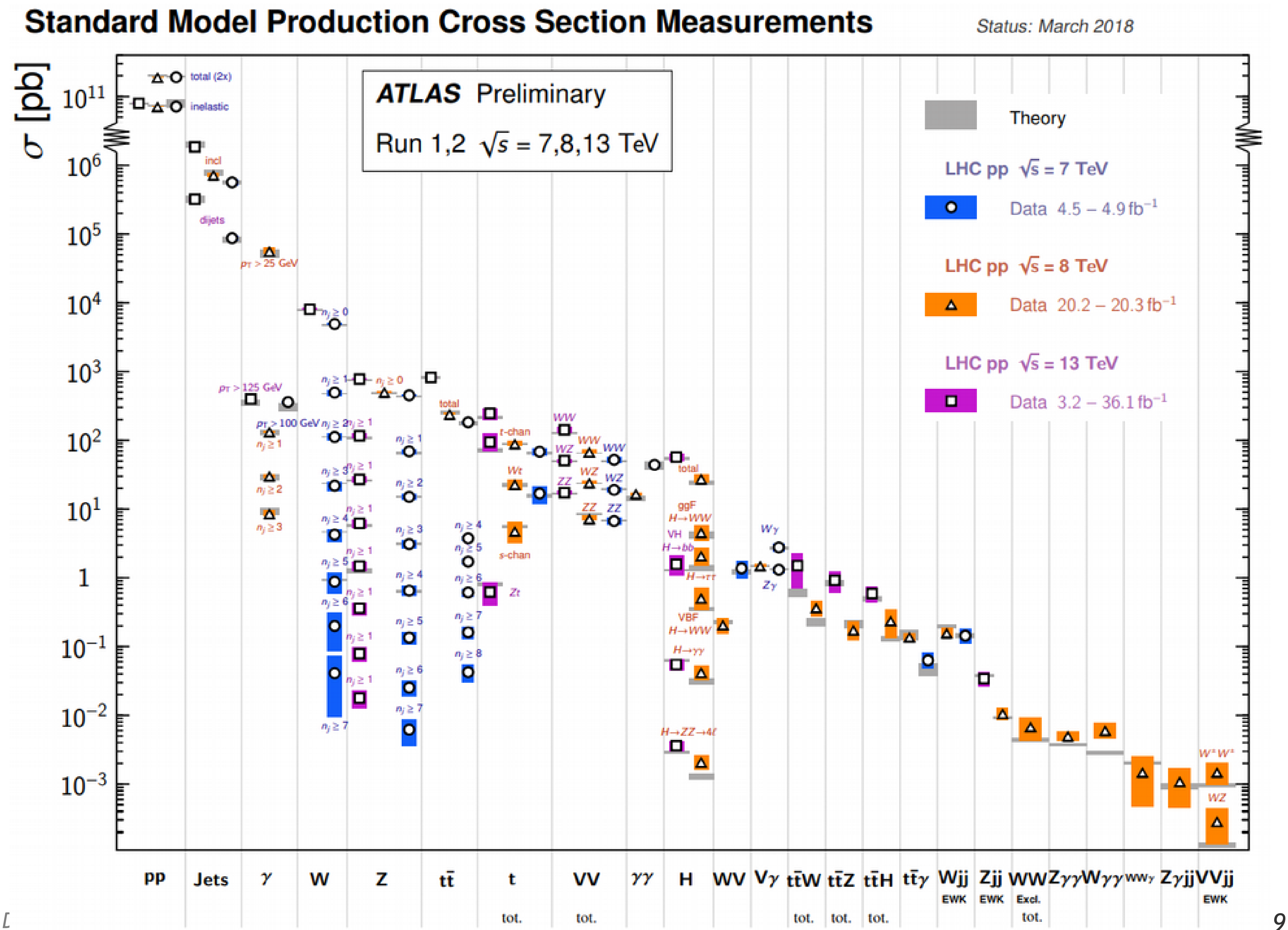
- Event generators → partons to particles
- Detector simulation with GEANT4

Excellent modelling of electron response after calorimeter calibration



Modelling of response of detector to hadronic jets – not precisely 1, but measured using data, and corrected to ~1% level

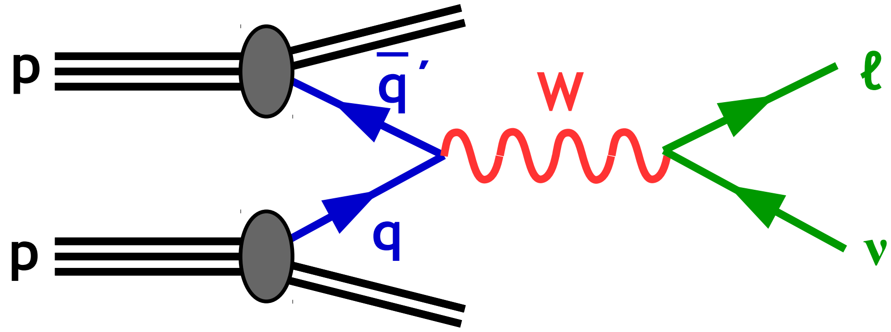
Cross-sections - 15 orders of magnitude

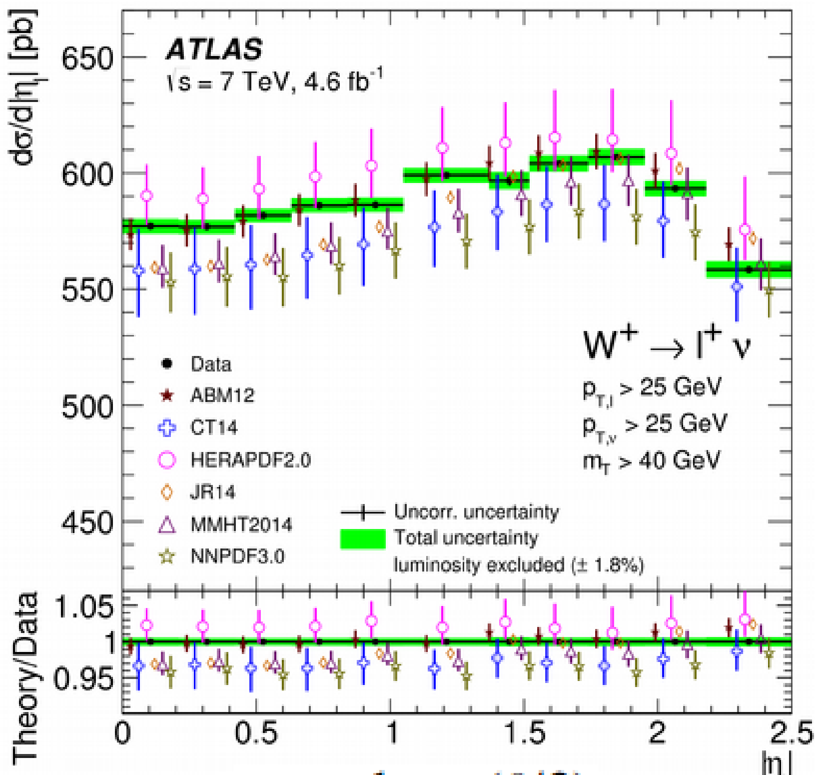


Measurements of W and Z bosons

Clean experimental signatures and large cross-sections

- High precision measurements
- Strong constraints on proton structure
- Tests of consistency of electroweak (EW) sector of SM



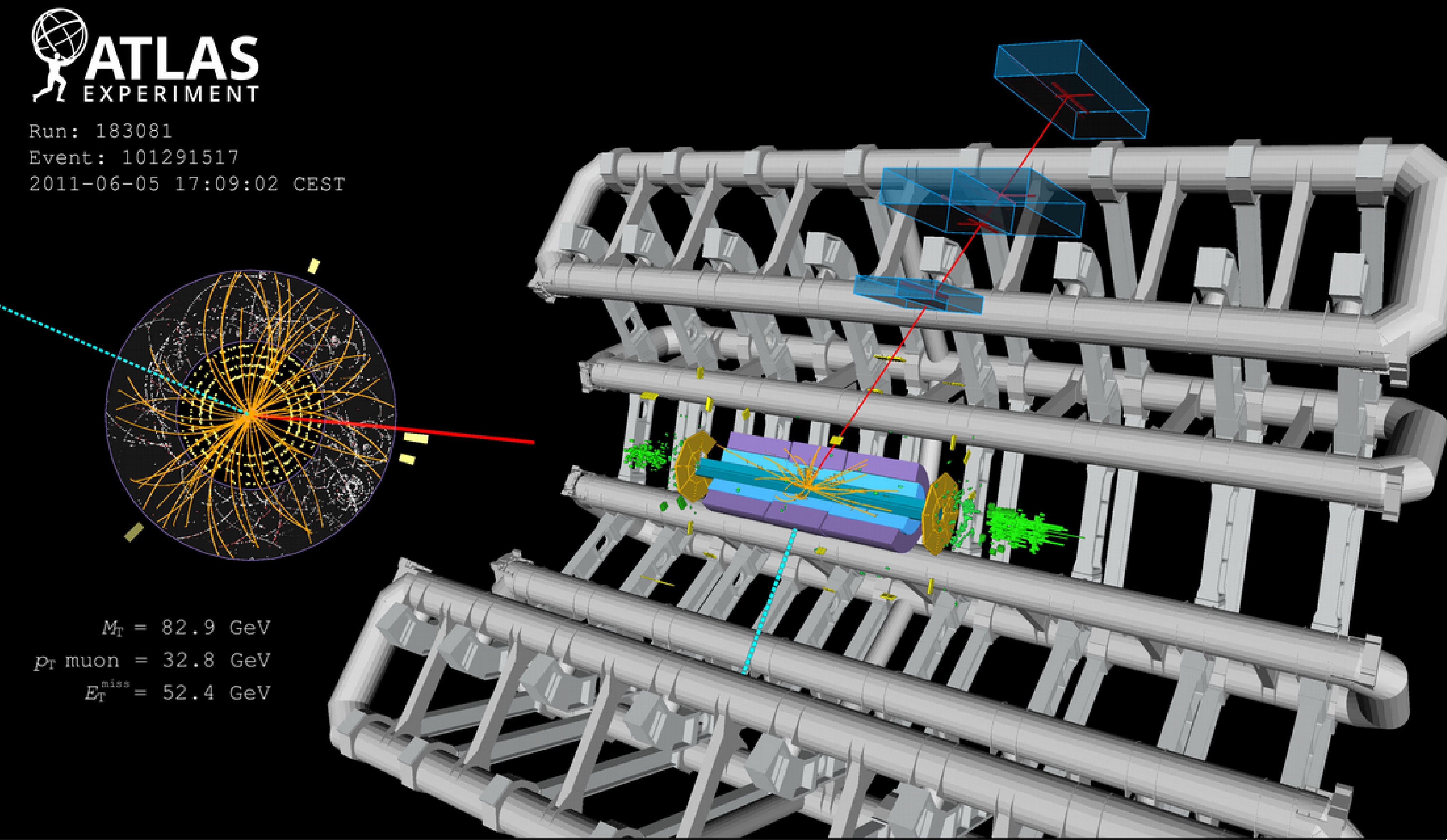


$$\eta = -\ln\tan(\theta/2).$$

Example: measurement of angular distributions of leptons relative to beam direction in $W\rightarrow\ell\nu$ decays

Green errors are from the data – errors on predictions from different proton structure (pdf) sets much larger

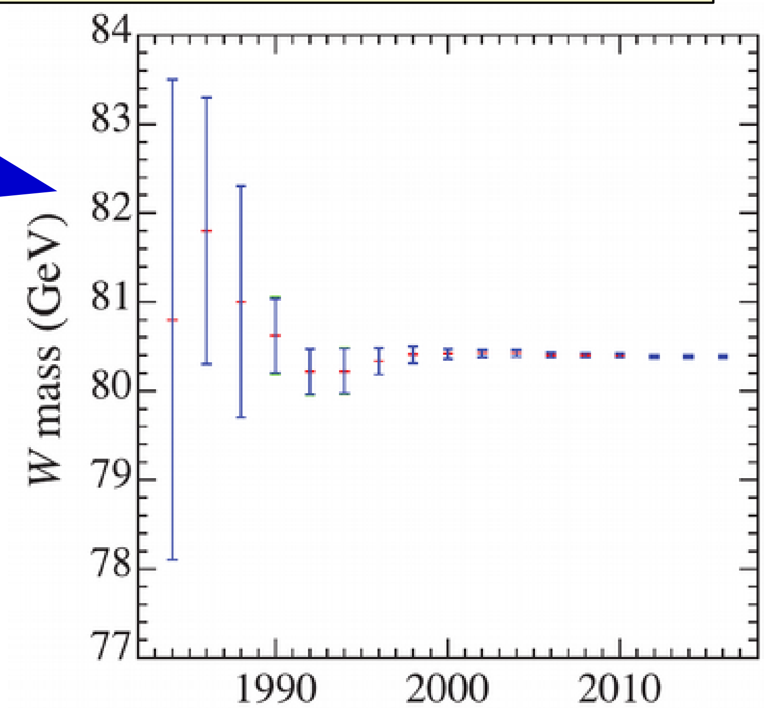
W→μν event


ATLAS
EXPERIMENT
Run: 183081
Event: 101291517
2011-06-05 17:09:02 CEST
M_T = 82.9 GeV
p_T muon = 32.8 GeV
E_T^{miss} = 52.4 GeV

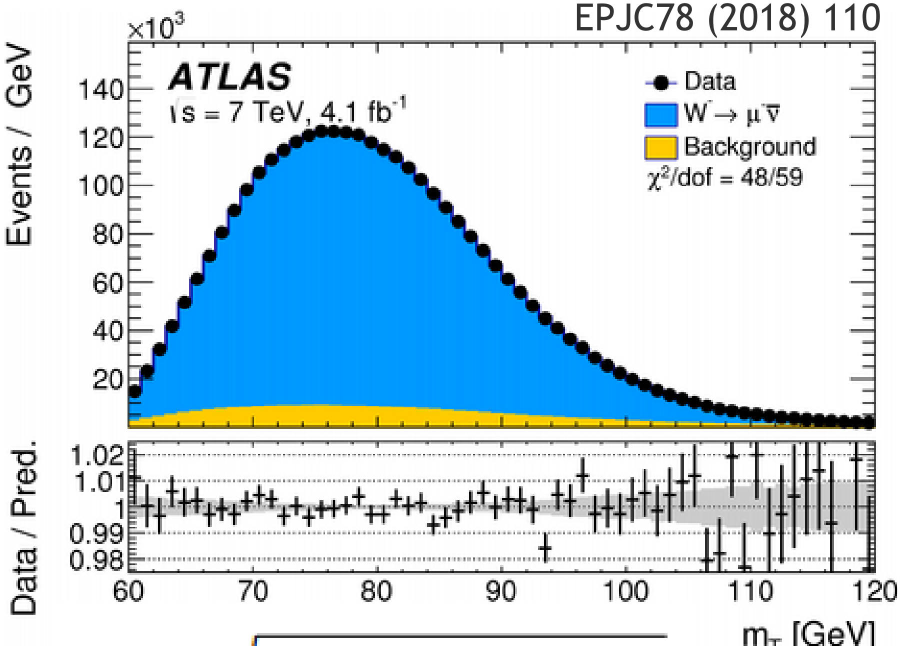
Measuring the W mass

W mass first measured directly back in the 1980's

- History of precision (Particle Data Group)
- Single ATLAS measurement so far from LHC

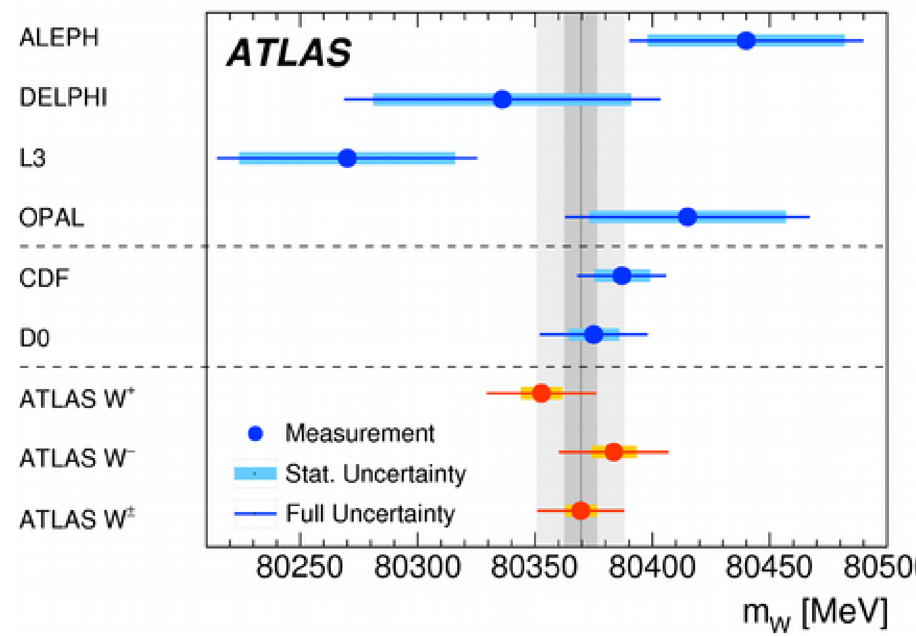


EPJC78 (2018) 110



$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)},$$

$$m_W \quad = \quad 80370 \pm 19 \text{ MeV}$$



arXiv:1806.00242

Precision electroweak fits

Within the SM framework, EW observables can be predicted using just five parameters

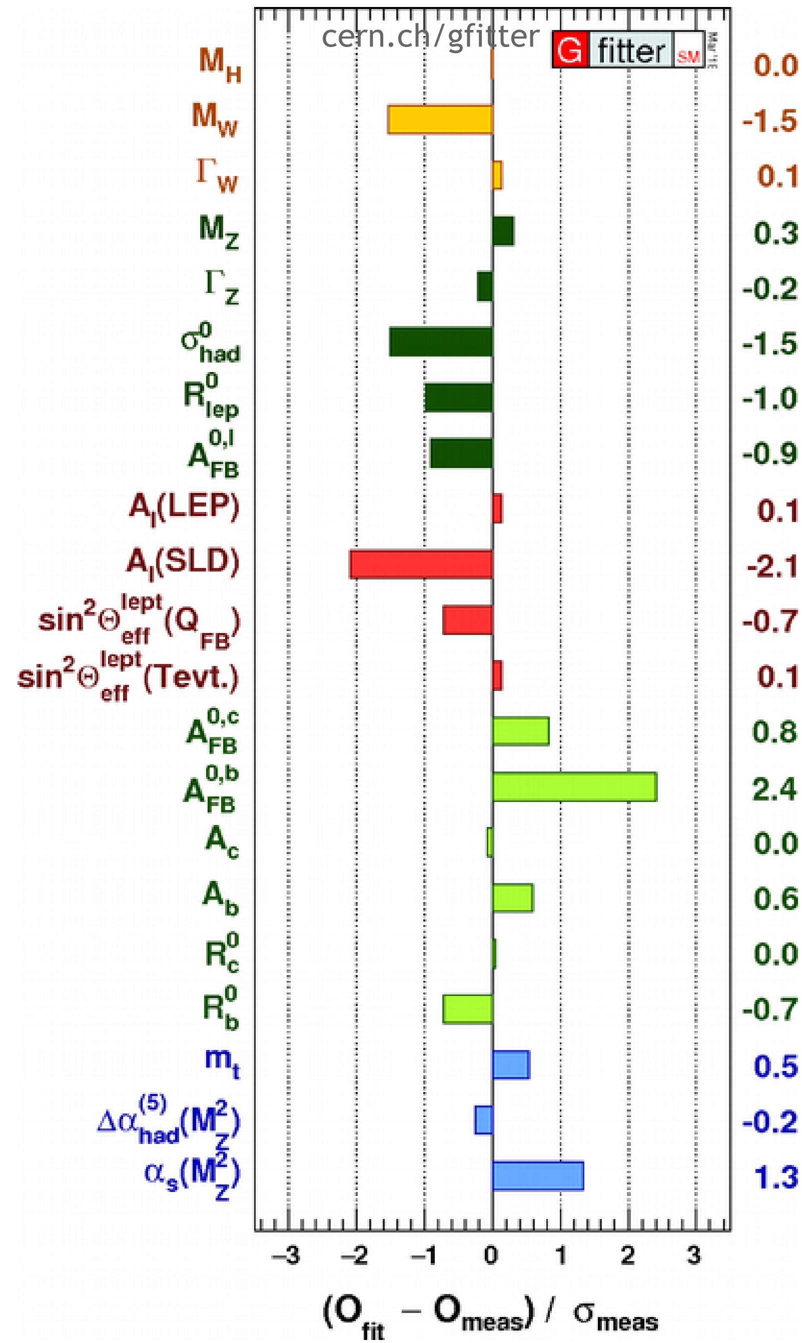
- Many more than five observables have been measured
- Requires theoretical predictions at as high a level as possible (must include loop diagrams!)

- We can fit all EW measurements for a *global EW precision test*

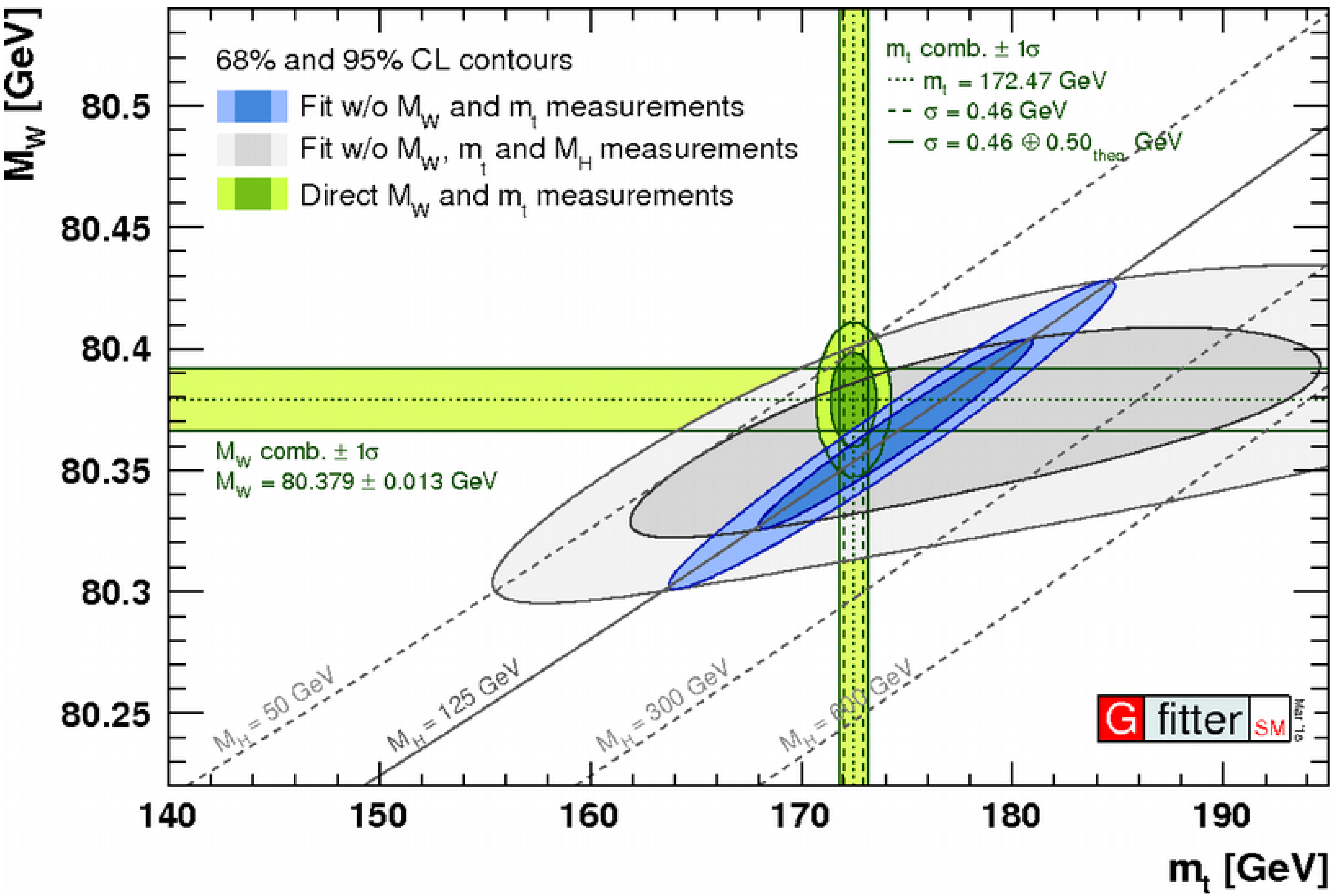
  Latest Gfitter fit: χ^2=18.6 for 15 d-of-f

- We can re-interpret the other results into a prediction of m_W and m_{top}

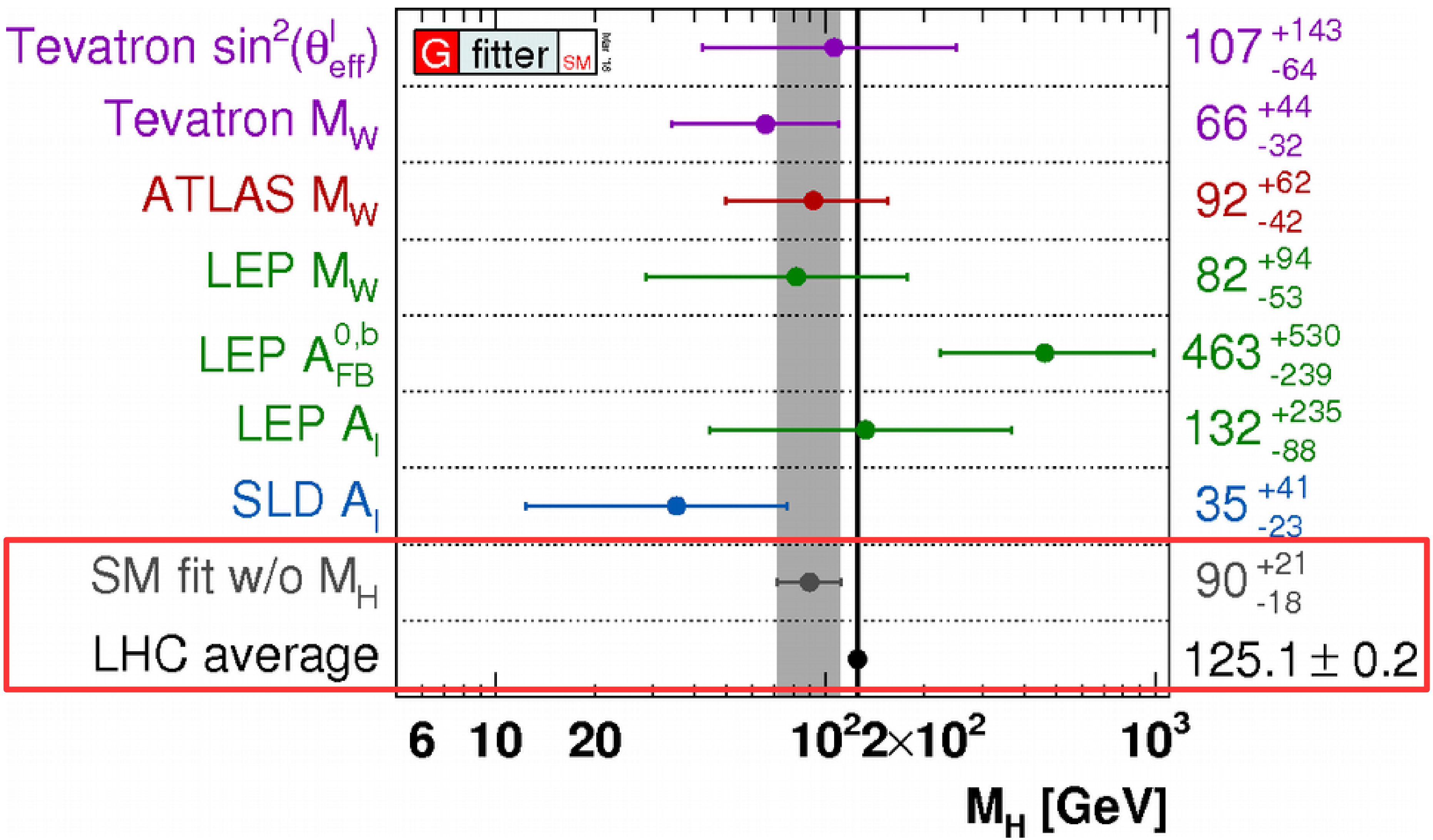
- We can try to predict the Higgs boson mass using all the other measurements



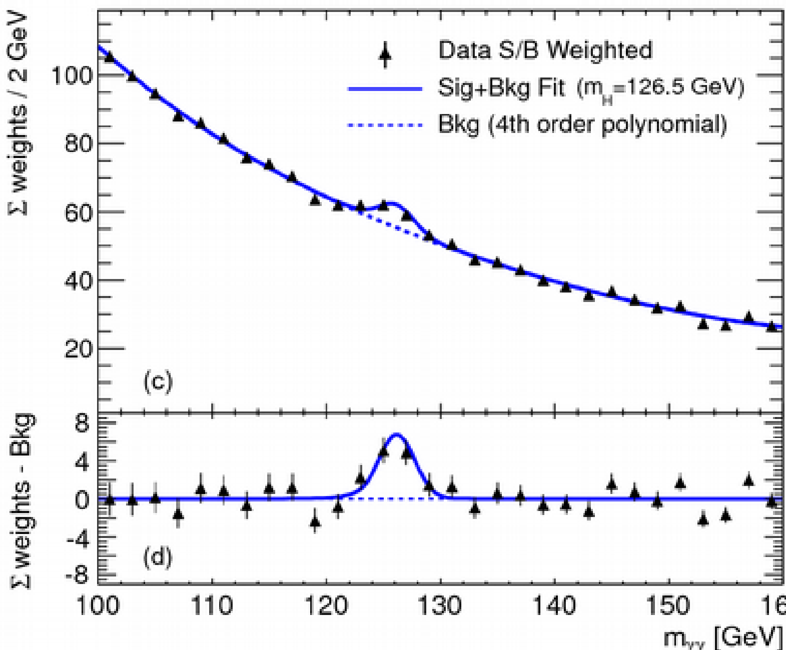
Precision electroweak physics

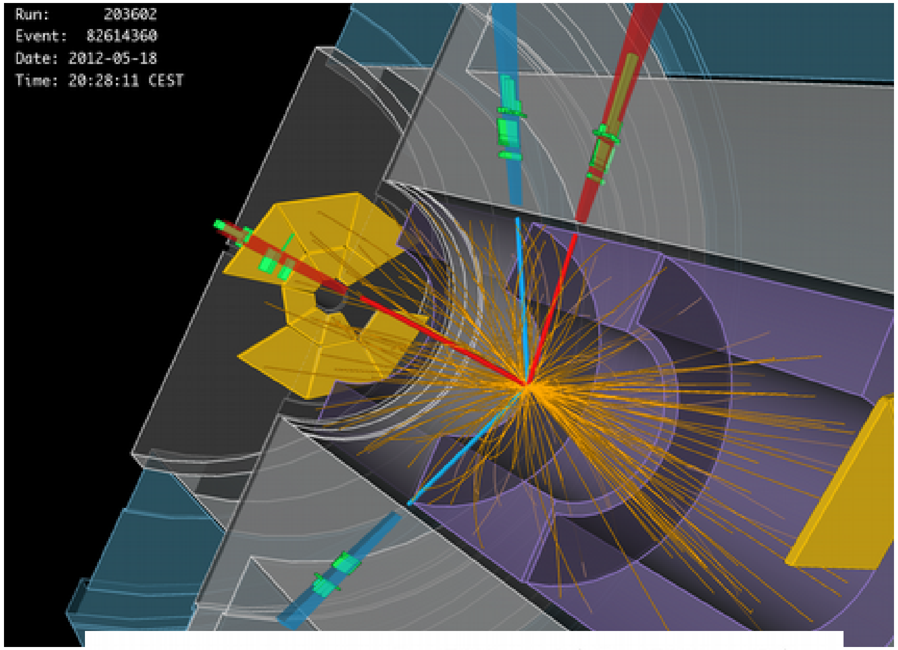


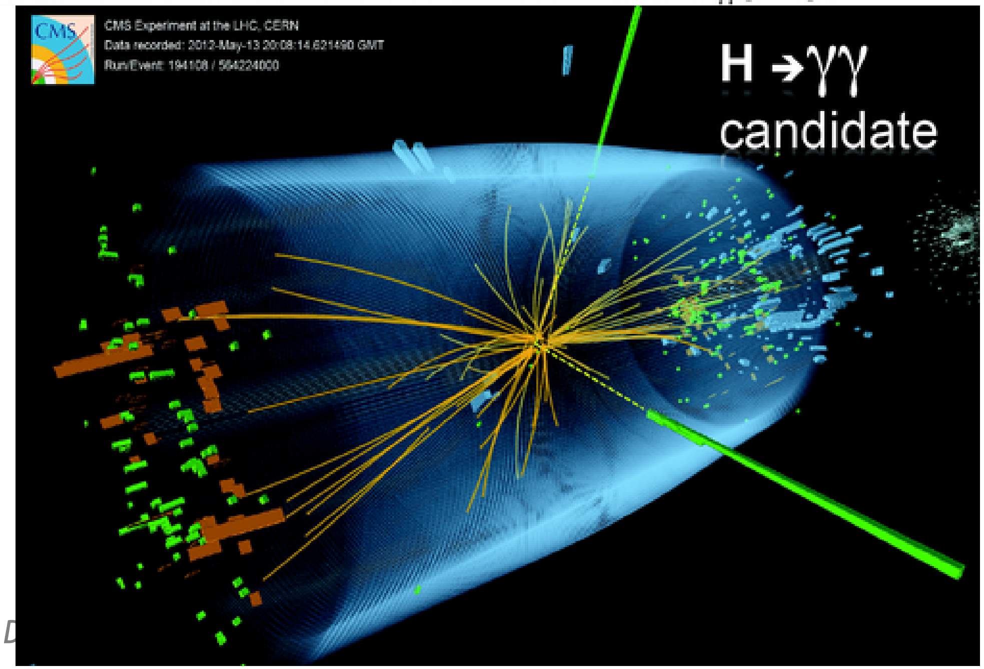
Precision EW fits: "predicting" m_H

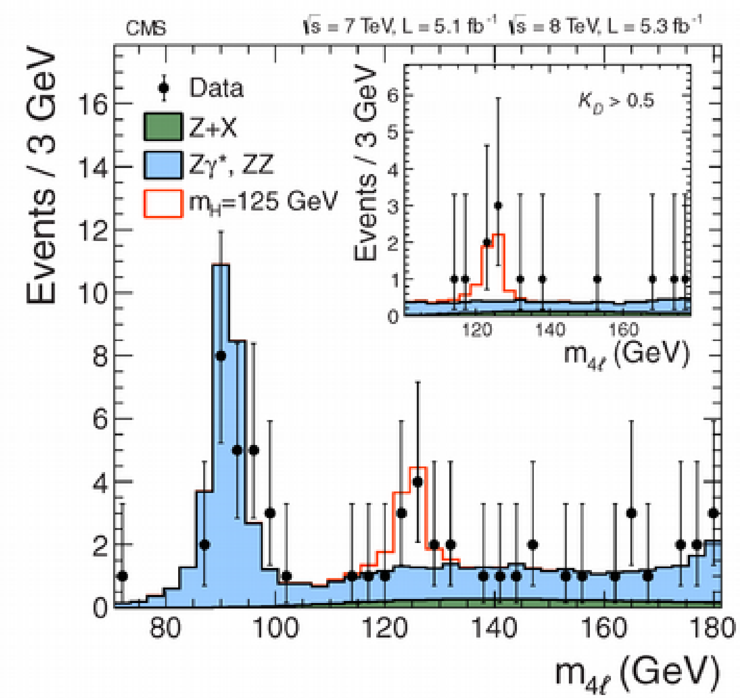


Beyond the discovery of the Higgs boson

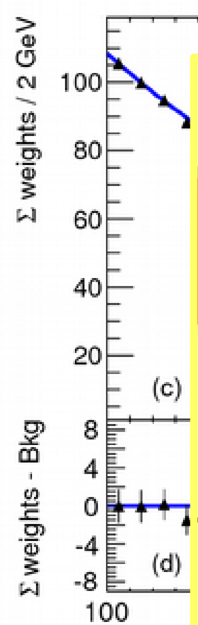


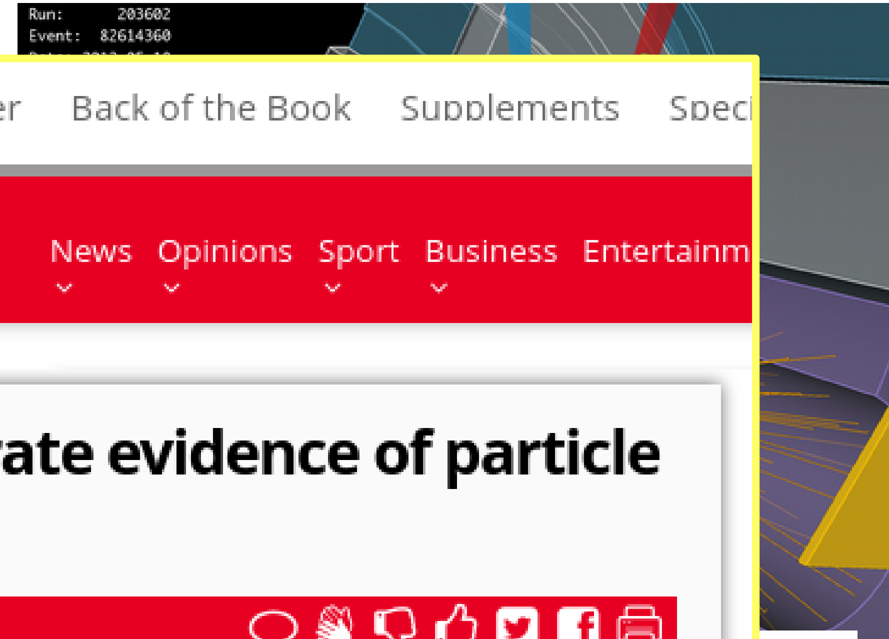






Beyond the discovery of the Higgs boson





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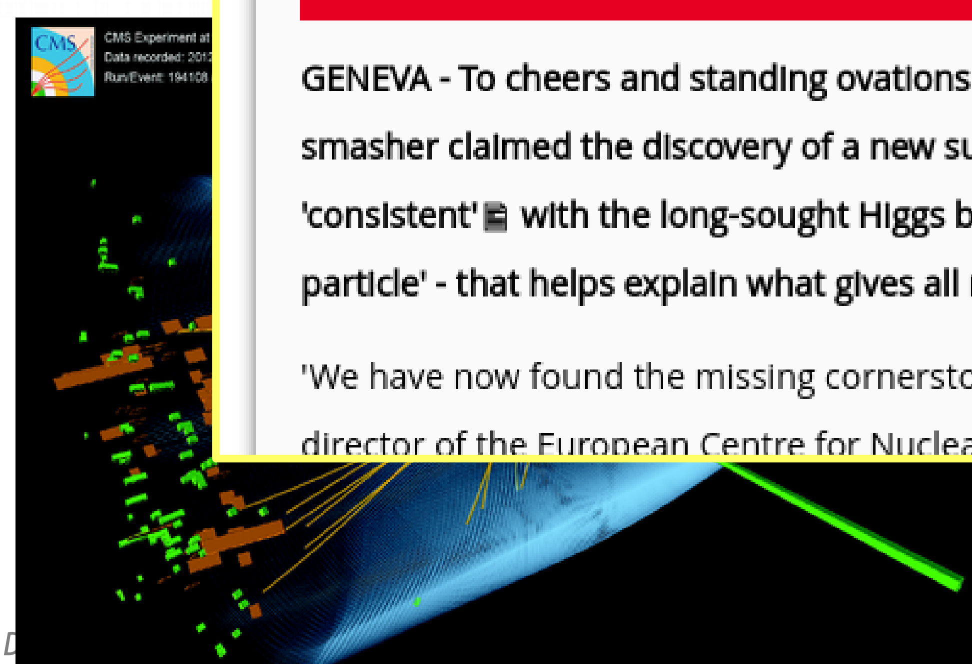
Eureka! Physicists celebrate evidence of particle

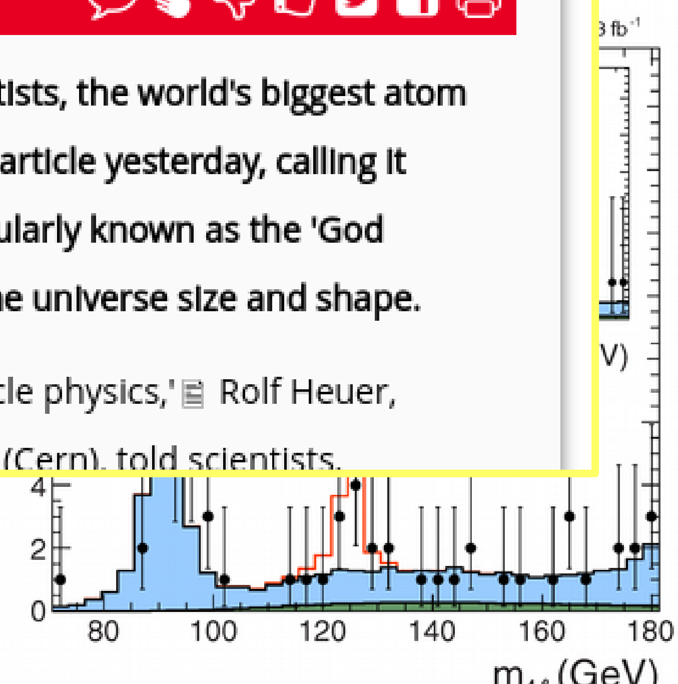
Front Page | 2012-07-05

by JOHN HEILPRIN

GENEVA - To cheers and standing ovations from scientists, the world's biggest atom smasher claimed the discovery of a new sub-atomic particle yesterday, calling it 'consistent' with the long-sought Higgs boson - popularly known as the 'God particle' - that helps explain what gives all matter in the universe size and shape.

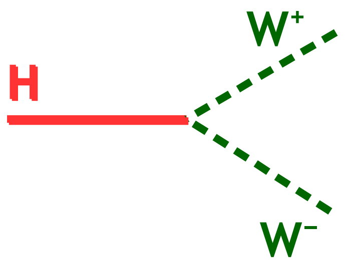
'We have now found the missing cornerstone of particle physics,' Rolf Heuer, director of the European Centre for Nuclear Research (Cern), told scientists.

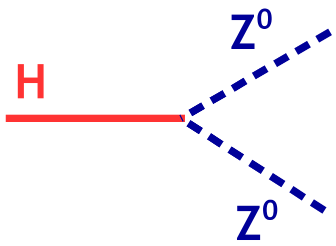




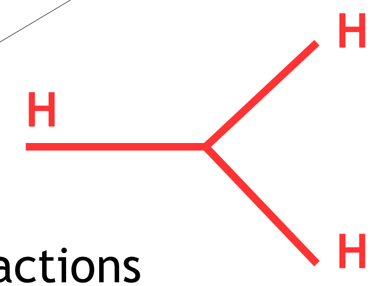
Higgs boson interactions in the SM

In the Standard Model, the couplings of the Higgs boson to the other SM particles is fully prescribed: *But is it right?*

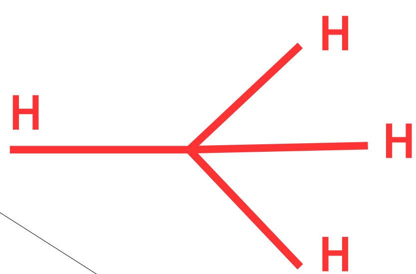




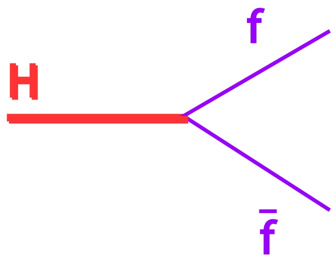
Interactions with electroweak gauge bosons



Self-interactions



Interactions with fermions – the *Yukawa interactions* – there are twelve coupling strengths (six quarks, six leptons [? neutrinos])



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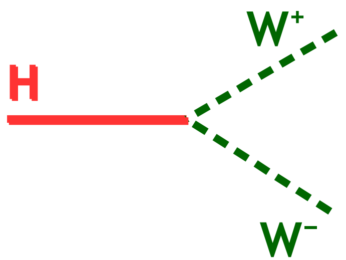
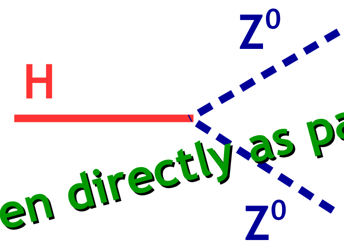
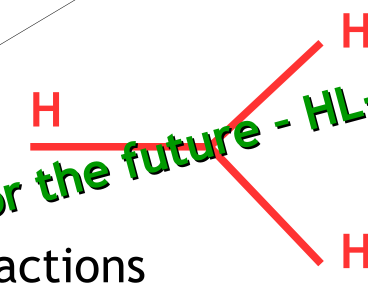




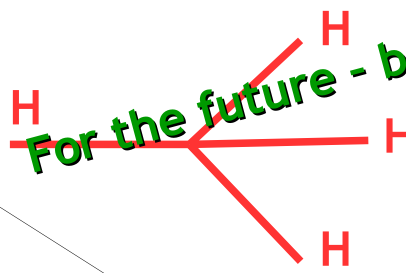
Seen directly as part of H discovery

Interactions with electroweak gauge bosons



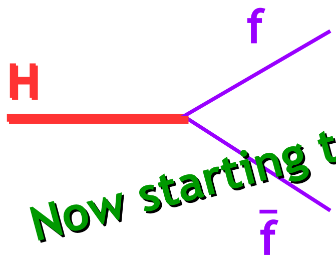
For the future - HL-LHC?

Self-interactions



For the future - but how?

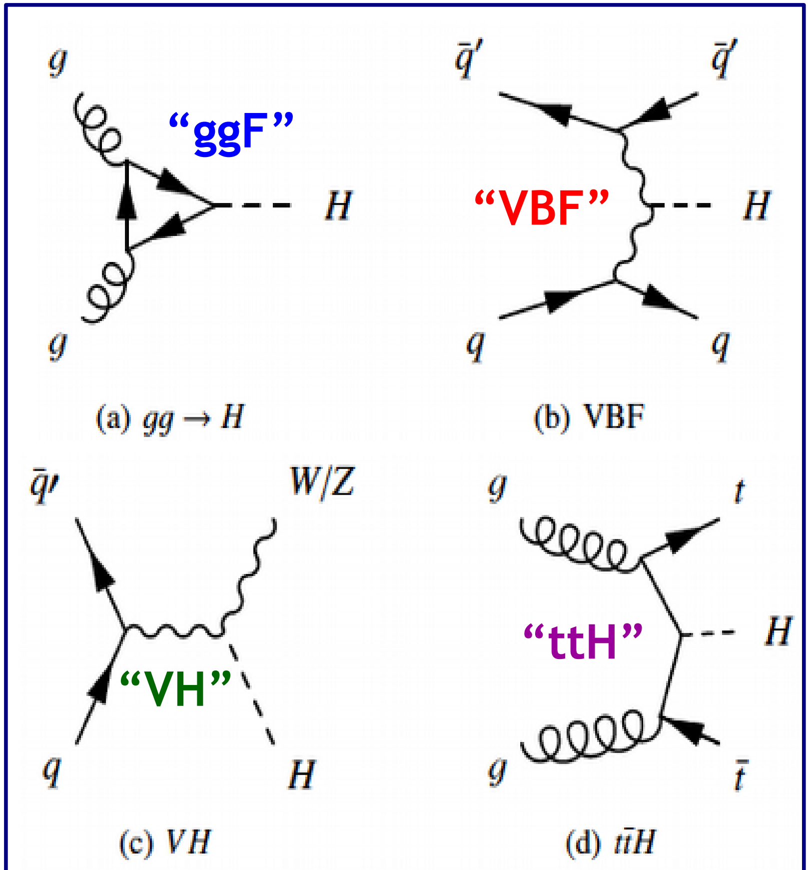
Interactions with fermions – the *Yukawa interactions* – there are twelve coupling strengths (six quarks, six leptons [? neutrinos])



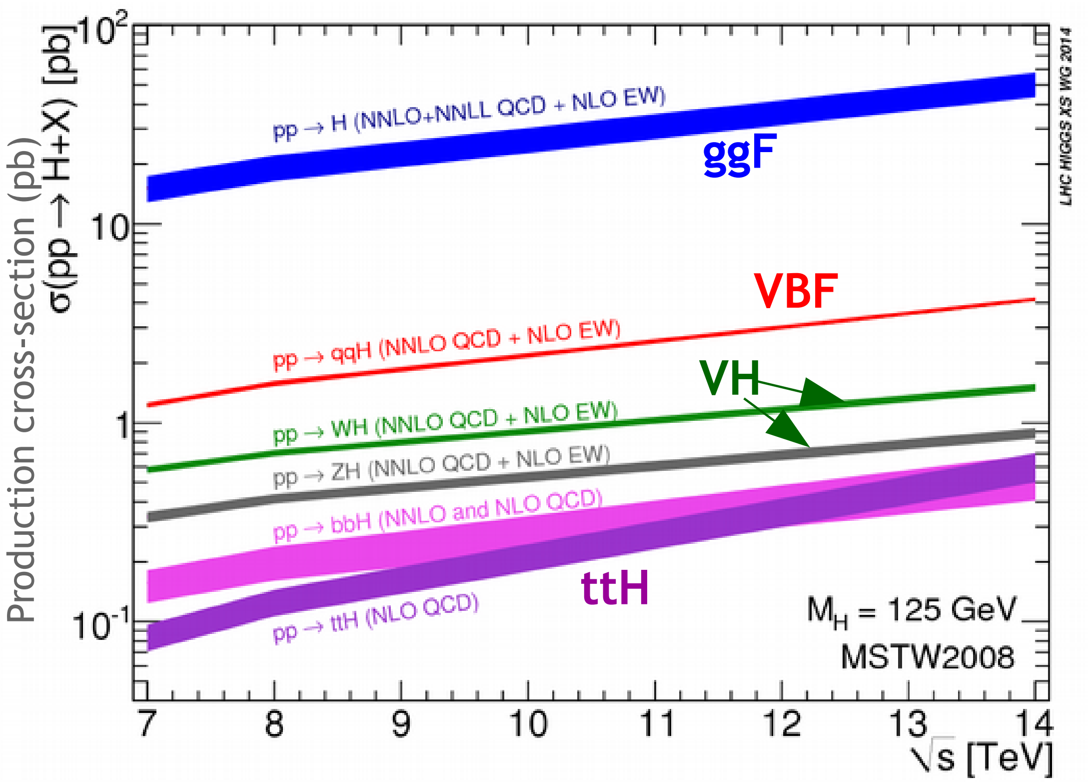
Now starting to measure these directly

Higgs boson production

Multiple production mechanisms with different event characteristics



Main (single H) production diagrams



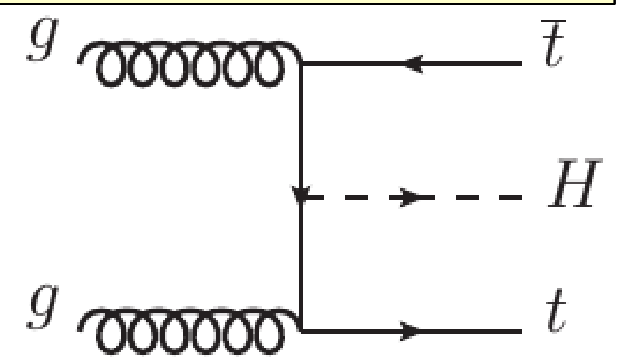
"ggF" dominates, but multiple processes should be detectable

H production via **ggF**, **VBF** and **VH** processes were established from earlier data

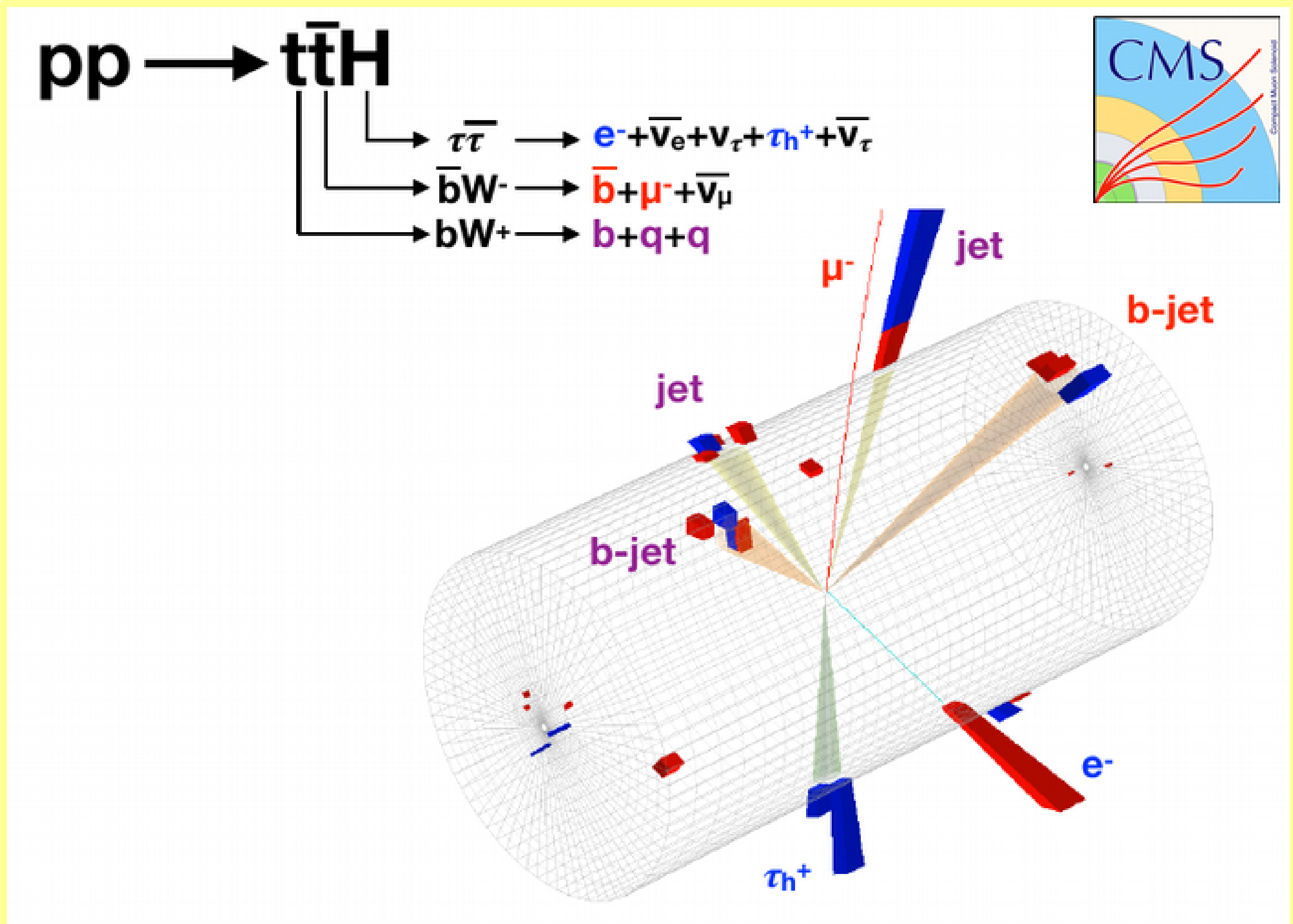
Three very massive particles: $t\bar{t}H$

New results in the last few weeks:
5σ observation of $t\bar{t}H$ from CMS and ATLAS

Very sophisticated analyses, pushing detector performance very far, many channels, multivariate analyses...



CMS $t\bar{t}H$ candidate event



$t\bar{t}H$ observation

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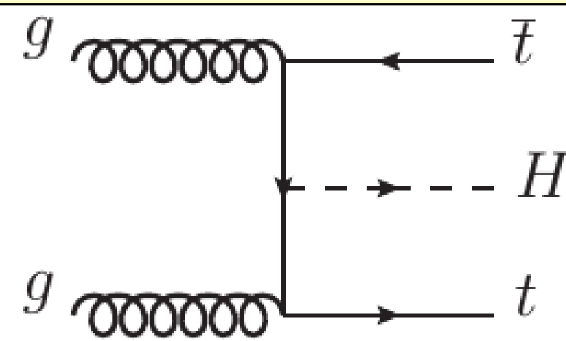
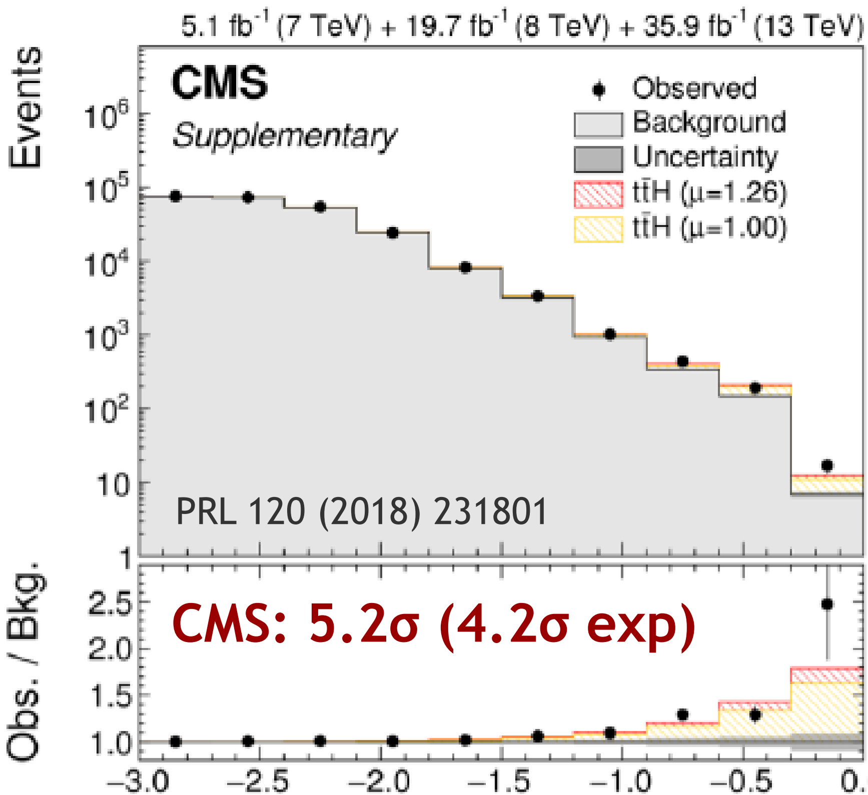
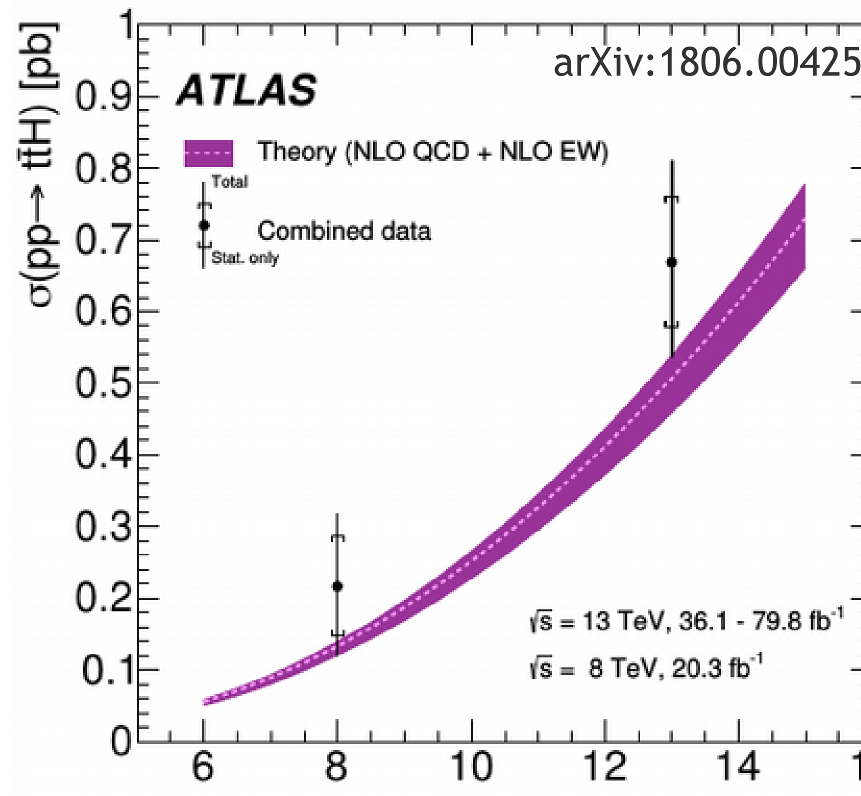
5σ observation of $t\bar{t}H$ from CMS and ATLAS

Very sophisticated analyses, pushing detector performance very far, many channels, multivariate analyses...





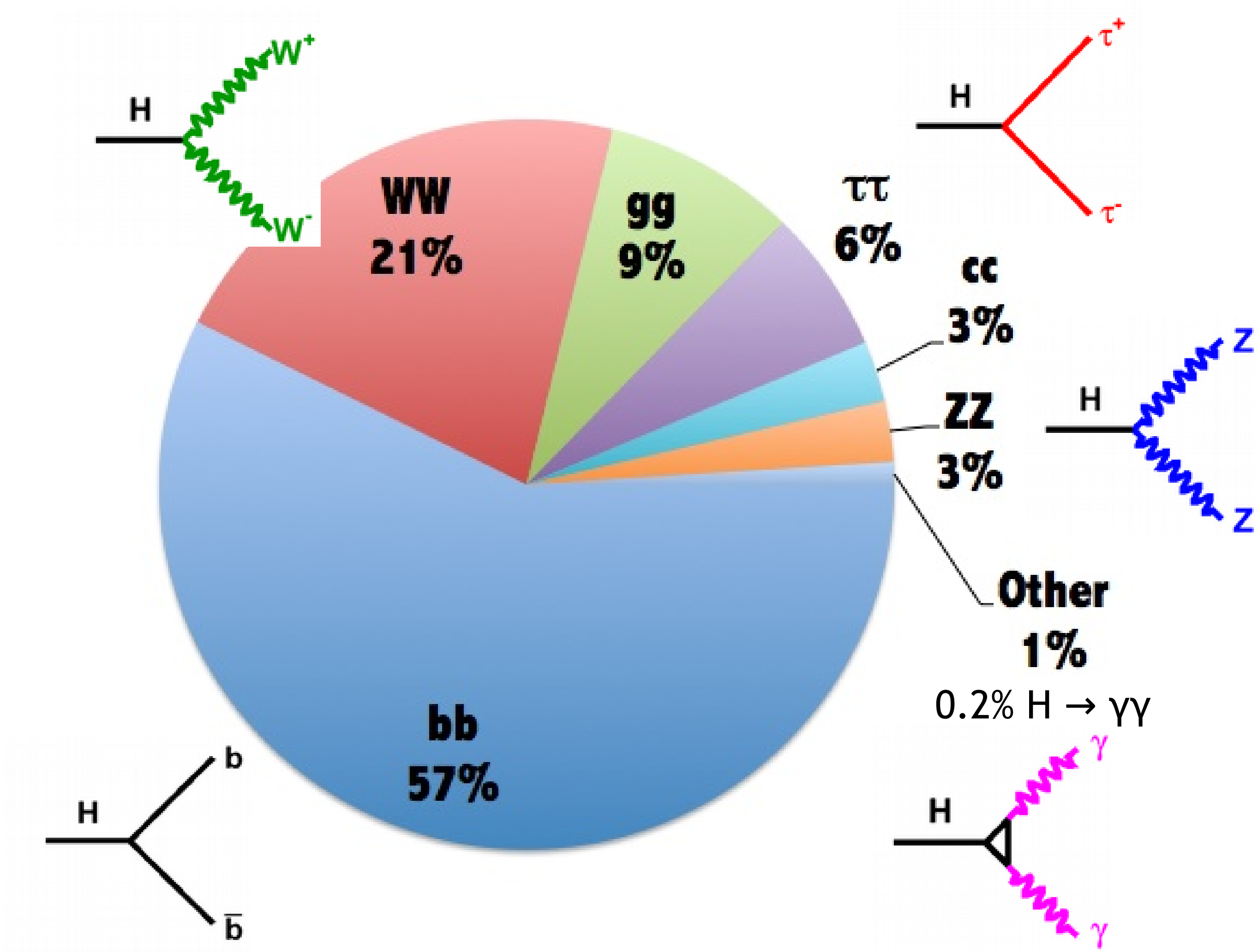
"How signal-like is the event"



ATLAS: 6.3σ (5.1σ exp)

Higgs boson decays

The Standard Model predicts the H decay branching ratios to known particles



Predicted decay modes

Higgs boson decays

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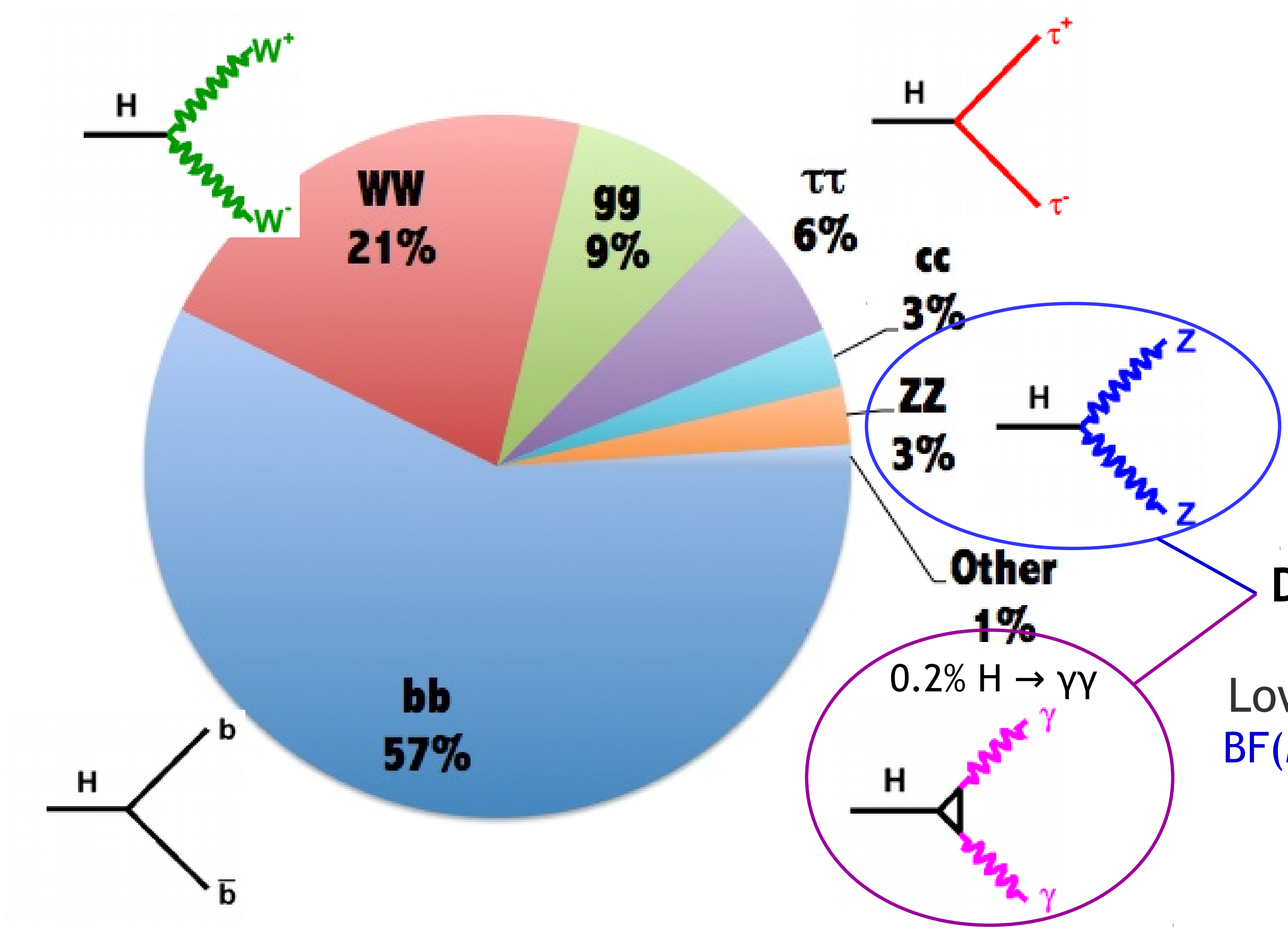


Discovery channels

Low branching fractions

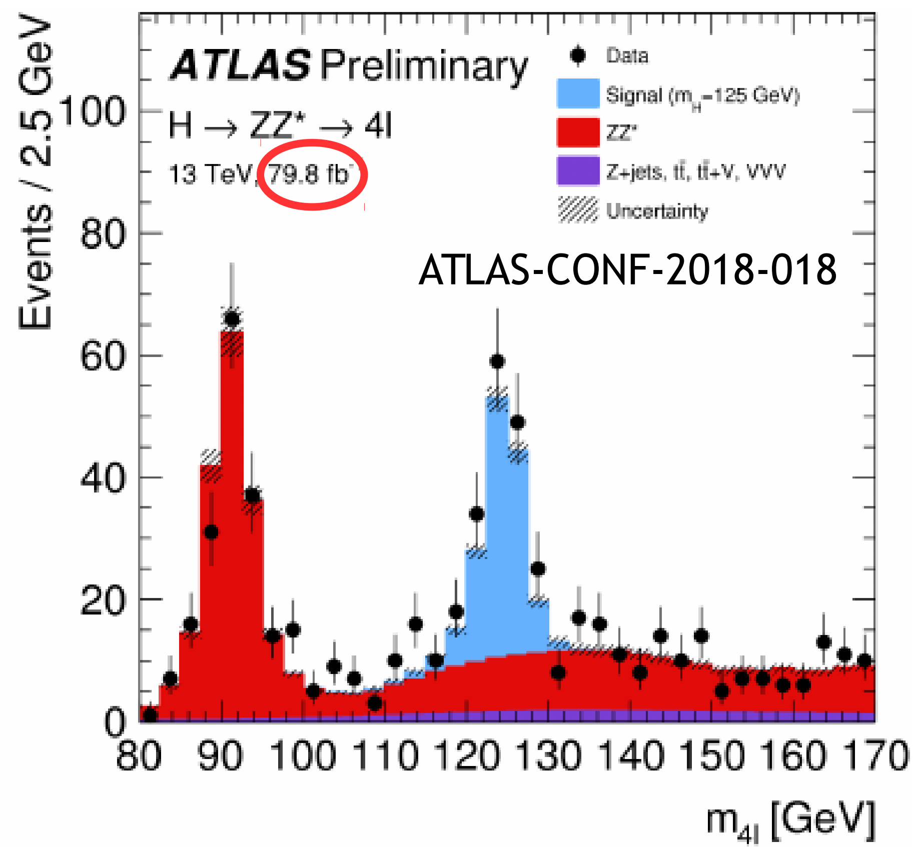
BF($H \to ZZ^* \to 4(e/\mu)$) ~ 0.01%

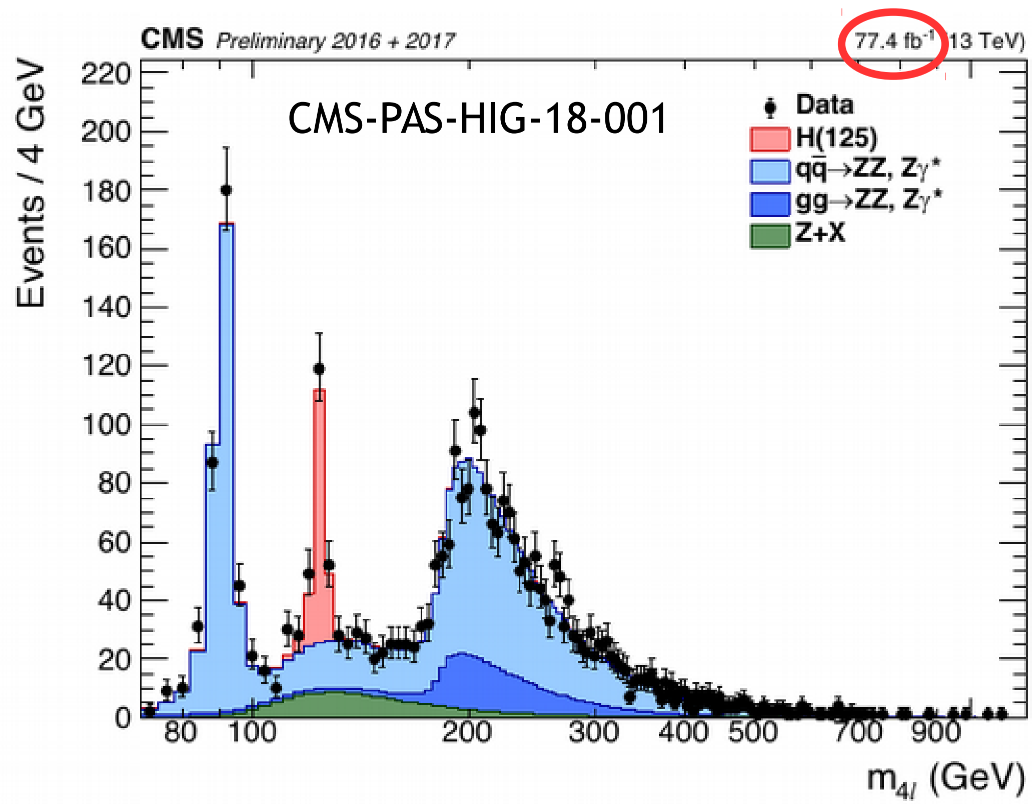
BF($H \to \gamma\gamma$) ~ 0.2%

Predicted decay modes

H decays to bosons – precision era

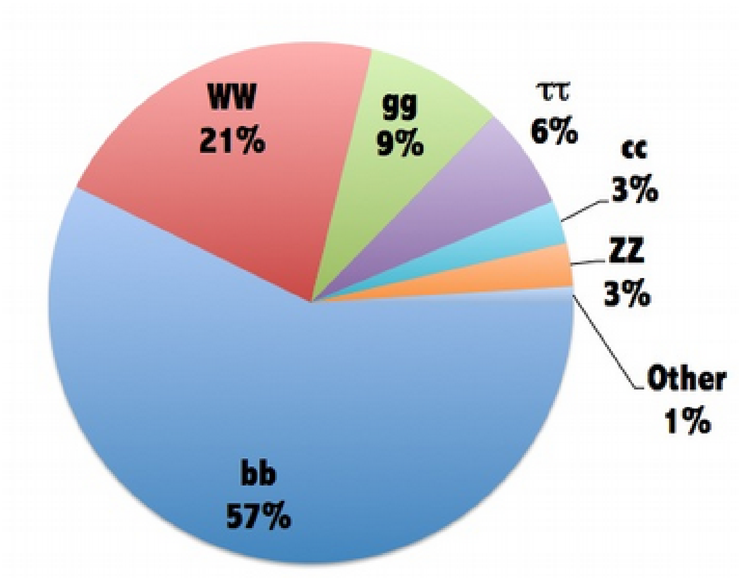
Run-2 analyses including data from 2017 (with 80 fb^{-1}) were reported this month, for the first time – higher precision is coming!

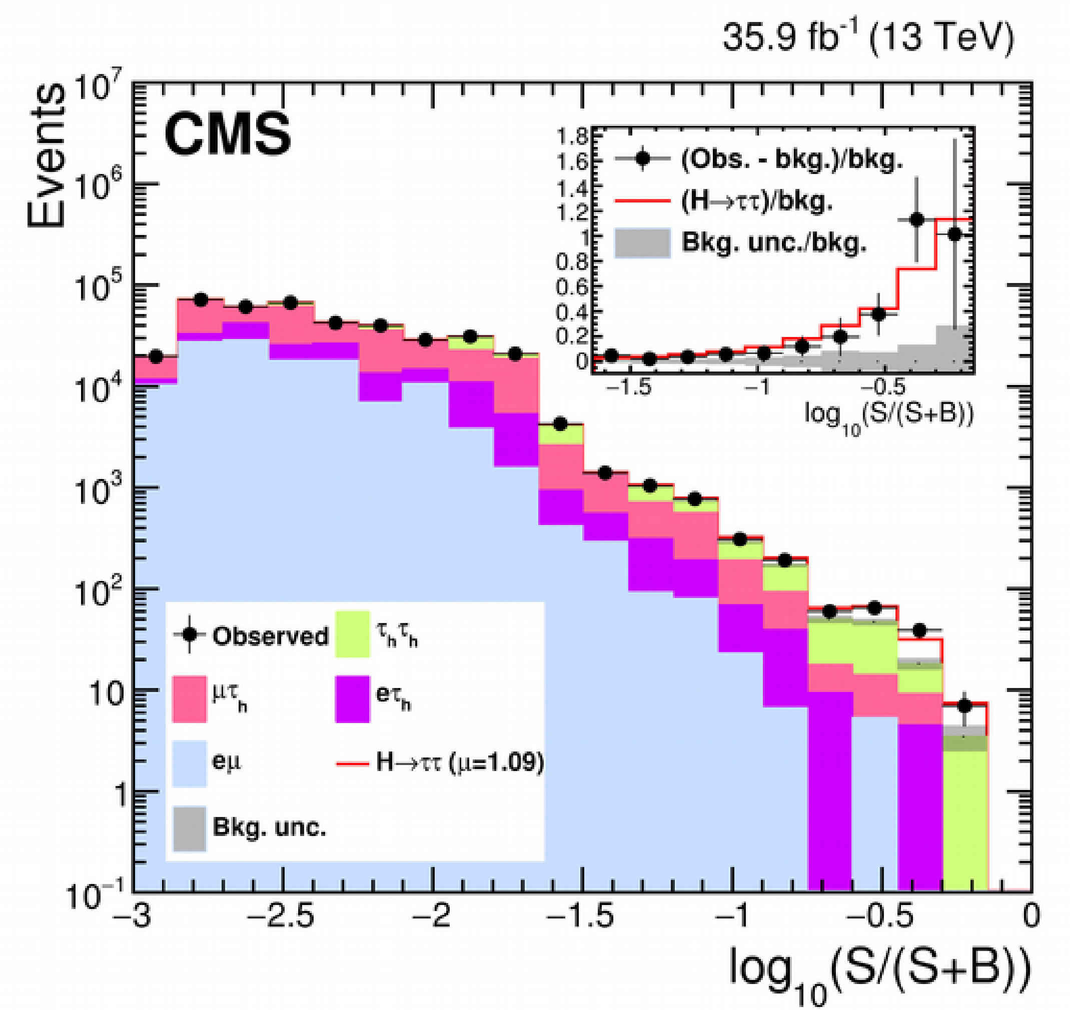




H decays to fermions: $\tau^+\tau^-$

Dominant decays of the H to fermions are expected to be to $b\bar{b}$, $\tau\tau$ (and $c\bar{c}$)





"How signal-like is the event"

Experimentally ττ most significant – both CMS and ATLAS have 5σ significances (Run-1+Run-2)

- CMS 5.9σ (5.9σ)
- ATLAS 6.4σ (5.4σ) new

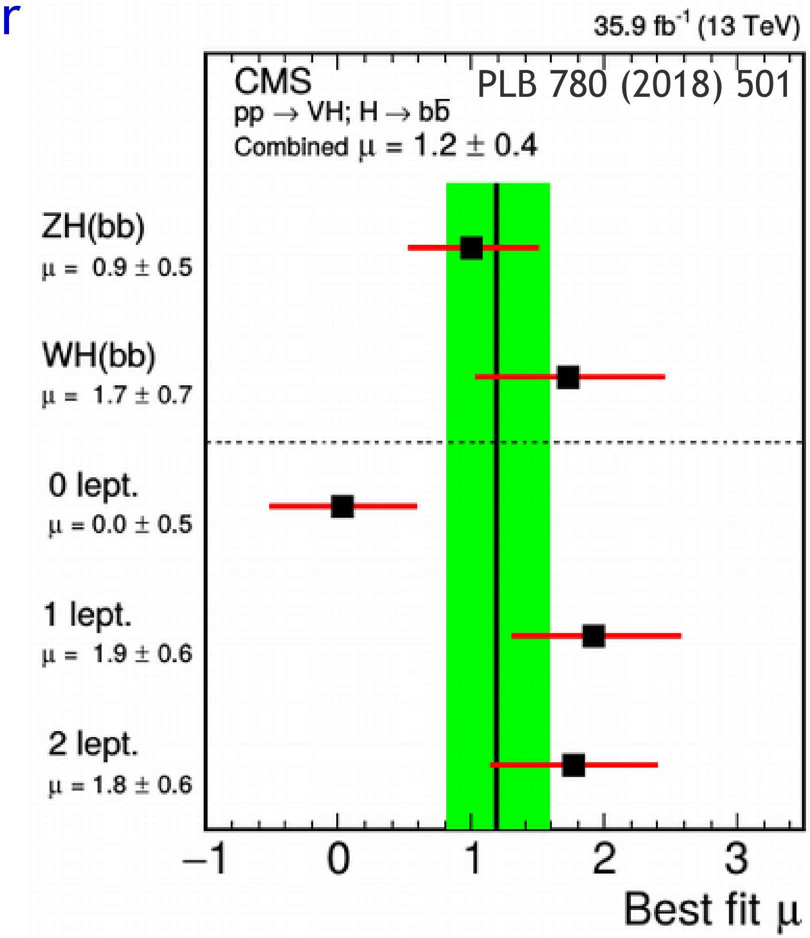
H decays to fermions: $b\bar{b}$

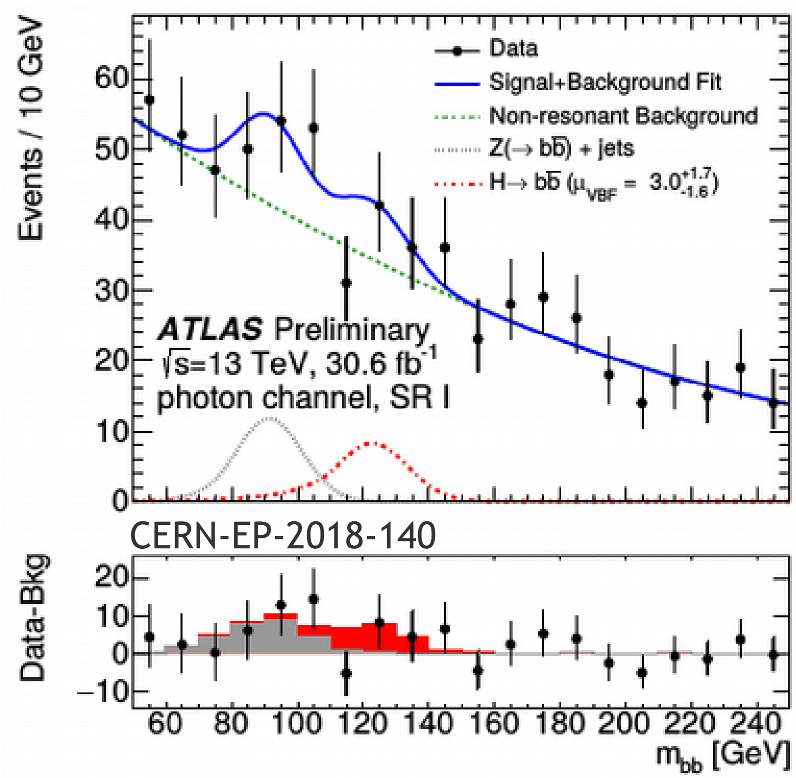
Results with 2016 data mainly released last year
- Difficult analyses with many tough points

Run-1+Run-2 signal strengths:

$$\mu_{VH}^{CMS} = 1.06^{+0.31}_{-0.29} \qquad \mu_{VH}^{ATLAS} = 0.90^{+0.28}_{-0.26}$$

Both correspond to evidence at 3.6-3.8σ





New this month: ATLAS update on H→bb from vector-boson fusion in 13 TeV data

Summary

The LHC is delivering larger and larger data samples, enabling a very wide range of studies

- ATLAS and CMS are exploring the Brout-Englert-Higgs mechanism by studying the Higgs boson in increasing depth
  - In the last year: we established that the H interacts with fermions (τ leptons and t quarks) – Yukawa couplings do exist in nature!
  - Latest step: observing ttH production at 5σ
- Many high-precision measurements match or exceed uncertainties on theory predictions, driving progress in higher-order calculations
- Only one percent of the full LHC data sample analysed! Twenty years of data ahead

The LHC is the world’s highest-energy particle physics collider - with global collaborations including institutes from all continents