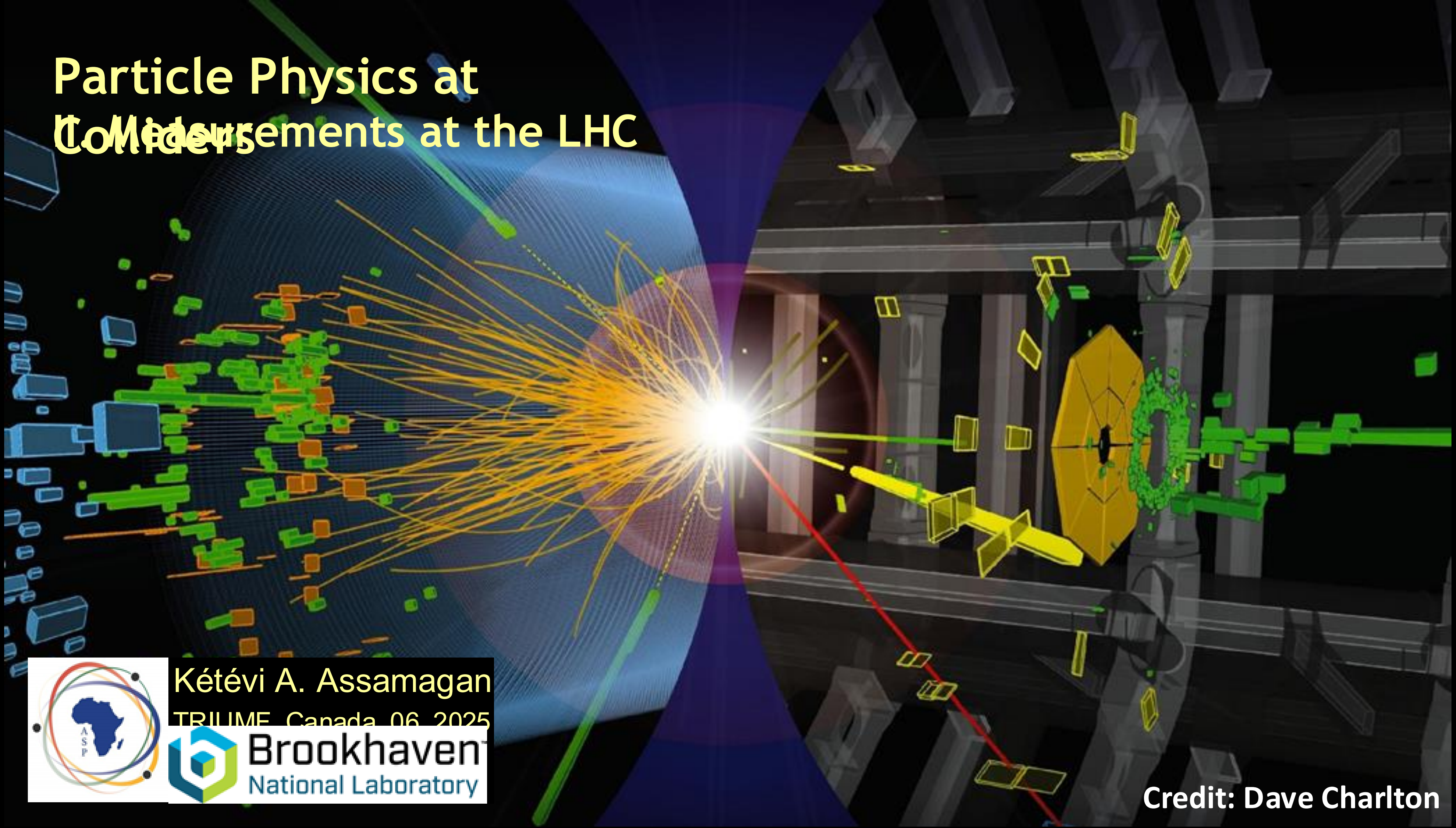
Particle Physics at Colliders

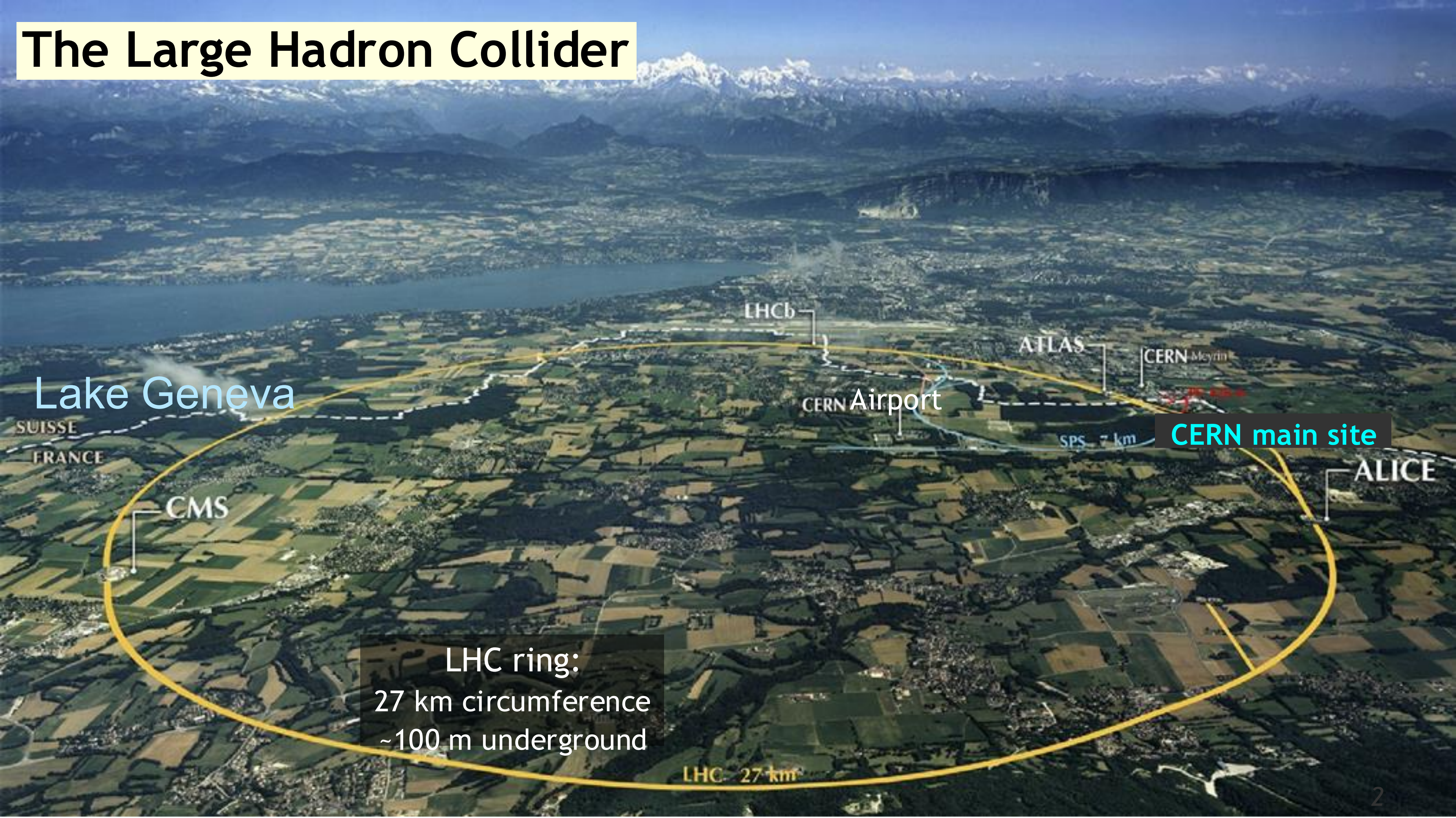
II. Measurements at the LHC



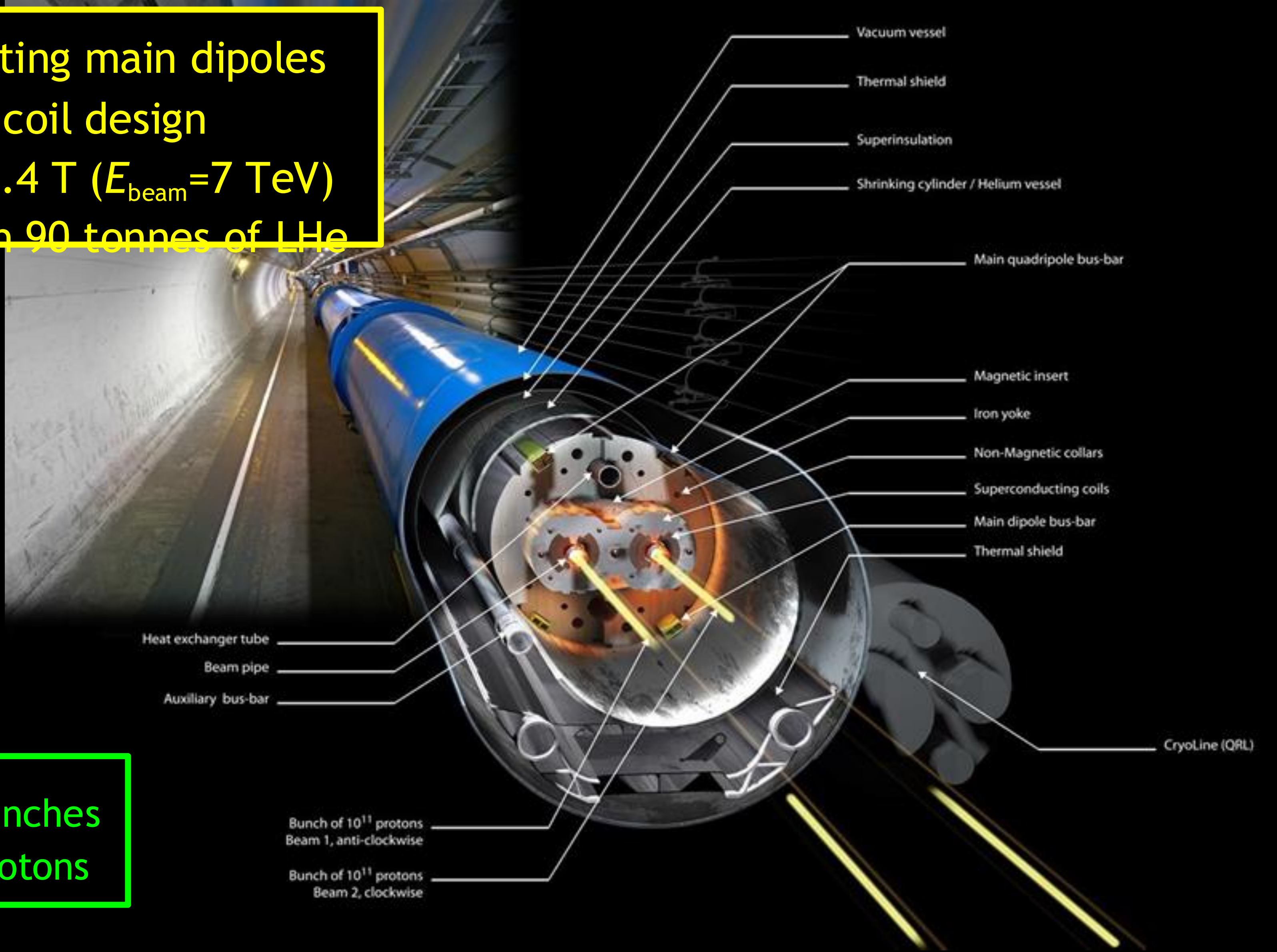
Kétévi A. Assamagan
TRIUMF Canada 06 2025
Brookhaven National Laboratory

Credit: Dave Charlton

The Large Hadron Collider

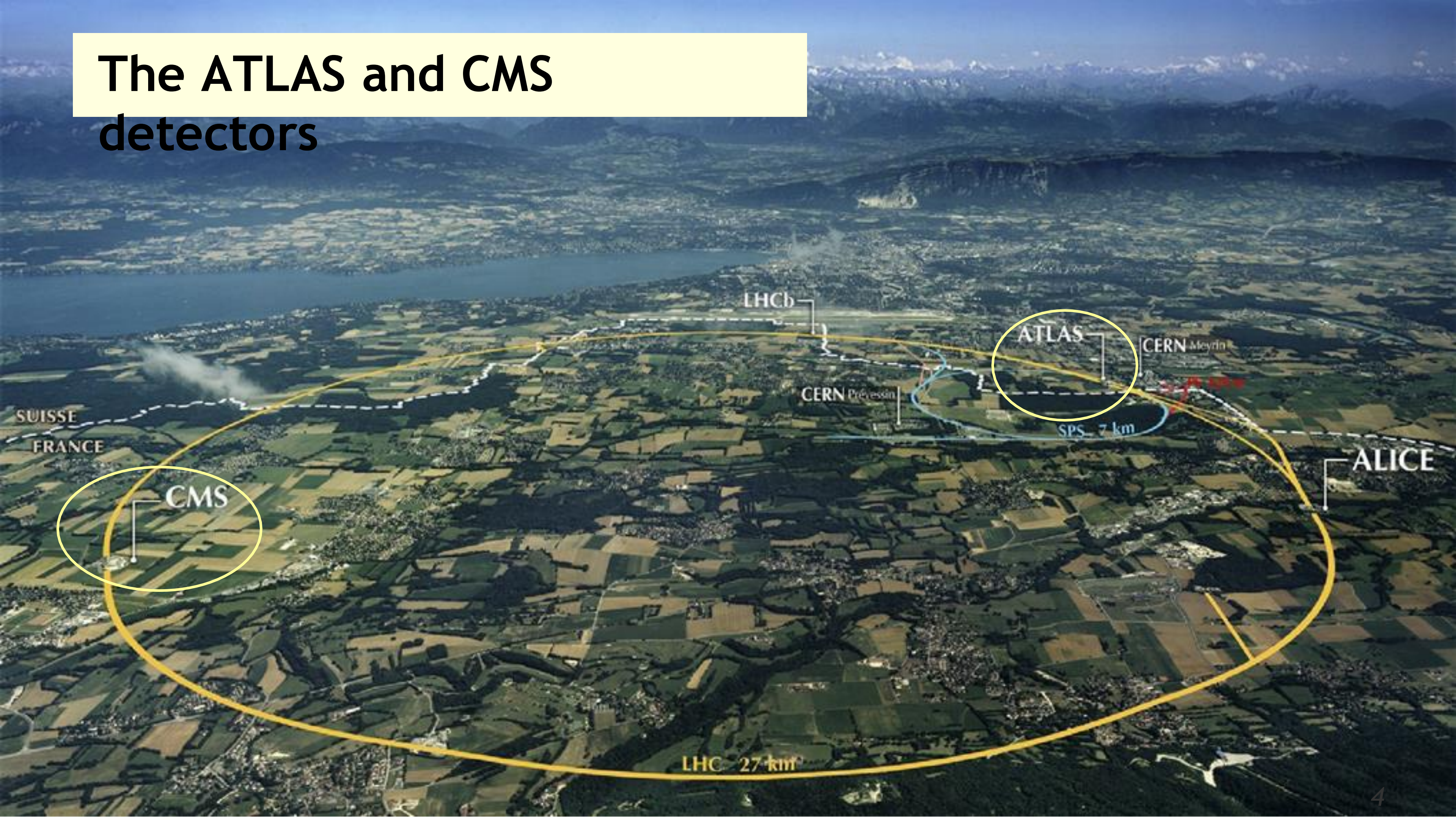


1232 superconducting main dipoles
Two-in-one coil design
Maximum B field 8.4 T (E_{beam}=7 TeV)
Cooled to 1.9K with 90 tonnes of LHe

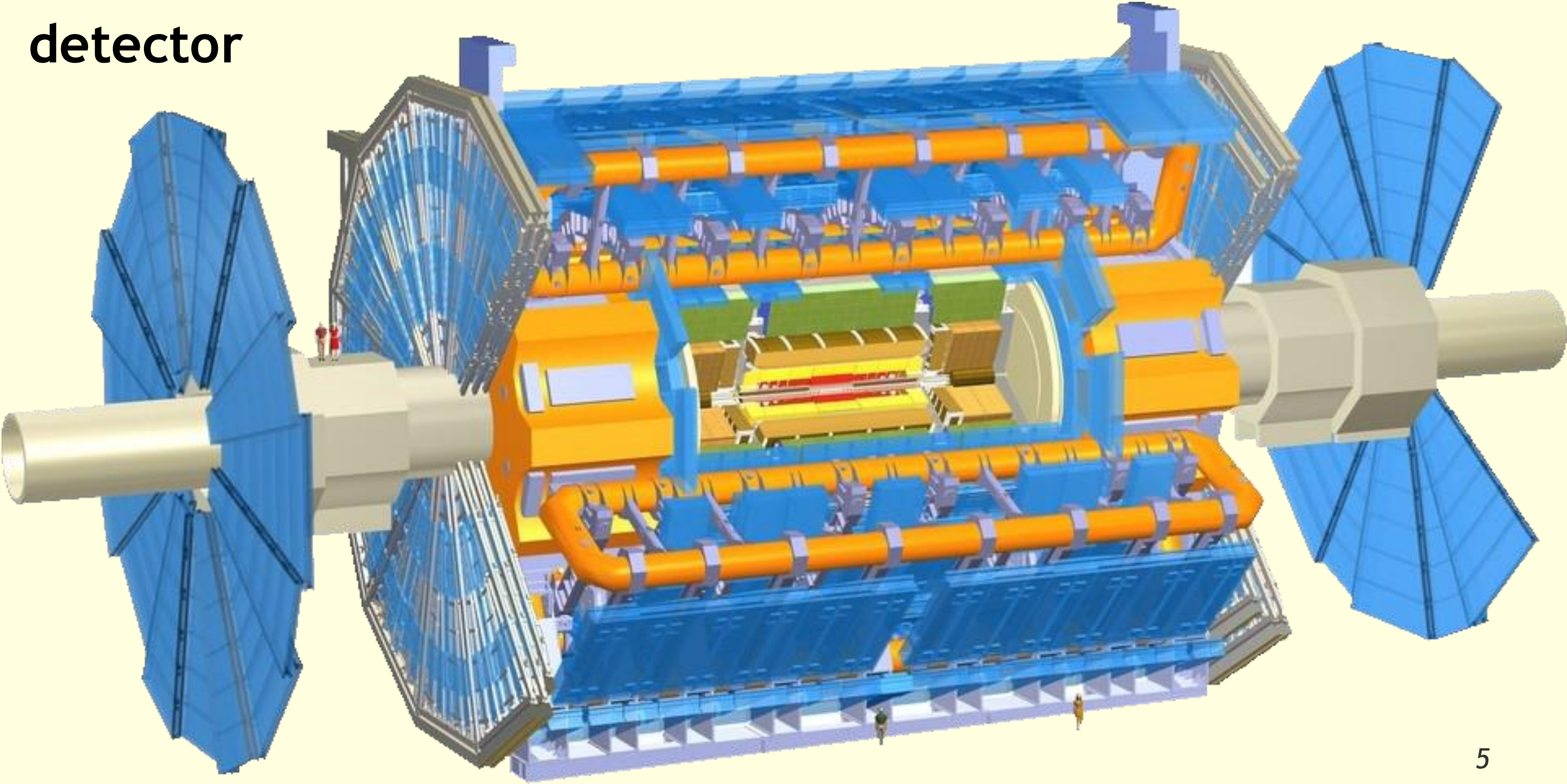


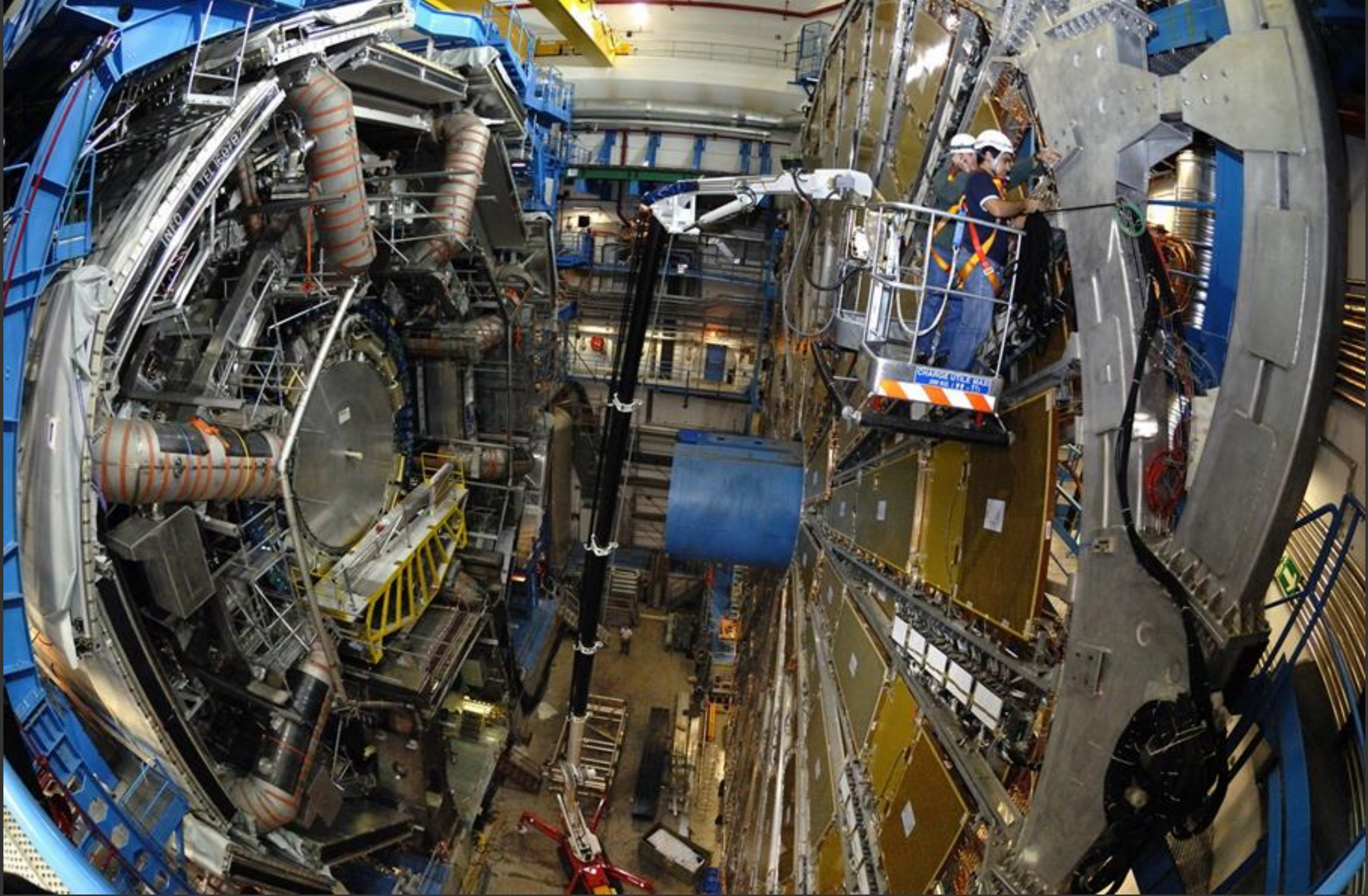
Each beam: 2800 bunches
each holding 10^{11} protons

The ATLAS and CMS detectors



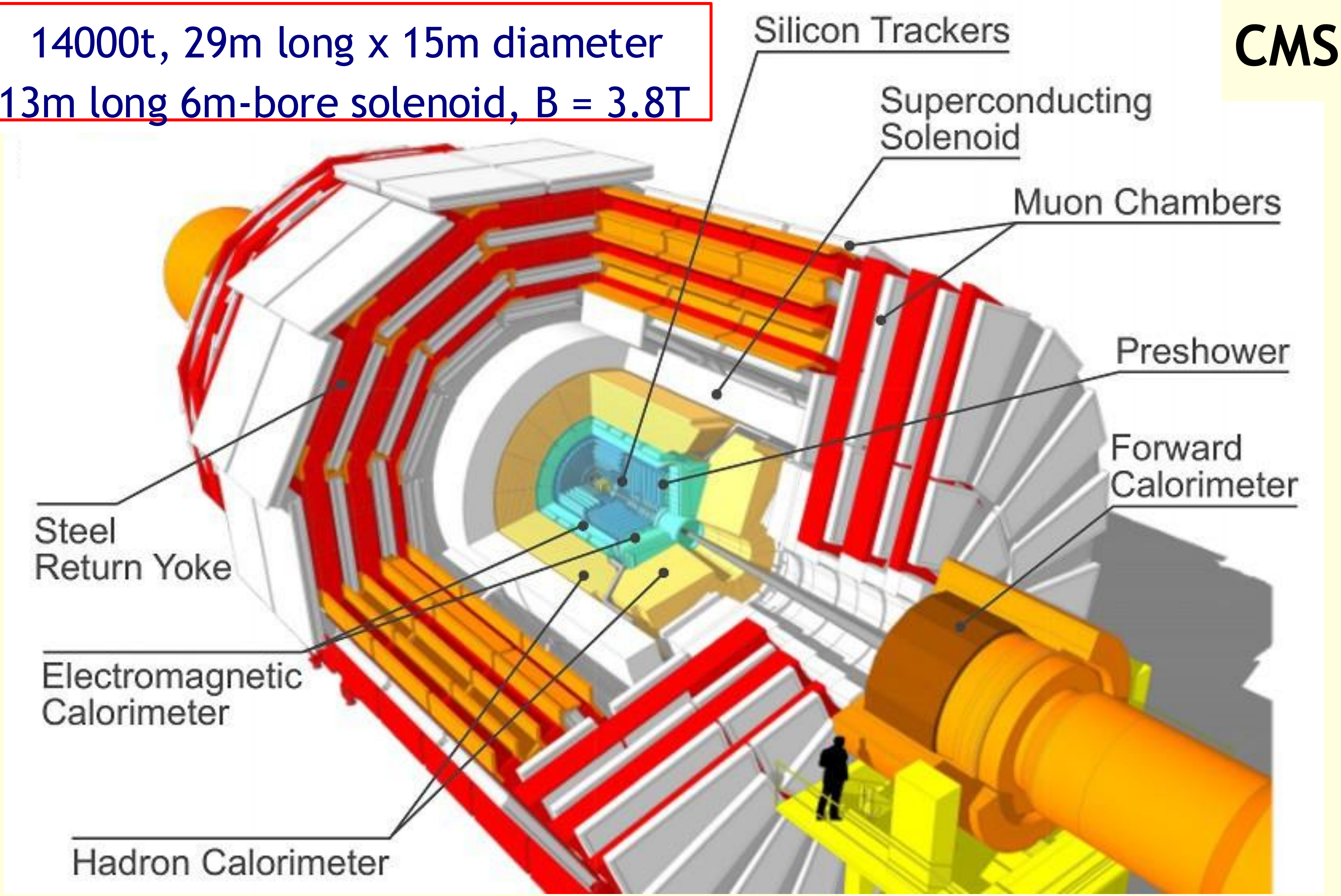
ATLAS detector

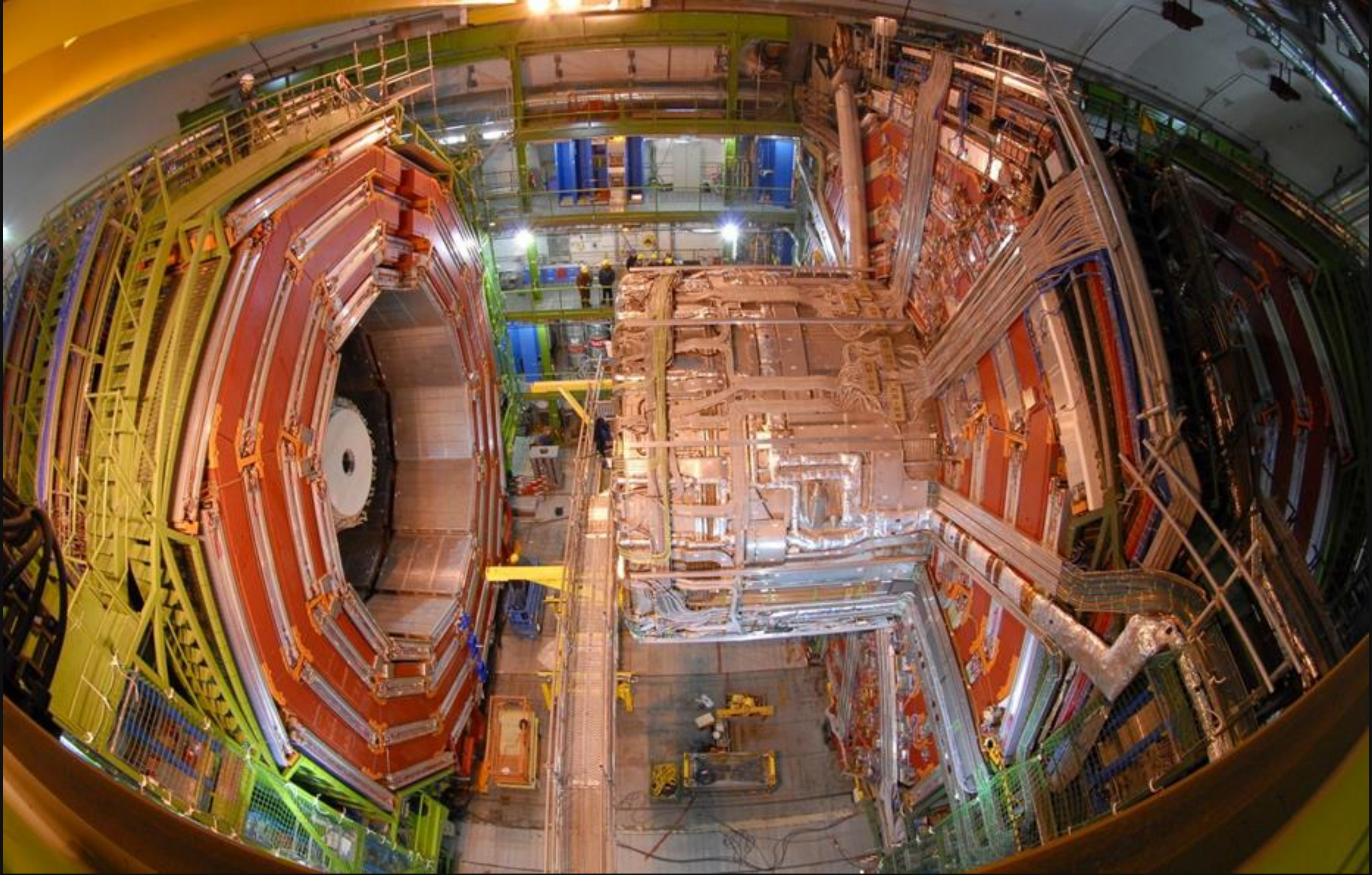




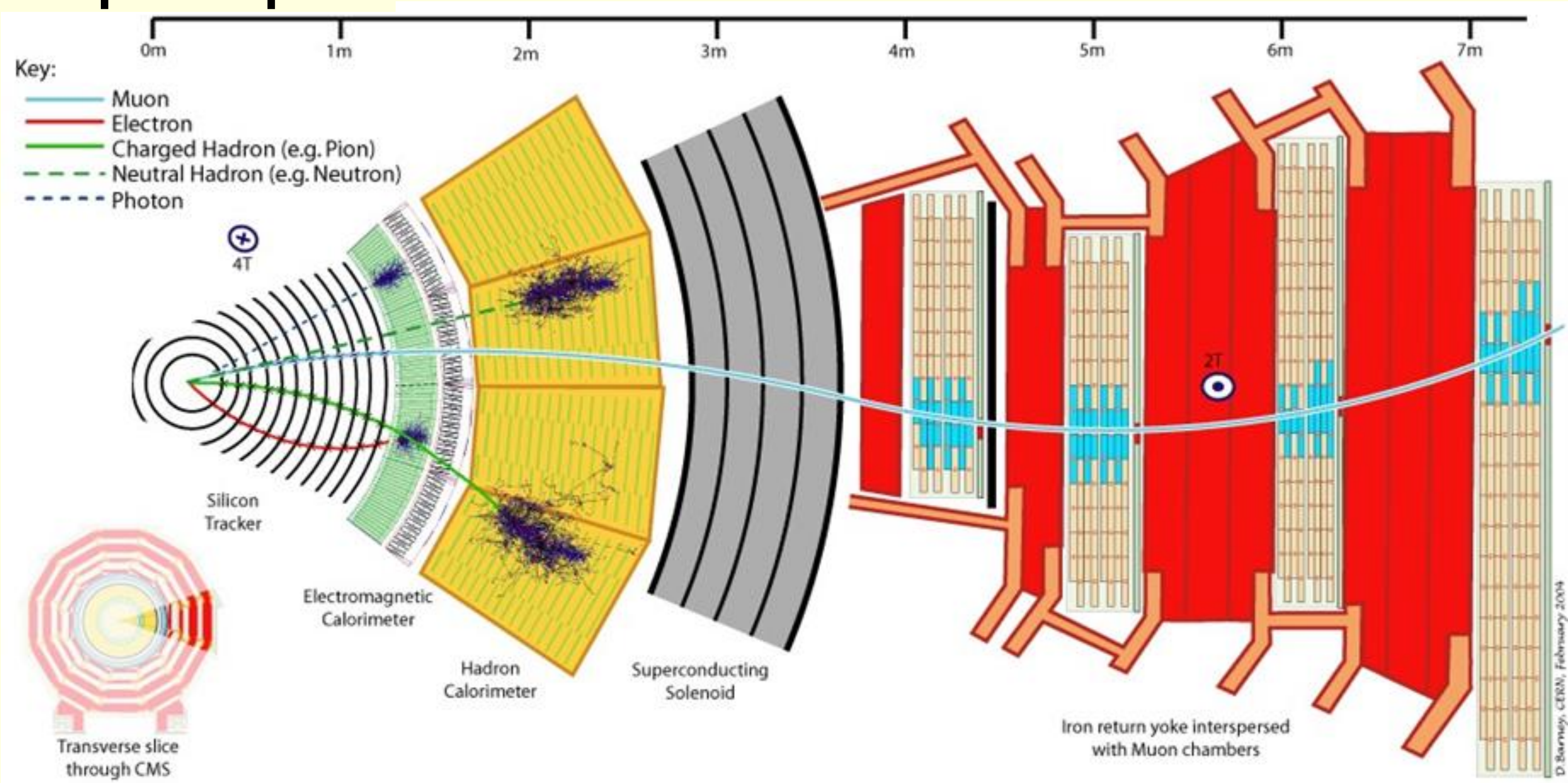
CMS detector

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





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

ATLAS and CMS are wide international collaborations

- Each ~5000 members in ~40 countries

Full *institutional* members from African countries

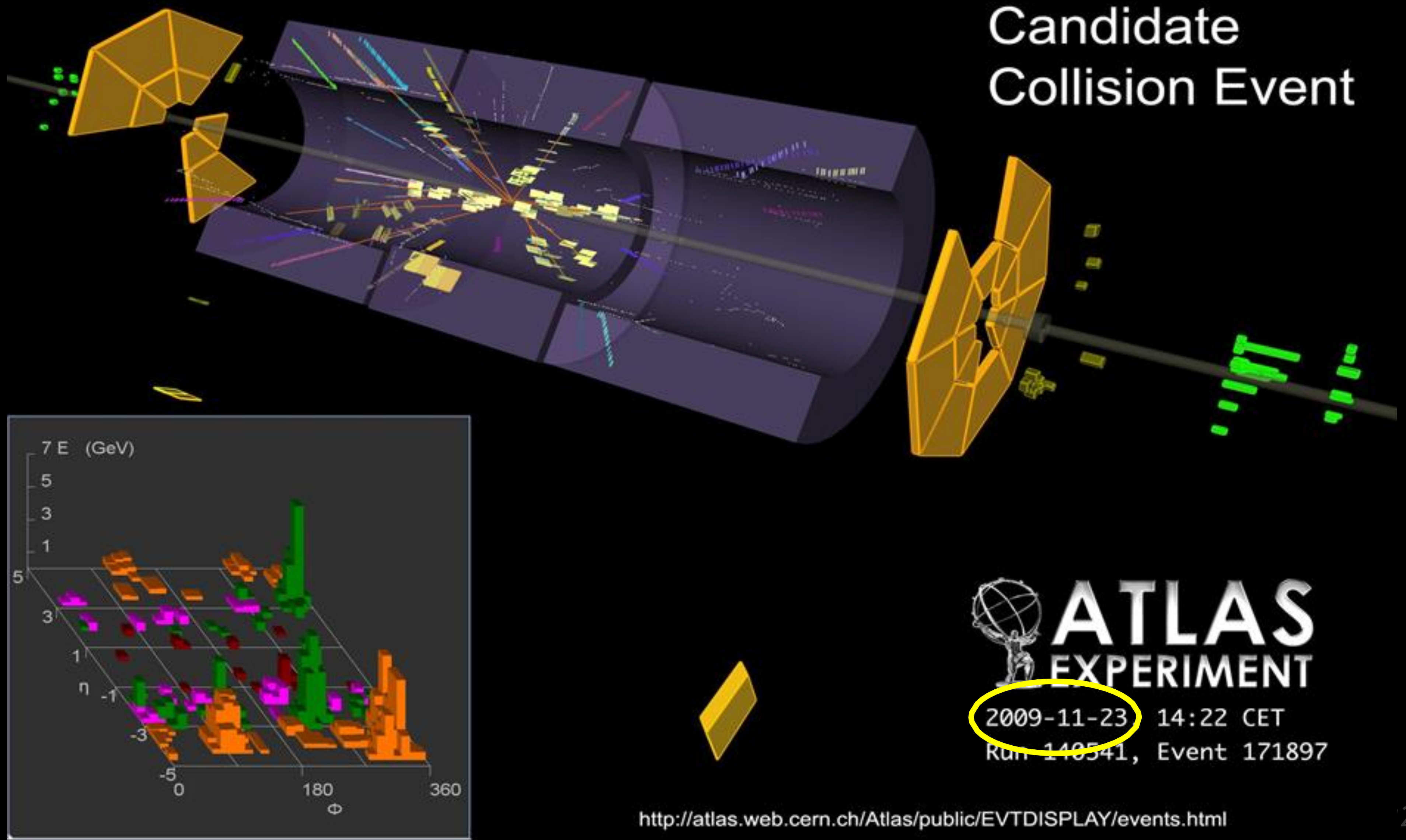
- ❑ Egypt (CMS)
- ❑ Morocco (ATLAS)
- ❑ South Africa (ATLAS, ALICE)
- ❑ Nigeria (CMS)

Individual members of more nationalities, e.g. for ATLAS members from Africa (2022 snapshot)

- Algeria, Botswana, Egypt, Ethiopia, Ghana, Kenya, Madagascar, Malawi, Mauritania, Morocco, Rwanda, Senegal, South Africa, Sudan, Uganda, Zambia, Zimbabwe

10 Sep 2008 “Big Bang Day”

Candidate Collision Event



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

LHC physics with ATLAS and CMS

Very broadly, divide the ATLAS/CMS proton-proton programme into

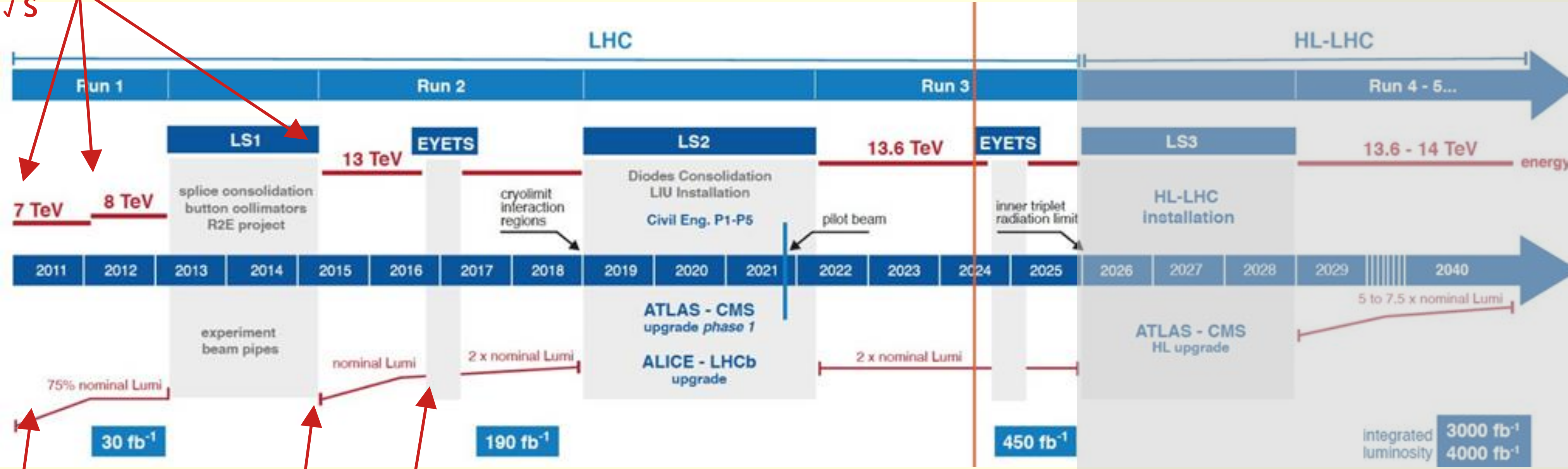
- Measurements (Part II)
  - Make precise measurements of previously known processes in the new LHC energy regime
    - Masses, angular distributions, decay modes, momentum spectra ... ...
  - Test parts of SM not tested before – e.g. massive electroweak boson self-interactions
  - *Now* includes the measurements in the Higgs (scalar) sector
- Searching beyond (Part III)
  - Hunt for new physics beyond the Standard Model
    - LHC advantages: high energy, high intensity (integrated luminosity)
    - High energy -> many heavy objects (H, t, W/Z) – look for new physics coupling to these
  - Prospects in the HL-LHC era

Lecture 3 will also briefly touch on physics at future colliders, beyond the LHC

I generally show ATLAS results to illustrate, because it is easier for me – CMS has equally good and broad results!!!

Long-term LHC schedule

Centre-of-mass energy, √s



Next lecture...

Peak instantaneous luminosity (nominal 10^{34} cm^{-2} s^{-1})

LHC pp data samples

Run-1 (2009-2012)

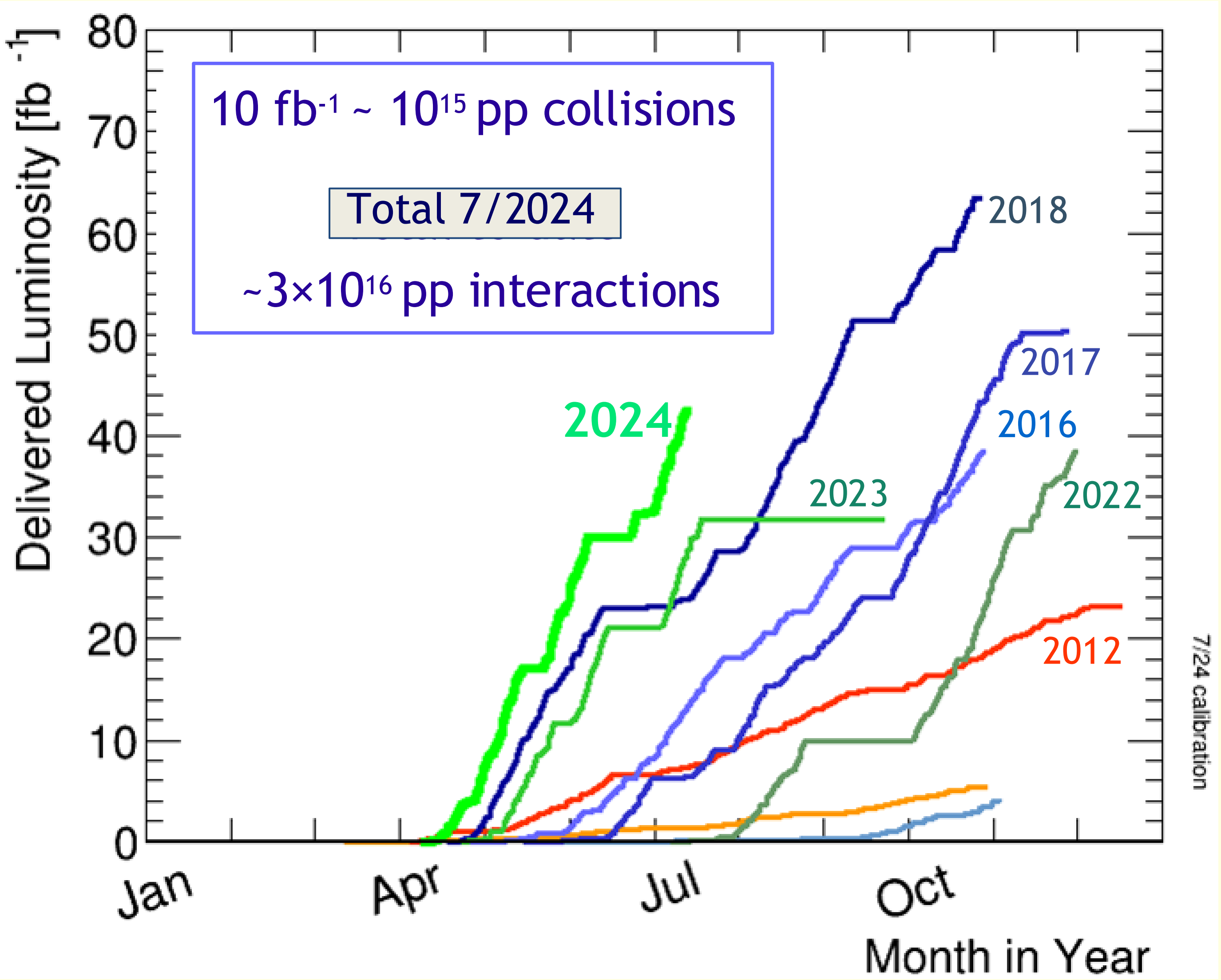
- $\sqrt{s}$ = 7-8 TeV
- ~25 fb^{-1}
- Measurements & searches H discovery!

Run-2 (2015-2018)

- $\sqrt{s}$ = 13 TeV
- ~140 fb^{-1}
- Measurements & searches, many with H

Run-3 (2021-2025)

- Ongoing, ~110 fb^{-1} (7/2024)
- Expect ~400 fb^{-1} Run-2+3
- 3× Run-2 alone



LHC physics landscape

Cross-sections to produce massive particles such as the W, Z, t, (b,) H rise with √s

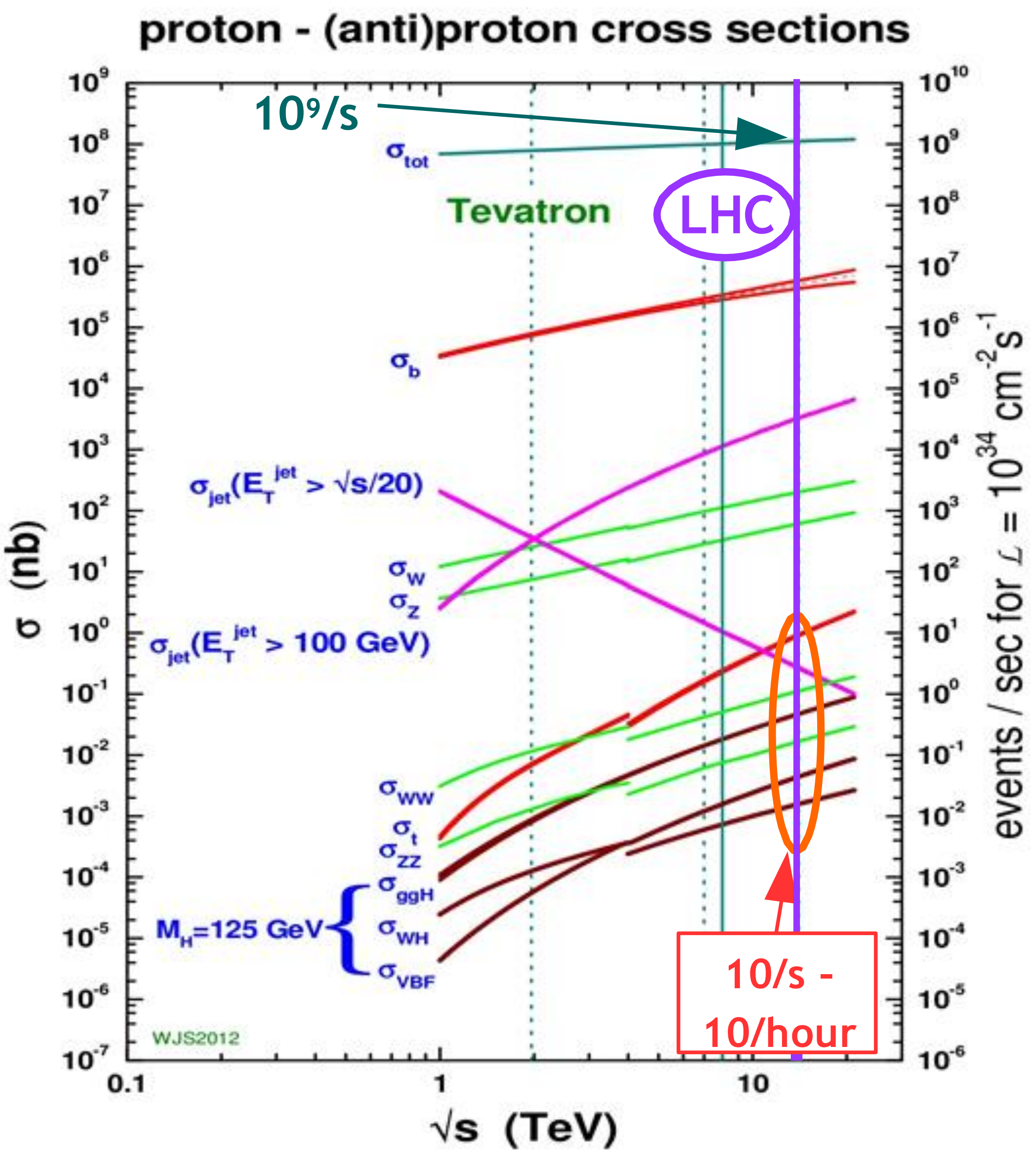
Range of cross-sections for processes studied, and so of their rates, from ~0.1 b to ~fb i.e. factor $O(10^{14})$

~2×10^9 events per second occur in at most 30M bunch crossings / second

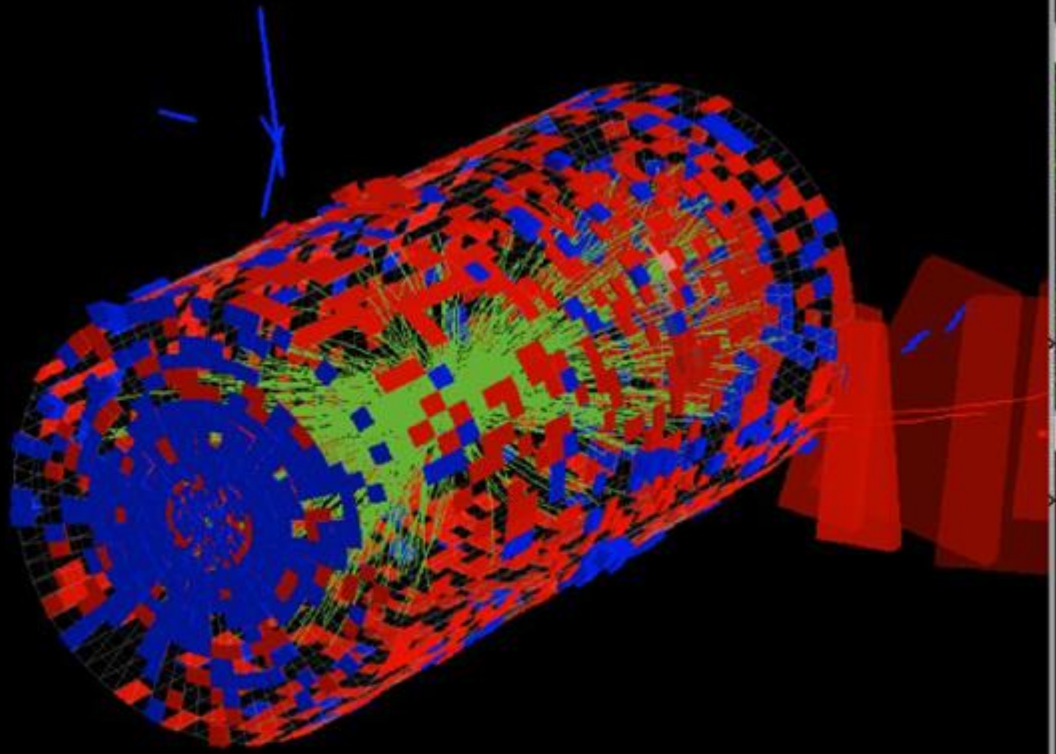
→ 60+ events per bunch crossing

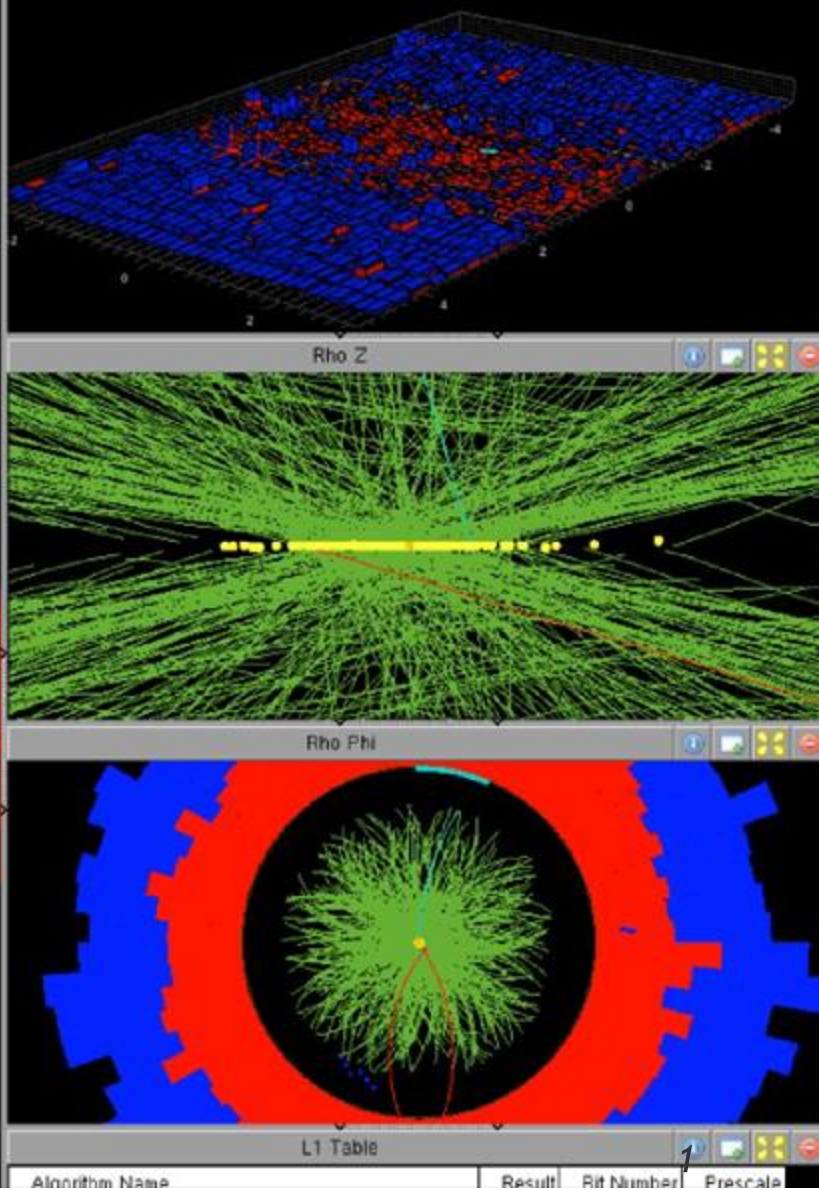
→ “pileup”

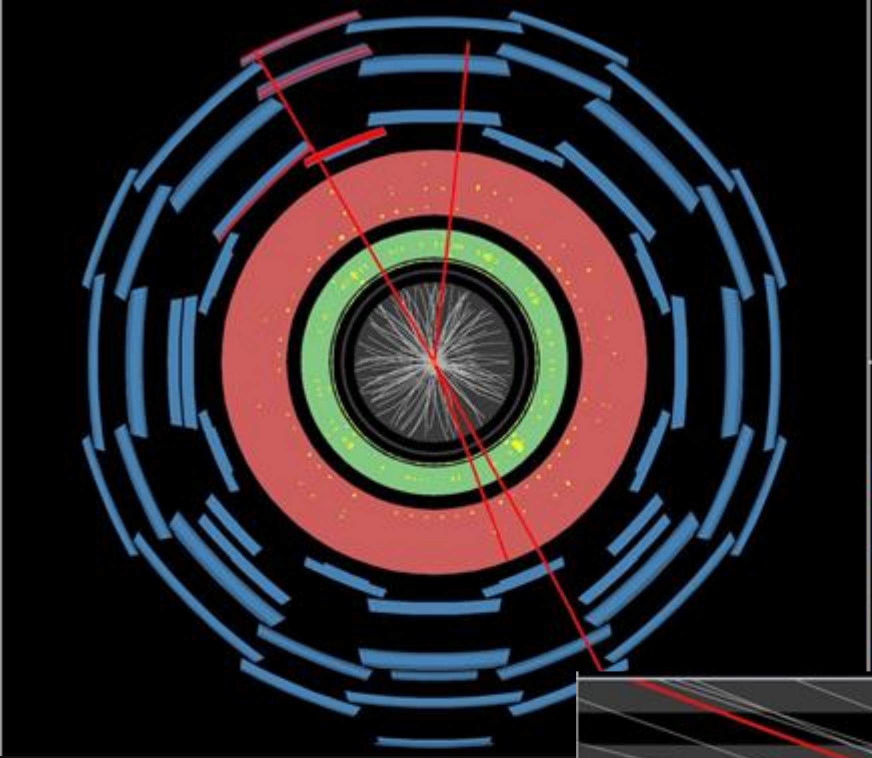
Big challenge for triggering too – only write ~1 kHz of the 30 MHz collision rate to storage

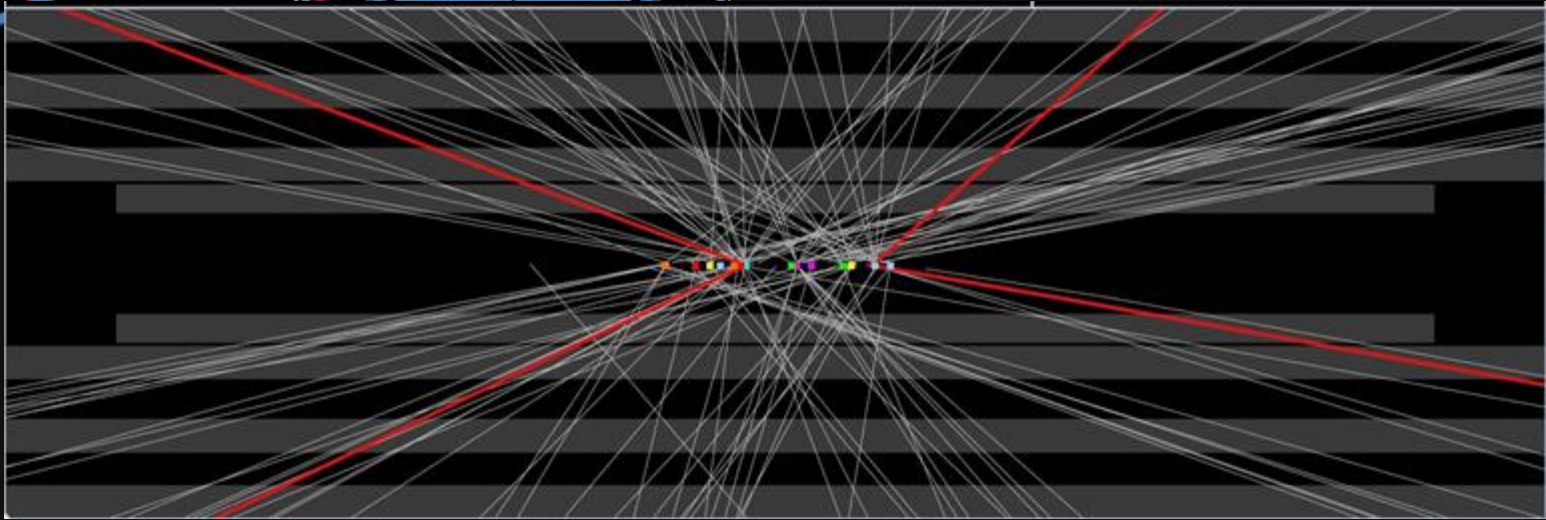


CMS event with 78 reconstructed
pileup interactions



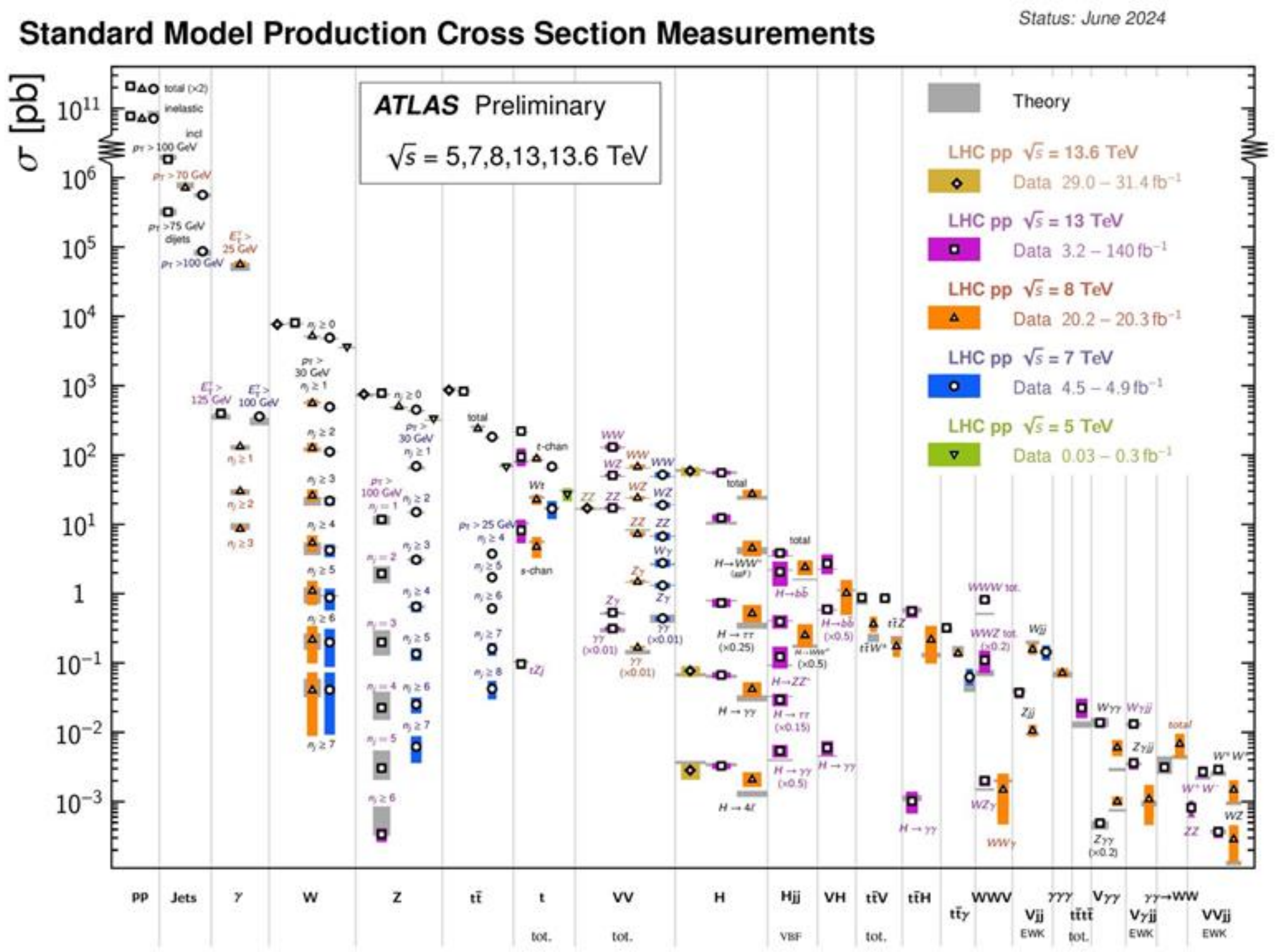






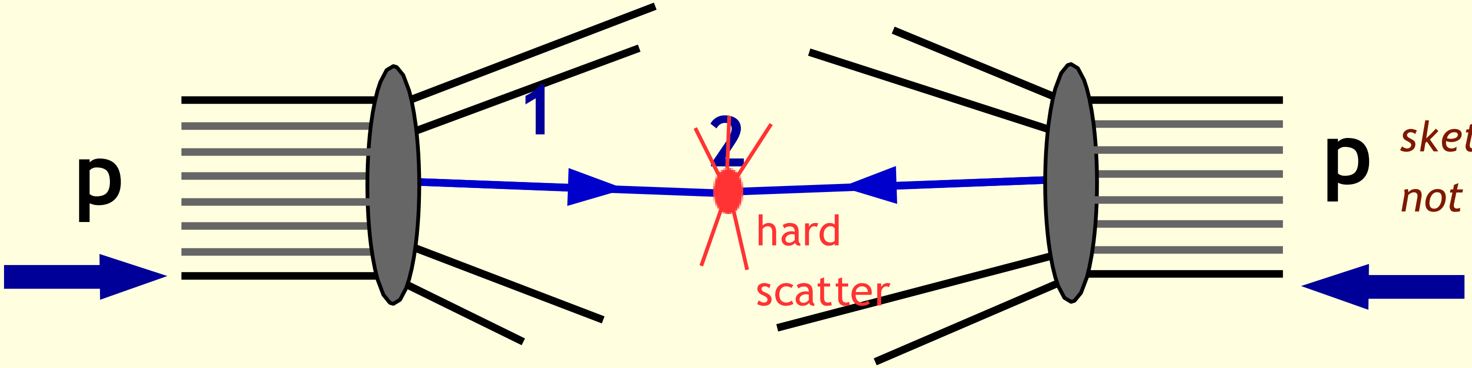
ATLAS event with two Z boson decays from different pp interactions in the same bunch crossing (very rare!)

Measured cross-sections



Predicting cross-sections

Although we collide protons in the experiments, at high energy we are really looking at high energy *parton-parton* collisions
(parton = quark or gluon)



NB this is a conceptual sketch in the detector frame, not a Feynman diagram!

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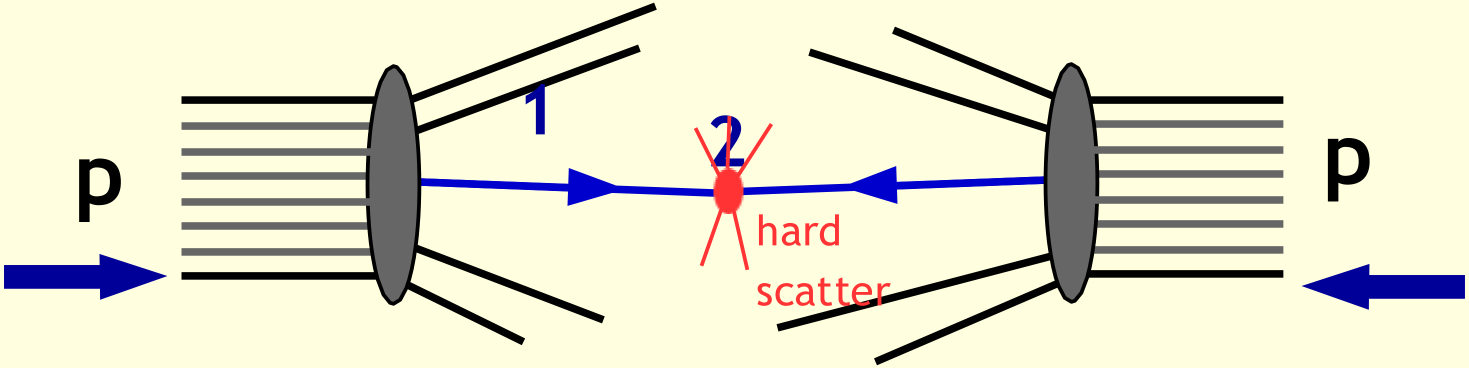


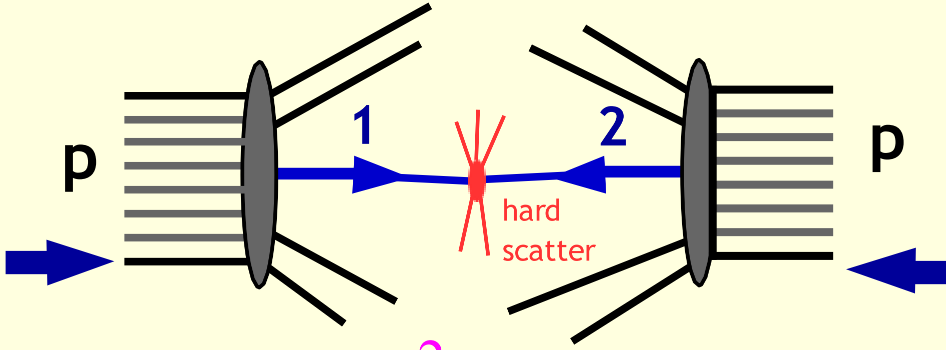
NB this is a conceptual sketch in the detector frame, not a Feynman diagram!

Partons 1 and 2 which collide in the *hard-scattering process* carry fractions x_1 and x_2 of the momentum of their original protons

Reduced ("effective") centre-of-mass energy of the colliding partons is given by:
$\sqrt{s_{12}} = \sqrt{(x_1 x_2 s)}$

Predicting cross-sections (2)

To *predict* the cross-section for a given process, must know cross-section as a function of $\sqrt{s_{12}}$, and the parton density functions (pdfs) f; then we have:



$$\sigma = \iint \hat{\sigma}(s_{12})\, f_1(x_1, Q^2)\, f_2(x_2, Q^2)\, dx_1\, dx_2$$

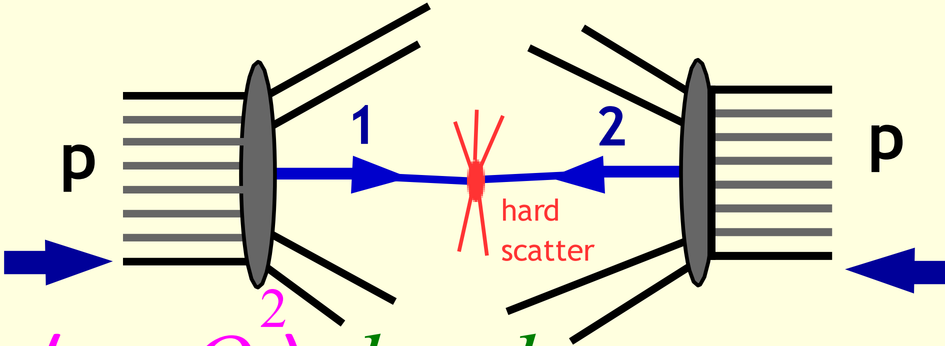
We measure this, and compare with the prediction

Theorists calculate this using Feynman diagrams and quantum field theory

We measure the pdfs at different experiments, and re- use them here

Predicting cross-sections (3)

To *predict* the cross-section for a given process, must know cross-section as a function of $\sqrt{s_{12}}$, and the parton density functions (pdfs) f; then we have:



$$\sigma = \iint \hat{\sigma}(s_{12}) f_1(x_1, Q^2) f_2(x_2, Q^2)\, dx_1\, dx_2$$

We measure the *total cross-section* σ, or more usually a *fiducial cross-section* σ^{fid}, which is the part of the total cross-section with the final-state particles from the hard-scattering process going into well-defined regions of phase-space (angle, momentum), measurable in the detector

We also measure *differential cross-sections*, which are typically a more finely divided (binned) set of fiducial cross-sections, e.g. we may measure

$d\sigma/dp_T$ or $d\sigma/d\eta$ or $\sigma(N_{jet})$

for a specified final-state particle or jet

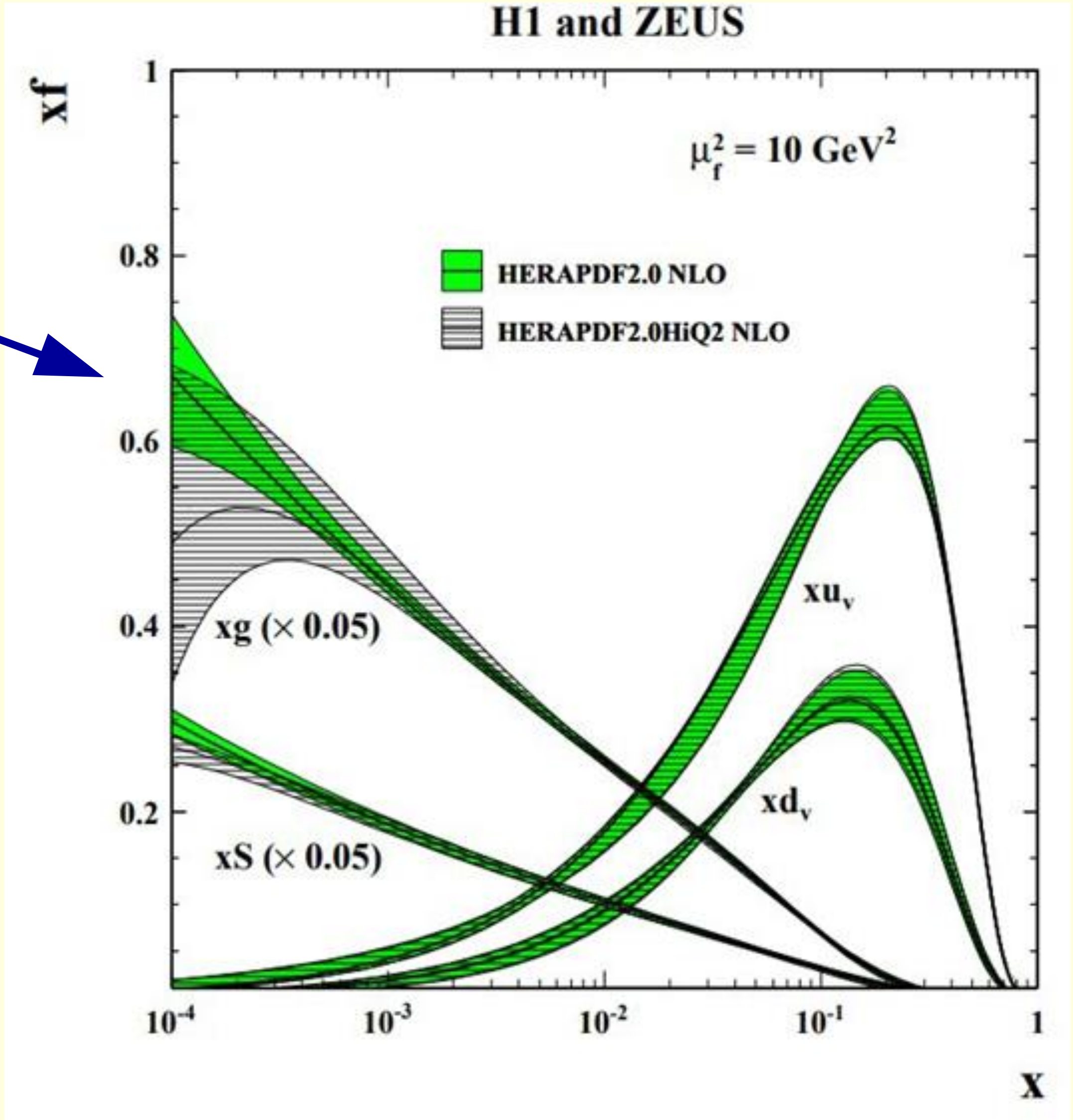
Parton density functions

Typical parton density functions

Measured in previous experiments (HERA, Tevatron colliders ...), and we update and refine them using LHC data

I've been ignoring Q^2 ($\sim\mu_{f\,2}$ on the plot)

so far – this is important, it characterises the momentum-scale (squared) of the hard scattering process



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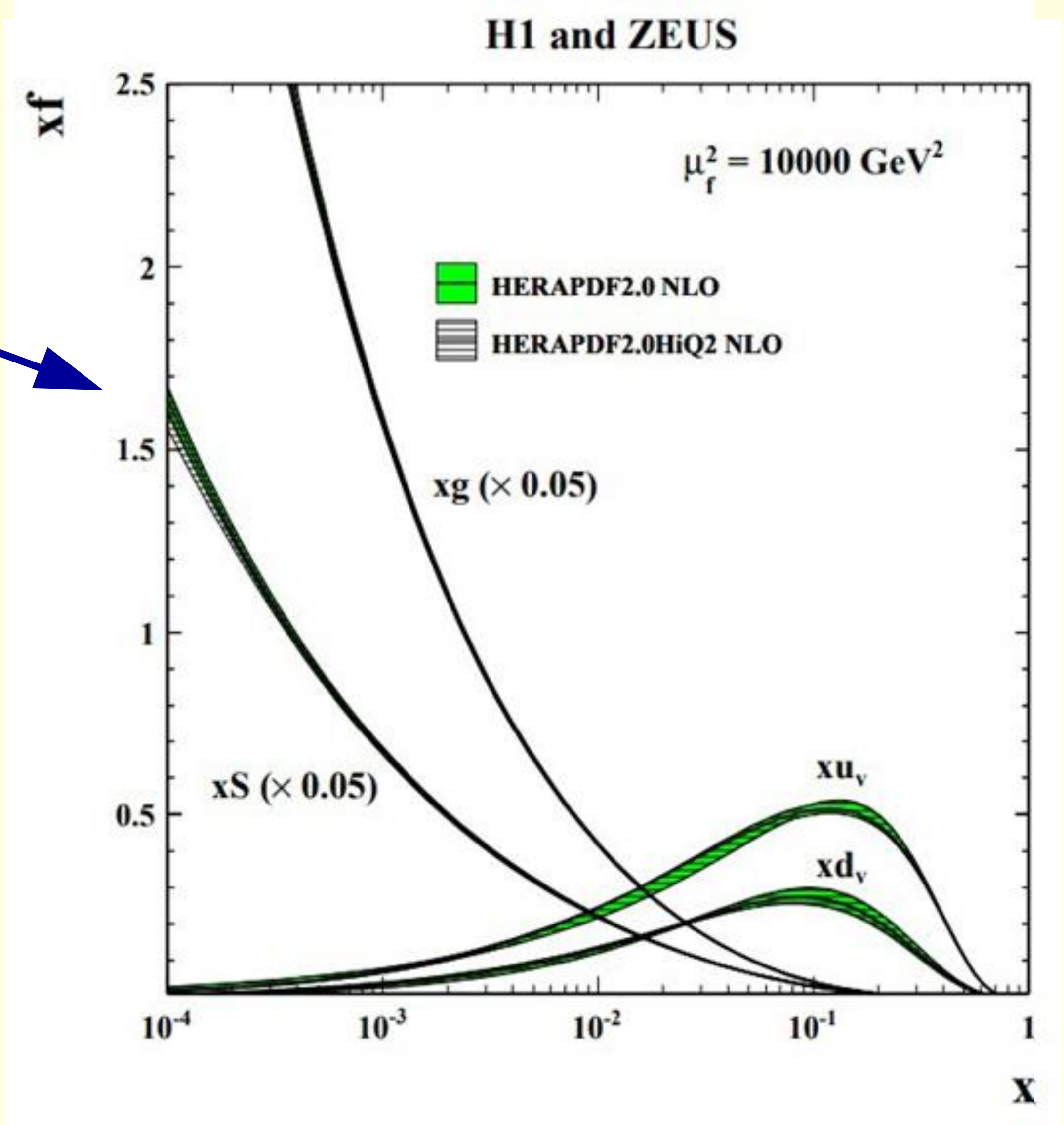
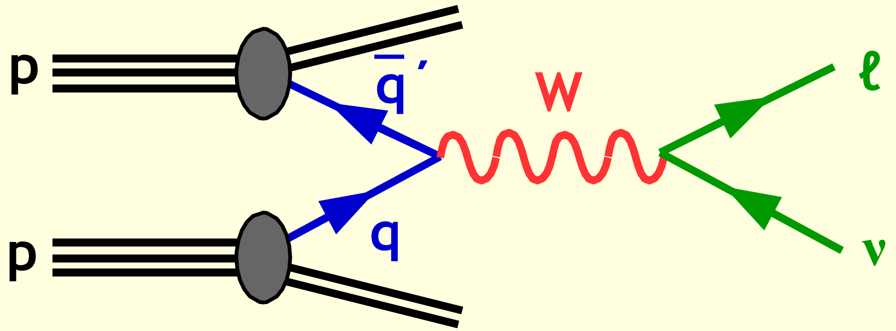
pdfs *evolve* with Q^2, but in a predictable way ("DGLAP")



Measurements of W and Z bosons

Clean experimental signatures and large cross-sections

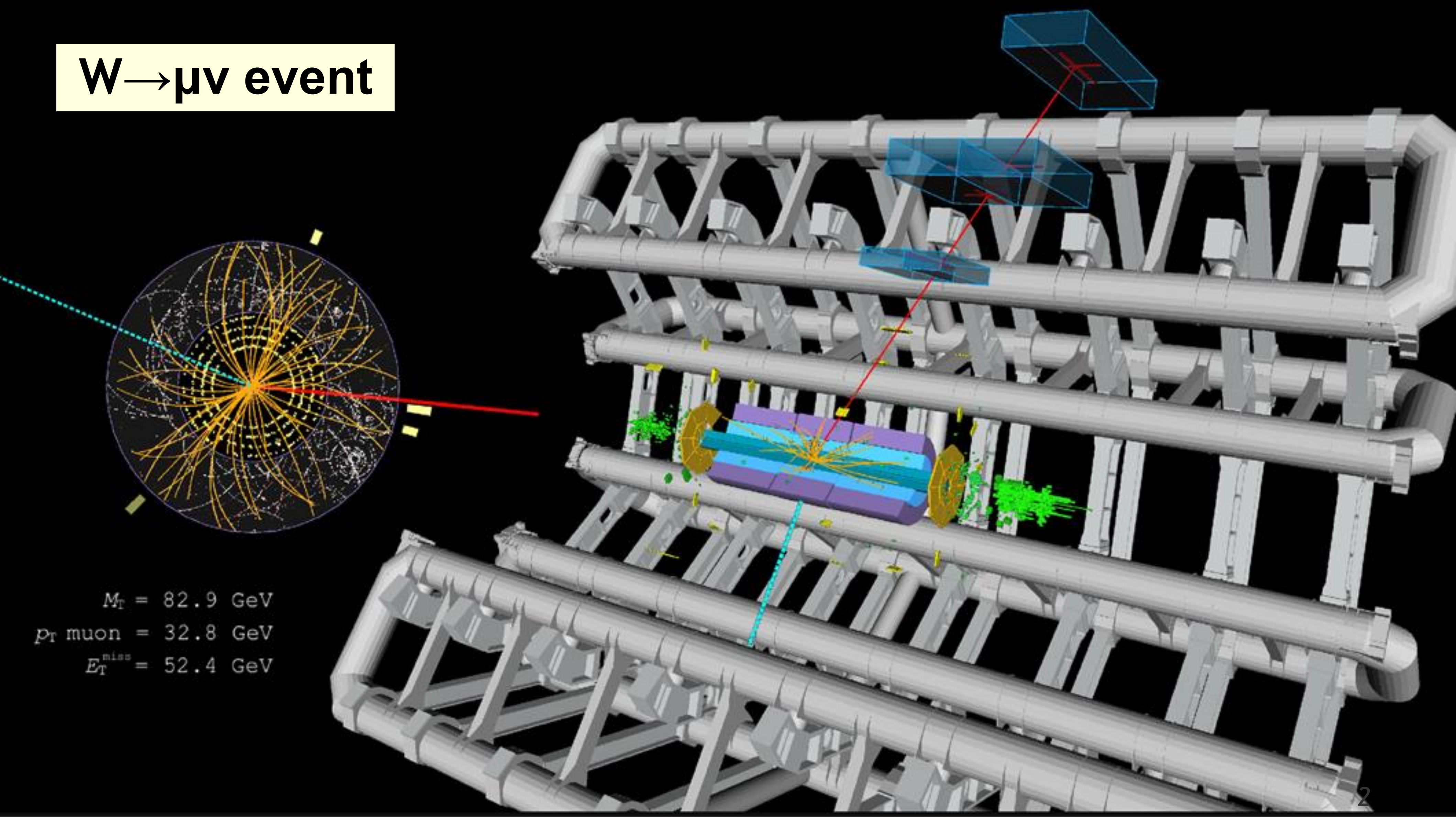
- High precision measurements
- Strong constraints on proton structure
- Tests of consistency of electroweak (EW) sector of SM



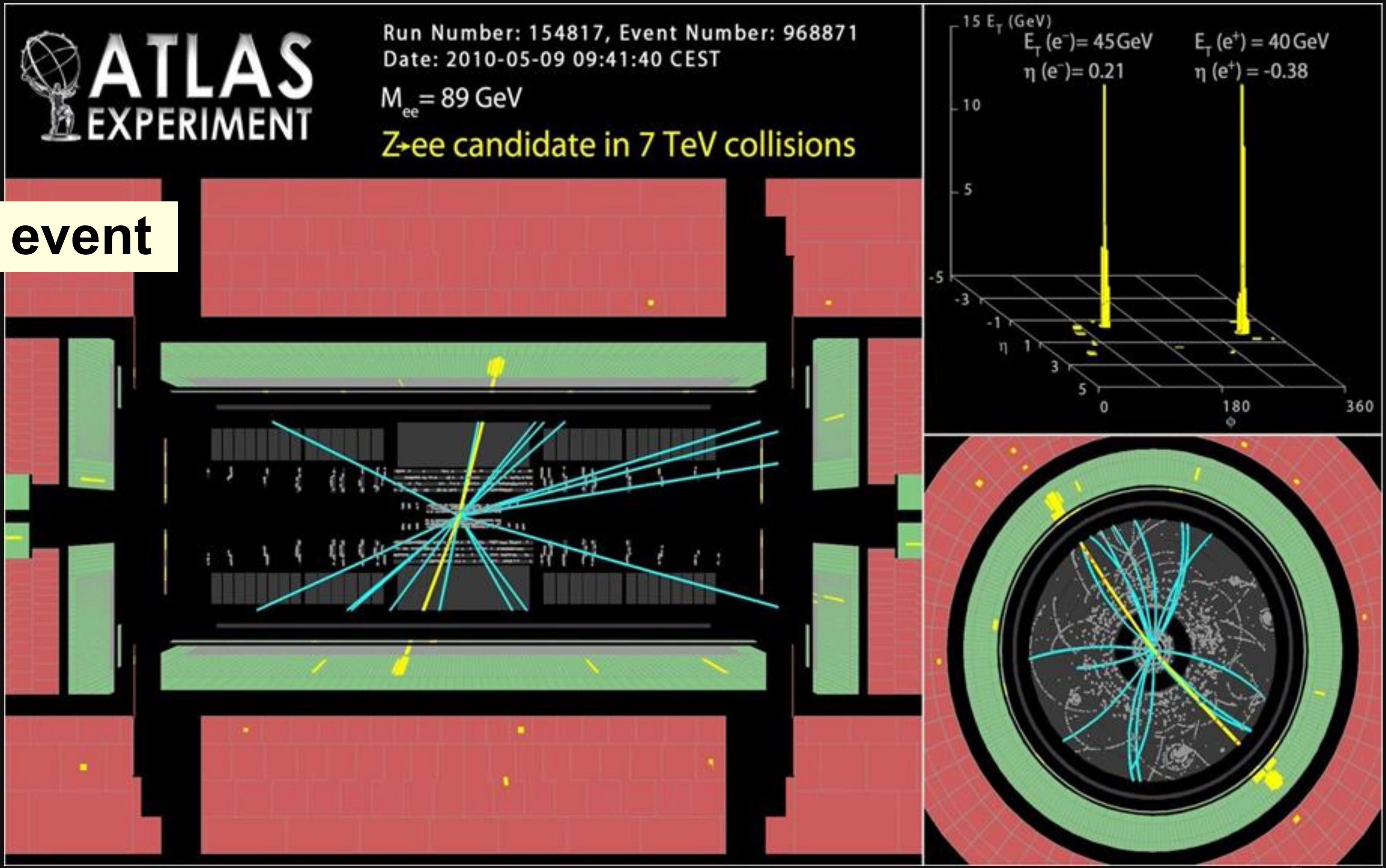
The diagram shown is for lowest-order production of a W boson

- In practice, to gain a good description of the data, radiative corrections (higher-order diagrams) must be included in the theory prediction
- Huge effort in the phenomenology community to provide such calculations for this and many other processes – state of the art is now often at next-to-next-to-leading order (NNLO), requires calculation of huge numbers of loop diagrams

W→μν event



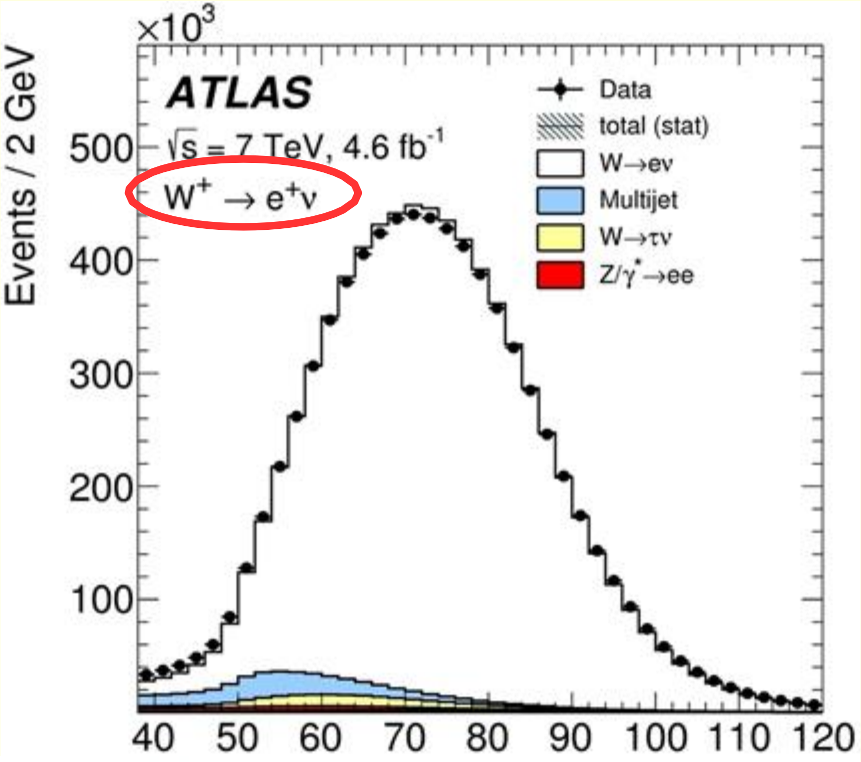
Z→ee event


ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_{ee} = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
$E_T(e^-)$ = 45 GeV
$\eta(e^-)$ = 0.21
$E_T(e^+)$ = 40 GeV
$\eta(e^+)$ = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
ϕ

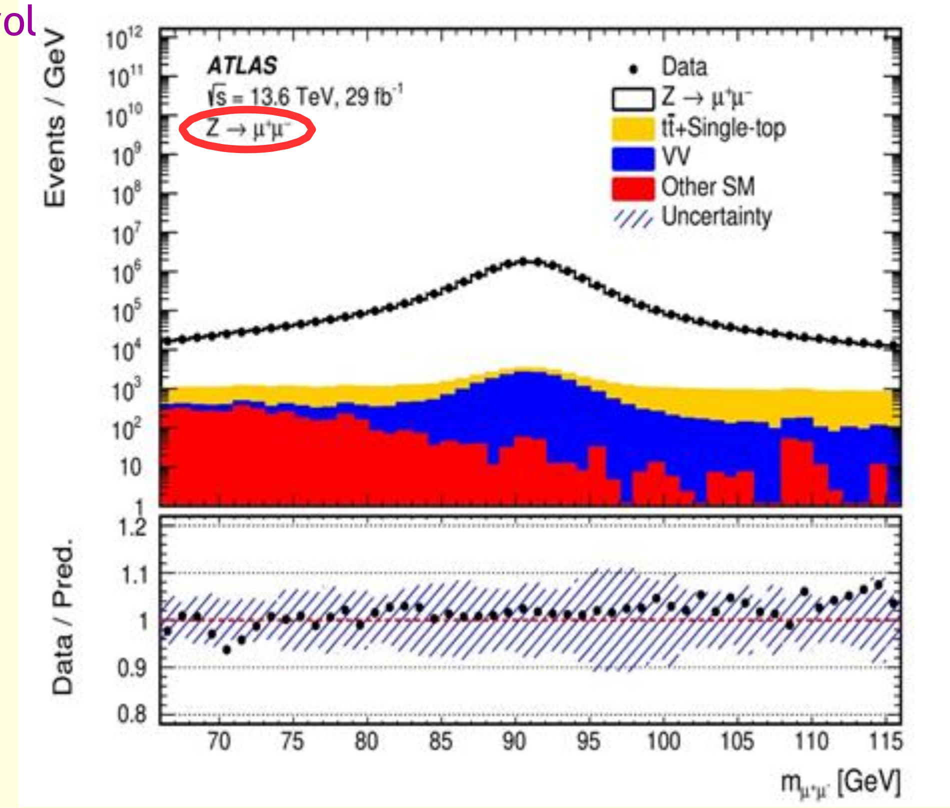
Precise W, Z production measurements

Detailed studies performed at each centre-of-mass energy: W^+, W^-, Z in e, μ decays

High statistics data well described by simulation Small backgrounds, under excellent control



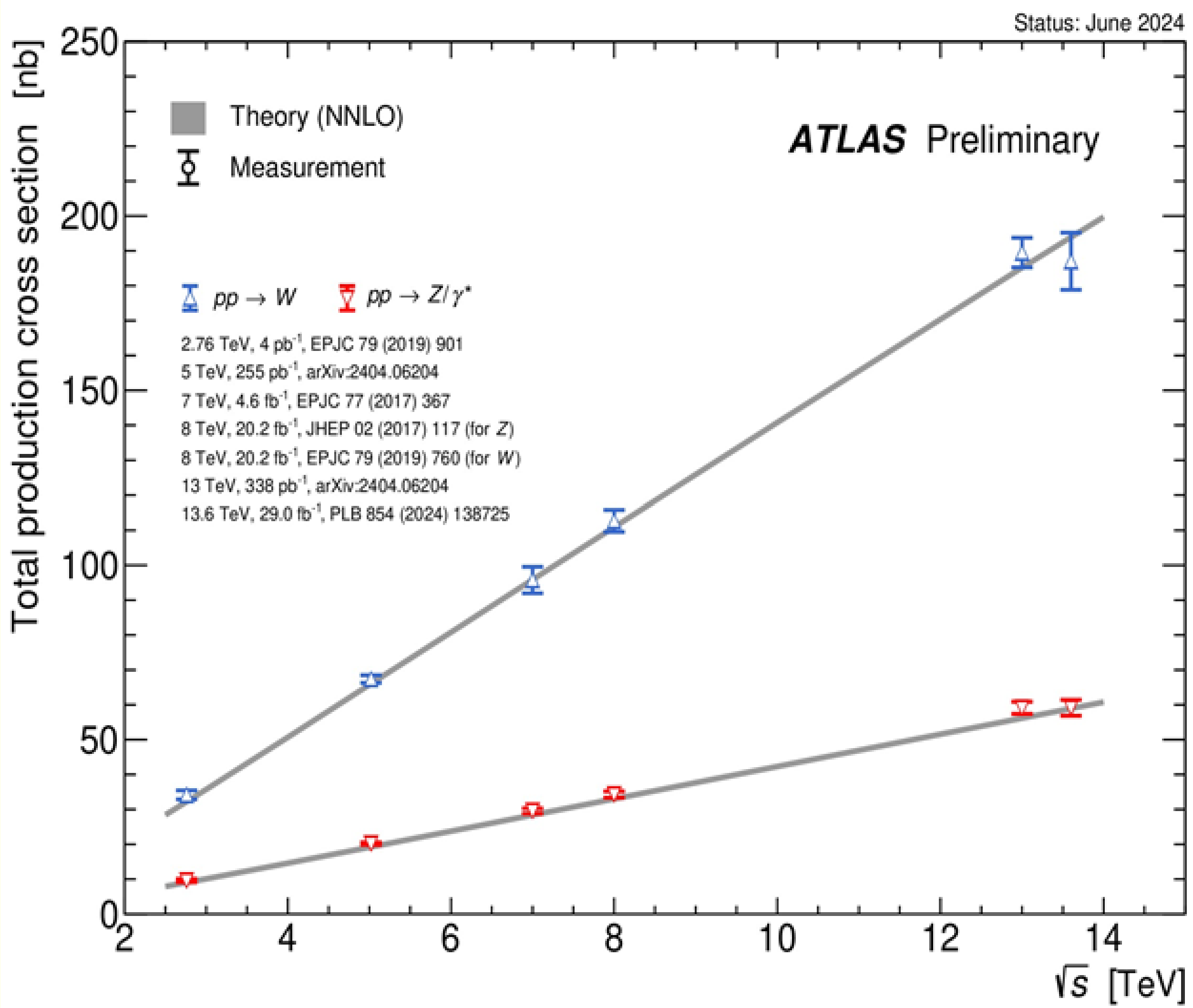
$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)},$$



W and Z total cross-sections

Measurements at various √s value explored at LHC

Measurements very well described by sophisticated modern calculations – *next-to-next-to-leading order (NNLO)* in QCD corrections

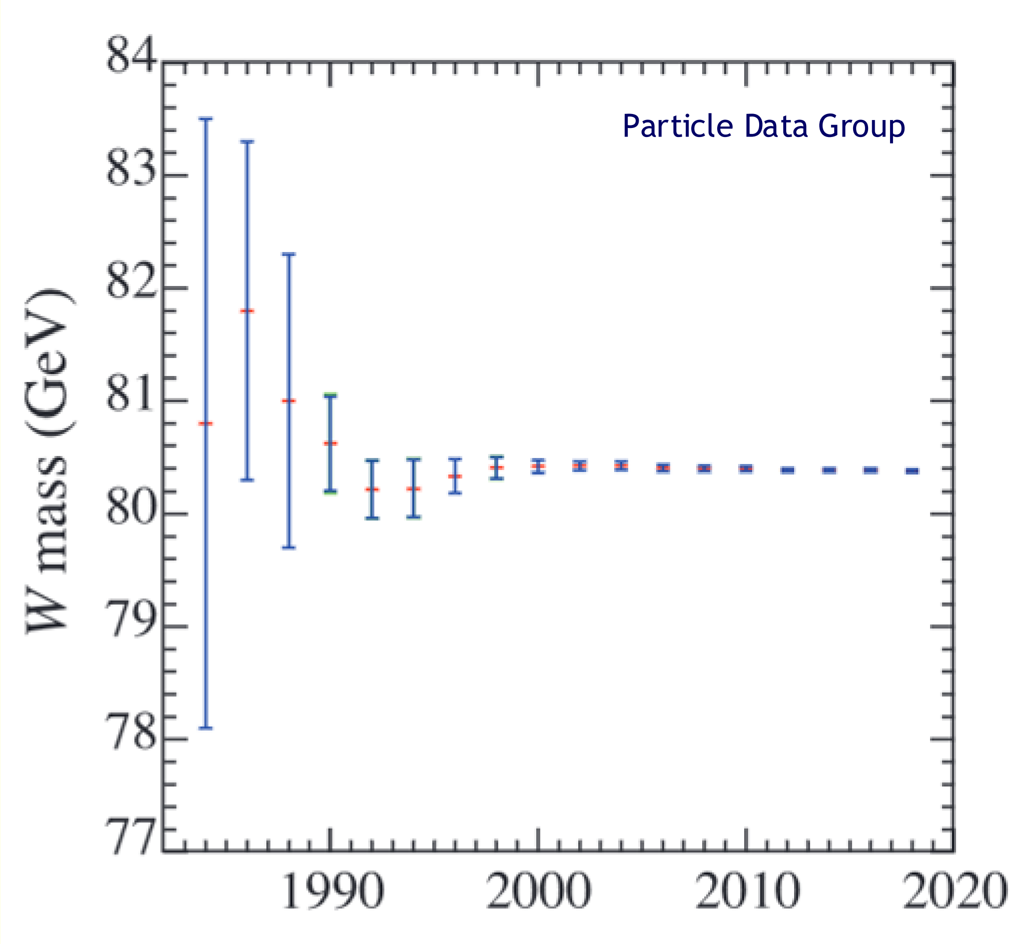


Measuring the W mass

Mass of the W boson is a fundamental parameter of the Standard Model

W mass was first measured directly by UA1 and UA2 back in the 1980's soon after it was discovered at CERN

- History of precision



Measuring the W mass

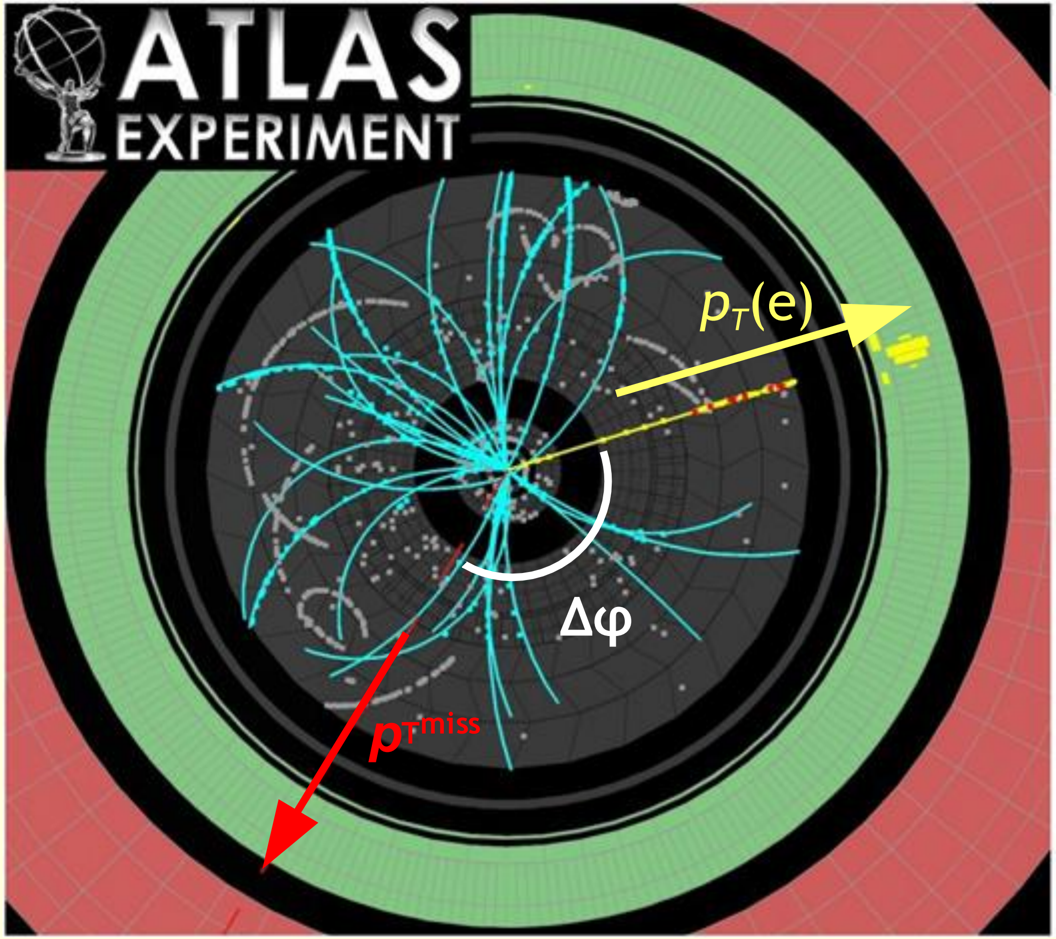
Mass of the W boson is a fundamental parameter of the Standard Model

W mass was first measured directly by UA1 and UA2 back in the 1980's soon after it was discovered at CERN

A standard method uses "transverse mass"

$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)},$$

W→eν event



W mass measurement

ATLAS measurement of m_W uses well-understood lower-pileup 2011 data (7 TeV)

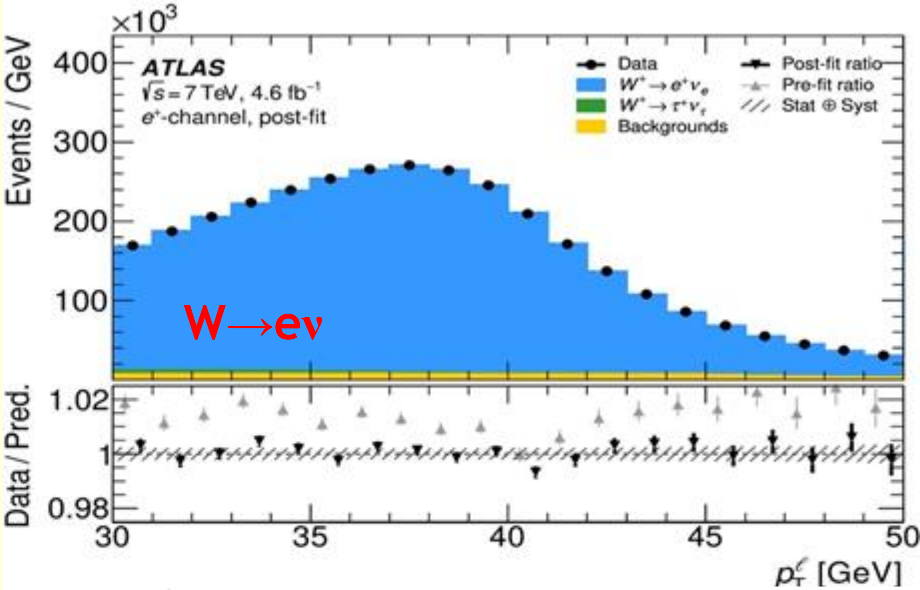
~15M W→ℓν decays

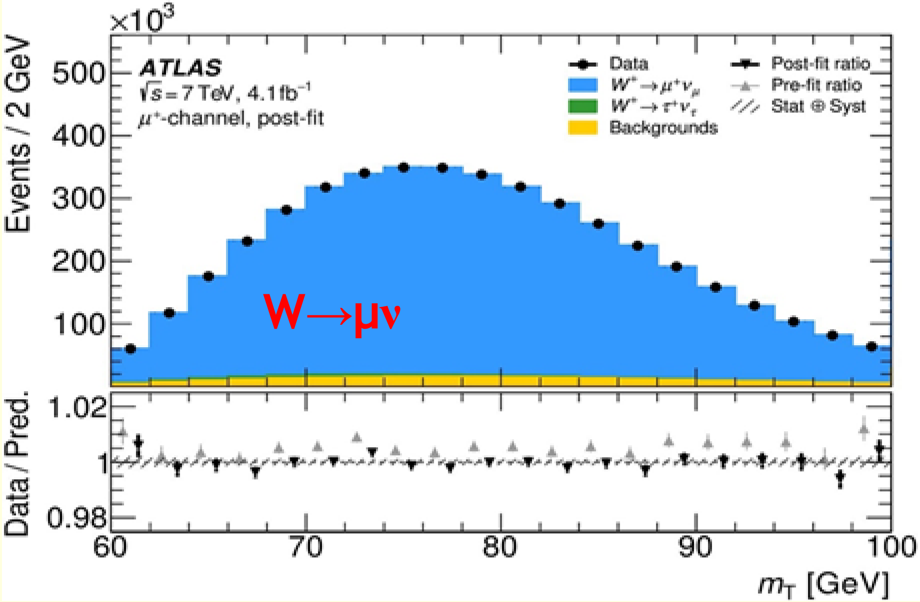
Both the lepton transverse momentum [$p_T(\ell)$] distribution, and the transverse mass [m_T] distributions are used – they are both sensitive to the value of m_W

Important experimental features:

- Lepton calibration using high statistics Z→ℓℓ sample
- Hadronic recoil (→p_T^{miss}) also calibrated against Z→ℓℓ
- LEP Z mass crucial input (2 MeV error)
- Detailed analysis of modelling uncertainties

$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)},$$





W mass results

The ATLAS analysis gives

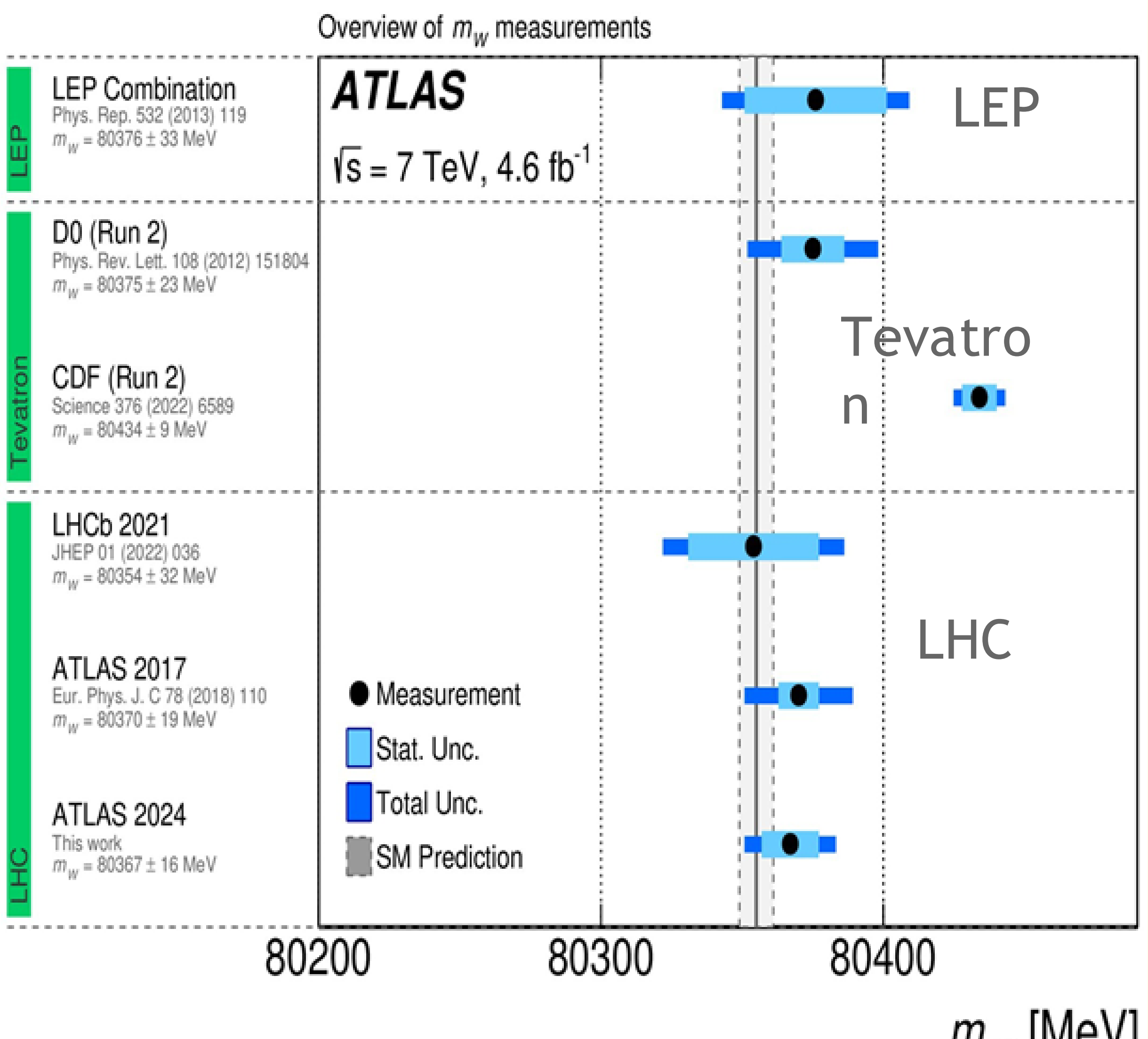
$m_W = 80.367 \pm 0.016$ GeV

However, a recent measurement from CDF (Tevatron) is not very consistent with other measurements, and quotes a very small 9 MeV error

Much work done to try to understand differences, without success

Combining all measurements *except* the one from CDF gives

$m_W = 80.369 \pm 0.013$ GeV

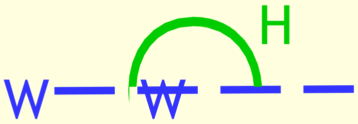


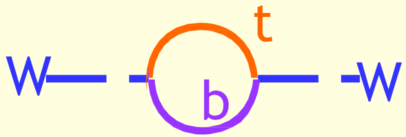
arXiv:2308.09417

Electroweak precision test in the LHC era

Within the SM framework, m_W is related to other quantities via:

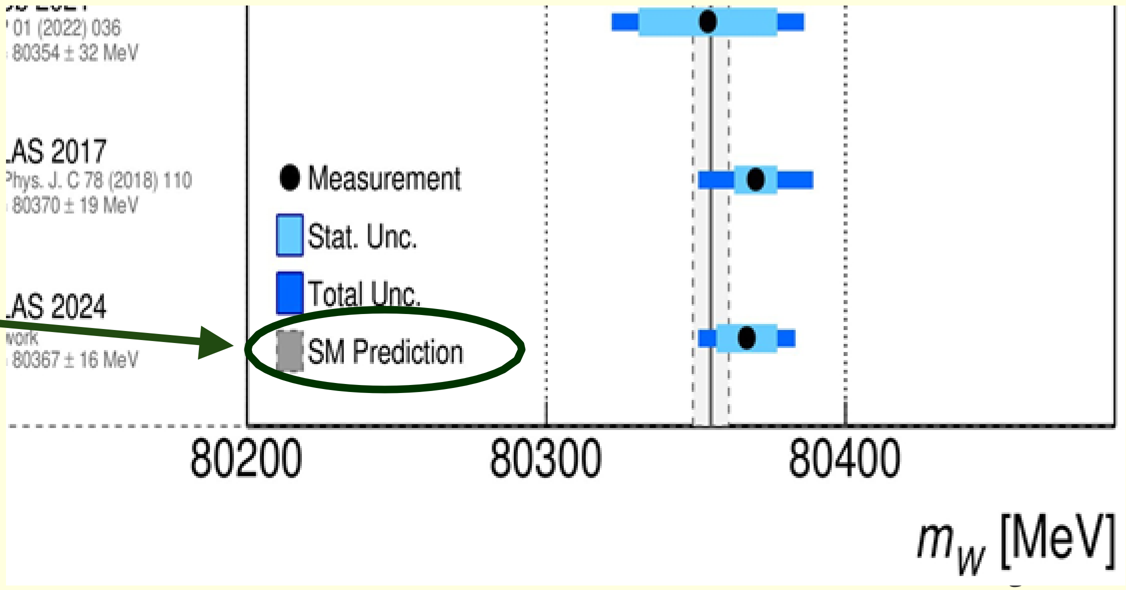
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r),$$



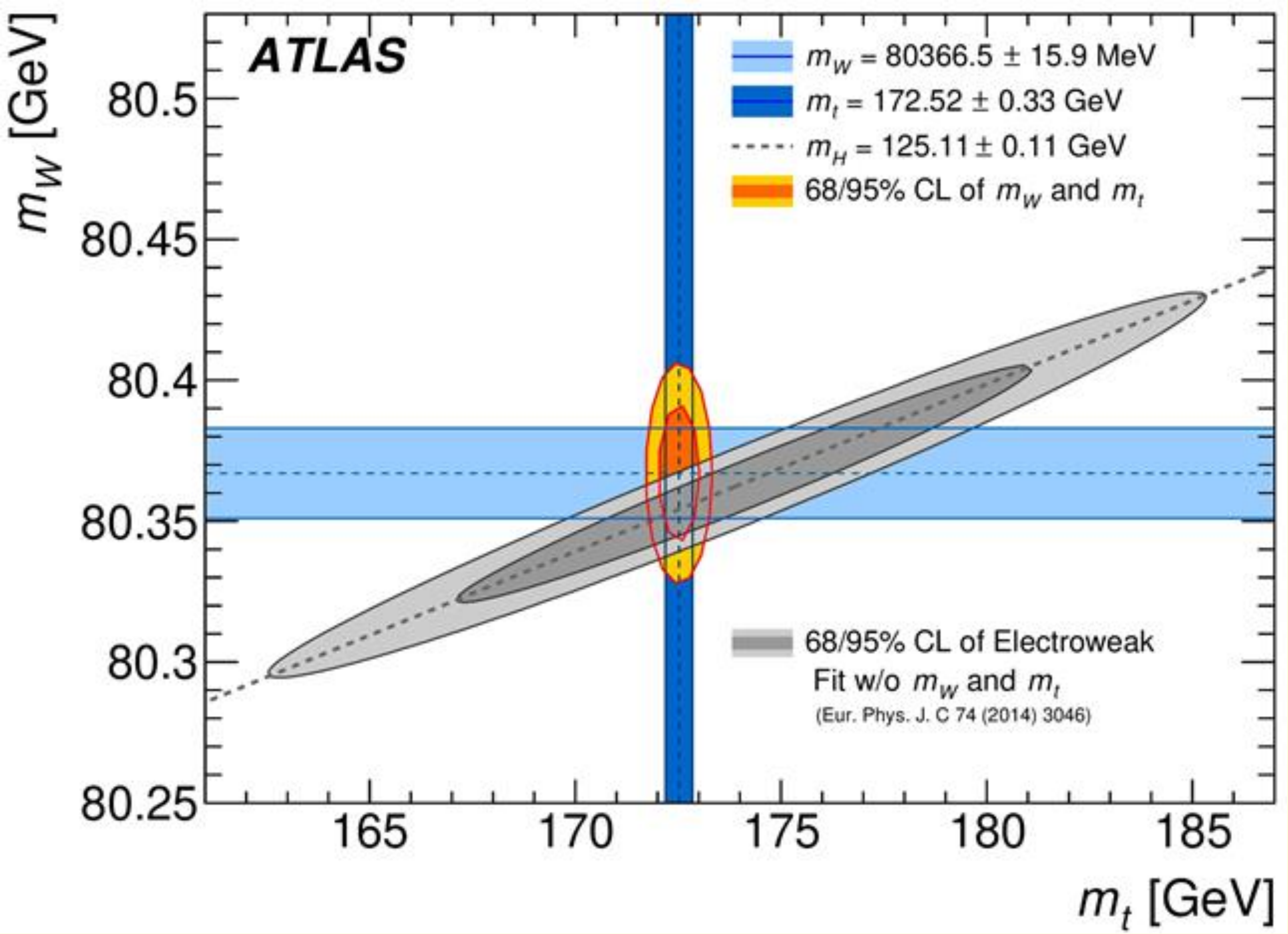


Δr includes radiative effects (loops), and so depends on m_H and m_{top}

Fits to precision electroweak data from LEP/SLD and others, plus the LHC m_H and Tevatron+LHC m_{top}, provides a prediction of m_W ("prediction of m_W in the framework of the SM")

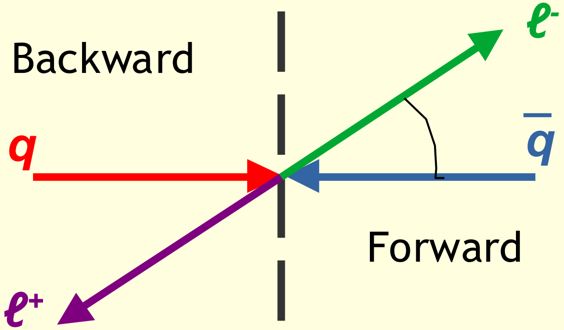


Precision electroweak fit and measured m_W, m_{top}



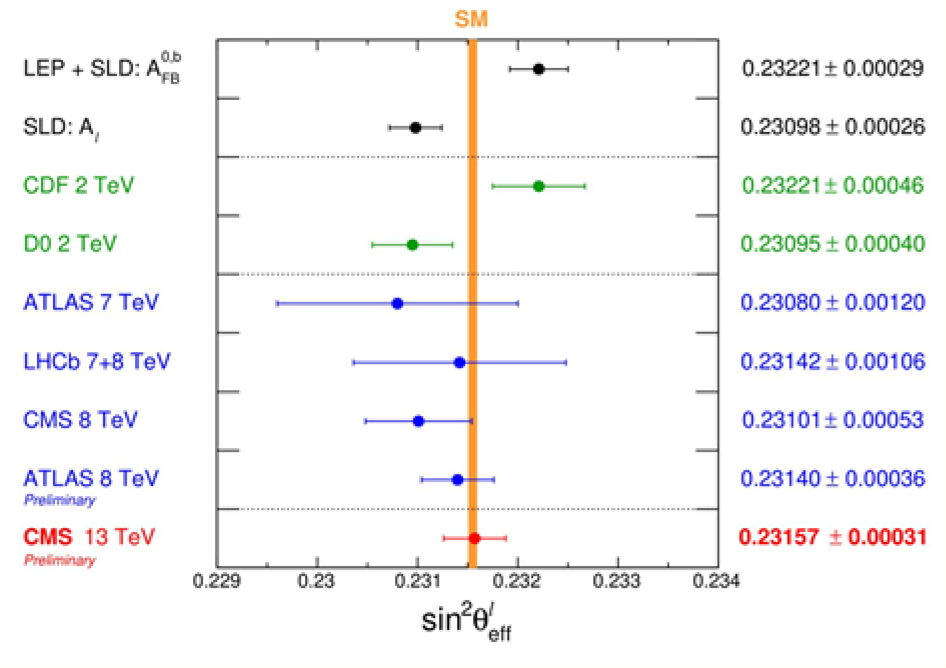
Measurement of $sin^2\theta_{eff}^{lept}$

At a proton-proton collider such as LHC, measuring forward-backward asymmetries in $Z\rightarrow\ell\ell$ decays is not as natural as at LEP



But

- the Z is not produced at rest
- proton pdf's not symmetric between q and $\bar{q}$ Z's travelling forward (or backward) in the detector should show a measurable decay asymmetry
- Size of effect varies with $m(\ell\ell)$
- Very forward-going leptons are hard to measure!



Tricky analysis, but we can measure the asymmetry vs $m(\ell\ell)$ and thus $sin^2\theta_{eff}^{lept}$

Precision is close to that from LEP!

Multi-boson production

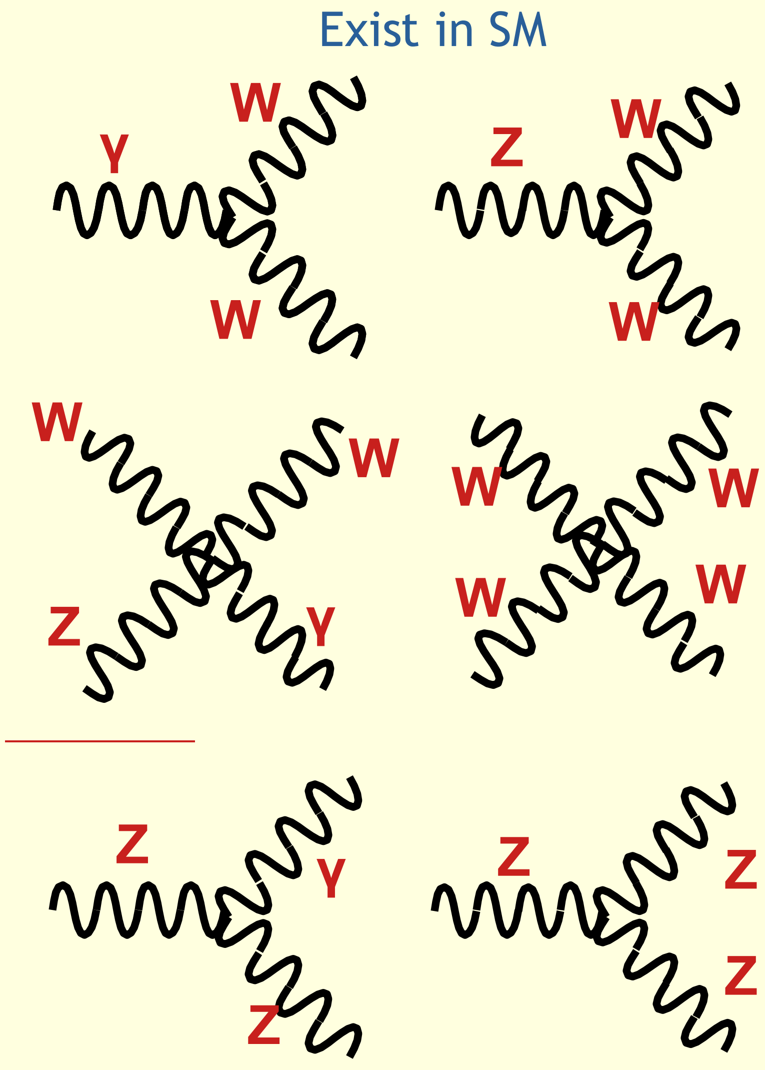
Energy available to make multiple (2 or 3) gauge bosons in the same collision

Sensitive to the triple- and quartic- boson vertices of the SM, with higher statistics and at higher energies than at LEP

- *Some* of the vertices are shown right

These bosons are spin-1

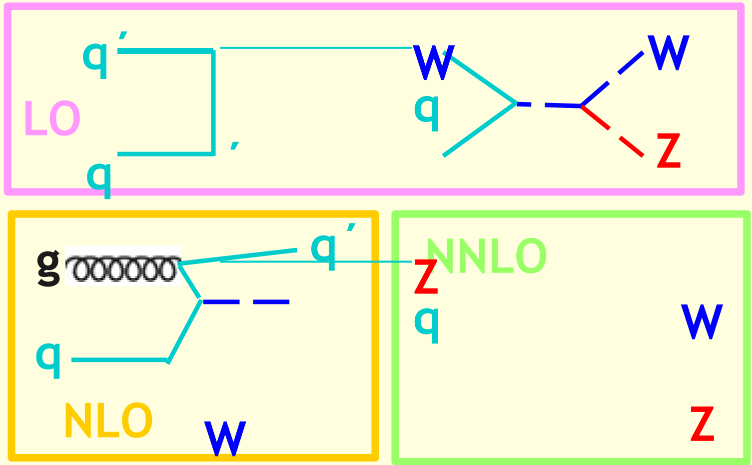
- Their **polarisation** can be accessed for leptonic decays
- **One polarisation state (longitudinal)**
- **arises from EW symmetry-breaking** Important probe of EWSB, separate from Higgs measurements



Massive diboson production

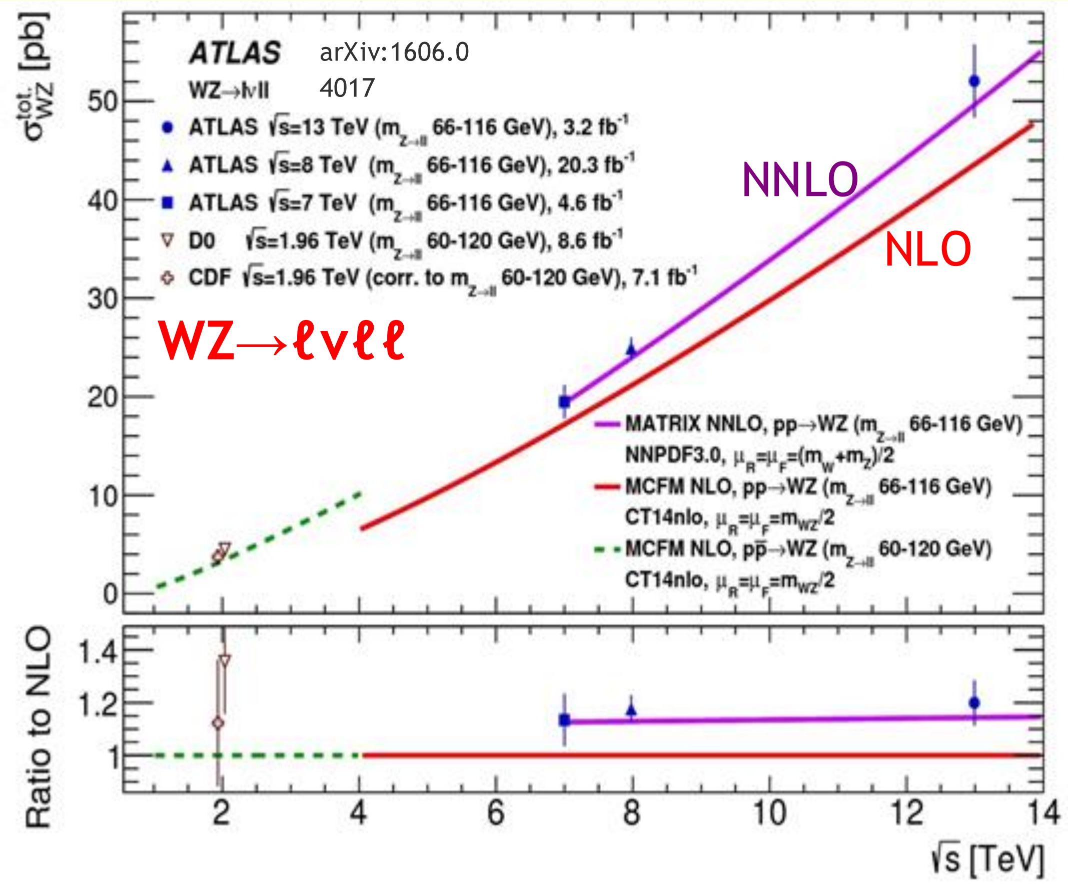
Measurement of diboson production done since Run-1 (2012 data)

- Theory (NLO) did not describe data



NNLO calculations → ~+20% corrections and better agreement

One of many places where NNLO is needed to describe data



Triboson production

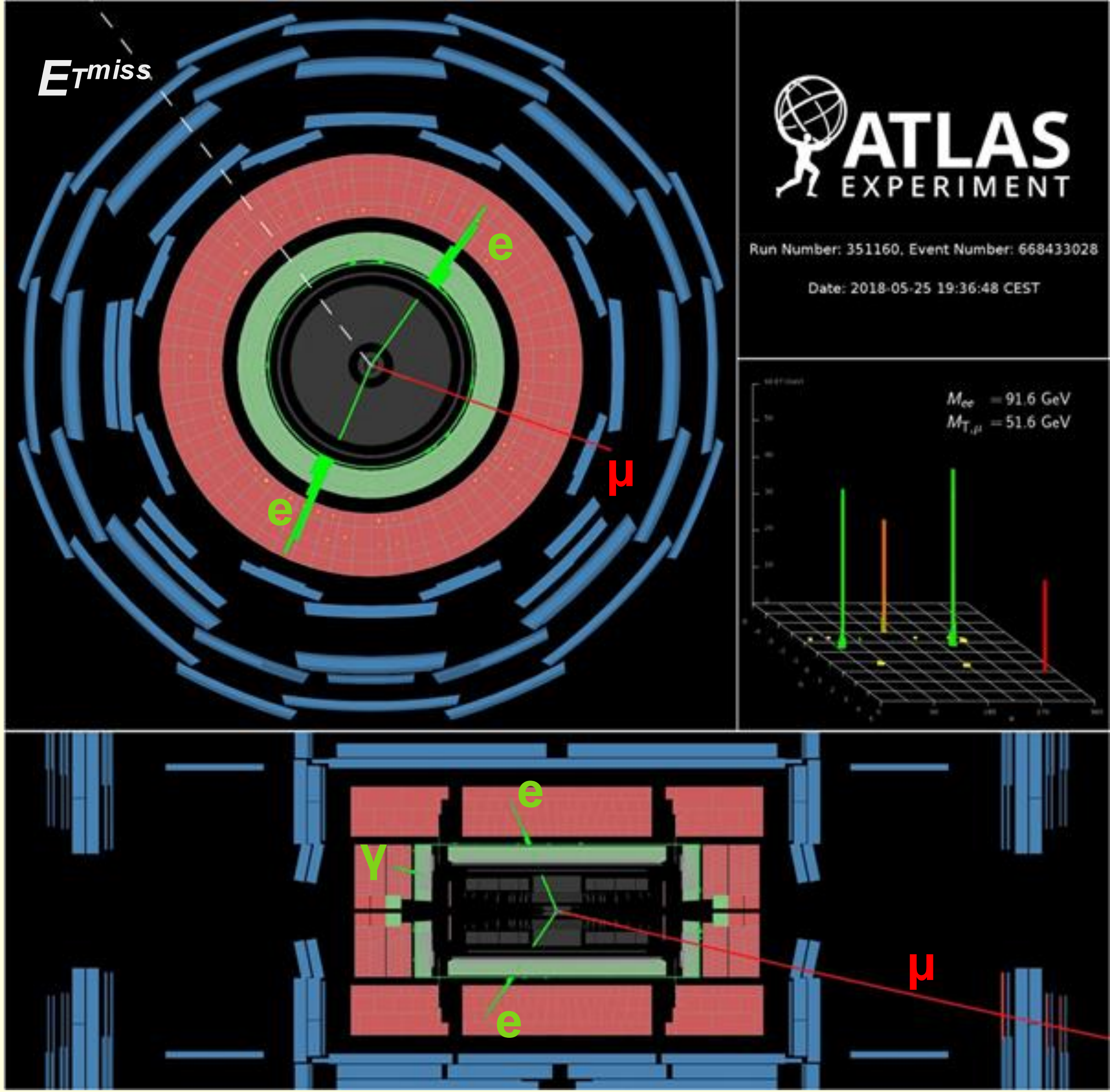
Just getting started due to low cross-sections

Measurements so far of WWW, WZγ, Wγγ, Zγγ

Event shown is a WZγ candidate (low-momentum tracks not shown)

- $Z \rightarrow ee$ in green
- $W \rightarrow \mu\nu$ muon in red, E_T^{miss} dashed
- γ in left endcap (also green)

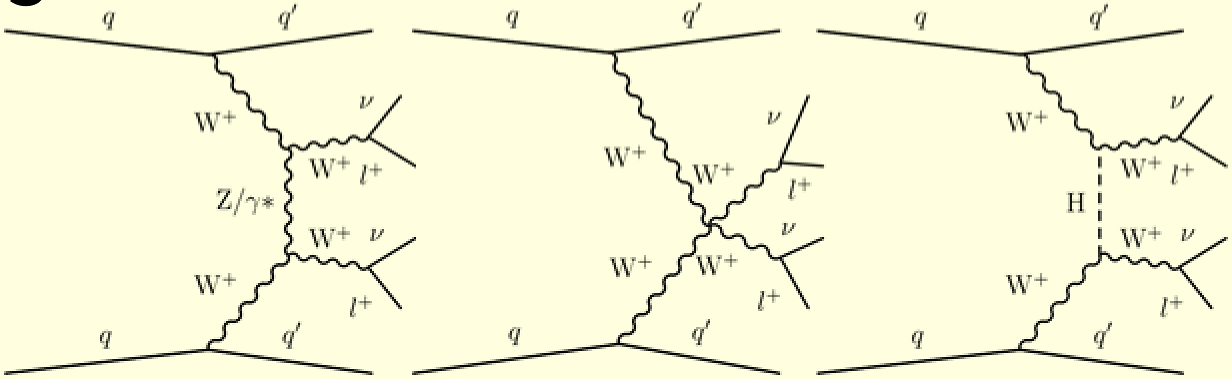
Lots more channels to explore in future, and to start probing polarisation of bosons



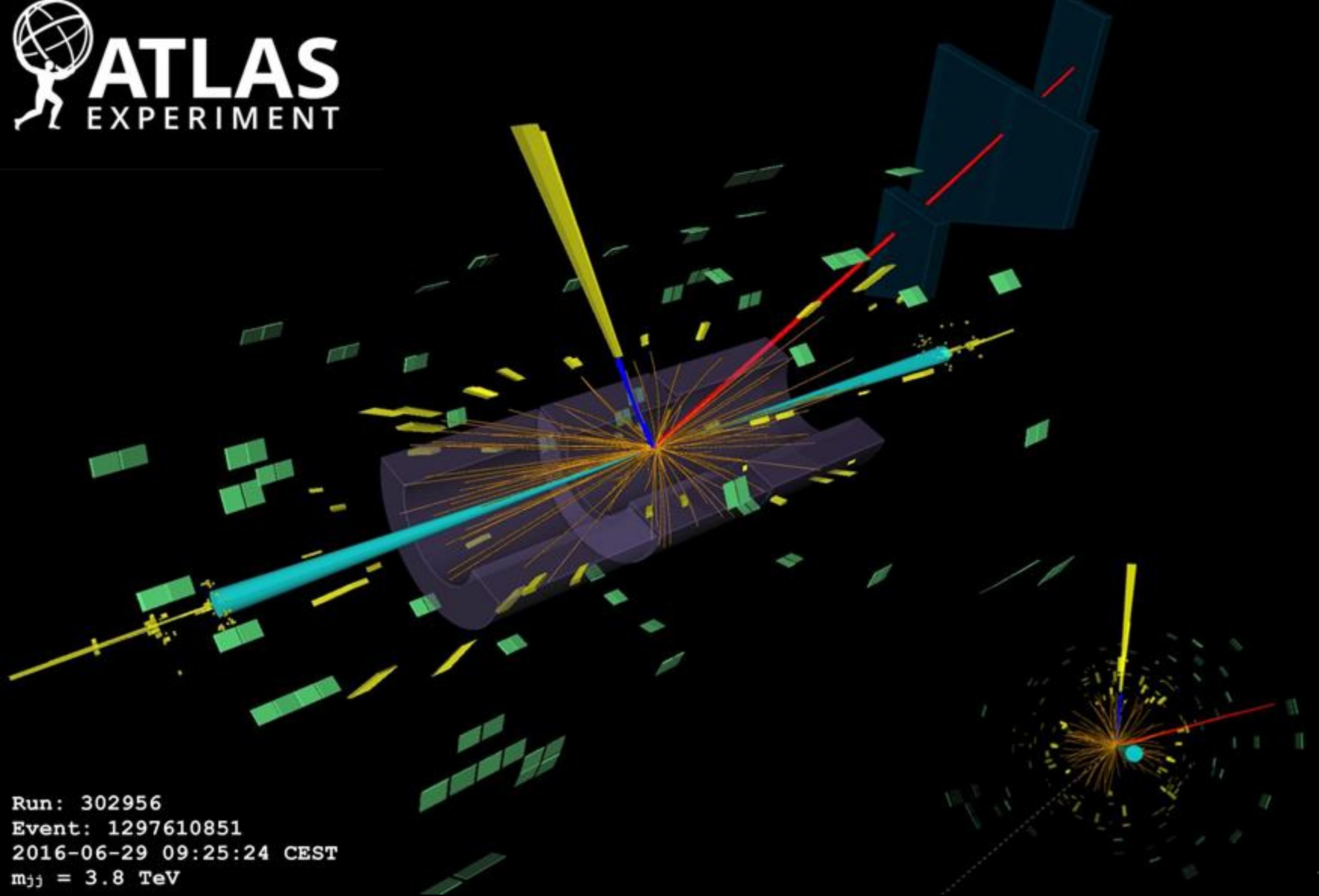
Vector-boson scattering (VBS)

Example: W^+W^+ scattering $W^+W^+ \to W^+W^+$

Conceptually, two W/Z bosons emitted from incoming partons scatter off each other to give two final state W/Z's, with also energetic jets going forward

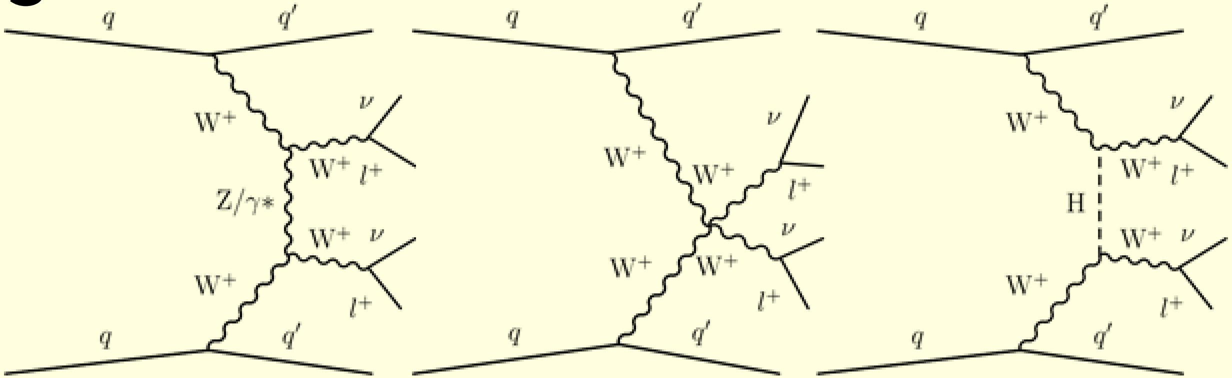


Diagrams involve quartic vertices as well (often) as H exchange


ATLAS
EXPERIMENT
Run: 302956
Event: 1297610851
2016-06-29 09:25:24 CEST
m_{jj} = 3.8 TeV

Vector-boson scattering (VBS)

Example: W^+W^+ scattering $W^+W^+ \to W^+W^+$



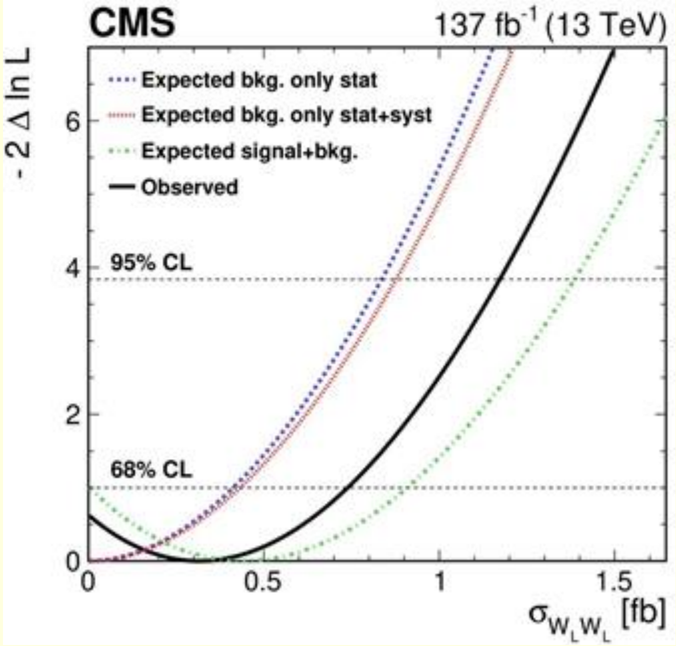
Conceptually, two W/Z bosons emitted from incoming partons scatter off each other to give two final state W/Z's, with also energetic jets going forward

Diagrams involve quartic vertices as well (often) as H exchange

VBS studied in $W^\pm W^\pm$, W^+W^-, WZ, ZZ, Wγ, Zγ

Recent CMS "proof of principle" paper studies polarisation states in $W^\pm W^\pm$ VBS

- No 3σ evidence yet of W_L contributions, needs more data



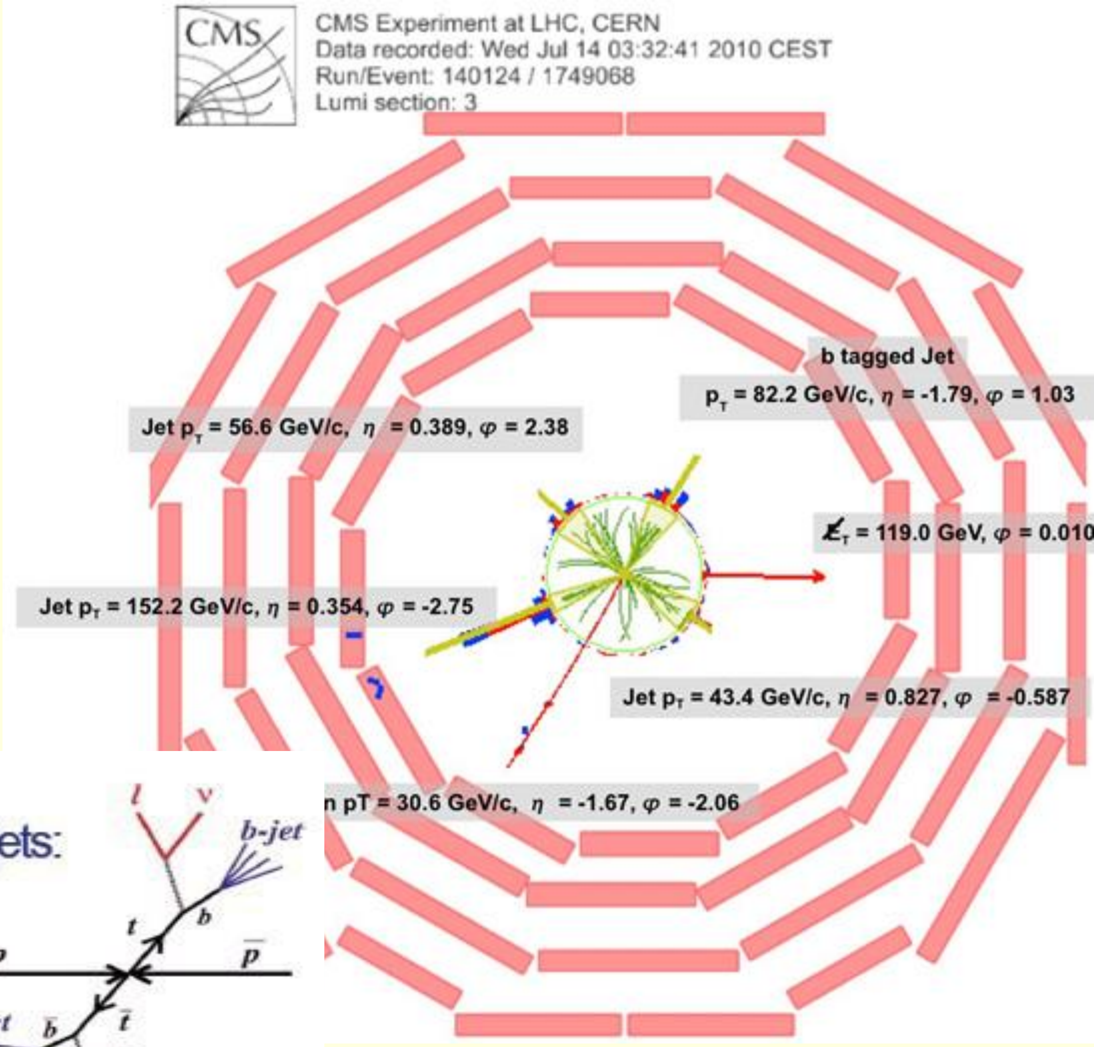
Top quarks at the LHC

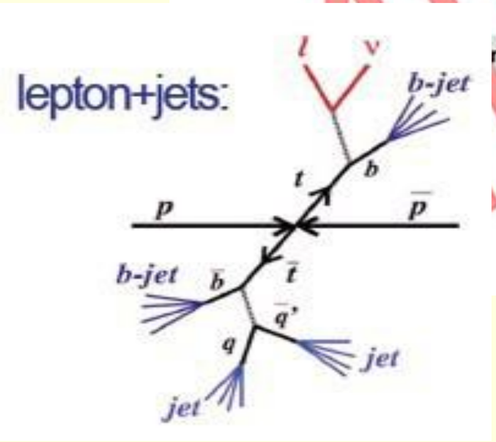
To date tens of millions of $t\bar{t}$ pairs produced at the LHC (cf ~75k at Tevatron, where the top quark was discovered)

Are top quarks "special" objects?

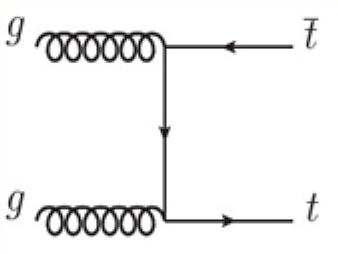
- The coupling y_t of the ttH vertex has a predicted strength y_t~1

→ Big programme to measure top production, properties and decays precisely



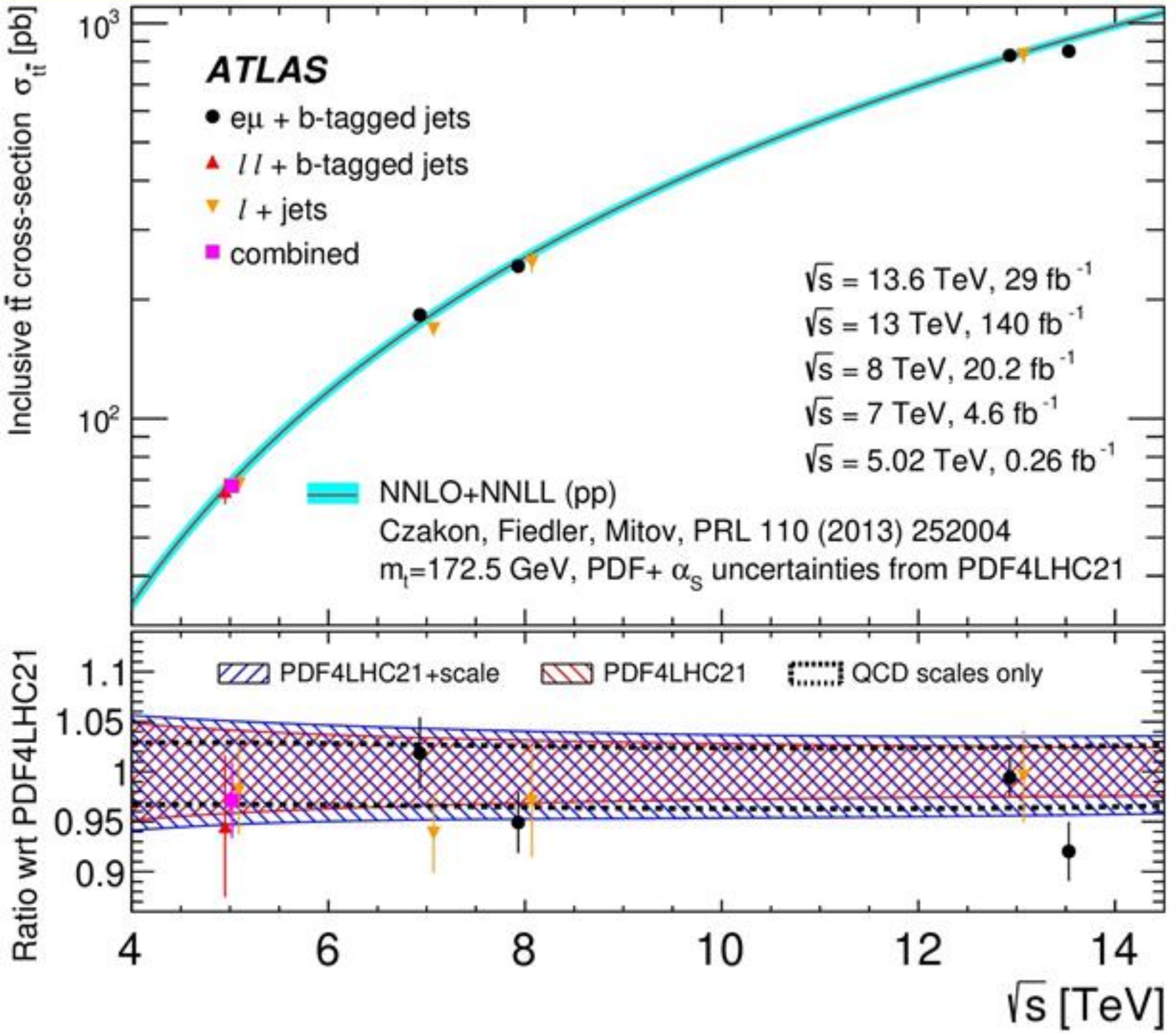


$t\bar{t}$ production



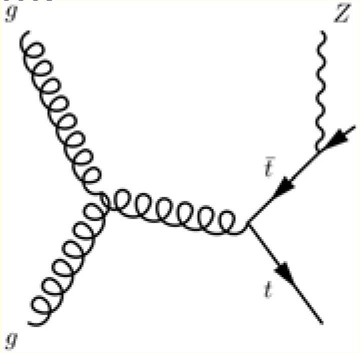
Single and double b-tagged $tt \rightarrow be\nu b\mu\nu$ events allow to measure tt cross-section and b-tagging efficiency simultaneously

Measurements can be more precise than predictions

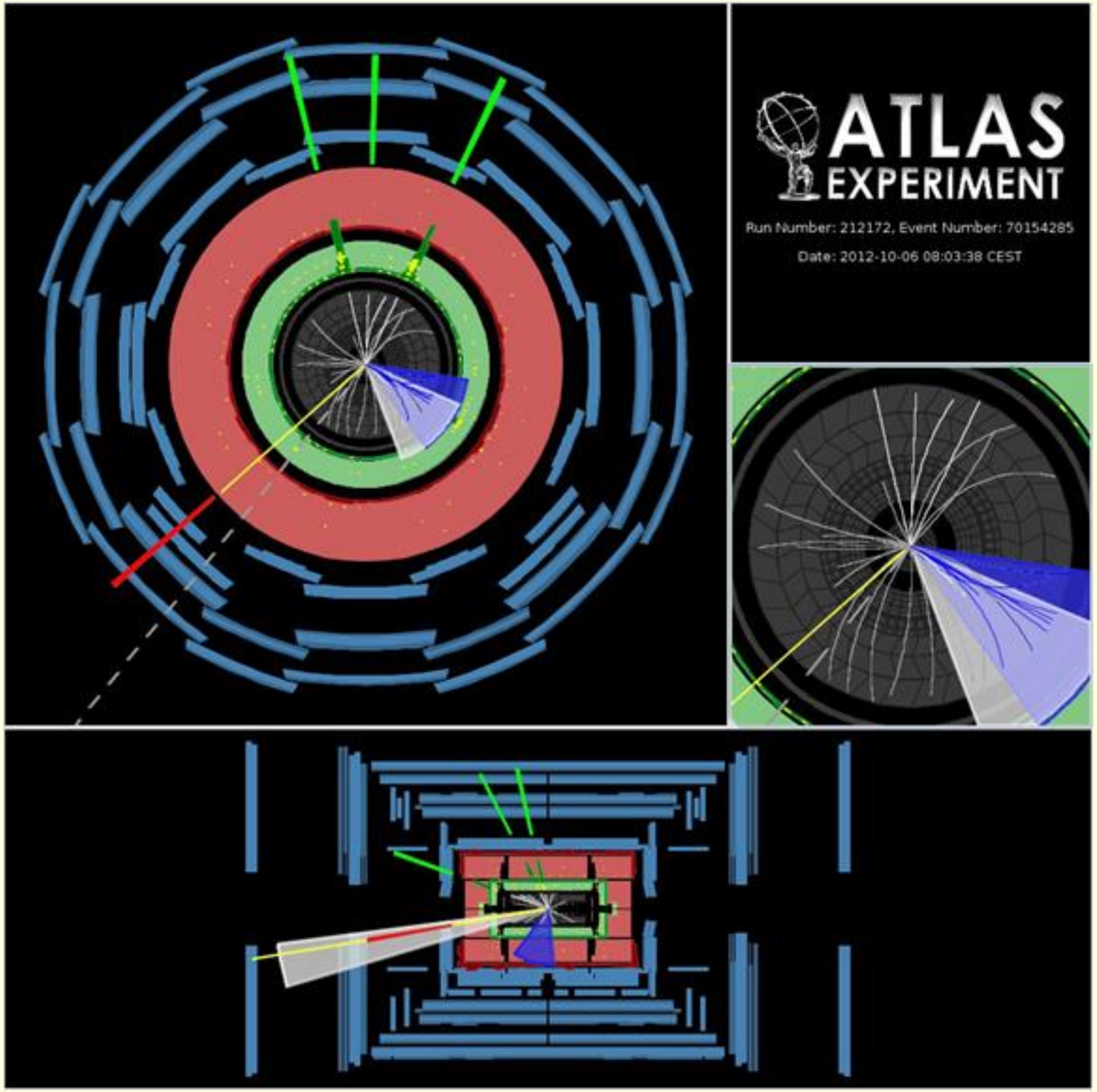


Two tops and a Z boson!

Three very massive particles produced together – example diagram:



In the event shown, both top quarks decay to Wb, and the W decays to lepton plus neutrino → total of four charged leptons (3e, 1μ) plus 2 b-jets



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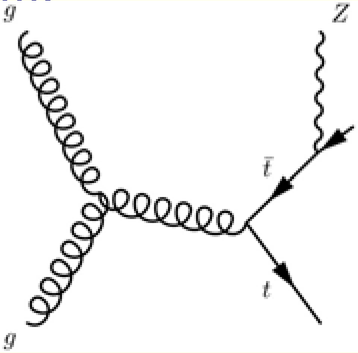
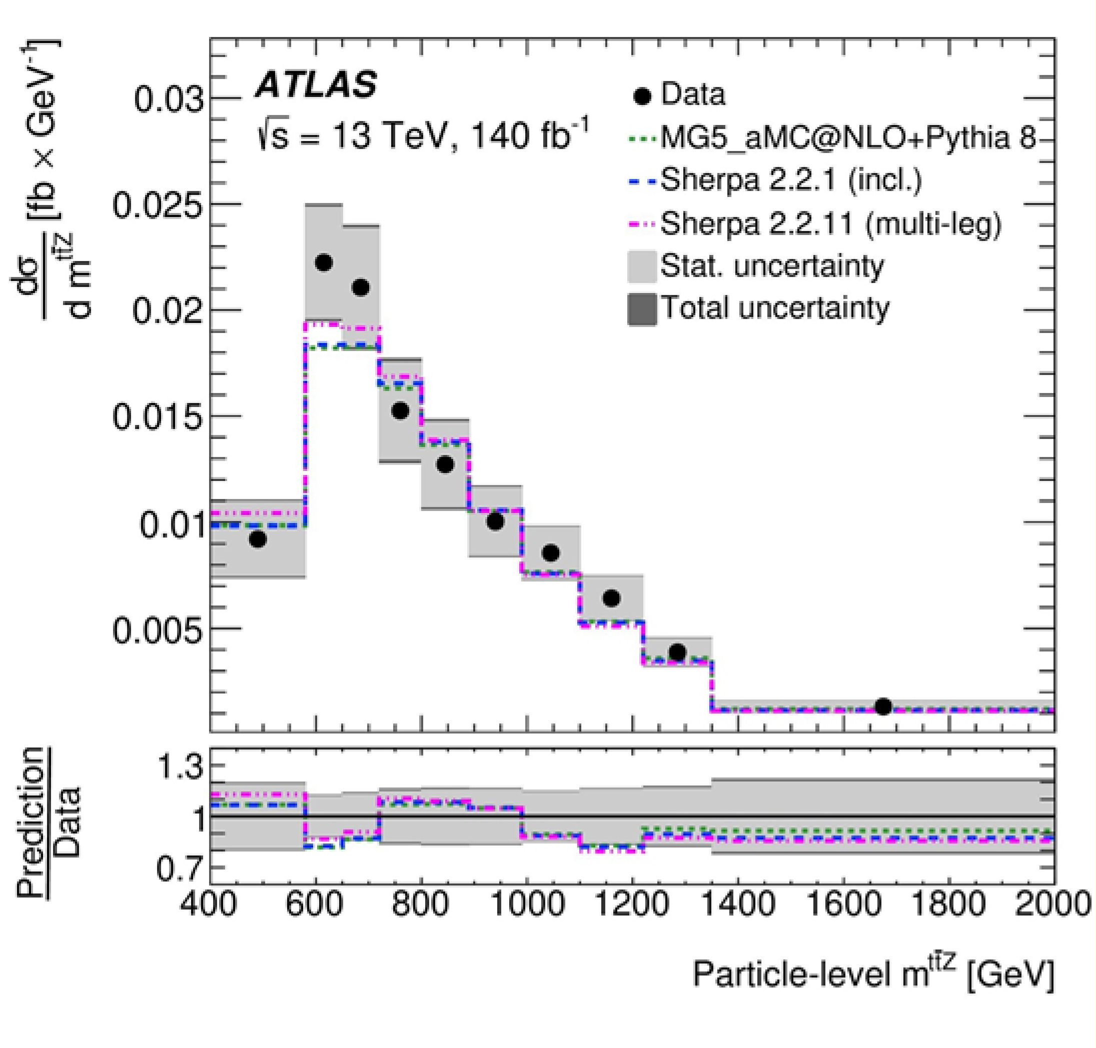


Enough events to measure cross-sections differentially

Good description of data by MC

Good understanding gives confidence in ttH analysis → later!



Masses in the Standard Model

Looking back to where we were at the start of the LHC...

Standard Model was (and is) amazingly successful

- Gauge symmetry seems to be a fundamental feature
  - Explains observed couplings of fermions to γ, gluons, W and Z
  - Allows renormalisable theories (t'Hooft & Veltman)
- Gauge symmetry forbids particle masses via simple mass terms in the Lagrangian

Principle of a solution came from multiple authors in 1964, including...

Englert Brout Higgs Guralnik Hagen Kibble

Masses in the Standard Model

Caution: this is not the only source of mass in the SM – e.g. a proton mass is not the sum of the constituent quark masses

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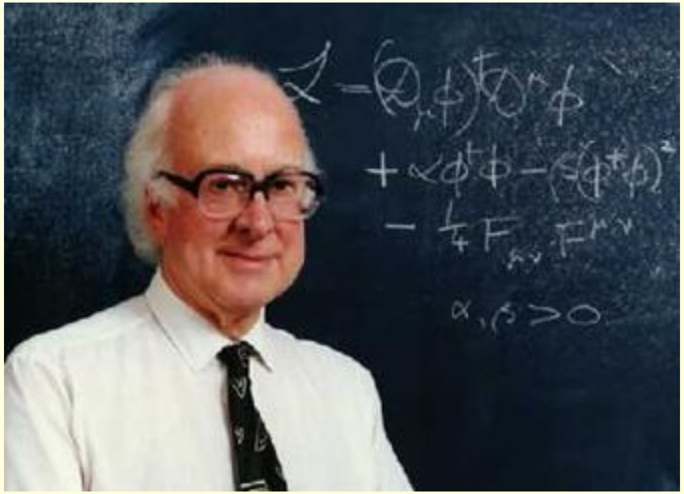
Brout-Englert-Higgs (BEH) mechanism



Peter Higgs (1929-2024)

The BEH "trick" was to add masses by coupling particles to a new scalar field with a non-zero value in the vacuum

- Basic mechanism gives masses to W^+, W^- and Z
- Can also add masses to the fermions "by hand" ("Yukawa couplings")
- Gives rise to (at least) one new physical scalar particle

Extension to the W and Z bosons was the collective work of many, including Kibble, Glashow, Weinberg, Salam, in the late 1960's

An interesting (lowest-order) prediction of the BEH mechanism in the SM:

$$\frac{M_W}{M_Z} = \cos\theta_W \rightarrow \qquad \sin\theta_W^2 \simeq 0.223$$

How to find it?

In the Standard Model, (almost) everything about the H boson is predicted

- Coupling strength to other particles – proportional to their mass
- Production cross-sections
- Decay rates
- Characteristics of production and decay (differential distributions)

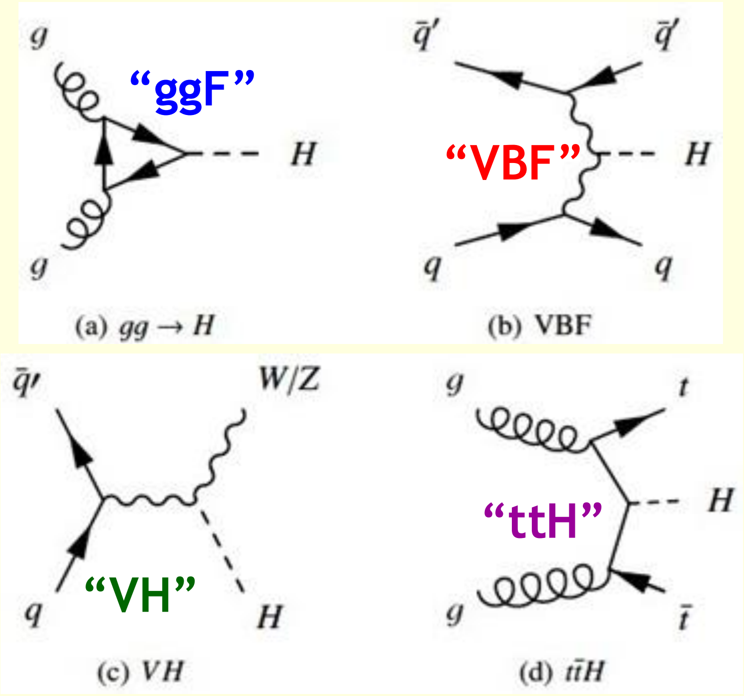
etc

But not its mass, m_H

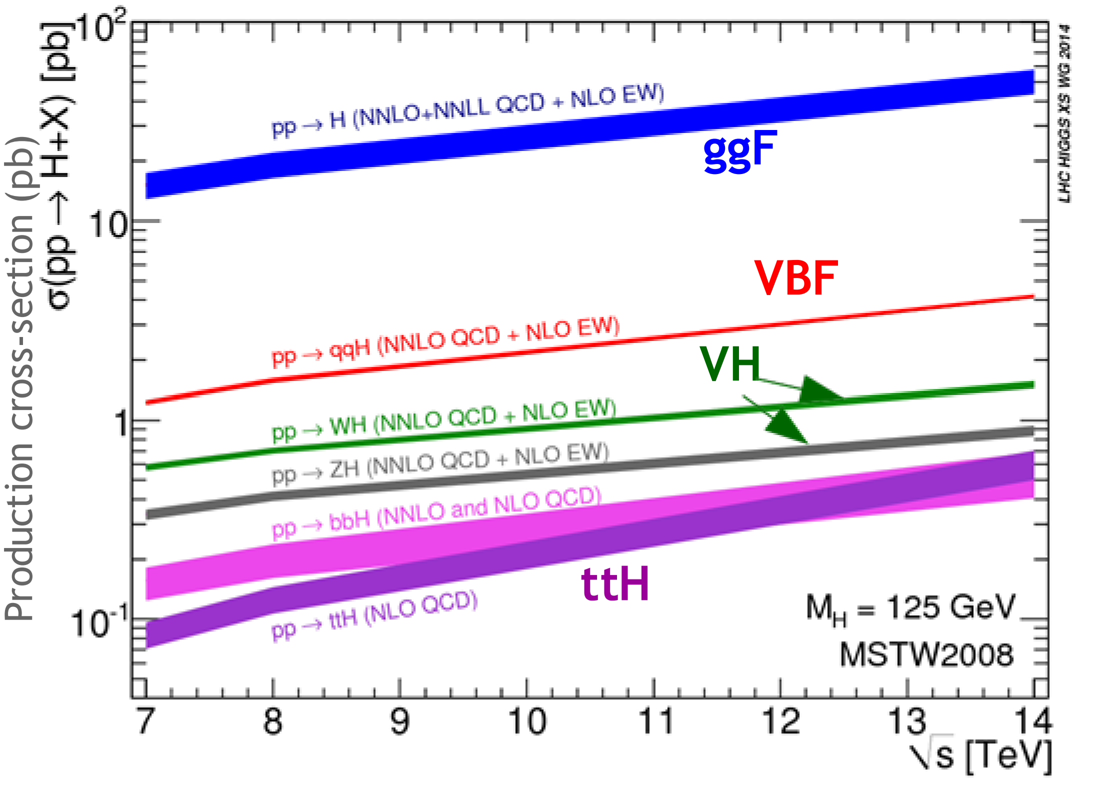
Not seen at LEP → $m_H > 114$ GeV

H production processes

A ~125 GeV Higgs boson is experimentally convenient – many production and decay modes should be measurable

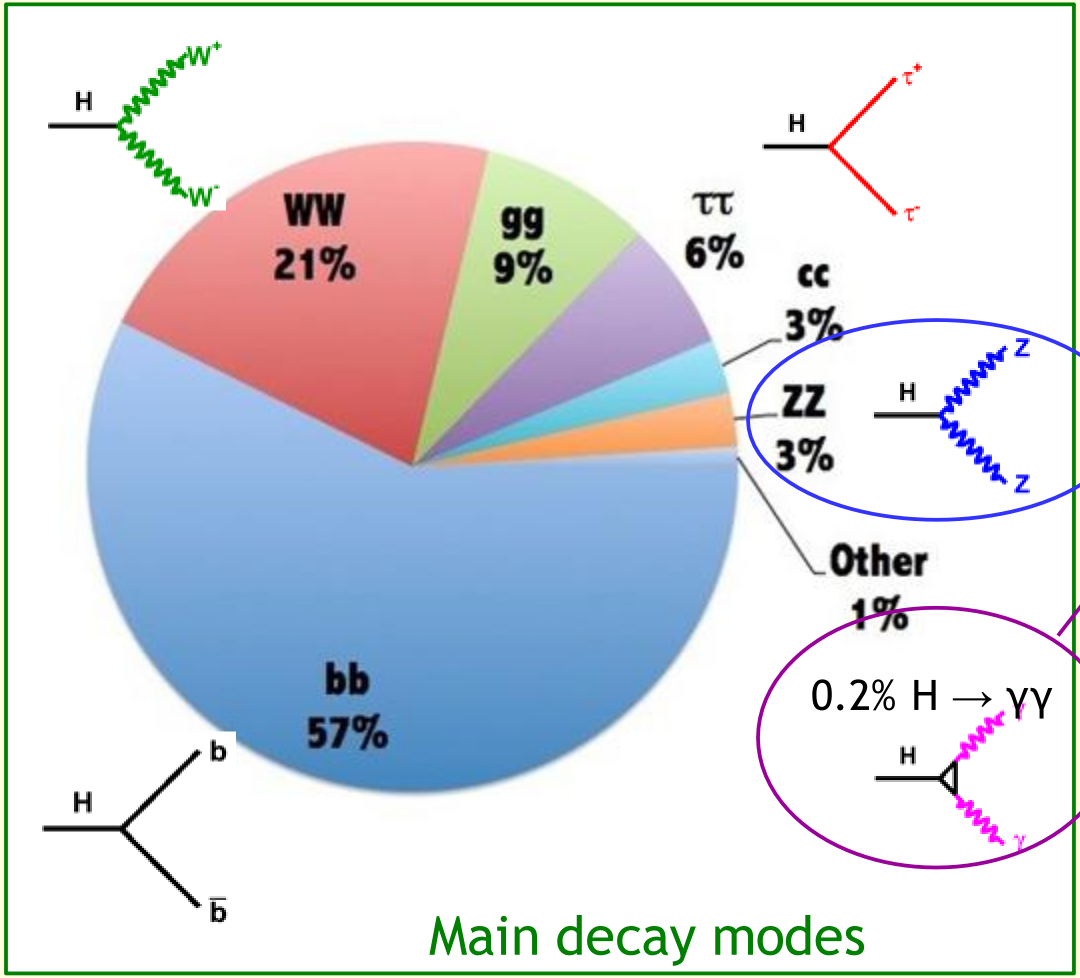


Main (single H) production diagrams



“ggF” dominates, multiple processes accessible
(inclusive rates are not tiny)

Higgs boson decays in the SM



Discovery channels

Low branching fractions

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

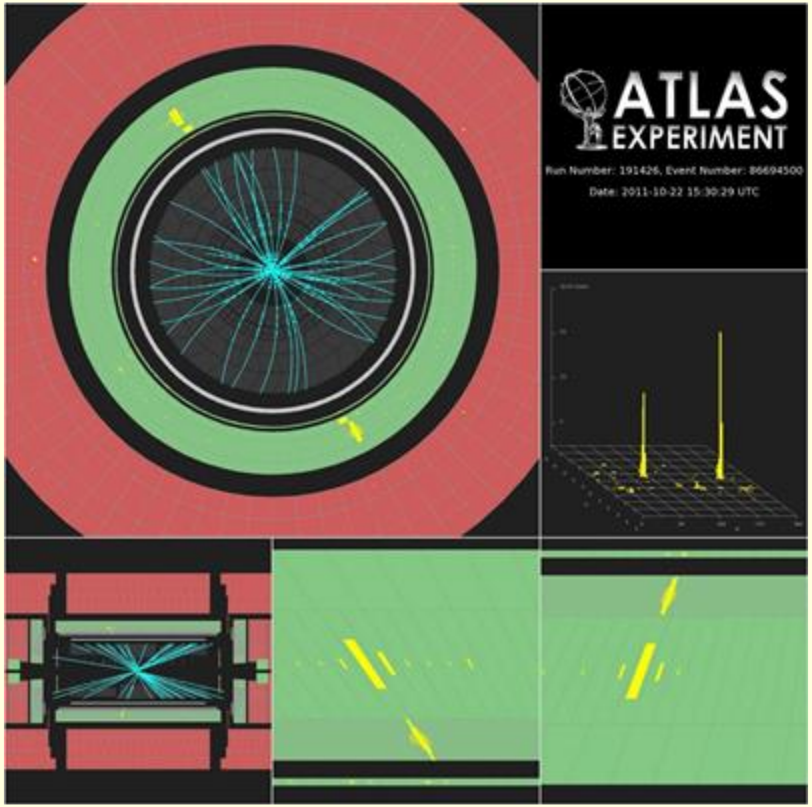
BF($H \to \gamma\gamma$) ~ 0.2%

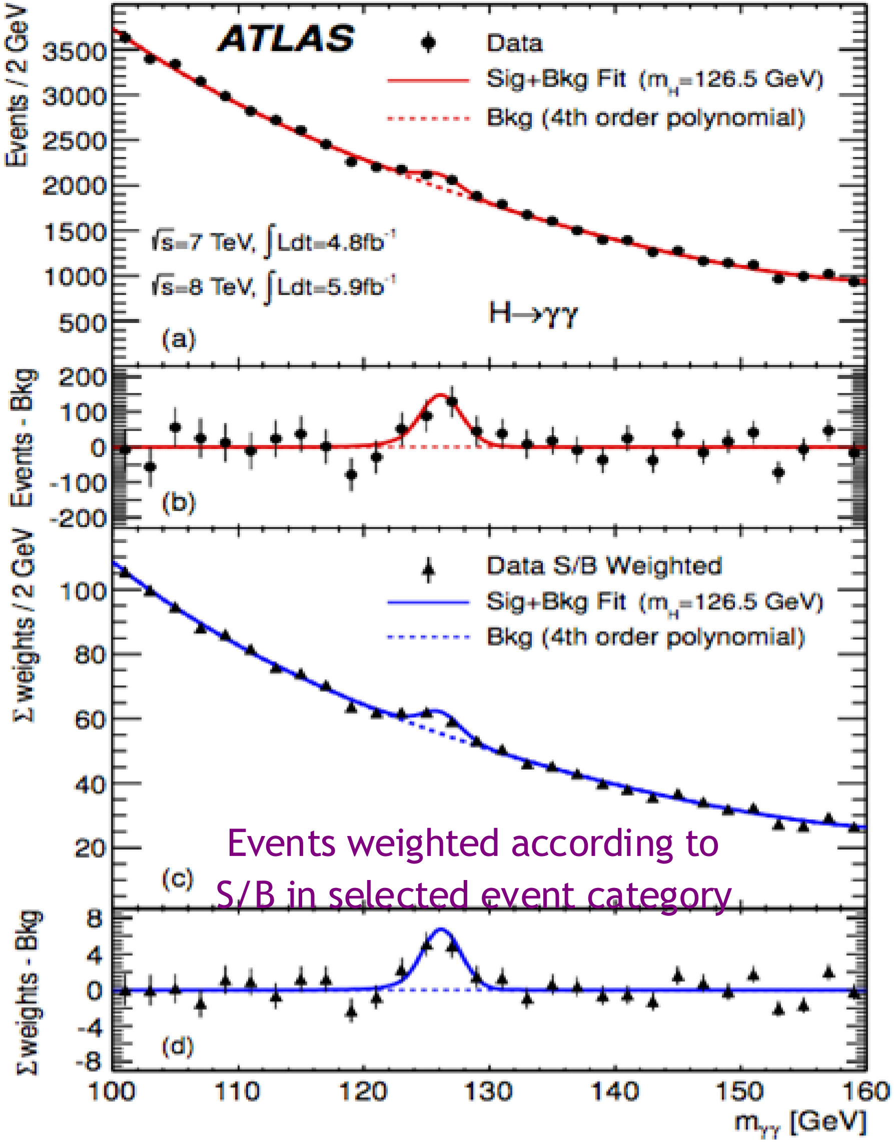
Higgs Discovery (ATLAS and CMS)

July 4th 2012 (CERN and Melbourne)

H discovery - July 2012

Excellent γγ mass resolution crucial, as well as γ-ID to reject jet/π^0 background

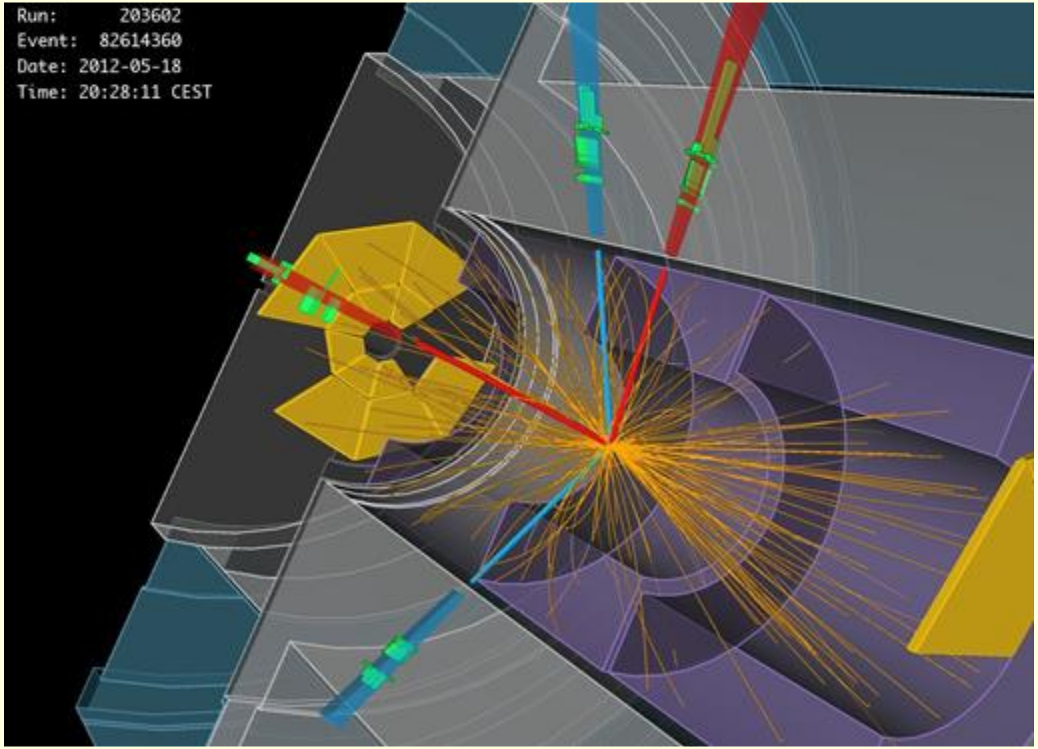


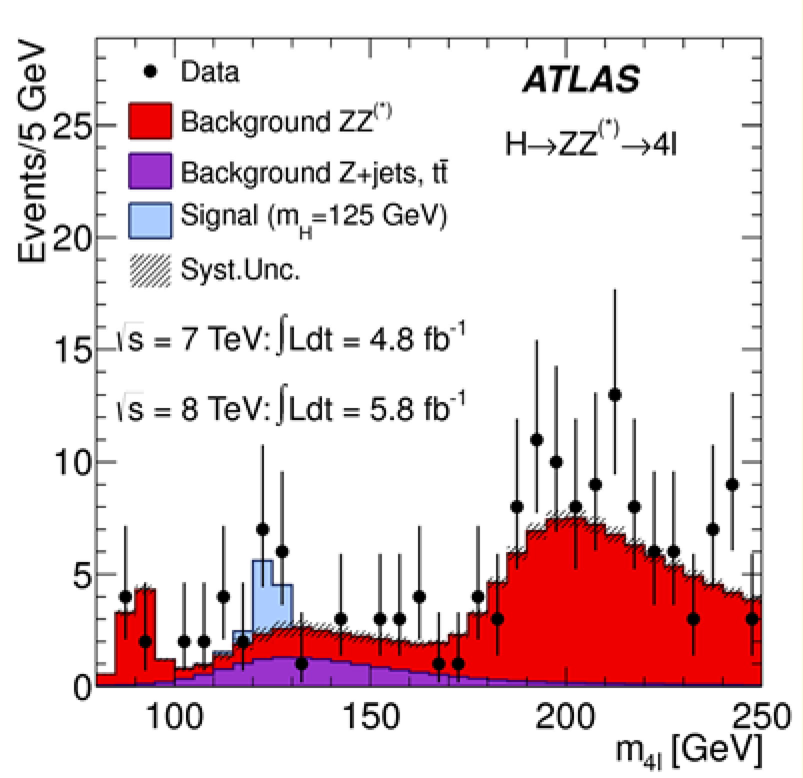


Events weighted according to S/B in selected event category

Inclusive signal/background S/B ~3%

H discovery - July 2012

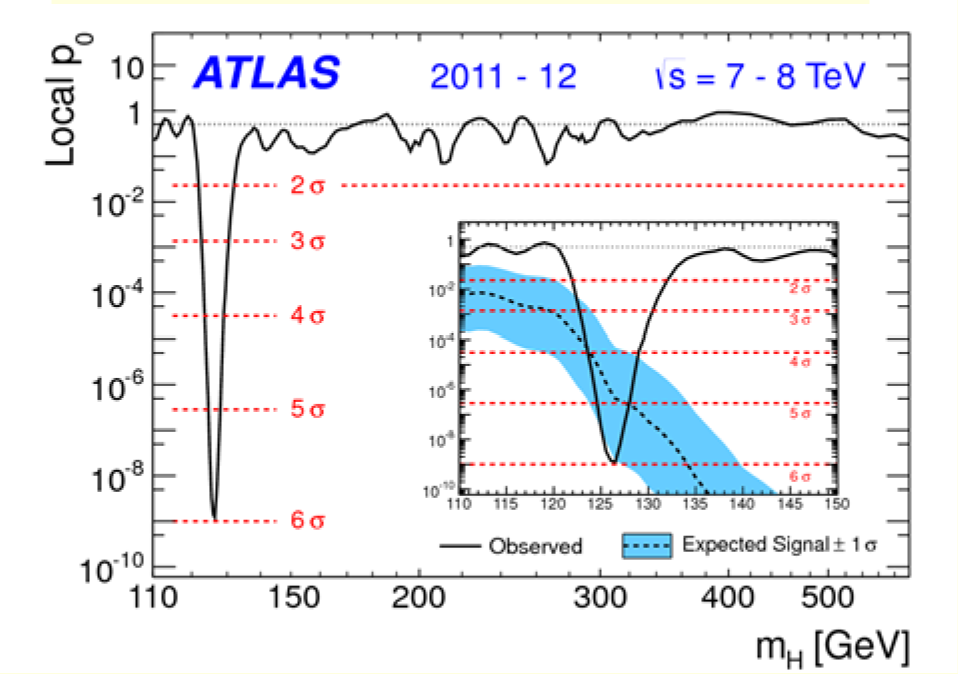




$H \to ZZ^* \to 4\ell$

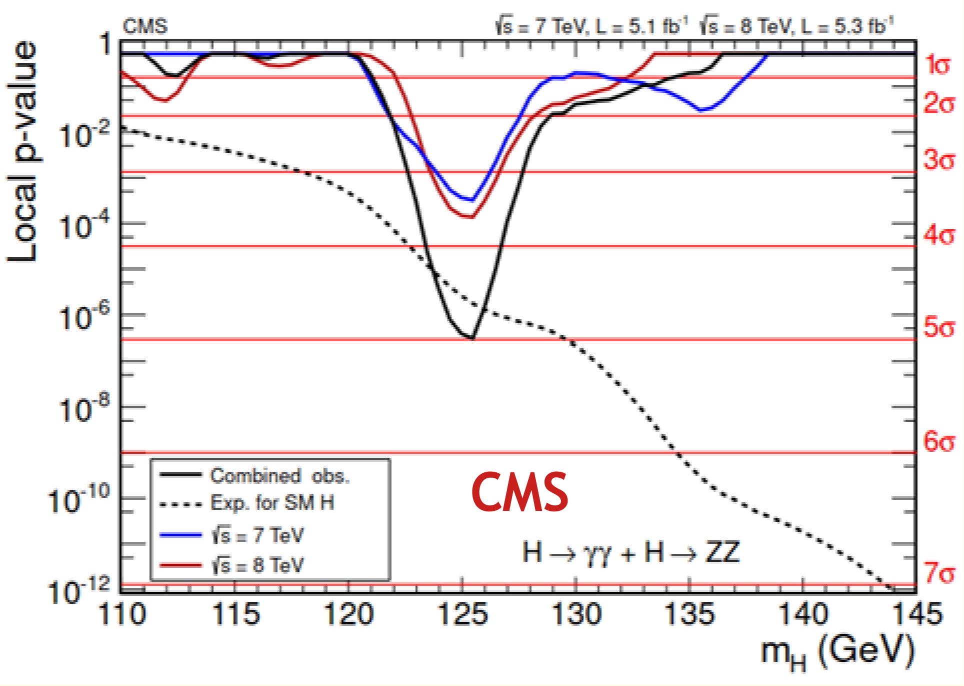
"Golden channel" - excellent mass resolution and S/B~1

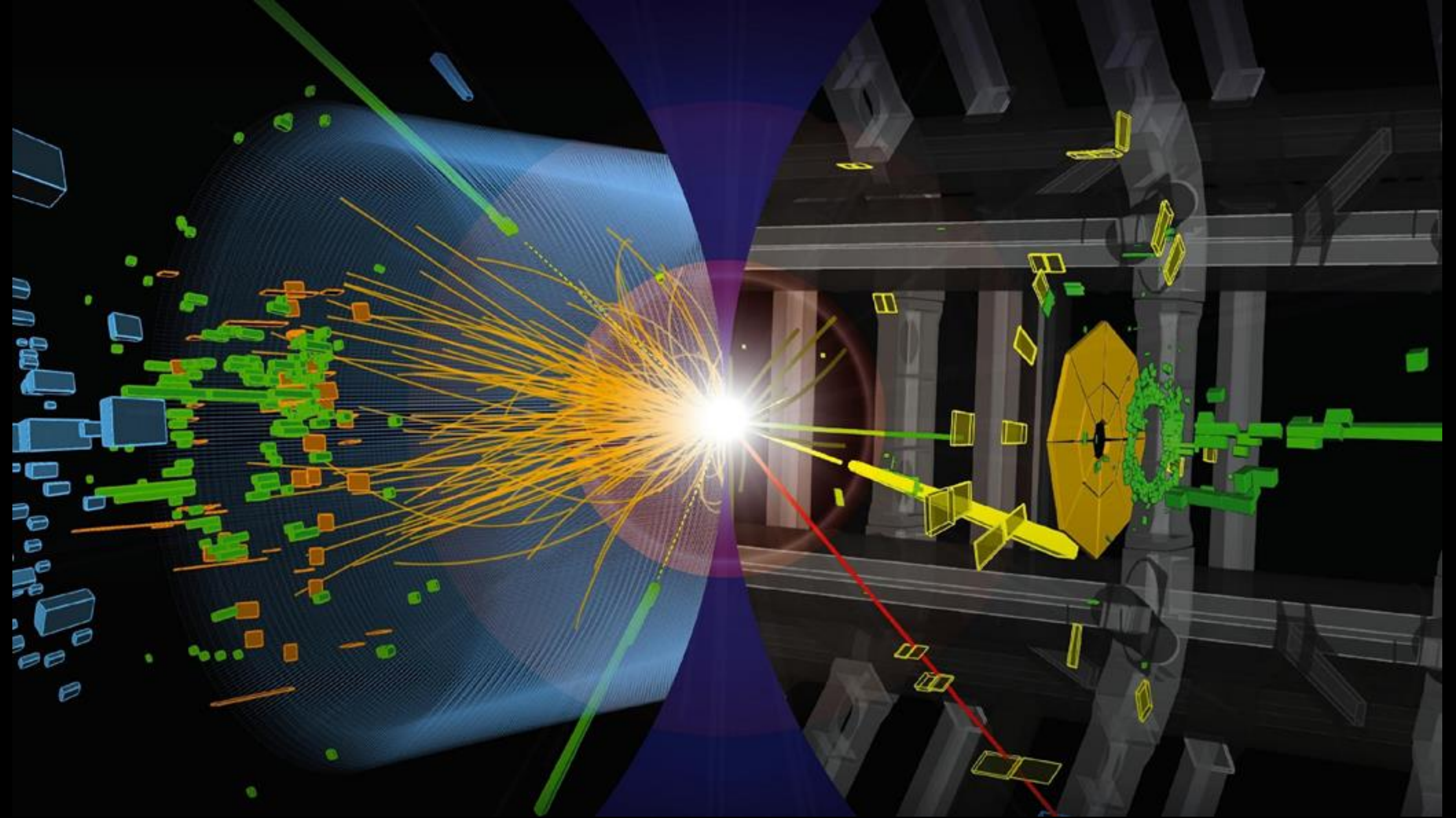
H discovery - July 2012



ATLAS overall significance (end 7/2012) 5.9σ, combining γγ, ZZ*(4ℓ) and WW*(ℓνℓν) channels

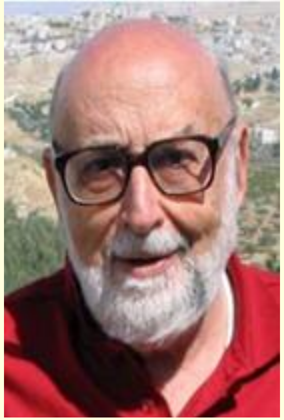
CMS results very comparable, and at a consistent mass!



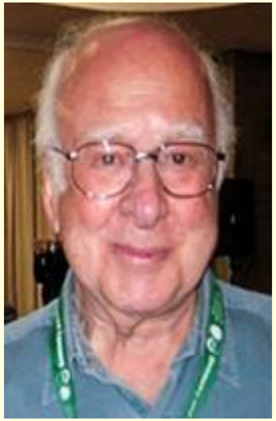


Nobel prize 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "*for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider*"



François Englert



Peter W. Higgs

H production

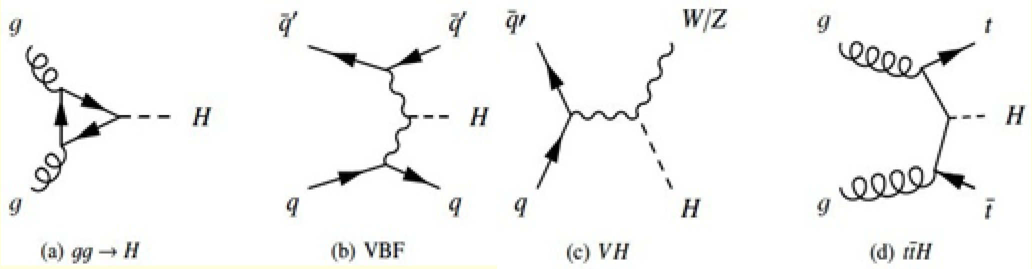
Separable using properties of other objects produced along with the H

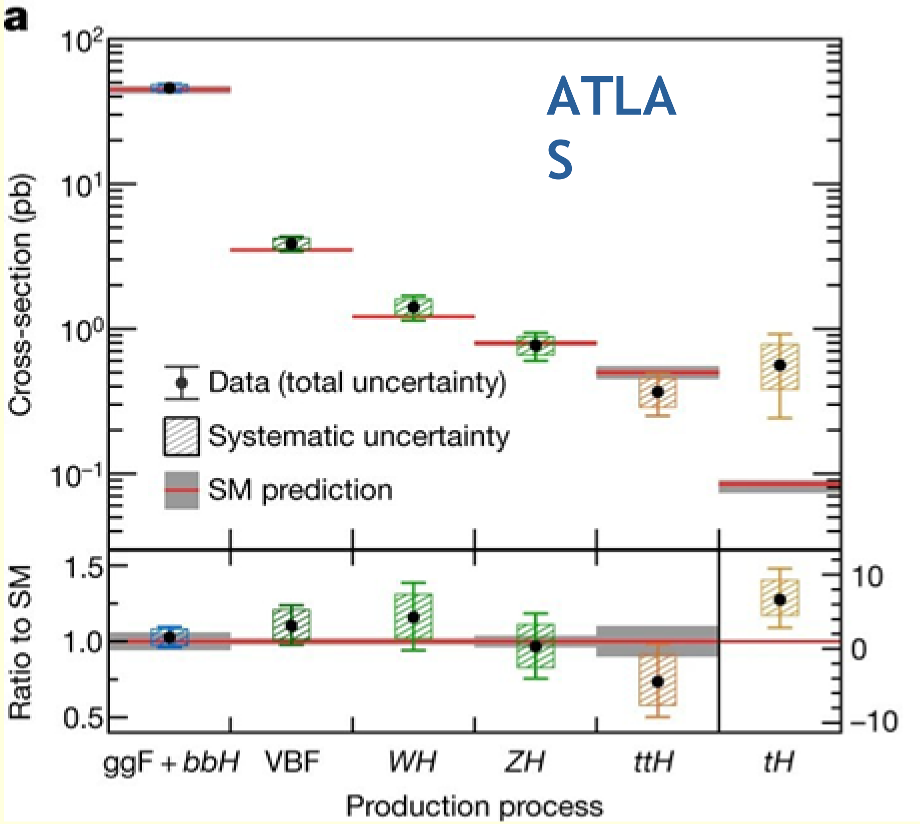
Overall cross-sections consistent with expectations

Measurements now focus on cross-sections in separate bins of phase-space of Higgs and other objects

"Simplified template cross-sections" (STXS)

Increasingly fine-grained measurements made as statistics increase



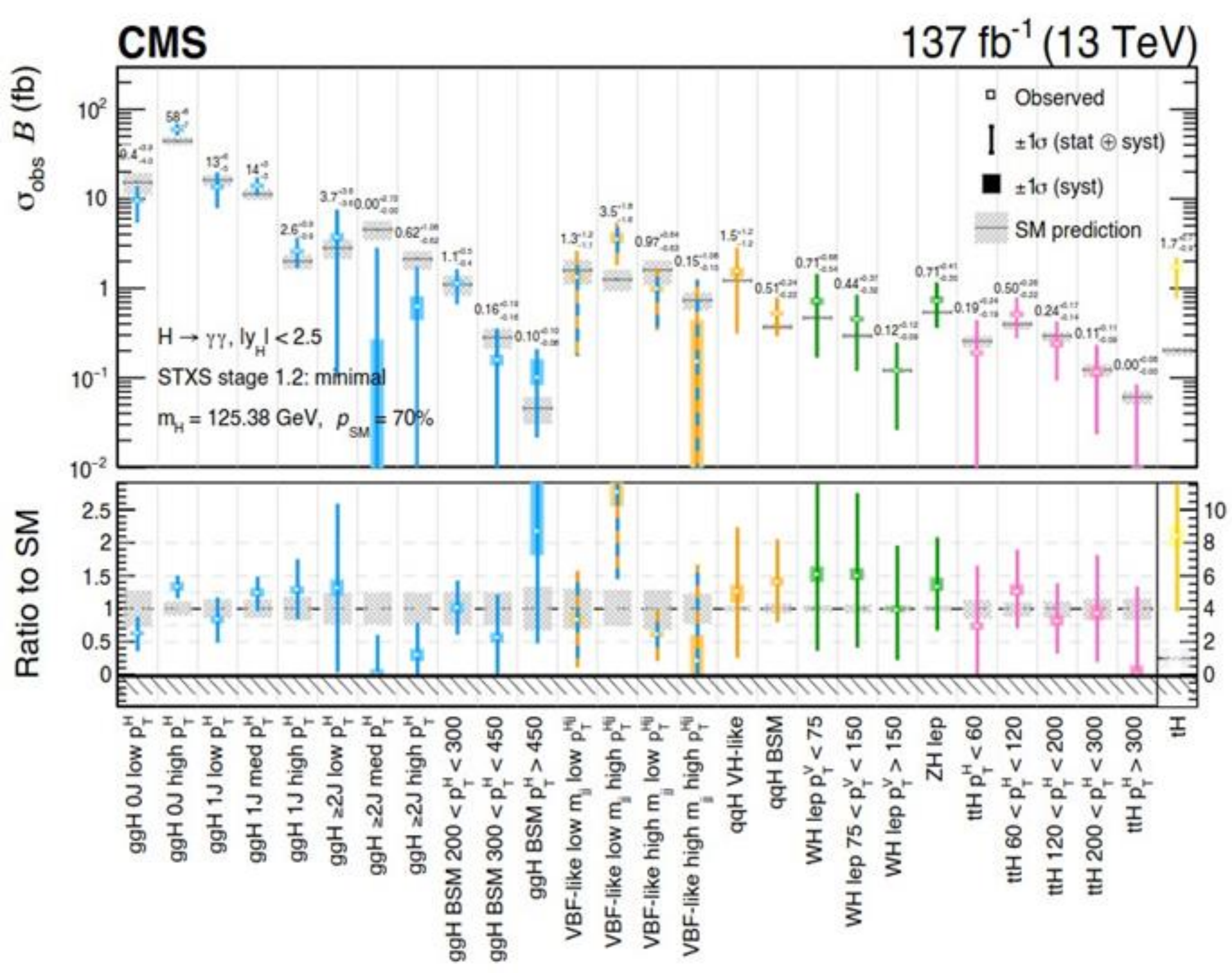


STXS results

Just one example

CMS $H \to \gamma\gamma$

Such measurements can be used to constrain possible new physics effects



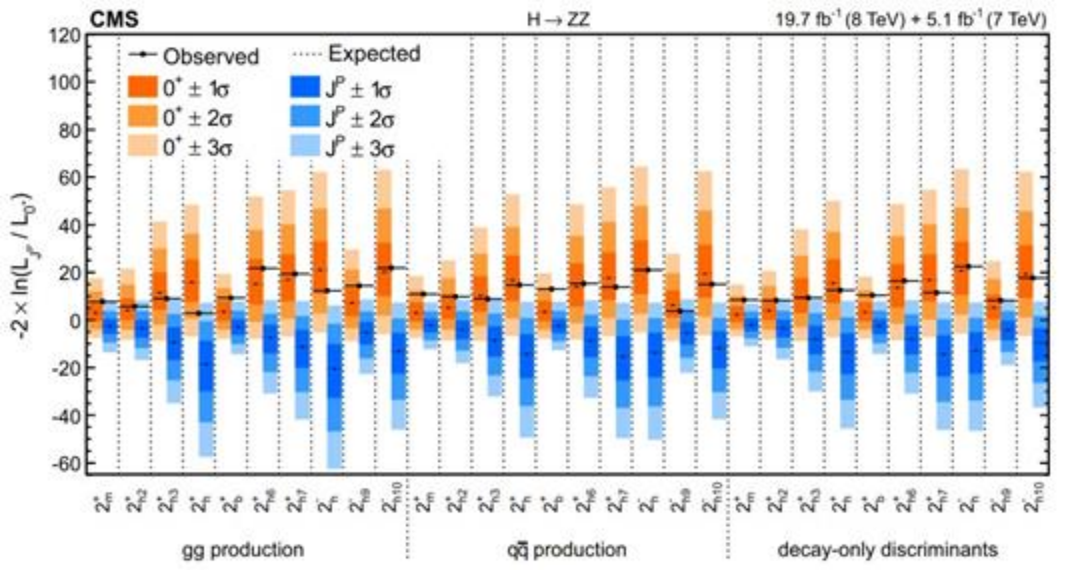
Is it a spin-0, scalar, state?

Study angular distributions of decay products

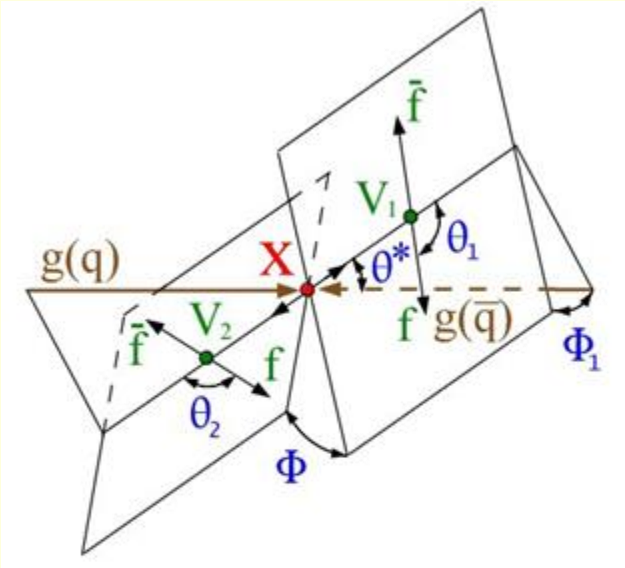
e.g. in $H \rightarrow ZZ^* \rightarrow 4\ell$

Discriminates different spin hypotheses

Comprehensive CMS study



Phys. Rev. D 92, 012004



Spin-parity 0^+ always favoured – significantly – over variou spin-2 hypotheses

Yes, H(125) is a scalar

Assuming its decays obey CP-symmetry, it is a 0^{++} state

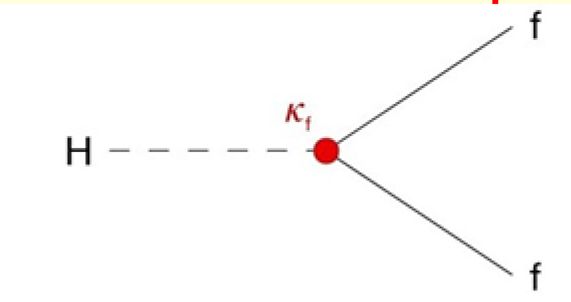
Does it give mass to bosons *and* fermions?

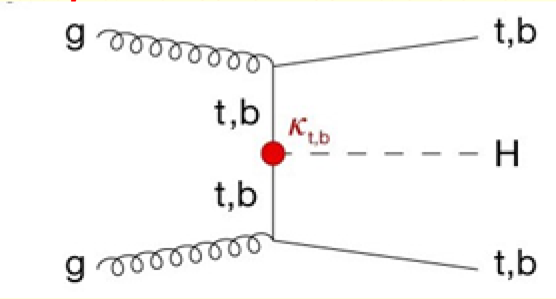
In the Standard Model, it is assumed that the same *H* fields in vacuum give rise to the masses of both

- the electroweak bosons W/Z (and giving rise to electroweak mixing)
- and the matter fermions

This is an assumption – Yukawa couplings *ffH* are added "by hand" to the Lagrangian

Crucial to test – does H couple to fermions at all, and with what strengths?





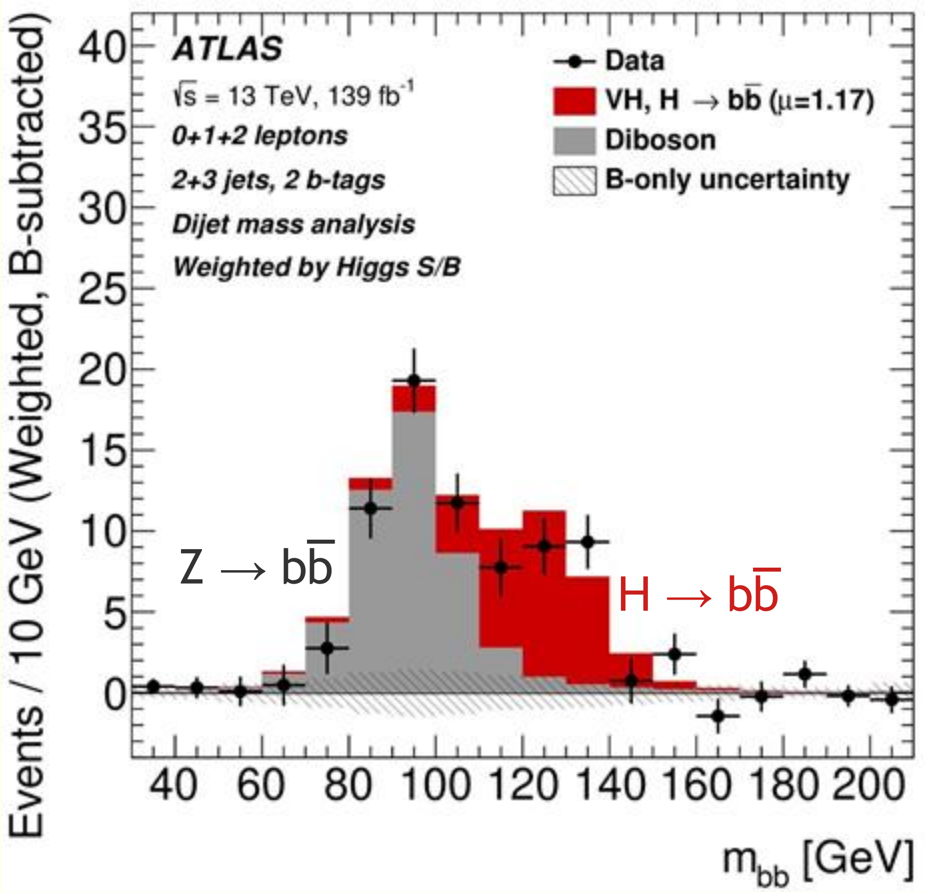
H → b$\bar{b}$ decays

Huge background to H→b$\bar{b}$ from strong interaction production of bb

Strongly reduced by looking for H→b$\bar{b}$ in events with a leptonic V=W or Z decay

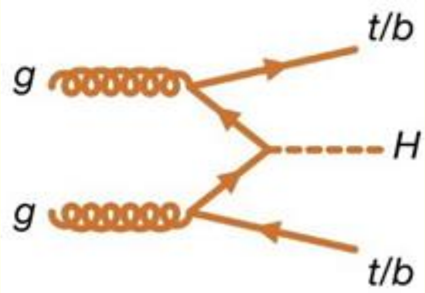
- VH production
  - V→ℓℓ, ℓv or vv
  - H→b$\bar{b}$

Background from V+bb production can be subtracted → shape shown



Clear observation of H→b$\bar{b}$, alongside Z→b$\bar{b}$ in VZ events

H production with top quarks - $t\bar{t}H$ production

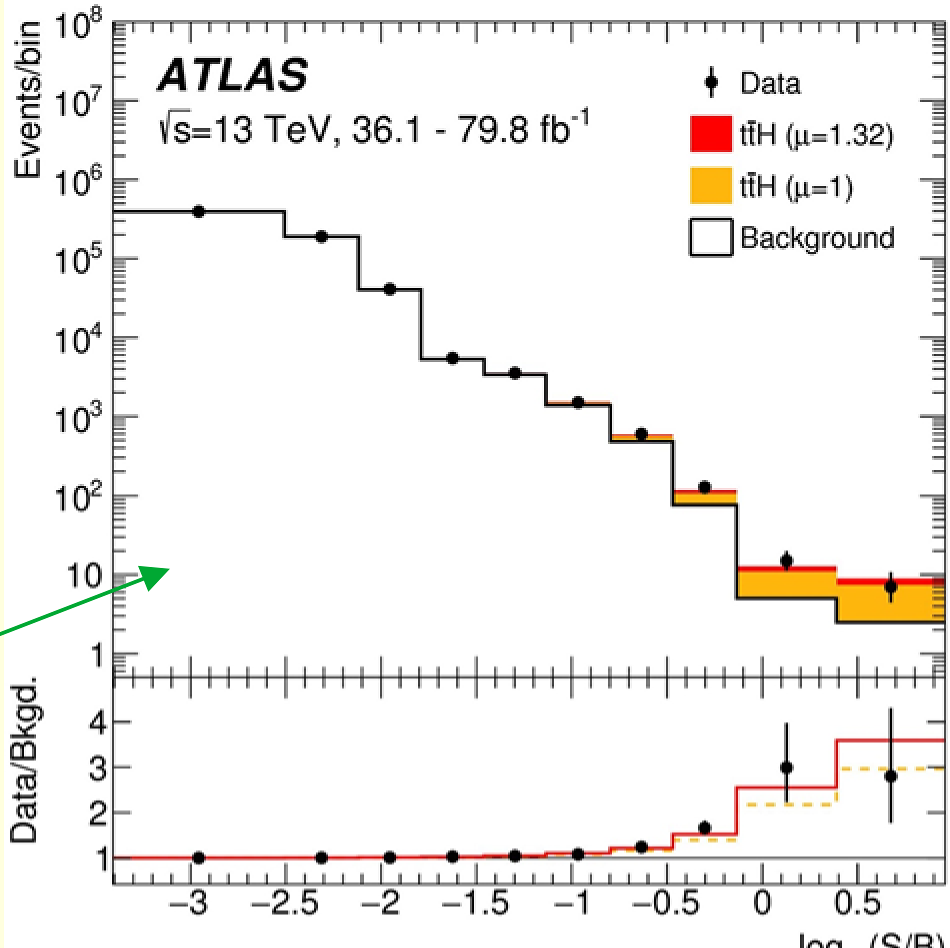


Complex analyses

- Different $t\bar{t}$ decay final states
- Multiple H decay modes included (bb, WW*, γγ, ττ, ZZ*)
- Multivariate discriminants used in multiple signal regions

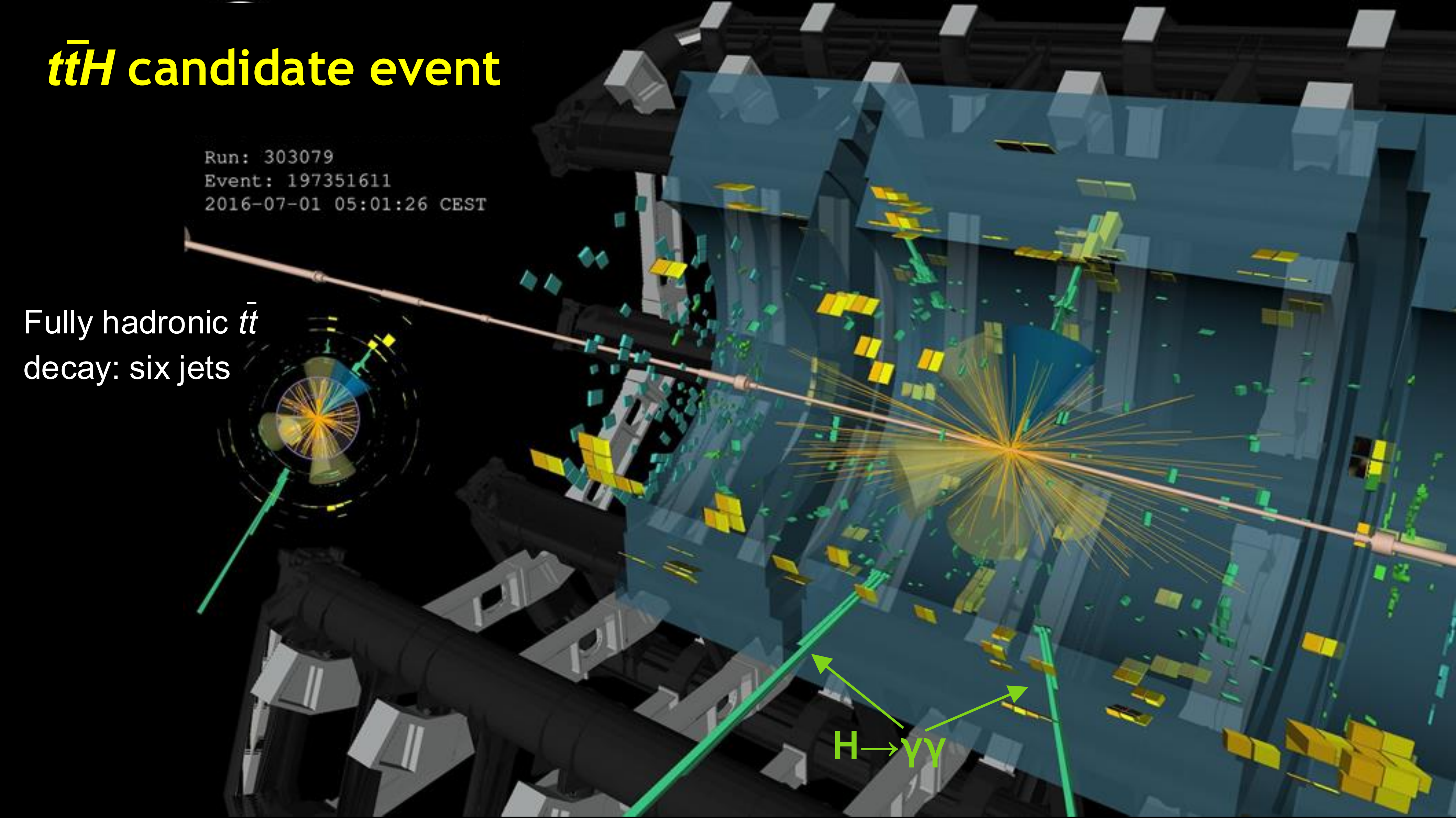
Distribution of S/B significance for selected events

Overall signal significance >6σ



Phys. Lett. B 784 (2018) 173

$t\bar{t}H$ candidate event



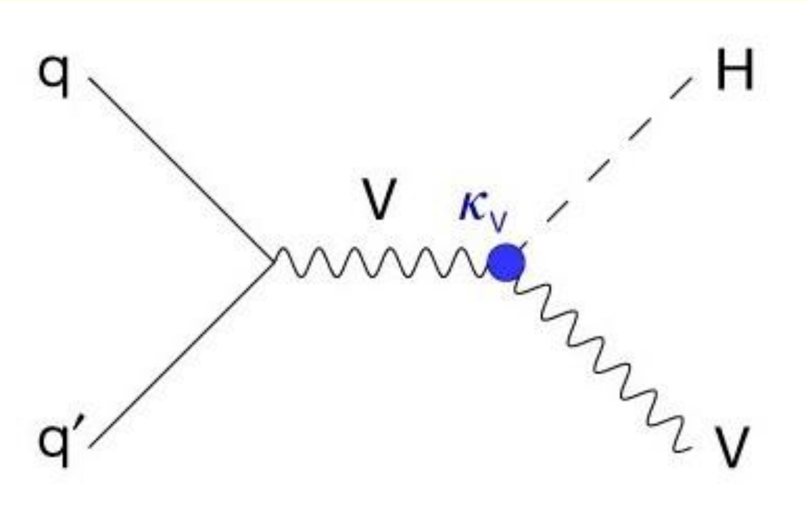
H couplings

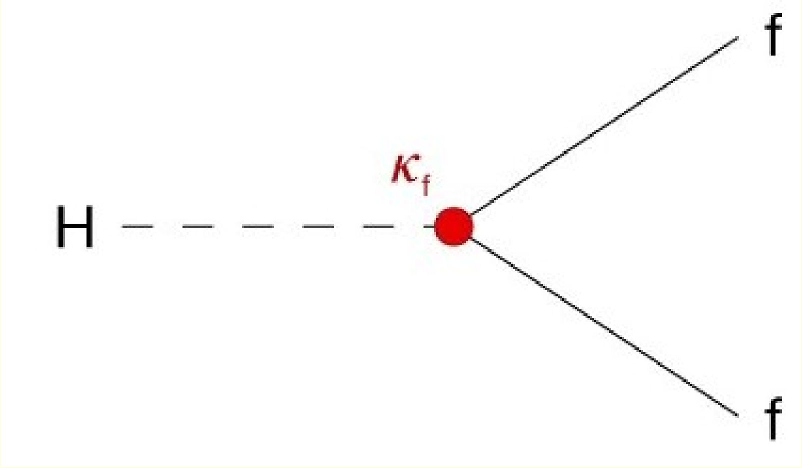
Conventional to consider coupling strengths at H Feynman-diagram vertices relative to the SM prediction

- H production cross-sections scale with appropriate $\sigma \sim (\kappa_{initial})^2$
- H decay rates $\Gamma_{final} \sim (\kappa_{final})^2$

So-called "κ framework"

Many detailed analyses – simple examples here





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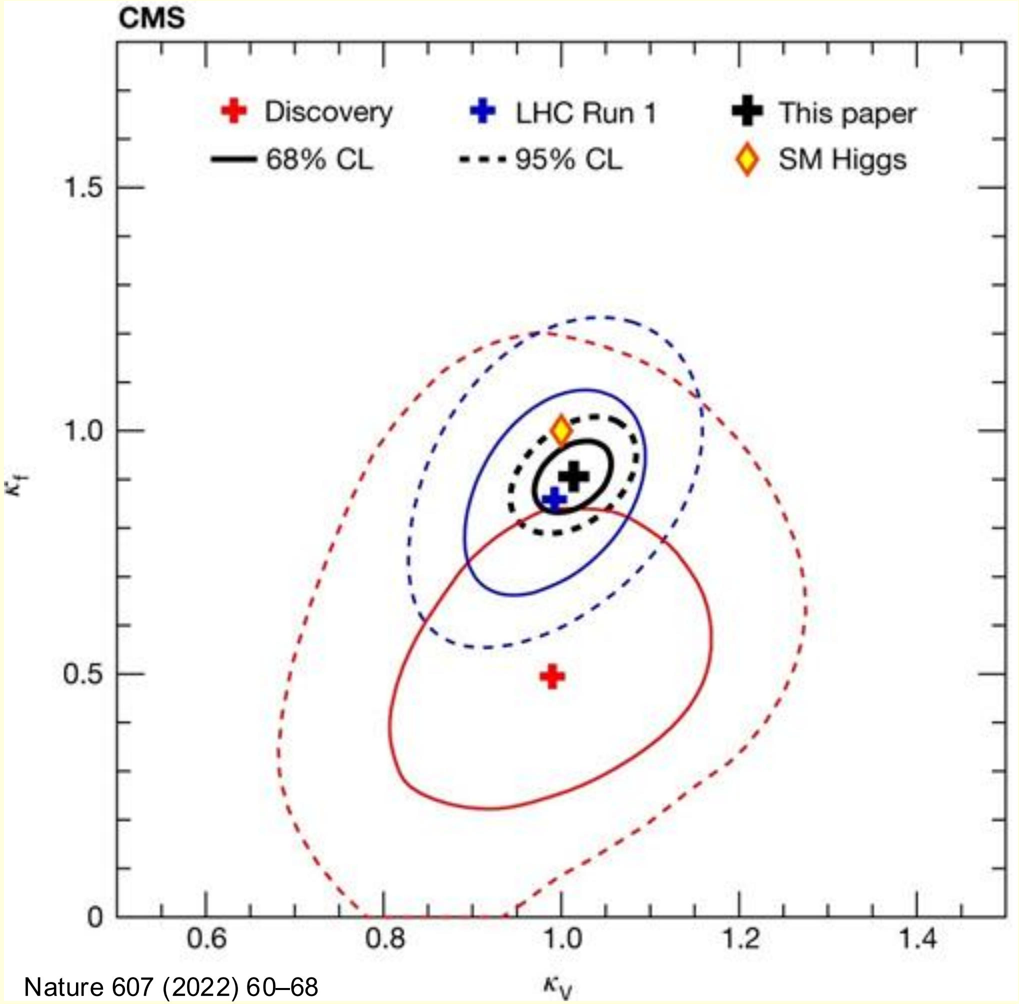

Nature 607 (2022) 60–68

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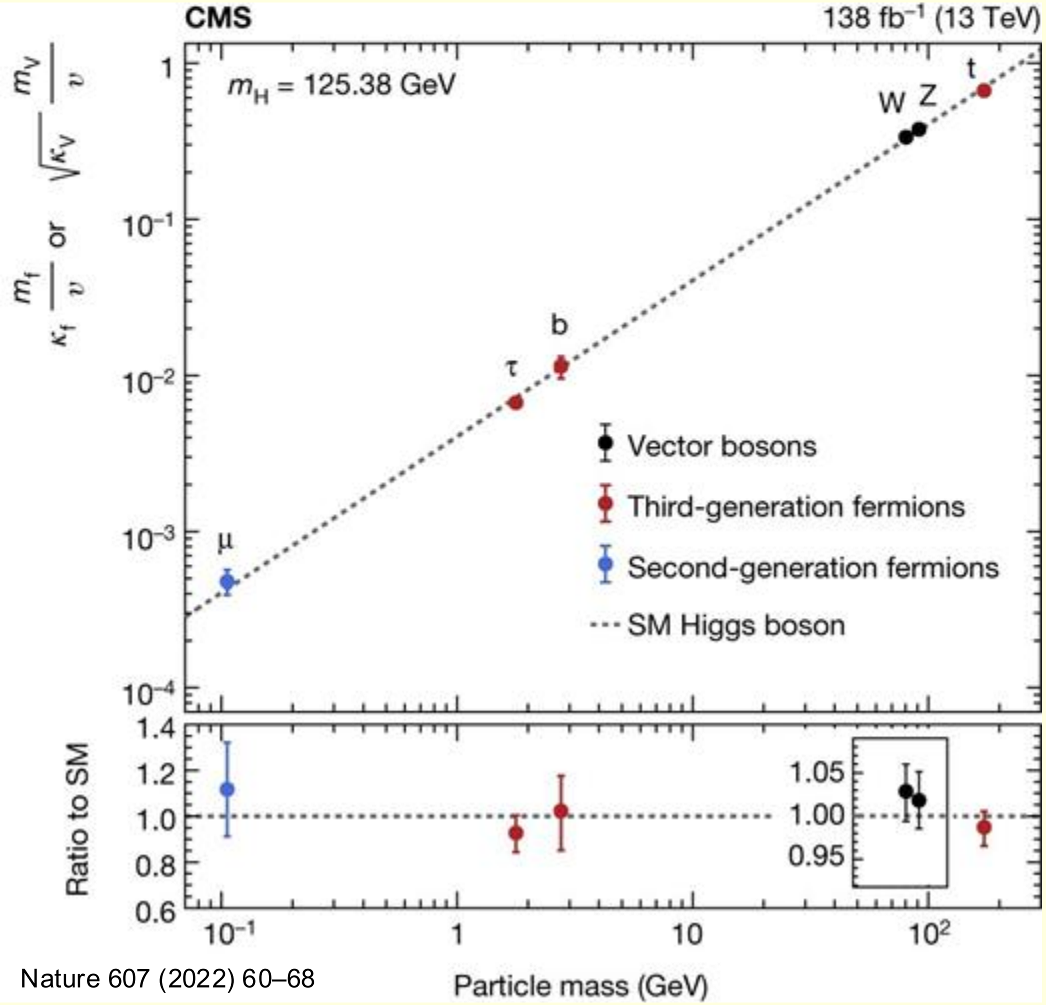


Nature 607 (2022) 60–68

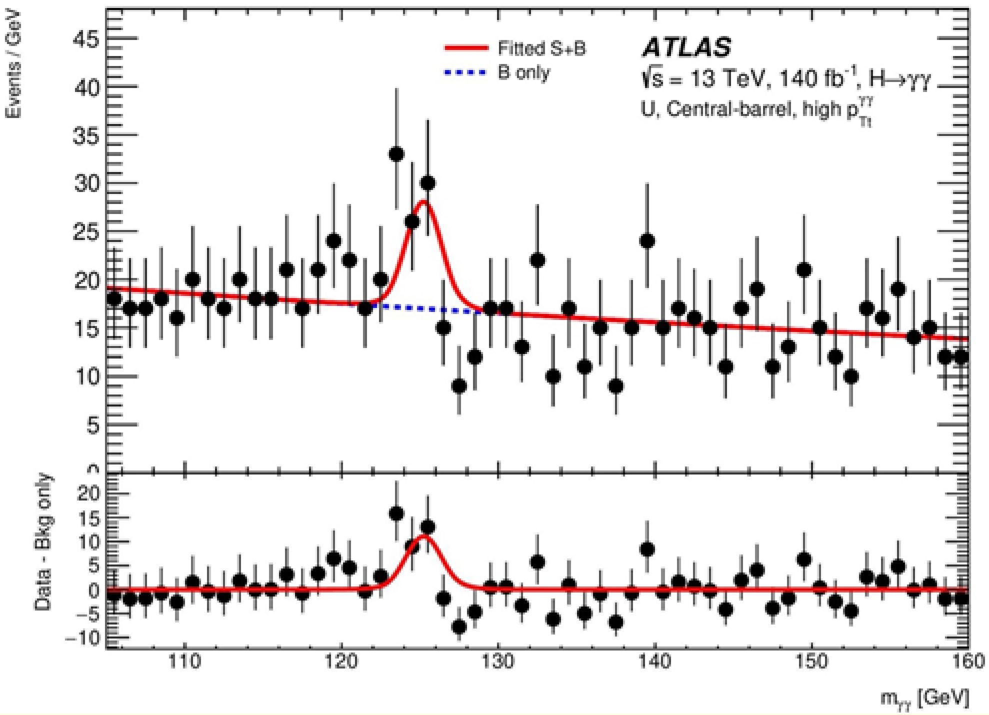
H mass measurement

Precise measurements possible if decay fully reconstructed into well-measured objects

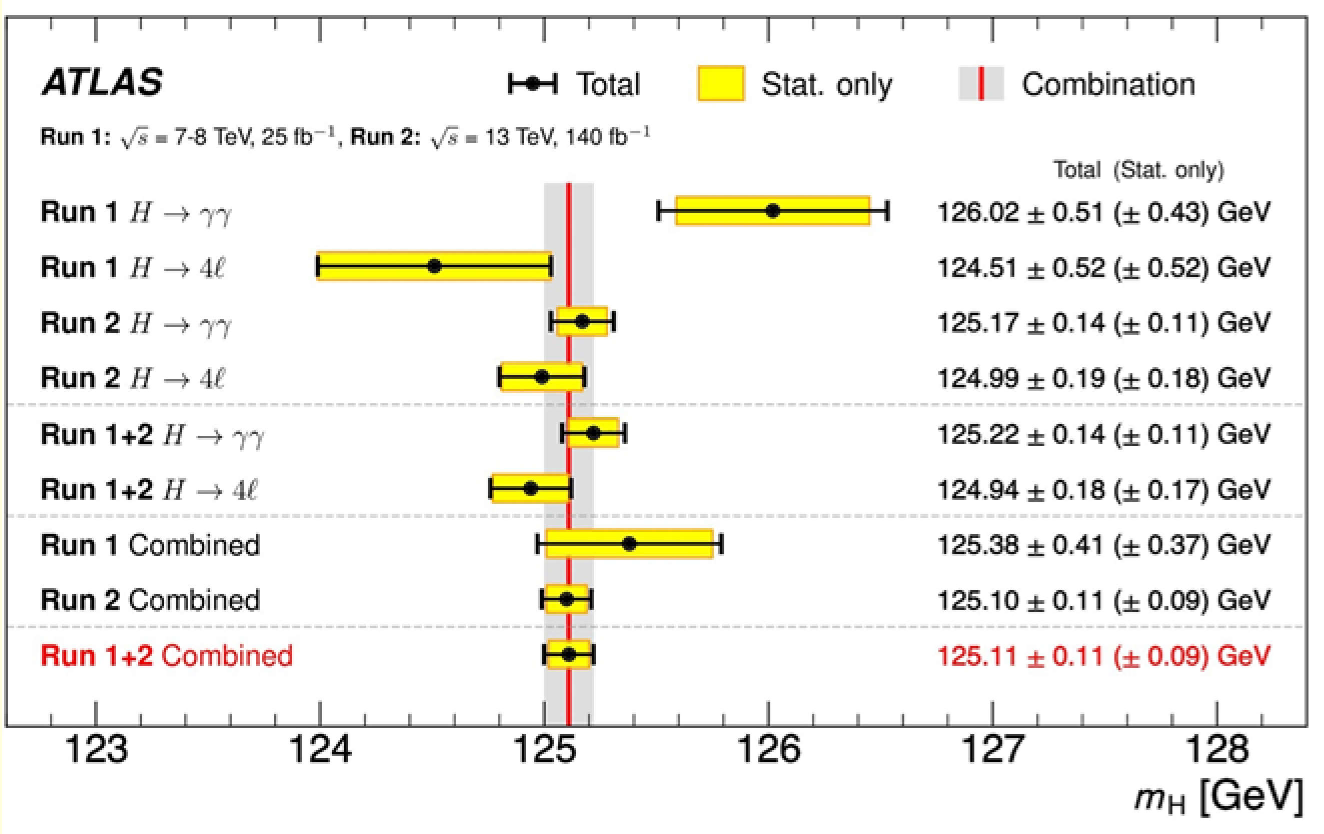
- H → γγ
- H → ZZ* → 4μ or 2μ2e or 4e

Fit the invariant mass distribution with background a signal shape

- Categorise events by their mass resolution



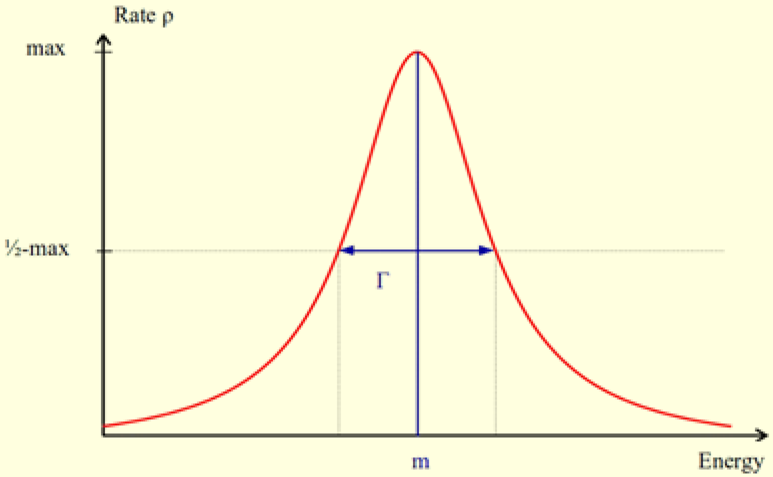
H mass measurement



Overall ATLAS m_H measurement precision
± 0.09%

CMS' latest average
m_H = 125.38 ± 0.14

H width



SM predicts the decay width of H boson

$\Gamma_H(SM) = 4.1$ MeV

Much smaller than

Γ_z (2.5 GeV) or Γ_{top} (~1.3 GeV)

Cannot measure Γ_H directly from the reconstructed lineshape (as we did for the Z at LEP!)

Why do we care?

- Similarly to the Z decay case (LEP, last time)

$$\Gamma_H = \sum_j \Gamma_j = \sum_{\text{measured } j} \Gamma_j + \sum_{\text{visible, unmeasured } j} \Gamma_j + \Gamma_{\text{inv}}$$

- In the H case, unlike for the Z at LEP, we expect many unmeasured H decay modes we haven't been able to detect in the messy pp collisions at the LHC

Probing the H width

One way to probe H width

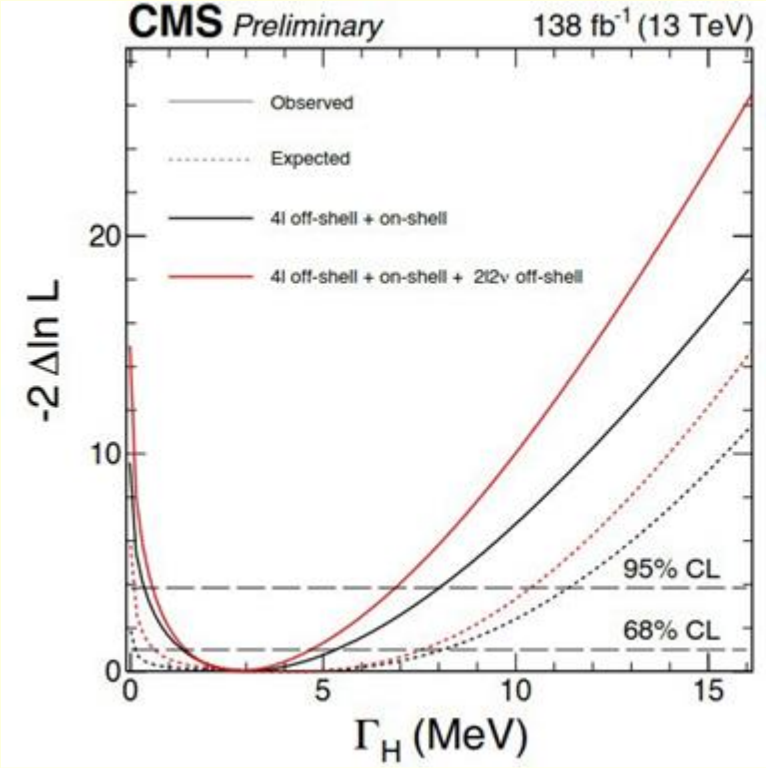
- Measure H production in 4ℓ channel around m_H – "on-shell production"
- Measure 4ℓ production for m(4ℓ)>>m_H and deduce the "off-shell" H contribution

Assuming that there is no other new physics affecting the H *couplings* with energy

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$$

CMS: $\Gamma_H = 2.9^{+1.9}_{-1.4}$ MeV

ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV



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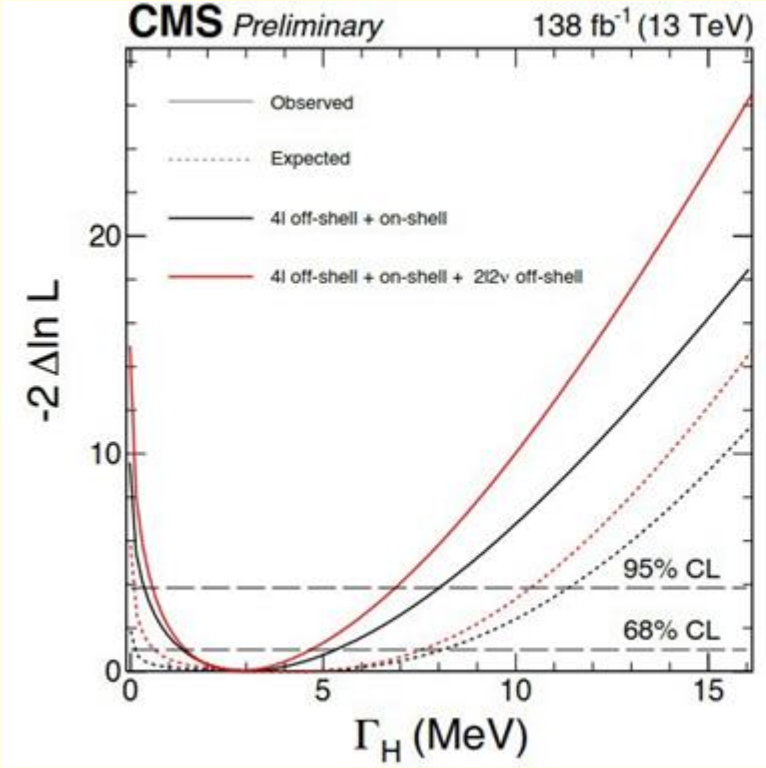
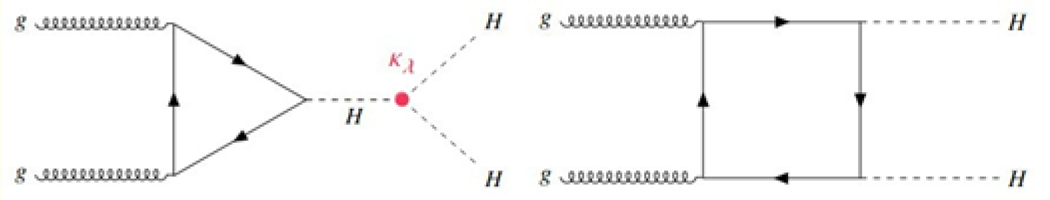


Assumptions made here are debatable…

Precision investigation of Higgs width and search for unobserved decays is a vital consideration for future colliders

H pair production



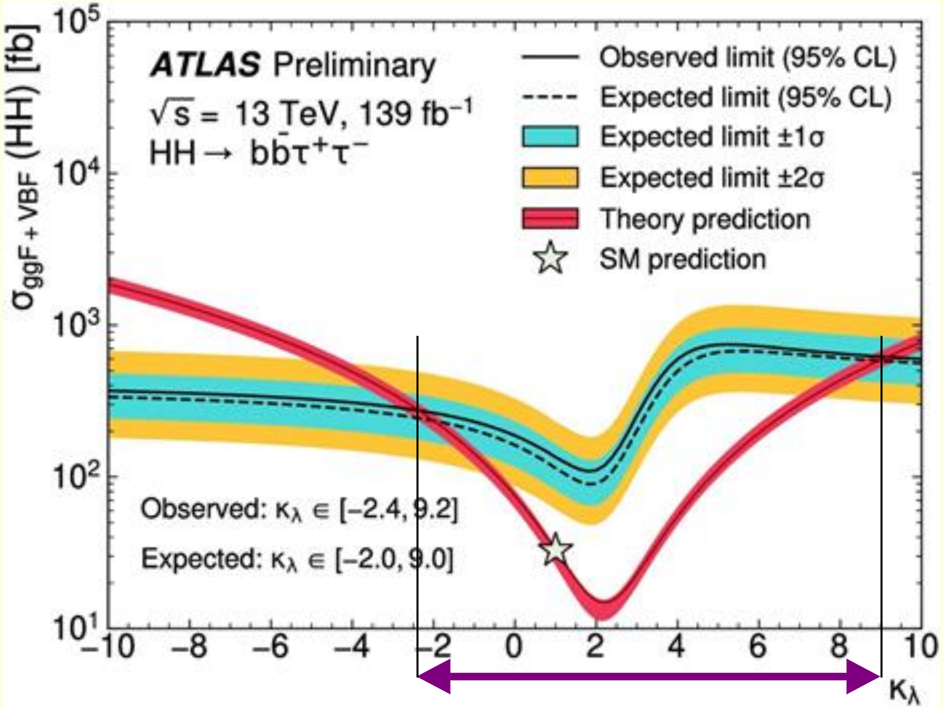
H couples to itself – of course: it is massive!

The *strength* of the Higgs self-coupling, κ_λ, needs to be measured to fully understand the shape of the Higgs potential

Di-Higgs production is sensitive to κ_λ

- Cross-section is very low, and effect of the triple-H vertex is negative interference in the SM!
- Current best ATLAS limit is that σ(HH) is not more than 3.1x SM expectation at 95% CL

Limits on κ_λ, shown right



Not excluded at 95% CL

We want to do much better – and to measure κ_λ!

Summary of part II

- Calculational technology to predict cross-sections of Standard Model process at the LHC is now pretty sophisticated (NLO, NNLO ...)
- Many processes have been measured, and generally are well described by the Standard Model
  - Measurements now often more precise than the predictions
    - Work for the theorists!!! (and experimenters, e.g. to constrain better the pdfs)
- Only a small part (<10%) of the LHC data sample has been collected – there is much more to explore, including precise measurements, and advancing our understanding of QCD and electroweak physics
- The hunt continues for other signs of new physics at the LHC...