SM Measurements at the LHC
QCD, Electroweak and Top Physics

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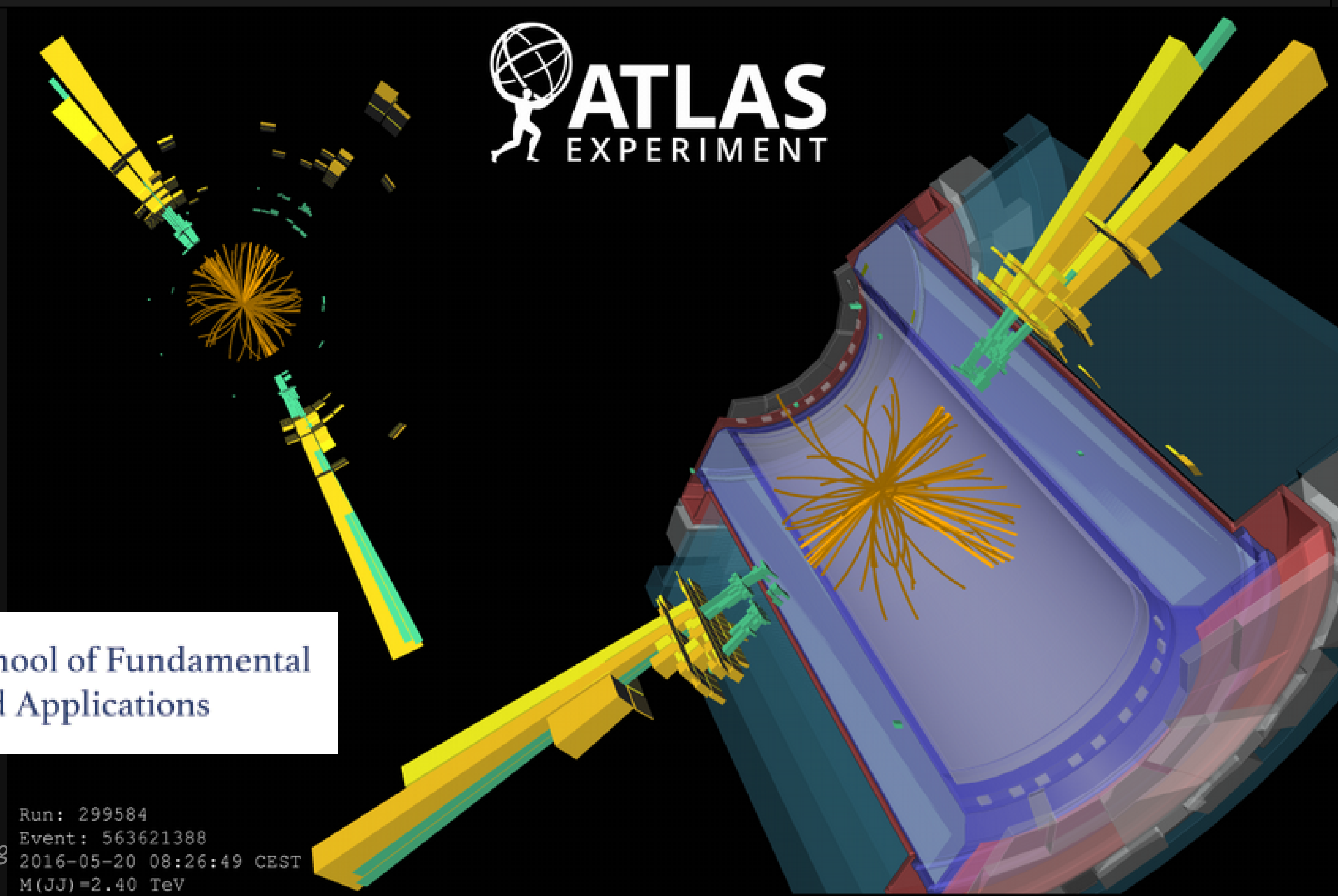
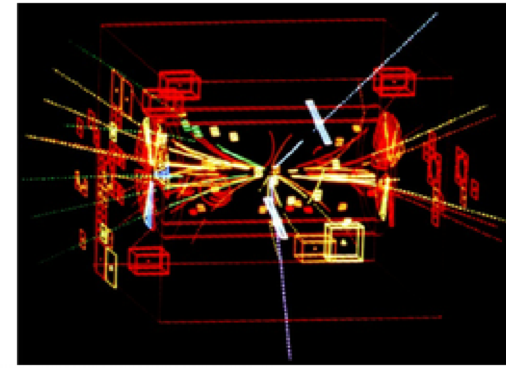
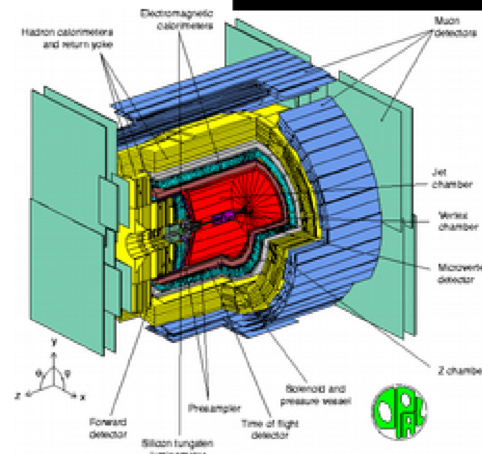


African School of Fundamental Physics and Applications

Dave Charlton



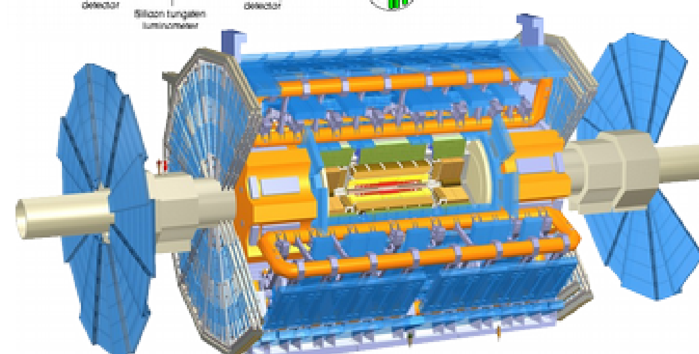
About me:



- PhD student on UA1 experiment 1985-1988 (search for the top quark)

- Moved at start of 1989 to OPAL experiment at LEP, stayed to the end (2000) – electroweak physics with Z and W bosons

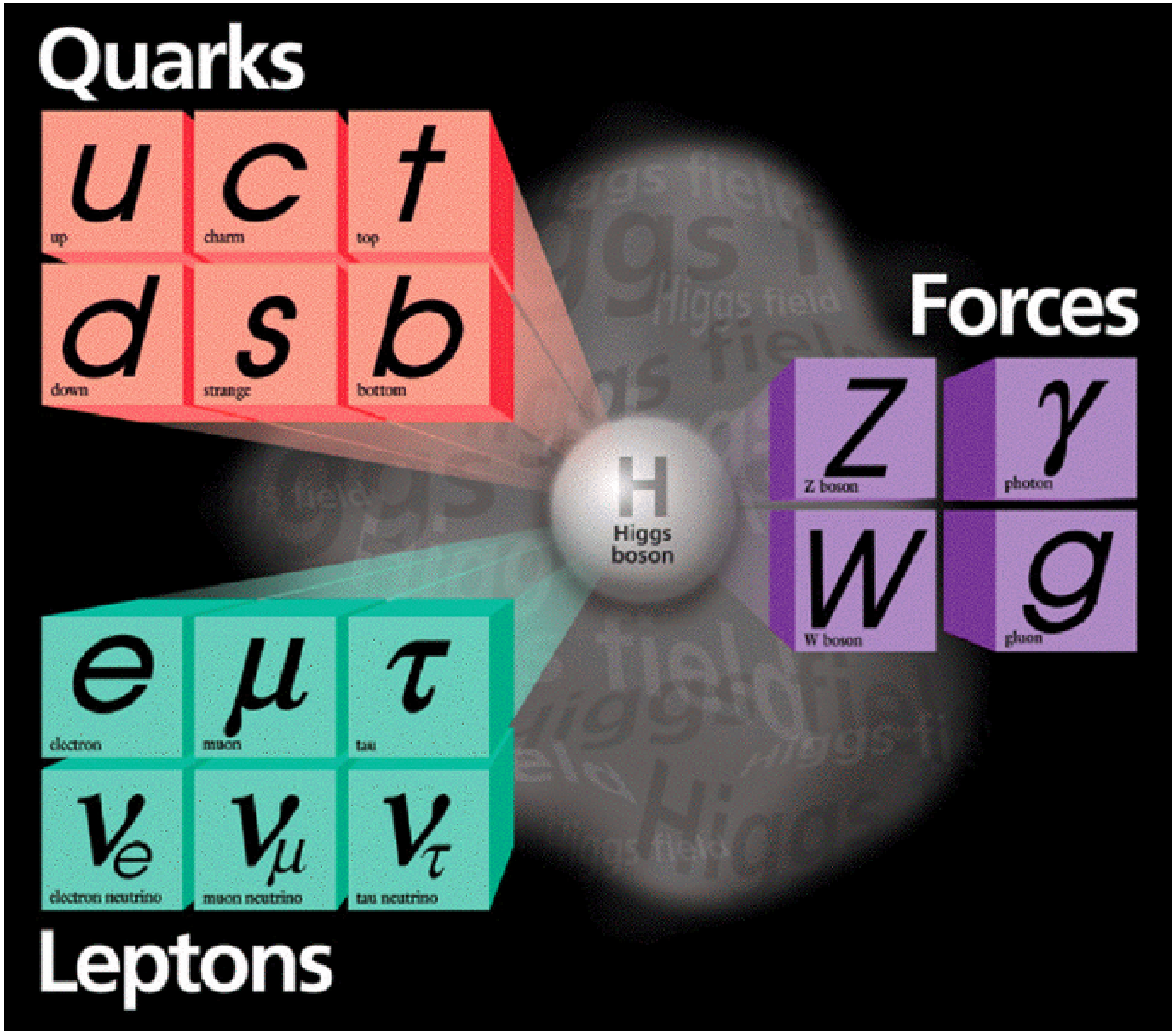
- Since 1998, ATLAS experiment at the LHC at CERN
  - Spokesperson (Head) of ATLAS 2013-2017
  - Previously deputy Spokesperson (2009-2013), Physics Coordinator (2008-2009)
  - Worked on calorimeter triggering, silicon tracker construction, analysis of multi-boson production



- Poynting Professor of Physics at the University of Birmingham in the UK since 2017 (I've been with Birmingham since 1994, professor since 2005)

The Standard Model

Matter Particles



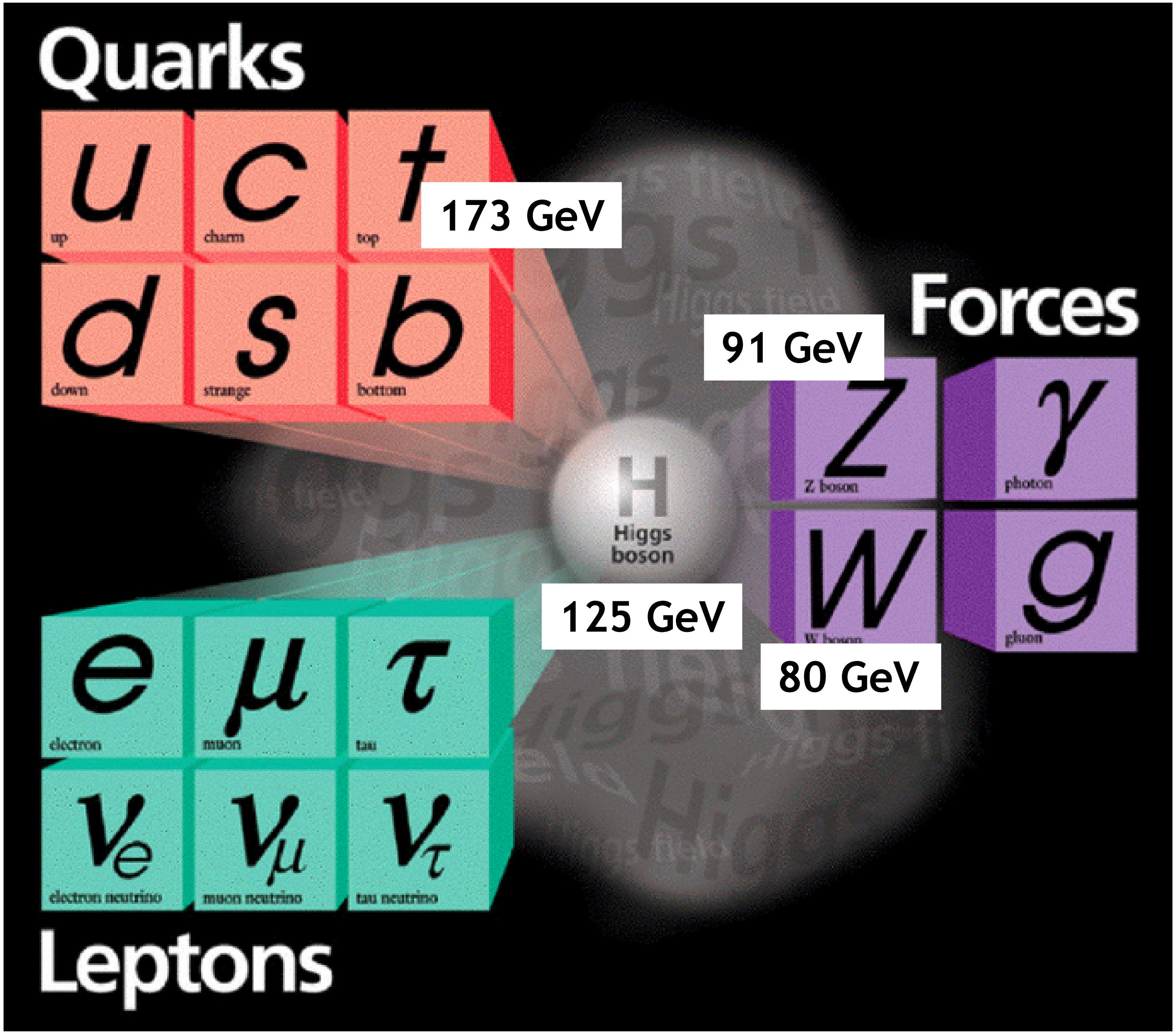
Force-carriers

Fermions

Bosons

The Standard Model

Matter Particles



Force-carriers

Fermions Bosons

Rates, luminosities and cross-sections

In a collider, the rate, dN_a/dt, of events produced for a given process *a* is:

$$dN_a/dt = \sigma_a L$$

where

- σ_a is the *cross-section* for the process
  - units of area (1 barn = 10^{-28} m^2 = 10^{-28} cm^2)
  - typically mb, μb, nb, pb and fb are (all) met for different processes!
  - it depends on the physics process, eg. pp → W + anything and the centre-of-mass energy $\sqrt{s}$
- L is the instantaneous luminosity, usually called the luminosity
  - units of inverse-area per unit time (typically ~10^{34} cm^{-2} s^{-1} at LHC)
  - Process-independent, depends only on the beam characteristics

Integrated version:

$$N_a = \sigma \int L dt$$

Where $\int L dt$ is the integrated luminosity, typically expressed in fb^{-1}

LHC physics landscape

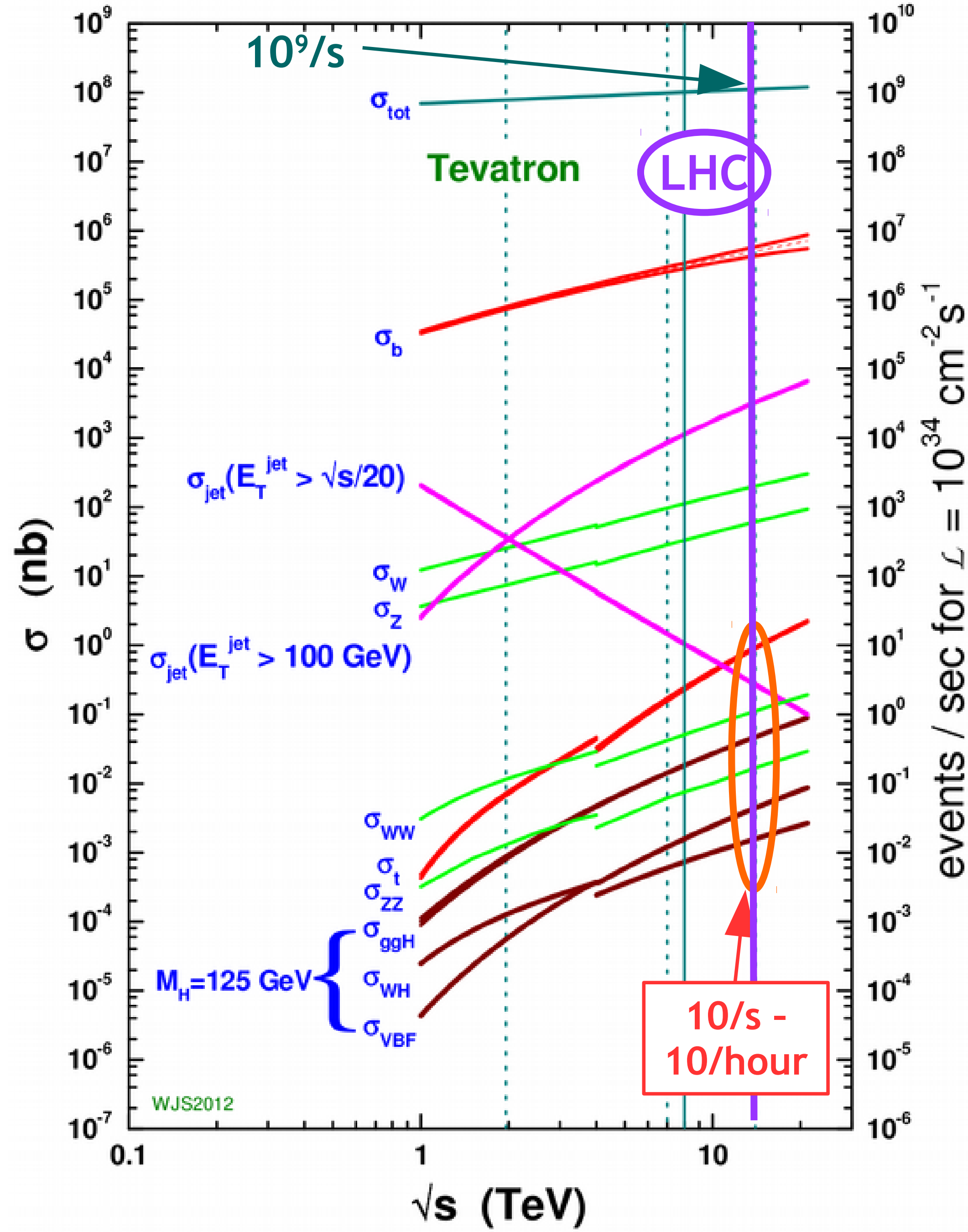
Cross-sections to produce massive particles such as the W, Z, t, (b,) H rise with √s

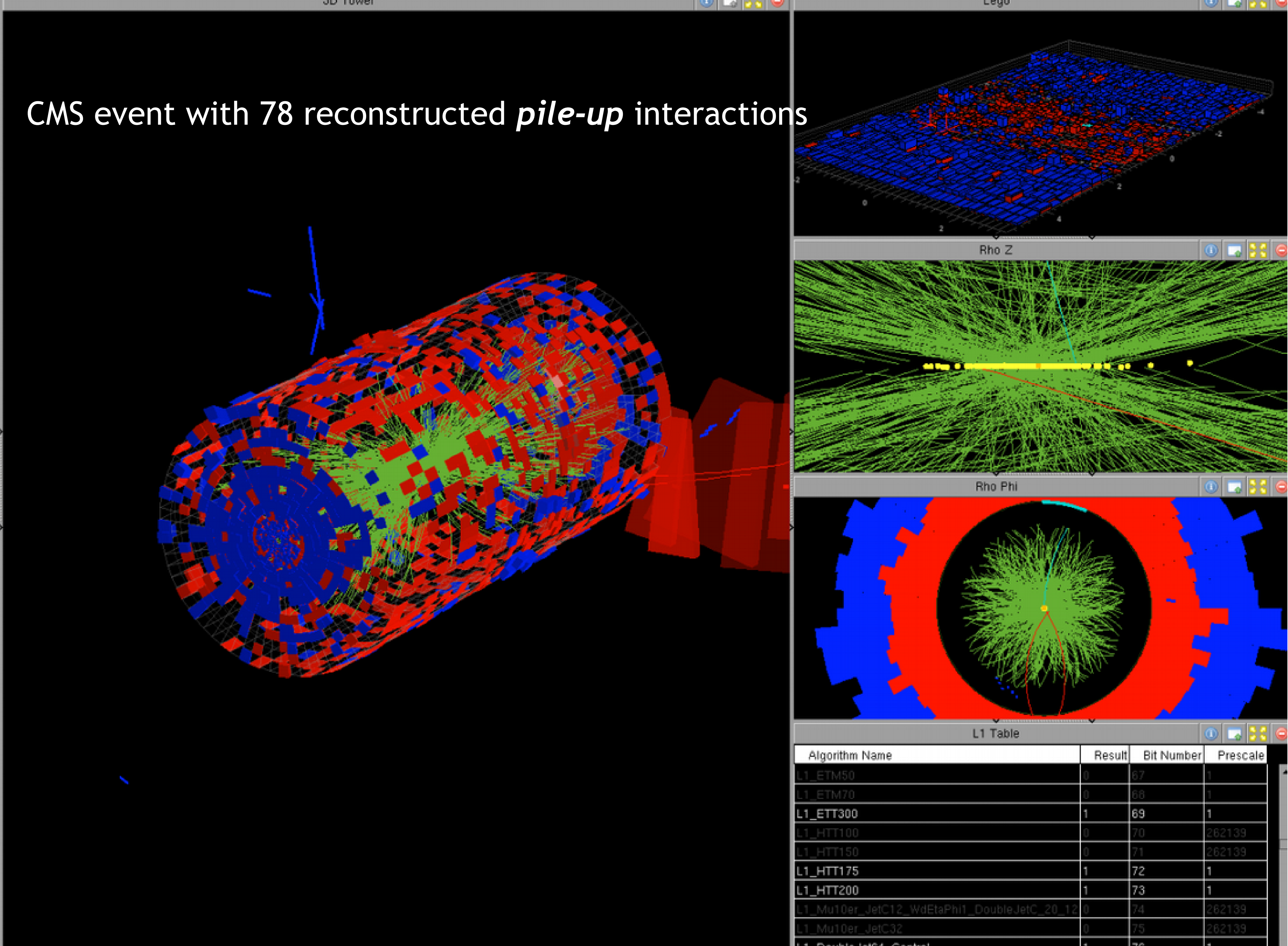
Range of cross-sections for processes studied, and so of their rates, from ~0.1 b to ~fb i.e. factor O(10^{14})

~10^9 events per second occur in at most 30 million bunch crossings per second

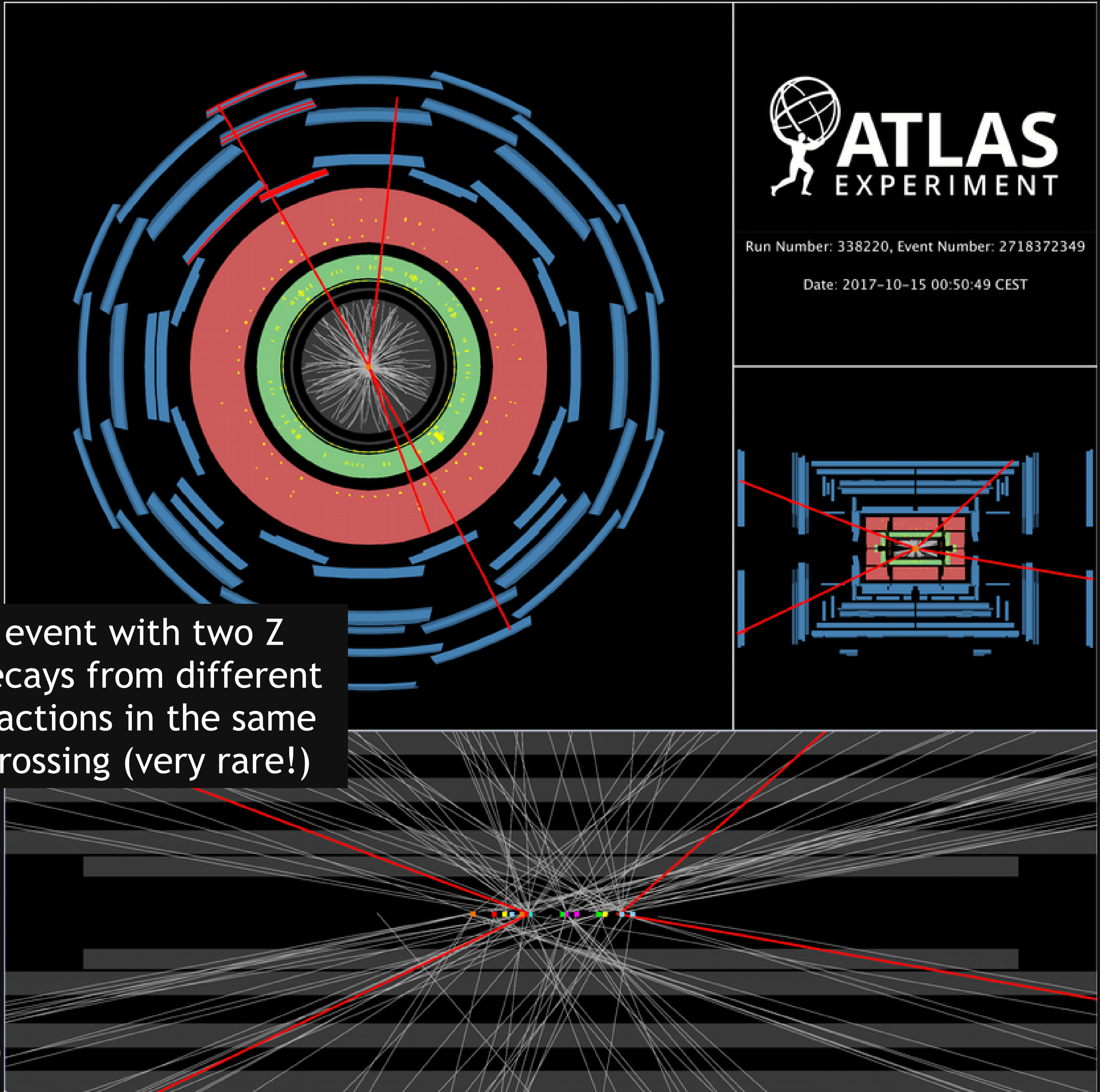
→ 30+ events per bunch crossing

→ “pileup”



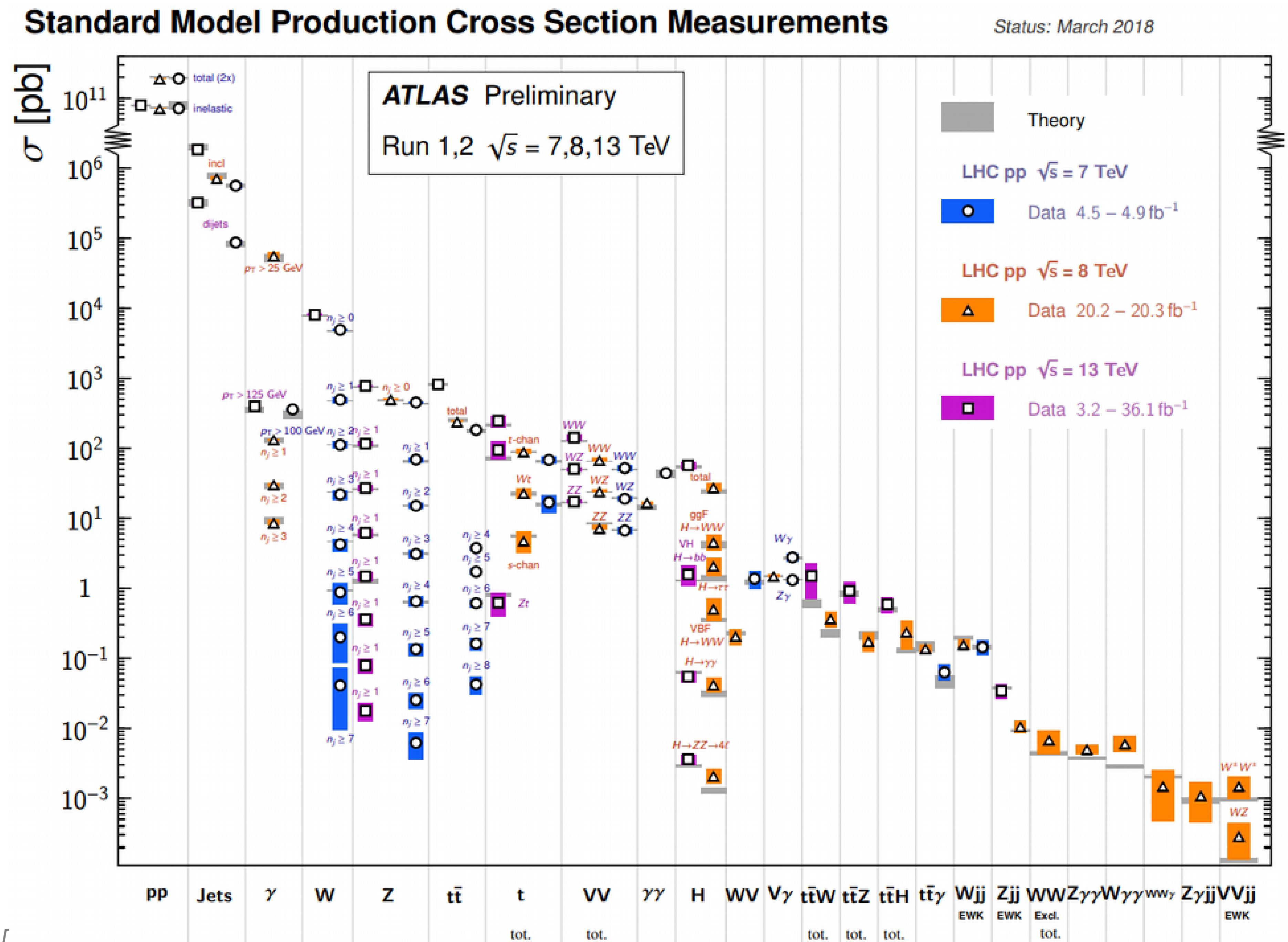


CMS event with 78 reconstructed *pile-up* interactions
Lego
Rho Z
Rho Phi
L1 Table
Algorithm Name | Result | Bit Number | Prescale
L1_ETM50 | 0 | 67 | 1
L1_ETM70 | 0 | 68 | 1
L1_ETT300 | 1 | 69 | 1
L1_HTT100 | 0 | 70 | 262139
L1_HTT150 | 0 | 71 | 262139
L1_HTT175 | 1 | 72 | 1
L1_HTT200 | 1 | 73 | 1
L1_Mu10er_JetC12_WdEtaPhi1_DoubleJetC_20_12 | 0 | 74 | 262139
L1_Mu10er_JetC32 | 0 | 75 | 262139
L1_DoubleJet64_Central | 1 | 76 | 1



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

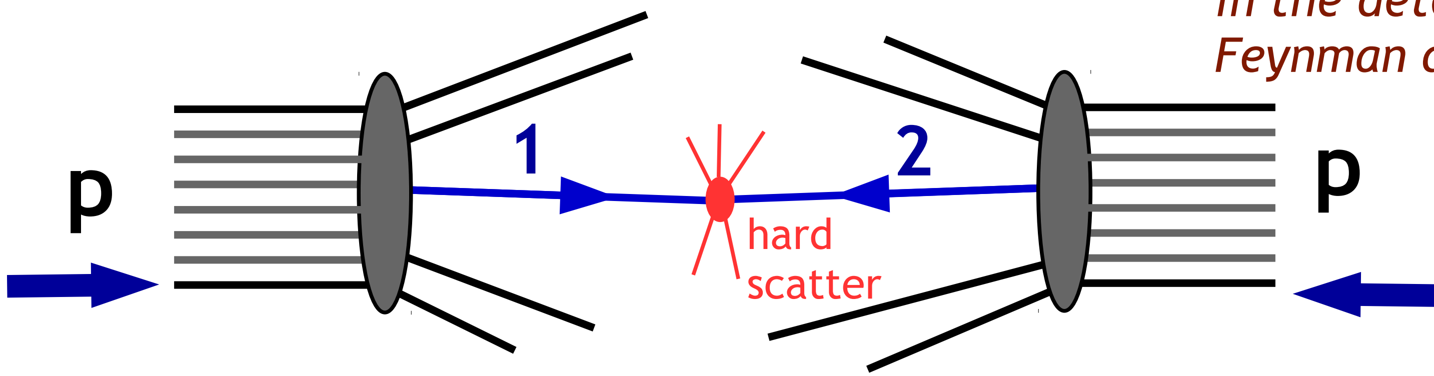
Measured cross-sections



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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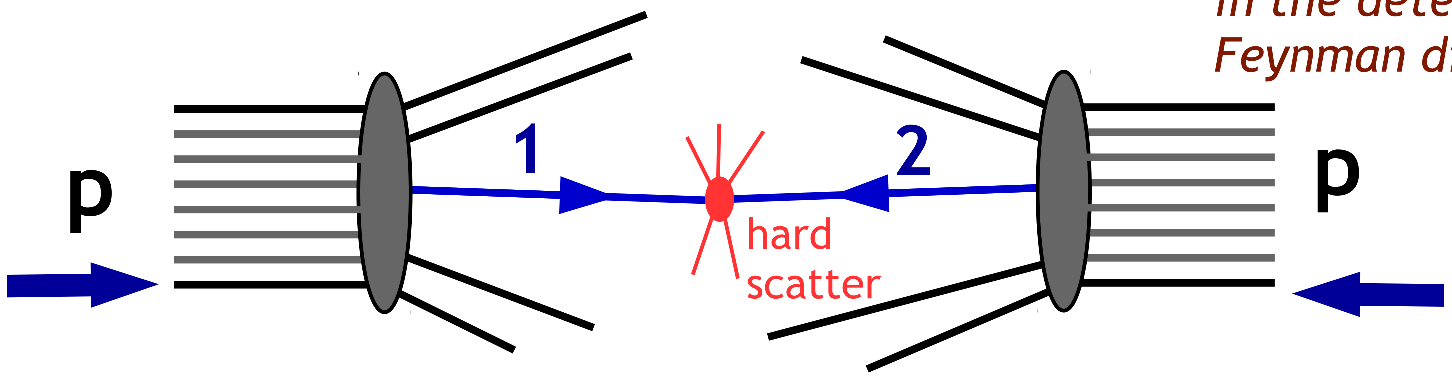


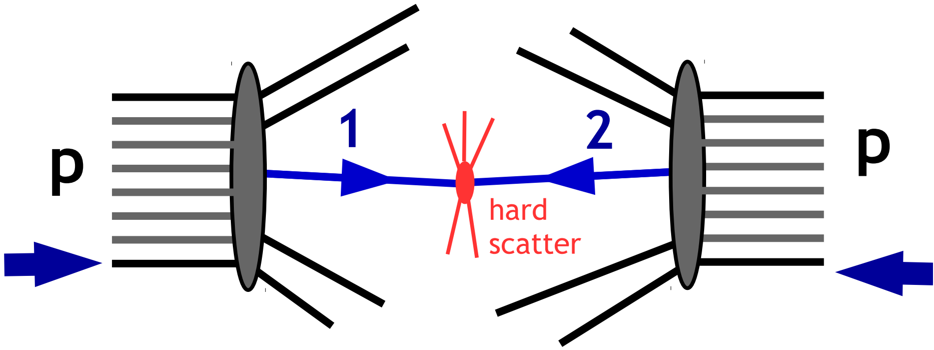
Partons 1 and 2 which collide in the *hard-scattering process* carry fractions x_1 and x_2 of the momentum of their original protons

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

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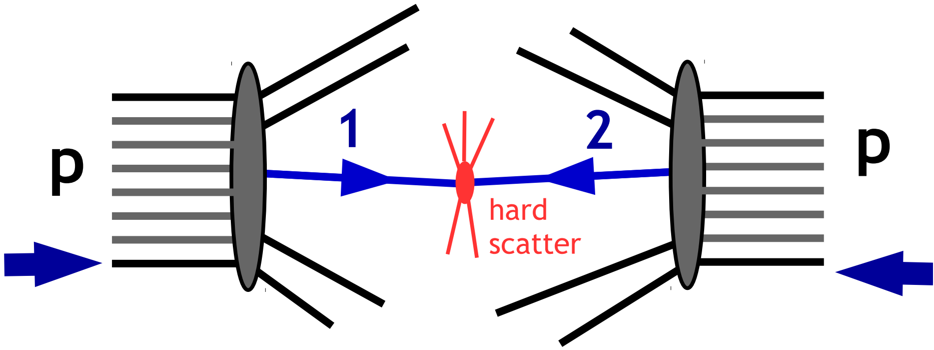


$$\sigma = \iint \hat{\sigma}(s_{12}) f_1(x_1, Q^2) f_2(x_2, Q^2) dx_1 dx_2$$

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 $\sigma(N_{jet})$

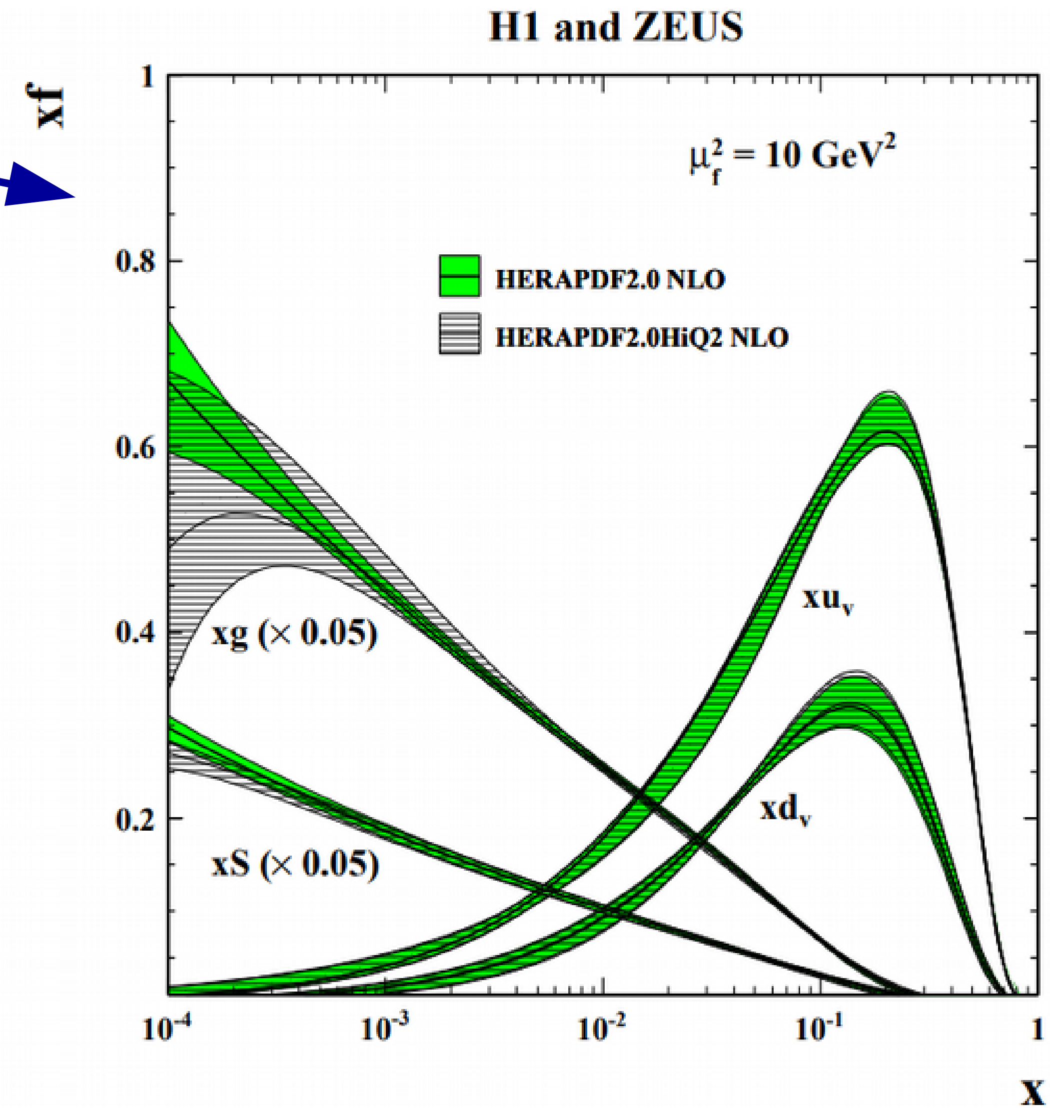
for a specified final-state particle or jet

Parton density functions

Typical parton density functions

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

I've been ignoring Q^2 (~μ_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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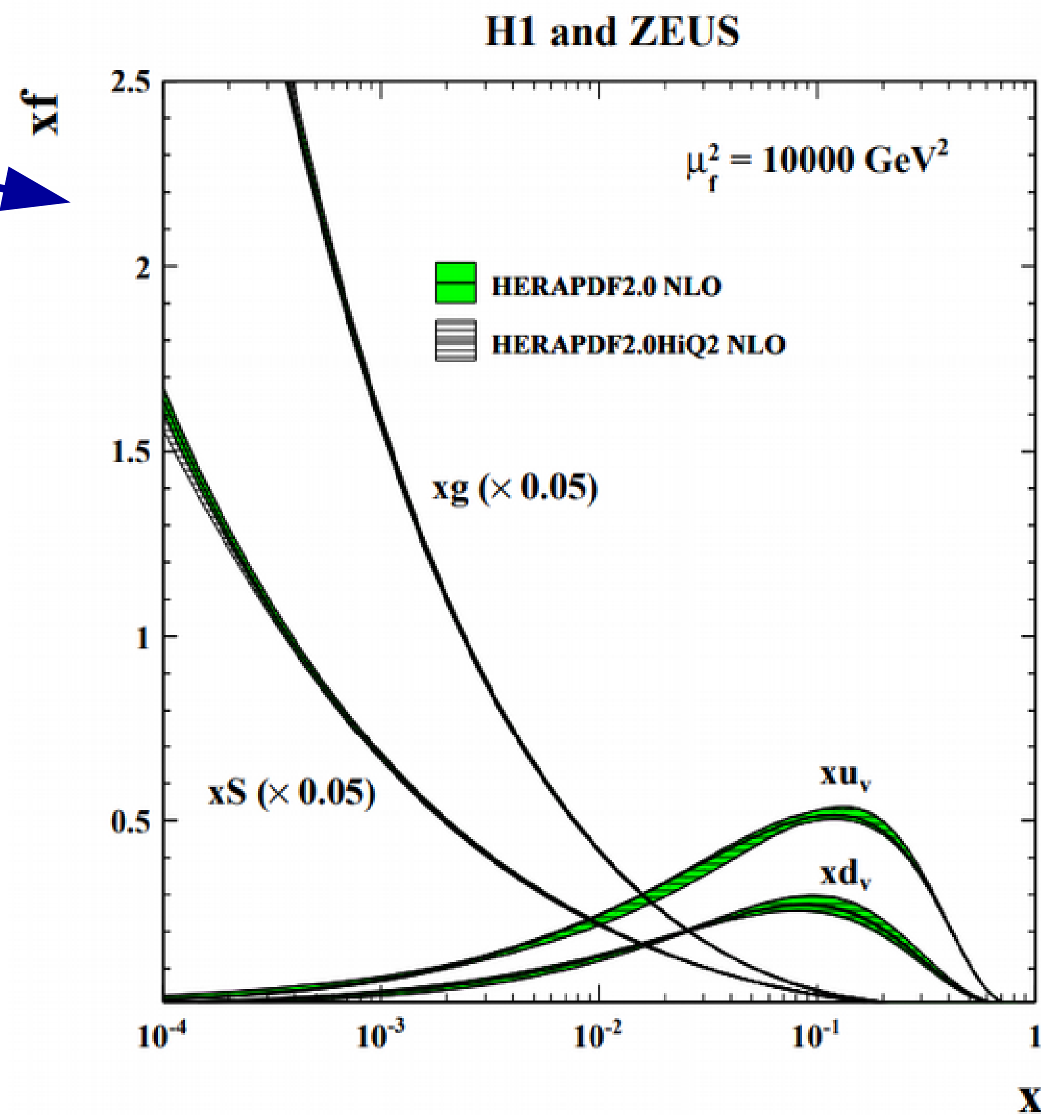
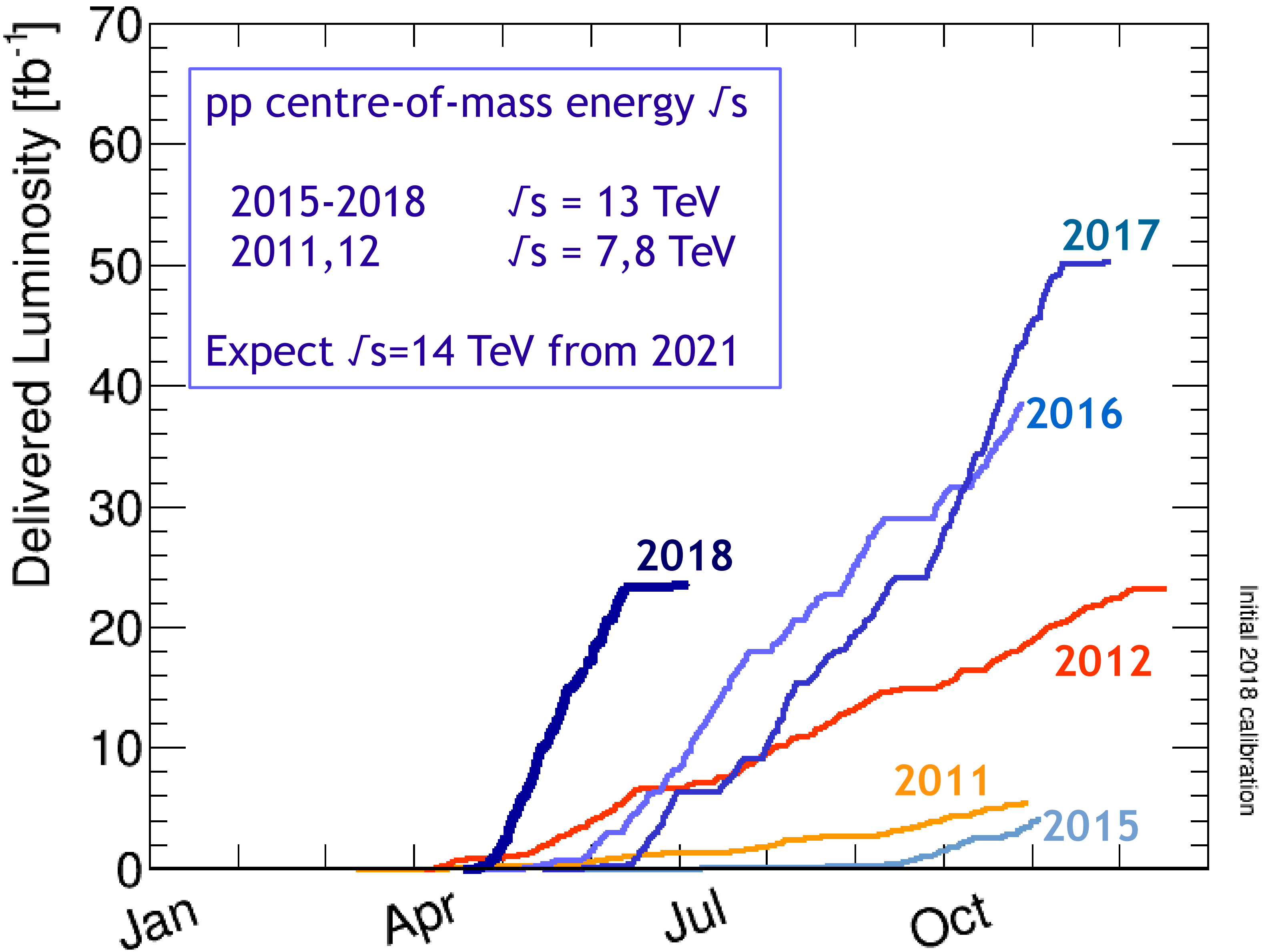
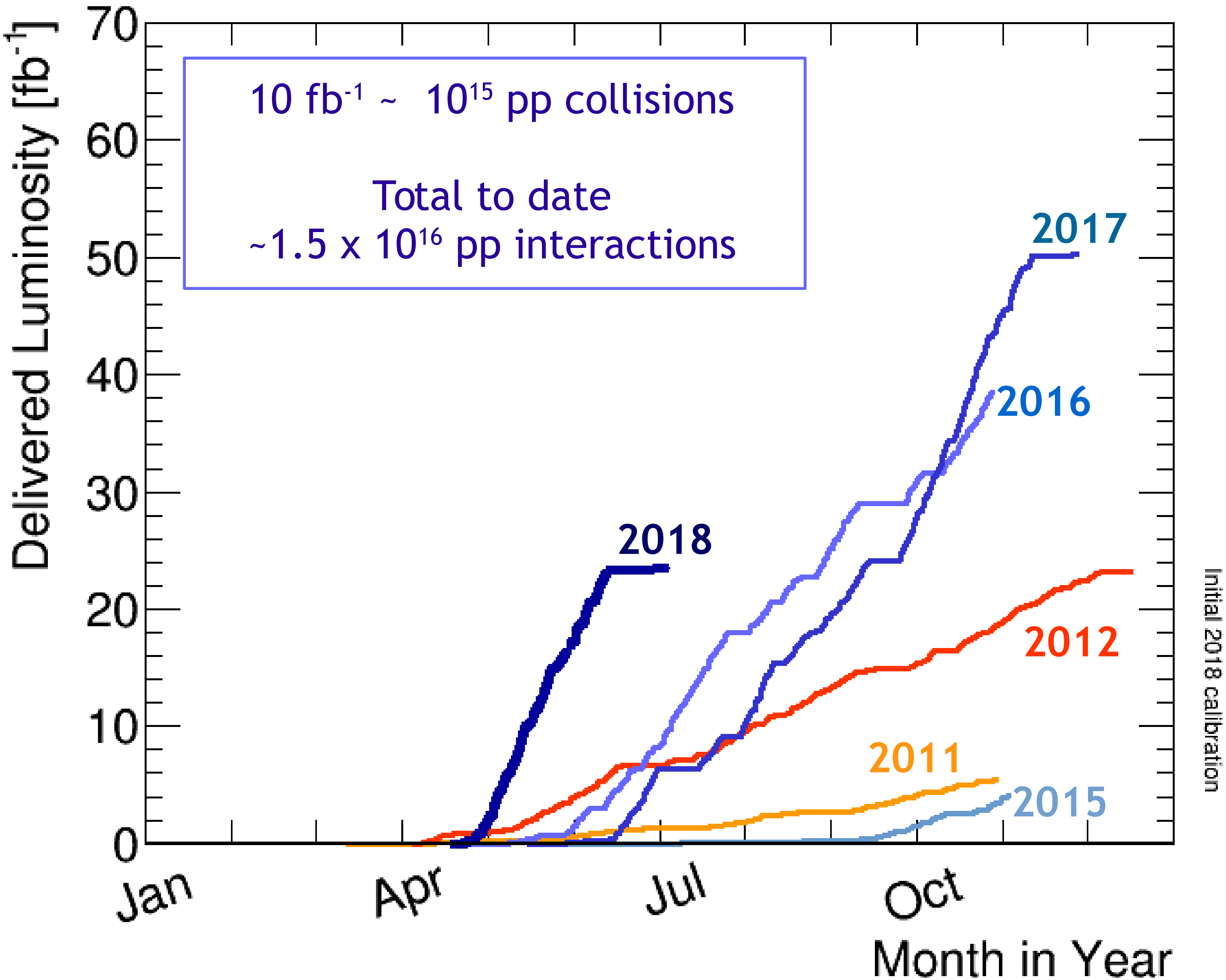
pdfs *evolve* with Q^2, but in a predictable way ("DGLAP")



Back to the LHC: pp data samples



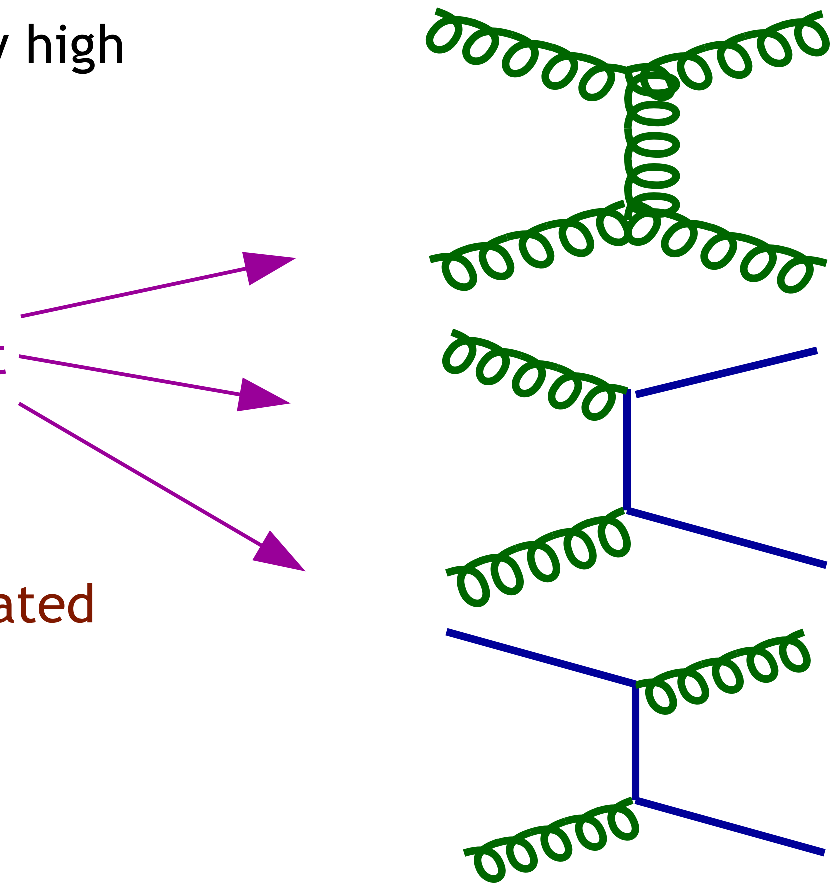
LHC pp data samples



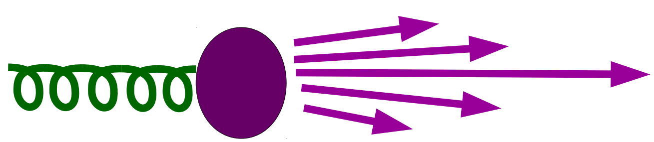
Measuring hadronic jets

Production of hadronic jets has a very high cross-section:

- Strong interaction (QCD) process
- Example parton-level Feynman diagrams, at lowest-order (fewest number of vertices)



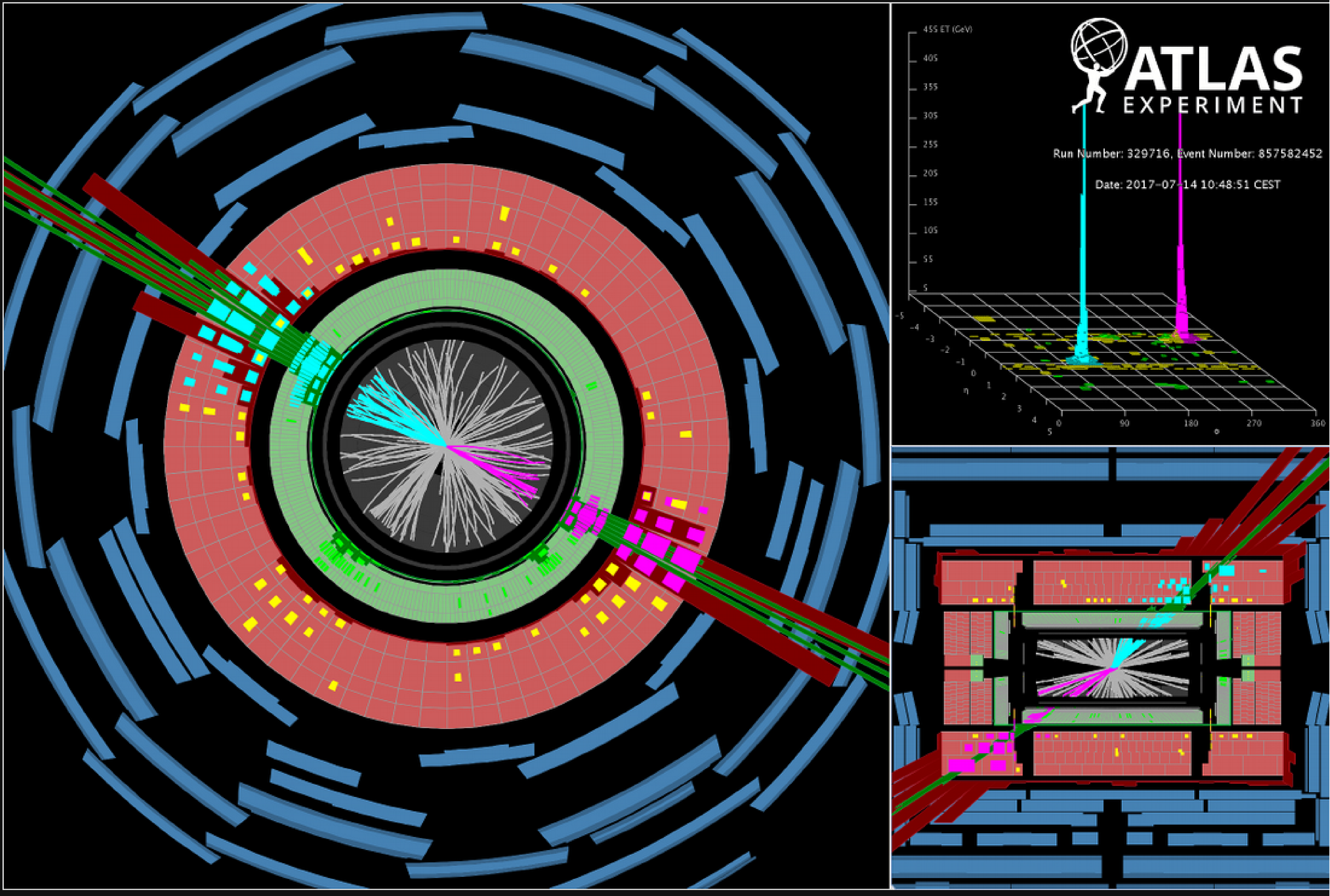
- Outgoing partons turn into collimated jets of hadrons within ~1 fm



"hadronisation"

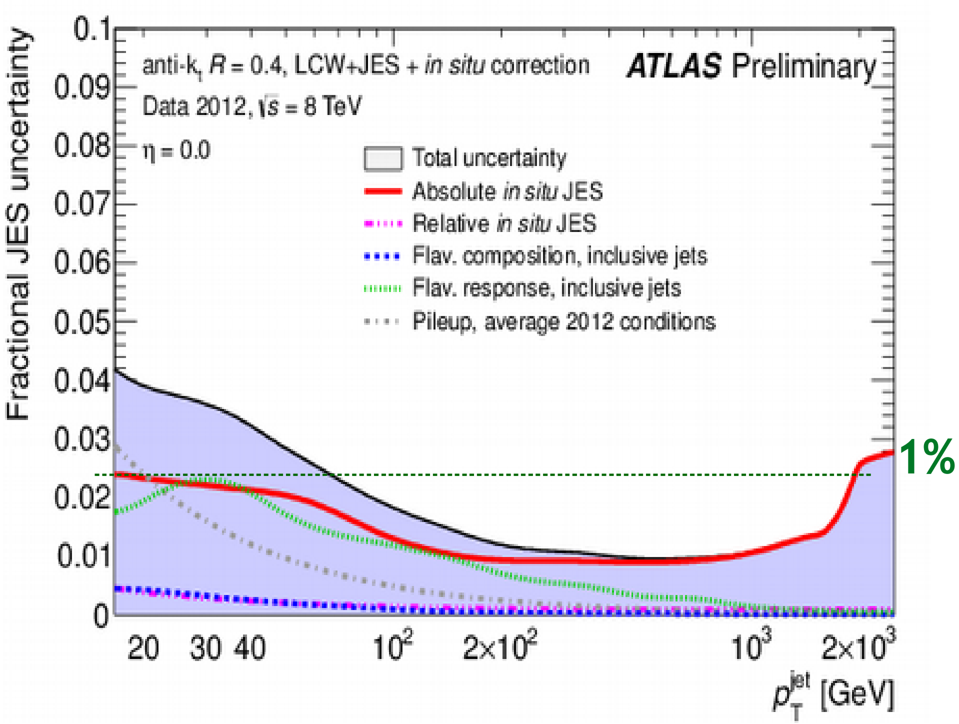
- Reconstruct these "hadronic jets" in the detector to discover the parton configuration using "jet algorithms" *(our favourite one is called "anti-k_t")*

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



Jet cross-sections

Needs best understanding we can get of the energy of jets
→ Jet energy scale ("JES") uncertainty
This takes a long time (years), lots of careful work



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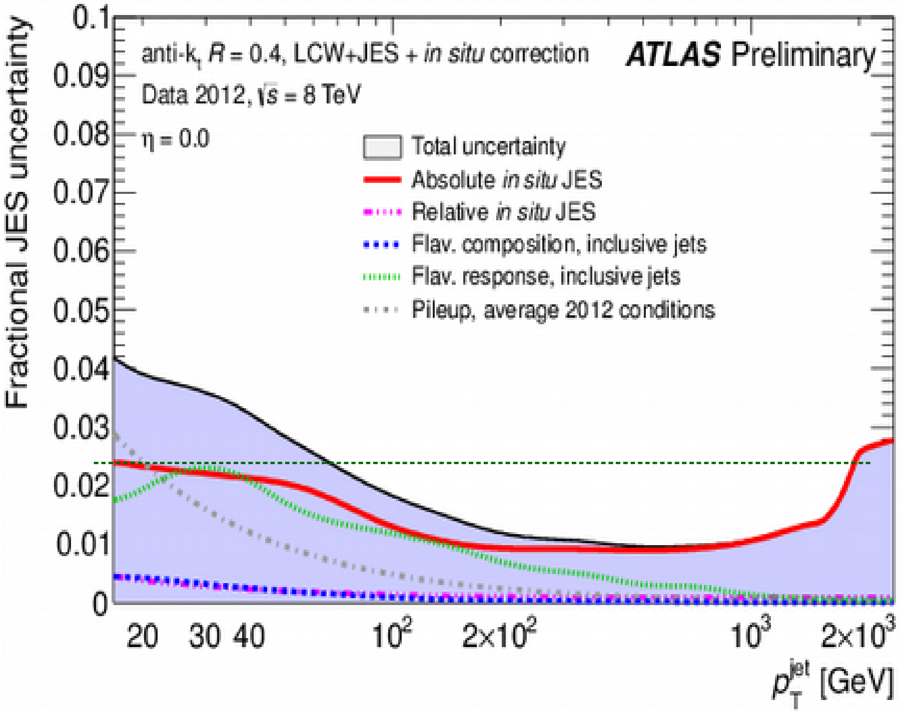
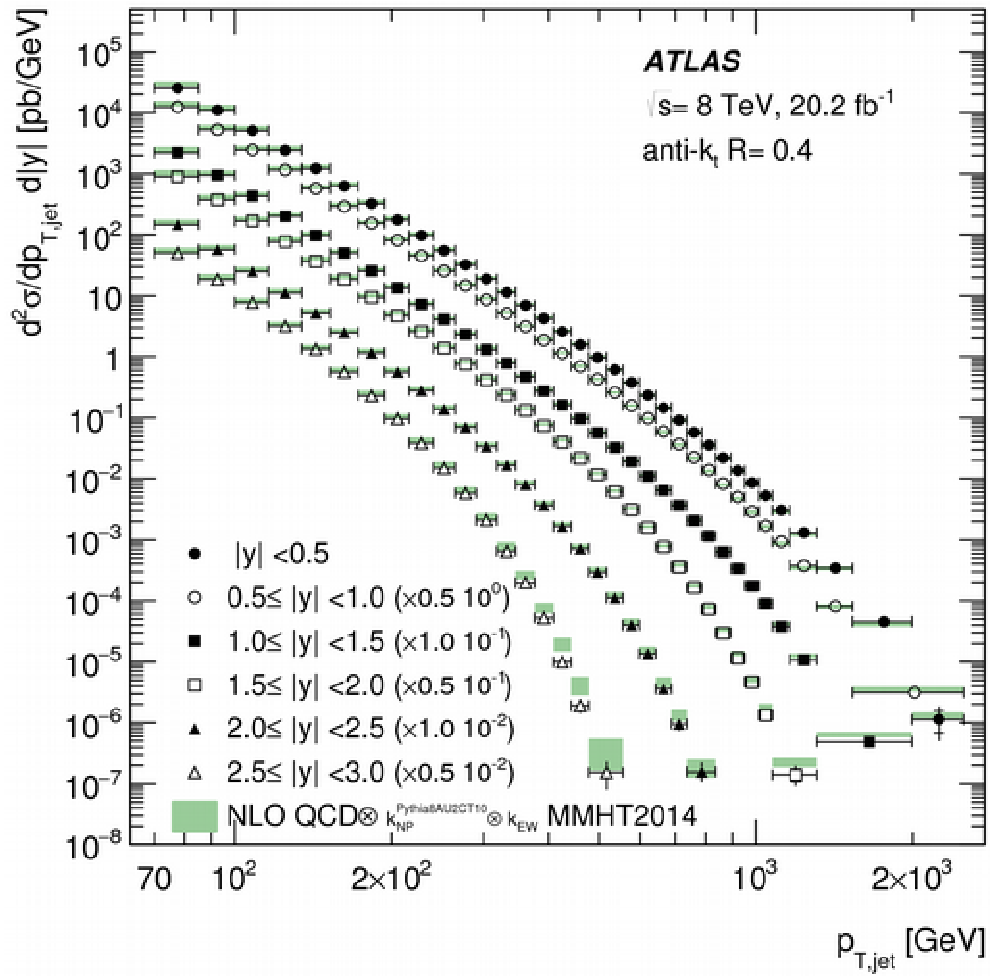


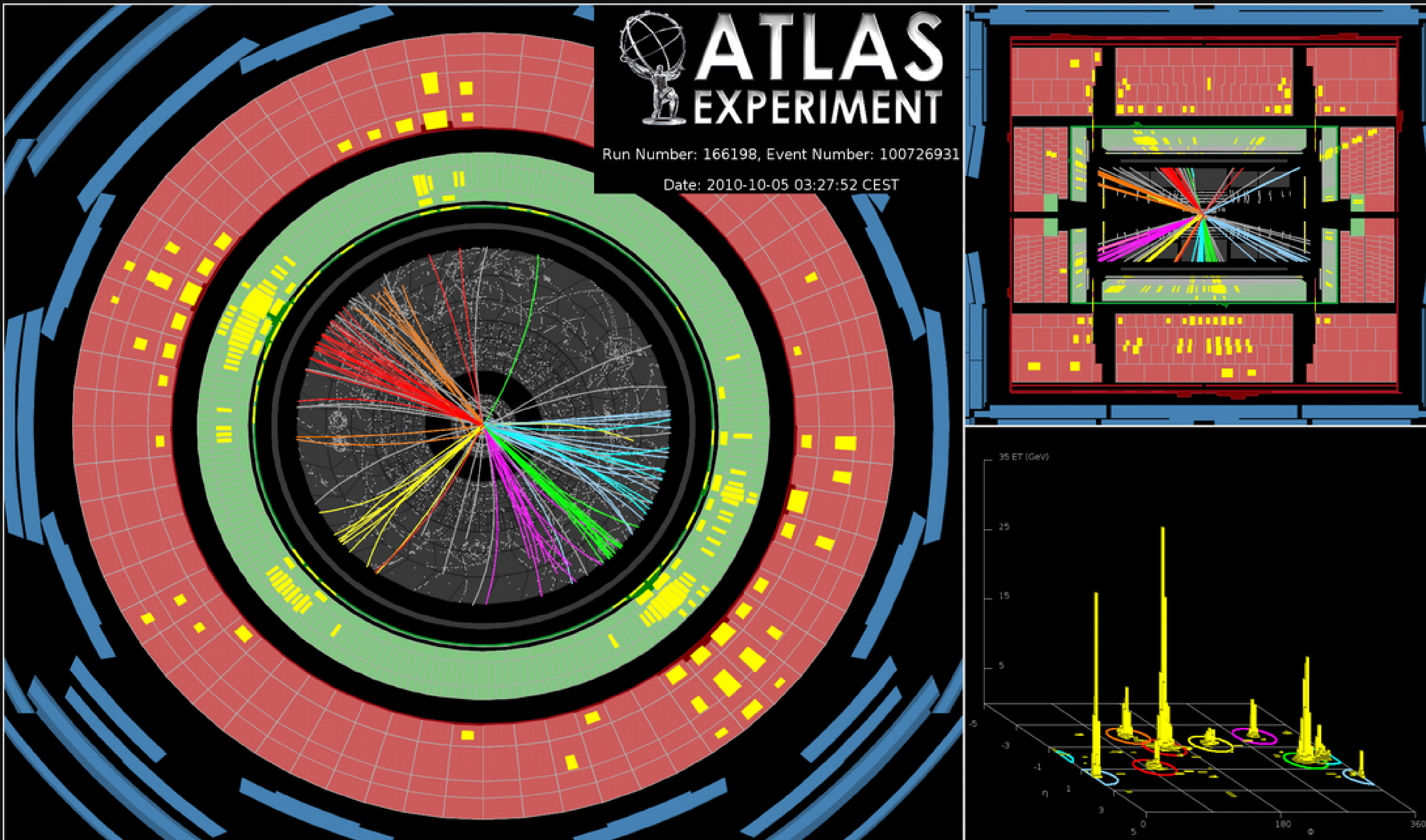
Jet energy scale uncertainty



Single jet cross-section vs jet p_T – spans 10 orders of magnitude

These data will be used to improve the parton density function (pdf) models

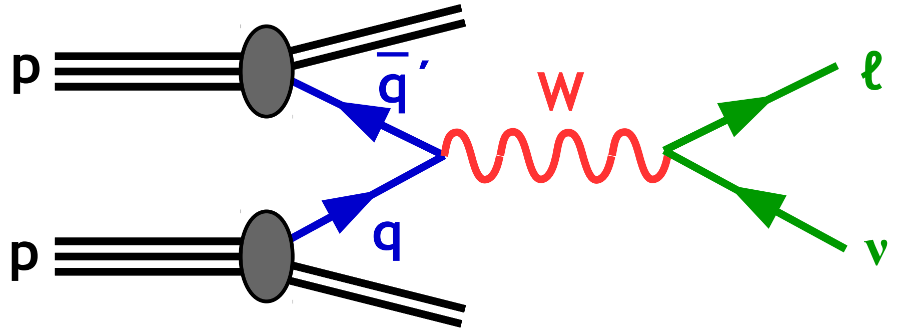
An 8-jet event, with each p_T(jet)>60 GeV



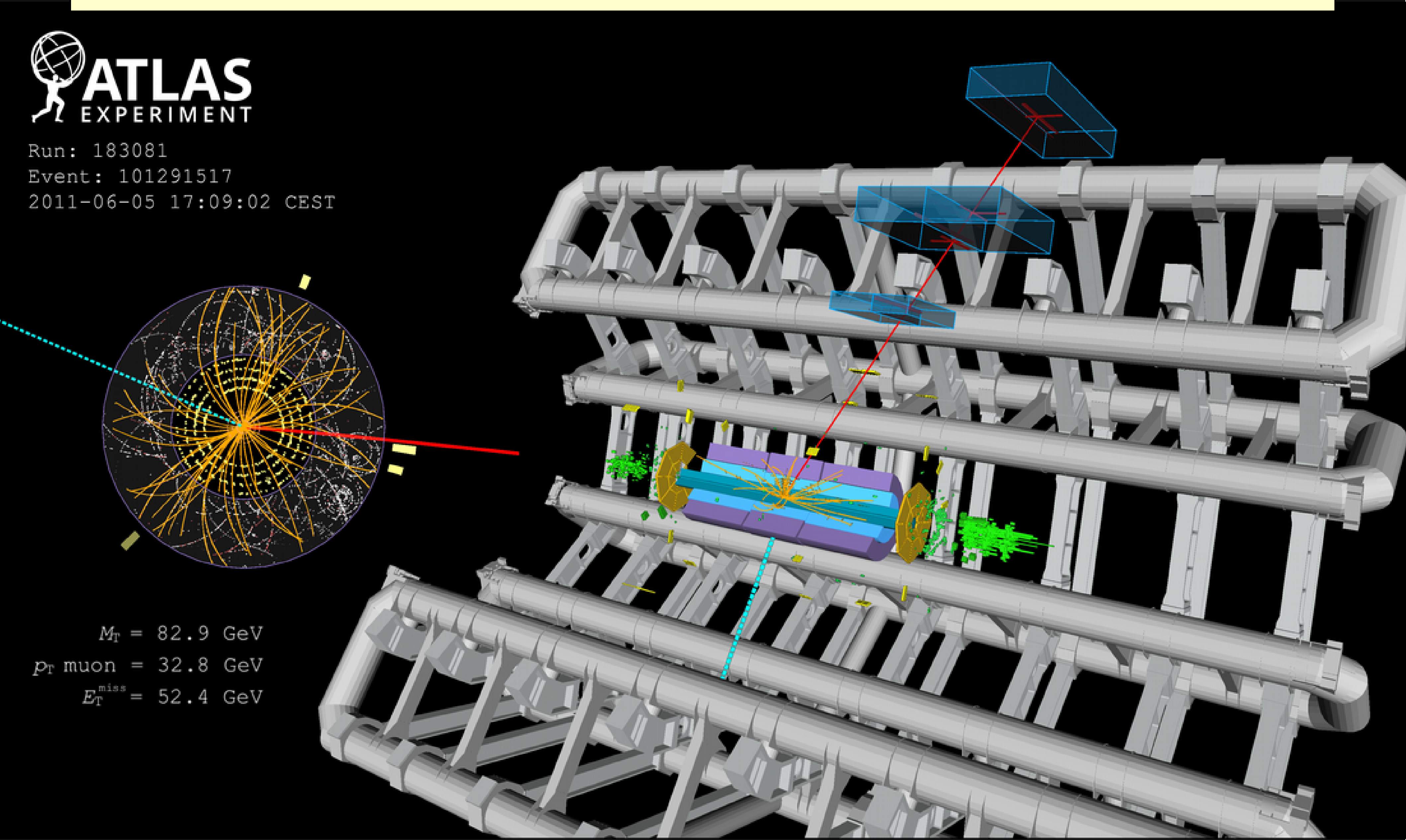
Measurements of W and Z bosons

Clean experimental signatures and large cross-sections

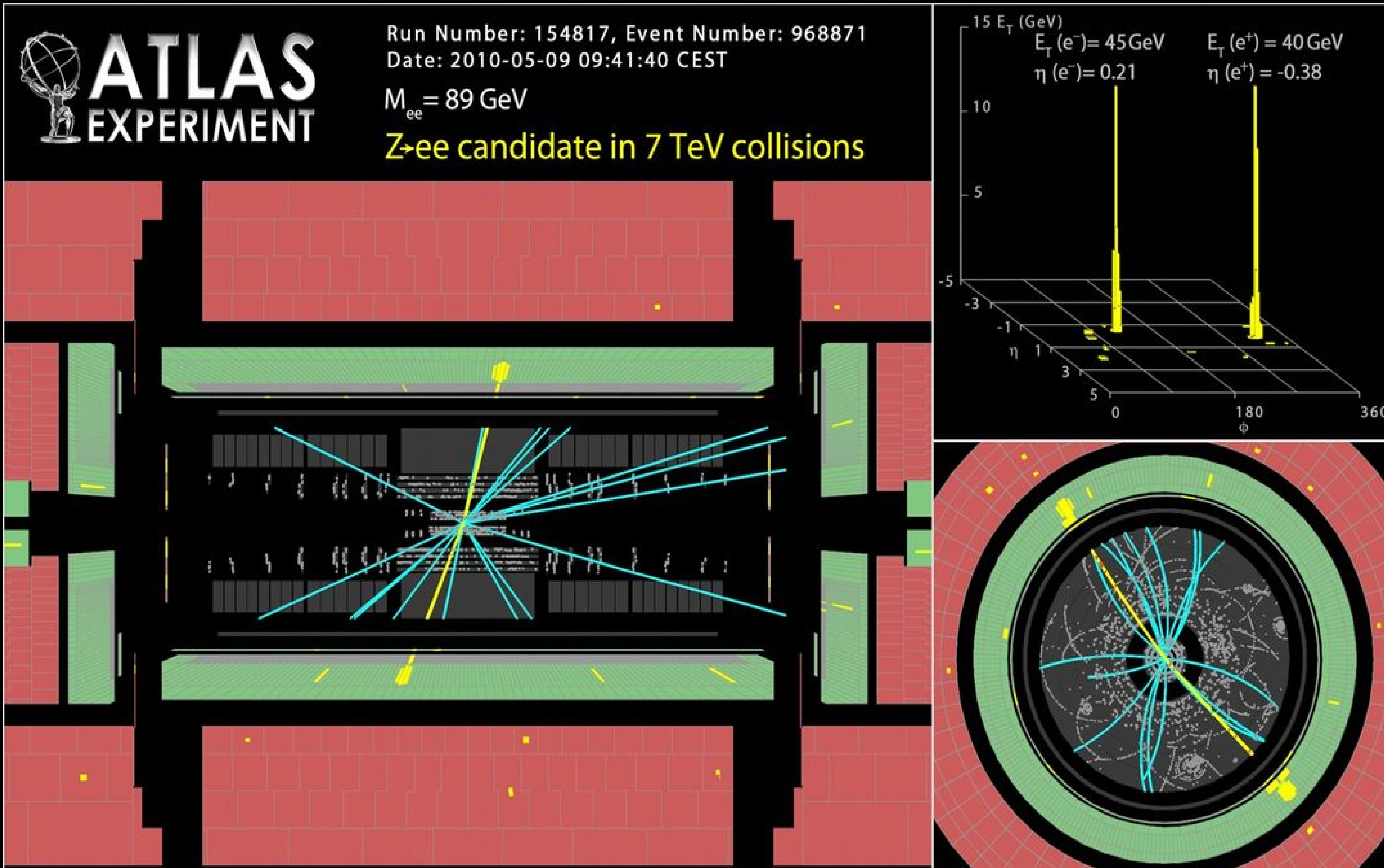
- High precision measurements
- Strong constraints on proton structure
- Tests of consistency of electroweak (EW) sector of SM



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

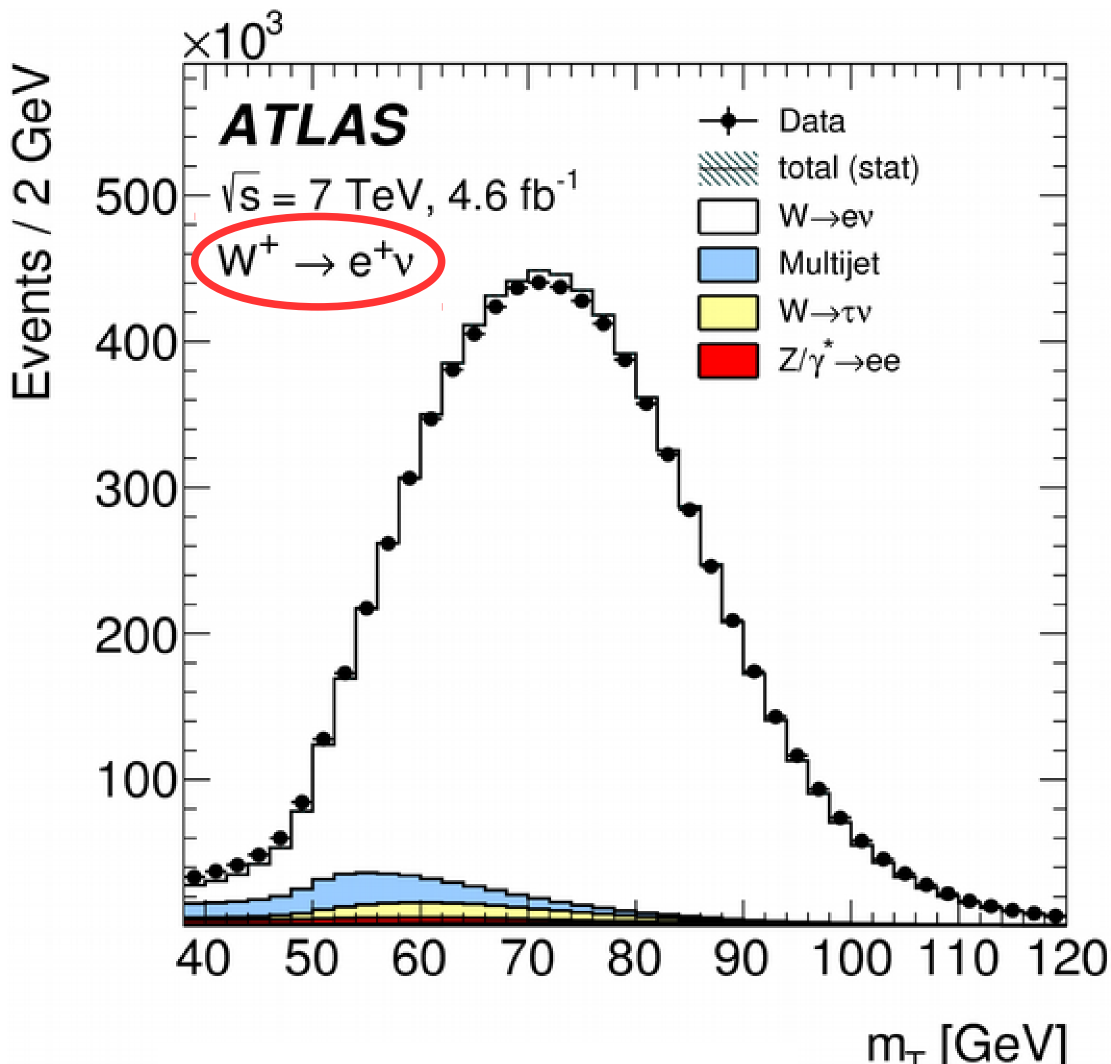
Z→ee event


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)
$E_T(e^-)$ = 45GeV
$\eta(e^-)$ = 0.21
$E_T(e^+)$ = 40GeV
$\eta(e^+)$ = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
φ

Precise W, Z production measurements

Detailed studies performed with 2011 data at 7 TeV: W^+, W^-, Z in e, μ decays

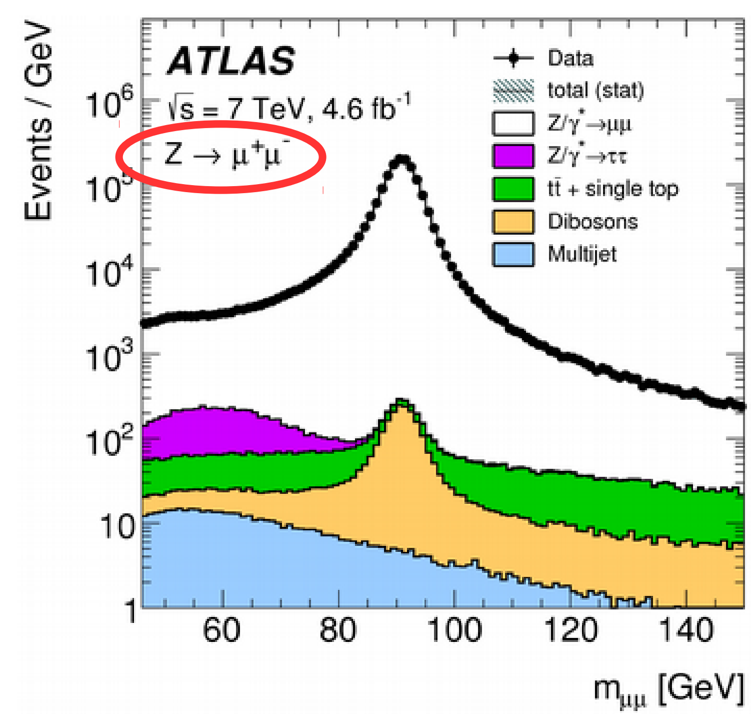
arXiv:1612.03016



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

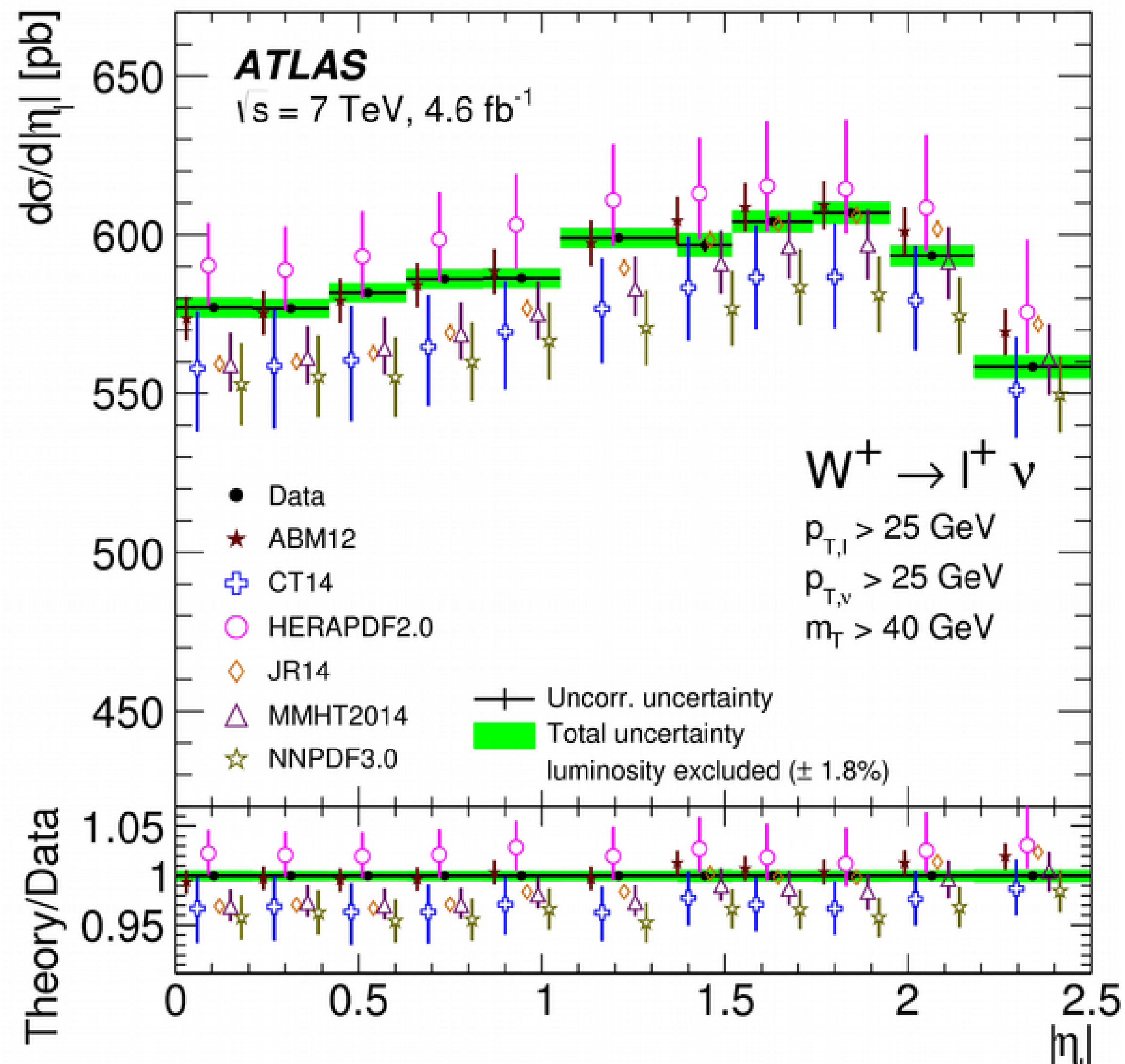
High statistics data well described by simulation

Backgrounds under excellent control



Precise W, Z production measurements

Detailed studies performed with 2011 data at 7 TeV: W^+,W^-,Z in e, μ decays



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

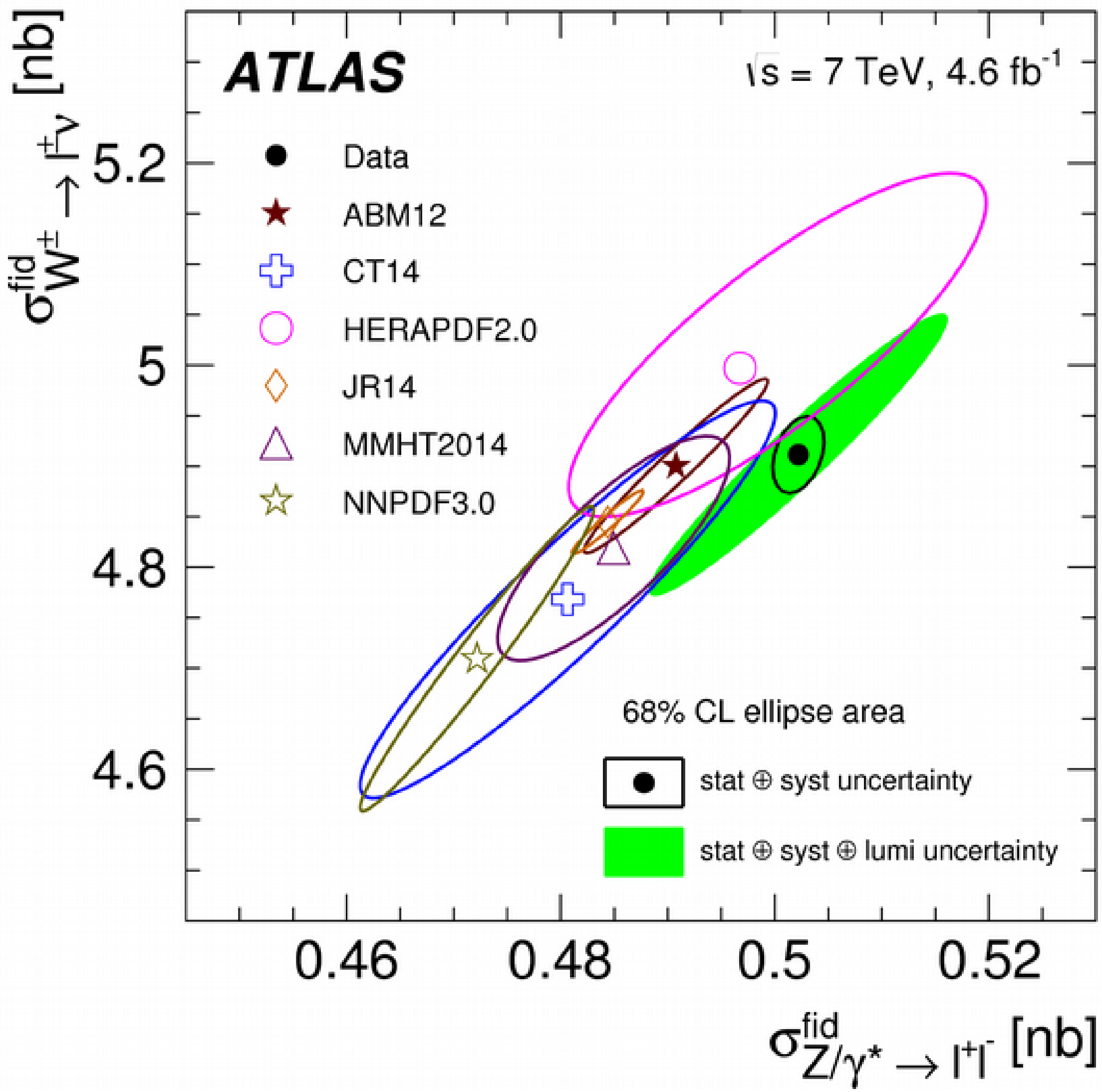
Example: measurement of angular distributions of leptons relative to beam direction, in $W \rightarrow \ell\nu$ decays

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

→ much sensitivity to the pdfs

Precise W, Z production measurements

Detailed studies performed with 2011 data at 7 TeV: W^+,W^-,Z in e, μ decays



Experimental errors better than theoretical/modelling uncertainties

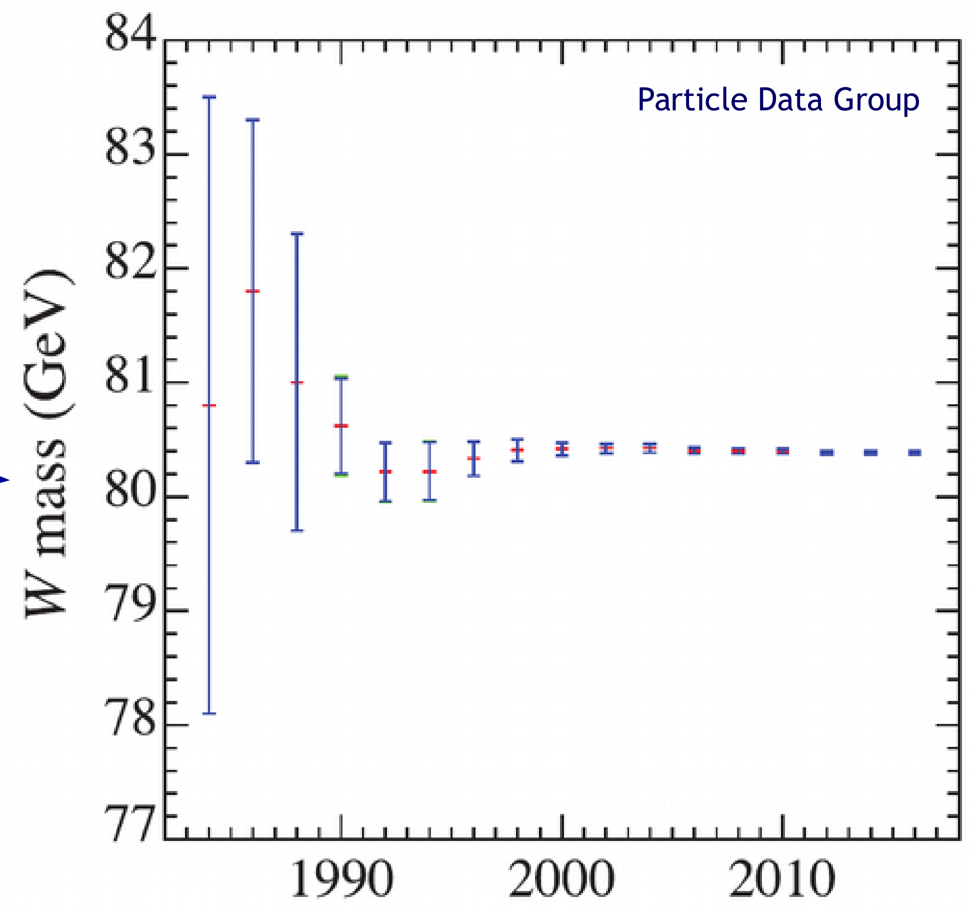
These data are used by ATLAS to make new pdfs

Measuring the W mass

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

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

- History of precision



Measuring the W mass

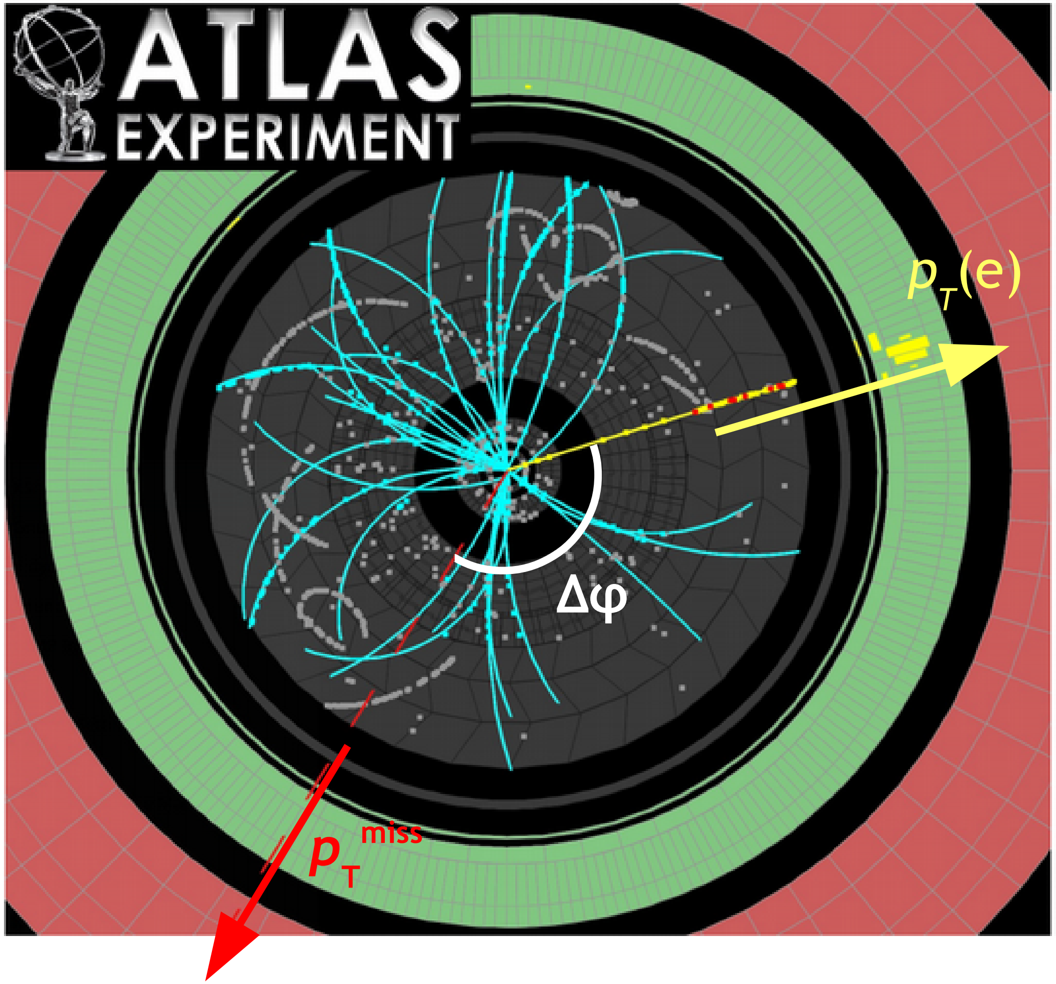
Mass of the W boson is a fundamental parameter of the Standard Model

W mass was first measured directly back in the 1980's soon after it was discovered at CERN
- History of precision

A standard method uses "transverse mass"

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

W→eν event



W mass measurement

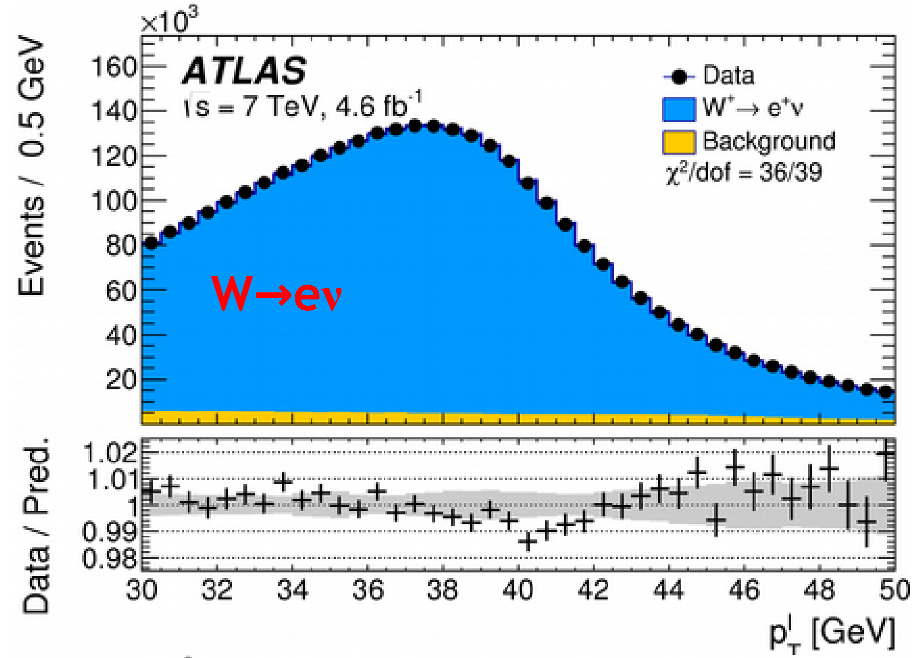
ATLAS measurement of m_W uses well-understood 2011 data (7 TeV)

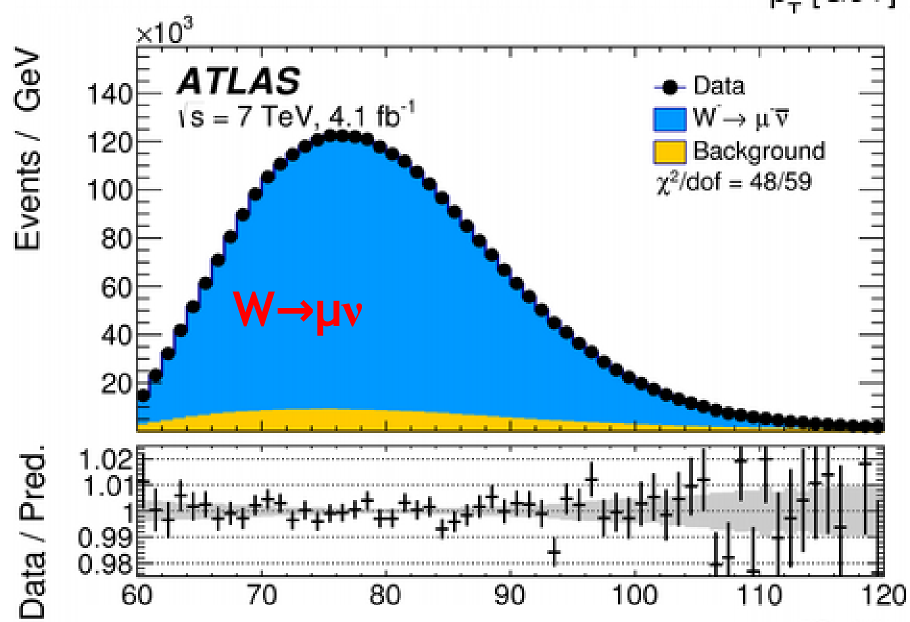
~15M $W \to \ell\nu$ decays

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 $Z \to \ell\ell$ sample
- Hadronic recoil ($\to p_T^{miss}$) also calibrated against $Z \to \ell\ell$
- LEP *Z* mass crucial input (2 MeV error)
- Detailed analysis of modelling uncertainties





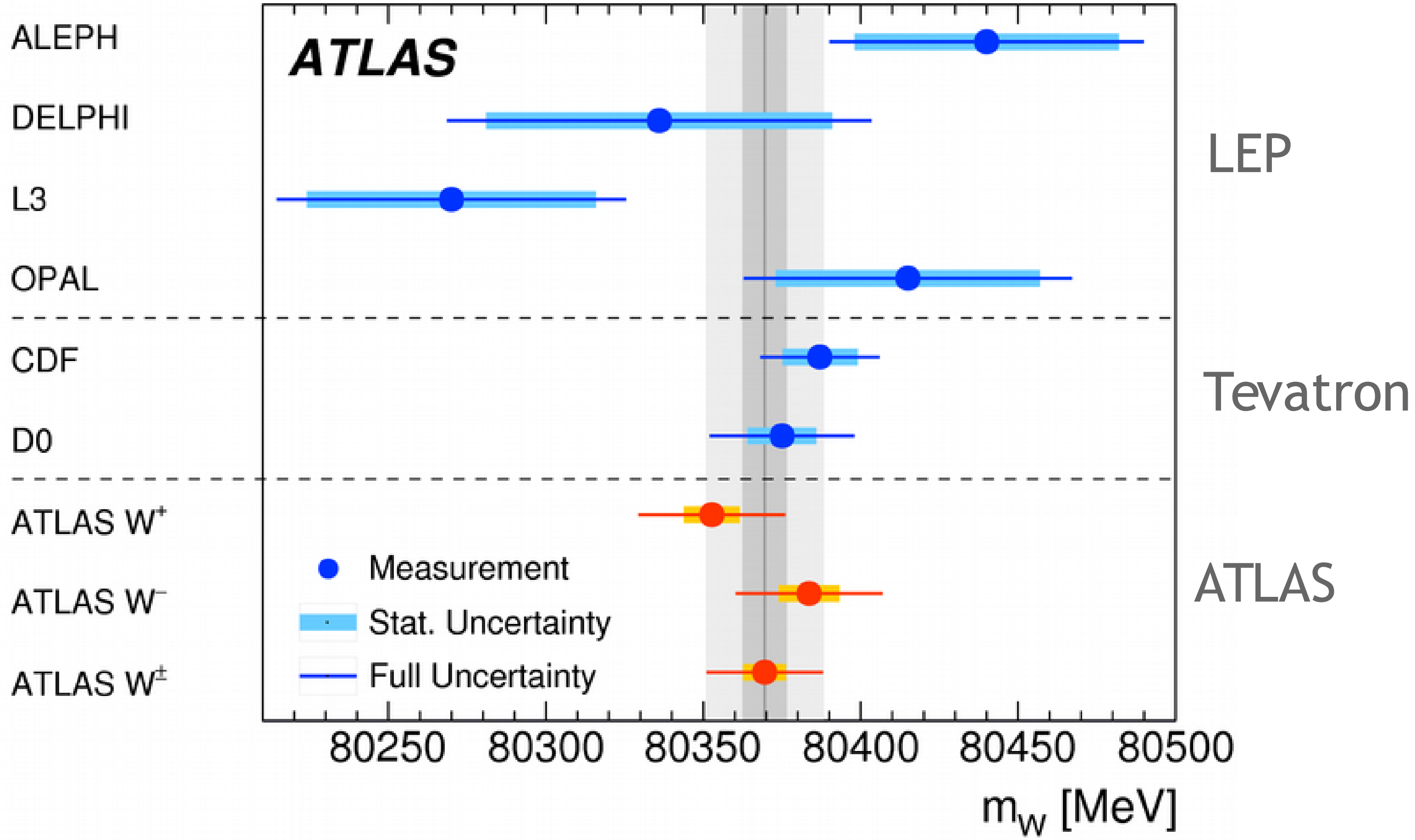
$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)},$$

W mass results

Combining the e and μ channels, charge signs and methods, overall:

$$m_W = 80370 \pm 19 \text{ MeV} \quad \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.) MeV}$$

Measurement precision of 19 MeV (0.024%) equals best previous uncertainty, from CDF



Electroweak precision test

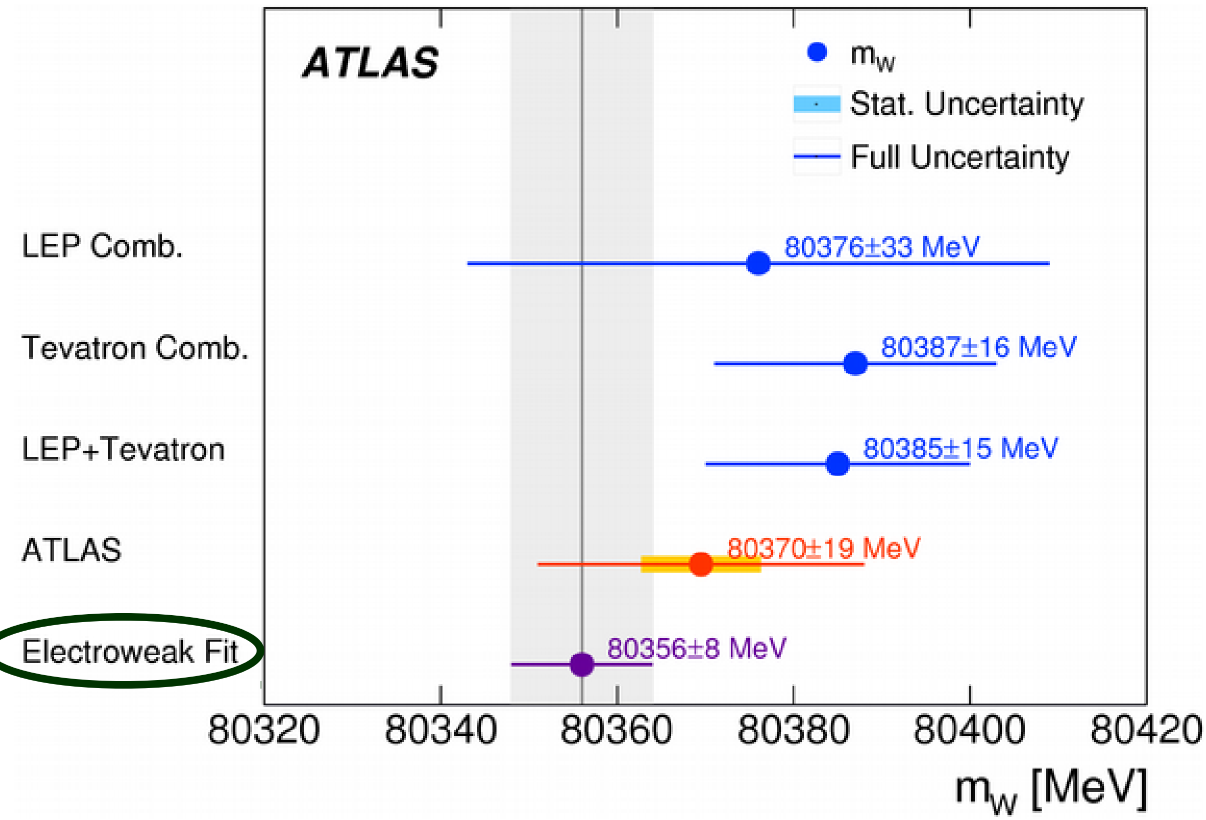
Within the SM framework, m_W is related to other quantities via:

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

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

("indirect measurement in the framework of the SM")



Precision electroweak fits

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

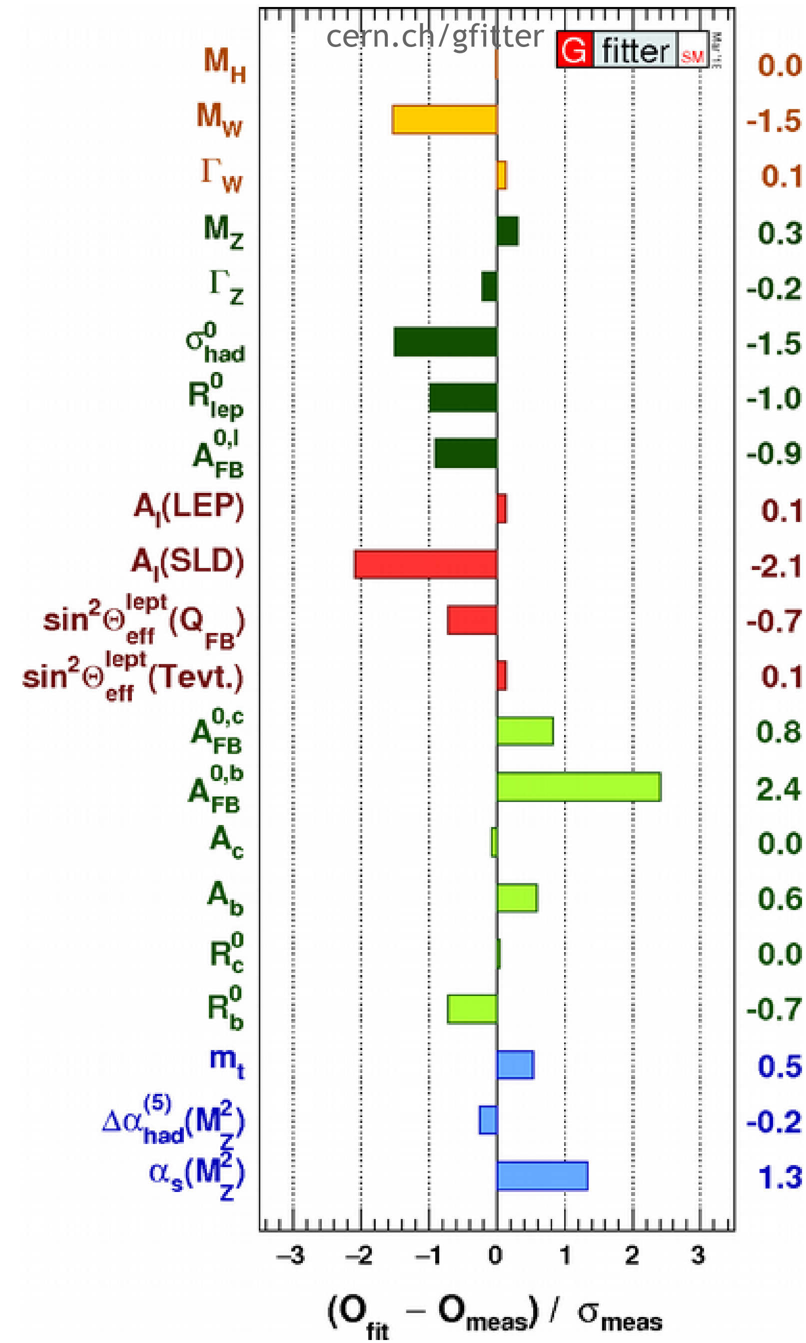
- Many more than five observables have been measured
- Requires theoretical predictions at as high a level as possible (must include loop diagrams!)

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

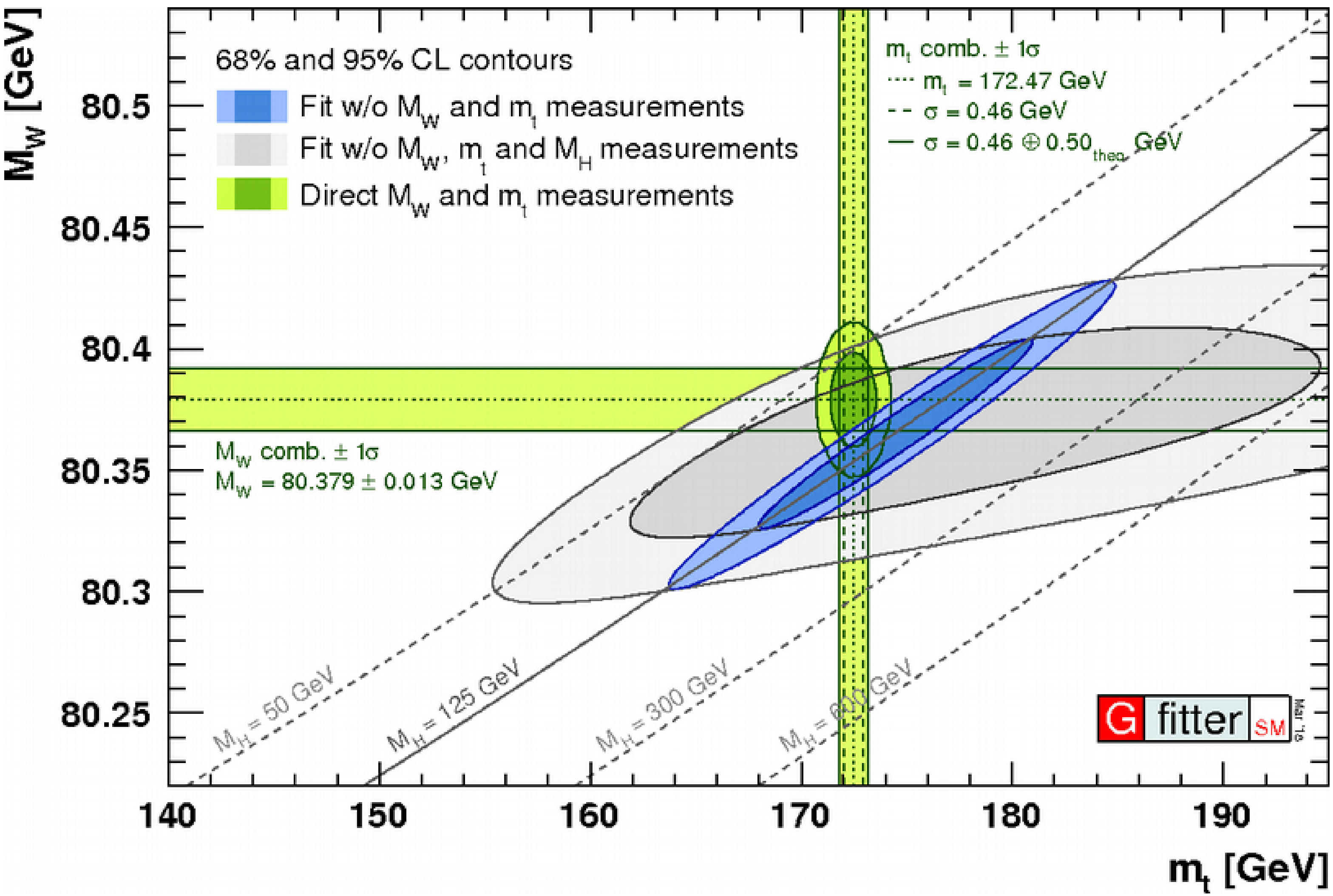
  Latest Gfitter fit: χ^2=18.6 for 15 d-of-f

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

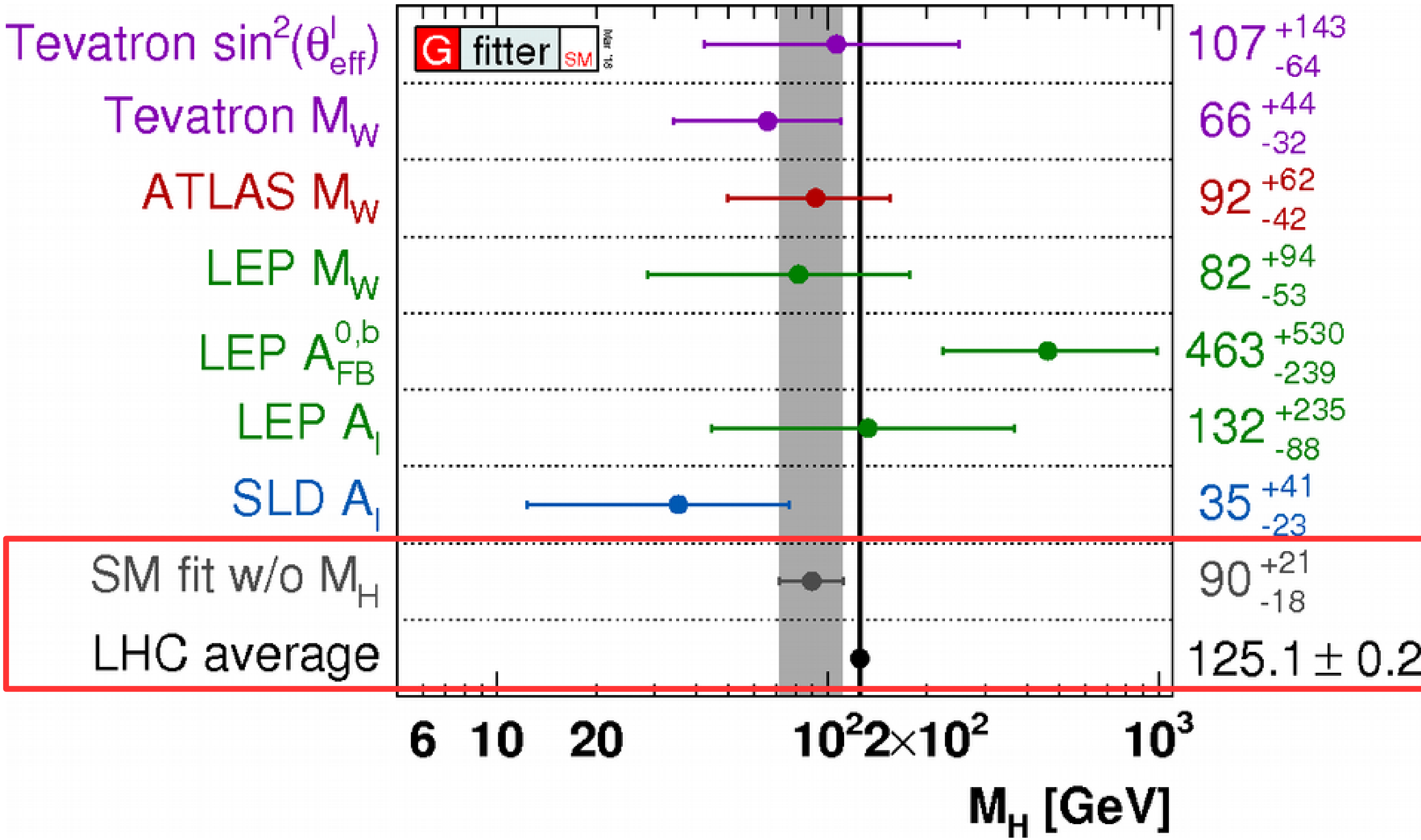
- We can try to predict the Higgs boson mass using all the other measurements



Precision electroweak physics



Precision EW fits: "predicting" m_H



Z+jets at 13 TeV

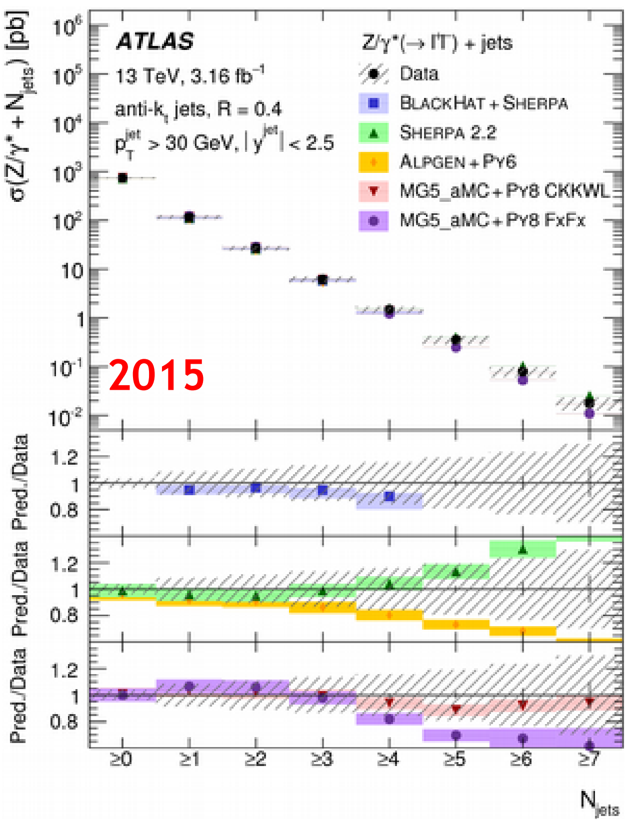
Access and measure high jet multiplicities in 13 TeV data

- Test NLO predictions on events with high jet multiplicities
- Vector-boson plus jet events are a major background in searches

Fully corrected fiducial and differential cross-sections

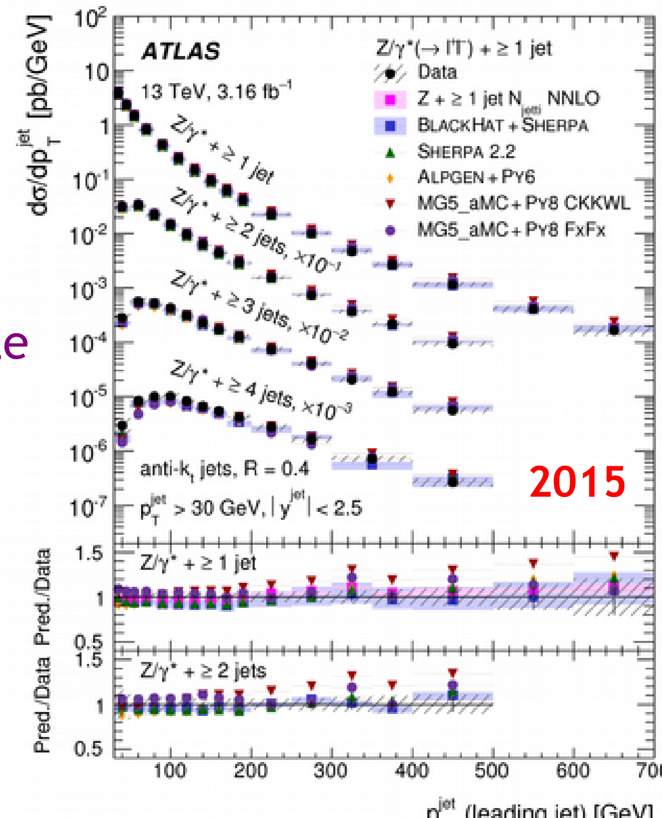
- Z with up to 7 additional jets measured

arXiv:1702.05725



NLO generators normalised to NNLO

~6M Z→ℓℓ event sample (3.2 fb^{-1})



NLO generators normalised to NNLO

Jet multiplicity: main NLO generators do a good job, at least up to 6 jets

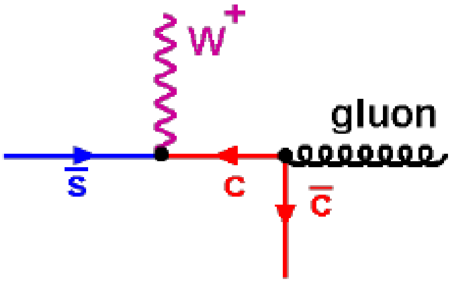
Leading jet p_T spectra:

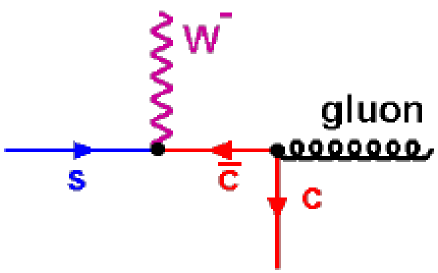
LO generators over-predict high-p_T tail

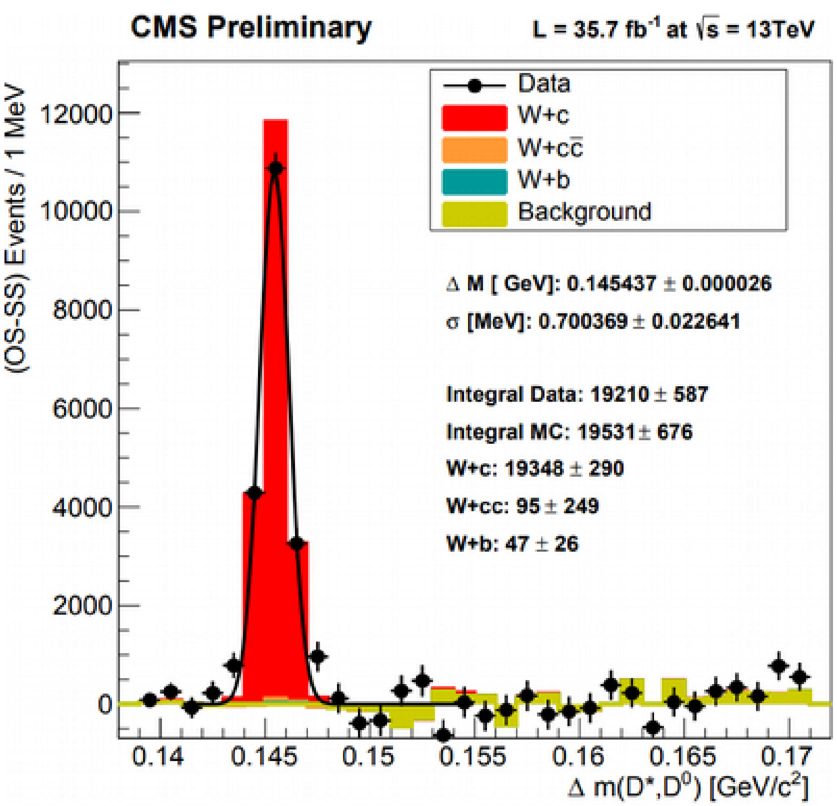
NLO generators provide better description

W + charm

A very new example:
New result from CMS on W+c at 13 TeV →
probes strange quark pdf – uses D*-tag

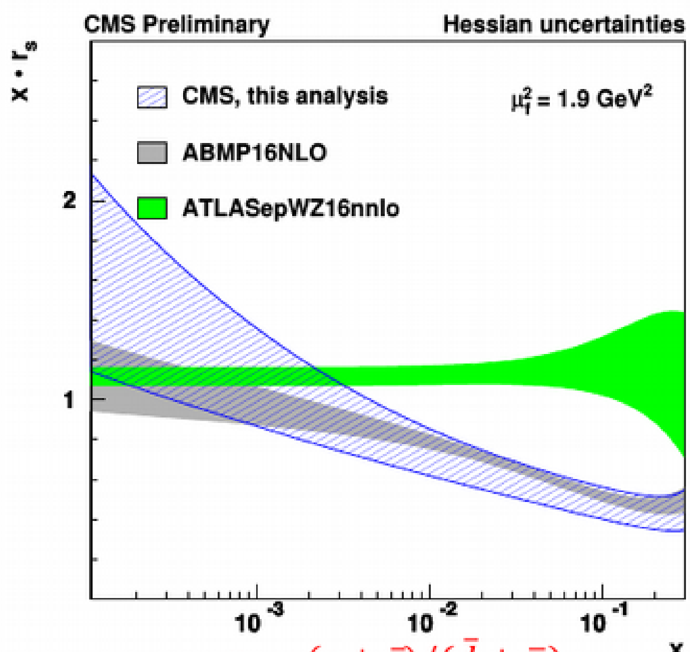






CMS-PAS-SMP-17-014

Sensitive to strange sea



$r_s = (s + \bar{s})/(\bar{d} + \bar{u})$

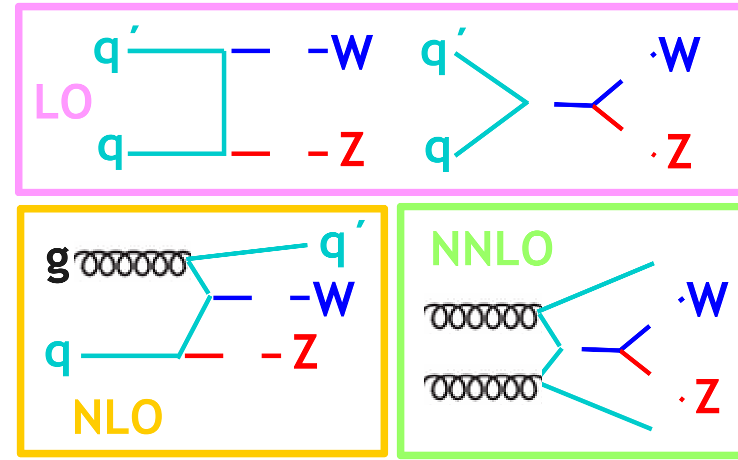
Tension with s-quark pdf from ATLAS - derived from inclusive W/Z production
Open question how this will be resolved!

Massive diboson production

Run-1 puzzle to describe inclusive diboson cross-sections

- Measurements tended to lie above next-to-leading order (NLO) calculations

NNLO calculations → ~+20% corrections and better agreement

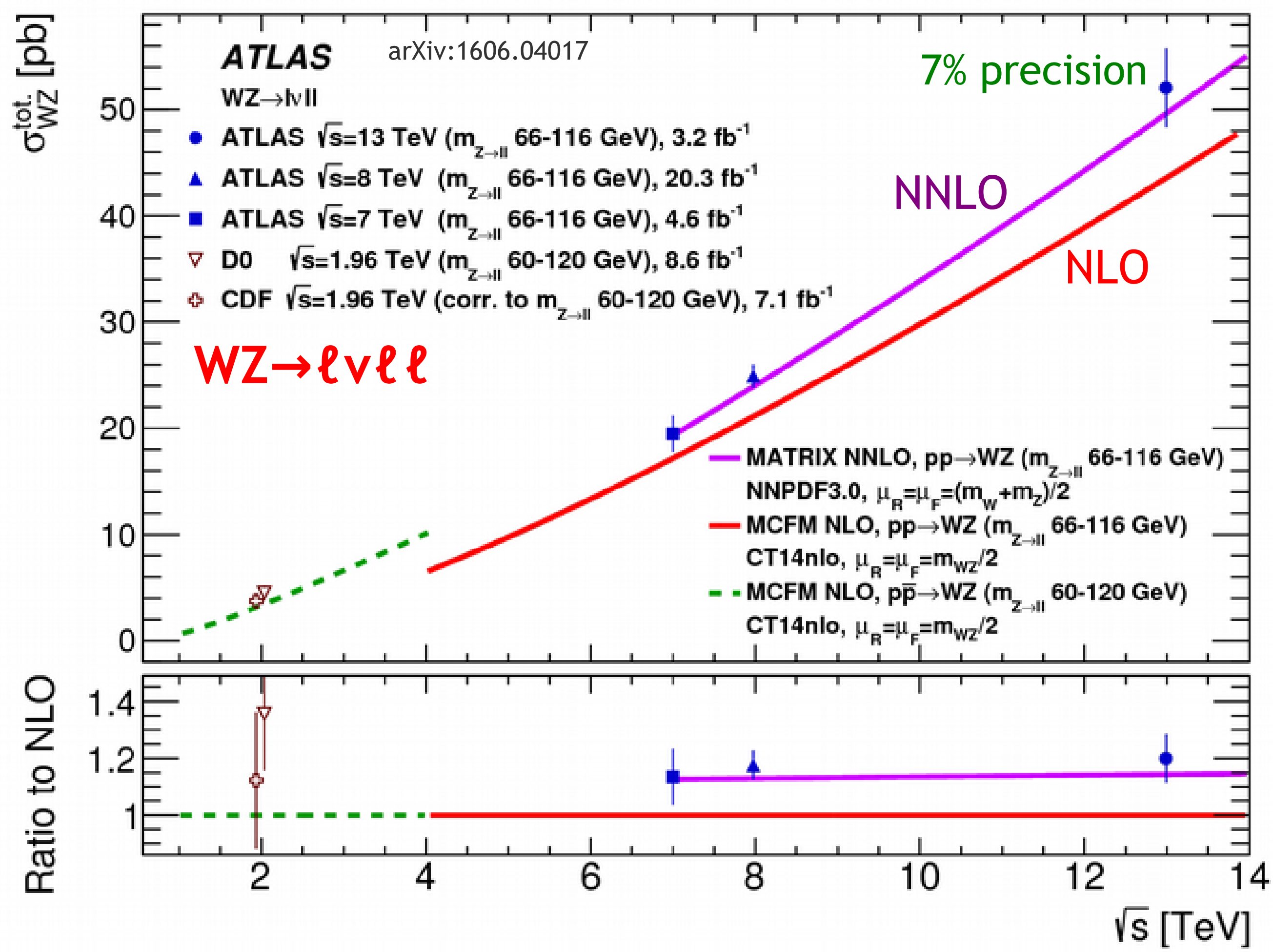


Example:

WZ leptonic decays

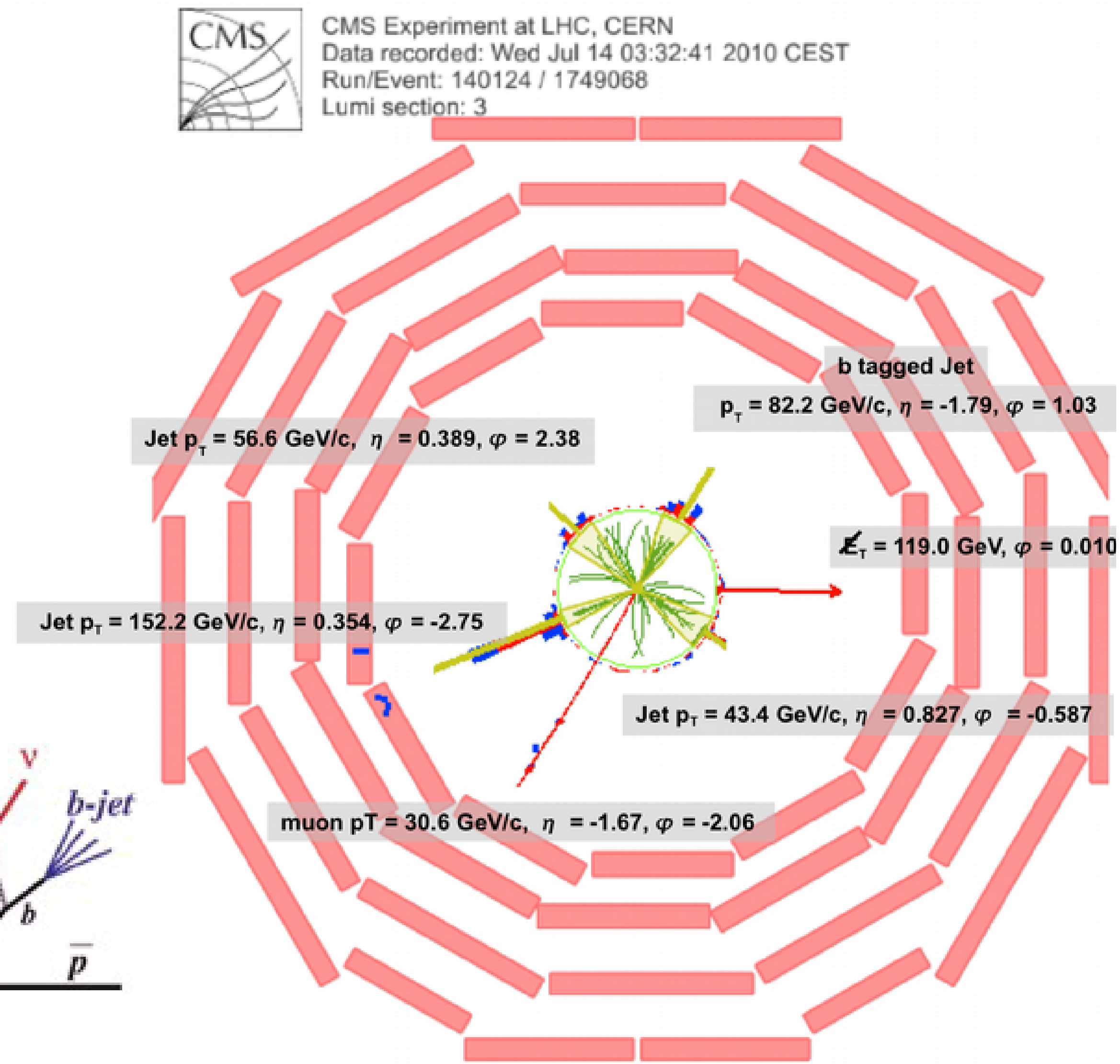
NNLO calculations describe data much better than NLO

This run-1 puzzle appears to be solved!



Precision top quark physics

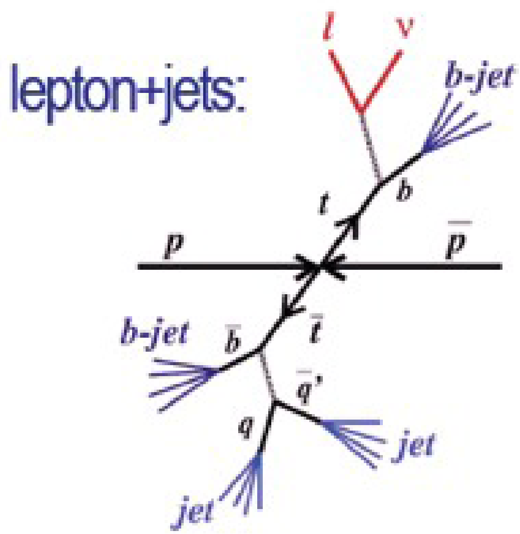
To date tens of millions of $t\bar{t}$ pairs produced at the LHC (cf ~75k at Tevatron, where the top quark was discovered)



Are top quarks "special" objects?

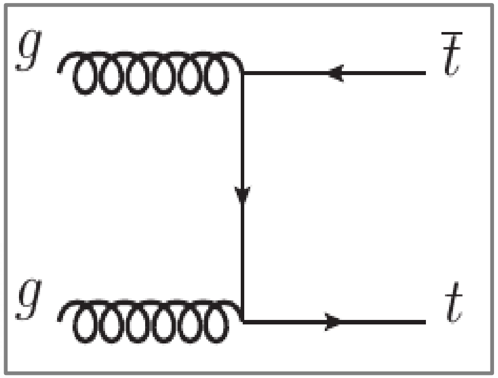
- The coupling y_t of the ttH vertex has a predicted strength y_t~1

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

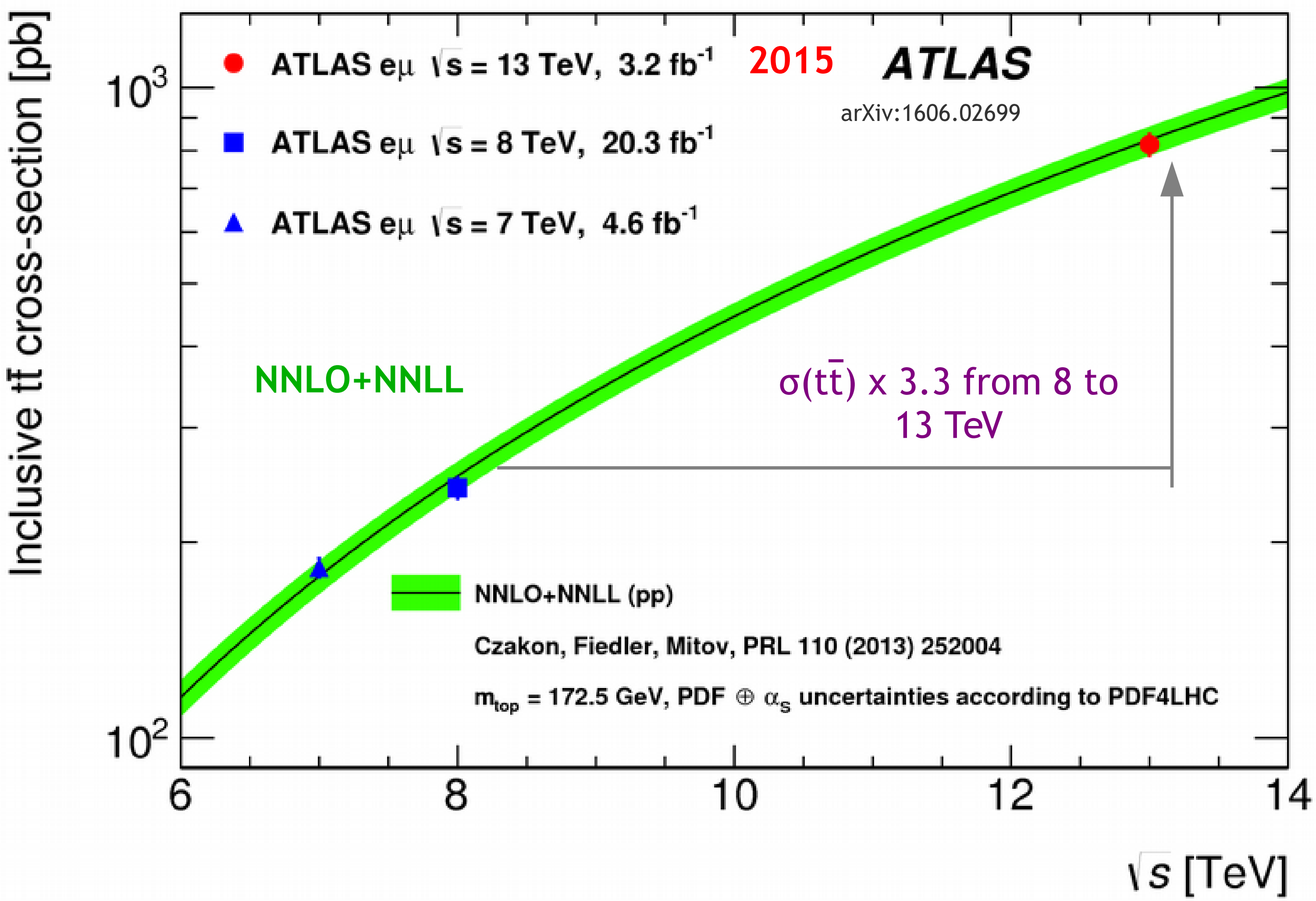


$t\bar{t}$ production

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



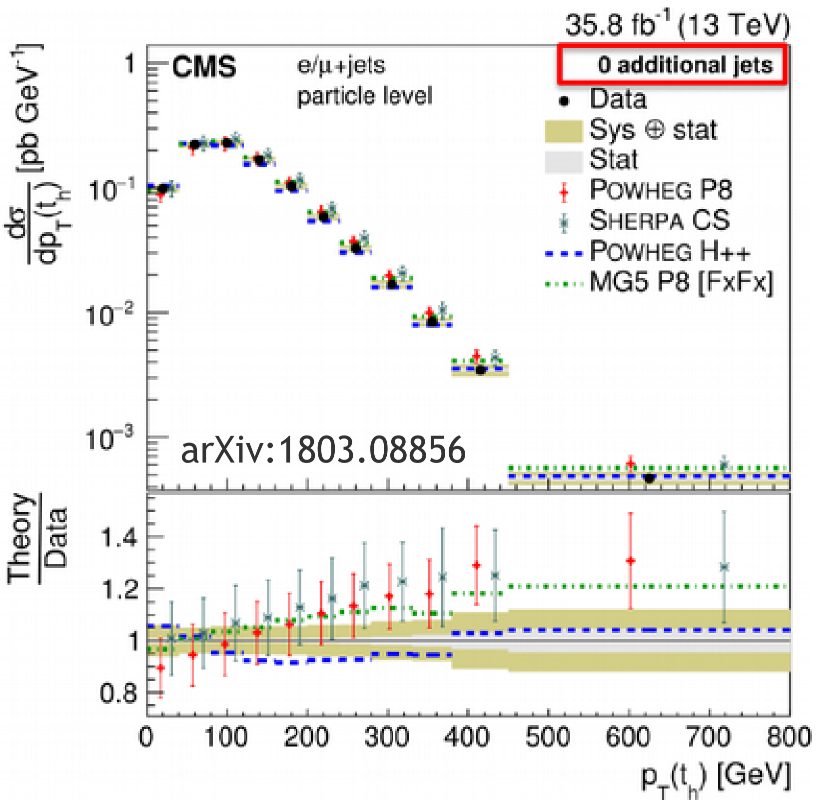
Precision ±(3.9-4.4)% (7-13 TeV) betters NNLO+NNLL predictions (~5%)

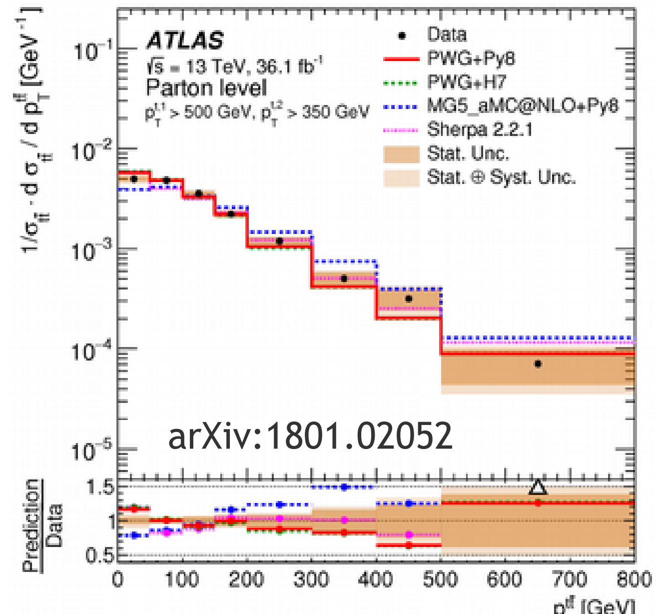


30 fb^{-1} @ 13 TeV
~25M $t\bar{t}$ produced

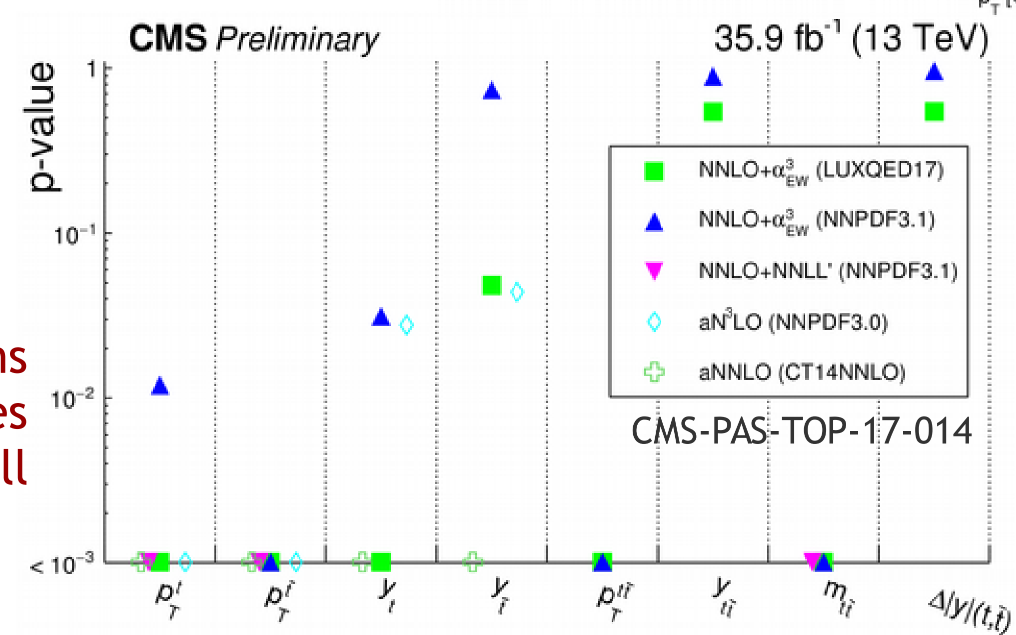
Top pair production

Long-standing (Run-1) difficulty to describe the observed p_T(top) spectrum, although NLO-based MC models much improved for Run-2



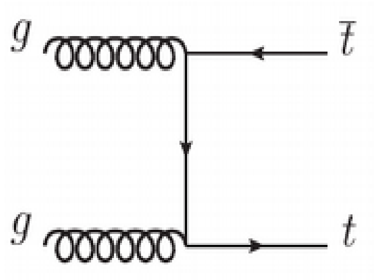


Still none of the predictions describe all of the observables well

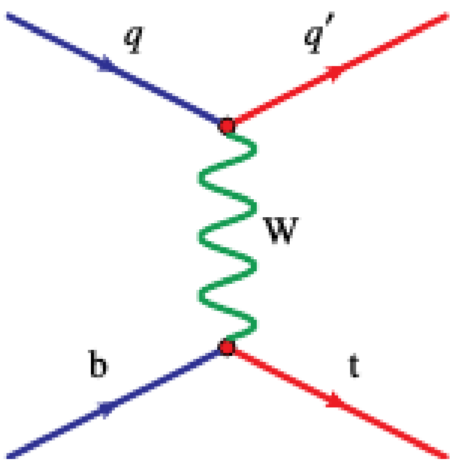


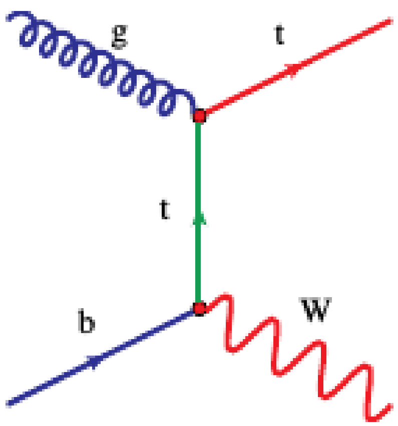
Single top

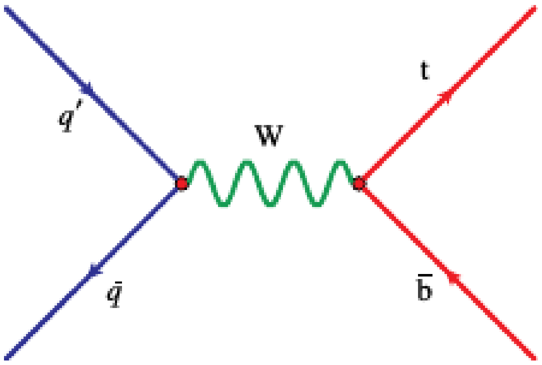
Top-anti-top quark pair-production is a strong interaction process with a high cross-section, as we just saw



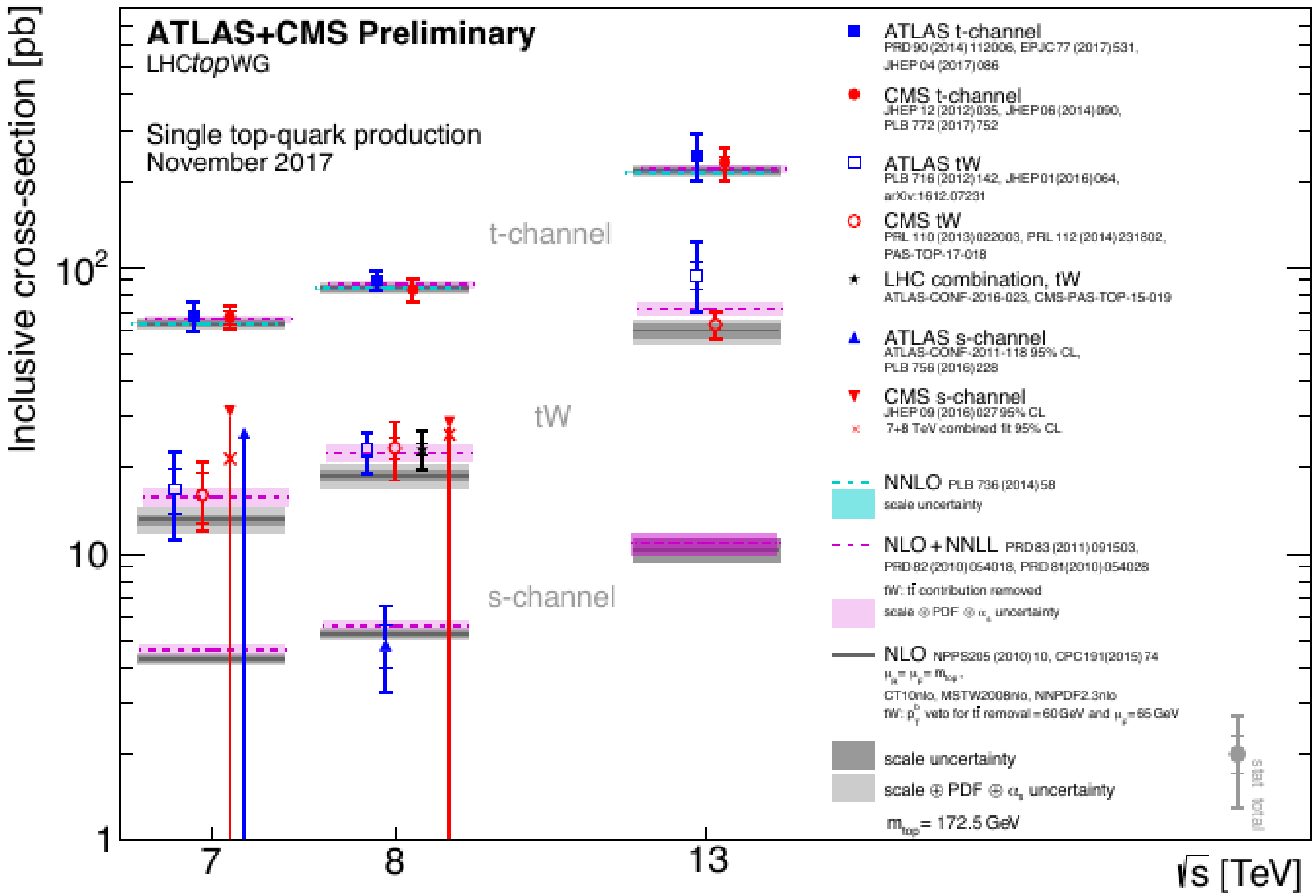
We can produce top quarks in other ways too at the LHC, for example singly, via electroweak processes with a W involved

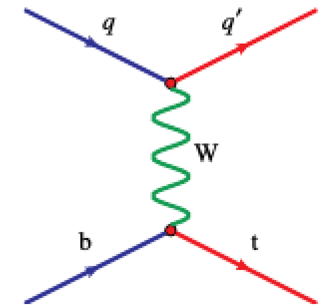


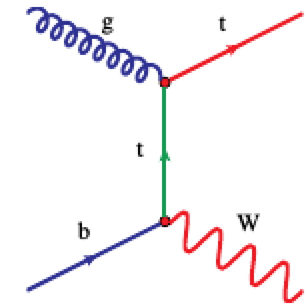


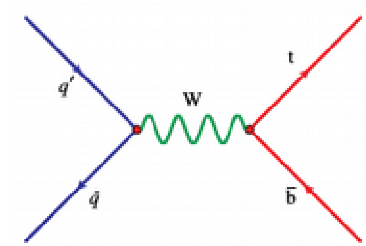


Single top cross-sections





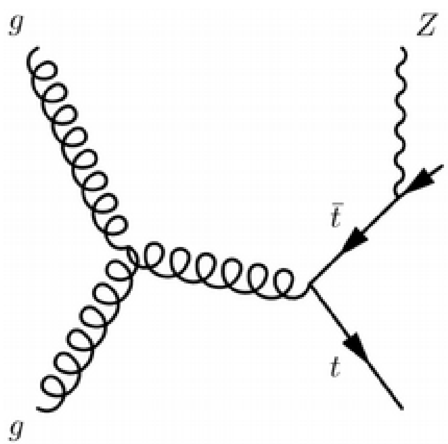




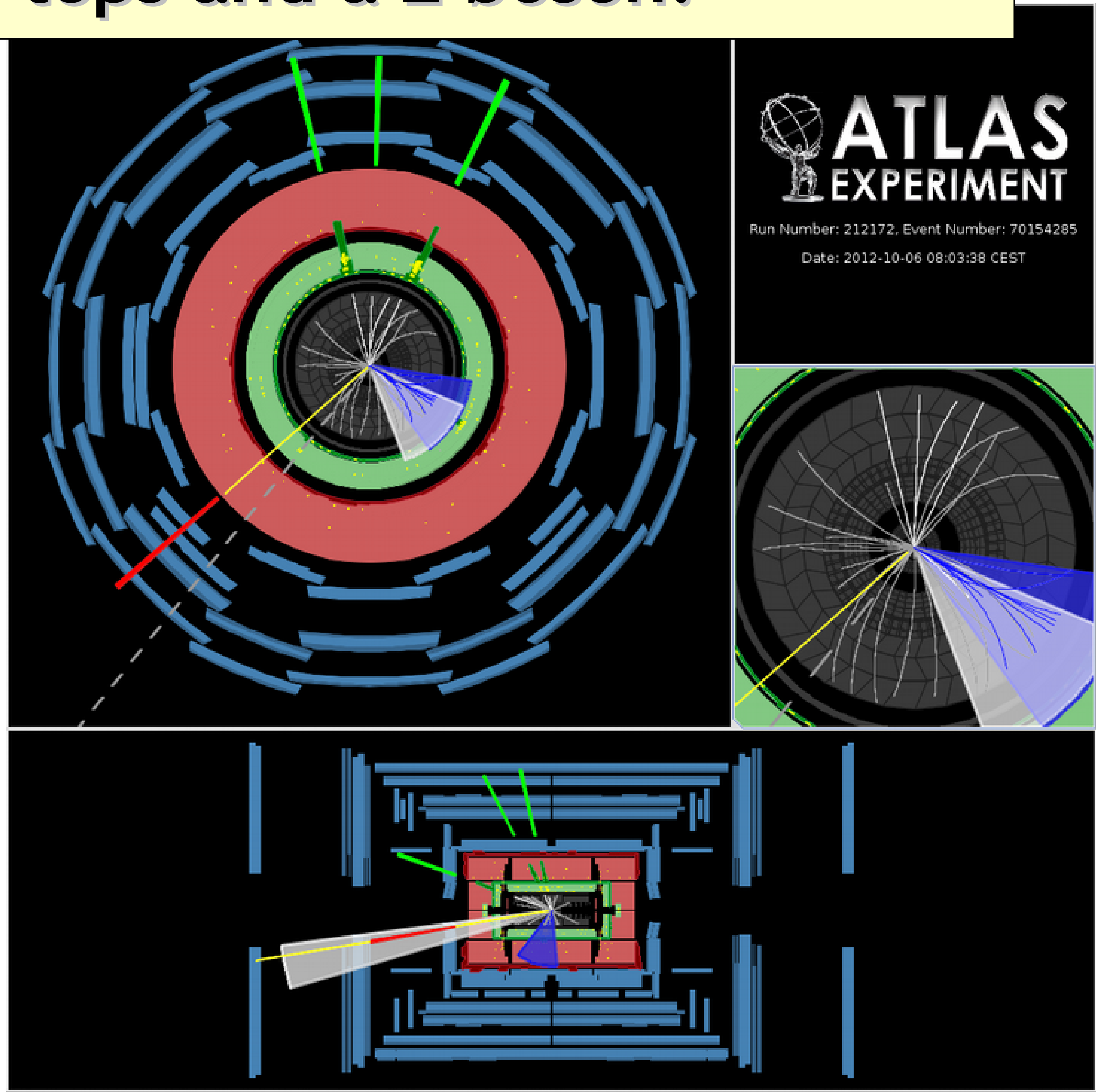
t-channel and Wt production measured differentially
s-channel still unobserved at LHC - observed at Tevatron
Other associated production channels tZq and tγq should be seen soon

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



Summary

- 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 (<5%) of the LHC data sample has been collected – there is much more to explore with precision measurements, and advancing our understanding of QCD and electroweak physics – even ignoring the Higgs (next talk) and possible new physics (this morning)!

All the best to all of you with your studies and research - we hope to see some of you working at the LHC in future!

Measuring the luminosity

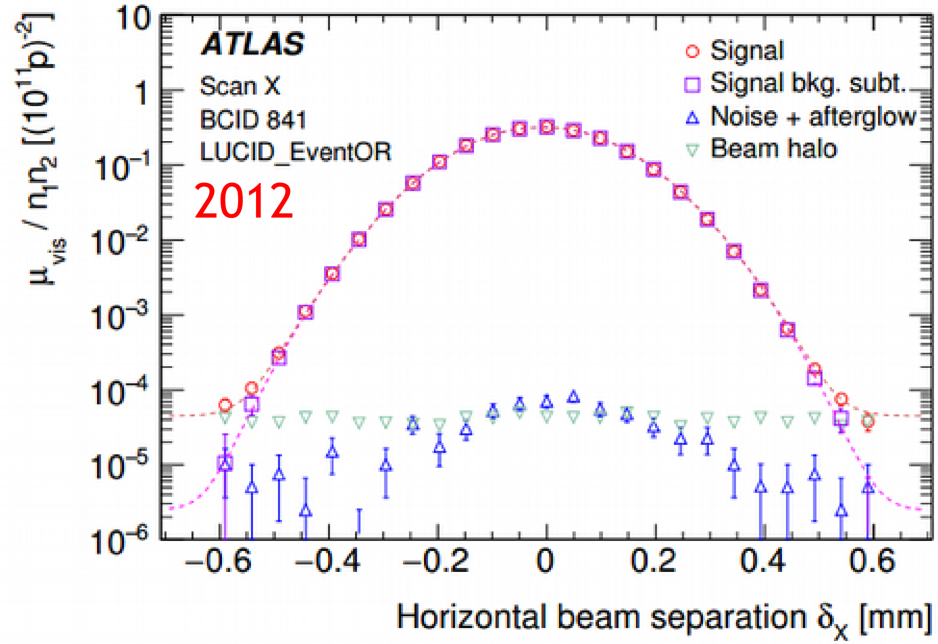
Van Der Meer (VDM) beam-beam separation scans allow to determine the absolute bunch luminosity from measured beam parameters:

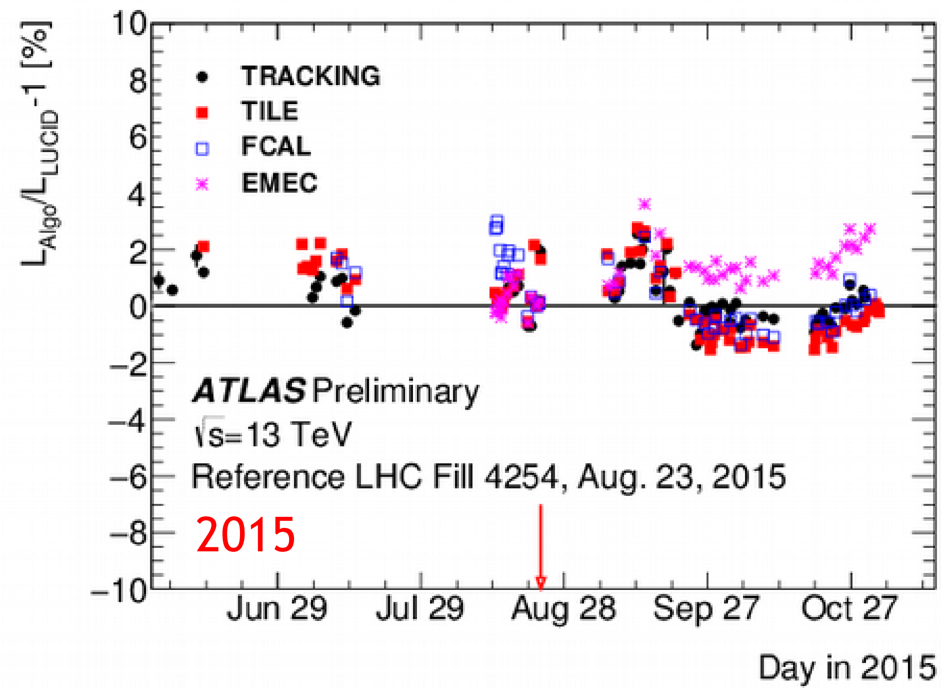
$$\mathcal{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

f_r revolution frequency; n_i number of p/bunch
$\Sigma_{x,y}$ convolved beam sizes, from the scans

Multiple detectors allow to map between VDM-scan conditions and normal operations

Luminosity uncertainty ~ ±2%

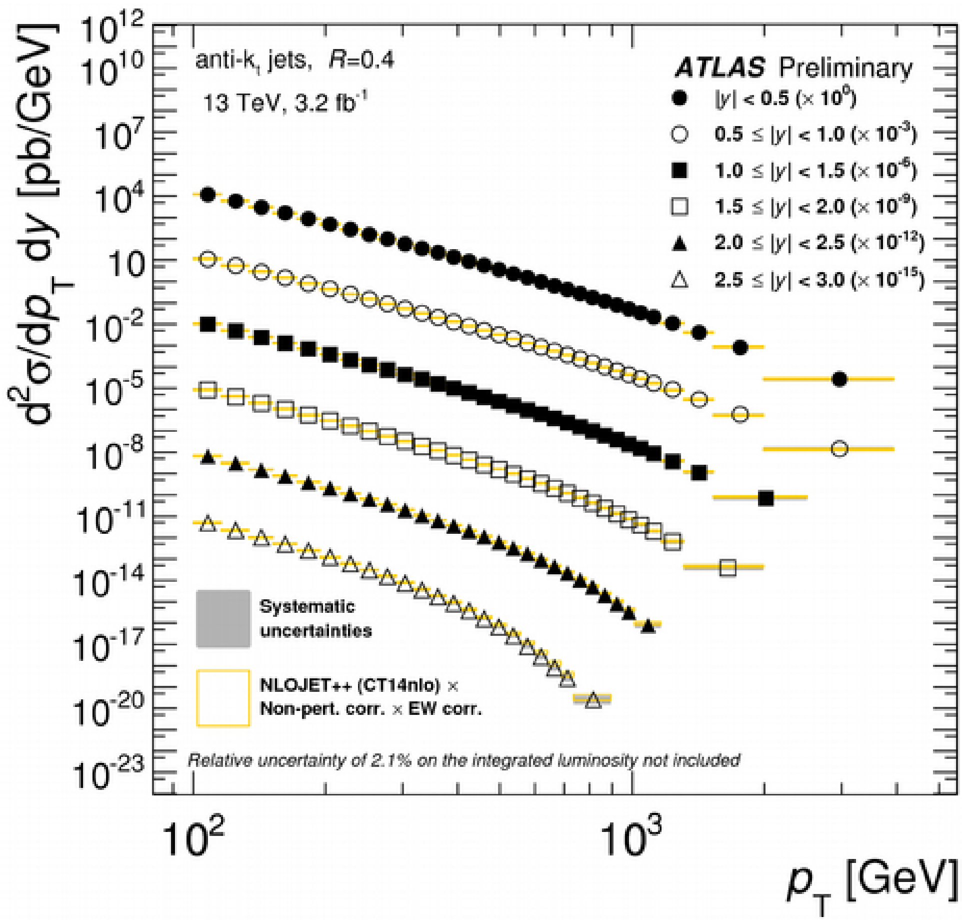


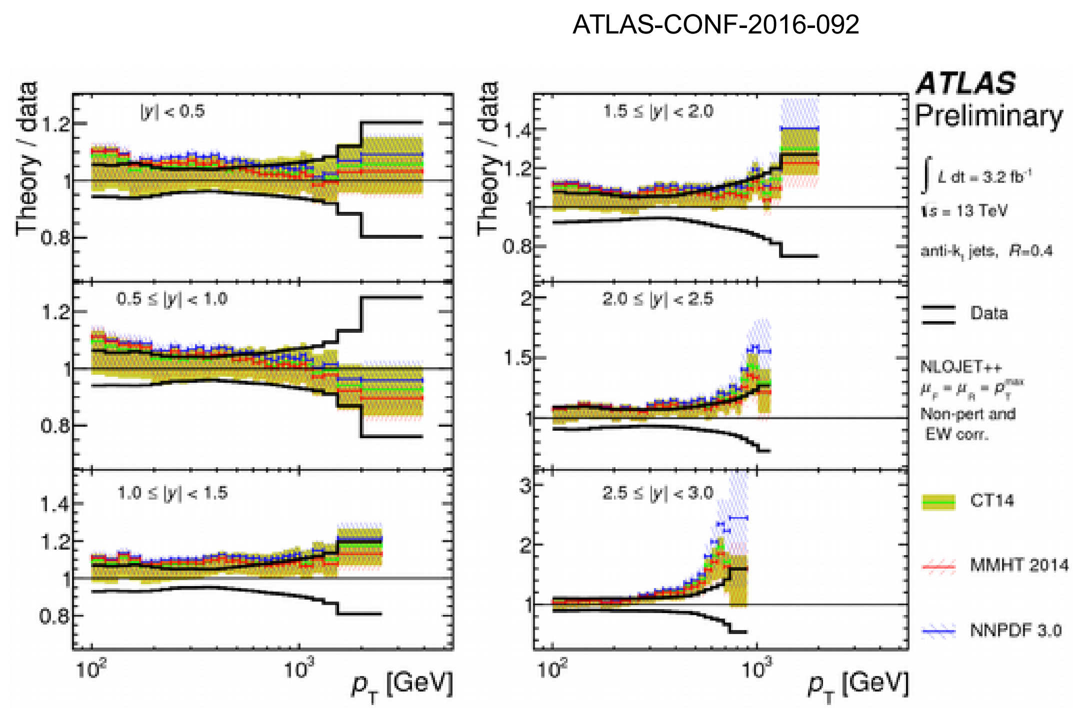


Dijet cross-sections at 13 TeV

Measurements in progress on 13 TeV data – preliminary results released with 2015 data in August last year

- Range of corrected measurements extends to jet transverse momentum p_T ~ 3.2 TeV





Ratios of measured spectrum compared to models using different pdfs