Precision measurements @ hadron colliders - 1

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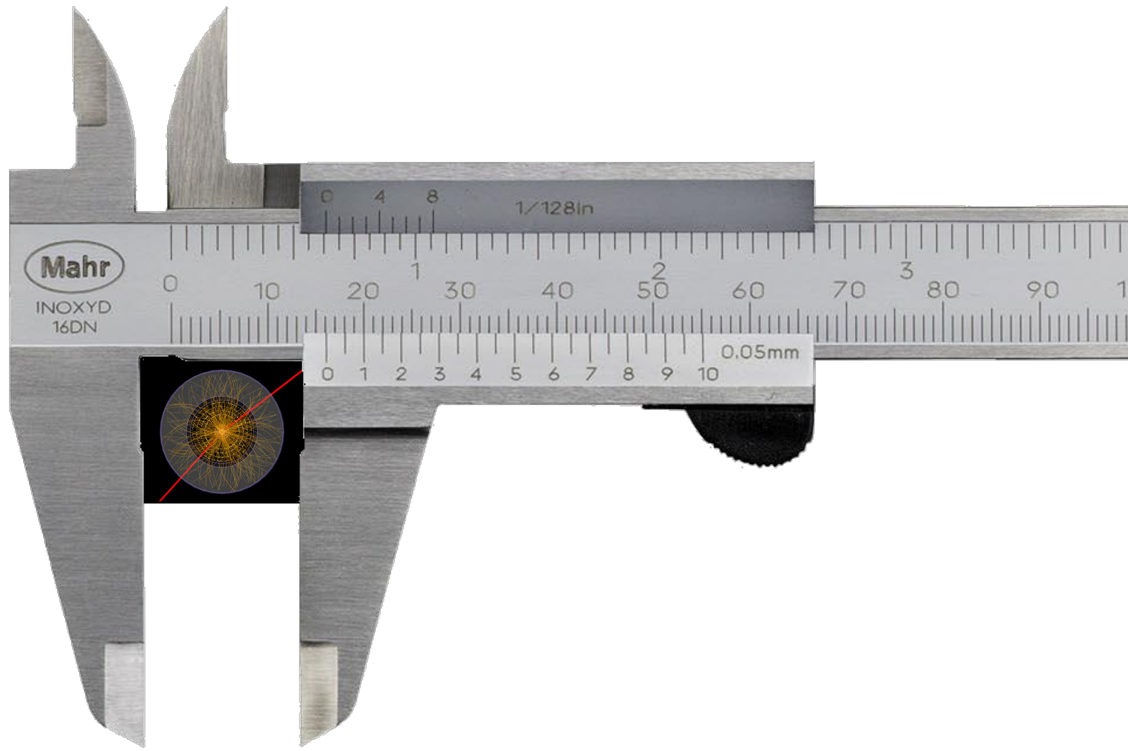
Hadron Collider Physics Summer School, 29/8/17

- Introduction, measurement foundations and W/Z physics



Introduction

- Precision measurements at hadron colliders
  - Hadron colliders are 'messy', but can still do relevant 'precision' measurements
  - Precision can mean a few % (cross-sections), or even <<1% (W mass)
  - Not a complete overview of all precision measurements at hadron colliders, but showcase a few measurements in some detail
    - Also illustrating some of the 'foundations' – e.g. object calibration, luminosity and beam energy measurements
  - Examples mainly from ATLAS, and from CMS, a few Tevatron comparisons

- Lecture 1
  - Introduction, W and Z final states, luminosity, parton distribution functions (PDFs)
- Lecture 2
  - Electroweak mixing angle, W mass, jet measurement and jet physics
- Lecture 3
  - Top physics – (differential) cross-sections, top quark mass

Outline of lecture 1

- Introduction
  - Precision measurements and the electroweak fit
- The experimental environment
  - Comparison of LHC, Tevatron and LEP
- W/Z cross-sections
  - Importance of fiducial measurements
  - Calibration of lepton efficiencies and scales – role of m_Z
  - LHC luminosity measurement
  - Parton distribution functions
- W/Z cross-section results
  - Results and constraints on PDFs

  - Thanks to Gautier Hamel de Monchenault for some diagrams …

Why precision measurements?

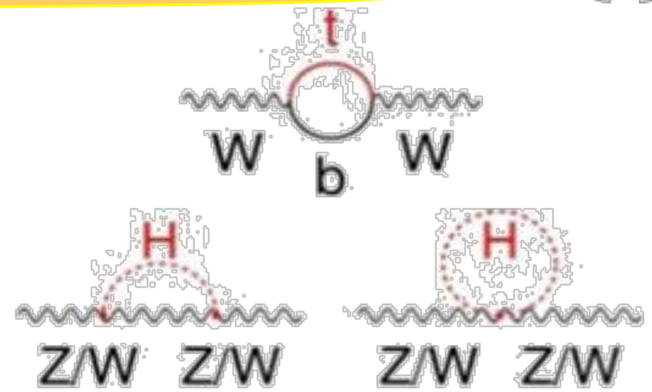
- LHC is primarily a 'discovery machine' – explore a new energy regime
  - Found the/a Higgs boson, what else will we find…?
- Can also perform precision measurements within the Standard Model
  - Improve on measurements of SM parameters
    - E.g. W vs top quark vs Higgs masses
    - E.g. $\boldsymbol{\alpha}_s$ in different processes, electroweak mixing angle $\sin^2\theta_W$
  - Study QCD dynamics at high energy, test QCD calculations
    - Improve knowledge of proton parton distribuiton functions (PDFs)
    - Test QCD with multiple high scales
    - Understand the physics of the top quark (the heaviest, and strangest quark)
  - Study the properties of the Higgs boson
  - Test SM predictions for very rare processes
- SM physics also forms the backdrop to any new physics search
  - Essential to fully understand background (particularly W/Z+jets and top) in order to search for new physics
  - SM physics processes (particularly W and Z decays to leptons) provide 'standard candles' to understand and calibrate the detector performance

Testing the consistency of the Standard Model

- Electroweak parameters

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \;\; (= 1) \qquad s_W^2 \equiv 1 - \frac{m_W^2}{m_Z^2} \;\; (= \sin^2\theta_W)$$

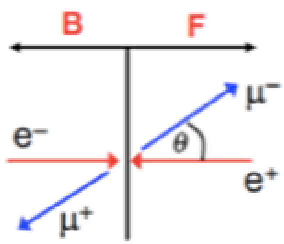
  - Physical observables modified by radiative corrections at the % level



$$\bar{\rho} = 1 + \Delta\rho \qquad M_W^2 = m_W^2\,(1 + \Delta r) \quad \sin^2\theta_W^{\mathrm{eff}} = s_W^2(1 + \Delta\kappa)$$

$$\Delta r, \Delta\rho, \Delta\kappa = f(m_t{}^2, \ln(m_H), \ldots)$$

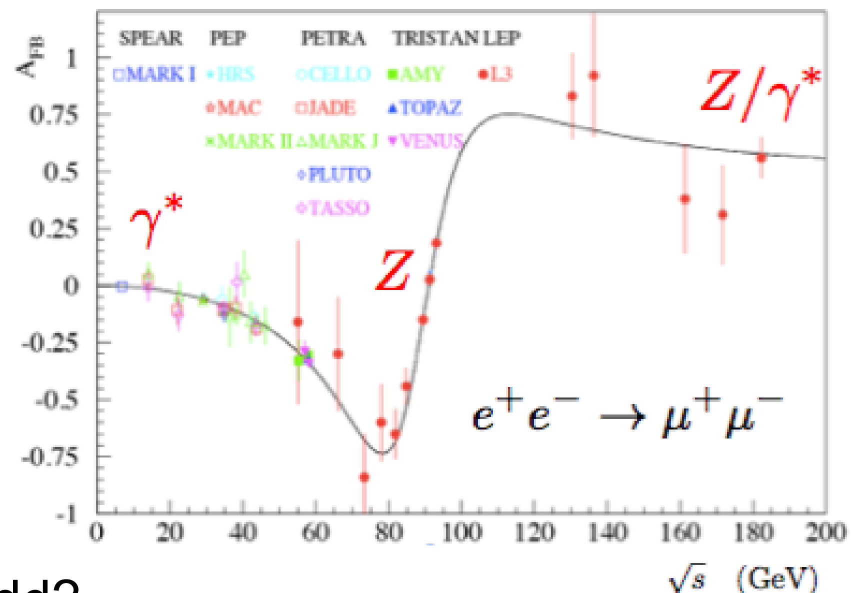
- Complementary info. from asymmetries
  - $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, bb~ etc.



FB Asymmetry

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \cos^2\theta + \frac{3}{8} A_{\mathrm{FB}} \cos\theta$$



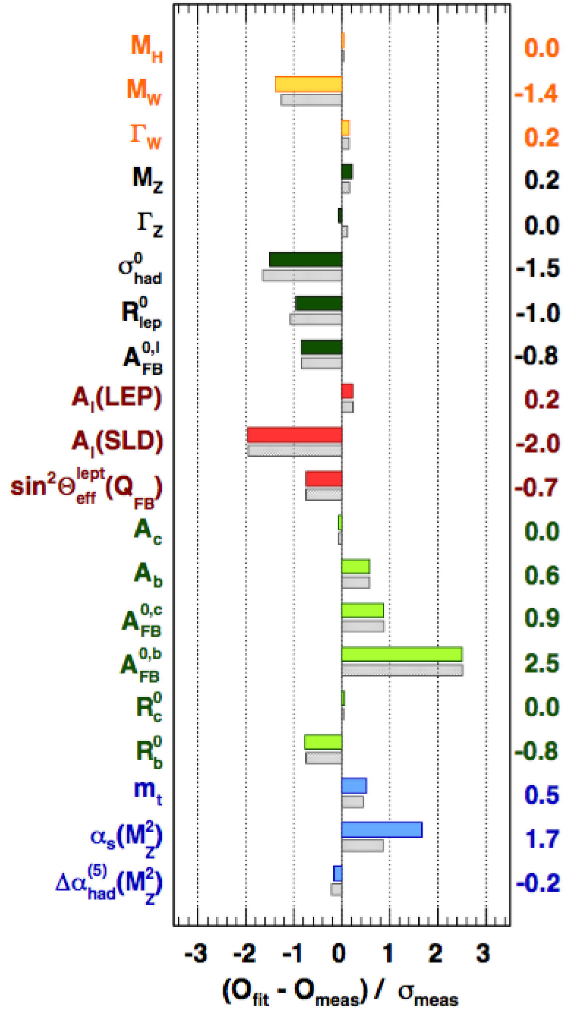
at the Z pole: $A_{\mathrm{FB}}^{0,f} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_f$

- Major achievement of LEP – what can LHC add?
  - Mass measurements, but also asymmetries…

Global electroweak fit

GFitter group
arXiv:1407.3792

- Comparison of measured and fitted electroweak parameters

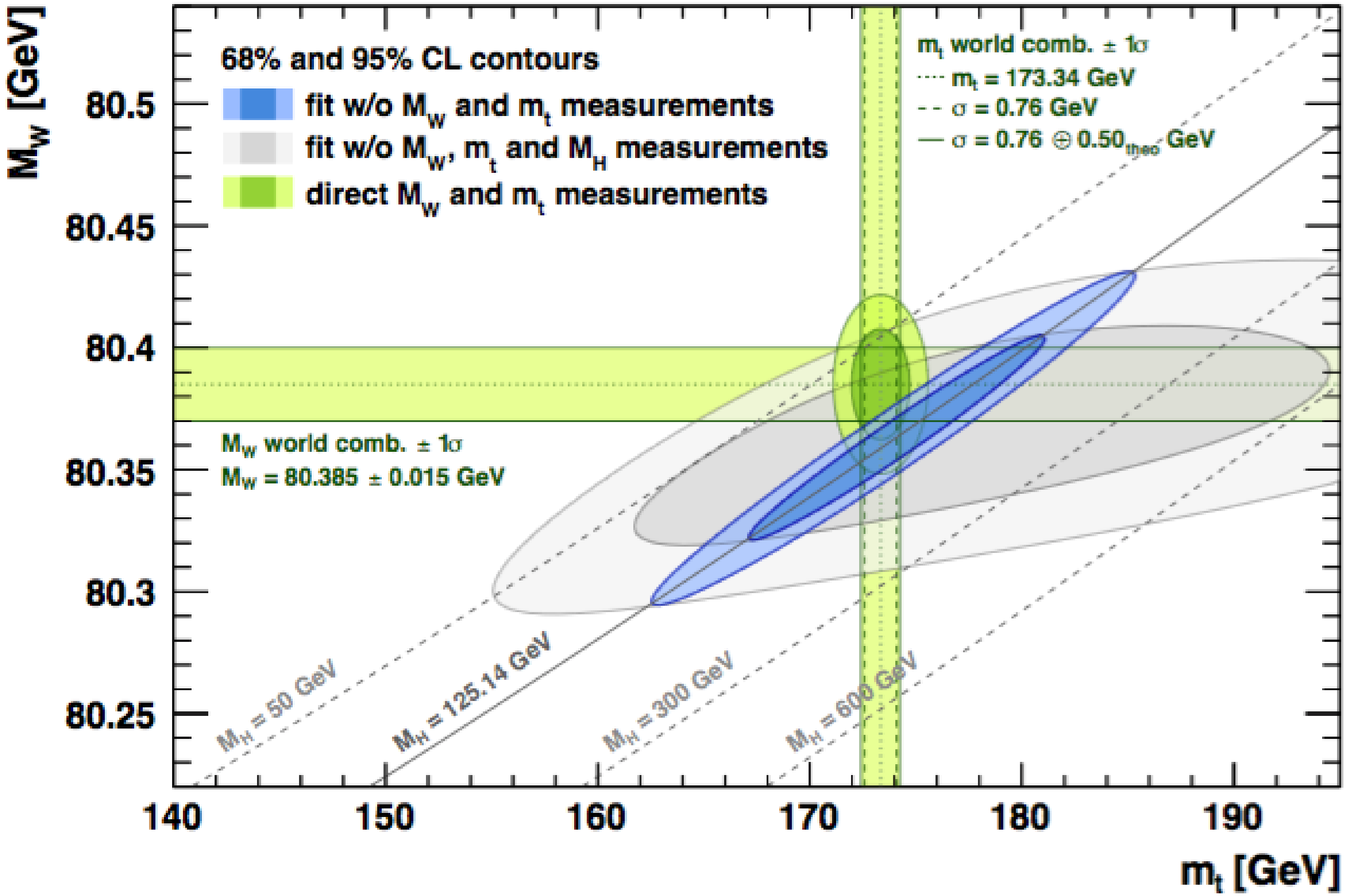


	Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line
LHC/ Tevatron	M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}
	M_W [GeV]	80.385 ± 0.015	–	80.364 ± 0.007	80.358 ± 0.008
	Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001
LEP/ SLD	M_Z [GeV]	91.1875 ± 0.0021	yes	91.1880 ± 0.0021	91.200 ± 0.011
	Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4946 ± 0.0016
	$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016
	R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.017	20.722 ± 0.026
	$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01626 ± 0.0001	0.01625 ± 0.0001
	A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0005	0.1472 ± 0.0005
	$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23150 ± 0.00006	0.23149 ± 0.00007
	A_c	0.670 ± 0.027	–	0.6680 ± 0.00022	0.6680 ± 0.00022
	A_b	0.923 ± 0.020	–	0.93463 ± 0.00004	0.93463 ± 0.00004
	$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0003	0.0738 ± 0.0003
	$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0004	0.1034 ± 0.0004
	R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008
	R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00011	0.21577 ± 0.00011
LHC/Tev	m_t [GeV]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\bigtriangledown)}$	$177.0^{+2.3}_{-2.4}{}^{(\bigtriangledown)}$

- LHC/Tevatron: m_W (and m_H, m_{top}), asymmetries also interesting

W, top and Higgs masses

- Impressive consistency of the direct and indirect determination of masses

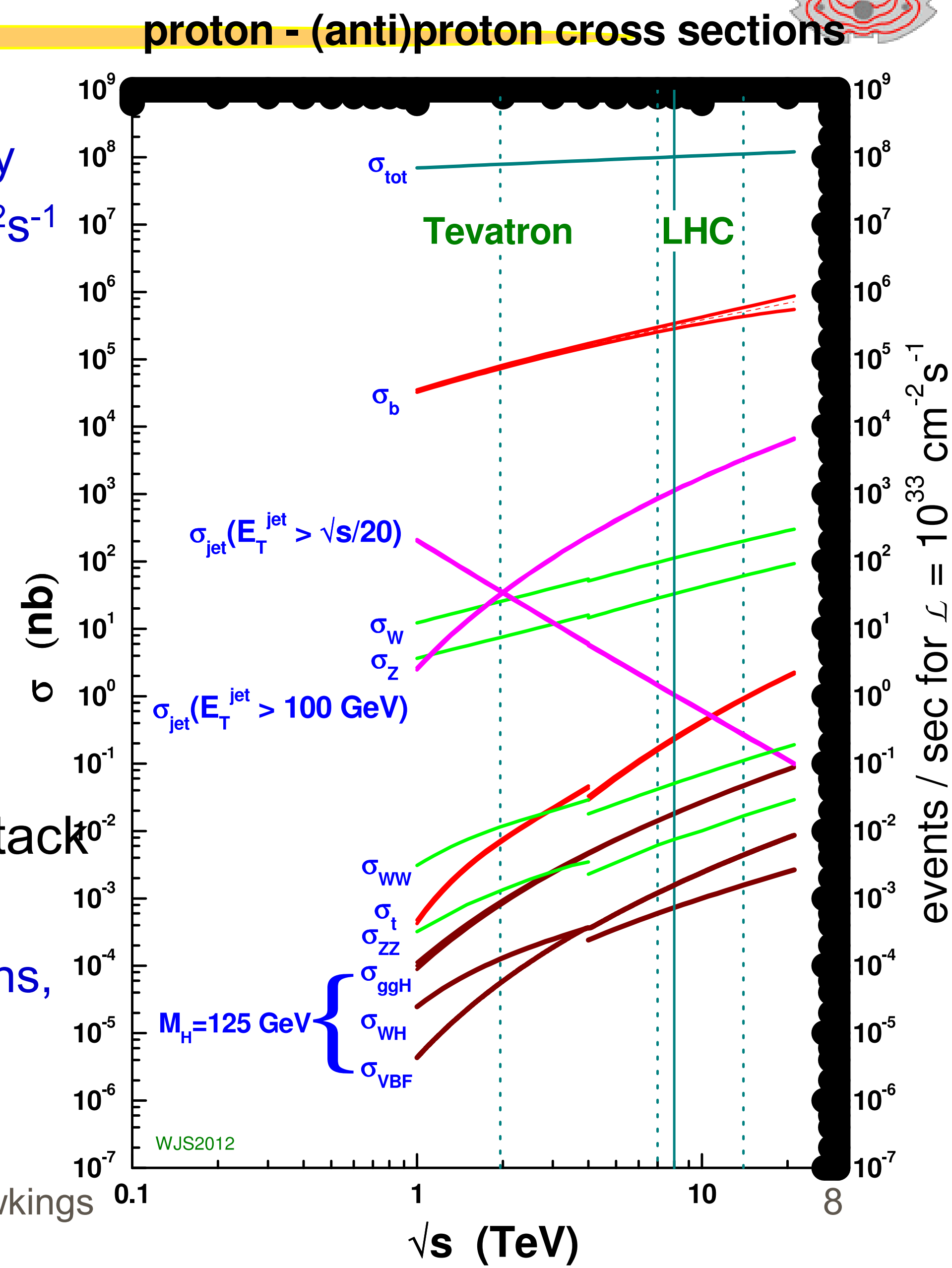


- Important in particular to measure m_W better (but already $\Delta m_W/m_W$=0.02%)

The physics landscape at LHC

- LHC is a W/Z/H/top factory
  - But it is also a jet / b / soft interaction factory
  - Rates for nominal LHC, 13 TeV, $L=10^{34} cm^{-2}s^{-1}$

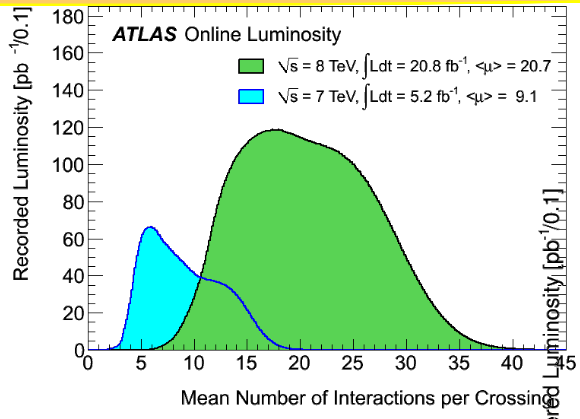
Process	Rate @13TeV
Inelastic pp collision	10^9 Hz
b-quark pair production	10^6 Hz
Jet production, E_T>250 GeV	10^3 Hz
$W \rightarrow l\nu$	10^2 Hz
Top-quark pair production	10 Hz
Higgs (m_H=125 GeV)	0.1 Hz

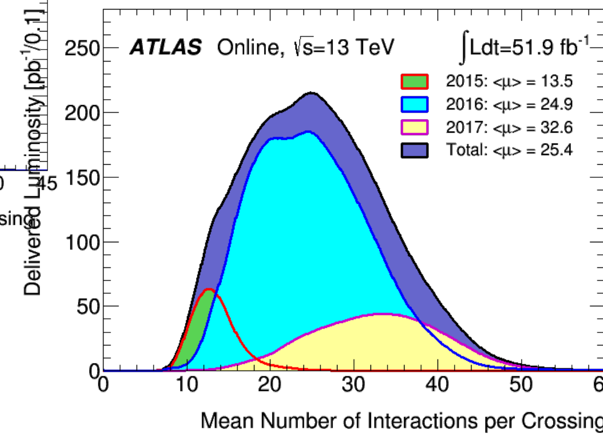


- Interesting processes – a needle in a haystack
  - Limited to recording 10^2 - 10^3 Hz of events
  - Trigger selections based on high-p_T electrons, photons, muons, taus, jets, E_T^{miss}
  - Cannot record all $W \rightarrow l\nu$ events
    - Control of trigger biases is crucial

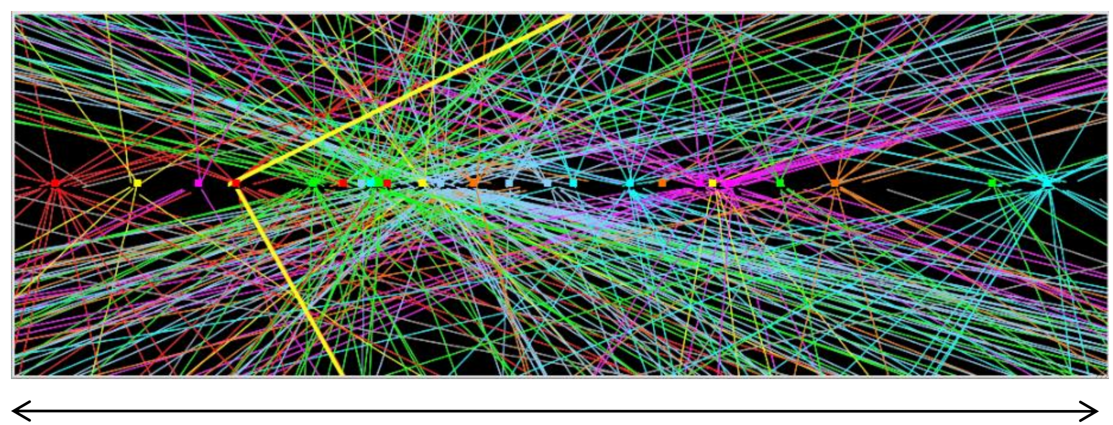
The LHC experimental environment

- High pileup complicates precision physics measurements
  - Additional pp interactions in same bunch crossing, and in nearby bunch crossings for slow detectors
  - $<\mu>\approx 20$ in run-1, higher in run-2
- Effects of pileup
  - Deterioration of jet and E_T^{miss} resolution, additional pileup jets
    - Higher trigger thresholds
  - Additional jets from pileup
  - Misidentification of primary vertex
  - Pileup-dependent efficiencies, even for leptons
- Pileup mitigation techniques
  - Particle flow (jets, E_T^{miss}, isolation)
  - Jet-area based pileup corrections





Z→μμ event with ~25 reconstructed vertices



20 cm

Comparison of LHC with LEP and Tevatron

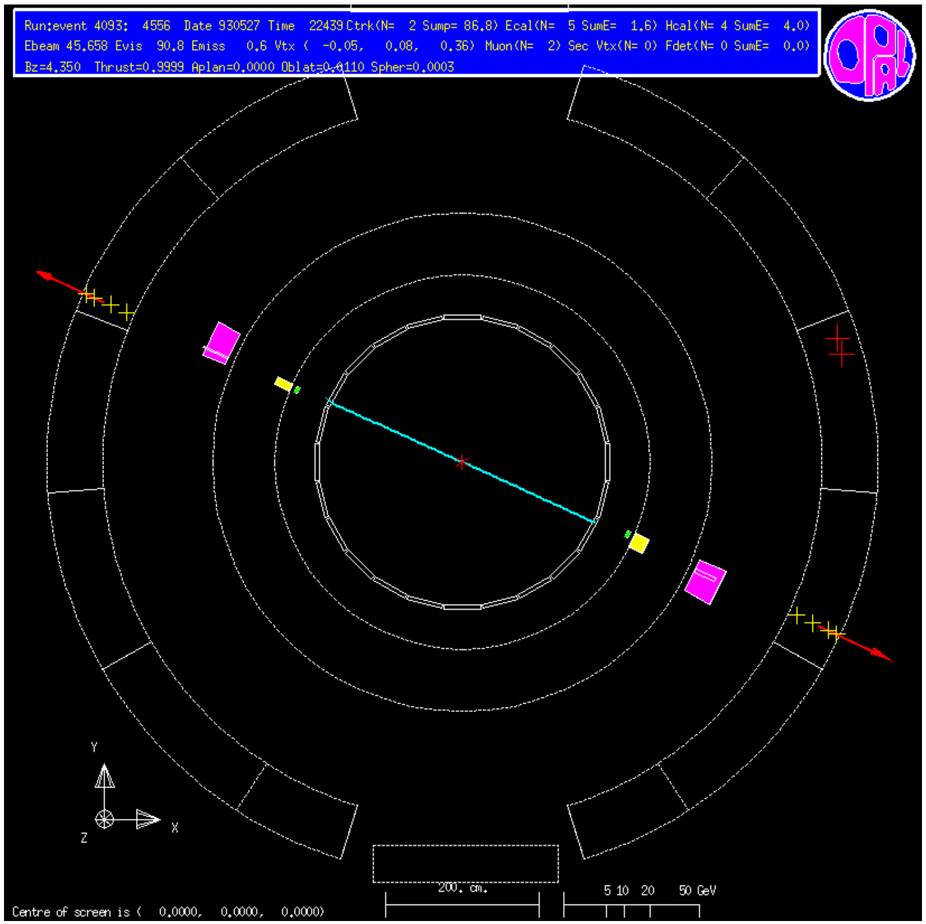
- Samples of W, Z and top-pair events at the different colliders

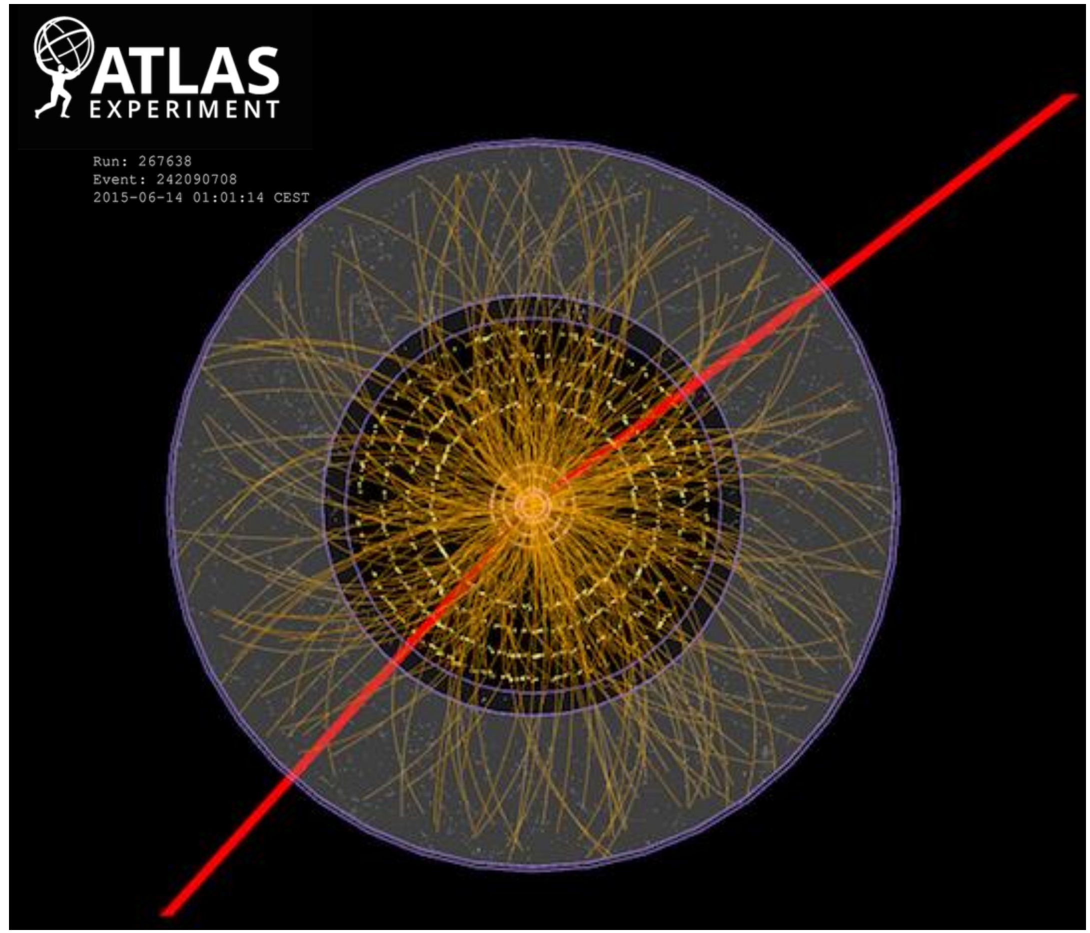
	LEP	Tevatron	LHC
Particles	e^+e^-	p-pbar	pp
$\sqrt{s}$ (GeV)	88-209 GeV	1.8-1.96 TeV	7-13 TeV
Int. L/ expt	200-700 pb^{-1}	2-10 fb^{-1}	5-300 fb^{-1}
Typical $<\mu>$	<<1	~1-10	20-40
# $W\rightarrow l\nu$ /expt	10k	~1-2M	10M (in 5 fb^{-1})
# $Z\rightarrow ll$ / expt	0.5M	~100k	1M (in 5 fb^{-1})
# ttbar / expt	-	10^5	10^7

- LEP e+e- collider
  - Very clean e^+e^- events, Ws only produced in pairs, full event reconstruction, limited data samples, no top quarks
- Tevatron/LHC
  - Larger samples, pileup and underlying event, no complete reconstruction, tops

$Z \rightarrow \mu\mu$ at LEP and LHC

- OPAL $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ from 1993, ATLAS 13 TeV $pp \rightarrow Z \rightarrow \mu^+\mu^-$ from 2015

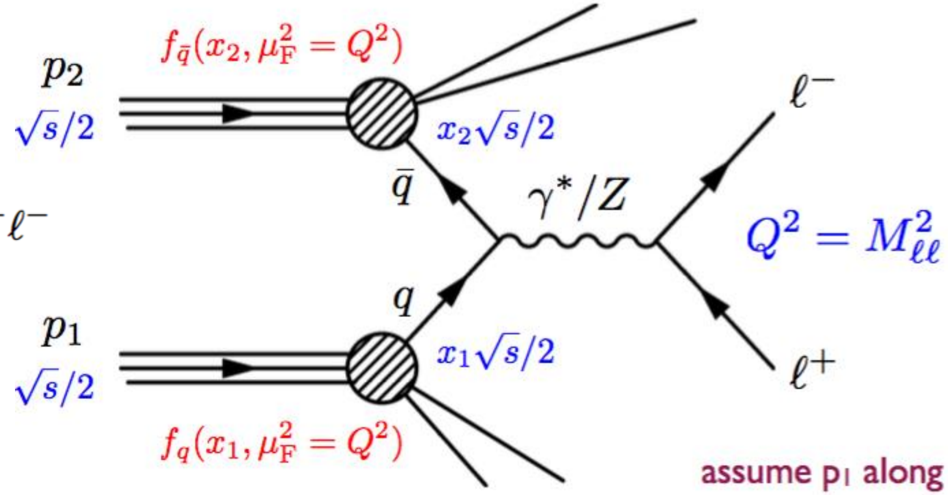




Z and W cross-section measurements

- Drell-Yan production: lepton pairs from quark-antiquark annihilation

$$q(x_1) + \bar{q}(x_2) \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^-$$

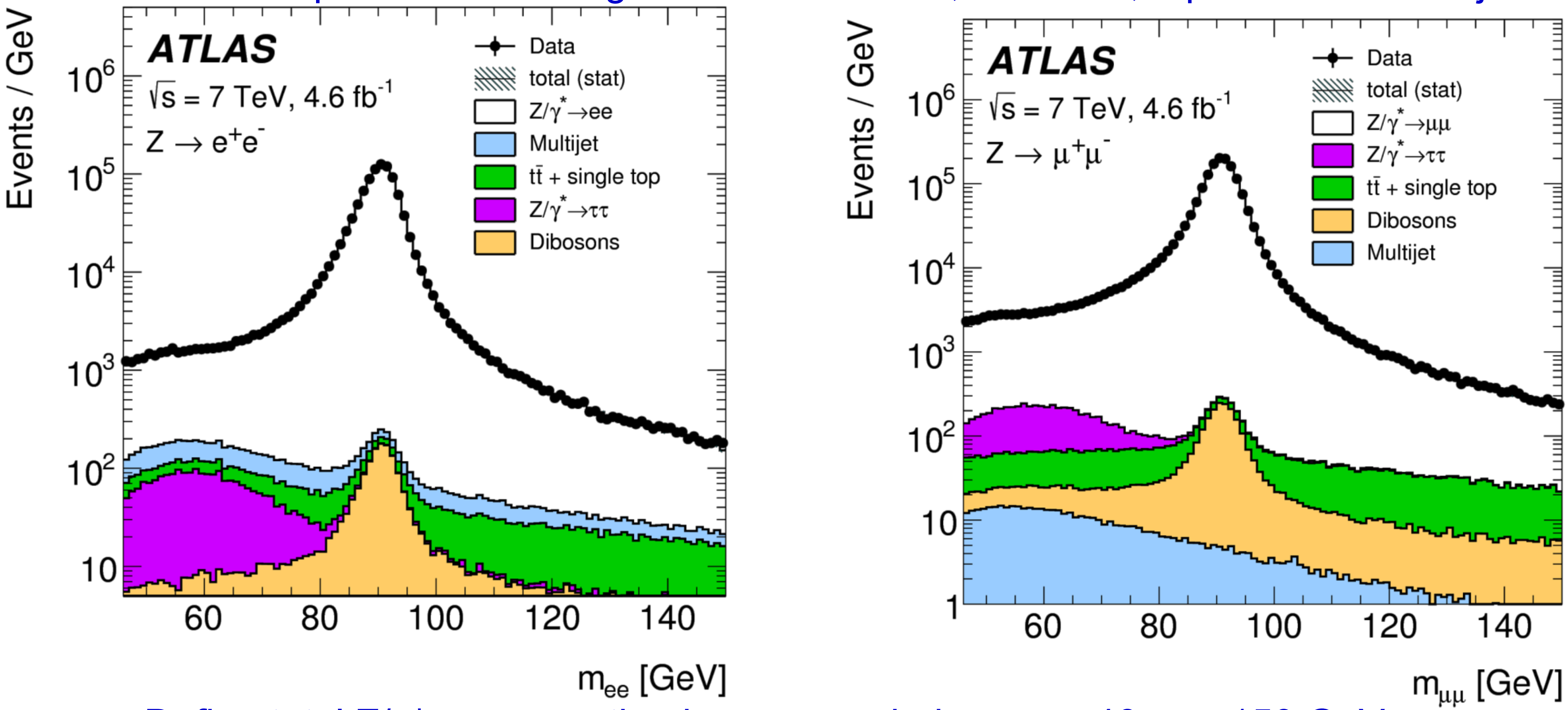


$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$$

  - Boson rapidity is correlated with parton x_1, x_2 – gives information on proton PDFs
  - Studying both $Z/\gamma^* \rightarrow l^+l^-$ and $W \rightarrow l\nu$ allows disentangling quark flavours
- Experimentally, very attractive process:
  - High p_T(>20 GeV) leptons easy to trigger, identify offline and measure precisely
  - Low backgrounds (dominant process giving high p_T leptons at LHC)
  - 'Standard candle' for calibration measurements
    - Z has two leptons and the Z mass is precisely known from LEP

Z→ee and Z→$\mu\mu$ event samples

- Large cross-section: σ(pp→Z) × BR(Z→ll)=0.9 nb at 7 TeV, ×2 at 13 TeV
  - Final ATLAS 7 TeV analysis (4.6 fb^{-1}) has 1M Z→ee and 1.6M Z→$\mu\mu$
  - Pure samples – <1% backgrounds from Z→$\tau\tau$, dibosons, top and QCD multijet

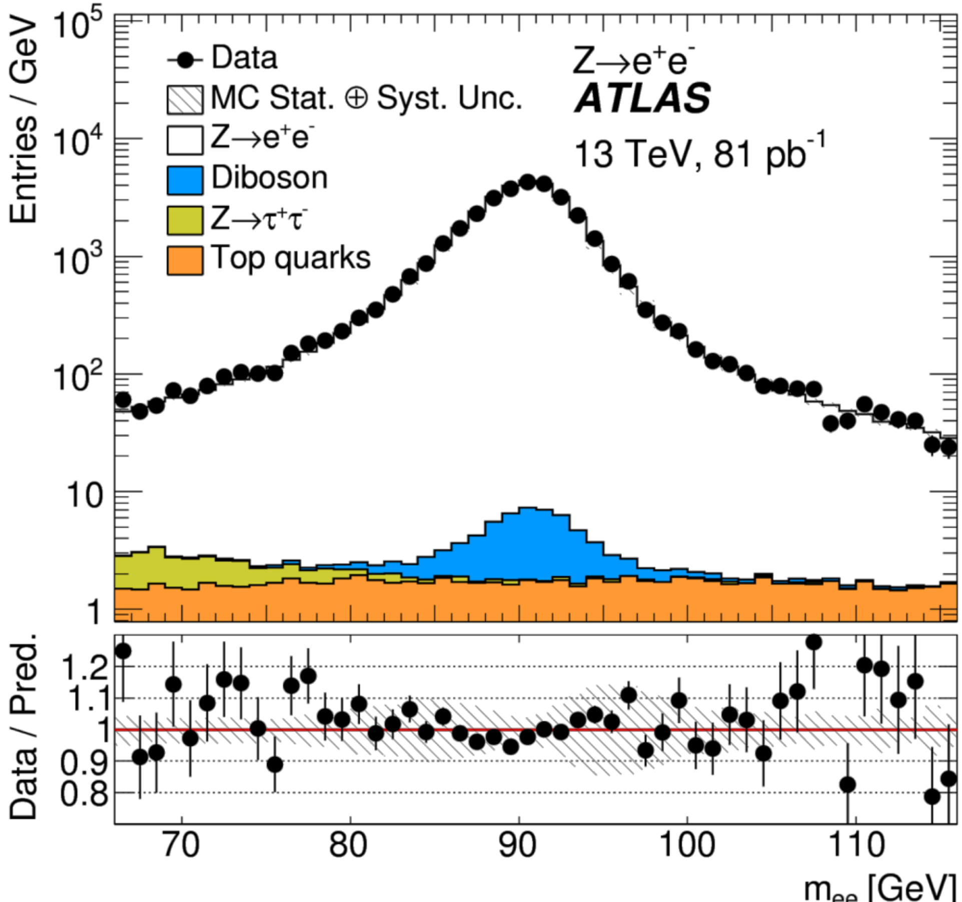


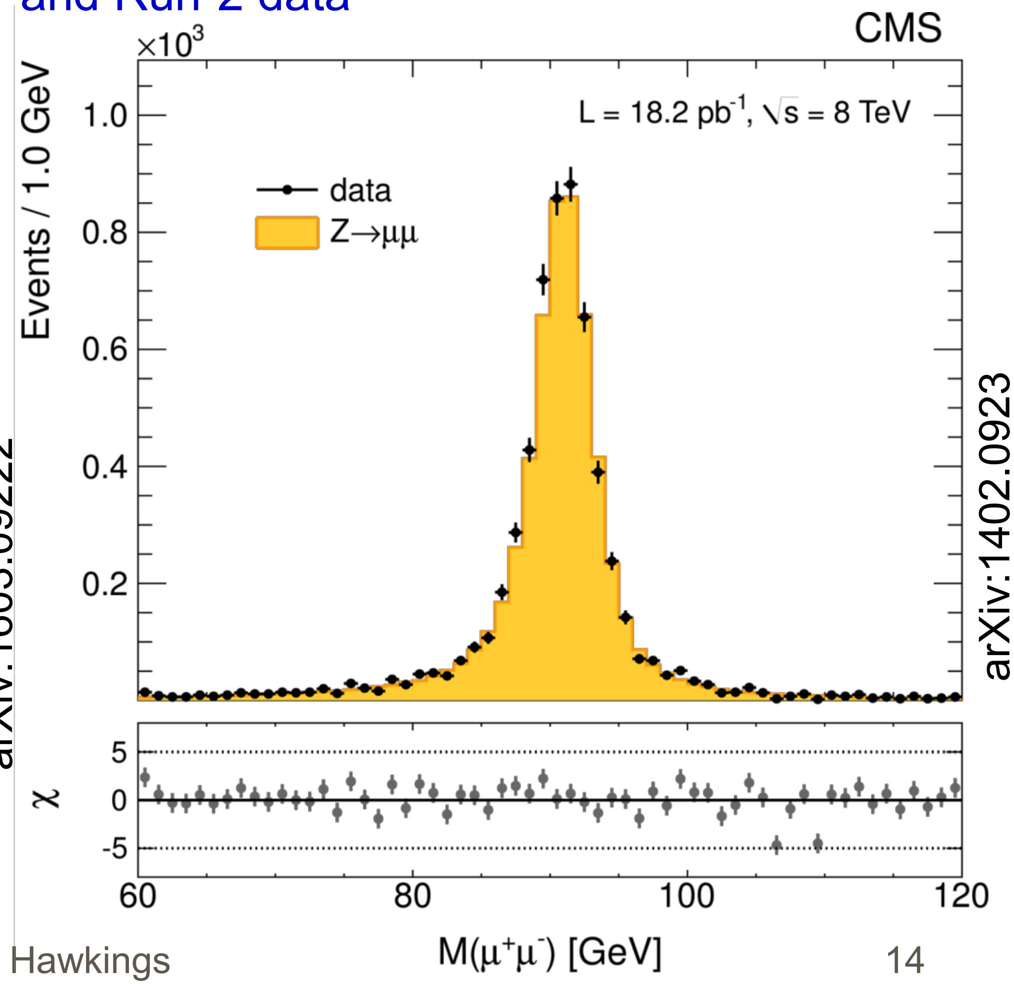
arXiv:1612.03016

  - Define total Z/γ* cross-section in a mass window, e.g. 46<m_{ll}<150 GeV

More Z→ee and Z→$\mu\mu$ event samples

- Even small samples (<100 pb^{-1}) lead to 10^4-10^5 Z→ll event samples
  - Inclusive cross-section analyses do not need the full data statistics
  - Early analyses done with both Run-1 and Run-2 data





Total and fiducial cross-section definitions

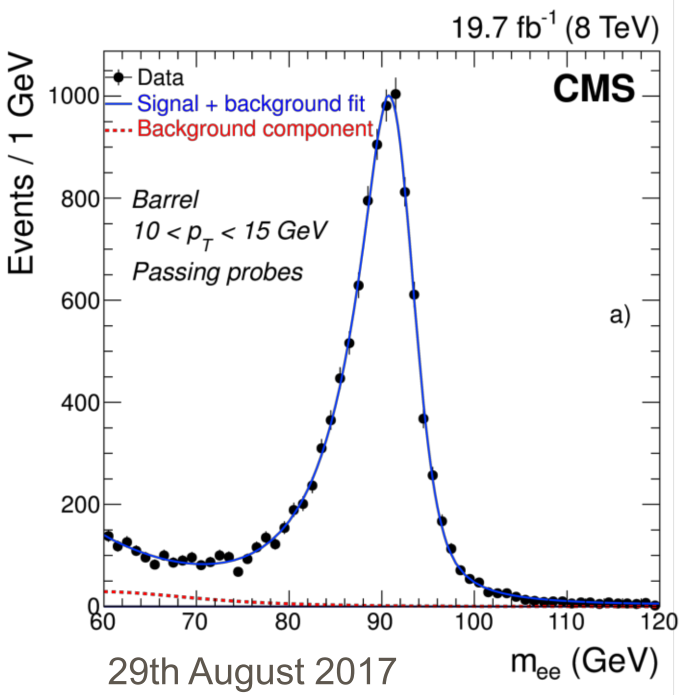
- Measurement of total cross-section from event counting in mass window
  - $\sigma^{tot} = (N-B) / (\varepsilon L)$
  - Efficiency ε includes both the lepton identification efficiencies ...
  - ..and probability of event to satify kinematic requirements for detector acceptance
    - E.g. p_T>20 GeV (trigger, reconstruction) and $|\eta|$<2.5 (coverage of detector)
    - Acceptance calculation needs a MC simulation model – uncertainties can be large
- Alternative of fiducial cross-section – 'measure what you detect'
  - Split efficiency ε into an acceptance A and recon effiencicy C; $\varepsilon = A \times C$
  - Define a fiducial phase space at particle level: p_T^{fid}>20 GeV, $|\eta^{fid}|$<2.5

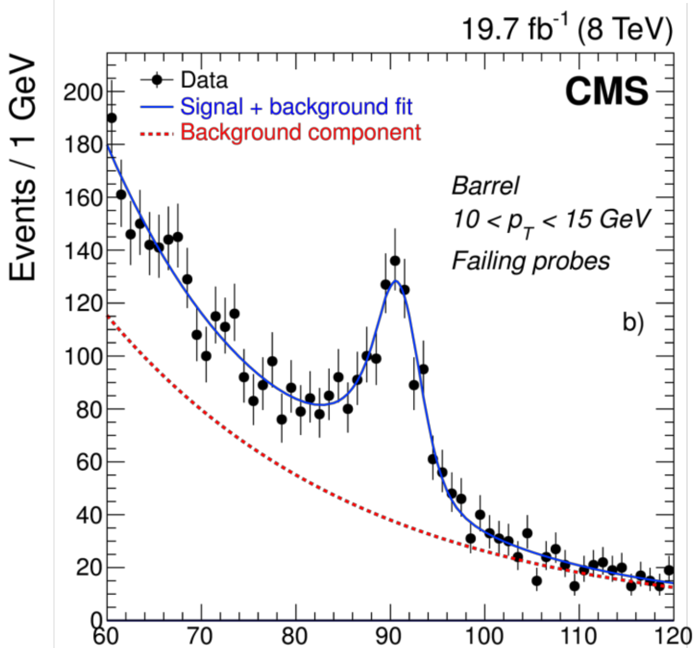
$$\sigma^{\mathrm{fid},e(\mu)}_{W\to e(\mu)\nu[Z\to ee(\mu\mu)]} = \frac{N_{W[Z]} - B_{W[Z]}}{C_{W[Z]} \cdot L_{\mathrm{int}}} \qquad C_{W[Z]} = \frac{N^{\mathrm{MC,rec}}_{W[Z]}}{N^{\mathrm{MC,gen,fid}}_{W[Z]}}$$

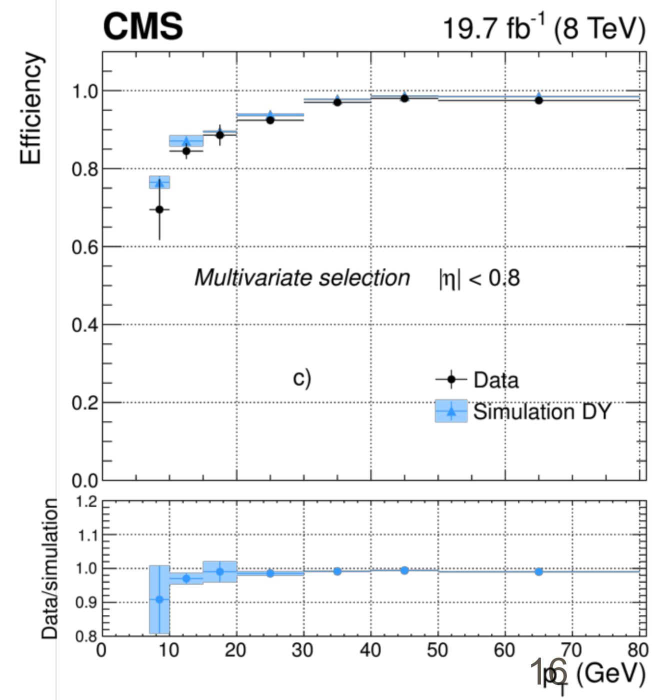
- Advantages – avoid extrapolations into unmeasured phase space
  - Can make use of updated acceptance predictions once they become available
- Disadvantage – acceptance calculation moved to theory (prediction)
  - Need to calculate $pp\to Z\to ll$ with decay kinematics (at NLO, NNLO), not just $pp\to Z$
    - Becomes challenging for more complex final states, e.g. top-pair production

Lepton efficiency measurements

- $Z \to ll$ (and $J/\psi, \Upsilon \to ll$) used for **tag and probe** efficiency measurements
  - One tightly-identified lepton (tag), other with just a subset of requirements
    - E.g. loose track+calo match for electron, ID track only for muon
  - Z-mass requirement ensures probe sample is still dominated by real leptons
  - Efficiency of requirement under test can then be calibrated on this pure sample
    - Need careful background subtraction in the sample failing the requirement
  - Compare data and simulation results to derive correction factors for simulation



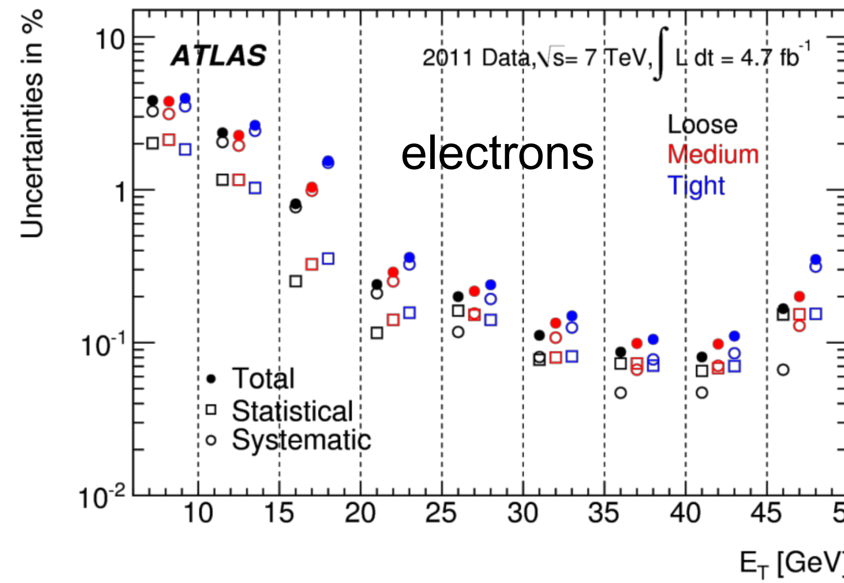




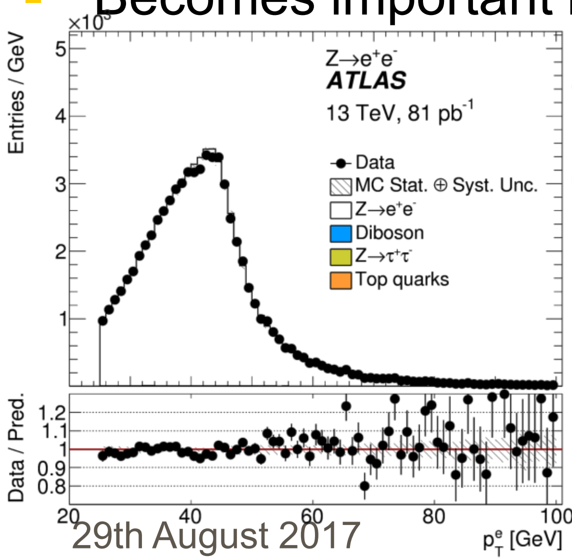
arXiv:1502.02701

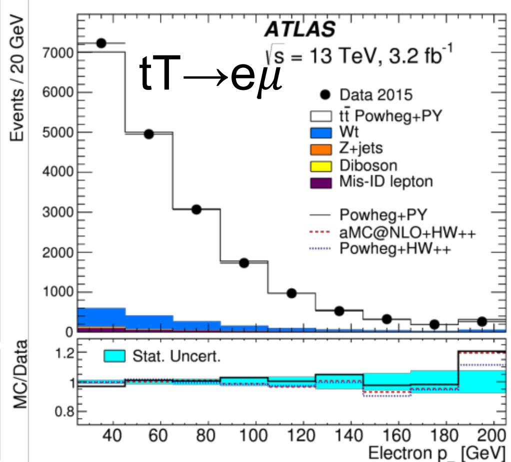
Lepton efficiency measurements – continued

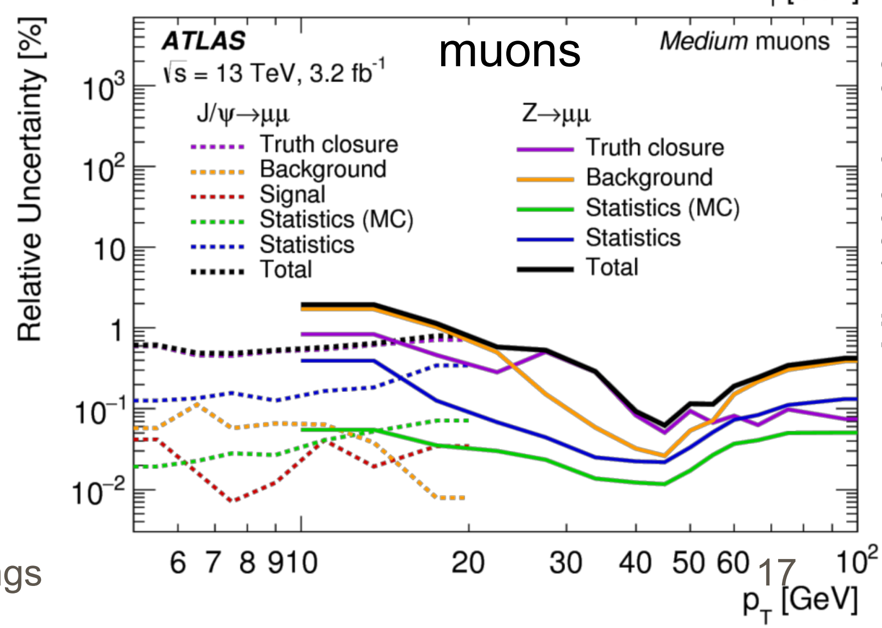
- Typically achieve sub-percent precision
  - For lepton p_T close to those in Z decays
- More difficult at low p_T
  - $J/\psi,\Upsilon \rightarrow ll$ harder to trigger on, poorer S/B
- More difficult at high p_T
  - Run out of statistics beyond Z-peak region
    - And relatively more background at high p_T
  - Extrapolation with MC-based inputs
- Becomes important in top-quark analyses



arXiv:1404.2240



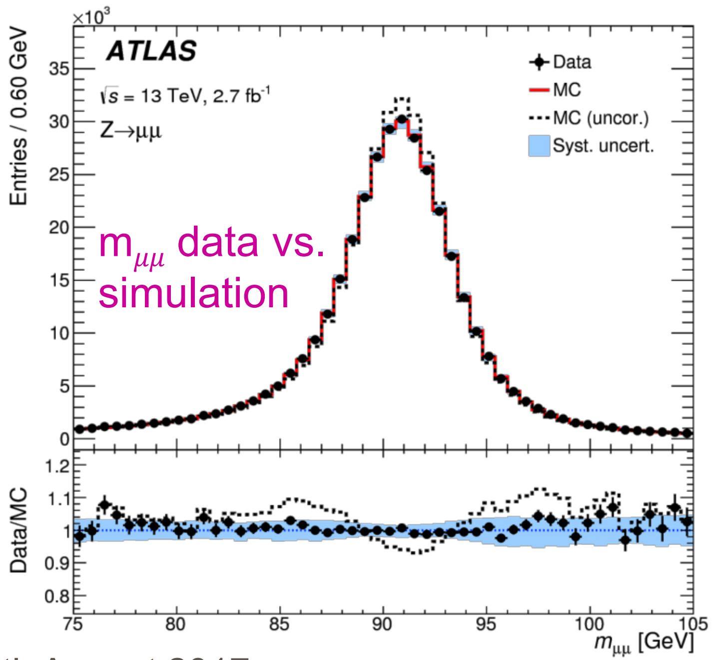


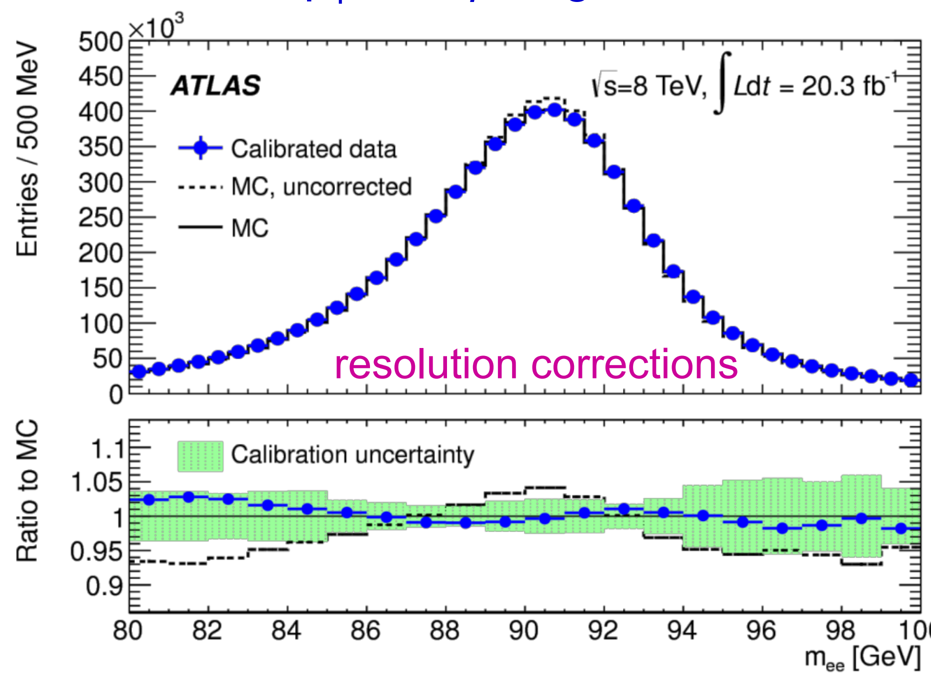


arXiv:1603.05598

Lepton energy/momentum calibration

- Z→ll samples (+J/ψ,Υ→ll) also used for electron and muon energy calibration
  - For electrons, typically 'bottom up' cluster calibration+detailed material model
    - Final in-situ corrections using template fits to Z→ee data in bins of electron $|\eta|$
  - For muons, scale and resolution depend on ID alignment, muon chamber alignment and drift time calibration, magnetic field map, material, …
    - In-situ corrections using Z→μμ template fits in bins of η and ϕ
  - Typical scale uncertainties are below 10^{-3} in relevant p_T and η ranges





arXiv:1407.5063

How do we know m_Z?

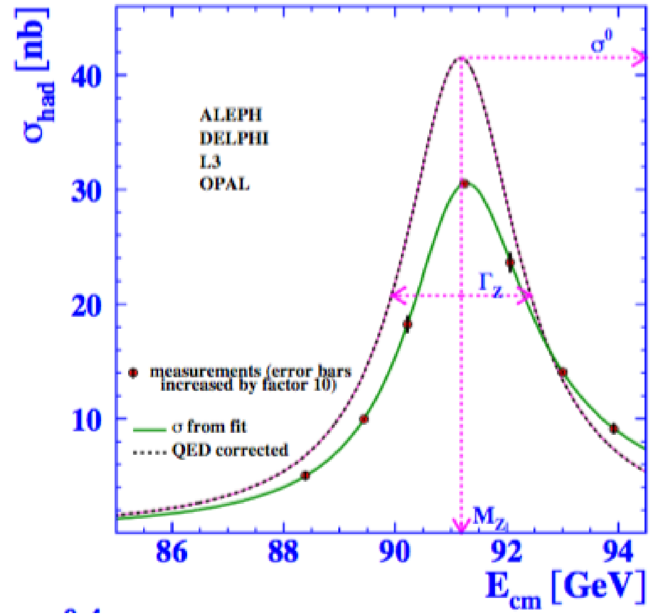
- m_Z determined from Z-lineshape at LEP
  - Total cross-section for $e^+e^- \to$ hadrons vs $\sqrt{s}$
  - Measurements at peak and 6 off-peak energies
  - Fit to model to determine mZ, Γ_Z and σ^0_{had}
    - 6 years of data-taking, 10 years of analysis…

$$m_Z = 91.1875 \pm 0.0021 \text{ GeV} \quad (0.002\%)$$

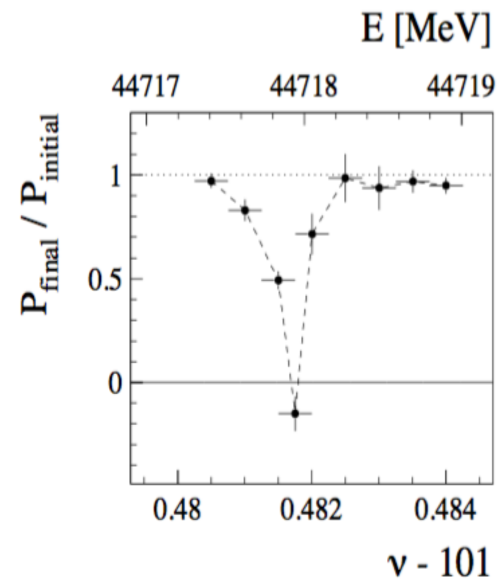
- Uncertainty dominated by energy calibration
  - Based on technique of resonant depolarisation
  - Spin precession frequency of electrons

$$\nu = \frac{E[\text{MeV}]}{440.6486(1)[\text{MeV}]}$$

    - Wait for polarisation to build up due to synchrotron radiation, find frequency of a depolarising magnetic field
  - Many corrections to translate to physics data, e.g.
    - Lunar tides change the radius of LEP/LHC tunnel
    - Return current from electric trains (TGV)
  - Only at LEP1 – polarisation too weak above 100 GeV

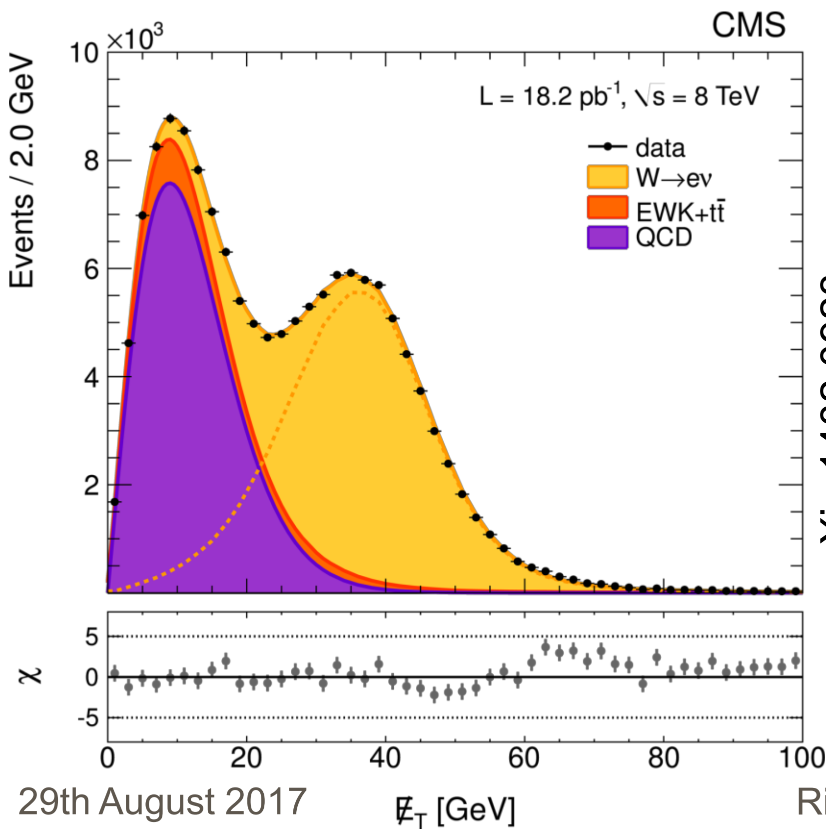


arXiv:hep-ex/0509008



W→eν and W→μν samples

- W selections also require the use of E_T^{miss} to measure the neutrino p_T
  - Cannot fully reconstruct the W boson mass as the neutrino p_Z is not measured
  - Use the transverse mass m_T: $m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)}$,
  - Extract signal from E_T^{miss} or m_T distributions, cut and count or shape fit
  - Significant background from QCD multijet events; ~10% in W→eν, ~5% in W→μν



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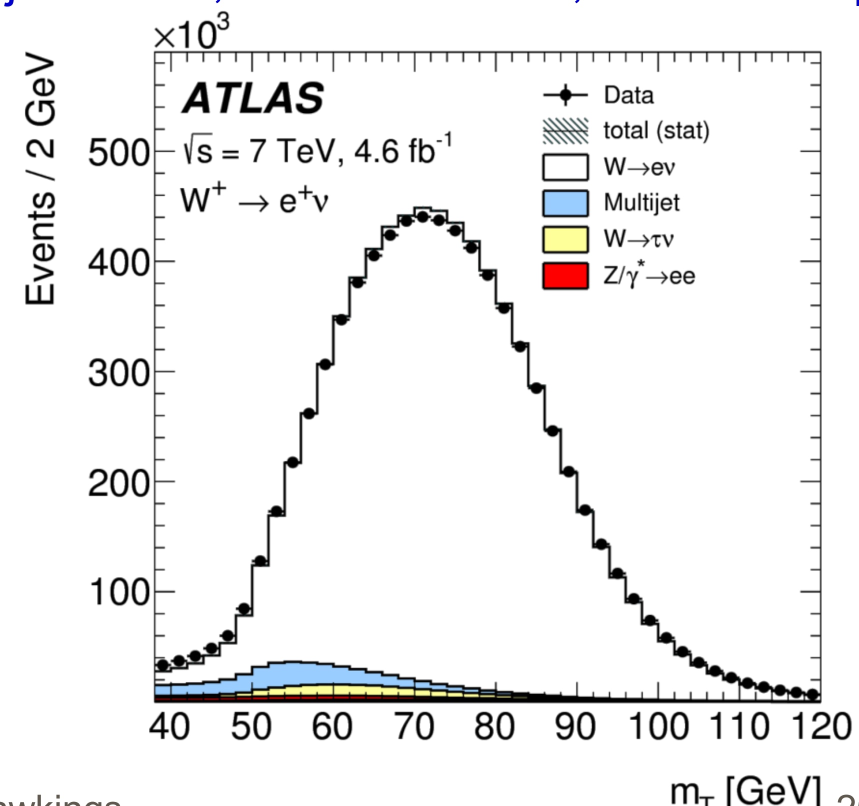
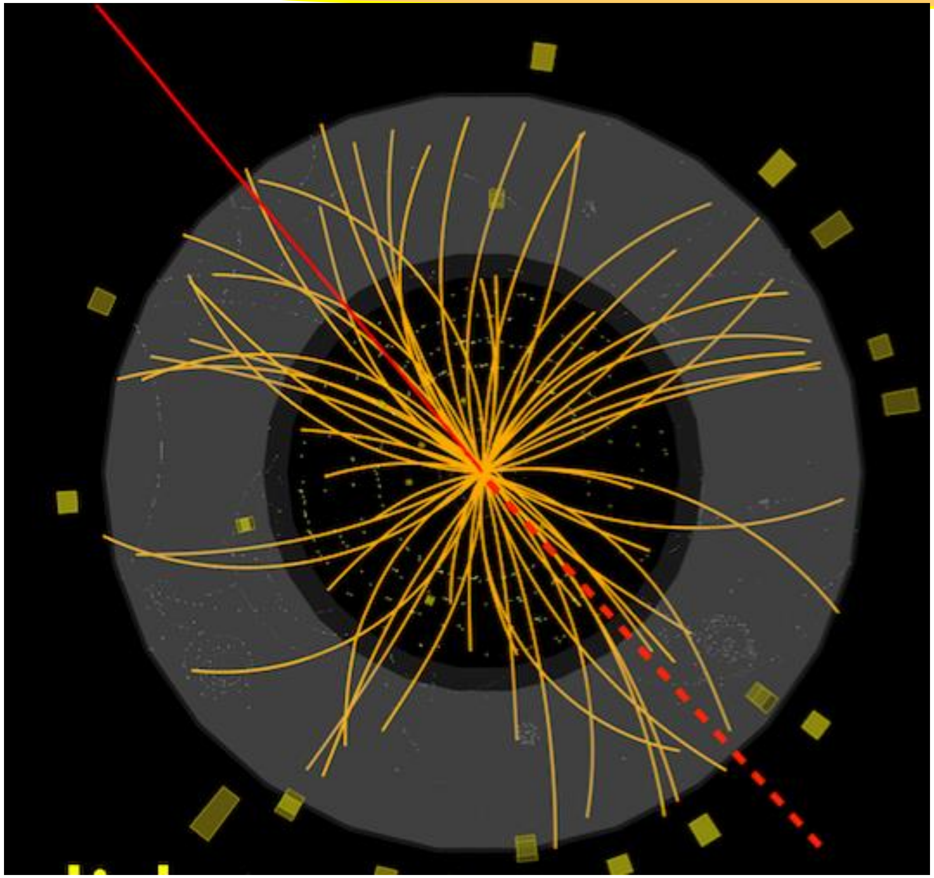
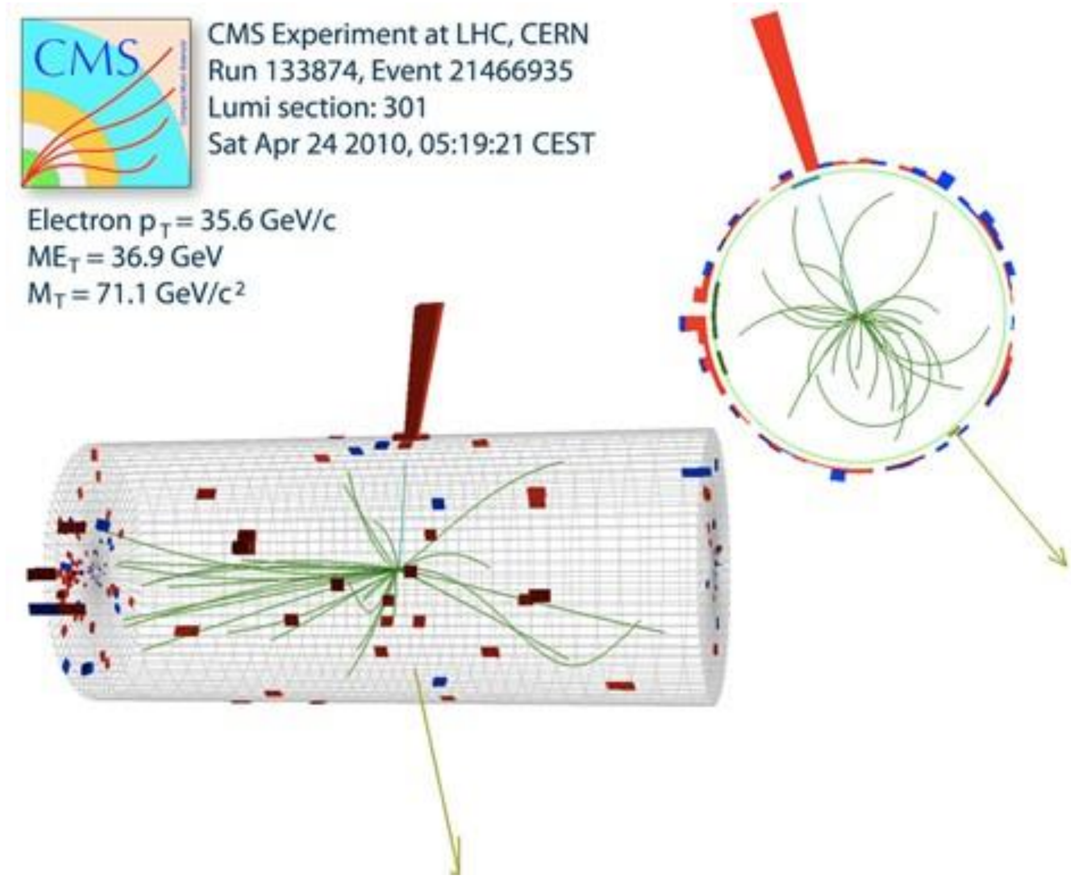


W→$\mu\nu$ and W→eν event displays





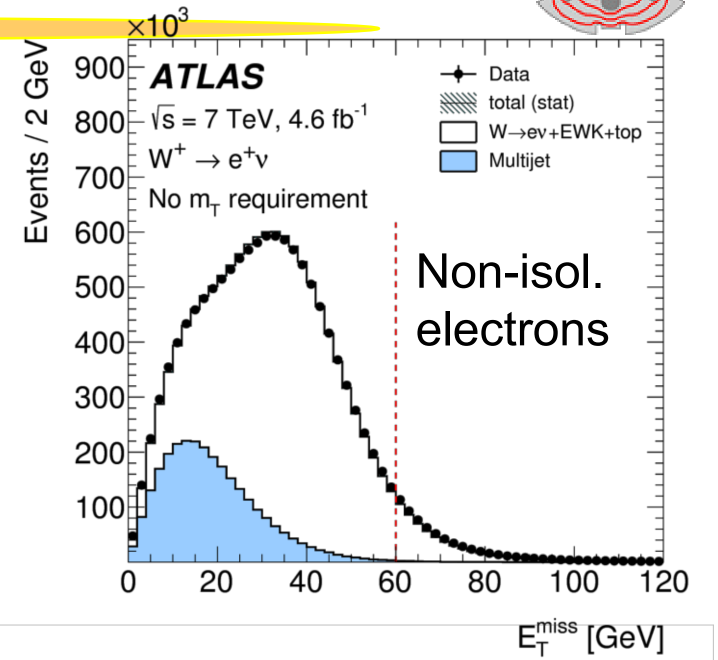
ATLAS EXPERIMENT

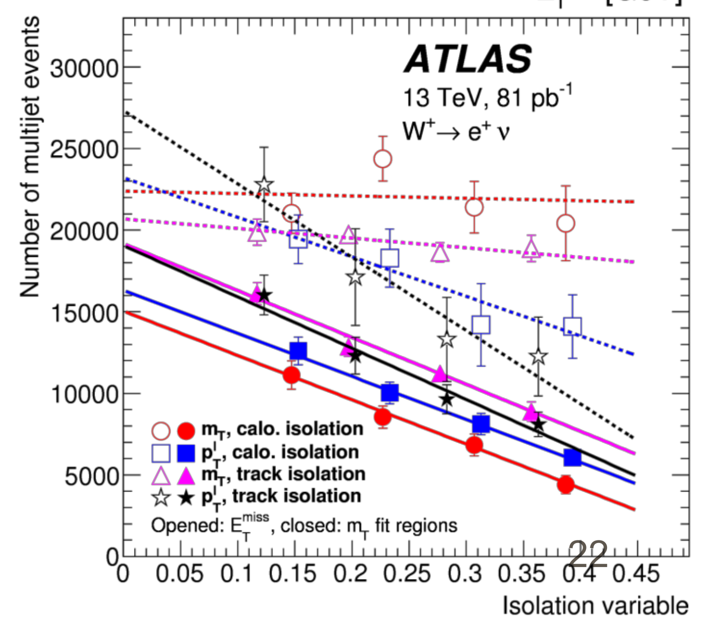
$p_T(\mu-) = 40$ GeV
$\eta(\mu-) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV

- Events from early 2010
  - Very little pileup, but still see tracks from underlying event accompanying the W boson production

Backgrounds in W (and Z)

- Backgrounds with **prompt** leptons (mainly top) evaluated from simulation
  - Reliable simulation of physics and selection efi.
- Backgrounds from QCD multi-jet more difficult
  - Jet misidentified as electron or muon due to
    - b/c hadron decay (b,c→e,μ)
    - Hadron mis-ID as lepton (EM-like shower, K,$\pi\rightarrow\mu$)
    - Electron from photon conversion
  - Hard to model in simulation, uncertain jet x-sec
  - Rejection factors of ~10^5 from lepton ID and isolation cuts – cannot simulate enough events
- Measure backgrounds from data control samples
  - E.g. invert lepton isolation or ID cuts and fit background in a control region close to signal
  - Shapes in signal region are distorted by relaxed cuts
    - Fit in different slices of isolation or kinematic variables and extrapolate to signal region





Uncertainties in W/Z fiducial cross-sections

- Systematic uncertainties on ATLAS 7 TeV precision W/Z fiducial x-sec

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]	$\delta\sigma_{\text{forward } Z}$ [%]
Trigger efficiency	0.03	0.03	0.05	0.05
Reconstruction efficiency	0.12	0.12	0.20	0.13
Identification efficiency	0.09	0.09	0.16	0.12
Forward identification efficiency	–	–	–	1.51
Isolation efficiency	0.03	0.03	–	0.04
Charge misidentification	0.04	0.06	–	–
Electron p_{T} resolution	0.02	0.03	0.01	0.01
Electron p_{T} scale	0.22	0.18	0.08	0.12
Forward electron p_{T} scale + resolution	–	–	–	0.18
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.14	0.13	–	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.06	0.04	–	–
Jet energy scale	0.04	0.02	–	–
Jet energy resolution	0.11	0.15	–	–
Signal modelling (matrix-element generator)	0.57	0.64	0.03	1.12
Signal modelling (parton shower and hadronization)	0.24	0.25	0.18	1.25
PDF	0.10	0.12	0.09	0.06
Boson p_{T}	0.22	0.19	0.01	0.04
Multijet background	0.55	0.72	0.03	0.05
Electroweak+top background	0.17	0.19	0.02	0.14
Background statistical uncertainty	0.02	0.03	<0.01	0.04
Unfolding statistical uncertainty	0.03	0.04	0.04	0.13
Data statistical uncertainty	0.04	0.05	0.10	0.18
Total experimental uncertainty	0.94	1.08	0.35	2.29
Luminosity		1.8		

arXiv:1612.0301

Luminosity measurement – principles

- Luminosity from a single pair of colliding bunches, rotation freq. f_r:

$$\mathcal{L}_b = \frac{\mu f_r}{\sigma_{inel}} \qquad \mathcal{L}_b = \frac{\mu_{vis} f_r}{\sigma_{vis}}$$

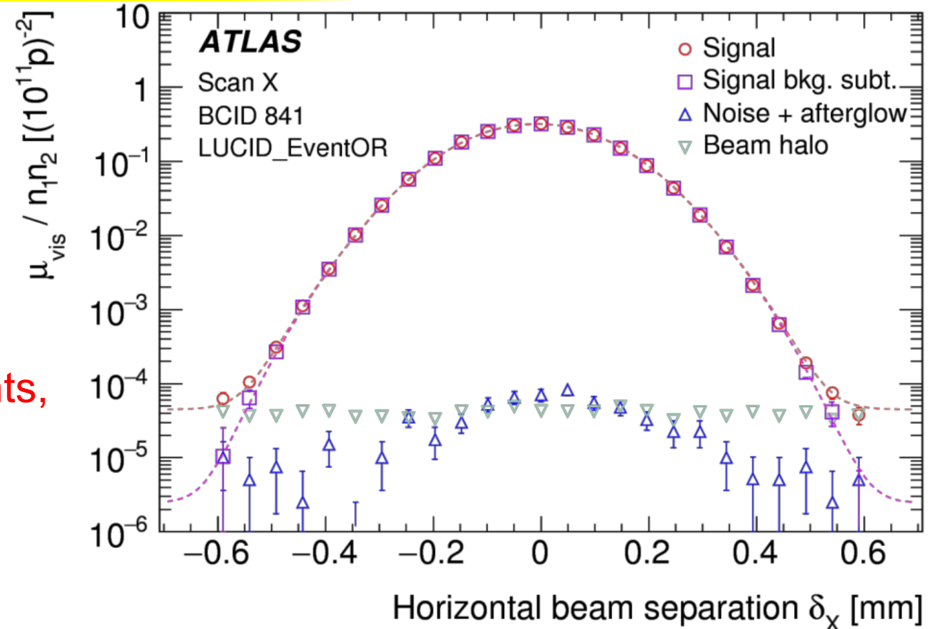
- Measure counting rate per bunch-crossing μ_{vis} for any lumi-dependent signal
  - Hit rate in a detector, current in a calorimeter, number of tracks/clusters …
    - Poisson fluctuations in μ_{vis}, becomes saturated if μ_{vis}>>1
- Calibrate σ_{vis} from accelerator/beam parameters in dedicated low-lumi fills

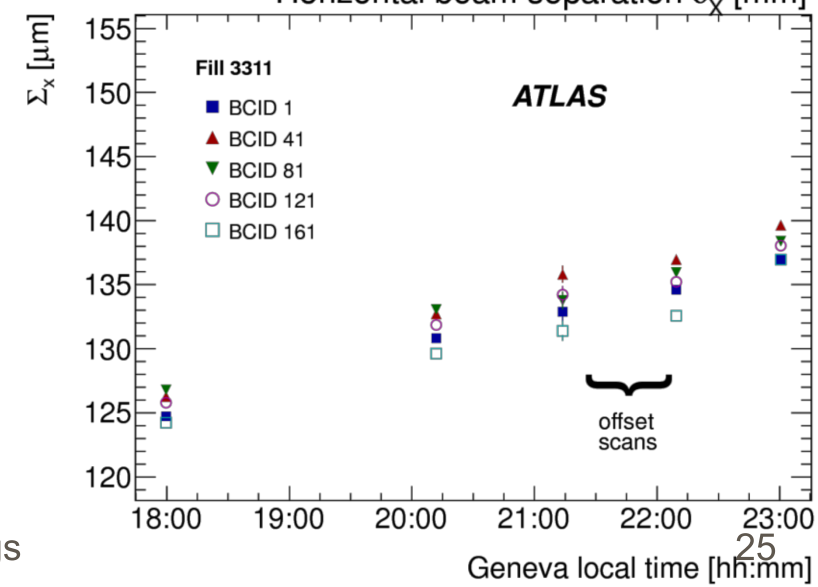
$$\mathcal{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \qquad \sigma_{vis} = \mu_{vis}^{MAX} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

  - Absolute luminosity calculated from number of protons per beam (n1,n2) – bunch currents, and size of the overlap of the beams Σ_x, Σ_y in x and y planes
    - Dedicated 'van der Meer' fills with larger beam sizes and well-controlled conditions
- Many luminosity-dependent signals employed
  - Forward Cerenkov counters, diamond beam conditions monitors
    - Need to have deadtime-less readout, independent of high-level trigger
  - Calorimeter photomultiplier and HV gap currents – integrate over all bunches
  - Pixel cluster counting and track counting

Luminosity measurement – vdM scan

- Scan beam separation in x or y plane
  - Determine beam widths Σ_x, Σ_y
  - Determine maximum count rate μ_{vis}^{MAX}
  - Measure bunch currents n_1 and n_2 from precise LHC instrumentation (DCCT)
    - O(1 min) per scan point, many scan points, (x,y), repeat scans…
    - Several days dedicated beam time
- Many complications
  - Absolute x/y displacement calibration
    - Use beamspot movement in tracker
  - Beam size (emmitance) growth within fill
  - Satellite bunches, ghost charge
  - Non-Gaussian beam shapes, tails
  - Non-factorisation: overlap ≠ $\Sigma_x \Sigma_y$
    - Check with 'off-axis' scans
  - Beam-beam kicks, bunch-bunch variations

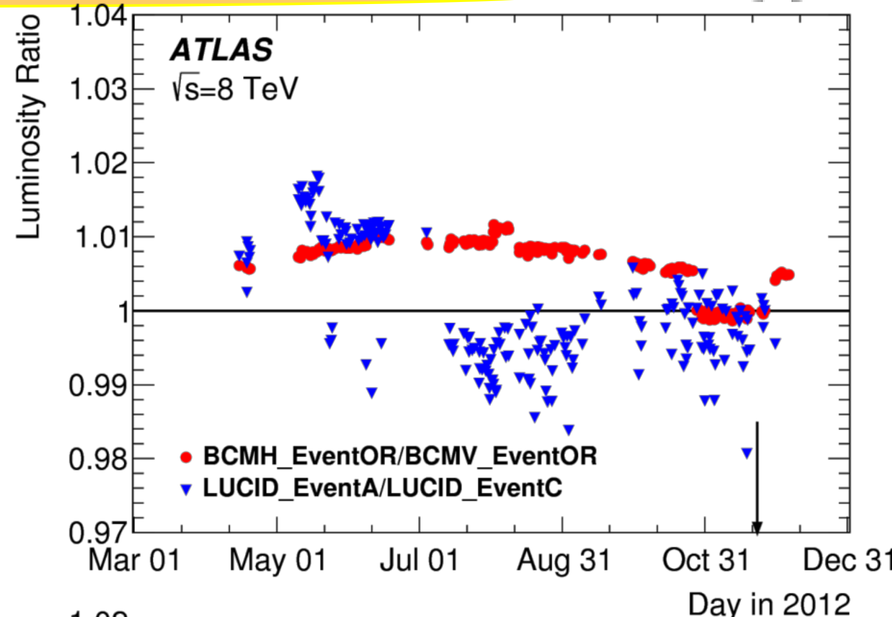


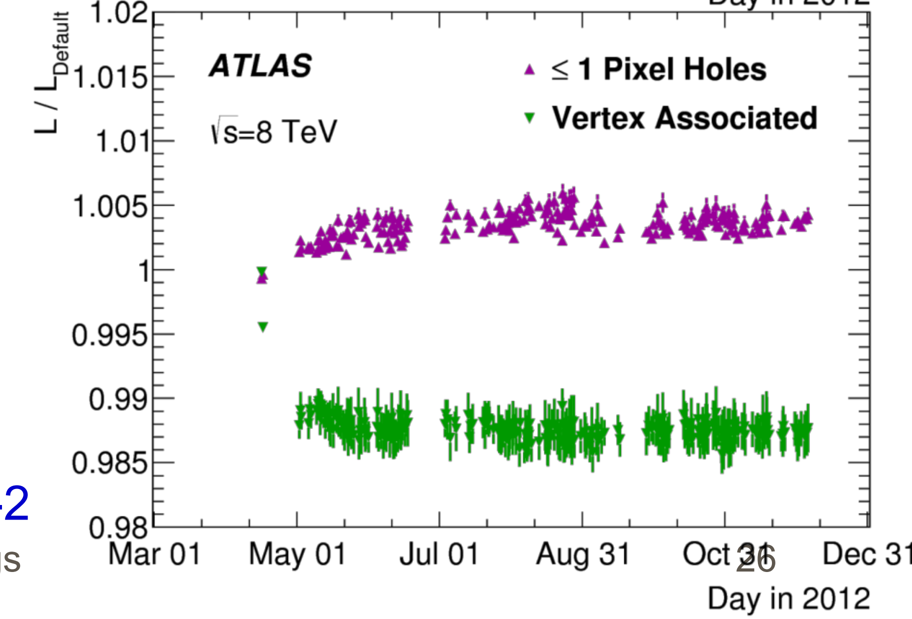


arXiv:1608.03953

Luminosity measurement – transfer and stability

- vdM scans done 1-3 times/year, <μ>≈1
  - Calibrate each detector/algorithm σ_{vis}
- Extrapolate to physics environment
  - <μ>=20—50, even higher soon
  - Higher counting rates, non-linear effects, bunch trains, detector ageing
- Check consistency of different methods
  - Typically agreeing at ~% level after lots of effort, corrections several %
  - Differences evolve with time, can be pileup dependent
  - Which algorithms do you trust most?
    - E.g. two track-counting selections with the same detector diverge at 2% level
  - ATLAS mainly used BCM and Lucid, CMS pixel counting and FCal for final run-1 results
  - Additional approaches being explored at run-2





Luminosity measurement – final uncertainties

- Final uncertainties on integrated luminosity O(2-3%)
  - Tend to be dominated by calibration transfer to high-L, rather than vdM scans

ATLAS 8 TeV pp – ΔL/L=1.9%

vdM calibration

Source	Uncertainty [%]
Reference specific luminosity	0.50
Noise and background subtraction	0.30
Length-scale calibration	0.40
Absolute ID length scale	0.30
Subtotal, instrumental effects	0.77
Orbit drifts	0.10
Beam-position jitter	0.20
Beam–beam corrections	0.28
Fit model	0.50
Non-factorization correction	0.50
Emittance-growth correction	0.10
Bunch-by-bunch consistency	0.23
Scan-to-scan consistency	0.31
Subtotal, beam conditions	0.89
Bunch-population product	0.24
Total	1.20

transfer

Uncertainty source	$\delta\mathcal{L}/\mathcal{L}$ [%]
van der Meer calibration	1.2
Afterglow subtraction	0.2
Calibration transfer from -scan to high-luminosity regime	1.4
Long-term drift correction	0.3
Run-to-run consistency	0.5
Total	1.9

CMS 8 TeV pp – ΔL/L=2.5%

transfer

vdM calibration

Systematic	correction (%)	uncertainty (%)
Stability	-	1
Dynamic inefficiencies	-	0.5
Afterglow	~ 2	0.5
Fit model	-	2
Beam current calibration	-	0.3
Ghosts and satellites	-0.4	0.2
Length scale	-0.9	0.5
Emittance growth	-0.1	0.2
Orbit Drift	0.2	0.1
Beam-beam	1.5	0.5
Dynamic-β	-	0.5
Total		2.5

- C.f. Tevatron ΔL/L=6%, from counting rates wrt total inelastic cross-section
  - Latter inferred from inelastic/elastic rates, not vdM scans
  - Some measurements normalised to **assumed** Z cross-section

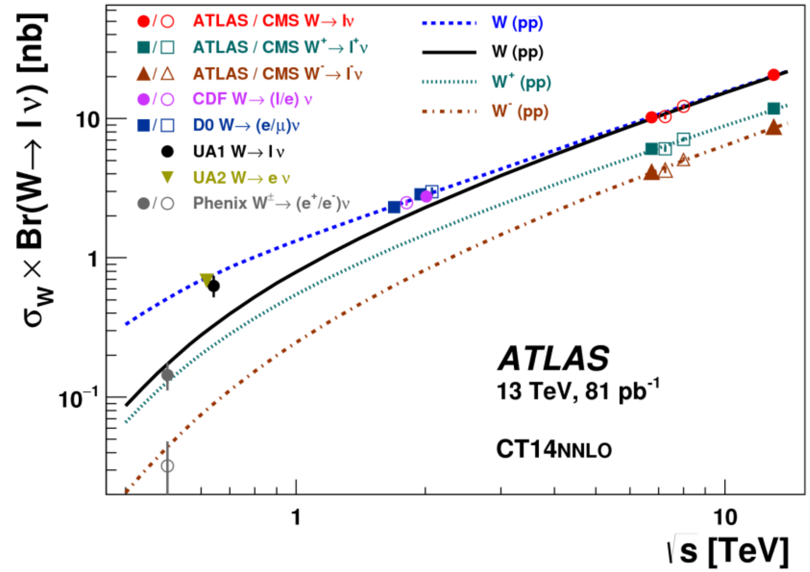
W and Z cross-section results

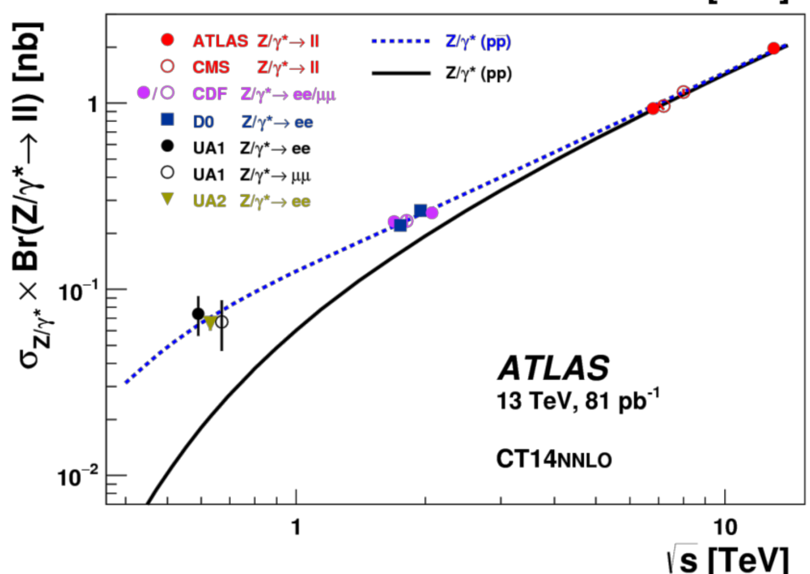
- Results from 7 TeV ATLAS analysis

Electrons	$\sigma^{\text{fid},e}_{W\to e\nu}$ [pb]
$W^+ \to e^+\nu$	$2726 \pm 1\,(\text{stat}) \pm 28\,(\text{syst}) \pm 49\,(\text{lumi})$
$W^- \to e^-\bar{\nu}$	$1823 \pm 1\,(\text{stat}) \pm 21\,(\text{syst}) \pm 33\,(\text{lumi})$
	$\sigma^{\text{fid},e}_{Z/\gamma^*\to ee}$ [pb]
Central $Z/\gamma^* \to e^+e^-$	$439.5 \pm 0.4\,(\text{stat}) \pm 1.5\,(\text{syst}) \pm 7.9\,(\text{lumi})$
Forward $Z/\gamma^* \to e^+e^-$	$160.2 \pm 0.3\,(\text{stat}) \pm 3.7\,(\text{syst}) \pm 2.9\,(\text{lumi})$

Muons	$\sigma^{\text{fid},\mu}_{W\to \mu\nu}$ [pb]
$W^+ \to \mu^+\nu$	$2839 \pm 1\,(\text{stat}) \pm 17\,(\text{syst}) \pm 51\,(\text{lumi})$
$W^- \to \mu^-\bar{\nu}$	$1901 \pm 1\,(\text{stat}) \pm 11\,(\text{syst}) \pm 34\,(\text{lumi})$
	$\sigma^{\text{fid},\mu}_{Z/\gamma^*\to \mu\mu}$ [pb]
$Z/\gamma^* \to \mu^+\mu^-$	$477.8 \pm 0.4\,(\text{stat}) \pm 2.0\,(\text{syst}) \pm 8.6\,(\text{lumi})$

- Statistical uncertainties negligible
- Systematics ~1.8/0.6% (e/μ) for W and 0.2/0.3% (ee/$\mu\mu$) for Z fiducial x-sec
  - Plus 1.5-3% on acceptance for total x-sec
- 1.8% luminosity uncertainty dominates absolute fiducial cross-sections
  - Use normalised distribitions or ratios





arXiv:1612.0301

Electron-muon universality

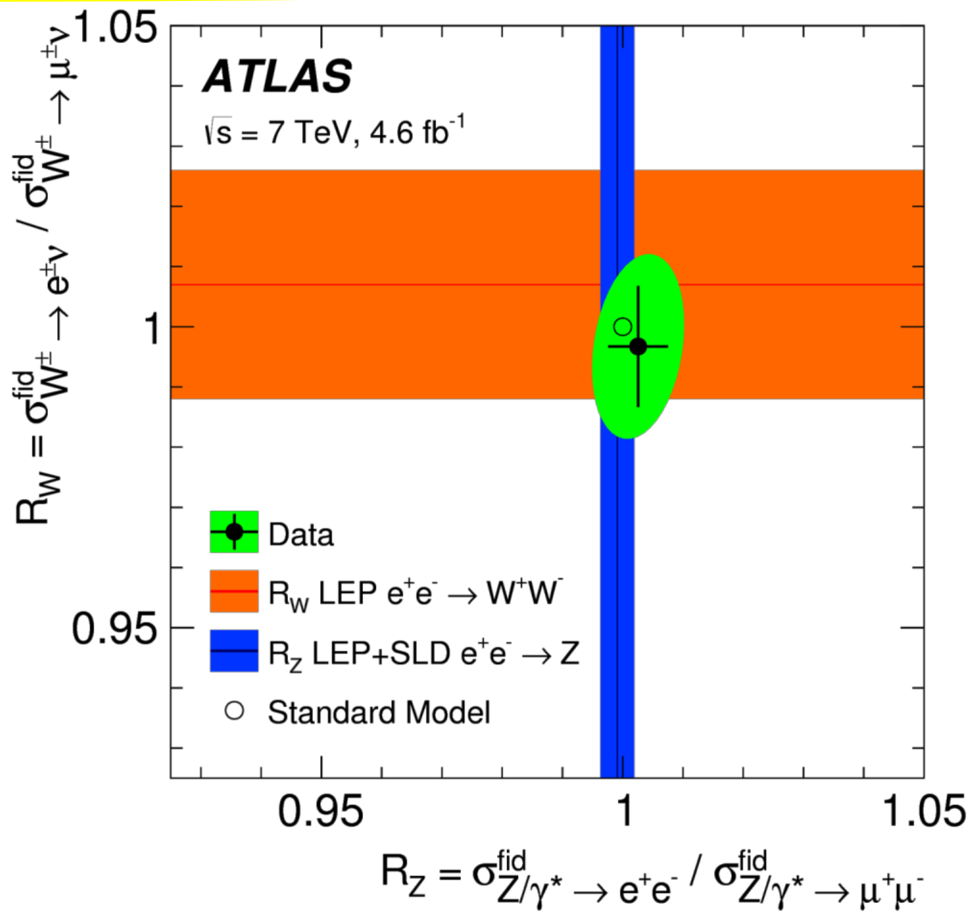
- BR for $W \to e$ and $W \to \mu$ should be equal
  - E_{eW} and $E_{\mu W}$ correct to same fiducial def^{n}

$$R_W = \frac{\sigma^{\mathrm{fid},e}_{W\to e\nu}/E^e_W}{\sigma^{\mathrm{fid},\mu}_{W\to\mu\nu}/E^\mu_W} = \frac{\sigma^{\mathrm{fid}}_{W\to e\nu}}{\sigma^{\mathrm{fid}}_{W\to\mu\nu}} = \frac{BR(W\to e\nu)}{BR(W\to\mu\nu)}$$
$$= 0.9967 \pm 0.0004\,(\mathrm{stat}) \pm 0.0101\,(\mathrm{syst})$$
$$= 0.997 \pm 0.010\,.$$

- Compare with other measurements

Measurement	**R_W**
ATLAS pp 7TeV	0.997±0.010
CDF pbar-p 1.96 TeV	1.018±0.025
LHCb pp	1.020±0.019
LEP2 W^+W^-	1.007±0.019
τ decays average	0.9964±0.0028
K decays NA62	1.0044±0.0040
π decays	0.9992±0.0024

  - Electron-muon universality confirmed at <1%

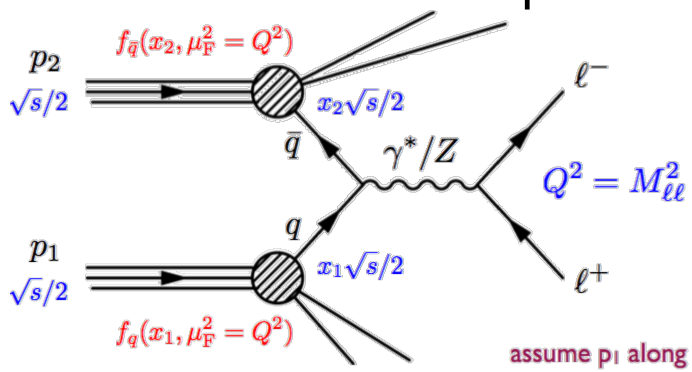


Also R_Z=1.0026±0.0050

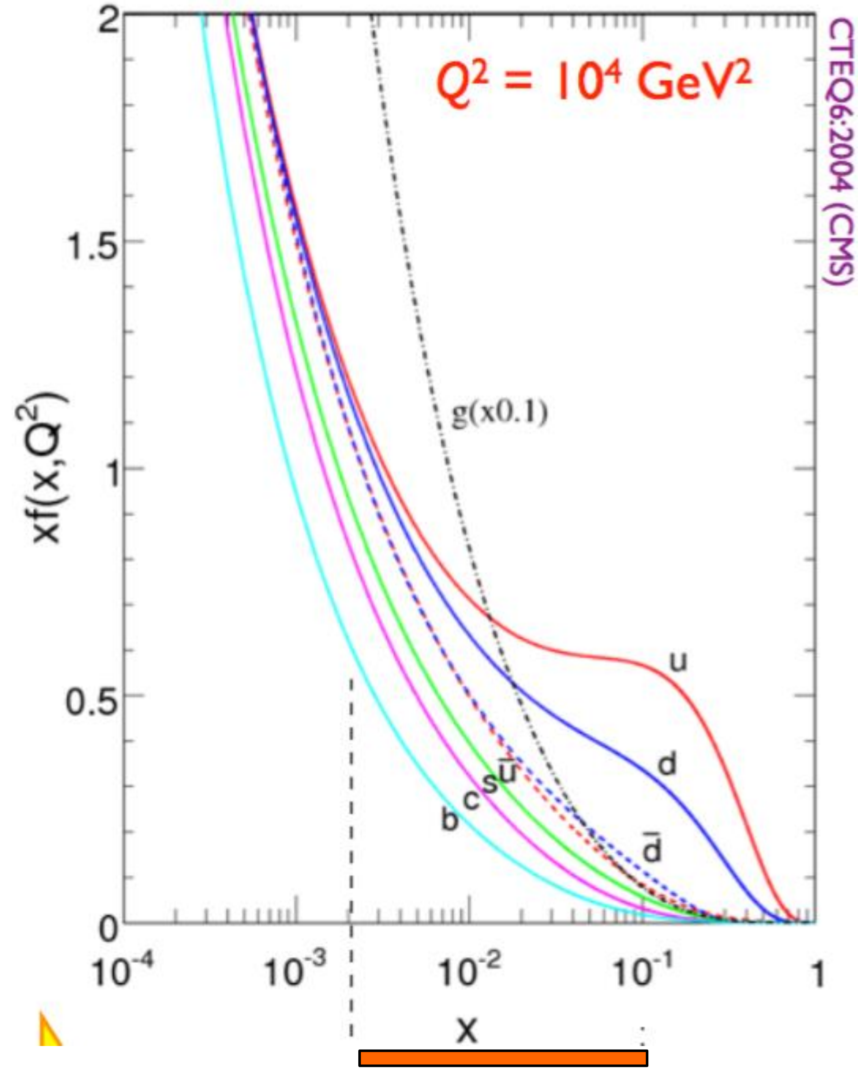
Less precise than LEP/SLC: R_Z=0.9991±0.0028

Theoretical predictions and PDFs

- Calculations available at NNLO in QCD
  - DYNNLO and FEWZ codes, with additional NLO EW corrections (several % for Z)
- Large uncertainties from the proton PDFs



- Region $10^{-3}<x<10^{-1}$ relevant for central W and Z production with $|y|<2$
- Use 'global' PDF sets CT10/14, MSTW/MMHT, NNPDF2-3 from fits to DIS and collider data (Tevatron +LHC)



- LHC W/Z data adds to PDF knowledge
  - W^+: ud~, us~, (cd~, cs~), opp. for for W^-
  - Z: uu~, dd~, ss~ (cc~,bb~)

More on PDFs

- Industry of PDF fitting groups, with different input datasets and assumptions

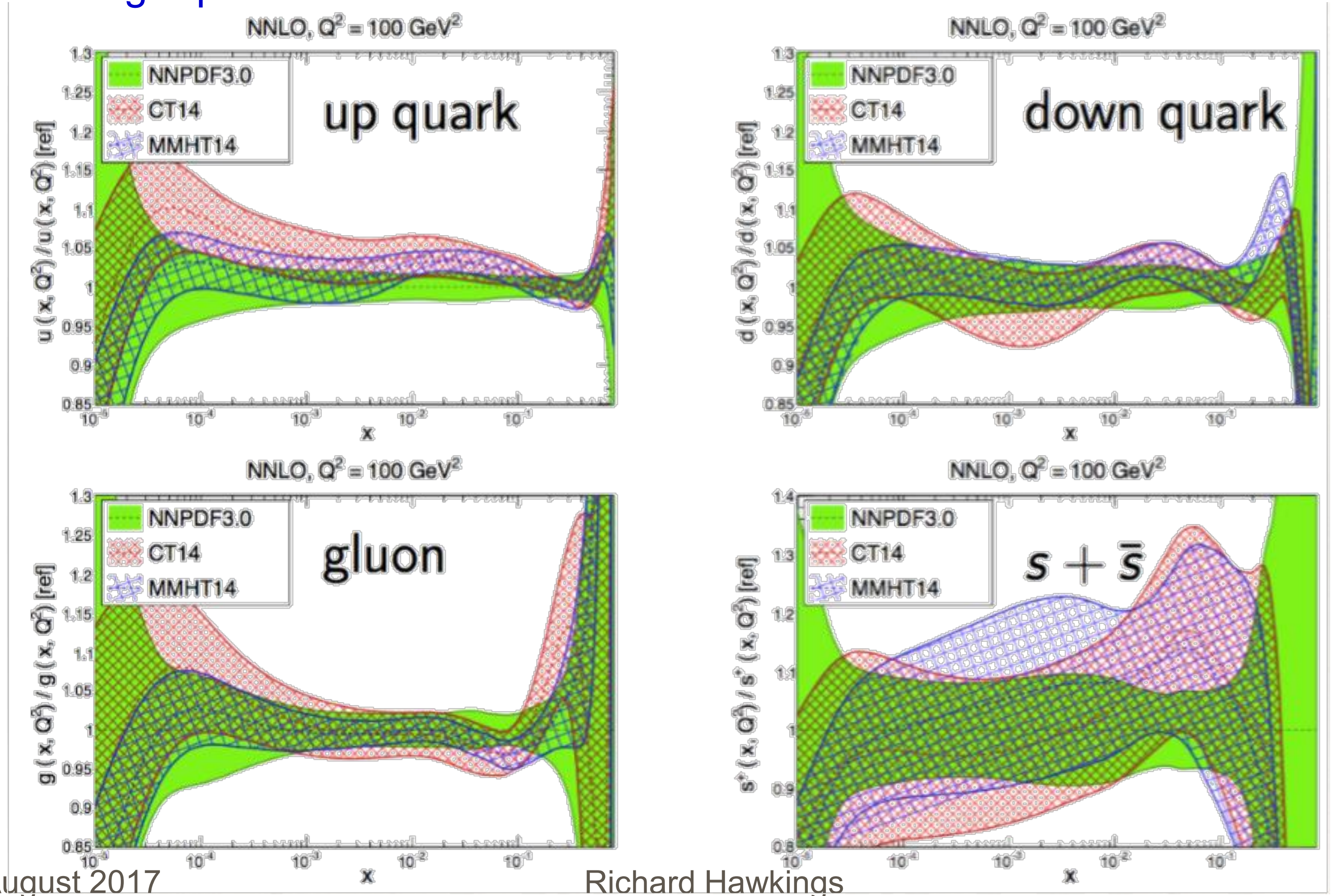
	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ12(15)	JR14
HERA data	HERA I+ charm	HERA I charm jets	HERA I+ H1 and ZEUS II charm	HERA I+II	HERA I charm	HERA I	HERA I charm jets
Fix. Target DIS	✓	✓	✓	✗	✓	JLAB, high x ✓	JLAB, high x ✓
Tevatron W,Z	✓	✓	✓	✗	✗/✓	✓	✗
Tevatron Jets	✓	✓	✓	✗	✗	✗	✓
Fix. Target DY	✓	✓	✓	✗	✓	✓	✓
LHC WZ	✓	✓	✓	✗	✓	✗	✗
LHC jets	✓	✓	✓	✗	✗	✗	✗
LHC top	✗	✓	✓	✗	✓	✗	✗
LHC charm	✗	✗	✓	✗	✗/✓	✗	✗
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

V. Radescu, QCD@LHC 2016

  - HERA ep DIS data is the 'backbone' of all modern PDF sets, supplemented by various choices of fixed target DIS, Drell-Yan and jet data from Tevatron and LHC
  - Groups also differ in data treatment (e.g. tensions between datasets), theory calculations used, parameterisation of PDFs vs x,Q^2, treatment of heavy quarks
- Important to consider uncertainties from a particular PDF set AND predictions of different PDF sets

Differences between PDF sets

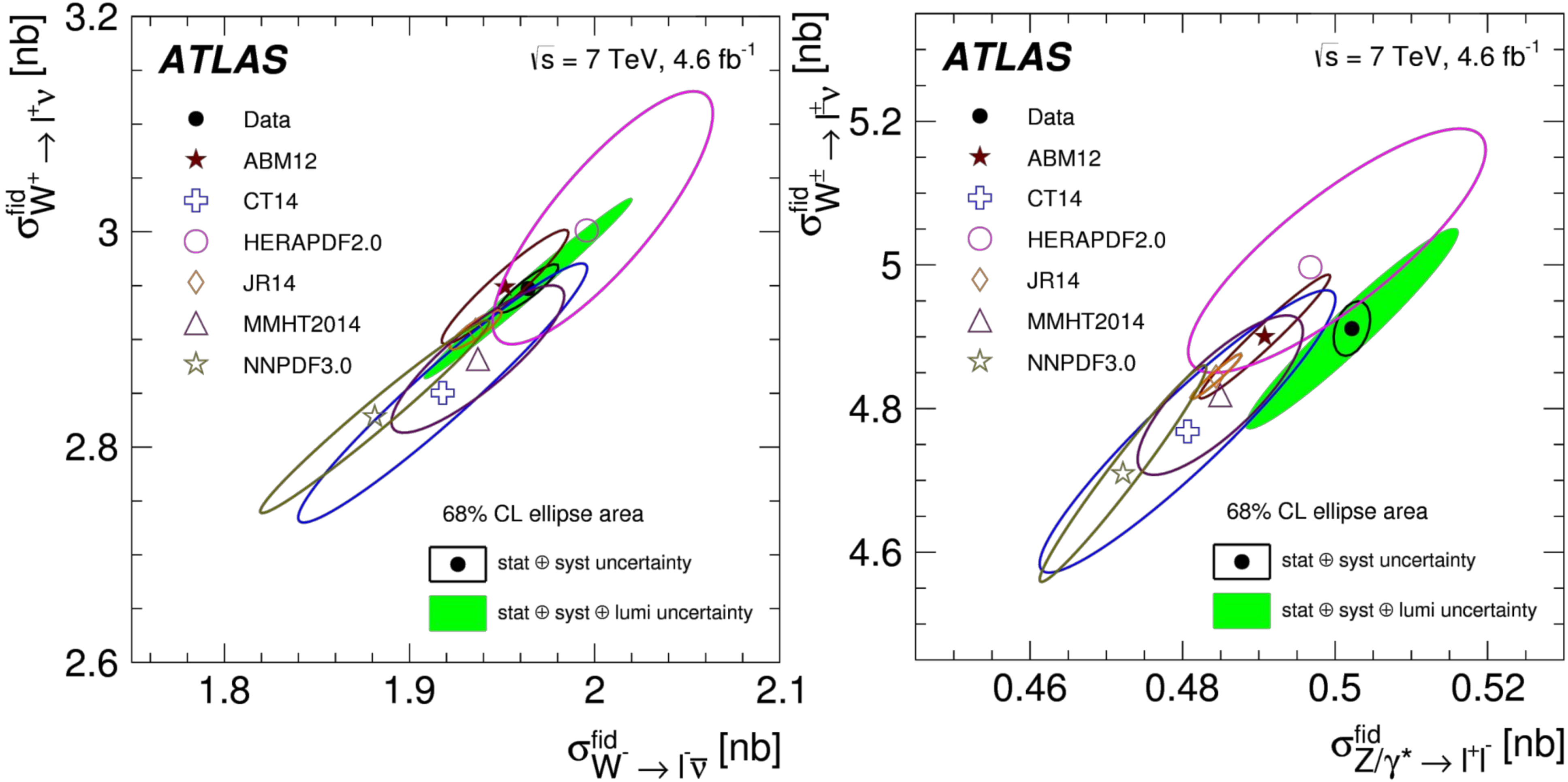
- u, d and g: differences of 5-10% in range $10^{-3}<x<10^{-1}$, non-overlapping bands
  - Strange quark contribution less well-determined



V. Radescu, QCD@LHC 2016. APFEL

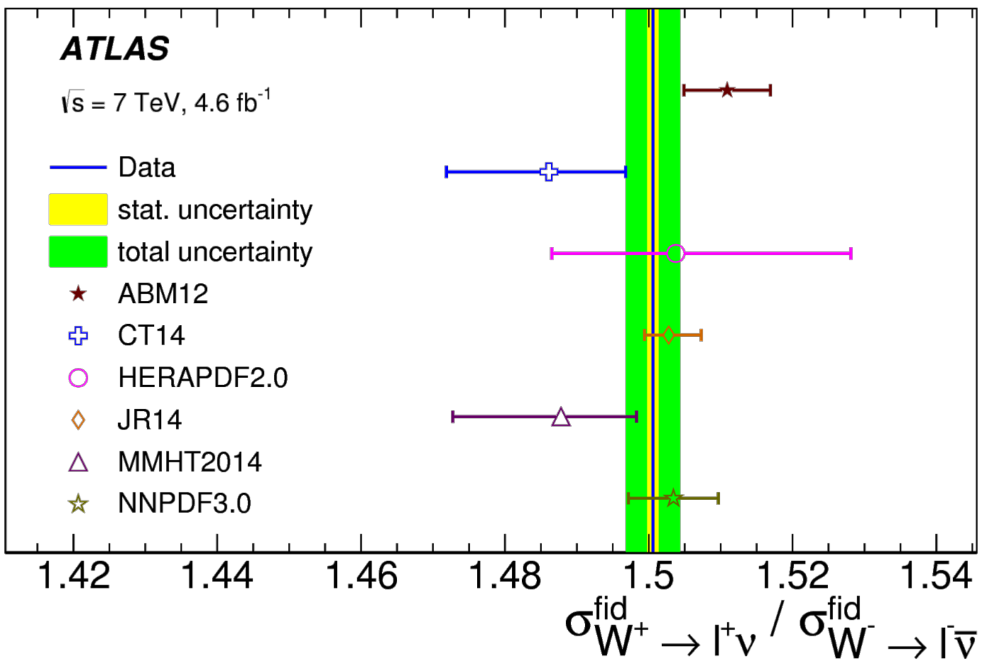
W and Z cross-section comparisons

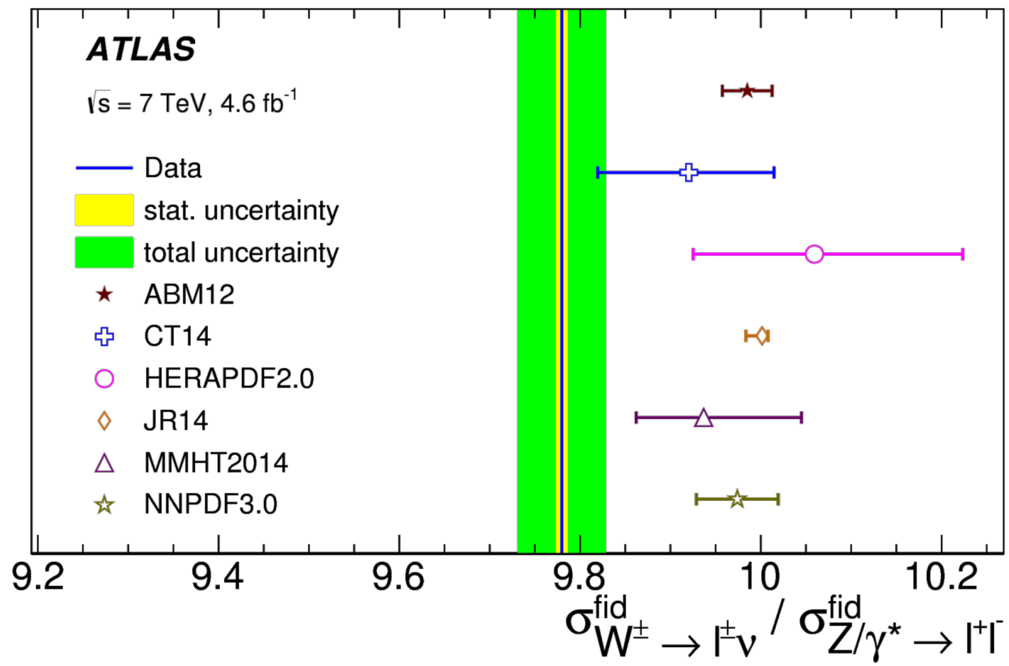
- 2D plots of W^+ vs W^- and W vs Z make expt. and pred. correlations clear
  - Most PDFs (in particular global sets) a little below the data for $\sigma(Z)$



W^+/W^- and W/Z cross-section ratios

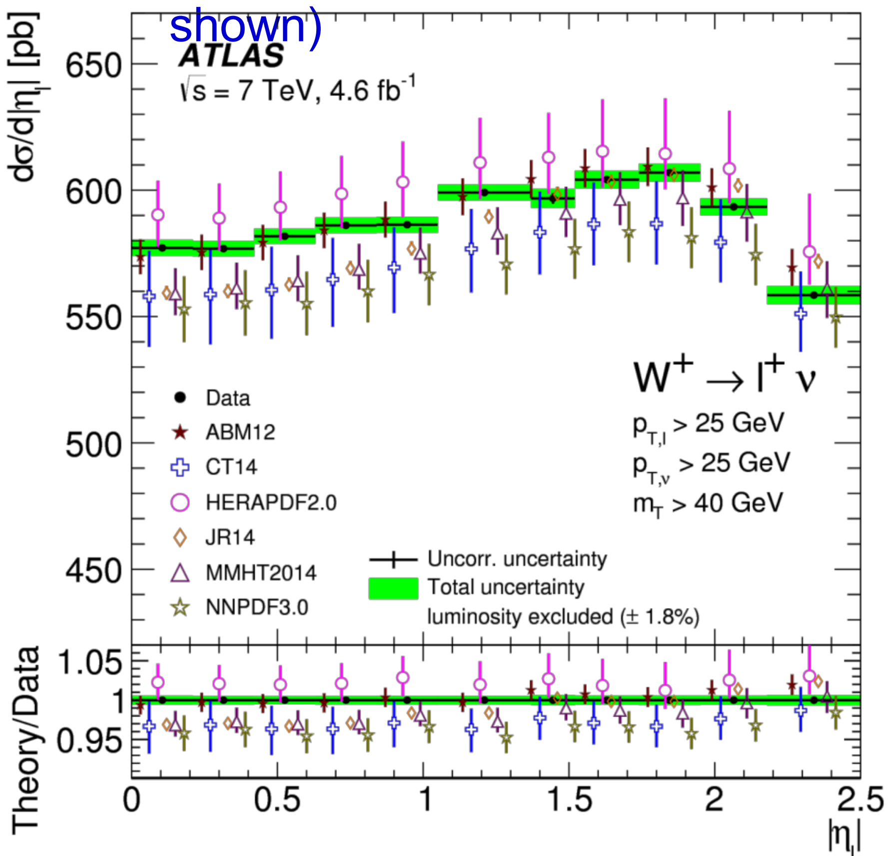
- Significant uncertainty cancellations in ratios of cross-sections
  - W^+/W^- measured to 0.25%, W/Z to 0.5%, much smaller than PDF uncertainties
  - W/Z smaller than all predictions
  - Considerable spread in predictions and their uncertainties with different PDFs

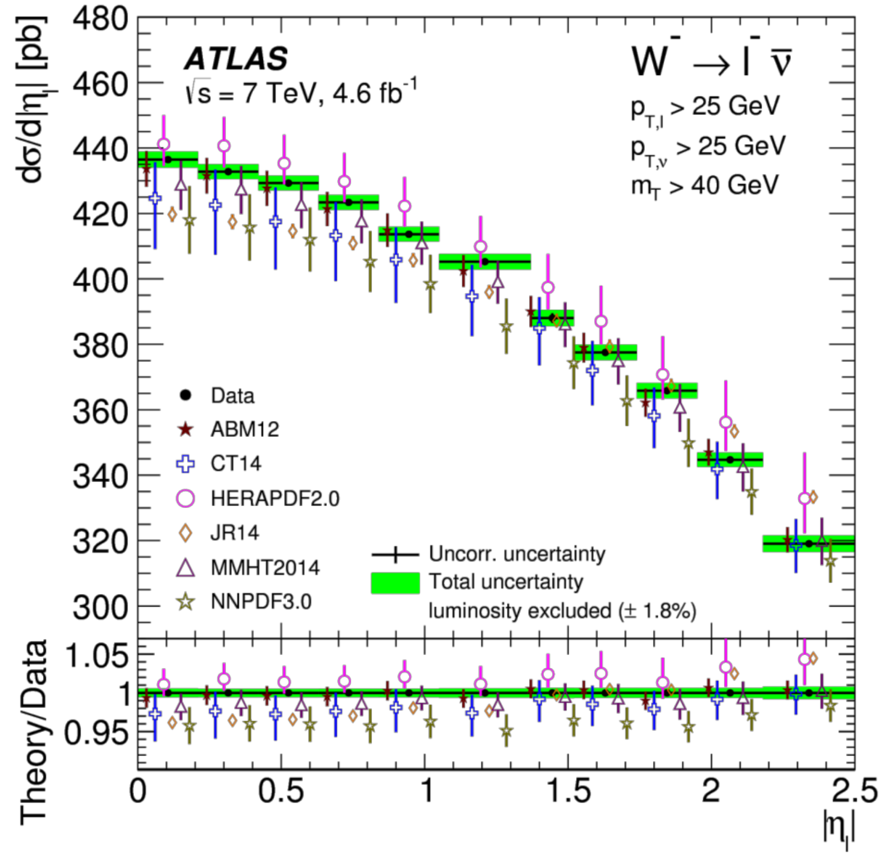




Lepton rapidity distributions

- More information in the rapidity distributions – sampling different x-values
  - Big difference in cross-section and shape between W^+ and W^-
    - More up than down quarks in the proton, with larger momentum fractions
  - Most ‘global’ PDF sets below the data for both W^+ and W^- (±1.8% lumi not shown)



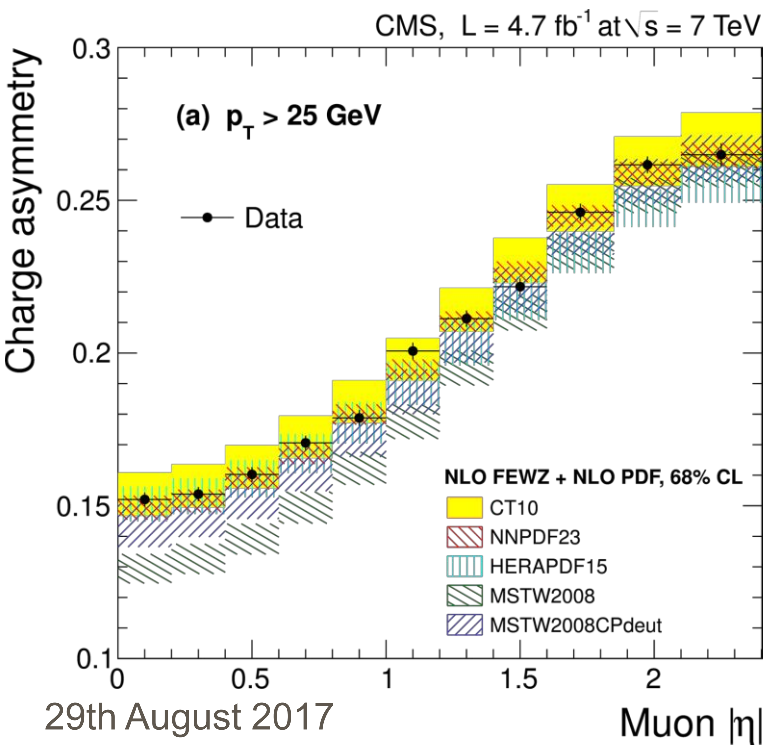


W charge asymmetry

- Another ratio measurement:

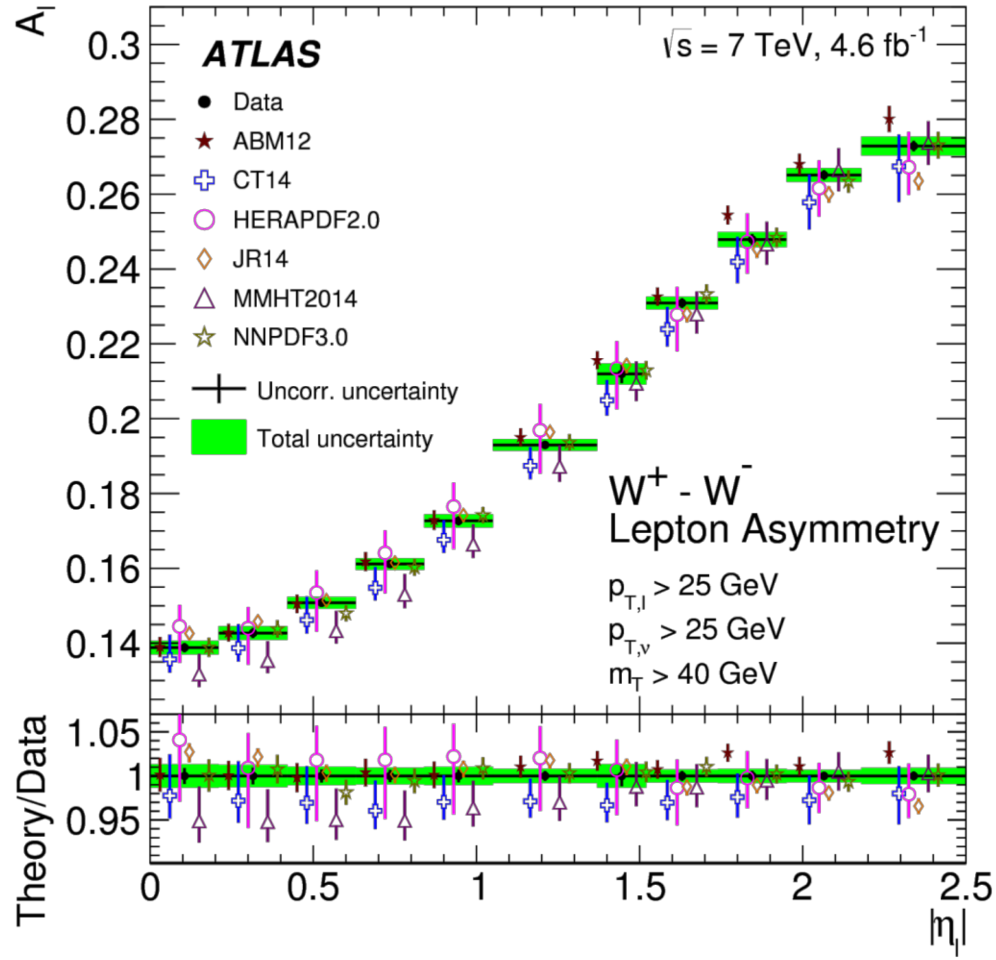
$$A_\ell = \frac{d\sigma_{W+}/d|\eta_\ell| - d\sigma_{W-}/d|\eta_\ell|}{d\sigma_{W+}/d|\eta_\ell| + d\sigma_{W-}/d|\eta_\ell|}$$

  - Expt. uncertainties 0.5-1%/bin
  - NNPDF 3.0 agrees particularly well
    - Already includes W data from CMS



arXiv:1312.6283

arXiv:1612.0301



PDF profiling using W and Z distributions

- Form a data vs. χ^2 across all bins of all rapidity-differential cross-sections

$$\chi^2(\vec{b}_{\rm exp},\vec{b}_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left[\sigma_i^{\rm exp} - \sigma_i^{\rm th}(1-\sum_j \gamma_{ij}^{\rm exp} b_{j,{\rm exp}} - \sum_k \gamma_{ik}^{\rm th} b_{k,{\rm th}})\right]^2}{\Delta_i^2} + \sum_{j=1}^{N_{\rm exp.sys}} b_{j,{\rm exp}}^2 + \sum_{k=1}^{N_{\rm th.sys}} b_{k,{\rm th}}^2$$

  - $\gamma_{ij}^{\rm exp}$ express experimental uncertainties j via nuisance parameters $\beta_{j,\rm exp}$
  - $\gamma_{ik}^{\rm th}$ express theoretical (PDF and other) uncertainties k via nuisance parameters $\beta_{k,\rm th}$
  - $\beta=\pm1$ represents changes in results/predictions corresponding to $\pm1\sigma$ uncertainties
  - 'Profiled' values of $\beta_{k,\rm th}$ after χ^2 minimisation represent 'improved' PDF
    - But only if the original distributions are reasonably close to data
- χ^2 results for fit to all ATLAS 7 TeV W/Z data (including | excluding PDF unc.)

Data set	n.d.f.	ABM12	CT14	MMHT14	NNPDF3.0	ATLAS-epWZ12
$W^+ \to \ell^+\nu$	11	11|21	10|26	11|37	11|18	12|15
$W^- \to \ell^-\bar{\nu}$	11	12|20	8.9|27	8.1|31	12|19	7.8|17
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 46-66$ GeV)	6	17|21	11|30	18|24	21|22	28|36
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66-116$ GeV)	12	24|51	16|66	20|116	14|109	18|26
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66-116$ GeV)	9	7.3|9.3	10|12	12|13	14|18	6.8|7.5
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116-150$ GeV)	6	6.1|6.6	6.3|6.1	5.9|6.6	6.1|8.8	6.7|6.6
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116-150$ GeV)	6	4.2|3.9	5.1|4.3	5.6|4.6	5.1|5.0	3.6|3.5
Correlated χ^2		57|90	39|123	43|167	69|157	31|48
Total χ^2	61	136|222	103|290	118|396	147|351	113|159

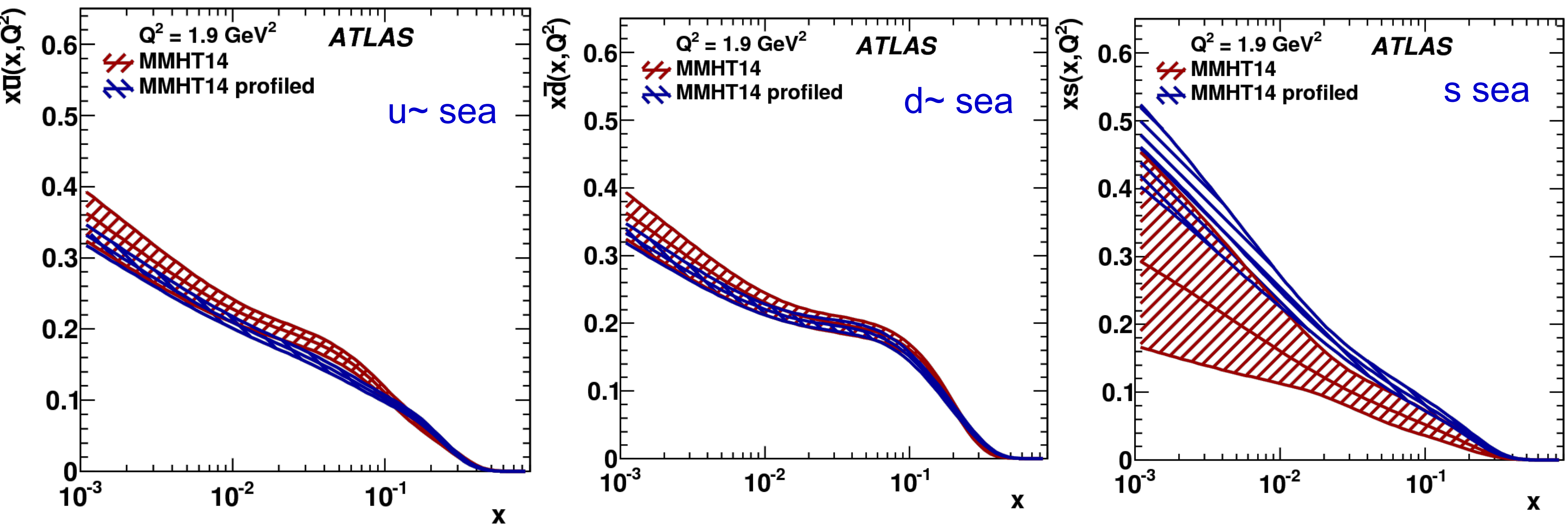
  - CT14 best, MMHT and ATLAS epWZ OK, ABM12 and NNPDF3.0 less good

PDF profiling results

- Fitted $\beta_{k,th}$ can be used to generate new profiled PDF, reduced uncertainties

$$f_0' = f_0 + \sum_k \left[b_{k,\mathrm{th}}^{\mathrm{min}} \left(\frac{f_k^+ - f_k^-}{2} \right) + \left(b_{k,\mathrm{th}}^{\mathrm{min}} \right)^2 \left(\frac{f_k^+ + f_k^- - 2f_0}{2} \right)^2 \right]$$

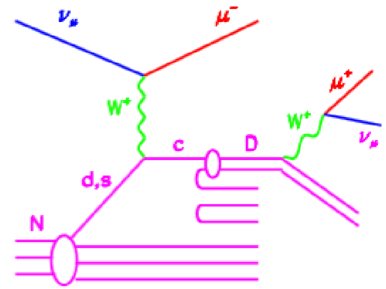
  - f_0 (f'_0) original (new) central PDF, f^+_k and f^-_k the ± variations for PDF eigenvector k
- Effect of profiling on MMHT14 sea quarks – increased s-quark contribution



- Indicative, but not a substitute for full PDF fit with new data…

Flavour composition of light-quark sea

- Full QCD analysis of W/Z data + HERA DIS data to fit a PDF from scratch
  - Computationally challenging – MCFM NLO predictions + APPLGRID tools to convolve PDF, fixed NLO→NNLO corrections

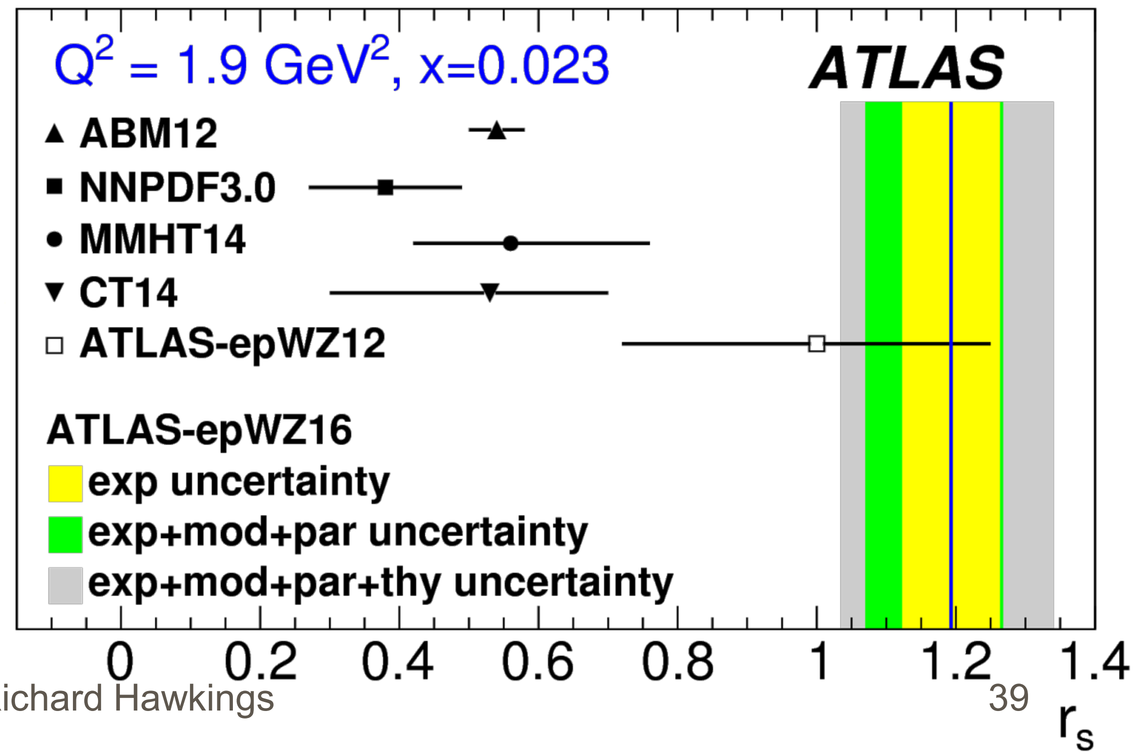


- Neutrino-nucleon scattering (νN→cμ) suggested strange sea < u/d sea
  - Included in most global PDF sets
- Ratio of W/Z production at LHC is sensitive to strange sea vs u/d sea

$$r_s = \frac{s+\bar{s}}{2\bar{d}}$$

$$r_s = 1.19 \pm 0.07\,(\text{exp})\;^{+0.13}_{-0.14}\,(\text{mod}+\text{par}+\text{thy})$$

  - Result limited by modelling/theory
  - Suggests no strange suppression



Summary of lecture 1

- Precision physics is possible at LHC
  - Can contribute to electroweak fit and other important SM parameters
- W/Z cross-section fiducial and differential cross-section measurements
  - Clean experimental signatures, Z provides 'in-situ' calibration for leptons
  - Absolute uncertainties (excluding luminosity) of ~1% for W, <0.5% for Z
  - Luminosity measurement reaches 2% precision at LHC
    - Benefitting from dedicated vdM scan campaigns (few days beamtime per year)
- W/Z measurements provide important constraints on PDFs
  - Previously mainly determined using DIS and jet data
  - Leading source of uncertainty in predicting the W/Z cross-sections
  - Constrain the u/d PDFs in $10^{-3}<x<10^{-1}$, unique information on strange quarks

- Next … using W and Z to constrain electroweak parameters, physics with jets