Precision measurements @ hadron colliders - 2

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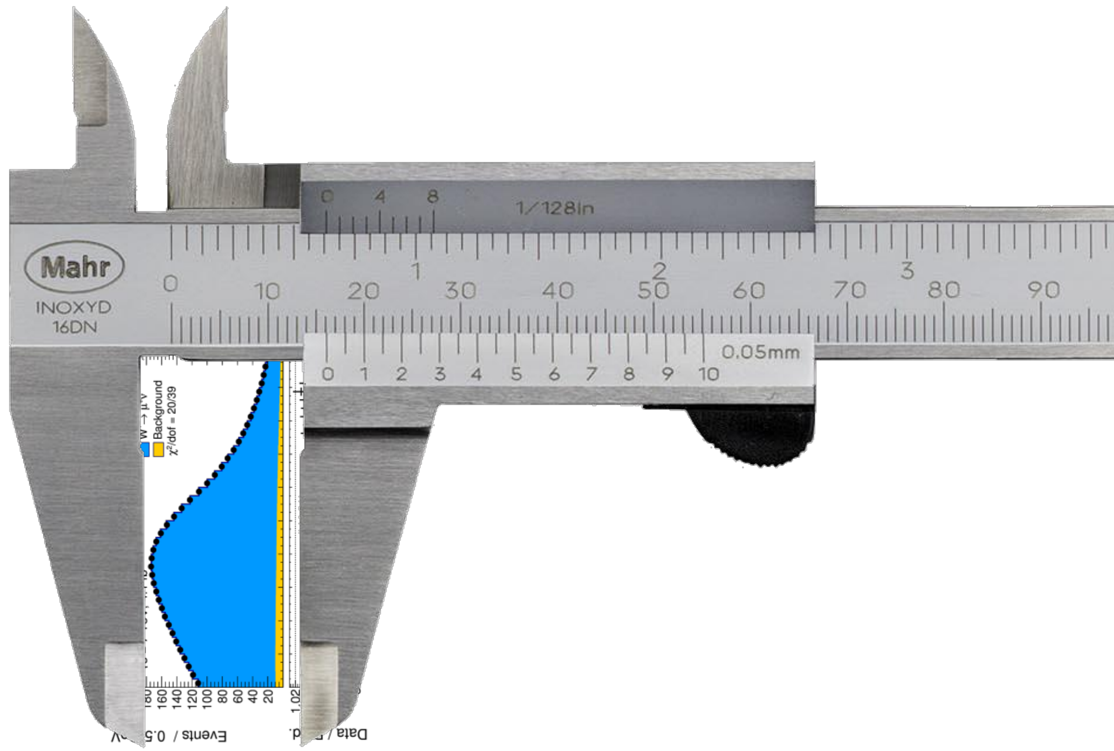
Hadron Collider Physics Summer School, 31/8/17

- Electroweak parameters, the W mass, and physics with jets



Outline of lecture 2

- Previously
  - Precision measurements, W and Z cross-section measurements, luminosity, applications to PDF determination
- Lecture 2
  - Determination of the electroweak mixing angle $\sin^2\theta_W$ from $Z/\gamma^*\rightarrow ll$
  - Measurement of the W mass
  - Measurement of jets, with W/Z+jets and inclusive jet measurements

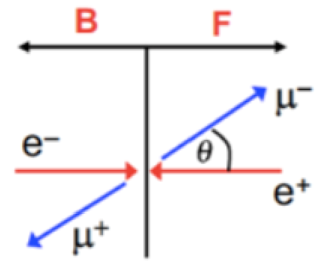
  - Thanks to Gautier Hamel de Monchenault and Maarten Boonekamp for some diagrams

Asymmetry measurements and $\sin^2\theta_{lep}^{eff}$

- Angular distribution of leptons in $q\tilde{q} \to Z/\gamma^* \to ll$

$$\frac{d\sigma}{d(\cos\theta)} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}A(1+\cos^2\theta) + B\cos\theta\right]$$

  - B term represents a forward-backward asymmetry in the direction of the –ve lepton vs. incoming quark
  - A and B are functions of centre-of-mass energy
    - B changes sign across the Z resonance



FB Asymmetry

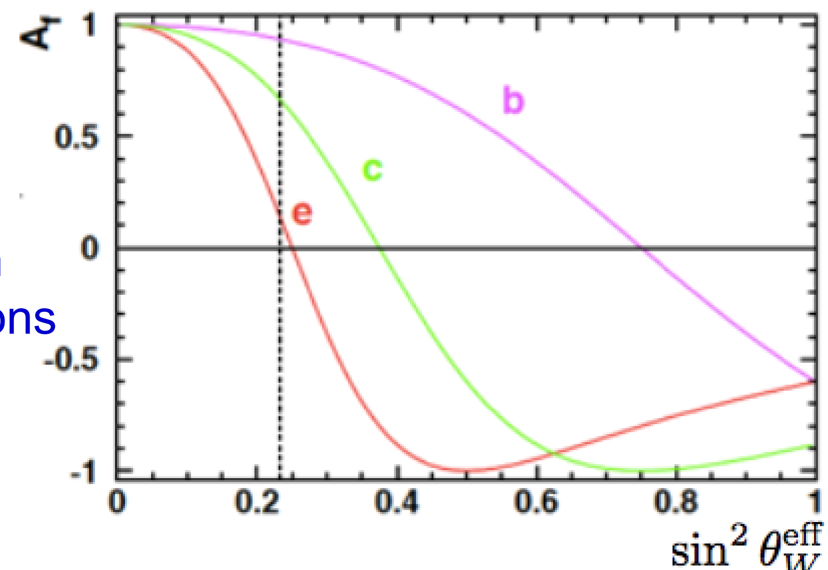
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$A_{FB}^{0,\ell} = \frac{3}{4}A_q A_\ell$$

- At Z pole, asymmetry sensitive to ratios of fermion vector and axial vector couplings, and to $\sin^2\theta_W$

$$\mathcal{A}_f \equiv 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2} \qquad g_{Vf} = \sqrt{\bar{\rho}}\,(T_f^3 - 2Q_f\sin^2\theta_W^{eff}) \qquad g_{Af} = \sqrt{\bar{\rho}}\,T_f^3$$

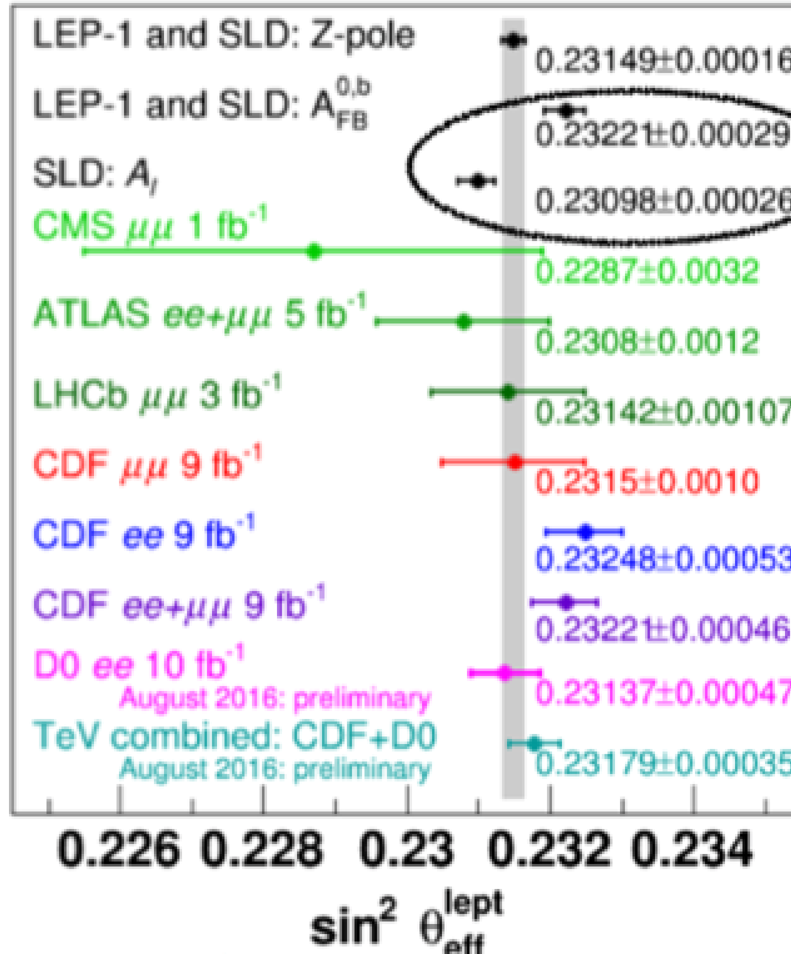
  - Work in terms of 'effective' angle $\sin^2\theta_{lep}^{eff}$, which absorbs various fermion-dependent EW corrections

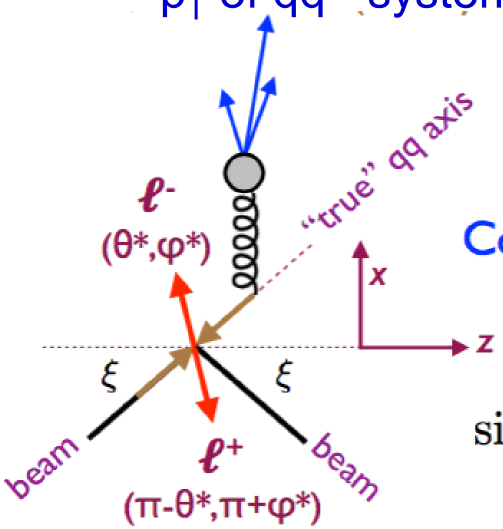


- Information on $\sin^2\theta_{lep}^{eff}$ from $e^+e^- \to f\tilde{f}$, from $q\tilde{q} \to l^+l^-$ and from tau polarisation
  - Powerful consistency check of Standard Model

Measurements of $\sin^2\theta_{lep}^{eff}$

- Tension between LEP and SLD measurements
  - $A_{FB}^{0,b}$: $e^+e^- \rightarrow Z \rightarrow b\tilde{b}$
  - A_{LR}: $e^+e^- \rightarrow Z$ with left and right polarised e^-
- Hadron colliders contribute with $q\tilde{q} \rightarrow Z/\Upsilon^* \rightarrow ll$
  - But don't know the direction of incoming quark!
  - Assume quark direction corresponds to boost of dilepton system (valance quark in proton)
  - Use of Collins-Soper frame minimises effects of p_T of $q\tilde{q}$ system with respect to beamline





Collins-Soper frame

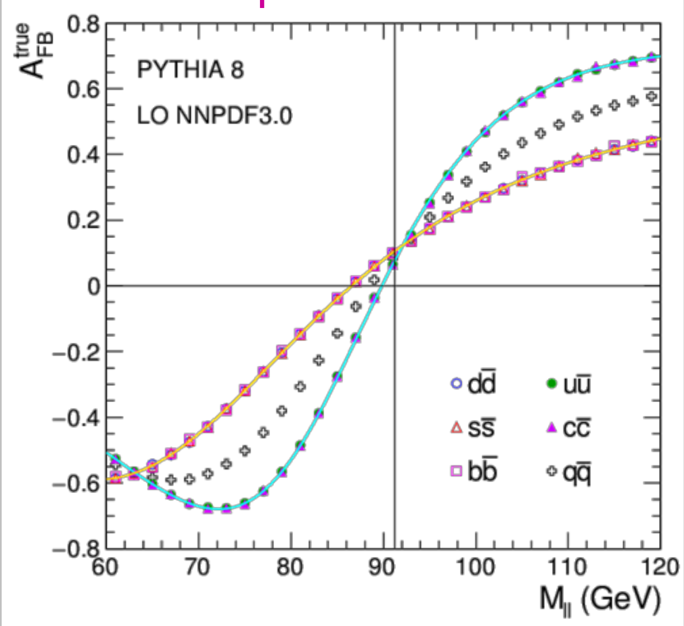
$$\sin^2\xi = \frac{q_T^2}{q_T^2 + M_{\ell\ell}^2} \qquad \cos\theta^* = \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{\sqrt{M^2(M^2+P_T^2)}} \times \frac{P_z}{|P_z|}$$

$$p_i^{\pm} = (e_i \pm p_{z,i})/\sqrt{2}$$

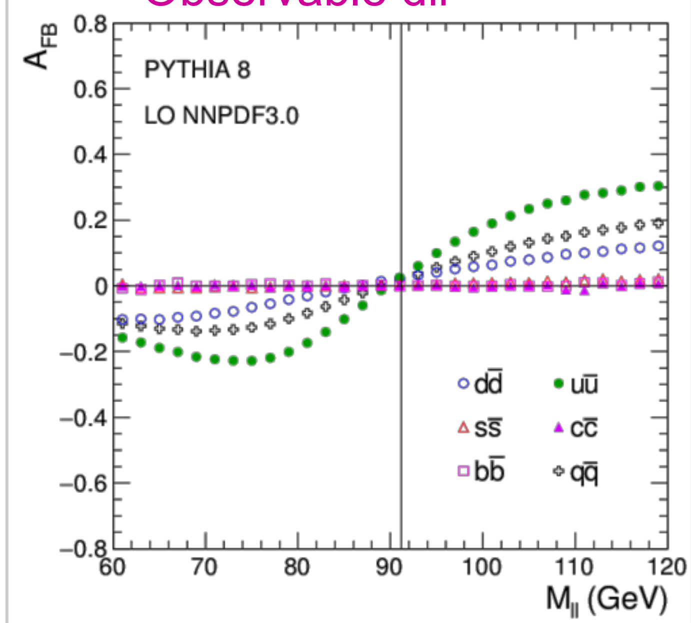
Dilution of the asymmetry

- Asymmetry diluted by two effects
  - Larger for up-type quarks than down-type quarks (measuring a mixture)
  - Mistakes in signing the direction of the incoming quark
- Final asymmetry is larger at high dilepton system rapidity
  - Value at Z-pole (main sensivity to $\sin^2\theta_{lep}^{eff}$) is only a few %

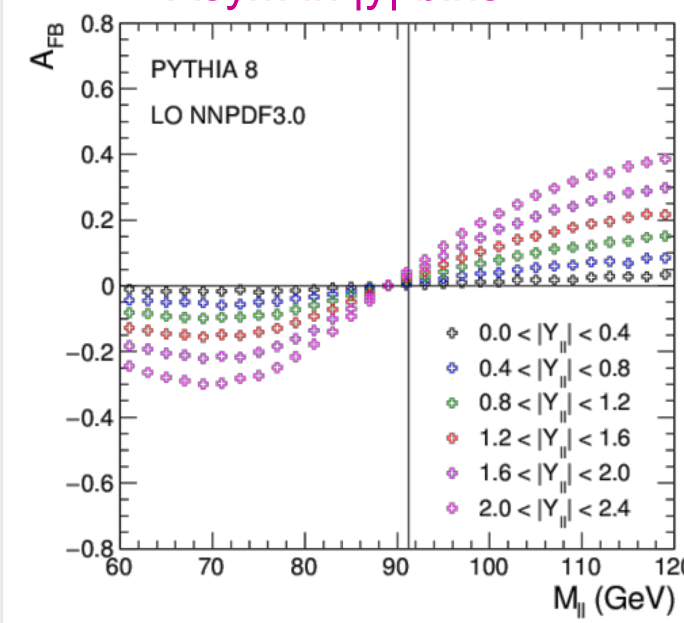
True quark dir^n



Observable dir^n



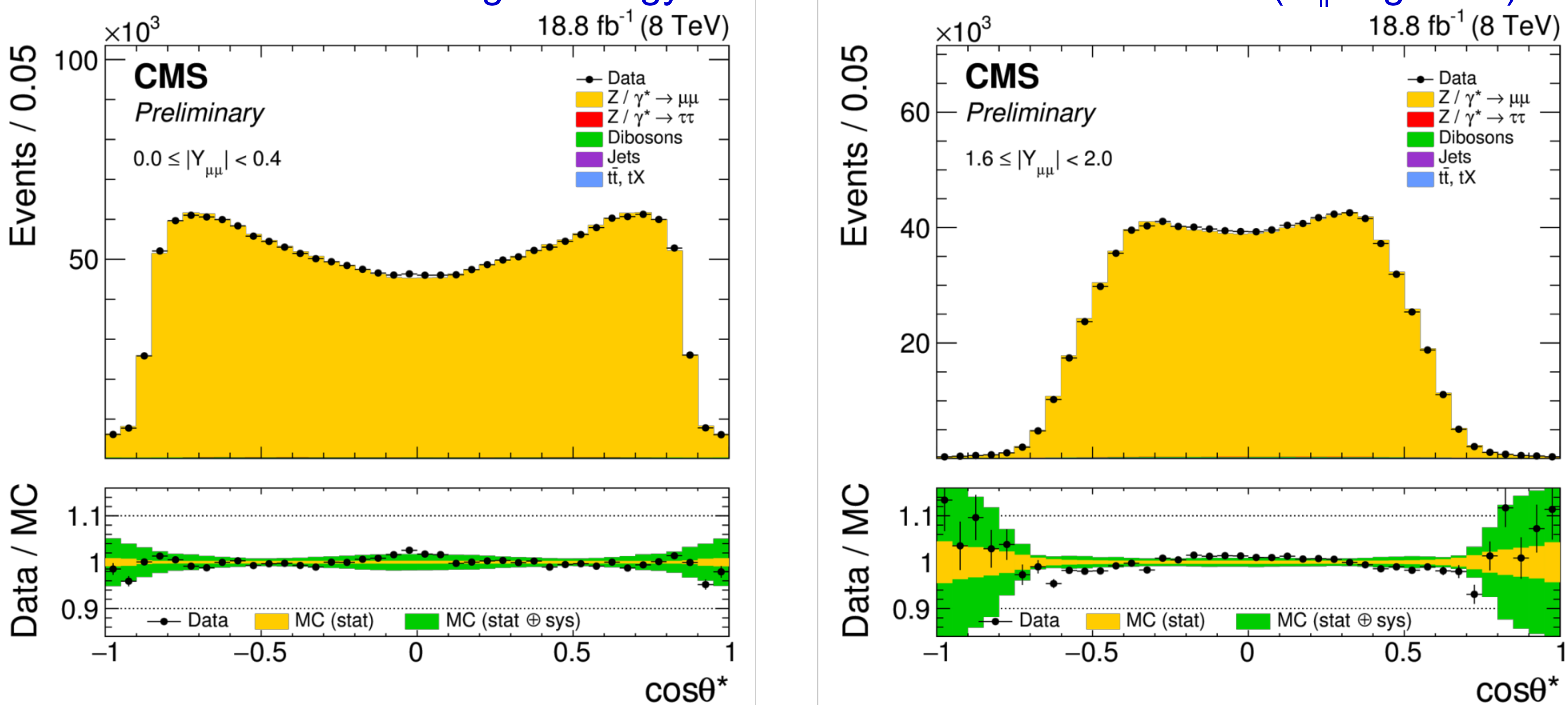
Asym in |y| bins



  - Asymmetry prediction will be sensitve to PDF uncertainties

Asymmetry distributions in data

- Standard $Z/\gamma^*\rightarrow$ee and $\mu\mu$ event selections, very small b/g near Z peak
  - Precise control of efficiency (in particular charge dependence and mis-assignment)
  - Precise understanding of energy/momentum scale and resolution (m_{ll} migration)

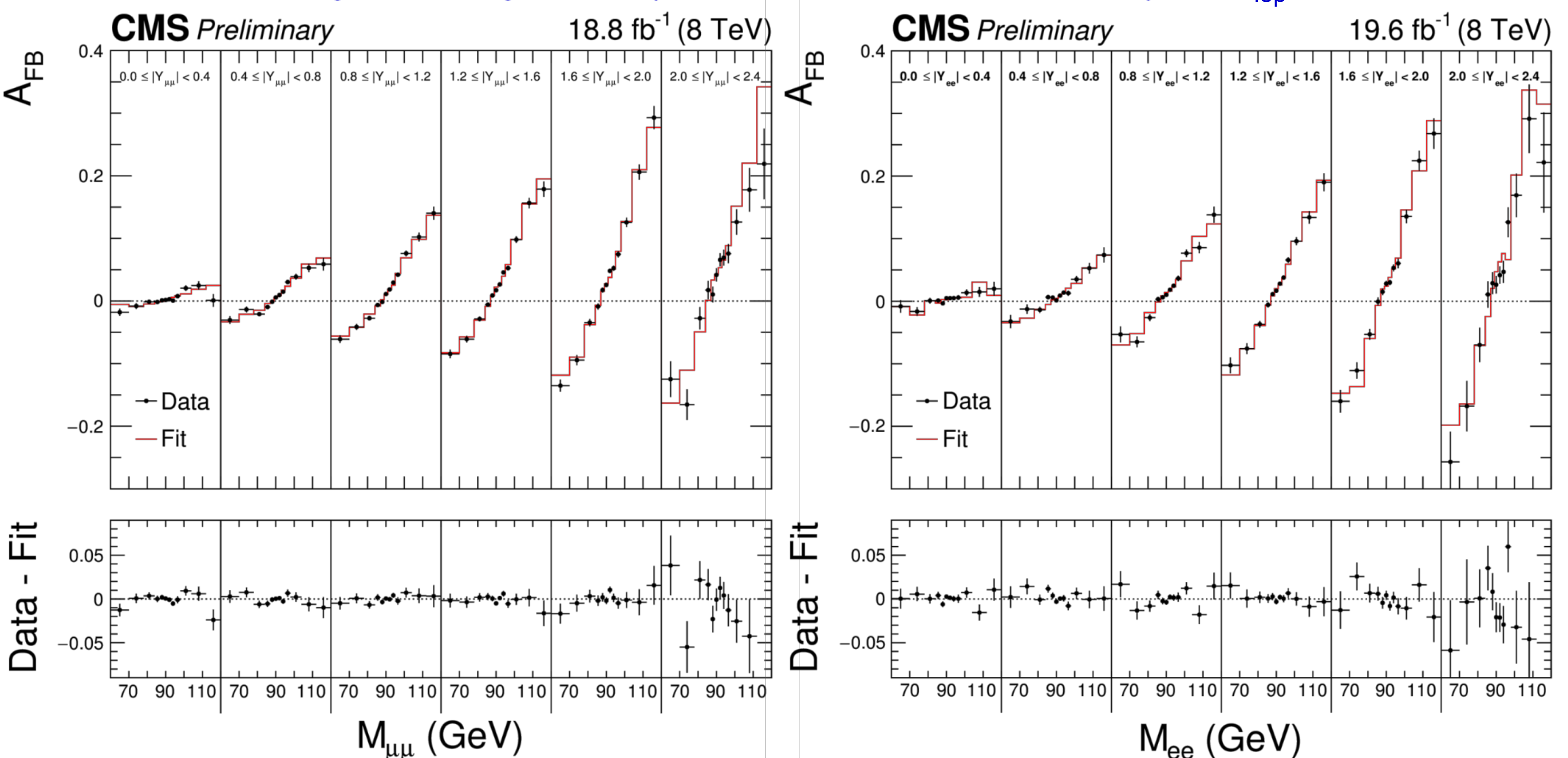


CMS-PAS-SMP-16-007

- Weight events vs. cosθ^* to maximise statistical significance of measurement

Extraction of $\sin^2\theta_{lep}^{eff}$

- χ^2 fit between data A_{FB} distributions and prediction in 72 dilepton (m_{ll},y_{ll}) bins
  - MC reweighted using event-by-event matrix elements to vary $\sin^2\theta_{lep}^{eff}$



Systematic uncertainties

- Largest uncertainty from data statistics
- Systematic uncertainties
  - Significant contribution from MC statistics, even after smoothing
  - Selection efficiencies which are correlated between lepton charges cancel out
  - Energy/momentum calibration performed using $Z \to ll$ samples
    - Coherent treatment of uncertainties in calibration and asymmetry analyses

channel	statistical uncertainty
muon	0.00044
electron	0.00060
combined	0.00036

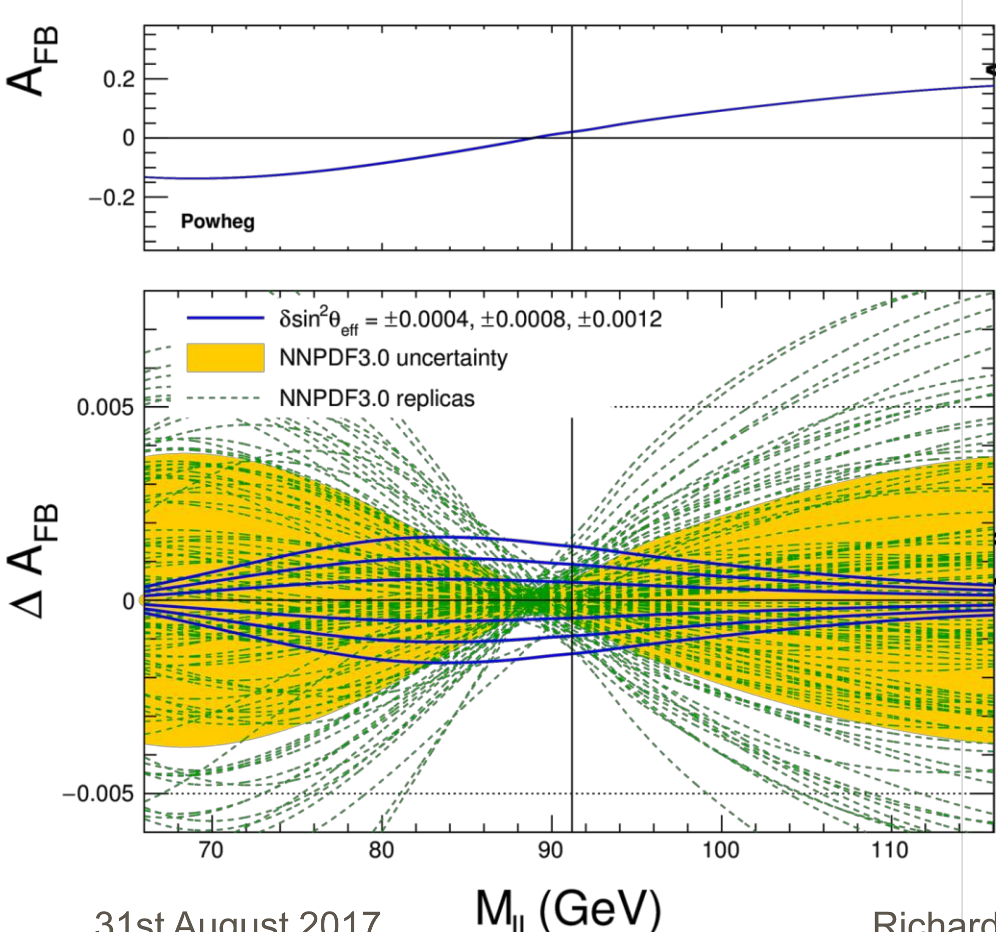
Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

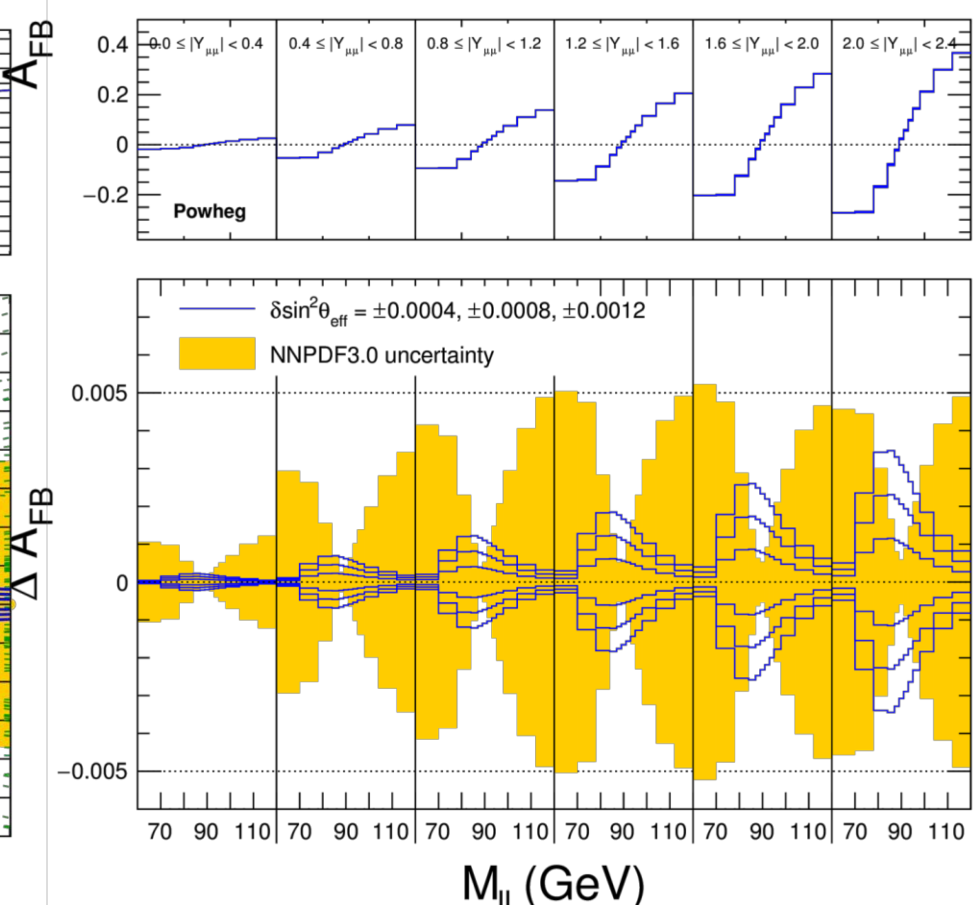
- Theoretical uncertainties subdominant
  - Various uncertainties in modelling of Z/γ^* p_T spectrum including Z+jets
  - PDF uncertainties accounted separately

model variation	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
QCD $\mu_{R/F}$ scale	0.00011	0.00013
POWHEG MiNLO Z+j vs NLO Z model	0.00009	0.00009
FSR model (PHOTOS vs PYTHIA)	0.00003	0.00005
UE tune	0.00003	0.00004
Electroweak ($\sin^2\theta^{lept}_{eff} - \sin^2\theta^{u,d}_{eff}$)	0.00001	0.00001
Total	0.00015	0.00017

PDF uncertainties

- Large PDF uncertainties due to dilution and u/d valance quark uncertainties
  - But PDF uncertainties are largest away from Z-pole, small $\sin^2\theta_{lep}^{eff}$ sensitivity





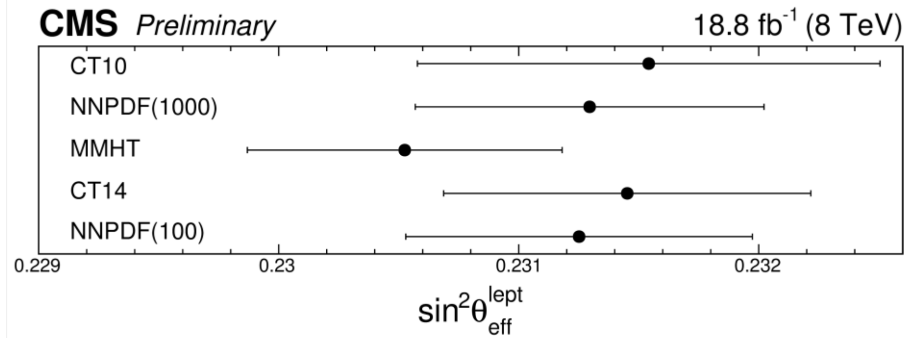
PDF uncertainties - continued

- Constrain PDF uncertainties using data
  - NNPDF3.0 uncertainties expressed as 100 replicas to span the uncertainty
    - Typically take RMS to calculate uncertainty on an observable
    - C.f. quadrature sum of eigenvectors for other PDFs e.g. CT14 and MMHT
- Weight the various replicas acoording to their χ^2 compatibility with the data

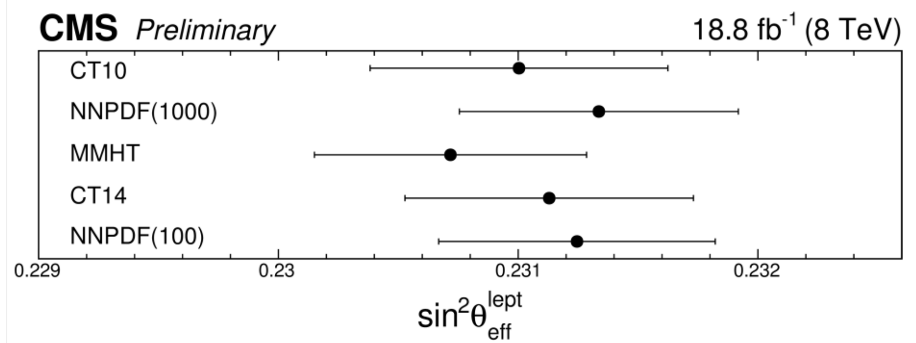
$$w_i = \frac{e^{-\frac{\chi^2_{min}}{2}}}{\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{\chi^2_{min}}{2}}}$$

  - Final $\sin^2\theta_{lep}^{eff}$ from weighted average
- Reduces PDF uncertainty by factor ~2
  - Also for other PDFs

Nominal PDFs



Constrained PDFs



[PDF uncertainties only]

Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

$\sin^2\theta_{lep}^{eff}$ results

- New CMS result:

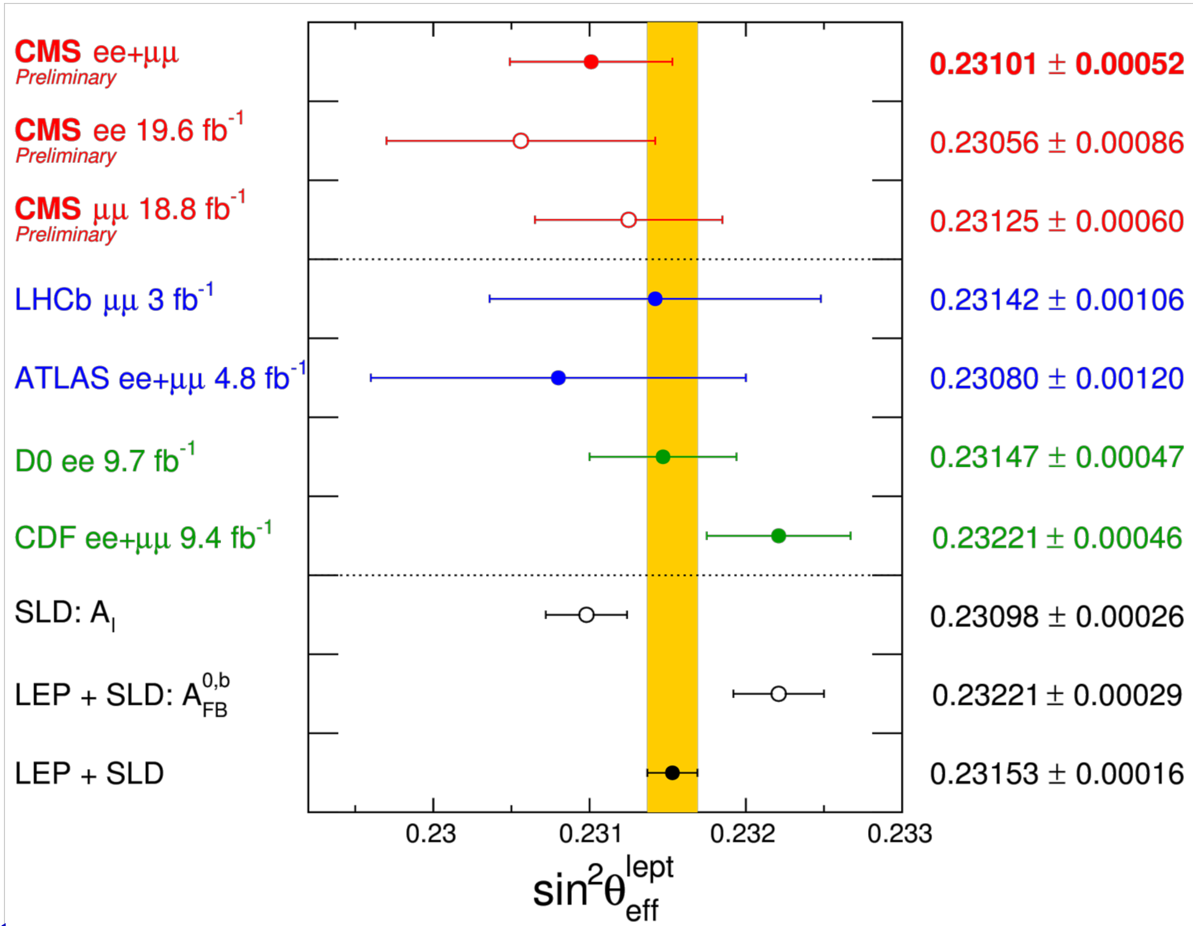
$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00052$$

  - Competitive with Tevatron, despite quark direction dilution
- Breakdown at hadron colliders

Error (10^{-3})	Stat	Syst	PDF
CMS 8 TeV	0.36	0.24	0.30
ATLAS 7 TeV	0.5	0.6	0.9
LHCb ($\mu\mu$ only)	0.73	0.52	<0.56
D0 (ee only)	0.43	0.08	0.17
CDF	0.43	0.07	0.16

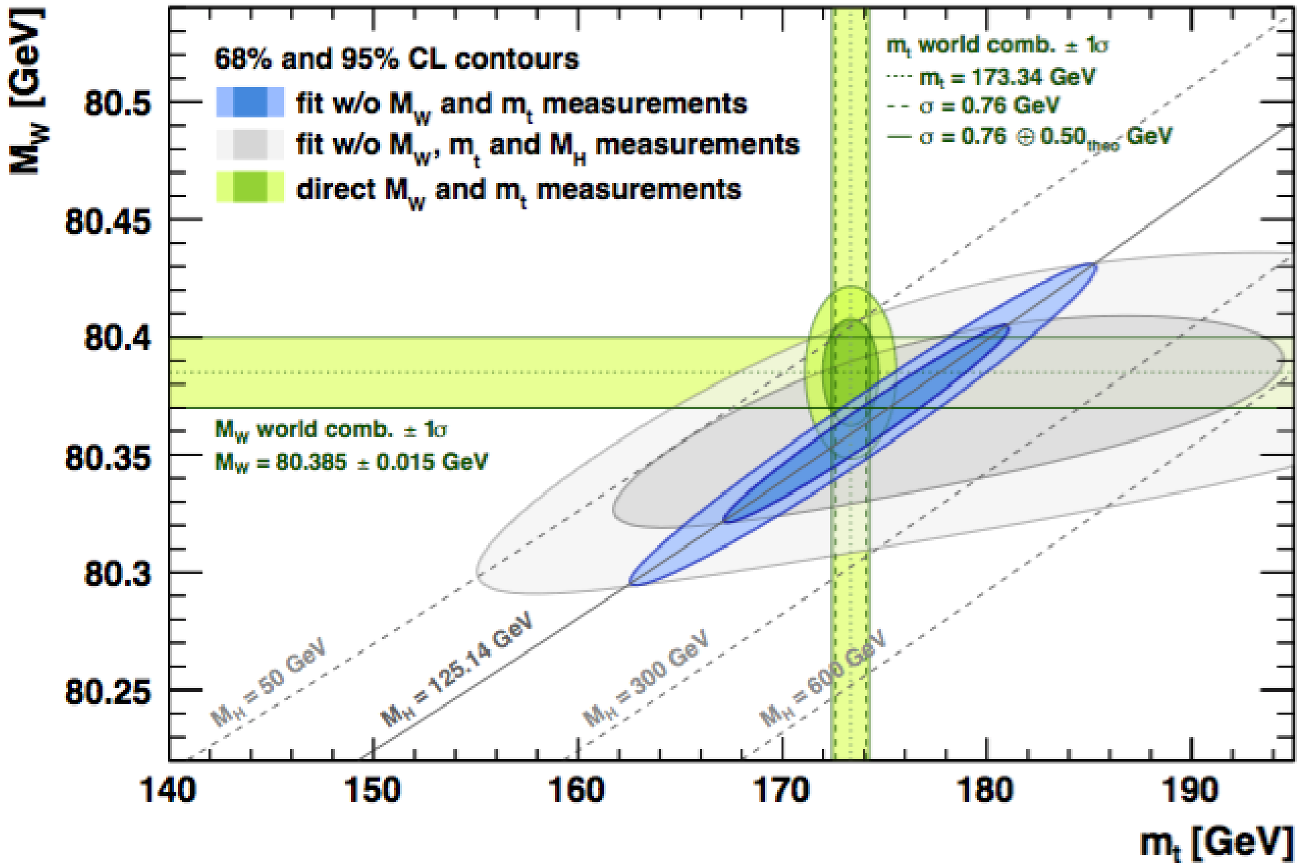
- Impressive progress in the last years from 7 to 8 TeV analyses
  - Will soon hit limit from PDFs, but could get close to $A_{LR}/A_{FB}^{0,b}$ precision with 13 TeV data

CMS-PAS-SMP-16-007



Measurement of the W mass

- Comparison of indirect and direct measurements of m_W and m_t

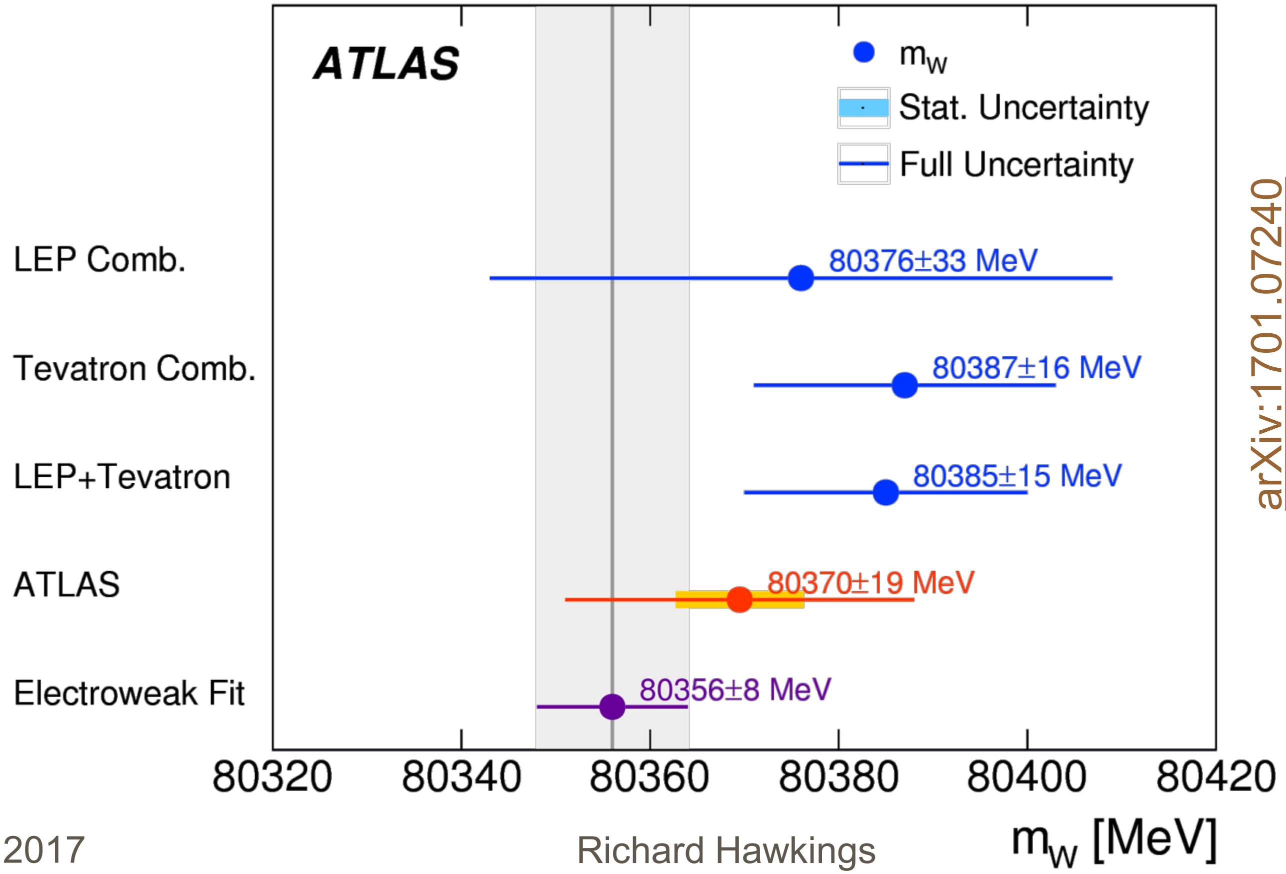


arXiv:1407.3792

- m_t and m_H have been measured – prediction for m_W is 80.358±0.008 GeV
- Compared to experimental average of m_W=80.385±0.015 GeV (before LHC)
  - Dominated by CDF and D0 measurements (±0.019 and ±0.023 GeV), then LEP

Spoiler - first LHC measurement of W mass

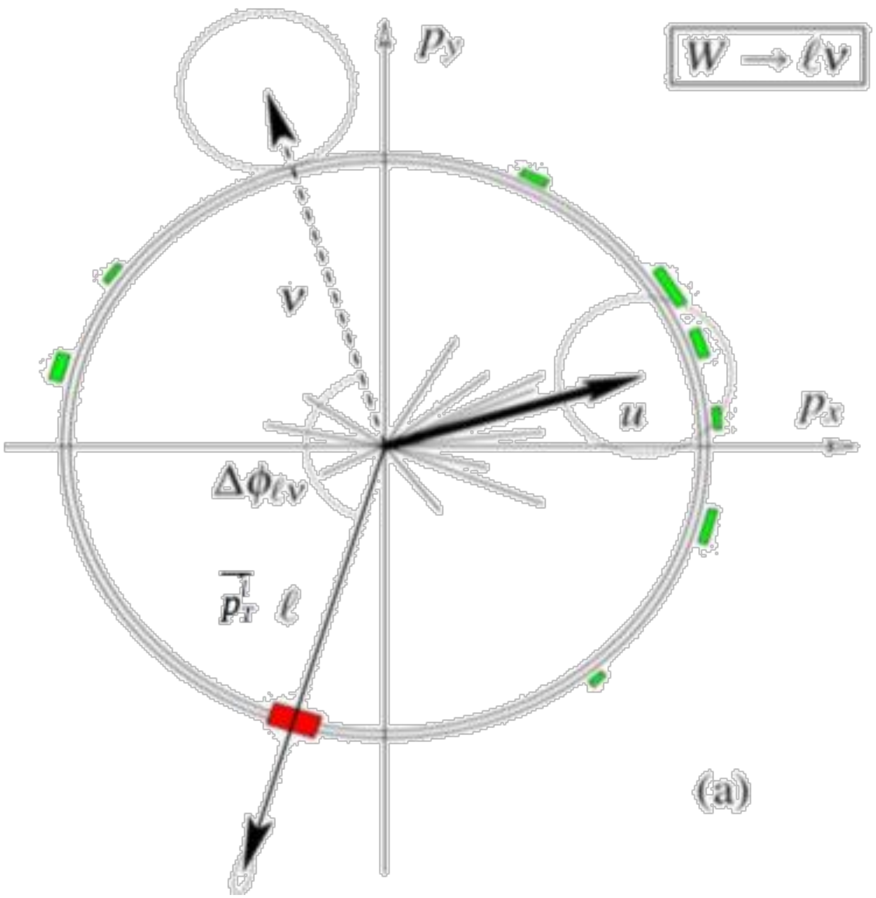
- ATLAS measurement from 7 TeV data (2011) released in December 2016
  - Precision of 19 MeV, same as best previous result (CDF)
  - Pulling back towards the EW fit result … another triumph for the Standard Model?
    - With more data (some already available) and **lots** of work, hope to approach 10 MeV?



arXiv:1701.07240

m_W measurement at hadron colliders

- Only leptonic decay modes accessible: $W\rightarrow e\nu$, $W\rightarrow \mu\nu$
  - Neutrino p_T from E_T^{miss}, but p_Z not measured – cannot reconstruct m_W event-by-event
- Mass-sensitive observables: $p_T(l)$, E_T^{miss} (or p_T^{miss}), $m_T(W)$



- Define **recoil** as sum of 'everything else' projected into transverse plane

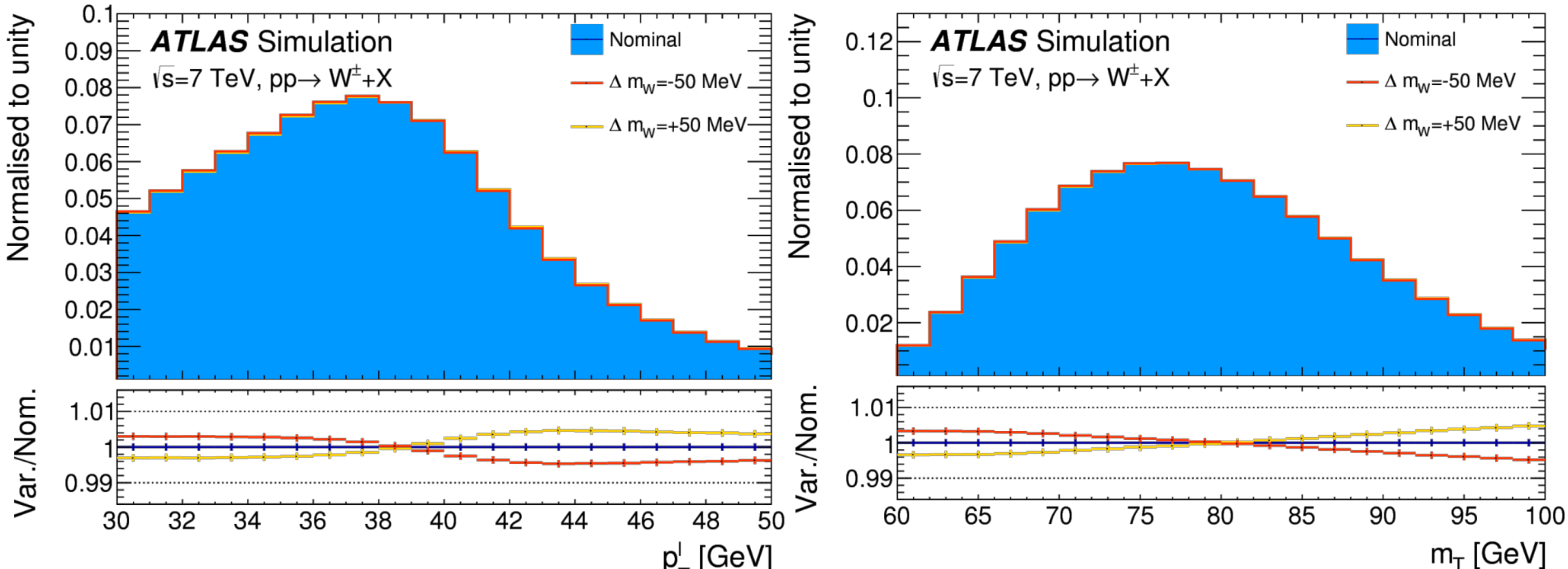
$$\vec{u}_T = \sum_i \vec{E}_{T,i} \qquad \vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$$

  - Calculated from calorimeter energy deposits alone, no jet reconstruction
    - Remove cone around lepton, replace with rotated cone from random ϕ
  - $-u_T$ corresponds to the p_T of the W boson
  - In Z events ($\nu\rightarrow l$), $p_T(Z)$ can also be obtained from the charged leptons $p_T(ll)=-u_T$
- Transverse mass definition:

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

Sensitivity of the observables

- W mass extracted using template fits to reconstructed observables
  - Reweight MC (exploiting 2 GeV W width) or use parameterised simulation to generate predictions for different values of m_W
  - Changes in peak / shape up to 0.5% for 50 MeV change in m_W
  - Need control of absolute momentum scales at 10^{-4} level (via $Z \rightarrow ll$ calibration)
  - Need precise physics model for W production and decay (in particular $p_T(W)$)



LHC vs Tevatron

- W boson statistics
  - 10x more at LHC, even with 7 TeV data sample (another factor x20 now available)
- Calibration of leptons and recoil
  - LHC benefits from large Z→ll calibration samples with similar lepton p_T
    - Tevatron relies more on J/ψ→ll and Υ→ll, with smaller Z→ll samples for validation
  - LHC has 'state of the art' detectors, and more sophisticated detector simulation
  - Tevatron has much less pileup, recoil is easier to measure and model
- Modelling of W production
  - W^+ and W^- kinematics identical at Tevatron (pbar-p collider), but different at LHC (more W^+, fewer but more central W^-)
  - 25% of W bosons from s or c quark in initial state at LHC, c.f. 5% at Tevatron
    - More difficult to model W production, uncertainties from PDFs and p_T(W)
- More Z statistics at LHC for complementary studies

ATLAS measurement – simulation & categories

- W/Z modelled with Powheg+Pythia8 (NLO QCD+parton shower)
  - Photos for QED FSR, full Geant4 detector simulation
  - Sample reweighted to improve physics modelling and change $m_{W,}$ value blinded
- Tighter event selection c.f. cross-section measurements
  - Lepton p_T>30 GeV, $|\eta|$<2.4, remove 1.4<$|\eta|$<2.0 for electrons (EM calo transition)
  - Also require p_T^{miss}>30 GeV, m_T(W)>60 GeV and u_T<30 GeV (i.e. small W p_T)
  - Separate measurements for p_T(l) / m_T(W), $W^{+/-}$, W→e/μ and $|\eta|$ bins

$\|\eta_\ell\|$ range	0–0.8	0.8–1.4	1.4–2.0	2.0–2.4	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\|\eta_\ell\|$ range	0–0.6	0.6–1.2		1.8–2.4	Inclusive
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3 397 716
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525

14M W→lν in total

  - Final fitting ranges for p_T(l) and m_T(W) optimised to minimise total uncertainty

Physics modelling

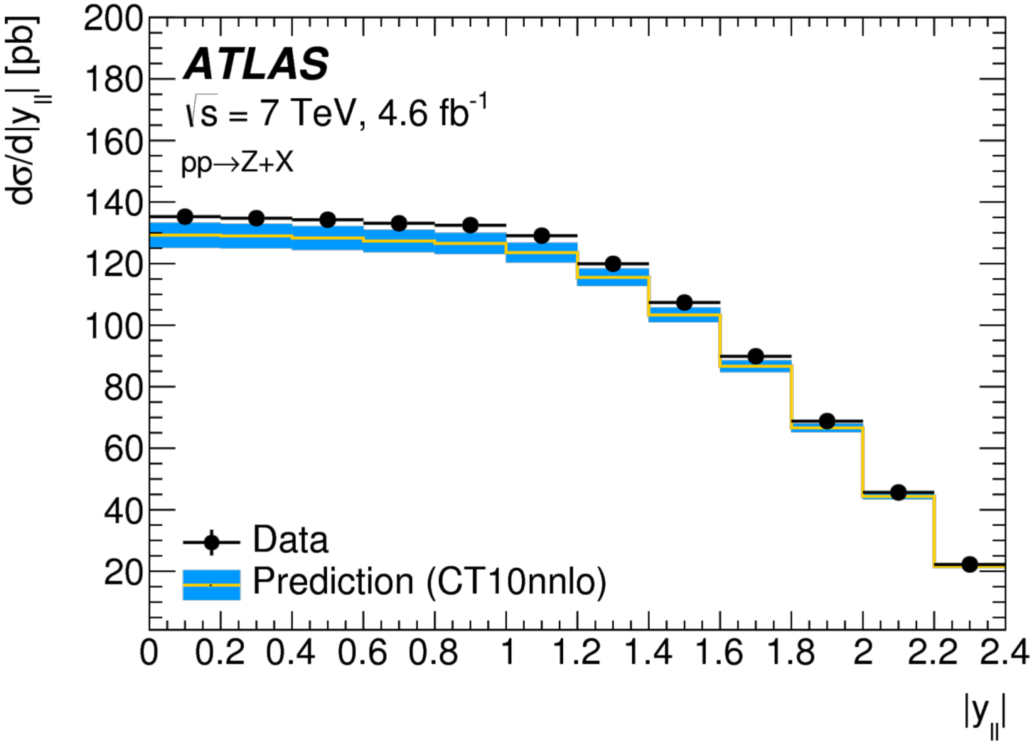
- Drell-Yan ($W\to l\nu$ and $Z/\gamma^*\to ll$) differential cross-section factorises in 4 terms:

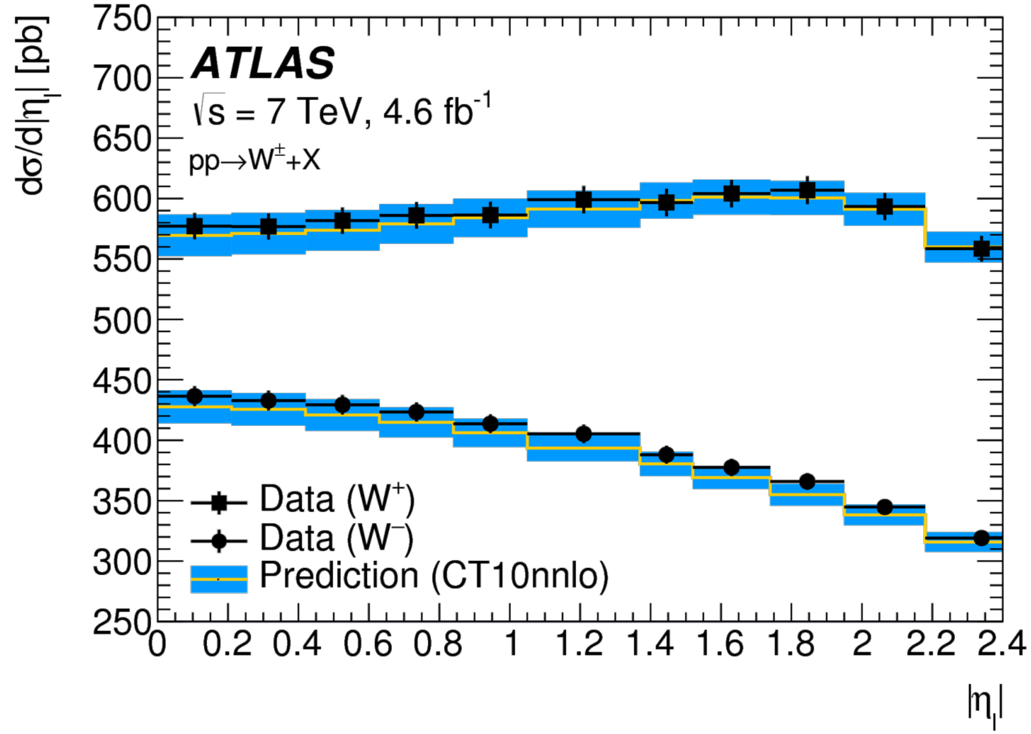
$$\frac{d\sigma}{dp_1\, dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\, dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7} A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

  - Lepton 4-mom. p_1 and p_2, dilepton m, p_T, and rapidity y; θ,ϕ lepton decay angles in Collins-Soper frame
- 1st term: Breit-Wigner for mass (including γ propagator for Z)
- Rapidity distribution (2nd term) and angular coefficients (4th term) – QCD fixed-order predictions with DYNNLO
  - Validated with measured W and Z data at 7 TeV
- 3rd term: Boson pT at given rapidity
  - Modelled with Pythia8 based on tuning to measured $p_T(Z)$ distribution at 7 TeV
  - Tevatron experiments used resummation approach based on RESBOS
- PDFs enter into both rapidity/angular and transverse momentum terms
  - Baseline choice is CT10 – weaker suppression of strange quark than e.g CT14

Rapidity distributions

- Model predictions validated by comparing to W/Z diff. cross-sections at 7 TeV
  - Data consistent with DYNNLO+CT10 prediction (within correlated uncertainties)
  - Compatibility reasonable: χ^2=45/34 (10%)
  - Other PDFs worse, retain CT14 and MMHT for systematic uncertainty studies





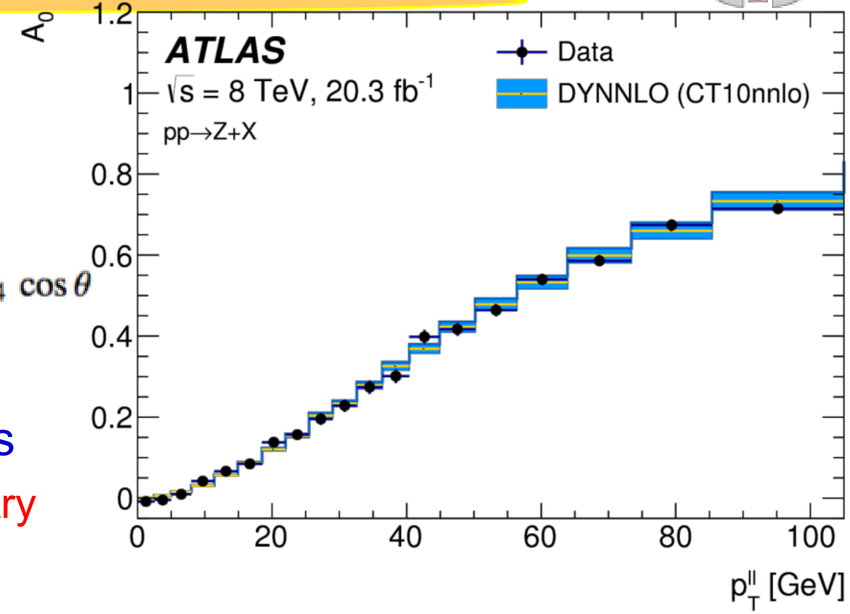
  - Could eventually try **profiling** the PDFs to reduce uncertainties on m_W

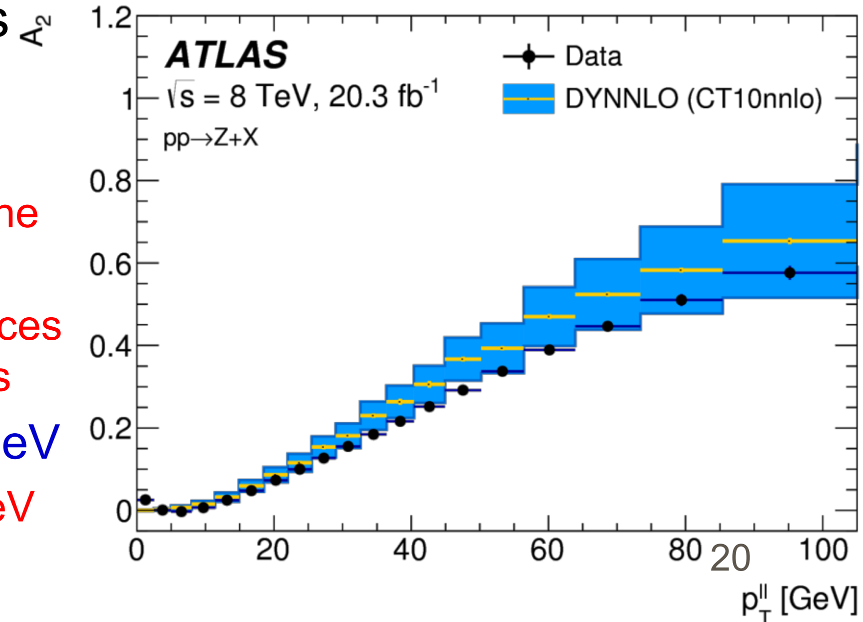
Angular distributions

- Decay angle distributions in terms of θ, ϕ:

$$\frac{d\sigma}{dp_T^2\,dy\,dm\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dp_T^2\,dy\,dm} \times [(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta)$$
$$+ A_1\sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$

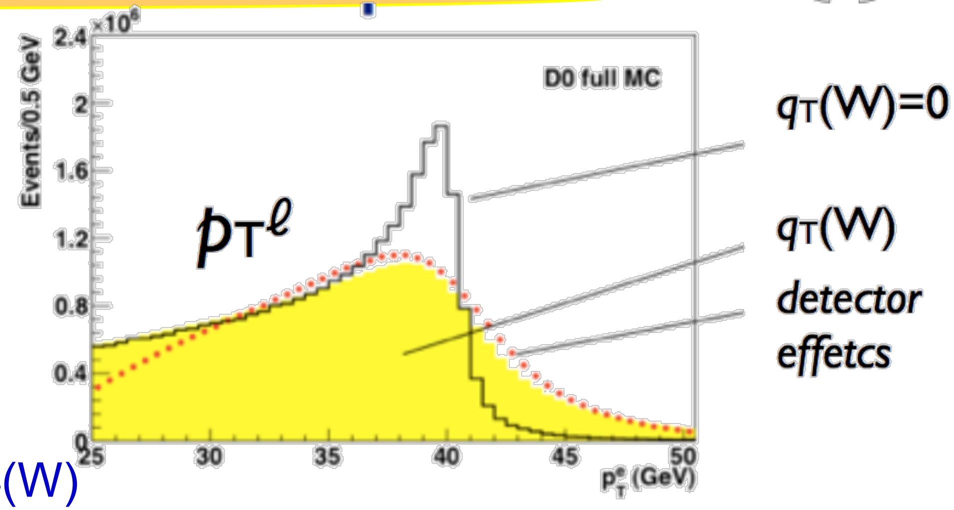
  - A_i are functions of boson p_T and y (and m)
  - Coefficients A_0-A_4 relevant for W mass analysis
    - Coefficient A_4 is the forward-backward asymmetry
    - Coefficients A_5-A_7 neglected (≠0 only from α_s^2)
- Coefficients can be measured in Z→ll decays
  - Predictions of DYNNLO checked with ATLAS data at 8 TeV [arXiv:1606.00689]
    - Fit decay angle distributions to templates with the different harmonic functions to derive A_i
    - Propagate uncertainties and significant differences wrt DYNNLO prediction from Z to W coefficients
  - A_2 not described well – data-pred. gives 1.6 MeV
    - Full set of coefficient uncertainties gives 5-6 MeV





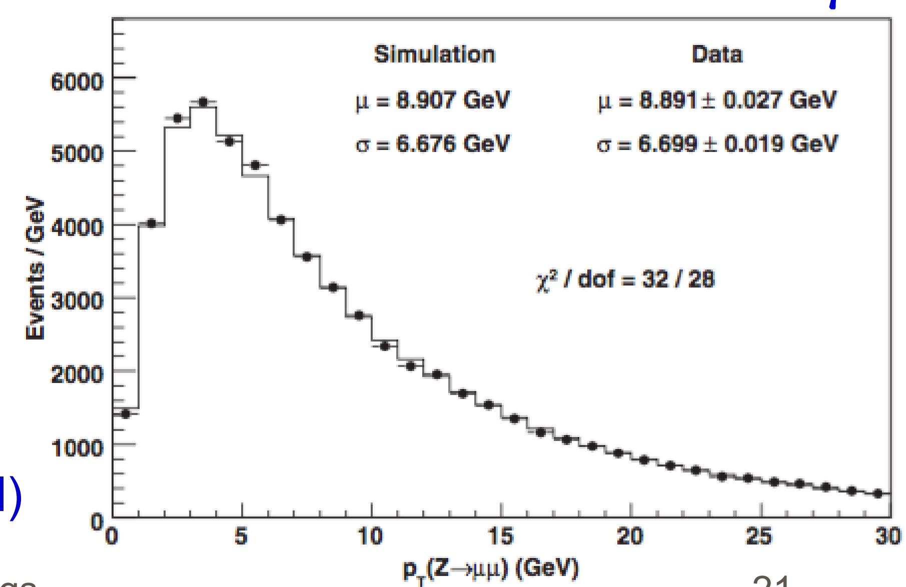
Boson transverse momentum

- Modelling $p_T(W)$ critical for $p_T(l)$ method
  - Smears out the Jacobian edge
  - Also significant for $m_T(W)$ (e.g. selection)
- $p_T(W)$ determined by several effects
  - Intrinsic k_T of quarks in proton (non-pert.)
    - Can be handled with form factor approach
  - Multiple soft gluon emission for moderate $p_T(W)$
    - Handle with resummation – log (m_W/p_T) terms
  - Perturbative QCD (W+1,2 .. jets)
    - Dominant at large p_T (but require p_T<30 GeV)
- Tevatron experiments used RESBOS
  - Implements the 3 components
  - Parameter variations (non-pert. g, α_s) fitted to measurements of $p_T(Z)$ in Z→ll events
    - Same physics processes involved
  - Resulting uncertainties on m_W ~5 MeV for $p_T(l)$



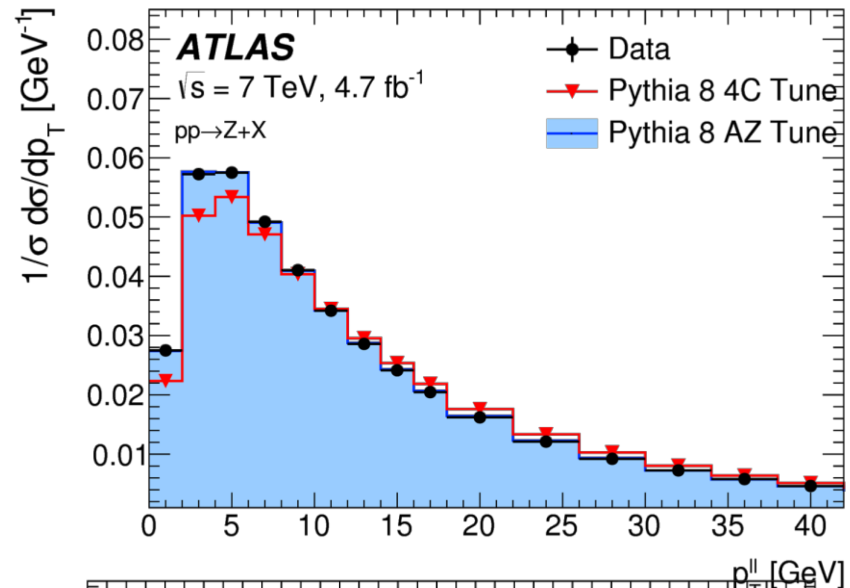
arXiv:1311.0894

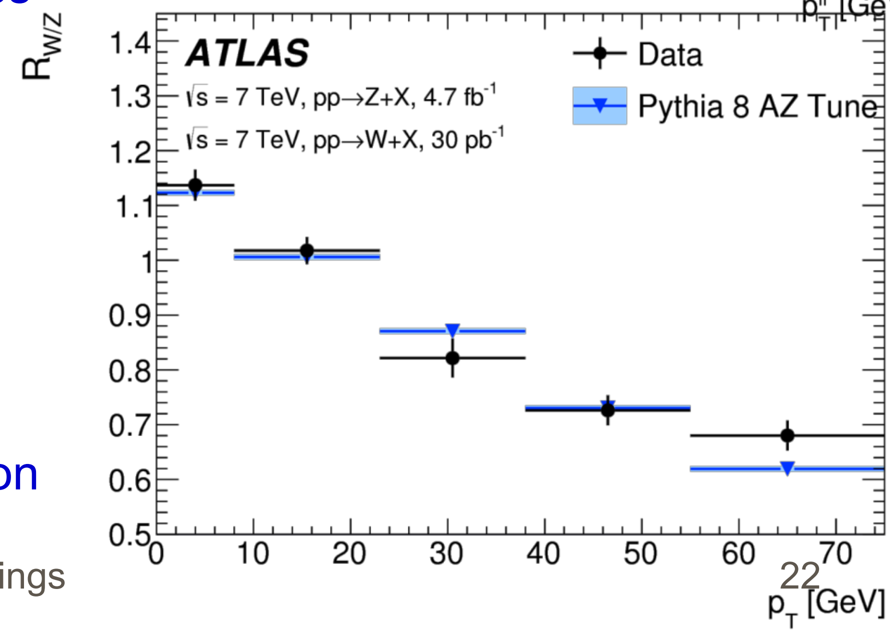
CDF Z→μ



Boson transverse momentum at LHC

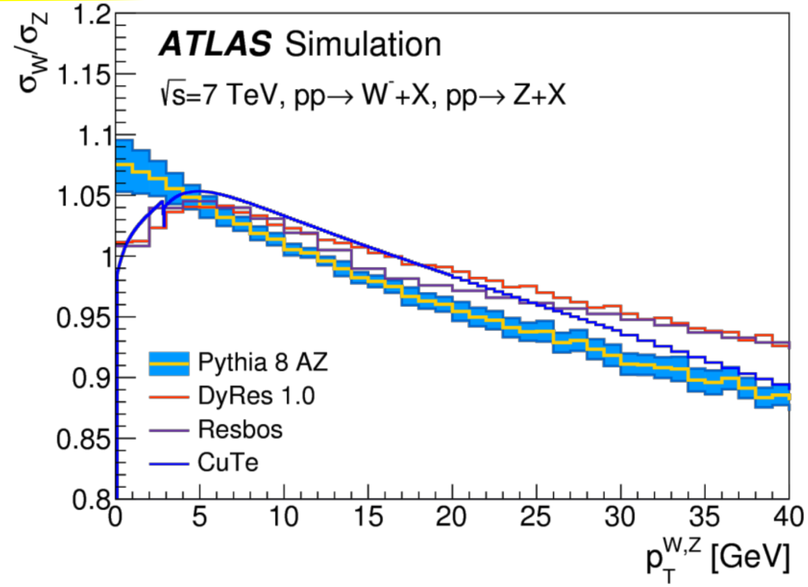
- Also rely on $p_T(Z)$ measurement at ATLAS
  - Data can be well described by Pythia8 with dedicated parameter tune ('AZ')
    - Pythia8 description equivalent to NLO+PS plus NLL resummation
    - Tune intrinsic k_T, $\alpha_s(m_Z)$ and ISR cut-off
  - Try to use this to also describe $p_T(W)$
- Consider Pythia8 prediction for $p_T(W)/p_T(Z)$
  - And related uncertainties, due to differences between W and Z production
    - Different initial state quarks, which give different $p_T(W)$ spectra
    - Uncertainties due to heavy quark masses, QCD scale choices, PDFs in parton shower
- Also a direct measurement of $p_T(W)$
  - Results for $p_T(W)/p_T(Z)$ consistent with Pythia8 AZ tune prediction, but low precision

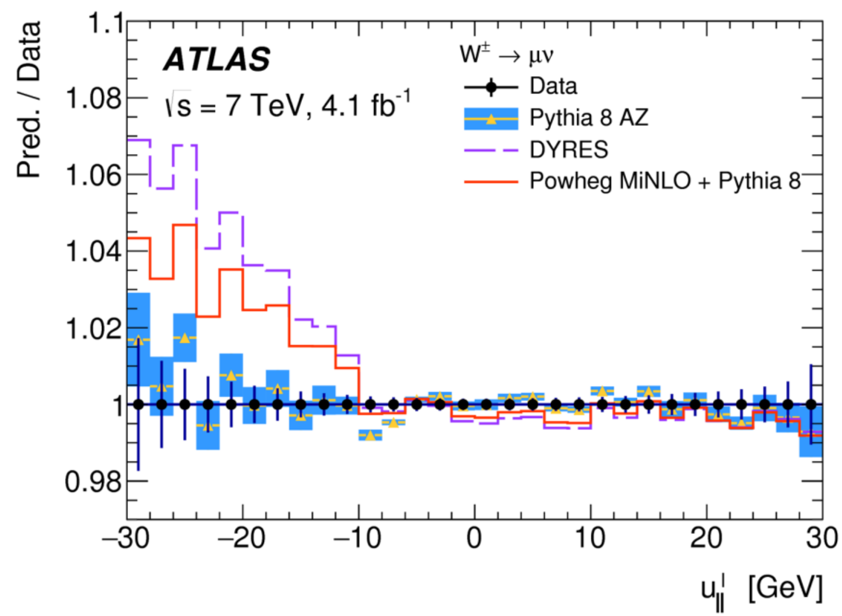




Boson transverse momentum - validation

- Also looked at resummation approaches to describe $p_T(W)/p_T(Z)$
  - Resbos, DyRes and Cute give a turn-over at low pT – believed to be unphysical
  - In data, negative tail of u|| (u_T projected onto lepton direction) is sensitive to $p_T(W)$
    - DyRes prediction disagrees with data, while Pythia8 AZ tune agrees
  - Open question – why doesn't resummation approach work for $p_T(W)$ @ LHC?





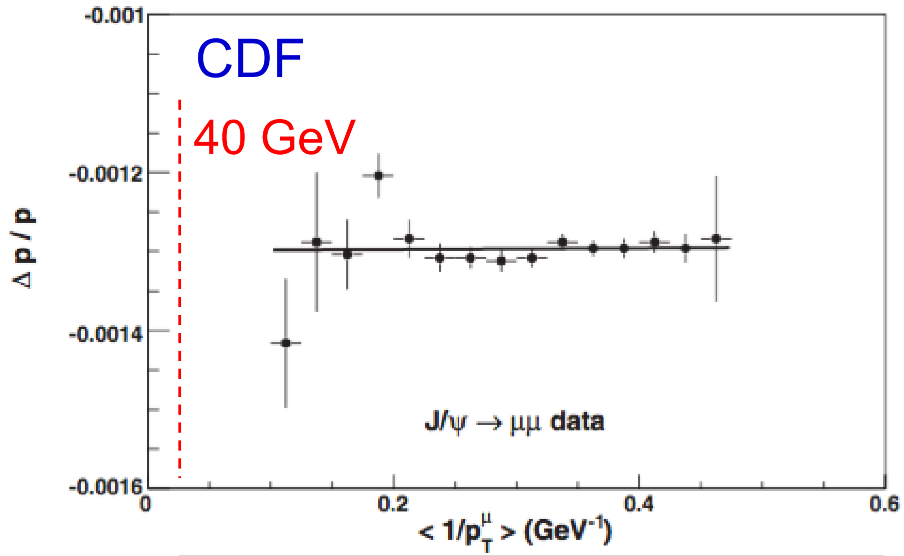
- Final QCD modelling uncertainties:

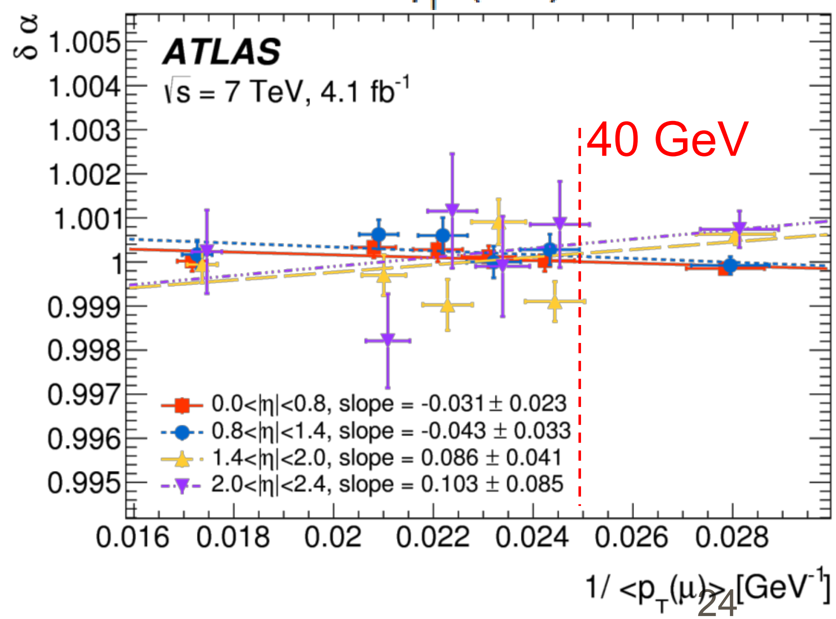
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

  - $p_T(W)$ uncertainties ~6 MeV in optim. fit range

Muon momentum calibration

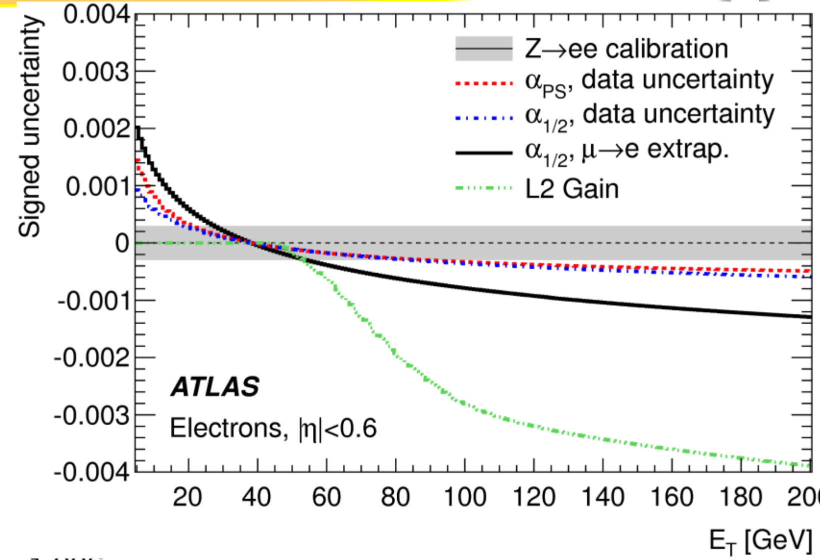
- Muon momentum determined from ID only
  - External muon chambers only for tagging
- Calibration depends on ID alignment and B-field map accuracy
  - ‘Weak modes’ unconstrained by track residuals are particularly dangerous
    - ϕ rotation ∝r gives charge-dependent biases
    - Use E/p measurements for $e^{\pm}$ in $W^{\pm}\rightarrow e\nu$
  - Check ‘standard candle’ masses vs p_T, η, ϕ
- Non-linearity vs. p_T
  - CDF primary calibration from $J/\psi,\Upsilon\rightarrow\mu\mu$
    - Typical muon p_T~3 GeV, large extrapolation up to 40 GeV for $W\rightarrow\mu\nu$
    - Validate by reconstructing Z→μμ mass peak with precision of 16 MeV
  - ATLAS primary calibration from Z→μμ
    - Linearity check over relevant region using p_T variation within Z decays

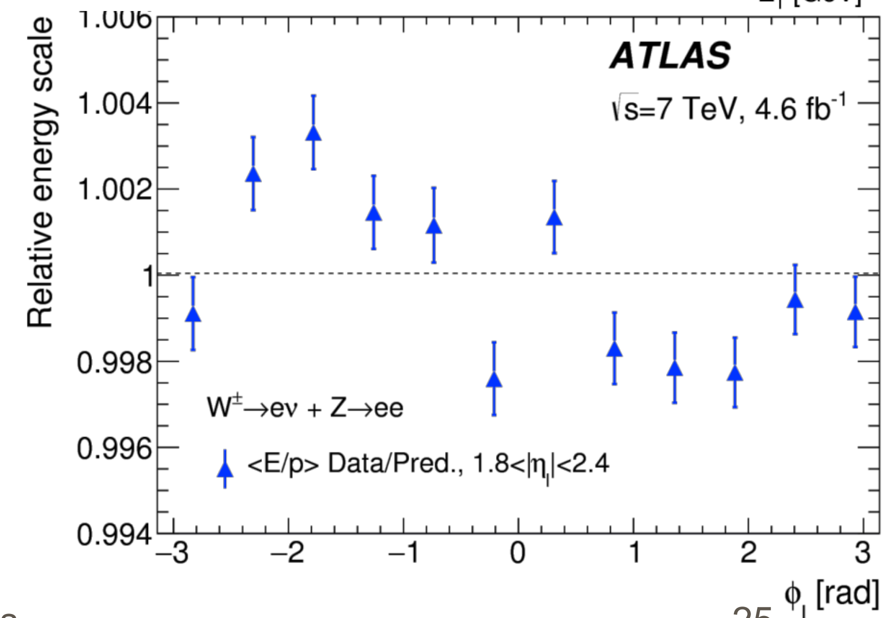




Electron energy calibration

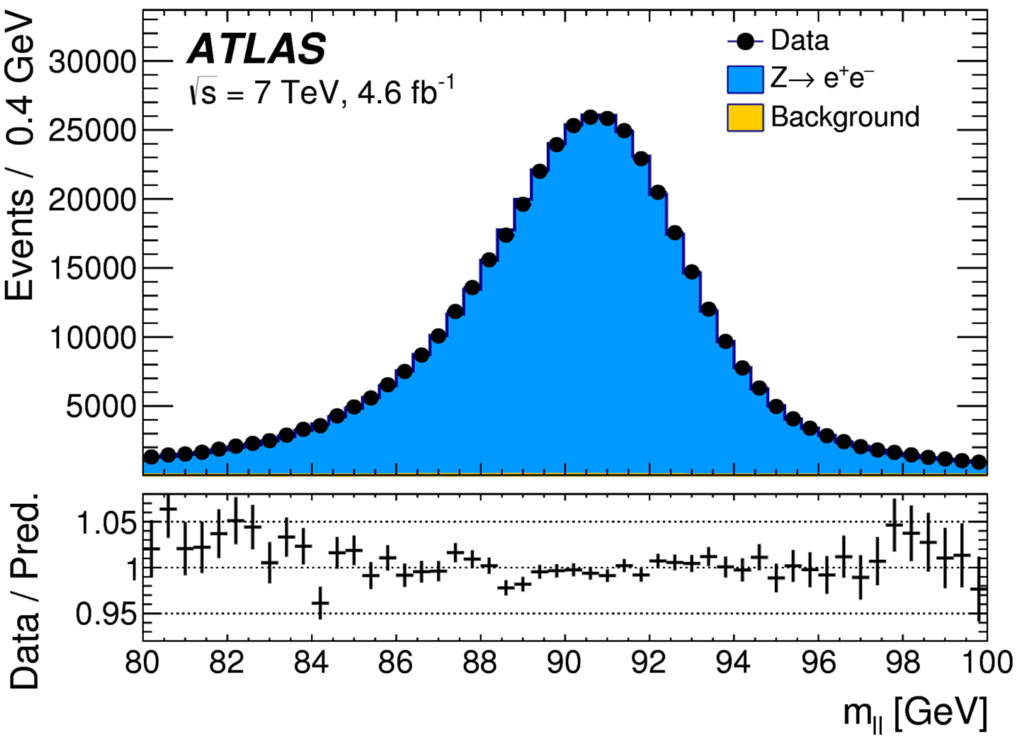
- Electron E from EM calo, η & ϕ from tracks
  - Bottom-up calibration procedure benefittining from calorimeter segmentation in depth
    - Inter-calibration of calorimeter layers using muon energy deposits
    - Corrections for passive material using longitudinal shower profile
    - Energy linearity uncertainties from variation of components with energy
  - Final in-situ corrections from Z→ee vs η using known Z mass
    - Electron uncertanties smallest around 45 GeV
- Subtle effects - ϕ-dep energy scale
  - From EM calo sagging under gravity
    - Z calibration averages over ϕ, but W→eν sample is not uniform in ϕ
  - Dedicated correction using <E/p> in W→eν

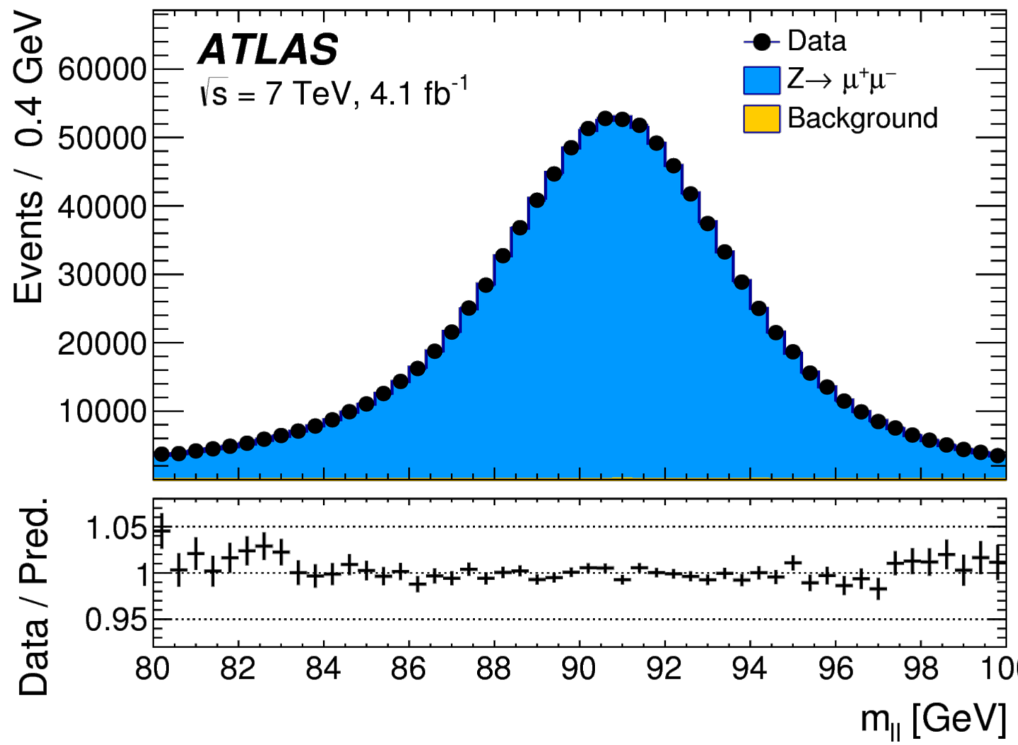




Description of Z mass peaks

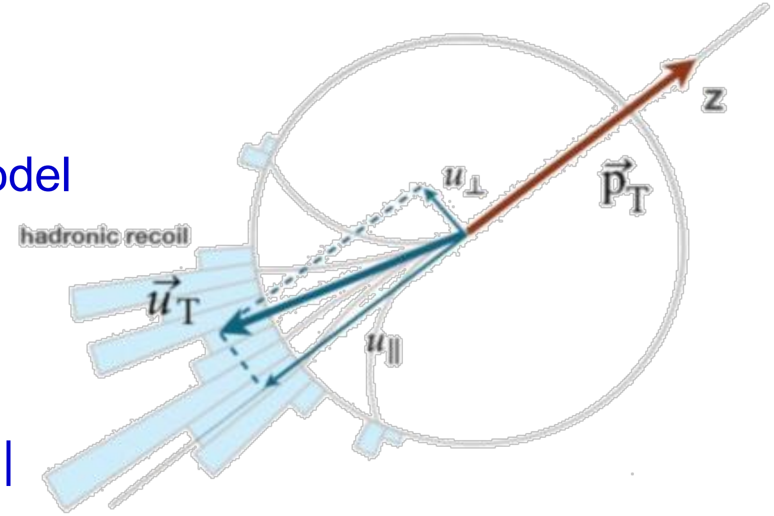
- After all corrections to electron and muon efficiencies, scales, resolutions, get sub-% level description of Z mass peaks for both electrons and muons
  - Validation of all the calibration procedures

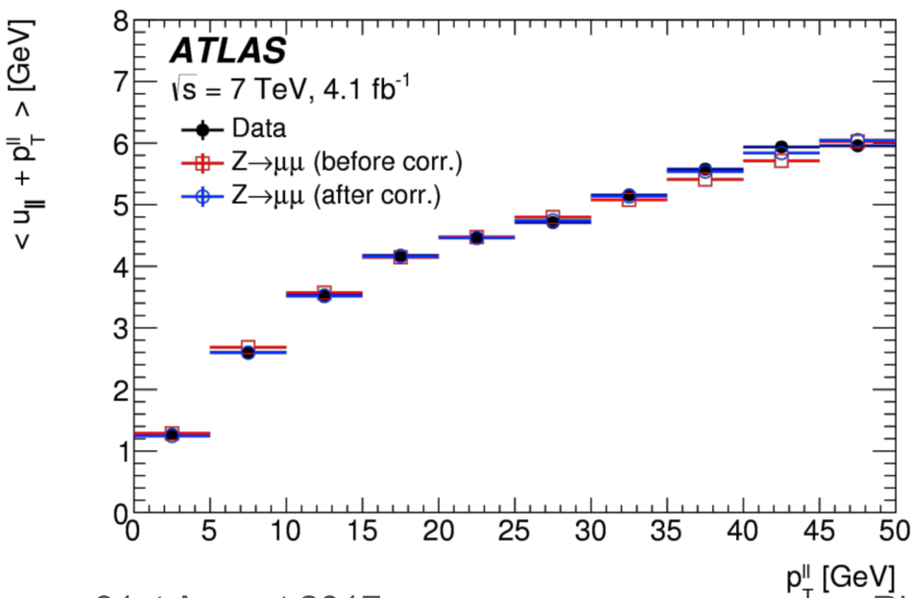


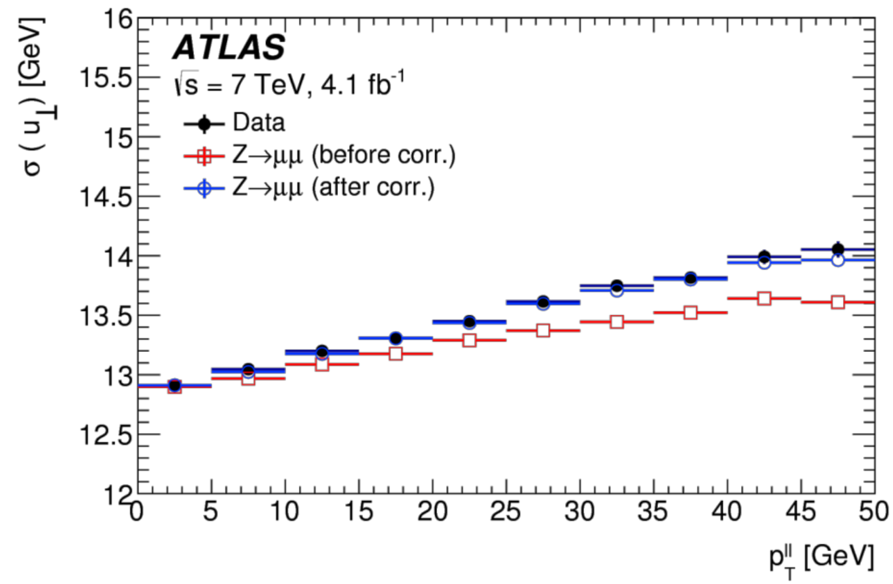


Recoil modelling

- Recoil resolution probed in Z→ll events
  - Projection u-perp sensitive to resolution
  - Projection u|| sensitive to recoil scale and p_T model
- Various corrections to get good modelling
  - Correct MC pileup <μ> to match data
  - Correct sum(E_T) to match data
  - Residual response corrections for u-perp and u||

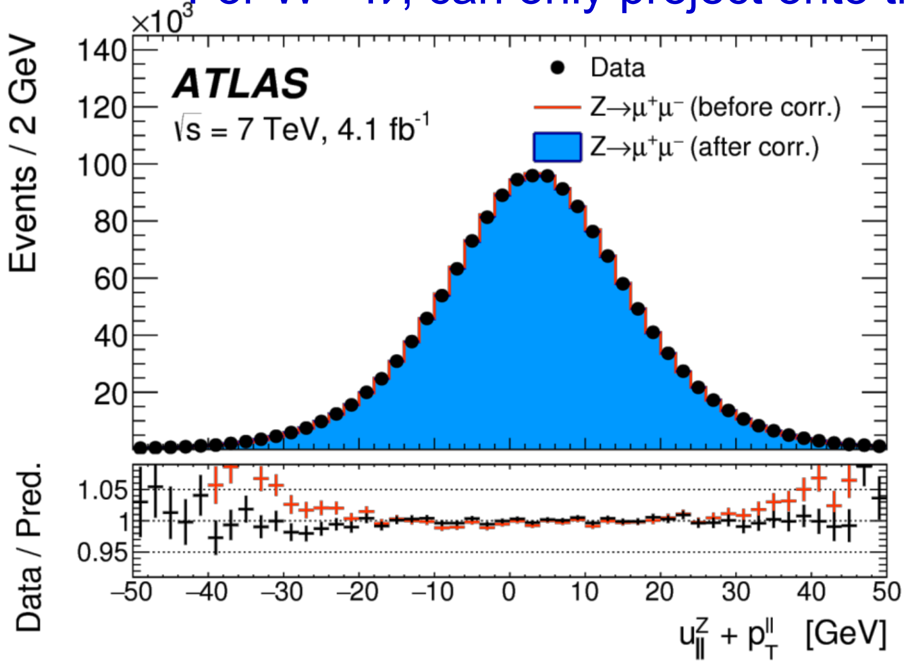


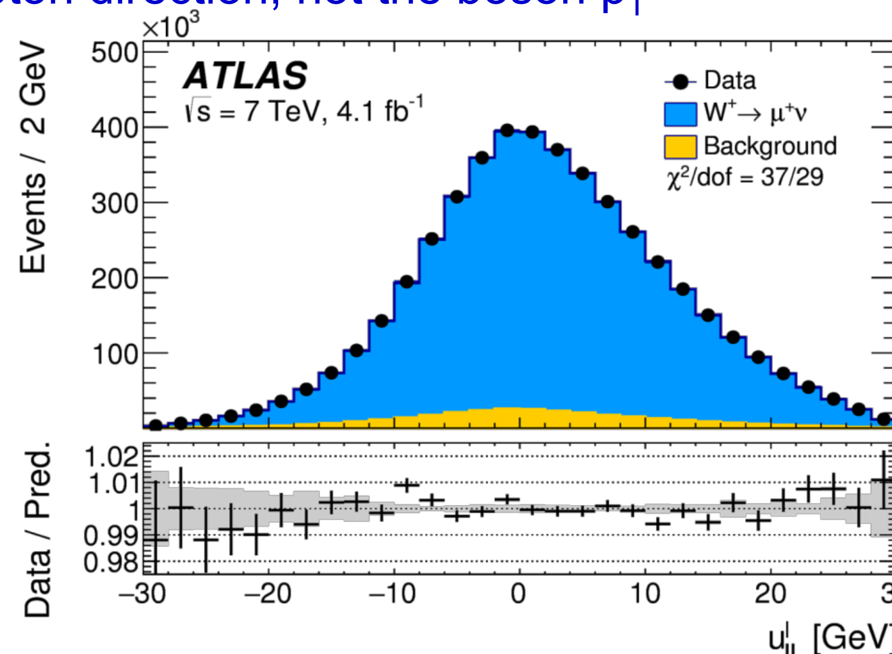




Recoil distributions in data

- After all corrections, get good description of recoil projections
  - For $W \to l\nu$, can only project onto the lepton direction, not the boson p_T



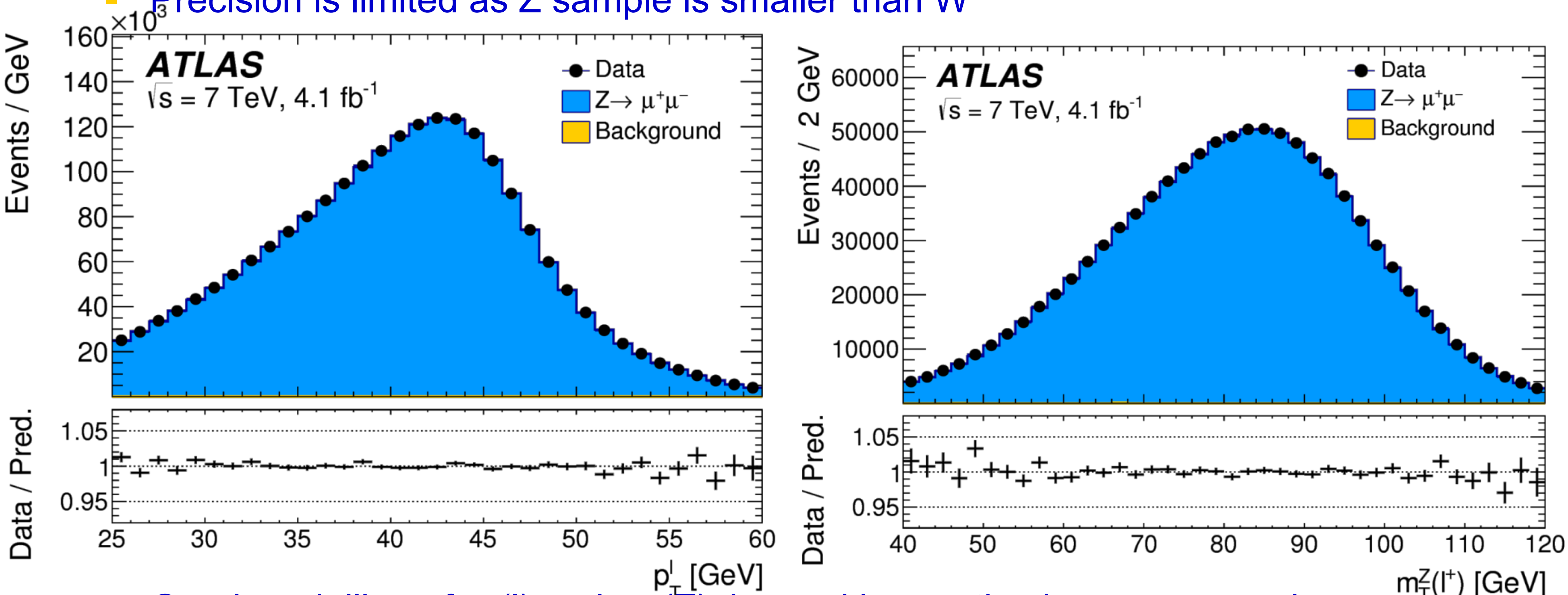


- Uncertainties on $m_T(W)$ measurement dominated by sum(E_T) corrections
  - Then $Z \to W$ extrapolation
- Uncertainties on $p_T(l)$ measurement are small (event selection only)

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

Consistency checks with Z→ll

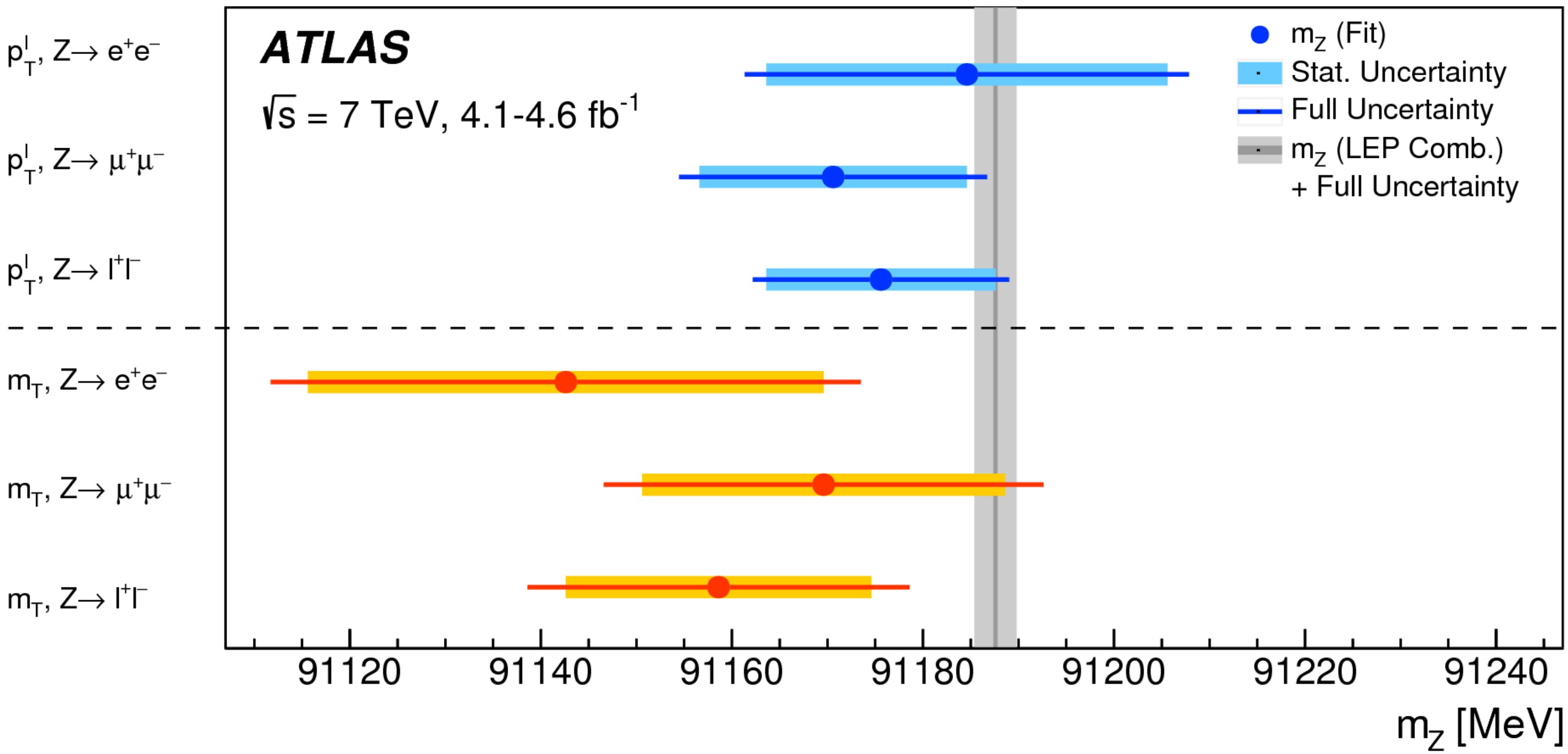
- With all ingredients ready, test analysis on Z→ll events
  - Ignore one lepton, in order to mimic a W→lν with undetected neutrino
  - Tests detector calibration, physics modelling and recoil corrections
    - Does not test extrapolations from Z→W
  - Precision is limited as Z sample is smaller than W



- Good modelling of p_T(l) and m_T(Z), here with negative lepton removed

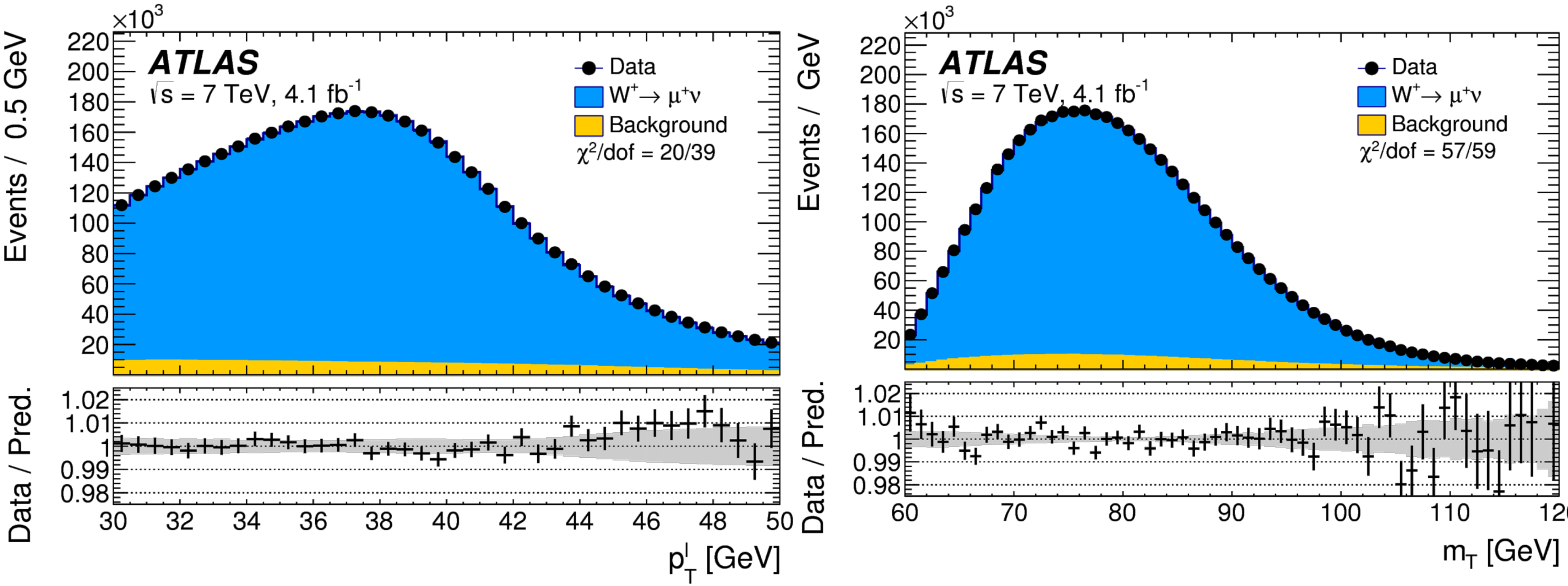
Fitted Z-mass

- All results consistent with the measured Z mass value from LEP
  - Only statiscal and detector uncertainties are included
  - N.B. Strong correlations between the various measurements



ATLAS W mass fits

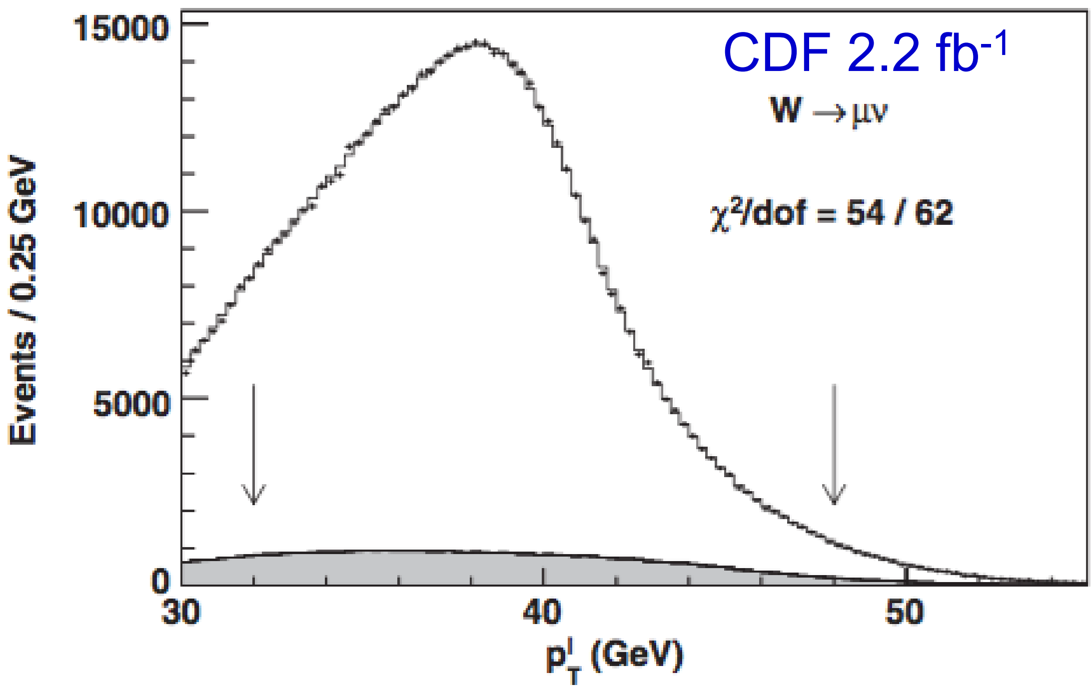
- $W \rightarrow \mu\nu$ fit results for $p_T(l)$ and $m_T(W)$ distributions
  - Optimised fit ranges: $32<p_T(l)<45$ GeV and $66<m_T(W)<99$ GeV
  - Good description of the data by the templates at the best fit m_W (from the combination of all channels)



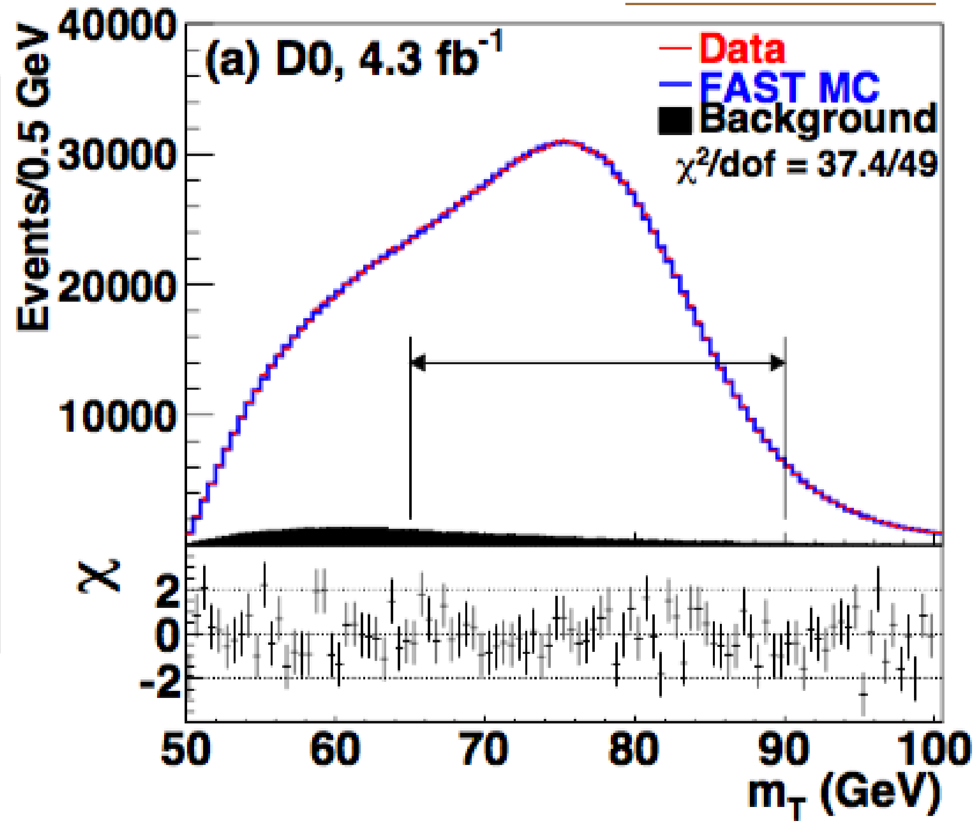
Tevatron W mass fits

- Data compared to best fit templates
  - CDF $W \to \mu\nu$ $p_T(l)$ fit (left) and D0 $W \to e\nu$ $m_T(W)$ fit (right)
  - Good description of the data by prediction template in both cases
  - Fit range optimsed to minimise total uncertainty

arXiv:1311.0894

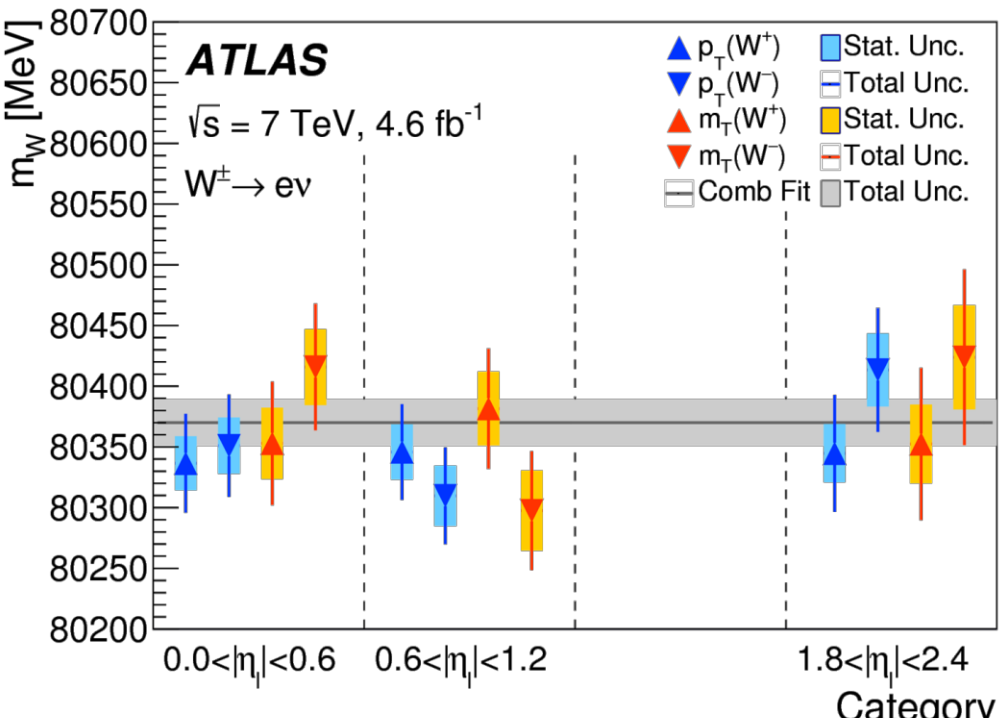


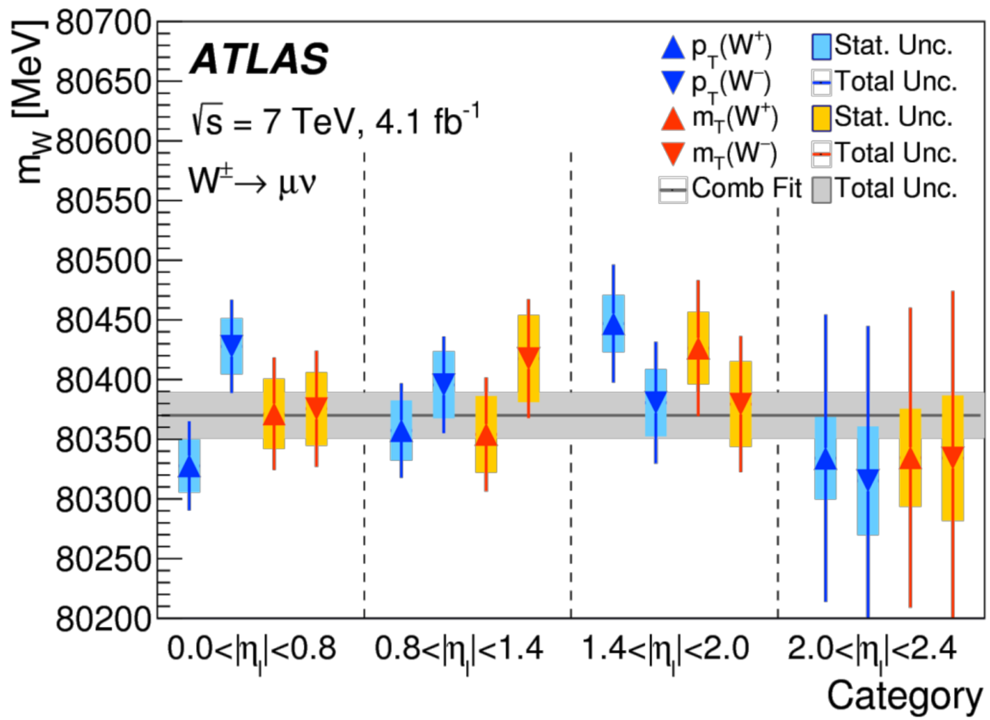
arXiv:1310.8628



ATLAS – results in measurement categories

- Check consistency of results across different measurement categories
  - Electrons vs. muons probes detector uncertainties specific to each lepton species
  - W^+ vs. W^- and results in $|\eta|$ slices probes physics modelling (especially PDFs)
  - $p_T(l)$ vs. $m_T(W)$ probes physics and recoil modelling
- Consistency between channels verified (with unknown common m_W offset) before 'unblinding' the result





Systematic uncertainty breakdown

- Combinations of various categories, with uncertainties and χ^2

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

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

- Full-combination $\pm$18.5 MeV, $p_T(l)$ alone 18.7 MeV, $m_T(W)$ alone 25.1 MeV

Systematics compared to Tevatron

- Compare ATLAS uncertainties to latest (last?) CDF measurement

Source	Uncertainty (CDF 2.2 fb^{-1})	ATLAS 4.6 fb^{-1}
Lepton energy scale and resolution	7	7/6
Recoil energy scale and resolution	6	3
Lepton tower removal	2	-
Backgrounds	3	5
PDFs	10	9
$p_T(W)$ model	5	8
Photon radiation	4	6
Statistical	12	7
Total	19	19

- LHC is already winning on statistics, with 5 fb^{-1} of 7 TeV data
  - Recoil uncertainty smaller, reflecting dominance of $p_T(l)$ in ATLAS combination
  - $p_T(W)$ uncertainty a bit larger, may be reduced with theoretical progress
- Can expect statistical and detector systematics to reduce with more data
  - Need progress on PDFs and $p_T(W)$ modelling – ball in the theorists court!

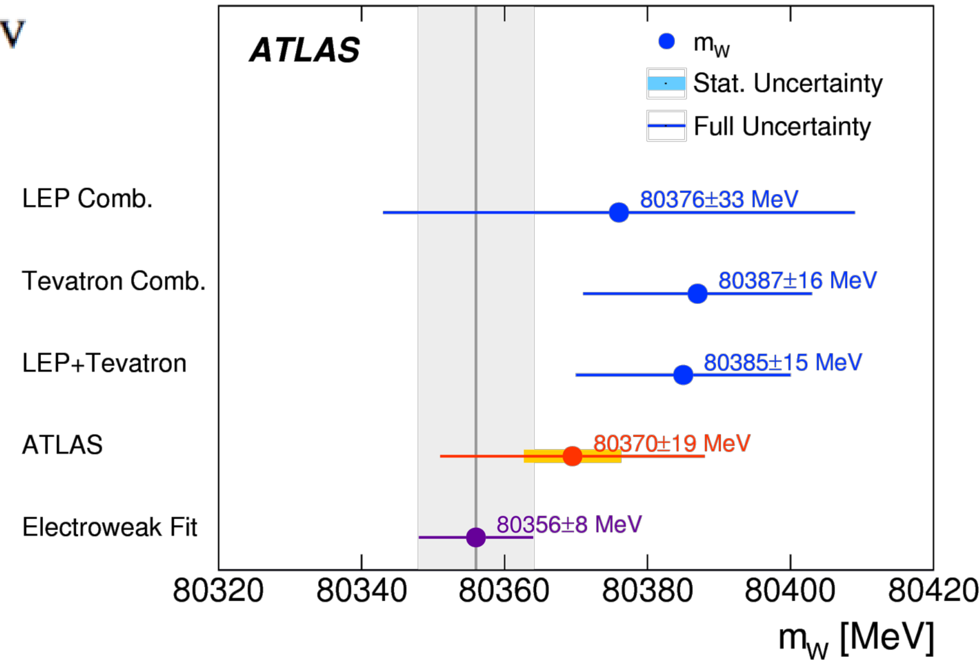
W mass results in context

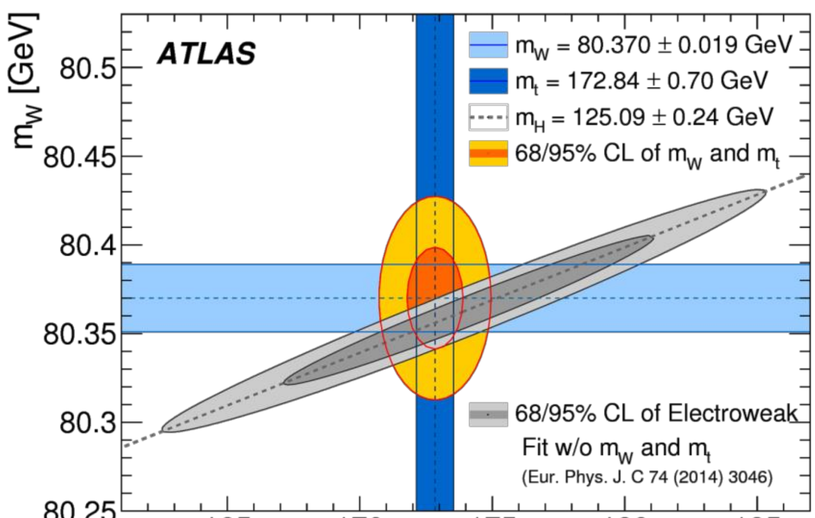
arXiv:1701.07240

- ATLAS 7 TeV result

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

  - Uncertainty comparable to best previous measurement (CDF)
  - Central value a bit lower – pulls the m_W average closer to the electroweak fit
  - No official world-combination available yet
    - Combination needs a proper treatment of physics modelling correlations (e.g. PDFs)

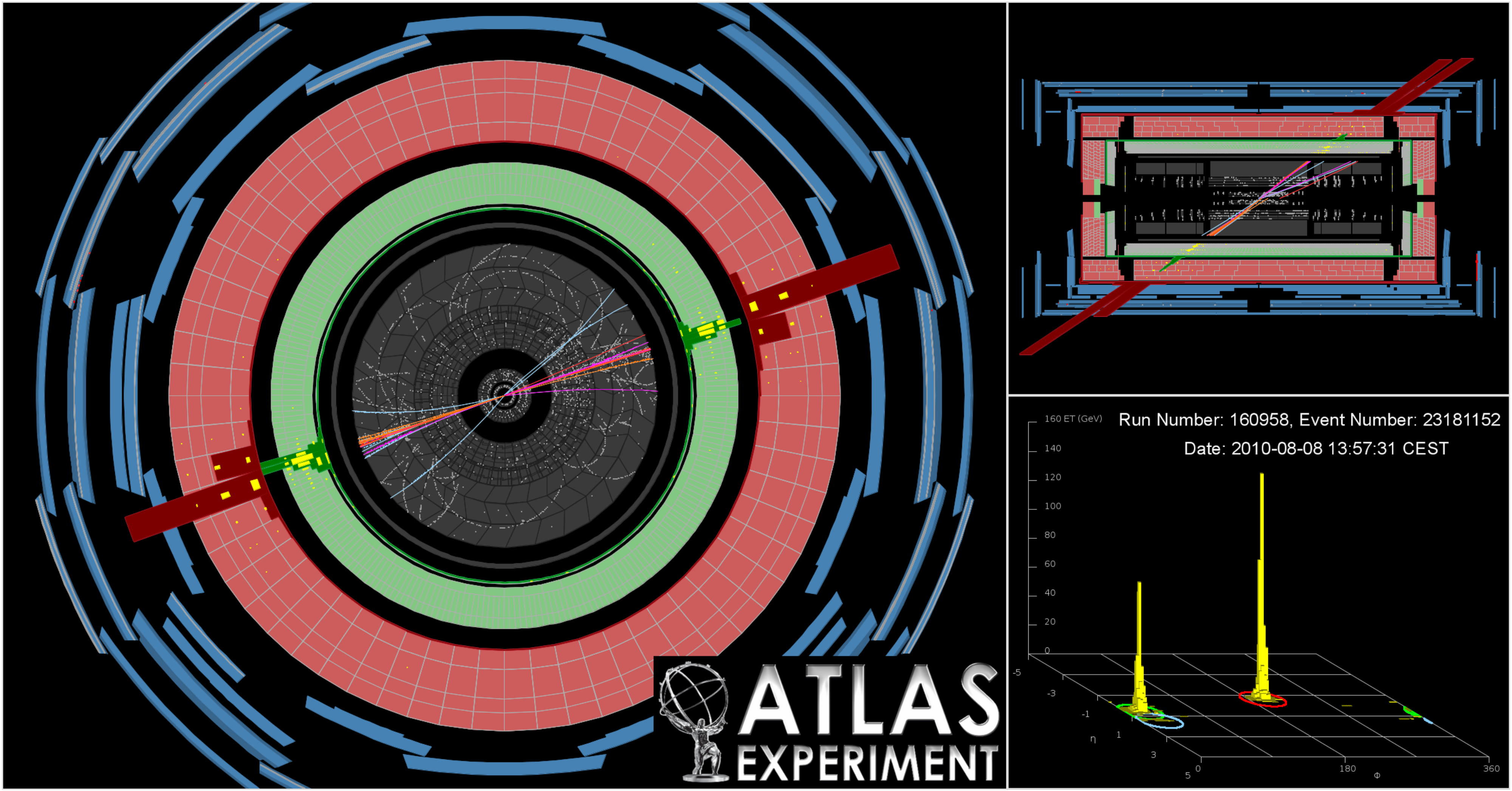




EW fit with ATLAS m_W and m_t measurements (ATLAS+CMS m_H average)

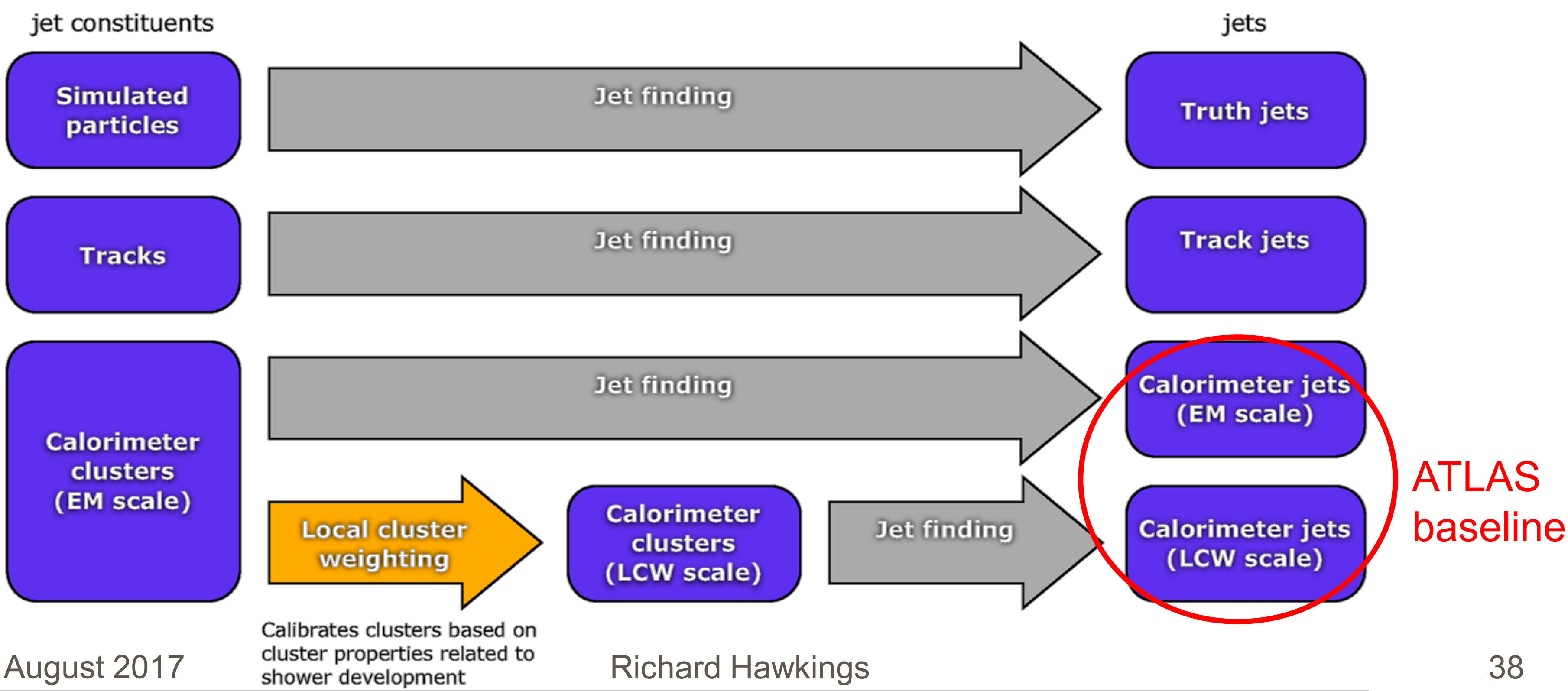
Jets

- Visible signature of high-energy quarks/gluons produced from hard-scattering



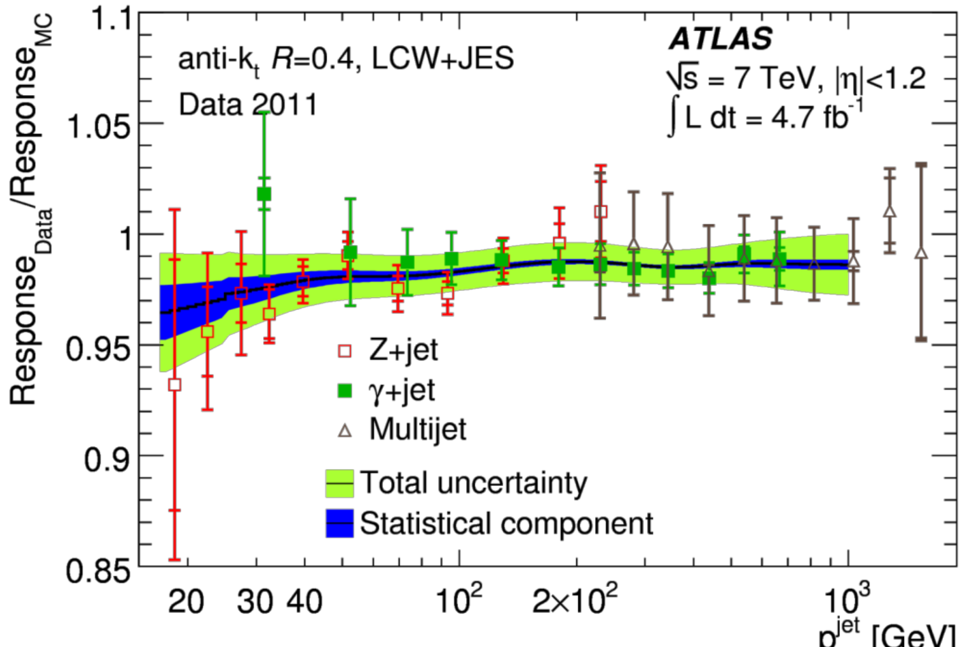
Jet reconstruction

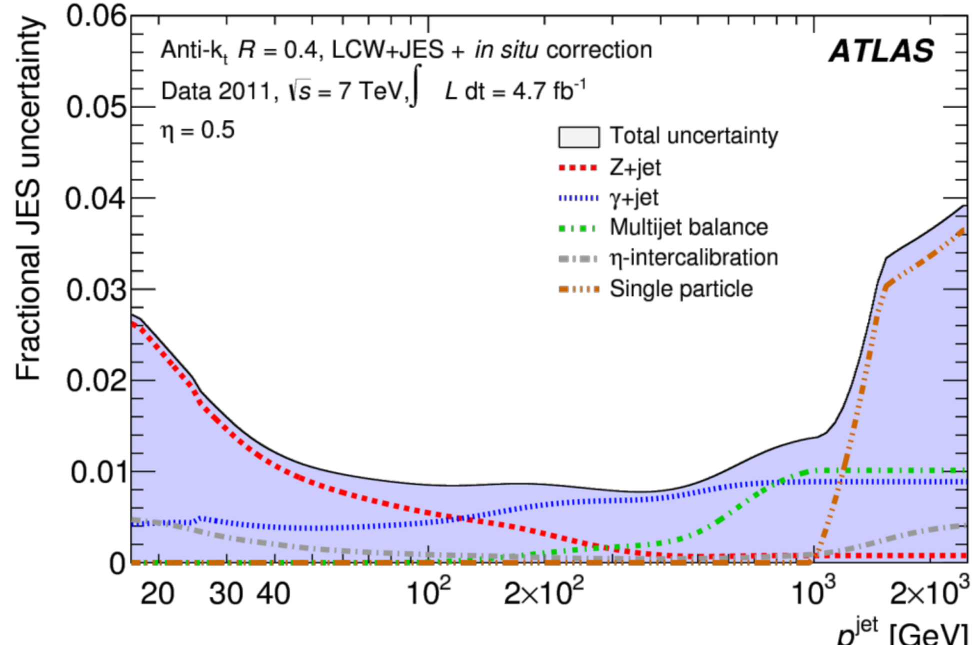
- Jet algorithm clusters constituent objects into jets with well-defined procedure
  - LHC experiments standardised on anti-k_T algorithm, typically R=0.4 – 0.6
  - Well-behaved theoretical properties – connect to QCD calculations
- Detector-level jet reconstruction aims to reproduce particle level jets
  - Cluster weighting to equalise energy response to different particle types



Jet energy scale calibration

- Jet energy scale calibration adjusted with in-situ corrections from data
  - Use p_T balance in photon+jet and Z(→ee)+jet events to calibrate against well-known EM scale (from Z mass)
  - Multijet events (1 high p_T recoils against 2 or more lower p_T) to extend to higher p_T
- Energy scale known to e.g. 1% at p_T≈100 GeV in 2011, worse for low p_T
  - Larger uncertainty away from central $|\eta|$ region, e.g. 3% at $|\eta|$=2.0
  - Significant additional dependence on jet flavour composition(quark, gluon, b-jet)





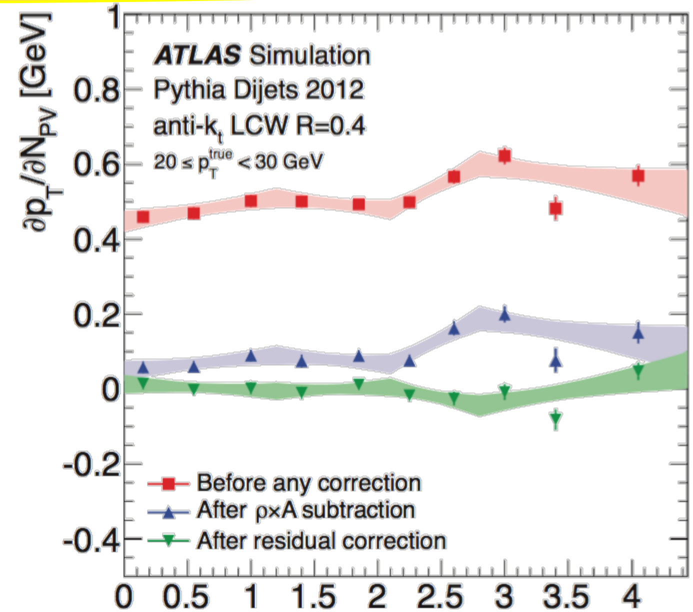
arXiv:1406.0076

Pileup suppression

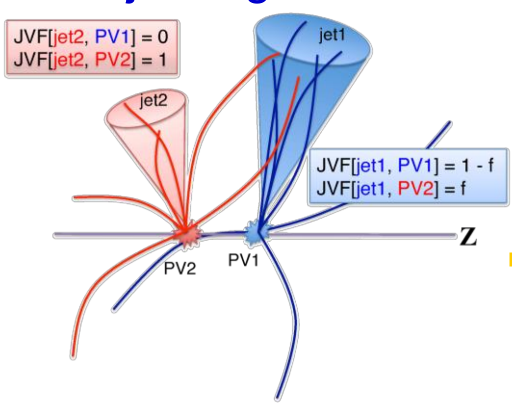
- Pileup adds energy to each measured jet
  - e.g. 0.5 GeV per reconstructed primary vertex
  - Subtract using 'jet-area' correction, assuming a uniform background energy density due to pileup

$$p_T^{corr} = p_T^{jet} - \rho \times A^{jet}$$

    - p_T density ρ from median of k_T jets in $|\eta|<2$
  - Removes most of the pileup dependence
    - After residual corr^n of N_{pv},$<\mu>$ effects, $dp_T/dN_{pv} \approx 0$

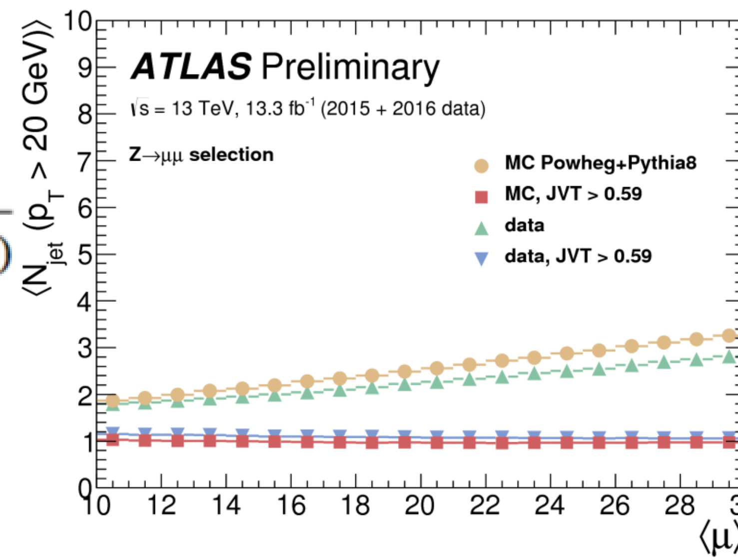


- Pileup gives rise to additional jets above p_T cut
  - Remove by requiring most tracks associated to the jet originate from the correct primary vertex



$$\mathrm{JVF}(\mathrm{jet}_i, \mathrm{PV}_j) = \frac{\sum_m p_T(\mathrm{track}_m^{\mathrm{jet}_i}, \mathrm{PV}_j)}{\sum_n \sum_l p_T(\mathrm{track}_l^{\mathrm{jet}_i}, \mathrm{PV}_n)}$$

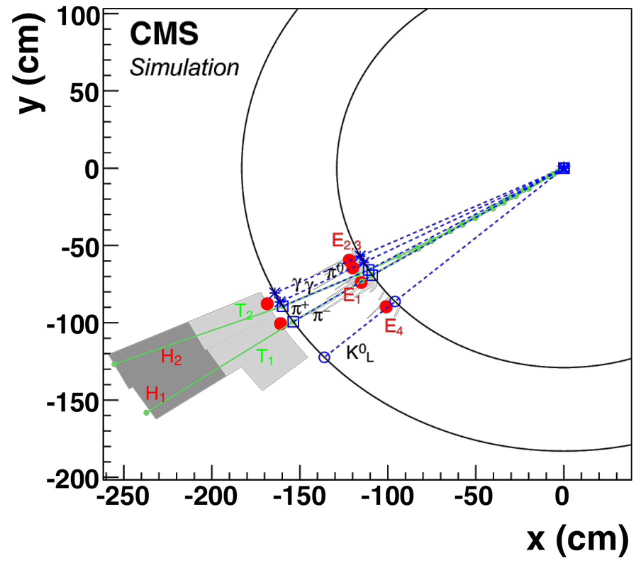
- Jet multiplicity in $Z \rightarrow \mu\mu$ events stable vs pileup $<\mu>$ after cut



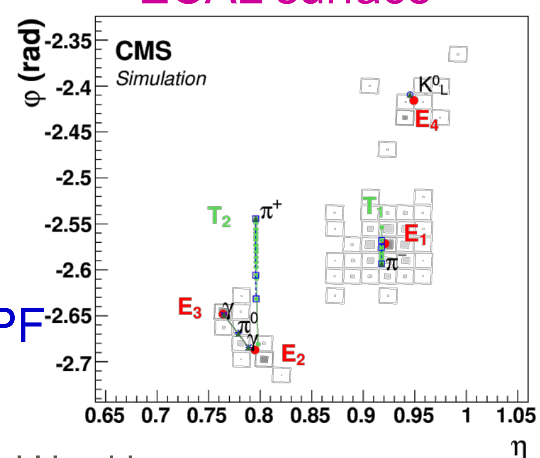
Particle flow ('PF') jets

- Particle flow approach using all detectors
  - Separate energy deposits from charged and neutral particles using track-EMCalo-HCalo matching information
    - Identify electrons, photons, charged and neutral hadrons, and overlaps
    - Apply best calibration to each particle
  - Apply jet finding to PF objects, not calorimeter clusters
- Works well for CMS detector
  - Strong (4T) magnetic field separates charged and neutral particles
  - Fine transverse segmentation in ECAL
- C.f. ATLAS use of calorimeter jets
  - Lower field, longitudinal calorimeter segmentation give smaller gains from PF

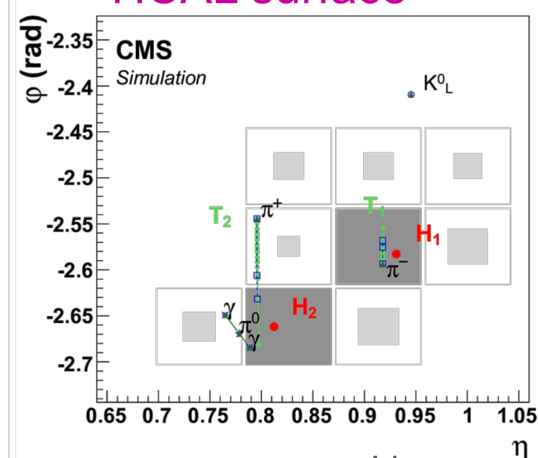
arXiv:1706.04965



ECAL surface

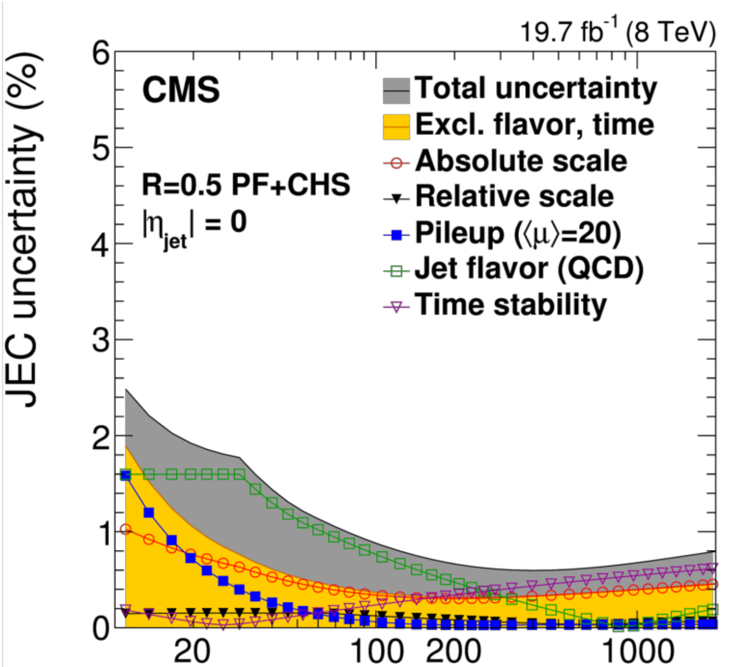


HCAL surface

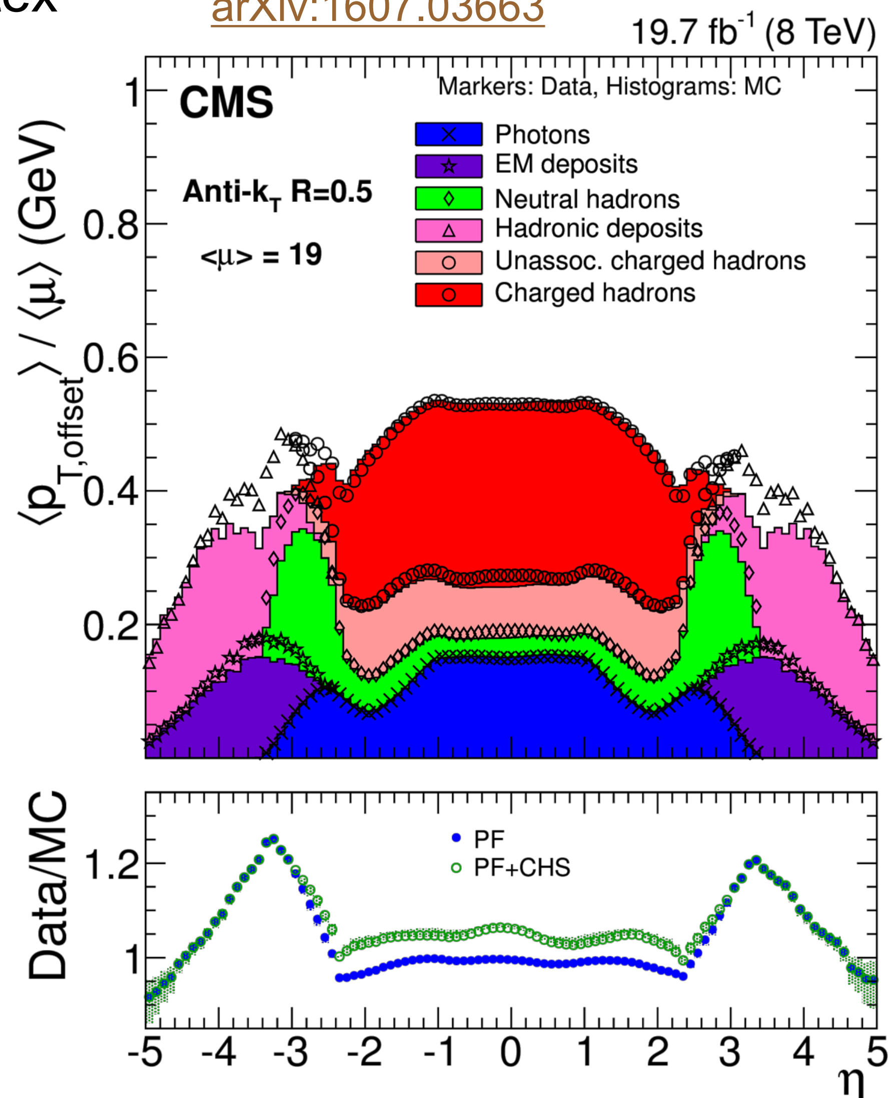


Pileup subtraction / jet energy scale in CMS

- Charged hadrons associated to a primary vertex
  - Remove those not associated to hard scatter vertex before jet finding
    - Removes around 50% of pileup for $|\eta|<2.5$
    - Also removes corresponding calorimeter energy
  - Also use jet area subtraction technique
- Final JES uncertainty <1% at 100 GeV

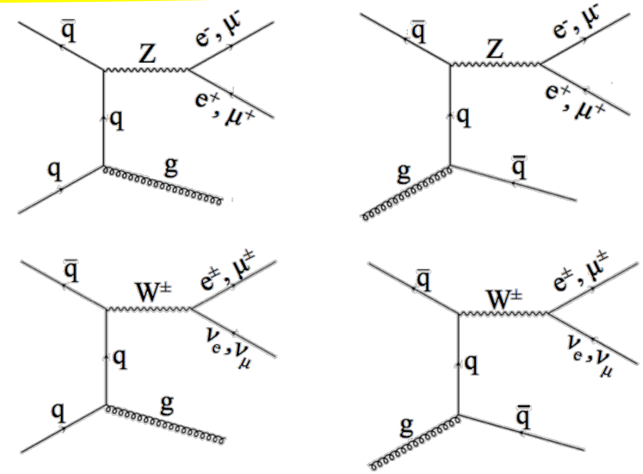


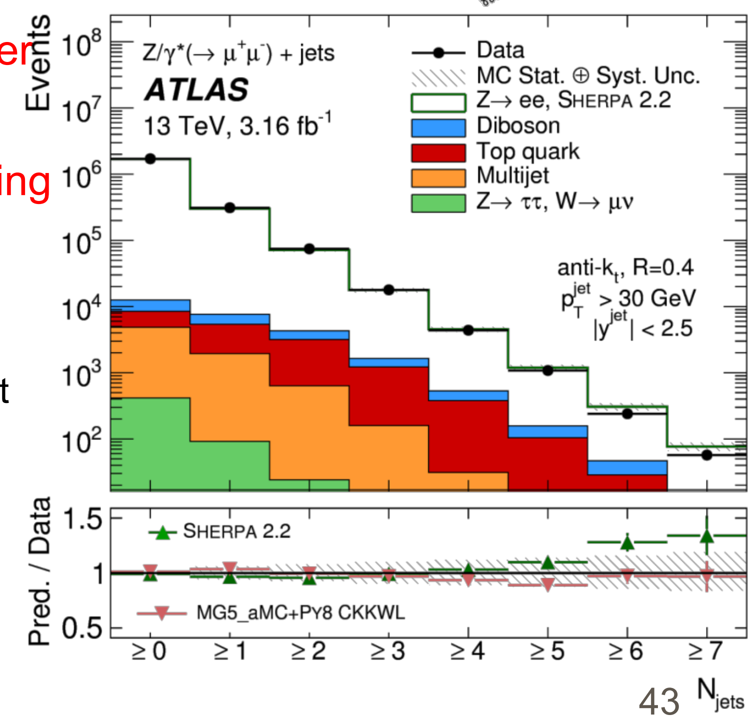
arXiv:1607.03663



W/Z+jets production

- W/Z+jets produced from qg as well as qq scattering
  - Increasing complexity with more jets
  - Important background for top and Higgs analysis
- Various MC approaches to modelling W/Z+jets
  - LO matrix elements for N jets + parton shower
  - NLO matrix elements for N jets + parton shower
    - Various matching schemes to resolve the double counting between matrix elements and parton shower
  - QCD fixed order predictions at NLO and NNLO
    - Multiple scales involved – W/Z mass, HT, p_T of leading jet or system of jets
  - … a testing ground for state-of-the-art QCD tools
- Z+jets analysis – 1-15% backgrounds dep on N_{jet}
- Measure cross-sections in a fiducial region
  - ll+N_{jets} at particle level with p_T>30 GeV, |y|<2.5
  - Correct for efficiencies and resolution with matrix-based unfolding procedure

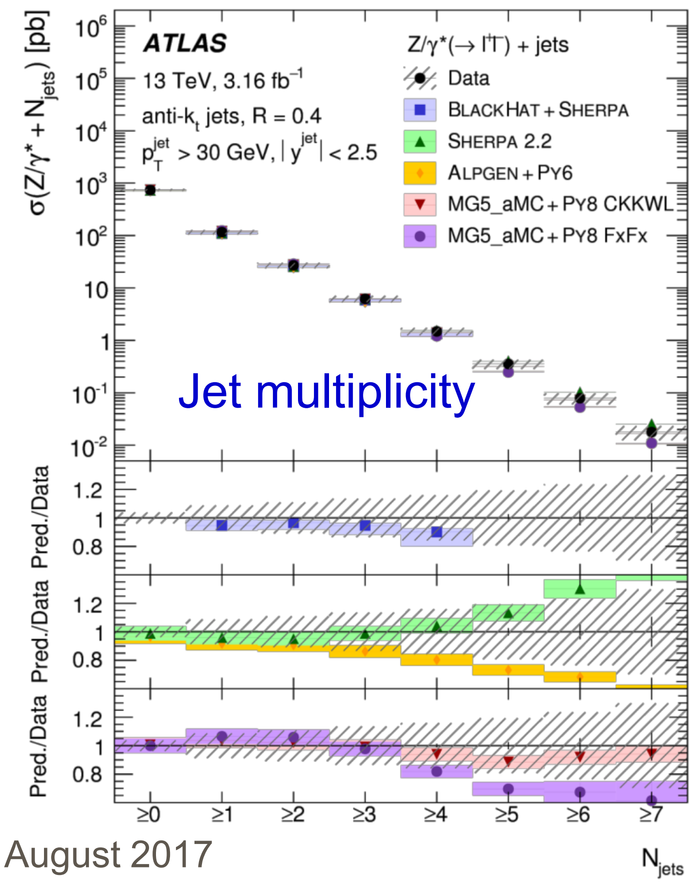


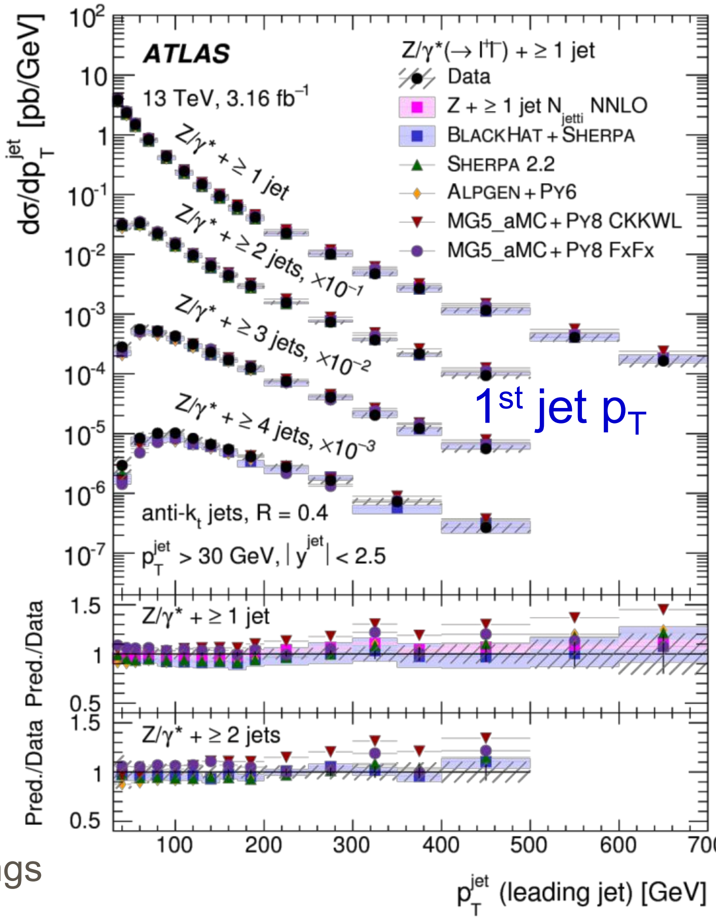


arXiv:1702.05725

Z+jets measurements from ATLAS at 13 TeV

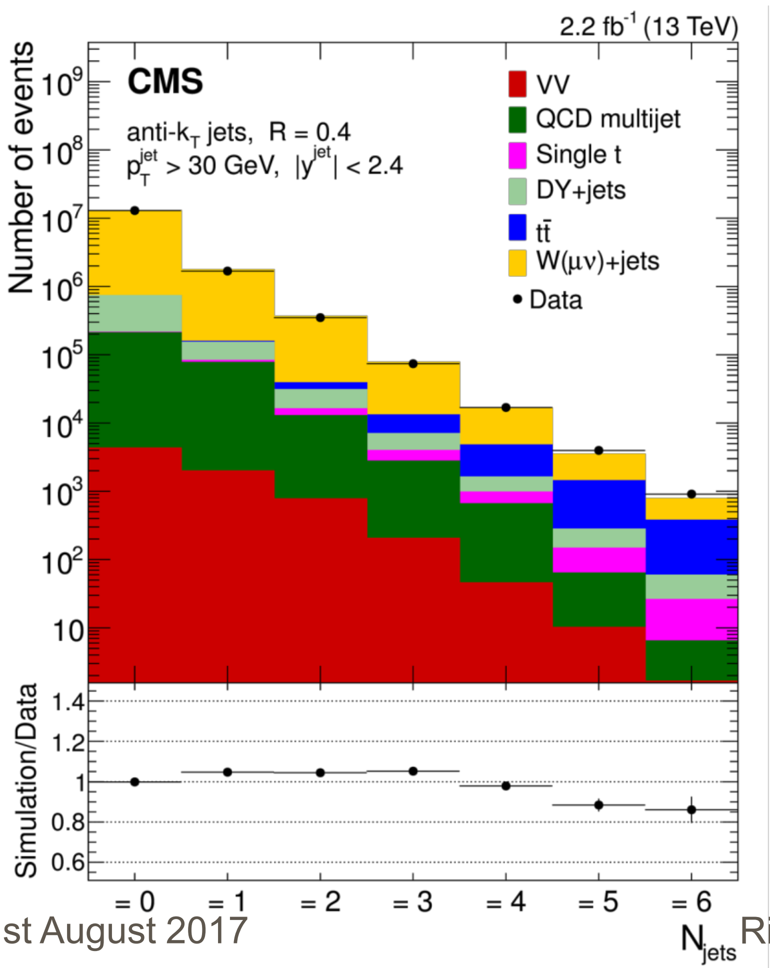
- Multiplicities up to ≥7 jets measured, uncertainties 4-30% for ≥0-≥7 jets
  - Uncertainties dominated by jet energy scale for ≥1 jet
  - Jet multiplicities well described except for ≥5 jets, where predictions relying on PS
  - MG5_aMC@NLO with CKKWL merging has too hard leading jet p_T spectrum

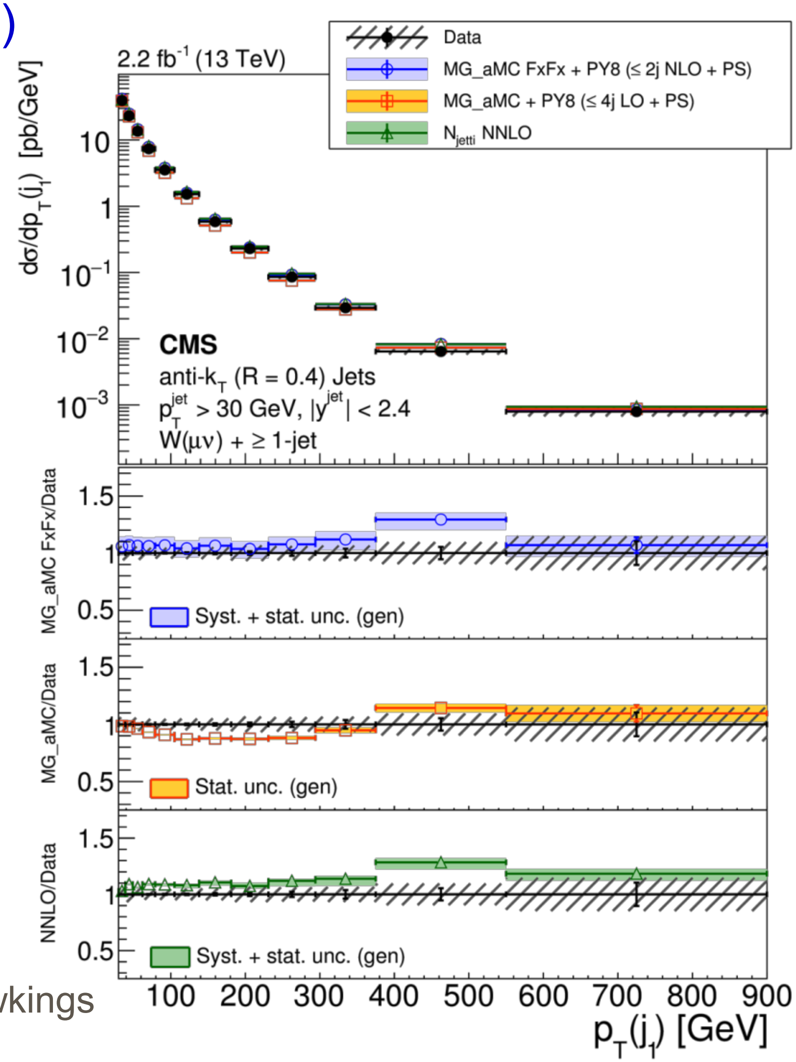




W+jets measurements from CMS at 13 TeV

- W+jets suffers from more background (multijet/Z/γ*+jet, top pair at high N_{jet})
  - Leading jet p_T distribution better described by NLO+PS MG5_aMC@NLO prediction than LO version (as expected)



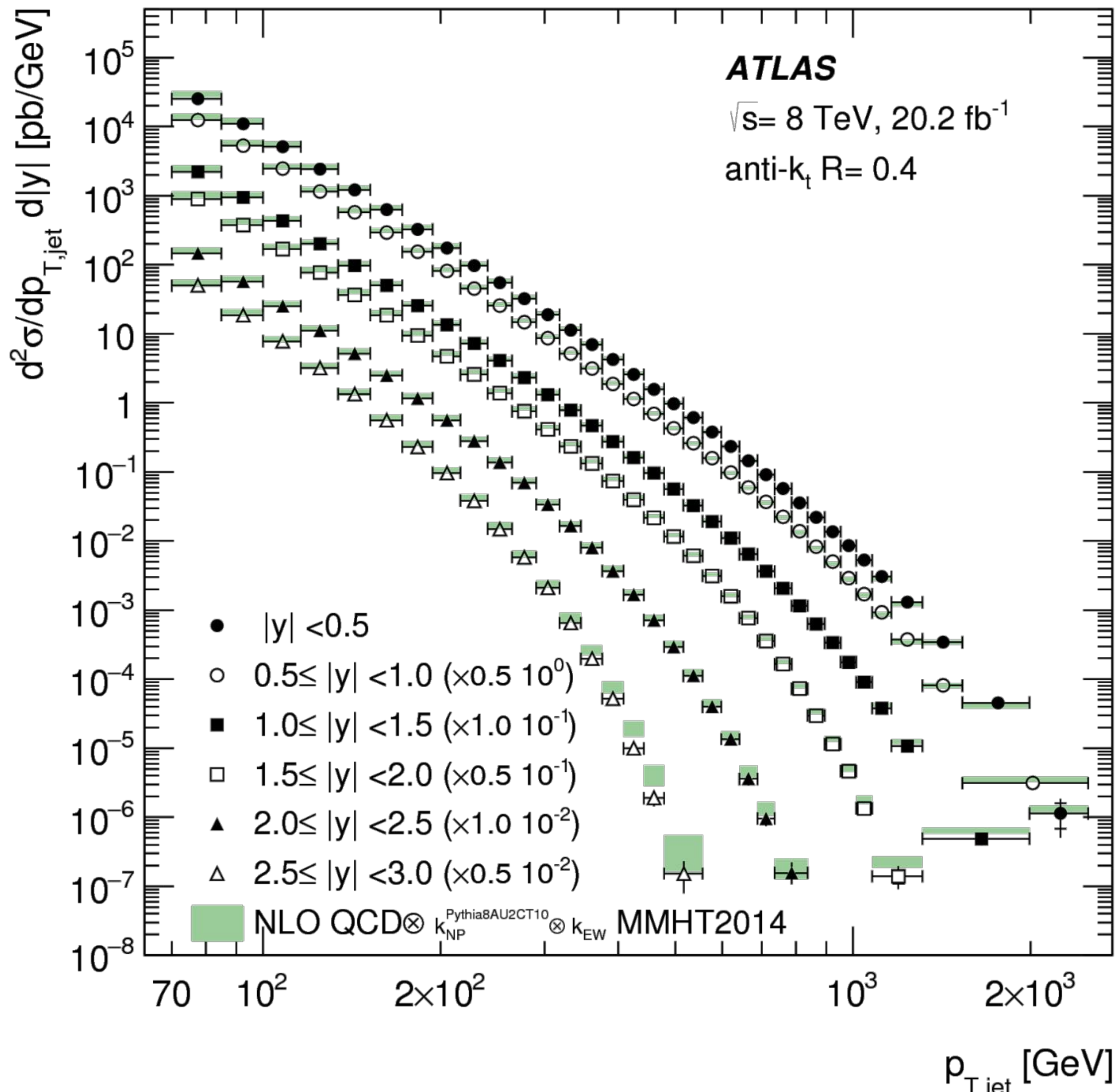


arXiv:1707.05979

Precision jet cross-section measurements

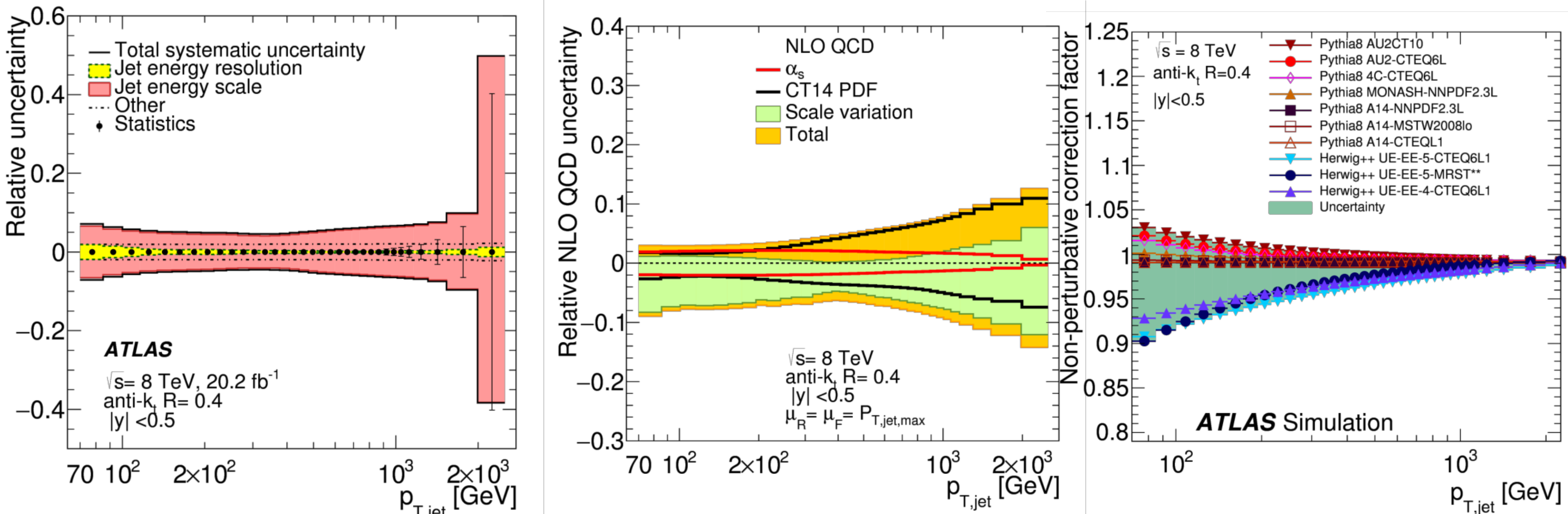
arXiv:1706.03192

- Inclusive jets: pp→jet+X
  - Depends on proton PDFs and α_S
  - Test of QCD at high energy scales
- At LHC, access jets up to ~2 TeV
  - Combination of prescaled jet triggers to maximise statistics
  - Measure double-differential x-sec. as function of jet p_T and rapidity
  - R=0.4 (and R=0.6) anti-k_T jets
  - Data unfolded to particle level jets in fiducial phase space
- Impressive agreement with NLO QCD over 11 orders of magnitude
  - 100 jets/millisec → 1 jet / month



Jet cross-section uncertainties and predictions

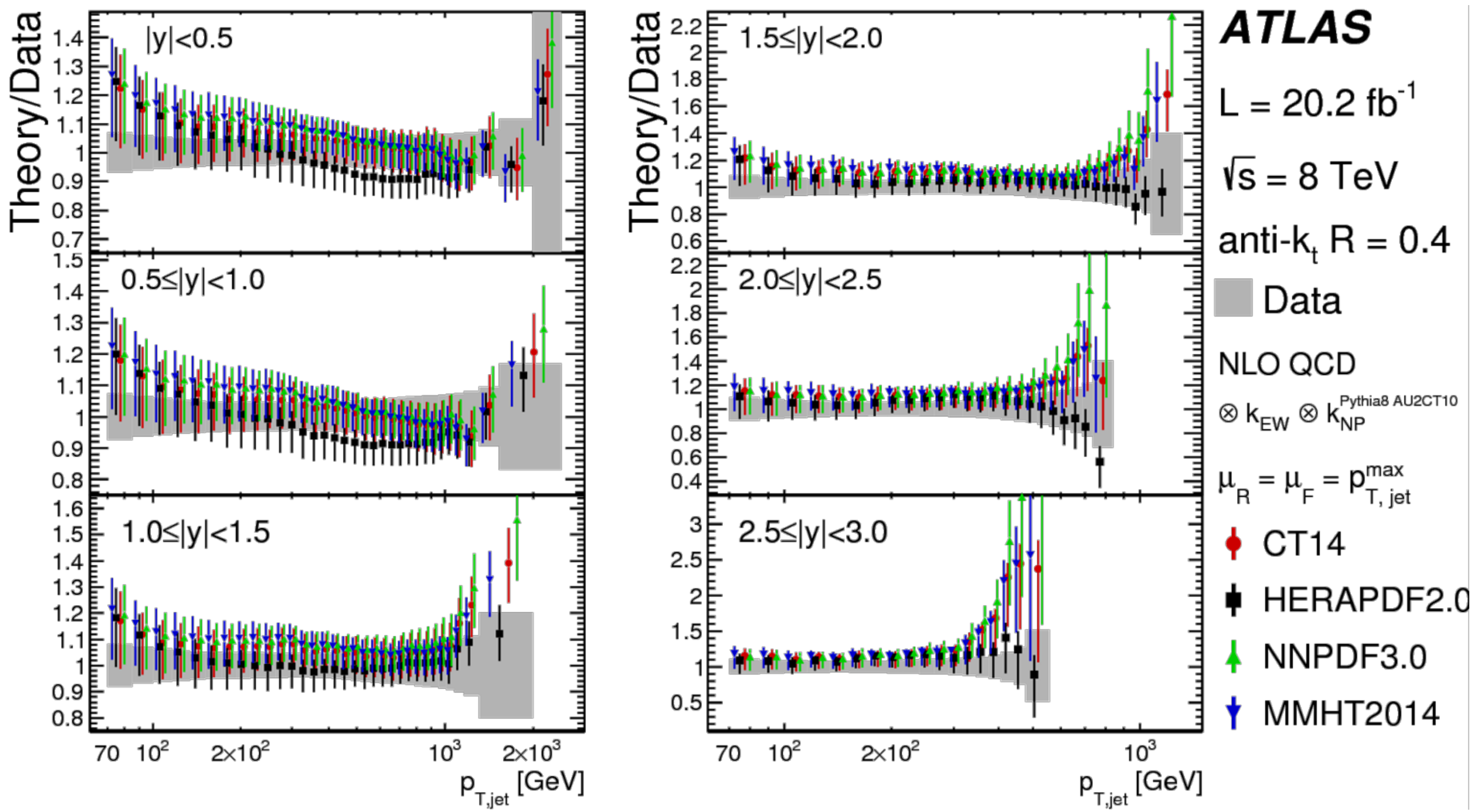
- Experimental uncertainties dominated by jet energy scale
  - ~5% in the best measured region around 300 GeV
- Theoretical predictions from NLO QCD (NLOJet++) + electroweak corrections
  - Uncertainties from QCD scales (largest), PDF and α_S – 5-10% in total
  - Non-perturbative corrections – hadronisation, underlying event, ~10% at low p_T



  - Not as precise as lepton-based W/Z measurements, but huge dynamic range

Comparisons of data with predictions

- Prediction/data ratios - reasonable agreement with predictions in each bin
  - Large prediction uncertainties from non-perturbative corrections at low jet p_T
    - Assessed by comparing corrections calculated with Pythia8 and Herwig++



  - Systematic trends visible – what about correlations between bins?

Quantitative comparisons and tensions

- Evaluate χ^2 for data/prediction compatibility including correlations

Separate $|\eta|$ slices, p_T>100 GeV

Rapidity ranges	P_{obs} CT14	MMHT2014	NNPDF3.0	HERAPDF2.0
Anti-k_t jets $R = 0.4$				
$\|y\| < 0.5$	44%	28%	25%	16%
$0.5 \leq \|y\| < 1.0$	43%	29%	18%	18%
$1.0 \leq \|y\| < 1.5$	44%	47%	46%	69%
$1.5 \leq \|y\| < 2.0$	3.7%	4.6%	7.7%	7.0%
$2.0 \leq \|y\| < 2.5$	92%	89%	89%	35%
$2.5 \leq \|y\| < 3.0$	4.5%	6.2%	16%	9.6%
Anti-k_t jets $R = 0.6$				
$\|y\| < 0.5$	6.7%	4.9%	4.6%	1.1%
$0.5 \leq \|y\| < 1.0$	1.3%	0.7%	0.4%	0.2%
$1.0 \leq \|y\| < 1.5$	30%	33%	47%	67%
$1.5 \leq \|y\| < 2.0$	12%	16%	15%	3.1%
$2.0 \leq \|y\| < 2.5$	94%	94%	91%	38%
$2.5 \leq \|y\| < 3.0$	13%	15%	20%	8.6%

All $|\eta|$ slices together – p_{obs}<10^{-3}

χ^2/ndf	$p_T^{jet,max}$ $R = 0.4$	$p_T^{jet,max}$ $R = 0.6$	p_T^{jet} $R = 0.4$	p_T^{jet} $R = 0.6$
$p_T > 70$ GeV				
CT14	349/171	398/171	340/171	392/171
HERAPDF2.0	415/171	424/171	405/171	418/171
NNPDF3.0	351/171	393/171	350/171	393/171
MMHT2014	356/171	400/171	354/171	399/171
$p_T > 100$ GeV				
CT14	321/159	360/159	313/159	356/159
HERAPDF2.0	385/159	374/159	377/159	370/159
NNPDF3.0	333/159	356/159	331/159	356/159
MMHT2014	335/159	364/159	333/159	362/159
100 ¡ $p_T < 900$ GeV				
CT14	272/134	306/134	262/134	301/134
HERAPDF2.0	350/134	331/134	340/134	326/134
NNPDF3.0	289/134	300/134	285/134	299/134
MMHT2014	292/134	311/134	284/134	308/134
100 ¡ $p_T < 400$ GeV				
CT14	128/72	149/72	118/72	145/72
HERAPDF2.0	148/72	175/72	141/72	170/72
NNPDF3.0	119/72	141/72	115/72	139/72
MMHT2014	132/72	143/72	122/72	140/72

- OK in individual $|\eta|$ slices, but no satisfactory description of all slices together
  - Hard to attribute to experimental uncertainties – missing higher-order corrections?
- The data has outrun our understanding of the theory … ☹

Summary of lecture 2

- Discussed several precision measurements in detail …
- Electroweak mixing angle $\sin^2\theta_W$ from $Z \rightarrow ll$
  - Simultaneous measurement of $\sin^2\theta_W$ with in-situ constraint of PDFs
- First LHC W mass measurement
  - Competitive with the ultimate Tevatron precision (±19 MeV, 0.02%)
  - Fully exploiting the LHC data will require advances in modelling of W/Z production, in particular the W boson p_T distribution
- Jet energy measurement and calibration
  - W/Z+jets measurements – an important testing ground for QCD
  - Inclusive jet measurements – challenging the theory
- … In all cases, interplay of precise measurements and predictions needed
  - Will become increasingly important as LHC programme progresses

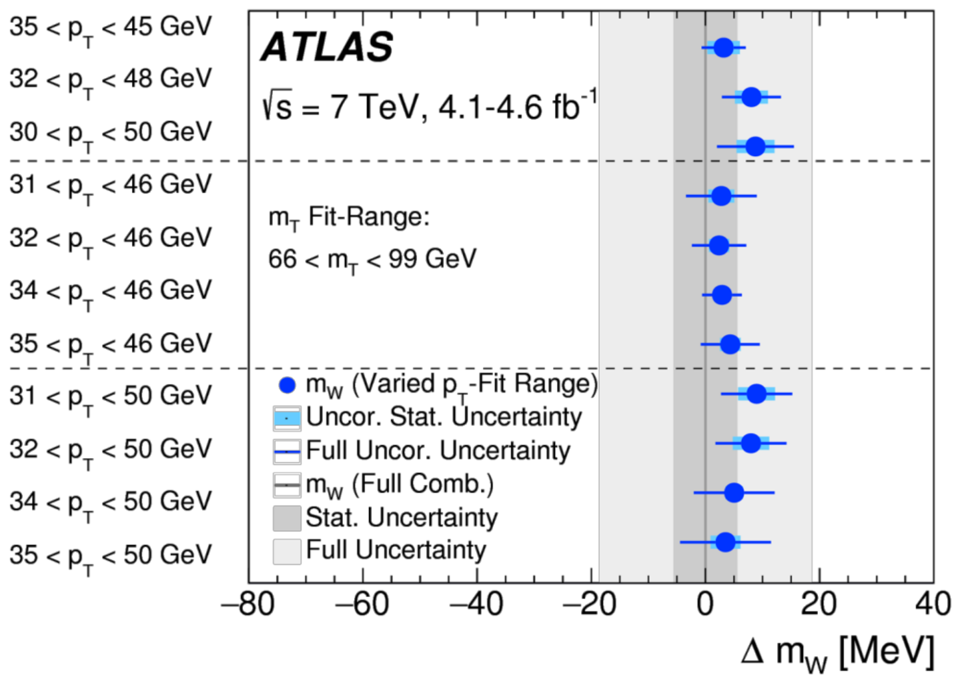
- Next lecture – the top quark
  - Leptons, jets, QCD, and the fate of the universe itself ...

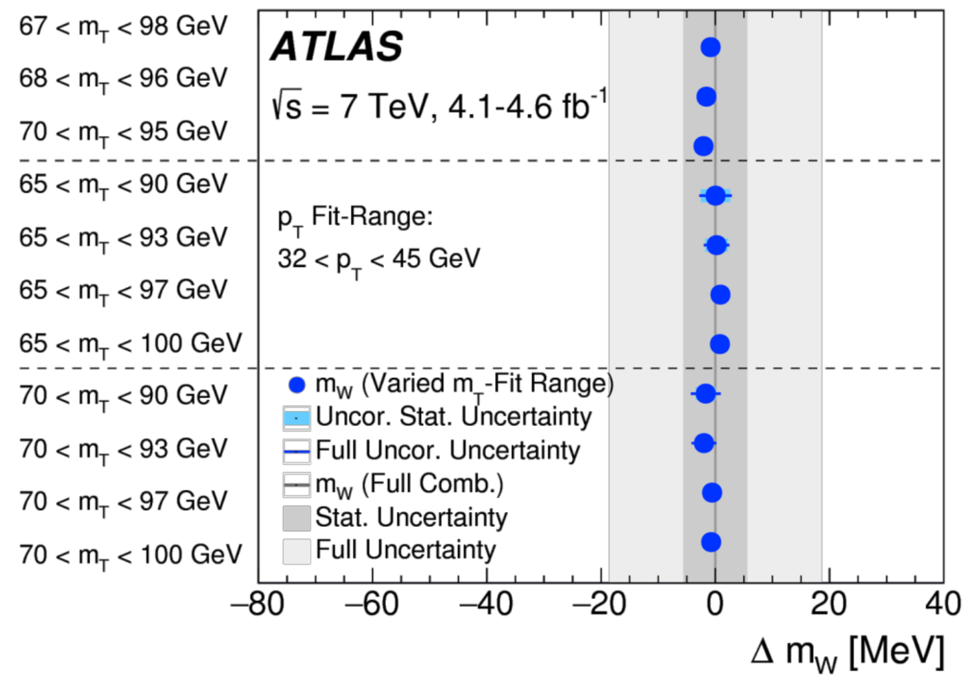
Backup

- Backup slides

Stability vs. fit range changes

- Also verified stability when changing the fit range cuts
  - Shifts in **combined** result when changing range for $p_T(l)$ or $m_T(W)$
  - Need careful handling of uncorrelated components of statistical and systematic uncertainties in order to understand significance of any changes





- Also checked result in bins of pileup <μ> and recoil u_T, and without p_T^{miss} cut in event selection – no significant effects