Electroweak Production and QCD at LHC Experiment Part 2

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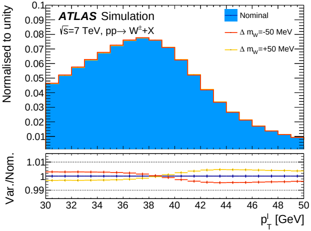
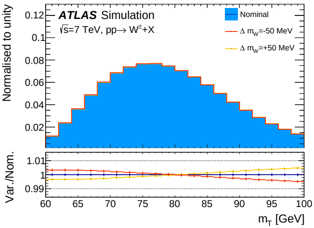
Outline

- Previously:
  - Z as a standard candle
  - Some background on object reconstruction and identification
  - Some background on detector simulation and Monte Carlo
  - Tag and probe for efficiency measurements
  - Precision electroweak measurements with W and Z: $\sin^2\theta_W$
- **Today:**
  - Precision electroweak measurements with W and Z: m_W
  - Precision measurements of W and Z cross sections and constraints on PDFs
  - Jet reconstruction and Jet energy corrections
  - Measurements with jets
  - Multiboson Production
  - Top physics

W mass at LHC

- **W cannot be fully reconstructed due to neutrino** → mass must be inferred from lepton p_T or transverse mass distributions
- Current ATLAS measurement of m_W performed using 1D p_T^ℓ and M_T distributions (in bins of η^ℓ), but note p_T^ℓ has ∼90% weight in combination
- Highest possible precision required on lepton momentum and hadronic recoil scale/resolution
- p_T^ℓ (and p_T^ν) distributions depend not only on m_W but also critically on p_T^W as well as polarization → strong dependence on QCD calculation and PDFs
- M_T distribution still sensitive to p_T^W and polarization due to finite detector acceptance





W mass: PDF Uncertainties

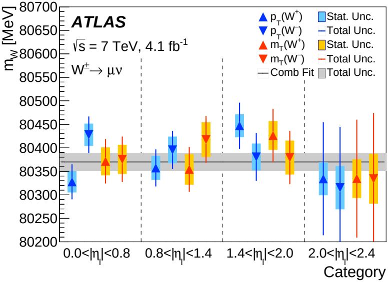
Eur. Phys. J. C 78 (2018) 110

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

$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp.}) \pm 8.3(\text{QCD})\ \pm 5.5(\text{EWK}) \pm 9.2(\text{PDF})\ \text{MeV}$$

	PDF Uncertainty (MeV)
per $\|\eta\|$-charge cat.	20-34
per-charge	14-15
full combination	9.2

- PDFs determine the W rapidity spectrum and lepton decay angles through W polarization
- Well-defined correlations between phase space regions and processes which are already partly exploited in present measurement to reduce uncertainty
- Can be further exploited in the future



W mass: QCD Modelling Uncertainties

Eur. Phys. J. C 78 (2018) 110

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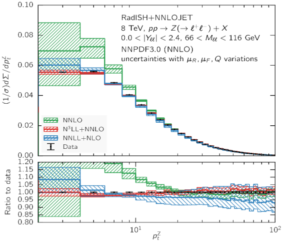
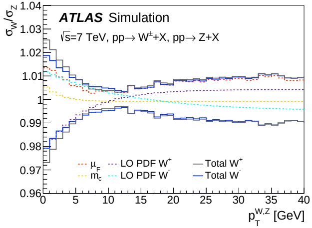
- W p_T spectrum in relevant region driven by large logarithms in QCD calculation
- Relatively large theoretical uncertainties, and ambiguities in correlations across phase space and processes
- Current measurement using Z p_T spectrum to constrain W, assuming strong correlations between Z and W production across p_T, but decorrelating contribution of different quark flavours

arXiv:1805.05916





W mass: QCD Modelling Uncertainties

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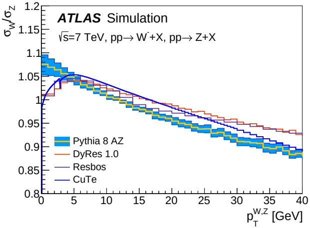
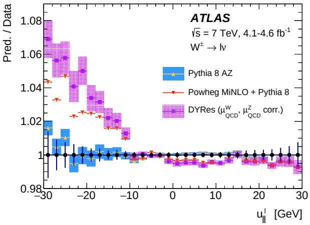
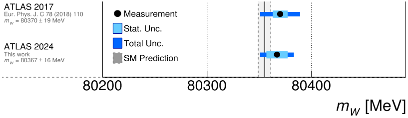


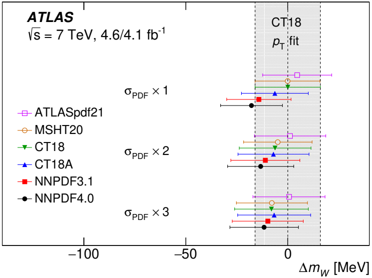


- Measured hadronic recoil (missing energy) distribution has some sensitivity to W p_T distribution, appears to disfavour more advanced calculations of W/Z p_T ratio
- Future directions for W p_T spectrum:
  - Better direct measurement (special low pileup runs)
  - In-situ constraints
  - Reducing theoretical uncertainties (higher logarithmic accuracy)
  - Better understanding of heavy-flavour contributions
  - More systematic correlations of theory uncertainties across phase space and between W and Z

Updated ATLAS Measurement

arXiv:2403.15085

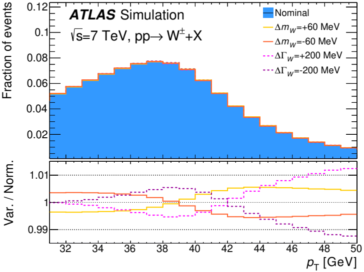


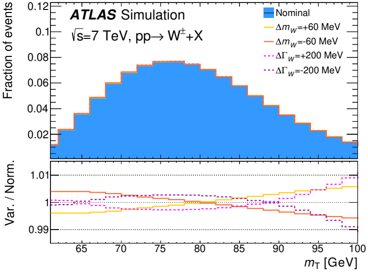


- Updated ATLAS measurement using the same 7 TeV dataset
- Main feature: Use of profile-likelihood fit for reduced uncertainties via in-situ constraints (especially on PDFs)
- Also an opportunity to directly update measurement with newer PDF sets and further explore the compatibility between them
- Interesting study: inflating PDF "prefit" uncertainties increases the effective weight of the in-situ constraint and brings the results closer together

Updated ATLAS Measurement: W Width

- The **width** of the W is also an interesting quantity to measure: predicted by the SM given the W mass and other EW parameters
- In this case the transverse mass is much more sensitive than the lepton p_T

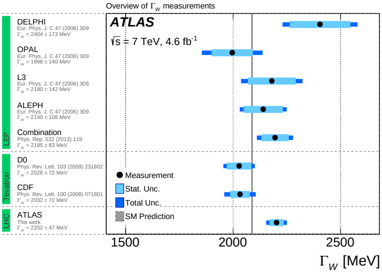


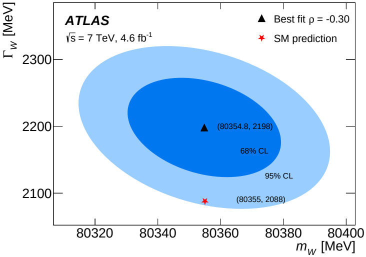


arXiv:2403.15085

Updated ATLAS Measurement: W Width

- Width can be extracted simultaneously with mass (albeit with somewhat increased uncertainty)
- Correlations then become relevant

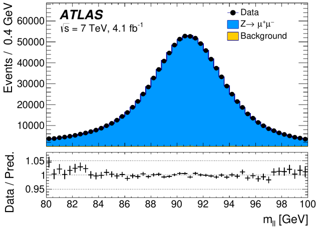




arXiv:2403.15085

Muon Momentum Scale (and Resolution)

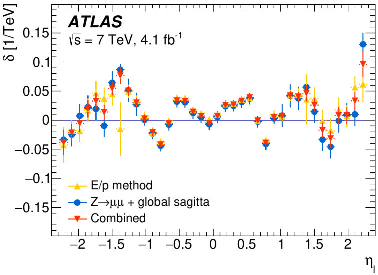
- $Z \rightarrow \mu\mu$ can also be used as a standard candle for the muon momentum scale and resolution, since the mass (and width) are known very precisely from the LEP beam energy scan and calibration (mass is known to 2.3×10^{-5} relative precision)
- J/ψ and Υ can also be used (Υ mass is known to similar precision, and J/ψ mass to 2×10^{-6})
- **To first order calibration is trivial:** Match the Z peak (+ width) between data and MC (in bins of η for example)
- **More complicated:** Account for possible charge/p_T dependence of any momentum scale or resolution bias



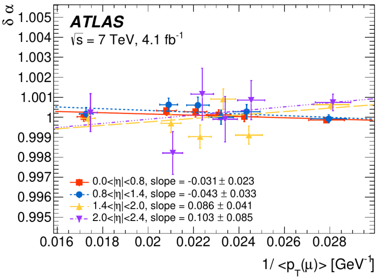
Muon Momentum Scale (and Resolution) p_T dependence

- For curvature $k \equiv 1/p_T$, the momentum scale bias can be written as
  $\delta k/k \sim= A + qM/k - \epsilon k$
  (e.g. CMS PAS SMP-14-007)
- The three terms correspond to magnetic-field bias, misalignment (e.g. from weak modes in the global alignment procedure), and the average effect of material mis-modelling on the energy loss assumed in the track reconstruction
- Resolution can be written as:
  $\sigma_k^2/k^2 \sim= a + c/k^2$
  Where the two terms correspond to average contributions from multiple scattering and hit resolution
- For CMS W-like measurement, all 5 terms are explicitly determined/corrected for using the J/ψ

Muon Momentum Scale (and Resolution) p_T dependence



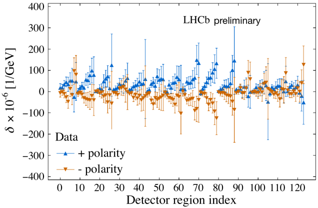
(a) Alignment-like bias



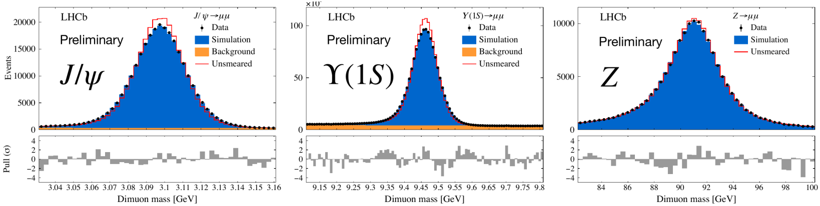
(b) Material-like bias

- In the ATLAS measurement, the alignment and b-field like biases are explicitly corrected for (using the Z) together with the hit resolution contribution to the resolution
- Material-like bias is checked (again with Z) and upper bound is propagated as a systematic uncertainty (also cross-checked with explicit ±10% variation of material model)

Muon Momentum Scale (and Resolution) p_T dependence



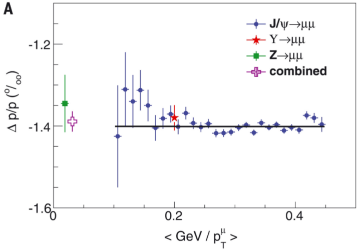
- In the LHCb m_W measurement, alignment-like bias is first corrected in a fine-grained binning using the Z
- Subsequently remaining alignment-like, bfield-like, and resolution corrections (both hit resolution and multiple scattering) are determined from combined fit of J/ψ, $\Upsilon(1S)$ and Z
- Material impact on scale is assessed through explicit variation of material model



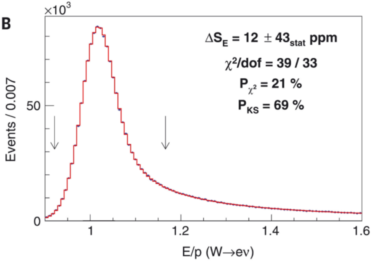
CDF: Energy/Momentum Scale Calibration

Science 376 (2022) 6589,

- Recent measurement with 8.8/fb of Tevatron data (1.96 TeV ppbar)
- Both electron and muon channels with high precision energy/momentum calibration

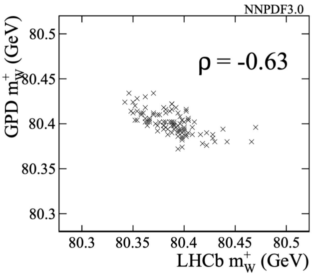


- Ultra-precise calibration of tracking momentum scale from J/psi and Y validated and combined with Z->mu mu
- After corrections for residual misalignment and material, momentum scale determined to relative accuracy of 25ppm



- Tracking momentum scale transported to electron energy scale in calorimeter with E/p
- Residual uncertainties from material model in inner detector (~0.2 radiation lengths) and calorimeter, non-linearity
- Total uncertainty of ~80ppm

LHCb m_W measurement



- LHCb measurement is complementary because of forward rapidity coverage (2.2 ¡ η ¡ 4.4) → PDF uncertainties expected to be anti-correlated with ATLAS and CMS
- Current measurement is statistically limited, but only ∼ 1/3 of the run 2 dataset is used

Measurement uncertainty summary

Source	Size [MeV]	
Parton distribution functions	**9.0**	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	**17.4**	
Transverse momentum model	12.0	Envelope from five different models
Angular coefficients	9.0	"Uncorrelated" 31 point scale variation
QED FSR model	7.2	Envelope of Pythia, Photos and Herwig
Additional electroweak corrections	5.0	Test with POWHEGew
Experimental total	**10.6**	
Momentum scale and resolution modelling	7.5	Includes simple statistical contributions, dependence on external inputs and details of the methods.
Muon ID, trigger and tracking efficiency	6.0	
Isolation efficiency	3.9	
QCD background	2.3	
Statistical	**22.7**	
Total	**31.7**	

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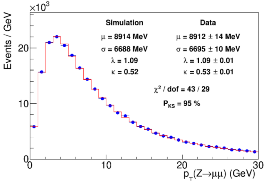
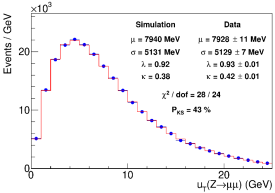
CDF: Z->ll Standard Candle

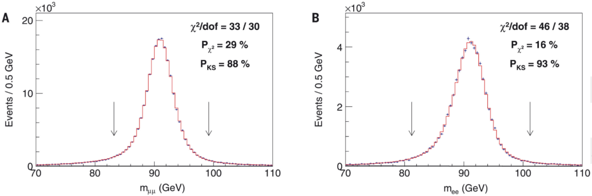


Tuned production model (Resbos)



Calibrated Hadronic Recoil

- Z->ll data used extensively for calibration and validation
  - Theory model tuning
  - Hadronic Recoil Calibration
  - Lepton Efficiencies



Final Z mass measurements consistent with world average:

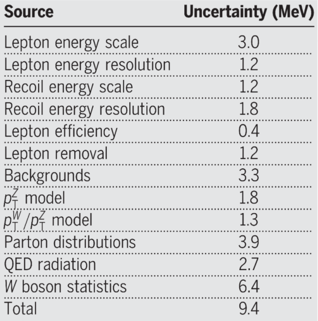
Muons:

$$M_Z = 91,192.0 \pm 6.4_{\text{stat}} \pm 4.0_{\text{syst}}\ \text{MeV}$$

Electrons:

$$M_Z = 91,194.3 \pm 13.8_{\text{stat}} \pm 7.6_{\text{syst}}\ \text{MeV}$$

CDF: Results



Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

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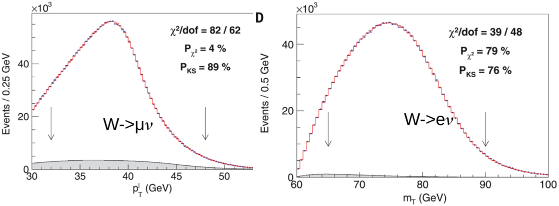
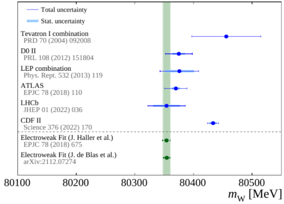
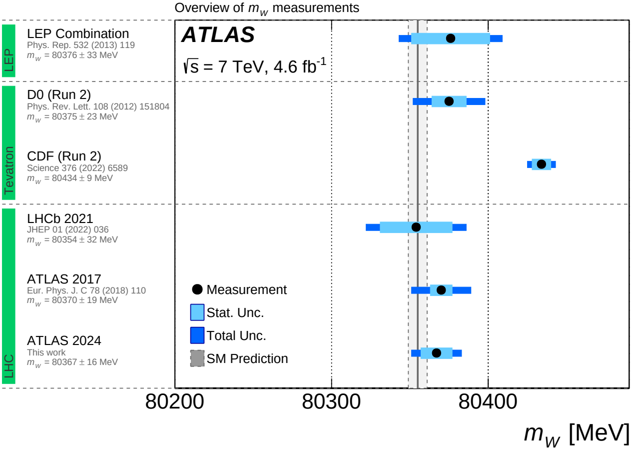




- Most precise measurement
- In significant tension with Standard Model prediction

$$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4\ \text{MeV}/c^2$$

m_W summary



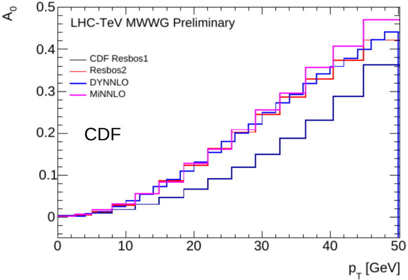
- CDF result is in significant tension with both the SM prediction (7σ) and the other measurements

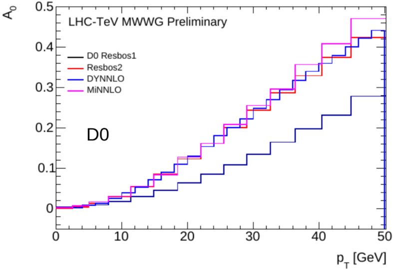
m_W Combination

- m_W Combination Working group set up between ATLAS, CMS, LHCb, D0, CDF for combination of *LHC* and Tevatron m_W measurements
- Tension of CDF measurement with SM and other measurements motivates more careful study
- Measurements are correlated mainly due to theoretical predictions and uncertainties
- General strategy: First correct individual measurements so they are on coherent theoretical grounds
    - Common treatment of angular coefficients
    - Common PDF (in fact multiple PDF sets are explored)
    - Changes in (fiducial) pTW distributions from different predictions or theoretical treatment are assumed ot be reabsorbed by the tuning to Z data in each experiment
- Then uncertainties are evaluated on top of this starting point and correlations properly evaluated

Angular Coefficient Comparison: CDF/D0 vs newer generators

CERN-LPCC-2022-06
FERMILAB-TM-2779-V

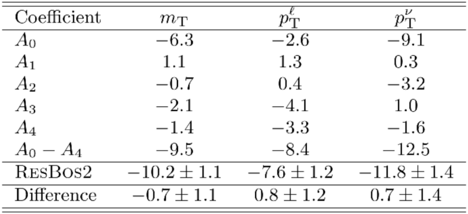




- CDF and D0 both used older (and not identical) versions of “Resbos 1” to predict W production and decay kinematics
- Older Resbos versions predict quite different angular coefficients compared to modern generators due to evolving understanding of interplay between helicity components and resummation
- Difference in fixed order accuracy (NLO vs NNLO QCD) is **NOT** the main effect here
    - CDF Resbos 1, Resbos 2 are NLO accurate, DYNNLO/MiNNLO are NNLO, D0 Resbos1 somewhere in between

arXiv:2308.09417

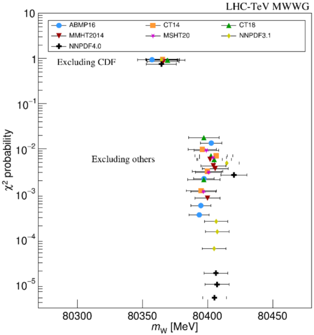
Angular Coeff Effect on mW measurement (CDF)



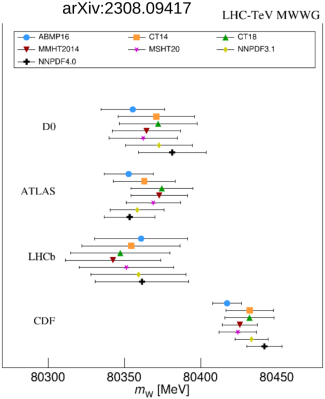
Coefficient	m_T	p_T^ℓ	p_T^ν
A_0	-6.3	-2.6	-9.1
A_1	1.1	1.3	0.3
A_2	-0.7	0.4	-3.2
A_3	-2.1	-4.1	1.0
A_4	-1.4	-3.3	-1.6
$A_0 - A_4$	-9.5	-8.4	-12.5
ResBos2	-10.2 ± 1.1	-7.6 ± 1.2	-11.8 ± 1.4
Difference	-0.7 ± 1.1	0.8 ± 1.2	0.7 ± 1.4

- 7-12 MeV shift of CDF measurement to **lower** mW values
- **HOWEVER** published CDF result “accidentally” included this correction as part of the CTEQ6M -> NNPDF 3.1 PDF correction

Combination and Compatibility

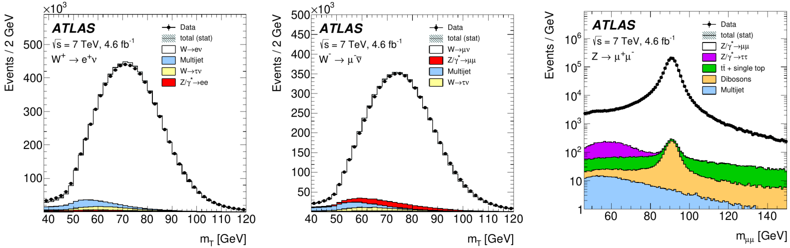


arXiv:2308.09417



- Tension persists after correcting for all known theoretical effects and with any choice of PDF set
- Only combination with acceptable compatibility is that with CDF measurement excluded
- Tension between measurements reduced to “only” 3.6σ with more conservative treatment of PDFs and uncertainties
- Additional measurements needed. . .

Precision W/Z Cross Section Measurements

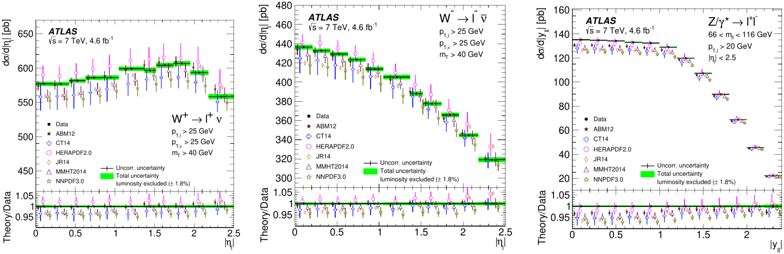


Detector level plots of selected W and Z events

Eur. Phys. J. C 77 (2017) 367 (ATLAS)

- Multijet backgrounds to W determined in this case using combination of M_T distribution and inverted identification and/or isolation criteria (more details on this type of background estimate later in the week)

Precision W/Z Cross Section Measurements

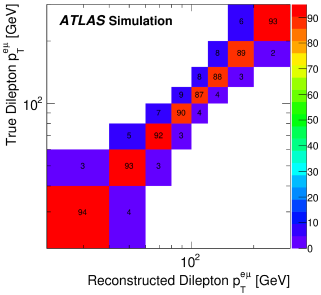


Unfolded cross sections

Eur. Phys. J. C 77 (2017) 367 (ATLAS)

- Going from detector level distributions to unfolded cross sections:
  - Backgrounds are subtracted
  - Acceptance/efficiency is corrected
  - **Migration** of events between bins due to reconstruction biases and/or resolution effects are corrected for
  - (+ propagation of systematic uncertainties)

Unfolding

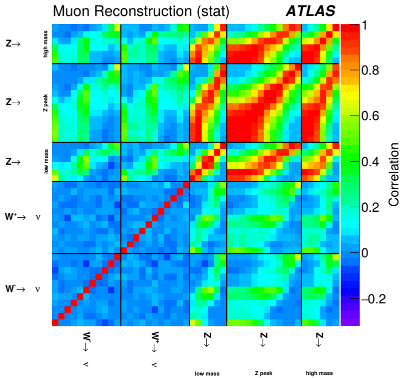


Response matrix from unrelated example from

top physics

- Going from detector level distributions to unfolded cross sections:
  - Backgrounds are subtracted
  - Acceptance/efficiency is corrected
  - **Migration** of events between bins due to reconstruction biases and/or resolution effects are corrected for
  - (+ propagation of systematic uncertainties)
- Migrations can be corrected for via a response matrix (by simple inversion, or an alternative method incorporating some degree of regularization)
- Alternatively, backgrounds, acceptance, efficiency and migrations can be corrected for implicitly by means of a maximum likelihood fit, aka likelihood based unfolding

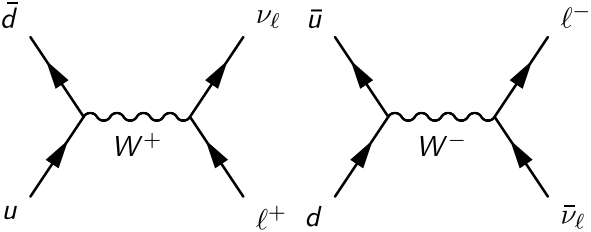
Correlations of Lepton Efficiency Uncertainties

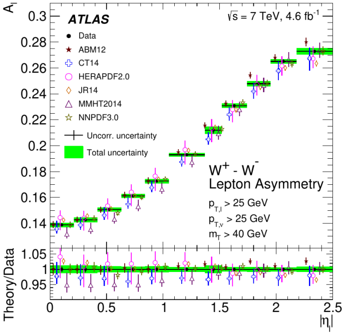


Eur. Phys. J. C 77 (2017) 367 (ATLAS)

- Example shown here for **statistical** component of uncertainty on muon reconstruction efficiency for ATLAS W/Z measurement
- Underlying uncertainty is uncorrelated in bins of single muon p_T and η in which efficiencies were measured with tag and probe, leading to non-trivial correlations in particular for $Z/\gamma^* \to \mu\mu$ measurements
- Consistent propagation of correlations of uncertainties is crucial to the (re)-interpretability of the result, its use in PDF fits, etc

W lepton charge asymmetry and PDF constraints

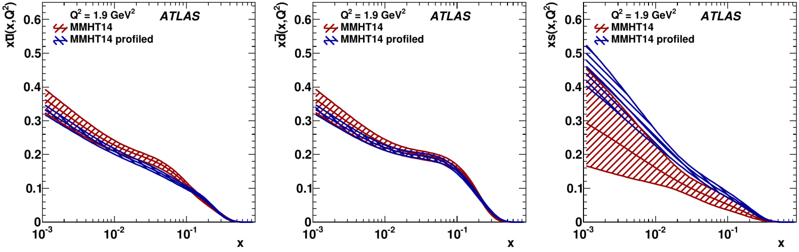


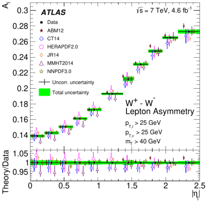


$$A_\ell = \frac{d\sigma_{W^+}/d|\eta_\ell| - d\sigma_{W^-}/d|\eta_\ell|}{d\sigma_{W^+}/d|\eta_\ell| + d\sigma_{W^-}/d|\eta_\ell|}$$

- Lepton charge asymmetry is especially sensitive to the ratio of *u* to *d* quarks in the proton

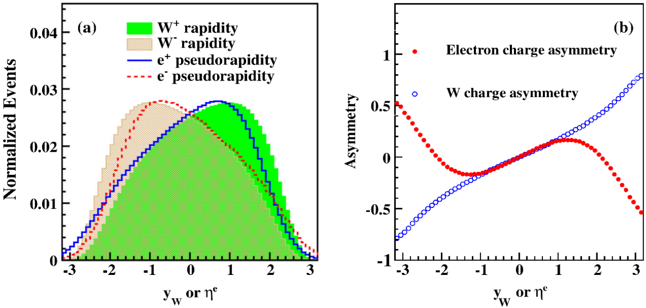
PDF Constraints from ATLAS Precision W/Z cross sections





- Significant constraints on especially sea quark distributions

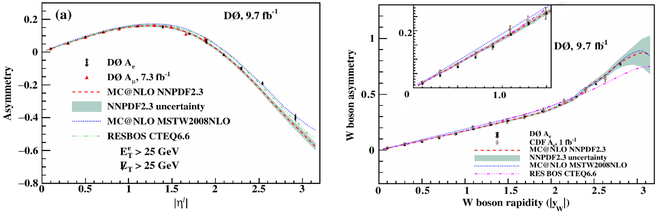
W vs lepton charge asymmetry at the Tevatron



Phys. Rev. D 91, 032007 (2015) (D0)

- Lepton charge asymmetry vs η is a convolution of PDF effect with V-A structure of W decay
- W charge asymmetry as a function of W rapidity more directly probes the PDFs (but less directly accessible experimentally)
- Tevatron experiments historically provided both measurements
- n.b. at Tevatron, asymmetries are sensitive to sign of η or y due to $p\bar{p}$ collisions → final results are "CP" folded $A(-\eta/y) \rightarrow -A(\eta/y)$

W vs lepton charge asymmetry at the Tevatron

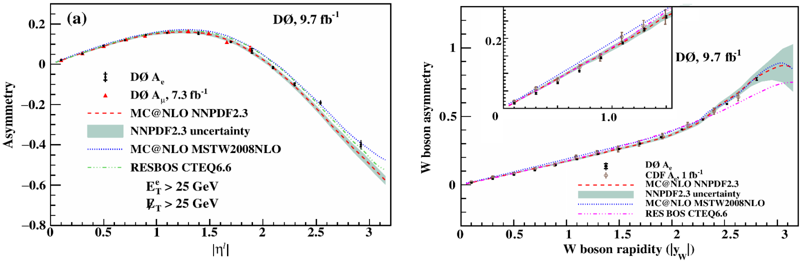


(a) Lepton Charge Asymmetry (b) W Charge Asymmetry

Phys. Rev. D 91, 032007 (2015) (D0), Phys. Rev. Lett. 112, 151803 (2014) (D0)

- Unfolding to W rapidity using missing transverse momentum and M_W constraint
- Resolving resulting twofold ambiguity requires assumption about relative fractions of incoming quark vs antiquark in proton beam (plus smaller effect from gluon-initiated production) → 10% effect in total, with non-negligible uncertainty from PDF's → some circularity in using data in this form for PDF determination

W vs lepton charge asymmetry at the Tevatron



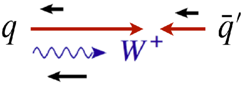
(a) Lepton Charge Asymmetry

(b) W Charge Asymmetry

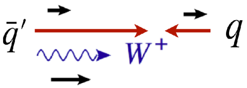
Phys. Rev. D 91, 032007 (2015) (D0), Phys. Rev. Lett. 112, 151803 (2014) (D0)

- On the other hand, lepton charge asymmetry vs η^ℓ does not contain all available information, since information on p_T^ℓ, p_T^ν and $\Delta\phi_{\ell,\nu}$ are lost

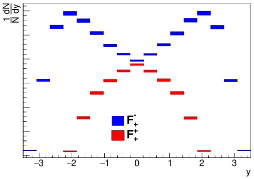
W Helicity/Rapidity at LHC



(a) left-handed W^+



(b) right-handed W^+

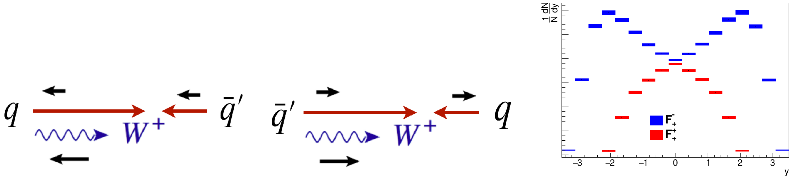


(c) W^+ Rapidity

- At tree level:
  - All W production at LHC is $q\bar{q}$ induced
  - Direction of the W relative to the incoming quark determines the helicity
  - Only two helicity amplitudes/polarization states
  - W has zero transverse momentum
  - **Full information on valence quark PDF's in the relevant x range contained in $d\sigma/dy$ broken down into the two helicity states**

JHEP12(2017)130 E. Manca, O. Cerri, N. Foppiani, G. Rolandi

W Helicity/Rapidity at LHC

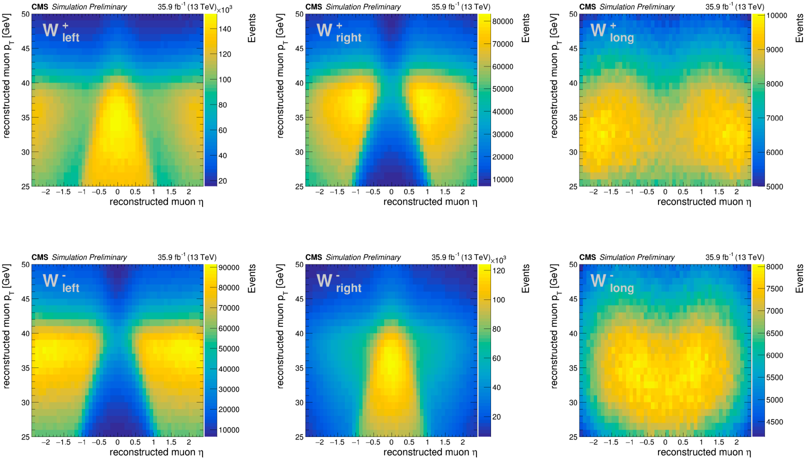


(a) left-handed W^+ (b) right-handed W^+ (c) W^+ Rapidity

- Direction of incoming quark depends even more on PDF's in *pp* vs $p\bar{p}$ collisions
- gluon-induced contribution from higher order effects larger and more uncertain (also due to higher E_{cm} compared to Tevatron)

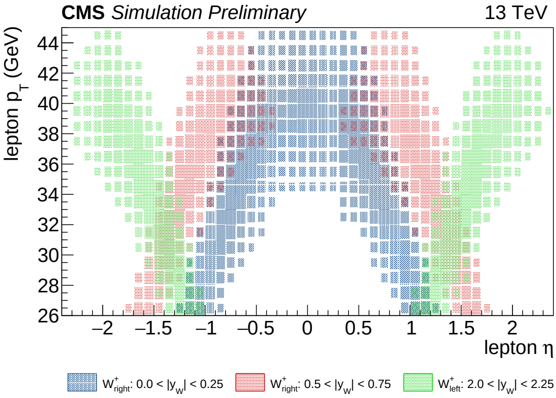
JHEP12(2017)130 E. Manca, O. Cerri, N. Foppiani, G. Rolandi

W Helicity/Rapidity at LHC



- 2D distribution of charged lepton p_T and η can discriminate between helicity states as well as rapidity of the W

W Helicity/Rapidity at LHC



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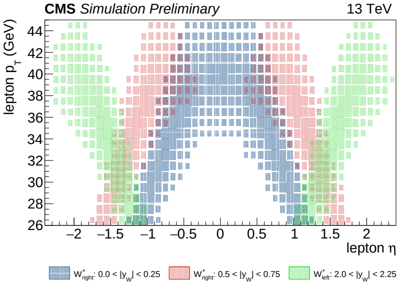
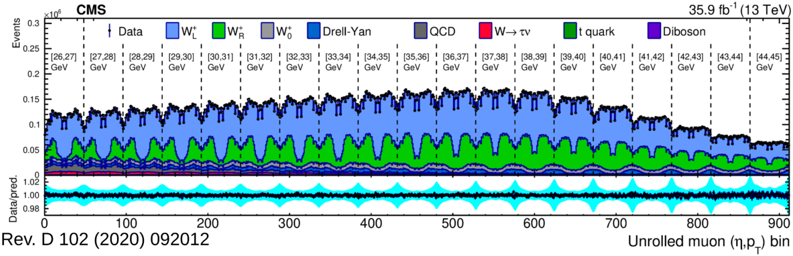
W Helicity/Rapidity at LHC



- Left and right polarization components can be extracted simultaneously as a function of W rapidity, using only charged lepton kinematics (likelihood-based unfolding)
- Avoids dependence on less precisely measured missing transverse momentum (at the cost of some statistical dilution)
- Avoids circular dependence on PDFs since quark vs anti-quark fraction for each rapidity is **measured**

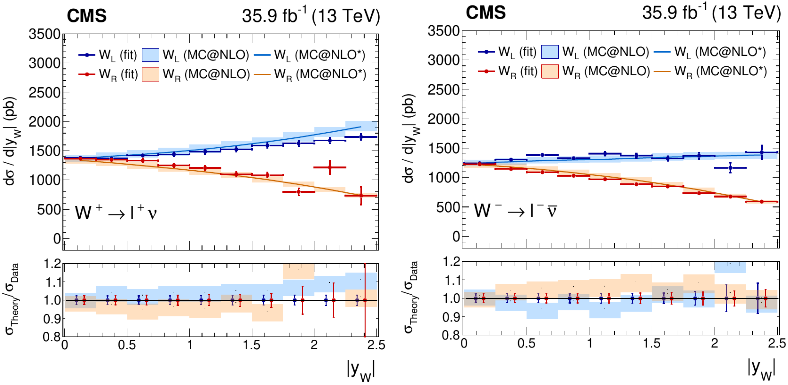
Measurement of W helicity/rapidity

- Develop physics, experimental and technical aspects towards an mW measurement with reduced PDF uncertainties
  - High precision efficiencies building on 13 TeV differential Z cross section publication
  - Less stringent requirements on MC/theory uncertainties/energy/momentum calibration compared to full m_W measurement
  - Complex profile likelihood fit to lepton pT-η distributions with ~300M W candidates, O(1000) nuisance parameters -> dedicated tensorflow-based implementation of likelihood and minimization



Phys. Rev. D 102 (2020) 092012

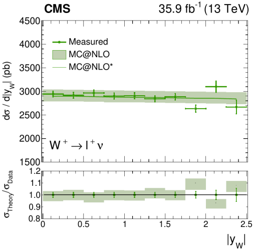
W Helicity/Rapidity at LHC

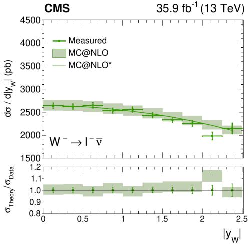


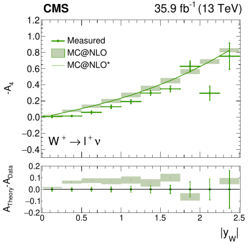
10.1103/PhysRevD.102.092012

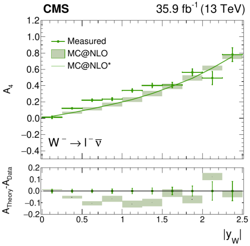
- Polarized cross sections (+ covariance matrices) contain the full set of information

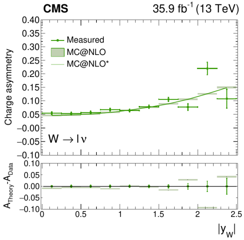
W Helicity/Rapidity at LHC





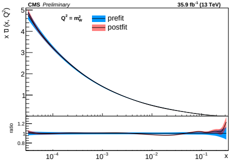




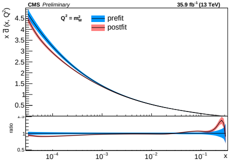


- Unpolarized xsecs or charge asymmetry can be produced by integrating over polarization (**without** assuming underlying polarization)

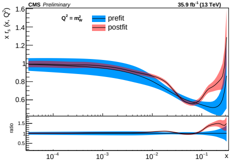
W Helicity/Rapidity at LHC: PDF Constraints



(a) $\bar{u}$



(b) $\bar{d}$

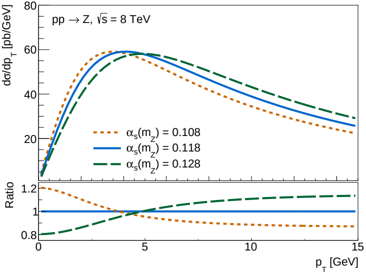


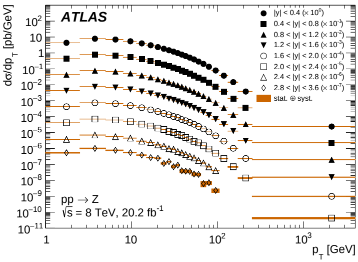
(c) $r_s = (s + \bar{s})/(\bar{u} + \bar{d})$

- Strong PDF constraints possible here as well, and a step towards further reduced PDF uncertainty in future m_W measurements

α_S extraction from Z p_T distribution

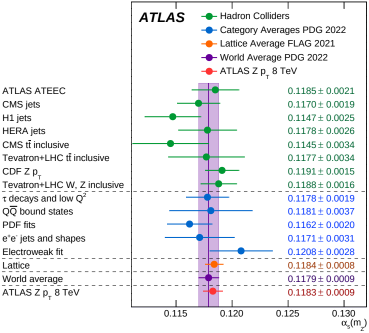
- Z transverse momentum distribution is sensitive to the strong coupling constant via initial state gluon radiation
- ATLAS has extracted this using very precisely measured Z p_T spectrum

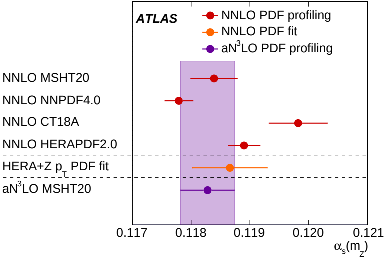




α_S extraction from Z p_T distribution

- Uncertainty on α_S in principle competitive with the world average or with lattice determinations, but significant sensitivity here as well to the treatment of the PDFs

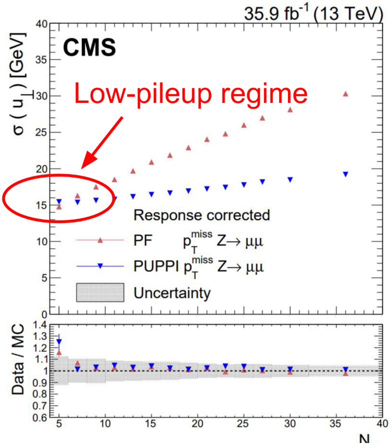


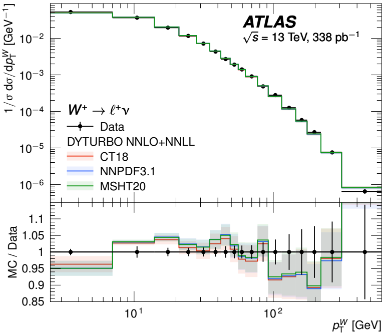


Low Pileup Runs

- Current LHC running conditions have around 60 pp collisions per bunch crossing (140-200 for HL-LHC)
- Hadronic recoil/MET resolution degrades with pileup due to additional hadronic activity
- Special low pileup runs (low intensity or intentionally separated or de-focused beams) can be used for more precise measurement of e.g. W p_T spectrum or (with more data) W mass
- Tradeoff in terms of integrated luminosity (several weeks to one month low PU run under discussion for 2025-26)

Low Pileup Runs





Digression: Object Reconstruction, Identification and Mis-identification

- **Main "high level" objects:**
    - **Jets** (+b or c tagging)
    - **Missing transverse momentum** (aka Missing Energy aka MET), e.g. from neutrinos in final state
    - (Isolated high p_T) photons
    - (Isolated high p_T) electrons
    - (Isolated high p_T) muons
    - (Isolated high p_T) taus

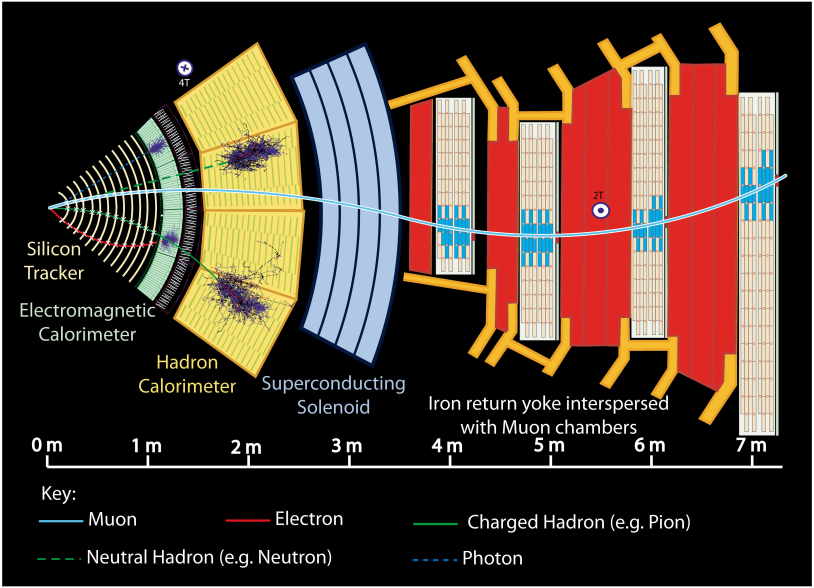
Digression: Object Reconstruction, Identification and Mis-identification

- **What is actually measured in the detector: Stable* particles**

  *given relativistic boost and size of the detector

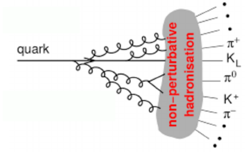
  - Charged hadrons
  - Stable neutral hadrons (e.g. neutral Kaons)
  - Photons
  - Electrons
  - Muons
- **Important special cases:**
  - π^0 is the lightest and most copiously produced neutral hadron, but promptly decays to $\gamma\gamma$ (99%) or $e^+e^-\gamma$(1%)
  - τ has a short but measurable lifetime (decay length 87μm) $\rightarrow$ decays to slightly displaced electrons or muons + neutrinos ($\sim$ 18% each) or hadrons + neutrino
- Jets are a collection of all of the above, but mostly charged hadrons, photons (mainly from π^0) and neutral hadrons in very roughly 60/30/10 proportions on average (but with large fluctuations from jet to jet)

Particle Identification in General Purpose Detectors



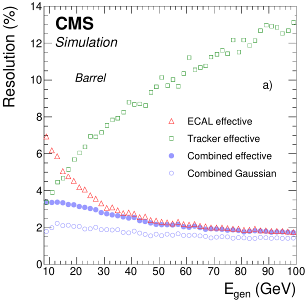
Jet and Missing Energy Reconstruction

- Jets originate from fragmentation of a quark or gluon produced by the hard interaction and tend to be collimated in the detector → define (and reconstruct) jets based on clustering of final state particles and/or energy deposits
- Simplest possible clustering would be based on ΔR cones, but e.g. anti-kT is usually preferred for theoretical considerations
- Experimentally a few possibilities:
  - Cluster calorimeter deposits (typically jet clustering of smaller calorimeter clusters)
  - Cluster tracks (this is generally not a good idea, since only charged hadron component can be included, with large fluctuations from jet to jet → poor resolution)
  - Cluster Particle Flow candidates
  - Missing energy can be constructed from the same constituents as jets in general

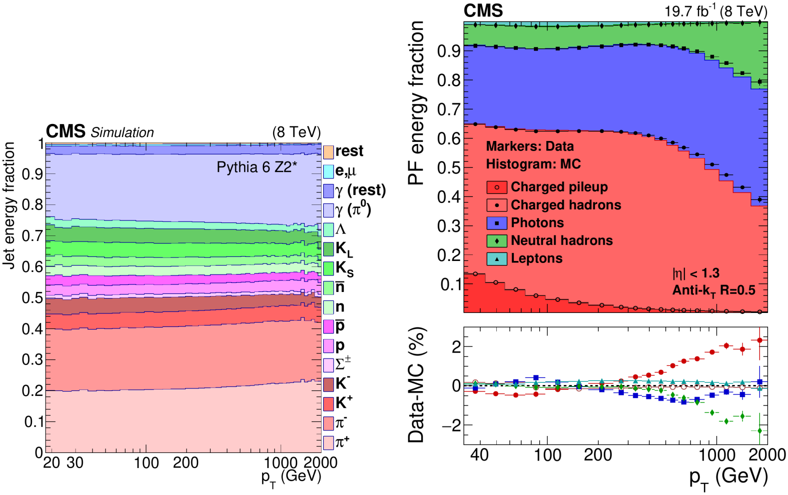


Particle Flow

- In a nutshell: **Match tracks to calorimeter deposits** and assign energy based on (resolution-weighted) **combination of track momentum and calorimeter energy**
- This can greatly improve the energy and angular resolution for charged hadrons (and electrons), especially at low energies, and depending on the relative performance of the inner tracker with respect to the calorimeters
- Per-particle pileup subtraction becomes natural in this approach
- Accurately matching calorimeter energy deposits to individual tracks can be challenging depending on calorimeter granularity, density of tracks, etc



Jet Composition Example

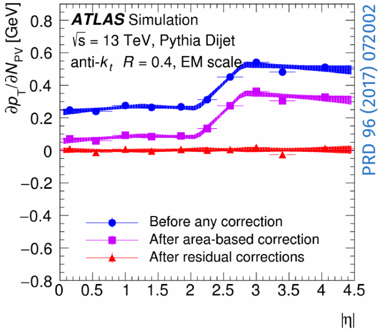


(a) Generator

(b) Reconstruction

Pileup Subtraction

- Additional energy/particles from pileup interactions can contaminate reconstructed jets (especially relevant at lower energies)
- Subtraction can be done on average (depending on size of jet and median pileup density) or per particle using track association to primary vertex



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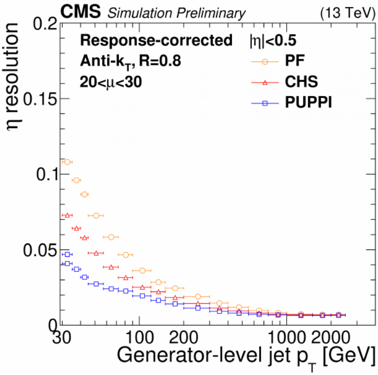
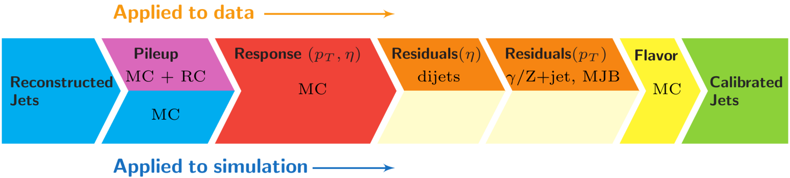


Jet Energy Corrections

- Ideally, the energy of the reconstructed jet should match as close as possible the energy which would be measured by clustering the stable particles (at generator level in the MC, or from a hypothetical detector which could perfectly separate particles and measure their energy)
- In practice this is not the case out of the box due to a number of reasons
    - Imperfect calibration of calorimeters (and/or biases in track momentum reconstruction)
    - Calorimeter gaps/cracks (and/or tracking inefficiencies)
    - Misidentification of particles in case particle-dependent corrections are used
    - Zero suppression thresholds
    - Noise
    - Pileup
    - etc

Jet Energy Corrections



Applied to data

Reconstructed Jets

Pileup MC + RC / MC

Response (p_T, η) MC

Residuals(η) dijets

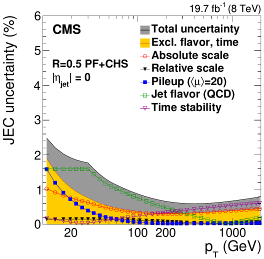
Residuals(p_T) γ/Z+jet, MJB

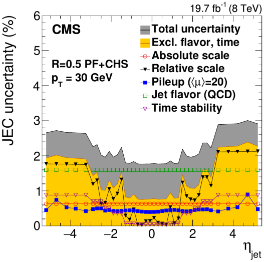
Flavor MC

Calibrated Jets

Applied to simulation

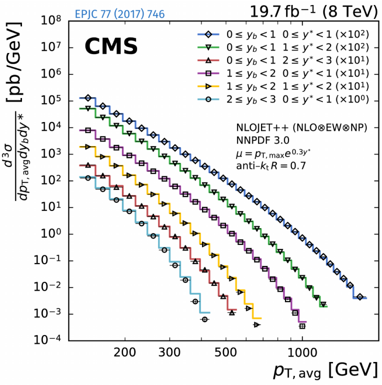
- Derive and apply a sequence of corrections to the jet energy, based on MC to start with, and with residual corrections to account for Data vs MC differences

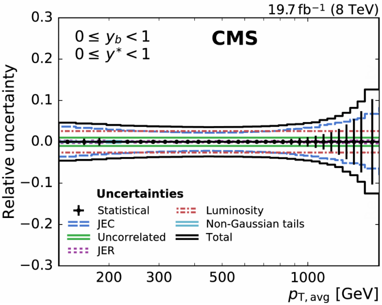




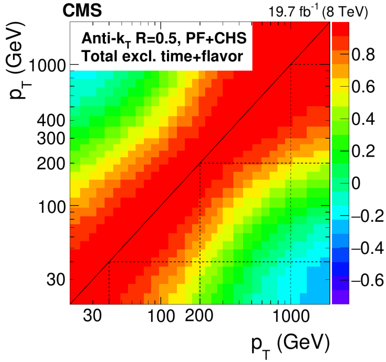
Inclusive/Dijet Measurements

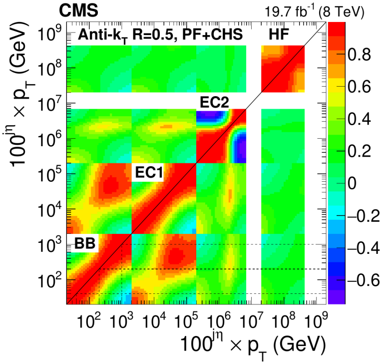
- Measurements of jet production relevant for e.g. PDF constraints, determination of strong coupling constant α_S





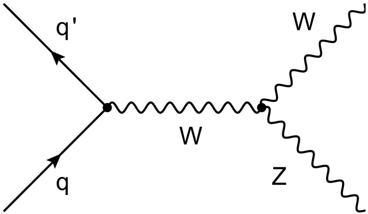
Correlations of Jet Energy Scale Uncertainties

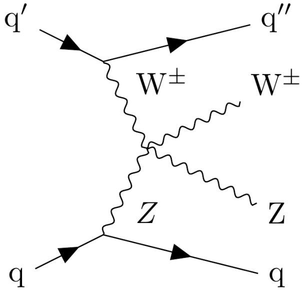




- Consistent determination and propagation of correlations of uncertainties is crucial to the (re)-interpretability of the result, its use in PDF fits, etc
- Accurate assessment of correlations across phase space can be challenging, especially for uncertainty sources related to MC modelling

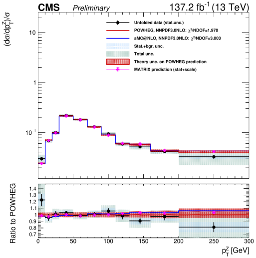
Multiboson Production

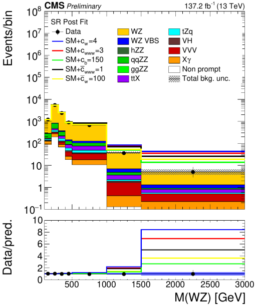


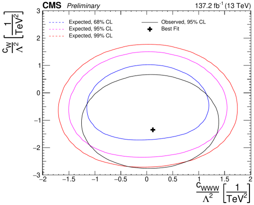


- Multiboson production at the LHC can test SM triple and quartic gauge couplings, search for anomalous gauge couplings (EFT interpretations), etc
- Special importance to vector boson scattering production modes with forward jets

Example: WZ Production: Cross Section and anomalous coupling limits

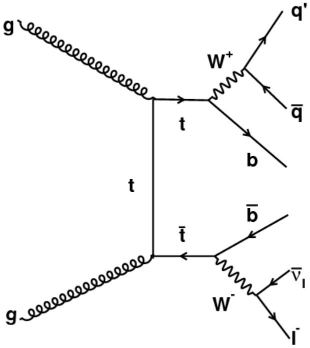






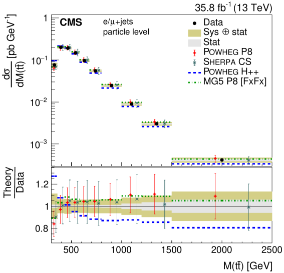
- Typical case, measure cross sections (polarization states), etc, but also use tails of distributions to set limits on anomalous couplings/EFT operators

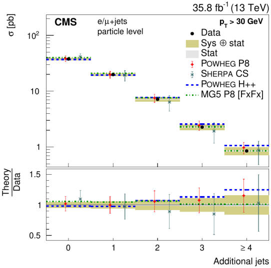
$t\bar{t}$ production at the LHC

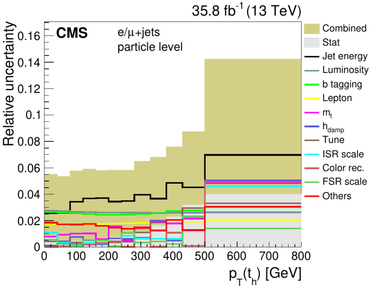


- large $t\bar{t}$ production cross section at the LHC
- Heavy final state, gluon induced production → large rate of additional jets
- Complex final states with b-jets, leptons and/or additional jets from W decays
- Possibility of colour reconnection complicates modelling, mass measurement, etc
- Study QCD, top couplings, PDF constraints, m_t, α_S determination, understand backgrounds to other measurements and searches, etc

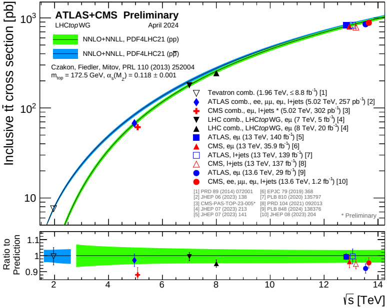
$t\bar{t}$ Differential Cross Sections

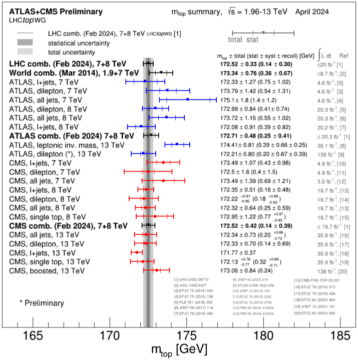






$t\bar{t}$ production at the LHC

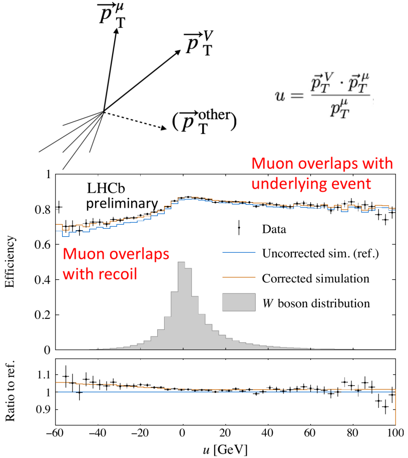




- Several different channels and complementary methods for top mass measurements

Lepton Efficiencies: Tag and Probe: Caveats

- Lepton efficiency may be **dependent on event topology**
    - Must control associated extrapolation/variation of efficiencies when measuring in one process/phase space and applying to another
    - Example shown here concerns orientation of muon with respect to hadronic recoil in drell-yan events, but the effect may be even larger e.g. in $t\bar{t}$ events with more additional jet activity



$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}}$$

Muon overlaps with underlying event

Muon overlaps with recoil

Conclusions

- We have covered a selection of topics in some detail
- Much more I could not cover or have glossed over
- (Note that the slides have references to the original paper in most cases)
- Precision measurements of electroweak and QCD physics at the LHC are possible despite the challenging conditions
- They provide the means for some of the most stringent tests yet of the Standard Model and of our understanding of QCD and its predictions
- They also constitute indirect searches for new physics, complementary to direct ones
- Experimental, theoretical and statistical techniques being developed are an important foundation for higher precision Higgs measurements at HL-LHC, and for the ultra-precision physics program at a future e^+e^- collider