Electroweak Production and QCD at LHC Experiment Part 1

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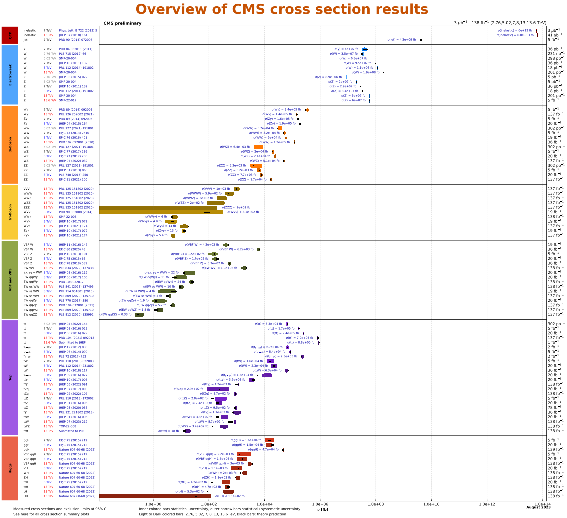
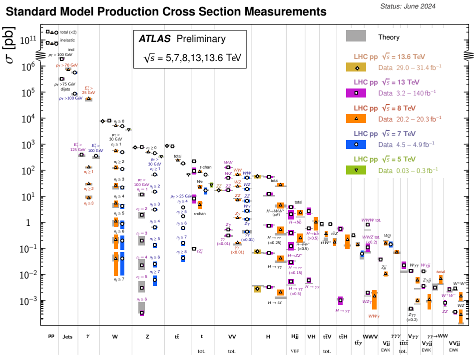
The Standard Model at the LHC



- Broad and spectacular confirmation of the Standard Model (and perturbative QCD/factorization)

The Standard Model at the LHC

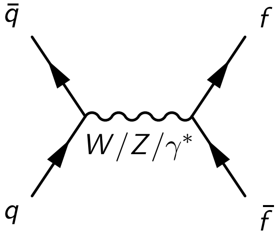


- LHC provides:
  - Unprecedented production rates for W, Z, $t\bar{t}$, high energy photons/jets with respect to previous colliders
  - Access to the Higgs for the first time (and across a range of production modes)
  - A wide range of rare and complex SM processes/final states

Outline

- **Today:**
  - 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: $\sin^2\theta_W$, m_W
  - Precision measurements of W and Z cross sections and constraints on PDFs (maybe)
- Thursday:
  - Measurements of the strong coupling constant at the LHC
  - More on Jet/MET/tau reconstruction/identification
  - Overview of Jet/multiboson/top measurements

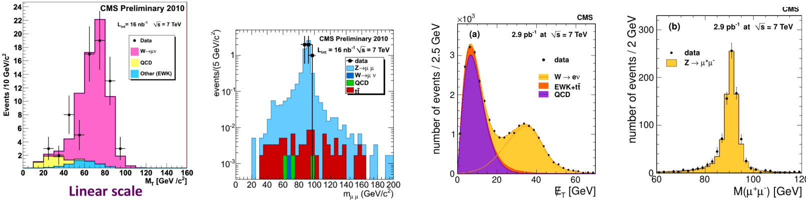
Single W and Z(γ^*) production



- W branching ratios
  - $W \to \ell\nu$ ($\ell = e, \mu, \tau$): $\sim 11\%$ per flavour
  - $W \to$ hadrons ($q\bar{q}$): $\sim 67\%$
- Z branching ratios
  - $Z \to \ell^+\ell^-$ ($\ell = e, \mu, \tau$): $\sim 3.4\%$ per flavour
  - $Z \to \nu\nu$: $\sim 20\%$
  - $Z \to$ hadrons ($q\bar{q}$) : $\sim 70\%$
- Significant branching ratios with charged leptons in the final state
- Widths are non-negligible ($\Gamma_W \sim 2.1$ GeV, $\Gamma_Z \sim 2.5$ GeV)

Single W and Z(γ^*) production

- Why measure this process?
  - Z especially is a "standard candle" processes which can be used to calibrate simulation and reconstruction, derive correction factors for charged lepton energy/momentum scale, efficiencies, etc
  - Large cross section allows continuous monitoring of detector/reconstruction performance
  - Inclusive and differential production cross sections are tests of perturbative QCD, and sensitive to parton distribution functions
  - Precision electroweak measurements: m_W, $\sin^2\theta_W$



Very Early detector performance plots (CMS-DP-2010/016) and early xsec measurements

(10.1007/JHEP01(2011)080)

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

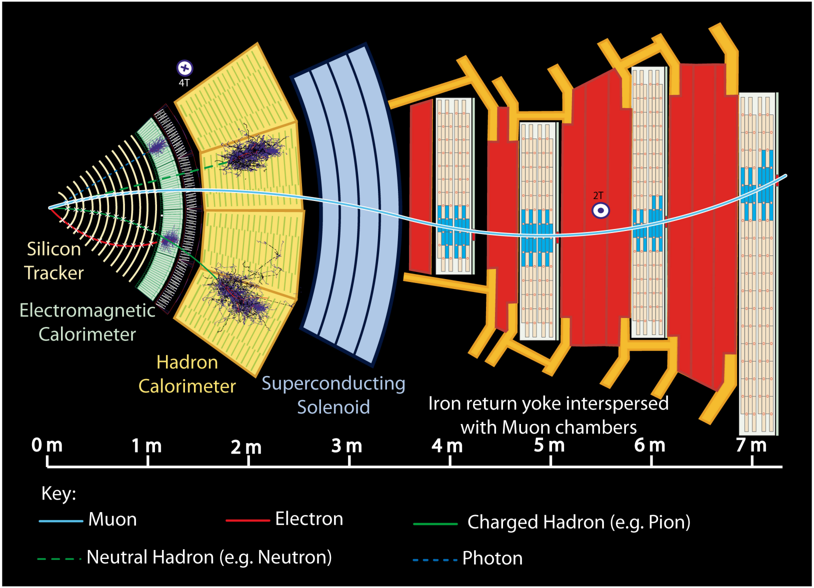
Digression: Object Reconstruction, Identification and Mis-identification

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

  *given relativistic boost and size of the detector

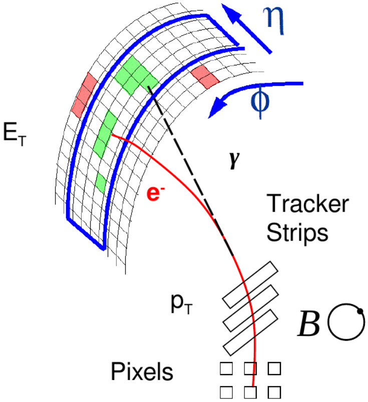
  - Charged hadrons
  - Stable neutral hadrons (e.g. neutral Kaons)
  - Photons
  - Electrons
  - Muons
- **Important special cases:**
  - π^0 is the lightest and most copiously produced neutral hadron, but promptly decays to $\gamma\gamma$ (99%) or $e^+e^-\gamma$(1%)
  - τ has a short but measurable lifetime (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



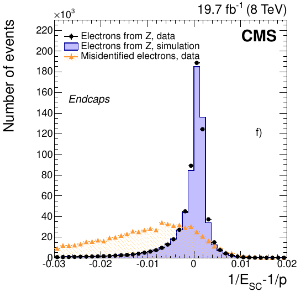
Electron Reconstruction/Identification

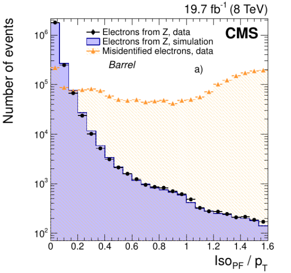
- **Prompt High p_T Electrons:**
  - Clusters of energy in electromagnetic calorimeter (grouped to recover bremsstrahlung/secondary conversions), matched to reconstructed track
  - hardware trigger from calorimeter
  - Electron-like shower profile and track properties
  - No large deposits in hadronic calorimeter behind
  - Well-isolated (e.g. sum of transverse energy/momentum in a cone around the electron)



Electron Reconstruction/Identification

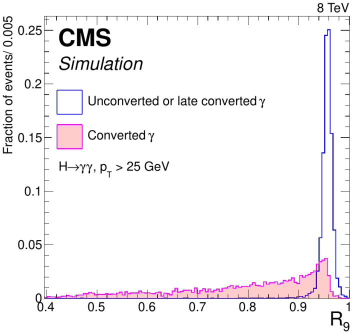
- **Main sources of Misidentified Prompt Electrons:**
  - **Heavy flavour** decays (e.g. B and D hadrons) producing displaced electrons
  - **Photon conversions** (attempt to reconstruct or identify them, but difficult to do efficiently)
  - Early showering of **charged hadrons** in EM calorimeter (e.g. via inelastic charge exchange $\pi^+ p \to \pi^0 n$)





Photon Reconstruction/Identification

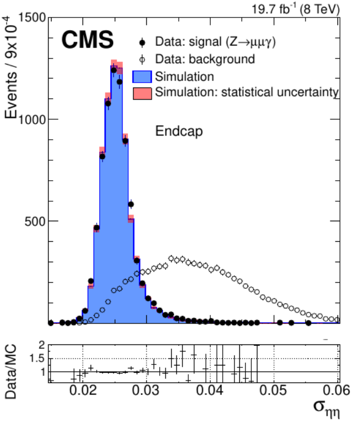
- **Prompt High p_T Photons:**
    - Clusters of energy in electromagnetic calorimeter (grouped to recover conversions/bremsstrahlung)
    - hardware trigger from calorimeter
    - Photon-like shower profile
    - No large deposits in hadronic calorimeter behind
    - Well-isolated (e.g. sum of transverse energy/momentum in a cone around the photon)



n.b. shower profile can look significantly different depending on whether the photon converts to an electron positron pair before reaching the calorimeter

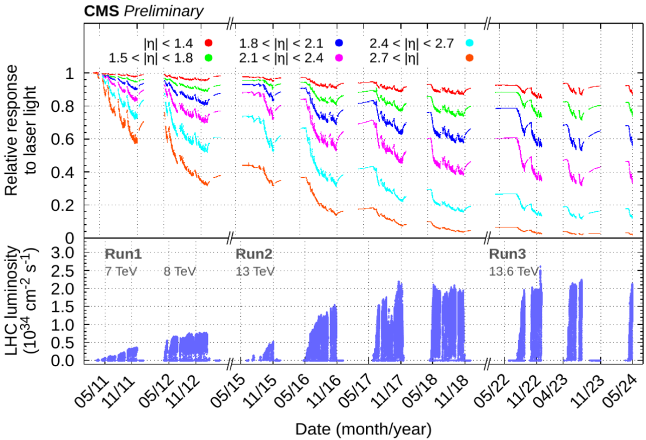
Photon Reconstruction/Identification

- **Main sources of Misidentified Prompt Photons:**
  - $\pi^0 \rightarrow \gamma\gamma$ (at high energies, the decay is collimated and tends to merge into a single shower)
  - **Electrons** where primary track is not reconstructed, or misidentified as belonging to a conversion



Transverse shower width (parallel to B-field)

Aside: ECAL aging and laser monitoring



- Lead tungstate crystals lose transparency with radiation exposure (but partially recover)
- Dose much higher closer to the beam, endcaps ($|\eta| > 1.5$) will be replaced in LS3

Muon Reconstruction/Identification

- **Prompt High p_T Muons:**
  - Reconstructed track in inner tracker and muon chambers
  - hardware trigger from muon chambers
  - No large deposits in calorimeter
  - Well-isolated (e.g. sum of transverse energy/momentum in a cone around the muon)

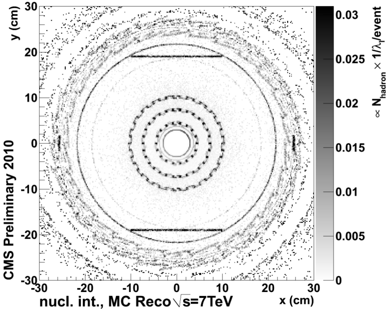
- **Main sources of Misidentified Prompt Muons:**
  - **Heavy flavour** decays (e.g. B and D hadrons) producing displaced muons
  - **Decay in flight** of charged hadrons (e.g. $\pi^+/K^+ \to \mu^+\nu$), can be supressed with track quality, "kink-finding"
  - **"Punch through"** of charged hadrons (negligible with enough hadronic interaction lengths upstream)

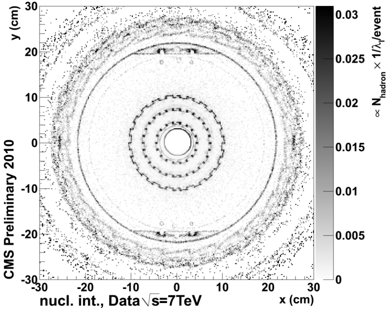
Monte Carlo + Detector Simulation as an Analysis Tool

- A “Monte Carlo Sample” as produced by the LHC experiments typically consists of a full chain of Monte Carlo Generator $\rightarrow$ Detector Simulation $\rightarrow$ “digitization” $\rightarrow$ reconstruction, to produce events which look as close as possible to data given the input physics assumptions
- **Monte Carlo Generator:** Simulate proton collisions up to stable particle level (PDFs, matrix element/hard interaction, hadronization, prompt decays, MPI/underlying event, etc)
- More details on Monte Carlo generators themselves in Marius’ lectures
- **Detector simulation:** Simulate the interaction of the generated particles with the detector using **Geant4**
  - Energy loss
  - Multiple scattering
  - Bremsstrahlung
  - Photon conversions
  - Nuclear interactions
  - Electromagnetic and hadronic showers
  - Many many other small details with input from many sources of experimental data on interactions of particles with matter

Material map with nuclear interactions

- Aside from the details of the physics model (e.g. modelling details of showers in calorimeters can be challenging), simulation quality depends on accuracy of **geometry** and **material model** → notoriously difficult
- One method of checking this is with reconstructed nuclear interactions (nuclear interaction probability depends on material density)





Monte Carlo + Detector Simulation as an Analysis Tool

- A "Monte Carlo Sample" as produced by the LHC experiments typically consists of a full chain of Monte Carlo Generator $\rightarrow$ Detector Simulation $\rightarrow$ "digitization" $\rightarrow$ reconstruction, to produce events which look as close as possible to data given the input physics assumptions
- **Digitization:** Simulate the readout/electronics of the detector
  - Energy deposits in active detector elements converted to raw hits/ADC counts etc
  - Electronics noise, inefficiencies, dead channels, etc can be simulated at this stage
  - Pileup is typically also overlaid at this stage (from independently simulated Minimum Bias events)
- **Reconstruction:** Unpack the raw data and run the reconstruction chain up to high level objects (four-vectors, ID variables, etc)
  - Ideally this is algorithmically exactly the same between data and simulation
  - Typically depends on a large set of calibration and/or alignment constants depending on the detector
  - Try to reproduce in the MC known inaccuracies and precision limitations on the data calibration constants

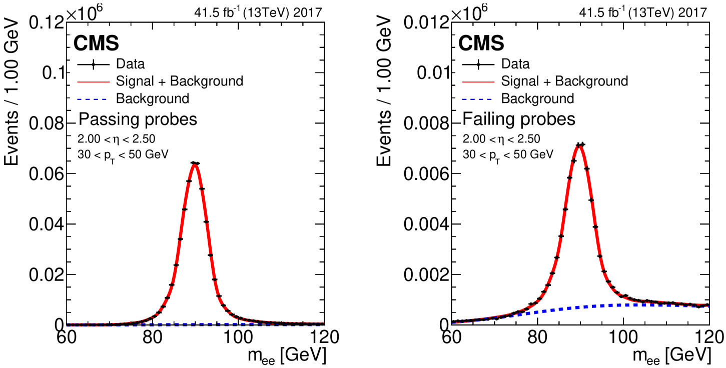
Monte Carlo + Detector Simulation as an Analysis Tool

- **In general: The Monte Carlo at the LHC experiments is good, but not perfect**
- Accuracy and uncertainties associated with the generator part depends very much on the generator and process
- Detector simulation/response for well-reconstructed objects is not terrible $\rightarrow$ use the Monte Carlo as a starting point and derive (hopefully small) residual corrections from data which can be used in the analysis
- Residual systematic uncertainties may be limited by the degree of (in)accuracy of the simulation $\rightarrow$ particularly difficult/high precision cases may benefit from dedicated refinement efforts
- Mis-identified objects tend **not** to be well predicted by the Monte Carlo, depend on details of jet flavour composition in QCD multijet events, tails of jet fragmentation functions, probability of rare interactions in the detector, etc $\rightarrow$ **strong preference for data-driven methods to predict the rate and kinematic distributions of these backgrounds, especially in precision measurements**

Lepton Efficiencies: Tag and Probe

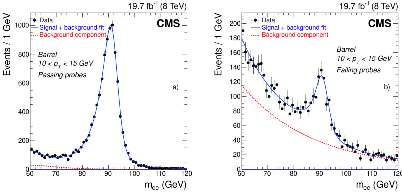
- $Z \to \ell^+\ell^-$ is a very special standard candle: the presence of two leptons in the event gives the possibility to select the event based on one lepton (the **tag**) in order to construct an unbiased sample from the second lepton in the event (the **probe**)
- In particular this allows the **efficiency** of various reconstruction and selection steps to be **directly measured in data**
- Trigger efficiencies can also be measured in this way (typically using **single lepton** triggers for the tag)
- Efficiencies are typically measured in bins of p_T and η of the probe

Lepton Efficiencies: Tag and Probe



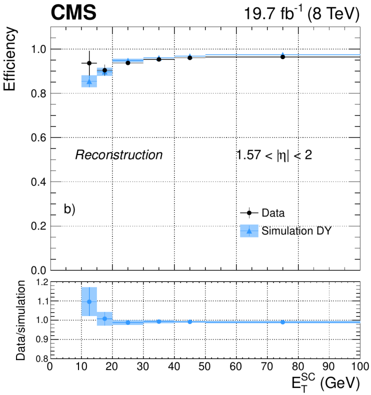
- **Concrete example:** Electron identification efficiency
  - **Tag:** reconstructed electrons passing all ID and isolation requirements
  - **Probe:** reconstructed electrons with no ID requirements applied
  - **Passing probe:** Probe passing the ID requirements
  - **Failing probe:** Probe failing the ID requirements

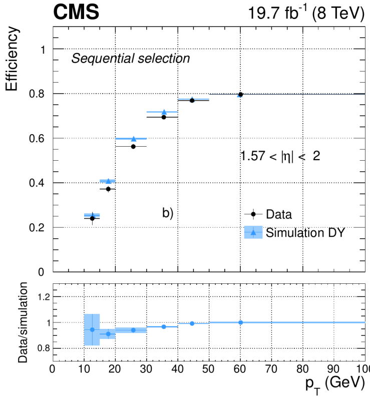
Lepton Efficiencies: Tag and Probe



- Background is subtracted by performing a likelihood fit (always larger in failing probe case)
- Typically with analytic functional form for the background (erf*exp in this case), analytic (e.g Breit Wigner $*$ Crystal Ball) or smeared MC templates for signal
- Efficiency and corresponding statistical uncertainty can be extracted directly from a simultaneous fit of passing and failing probes $\epsilon = N^{\text{sig}}_{\text{pass}}/(N^{\text{sig}}_{\text{pass}} + N^{\text{sig}}_{\text{fail}})$
- Systematic uncertainties typically from alternate signal or background models, alternate fitting range, variations in tag selection, etc
- Typically applied to analysis as **scale factors** to MC: $\epsilon_{\text{data}}/\epsilon_{\text{MC}}$ to exploit e.g. mostly correct MC modelling of efficiency variations within a bin

Lepton Efficiencies: Tag and Probe: Example Results





- In this particular case (electrons in a region with a large amount of material), MC models the pt-dependence of the efficiency qualitatively, but some corrections are still needed

Lepton Efficiencies: Tag and Probe: Caveats

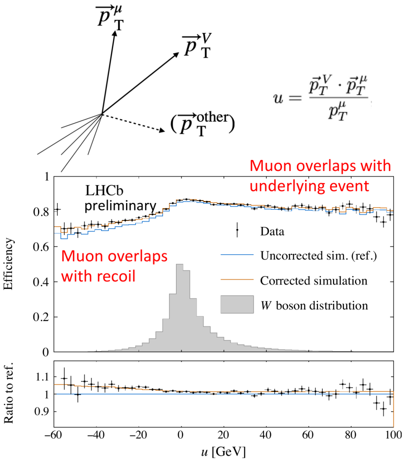
- Defining a suitably inclusive probe selection for **reconstruction efficiency** can sometimes be challenging
  - e.g. for muons use inner tracks as probes to measure muon chamber efficiency and vice versa
  - e.g. for electrons use tracks as probes to measure EM calorimeter cluster efficiency and vice versa
  - need to carefully consider possibly correlated sources of uncertainty in such cases

Lepton Efficiencies: Tag and Probe: Caveats

- **Sometimes inefficiencies can be correlated with poor energy/momentum measurement** (e.g. electrons incident on gaps or cracks in the calorimeter which are more likely to fail shower profile cuts, but also more likely to have their energy undermeasured)
  - These effects must be accounted for in the signal model and/or associated systematic uncertainties
  - Dedicated or multivariate energy corrections can sometimes mitigate these effects (but be careful about deriving energy corrections on tight objects and applying them to looser ones)

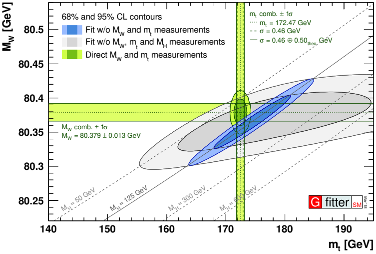
Lepton Efficiencies: Tag and Probe: Caveats

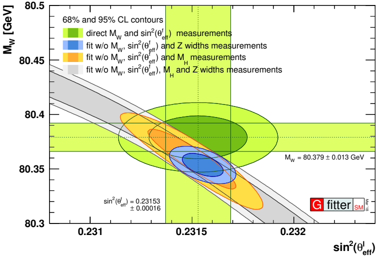
- Lepton efficiency may be **dependent on event topology**
  - Must control associated extrapolation/variation of efficiencies when measuring in one process/phase space and applying to another
  - Example shown here concerns orientation of muon with respect to hadronic recoil in drell-yan events, but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



Lepton Efficiencies: Tag and Probe: Caveats

- Sources of inefficiency which are **correlated** between the tag and the probe cannot be measured by this method and must be accounted for by other means
  - **Pathological example:** Cut on d_{xy}(muon, beamspot), but beamspot is mismeasured or otherwise incorrect in the reconstruction $\rightarrow$ corresponding failing probes will be missing from the tag and probe sample because the tag will also fail the cut!
  - **Real life example:** Trigger pre-firing: probe lepton is reconstructed by the hardware trigger one bunch crossing too early, correct trigger of the tag is suppressed by trigger rules/deadtime $\rightarrow$ failing probe won't appear in the sample because the event is never triggered in the correct bunch crossing





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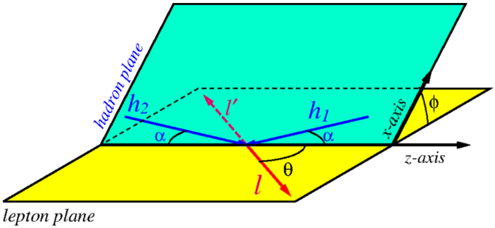
- Precise measurements of the Higgs mass enable more precise consistency tests of the Standard Model using m_W and $\sin^2\theta_W$

Drell Yan Production at the LHC

- Production and decay of $Z/\gamma^* \to \ell^+\ell^-$ or $W \to \ell\nu$ at the LHC, inclusive in additional hadronic activity, can be characterized by a 5-dimensional differential cross section

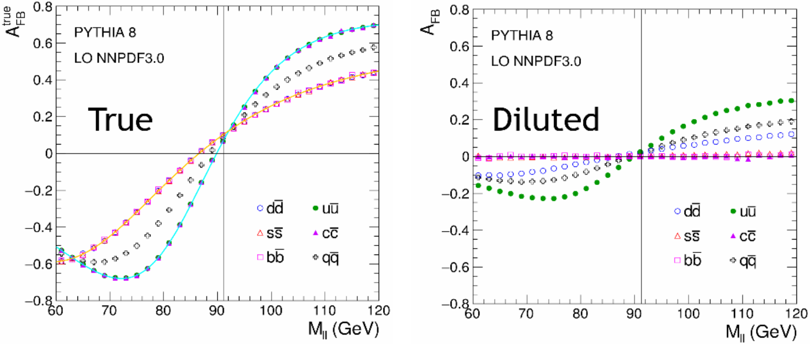
$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z} \times \Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}. \quad (1.1)$$



- θ and ϕ are the decay angles of the lepton/neutrino in the rest-frame of the Z/γ^* or W, defined e.g. in the Collins-Soper frame

Weak Mixing Angle

- Angular distributions of leptons in Z rest frame are sensitive to weak mixing angle
- Leading sensitivity through forward-backward asymmetry or A4 angular coefficient (equivalent up to a constant in the full phase-space)
- Sensitivity diluted in p-p collisions due to unknown direction of incoming quark vs anti-quark



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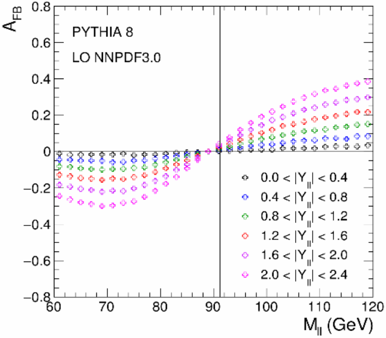
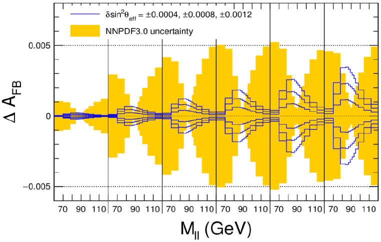
Weak Mixing Angle

- Size of dilution effect is rapidity-dependent and sensitive to PDFs
- $\sin^2\theta_W$ sensitivity mainly at Z peak, PDF sensitivity mainly above/below $\rightarrow$ perform measurements differential in $m_{\ell\ell}$ and $y_{\ell\ell}$





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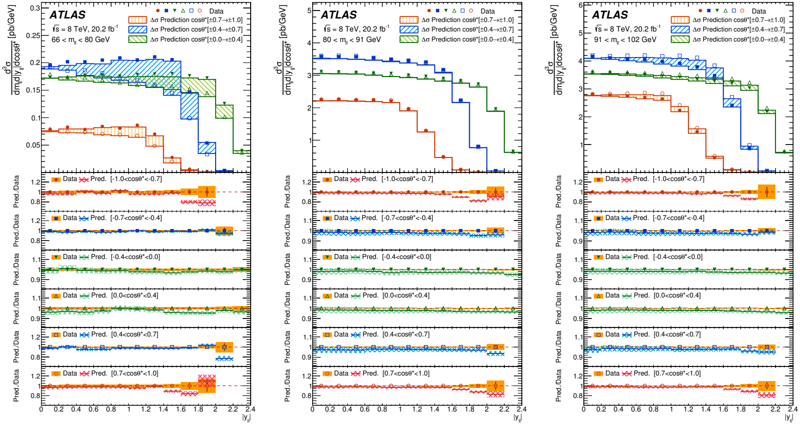
Drell-Yan Angular Distributions

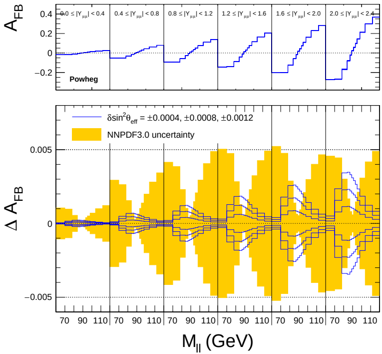


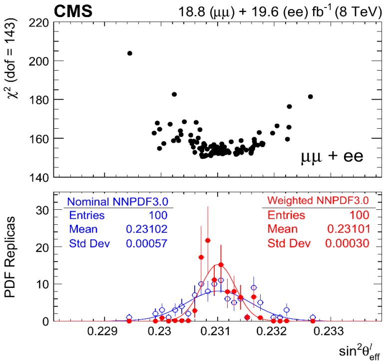
JHEP 12 (2017) 059

- Unfolded triple-differential $(d^3\sigma/dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*)$ cross sections containing information relevant for $\sin^2\theta_W$ determination and in-situ PDF constraints

In-situ PDF constraints: Weak Mixing Angle Case

- CMS and ATLAS weak mixing angle measurements exploit in-situ constraints to reduce PDF uncertainties with Bayesian reweighting of Monte Carlo replicas/profiling of nuisance parameters associated with Hessian representation (numerically equivalent in the Gaussian limit)





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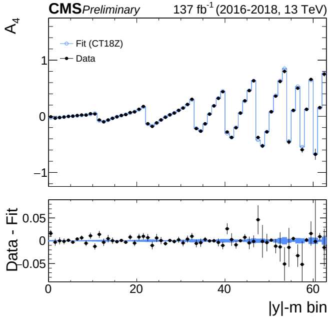
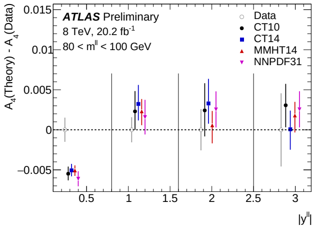
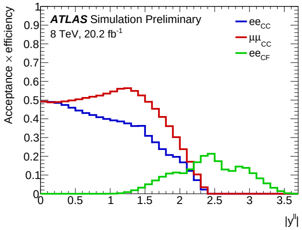
Weak Mixing Angle Measurements

CMS-PAS-SMP-22-010, ATLAS-CONF-2018-037, LHCb-PAPER-2024-028





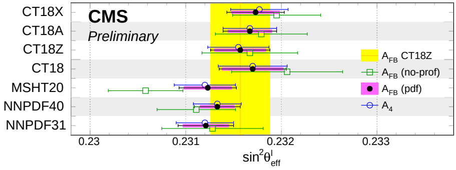


- Both ATLAS and CMS significantly improve sensitivity through inclusion of forward electrons (beyond tracking acceptance) to extend acceptance to higher rapidity
- LHCb has forward rapidity coverage, but less integrated luminosity

Weak Mixing Angle Measurements

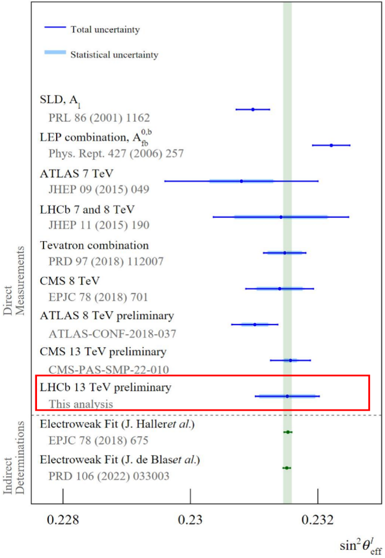
	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{\mathrm{eff}}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

PDF set **Preliminary**	Value	PDF uncertainty	Shift
NNPDF31_nlo_as0118	0.23155	0.00023	–
CT18NLO	0.23165	0.00022	+0.00010
MSHT20nlo_as118	0.23137	0.00017	−0.00018
Arithmetic average	–	0.00021	−0.00003



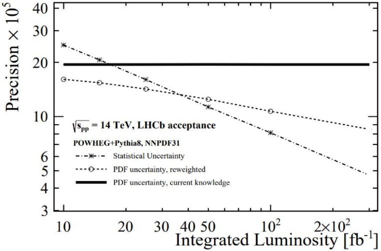
- ATLAS and CMS provide results for multiple PDF sets, but choose one nominal set for the final result, LHCb provides an arithmetic average as the nominal
- Assessing compatibility between different PDF sets non-trivial since largely common input datasets and methodology imply large correlations
- Central values with different PDF sets do not necessarily agree within the quoted PDF uncertainty

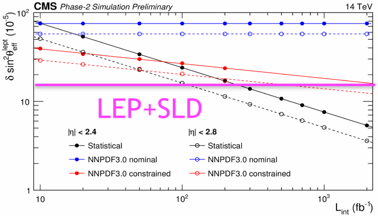
Weak Mixing Angle Measurements



- For current results, main contributions to uncertainties are statistical and PDFs
- LHCb is currently statistically limited due to smaller PDF uncertainty at forward rapidity, but smaller dataset

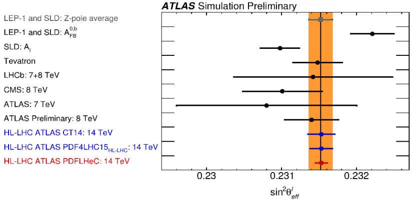
Weak Mixing Angle Prospects





Eur. Phys. J. C 78 (2018) 701, CMS-PAS-FTR-17-001,

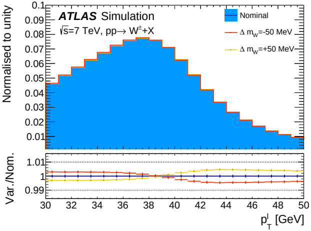
ATL-PHYS-PUB-2018-037, LHCb-PAPER-2024-028

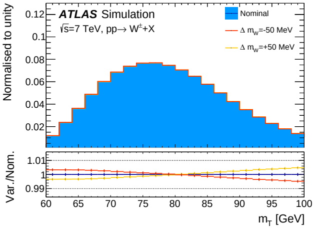


- Existing measurements already reduce PDF uncertainties with in-situ constraint
- Measurements with full HL-LHC data can reach or surpass LEP+SLD precision, depending also on improved knowledge of PDFs from external sources

W mass at LHC

- **W cannot be fully reconstructed due to neutrino** $\rightarrow$ 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 $\sim$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 $\rightarrow$ 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

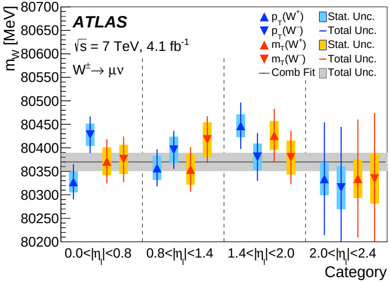
Eur. Phys. J. C 78 (2018) 110

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

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

	PDF Uncertainty (MeV)
per $\lvert\eta\rvert$-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

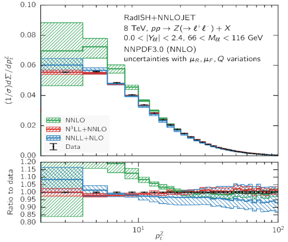
Eur. Phys. J. C 78 (2018) 110

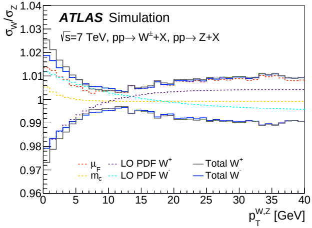
$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst}) \pm 14(\text{mod. syst.})$ MeV

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

- 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

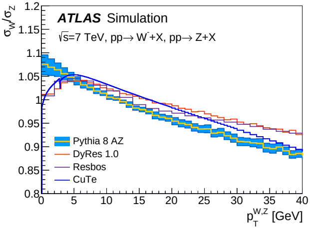
arXiv:1805.05916

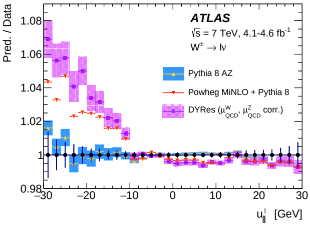




W mass: QCD Modelling Uncertainties

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

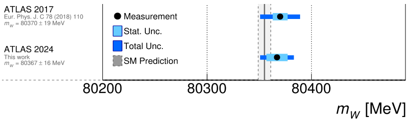


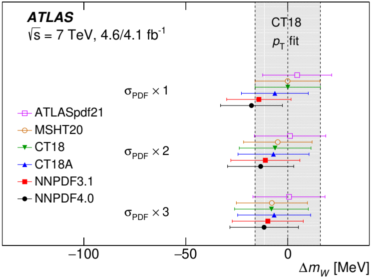


- Measured hadronic recoil (missing energy) distribution has some sensitivity to W p_T distribution, appears to disfavour more advanced calculations of W/Z p_T ratio
- Future directions for W p_T spectrum:
  - Better direct measurement (special low pileup runs)
  - In-situ constraints
  - Reducing theoretical 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

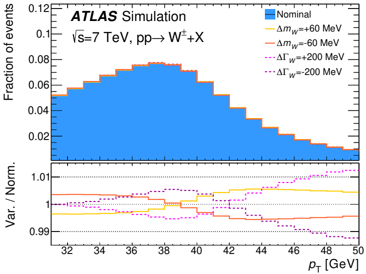


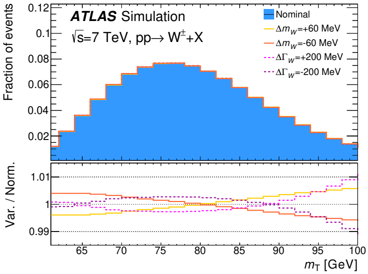


- Updated ATLAS measurement using the same 7 TeV dataset
- Main feature: Use of profile-likelihood fit for reduced uncertainties via in-situ constraints (especially on PDFs)
- Also an opportunity to directly update measurement with newer PDF sets and further explore the compatibility between them
- Interesting 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

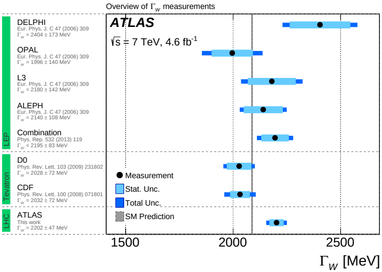


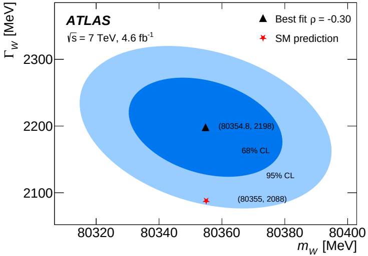


arXiv:2403.15085

Updated ATLAS Measurement: W Width

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

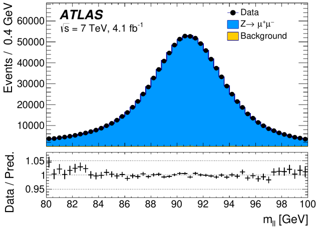




arXiv:2403.15085

Muon Momentum Scale (and Resolution)

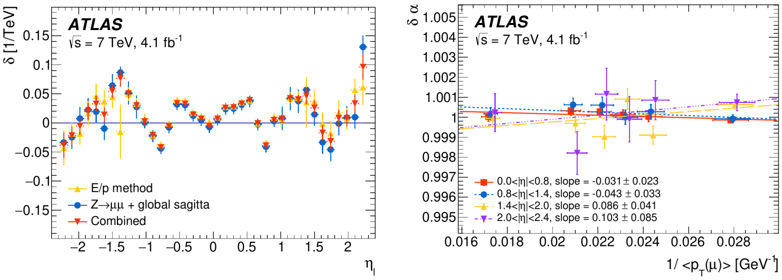
- $Z \to \mu\mu$ can also be used as a standard candle for the muon momentum scale and resolution, since the mass (and width) are known very precisely from the LEP beam energy scan and calibration (mass is known to 2.3×10^{-5} relative precision)
- J/ψ and Υ can also be used (Υ mass is known to similar 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

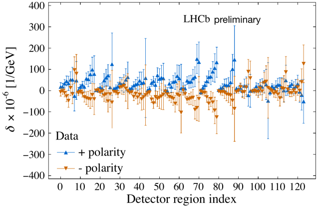
Muon Momentum Scale (and Resolution) p_T dependence



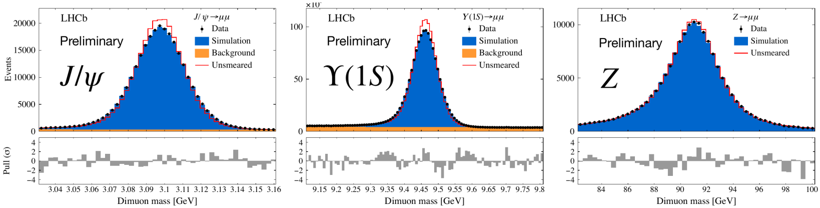
(a) Alignment-like bias (b) Material-like bias

- 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 $\pm 10\%$ variation of material model)

Muon Momentum Scale (and Resolution) p_T dependence



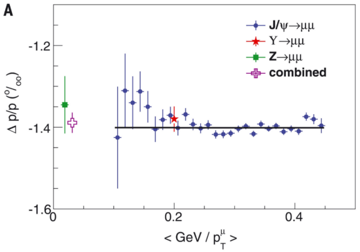
- In the LHCb m_W measurement, alignment-like bias is first corrected in a fine-grained binning using the Z
- Subsequently remaining alignment-like, bfield-like, and resolution corrections (both hit resolution and multiple scattering) are determined from combined fit of J/ψ, $\Upsilon(1S)$ and Z
- Material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

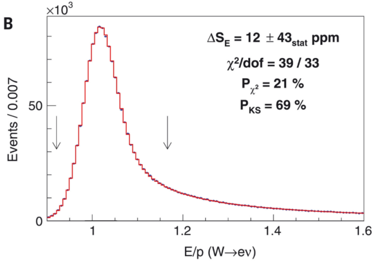


CDF: Energy/Momentum Scale Calibration

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

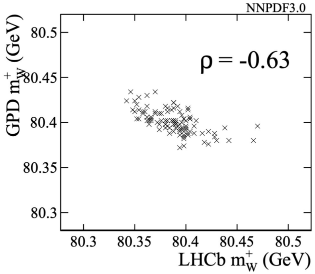




- Ultra-precise calibration of tracking momentum scale from J/psi and Y validated and combined with Z->mu mu
- After corrections for residual misalignment and material, momentum scale determined to relative accuracy of 25ppm

- 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) $\rightarrow$ PDF uncertainties expected to be anti-correlated with ATLAS and CMS
- Current measurement is statistically limited, but only $\sim 1/3$ 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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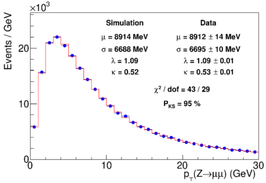
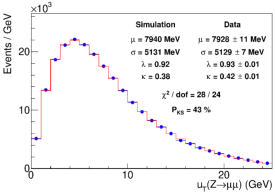
CDF: Z->ll Standard Candle

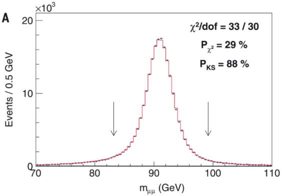


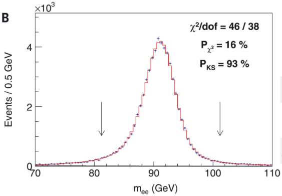
Tuned production model (Resbos)



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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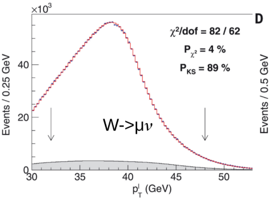
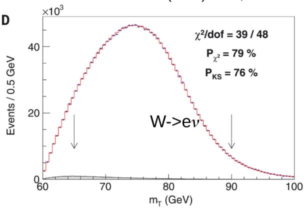
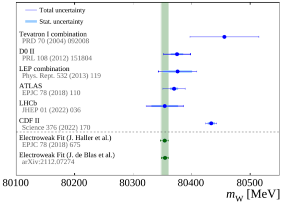


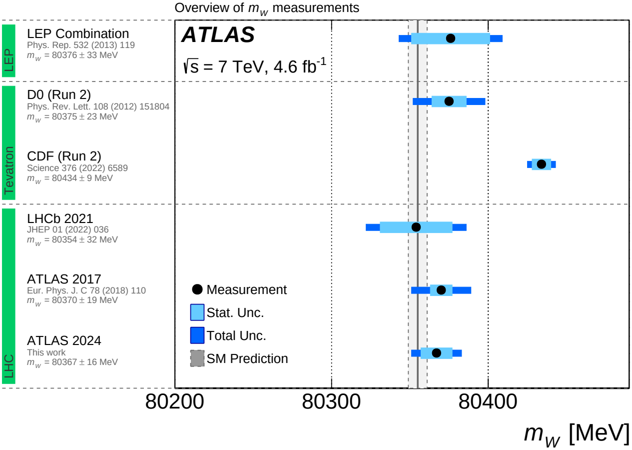




- Most precise measurement
- In significant tension with Standard Model prediction

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

m_W summary



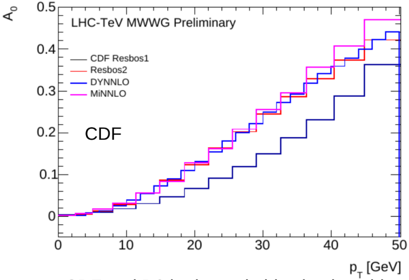
- CDF result is in significant tension with both the SM prediction (7σ) and the other measurements

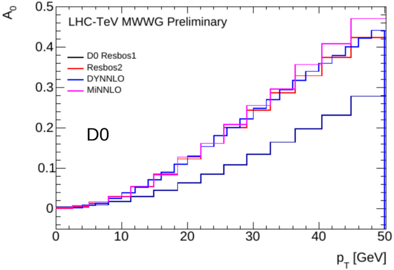
m_W Combination

- 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

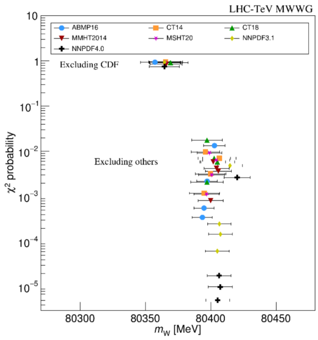
arXiv:2308.09417

Angular Coeff Effect on mW measurement (CDF)

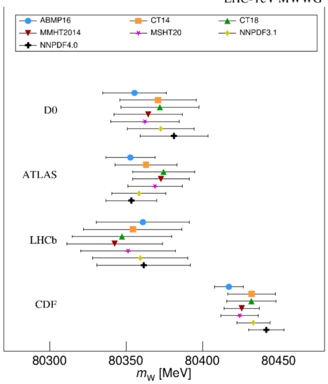
Coefficient	m_T	p_T^ℓ	p_T^ν
A_0	-6.3	-2.6	-9.1
A_1	1.1	1.3	0.3
A_2	-0.7	0.4	-3.2
A_3	-2.1	-4.1	1.0
A_4	-1.4	-3.3	-1.6
$A_0 - A_4$	-9.5	-8.4	-12.5
ResBos2	-10.2 ± 1.1	-7.6 ± 1.2	-11.8 ± 1.4
Difference	-0.7 ± 1.1	0.8 ± 1.2	0.7 ± 1.4

- 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

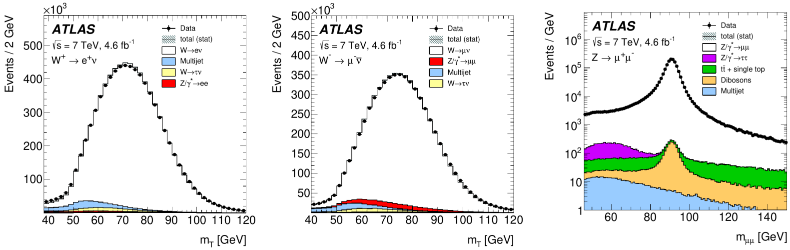


arXiv:2308.09417



- 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

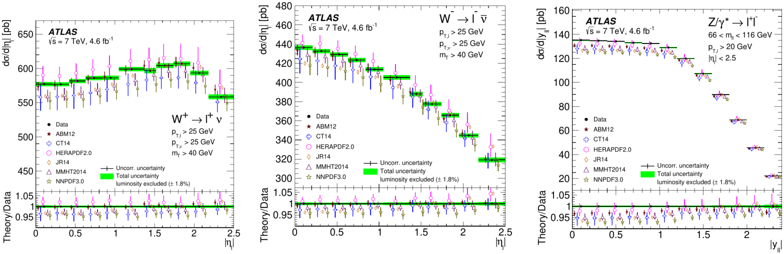


Detector level plots of selected W and Z events

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

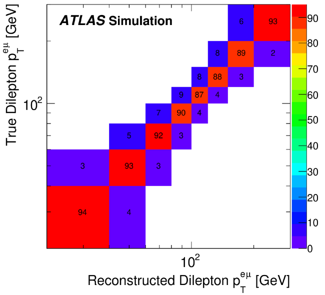


Unfolded cross sections

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)

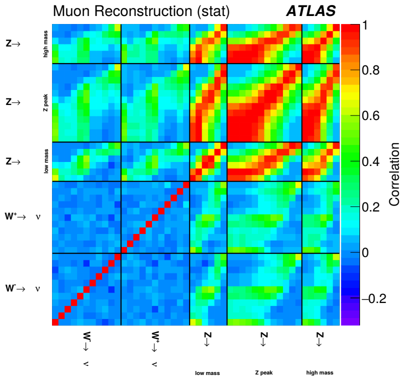
Unfolding



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

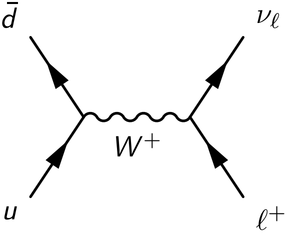


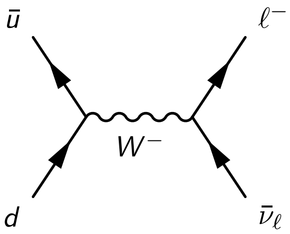
Eur. Phys. J. C 77 (2017) 367 (ATLAS)

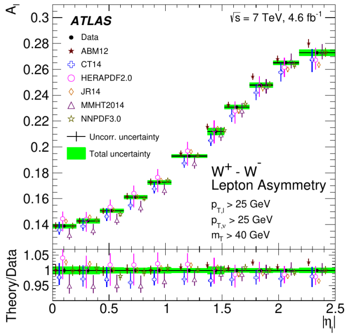
- Example shown here for **statistical** component of uncertainty on muon reconstruction efficiency for ATLAS W/Z measurement
- Underlying uncertainty is uncorrelated in bins of single muon p_T and η in which efficiencies were measured with tag and probe, leading to non-trivial correlations in particular 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



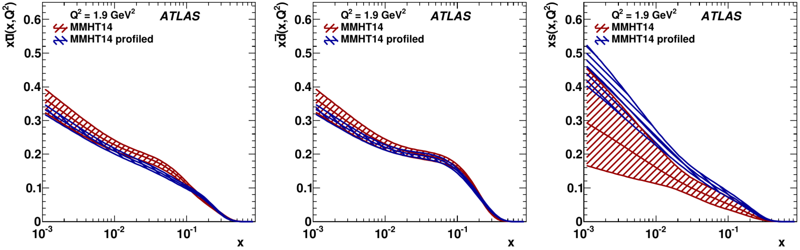


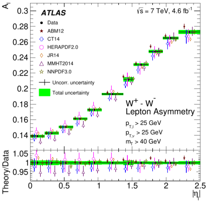


$$A_\ell = \frac{d\sigma_{W+}/d|\eta_\ell| - d\sigma_{W-}/d|\eta_\ell|}{d\sigma_{W+}/d|\eta_\ell| + d\sigma_{W-}/d|\eta_\ell|}$$

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

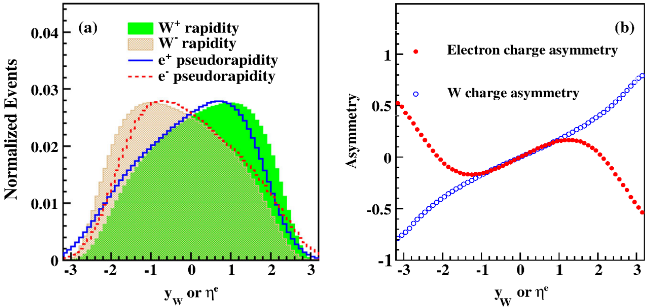
PDF Constraints from ATLAS Precision W/Z cross sections





- Significant constraints on especially sea quark distributions

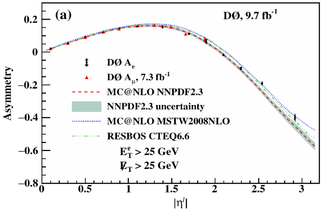
W vs lepton charge asymmetry at the Tevatron



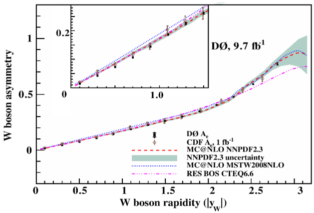
Phys. Rev. D 91, 032007 (2015) (D0)

- 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 $\rightarrow$ final results are "CP" folded $A(-\eta/y) \rightarrow -A(\eta/y)$

W vs lepton charge asymmetry at the Tevatron



(a) Lepton Charge Asymmetry

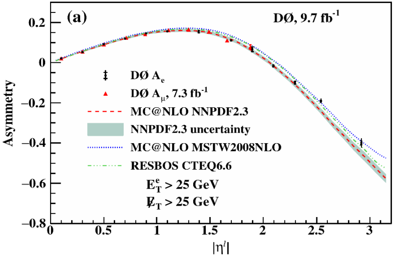


(b) W Charge Asymmetry

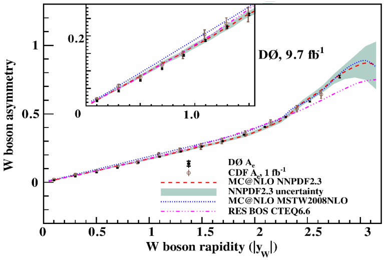
Phys. Rev. D 91, 032007 (2015) (D0), Phys. Rev. Lett. 112, 151803 (2014) (D0)

- 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) $\rightarrow$ 10% effect in total, with non-negligible uncertainty from PDF's $\rightarrow$ some circularity in using data in this form for PDF determination

W vs lepton charge asymmetry at the Tevatron



(a) Lepton Charge Asymmetry

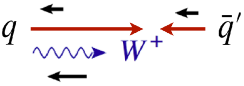


(b) W Charge Asymmetry

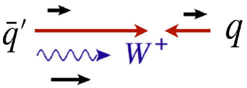
Phys. Rev. D 91, 032007 (2015) (D0), Phys. Rev. Lett. 112, 151803 (2014) (D0)

- 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

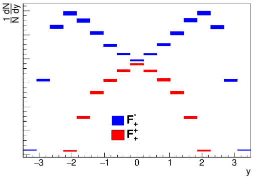
W Helicity/Rapidity at LHC



(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**

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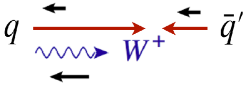
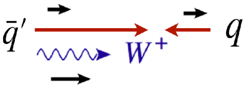
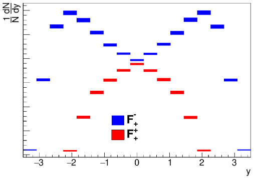
W Helicity/Rapidity at LHC







(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)

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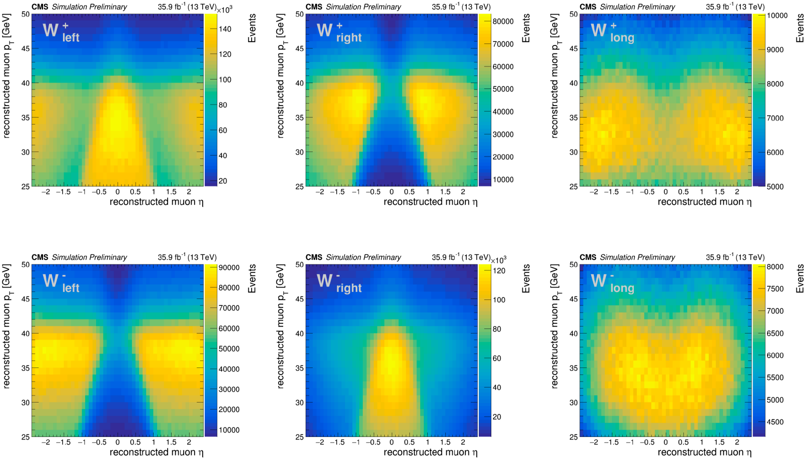
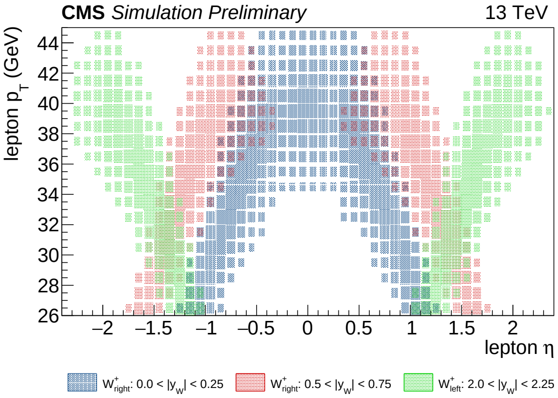
W Helicity/Rapidity at LHC



- 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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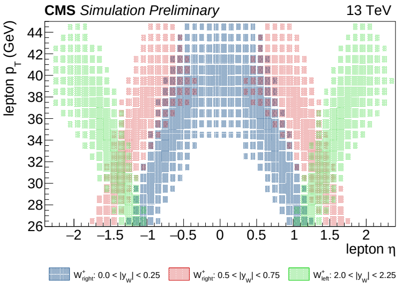
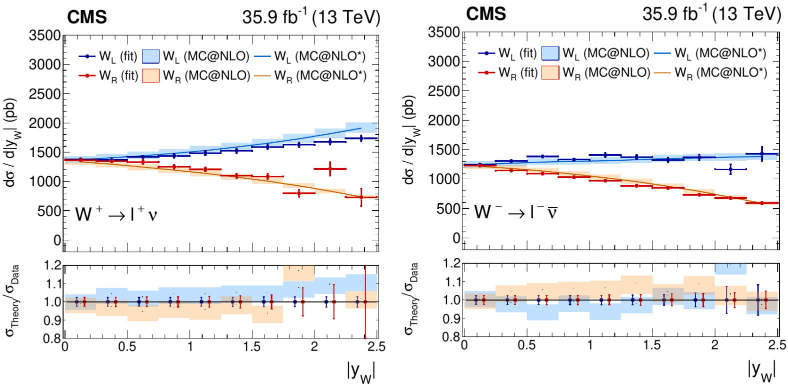
W Helicity/Rapidity at LHC



- 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**

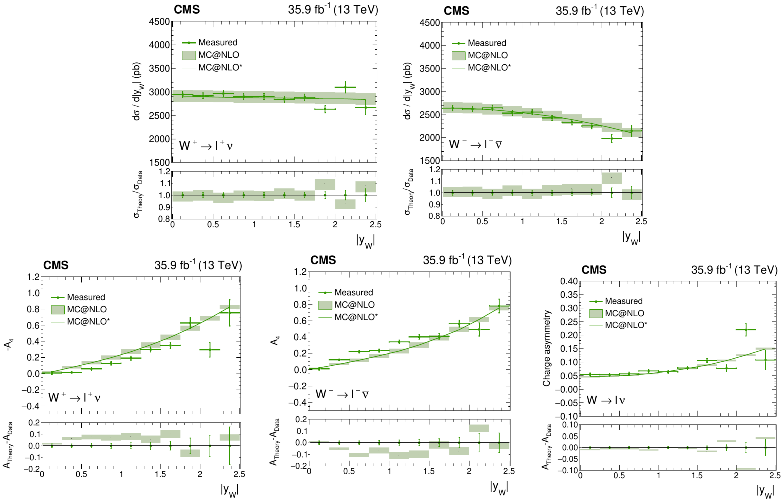
W Helicity/Rapidity at LHC



10.1103/PhysRevD.102.092012

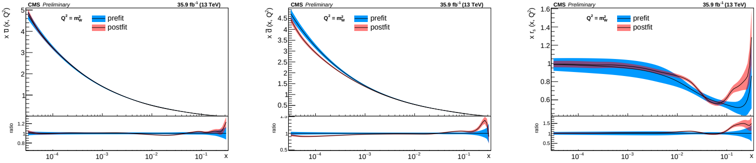
- Polarized cross sections (+ covariance matrices) contain the full set of information

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

Conclusions

- Questions welcome (now or in Q&A session tomorrow afternoon)
- Part 2 tomorrow morning
- If there is particular interest in certain topics or request for clarifications we can cover them in a bit more detail tomorrow as well