Towards a 1st measurement of M_W at the LHC

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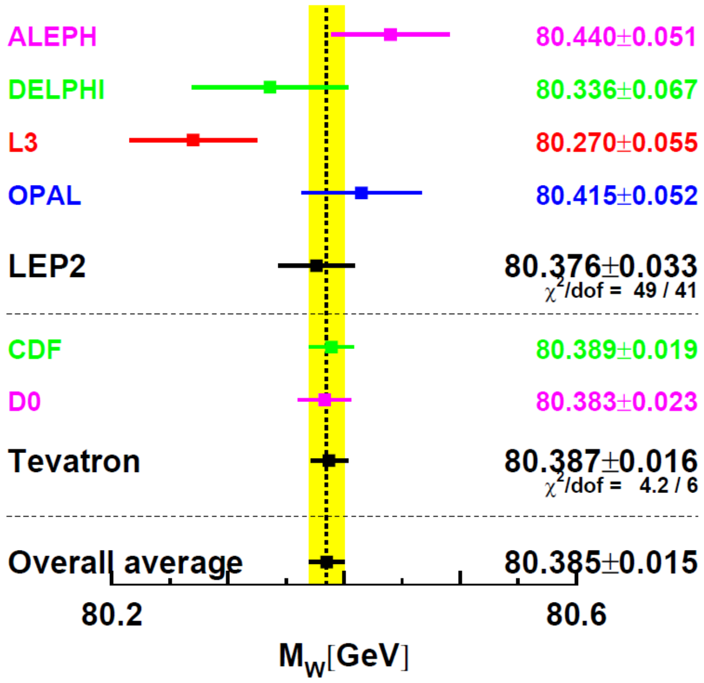
on behalf of the ATLAS and CMS Collaborations

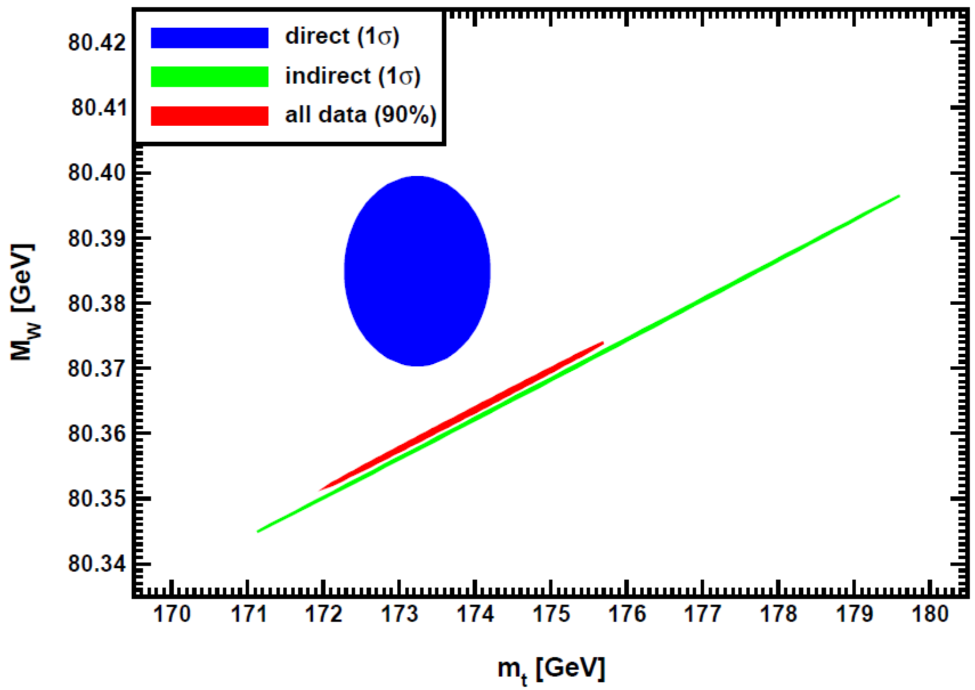
Outline

- Motivation. Principle of the measurement
- Statistical sensitivity and calibration systematics
- Modeling of W production and decay
- Uncertainties and constraints

Motivation

- M_W is the leading uncertainty in SM consistency tests.
- The indirect determination, and existing and future Tevatron measurements set a natural goal of $\delta M_W < 10$ MeV at the LHC





PDG 2014 - Chin.Phys. C38 (2014) 090001

Uncertainties – Tevatron experience and LHC expectations

Current best measurements: $\delta(stat) \approx \delta(QCD) \approx \delta(calib)$

Extrpolating to the LHC (and the next Tevatron): $\delta(QCD) > \delta(calib) > \delta(stat)$

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19

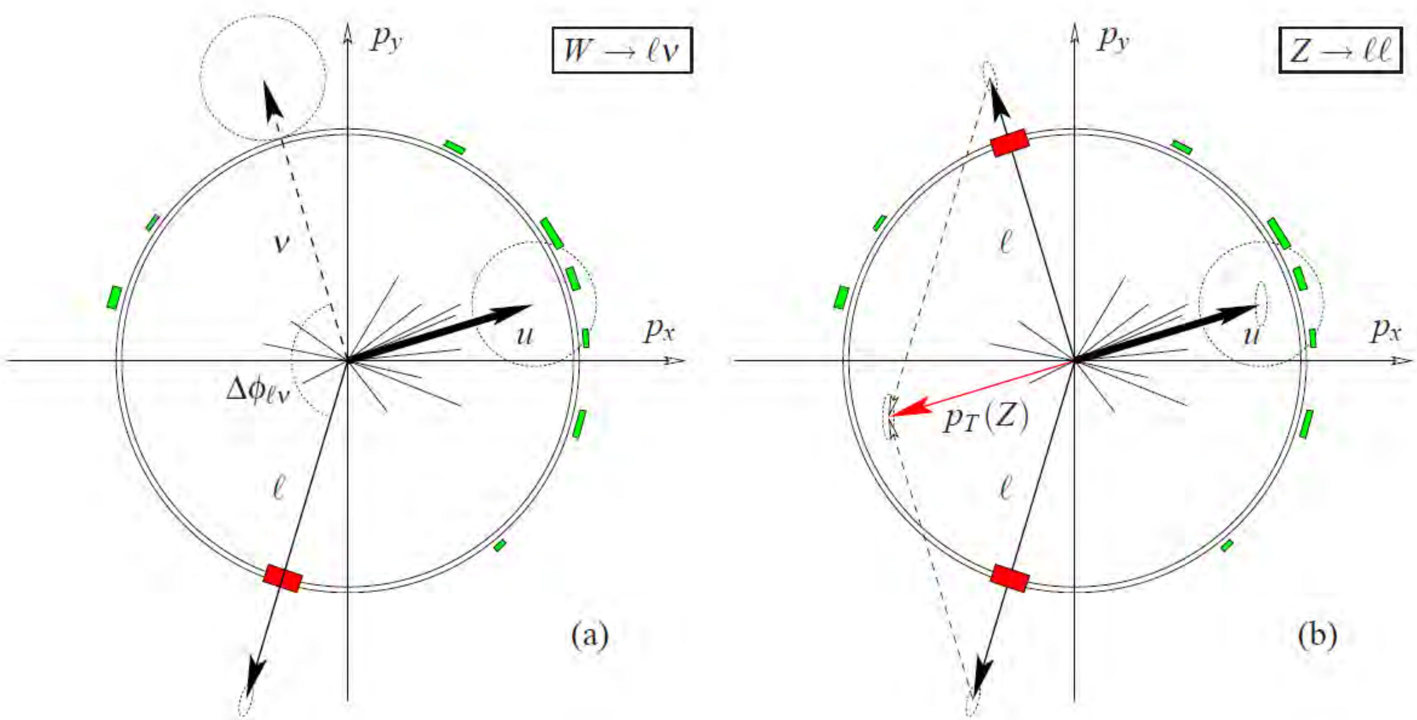
CDF, Phys. Rev. D 89, 072003 (2014)

M_W measurements now dominated by modeling. Requires investing in:

- Ancillary measurements (→ constrain physics model)
- Analysis strategy (→ minimize model-dependence)

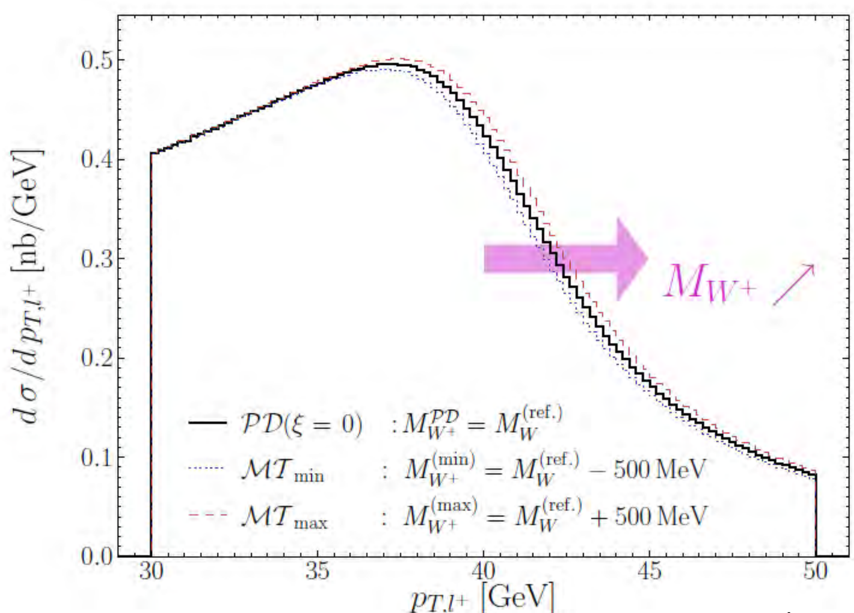
W & Z final states

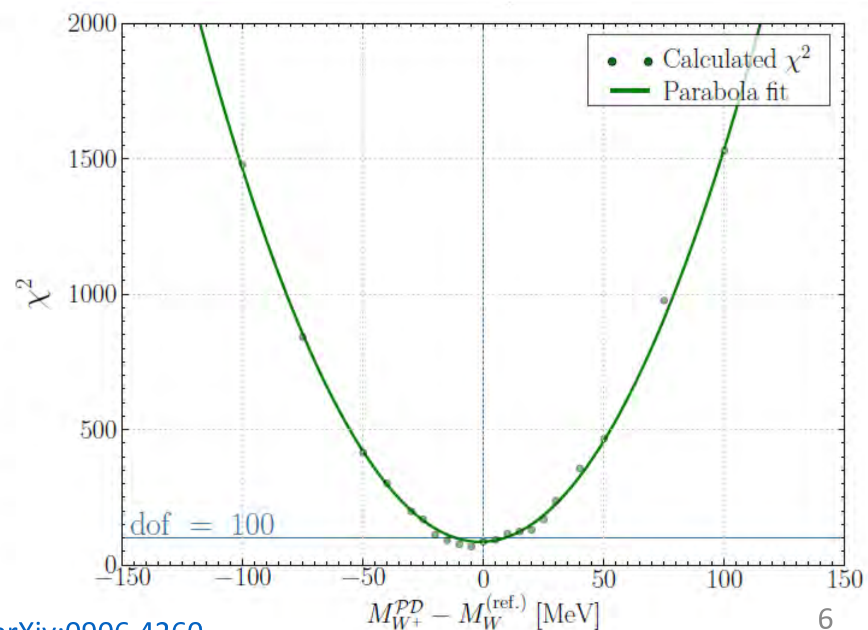
- Basic objects: electron or muon (l); recoil (u)
- Derived quantities in W events:
  - $\overrightarrow{p_T^{\nu}} = -\left(\overrightarrow{p_T^{l}} + \vec{u}\right), \quad E_T^{miss} = \left\|\overrightarrow{p_T^{\nu}}\right\|, \;\; M_T = \sqrt{p_T^{l} p_T^{\nu}(1 - \cos(\Delta\phi)}$
- Z events can be exploited for calibration: $M_{ll} \approx M_Z, \; \vec{u} \approx -\overrightarrow{p_T^{ll}}$



Measurement principle

- Example cuts at the LHC (compromise btw. statistics & systematics), at 7 TeV:
  - ATLAS: $p_T^{l,\nu} > 30$ GeV, $M_T > 60$ GeV, $u < 30$ GeV
    - 6-9M evts/channel $\delta M_W(stat) \approx 6\ MeV$
  - CMS: $55 > p_T^{l,\nu} > 30$ GeV, $100 > M_T > 60$ GeV, $u < 15$ GeV
    - 3-5M evts $\delta M_W\ (stat) \approx 10\ MeV$
- M_W is extracted from the comparison of data with Monte-Carlo templates of the mass-sensitive distributions: p_T^l, M_T

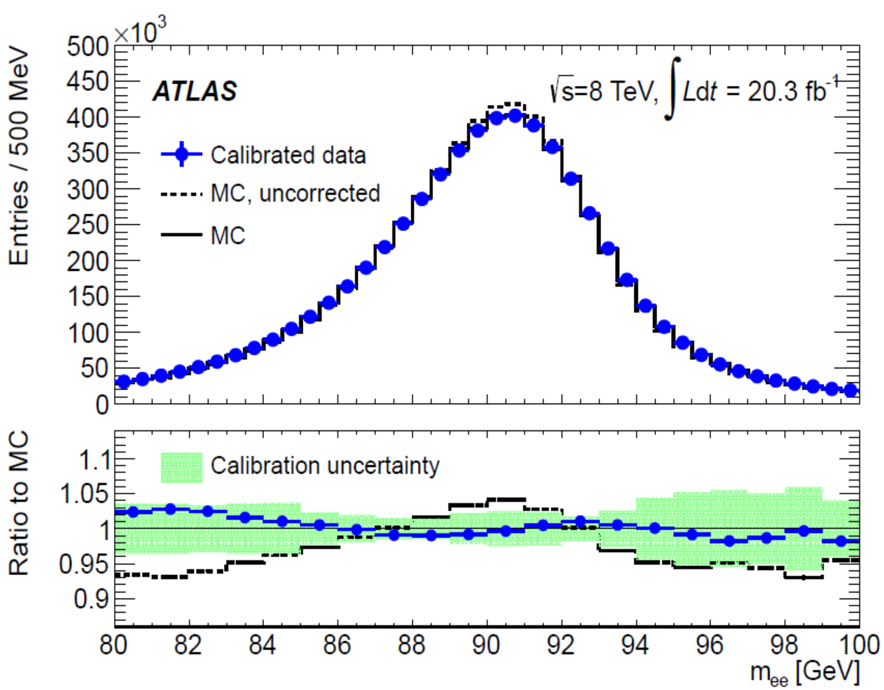




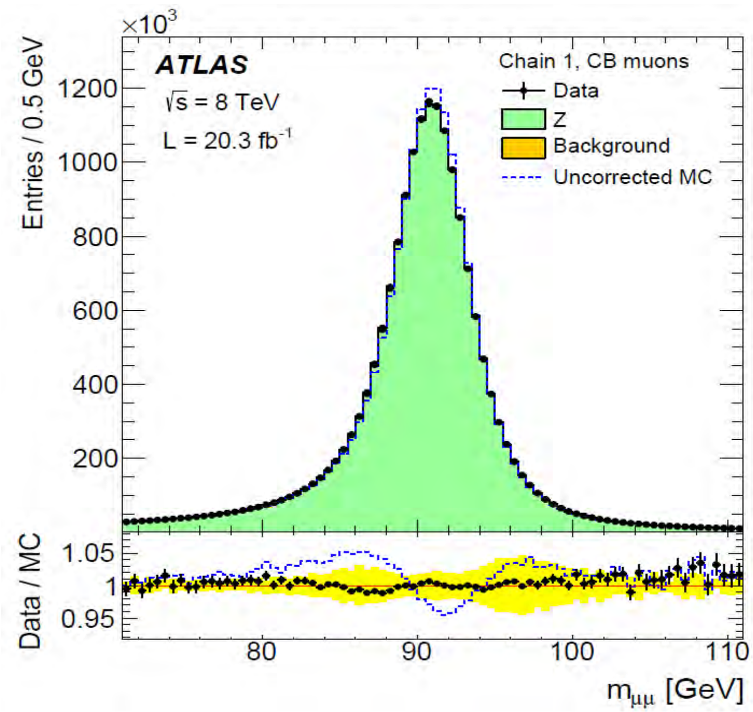
Thesis - arXiv:0906.4260

Lepton calibration

- Z boson sample constitutes the primary calibration reference
  - Probes the energy / momentum scale to <5 MeV/channel
  - >1M evts, RMS of M_{ll} distribution ~3 GeV
- In addition, consider an energy extrapolation uncertainty: $p_T^l \approx \frac{M_Z}{2} \rightarrow \frac{M_W}{2}$
  - E.g ATLAS, electron channel: $\delta E \approx 4 - 5$ MeV over this range.



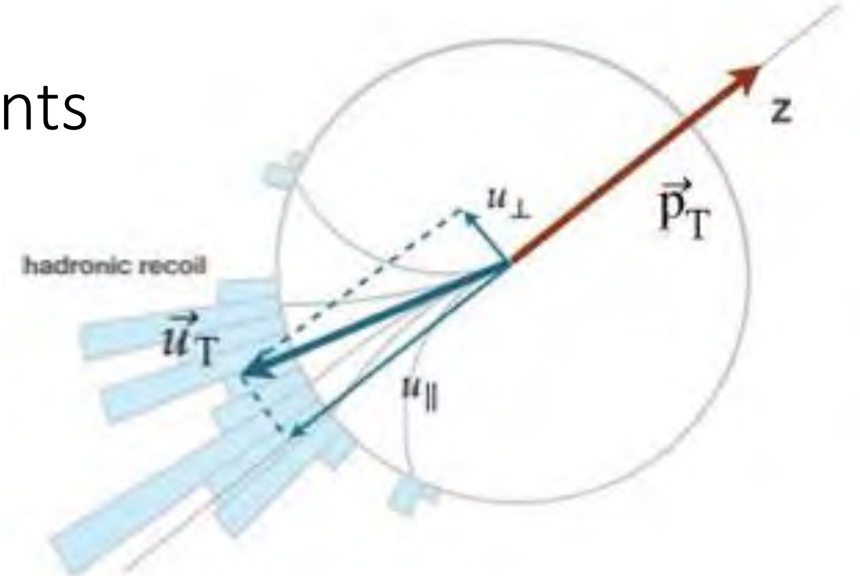
Eur.Phys.J. C74 (2014) 10, 3071

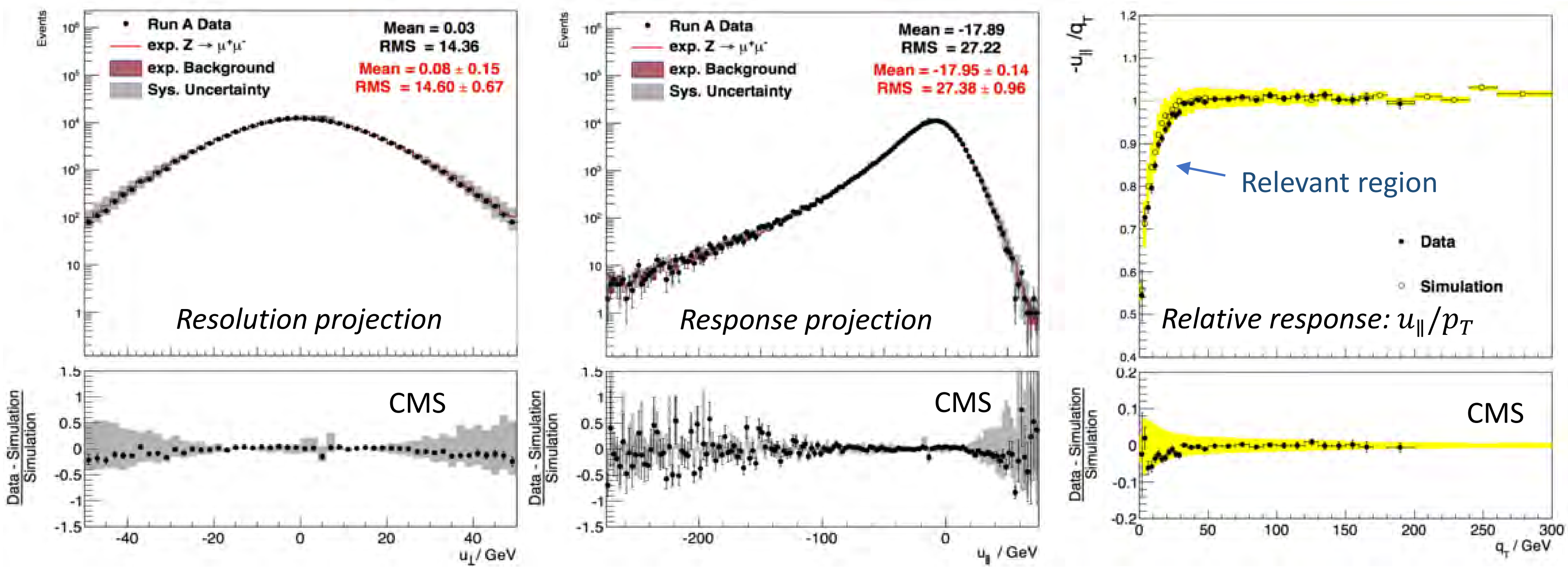


Eur.Phys.J. C74 (2014) 11, 3130

Recoil calibration with Z events

- Useful projections: $u_\perp, u_\parallel$
  - projections of $\vec{u}$ on axis perpendicular resp. parallel to $\overrightarrow{p_T^Z}$
- Use to compare recoil resolution and response in data and MC

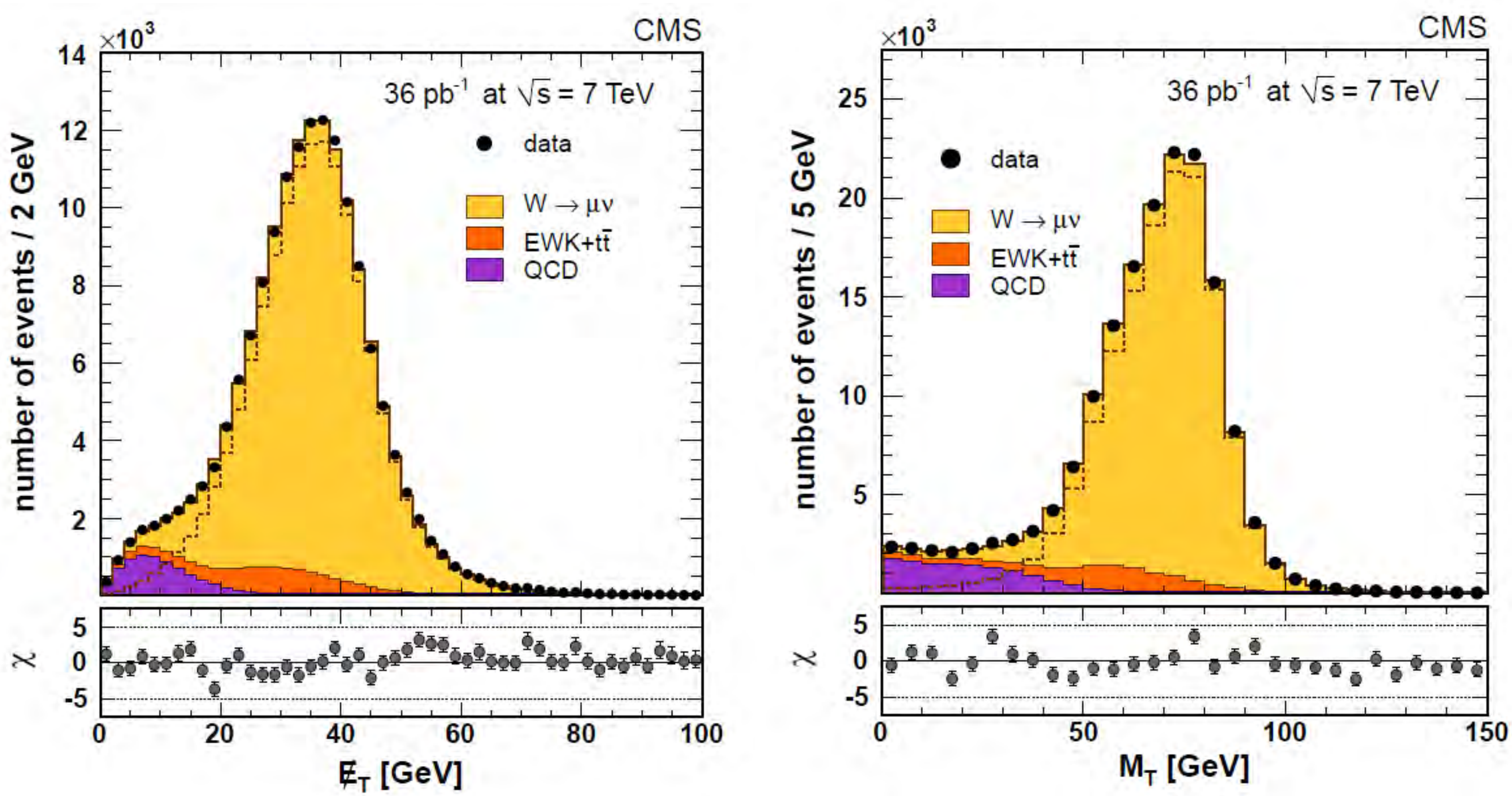




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME2012MET

Kinematic peaks after selections

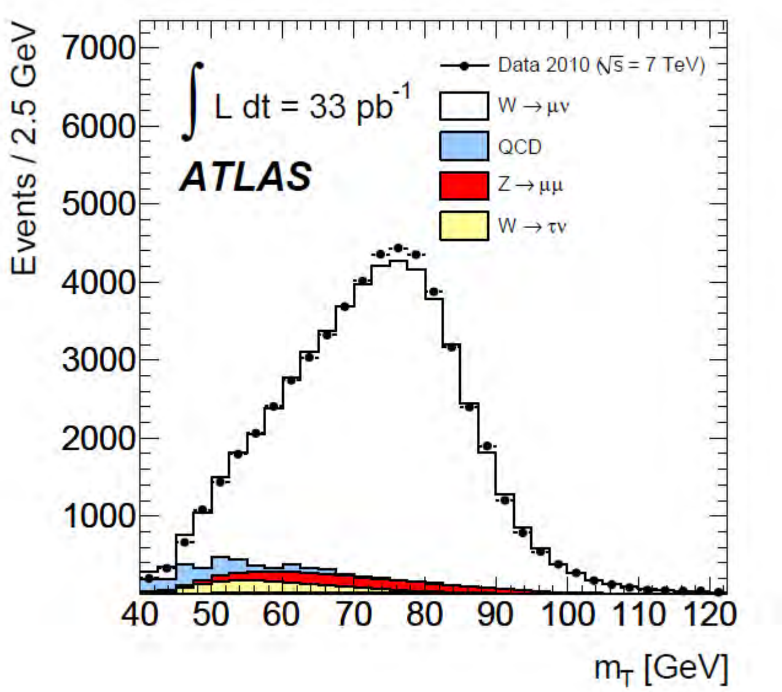
- CMS: from inclusive cross section measurement, 2010 data



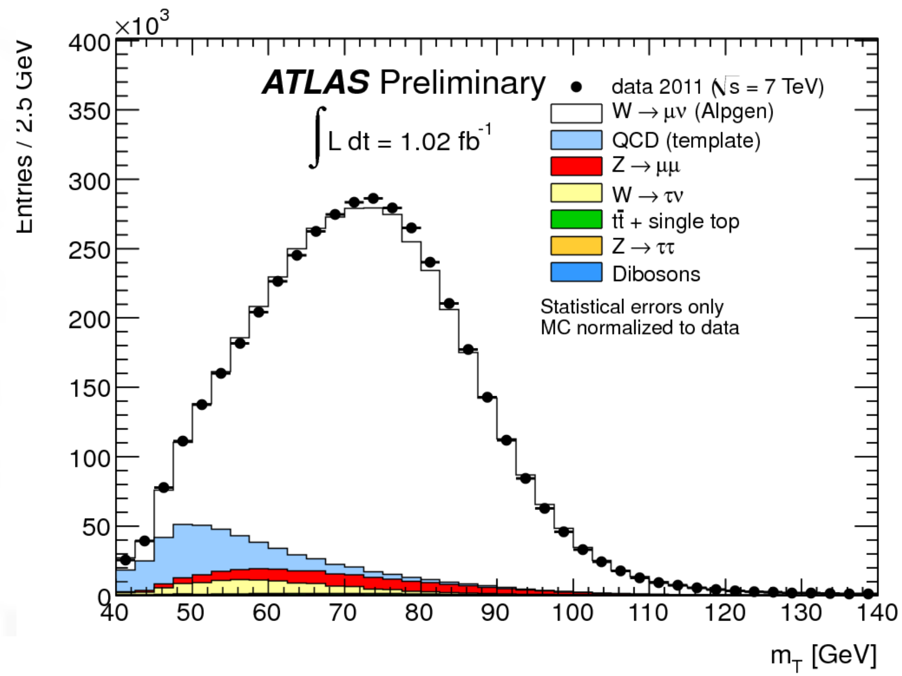
JHEP 10 (2011) 132

Kinematic peaks after selections

- ATLAS: M_T in $W \rightarrow \mu\nu$ at 7 TeV, in 2010 (33 pb^{-1}, μ~1) and 2011 (1st fb^{-1}, μ<5)
  - Visible degradation in the recoil resolution



Phys. Rev. D85, 072004 (2012)



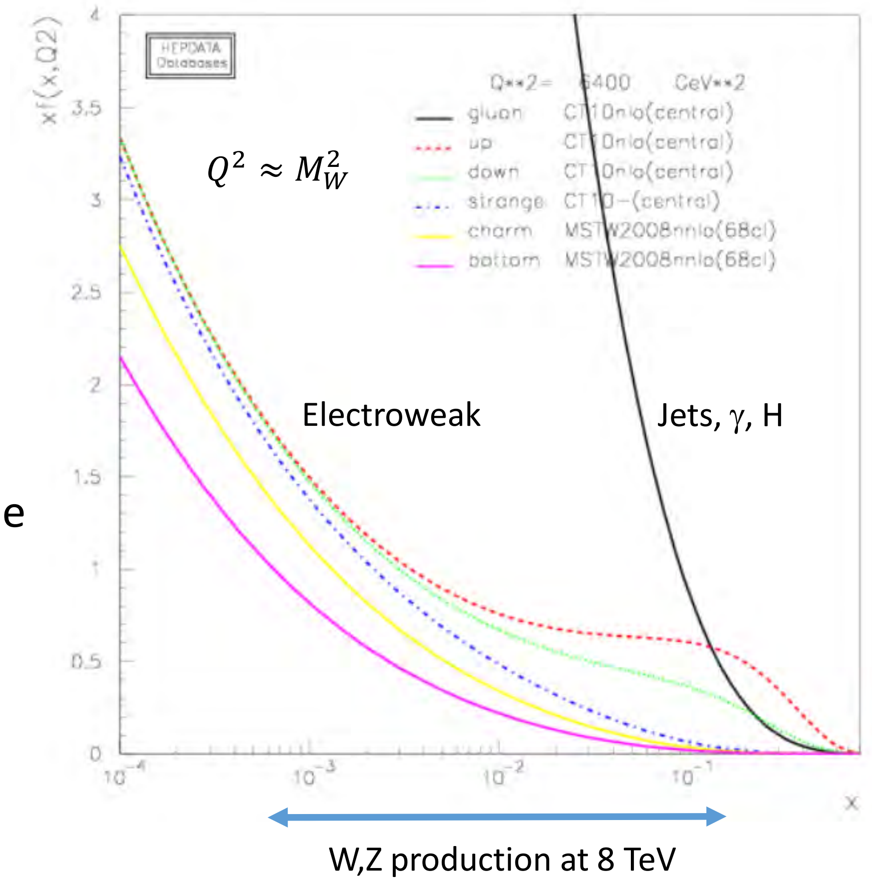
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicCollisionPlots

Proton PDFs and W, Z production

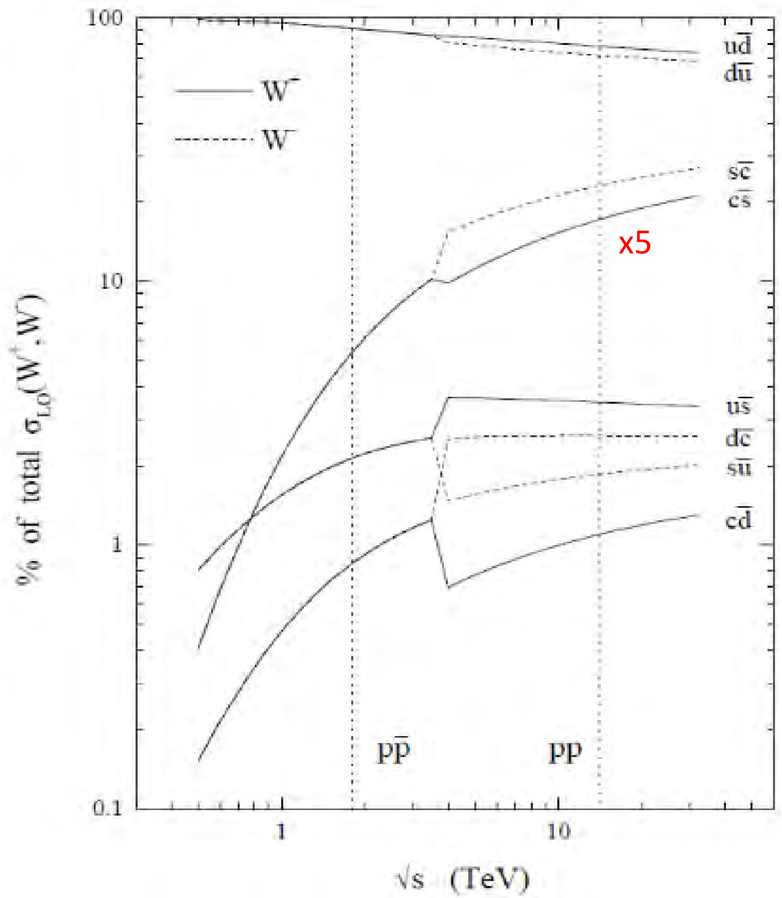
- Pre-LHC: proton model dominated by DIS
    - Measured/fitted: $u_V, d_V, g, sea \quad (\alpha_S)$
    - Theory: $c, b, \mathrm{evol}(Q^2) \quad (\alpha_S)$
    - Assumed: $\bar{u} \approx \bar{d}\ ;\ s \approx \bar{s} \approx \bar{d}/2$

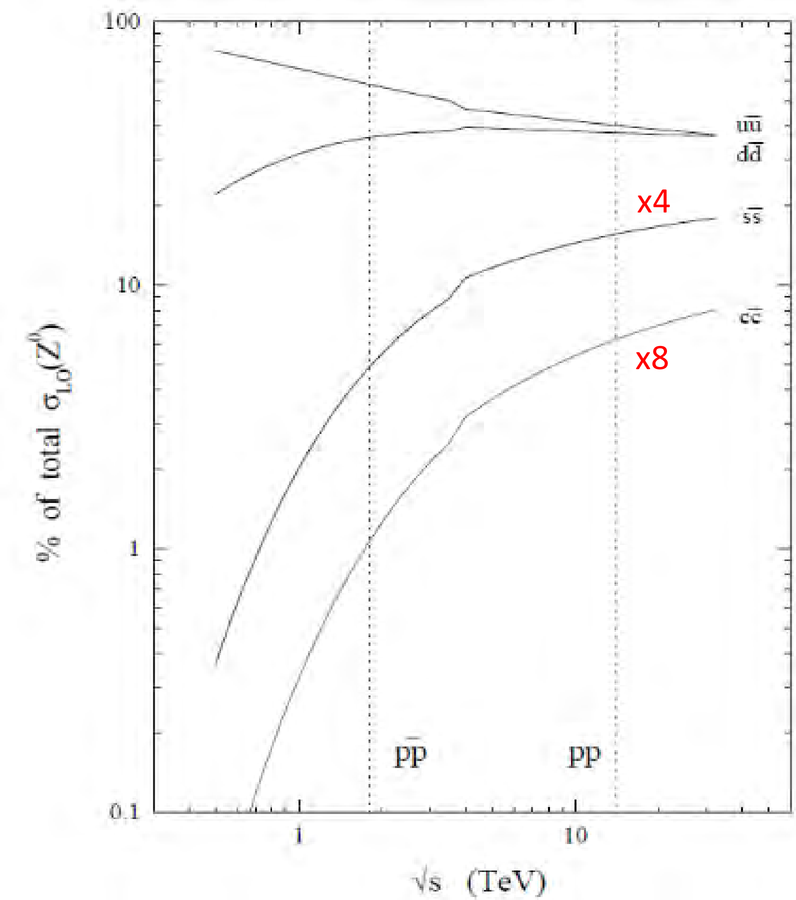
- Very precise data, but little experimental information on the flavour composition of the proton. A (very) simplified view:
    - $\sigma^{NC}, \sigma^{CC} \rightarrow u_V(x), d_V(x), sea(x)$
    - Jet prod. $\rightarrow g(x)$
    - $(F_2^c, \ldots)$

- $Wq\overline{q'}$ and $Zq\bar{q}$ couplings ~flavour democratic
  → Hadron colliders probe different parton combinations than those tightly constrained by DIS



Proton PDFs and W, Z production





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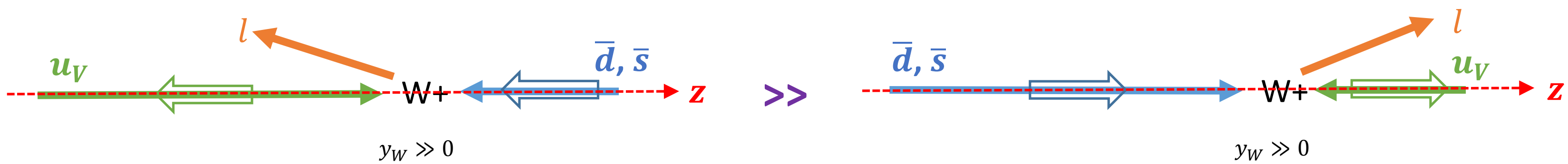
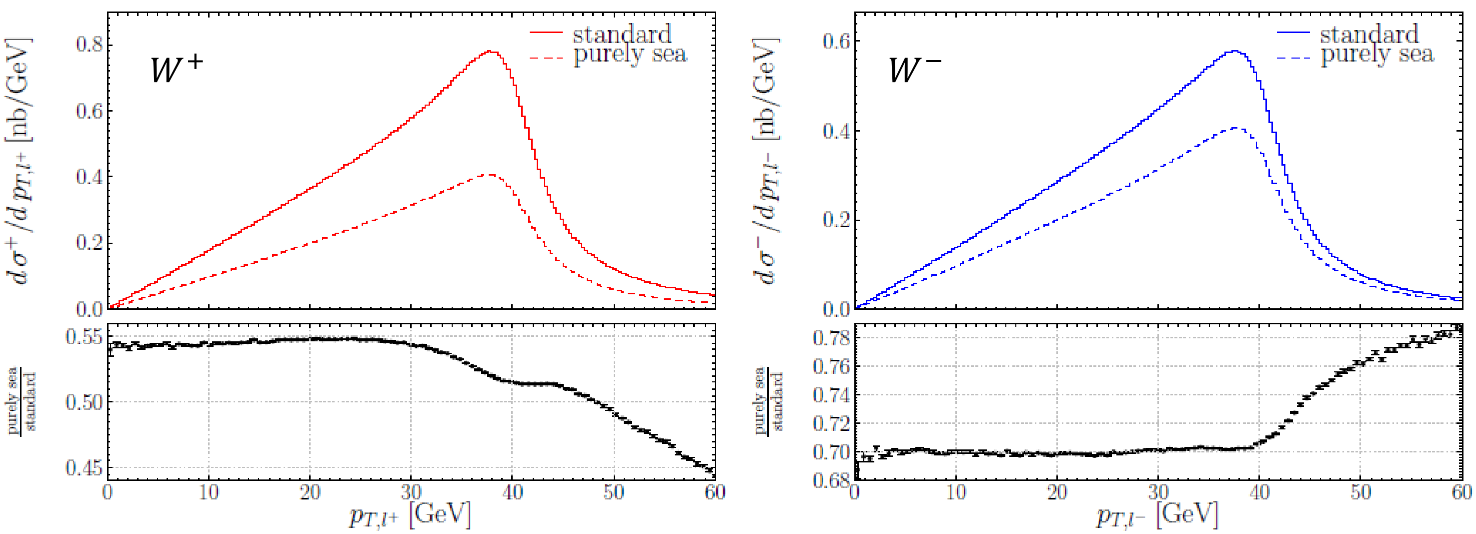
PDF effects on the p_T^l & M_T^W distributions

- Valence/sea PDF uncertainties
  - Determine the rapidity distribution → acceptance effects
  - Valence PDFs polarize the W decay (at any $y_W \neq 0$), with corresponding uncertainties:





Sea: symmetric, unpolarized

Including u_V, d_V leads to an overall polarization along z

Eur.Phys.J.C69:379-397,2010

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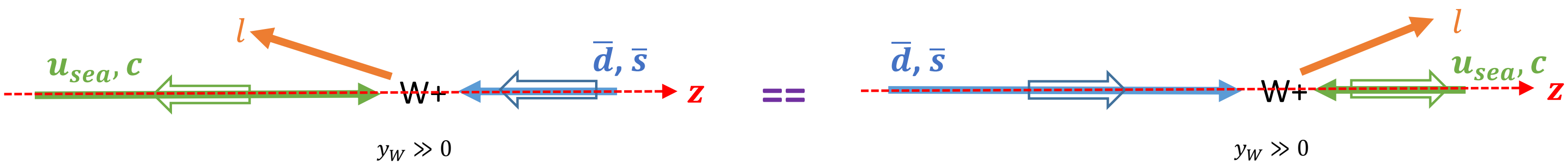

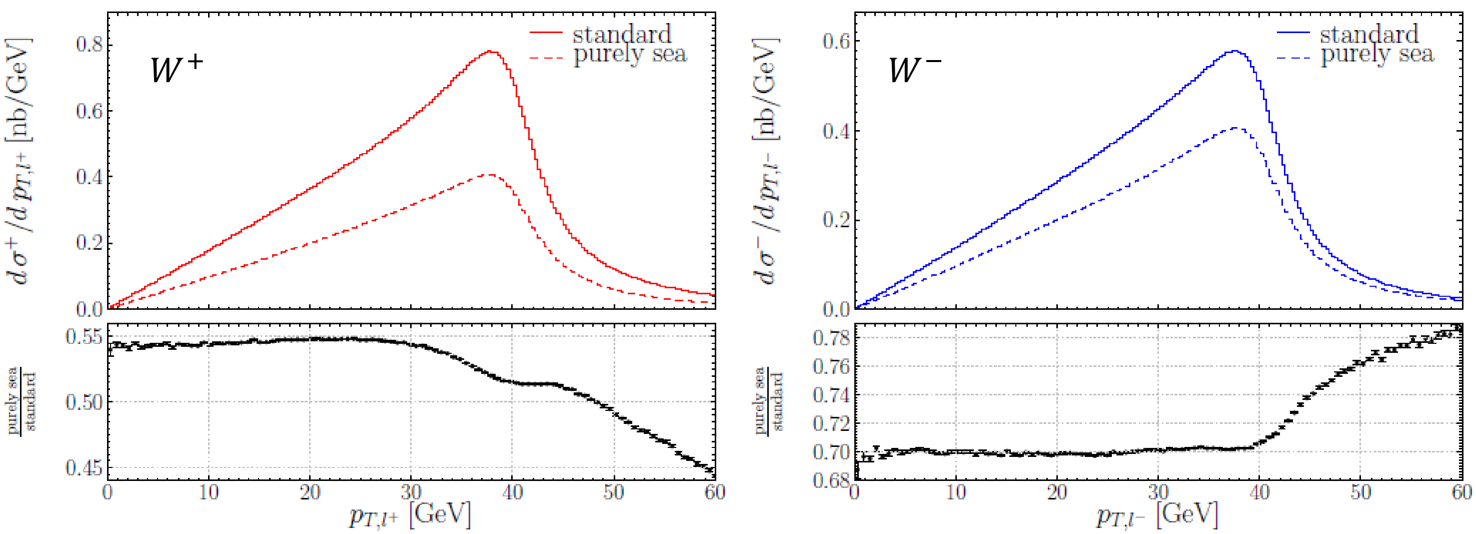

Sea: symmetric, unpolarized

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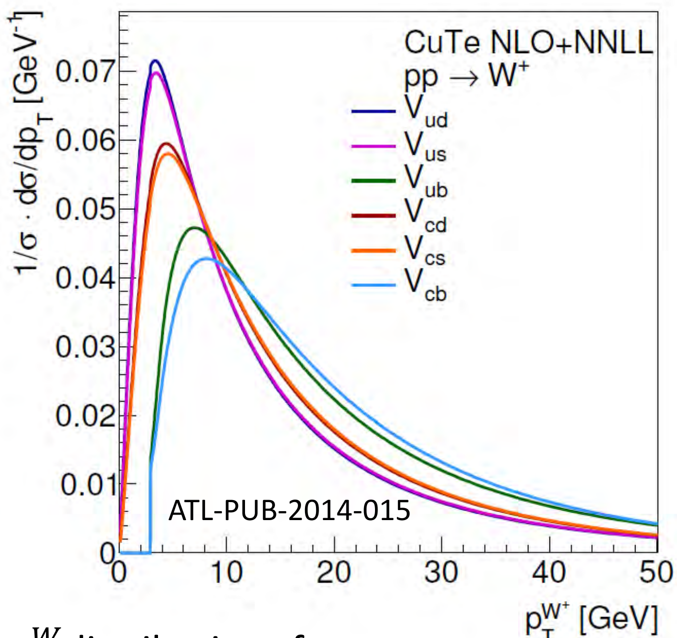
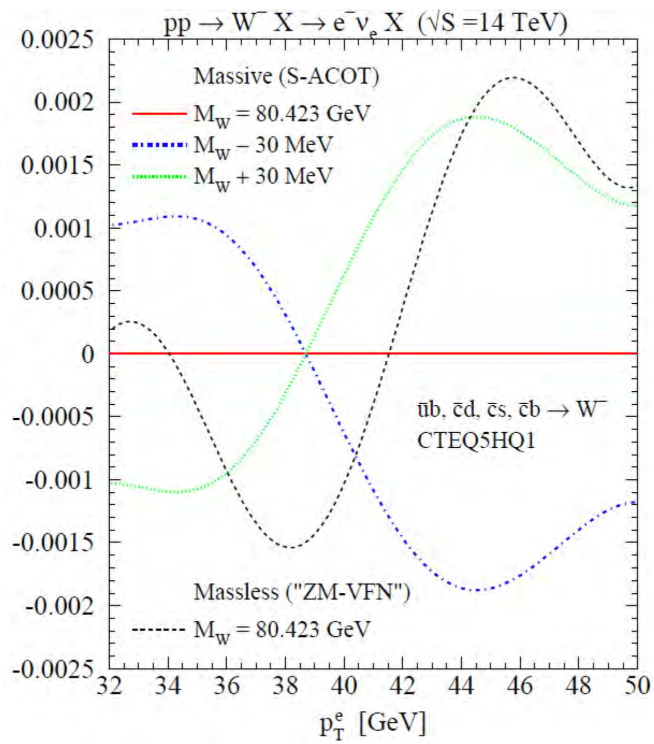
Eur.Phys.J.C69:379-397,2010

PDF effects on the p_T^l & M_T^W distributions

- Transverse momentum distribution uncertainties
  - « physics smearing » of the Jacobian peaks from uncertainties in the p_T^W distribution
  - Contributions from non-perturbative parameters (intrinsic k_T, …) and from heavy quark PDFs



p_T^W distributions for different sub-processes



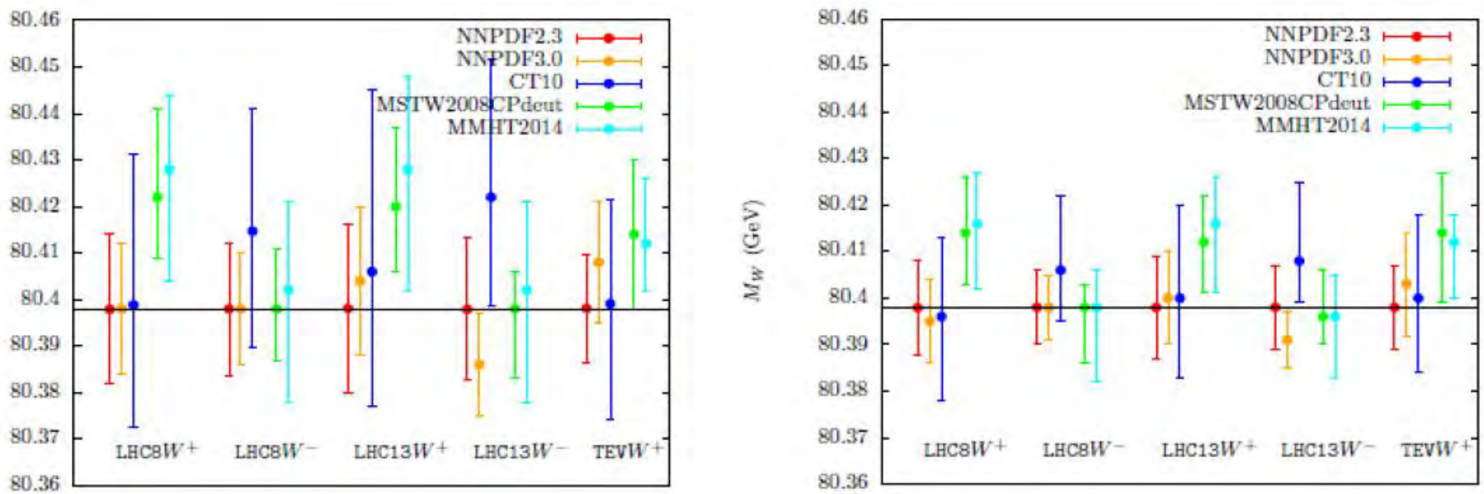
Uncertainty on HQ mass treatment vs. M_W variations

Phys.Rev.D73:013002,2006

PDF effects on the p_T^l & M_T^W distributions

- In short, PDF uncertainties on M_W are dominated by the valence/sea ratio, and by 2nd generation partons
  - (some) anti-correlation between the two effects: enhanced strange & charm PDFs increase the total sea, reducing the impact of valence uncertainties
- Current uncertainty estimates find ~10 MeV for the most optimistic/advanced sets, but differences between sets makes the envelope larger : 20-30 MeV

No u cut



$u < 15$ GeV (gen. level)

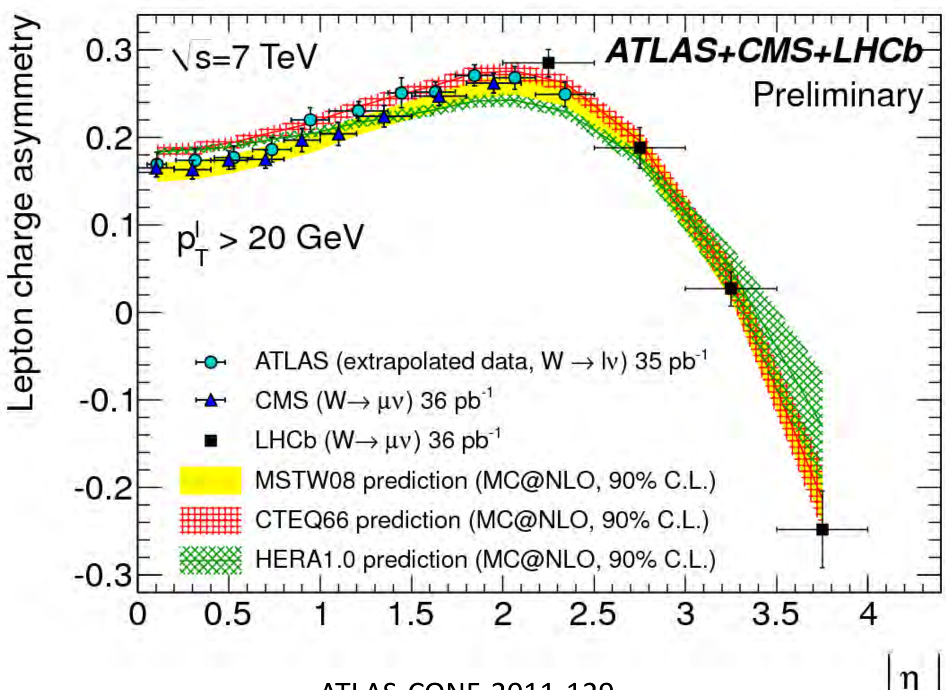
arXiv:1501.05587

- Caveats:
  - PDF uncertainties are generally estimated via an approximate reweighting
  - Detector effects at best partially taken into account

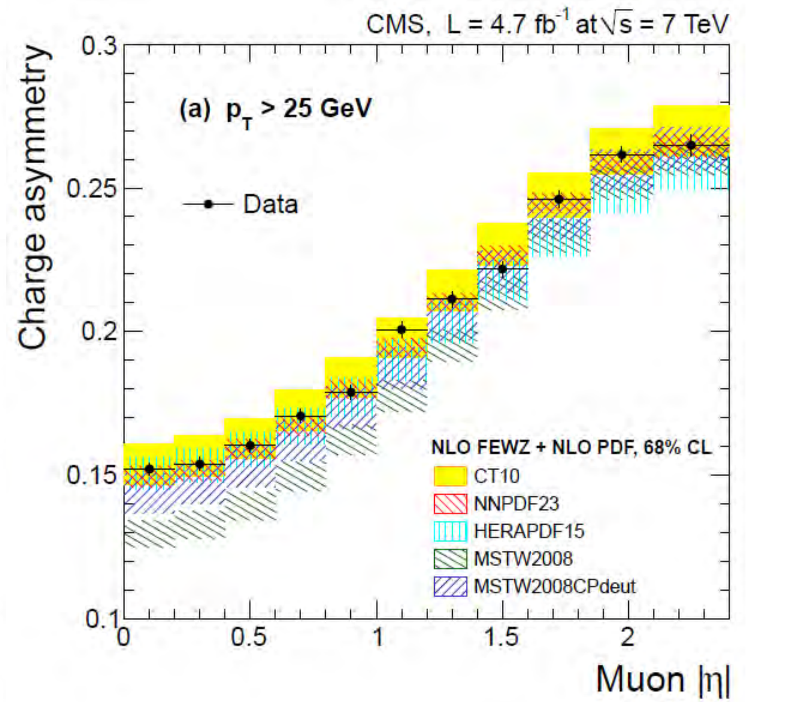
Constraining PDFs: W charge asymmetry

- vs rapidity: $A(y) \approx \dfrac{u_V - d_V}{u_V + d_V + 2\, r_s c}$ ($r_s \approx \bar{s}/\bar{d}$ and assuming $\bar{u} \approx \bar{d}$ and $s \approx \bar{s}$).

- Experiments only access η_{lep}: effect blurred by V-A. Still very discriminating information: probes a mixture of u_V/d_V and second generation quark PDFs



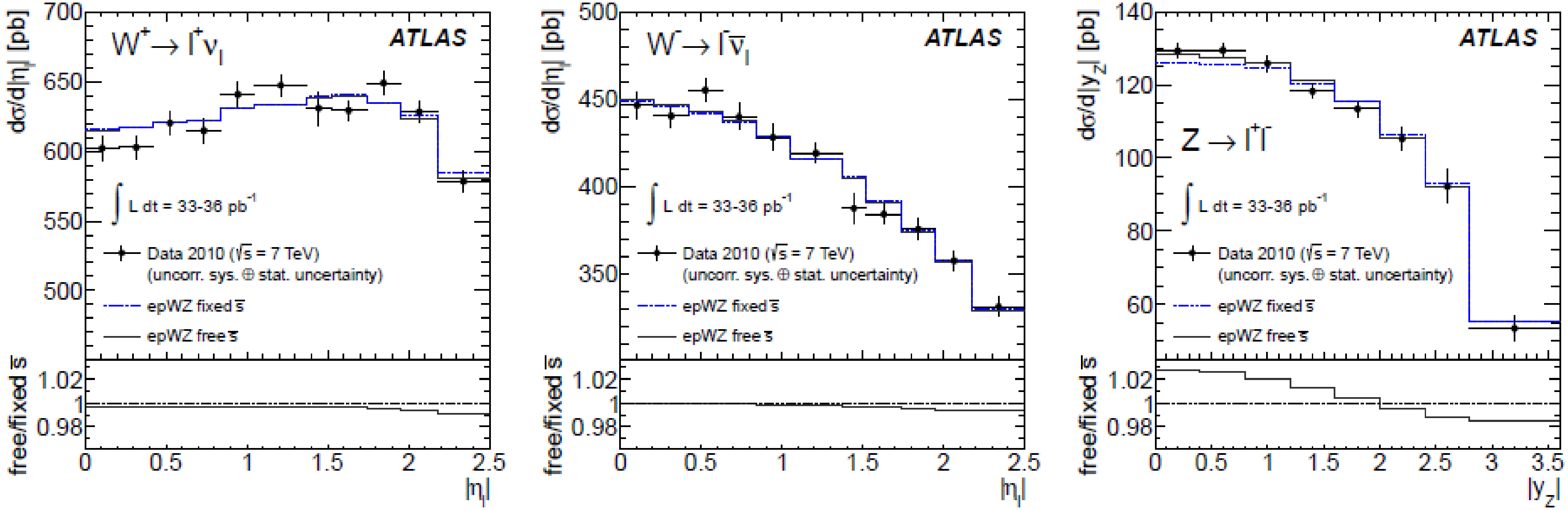
ATLAS-CONF-2011-129



Phys. Rev. Lett. 109 (2012) 111806

Constraining PDFs: W & Z cross sections and distributions

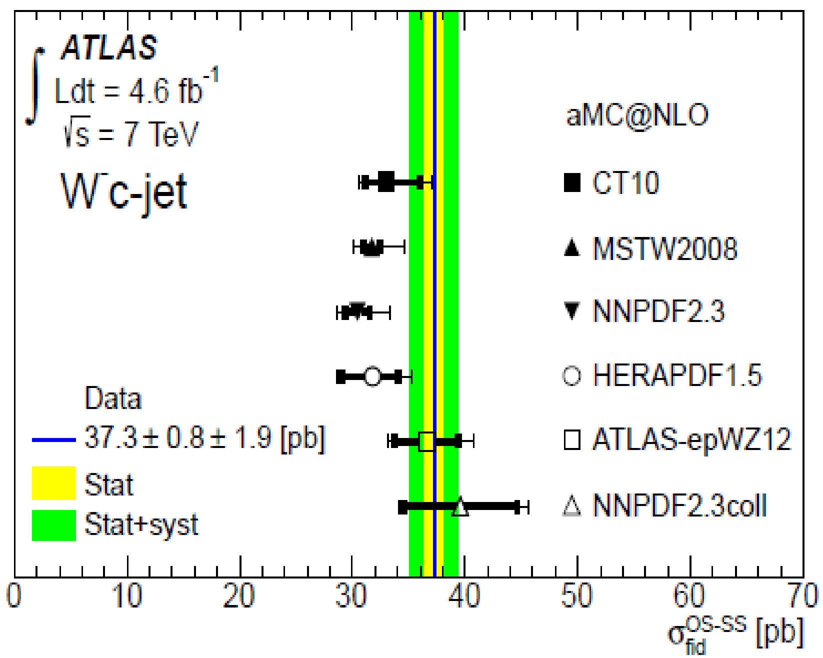
- Detailed measurements performed by ATLAS, CMS, LHCb
- Measured enhancement of Z production at $y_Z \approx 0$ is interpreted as enhanced strange density. Increasing $s(x)$ (to $r_s \approx 1$) catches the Z data, leaving W distributions mostly unchanged:



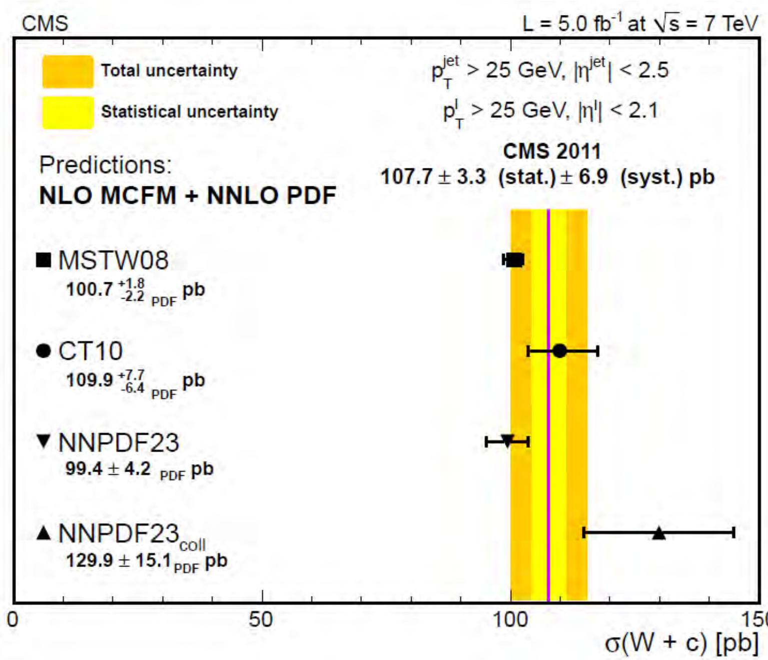
Phys.Rev.Lett. 109 (2012) 012001

Constraining PDFs: $W + D$ & $W + c$

- Direct probe of the strange density (at LO): $g\bar{s} \to W^+\bar{c}$, $gs \to W^-c$
- Final states used: $Wc(c \to \mu), WD^{\pm}, WD^*$
  - Complication: final state definition. Quark, parton or hadron level?
- ATLAS tends to « see » more charm:



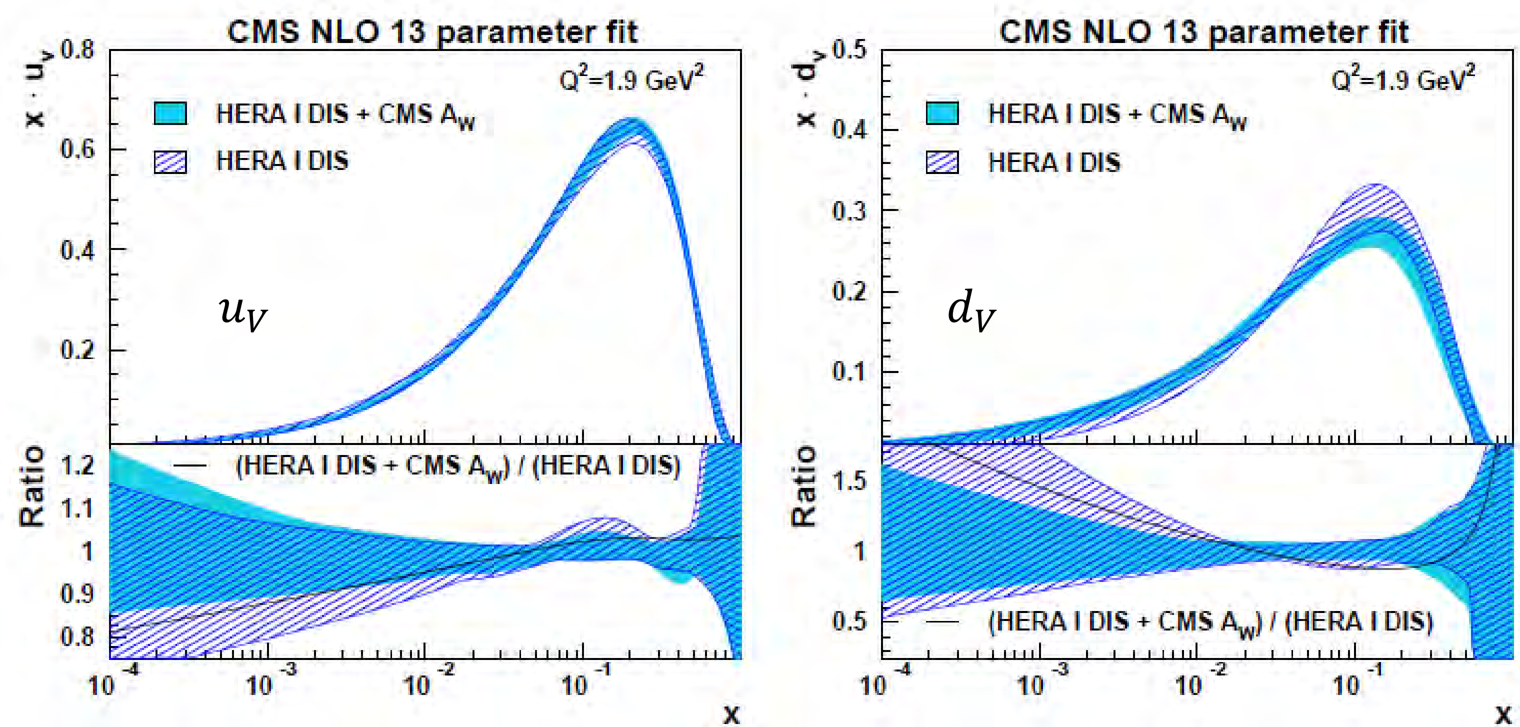
JHEP 05 (2014) 068



JHEP 02 (2014) 013

Implications: Valence distributions

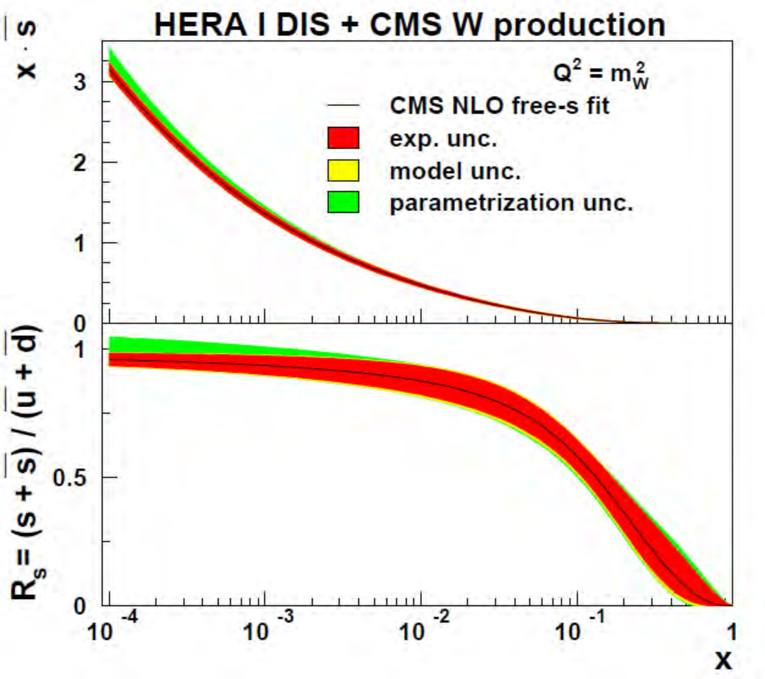
- Strategy (largely common to ATLAS and CMS): use HERA data by necessity; add only collider data
  - Avoid data subject to larger theoretical uncertainty
- Impact of asymmetry measurement: most significant improvement in d_V
  - d_V has more freedom as u_V is better constrained by HERA data



Phys. Rev. Lett. 109 (2012) 111806

Implications: Strange density

- Marginal agreement: ATLAS sees $r_s \approx 1$ (consistently in W/Z ratios and W+c), CMS prefers $r_s < 1$ for $x >\approx 10^{-2}$ at $Q^2 \approx M_W$
- Impact: ~20% difference in charm-induced W production, affecting y_W, p_T^W



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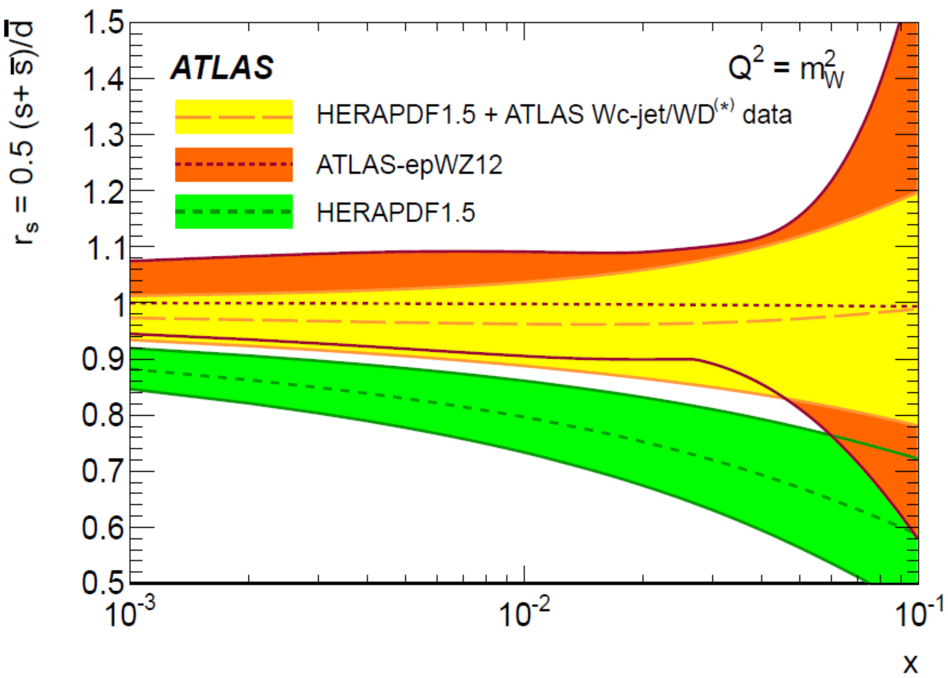
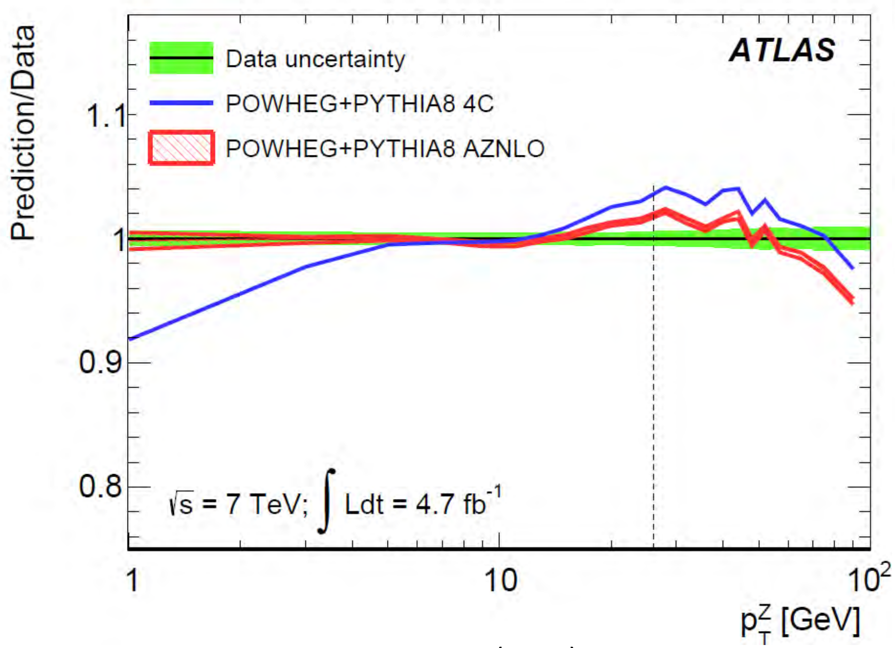


JHEP 05 (2014) 068

Modeling of p_T^W: constraints from p_T^Z

- Traditional ansatz: W and Z production are analogous, and non-perturbative effects are universal and factorize from PDFs
  - Measure p_T^Z, tune parton shower (or resummation params.), apply to W
  - Constraints from ATLAS measurement: $\delta M_W < 5$ MeV, assuming no extrapolation uncertainties
- Caution needed at the LHC: Z, $W^+$and W^-all have different contributions from 2nd and 3rd generation PDFs (4-8 times larger than at the Tevatron)



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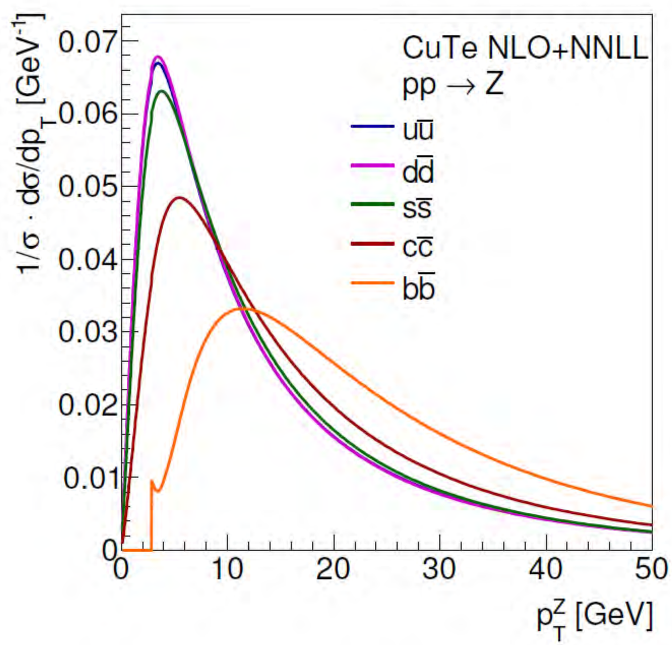
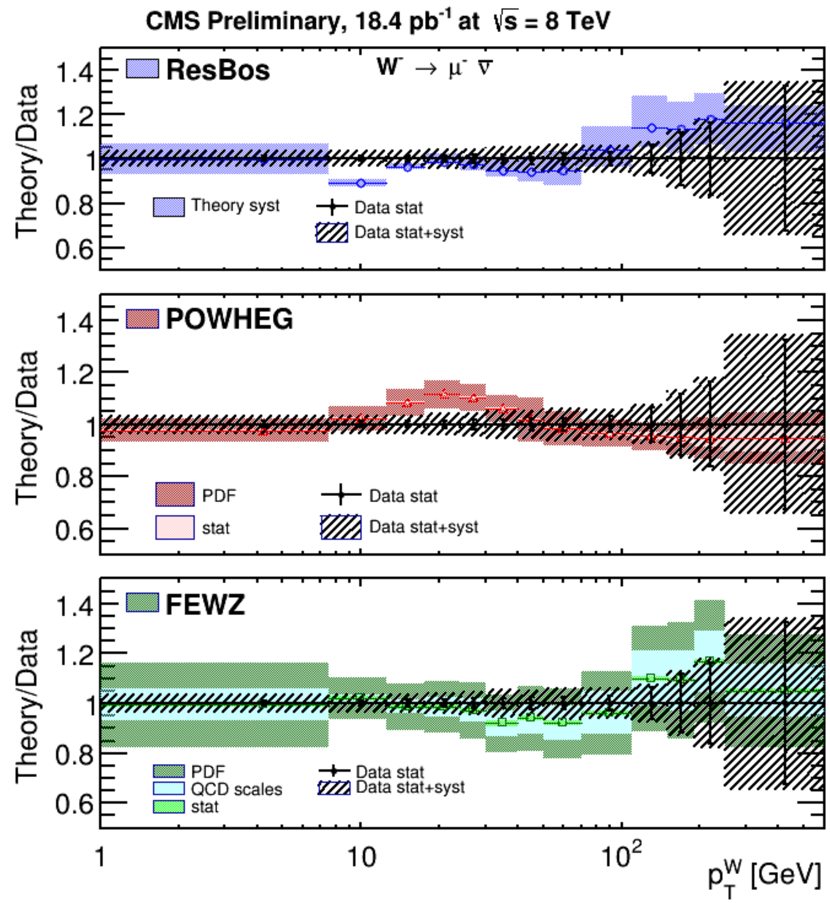


An alternative : direct measurement of p_T^W

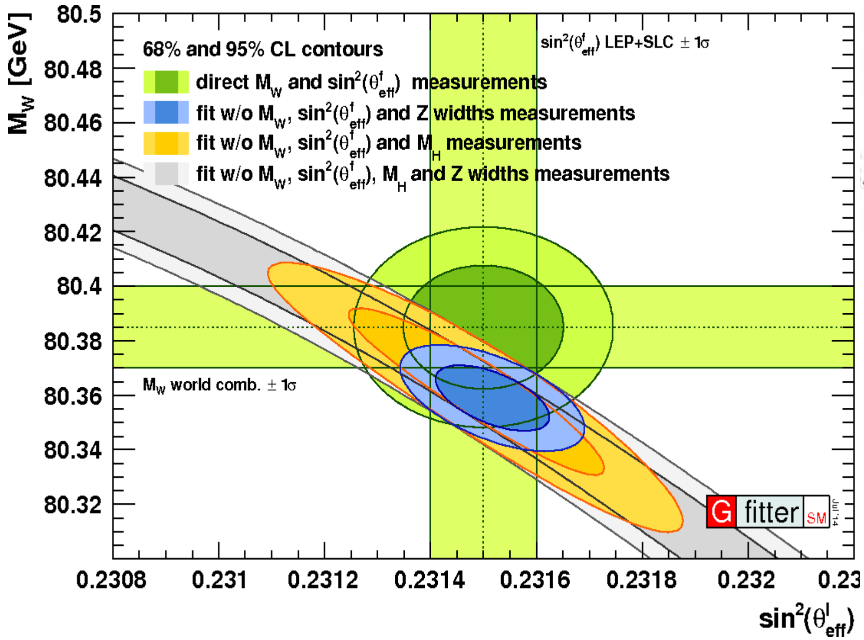
- Unfolded measurement of the recoil distribution, from ATLAS (35 pb-1, 7 TeV) and CMS (18 pb-1, 8 TeV). Requires low pile-up conditions
- Experimentally poorer than p_T^Z, but avoids a significant theoretical extrapolation
  - At low p_T: 3-5 bins, 2-3% accuracy for W (compared to ~10 bins with ~0.5% accuracy for Z)
- Worthwhile to pursue with larger luminosity
  - Needs $\approx 250\ \mathrm{pb}^{-1}$ at $\mu \approx 1$, driven by Z statistics

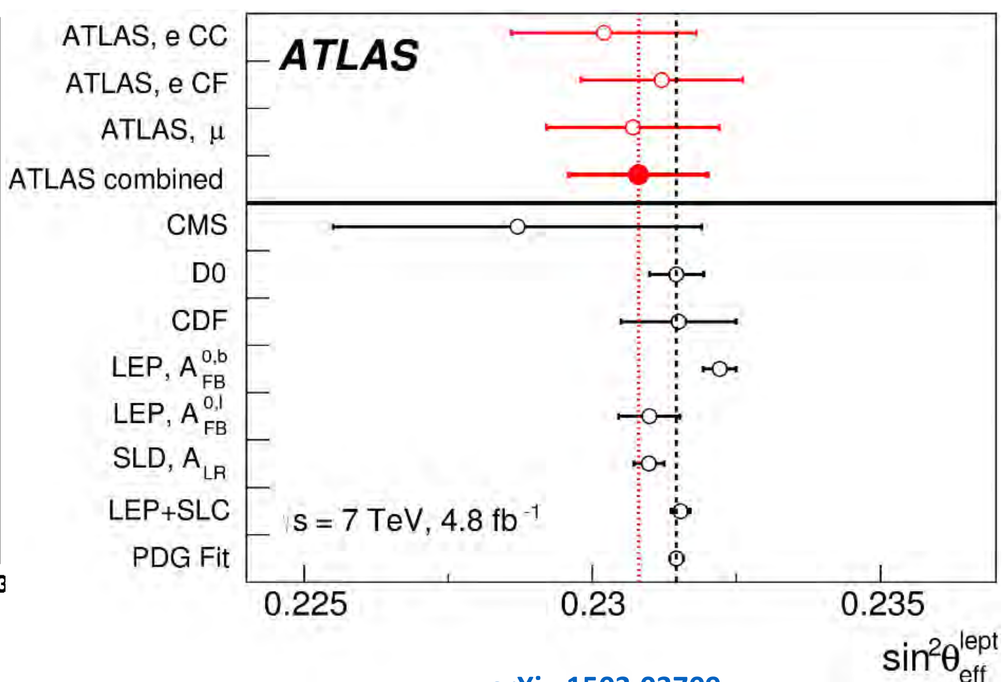


CMS-PAS-SMP-13-006

A_{FB} and $\sin^2\theta_W$

- Recent ATLAS result: $\sin^2\theta_W \approx 0.2308 \pm 0.0012$; PDFs contribute 75% of the uncertainty
- Uncertainty ~10 times the world average, but only ~4 times that of the leading (and discrepant) measurements, and near the size of the LEP-SLC discrepancy: pursuing this type of measurements will help clarifying the overall picture
- Improved PDF constraints are as critical as for M_W





arXiv:1503.03709

Summary

- Detector calibration is at the level required for a first competitive measurement.

- Physics modeling of W production is a major challenge. Factorizing the longitudinal and transverse QCD degrees of freedom is not maintainable.
  - A consistent treatment should rely on a combined PDF / resummation analysis.
  - Most relevant effects to disentangle:

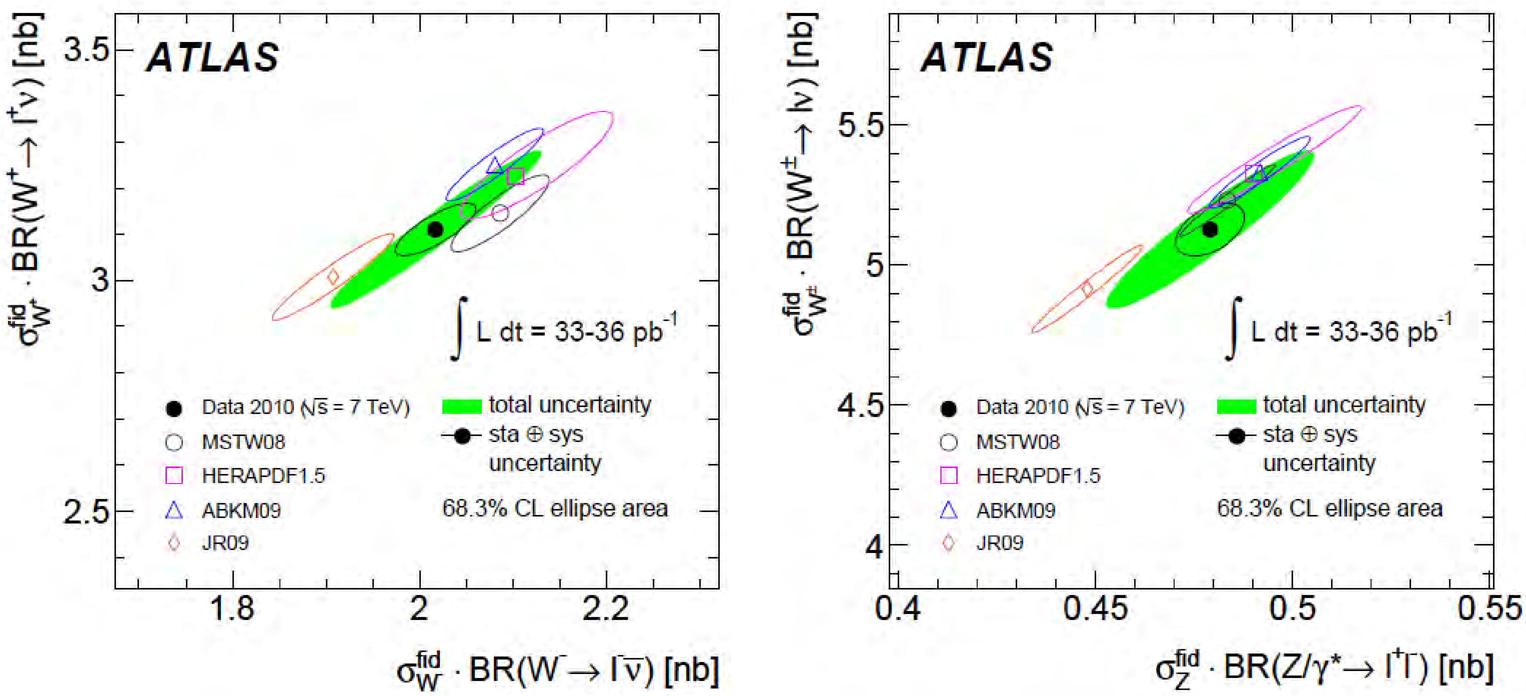
    valence PDFs; 2nd generation partons; resummation parameters
  - Theoretical estimates of PDF uncertainties give $\delta M_W \approx 20 - 30$ MeV. Precise estimates at the analysis level will strongly depend on the measurement procedure

- DY measurements are critical to constrain the models.
  - W&Z cross sections; W charge asymmetry; W+charm of particular importance for the PDFs
  - p_T^Z can be measured very accurately, but PDF flavour decomposition is a pre-requisite for a correct interpretation of this measurement.
  - Measuring p_T^W provides less ambiguous constraints. Needs a significant low-pile-up data sample
  - Existing measurements are %-level or below: check experimental consistency ahead of higher-level interpretation!

Back-up

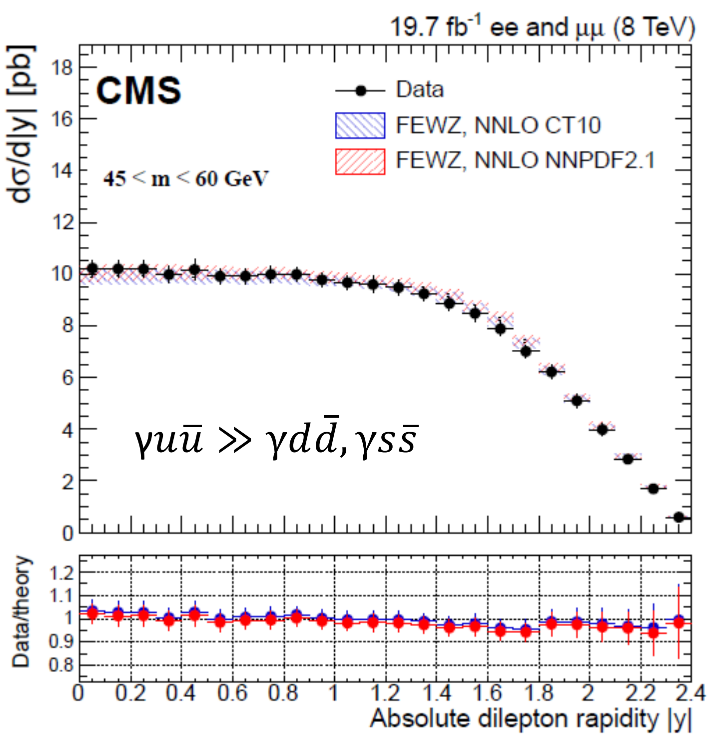
Constraining PDFs: W,Z inclusive cross sections & distributions

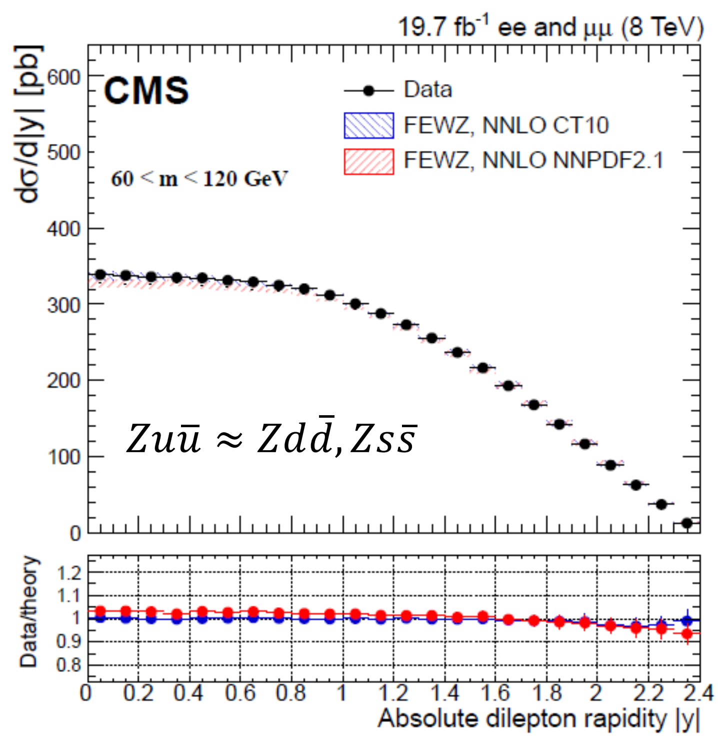
- Total cross sections are a test of the overall parton-parton luminosity. Ratios and distributions allow a partial decomposition of flavour contributions
- ATLAS: inclusive W & Z cross sections (7 TeV data, 33-36 pb-1)



Constraining PDFs: Drell-Yan production at and away from the Z peak

- Direct (x,Q2) mapping of neutral-current parton-parton luminosity
- Potential flavour separation via the different γ^* and Z couplings to quarks
  - Down-type fermions suppressed in $\gamma^* \rightarrow q\bar{q}$
- CMS rapidity distributions in DY production (8 TeV, 20 fb-1)





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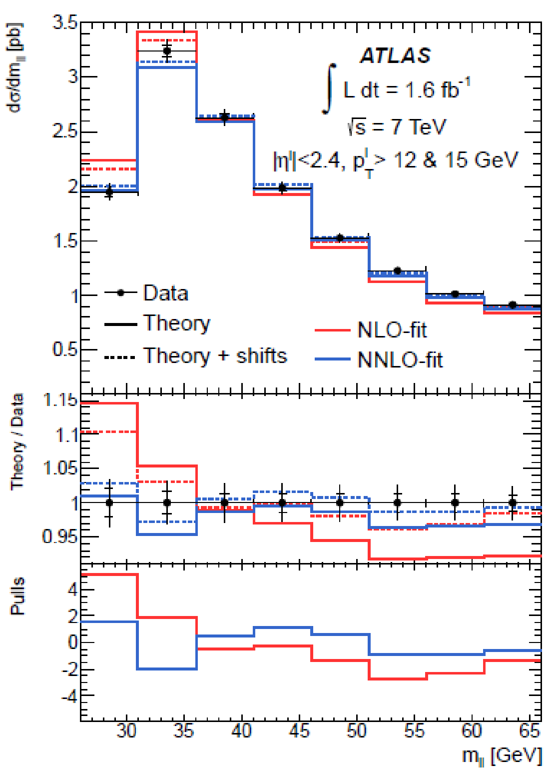
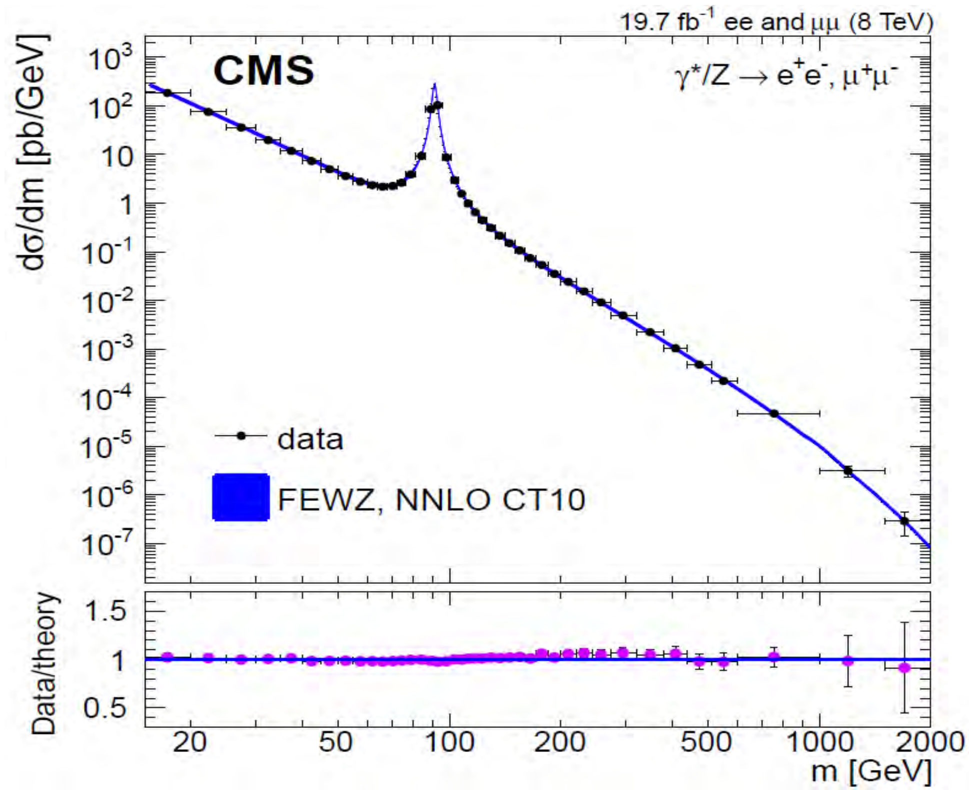
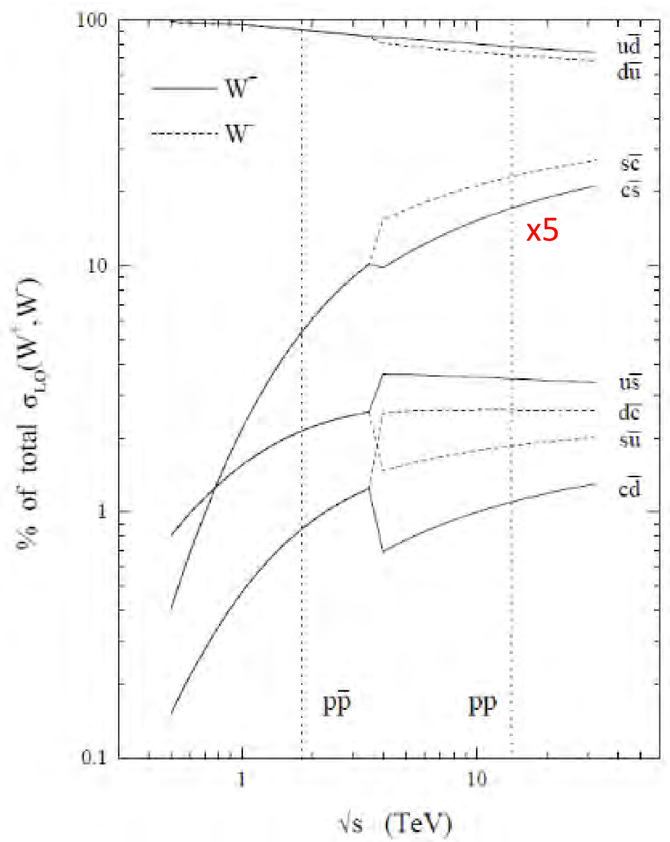
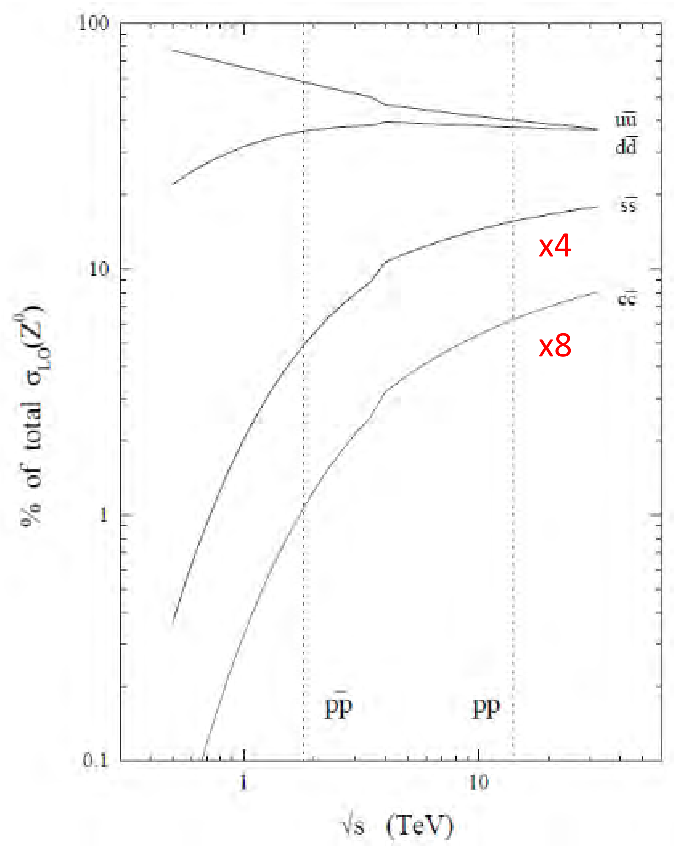
- Potential flavour separation via the different γ^* and Z couplings to quarks
  - Down-type fermions suppressed in $\gamma^* \rightarrow q\bar{q}$
- NNLO QCD is needed to describe the data; NLO predictions are insufficient.





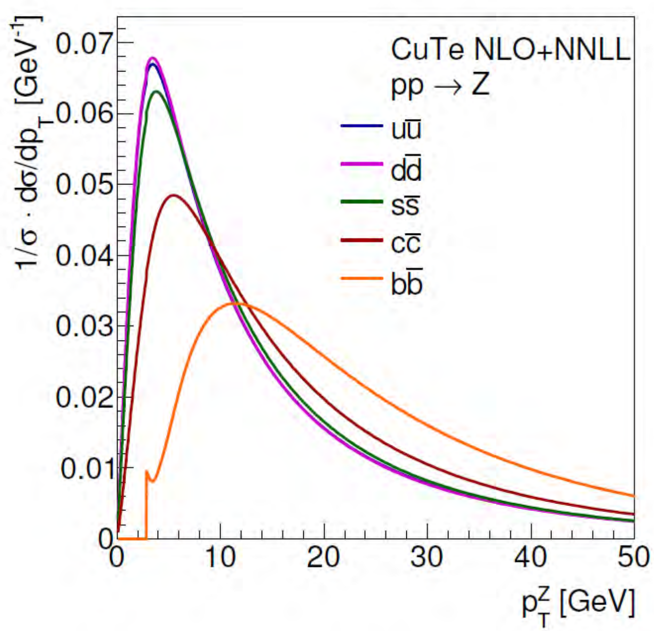
Partonic contributions to W,Z production : Tevatron → LHC

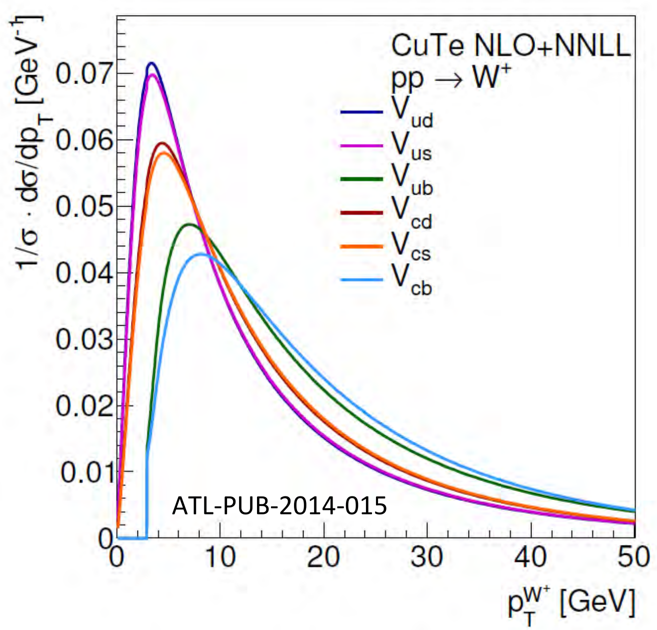




$p_T^Z \rightarrow p_T^W$ extrapolation: effect of flavour composition

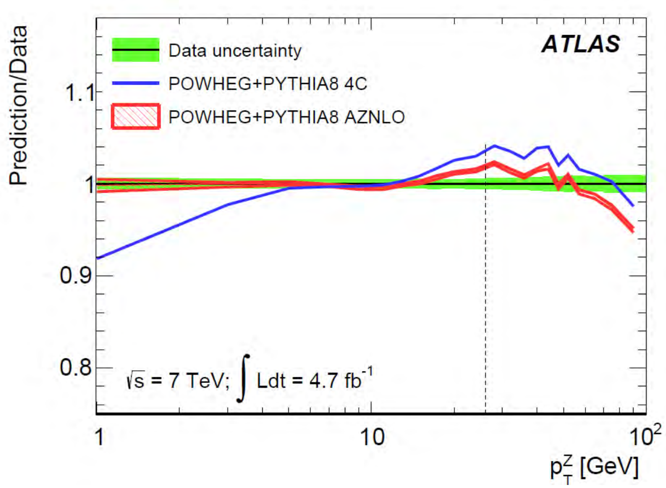
- The inclusive p_T^Z spectrum combines several parton configurations with different shapes. If the assumed u/d/s/c/b fractions are wrong, the resulting effect is wrongly absorbed in the non-perturbative parameters, and transmitted to p_T^W

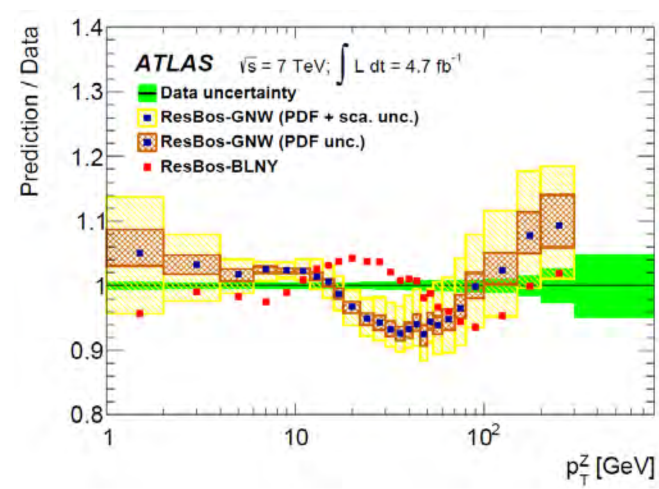




Modeling of p_T^W: constraints from p_T^Z

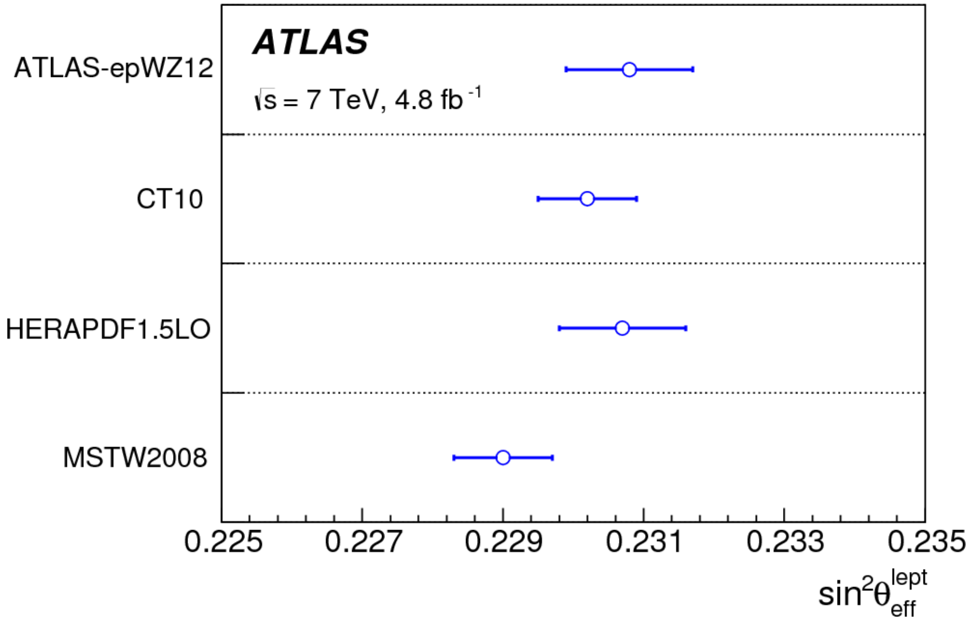
- Traditional ansatz: W and Z production are analogous, and non-perturbative effects are universal
  - Measure p_T^Z, tune parton shower or resummation, apply to W
  - Impact of ATLAS measurement: $\delta M_W < 5$ MeV, assuming no extrapolation uncertainties
- This was justified at the Tevatron (up to now) but is questionable at the LHC:
  - W+ and W- production very different in pp (vs $p\bar{p}$); influence of 2nd generation PDFs ~5 times larger
  - Visible PDF dependence in data/theory comparisons: ~3% in low-pT region





arXiv:1406.3660

Afb systematics



	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
CC electron	$0.2302 \pm 0.0009(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF}) = 0.2307 \pm 0.0015$
El. combined	$0.2308 \pm 0.0006(\mathrm{stat.}) \pm 0.0007(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2308 \pm 0.0013$
Combined	$0.2308 \pm 0.0005(\mathrm{stat.}) \pm 0.0006(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF}) = 0.2308 \pm 0.0012$