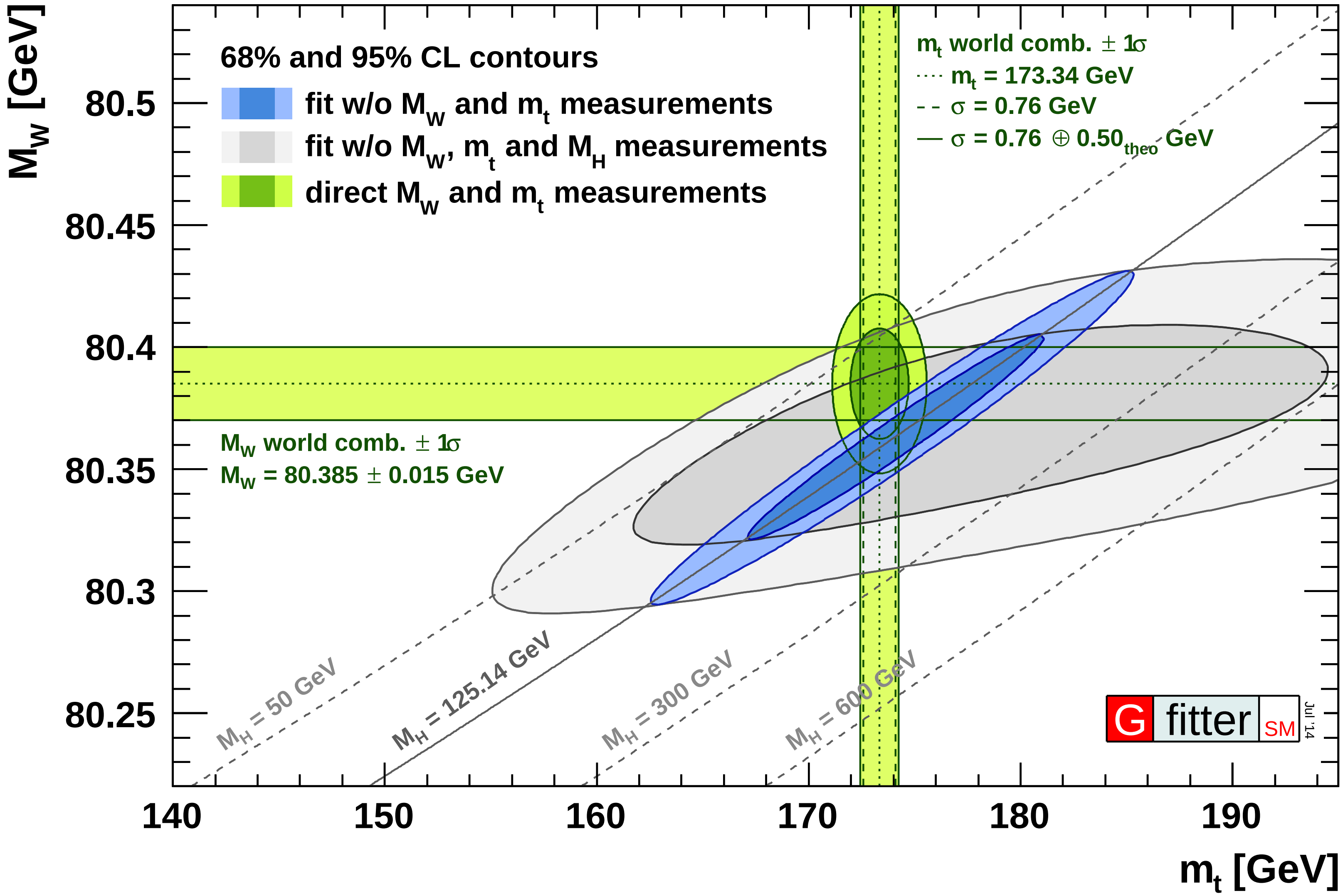
Towards W-boson mass measurement at the LHC

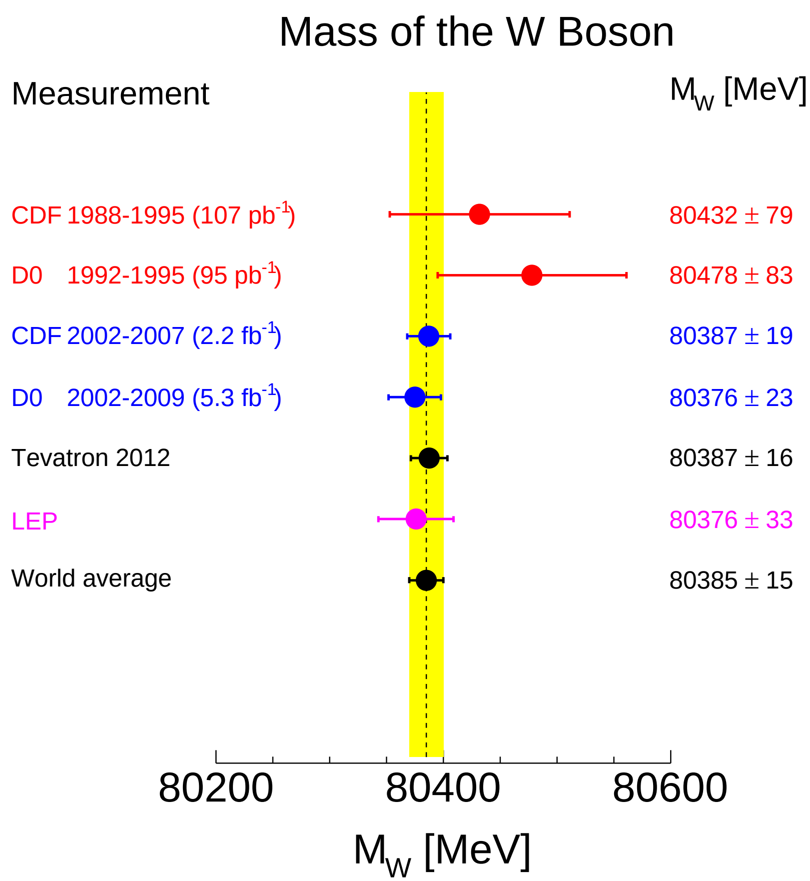
S. Glazov, UC Santa Barbara, 28 March 2016

Motivations for M_W measurement



Sensitive closure test of the Standard Model.

Status



- Measurements from Tevatron surpass LEP in accuracy
- Further results from Tevatron are expected
- Target accuracy for the LHC should be better than 10 MeV.

Experimental and theoretical challenges at the LHC

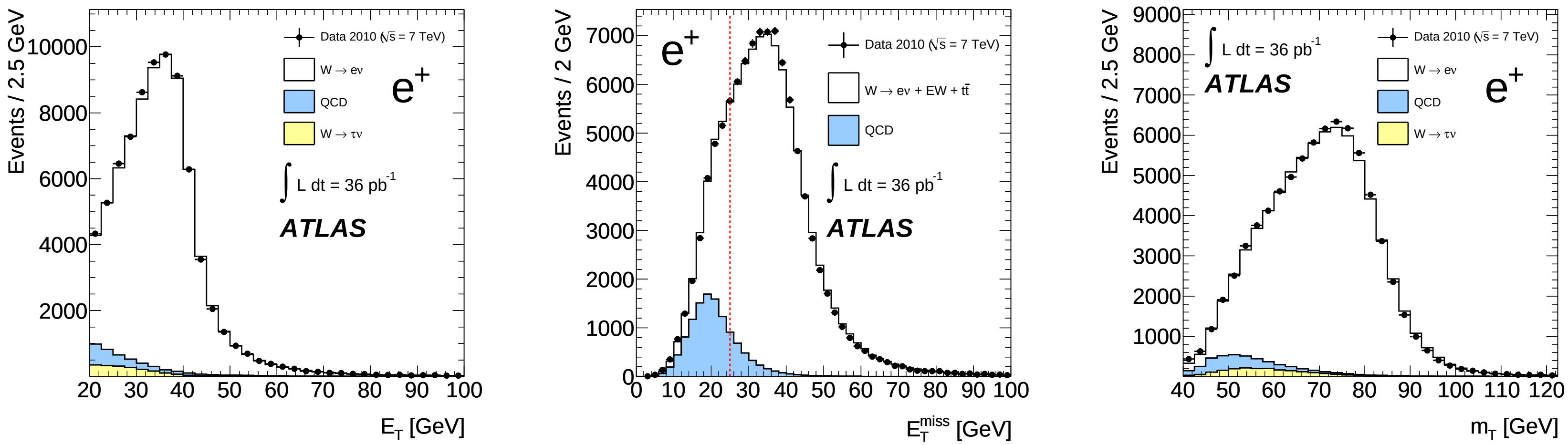
- Large samples of W and Z bosons (for calibration).
- Well understood ATLAS and CMS detectors, with wide rapidity coverage.

However:

- W^+ and W^- have different production/decay properties.
- The main calibration sample, Z boson production has different PDF decomposition
- W transverse momentum, polarisation need to be modeled with high accuracy.

$\rightarrow$ an accurate measurement of M_W is only possible by using a theoretical model which takes into account all aspects of W production and which is calibrated using accurate auxiliary measurements at the LHC.

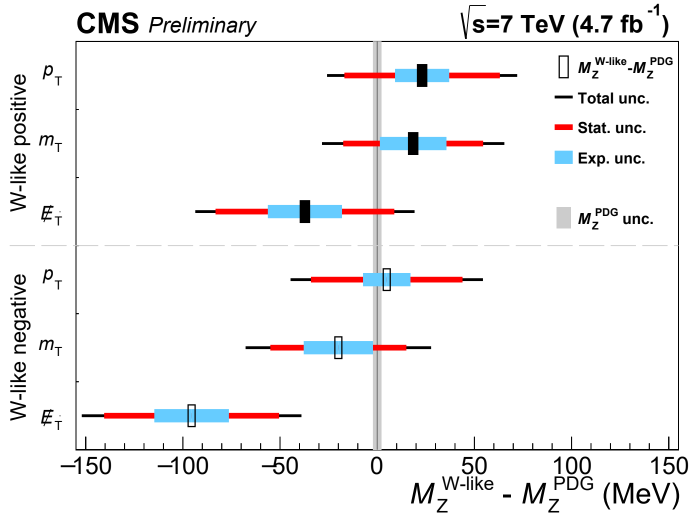
Main experimental techniques to measure M_W



- Fit lepton ($e^{\pm}$ and $\mu^{\pm}$) p_T distribution around Jakobian peak. Most accurate experimentally, robust to pileup, most prone to W p_T modeling problems.
- Fit missing energy distribution $E_T^{\rm miss}$. Requires modeling of hadron recoil. Hard in case of large pileup.
- Fit transverse mass M_T. Needs good $E_T^{\rm miss}$ reconstruction. Least prone to modeling issues.

Fits can be performed using binned in η-lepton, which can be useful to control PDF effects.

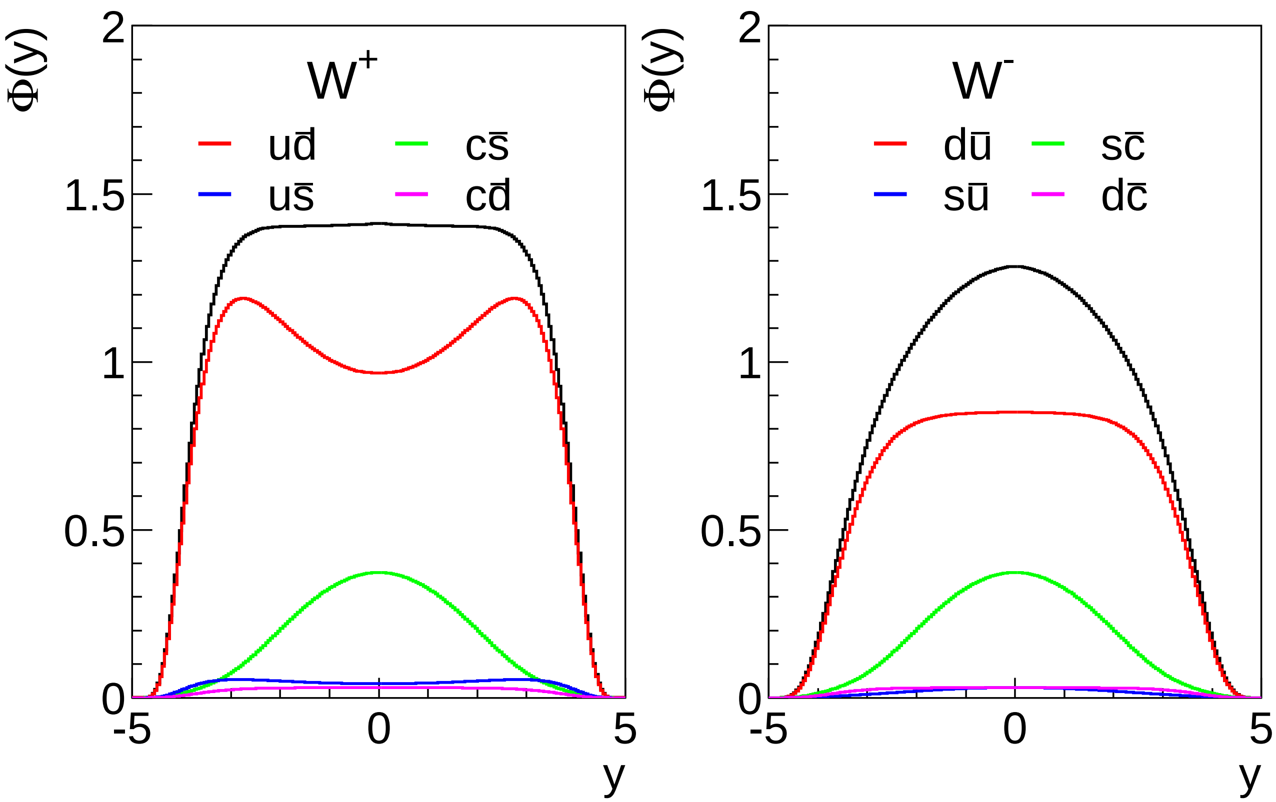
M_Z measurement by CMS (PAS SMP-14-007)



- W-like measurement of M_Z using muon p_T, E_T^{miss} and transverse mass M_T.
- Leptons removed, to emulate neutrinos from W events
- Calibration using J/ψ samples. A sample of $2x10^5$ events used.
- Fits and estimation of uncertainties adjusted to the W-mass analysis
- Leading systematics: QED radiation ($\sim$ 20 MeV), estimated by Powheg-NLO EW+QCD (+pythia8) vs Powheg-NLO QCD (+pythia8)

$$M_Z = 91206 \pm 36_{\text{stat}} \pm 30_{\text{syst}}\ \text{MeV}$$

W^+ and W^- production flavour decomposition

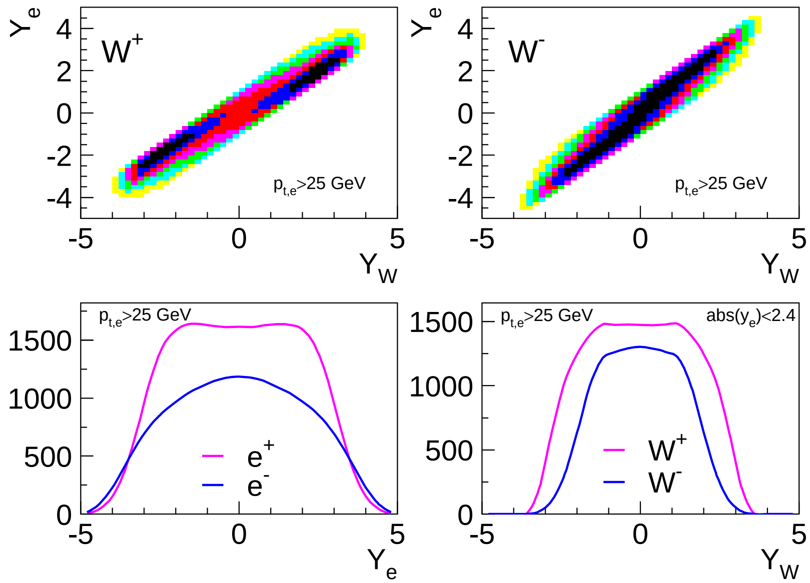


W^+ (W^-) production is sensitive to $u\bar{d}$ ($d\bar{u}$) as well as $c\bar{s}$ ($s\bar{c}$) flavour combinations and to lesser extend to Cabbibo suppressed pairs:

$$W^+ \quad \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$

$$W^- \quad \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

W decays

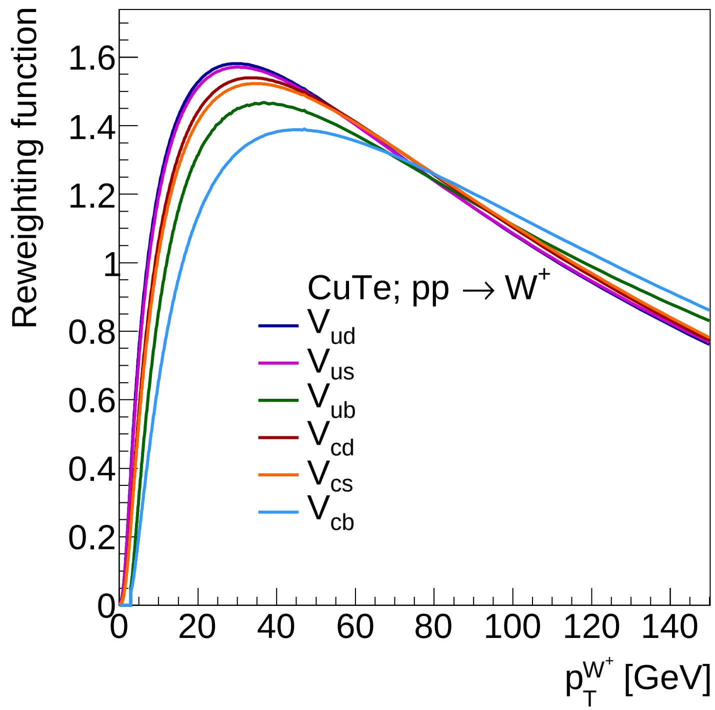


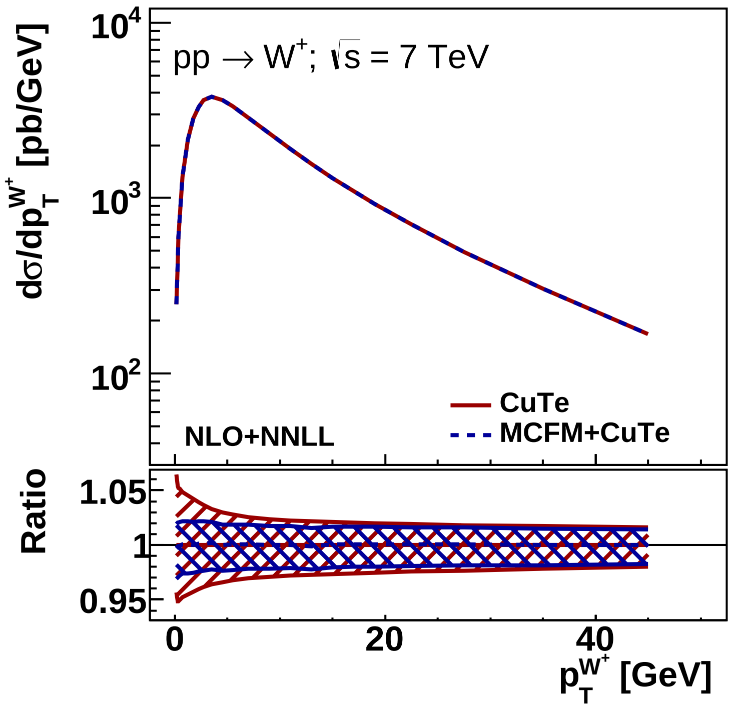
For 1st generation, W boson production at a given y is given by

$$\frac{d\sigma_{W^+(y)}}{dy} \sim u(x_1)\bar{d}(x_2)+u(x_2)\bar{d}(x_1) = (\bar{u}(x_1)+u_v(x_1))\bar{d}(x_2)+(\bar{u}(x_2)+u_v(x_2))\bar{d}(x_1)$$

For small x, $\bar{d}(x) \approx \bar{u}(x)$ thus $\bar{u}(x_1)\bar{d}(x_2) \approx \bar{u}(x_2)\bar{d}(x_1)$ and W is unpolorised along Z axis. However for $x_1 > x_2$, $u_v(x_1)\bar{d}(x_2) > u_v(x_2)\bar{d}(x_1)$ leading to W polarisation along proton 1 (which is direction of the boost). The polarisation changes correlation between y_W and y_ℓ and also p_T^ℓ distribution.

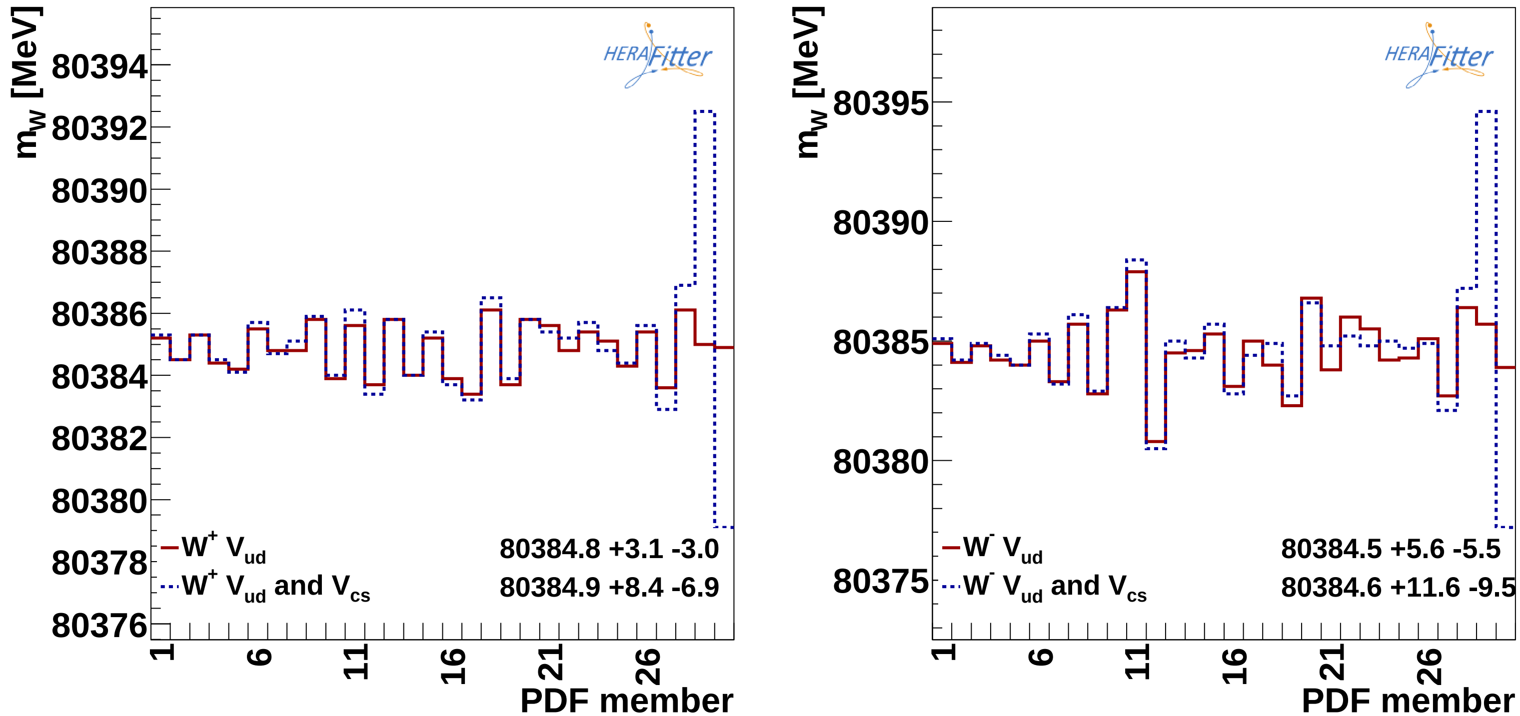
W production modeling: p_T





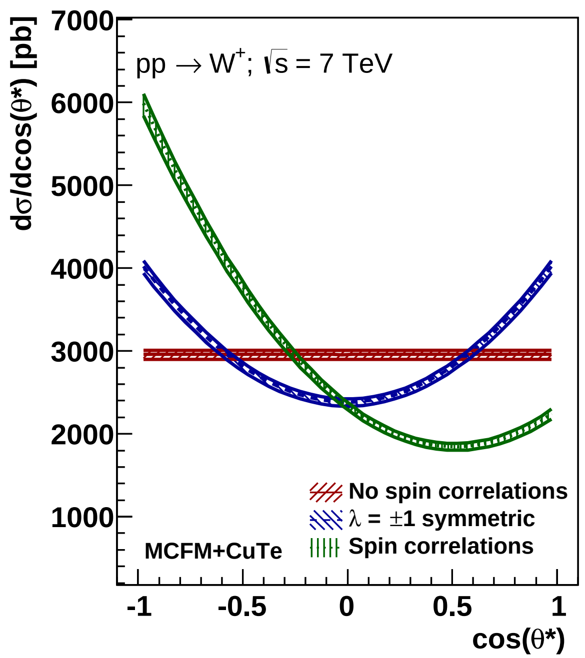
- Light vs heavy flavour production have different P_t distributions.
- Different PDF composition for $W^{\pm}$ and Z – PDF effects in parton shower do not cancel.
- Heavy-heavy ($b\bar{b}$,$c\bar{c}$) production for Z vs light-heavy ($s\bar{c}$, $\bar{s}c$) for $W^{\pm}$.

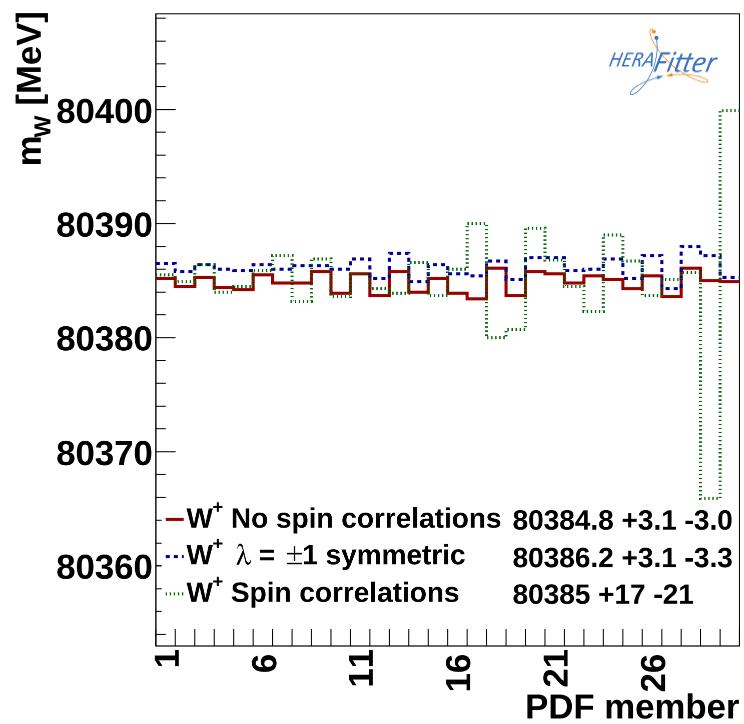
PDF uncertainties due to second generation quarks



- Impact of second generation can be studied by setting V_{cs} parameter to zero.
- Studied using a dedicated PDF set, obtained from the fit to HERA data, with the last PDF member: strange-quark distribution suppression variation, $s = \bar{s} = r_s \bar{d}$, $r_s = 1^{+0.25}_{-0.28}$.
- W production and decays are simulated using a mix of CUTE (resummation) and MCFM (NLO) calculations.

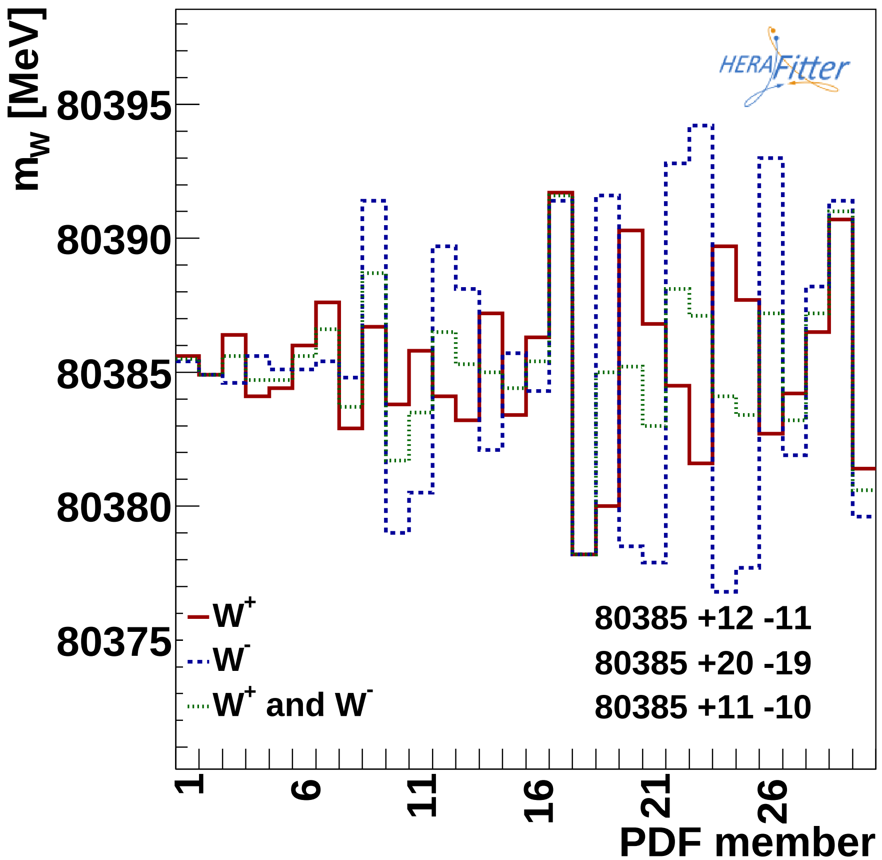
W production modeling: PDFs and polarisation





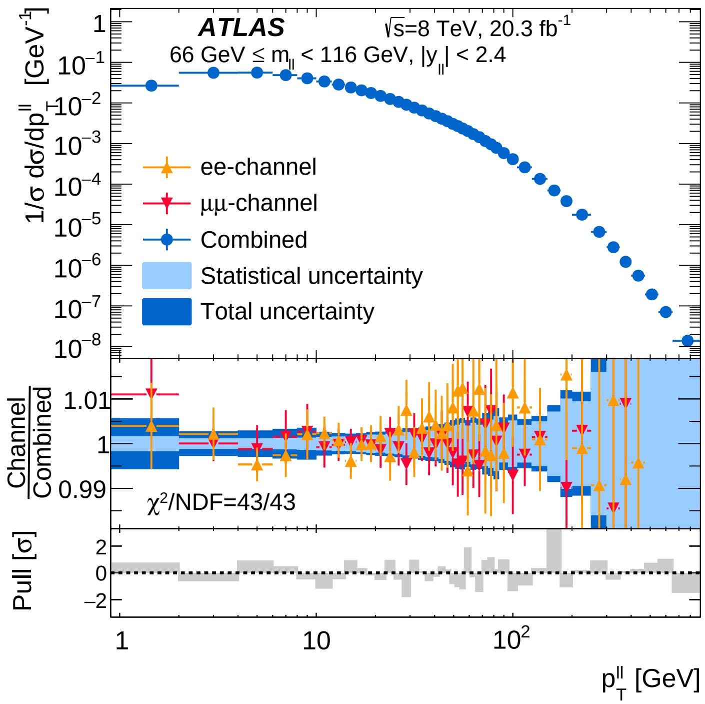
- Impact of W polarisation uncertainty can be studied by turning it off in simulation.
- Uncertainties in longitudinal polarisation due to $q\bar{q}$ vs qg production do not play large role, valence / sea uncertainty is very important.
- Opposite effect of r_s variation vs $V_{us} = 0$ fits, some compensation for the full effect expected.

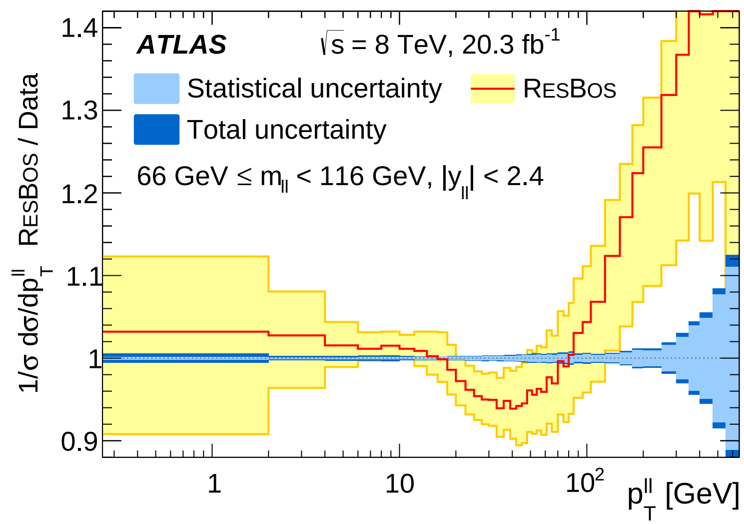
Summary of the uncertainties



- Some compensation of polarisation and P_T modeling effects, differences in W^+ and W^- lead PDF uncertainty < 15 MeV on M_W.
- Similar conclusion with other PDF sets.

Measurement of Z_{p_T}

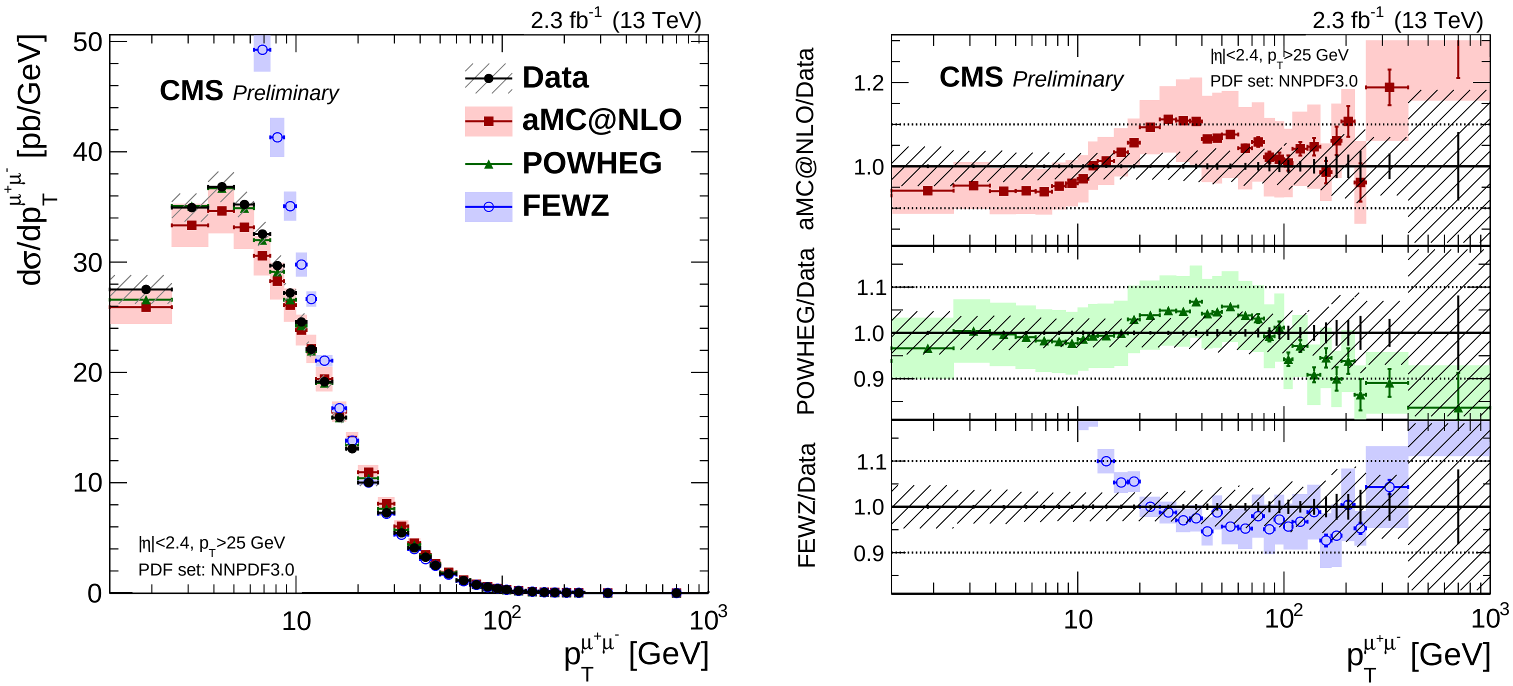




- Several measurements of Z_{p_T} at $\sqrt{s} = 7$ and 8 TeV by ATLAS and CMS.
- ATLAS measurements use both $Z \to ee$ and $Z \to \mu\mu$ channels, which have comparable accuracy. The combined result is accurate to better than 0.5% for $P_T < 100$ GeV range.
- Data can be used to fit theory parameters to propagate their impact to W mass analysis. Must be done coherently with PDF uncertainties.

ATLAS, arXiv:1512.02192

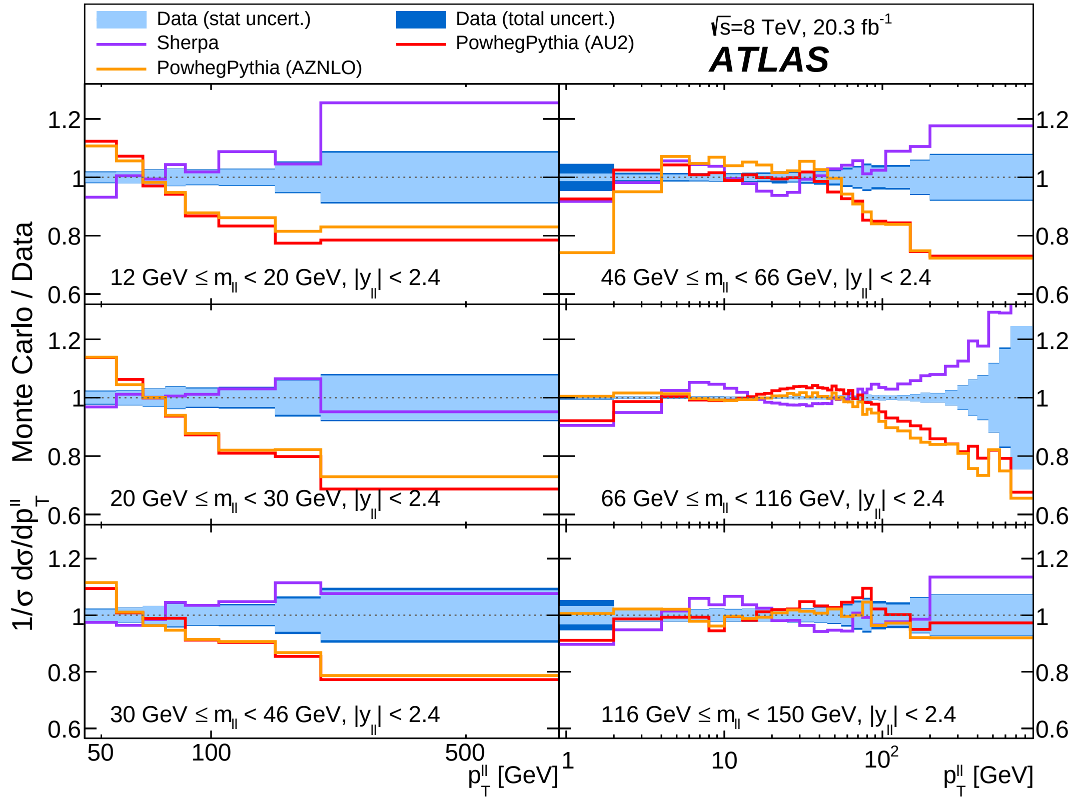
First 13 TeV results



- Very recently CMS released first differential Z_{p_T} and y_Z measurements using 2015 $\sqrt{s} = 13$ TeV data.
- With addition of 2016 data, the total sample of produced Z bosons is expected to exceed $\sqrt{s} = 8$ TeV sample by factor > 3.

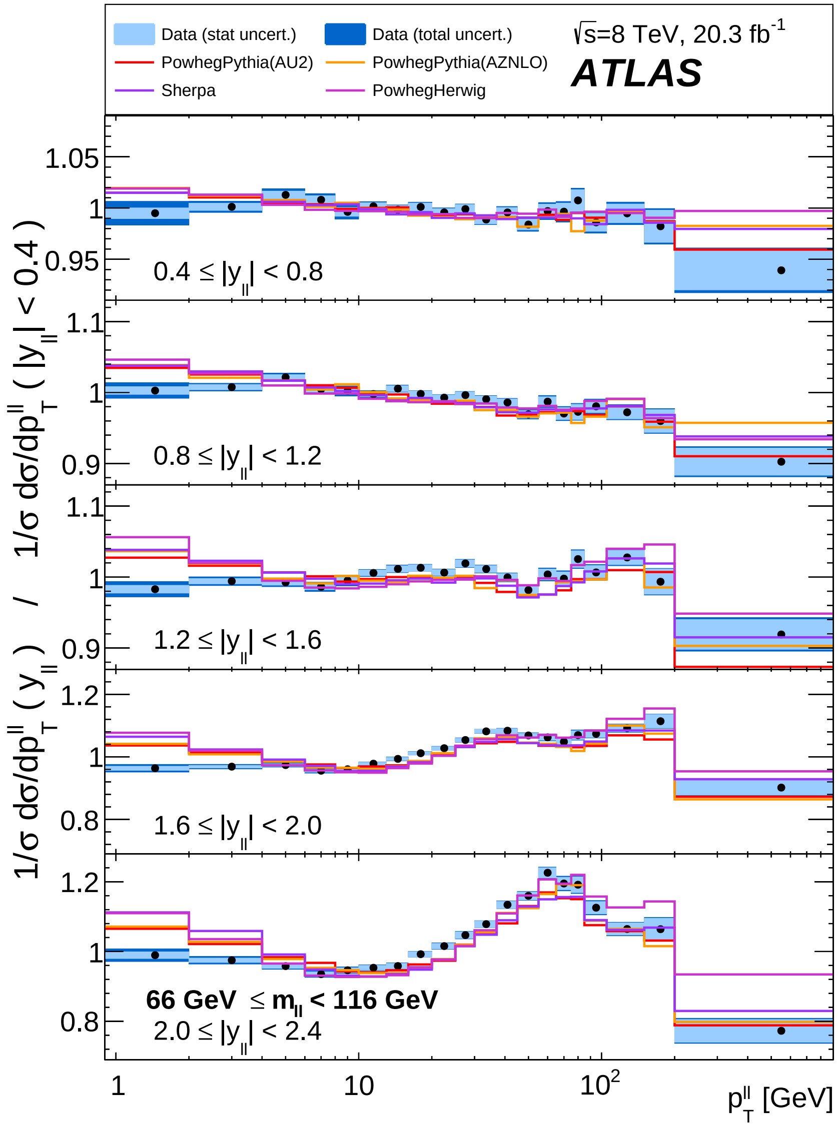
CMS PAS SMP-15-011

Off-peak p_T measurements



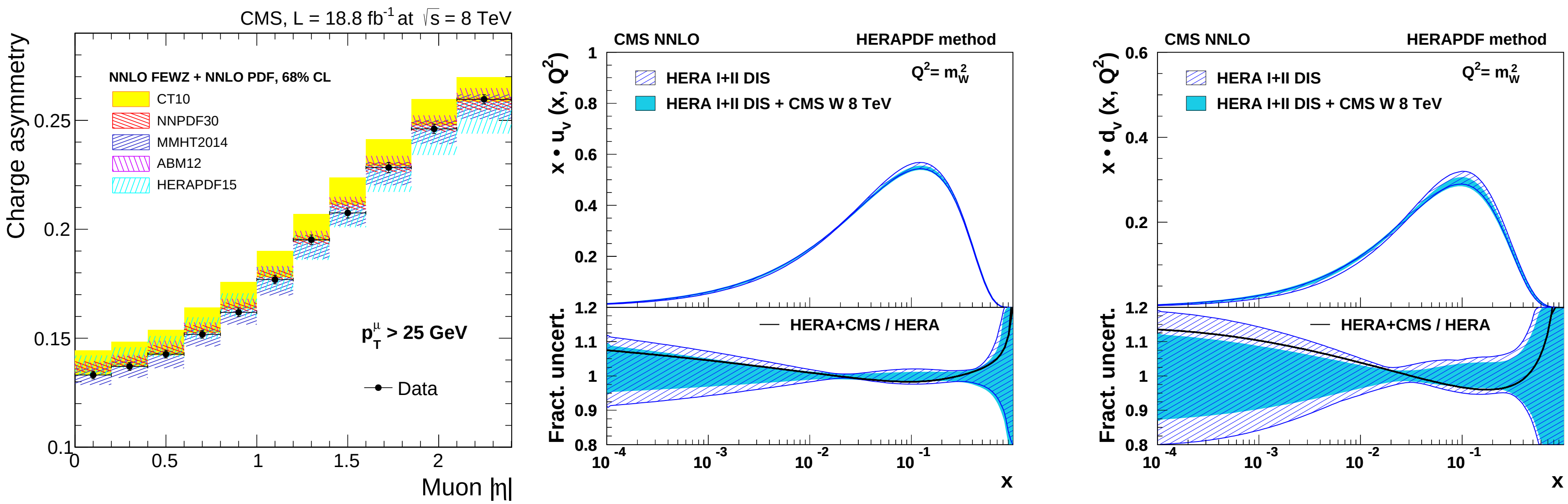
- Large $\sqrt{s} = 8$ TeV samples can be used to probe distributions double differentially. Studying dependence in mass can probe different PDF decomposition, scale dependence, electroweak effects.
- Dedicated Powheg tune AZNLO, developed using Z_{p_T} $\sqrt{s} = 7$ TeV data, works very well for the peak range but deviates at low masses.

Z_{p_T} as a function of y_Z



- Additional stringent tests can be performed using double ratios, e.g. to explore y_Z dependence.
- NLO+PS MC samples struggle to describe p_T dependence as a function of y_Z.

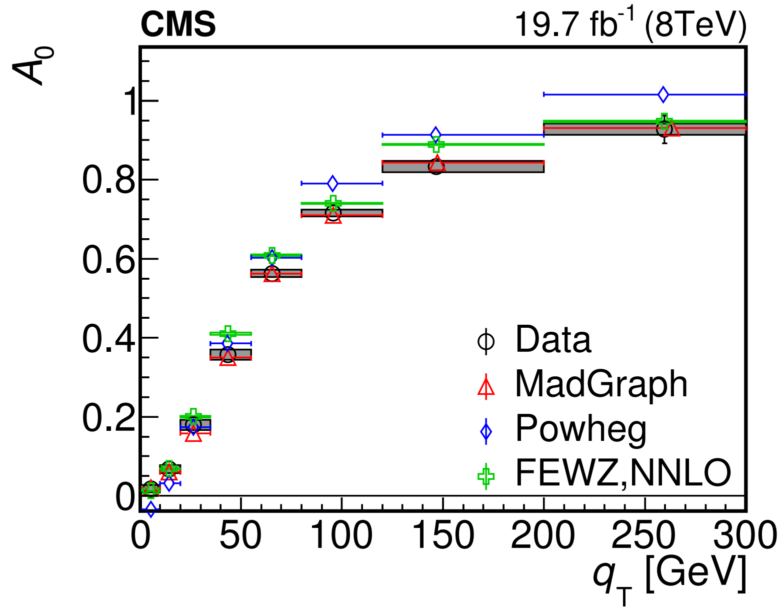
PDFs: valence quarks and W asymmetry



- Valence quarks at low x can be studies using lepton charge asymmetry as a function as lepton pseudorapidity.
- New $\sqrt{s}$ = 8 TeV result from CMS recently submitted.
- The data have significant impact to both u_v and d_v for $x \sim 0.01$

CMS, arXiv:1603.01803

Z polarisation: CMS



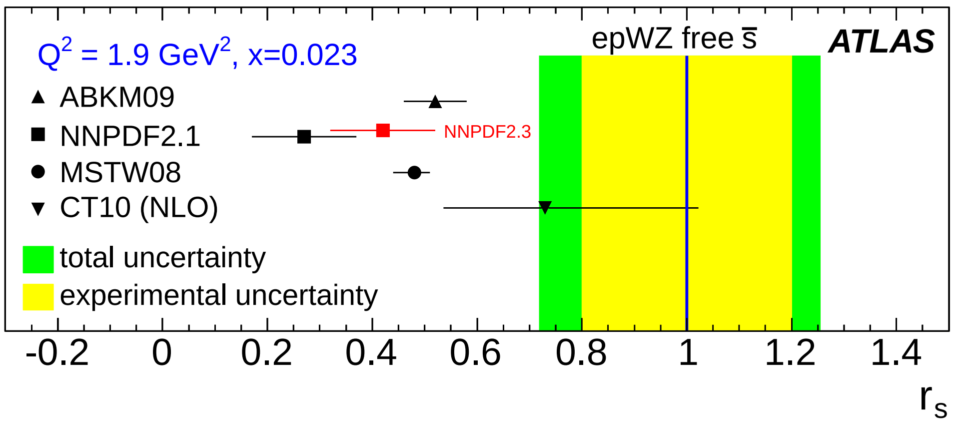
Z bosons are produced polarized, with $\cos\theta^*_{CS}$ dependence given by:

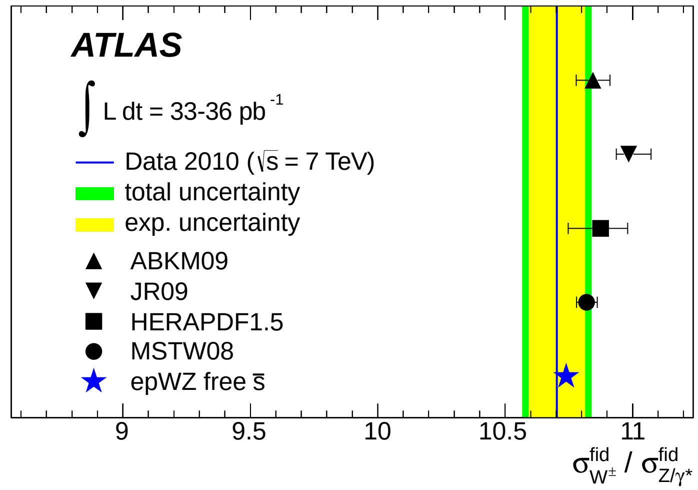
$$\frac{d\sigma}{d\cos\theta^*} \sim (1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_4\cos\theta^* \, .$$

For $q\bar{q}$ annihilation $A_0 = p_T^2/(M_Z^2 + p_T^2)$ while for the Compton qg process $A_0 \approx 5p_T^2/(M_Z^2 + 5p_T^2)$. For low p_T, FEWZ NNLO calculation agrees with the data well, however Powheg deviates from the data.

CMS, Phys. Lett. B 750 (2015) 154, arXiv:1504.03512

Strange-sea density determination





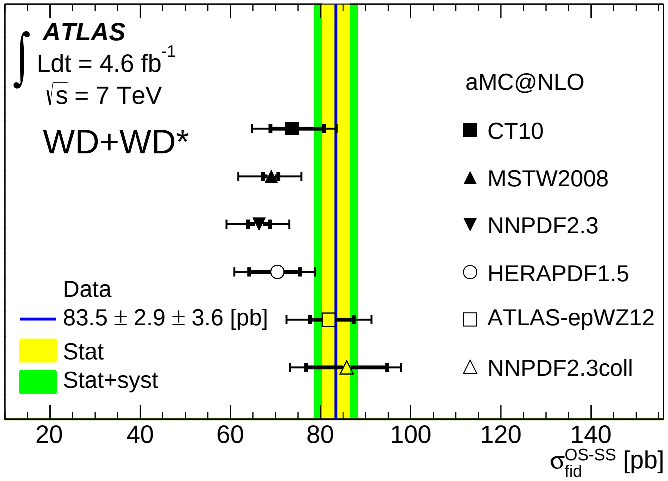
$$r_s = 0.5\frac{s+\bar{s}}{\bar{d}}$$

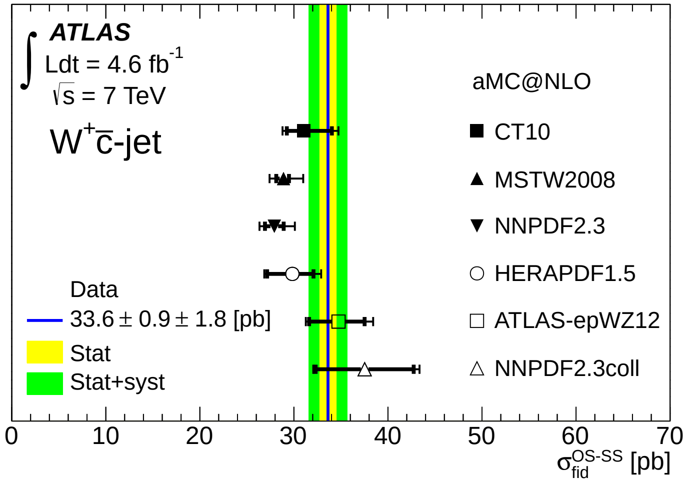
NNPDF2.3 result uses improved m_c threshold correction, affecting di-muon data (dominant effect) and includes ATLAS result (smaller effect).

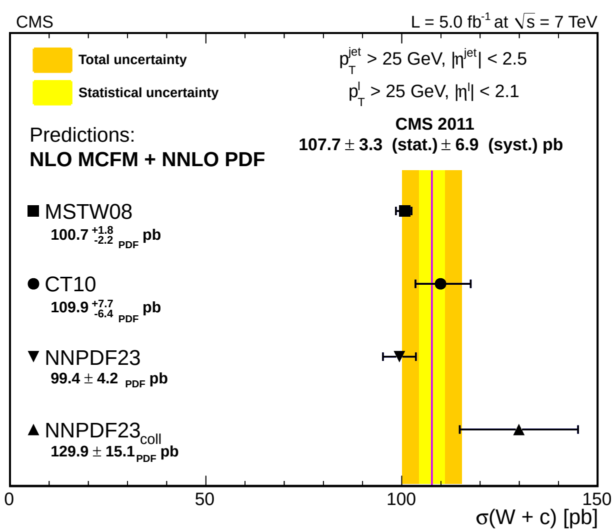
ATLAS fit provides the best description of the measured W/Z cross sections ratio.

ATLAS, PRL109 (2012) 012001

Measurements of W+c from ATLAS and CMS



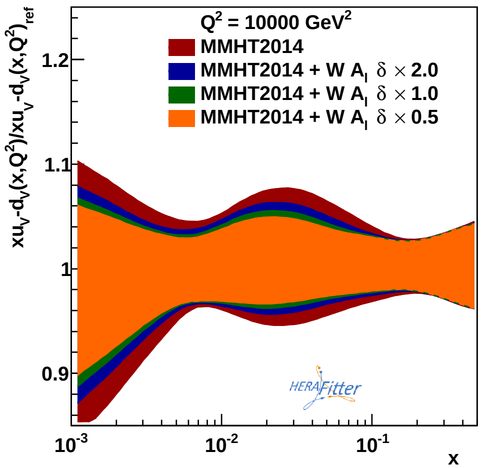


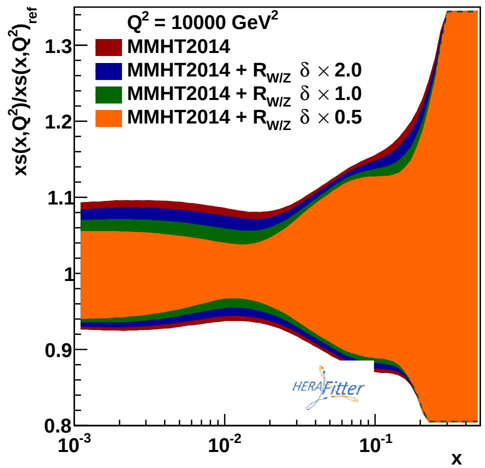


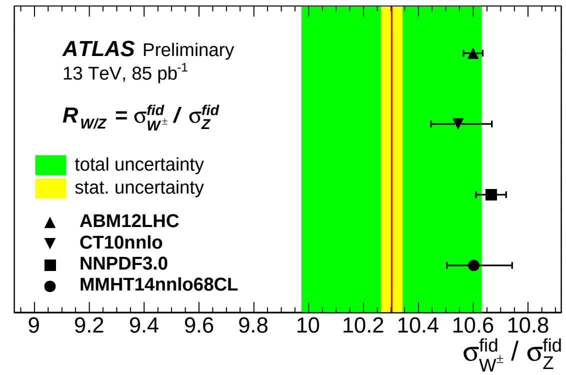
- Measurements of $\sigma(W^{\pm}c^{\mp}) - \sigma(W^{\pm}c^{\pm})$ from ATLAS and CMS, using c-jets tagged by soft muons and $D^{(*)}$ mesons, to probe strange-sea PDF using $gs \to Wc$ process.
- CMS finds best agreement with PDFs with somewhat suppressed strangeness while ATLAS results agree with ATLAS-epWZ predictions the best.

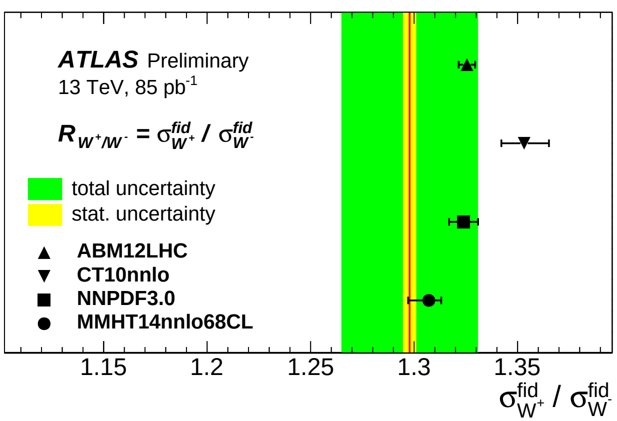
JHEP 02 (2014) 013, arXiv:1402.6263

PDFs: run2 expectations





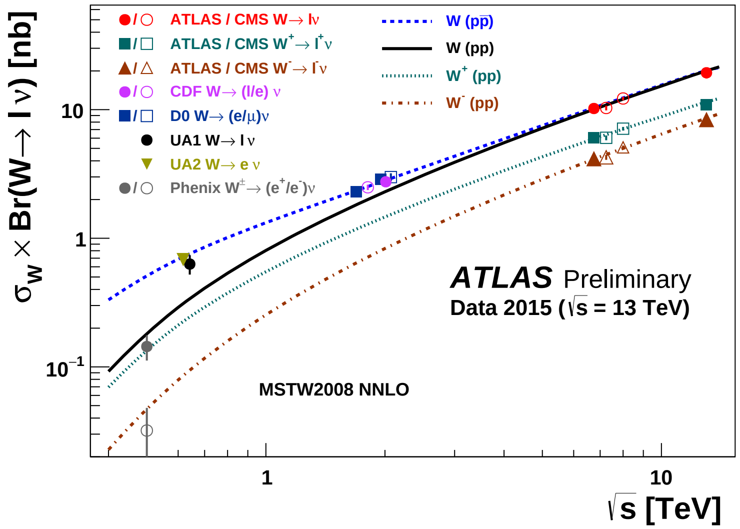


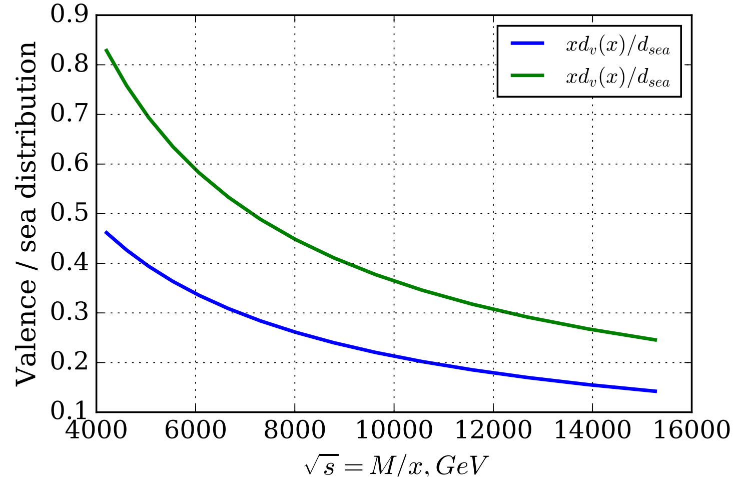


- Benchmarking studies of the run-II data sensitivity considering same, worse or improved by factor of two uncertainties vs Run-I results. $\sigma_{W^+}/\sigma_{W^-}$ constrains u_v/d_v while σ_W/σ_Z constrains the strange density.
- First preliminary ATLAS results are at the moment more close to conservative scenario, but can already distinguish between some PDFs.

arXiv:1507.00556, ATLAS-CONF-2015-039

Run2 vs Run1 for M_W





- Increased cross section, very large data samples
- Single lepton triggers can be maintained even for high pileup conditions.
- Dedicated low pileup run could be used for an accurate W_{p_T} measurement
- Lower average $x = M/\sqrt{S}$ allows to probe different valence/sea quarks regime.

Summary

- Measurement of the M_W is the holy grail of the precision SM tests at the LHC
- Detector calibration, experimental techniques are getting closer to obtaining the results.
- The measurement requires accurate theory which combines NNLO QCD, resummation, and EWK effects.
- A number of high precision measurements can probe the theory and constrain its uncertainties.
- Run-II data will allow to increase data statistics for Z-boson-based auxiliary measurements, probe the theory at lower x and with different valence to sea-quark balance.