W and Z boson production at the LHC and the implications for the knowledge of the proton structure

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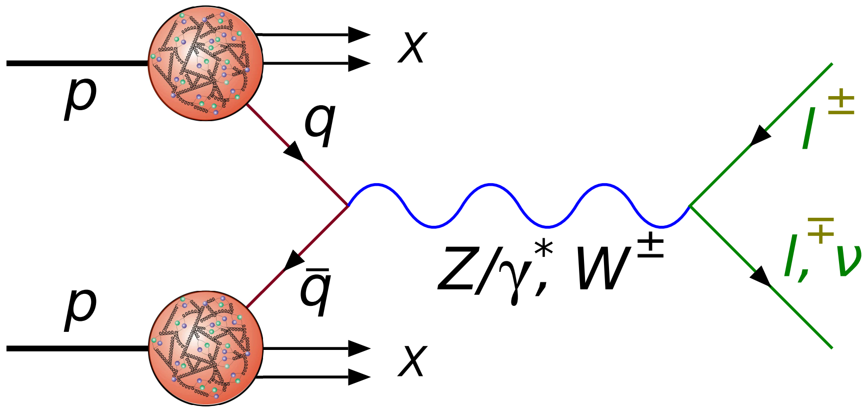
W and Z measurements at LHC

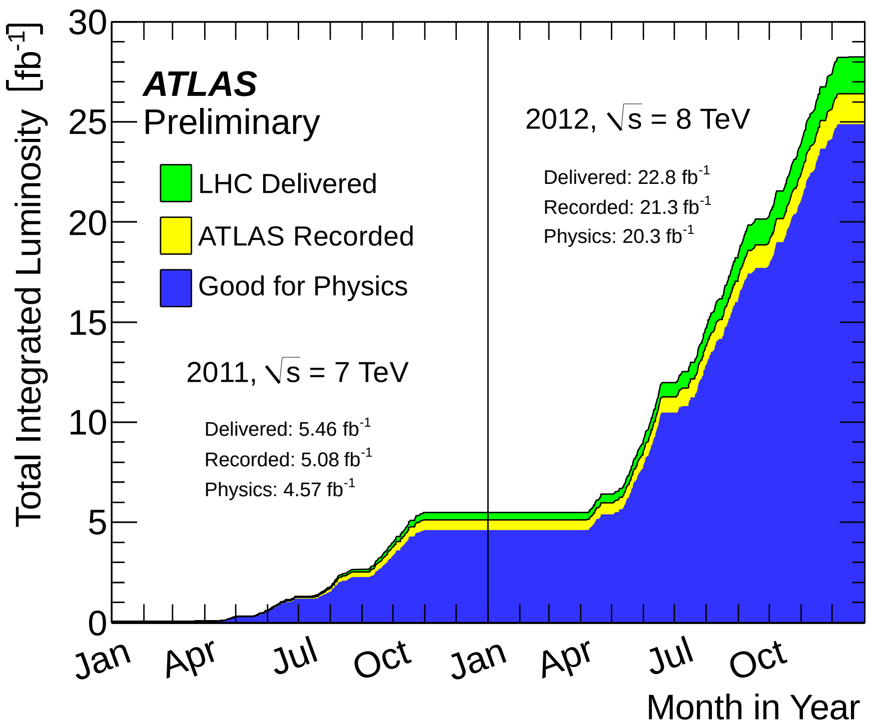
- Why study W and Z at LHC?
  - Precision electroweak measurements (m_W, $\sin^2\theta_W$)
  - Novel information on the proton structure (PDFs):
    - To improve knowledge PDFs and apply this in other measurements
    - To test and understand QCD
    - Main focus of this talk



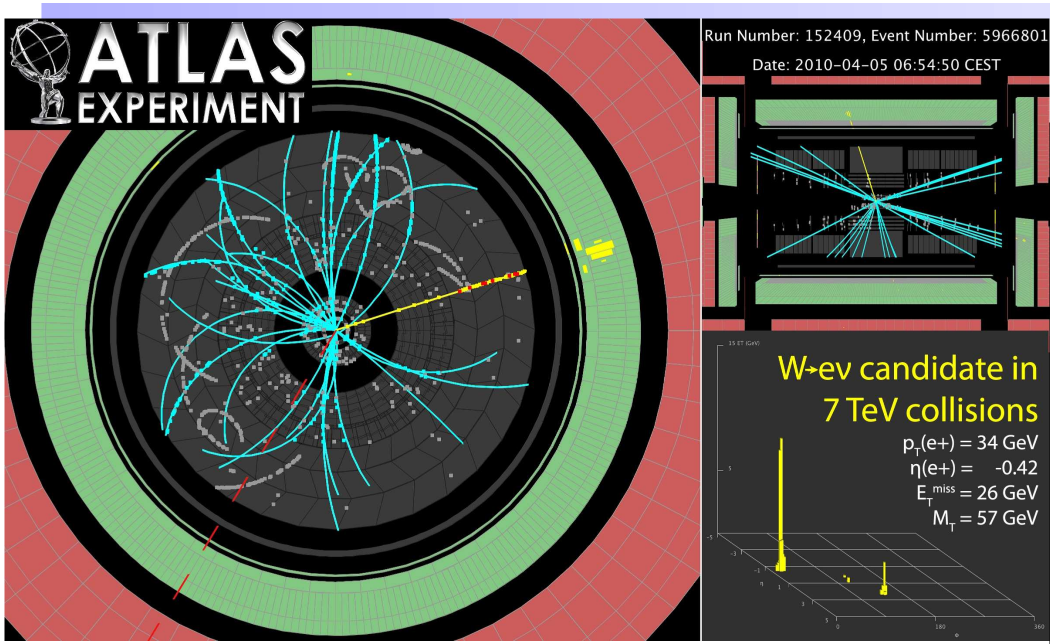
- Why use W, Z to learn about PDFs?
  - High precision experiment matched by high precision theory compared to other interesting measurements with PDF constraints possible at LHC (W,Z+jets, jets, isolated photons, $t\bar{t}$)
- Review of pre-LHC status and recent LHC results and their impact in PDF fits
- (For references see the end of talk)

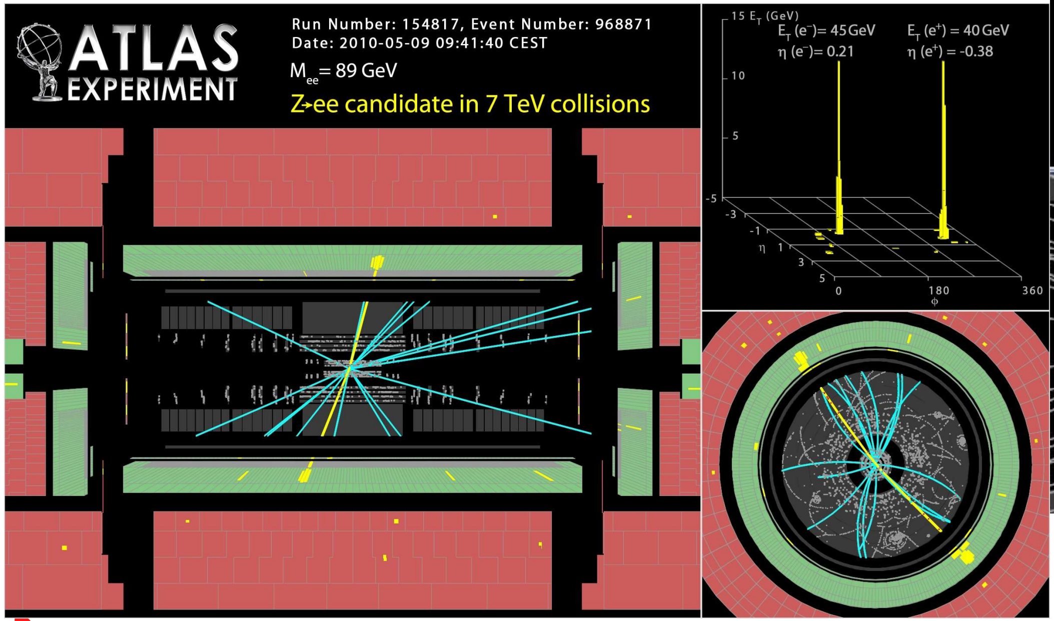
LHC and ATLAS, CMS & LHCb

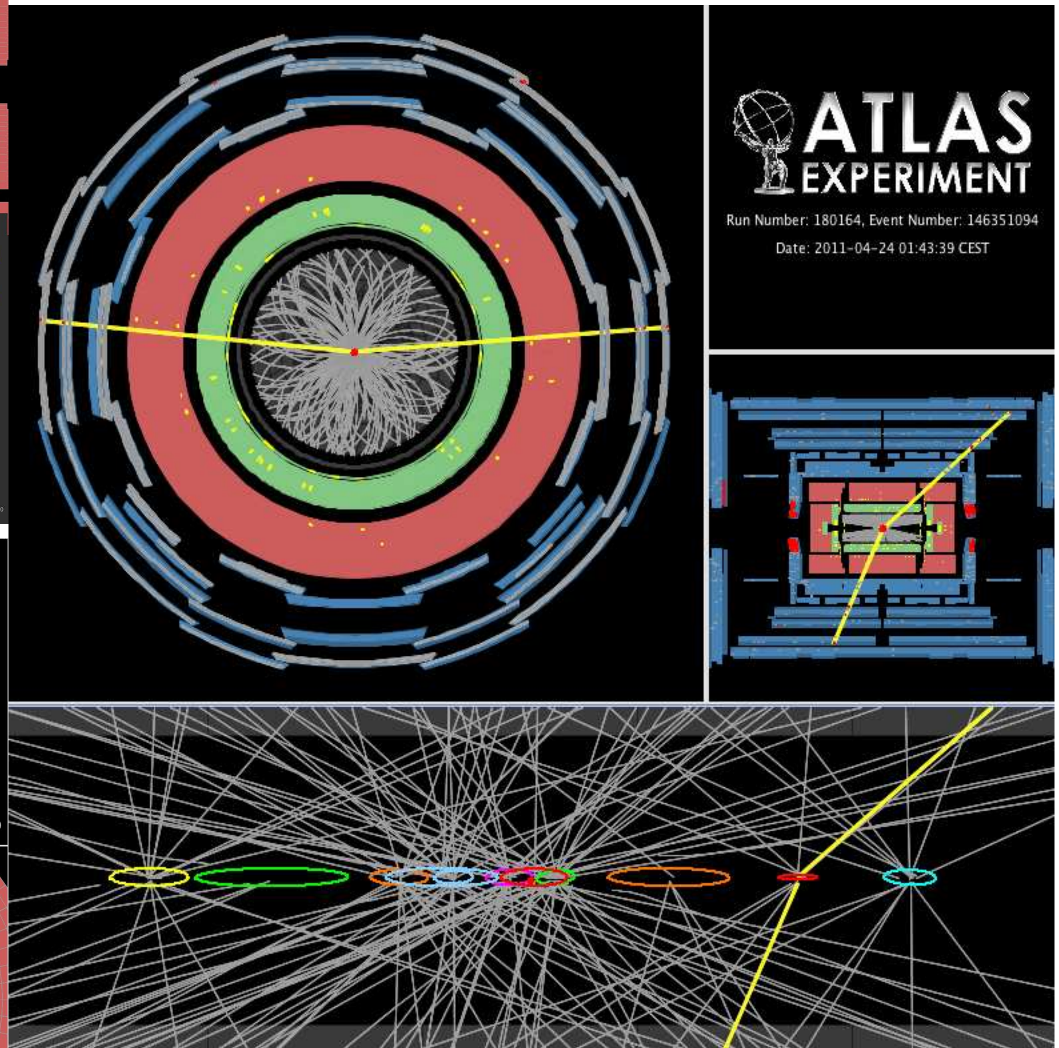
- Large Hadron Collider has successfully delivered luminosity since 2010
- Results shown here are typically high precision analyses and based on the 2010 or 2011 data set: $40\,\mathrm{pb}^{-1}$ and $5\,\mathrm{fb}^{-1}$ (1.8% lumi error for 2011)
- Personally involved in ATLAS, but reviewing some of the interesting recent results from CMS (and LHCb)



Some ATLAS events

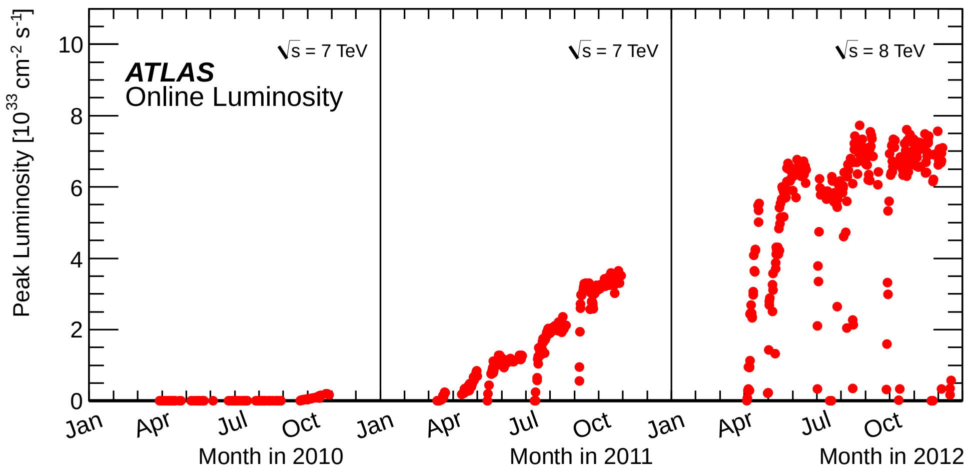


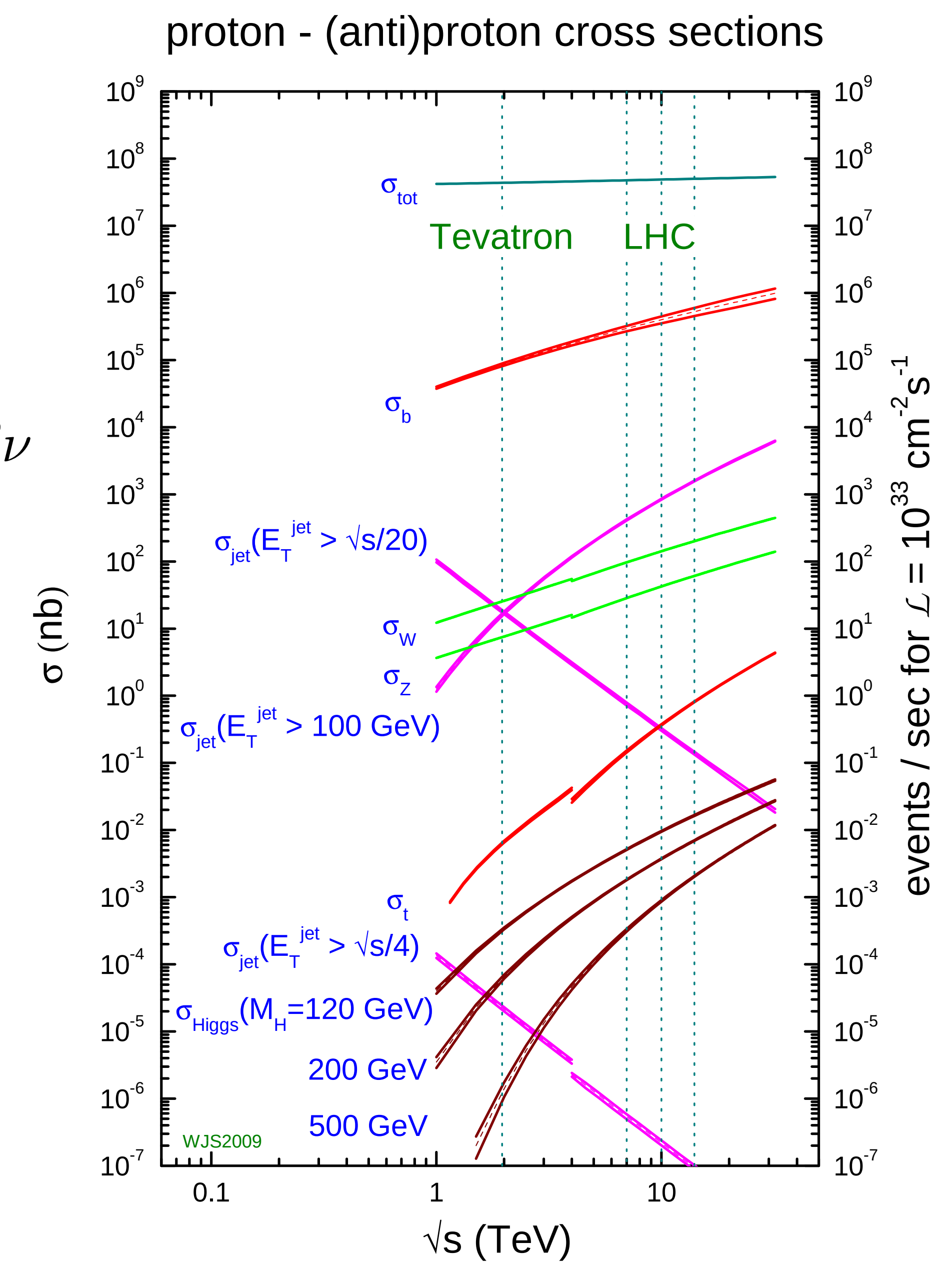




LHC: A W and Z "Factory"

- Large production cross section and acceptance for W and Z in leptonic decay channels ($\ell = e$ or μ)
- ATLAS collected $Z \to \ell\ell$ and $W^{\pm} \to \ell\nu$ at rates of ~ 2 Hz and 20 Hz in 2011

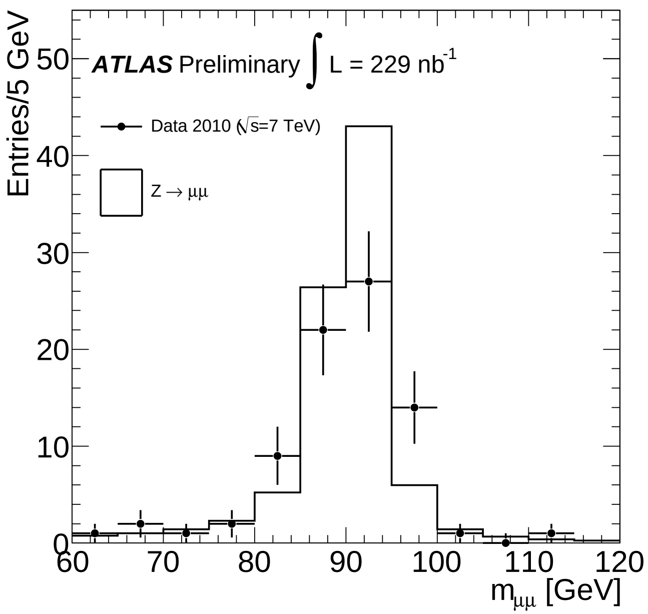




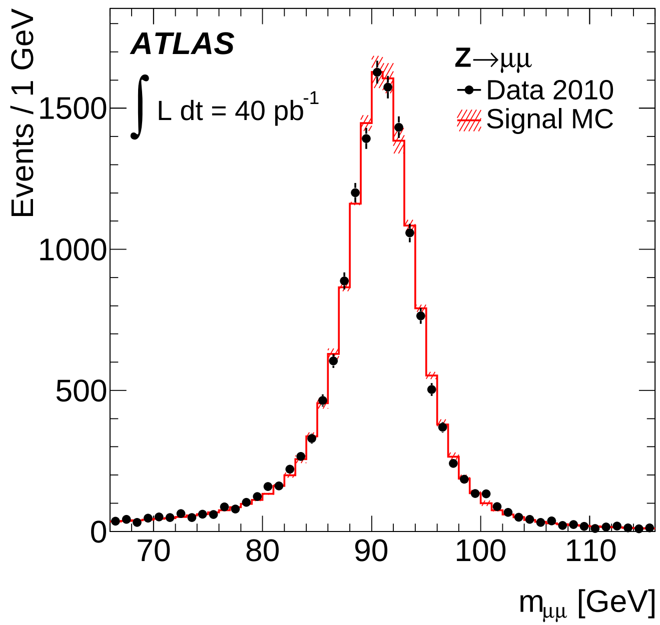
LHC: A W and Z "Factory"

- 2011 data set
  - ~ 1.5 million $Z \to \ell\ell$ events per channel and experiment
  - ~ 15 million $W \to \ell\nu$ events per channel and experiment
- For 2012 factor ~ 5 more
- In run 2 the $W \to \ell\nu$ rate will be an issue for the trigger & data handling

July 2010



Full 2010 data



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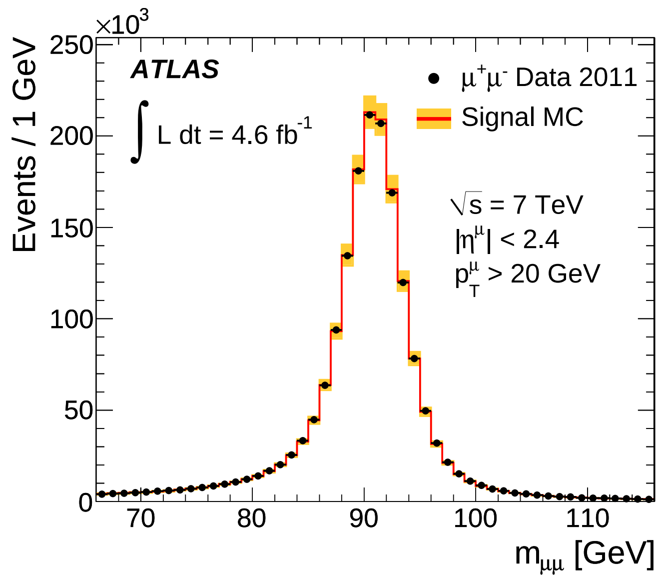

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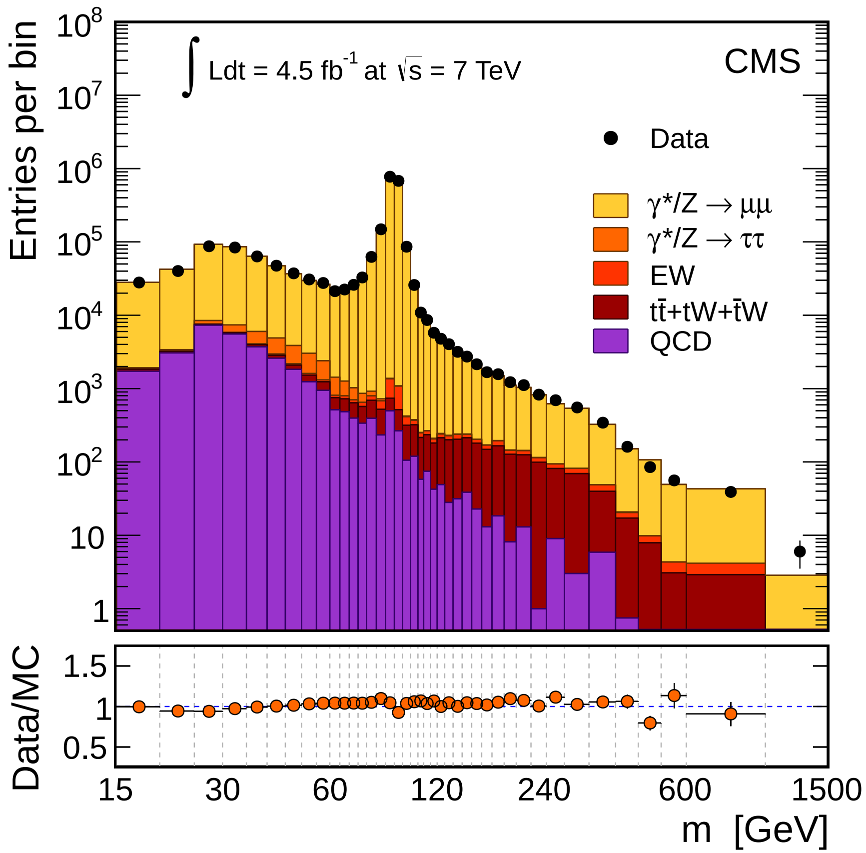
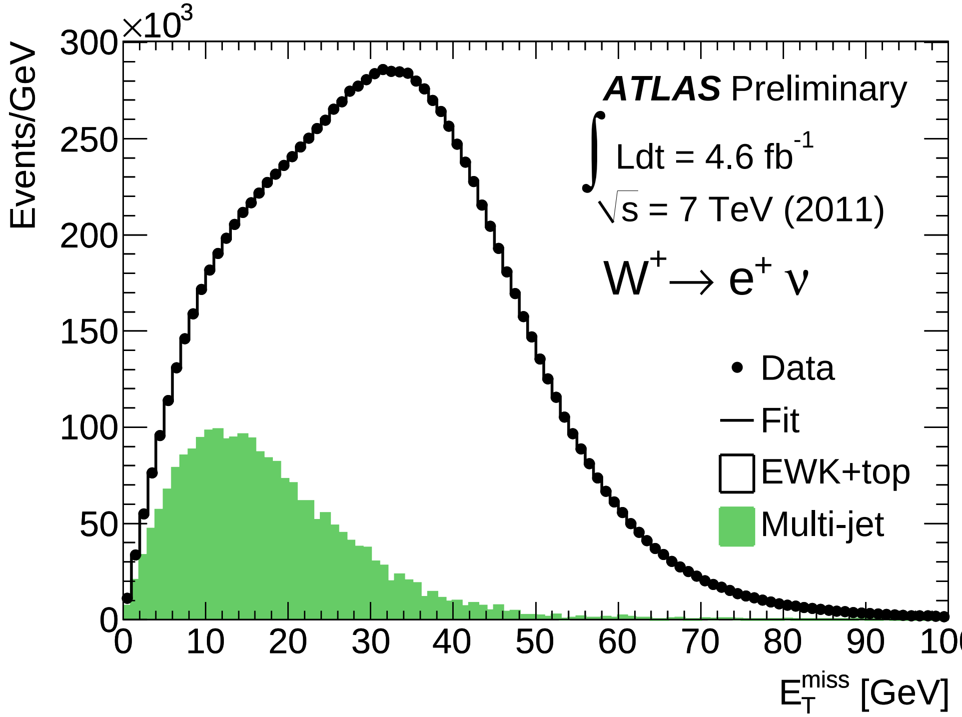
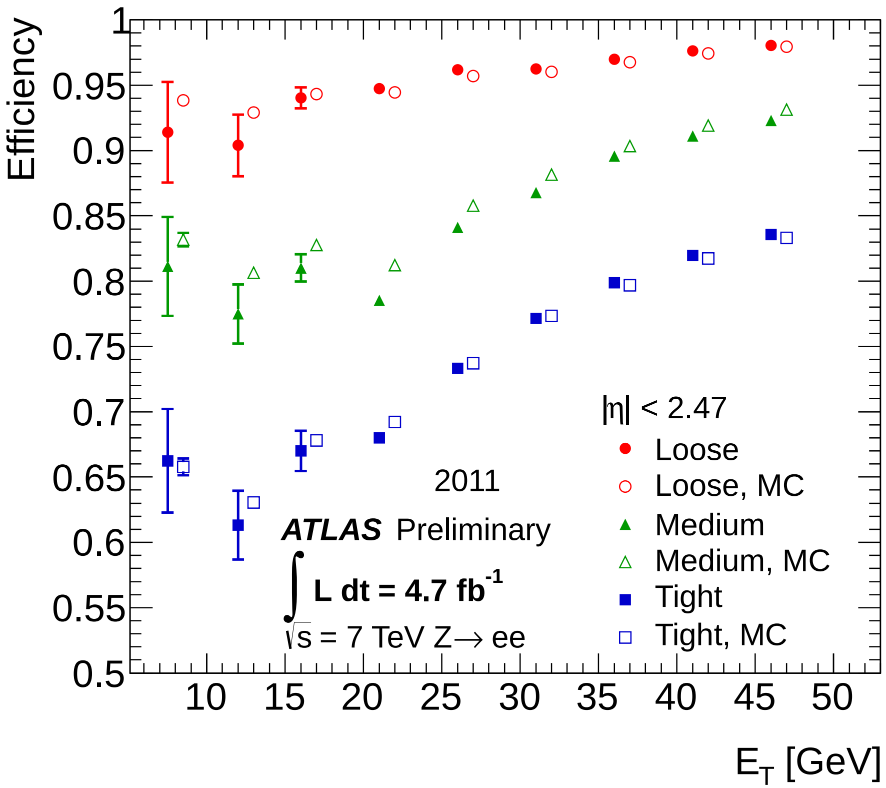
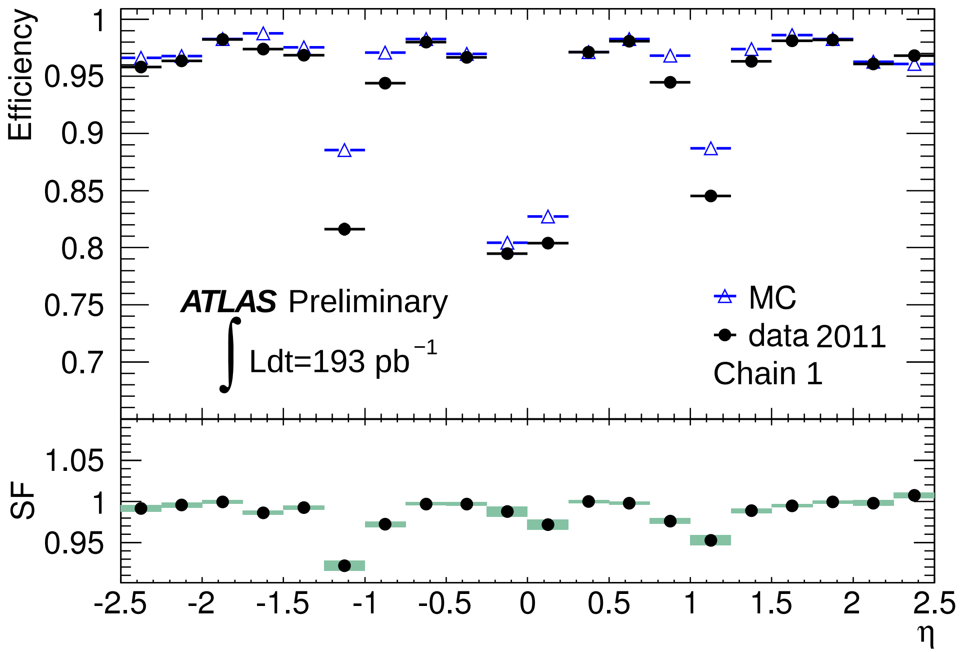




ATLAS: Lepton Performance

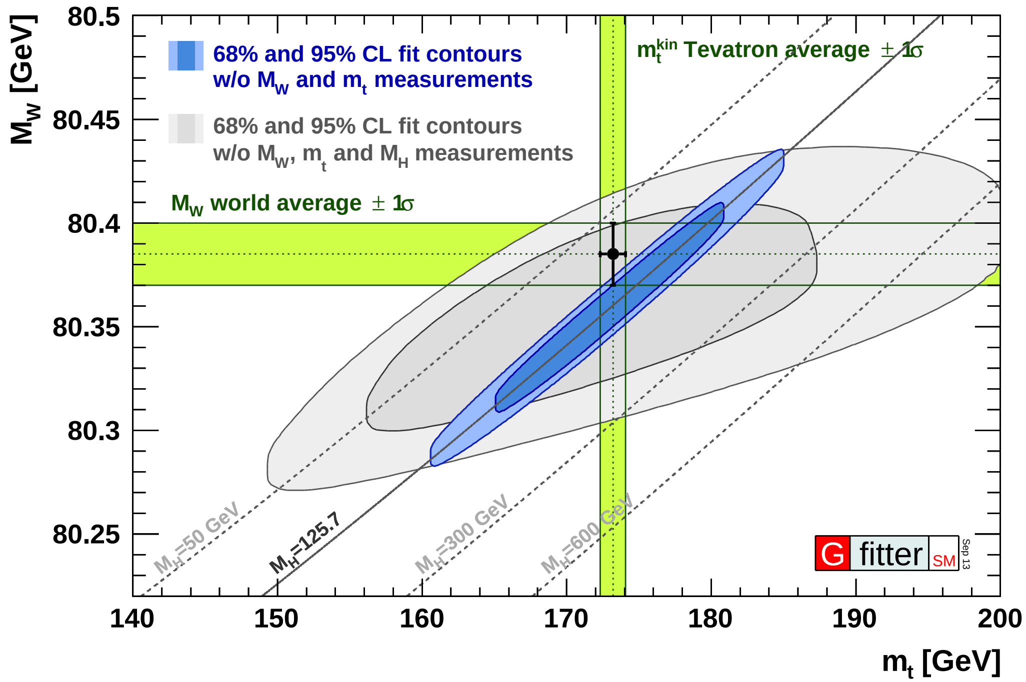
- Main issue for inclusive $W \to \ell\nu$ and $Z \to \ell\ell$ is quantitative understanding of lepton performance: selection efficiencies, energy and momentum scales
- With large $Z \to \ell\ell$ samples and sufficient efforts this can be understood to very high precision
- ... performance publications to come soon





Electroweak Precision at LHC: m_W

- A very precise m_W measurement remains an interesting test for the consistency of the SM
- Tevatron measurements with “just” $\sim 100,000$ Z and ~ 1 W million events
- Measurement at LHC will be completely systematics dominated, PDF uncertainties ($\sim 10\,\mathrm{MeV}$ at Tevatron) eventually a limiting factor

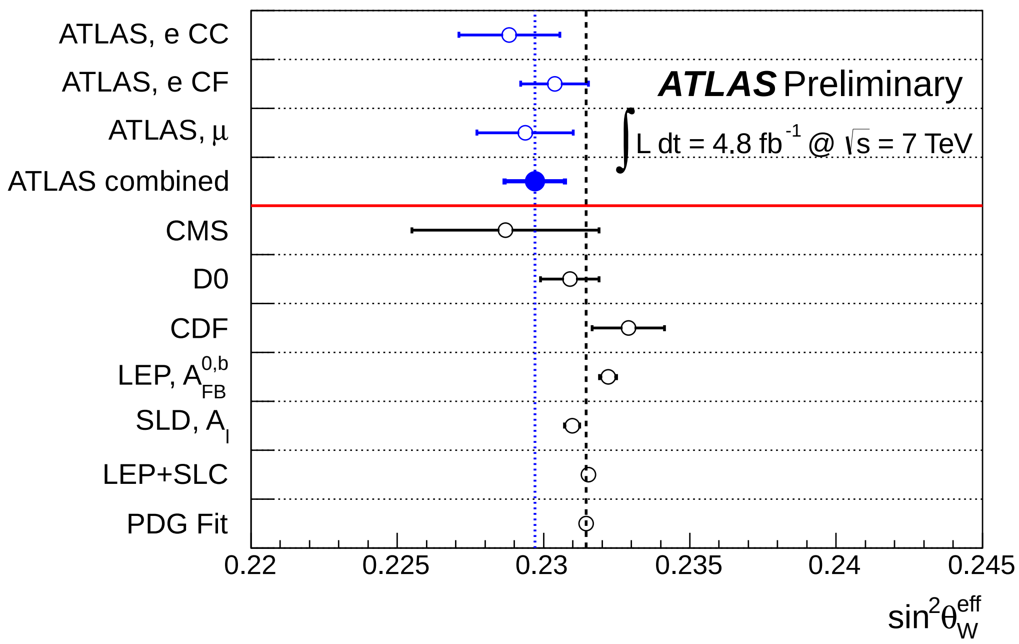


CDF m_W uncertainty in $[\mathrm{MeV}]$

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

Electroweak Precision at LHC: $\sin^2\theta_W$

- Precision $\sin^2\theta_W$ measurement statistical possible at LHC: current ATLAS analysis extrapolated to $\sim 100\,\mathrm{fb}^{-1}$ can reach LEP/SLD precision
- PDF systematics needs large improvement to reach this goal



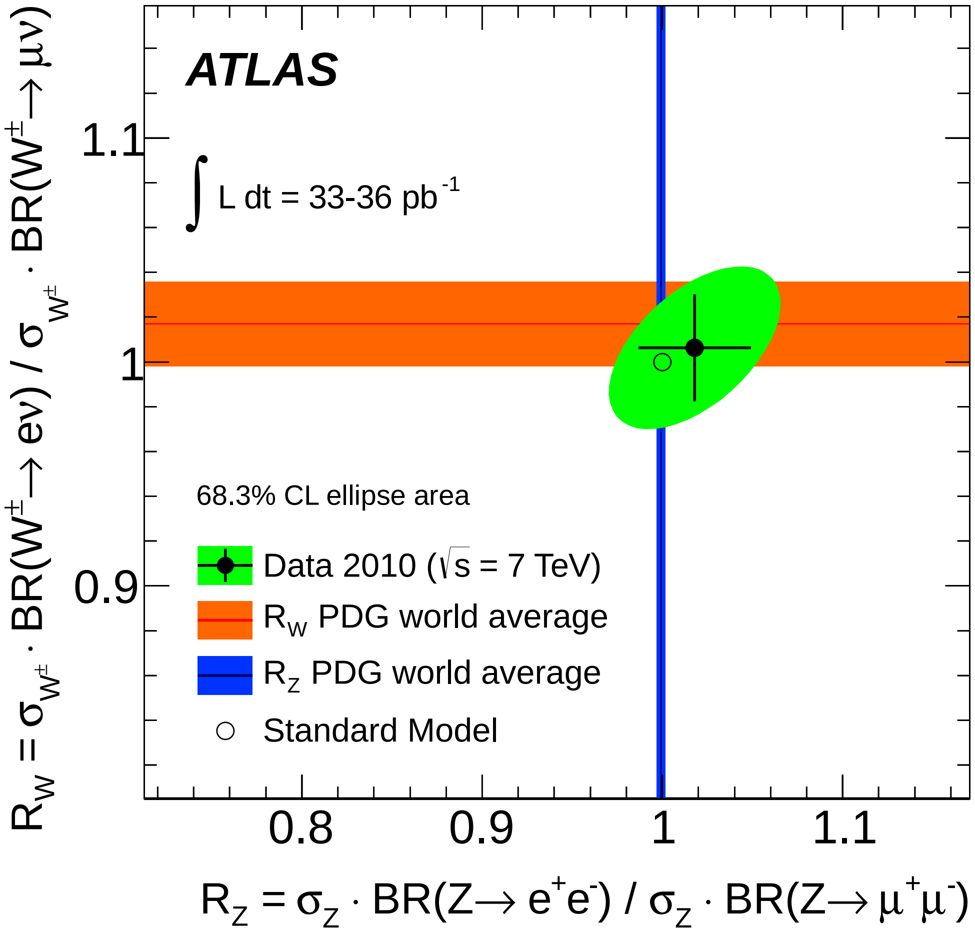
ATLAS preliminary 2011 $4.7\,\mathrm{fb}^{-1}$

$\sin^2\theta_W$ uncertainties

Uncertainty source	CC electrons (10^{-4})	CF electrons (10^{-4})	Muons (10^{-4})	Combined (10^{-4})
PDF	9	5	9	7
MC statistics	9	5	9	4
Electron energy scale	4	6	–	4
Electron energy smearing	4	5	–	3
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2
Data stat.	9	6	9	4

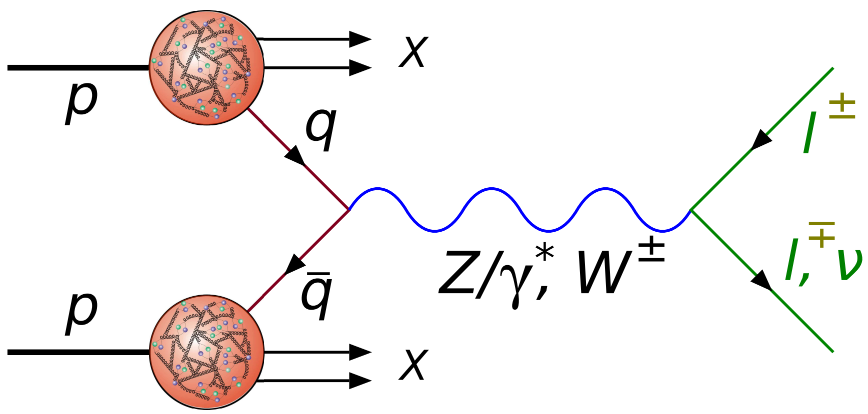
Electroweak Precision at LHC

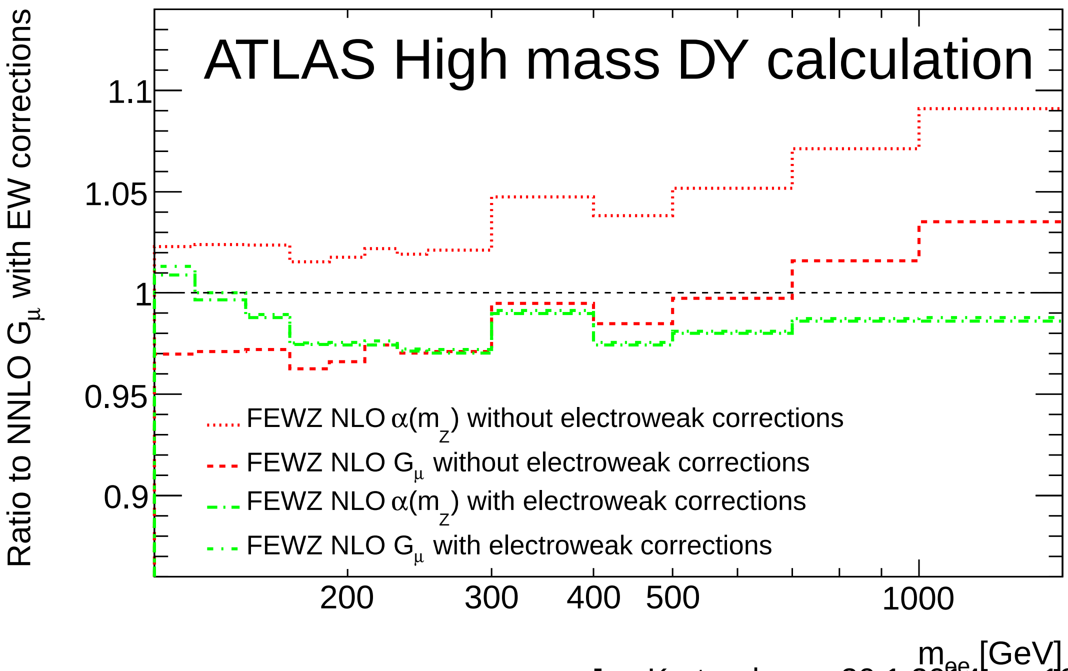
- $e-\mu$ lepton universality in W and Z decays primarily limited by lepton performance and statistics
- Precise $\mathrm{BR}(W \to \tau\nu)/\mathrm{BR}(W \to \ell\nu)$ measurement even more interesting, but more challenging



W and Z Production in Hadron Collisions

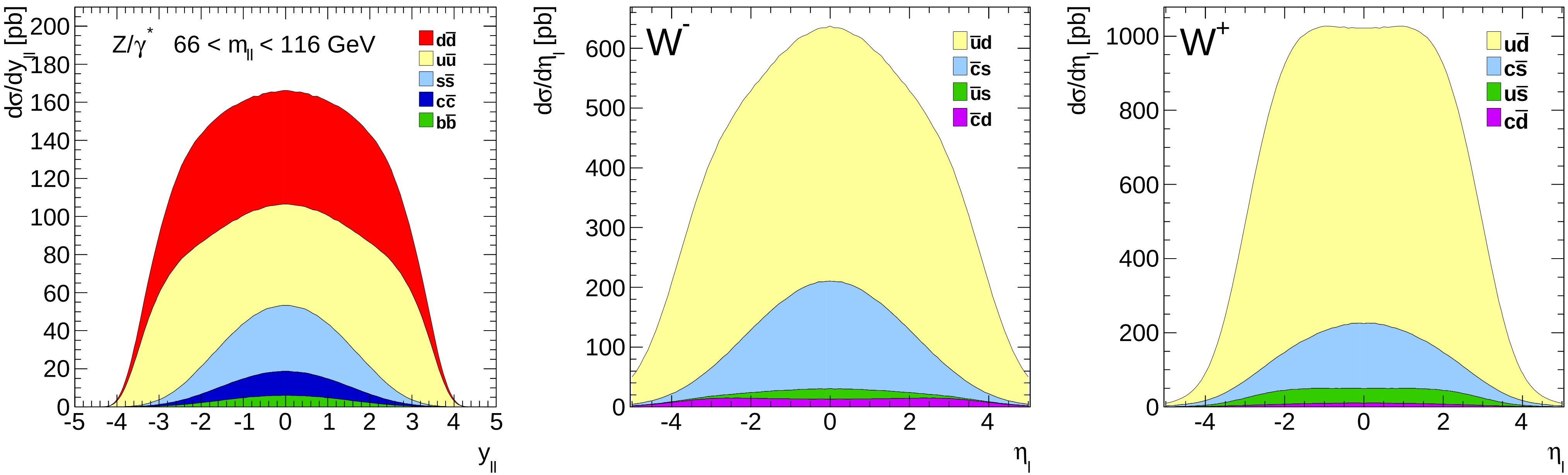
- Known at NNLO QCD (α_s^2): "Unlike other QCD processes the DY reaction seems to be one of the few cases where the calculation of the order α_s^2 corrections is feasible, a property it shares with deep inelastic lepton-hadron scattering." [Hamberg, van Neerven, Matsuura, 1991]
- NLO EWK corrections (beyond large QED FSR corrections) of similar size as NLO$\rightarrow$NNLO QCD
- Total theory uncertainty (excluding PDFs) $\lesssim 0.5 - 1.0\%$ absolute: benchmarking&combining tools, a lot of computation power





W and Z Production in Hadron Collisions

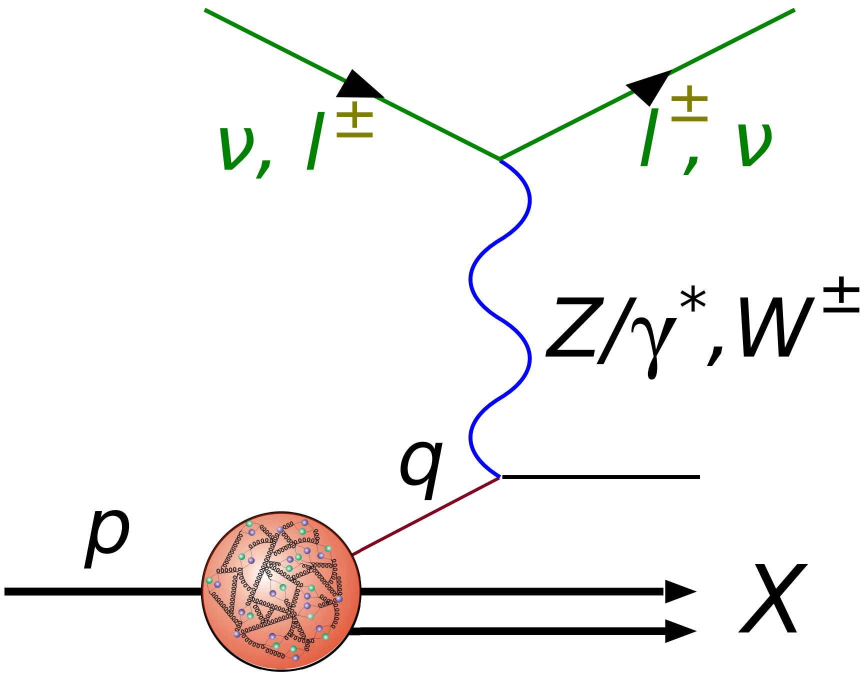
- Full prediction integral over parton distributions of the proton $f(x, Q^2)$
- Parton momentum fraction $x_{1,2} = m/\sqrt{s}\, e^{\pm y}$ related to boson rapidity, scale Q^2 given by boson mass^2
- At LO cross sections determined by sum of different $q\bar{q}$ combinations
  - Weighted by different electro-weak couplings for Z ($v_q^2 + a_q^2$) and γ^* (e_q^2) + their interference
  - Weighted by CKM elements $V_{q\bar{q}}$ for $W^\pm$

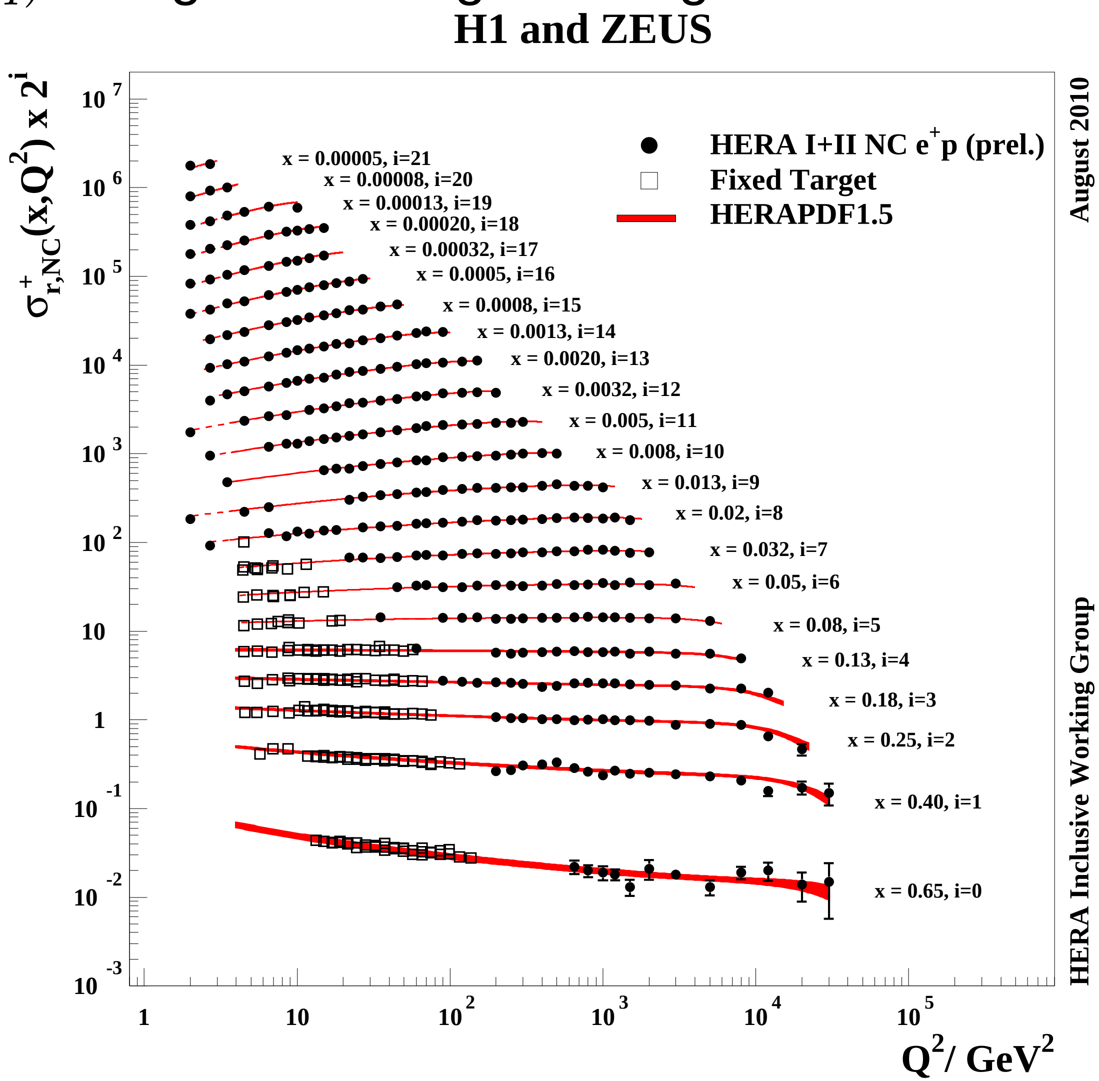


Lepton-hadron deep inelastic scattering

- Inclusive NC cross section measured precisely over many orders of magnitude in x and Q^2 at HERA and fixed target experiments: constrains primarily $\sum e_q^2(q+\bar{q})$ and gluon through scaling violations

- Final HERA 2 combination still to come

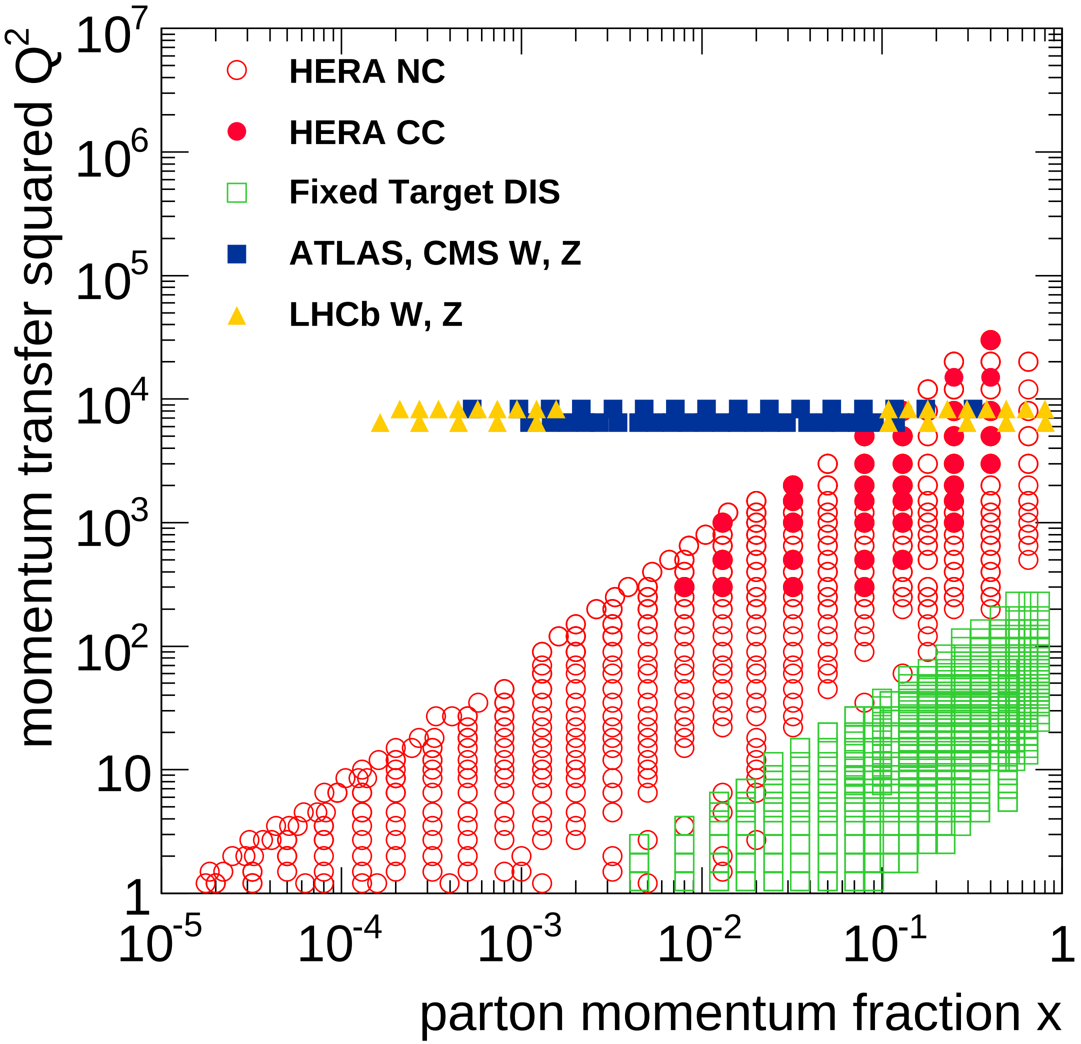




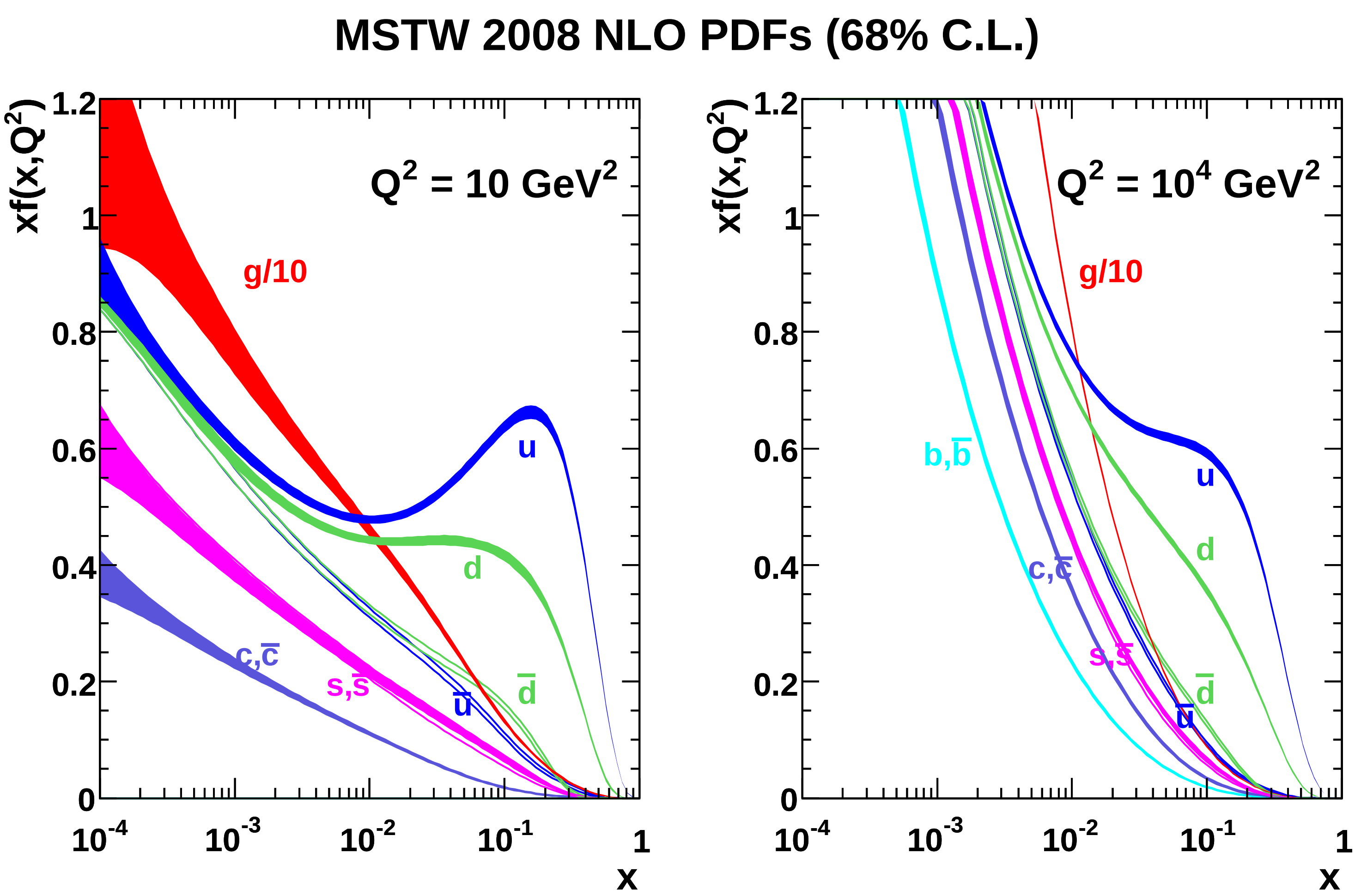
Lepton-hadron deep inelastic scattering

- Inclusive CC cross sections and deuterons/isoscalar targets bring additional information on up/down quark decomposition

- Potentially problematic nuclear corrections for fixed target experiments
- Limited HERA CC statistics and reach
- Parametrise all PDFs at fixed starting scale $f(x, Q_0^2)$: DGLAP evolution at (N)NLO gives result for all $f(x, Q^2)$
- Fix parametrisation by fit to all sensitive data
- Full LHC W, Z production x range only covered by HERA NC data



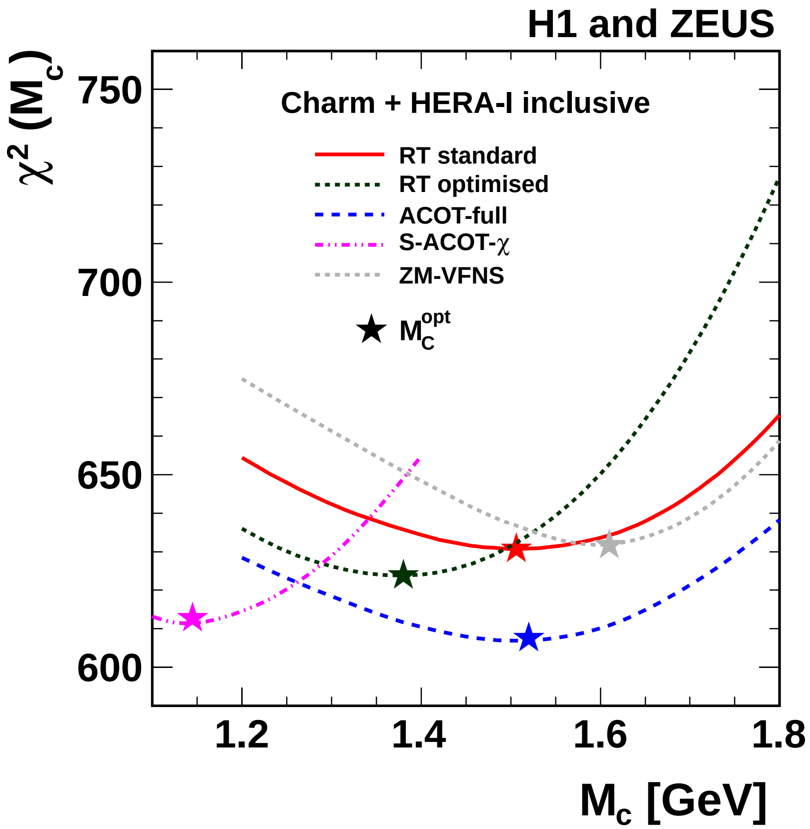
Flavour decomposition in typical PDF Fit

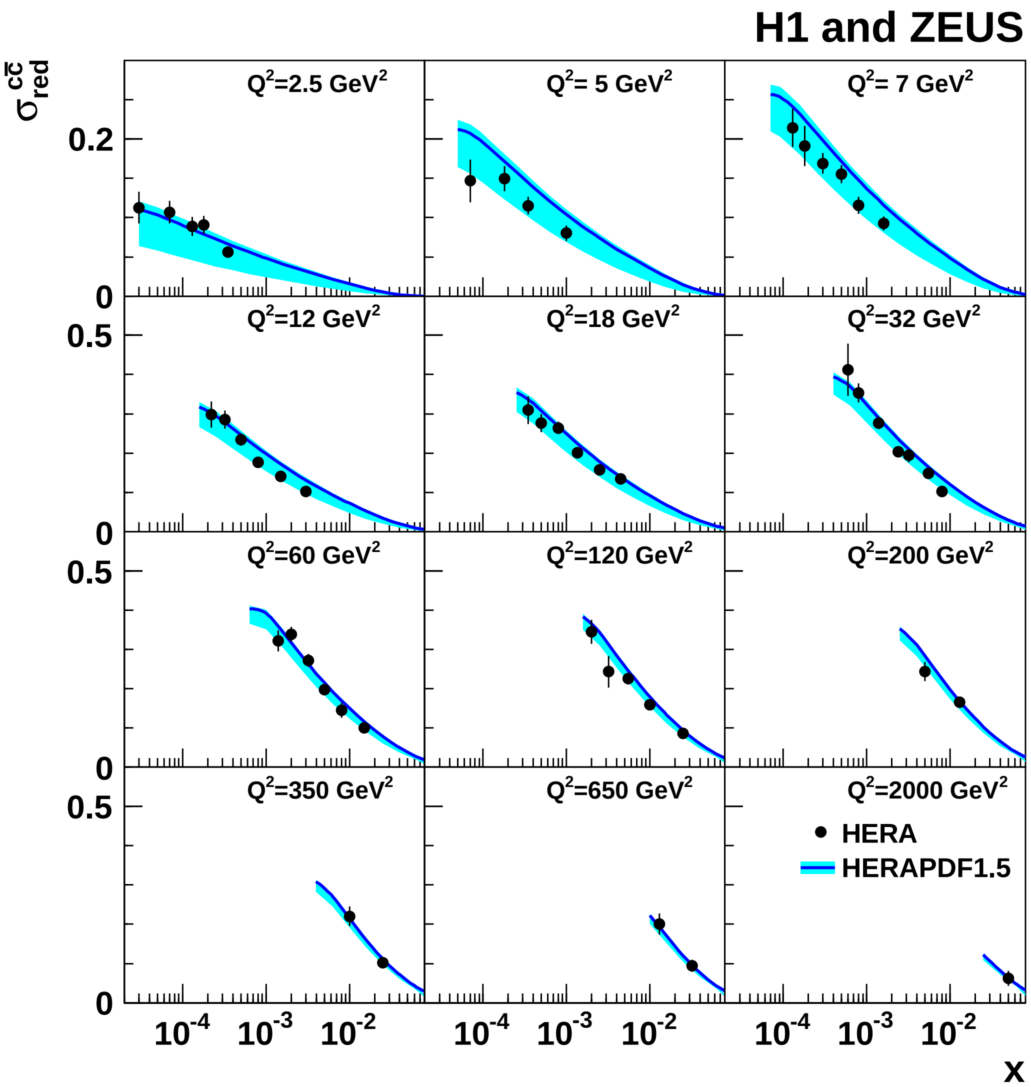


- Heavy quarks c, b: contribution calculated perturbatively, different calculation on the market
- Flavour decomposition of light sea at low $x < 10^{-2}$ mostly an educated guess: $\bar{u} \sim \bar{d}$; $r_s = \bar{s}/\bar{d} < 1$?

Charm content of the proton

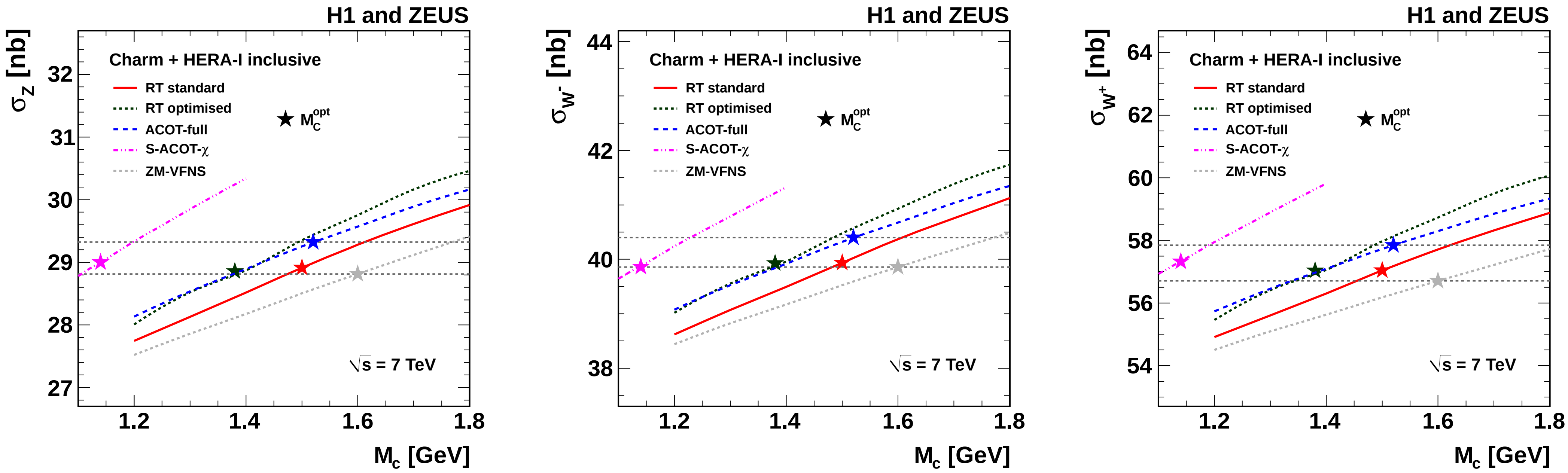
- HERA DIS + charm data has reached few % precision
- Can test the different heavy flavour calculations and constrain the model parameters (mainly charm mass M_c)





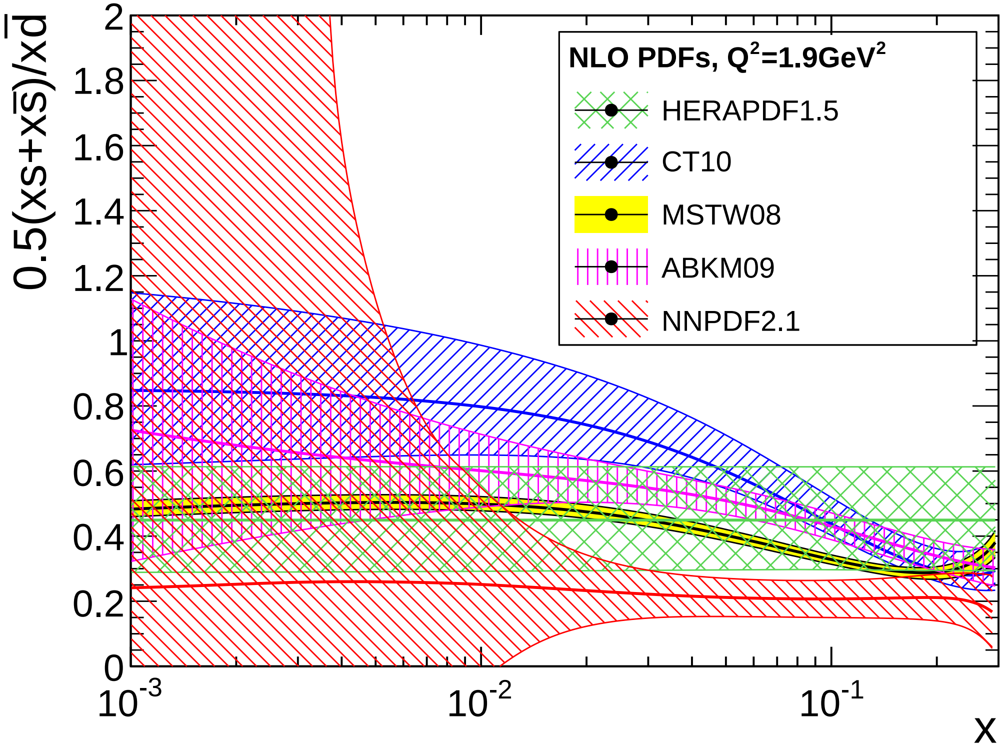
Effect of charm on W, Z @ LHC

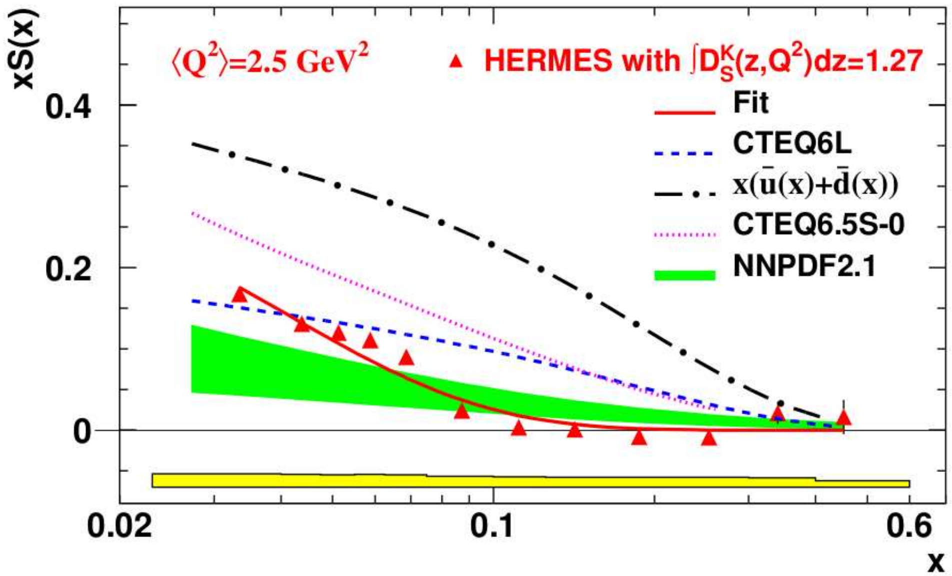
- Treatment of charm contribution to DIS has a strong effect on predicted W and Z cross sections at $\sim 5\%$ level
- If charm treatment is optimised to match the DIS+charm data, the resulting W and Z cross sections at LHC move closer
- Reversing the argument: precise LHC data should be able to tell us about the heavy flavour treatment



Strange Content of Proton

- Some indication of suppressed strange (w.r.t. down sea) at higher x:
  - Neutrino di-muon data (the DIS “equivalent” of W+charm production, see later) give $\sim$ MSTW2008, large spread
  - HERMES LO kaon multiplicities: new analysis reduced strange
- Low x essentially unconstrained

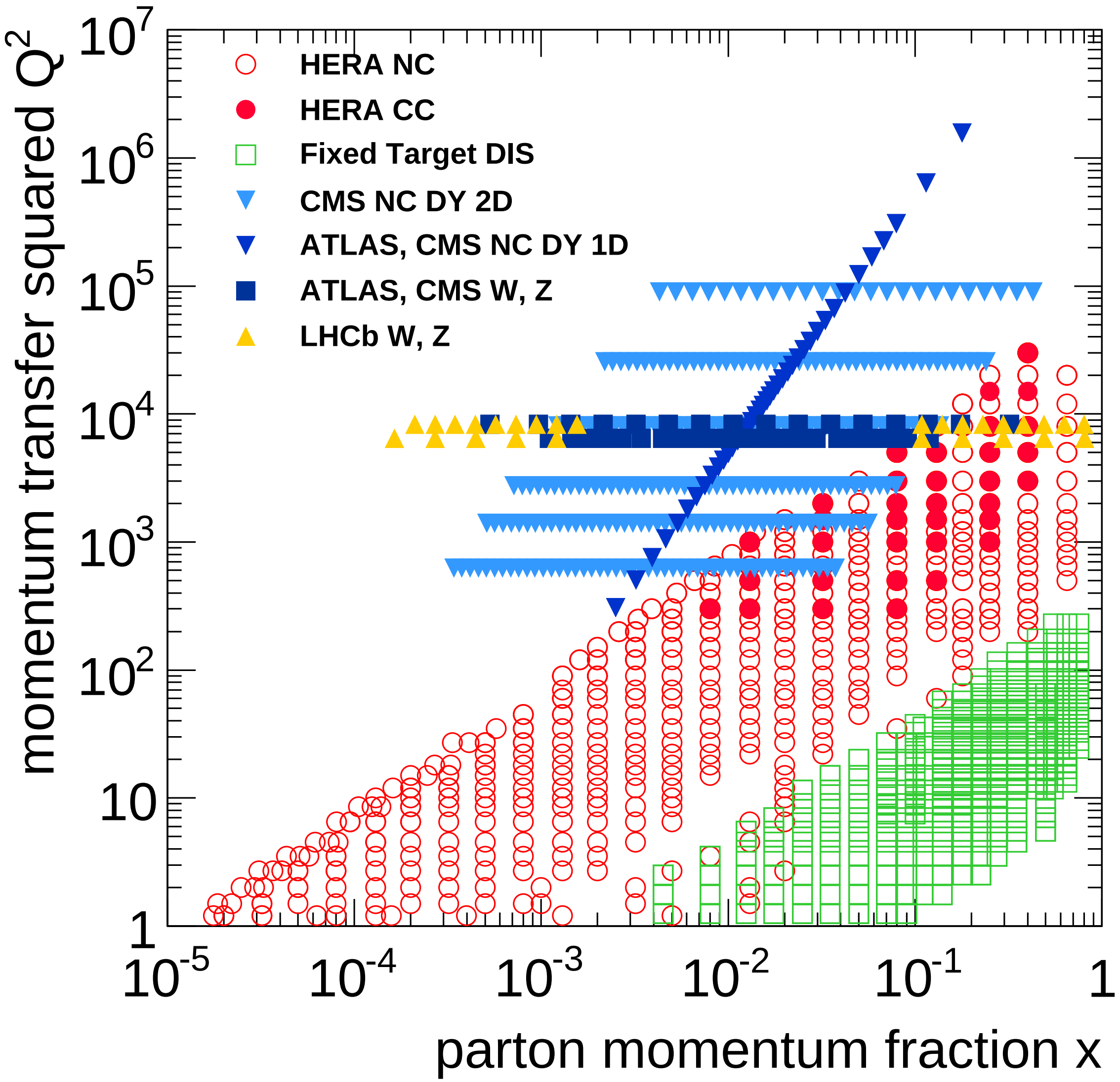




LHC Results on W and Z/γ^* Production

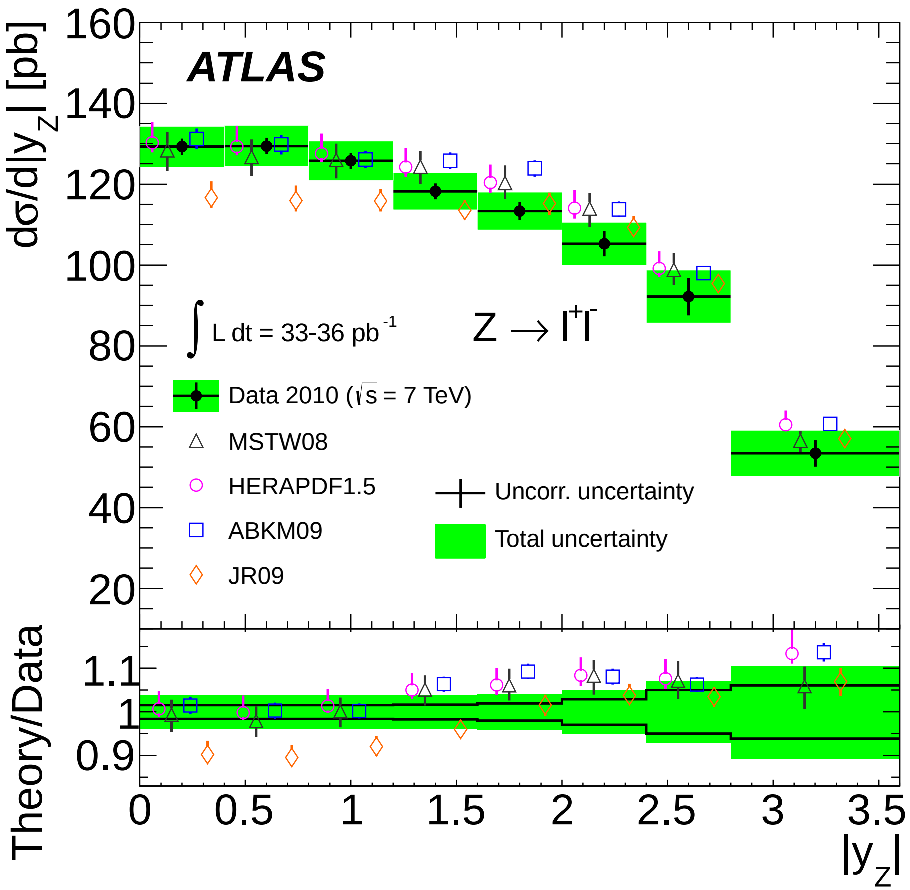
- High statistics, high precision measurements in novel (x, Q^2) range; different flavour sensitivity compared to (NC) DIS

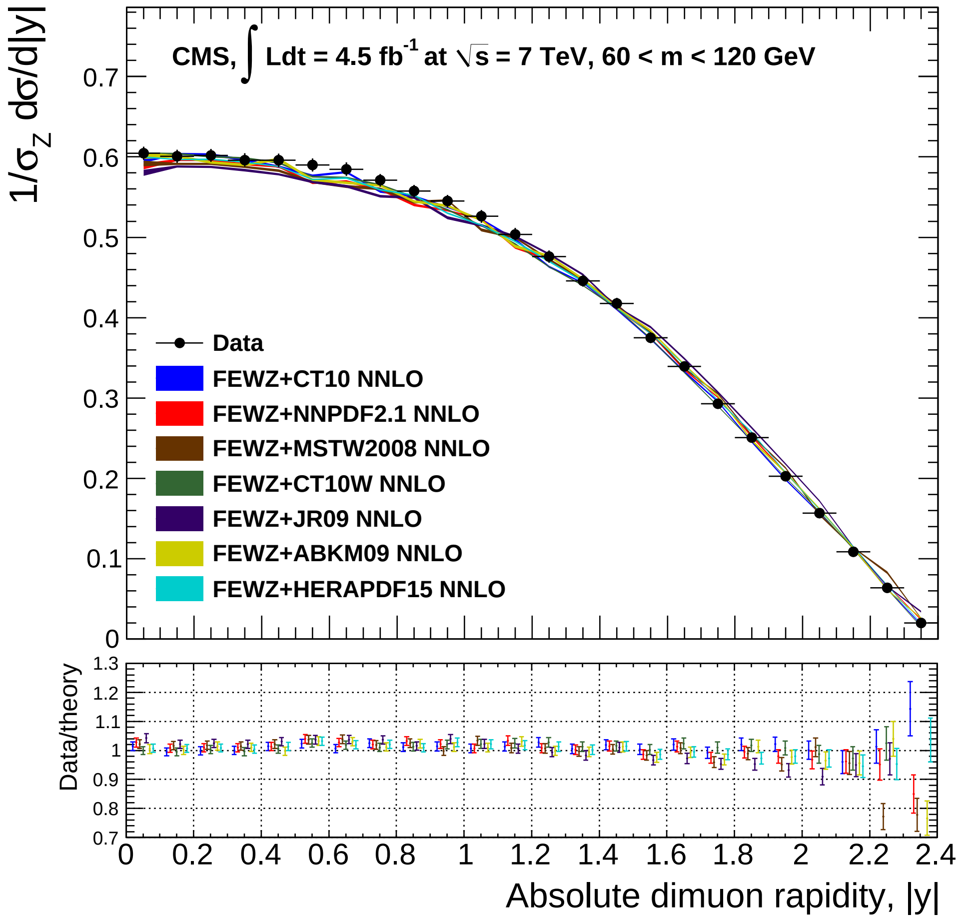
- Z peak differential in y_Z (ATLAS, CMS, LHCb)
- Z/γ^* differential in $m_{\ell\ell}$ (ATLAS, CMS, LHCb prelim.)
- Z/γ^* double differential in $y_{\ell\ell} - m_{\ell\ell}$ (CMS, LHCb prelim.)
- $W^\pm$ differential in η_l (ATLAS, CMS, LHCb)
- $W + \text{charm}$ (ATLAS prelim., CMS)



Z Peak vs. Rapidity

- Small backgrounds, high statistics: showcase for lepton performance
- ATLAS (and CMS) 2010 combine $Z \to ee$ (central+fwd) and $Z \to \mu\mu$ (~ 2-3%); CMS update 2011 $Z \to \mu\mu$ (~ 1-2%): absolute vs. normalised
- Comparison to NNLO PDFs: most sets show a slope vs. $y_{\ell\ell}$





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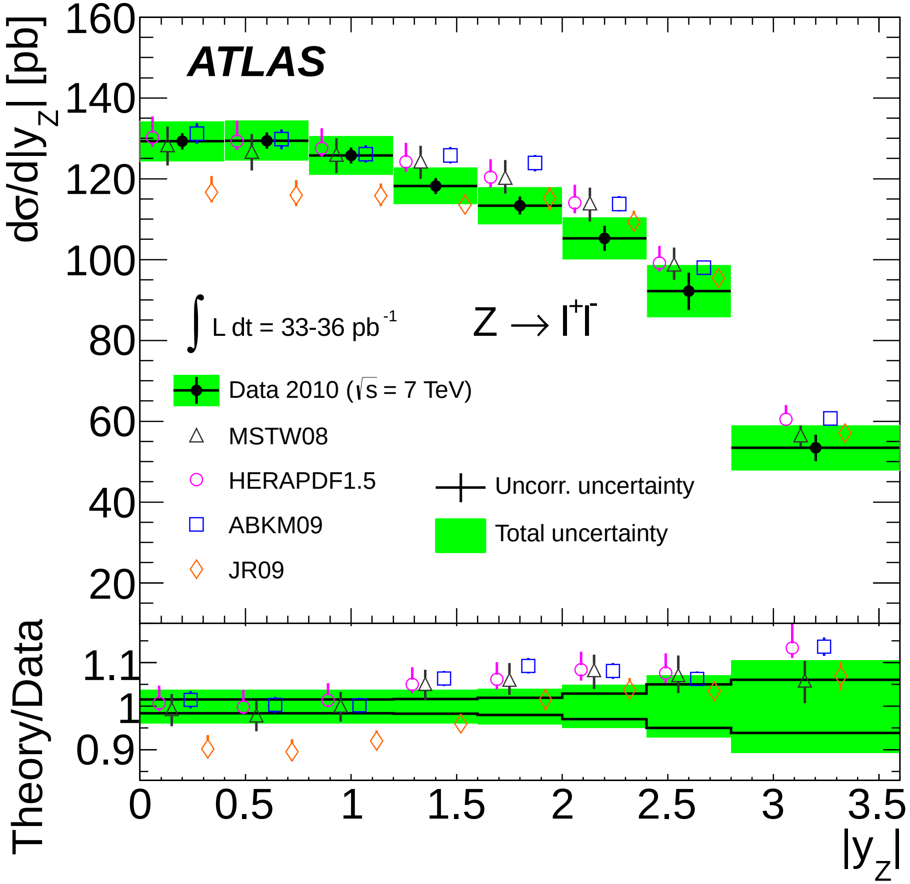
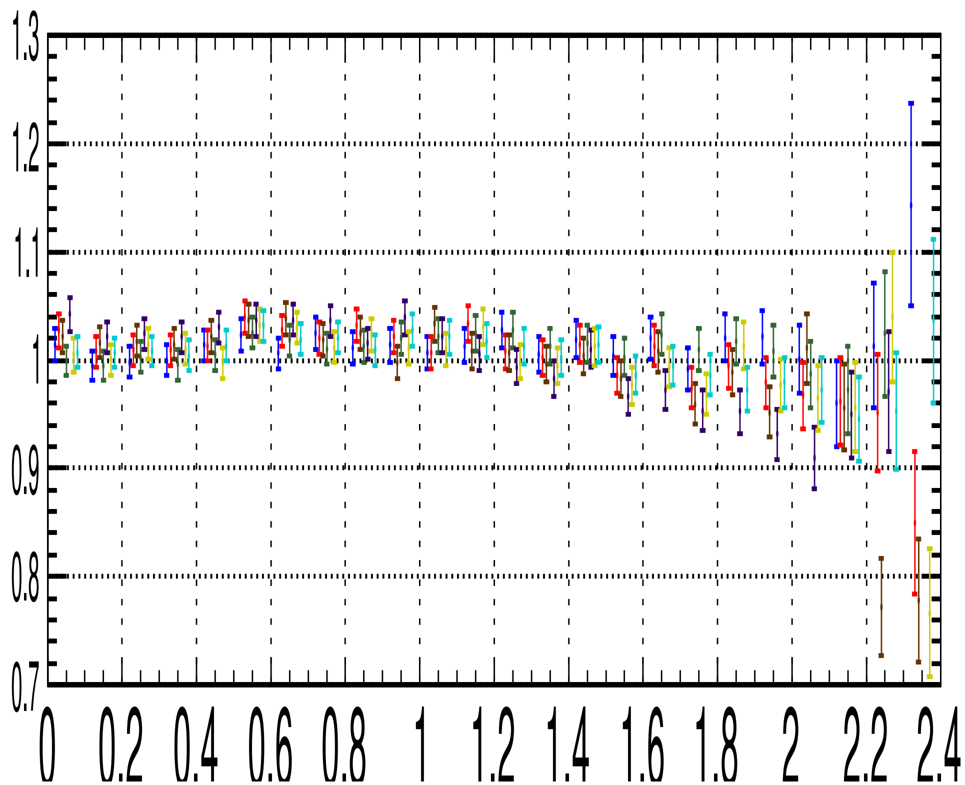
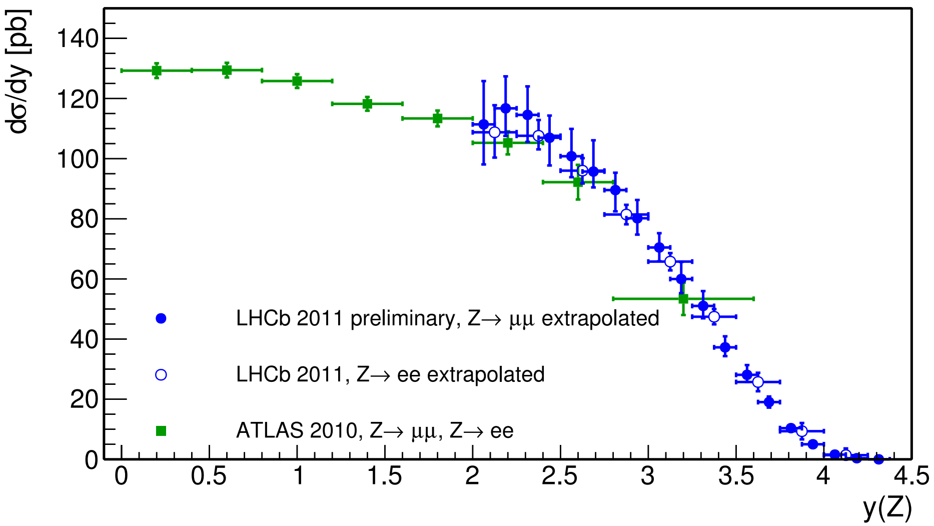
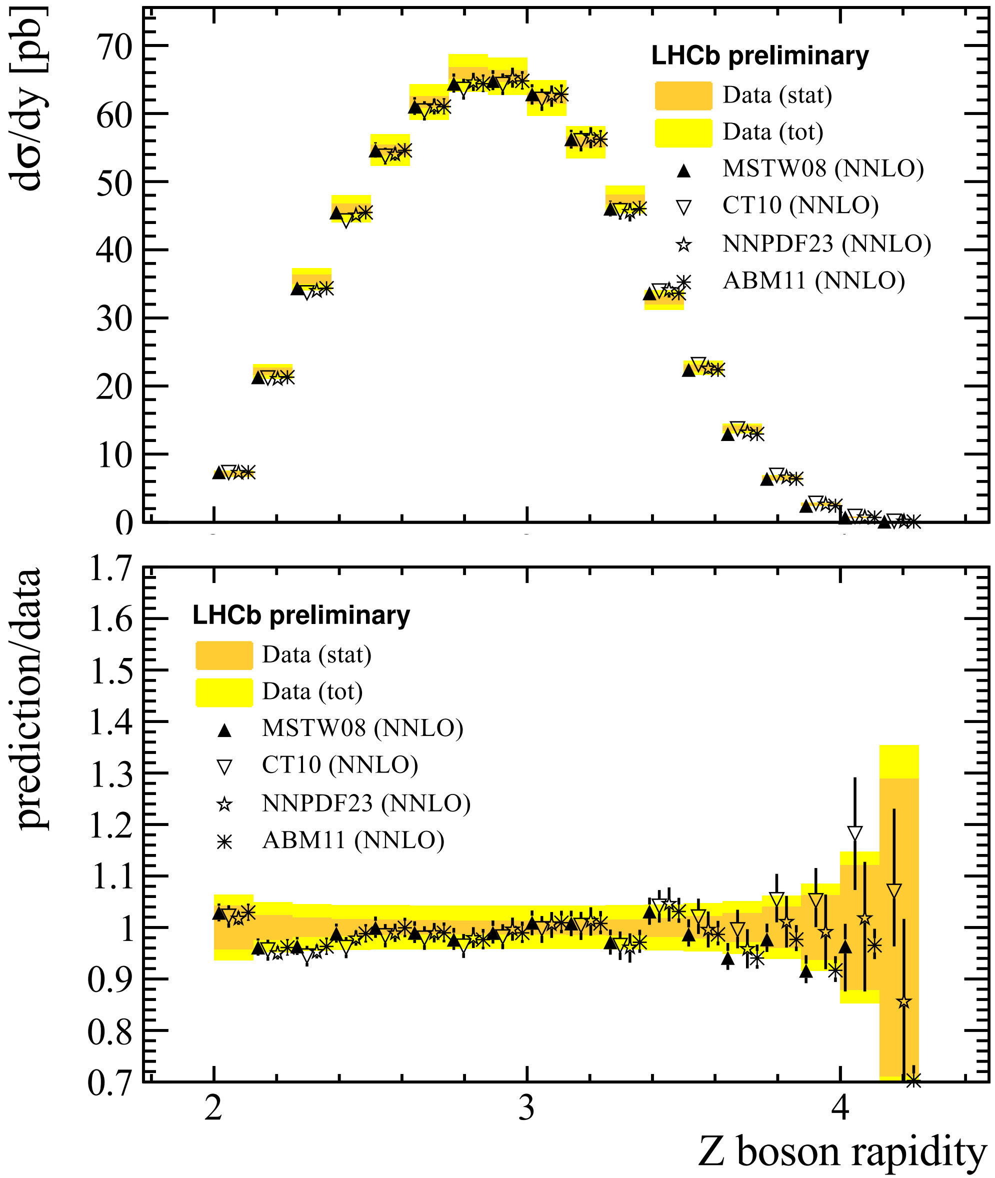




Z Peak vs. Rapidity

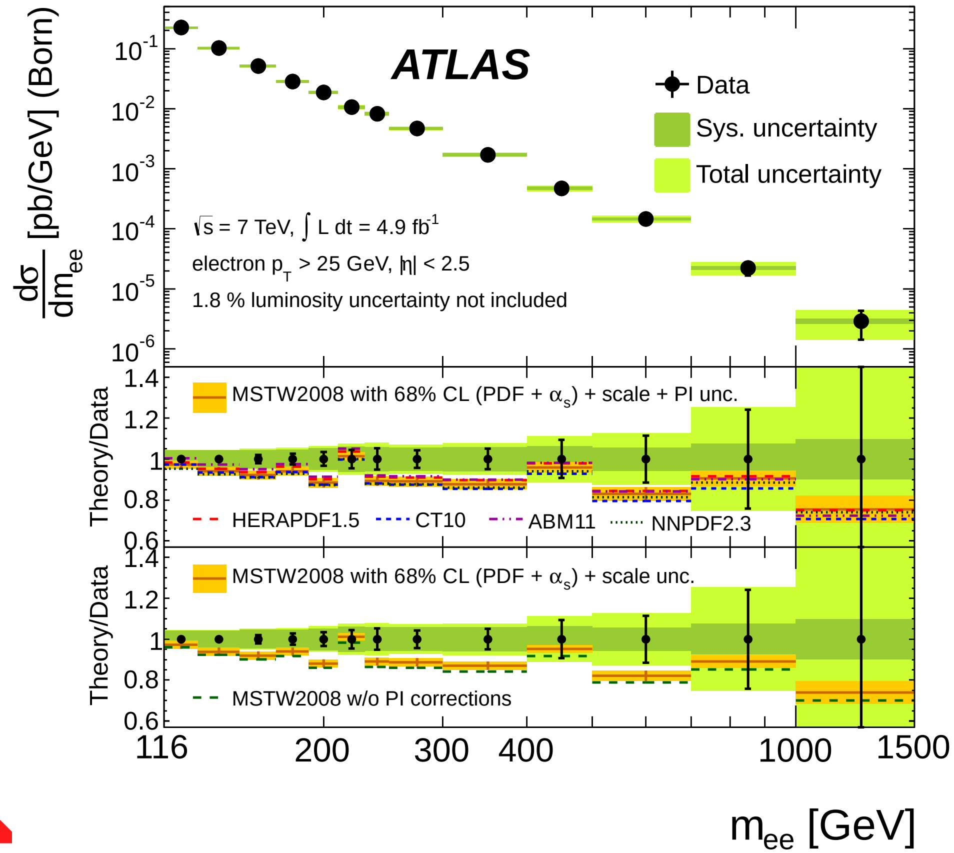
- LHCb extends the Z measurement to the full rapidity range using both $Z \to ee$ and $Z \to \mu\mu$ ($\sim$ 2-3% prelim.)
- Qualitative good comparison to ATLAS
- Comparison to NNLO PDFs good

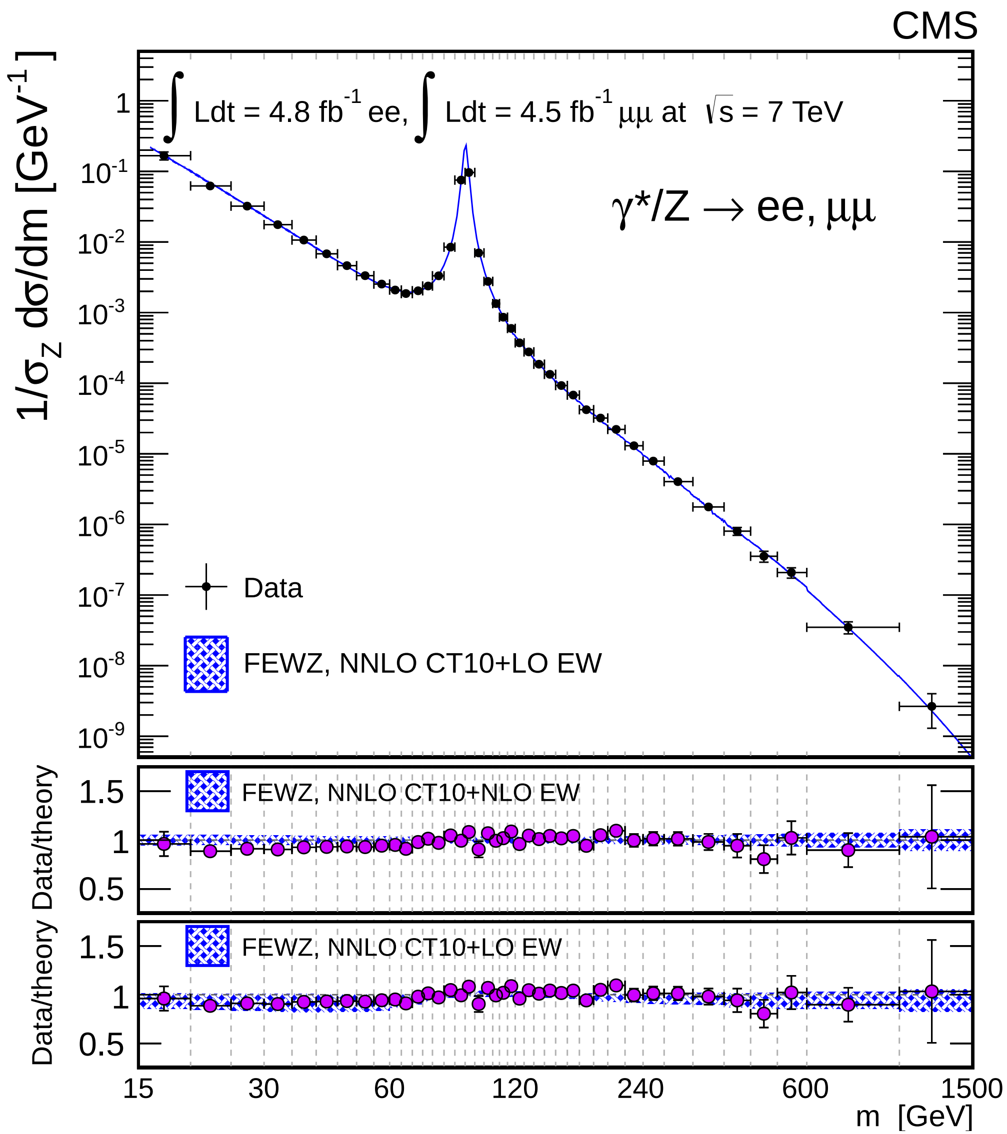




Z/γ^* vs. $m_{\ell\ell}$

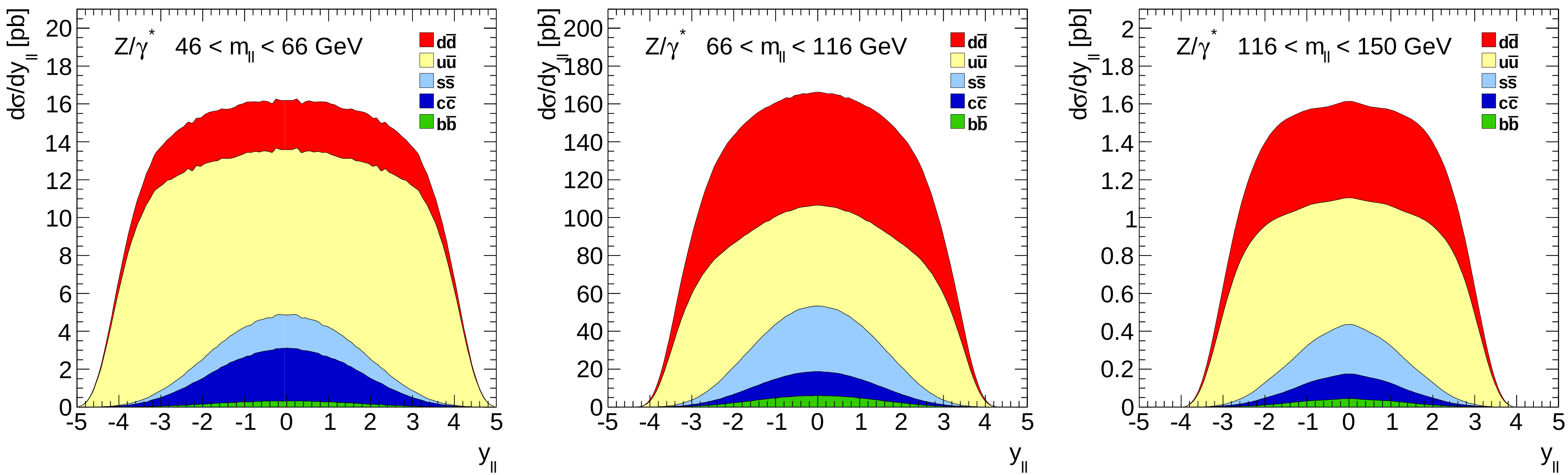
- Moving away from Z peak: change in probed x, Q^2, different quark couplings, important HO EWK corrections including photon-induced processes $\gamma\gamma \to \ell\ell$
- Limited PDF sensitivity (although NNPDF2.3QED γ based on this)



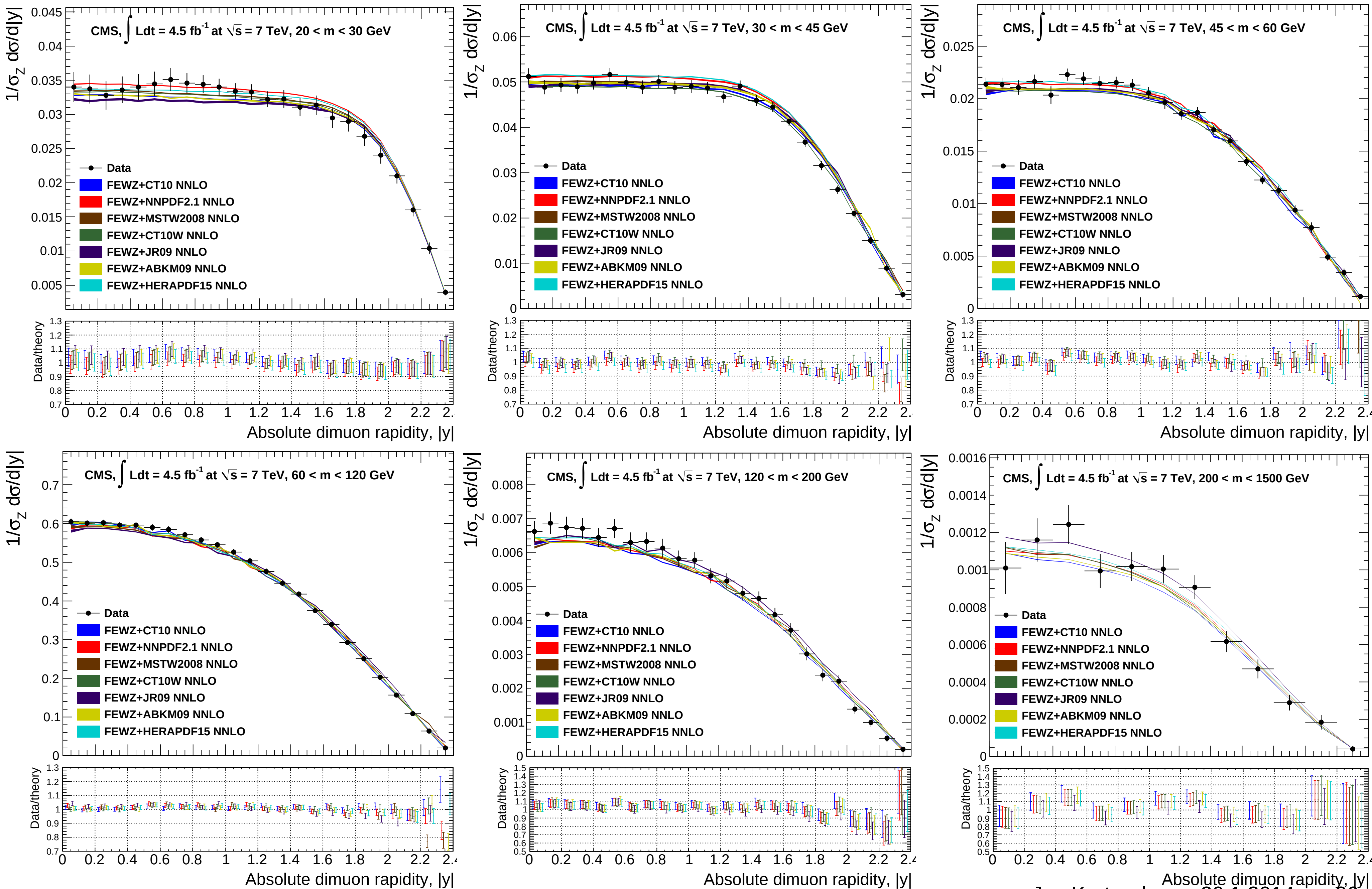


Z/γ^* double-differentially

- Next step: double-differential Z/γ^* in $y_{\ell\ell} - m_{\ell\ell}$
- Full exploitation of accessible x, Q^2 range and different quark couplings; experimental correlations: expect strong constraints on PDFs
- First preliminary results by LHCb, first CMS publication on full 2011 data using $\mu\mu$ final state $\rightarrow$ next page; need to see how this will work in a QCD fit...

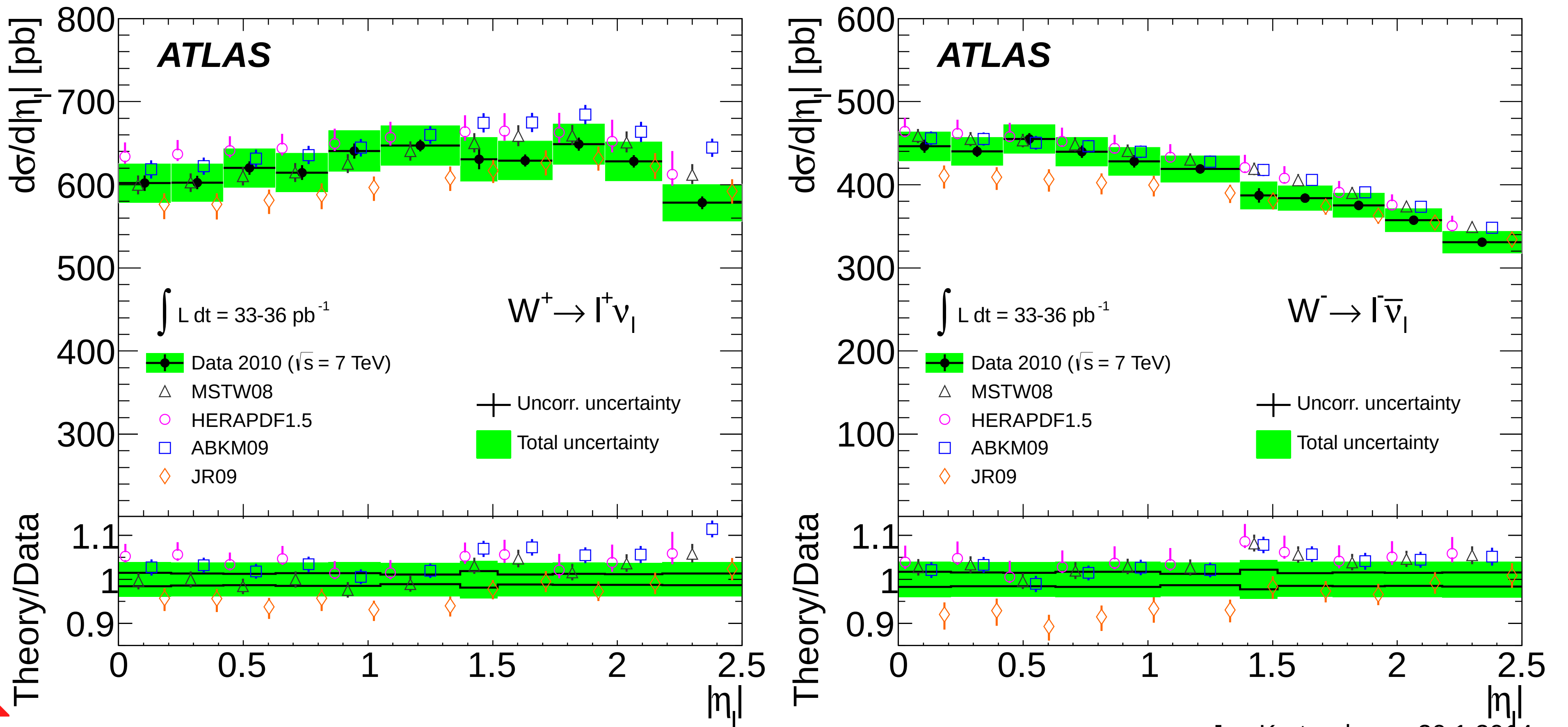


Z/γ^* double-differentially (CMS)



$W^{\pm}$ results

- Challenges: background, single ℓ trigger, ℓ and $\not{E}_T$ performance
- "Asymmetry" $(W^+ - W^-)/(W^+ + W^-)$ vs. separate W^+ and W^- with full correlations: robuster theory vs. more information
- ATLAS based on 2010 $e - \mu$ combination; CMS 2011 $p_{T,\ell} > 25$GeV based on muons: very precise



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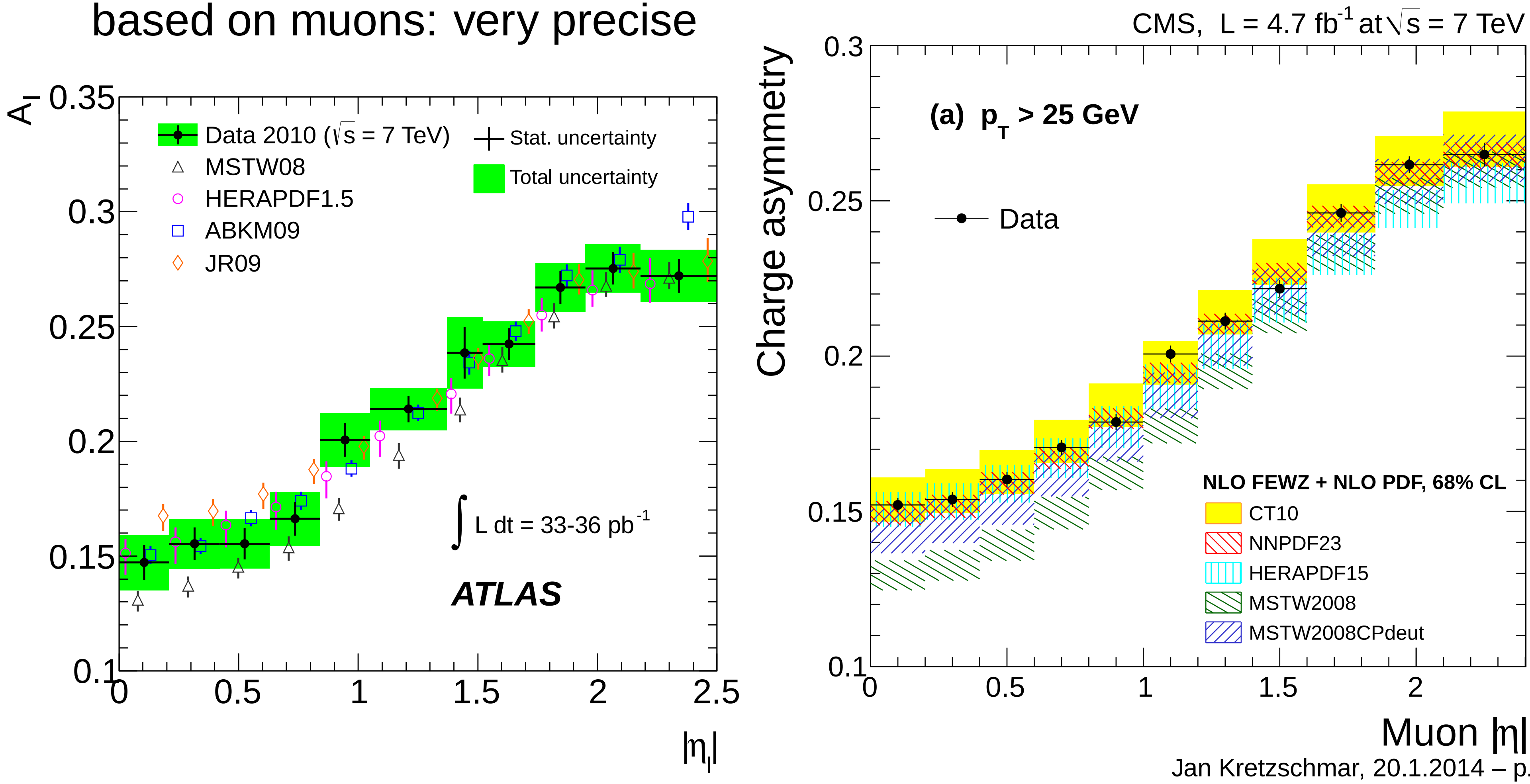

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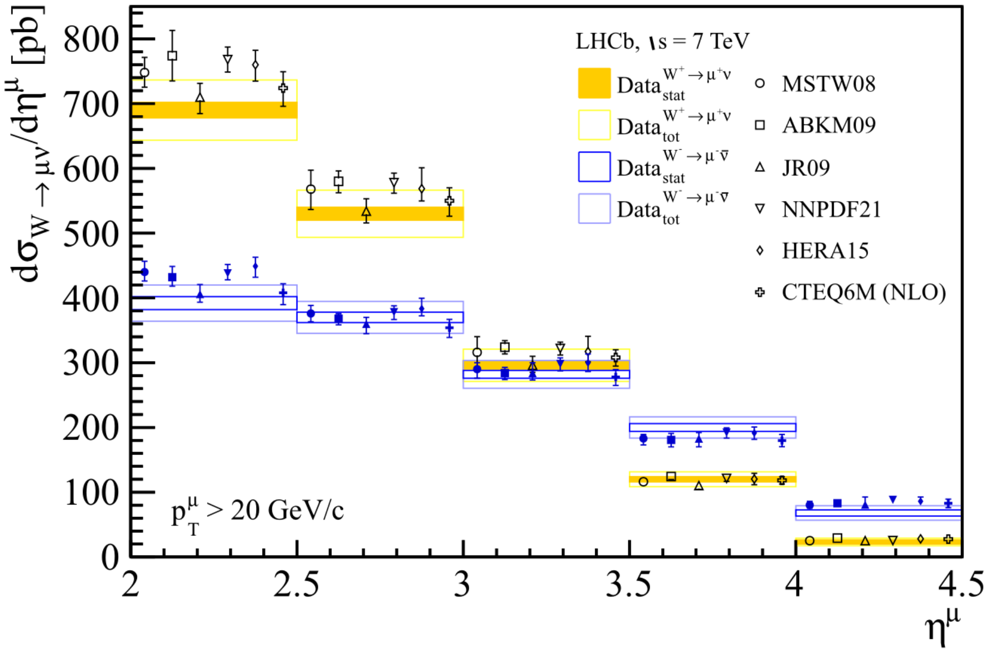
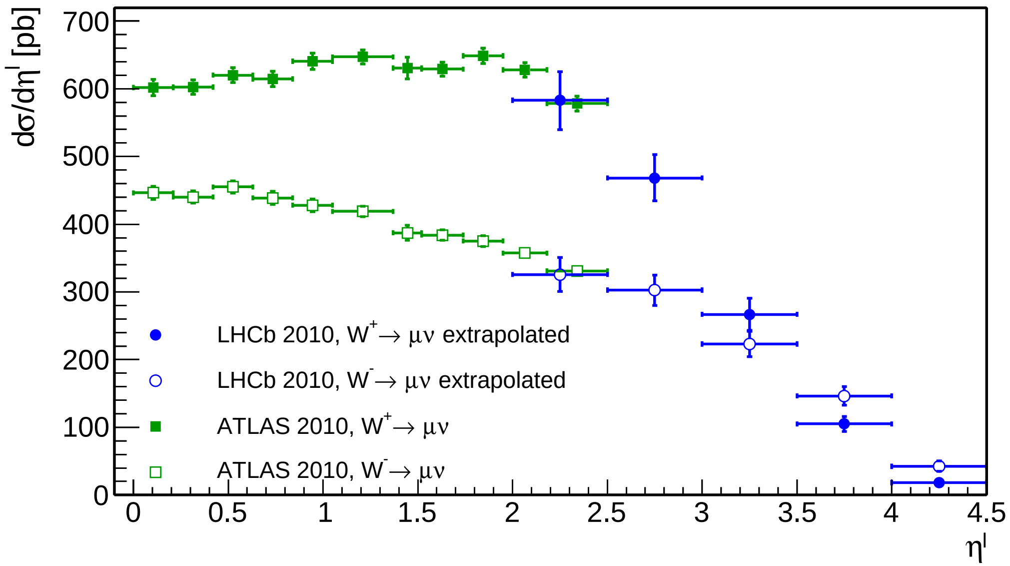
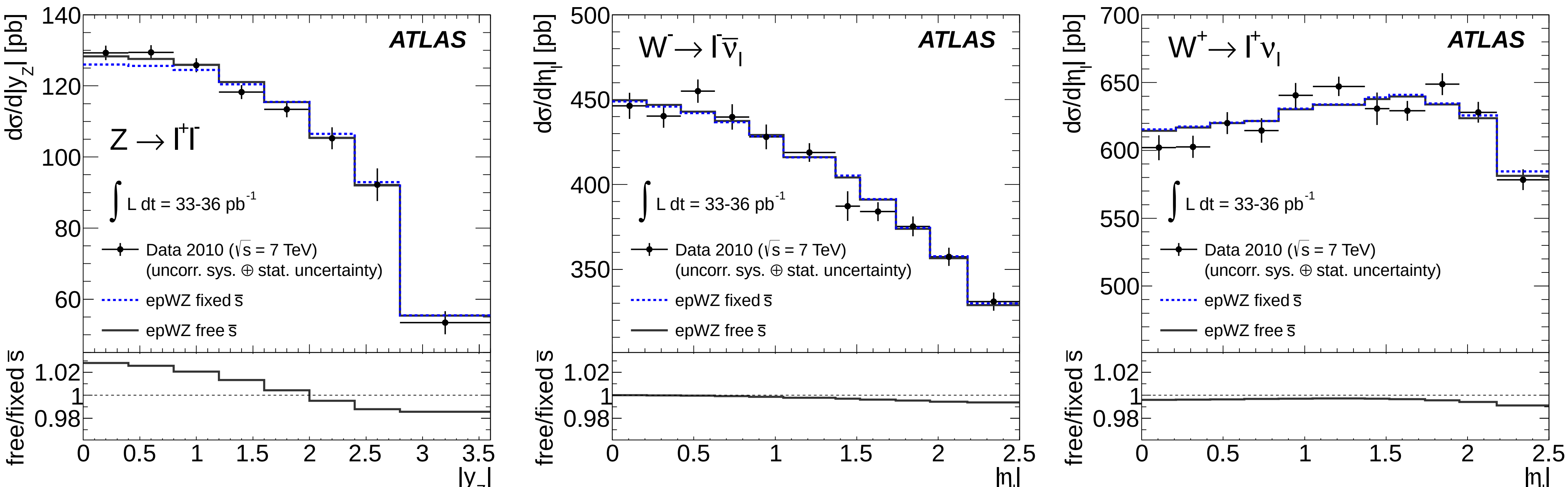




ATLAS PDF Fit to 2010 $W^{\pm}$ and Z

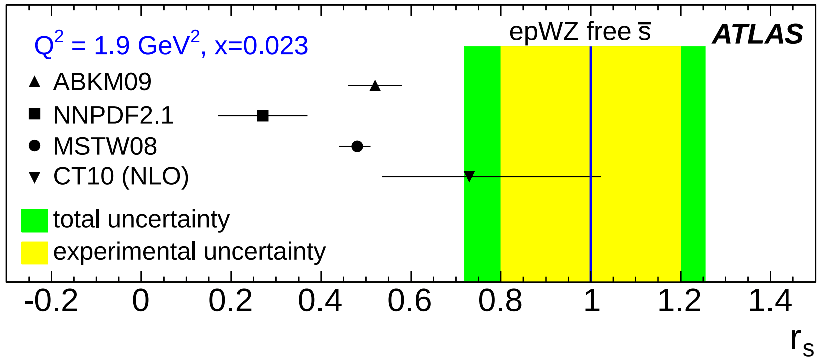
- Actual impact of the data and compatibility with QCD is best gauged by doing a full PDF fit
- ATLAS fit to $W^{\pm}$ and Z + HERA ep DIS cross sections (HERAFitter with MCFM+APPLGRID NLO QCD $\times$ NNLO k factors)
- Significant tension is observed, when strange quark fraction $r_s = 0.5 \cdot (xs(x) + x\bar{s}(x))/x\bar{d}(x)$ is fixed to $r_s = 0.5$ at $Q^2 = 1.9\,\mathrm{GeV}^2$
- ATLAS W, Z improves from $\chi^2/\mathrm{n.d.f.} = 44.5/30$ to $\chi^2/\mathrm{n.d.f.} = 33.9/30$ when releasing strange constraint

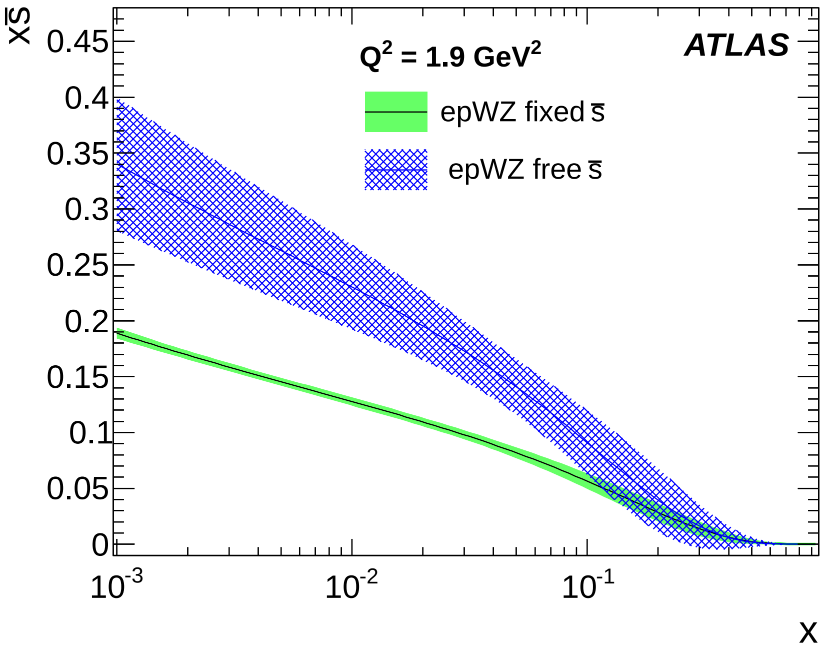


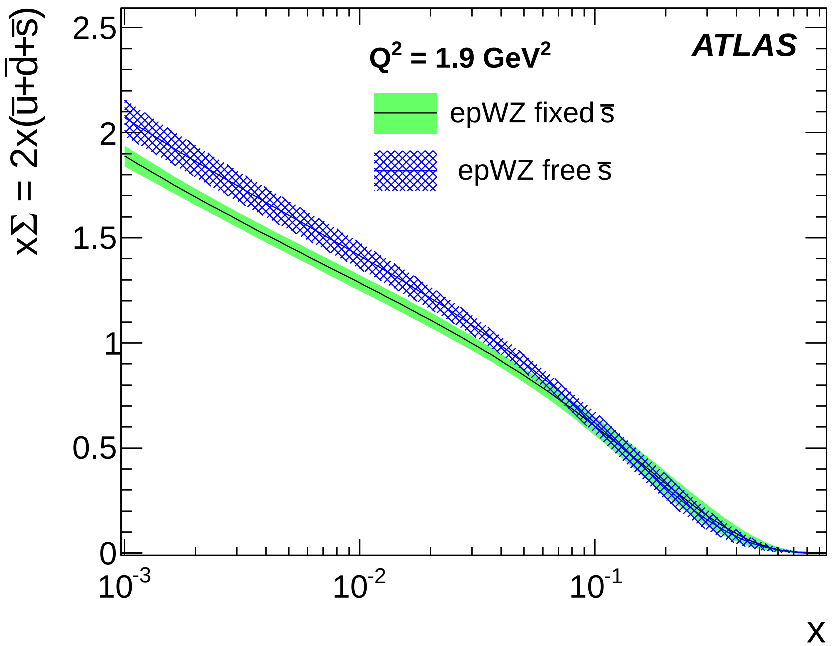
W, Z data sensitivity to strange sea

- Fit with free strange sea indicates no strange sea suppression at $Q^2 = 1.9\,\text{GeV}^2$ and $x = 0.023$: $r_s = 1.00 \pm 0.20_{\text{exp}}\ {}^{+0.16}_{-0.20}\,{}_{\text{sys}}$

- Knock-on effect on the remaining light sea as HERA constrains $\sim \sum e_q^2(q+\bar{q})$
- $r_s = 1$ just luck?

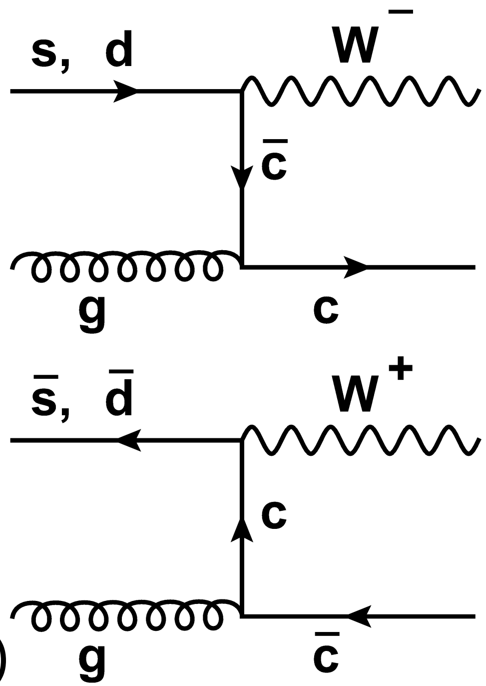


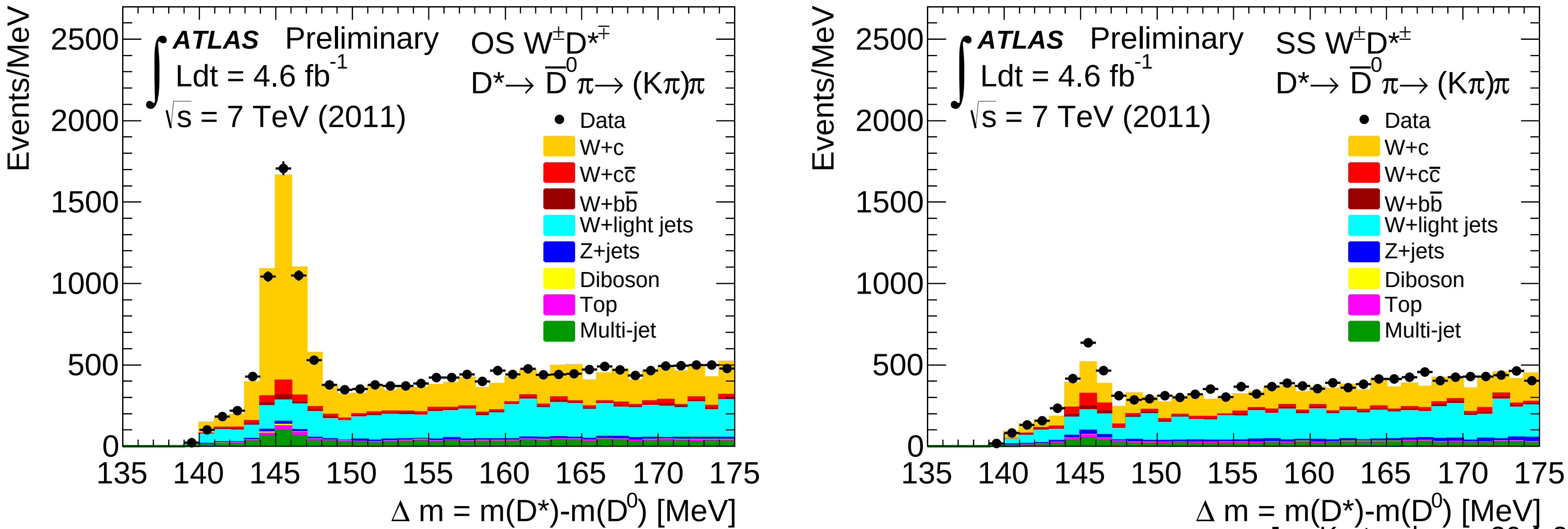




W+charm

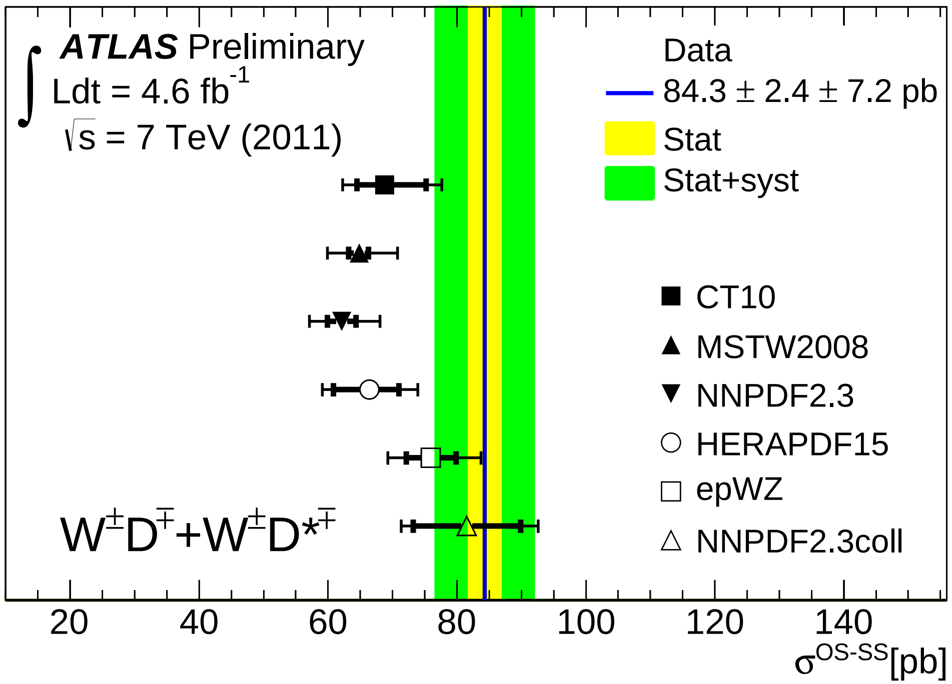
- A direct probe of the strange PDF: W+charm, $\sim 90\%$ of the cross section strange-induced
- Charm tagging methods:
  - $D^{(*)}$ reconstruction (CMS, ATLAS prel.)
  - $c \to \mu$ decays (CMS)
- Exploit charge correlation between $W^{\pm}(\to \ell^{\pm}\nu)$ and $c/\bar{c}$: signal is OS, background is OS/SS symmetric
- Drawbacks: statistics, theory only NLO (5-10% unc.)

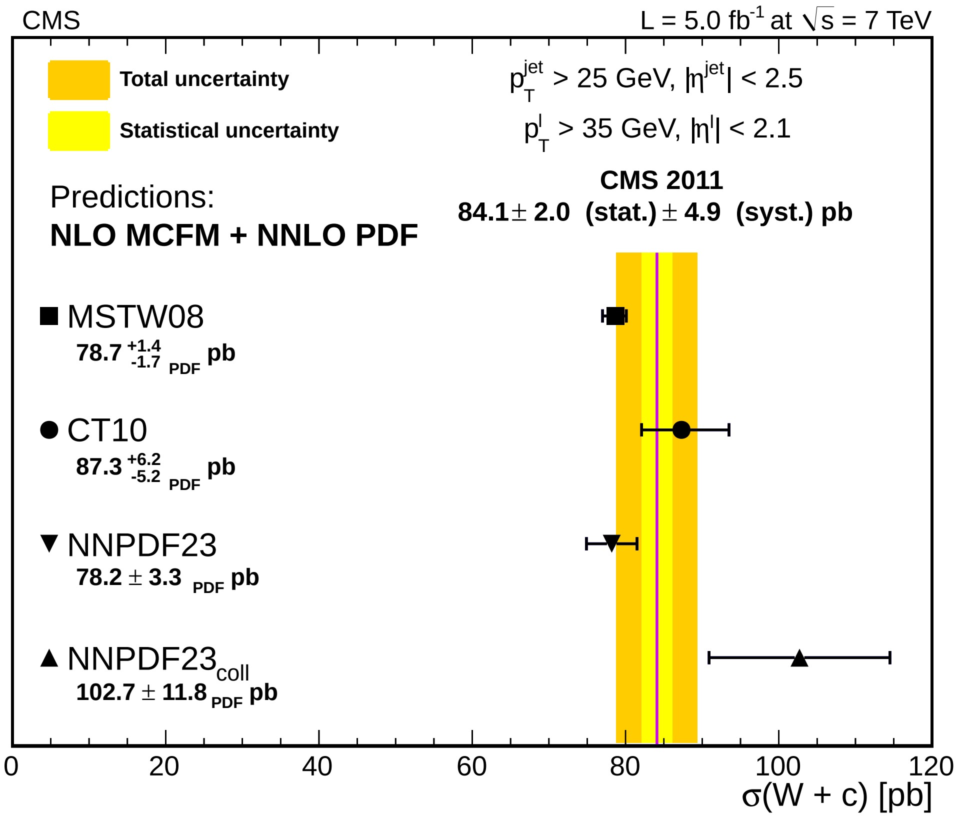




W+charm Integrated

- Phase spaces different, numerical closeness of measured cross sections a coincidence
- Compare final measurements vs. common PDFs, e.g. CT10
- ATLAS result has a clear preference for high strange, while CMS is more “in between” — to be continued with more (precise) data



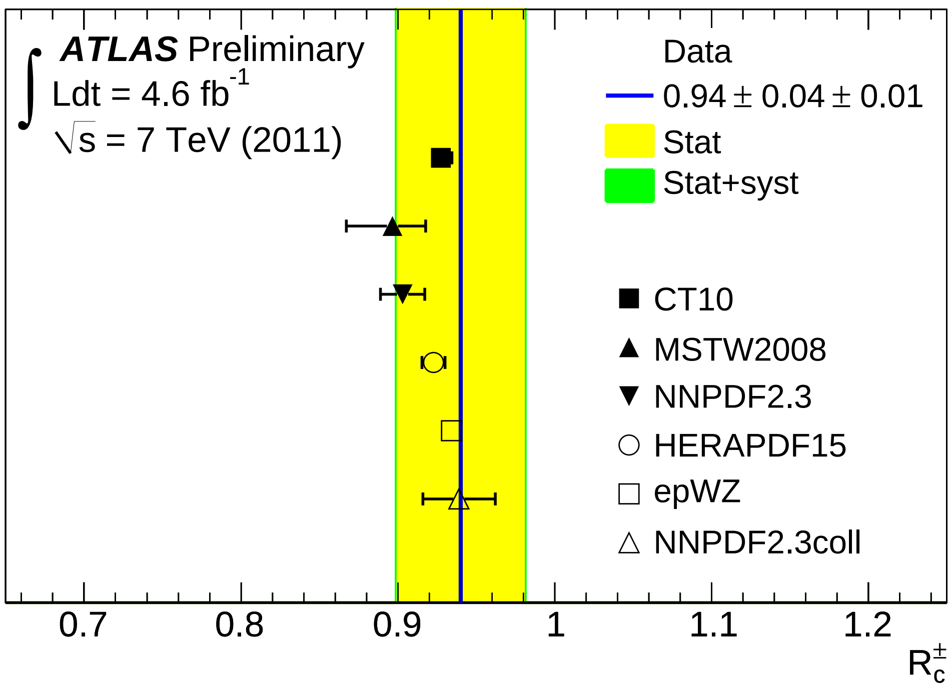


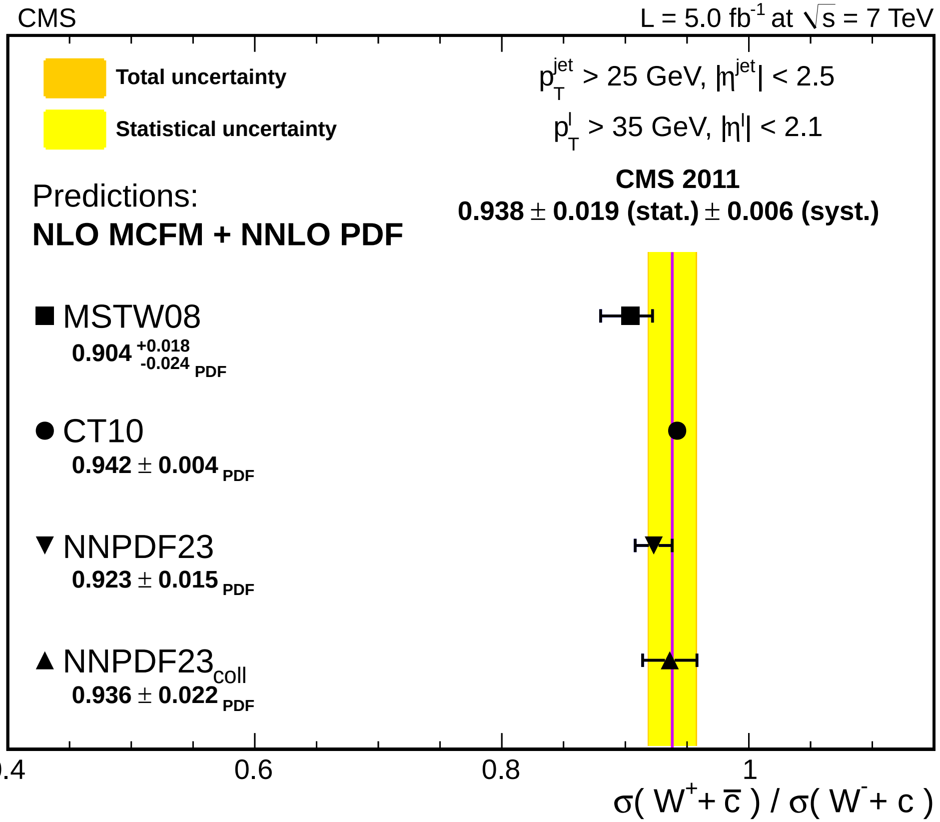
W+charm Charge Ratio

- Ratio $R_c^{\pm} = W^+\bar{c}/W^-c$ sensitive to potential $s/\bar{s}$ asymmetry

$$R_c^{\pm} \sim \frac{|V_{cs}|^2\bar{s} + |V_{cd}|^2\bar{d}}{|V_{cs}|^2 s + |V_{cd}|^2 d} \sim \frac{0.95\bar{s} + 0.05\bar{d}}{0.95s + 0.05d}$$

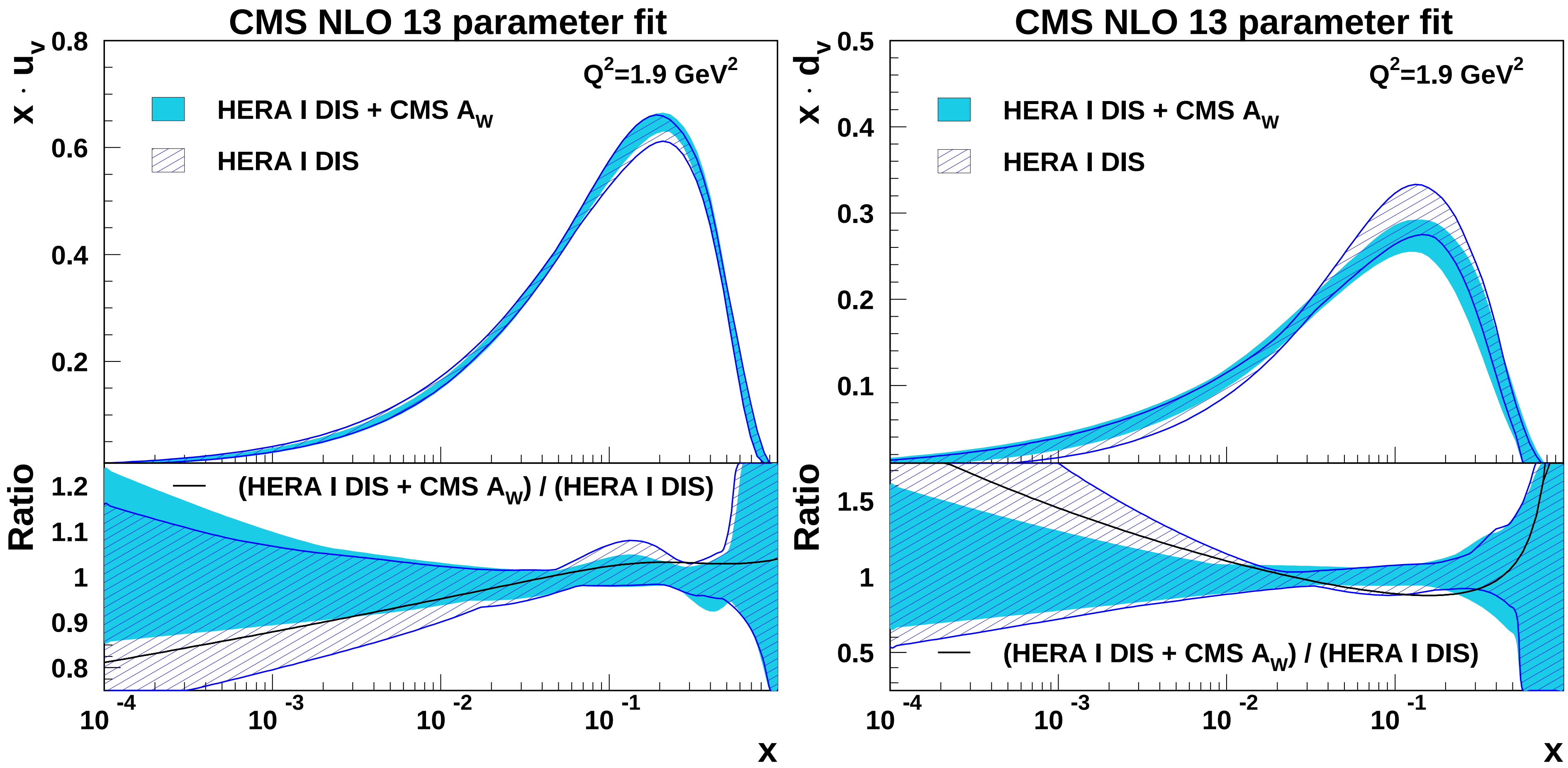
- Too low statistics to decide between PDF set with $s = \bar{s}$ (e.g. CT10) and others with asymmetry (e.g. MSTW2008)





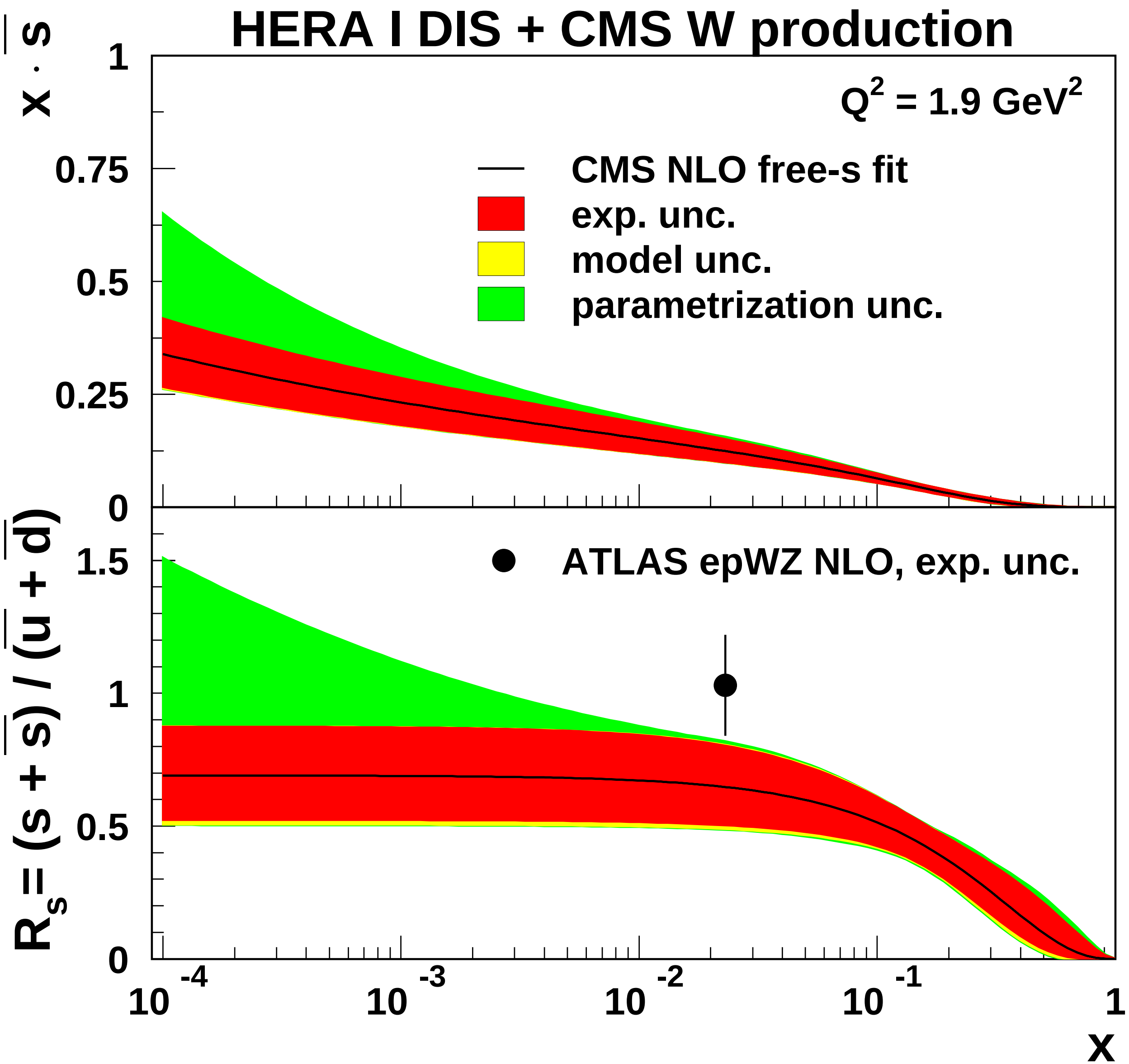
CMS QCD Fit to 2011 W and W+charm

- CMS has performed an NLO QCD fit to gauge the impact of the W production data (unfortunately not including Z/γ^*)
- Based on HERA 1 data and HERAFitter similar to ATLAS fit
- Inclusive W asymmetry has effect on valence quarks



CMS QCD Fit to 2011 W and W+charm

- Similar to ATLAS fit leave the strange distributions free



- CMS Strange enhanced, but not as much as in ATLAS fit; consistent
- More constraints in CMS fit at high x
- Note: Glossing over some details like NNLO vs. NLO, r_s vs. R_s

CMS QCD Fit to 2011 W and W+charm

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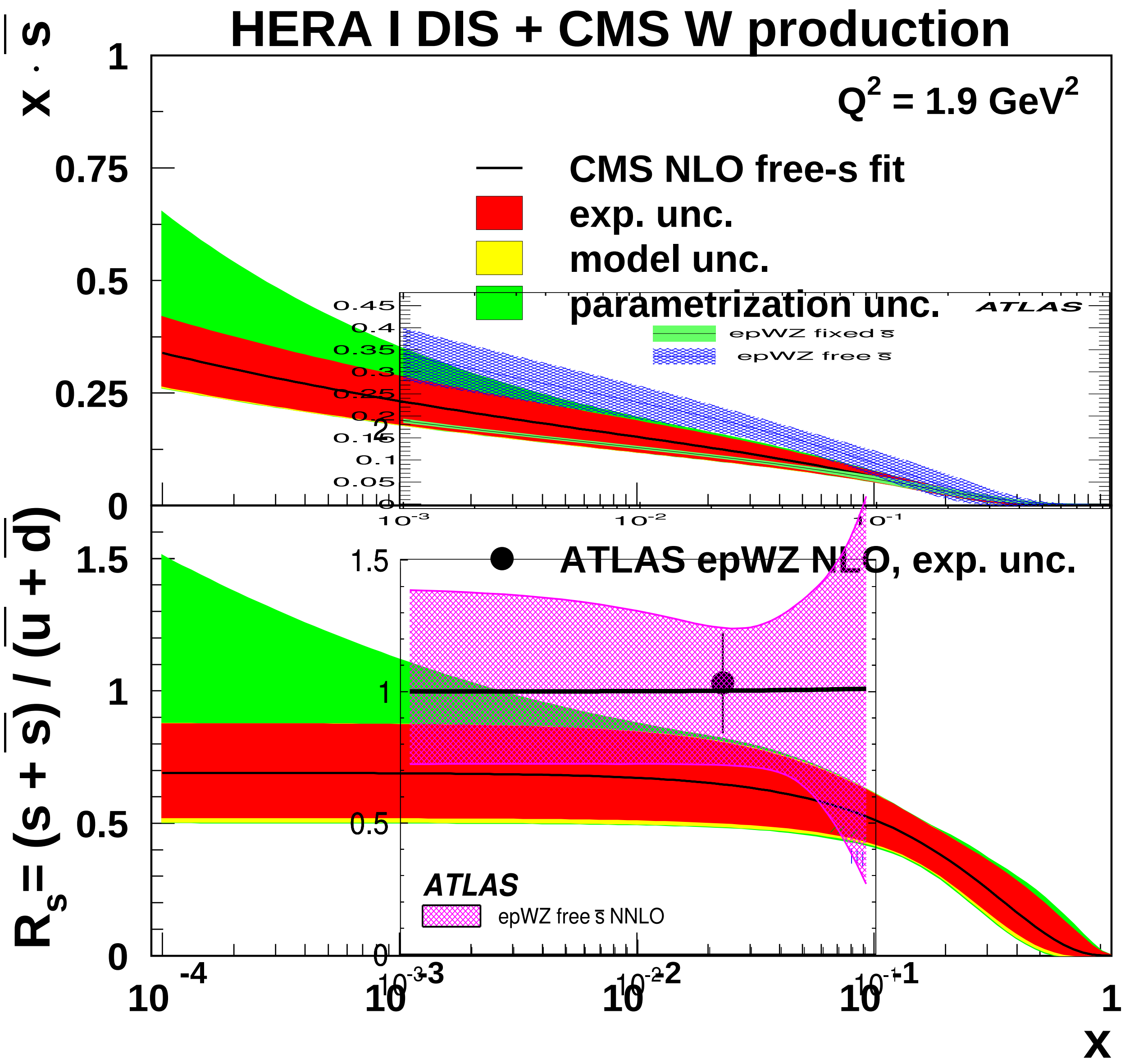

- CMS Strange enhanced, but not as much as in ATLAS fit; consistent
- More constraints in CMS fit at high x
- Note: Glossing over some details like NNLO vs. NLO, r_s vs. R_s

Conclusions

- After years of waiting, discussion and work the precision W and Z measurements from LHC are coming in
- 2010 results published since long: a few PDF fits clearly disfavoured, indication for large strange component
- 2011 results with $100\times$ larger data set just published (CMS) and hopefully coming soon from ATLAS and LHCb
- LHC W and Z data have novel sensitivity compared to HERA at low $x \lesssim 10^{-2}$: will help to verify or improve previous conventional assumptions like strange content
- Improvements at higher $x \gtrsim 10^{-2}$ compared to pre-LHC data require interplay of highly precise $W^{\pm}$ and Z/γ^{*} measurements

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Backup

PDF comparison