Measurements with W and Z bosons at ATLAS

Workshop on electroweak corrections for LHC physics

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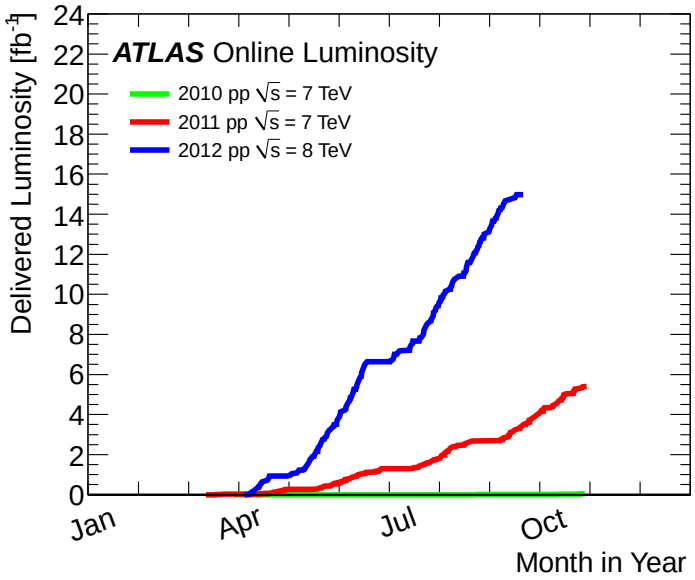
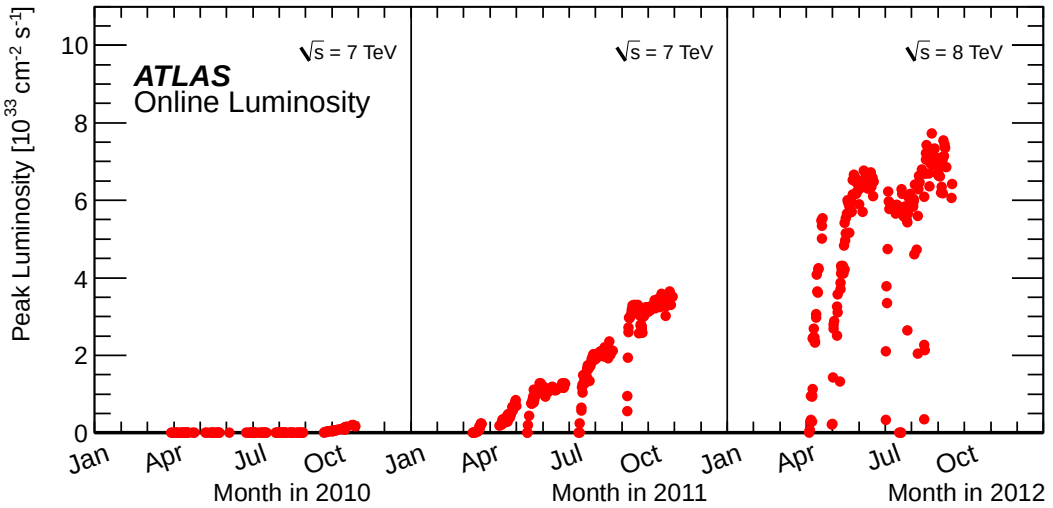
LHC Performance

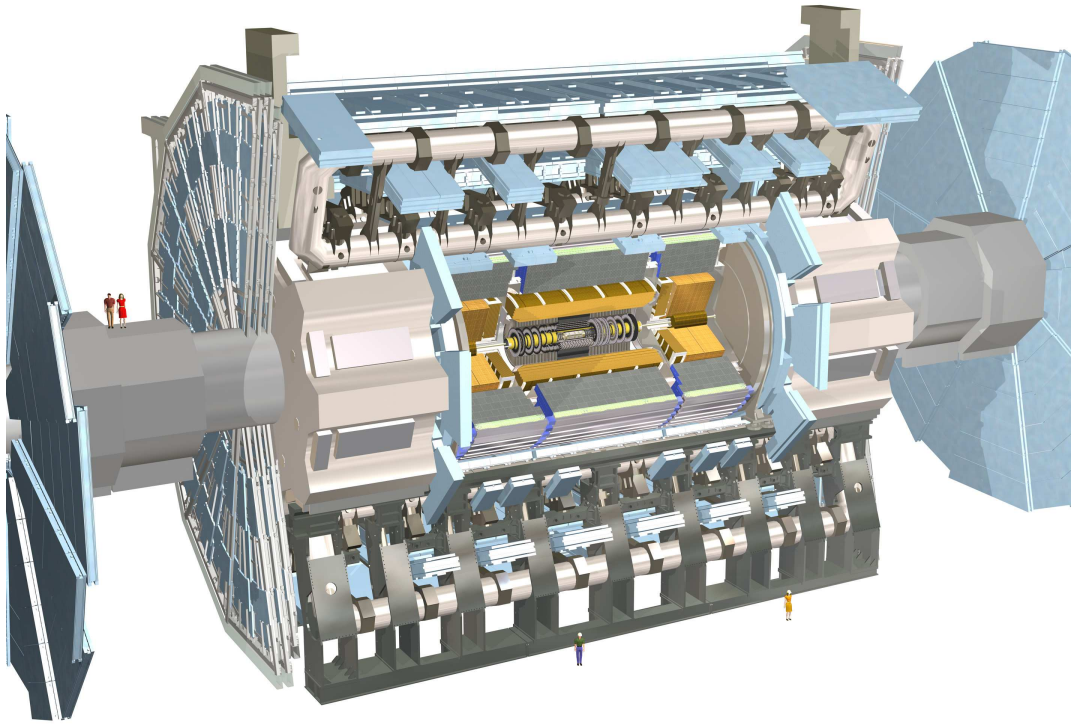
- LHC colliding protons at $\sqrt{s} = 8$ TeV, reaching up to $\mathcal{L} = 8 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 2010 data ($\int \mathcal{L} \approx 35\,\mathrm{pb}^{-1}$ @ $\sqrt{s} = 7\,\mathrm{TeV}$) basis for many precision results
- Many results based on 2011 data ($\int \mathcal{L} \approx 4.7\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 7\,\mathrm{TeV}$) to be published within coming weeks and months
- In 2012 accumulated so far $\approx 15\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 8\,\mathrm{TeV}$, expecting up to $2\times$ more before end of year and first long shut down





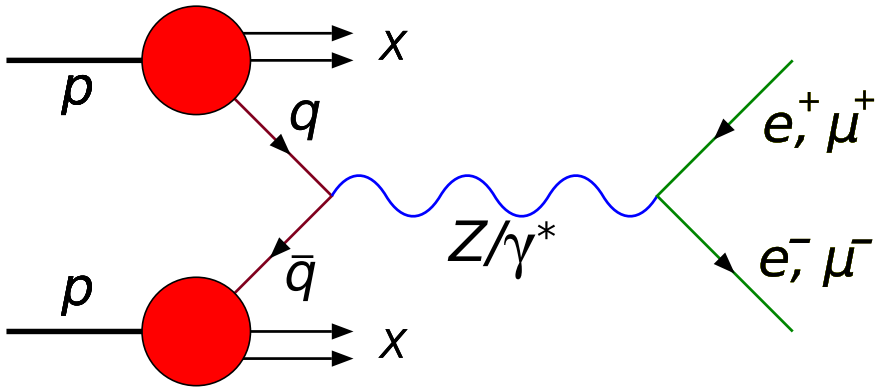
The ATLAS Detector

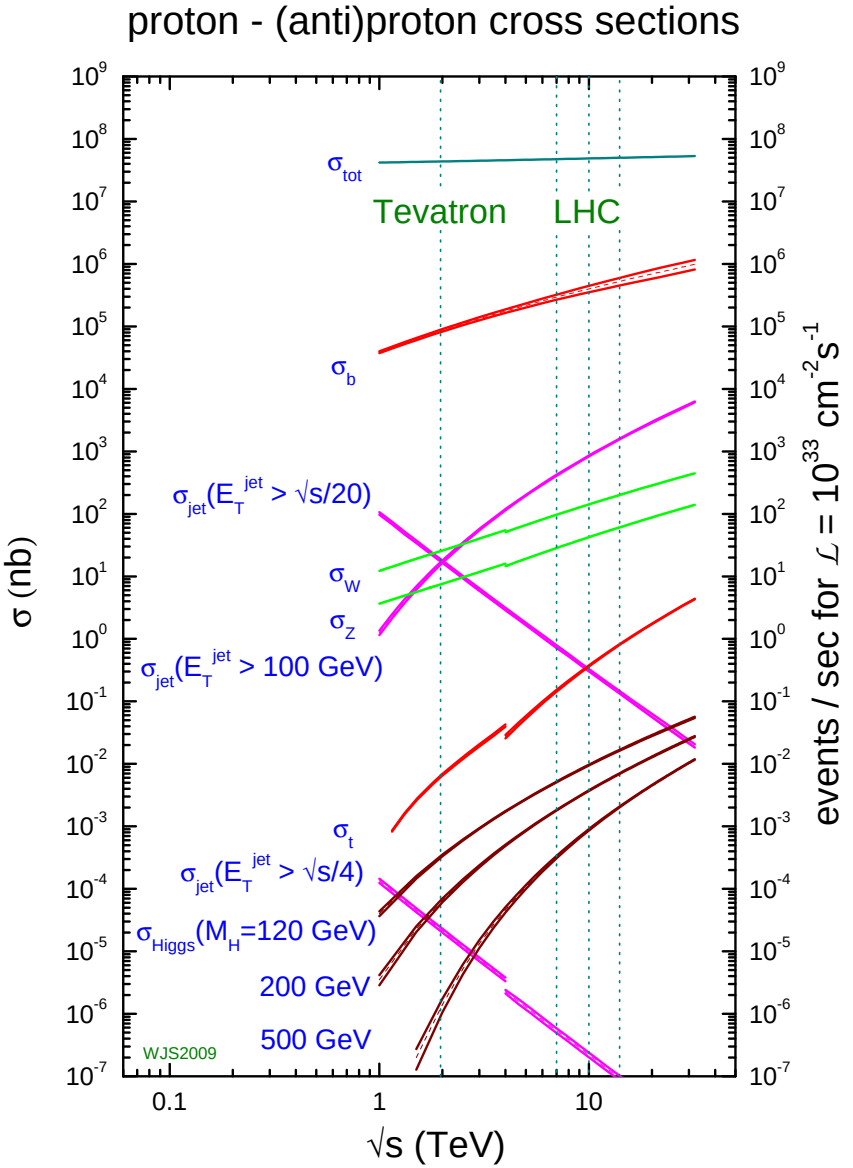
- Precision EM calorimeter and tracking up to $|\eta| < 2.5 \rightarrow$ electrons
- Muon chambers up to $|\eta| < 2.7$, trigger coverage to $|\eta| < 2.4 \rightarrow$ muons
- Calorimetric coverage up to $|\eta| < 4.9 \rightarrow$ jets, $\not{E}_T$, “forward electrons”
- Excellent performance, typically $\sim 85\%$ of delivered luminosity with good data quality for analysis



EWK Physics with the ATLAS Detector

- Unprecedented $\sqrt{s}$ and $\mathcal{L}$ for searches and discoveries
- Collecting millions of $W \to \ell\nu$ and $Z \to \ell\ell$ events, some with extreme kinematics
- Very capable detector and trigger to collect and identify large fraction of $\ell = e, \mu$ events
- E.g. unprescaled single e and μ triggers with $p_T > 25$ GeV for full 2012 data; significantly lower for di-lepton triggers





Overview of W and Z measurements

- Most results based on e and μ channels, some on τ; first studies of hadronic decays to appear soon
- Cross section measurements
  - W, Z inclusive production
  - W, Z + jets
  - W, Z + heavy flavour jets
- Boson properties
  - W polarisation
  - Lepton universality in W decays
  - τ polarisation in $W \to \tau\nu$

Cross section definitions

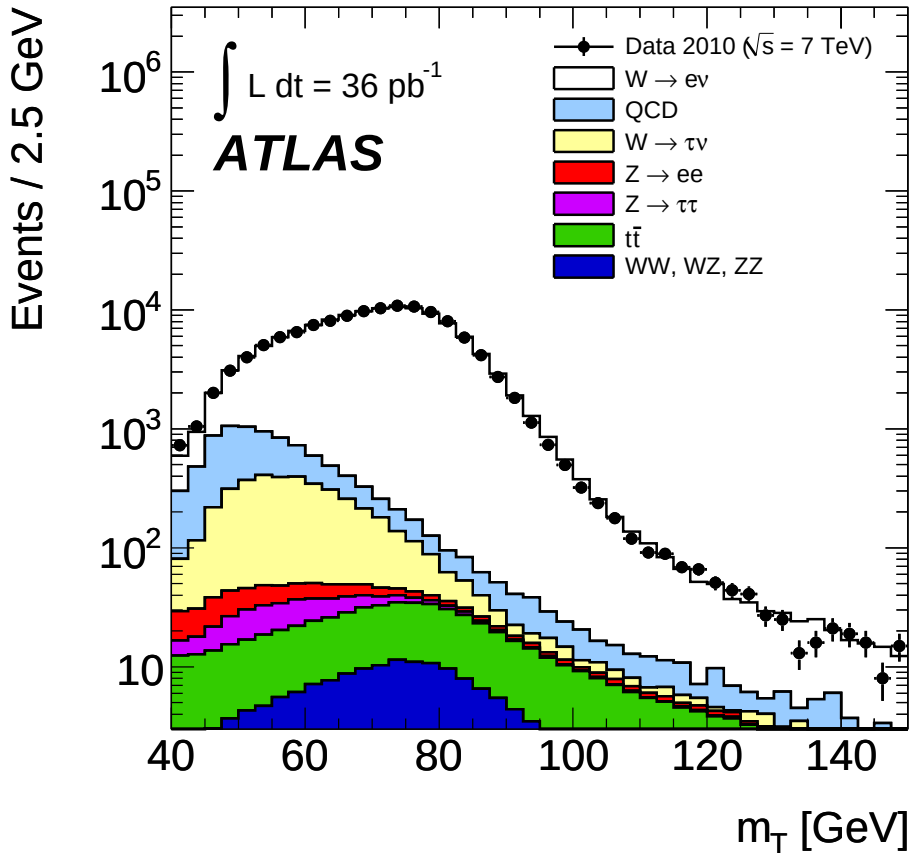
- Measurements are corrected to consistently defined “truth level” to allow proper theory comparisons
- General strategy is to publish *fiducial measurements* with minimal phase space extrapolations, typical phase space:
  - Charged leptons: $|\eta_\ell| < 2.5$ (or 2.4), $p_{T,\ell} > 20$ GeV
    - Extension for $Z \to ee$ for one lepton to $|\eta_\ell| < 4.9$
  - Neutrino and transverse mass for W: $p_{T,\nu} > 25$ GeV, $m_T > 40$ GeV
  - Mass for Z: $66 < m_{\ell\ell} < 116$ GeV (or $76 < m_{\ell\ell} < 106$ GeV)
  - For measurements with jets:
    - Jets: $|y_{\text{jet}}| < 4.4$, $p_{T,\text{jet}} > 30$ GeV
    - b-Jets: $|\eta_{\text{jet}}| < 2.1$, $p_{T,\text{jet}} > 25$ GeV
    - Jets are defined with anti-k_T, $R = 0.4$ algorithm, isolated from leptons $\Delta R(\ell, \text{jet}) > 0.5$, clustered excluding leptons

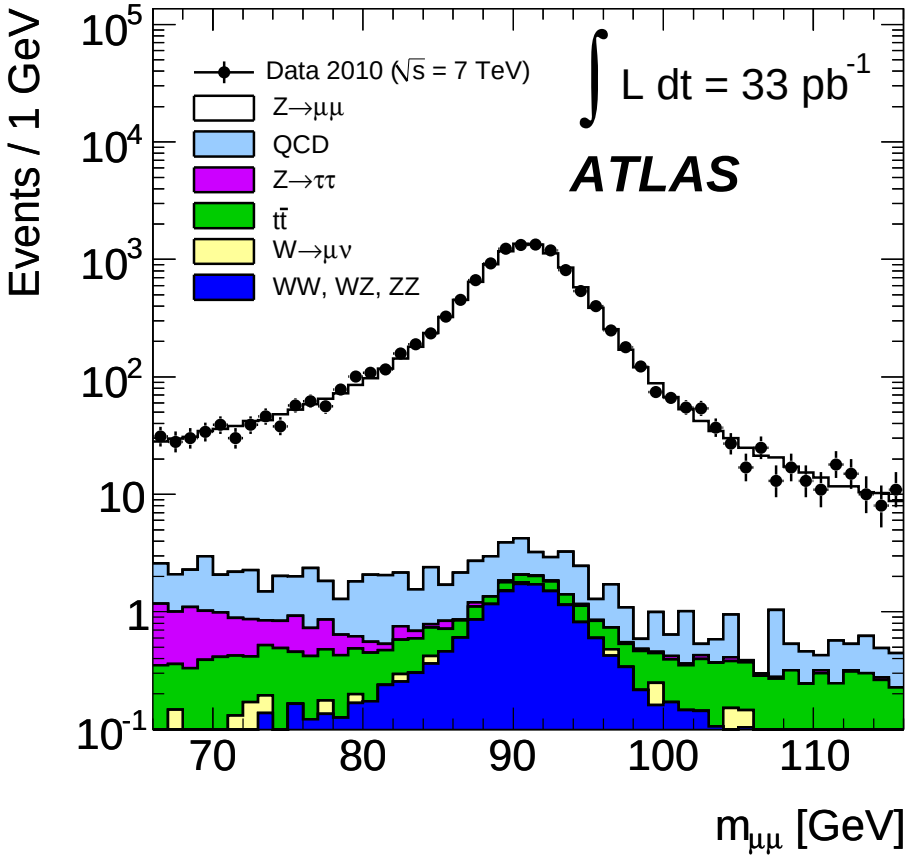
Cross section definitions II

- QED “Final State Radiation” off leptons is one of the most important higher order electroweak corrections
- Affects both the experimental and theoretical level; different for e and μ
- Many ATLAS cross sections are published for three lepton definitions:
  - “bare” leptons, after QED FSR
  - “dressed” leptons: “bare” leptons recombined with QED FSR photons in cone $\Delta R < 0.1$
  - “born” leptons, before QED FSR (usually used for $e - \mu$ channel combination)
- Example of ratios between “bare” or “dressed” to “born” level for inclusive (integrated and rapidity-differential) cross sections
- Corrections calculated with Photos interfaced to NLO or multi-leg generators

	W^-	W^+	Z
	Electron Channels		
δ^{bare}	0.973	0.970	0.936
δ^{dressed}	0.992	0.991	0.979
	Muon Channels		
δ^{bare}	0.987	0.985	0.966
δ^{dressed}	0.992	0.991	0.978

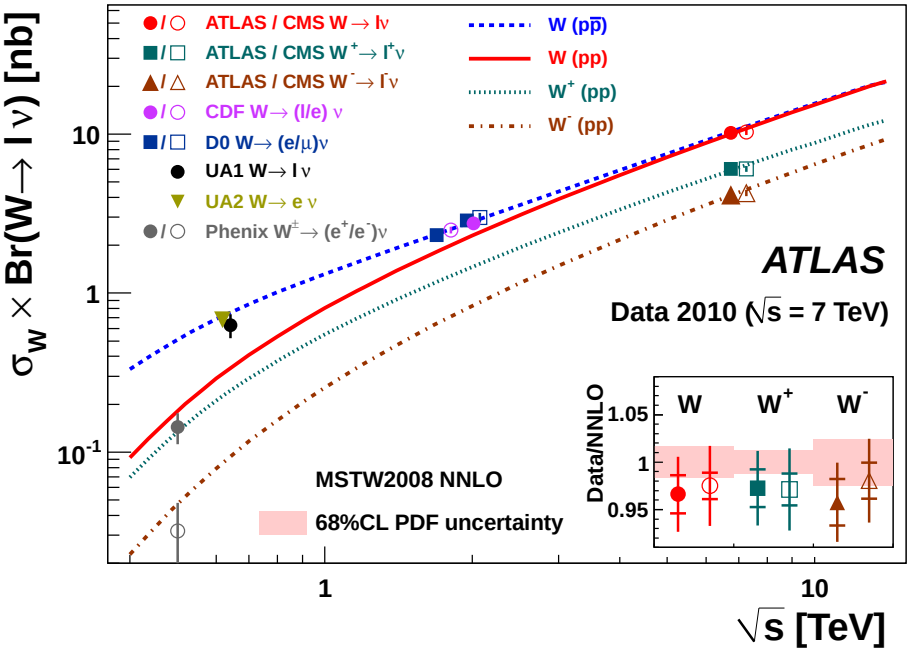
Inclusive W and Z Measurements

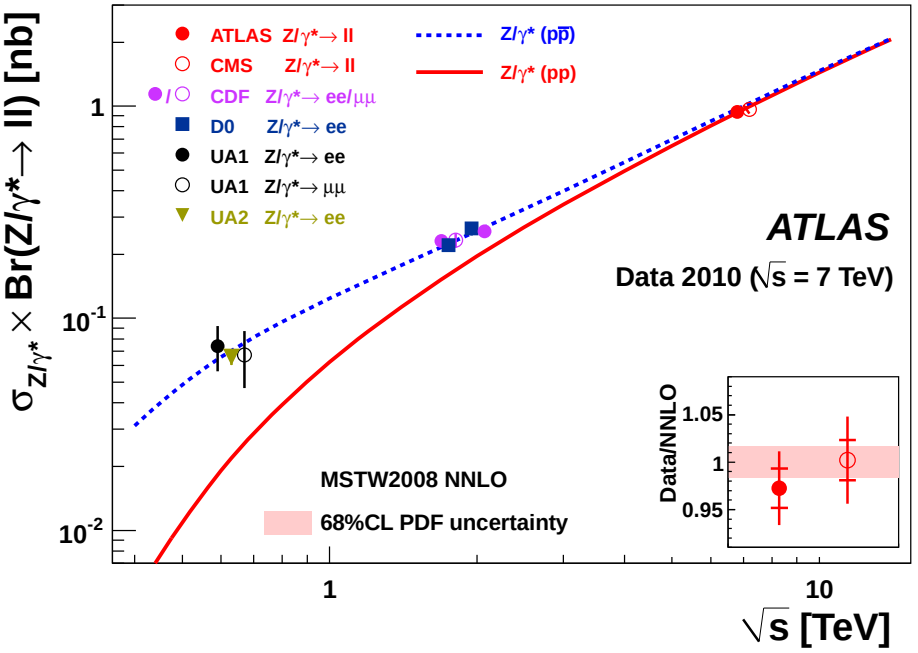




Integrated Total W and Z Cross Sections

- Classical measurements of weak boson production at hadron colliders compared to theory prediction at NNLO in QCD
- Experimental uncertainty small ($\sim 1\%$) compared to extrapolation to full phase space ($\sim 2\%$) and luminosity (3.4%)

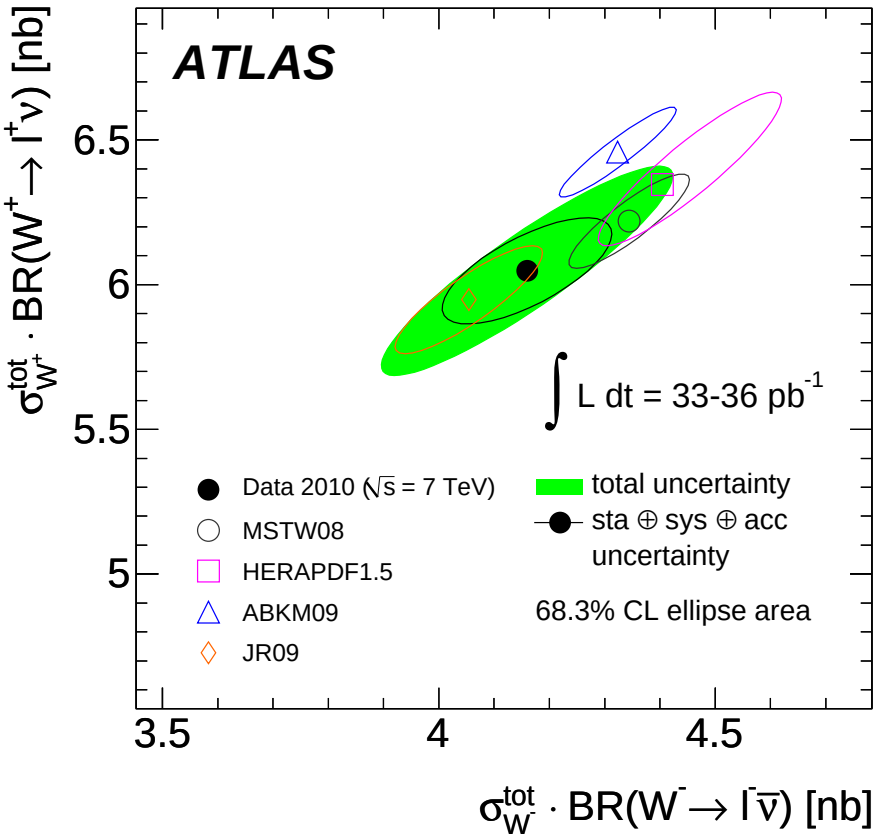


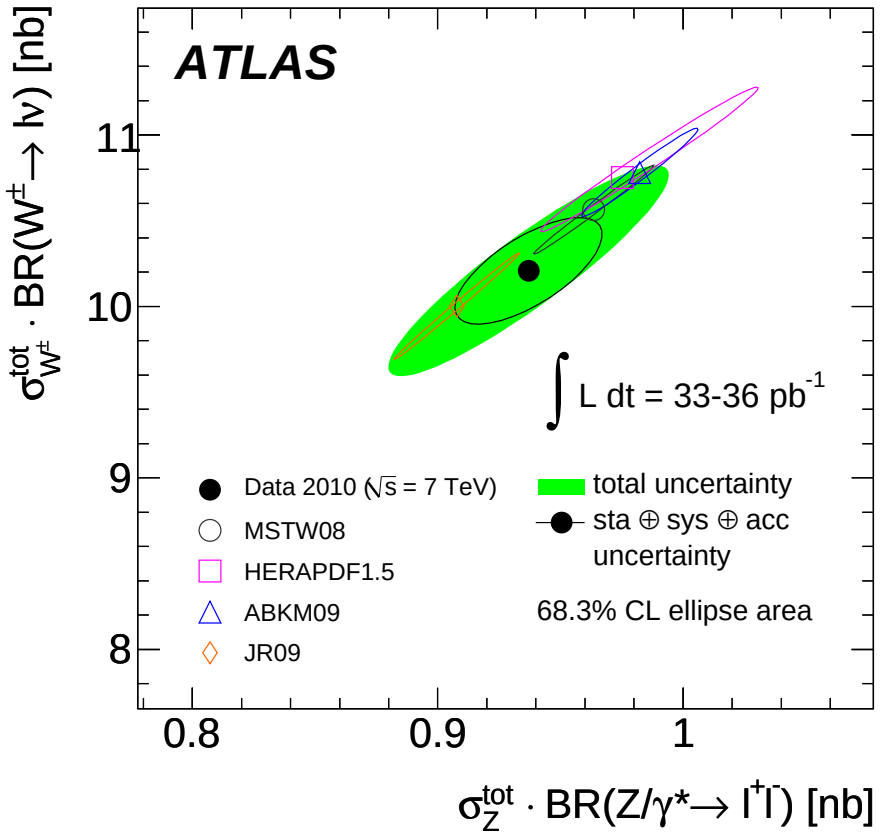


PRD85, 072004 (2012)

Integrated Total W and Z Cross Sections

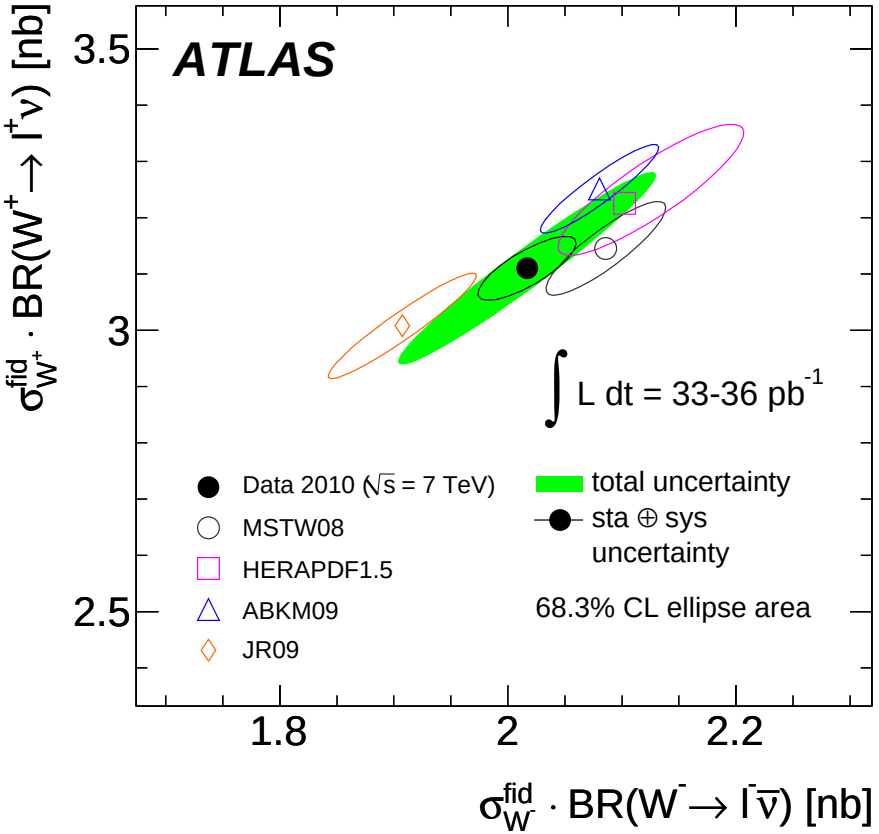
- More useful to consider correlations or ratios between measurements
- Measurement mostly in good agreement with the NNLO QCD prediction with 4 different PDFs

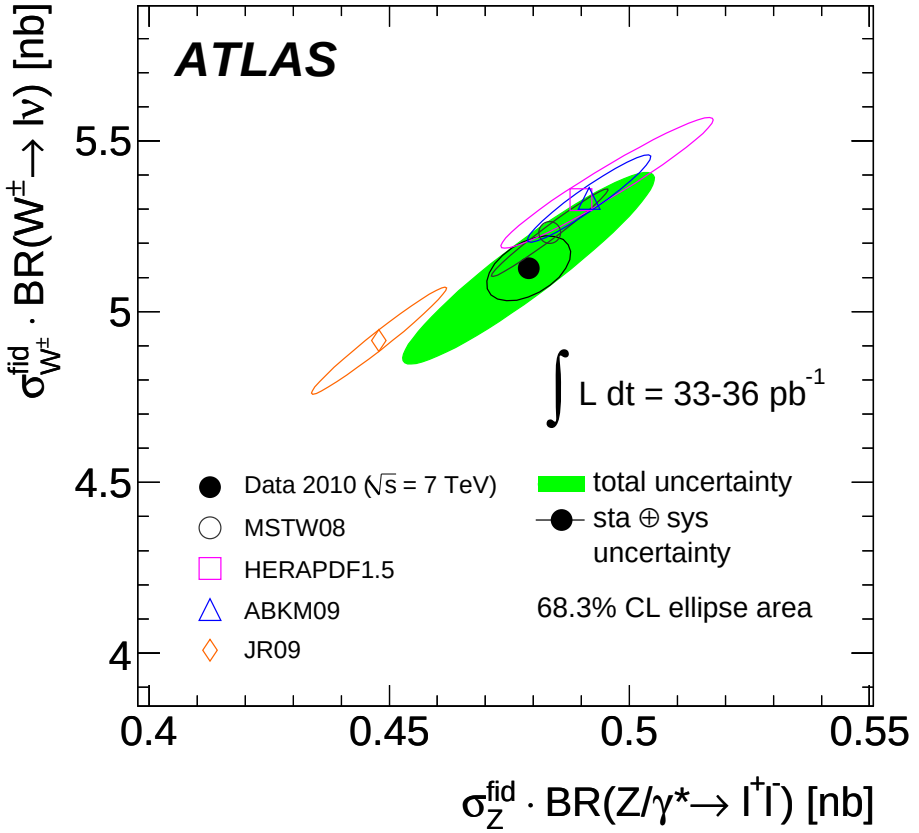




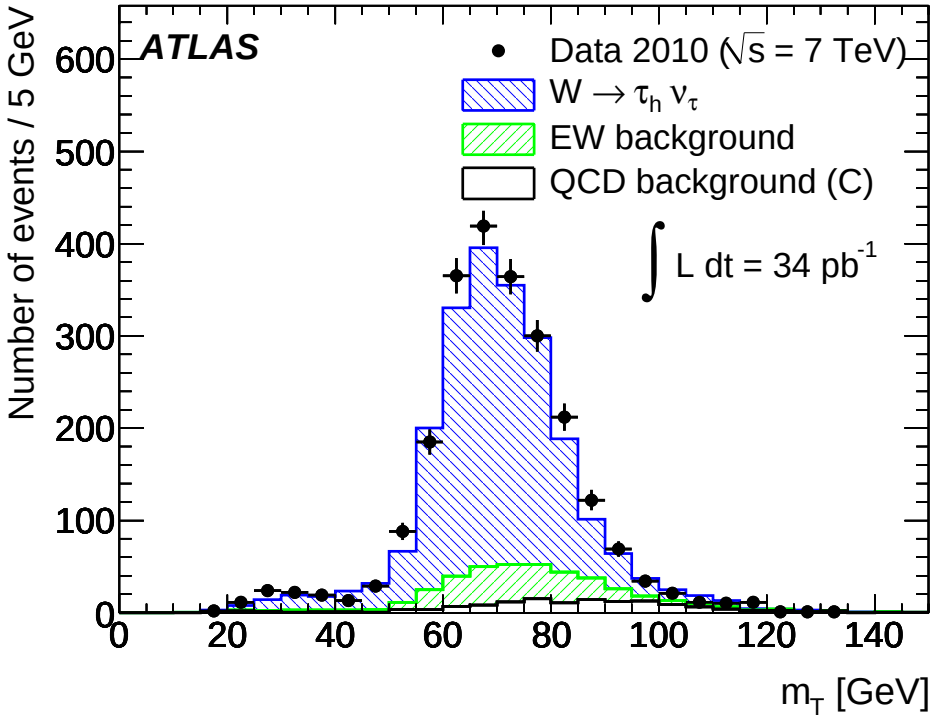
Integrated Fiducial W and Z Cross Sections

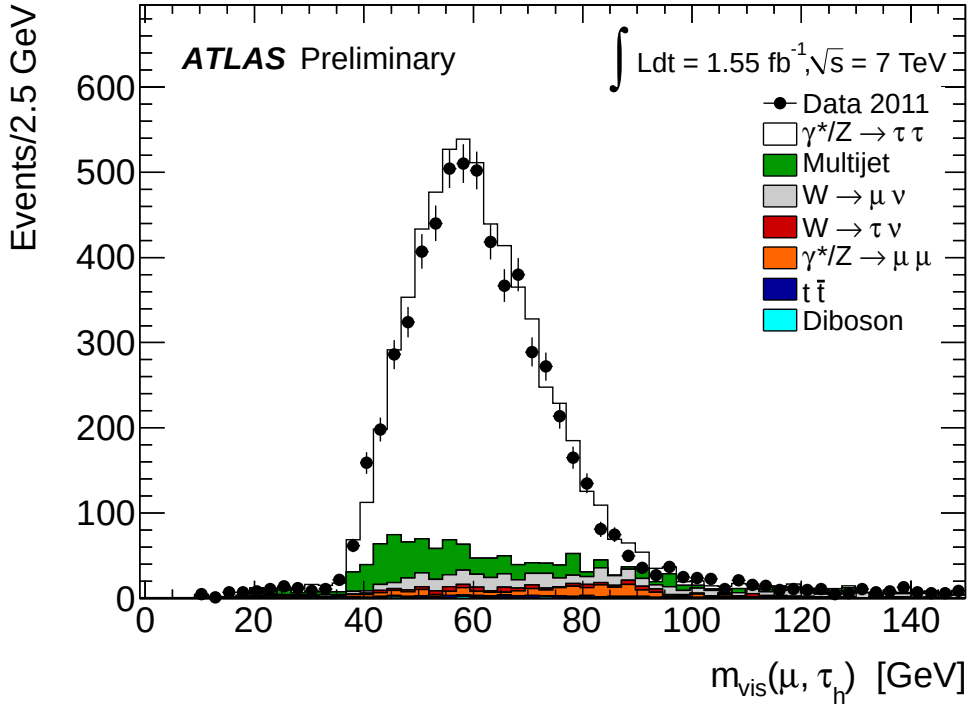
- Even more useful to consider fiducial integrated cross sections to avoid extrapolation uncertainty
- Measurement has more power to distinguish between different PDFs





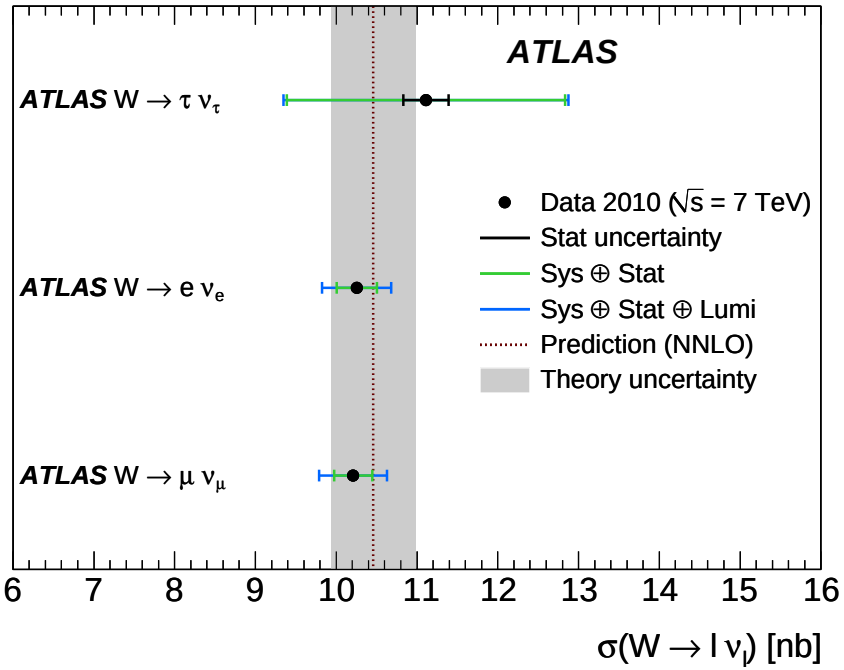
$W \to \tau\nu$ and $Z \to \tau\tau$

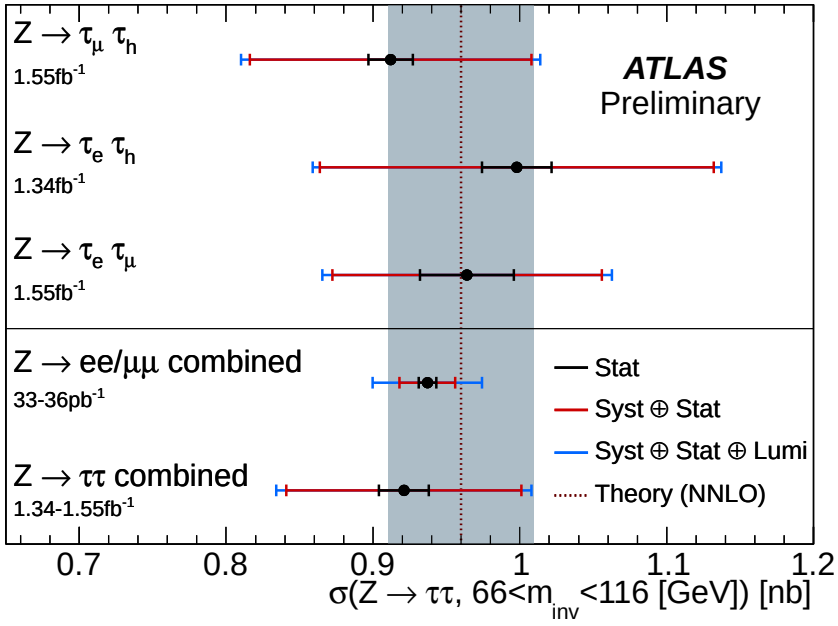




$W \to \tau\nu$ and $Z \to \tau\tau$

- Total W and Z production cross section have also been measured in their τ decay channels
  - $W \to \tau\nu$ using hadronic τ decays
  - $Z \to \tau\tau$ using hadronic and leptonic decays
- Uncertainties are significant: $10 - 20\%$

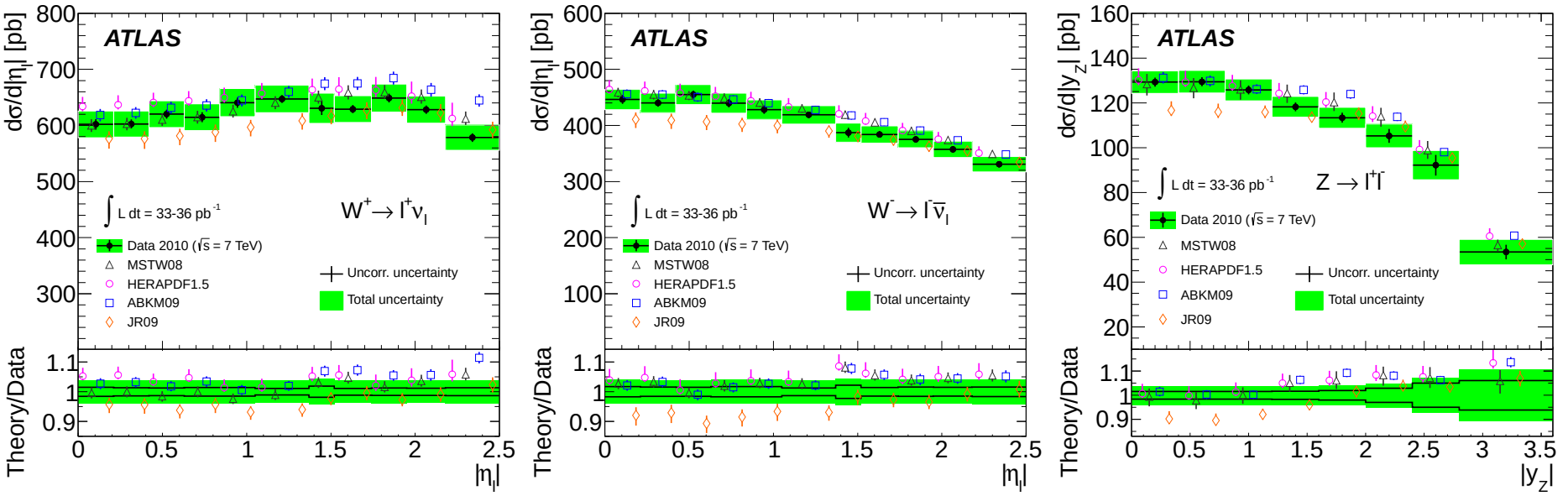




PRD 84 (2011) 112006; PLB 706 (2012) 276-294; ATLAS-CONF-2012-006

W and Z Rapidity Differential Measurements

- Boson rapidity y directly linked to parton momentum fractions $x_{1,2} = M_{W,Z}/\sqrt{s} \cdot e^{\pm y}$
- W: charged lepton pseudo-rapidity η_ℓ used
- Absolute differential cross sections for Z, W^+, W^- with correlations
- Comparison to 4 different PDF sets at NNLO in QCD: broad agreement, but also indicates sensitivity to proton structure



PRD85, 072004 (2012)

Inclusive Theory Predictions

- With measurement accuracy of $\sim 2\%$ per bin (expected $\lesssim 1\%$ for 2011), precision of the theory prediction becomes a significant issue
- Only considering NNLO QCD predictions: FEWZ and DYNNLO allow predictions with fiducial cuts applied; main practical issue is required running time and sometimes numerical stability
- Higher order electroweak corrections become important at this level:
  - QED FSR mostly under control; however PHOTOS authors recommend currently conservative 0.5% uncertainty on differential distributions – would like to reduce this
  - Using G_μ scheme to minimise missing higher order corrections
  - Missing higher order effects estimated by SANC colleagues to be at the level 0.25% for W and 0.7% for Z
  - Differences between FEWZ and DYNNLO at the level $0.2, 0.5, 1.0\%$ for Z, W^+, W^- — partially because of different treatment of electroweak parameter scheme

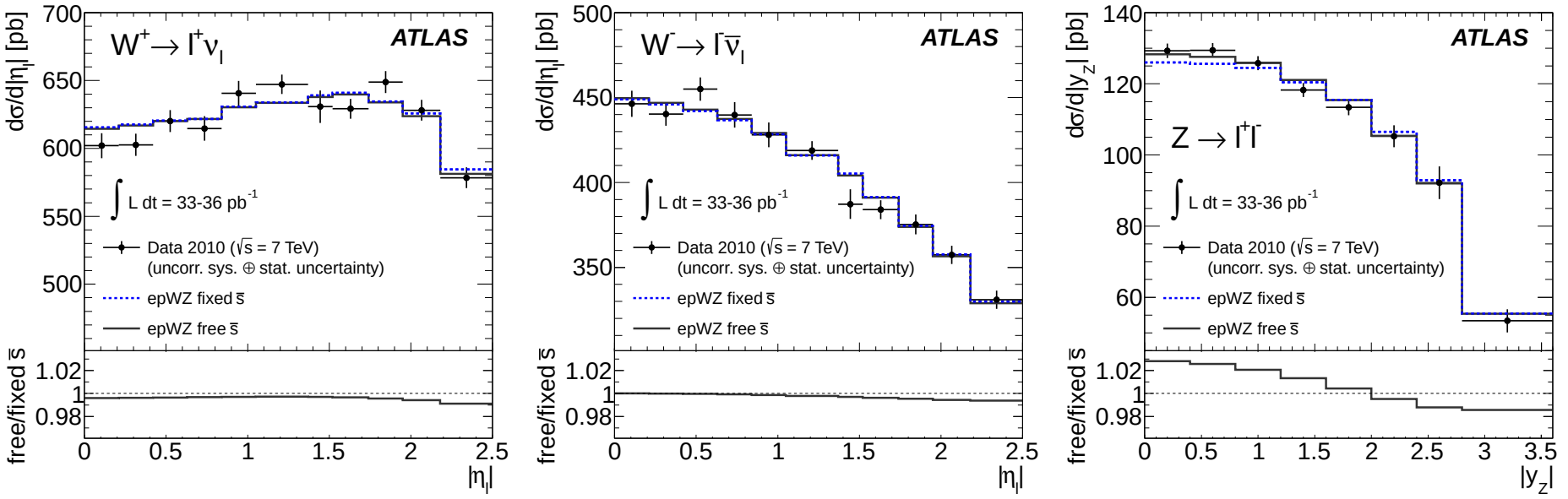
Inclusive Theory Predictions II

- Recent developments to combine HO QCD and EWK programs, e.g.:
  - FEWZ 3.1: $\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_{EW})$ for $Z/\gamma^* \to \ell\ell$ (arXiv:1208.5967)
  - Powheg: NLO QCD + NLO EW + Parton Shower for $W \to \ell\nu$ (arXiv:1202.0465)
  - Such tools are quite useful to get a complete overview of all effects and their interplay ($\mathcal{O}(\alpha_s\alpha)$ effects?)
- All published cross sections are quoted with a certain lepton definition ("bare", "dressed", "born"), which includes always some level of QED FSR corrections
- Mostly interested in the remaining higher order EWK effects (which should be applied to theory only)

W, Z data sensitivity to strange sea

- To test the impact of the W, Z data, ATLAS performed a QCD fit to Z, W^+, W^- + HERA ep DIS cross sections
- Using HERAFitter framework with fast MCFM+APPLGRID NLO QCD, corrected to NNLO QCD using 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

PRL 109 (2012) 012001

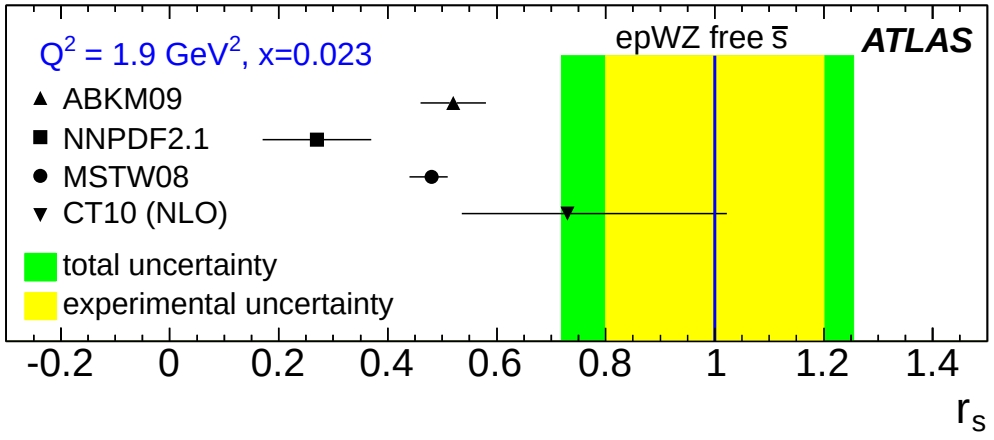


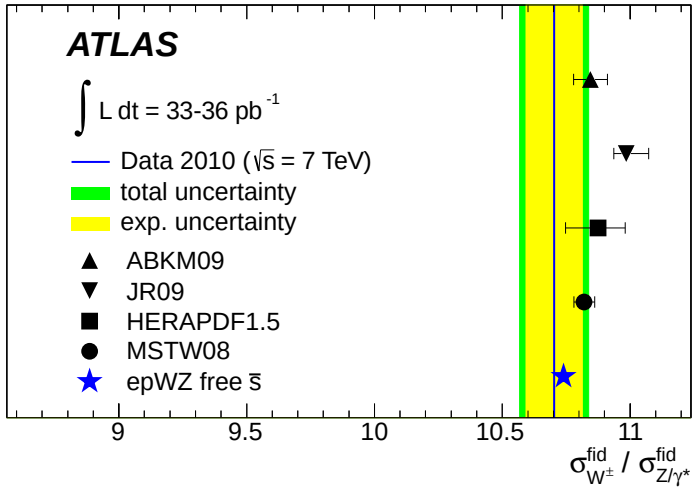
W, Z data sensitivity to strange sea

- Fit with free strange sea indicates no strange sea suppression at $Q^2 = 1.9\,\mathrm{GeV}^2$ and $x = 0.023$

$$r_s = 1.00 \pm 0.20_{\mathrm{exp}} \pm 0.07_{\mathrm{mod}} \,^{+0.10}_{-0.15}{}_{\mathrm{par}} \,^{+0.06}_{-0.07}{}_{\alpha_S} \pm 0.08_{\mathrm{th}}$$

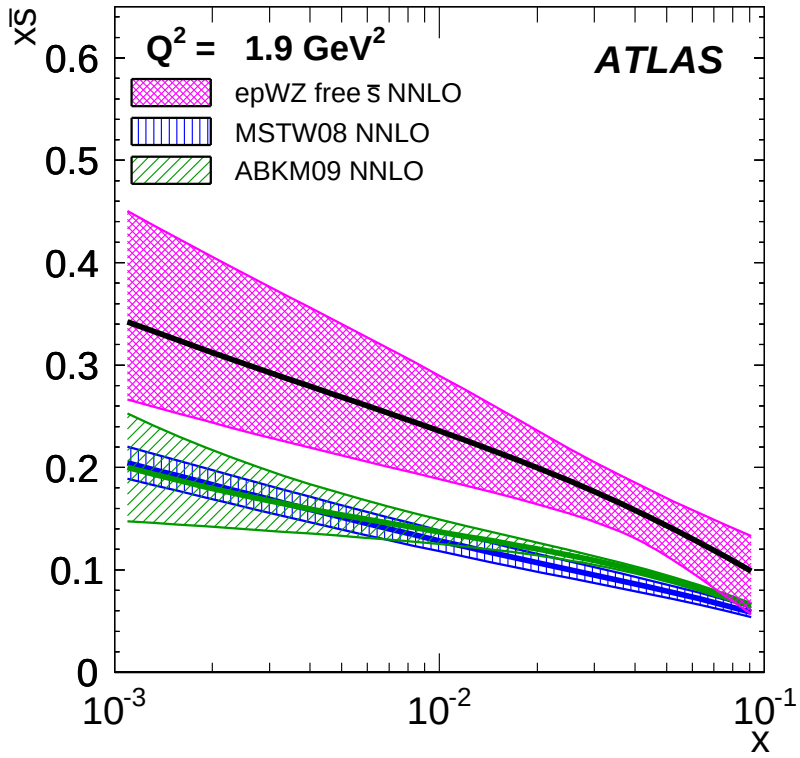
- Larger strange content also in better agreement with integrated W/Z cross section ratio

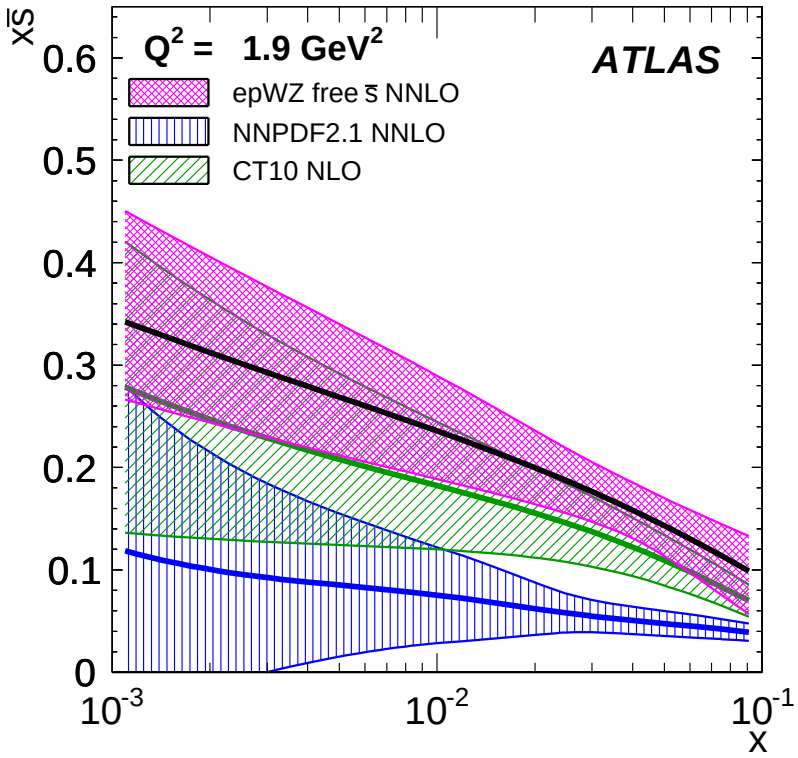




W, Z data sensitivity to strange sea

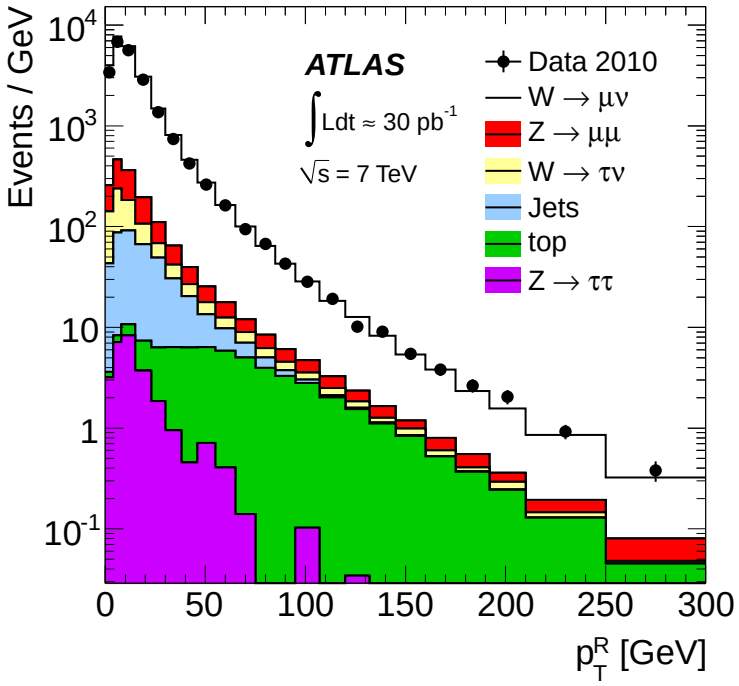
- Strange quark PDF compatible with CT10
- Significant differences observed to other PDF fits, where the strange density is constrained by fixed target data

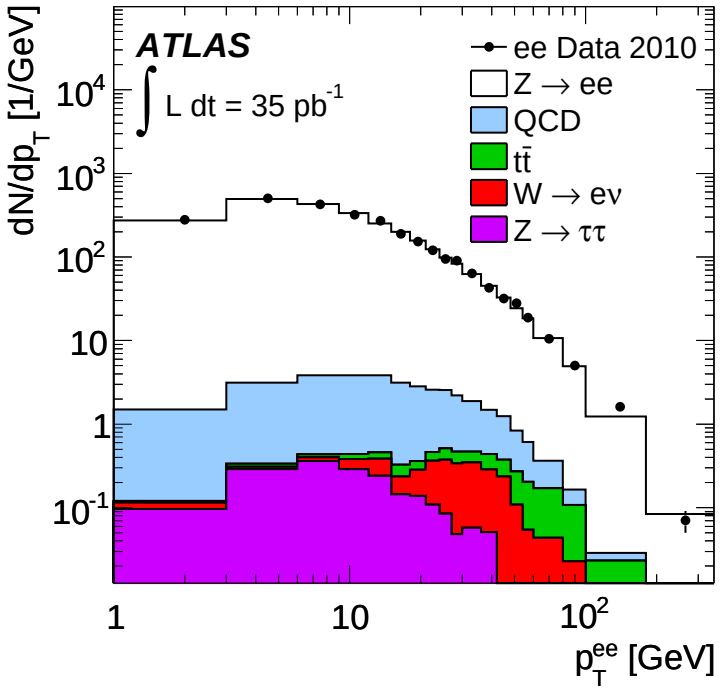




W, Z transverse momentum p_T

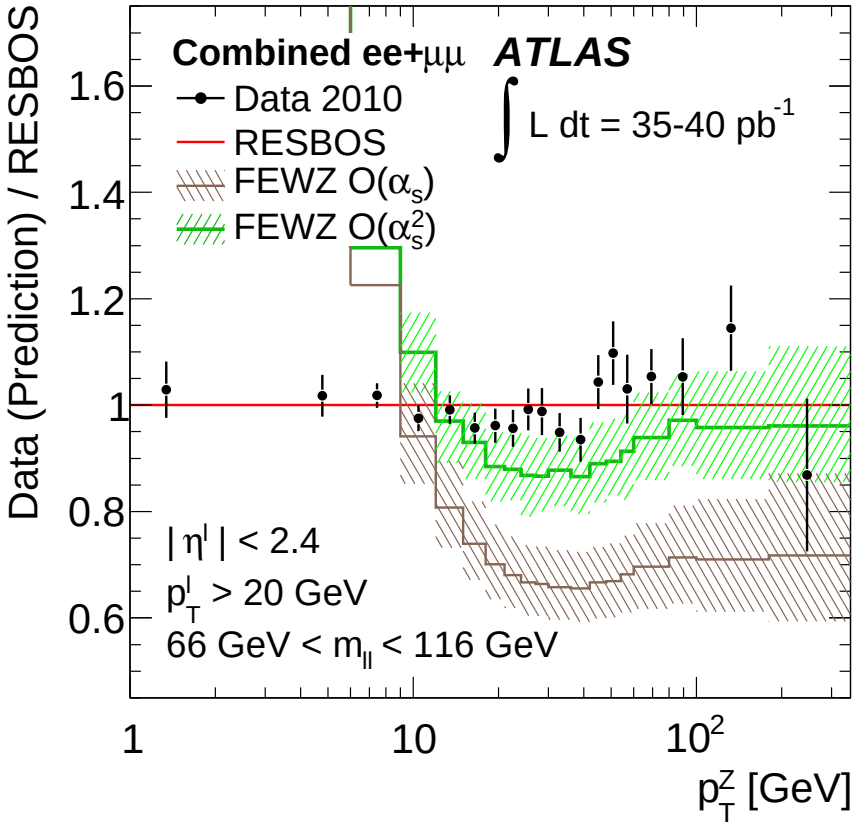
- Bosons are produced at non-zero transverse momentum p_T
- Small boson p_T dominated by soft gluon resummation: measurement input to MC tuning and tests of resummed calculations; vital input for precise W mass measurement
- For large p_T calculable in pQCD
- Distribution also expected to be significantly affected by HO EWK corrections at very high p_T (possibly visible with 2011 or 2012 data)

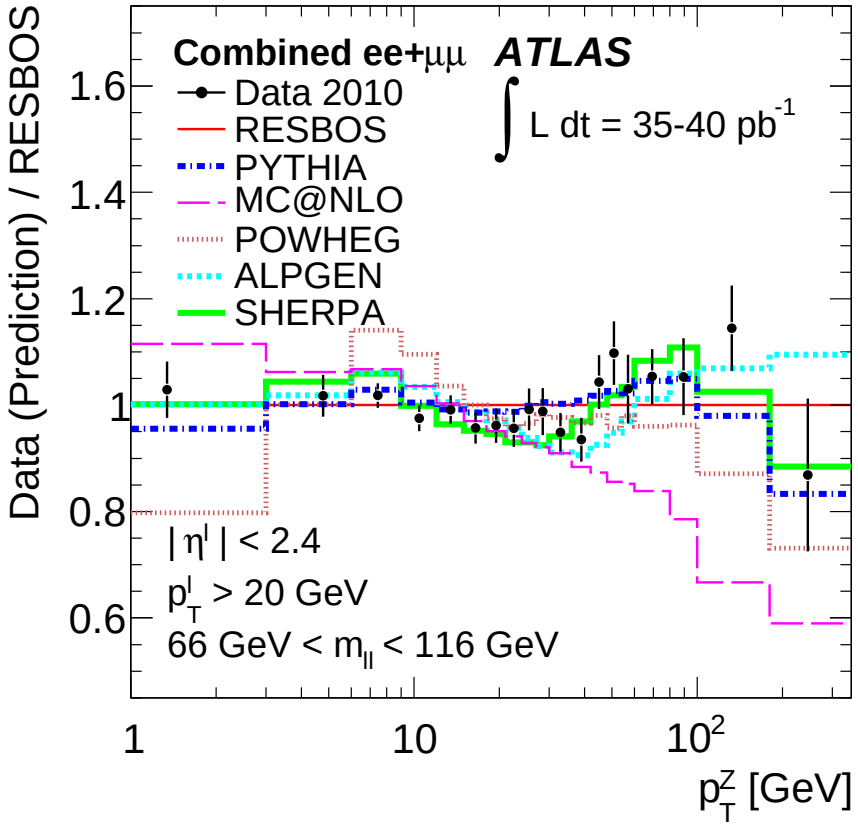




Z transverse momentum p_T

- normalised Z p_T distribution measured via di-lepton system
- Description of shape varies strongly between available models
- fixed order calculation needs $O(\alpha_s^2)$, significant scale uncertainty

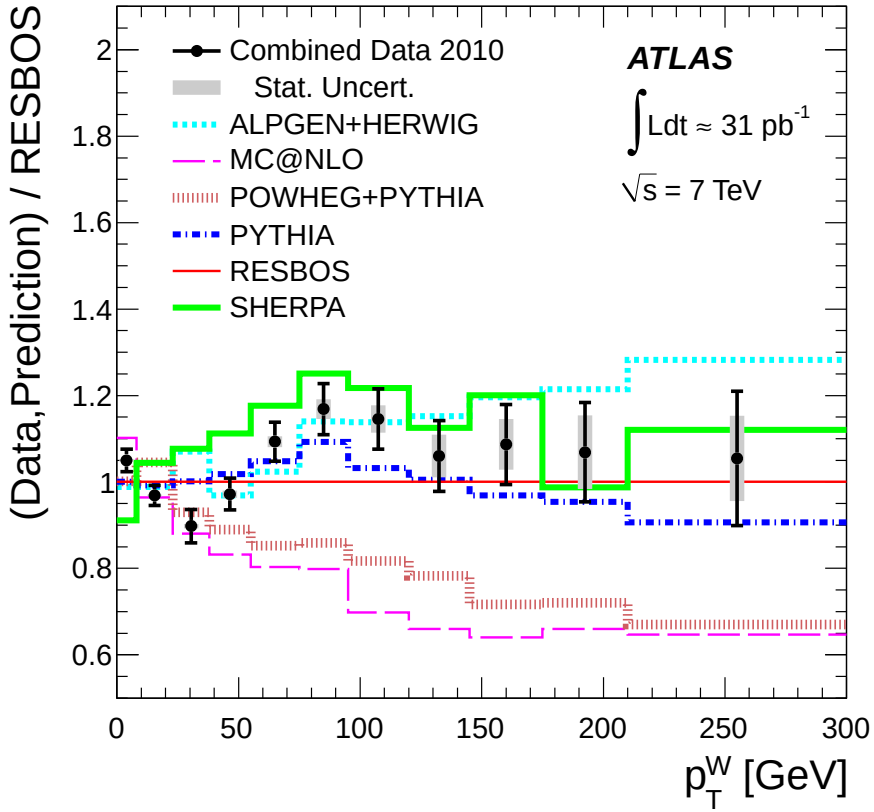


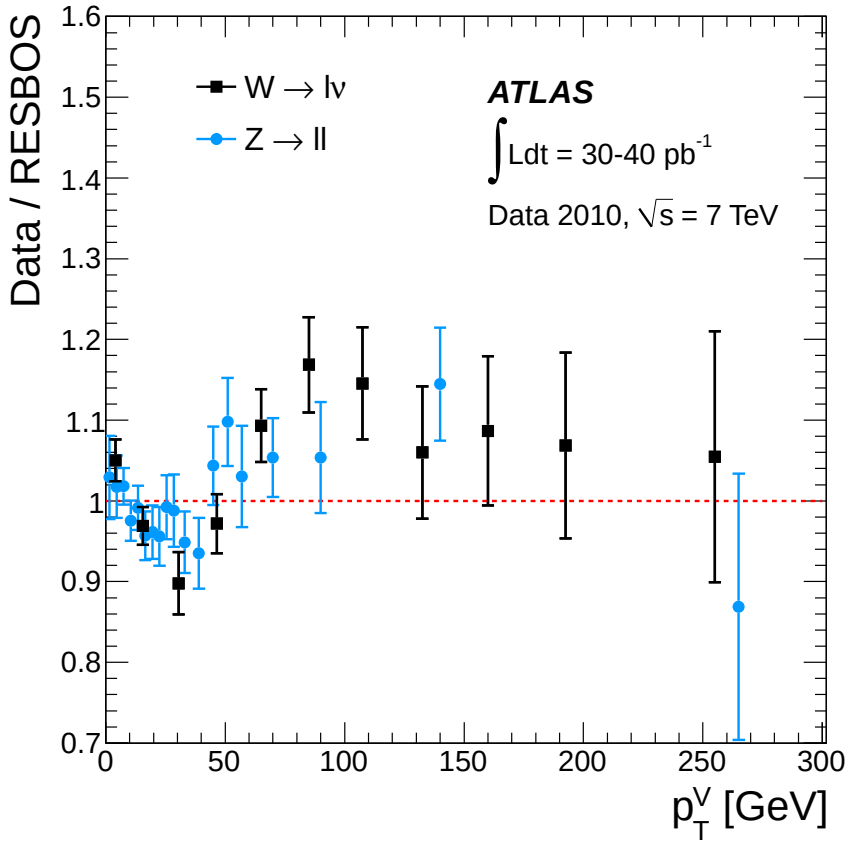


PLB 705 (2011) 415-434

W transverse momentum p_T

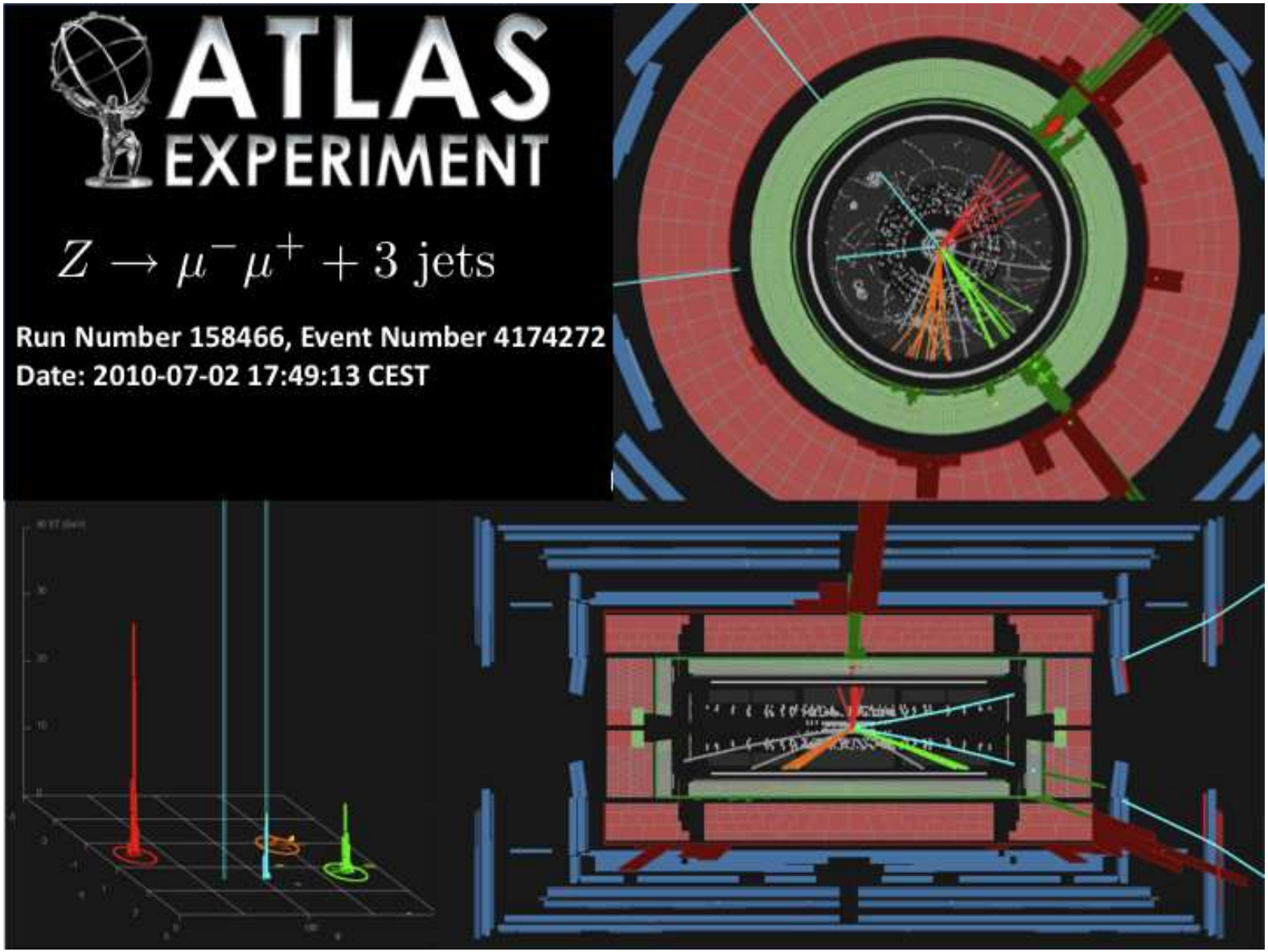
- normalised W p_T distribution measured via hadronic recoil
- Similar conclusions for comparison to MC models and pQCD





PRD 85 (2012) 012005

W, Z + jet production



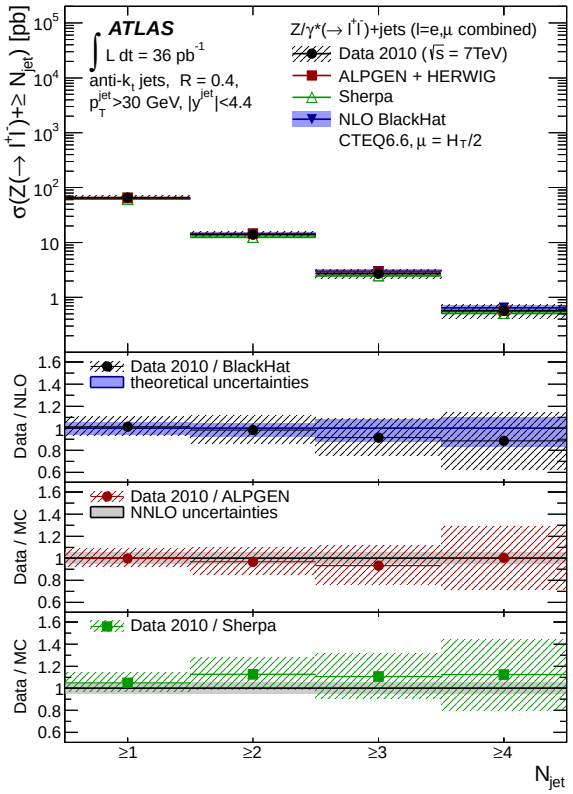
W, Z + jet production

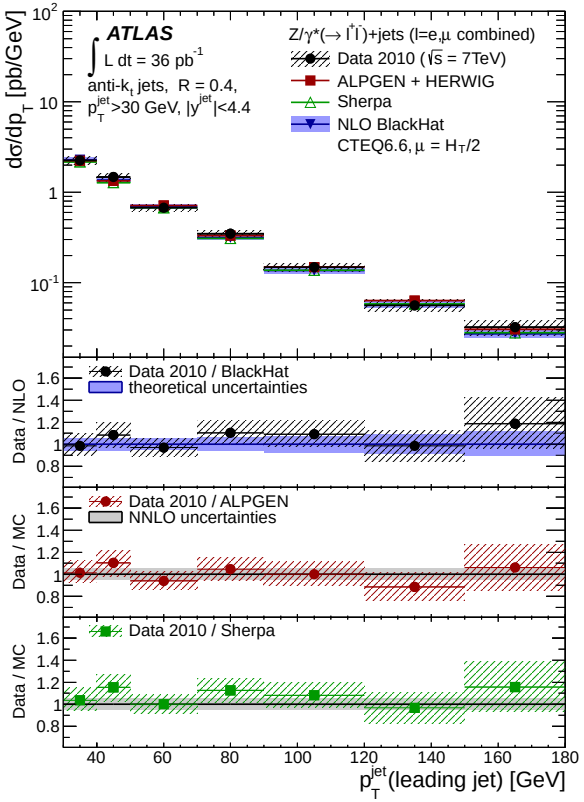
- Production of jets in association with W and Z bosons in an interesting test of higher order QCD effects
- Measurements typically limited by uncertainties on jets and hadronisation effects
- Results compared to:
  - NLO QCD calculation by *BlackHat+Sherpa*
  - Tree-level matrix element generators Alpgen and Sherpa: important validation and tuning input, e.g. for searches
  - Both available for $V + n\,\mathrm{jets}$ with $n \simeq 0 \ldots 5$
- No electroweak corrections considered so far (expected to be sizable at high jet p_T)

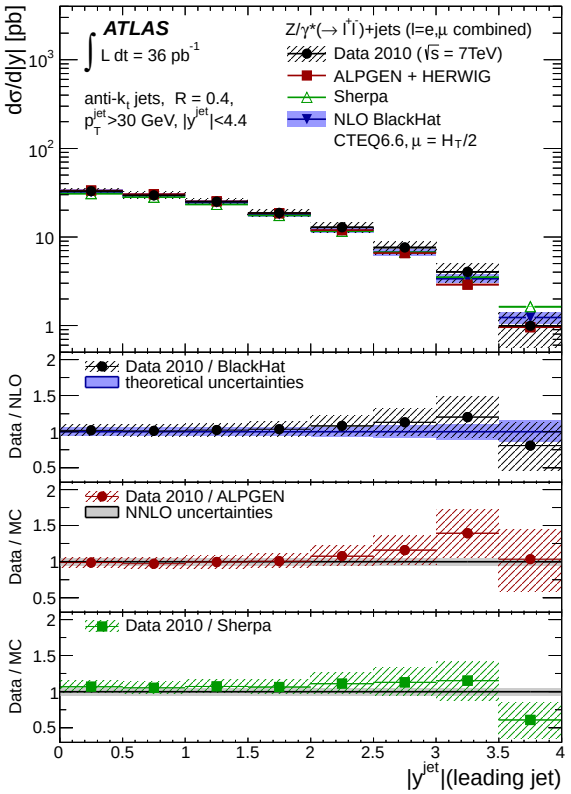
PRD85 (2012) 032009; PRD85 (2012) 092002; PLB 708 (2012) 221-240

Z + jets

- In general very good agreement of data with NLO QCD prediction
- Both Alpgen and Sherpa are able to describe the data well (after overall normalisation to NNLO prediction)
- 2010 results still mostly statistics limited at high jet p_T and high multiplicities

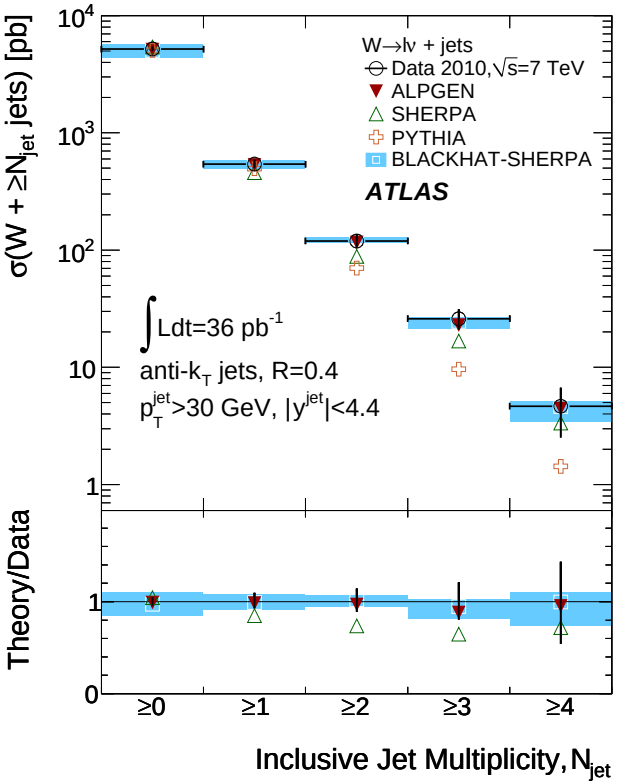


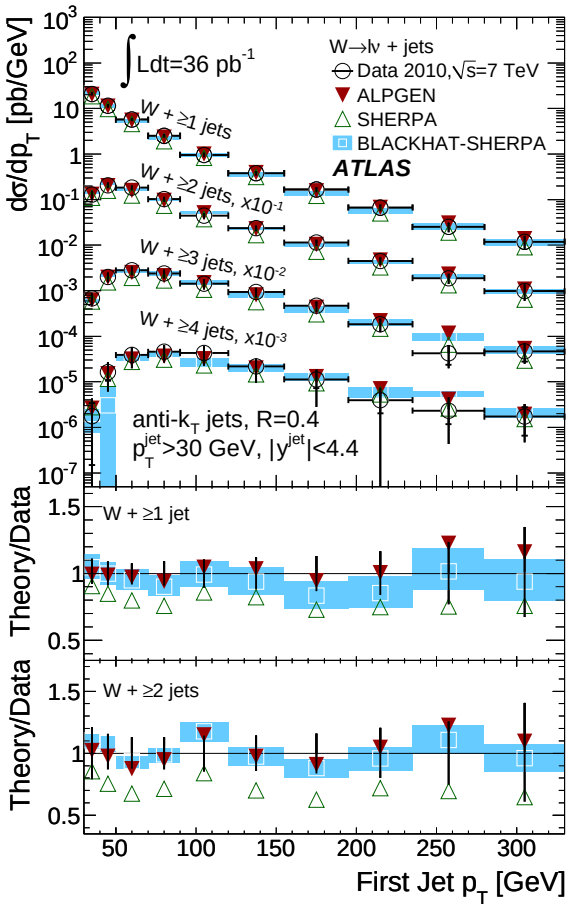


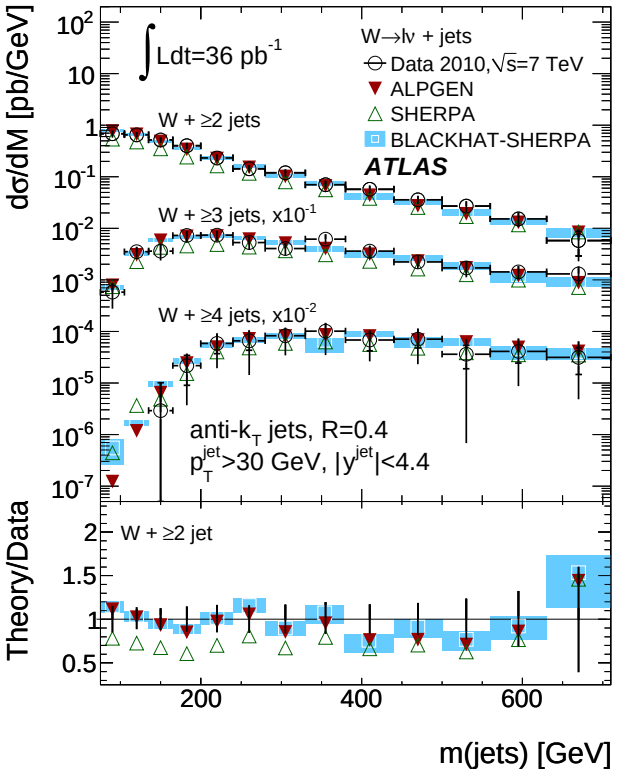


W + jets

- Less statistics limited than Z + jets
- In general very good agreement of data with NLO QCD prediction
- Alpgen working quite well, while Sherpa underestimates the jet activity (improved in newer Sherpa versions)

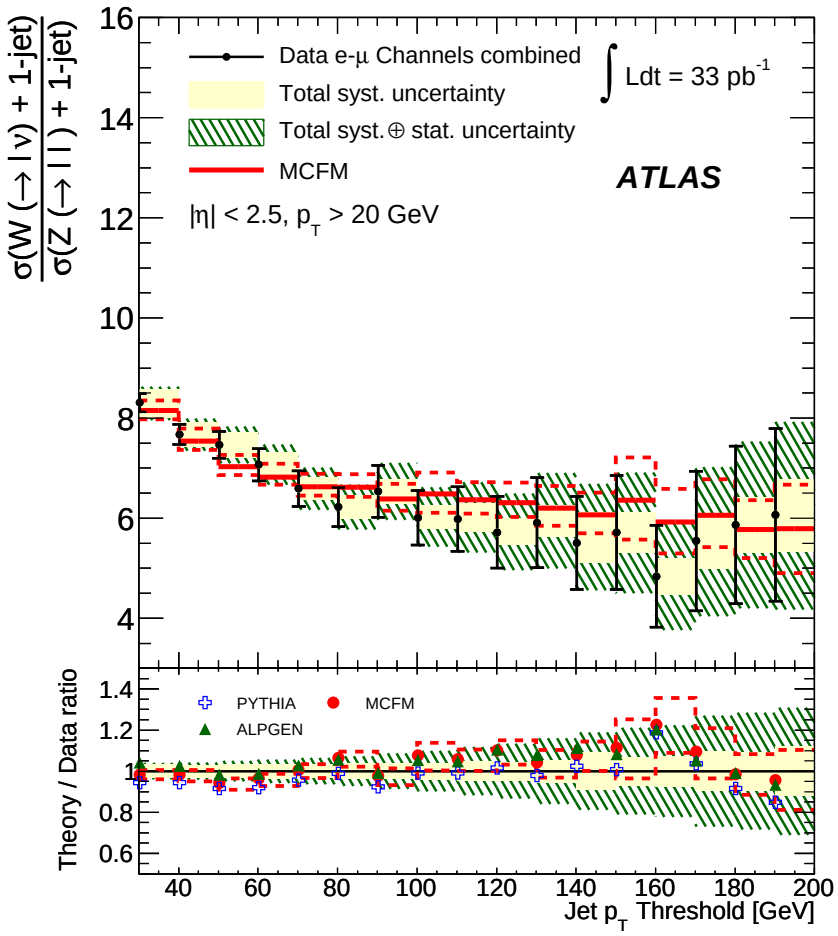






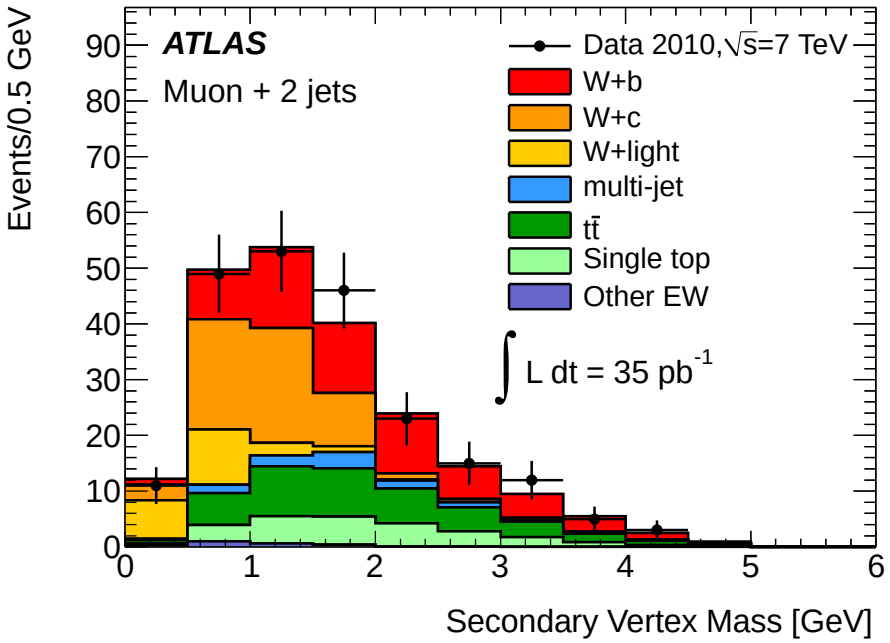
W/Z ratio with 1 jet

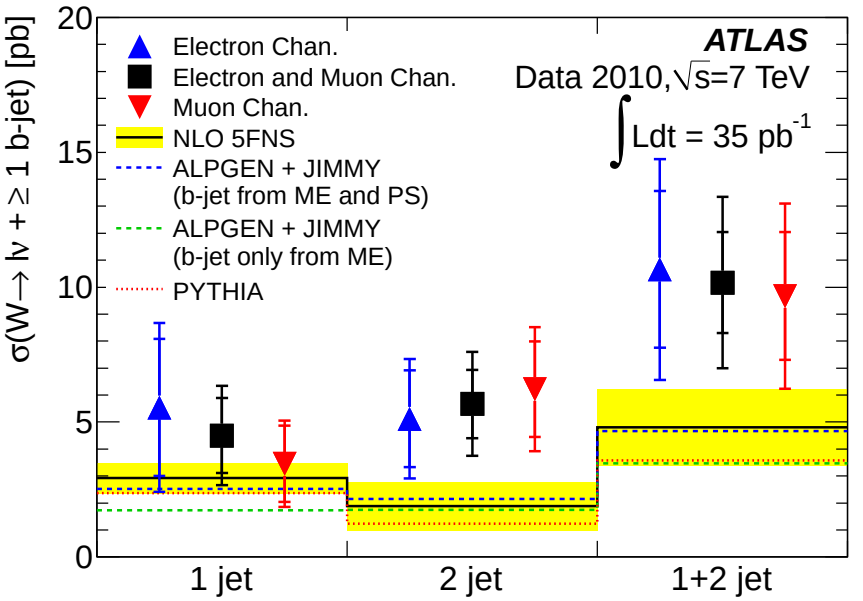
- To explicitly cancel correlated uncertainties, a W/Z ratio measurement was performed with exactly 1 jet produced and different $p_{T,\mathrm{jet}}$ thresholds
- Result in agreement with NLO QCD prediction



$W, Z + b$ jet production

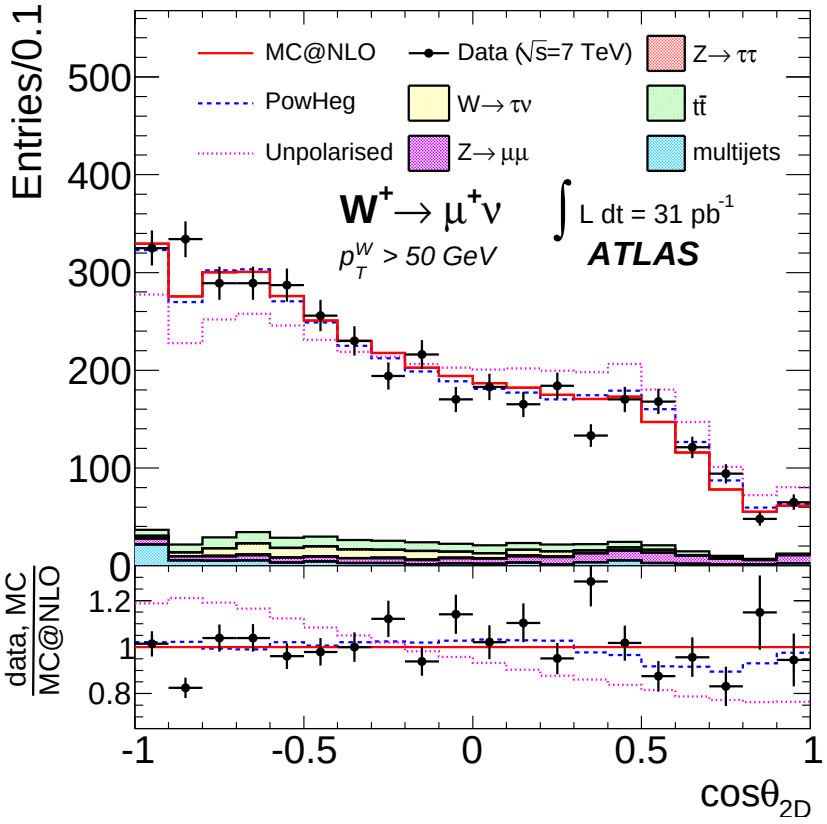
- W or Z production in association with heavy flavour jets (b and c) tests proton flavour structure and validates background description for searches
- Measured $W + b$ cross section $\sim 1.5\sigma$ higher than QCD NLO calculation or MC predictions
- $\sigma(Z + b)$ measured to $\sim 25\%$ accuracy, mainly driven by low statistics; in agreement with QCD NLO and MC predictions
- Expecting updated results from 2011 data soon

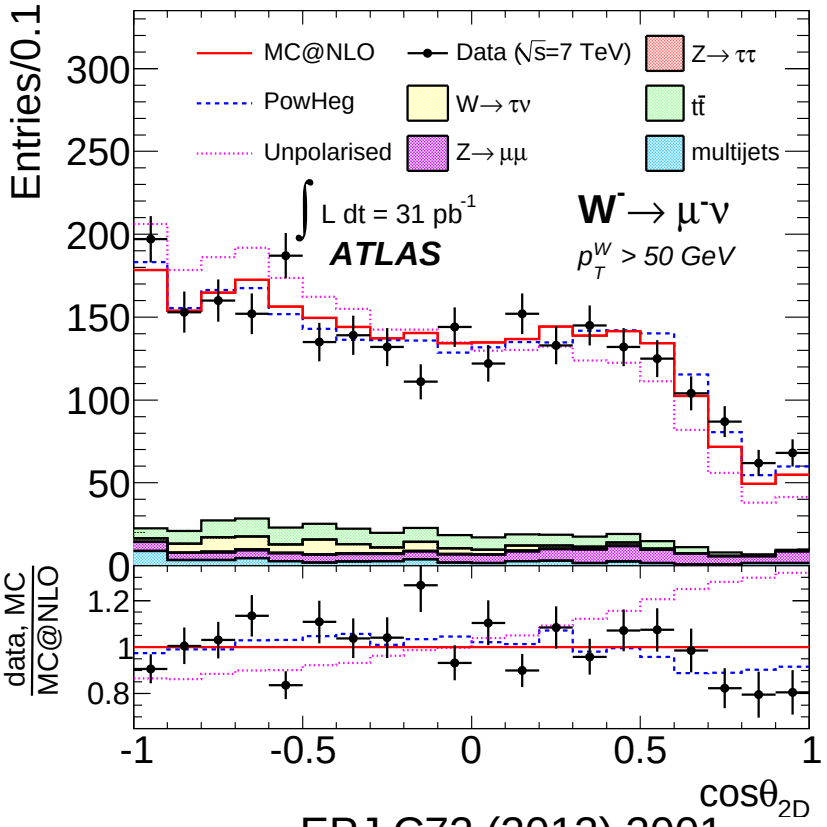




W polarisation

- W bosons can be produced in three polarisation states: f_L, f_R, f_0
- Measured at significant transverse momentum by analysing lepton p_T and angular distribution using $\cos\theta_{2D} = \vec{p}_T^{\,\ell *} \cdot \vec{p}_T^{\,W} / |\vec{p}_T^{\,\ell *}||\vec{p}_T^{\,W}|$
- Predominantly left-handed W production and non-zero longitudinal component as predicted by NLO Generators





EPJ C72 (2012) 2001

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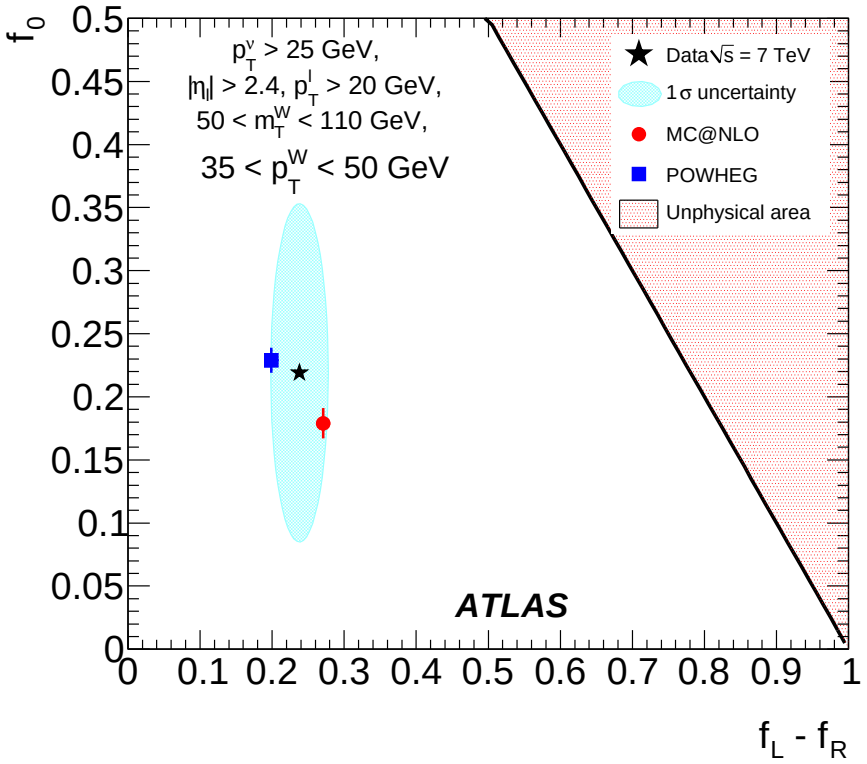
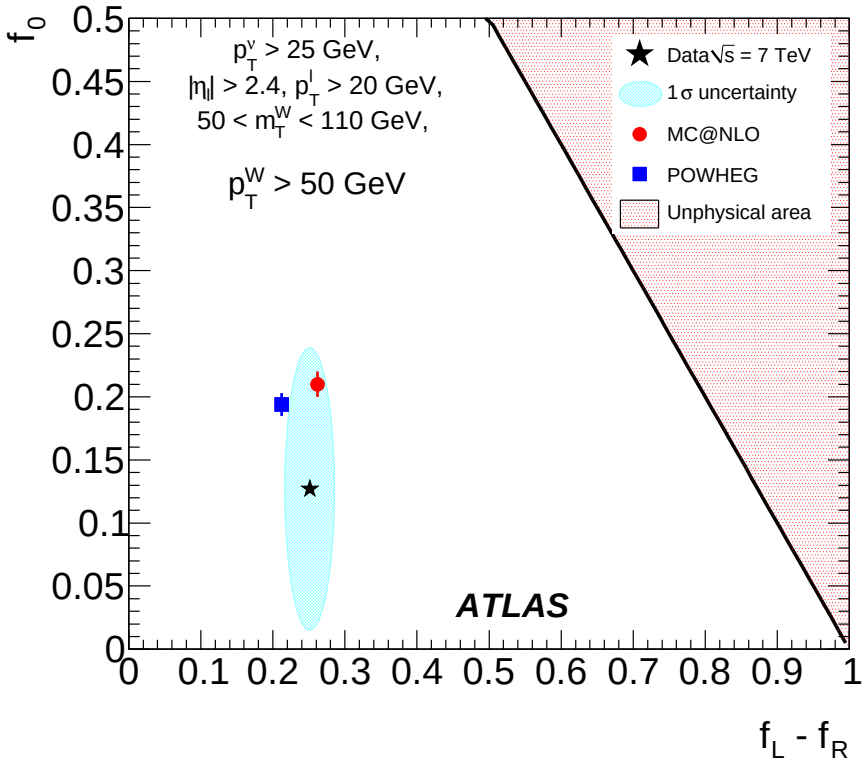
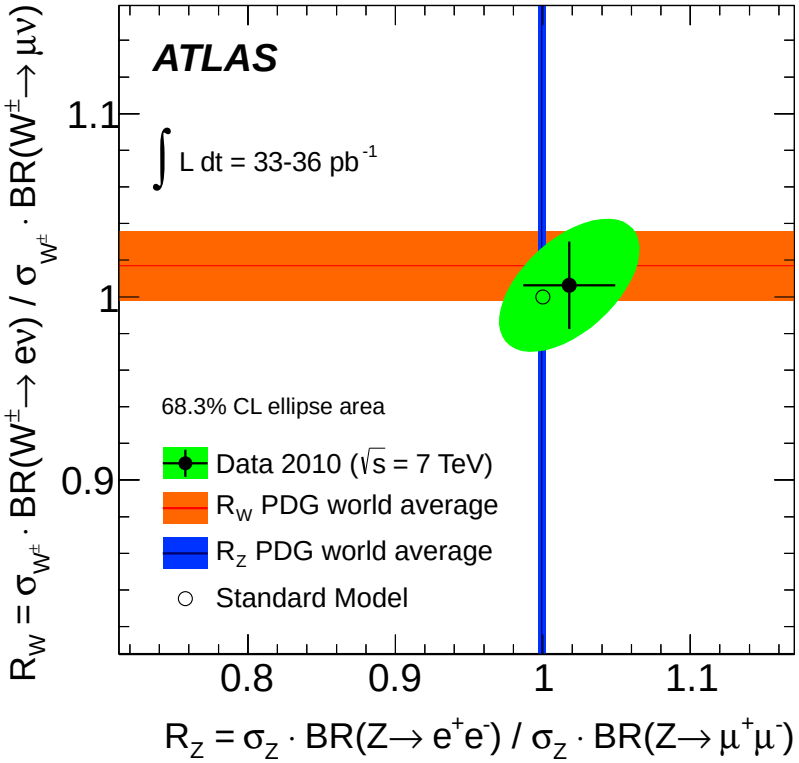




EPJ C72 (2012) 2001

Lepton Universality in $W \to \ell\nu$

- Integrated inclusive cross section measurements can be used to constrain W and Z leptonic branchings
- $Z \to \ell\ell$ branchings well know from LEP, but W less accurately constrained (for direct production)
- Current data confirm $e - \mu$ universality in W decays to 2%

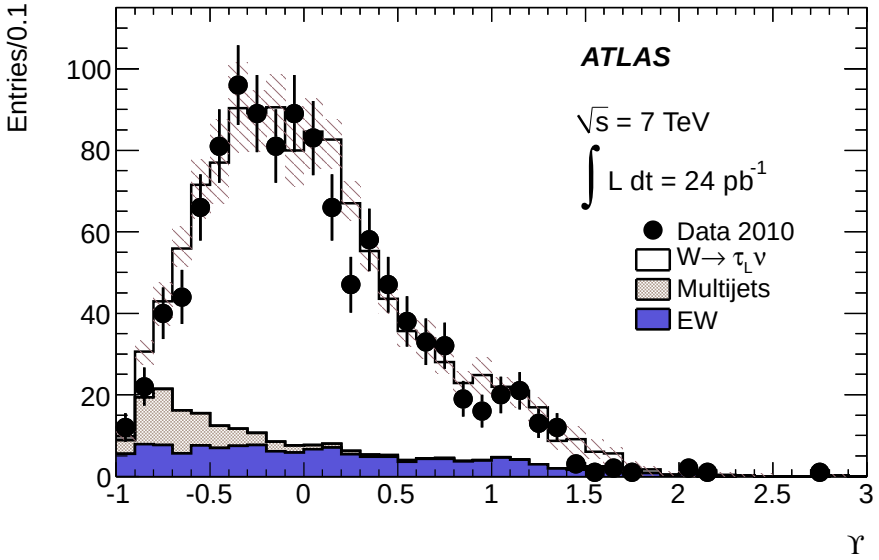


PRD85, 072004 (2012)

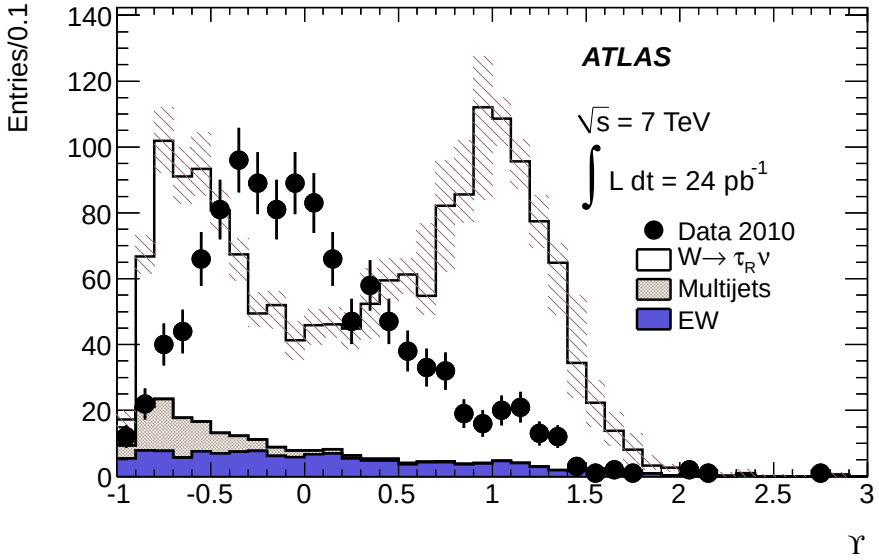
τ Polarisation in $W \to \tau\nu$

- First measurement of τ polarisation in $W \to \tau_h \nu$ at hadron collider
- Using hadronic one-prong τ decays, energy sharing of charged and neutral decay products: $\Upsilon = (E_T^{\pi^-} - E_T^{\pi^0})/(E_T^{\pi^-} + E_T^{\pi^0})$
- $P_\tau = -1.06 \pm 0.04_{\text{stat}}\,{}^{+0.05}_{-0.07}\,\text{syst}$
- Applications e.g. for $H \to \tau\tau$ ($P_\tau = 0$) and search for new physics

left-handed τ MC



right-handed τ MC



EPJ C72 (2012) 2062

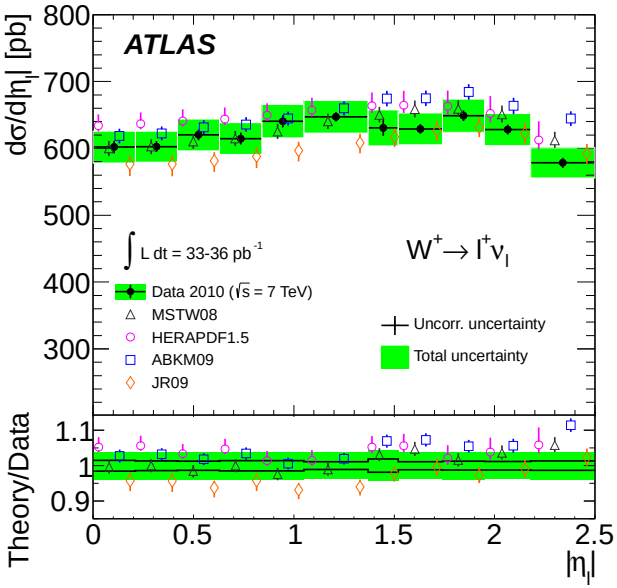
Summary

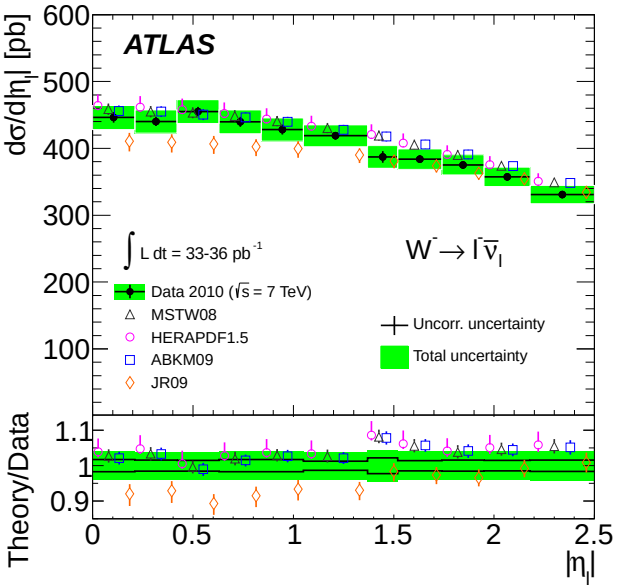
- High production rate of W and Z bosons enable detailed studies, e.g.
  - Precise differential cross sections with impact on our knowledge of proton structure (strange quark density)
  - Production in association with many jets or high boson p_T
  - Tests and measurements of properties and EWK parameters of the SM
- "Electroweak corrections" are naturally omnipresent in W and Z production and consistent estimation of higher order effects beyond QED FSR remains a challenge: coming data will cover more extreme kinematics, where so far unaccounted corrections become sizable (e.g. high mass Z/γ^*, high di-lepton $p_{T,Z}$)
- Further collaboration between experimentalists and theorists probably needed to bring theory to the accuracy level of the next generation of data

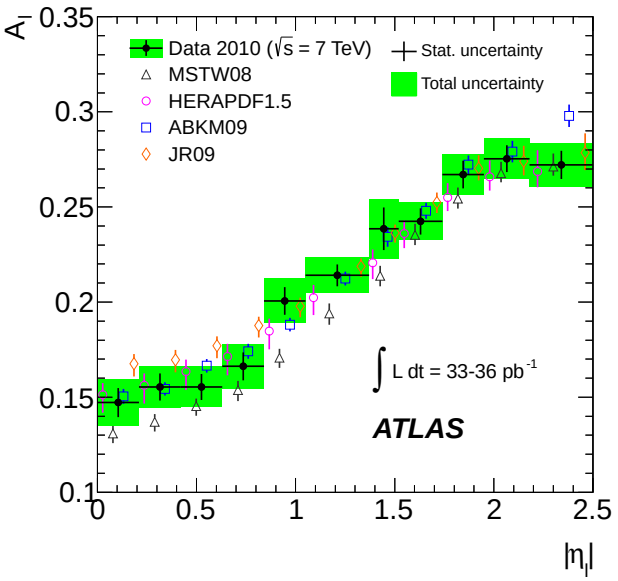
Experimentalists Wish List

- Better estimation of QED FSR effects on inclusive and more differntial distributions beyond the conservative "0.5%" uncertainty?
- Completion of "integrated" higher order tools:
  - EWK+QCD FEWZ for $W \to \ell\nu$?
  - EWK Powheg for $Z/\gamma^* \to \ell\ell$?
  - How much is still missing from these tools, e.g. "full" $\mathcal{O}(\alpha_s\alpha)$?
  - Effects at $m_{\ell\ell}$ below and above Z peak
- Same or similar tools for large boson p_T and/or V+jet?

Z, W DY Production

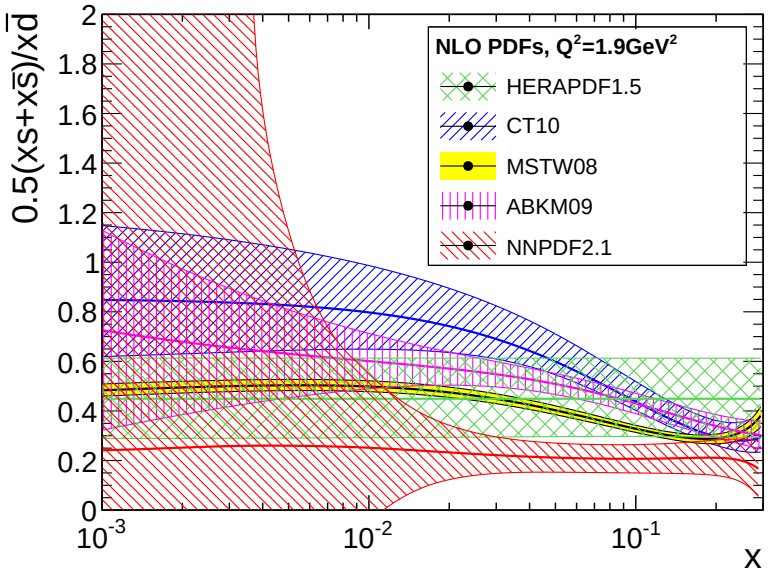


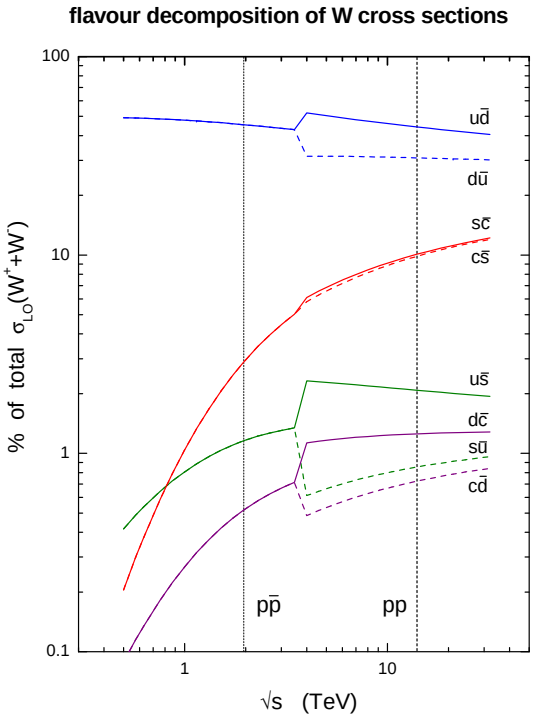


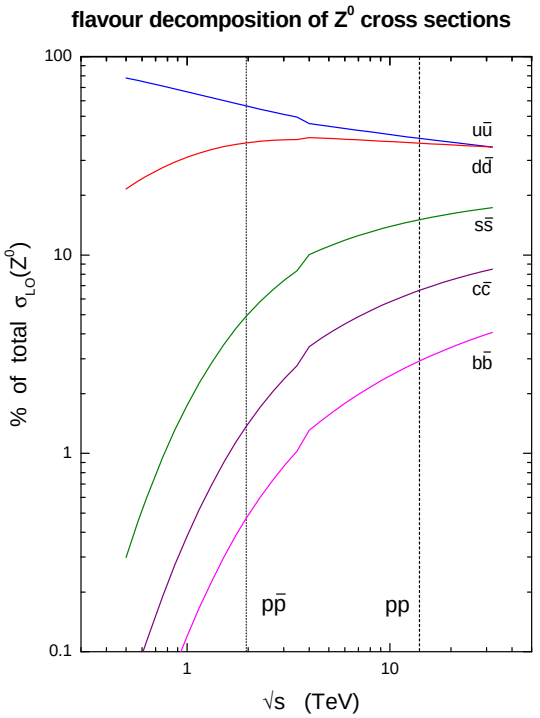


PRD85, 072004 (2012)

Strange Density

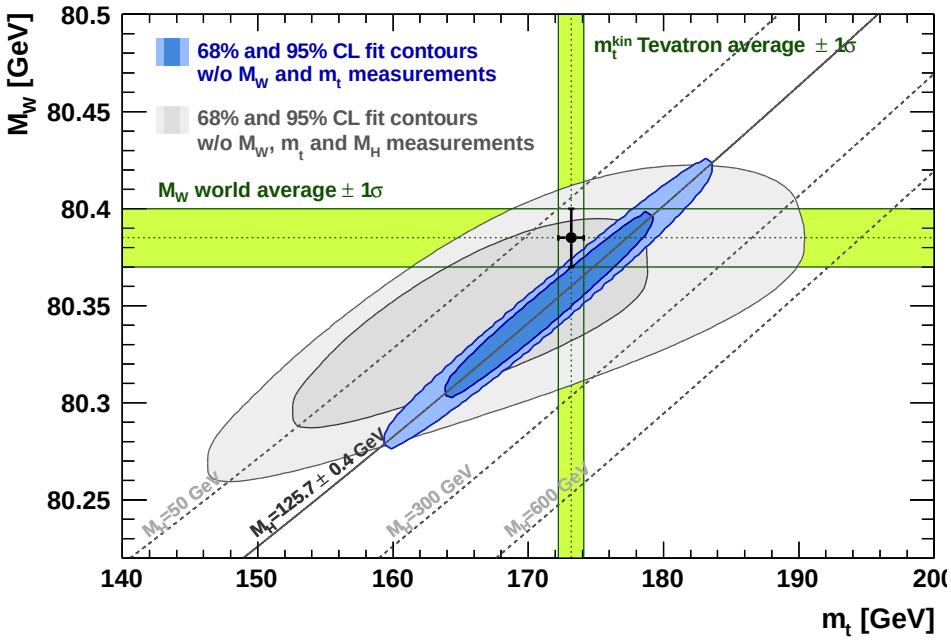


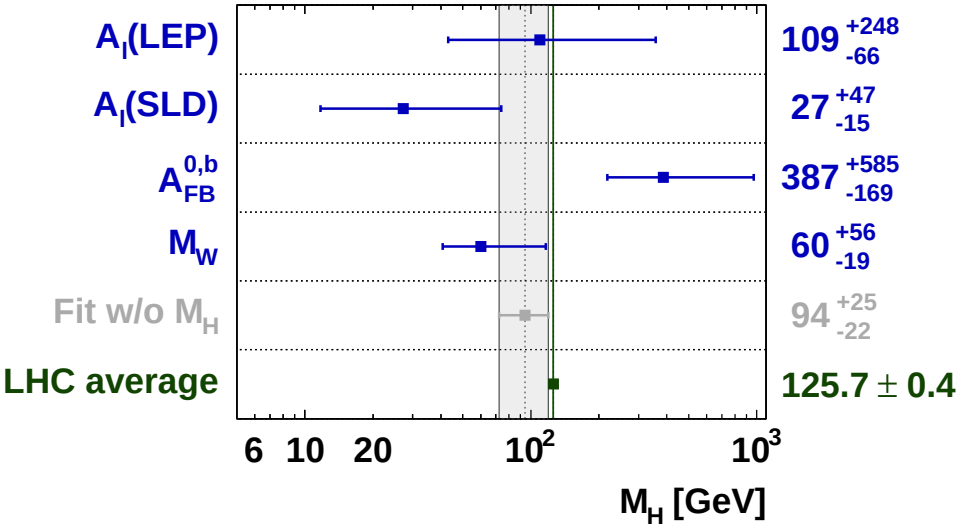




W.J. Stirling: MSTW2008 LO

W mass and EWK Fit arXiv:1209.2716





High Mass DY arXiv:1209.2535

- ATLAS search for high mass di-lepton resonances ("Z'")
- SM prediction of Z/γ^* at NNLO QCD using PHOZPR, EWK corrections using HORACE