W&Z Physics at the LHC

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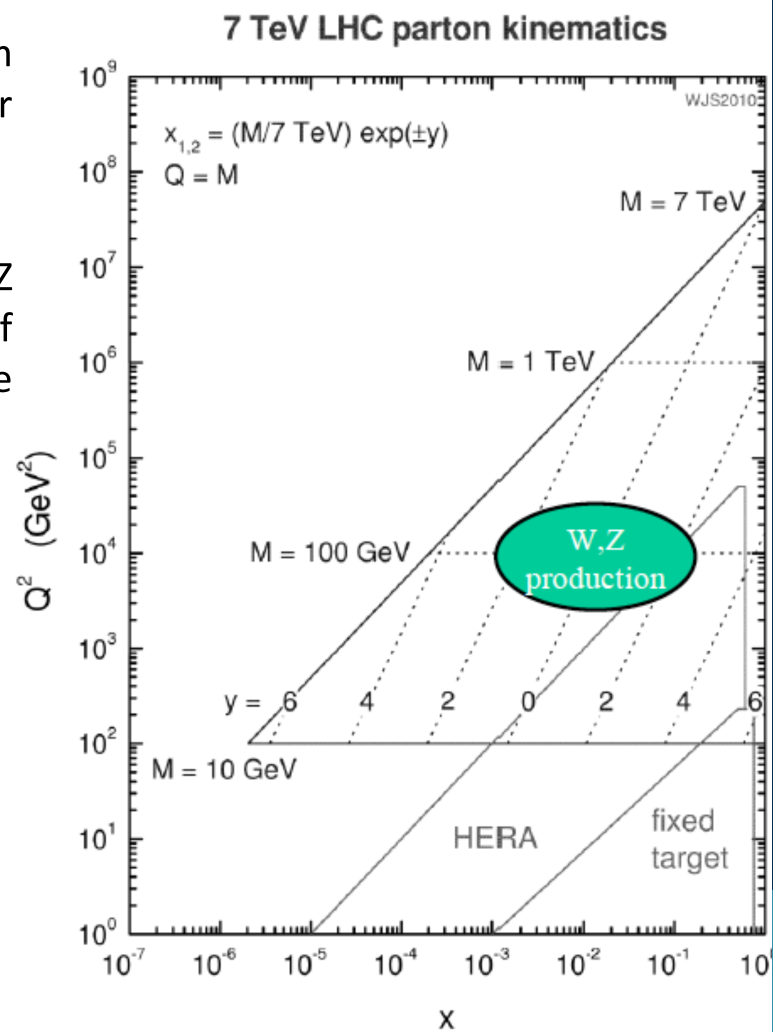
On behalf of the CMS, ATLAS and LHCb collaborations

Why study W&Zs in the LHC?

- On the path to discovery, the LHC program encourages us to measure in detail a great number of the Standard Model known "unknowns".

- The study of the production mechanism of W and Z in pp collisions and the precise measurement of electro-weak observables related to them to have already provided a plethora of results at 7 TeV.

- Thanks to them, we have been able to:
  - Obtain precision measurements in the TeV regime
  - Study in detail the building blocks for general analysis (leptons, met, jets, b-jets)
  - Test perturbative QCD predictions and PDFs in pp Collisions at the TeV scale
  - Cross-check our measurements of Luminosity
  - Understand in detail the backgrounds for most searches (Higgs, SuSy)



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Summary: Results at 7 TeV

- **Inclusive W/Z measurements**
  - Inclusive Cross-Sections and Ratios
  - Differential Cross-Sections
  - W Charge asymmetry
  - W polarization
  - Tau polarization
  - Z A_{FB} asymmetry
  - Measurement of the weak mixing angle
  - Z rapidity and transverse momentum
  - W transverse momentum
  - Study of the strange quark PDF density
- **V+jets / V+HF measurements**
  - V+Jets Cross-Sections
  - Cross-Section Ratios
  - Differential Cross-Sections
  - W asymmetry in jet bins
  - W+c study
  - W+b(b) cross-section measurement
  - Z+b / Z+bb cross-sections & kinematics

20 minutes is not enough to cover them all in the detail they deserve – just enough to focus on some of the highlights and news

Dedicated parallel talks by the three experiments for more detailed explanations:

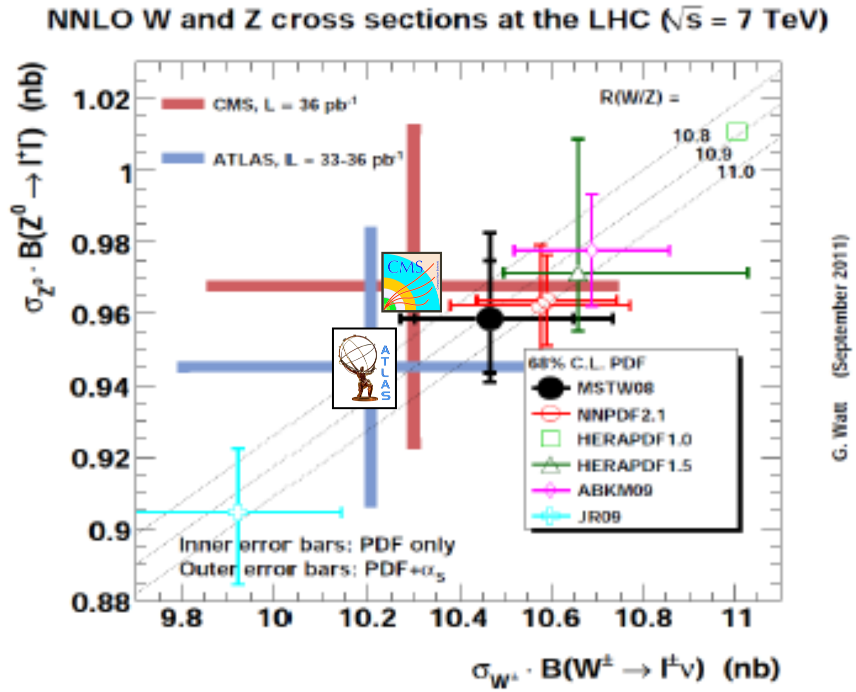
W. J. Barter (W and Z, LHCb)
R. Castello (W,Z+jets; CMS)
K. Nagai (W,Z ; ATLAS)
N. Neumeister (Drell-Yan; CMS)

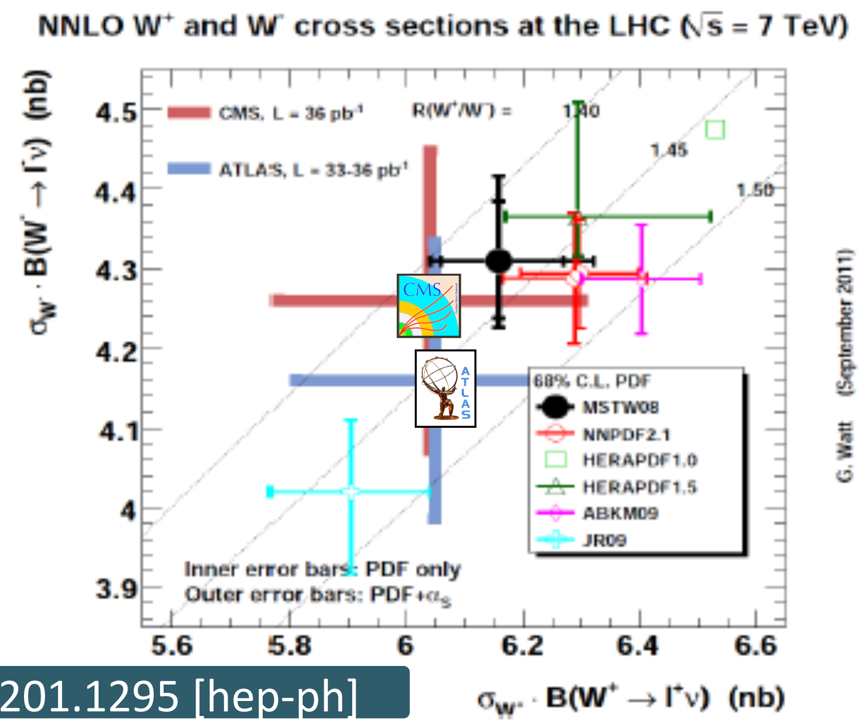
W/Z Cross-Sections

- W and Z decays are characterized by their **high production rates** and **clean and simple experimental signatures in their leptonic decay channels** :
  - **W: High pt, isolated lepton + high Missing Transverse Energy (ME_T)**
  - **Z: 2 high pt isolated leptons**

- ATLAS: Phys.Rev.**D85** (2012) 072004
- CMS: JHEP **10** (2011) 132

- “Central” leptons → pseudorapidity up to 2.1 (W muon, CMS) / 2.4 (muon ATLAS, Zmumu CMS) / 2.5 (electrons)
- Excellent agreement with theoretical predictions
- Already being used to provide further input to PDF measurements.

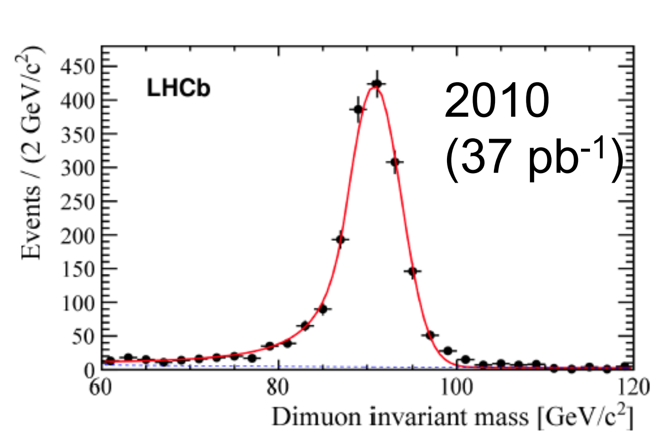


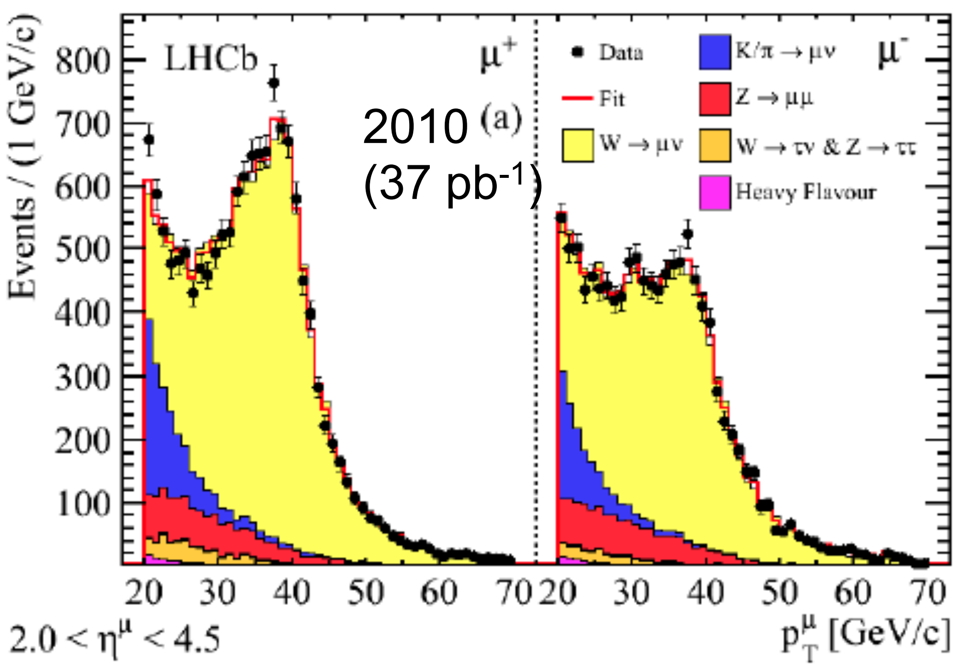


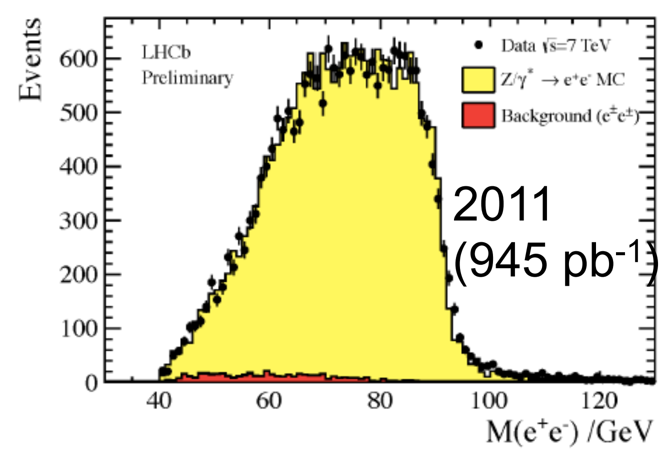
arXiv:1201.1295 [hep-ph]

Cross-Sections in the forward region

- New results from LHCb, complementary to the 2010 CMS/ATLAS measurements
- **Forward Muon/Electron → 2.0<eta<4.5**
- **P_T>20 GeV**
- For W → **isolated, Unbiased impact parameter < 40 μm, E/p < 0.04.** No MET → lepton p_T as a handle to identify Ws
- Z: Cut&Count (Muon and Electron)
- W: Fit to the pt distribution (only muon channel)



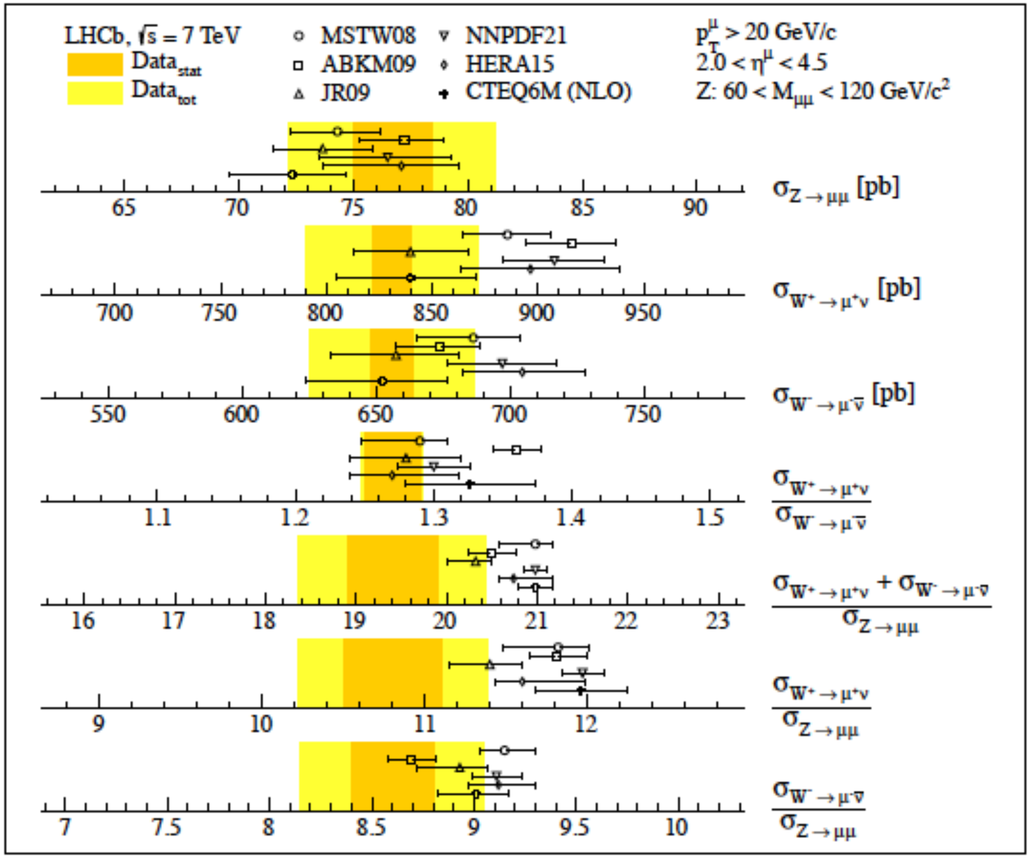




Muon: LHCb-PAPER-2012-008
Electron: LHCb-CONF-2011-011
Tau: LHCb-CONF-2011-041

W/Z Cross-Sections in LHCb

LHCb-PAPER-2012-008



$Z\to\mu\mu$

$W^+\to\mu\nu$

$W^-\to\mu\nu$

W+/W-

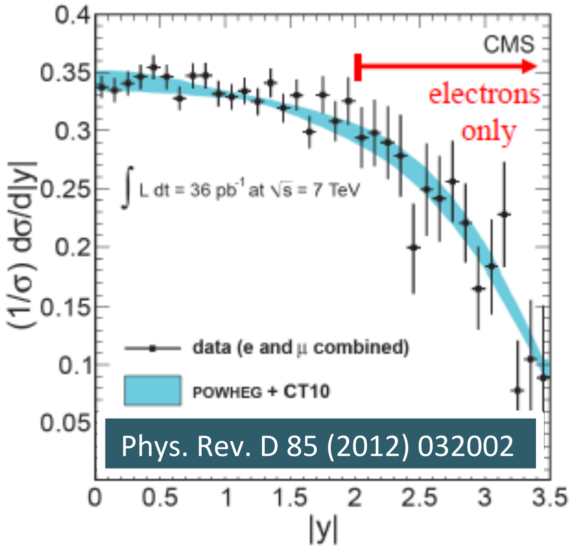
W/Z

W+/Z

W-/Z

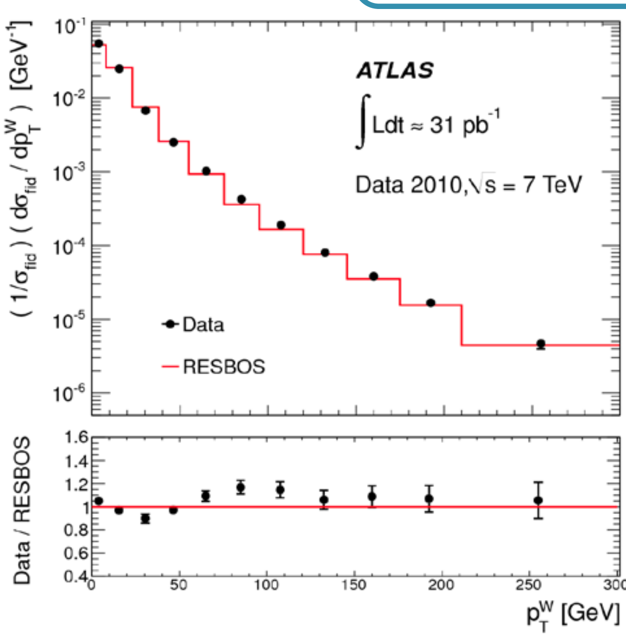
- d/u is not well determined from past experiments → LHC data at high η should help settle the PDF uncertainties in this region
- The results are in general agreement with theoretical predictions, performed at next-to-next-to-leading order in QCD, using different sets of recently calculated parton distribution functions.

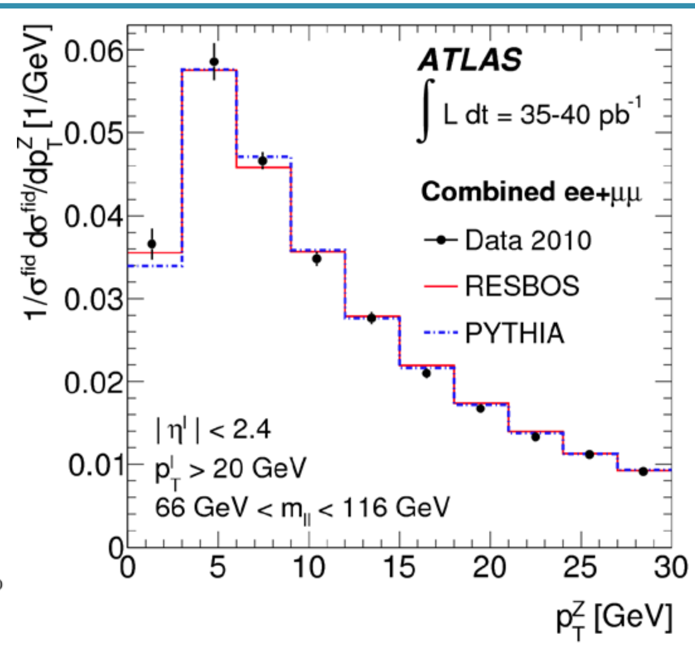
Differential Cross-Sections



Phys. Rev. D 85 (2012) 032002

- In addition to the inclusive cross-sections, differential cross-sections allow precision tests of our understanding of fine details of particle production at the LHC
- Examples: **Z rapidity** → sensitivity to PDFs (specially in the forward region). **q_T** → test of the underlying collision processes at low q_T and NNLO pQCD predictions at high q_T.
- Generally good agreement with the theoretical predictions, some discrepancies between PDF sets
- **ATLAS**: Z pt and rapidty, W pt and pseudorapidity
- **CMS**: Z pt and rapidity **LHCb**: W+- pseudorapidity, Z rapidity





Phys.Rev.D85 (2012) 012005,
Phys.Lett.B 705 (2011) 415

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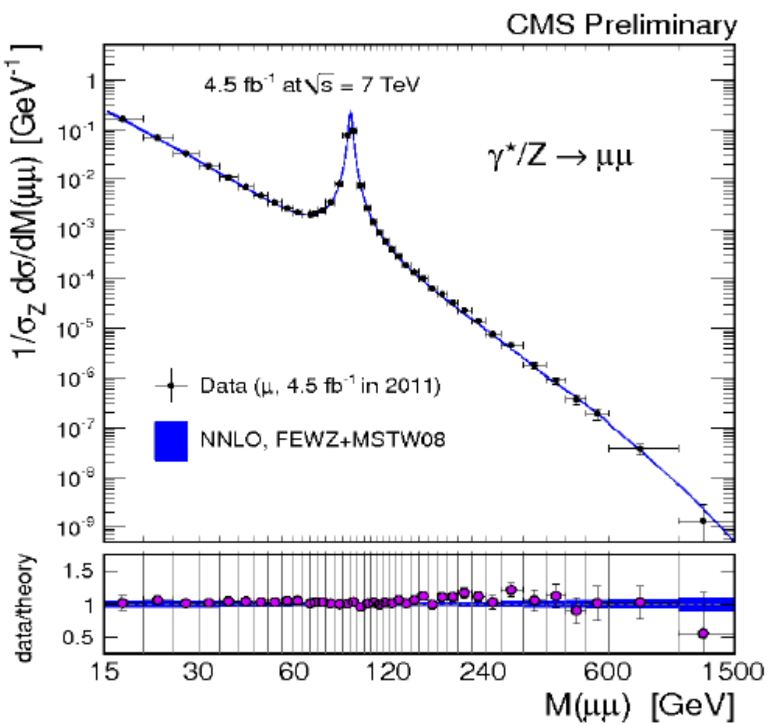
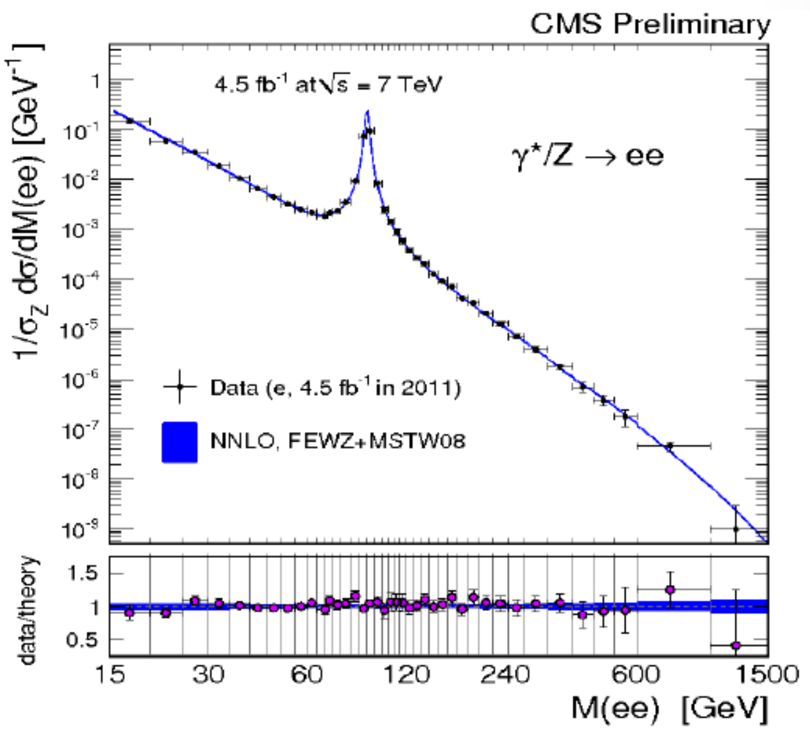
dσ/dM : Differential Drell-Yan X-Section

- Moving away from the Z peak we can further test pQCD predictions and probe PDFs.
- Normalizing the results to the Z peak → cancellation of luminosity uncertainties, reduction of overall uncertainties (eg: efficiencies)
- CMS: 40 invariant mass bins starting from 15 GeV
- Also studied in LHCb in the low mass region (See back-up, **LHCb-CONF-2012-013**)
- Data well described by NNLO
- Low mass range: dominated by modeling errors / High range: dominated by statistical errors



CMS-PAS-EWK-11-007



CMS-PAS-EWK-11-020

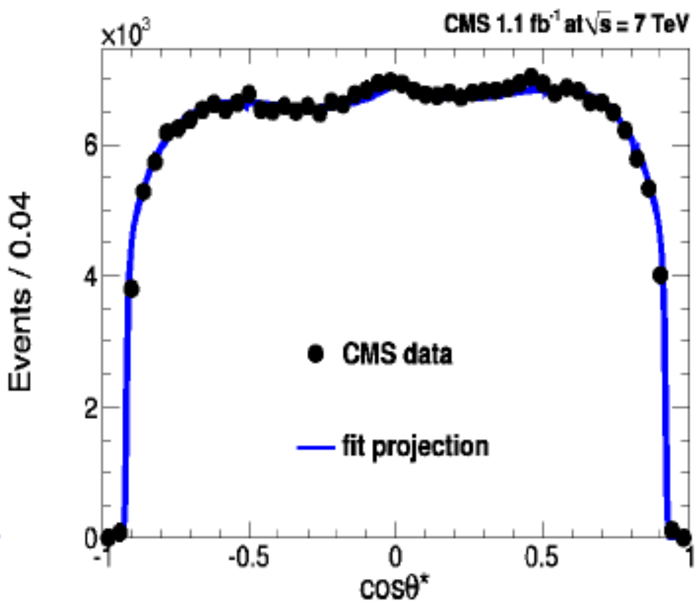
Weak Mixing Angle & A_{FB}

Kinematics of leptons produced in Z decays → Forward-Backward assymmetry of DY pairs, which:

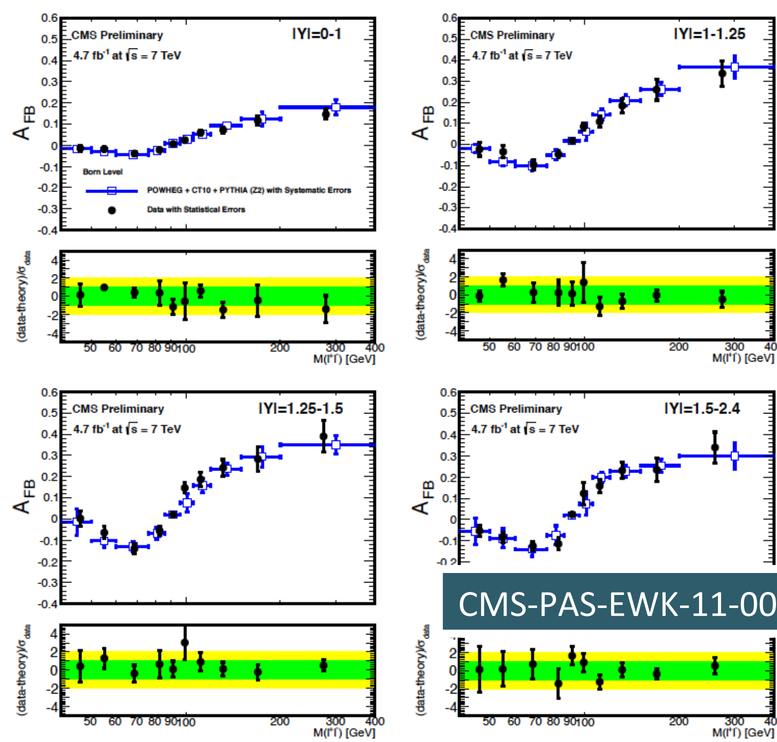
- At the Z pole → measure $\sin^2\theta_W$ with a 1% precision. Measured through an unbinned maximum-likelihood fit to the data di-muon rapidity, invariant mass and decay angle distributions (1.1 fb^{-1})

$$\sin^2\theta_{\mathrm{eff}} = 0.2287 \pm 0.0020\,(\mathrm{stat.}) \pm 0.0025\,(\mathrm{syst.})$$

- Away from the Z pole → Measure AFB as a function of rapidity and invariant mass. Observed AFB is heavily diluted wrt Born level one (results corrected) → Precision test on SM predictions around the Z peak region / sensitive to new physics at high mass (4.7 fb^{-1})



Phys. Rev. D 84 (2011) 112002



CMS-PAS-EWK-11-004

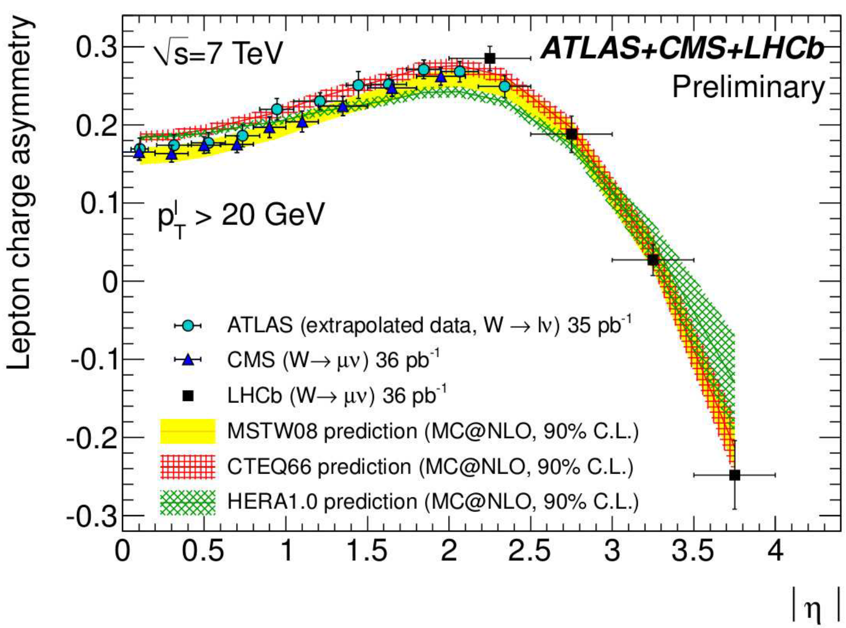
W Asymmetry

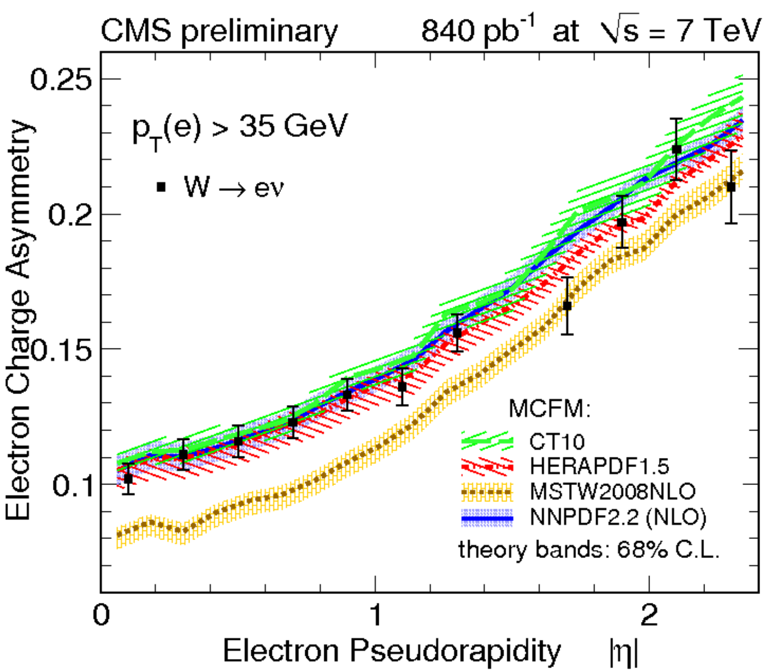
LHCb: LHCb-PAPER-2012-008
CMS: JHEP 04 (2011) 050, PAS-SMP-12-001
ATLAS: Phys.Lett. B701 (2011) 31-49

- More u-dbar than d-ubar in pp collisions → Charge Asymmetry in W production
- Excellent probe to study parton distributions in the proton

$$A_W \approx \frac{u\bar{d} - \bar{u}d}{u\bar{d} + \bar{u}d} \approx \frac{u_{val} - d_{val}}{u_{val} + d_{val} + 2\bar{q}}$$

$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\bar{\nu}_\mu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\nu_\mu)}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\bar{\nu}_\mu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\nu_\mu)}$$





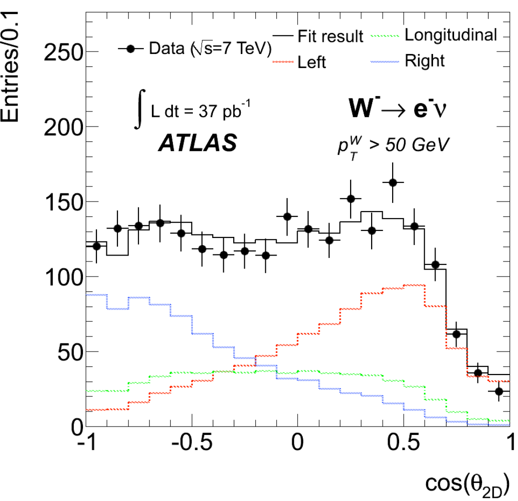
ATLAS: CERN-PH-EP-2012-016
CMS: PRL 107 (2011) 021802

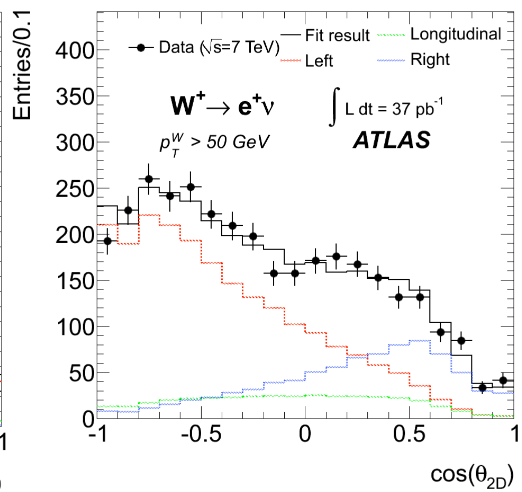
W polarization

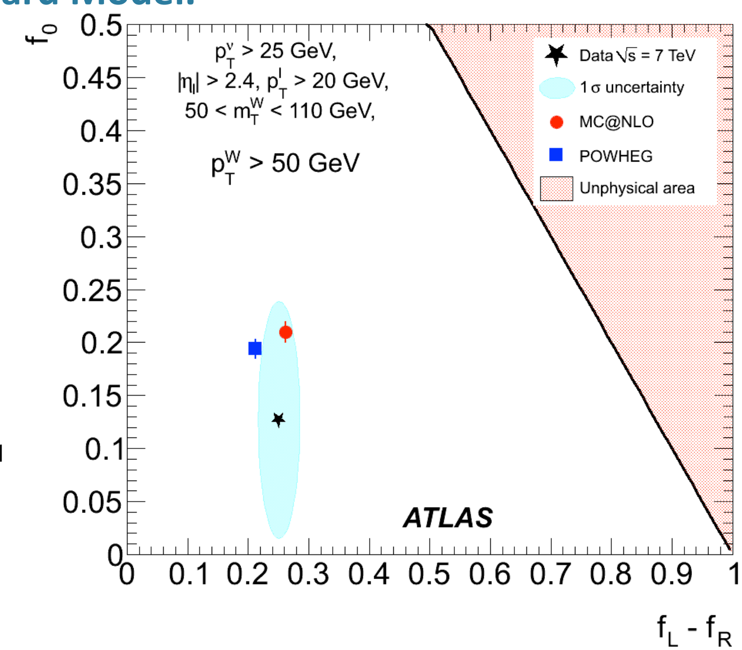
- Dominance of quark-gluon initial states, plus V-A W-fermion coupling leads to significant polarization of W bosons with large transverse momenta (>50 GeV) in pp collisions.
- The exact value of polarization depends on the proportion of the qg, qbarg, qqbar contributions, reflected in the **helicity angle (cos θ_{3D})**

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{3D}} = \frac{3}{8}f_L(1\mp\cos\theta_{3D})^2 + \frac{3}{8}f_R(1\pm\cos\theta_{3D})^2 + \frac{3}{4}f_0\sin^2\theta_{3D}$$

- Results computed in two ranges: 35<Pt(W)<50 GeV, Pt(W)>50 GeV
- The measurement confirm that **W bosons in pp collisions with large transverse momenta are predominantly left-handed as predicted in the Standard Model.**







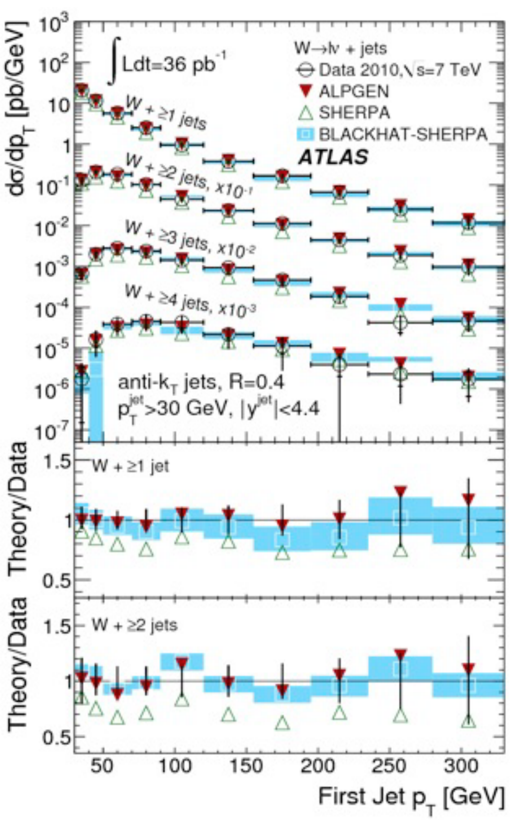
($\cos\theta_{2D} = \frac{\vec{p}_T^{\,\ell *}\cdot\vec{p}_T^{\,W}}{|\vec{p}_T^{\,\ell *}||\vec{p}_T^{\,W}|}$ used as an approximation of θ_{3D})

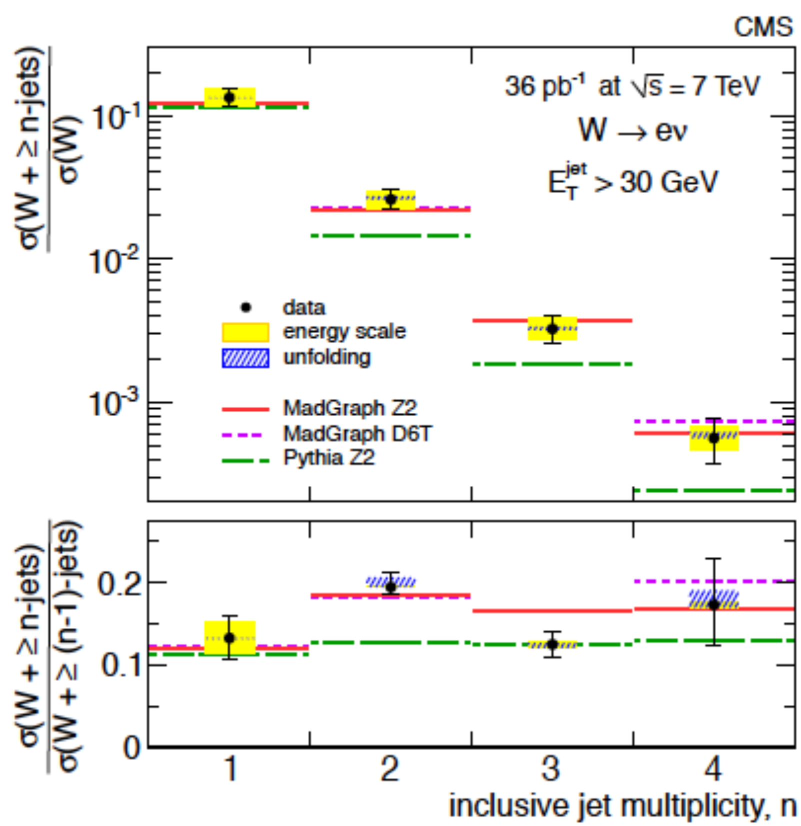
V+Jets Studies

CMS:
W, Z, R+jets: JHEP 01 (2012) 010
ATLAS:
W+jets: Phys. Rev. D85 (2012) 092002
Z+jets: Phys. Rev. D85 (2012) 032009
R+jets: Phys. Lett. B708 (2012) 221-240
LHCb:
Z+Jets: LHCb-CONF-2012-016 (NEW)

- CMS: focus on cross-sections and cross-section ratios
- ATLAS: extensive study of the kinematics (angles, differential distributions, etc)

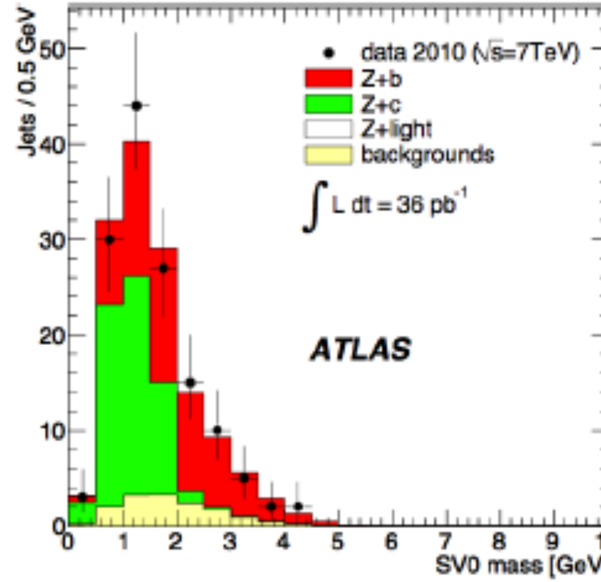
- Comparison of different MC generators and PDF sets → the different measurements performed provide **tests of α_S, PDFs, hard parton radiation and ME to PS matching schemes**
- In general good agreement with the theoretical predictions data for both CMS and ATLAS





Z+b / Z+bb

- Current cross-section predictions have large theory uncertainties, so a precise measurement by the LHC will have high impact in our understanding of V+HF production
- Tagging efficiency and template fits dominate the systematic uncertainties
- CMS observes a ‘larger though consistent’ cross-section in data than predicted. ATLAS is consistent within uncertainties.
- Some tension in the data/MC comparison of kinematic properties



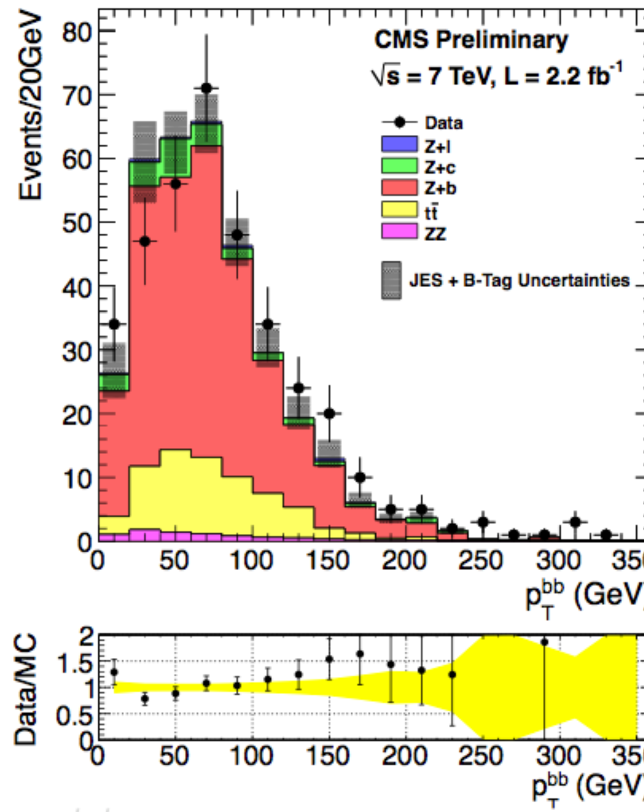
- **ATLAS:** (36 pb^{-1})

$$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})\ \text{pb}$$

- **CMS** (2.2 fb^{-1})

Z+>=1b $3.78 \pm 0.05(\text{stat.}) \pm 0.31(\text{syst.}) \pm 0.11(\text{theory})\text{pb}$

Z+>=2b $0.37 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.}) \pm 0.02(\text{theory})\text{pb}$

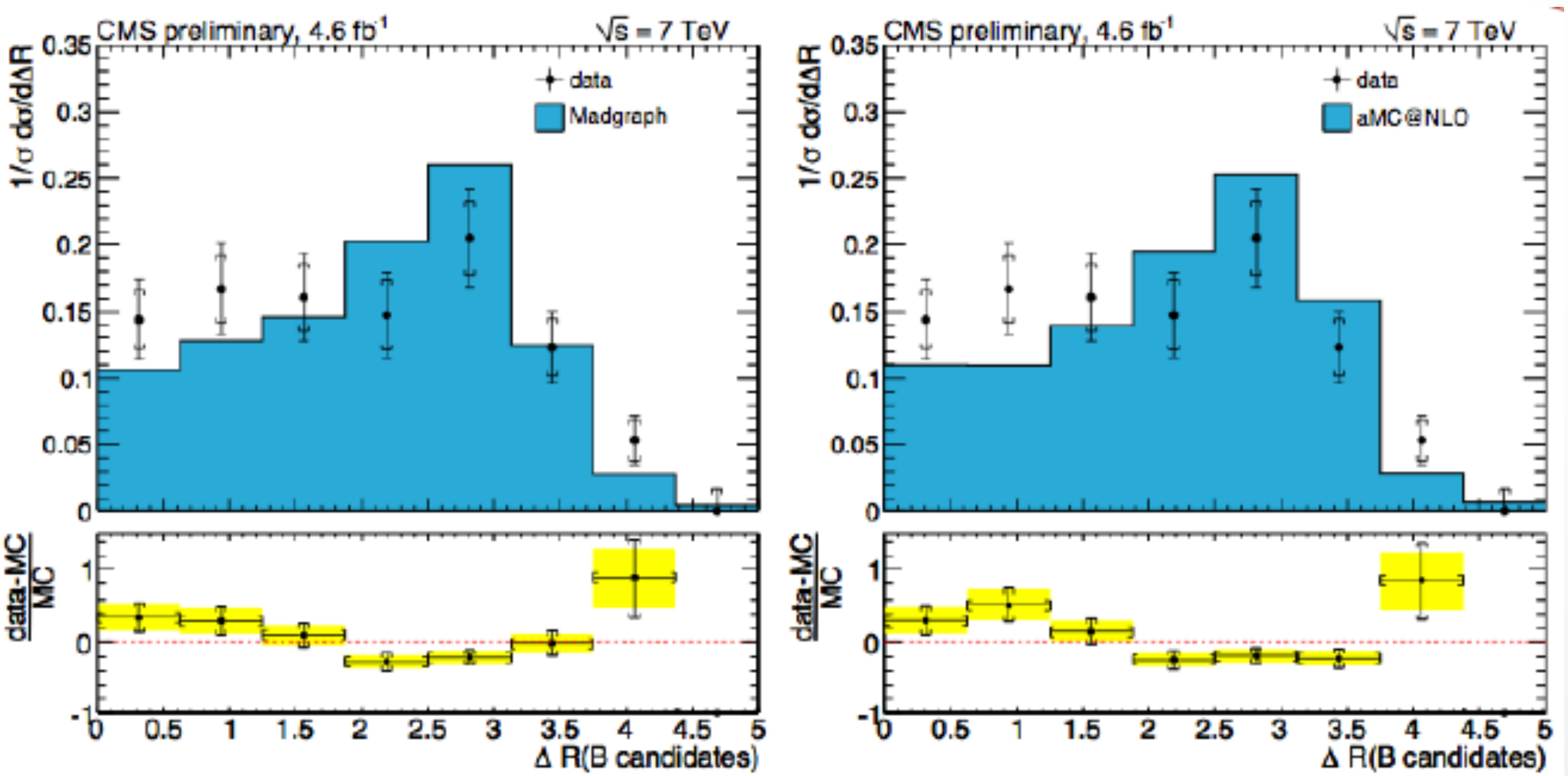


Z+b [Atlas, arXiv:1109.1403, 36 pb-1],
[CMS, arXiv:1204.1643, 2.1 fb-1]
Z+b/Z+j [CMS, SMP-10-015, 36 pb-1]
Z+bb [CMS, SMP-12-003; 2.1 fb-1]

Z+2SV

- Complementary approach to the standard jet-tagging procedure:
  - B-hadrons identification using secondary vertices (Inclusive Vertex Finder)
  - Not based on b-jets
  - Sensitivity at small angles → measurement of the ΔR(b1,b2) angle between the two displaced vertices
- Some discrepancies in shape observed between data and MC

CMS-EWK-11-015



W+c

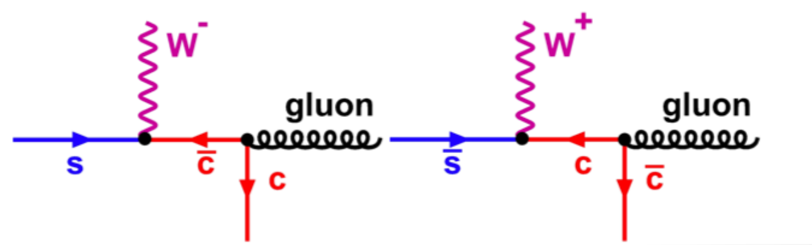
- The measurement of the cross section ratios

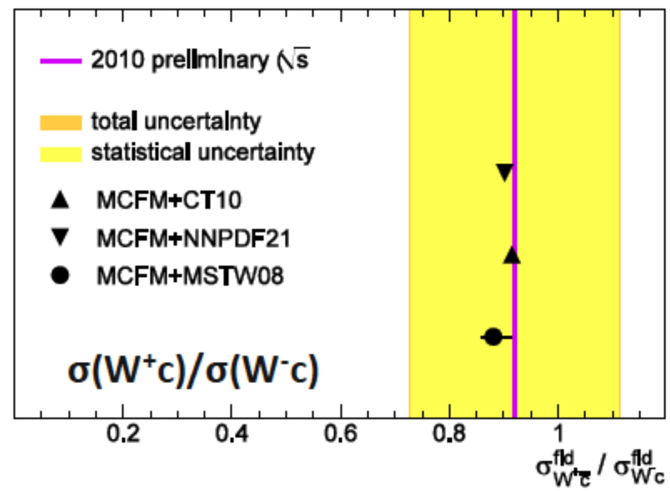
$$\boxed{\sigma(W^{+}\bar{c})/\sigma(W^{-}c)} \quad \text{and}$$

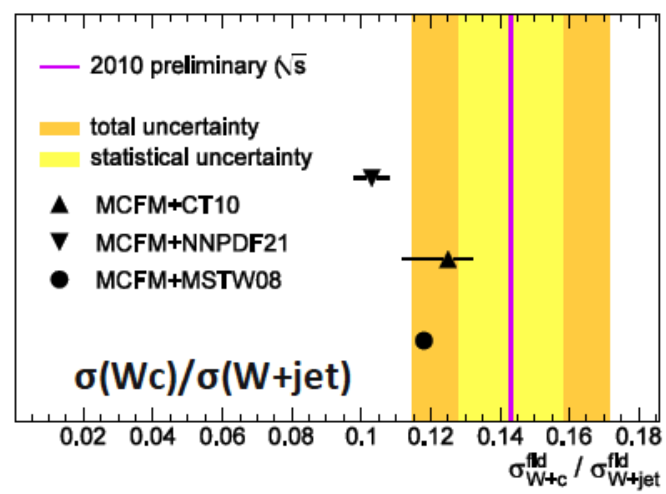
$$\boxed{\sigma(W+c)/\sigma(W+jets)}$$

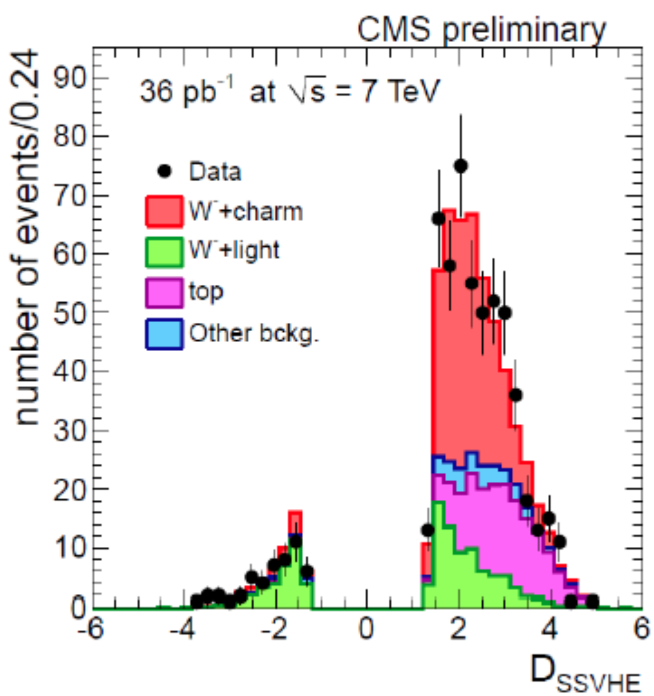
provides important information on the **strange and anti-strange quark parton density functions of the proton.**

- Measured in W+1 Jet events, through a fit to the significance of the secondary vertex decay length D_{SSVHE}









CMS-EWK-11-013

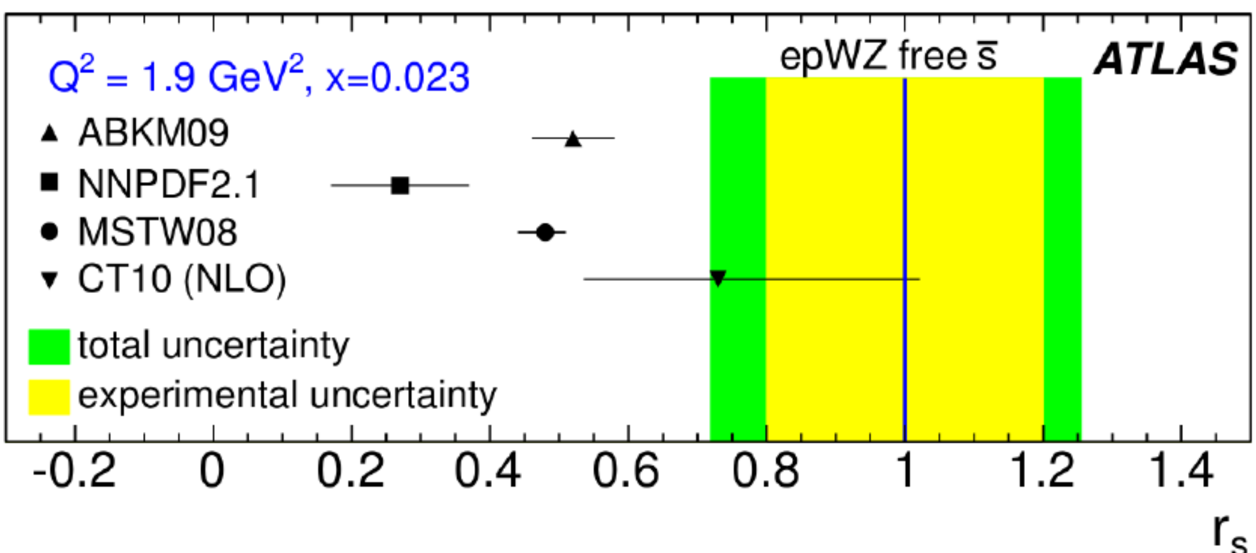
Determination of Strange Quark Density

- Complementary to the CMS measurement, ATLAS has studied the impact of the inclusive W/Z differential cross-sections and their correlations on our knowledge of the strange quark distribution in the proton
- 2 types of NNLO QCD fit of HERA DIS and ATLAS W/Z cross-section data (free sbar/fixed sbar)
- X^2/ndof improved in the free fit
- Considerable tension with most PDF sets

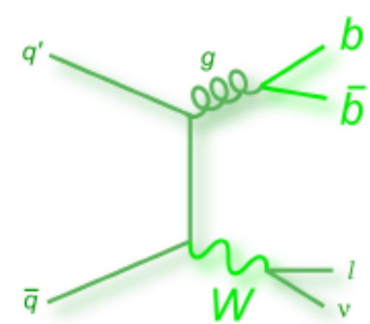
arXiv: 1203.4051

Fixed→ $\bar{s}/d = 0.5$

Free→ $r_s = 0.5(s+\bar{s})/\bar{d}$

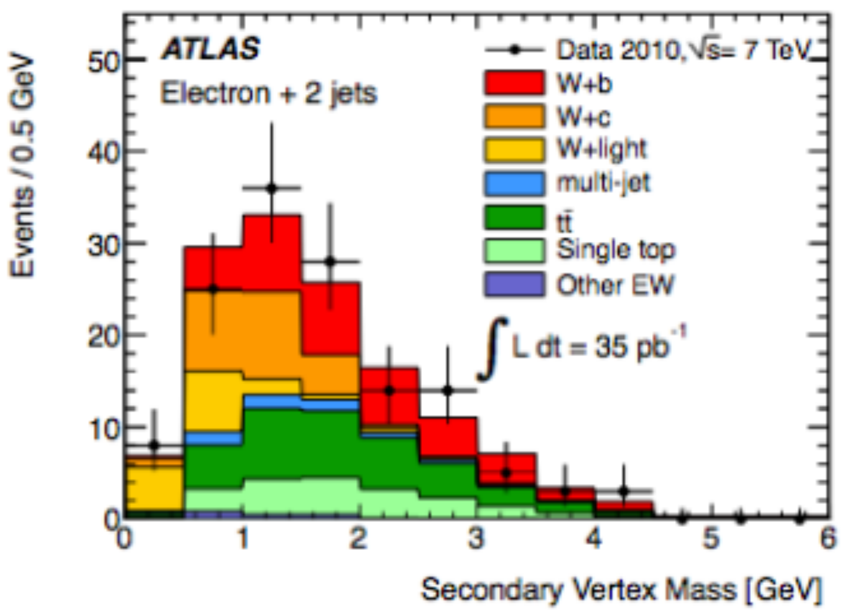


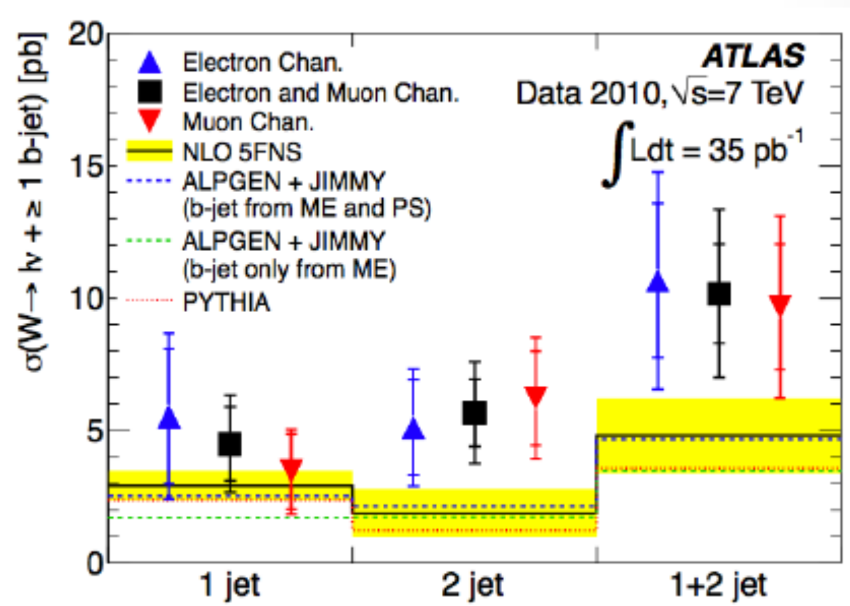
W+b(b)



Measured Cross-Section is **~1.5 sigma** larger than the theoretical prediction (both NLO(5FNS) and LO (Alpgen+Jimmy))

- Measurement performed in 3 bins: 1 btagged jet, 2 btagged jets, 1+2 btagged jets
- Significant background contributions, mostly from top (2 jets) and W+c (1 jet)
- The measurement is performed in the Electron/Muon channels, and based on a likelihood fit to the mass of the Secondary Vertex

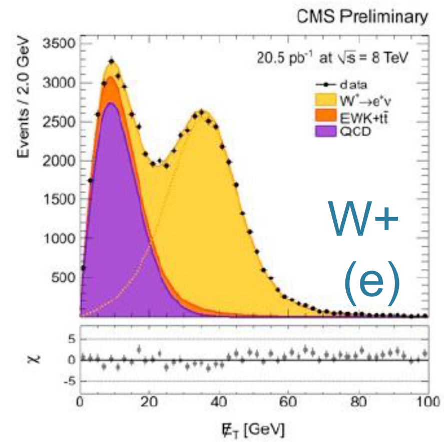


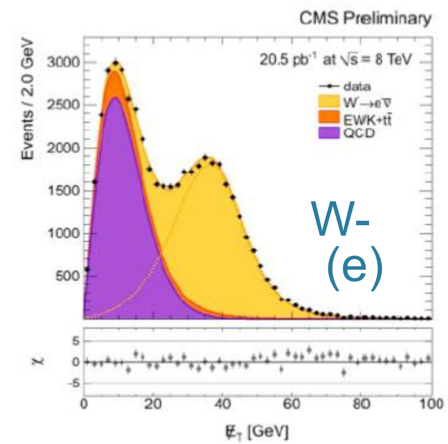


Phys.Lett. B698 (2011) 325-345

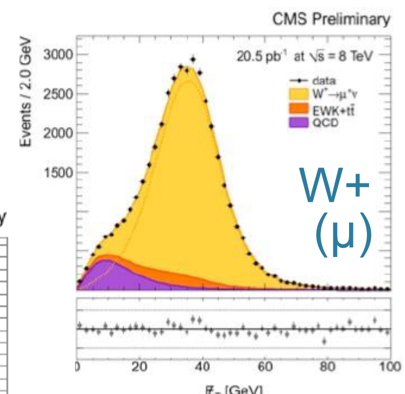
Towards the first 8 TeV results

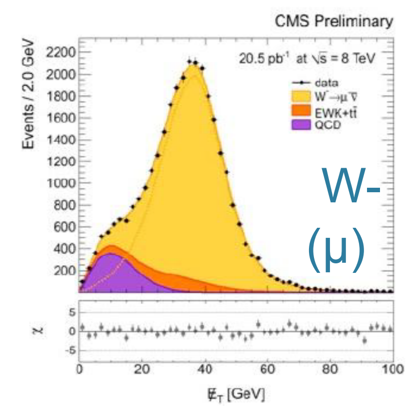
- The LHC SMP program will continue to yield results in 2012
  - Completing the ongoing analysis on 2011 data (7 TeV)
  - Extending and updating the results at 8 TeV

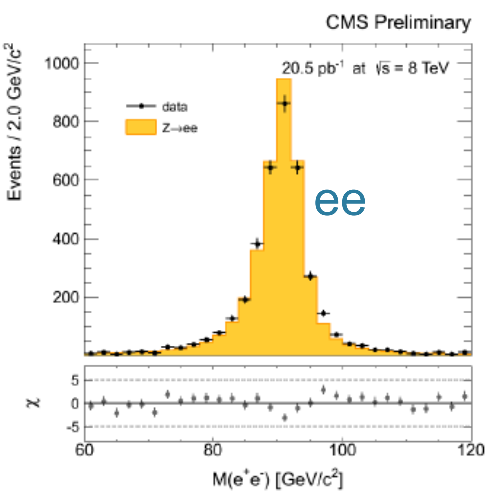


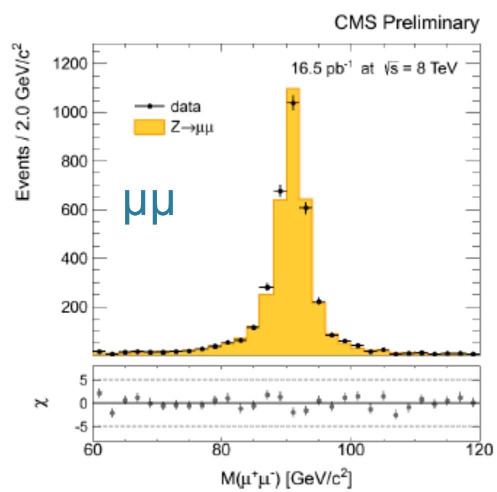


- The first results are starting to arrive: W^+, W^- MET and Z Invariant Mass distributions at 8 TeV









Note: Monte Carlo predictions fitted to the data yield (only shape comparison)

Conclusions

- ATLAS/CMS/LHCb have a healthy program of Standard Model physics studies, partially dedicated to the production of W/Z bosons at the LHC.
- At 7 TeV it has already provided:
  - **Precise cross section measurements** of W & Z bosons decaying into leptons, inclusively and in association with jets
  - **Detailed studies of differential cross sections**, in good agreement with the theoretical predictions
  - **Precise measurements of other EWK observables** (asymmetries, ratios, polarization), also in good agreement with NLO/NNLO predictions
  - **Insight on the Parton Density Functions**, both from inclusive measurements and from Vector Boson + jets production
  - First studies of the cross-sections and kinematics for **V+Heavy Flavour production** (which show interesting tensions with the theoretical predictions)
- Many measurements already systematics limited.
- The program will continue finishing the ongoing 2011 analysis, and moving forward to the 8 TeV era

A deep understanding of the physics behind W&Z production is mandatory in the LHC era. They are the building blocks on which TeV physics are based, without which searches could not have a solid ground.

References

- CMS Public Standard Model Results:

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

- ATLAS Public Standard Model Results:

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

- LHC Conference Notes on W/Z physics:

W->mu, Z->mu production (37pb-1)	http://cdsweb.cern.ch/record/1439627?ln=en
Z->ee production (945 pb-1)	http://cdsweb.cern.ch/record/1428904?ln=en
Z->tau tau production (247 pb-1)	http://cdsweb.cern.ch/record/1368211?ln=en
Low mass DY production (37 pb-1)	http://cdsweb.cern.ch/record/1434424?ln=en
Z+Jets Production	LHCb-CONF-2012-016

ADDITIONAL MATERIAL

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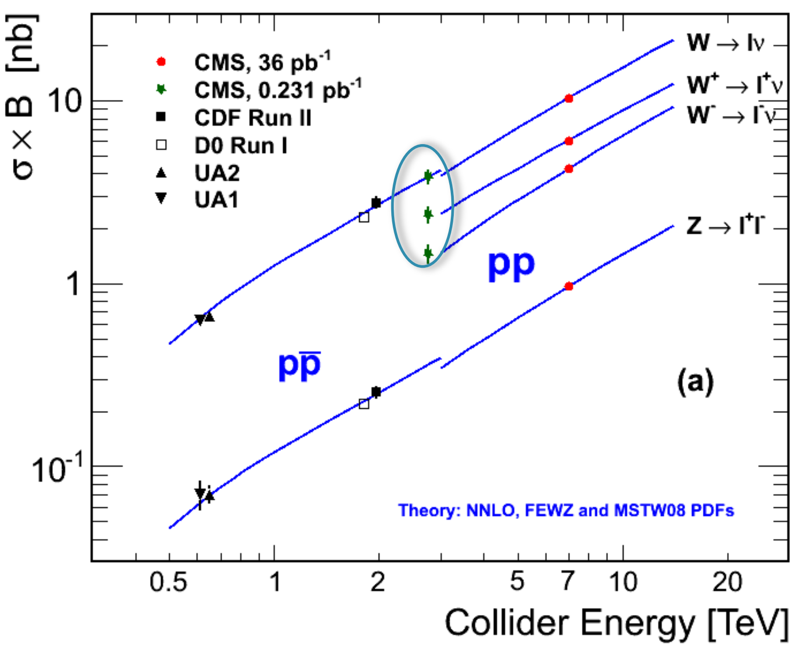
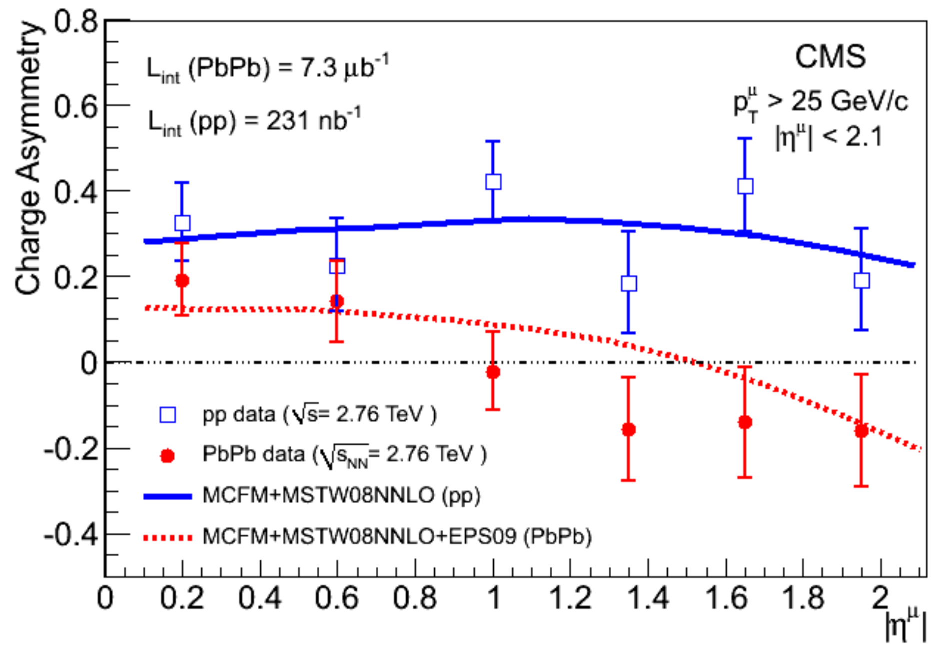
W Cross-Section at 2.76 TeV

- Measurement of W production at √s = 2.76 TeV is in agreement with Standard Model predictions (NNLO, FEWZ and MSTW08 PDF)
- Uncertainty = 5% (stat.) + 2.8% (syst.) + 6% (Lumi)

arXiv:1205.6334





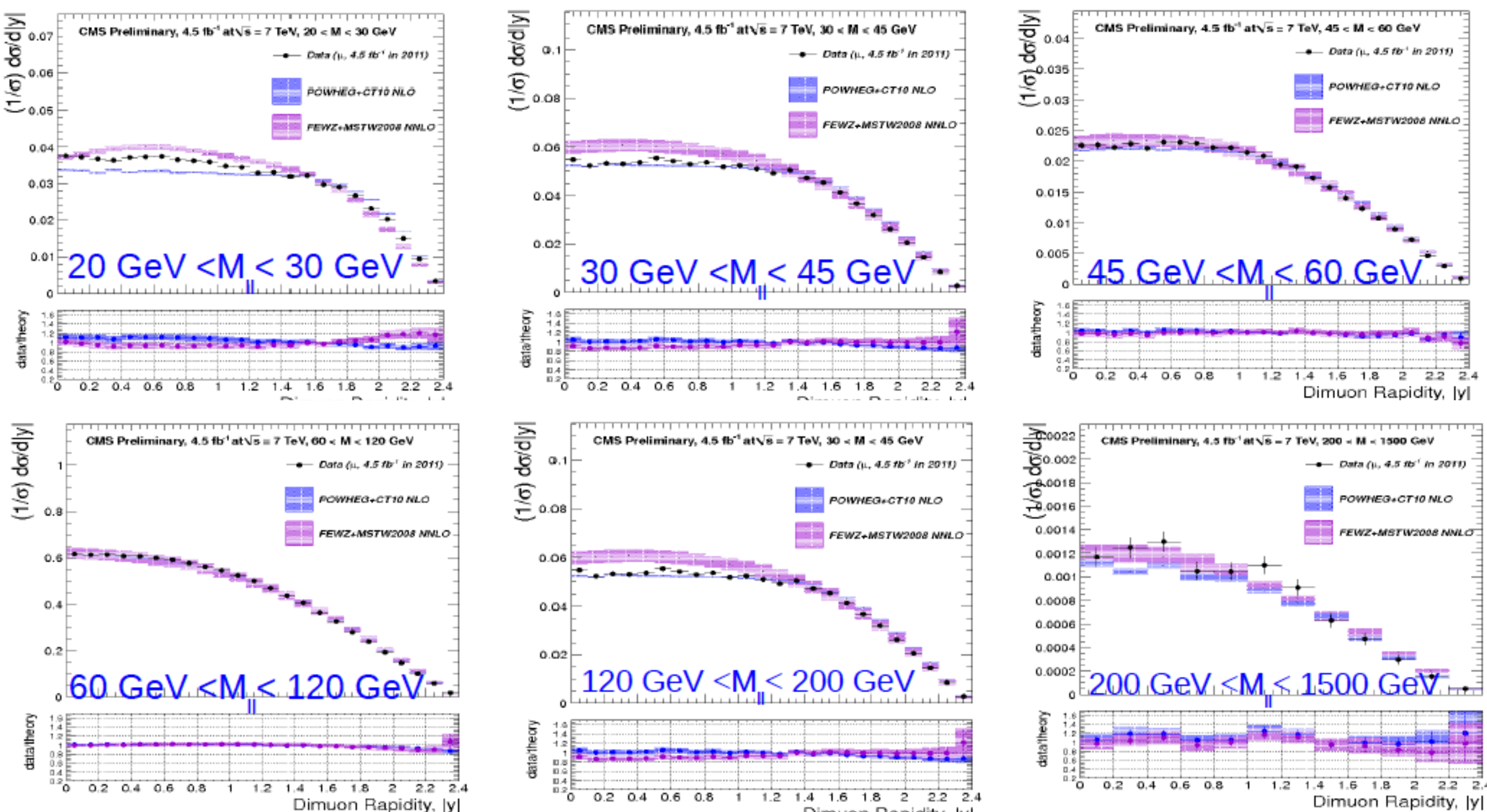
(First observation of W,Z production in HIC →**arXiv:1205.6334, PRL 106 (2011) 212301**)

dσ/dM/dY : Double Differential Drell-Yan X-Section

Moving to a measurement in bins of mass and rapidity we can constrain further our knowledge of PDFs (due to the different d/u composition outside the Z peak)

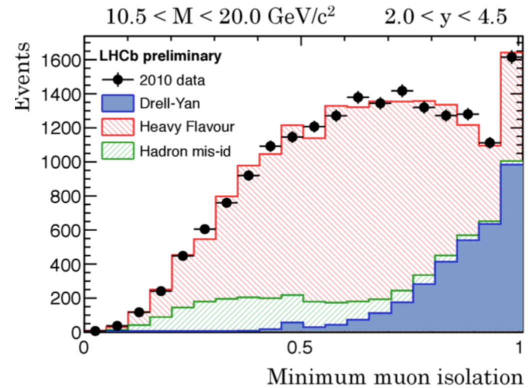
- 24 rapidity bins between 0 and 2.4, and 6 mass ranges
- Muon channel only

CMS-PAS-EWK-11-007

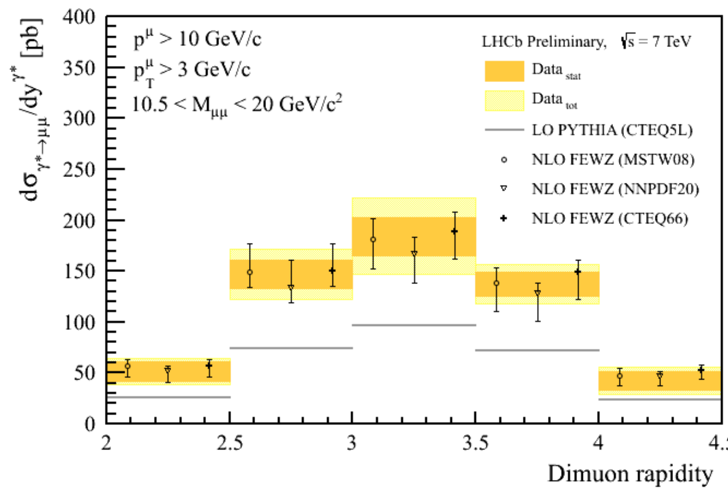


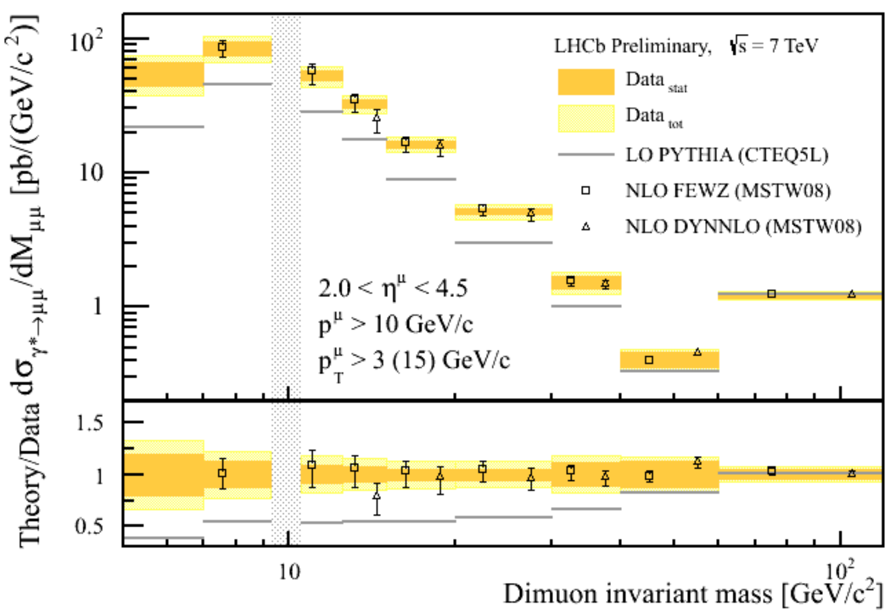
Low Mass DY in LHCb

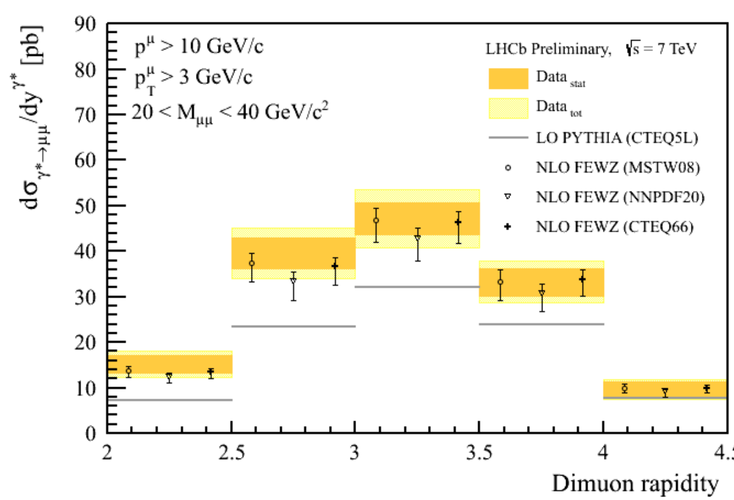
LHCb-CONF-2012-013



- 2010 data: **L = 37 pb-1**
- DiMuon (p_T > 3 GeV, p > 10 GeV, 2.0 < **η**(μ) < 4.5)
- 5 < M(μμ) < 120 GeV
- Yield extracted through a fit to the minimum muon isolation (**pT(μ)/pT(μ-Jet)**) in data to shapes expected for signal and background
- Cross-Section measured:
  - As a function of DiMuon Inv. Mass
  - As a function of rapidity in bins of Inv Mass.

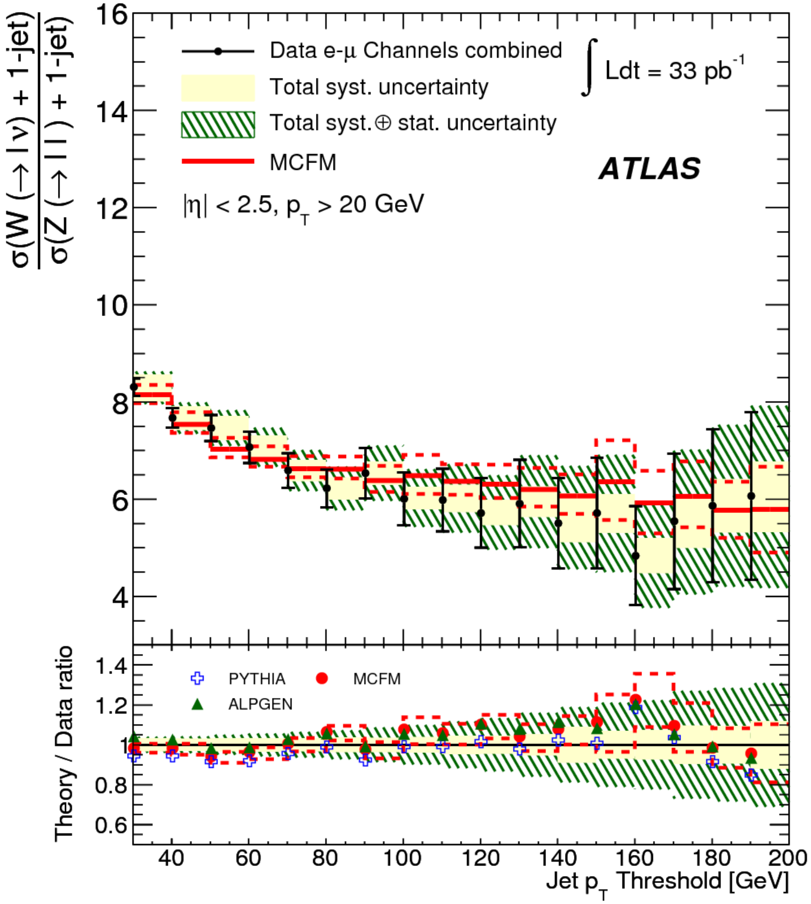


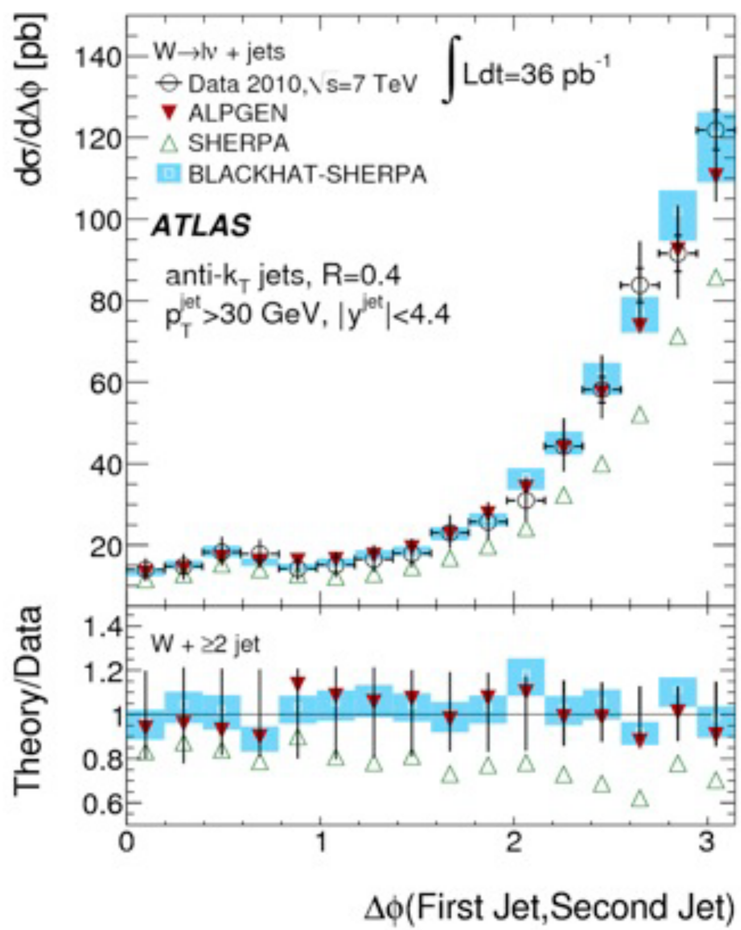




V+Jets Studies

- Jets reconstructed using anti-kt algorithms (cone: 0.4 ATLAS, 0.5 CMS)
- Systematics dominated by jet energy scale → larger at high jet multiplicities and high jet rapidity.
- The use of ratios provides some uncertainty cancellation





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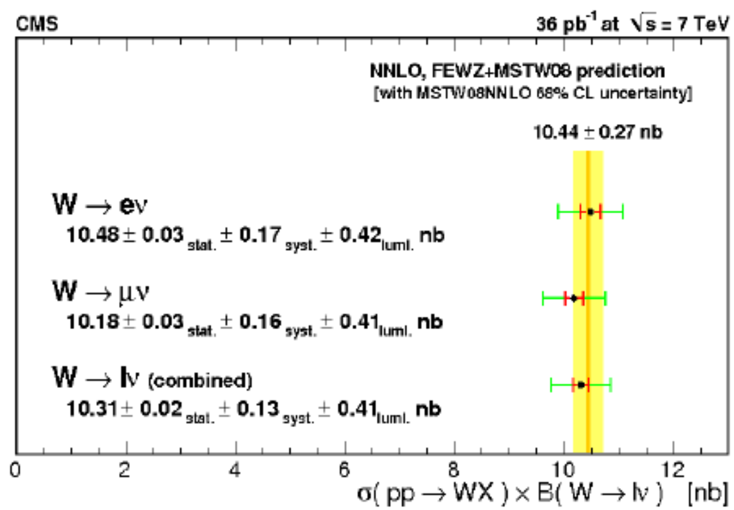
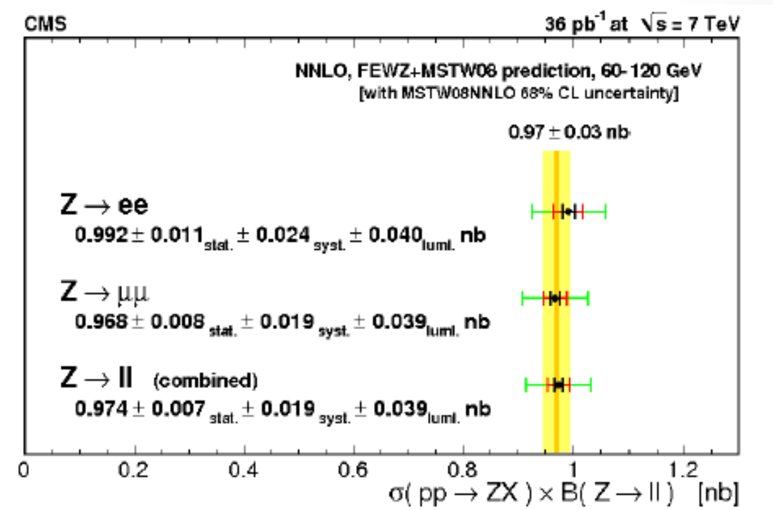
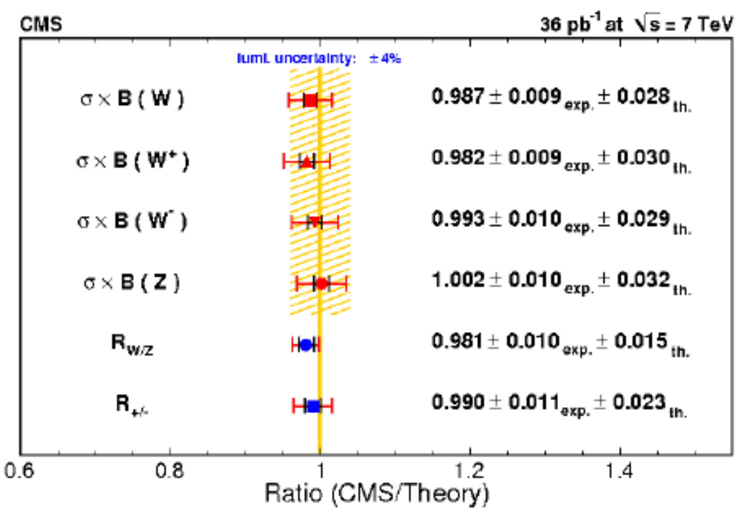
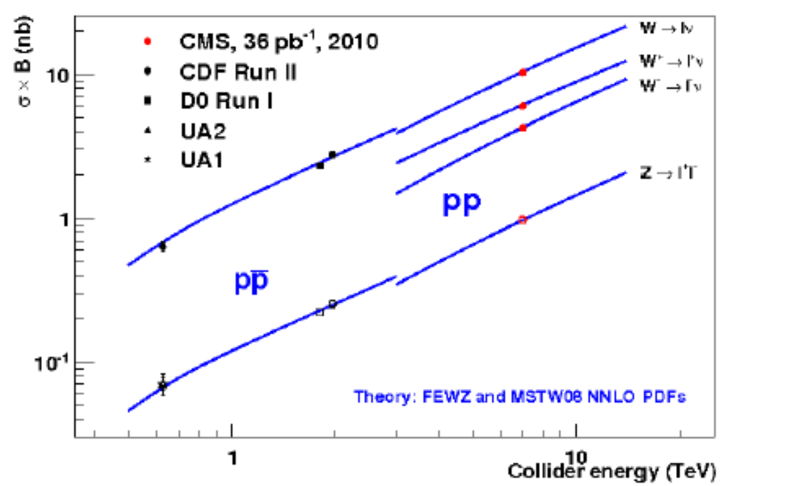
Integrated Total Cross-Sections









Fiducial Total Cross-Sections