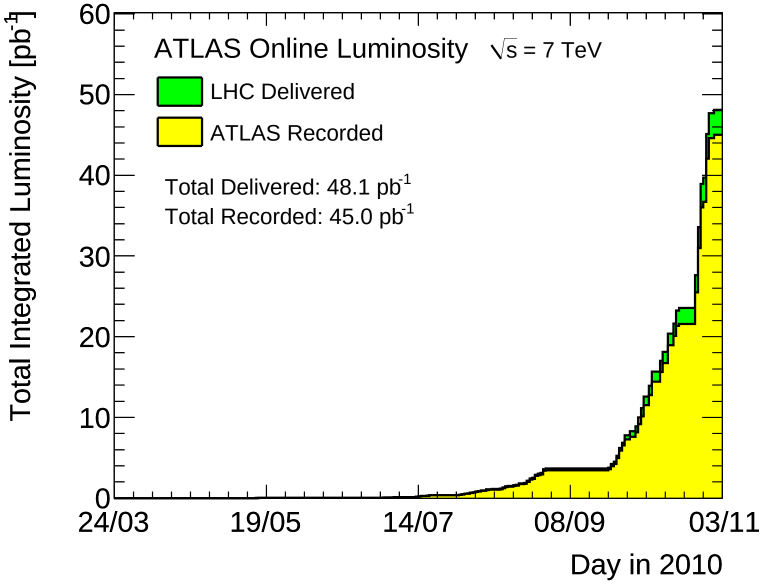
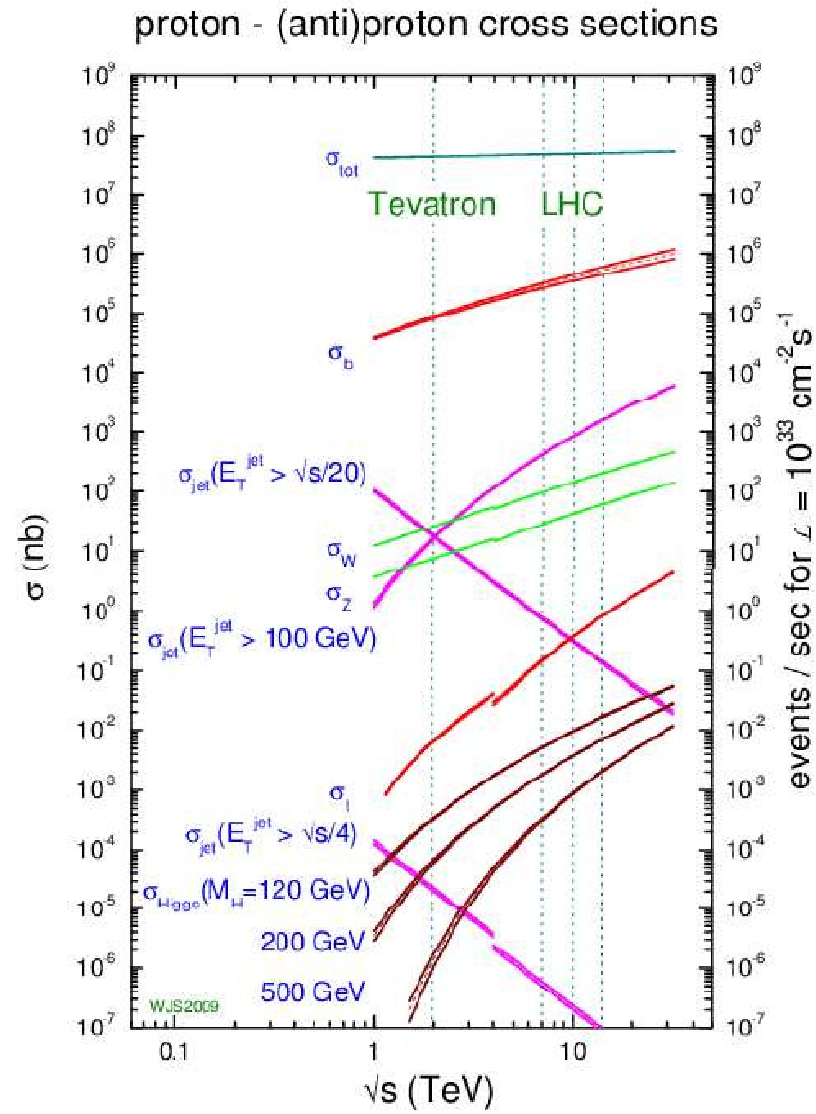
# Electroweak Results from ATLAS and CMS

S. Glazov, DESY Seminar, 3 May 2011

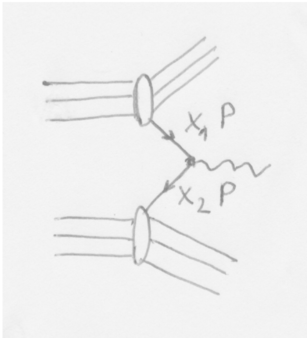
# Rediscovery of the Standard Model at the LHC




- Successful 2010 run of the LHC at $s = 7$ TeV.
- Sufficient luminosity to rediscover and measure precisely Standard Model production of $W, Z$ bosons, samples of few $10^4$ of $Z$ and $10^5$ of $W^\pm$ are collected by the experiments.



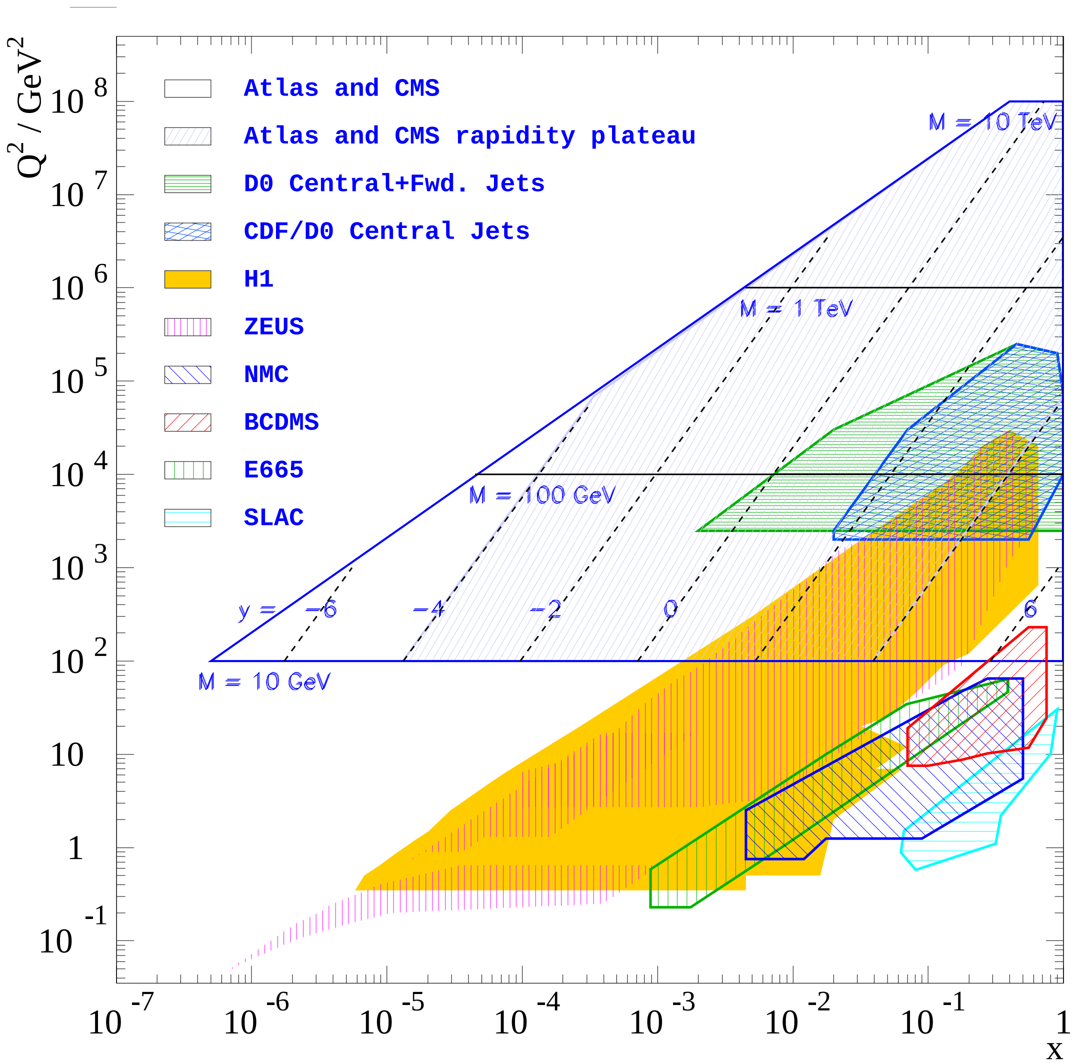
# *ep* and *pp* experiments




$x_1$, $x_2$ are momentum fractions carried by partons:

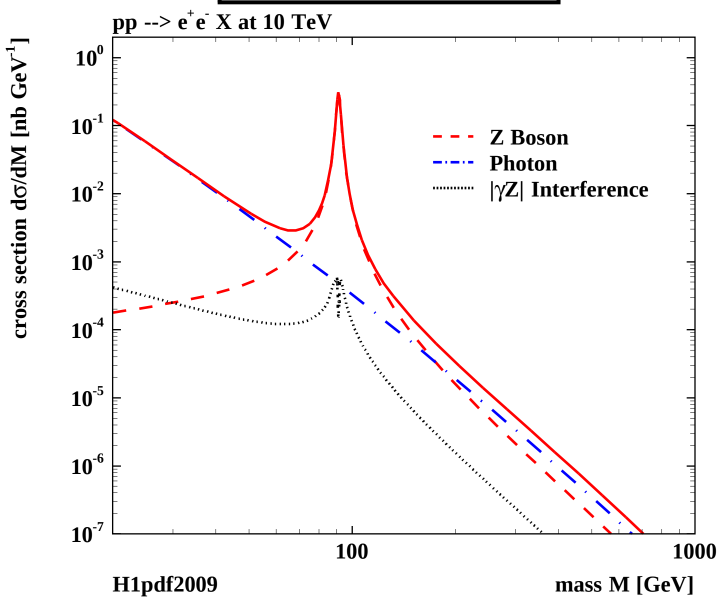
$$x_{1,2} = \frac{M}{\sqrt{S}} \exp(\pm y).$$

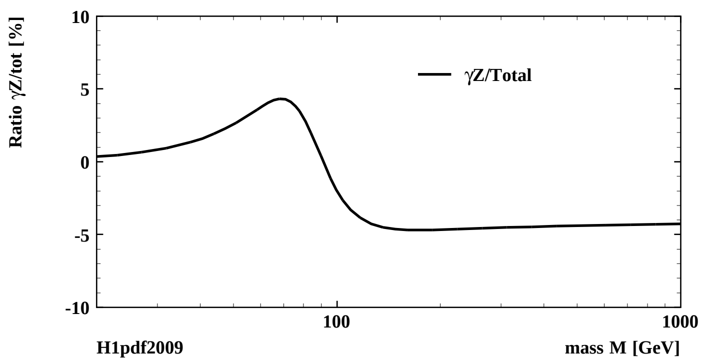
Factorization theorem states that cross section can be calculated using universal partons $\times$ short distance calculable partonic reaction.



# Neutral Current Drell-Yan Processes at the LHC

$$\boxed{pp \longrightarrow Xe^+e^-}$$




Double differential cross section:

$$\frac{d\sigma^2}{dM_{\ell\ell}dy} = \frac{4\pi\alpha^2(M_{\ell\ell})}{9} \cdot M_{\ell\ell} \cdot P(M) \cdot \Phi(y, M_{\ell\ell}^2).$$

Propogator for $\gamma$ exchange:

$$P_\gamma(M_{\ell\ell}) = \frac{1}{M_{\ell\ell}^4},$$

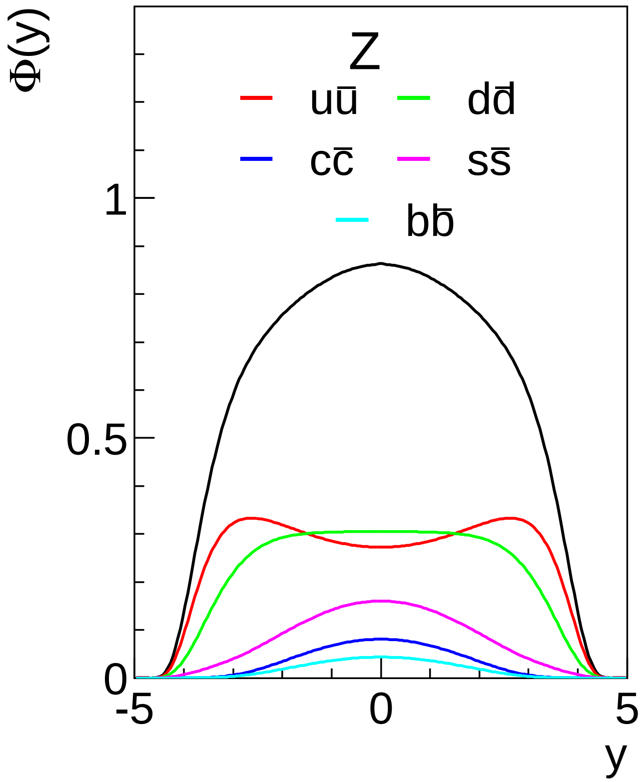
pure $Z$ exchange:

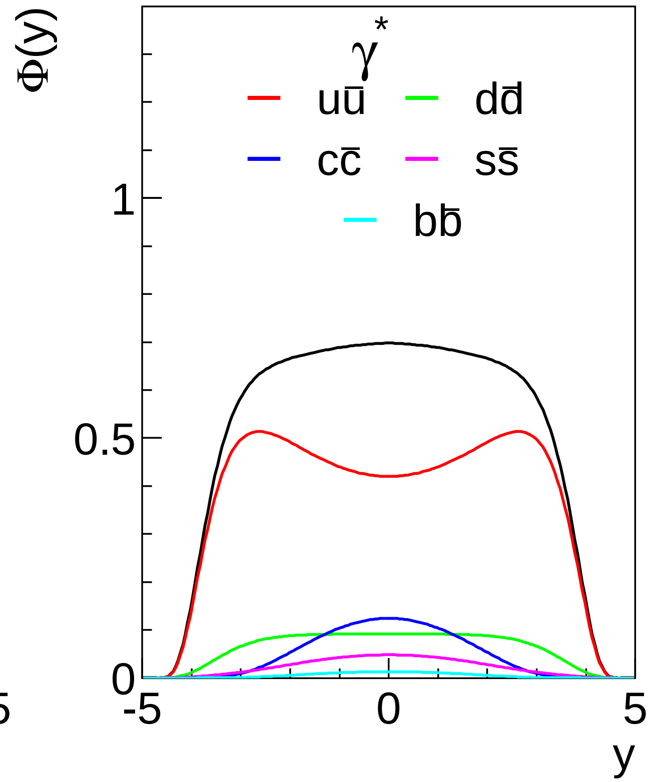
$$P_Z(M_{\ell\ell}) = \frac{k_Z^2(v_e^2 + a_e^2)}{\left(M_{\ell\ell}^2 - M_Z^2\right)^2 + \Gamma_Z^2 M_Z^2},$$

where $k_Z = (4\sin^2\theta_W\cos^2\theta_W)^{-1}$, and $\gamma Z$ interference:

$$P_{\gamma Z}(M_{\ell\ell}) = \frac{k_Z v_e(M_{\ell\ell}^2 - M_Z^2)}{M^2\left[\left(M_{\ell\ell}^2 - M_Z^2\right)^2 + \Gamma_Z^2 M_Z^2\right]},$$

# $Z$ and low(er) mass DY production flavour decomposition



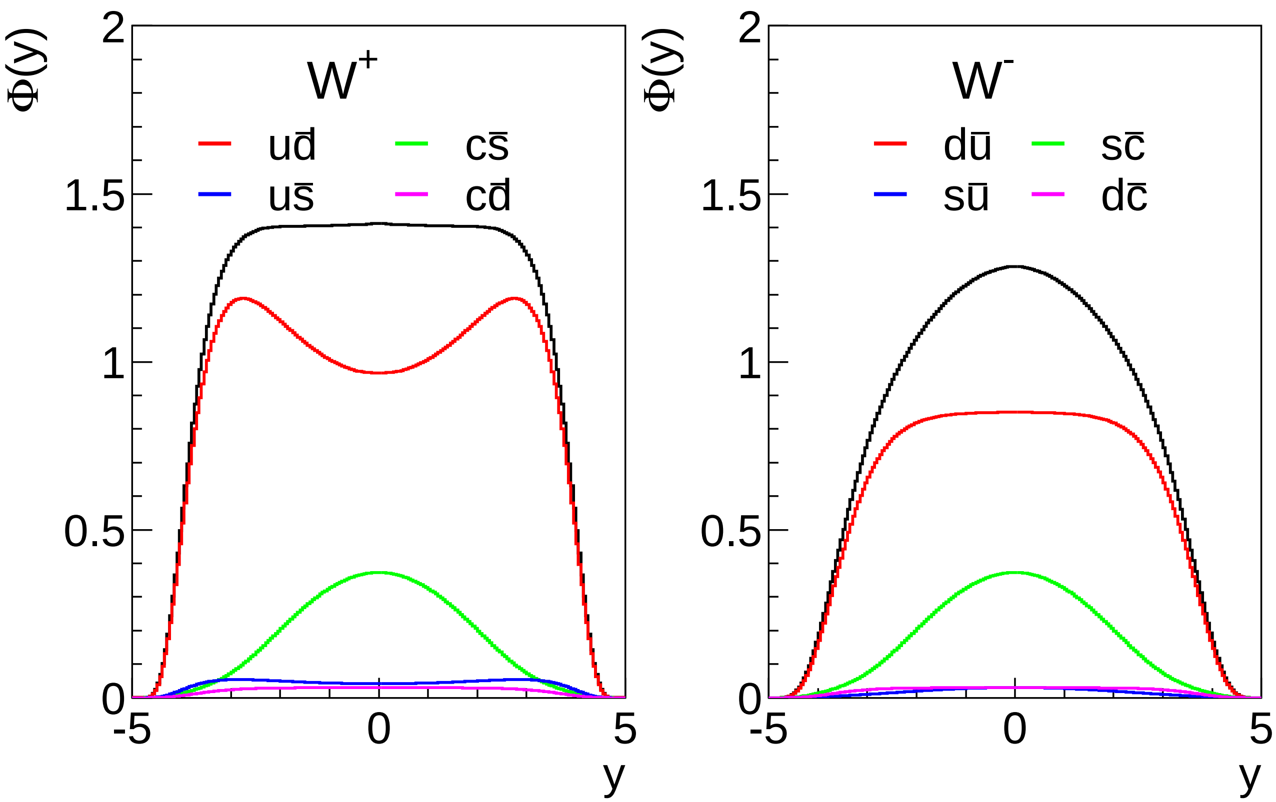

$Z$ vs $\gamma^*$ are sensitive to $U/D$ ratio:

$$Z \quad \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$

$$\gamma^* \quad \sim 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$

Contribution from $\gamma - Z$ interference is small.

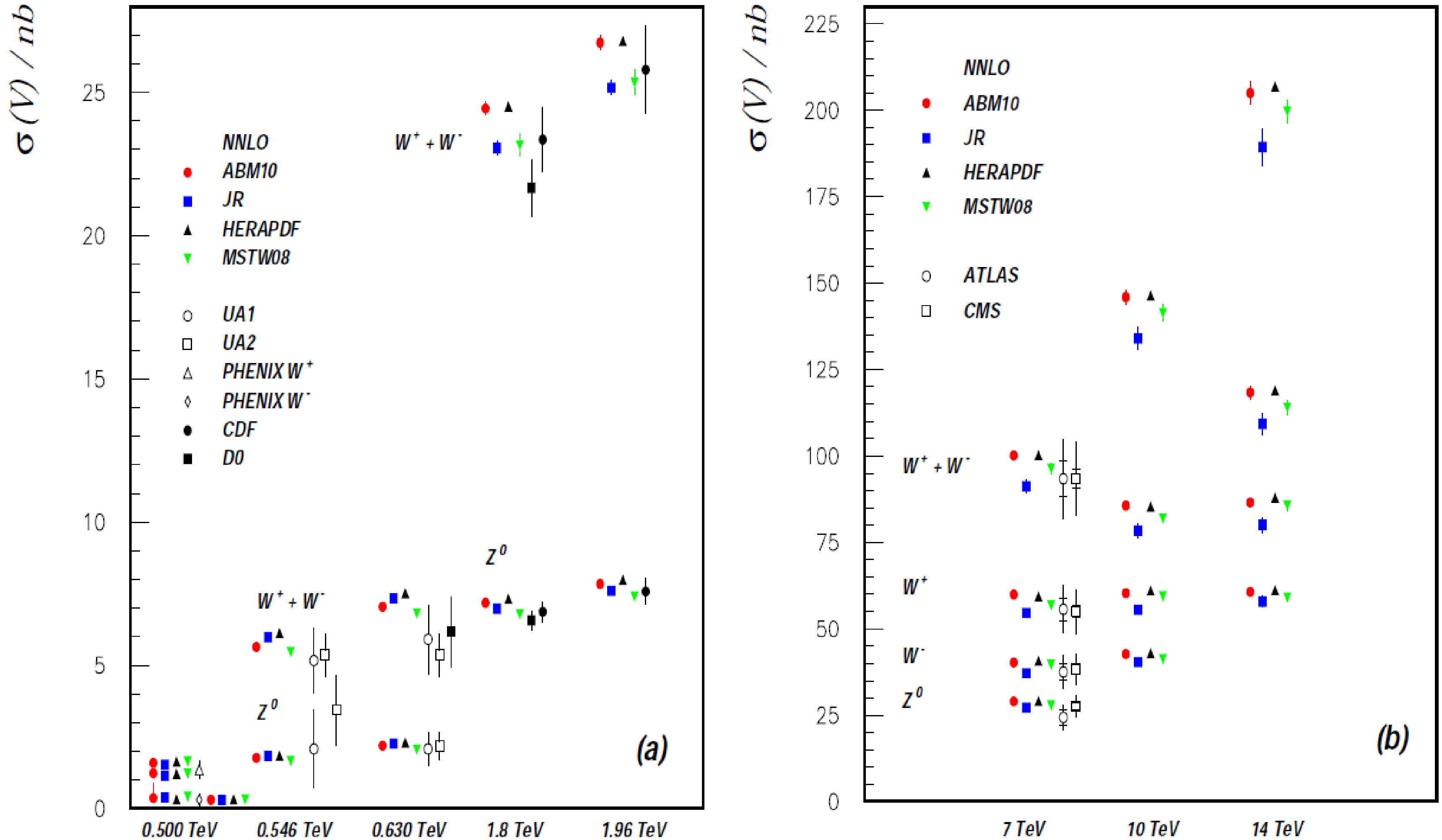
# $W^+$ and $W^-$ production flavour decomposition




$W^+$ ($W^-$) 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:

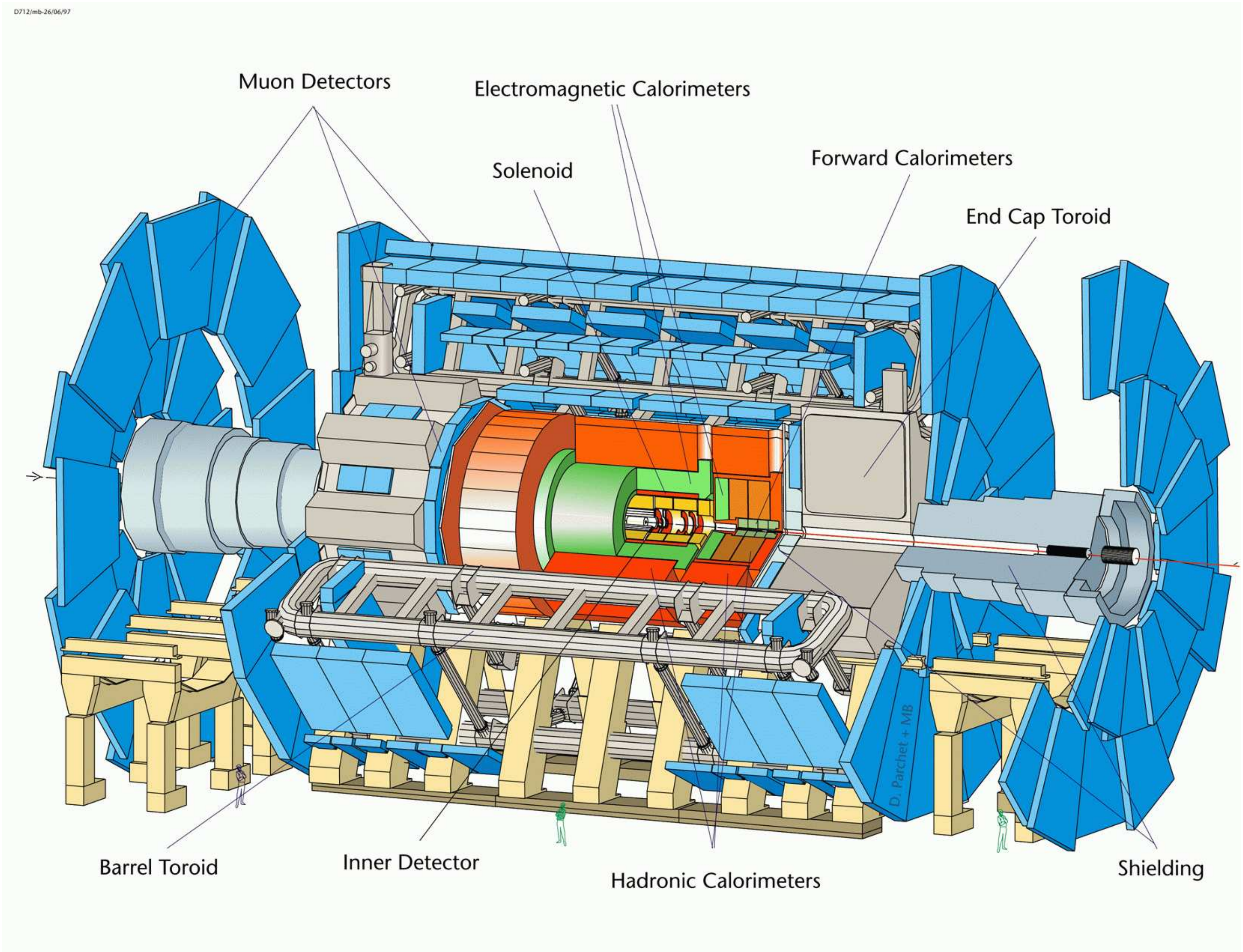
$$W^+ \quad \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$
$$W^- \quad \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

# NNLO Predictions for *W*, *Z* production cross sections

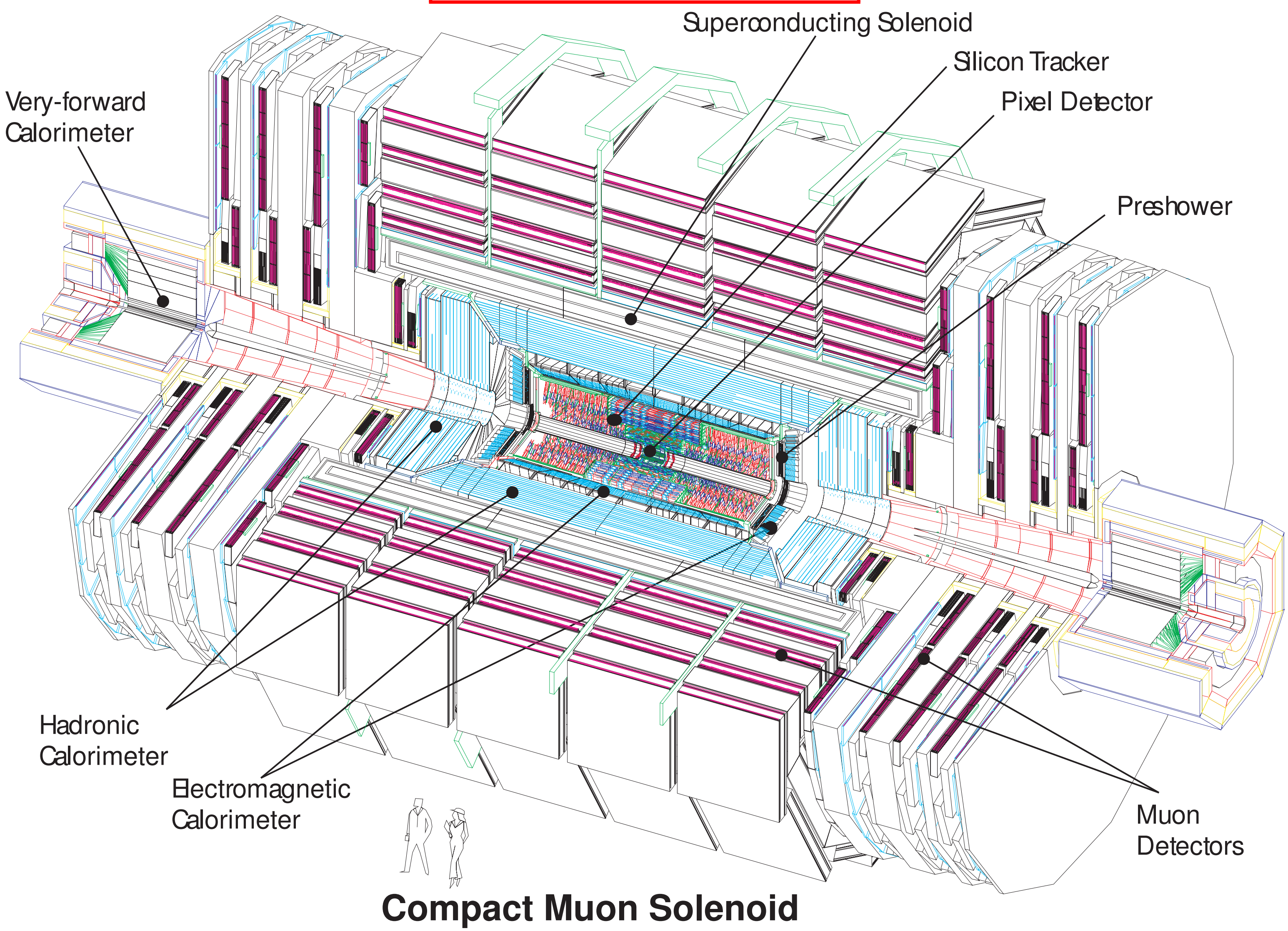



S. Alekhin J Blümlein, P. Jimenez-Delgado, S. Moch, E. Reya,
Phys.Lett.B697:127-135,2011, arXiv:1011.6259.

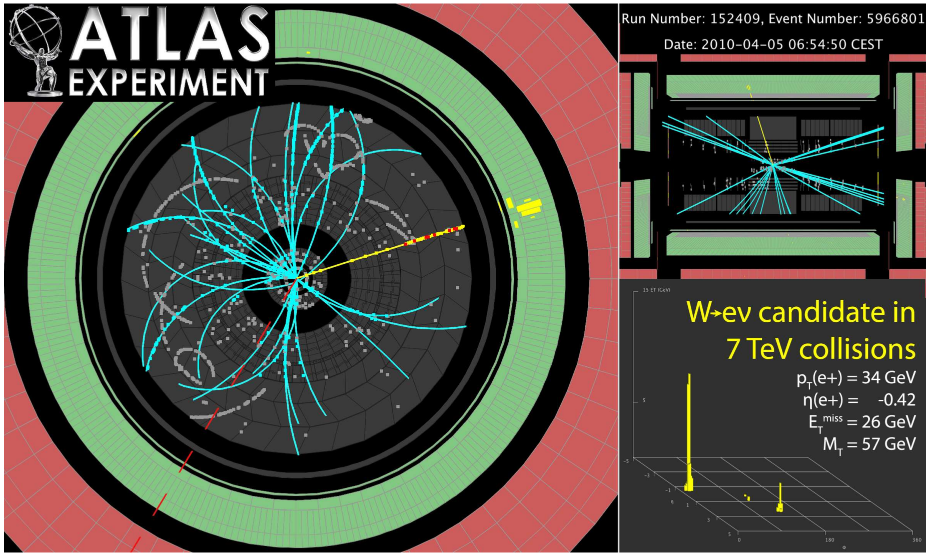
# ATLAS detector



# CMS detector



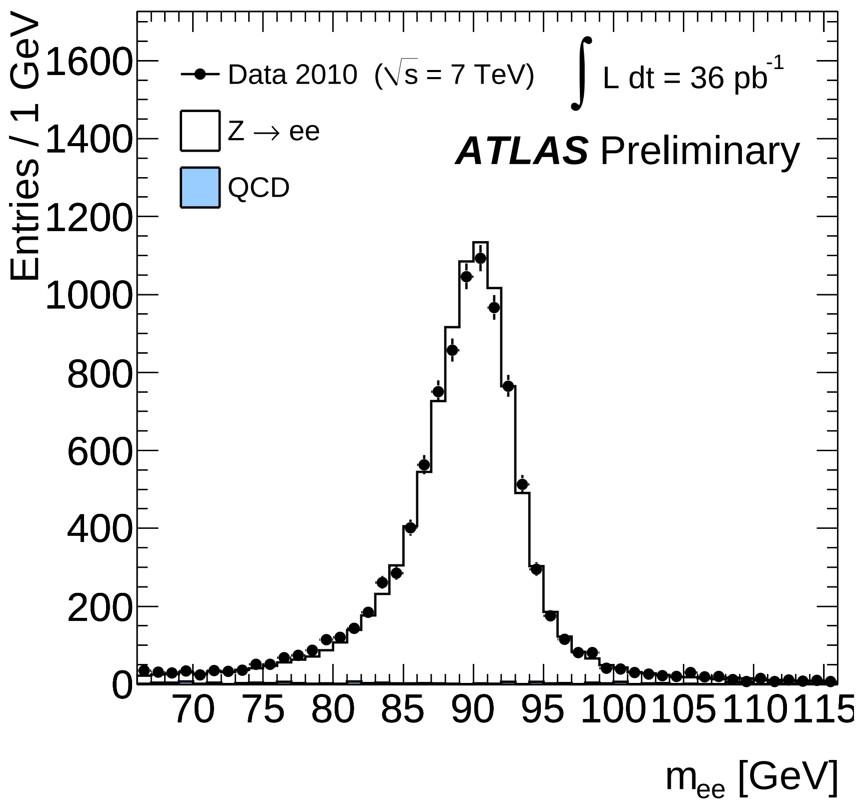
# DY Event Reconstruction/Selection

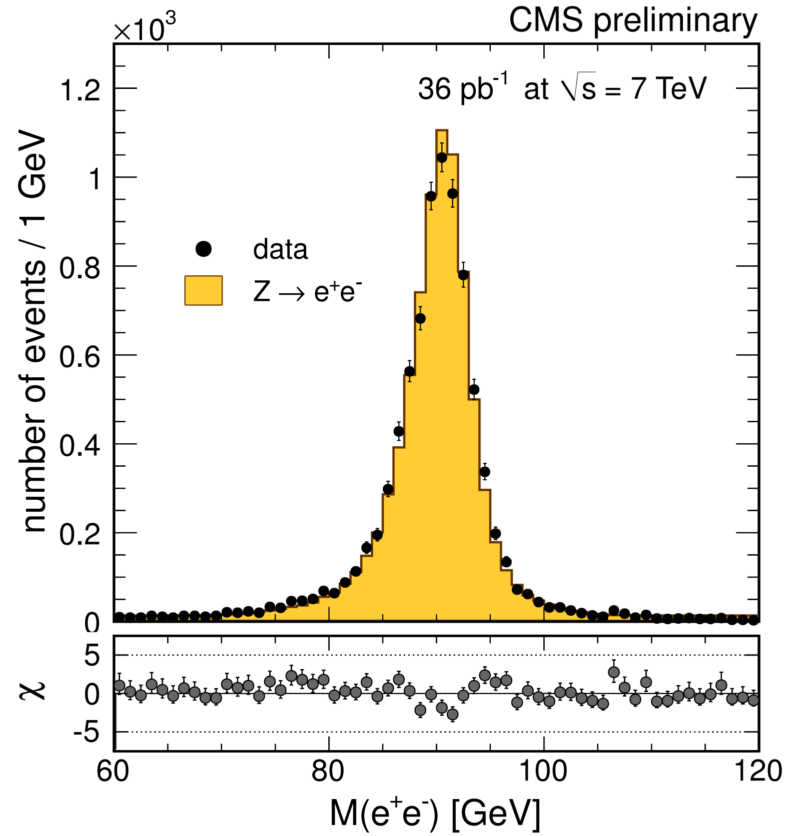



- Electron $E_t$, $\eta$: from calorimeter, inner detector.
- Muon $P_t$, $\eta$: from inner detector, muon system.
- $E_t^{\text{miss}}$: from combined HFS.

| ATLAS | CMS |
|---|---|
| $E_{e,t}, p_{\mu,t} > 20$ GeV<br>$\lvert\eta\rvert < 2.47$, Not $1.37 < \lvert\eta\rvert < 1.52$ (electrons)<br>$\eta < 2.4$ (muons) | $E_{e,t}, p_{\mu,t} > 25$ GeV,<br>$\lvert\eta\rvert < 2.5$ (electrons)<br>$\lvert\eta\rvert < 2.1$ (muons) |
| Extra $W^{\pm}$ selection | |
| Veto extra electrons/muons<br>$E_t^{\text{miss}} > 25$ GeV, $M_t > 40$ GeV | Veto extra electrons/muons |
| Extra $Z$ selection | |
| $66 < M_{\ell\ell} < 116$ GeV | $60 < M_{\ell\ell} < 120$ GeV |

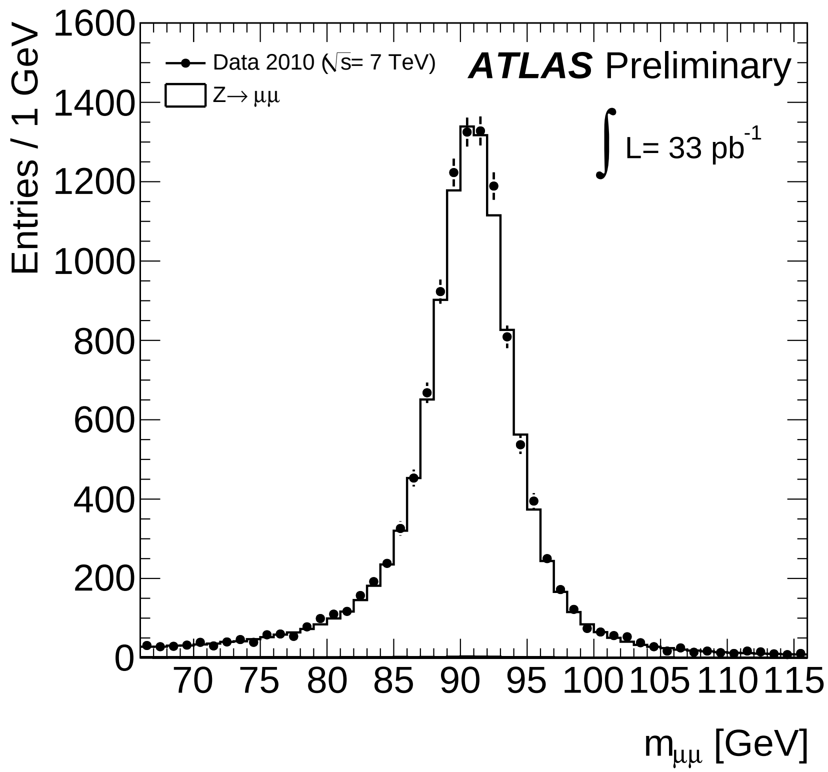
# Reconstruction of Electron(s) — Energy scale

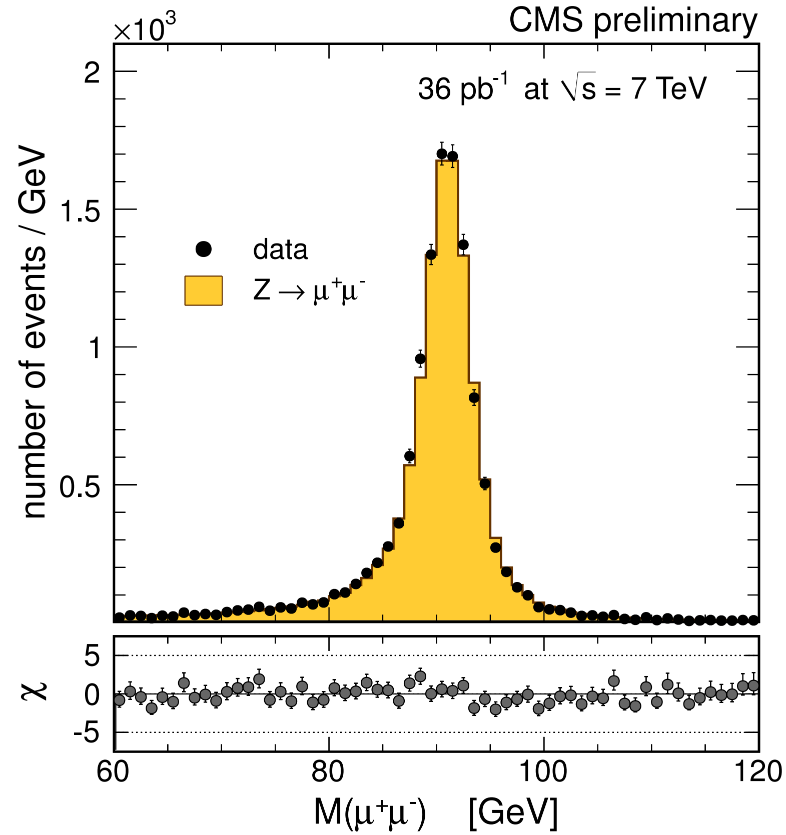



- Energy scale is important to reconstruct event kinematics.
- Calibrated using $Z \to e^+e^-$ events.
- Comparable resolution for ATLAS and CMS detectors.

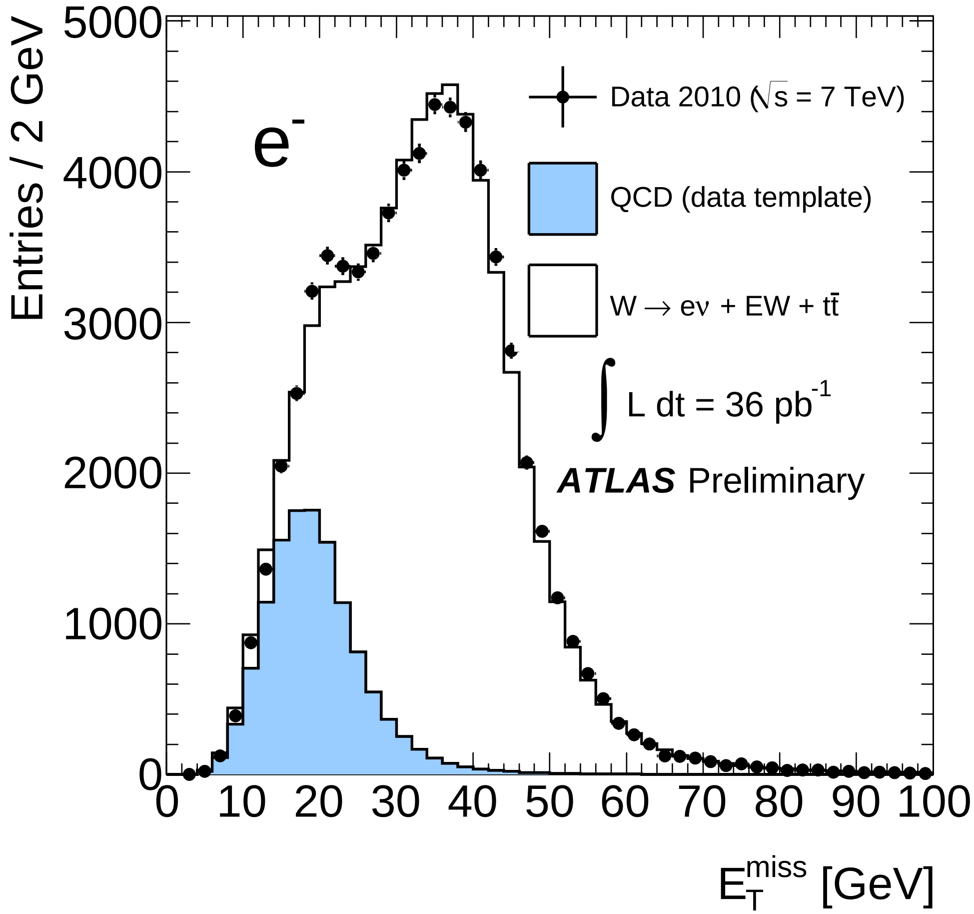
# Reconstruction of Muon(s) — Alignment and $p_t$ scale




- Muon momentum reconstruction critically depends on detector alignment, checked by comparing inner detector/muon system standalone measurements.
- Comparable resolution for ATLAS and CMS detectors.

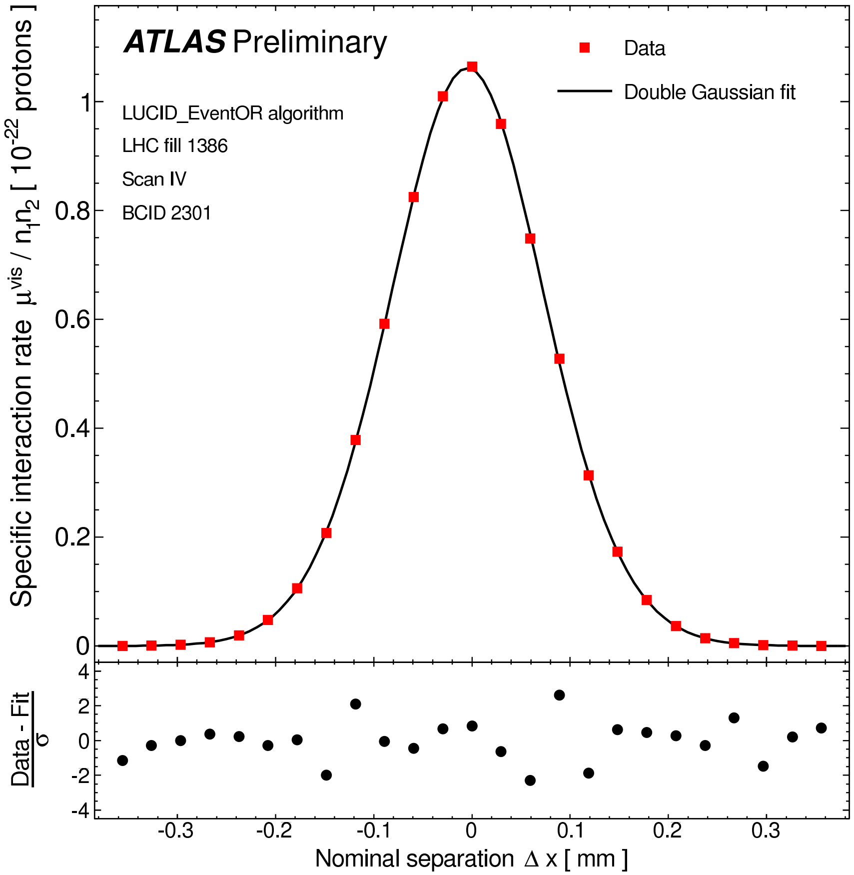
# Background Determination for $W^{\pm} \to \ell^{\pm}\nu$ channels




- Suppress QCD background by lepton identification/isolation cuts.
- Estimate EW background using MC simulation.
- Obtain data tempates for QCD background: revert cuts to obtain pure BG sample.
- Fit data with MC + data driven background template.

After $E_t^{miss} > 25$ GeV cut background level for ATLAS analyses is 4.3% for $W^- \to e^-\nu$, 2.6% for $W^+ \to e^+\nu$ and 1.7% for muon analyses.

# Luminosity Measurement




Determine luminosity from direct measurements of machine parameters:

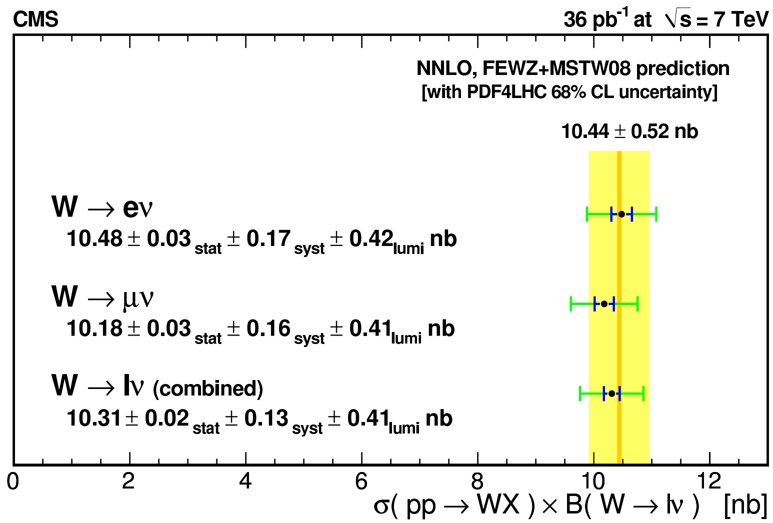
$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y},$$

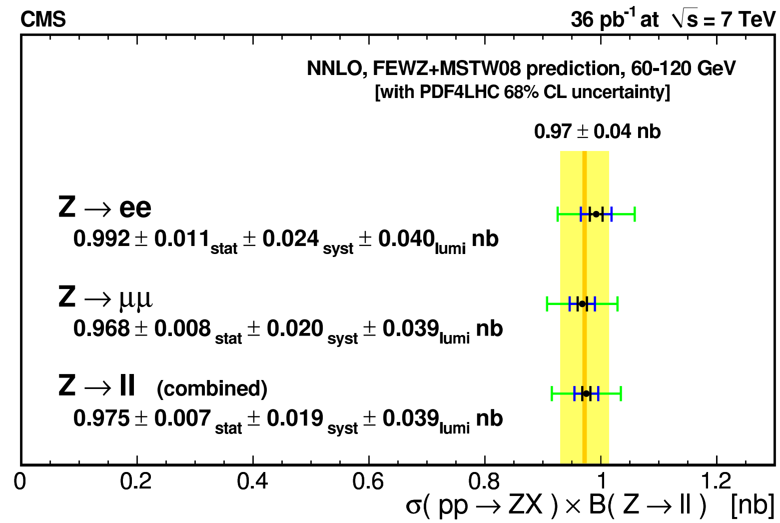
where $n_b$ — number of bunch crossings $n_{1,2}$ — bunch populations, $f_r$ — revolution frequency, $\Sigma_{x,y}$ — horisontal/vertical profiles of the beams.

$n_{1,2}$ are determined from the machine measurement of beam currents, $\Sigma_{x,y}$ — from Van der Meer scans, where distance scale between beams is calibrated by ATLAS primary vertex position reconstruction.

→ Total luminosity uncertainty: 3.4% (ATLAS-CONF-2011-011), 4% (CMS DPS-2011/002).

# $W, Z$ Total cross section measurement




- Perform measurement for $W^+, W^-, W^+ + W^-, Z^0$ for $ee$ and $\mu\mu$ decay channels in the corresponding fiducial volume.
- Extrapolate to the full phase space.
- Assume lepton universality, compare/combine $ee$ and $\mu\mu$ measurements.

For the combination, measurements need to be corrected for the FSR QED radiation.

# Total Cross Section Results

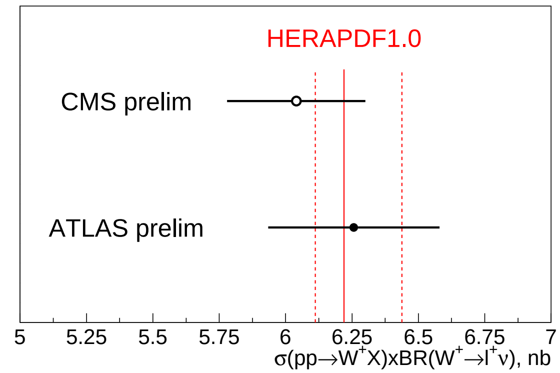
## $W^+$ production

ATLAS: (ATLAS-CONF-2011-041)

$6.257 \pm 0.017_{st} \pm 0.152_{syst} \pm 0.213_{lum} \pm 0.188_{acc}$ nb

CMS: (CMS PAS EWK-10-005)

$6.04 \pm 0.02_{st} \pm 0.06_{syst} \pm 0.24_{lum} \pm 0.08_{th}$ nb



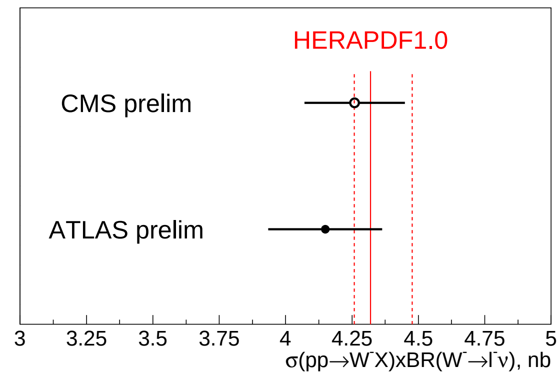

## $W^-$ production

ATLAS:

$4.149 \pm 0.014_{st} \pm 0.102_{syst} \pm 0.141_{lum} \pm 0.124_{acc}$ nb

CMS:

$4.26 \pm 0.01_{st} \pm 0.04_{syst} \pm 0.17_{lum} \pm 0.07_{th}$ nb



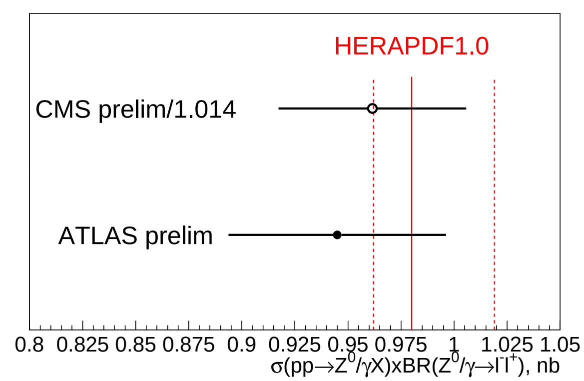

## $Z^0/\gamma$ production

ATLAS for, $66 < m_{\ell\ell} < 116$ GeV:

$0.945 \pm 0.006_{st} \pm 0.011_{syst} \pm 0.032_{lum} \pm 0.038_{acc}$ nb

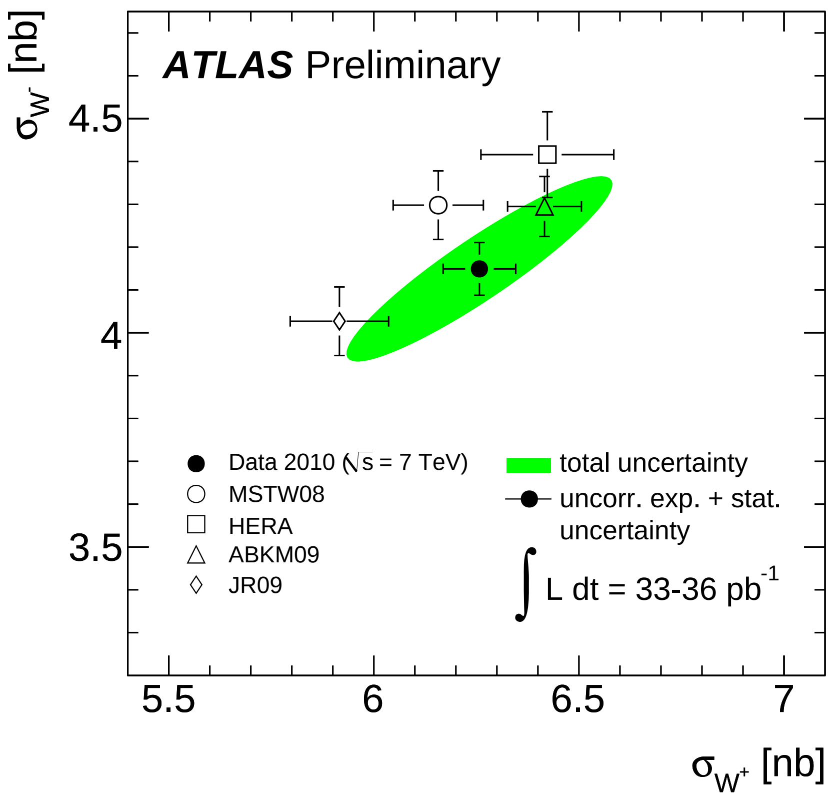
CMS for, $60 < m_{\ell\ell} < 120$ GeV:

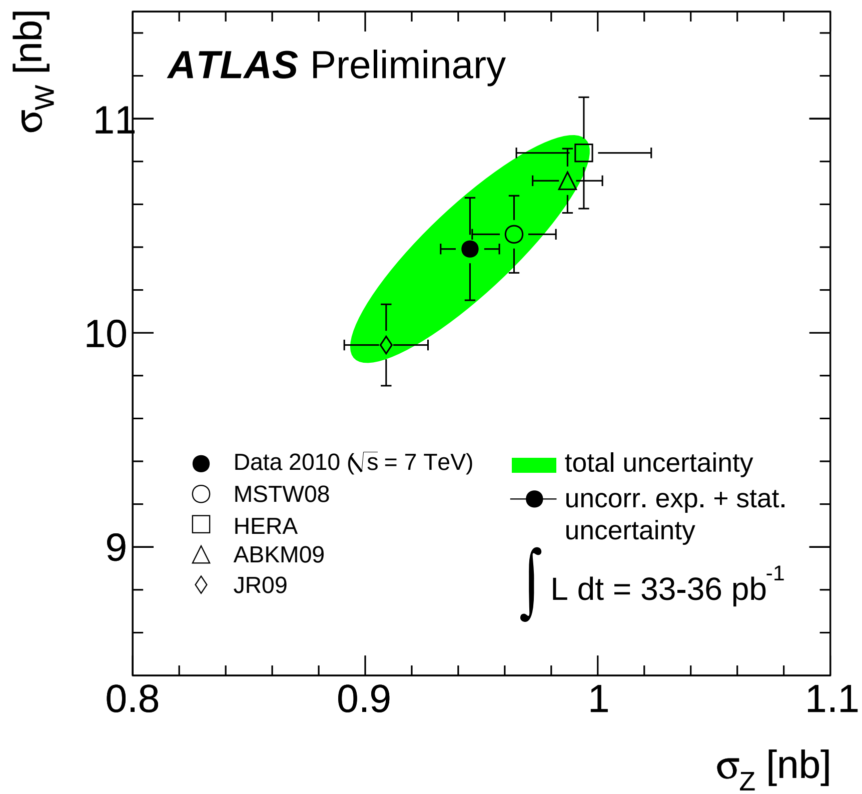
$0.975 \pm 0.007_{st} \pm 0.007_{syst} \pm 0.039_{lum} \pm 0.018_{th}$ nb




HERAPDF1.0: based on NLO PDF4LHC calculation, from arXiv:1101.0536

# $W, Z$ Total cross section correlations

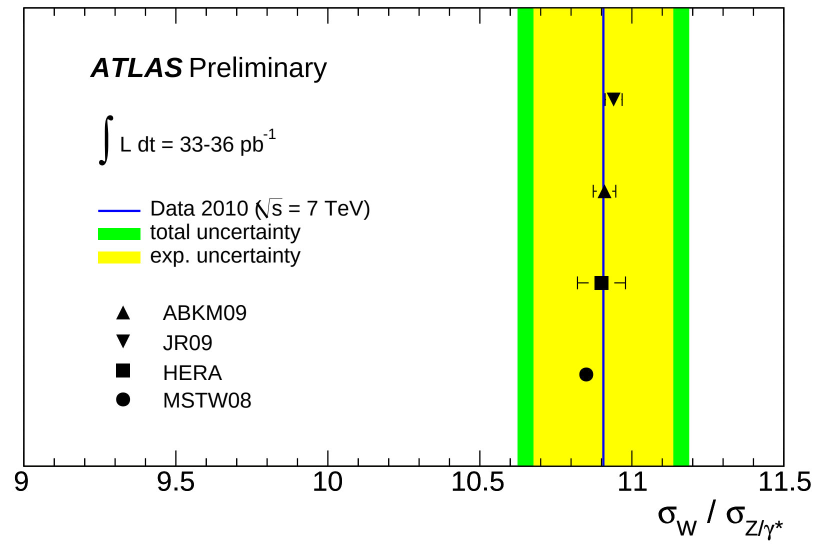


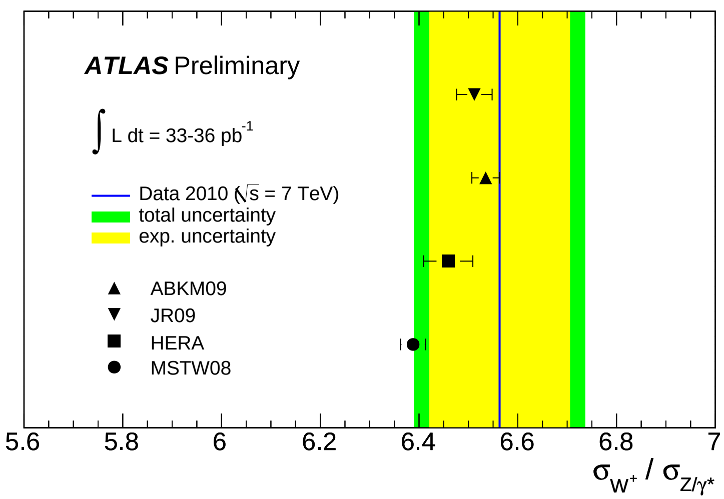



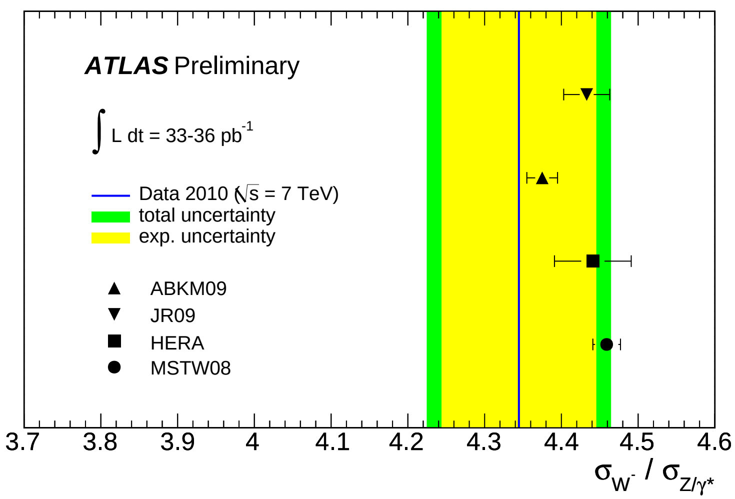

- Large correlation between uncertainties because of the dominant common luminosity error.
- Study correlation between measuremetns, compare to predictions calculated using FEWZ at NNLO.

# Ratios of $W, Z$ cross sections

Correlation due to lumi cancels in the ratio of the cross sections. For $\sigma_W/\sigma_Z$ PDF errors are reduced. (CMS result corrected to $66 \leq M_{\ell\ell} \leq 116$ GeV is $\sigma_W/\sigma_Z = 10.69 \pm 0.07_{\mathrm{stat}} \pm 0.18_{\mathrm{syst}}$). Ratios $\sigma_{W^+}/\sigma_Z$ and $\sigma_{W^-}/\sigma_Z$ are sensitive to $u/d$ at $x \sim 0.01$.



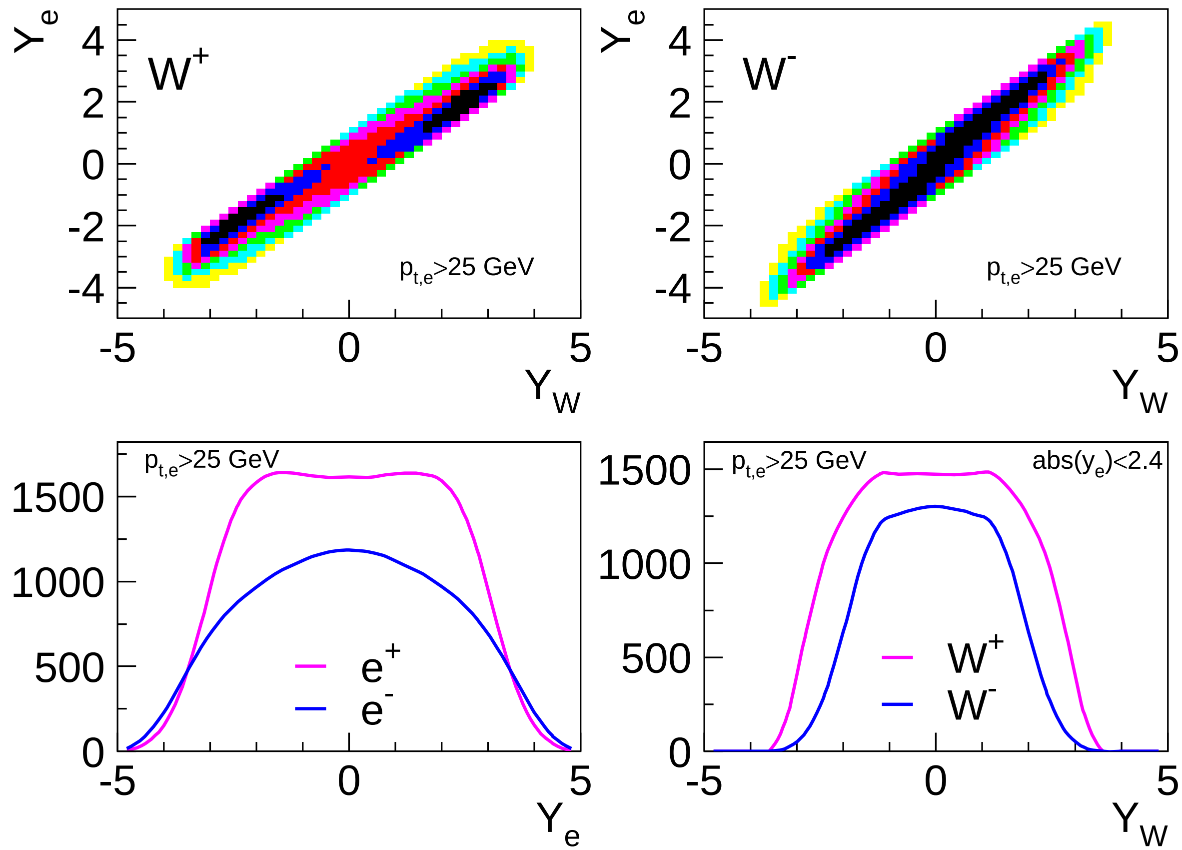



# Lepton charge asymmetry for $W^\pm \to \ell^\pm \nu$ decays

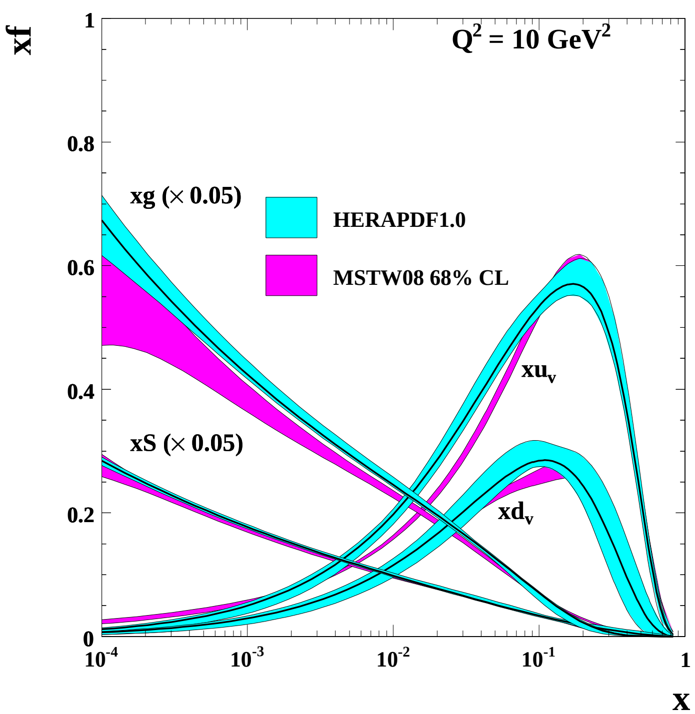
Master formula:

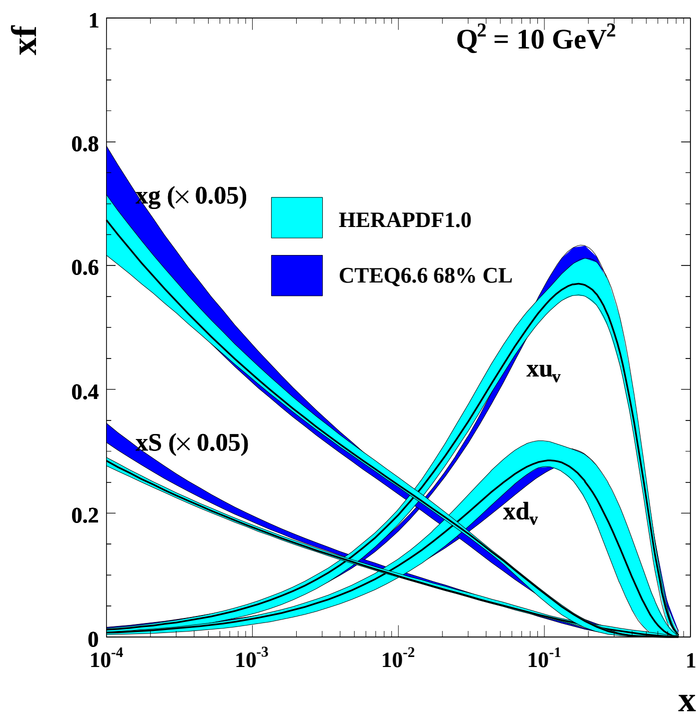
$$\mathcal{A}(\eta_\ell) = \frac{d\sigma_{W^+}/d\eta_{\ell^+} - d\sigma_{W^-}/d\eta_{\ell^-}}{d\sigma_{W^+}/d\eta_{\ell^+} + d\sigma_{W^-}/d\eta_{\ell^-}}$$

- Measured in fiducial volume (different for ATLAS and CMS).
- V-A structure of $W^\pm$ decays affects rapidity distribution of the lepton vs the boson. $W$ polarisation affects decay distributions as well.



# Valence quarks at low $x$



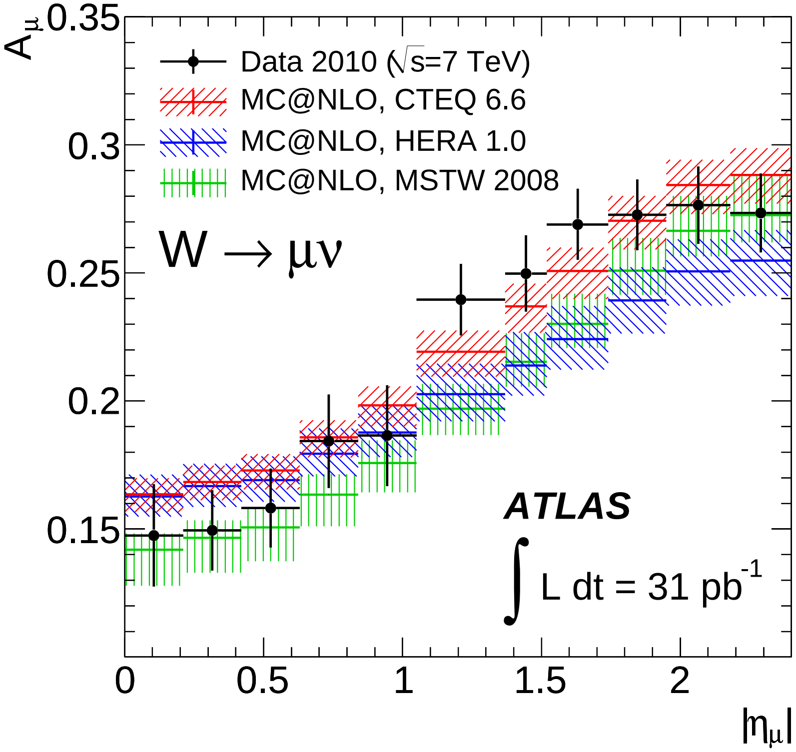



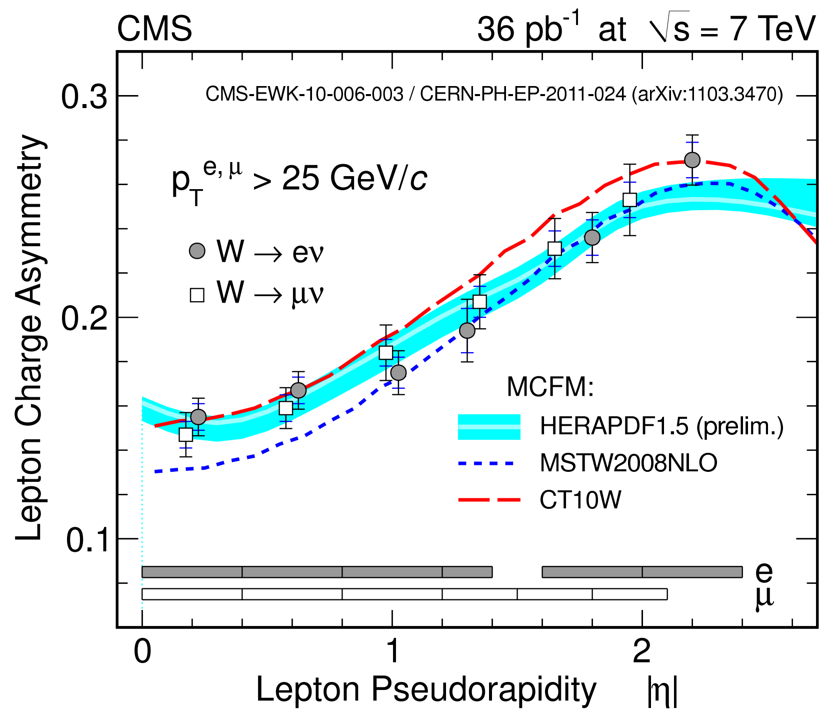

Significant differences between valence quark densities from different PDF groups. Assuming $\bar{u} \approx \bar{d}$, $W^{\pm}$ asymmetry is given by

$$\mathcal{A} \approx \frac{u_v - d_v}{u + d}$$

Discrepancy at $x = 0.01$ corresponds to $y_W = 0$ for $s = 7$ TeV.

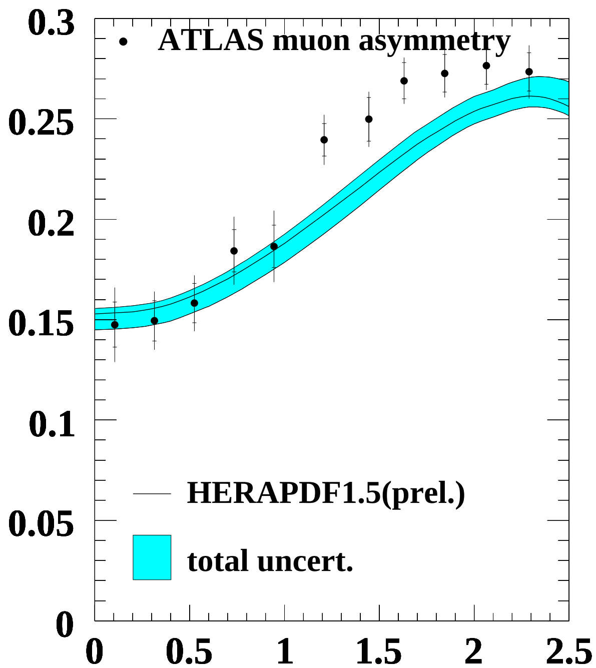
# Measurement of the lepton asymmetry



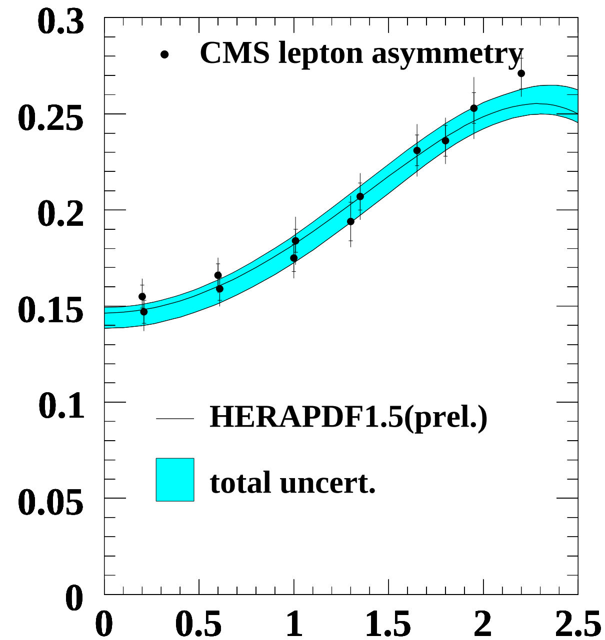




- ATLAS measurement (arXiv:1103.2929) uses $\mu\nu$ decay channel only, CMS (arXiv:1103.3470) provides both $e\nu$ and $\mu\nu$ channel results.
- Large spread in theory predictions is due to differences in $d_v/u_v$ at low $x$.
- CTEQ6.6 describes ATLAS data the best while CMS favours HERAPDF1.5.

# ATLAS and CMS $W$ Lepton Asymmetry




$P_{t,e} > 20$ GeV, $P_{t,miss} > 25$ GeV

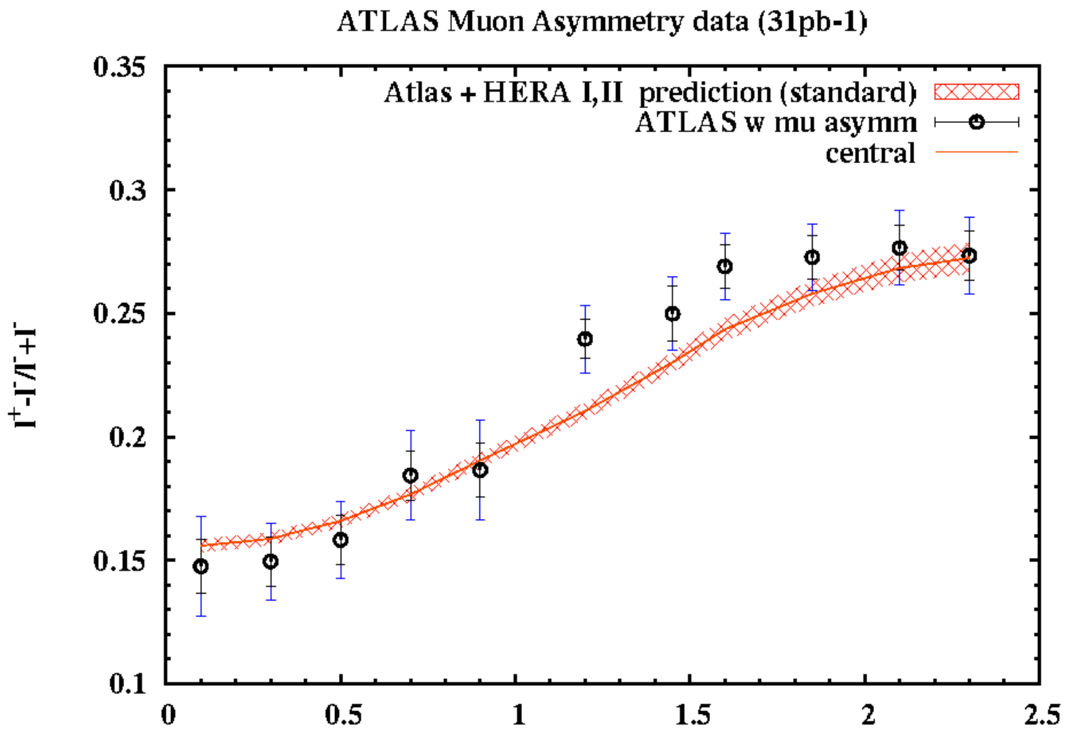



$P_{t,e} > 25$ GeV

- LO fits with $k$-factors calculated using MCFM, taking into account different cuts.
- HERAPDF1.5 provides good fit to CMS data with $\chi^2/dof = 6.5/12$ and not so good to ATLAS with $\chi^2/dof = 30/11$.

(A. Cooper-Sarkar, S. Glazov, V. Radescu, A. Sapronov, S. Whitehead.)

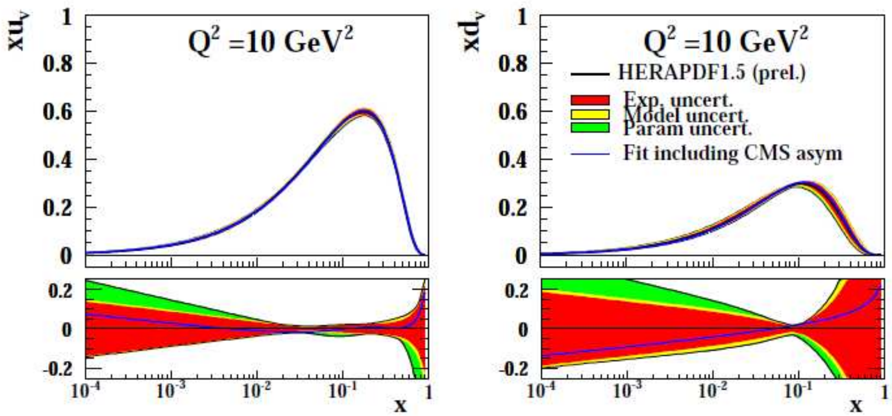
# Fit to ATLAS *W* asymmetry data




- 14 parameters fit, 6 free parameters for valence quarks, reasonable description of ATLAS asymmetry shape, partial $\chi^2/dof = 16/11$.
- Uncertainty estimated using MC method.

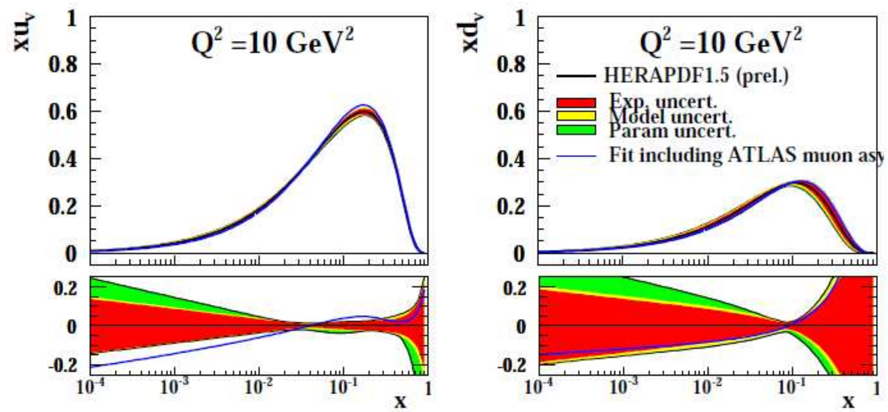
(A. Cooper-Sarkar, S. Glazov, V. Radescu, A. Sapronov, S. Whitehead.)

# Fits with LHC $W$ asymmetry data




CMS data keep the central line within HERAPDF1.5 error band, $\chi^2/dof = 3.7/12$ is extremely good.

For ATLAS data fit is pulled somewhat outside the bands, the $\chi^2/dof = 16/11$ is Ok.

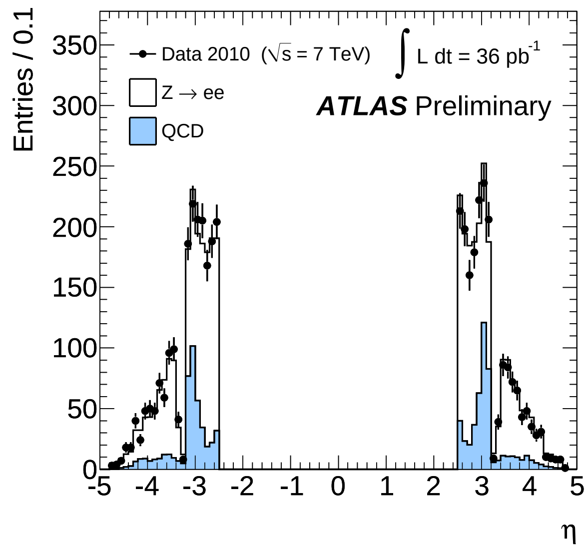


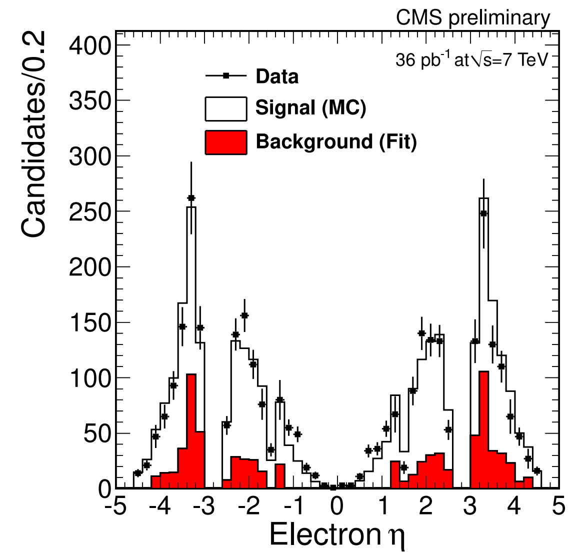

ATLAS and CMS pull $u_v$ in opposite direction.

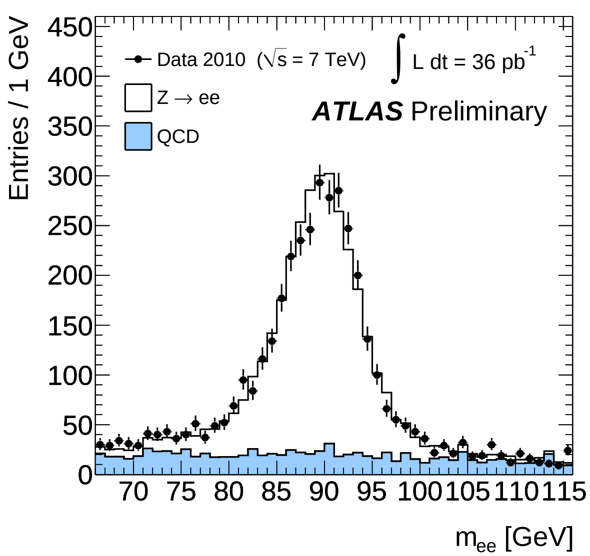
(A. Cooper-Sarkar, S. Glazov, V. Radescu, A. Sapronov, S. Whitehead.)

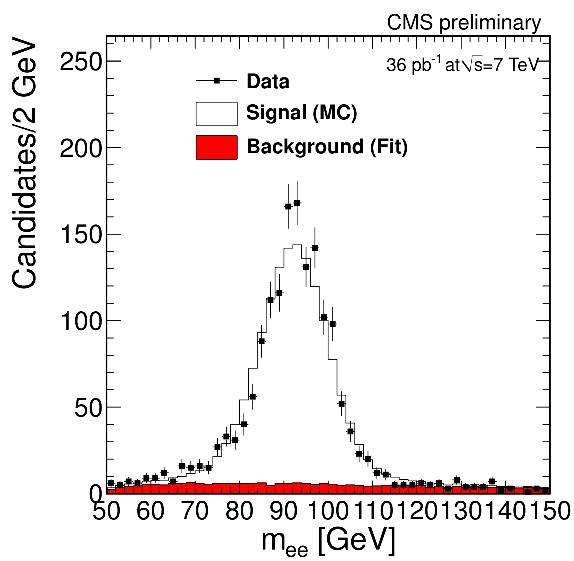
# Moving forward

Extend measurement of the *Z* boson rapidity by measuring one of the electrons in the forward calorimeter (FCAL for ATLAS, HF for CMS).



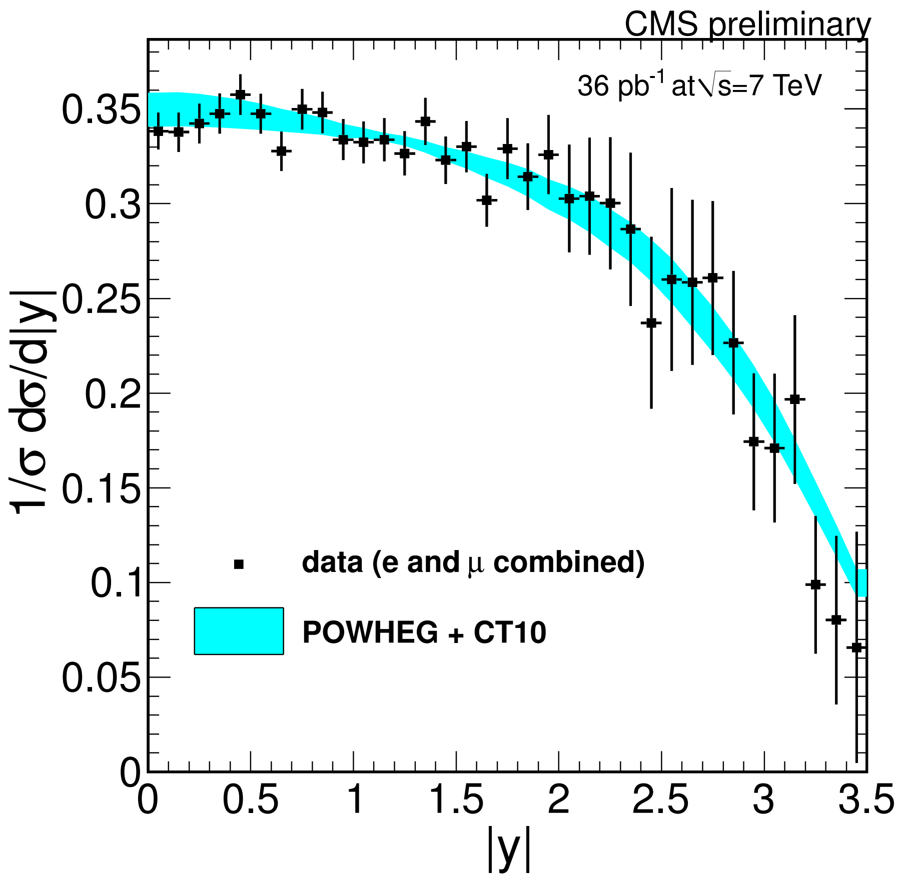




Looser electron identification leads to increased background. However, it is well under control.

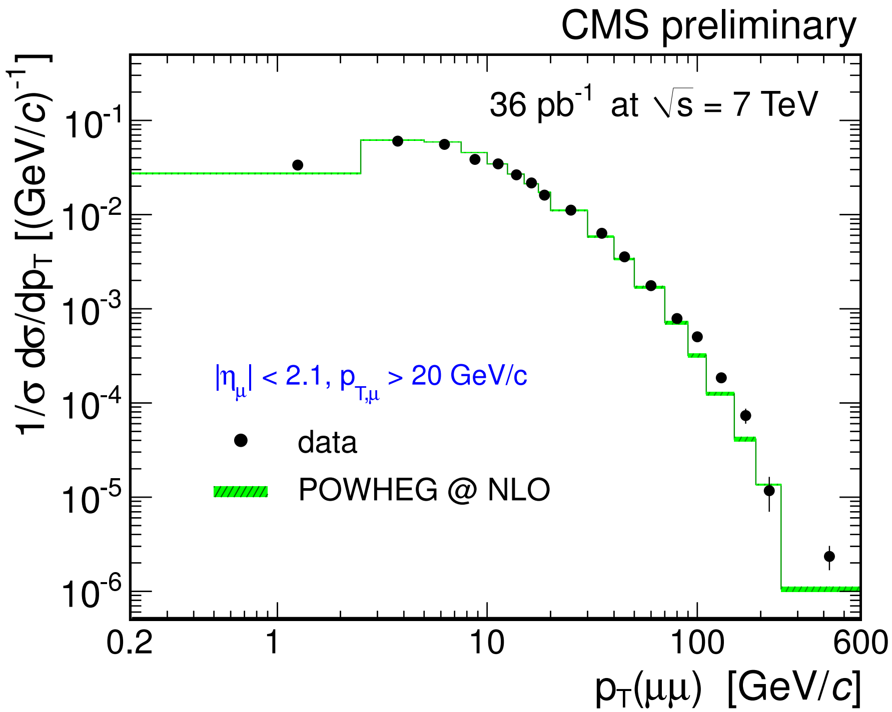
# $Z$ rapidity distribution measurement




Measurement of $1/\sigma d\sigma/dy_Z$ provides a constraint on PDFs:

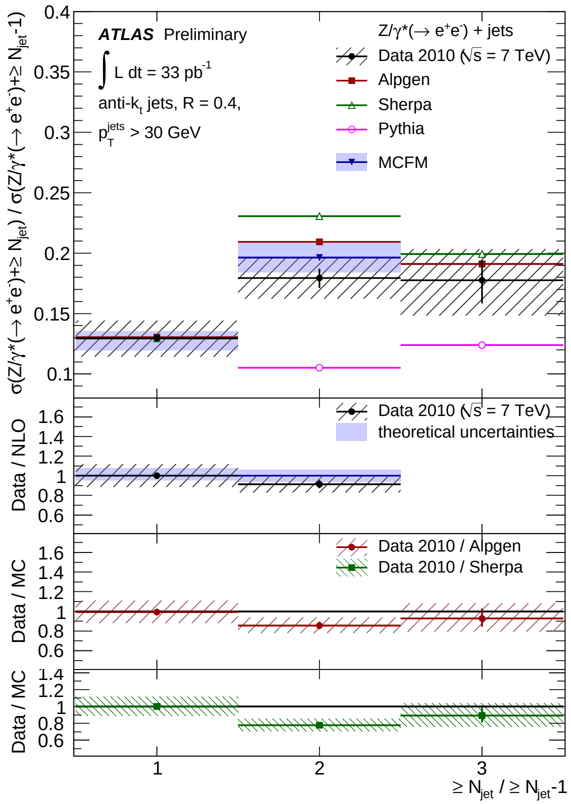
- $Z$ production is more sensitive to $d$-quarks compared to $F_2$ from HERA
- $y = 0$ corresponds to $x_{1,2} \sim 0.01$ and $y = 3$ to $x_1 = 0.3$, $x_2 = 6 \times 10^{-4}$.

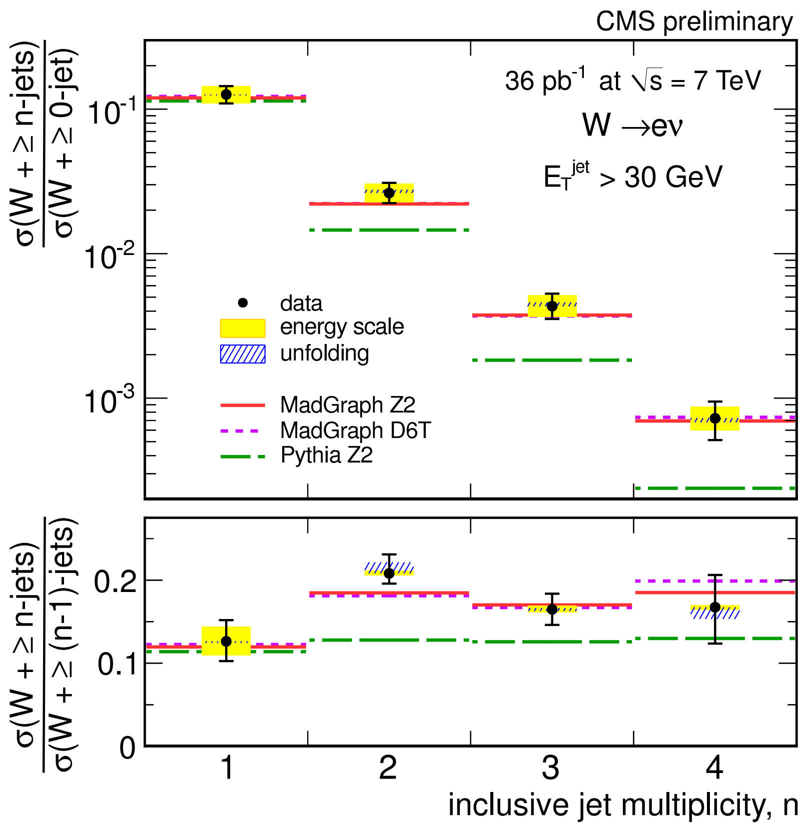
# Measurement of $Z$ $p_t$ distribution




- Measurement of $1/\sigma d\sigma/dp_{t,Z}$ provides a clean experimental signature to study hadronic recoil without need to reconstruct jets.
- Significant resummation effects for $p_t < 20$ GeV, included in RESBOS, NNLO QCD calculations (FEWZ) for higher $p_t$.
- Used to tune MC generators: LO PYTHIA, SHERPA, ALPGEN and NLO MCNLO, POWHEG.

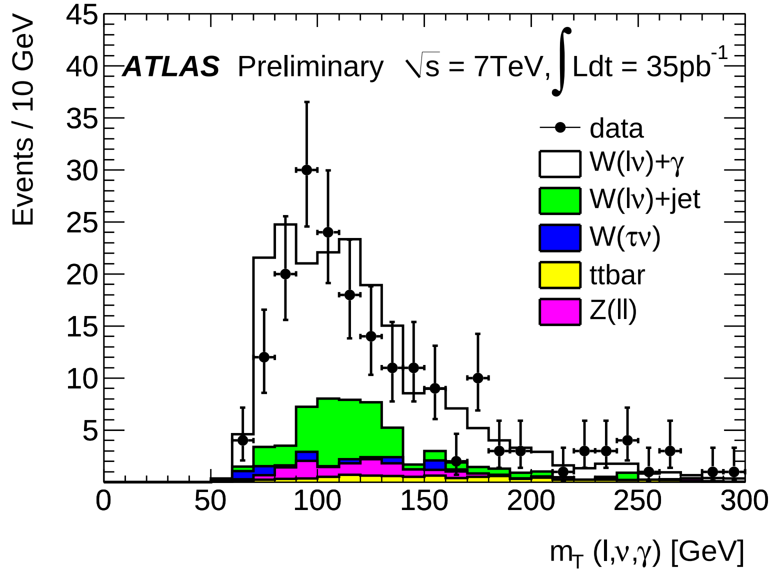
# Beyond inclusive measurements: $W, Z(\gamma)$+jets

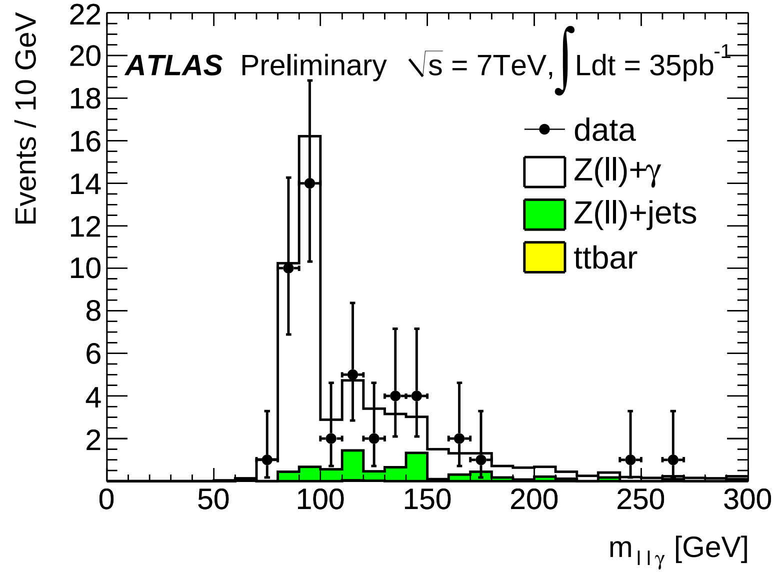



- *W, Z*+N jet production measurements by ATLAS (arXiv:1012.5382,ATLAS-CONF-2011-042) and CMS (CMS-PAS-EWK-10-012).
- Sensitive to higher order QCD effects, PDFs. Check of MC tunes.
- Good description of $\sigma_N/\sigma_{N-1}$ jet cross section by MCFM, MadGraph.

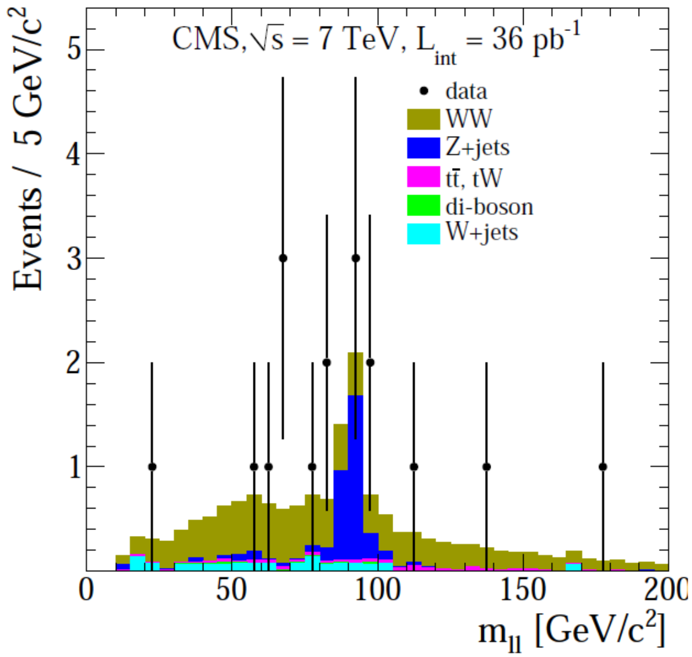
# Towards di-boson production: $W, Z + \gamma$

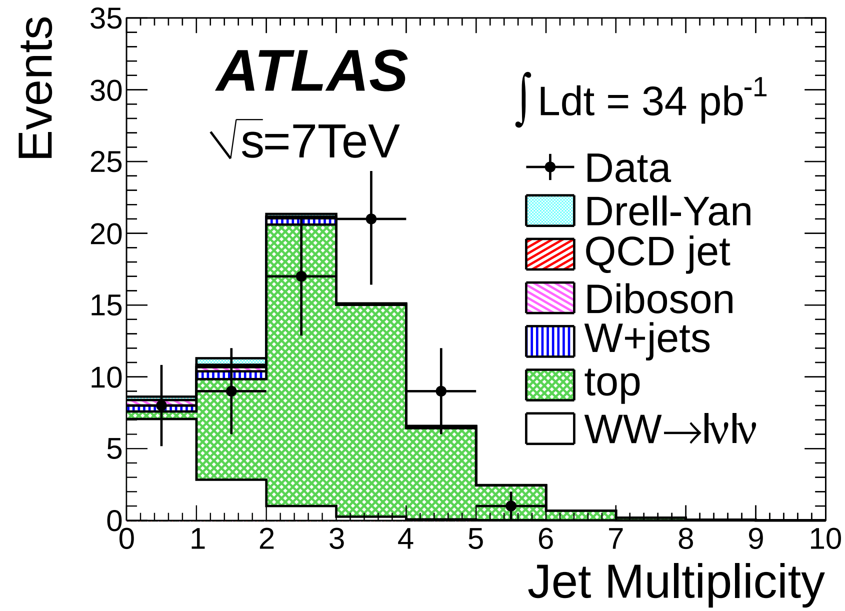



- Both ATLAS (ATLAS-CONF-2011-013) and CMS (CMS EWK-10-008) perform measurements of $W + \gamma$ and $Z + \gamma$ processes.
- Require an isolated photon with $E_{t,\gamma} > 15$ GeV (ATLAS) $E_T > 10$ GeV (CMS)
- Sensitive to anomalous $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ triple gauge couplings.
- Provides a check of hard FSR radiation simulation.

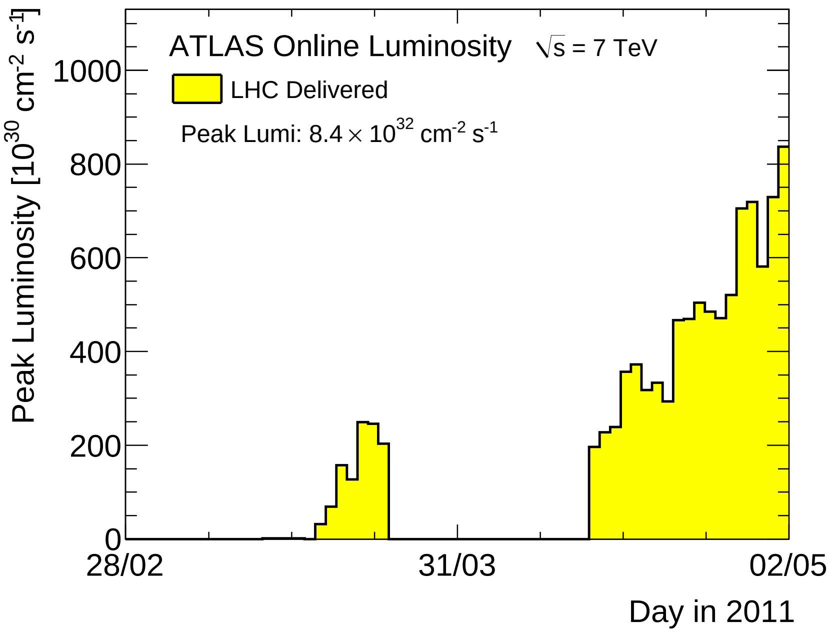
# $W^+W^-$ production

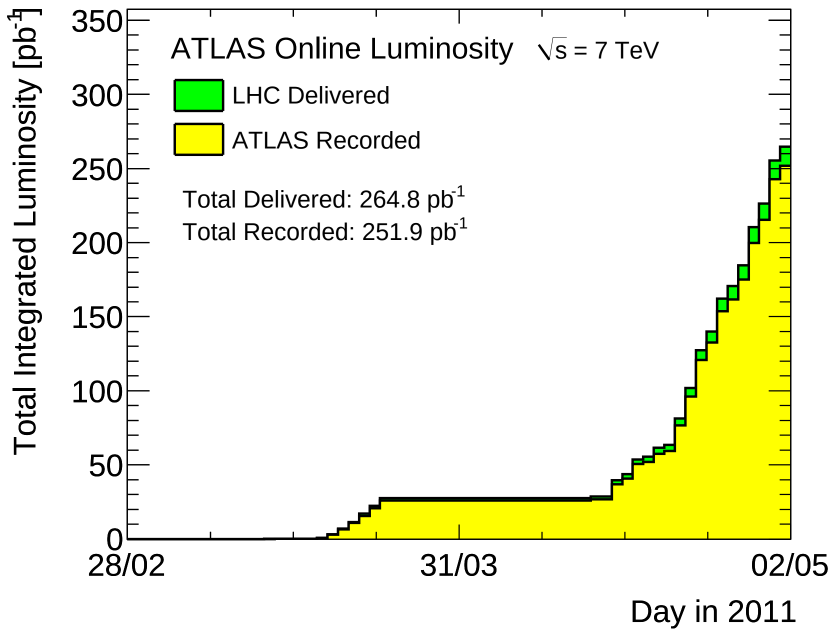



- Measurement of $W^+W^-$ using $e^+\nu e^-\nu$, $e^+\nu\mu^-\nu$ and $e^\pm\nu\mu^\mp\nu$ modes.
- Background from $Z \to \ell\ell$ suppressed by $E_t^{\text{miss}}$ requirement, background from $t\bar{t}$ by jet multiplicity veto.
- CMS observes 13 events with background of 3.3(1.2) (arXiv:1102.5429), ATLAS observes 8 events with background of 1.7(0.56)(arXiv:1104.5225). The cross section measurements by CMS, $\sigma_{W^+W^-} = 41.1 \pm 15(\text{stat.}) \pm 5.8(\text{syst.}) \pm 4.5(\text{lumi.})$ and ATLAS, $\sigma_{W^+W^-} = 41^{+20}_{-16}(\text{stat.}) \pm 5(\text{syst.}) \pm 1(\text{lumi.})$ are consistent with SM.

# Performance of the LHC in 2011




- Rapid increased of the instanteneous luminosity after shutdown
- Peak luminosity reached $8.4 \times 10^{32}$ cm$^{-2}$s$^{-1}$, exceeding previous Tevatron record.
- Total accumulated luminosity in 2011 already exceeds 2010 yield by factor 6.

# Conclusions and Outlook

- Successful start of the LHC operation with a lot of data for the ATLAS and CMS experiments.
- Rediscovery of the Standard Model electroweak physics, with remarkable accuracy: excellent agreement between the data and expectations; data precision is comparable to the PDF uncertainties and requires NNLO calculations.
- Rapid increase of accumulated luminosity should allow for improved accuracy for inclusive $W, Z$ measurements, rediscover new EW channels: $WZ$, $ZZ$.