Differential W/Z distributions I: Angles and mass

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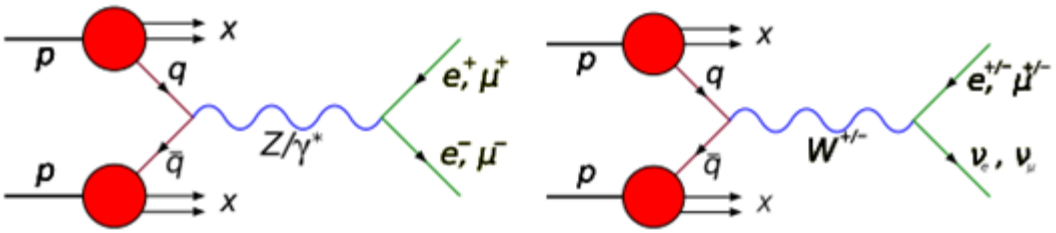
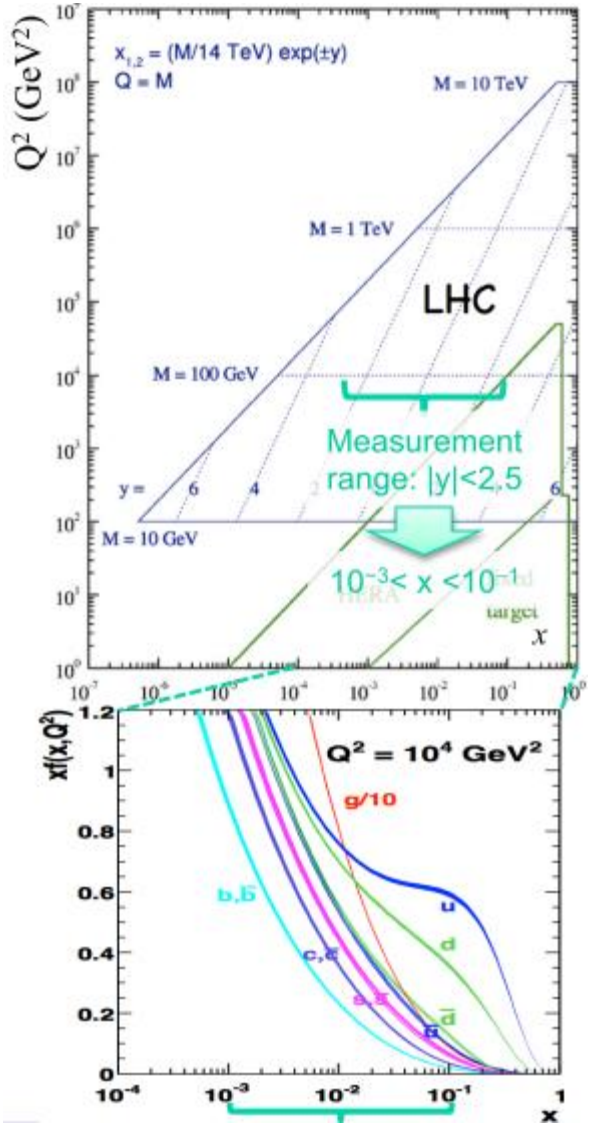
SM@LHC, April 8-11 2014

W and Z production at the LHC

- W and Z production in pp collisions proceeds mainly from scattering of valence quark with a sea anti-quark
- The involved parton fractions are low ($10^{-3} < x < 10^{-1}$) and scattering of a sea quark with a sea anti-quark is also important
- W production is charge asymmetric: $\sigma(W^+)/\sigma(W^-)\sim1.43$ (< 2 , as from valcente + sea only) in the Standard Model
- W and Z events produce very clean signals and allow to perform precision measurements
  - Large background control samples are available in data and reduce the need to rely on simulations
- Accurate theoretical predictions are available
  - NLO event generators: POWHEG and MC@NLO
  - NNLO cross section and differential distributions: FEWZ, RESBOS
  - Uncertainties in valence and sea PDF limit the accuracy of theoretical predictions
- Differential distributions are sensitive to PDF
- LHCb acceptance provides complementary information to CMS and ATLAS



$$Q^2 = m^2_{W,Z} = x_1 x_2 s$$



Angles and mass: the LHC grand menu

- W Polarization
  - ATLAS: Polarisation of W bosons produced at large momentum transfer [Eur. Phys. J. C72 (2012) 2001]
  - CMS: Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC [Phys.Rev.Lett.107:021802,2011]

- Differential DY mass cross sections
  - CMS: Measurement of the differential and double-differential Drell-Yan cross sections in proton-proton collisions at sqrt(s) = 7 TeV [JHEP 12 (2013) 030]
  - ATLAS: Measurement of the high-mass Drell-Yan differential cross-section in pp collisions at sqrt(s)=7 TeV [arXiv:1305.4192, submitted to PLB]
  - ATLAS: Measurement of the low-mass Drell-Yan differential cross section at sqrt(s)=7 [arXiv:1404.1212, submitted to JHEP]
  - LHCb: Inclusive low mass Drell-Yan production in the forward region at √s = 7 TeV [LHCb-CONF-2012-013]

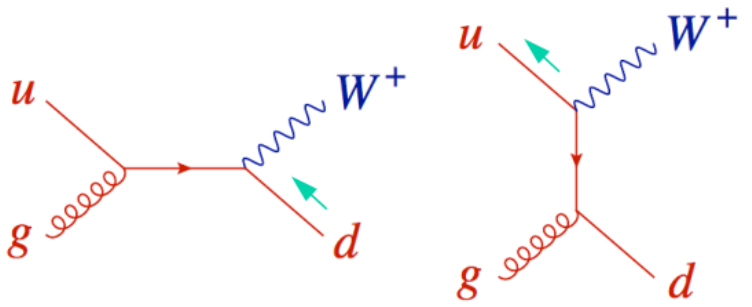
- Forward-backward asymmetry and Weak Mixing angle
  - CMS: Drell-Yan differential forward-backward asymmetry at 7 TeV [Phys. Lett. B 718 (2013) 752]
  - CMS: Measurement of the weak mixing angle with the Drell-Yan process in proton-proton collisions at the LHC [Phys. Rev. D 84, 112002 (2011)]
  - ATLAS: Measurement of the forward-backward asymmetry of Z/gamma* bosons decaying into electron or muon pairs with the ATLAS detector at sqrt(s) = 7 TeV [CONF-2013-043]

W polarization

- V-A W-quark coupling imposes L-polarized quarks (m~0), high W pT imply large W fL, the exact value depending on amounts of different contributions

$$\frac{d\Gamma}{\Gamma d\cos\theta^*} = \frac{3}{8}\left[f_R(1+\cos\theta^*)^2 + f_L(1-\cos\theta^*)^2\right] + \frac{3}{4}f_0\sin^2\theta^*$$

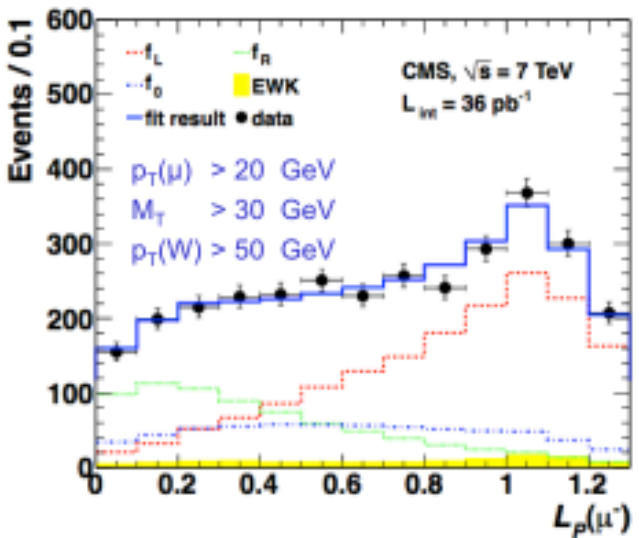
$$f_R + f_L + f_0 = 1$$

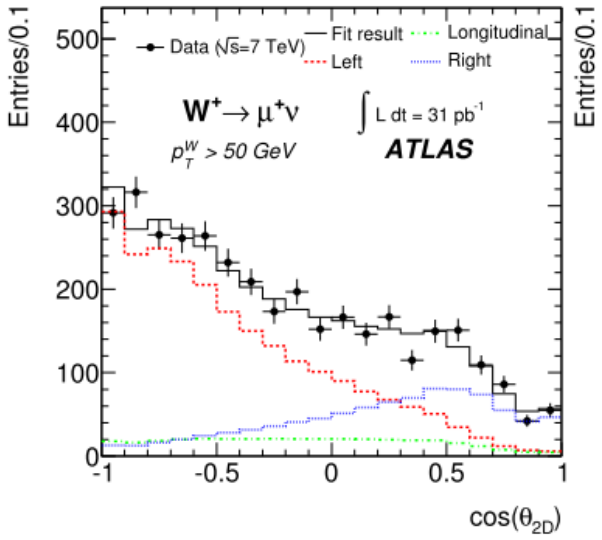


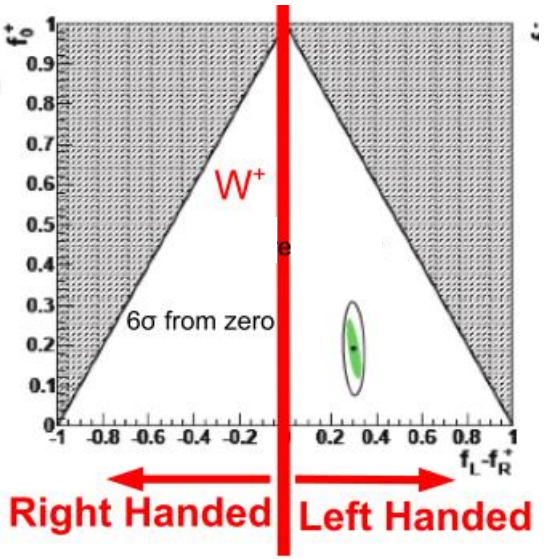
- Polarization should be measured in the W rest frame (experimentally inaccessible)
  - Using lepton projection instead
- Important for searches beyond SM with signal having different W polarization/lepton distributions
- Which precision needed for next LHC run?
- What about DY polarization?

CMS $$L_P = \frac{\vec{p}_T(l)\cdot\vec{p}_T(W)}{|\vec{p}_T(W)|^2} \simeq \frac{1+\cos\theta^*}{2}$$

ATLAS $$\cos\theta_{2D} = \frac{\vec{p}^{\,\ell*}_{\mathrm{T}}\cdot\vec{p}^{\,W}_{\mathrm{T}}}{|\vec{p}^{\,\ell*}_{\mathrm{T}}|\,|\vec{p}^{\,W}_{\mathrm{T}}|}$$

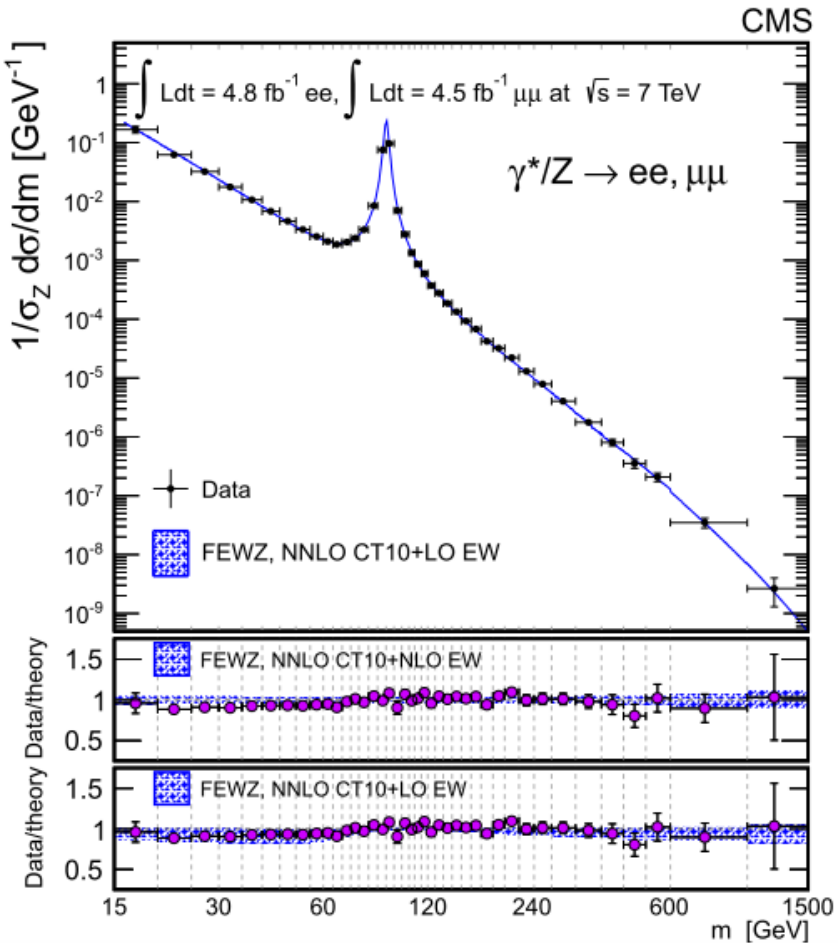


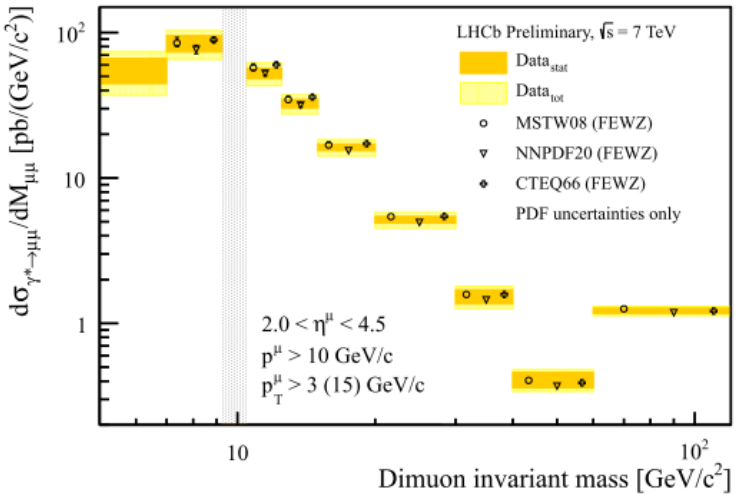


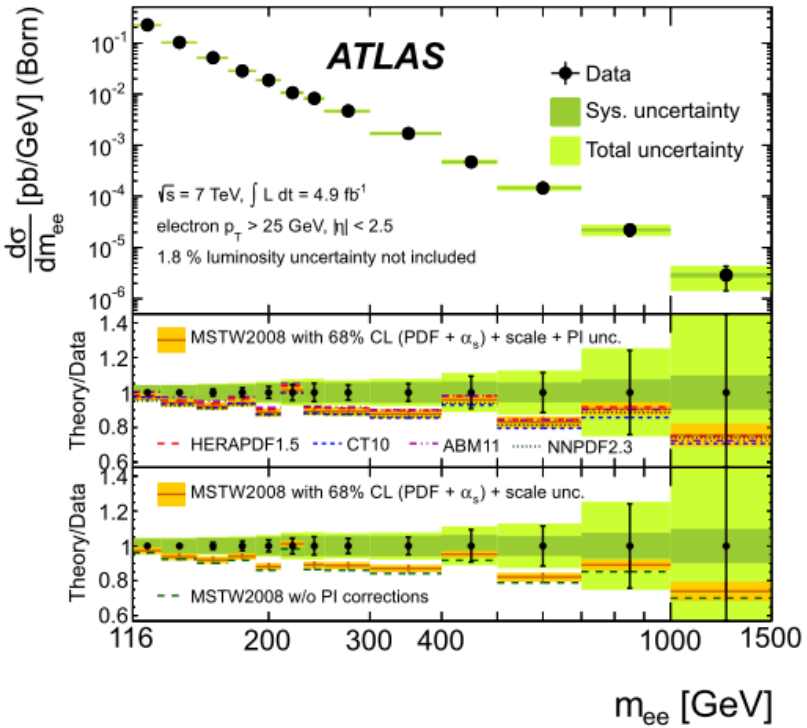


DY mass and rapidity

- Drell-Yan cross section vs mass
  - Test perturbative corr. (up to NNLO QCD + NLO EWK)
  - Constrain PDF
  - Major source of background for various interesting processes

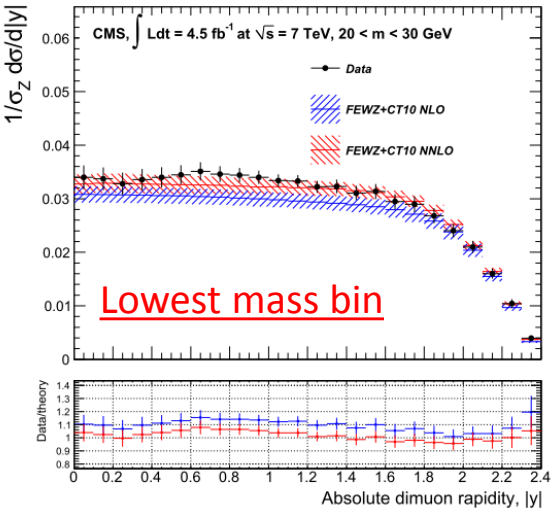


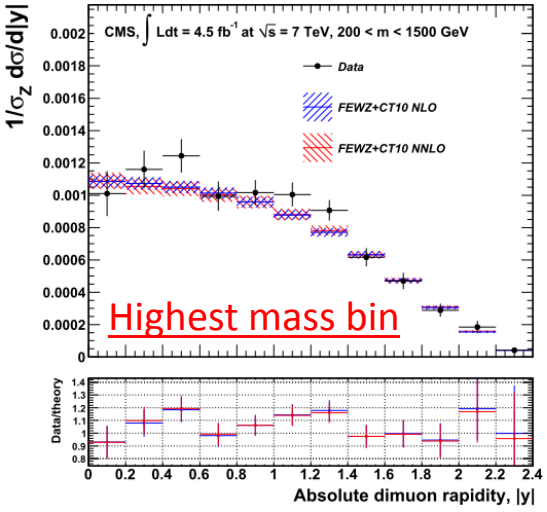


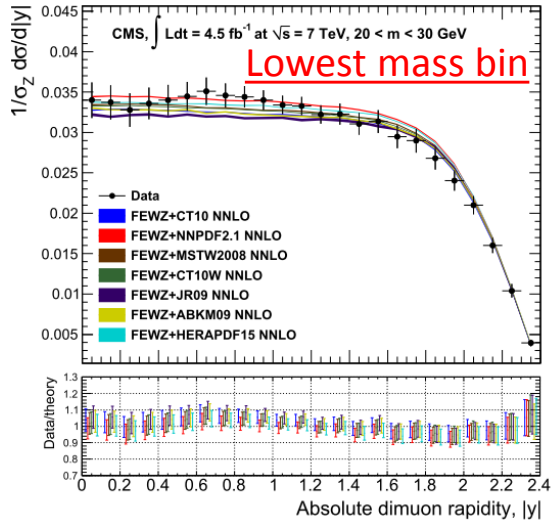


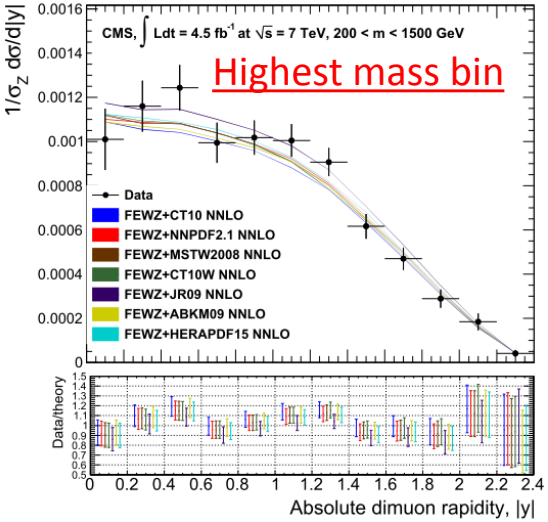
DY mass and rapidity

- CMS measures normalized distributions:
  - Mass range $20 < m_{ll} < 1500$ GeV
  - With muons and electrons
  - Rapidity integrated in the full phase space
  - Differential in rapidity in the visible phase space
  - Provide full covariance matrix for PDF fits
- Data are compared to FEWZ NNLO including EWK corrections
  - ATLAS includes also real W and Z boson emission in single-boson production



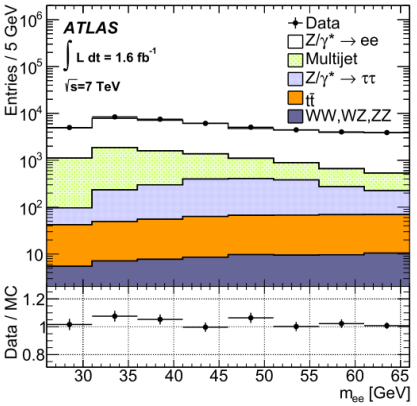


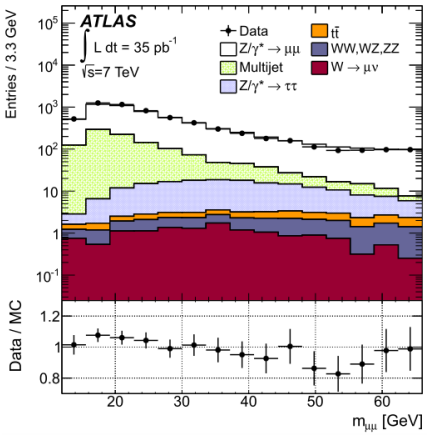


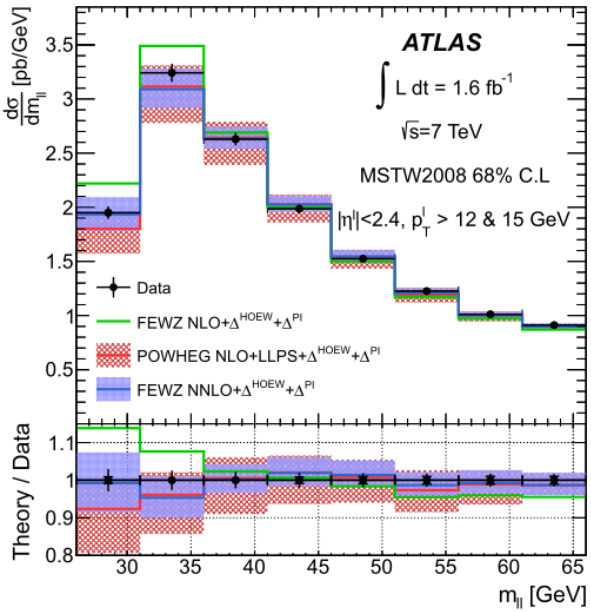


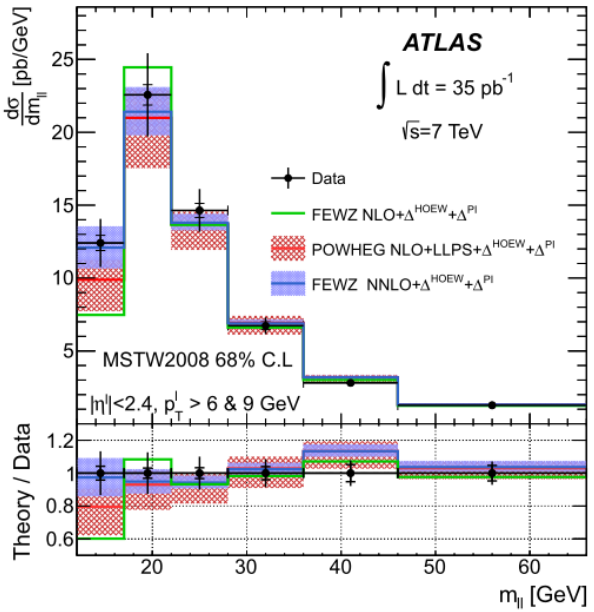
ATLAS: Low-mass Drell-Yan cross section

- Measurement performed in e and μ channels and combined
  - Invariant masses between 26 GeV and 66 GeV using 1.6 fb^{-1} collected in 2011
  - Extended down to 12 GeV in the muon channel using 35 pb^{-1} from 2010
- Cross sections provided at Born and dressed level, within acceptance and extrapolated to the full phase space, as well as correlated and uncorrelated uncertainty tables
  - Systematic uncertainties ~2-6% dominated by QCD bkg for electrons, isolation and trg eff. for muons
- QCD analysis performed to quantify data/prediction agreement
  - NNLO predictions significantly better than NLO, unless the latter are matched to a parton shower. EWK corrections are included









MSTW2008 PDF

Prediction	χ^2 (8 points) Nominal	χ^2 (6 points) Extended
POWHEG NLO+LLPS	22.4 (19.8)	22.3 (18.6)
FEWZ NLO	48.7 (28.6)	139.7 (133.7)
FEWZ NNLO	13.9 (12.9)	7.1 (7.1)

AFB: one measurement, many physics cases

- Test QCD and EWK calculations
- Sensitive to new particles for $m_{ll} > 500$ GeV
- Extraction of $\sin^2\theta_W$ around Z peak
  - Indirect measurement of m_W
- (Constraint PDF ?)
- Common keyword: go forward (i.e. use electrons)
  - Important to reconstruct Z events at large rapidity where direction of incoming quark is better determined

AFB: Theoretical framework

- Due to V−A nature of the EWK interaction, leptons produced via q qbar → Z/γ∗ → l^+l^- have forward-backward asymmetry (AFB) with respect to the quark direction in the rest frame of the dilepton system.

- Differential cross section for the lowest-order annihilation can be written as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}A(1+\cos^2\theta) + B\cos\theta\right]$$

- θ is the angle between lepton and the incoming quark in the dilepton rest frame , A and B are function of center of mass energy, and of the quark and lepton couplings and charges

- Measurement performed in Collins-Soper frame

$$\cos\theta^*_{\mathrm{CS}} = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_{\mathrm{T}}(\ell^+\ell^-)^2}}$$

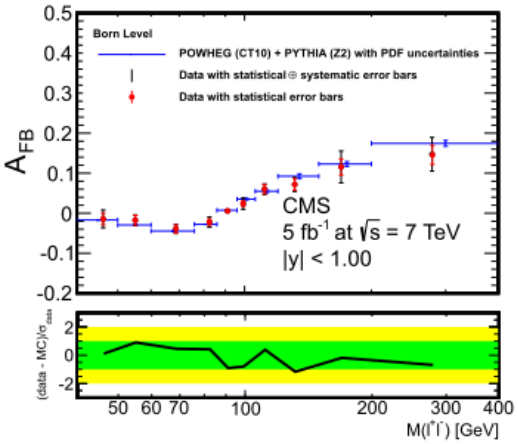
$$p_i^{\pm} = \frac{1}{\sqrt{2}}(E_i \pm p_{z,i})$$

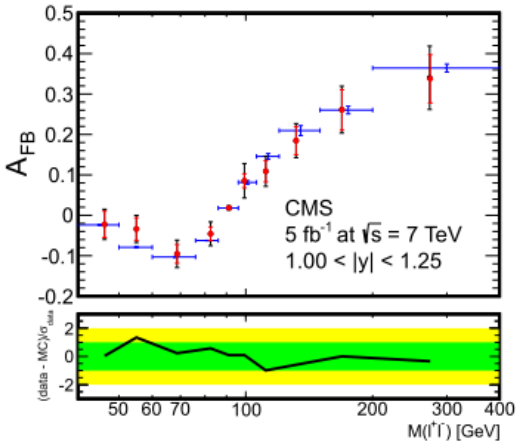
- Dileptons having $\cos\theta^*_{CS} > 0$ are classified as forward (F), those having $\cos\theta^*_{CS} < 0$ as backward (B). The asymmetry AFB is then defined as:

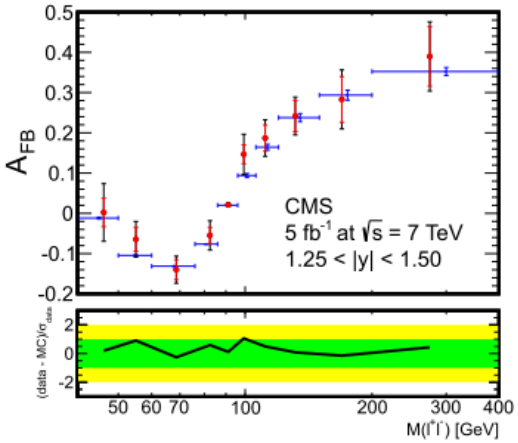
$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

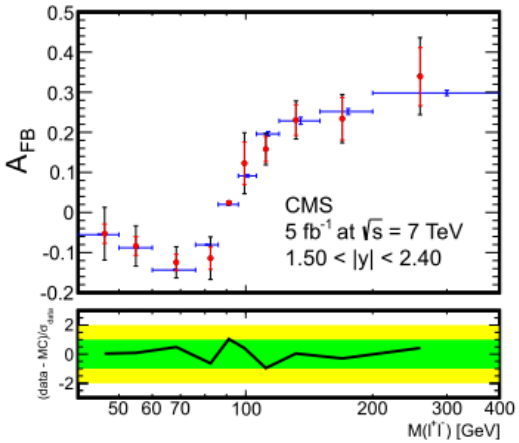
AFB: test QCD and EWK calculations

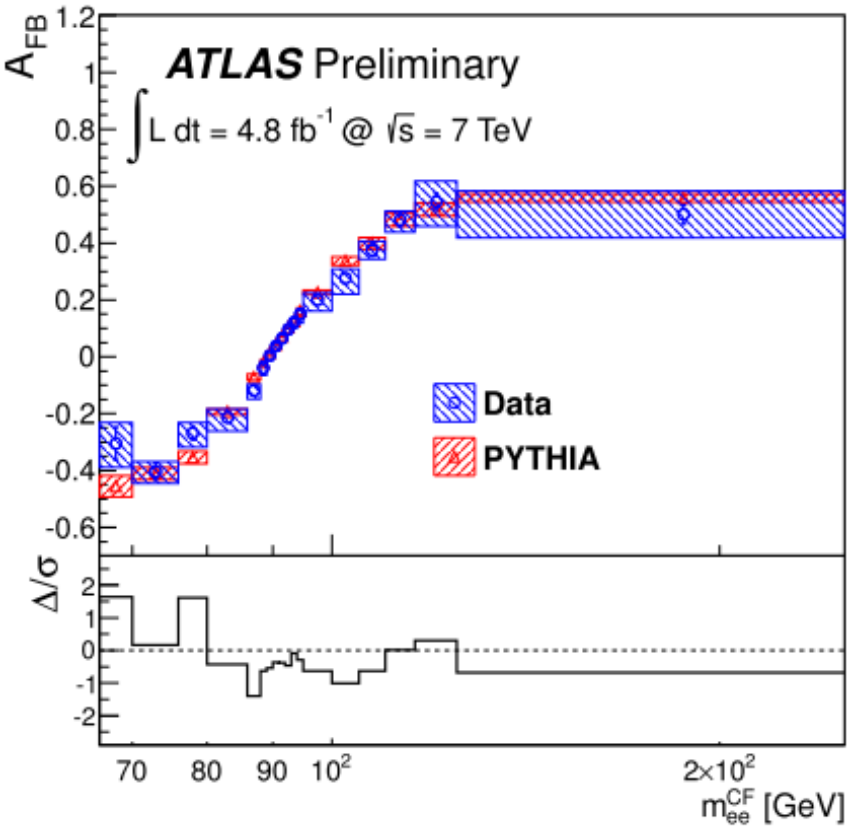
- Unfolded AFB is compatible with predictions





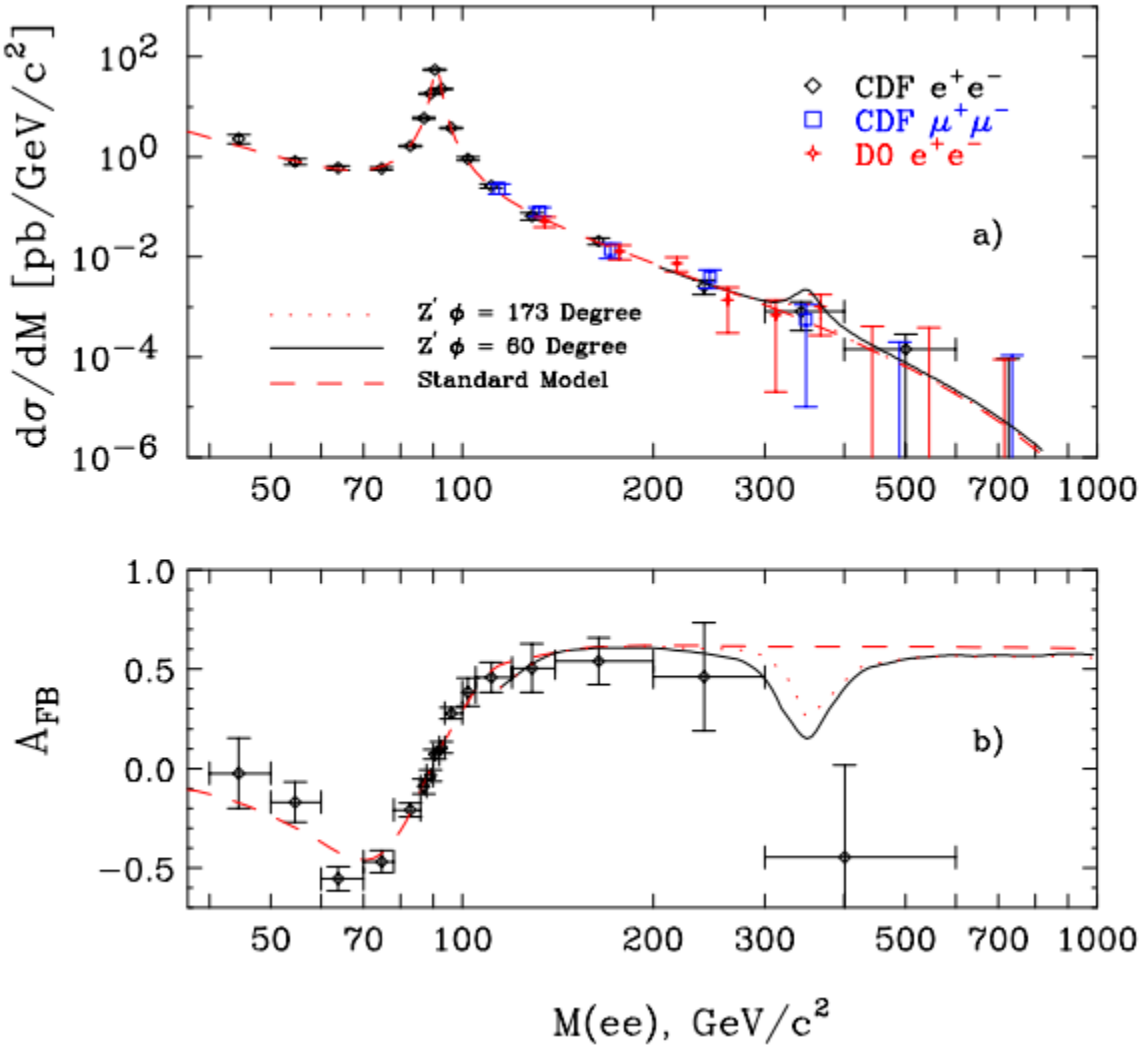






AFB: Sensitive to new particles for $m_{ll} > 500$ GeV

Eur.Phys.J.C21:607-611,2001



- Idea proposed back in 1987 and revived by Tevatron studies
- Deviations at high mass are expected in case a Z'-like particles

Extraction of $\sin^2\theta_W$ around Z peak

- From AFB is possible to extract the electroweak mixing angle, $\sin^2\theta_W$
  - Defined at tree level as $1-m^2_W/m^2_Z$
  - Higher-order loop corrections modify if to be the effective weak mixing angle, $\sin^2\theta_{W,eff}$

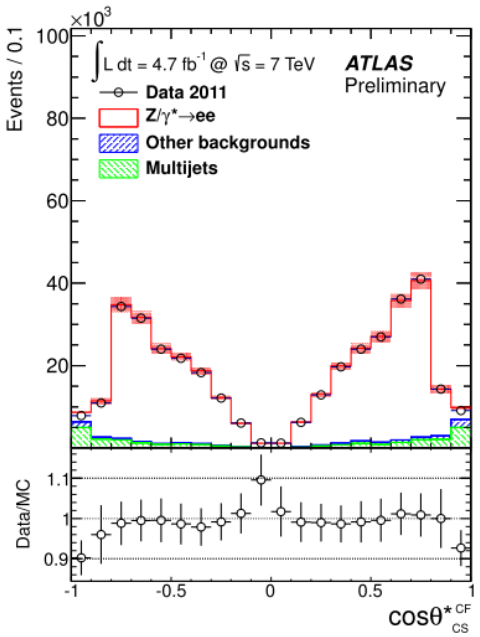
- At collider experiments, is most frequently quoted at the Z pole.

- The most precise measurements have come from the LEP and SLD experiments
  - Average of $\sin^2\theta_{W,eff} = 0.23153 \pm 0.00016$
  - BUT dominated by 2 measurements which differ by ~3 sigma
    - Forward-backward asymmetry in b-quark final states ($A^{0,b}_{FB}$) at LEP ($\sin^2\theta_{W,eff} = 0.23221 \pm 0.00029$)
    - Leptonic left-right polarization asymmetry (Al) at SLD ($\sin^2\theta_{W,eff} = 0.23098 \pm 0.00026$).

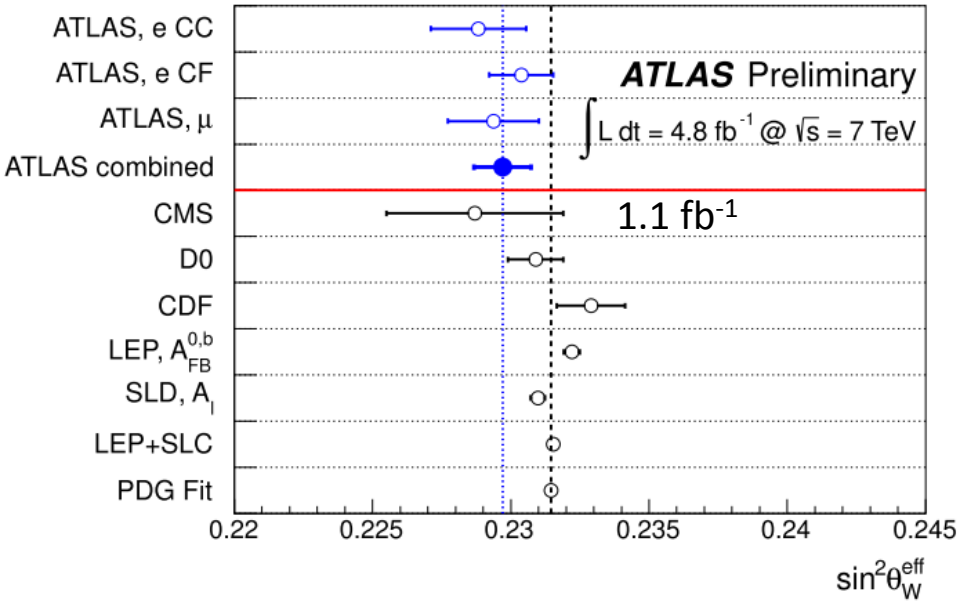
Extraction of $\sin^2\theta_W$ around Z peak

- Several techniques developed at Tevatron and LHC
- ATLAS has the best measurement at LHC
  - Using forward electrons $2.5 < |\eta| < 4.9$
  - Systematics dominated

$$\sin^2\theta_{W\ \text{combined}}^{\text{eff}} = 0.2297 \pm 0.0004(\text{stat.}) \pm 0.0009(\text{syst.})$$



Uncertainty (x10^{-4})	e_{CC}	e_{CF}	μ	Combined
PDF	9	5	9	7
MC stat	9	5	9	4
e energy scale	4	6	-	4
e energy resolution	4	5	-	3
μ momen. Scale	-	-	5	2
HO corrections	3	1	3	2
Other sources	1	1	2	2



Tevatron updates @ Moriond

- Full CDF RunII dataset with muons: 9.2 fb^{-1} [Phys. Rev. D 89, 072005 (2014)]
  - Tight muon cuts: pT > 20 GeV
  - Dimuon rapidity region: $|y| < 1$
  - Custom technique with weights, assumes εxA equal for μ^+ and μ^-

$\sin^2\theta_{W,eff} = 0.2315 \pm 0.0009_{(stat)} \pm 0.0004_{(syst)}$

Source	$\sin^2\theta^{lept}_{eff}$
Momentum scale	± 0.00005
Backgrounds	± 0.00010
QCD scales	± 0.00003
CT10 PDFs	± 0.00037
EBA	± 0.00012

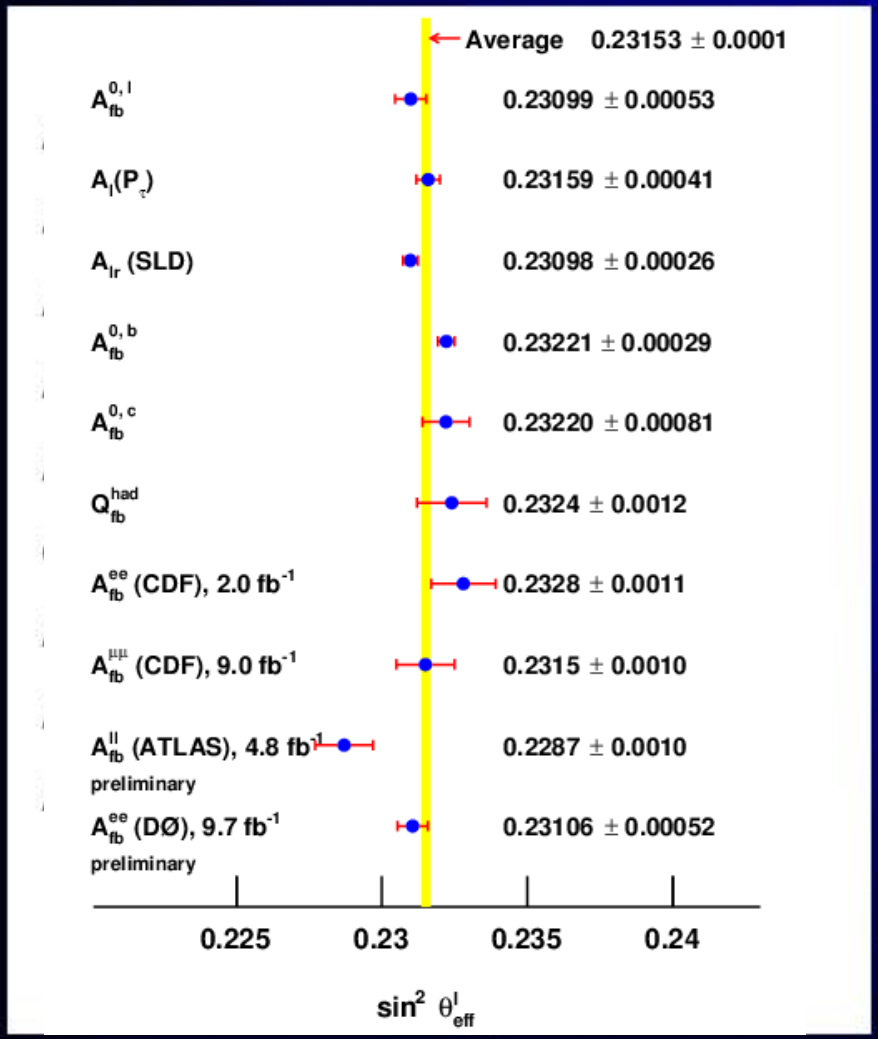
- Full D0 RunII dataset with electrons: 9.7 fb^{-1} (D0 Note 6426-CONF)
  - High-pT electrons: pT > 25 GeV
  - Central and endcap calorimeters (CC,EC)
  - Extend to $|\eta| < 1.1$, $1.5 < |\eta| < 3.2$
  - New method corrects energy as a function of L_{inst} first, then η

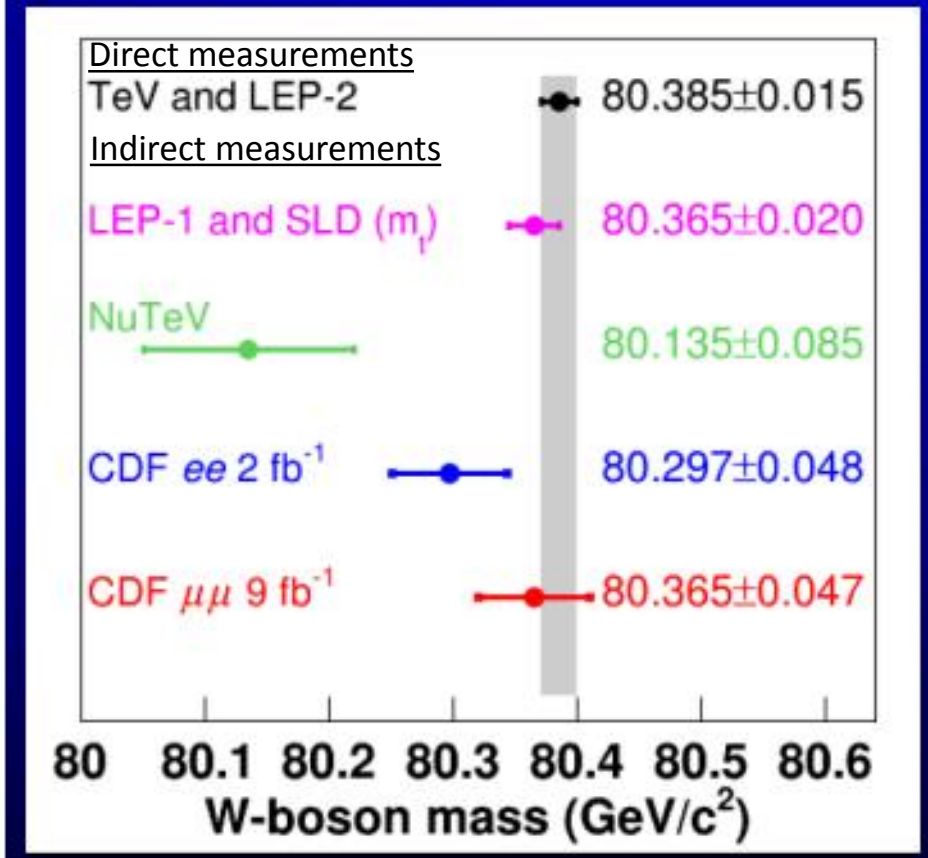
$\sin^2\theta_{W,eff} = 0.23098 \pm 0.00042_{(stat)} \pm 0.00014_{(syst)} \pm 0.00029_{(PDF)}$

	CC-CC	CC-EC	EC-EC	Combined
$\sin^2\theta_W$	**0.23086**	**0.23108**	**0.22910**	**0.23098**
statistical unc.	0.00116	0.00047	0.00276	0.00042
systematic unc.				0.00014
Energy scale	0.000002	0.000009	0.000059	0.00012
Energy smear	0.000010	0.000022	0.000126	0.000018
Background	0.000018	0.000010	0.000025	0.000008
Charge misID	0.000020	0.000036	0.000121	0.000030
Electron ID	0.000081	0.000078	0.000053	0.000066
total unc.				0.00044
PDF unc.				0.00029

N.B. Both measurements are statistically dominated

Measurement Comparisons





Reminder on ATLAS vs CMS open issues

- Unfolded lepton definitions
  - At the moment there are 3 lepton definitions:
    - Born: leptons before FSR (ISR-FSR ambiguity at NLO)
    - Dressed: leptons + photons within dR < 0.1 (works best for electrons)
    - Bare: leptons after FSR (works best for muons)
  - What is the best way to present (combine) the results? To include all?
  - Which is the minimalistic way to present the results?

- Z peak mass definitions and lepton pT cuts
  - Different ATLAS and CMS analyses use different lepton pT cuts for Z peak definitions
    - Symmetric vs asymmetric pT cuts
    - Different eta ranges
  - Different ATLAS and CMS analyses use different DY mass cuts. usually:
    - "Region around the DY peak" is $60 < M_Z < 120$ GeV
    - "Z Peak": $81 < M_Z < 101$ GeV or $71 < M_Z < 111$ GeV ?
  - Can we (or do we need to) agree on one single standard?
    - N.B. Different ranges imply different background contaminations and different sensitivity to FSR details

- W charge asymmetry
  - How to compare CMS and ATLAS?
    - ATLAS analysis applies MET cut, CMS doesn't
  - Both the experiments justify their choice
    - More robust wrt acceptance and detector effects
    - More robust wrt background and left out phase space is not relevant for PDF

Conclusions

- Many precision analyses carried out at LHC with W/Z looking at mass and angles
  - W Polarization
  - DY mass
    - New low DY mass result from ATLAS is out!
  - AFB and $\sin^2\theta_W$
    - Ultimate precision basically reached at Tevatron, limited by statistics
    - LHC trying to catch up.

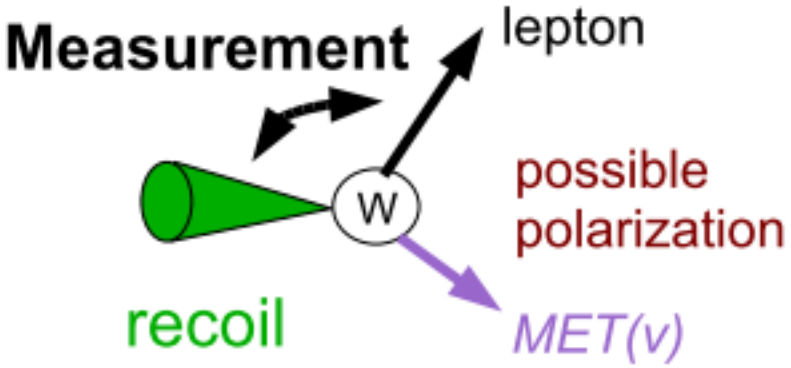
- Are we “forgetting” anything? Are we “ready” for the next LHC run?

- What about LHC standards on the DY mass and lepton definitions?

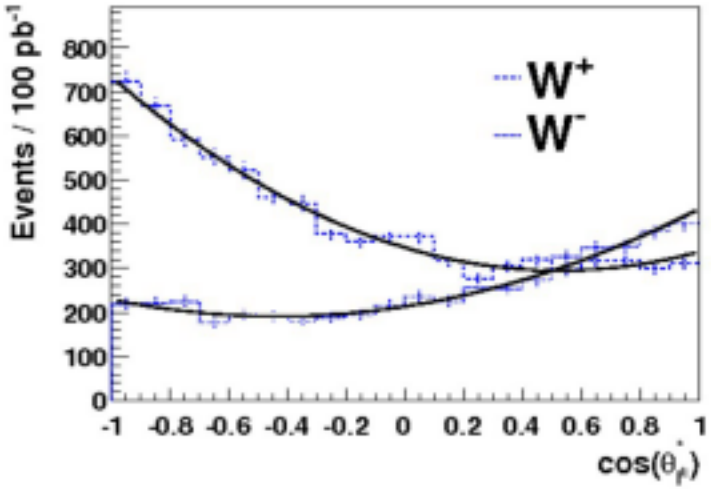
- Precision measurements require time, stay tuned for more results soon

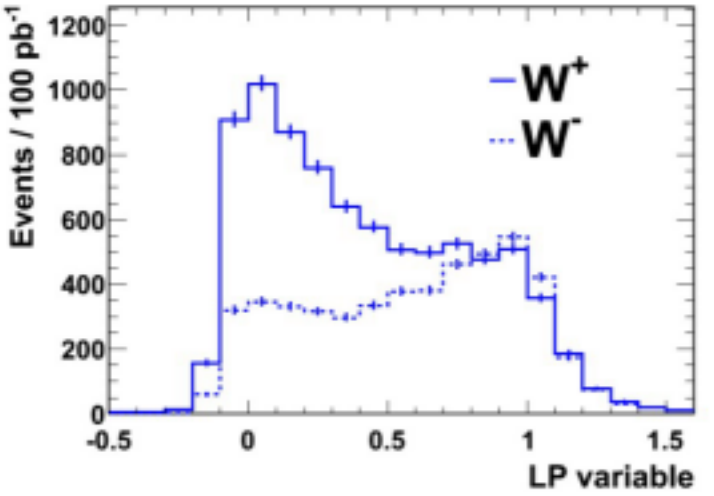
Backup slides

LP variable



$$\mathrm{LP} = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

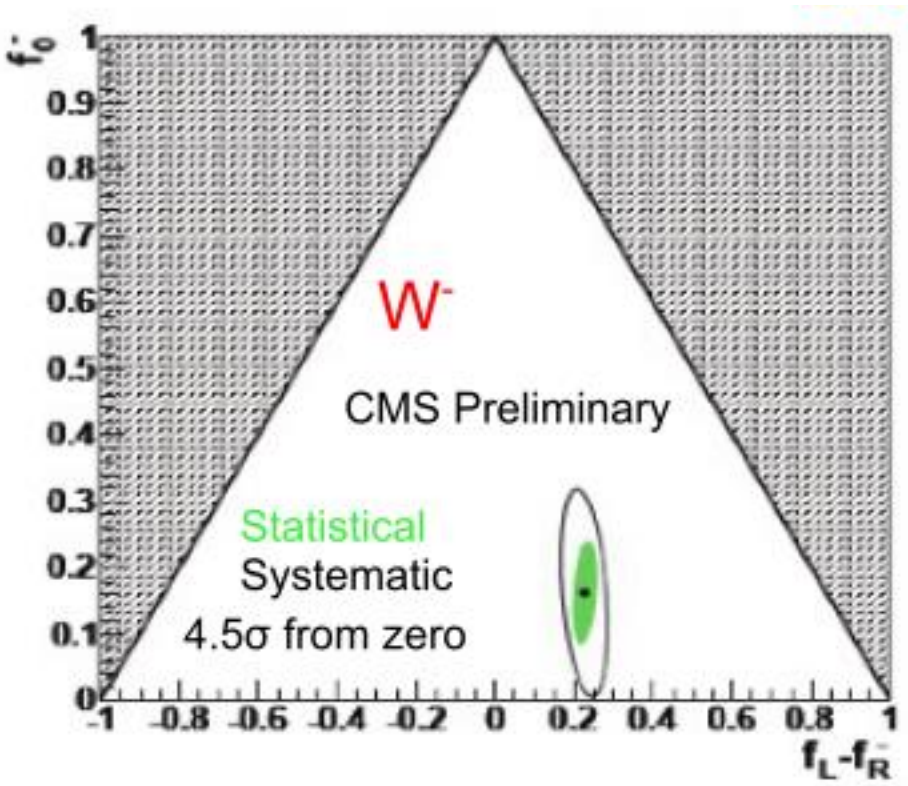




- Fraction of p(W) on lepton
  - Determined by cos(θ*) (Polarization)
- P_z(W) undetermined
  - **Transverse components necessary**
- LP variable
  - Addresses both of these

LP used to determine W Polarization

Combined Channels



- 68% confidence level contours

Summary

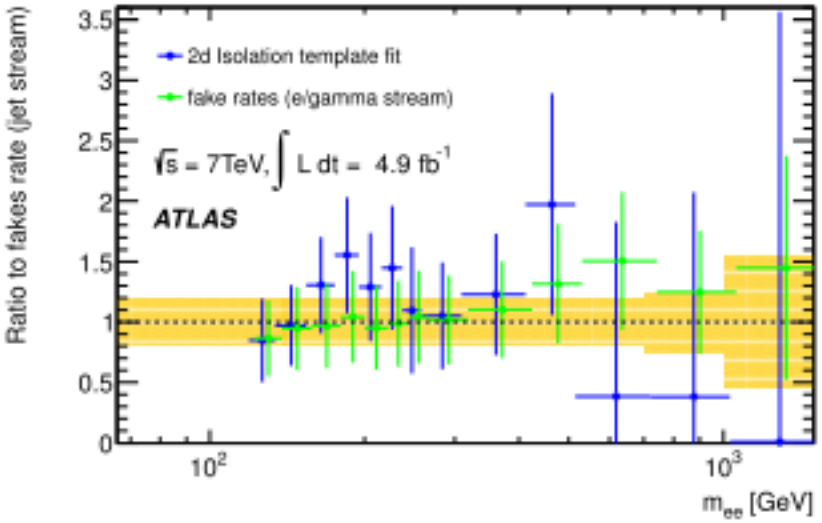
- Polarization of high p_T Ws measured
- Predominant left handed polarization for W^+ & W^-

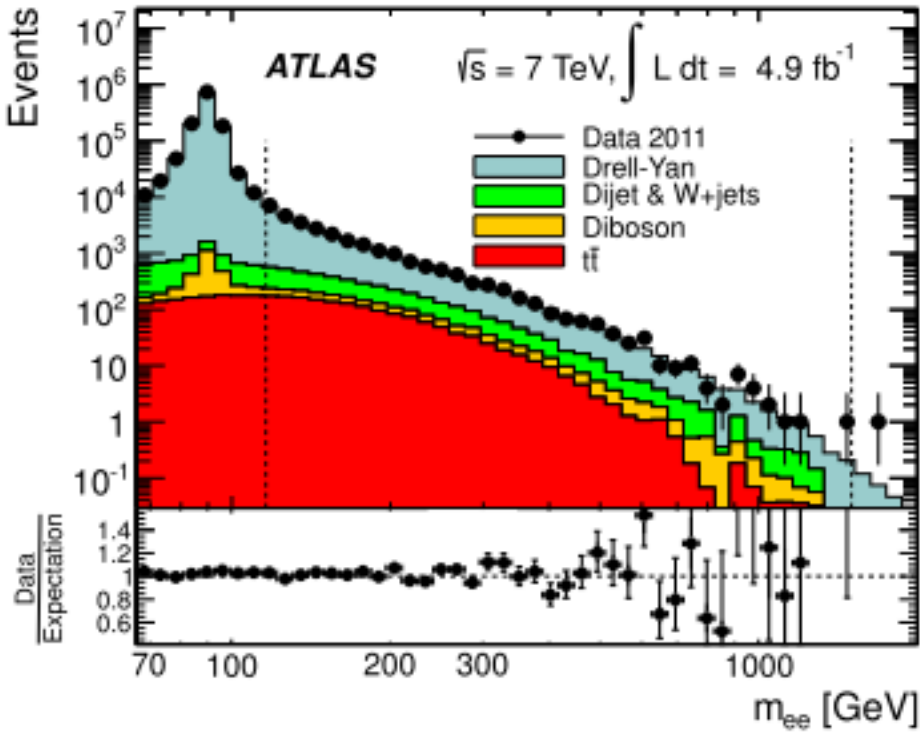
	Combined Results
$(f_L - f_R)^-$	0.226 ± 0.031 (stat) ± 0.050 (syst)
f_0^-	0.162 ± 0.078 (stat) ± 0.136 (syst)
$(f_L - f_R)^+$	0.300 ± 0.031 (stat) ± 0.034 (syst)
f_0^+	0.192 ± 0.075 (stat) ± 0.089 (syst)

High mass Drell-Yan cross-sections

arXiv:1305.4192

- Cross-sections are measured for $p_T^\ell > 25\ GeV$, $|\eta_\ell| < 2.5$ and $116 < m_{\ell\ell} < 1500\ GeV$
- Main backgrounds from dijet and W+jets (6-16%), derived from data measuring the jet-to-electron fake rate in jet-enriched control sample



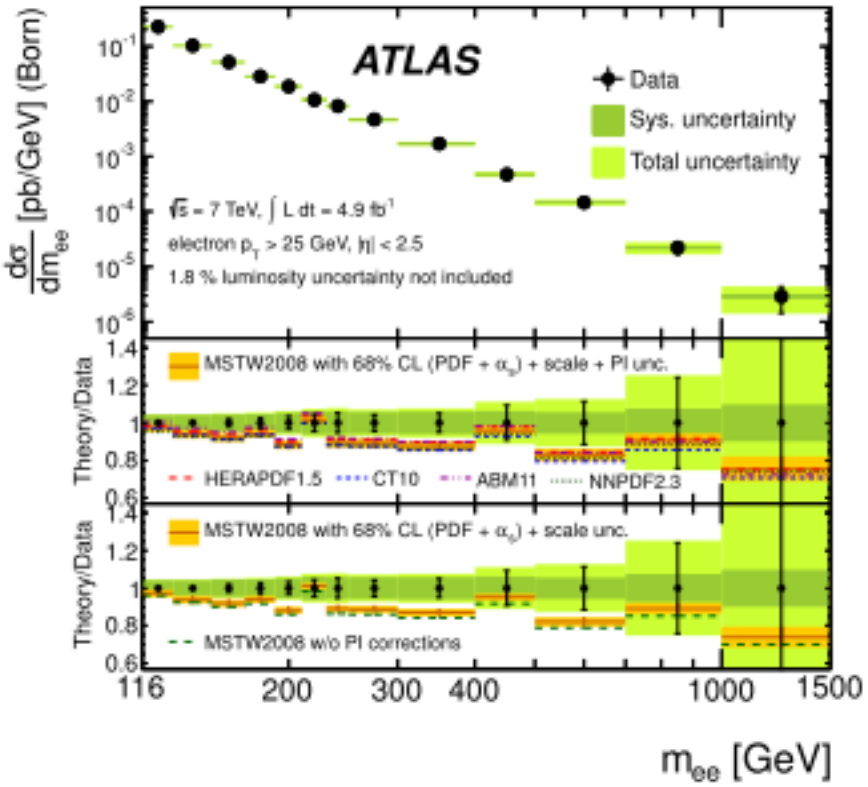


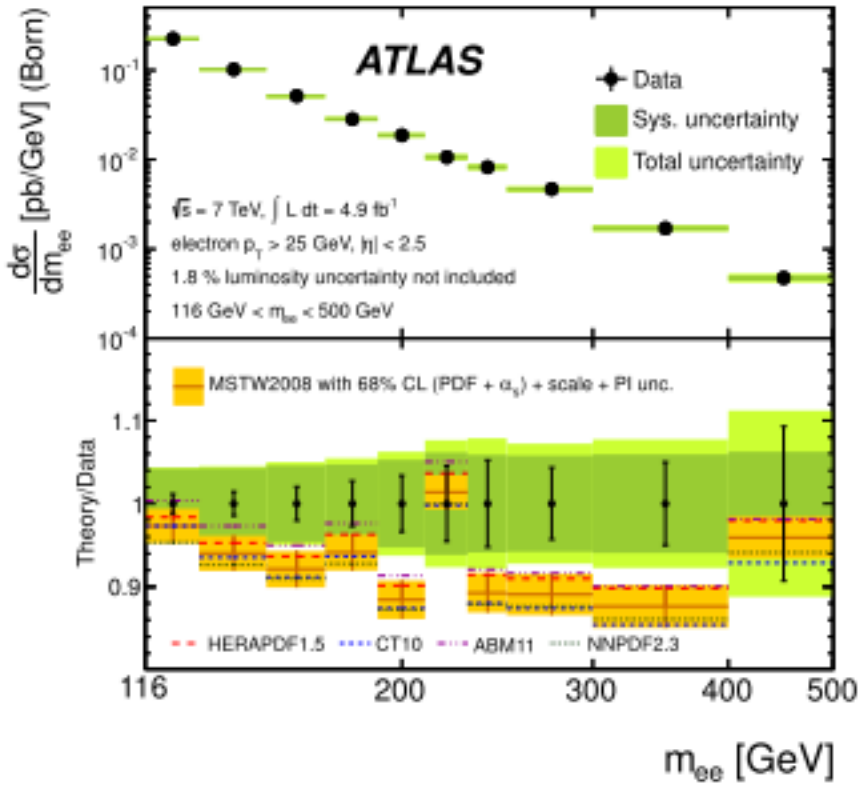
- $Z \to ee$ spectrum measured in data compared to prediction from PYTHIA w/ NNLO QCD and NLO EW k-factors (plus backgrounds)

High mass Drell-Yan cross-sections

arXiv:1305.4192

- Systematic uncertainty (4.2 – 9.8%) dominated by electron calibration and efficiencies, statistically dominated for $m_{ee} > 400\ GeV$



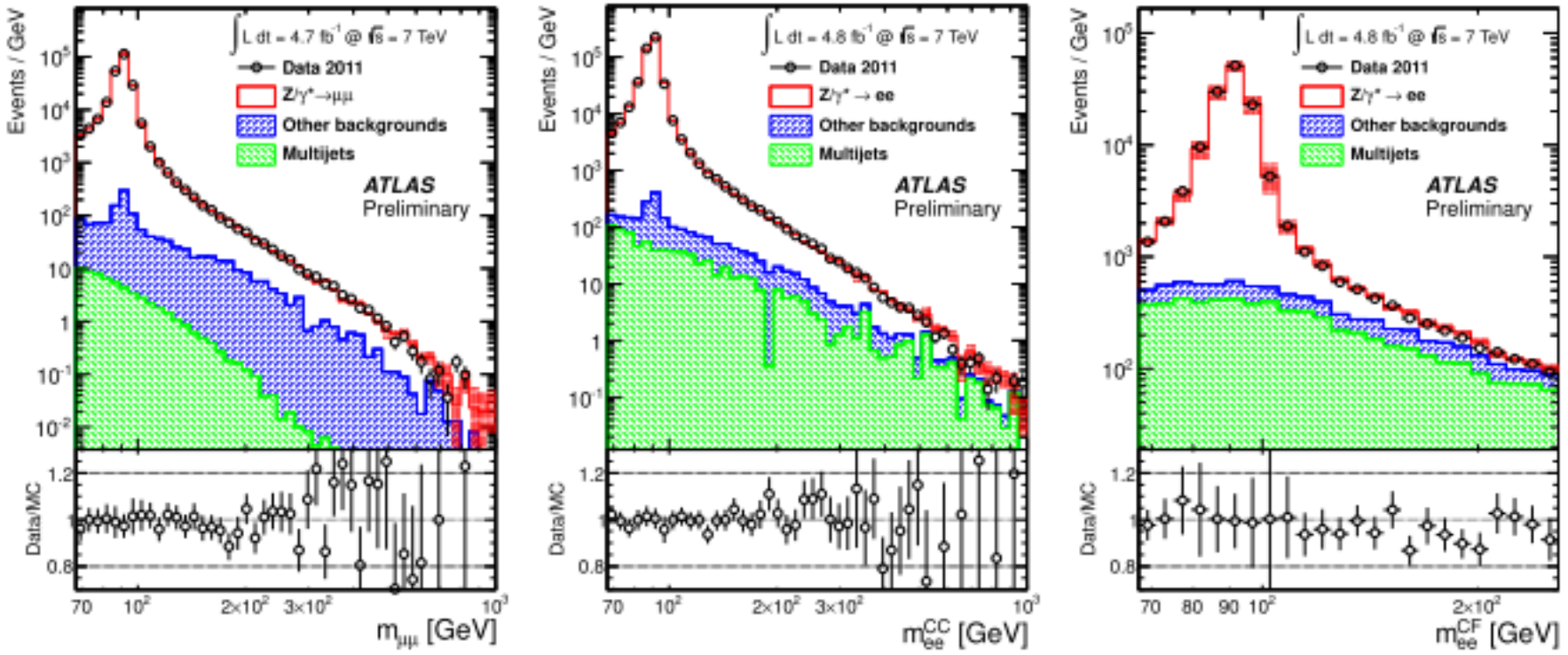


- Data compared to NNLO QCD FEWZ calculations, including NLO EW corrections, and with different NNLO PDFs
  - ✓ γ-induced contribution (1 – 8%) and real W, Z FSR (0.1 – 2%) also included

Forward-backward Z asymmetry measurement

ATLAS-CONF-2013-043

- ★ Measurement of A_{FB} in $Z \to \ell\ell$ decays $\Rightarrow$ extraction of $sin^2\theta_W^{eff}$
- ★ Electrons selected with $E_T > 25\,GeV$ in central ($|\eta| < 2.47$) and forward ($2.5 < |\eta| < 4.9$) regions
- ★ Muons from inner tracker and muon-spectrometer measurements selected with $p_T > 20\,GeV$ and $|\eta| < 2.4$

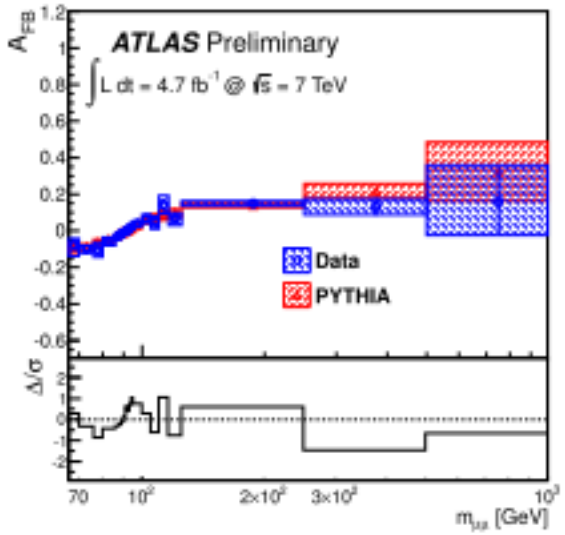


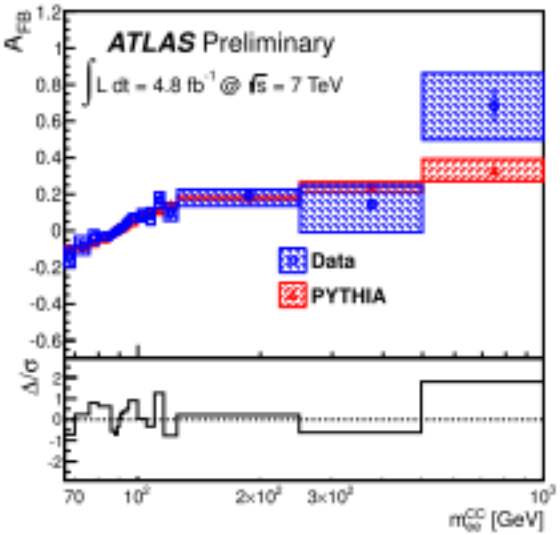
"CC" = two central electrons, "CF" = one central and one forward electron

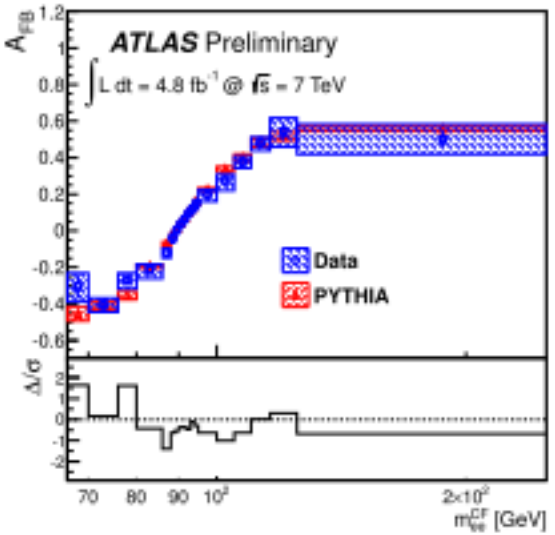
Forward-backward Z asymmetry measurement

ATLAS-CONF-2013-043

- ⋆ Bayesian unfolded A_{FB} spectrum compared to PYTHIA prediction including QED FSR and NLO QCD corrections
  - ✓ unfolding accounts for detector effects and QED corrections
- ⋆ Systematic uncertainties from unfolding (checked with a data re-weighting procedure), MC dependence and higher order QCD and EW corrections, PDFs, MC statistics, backgrounds and other experimental effects

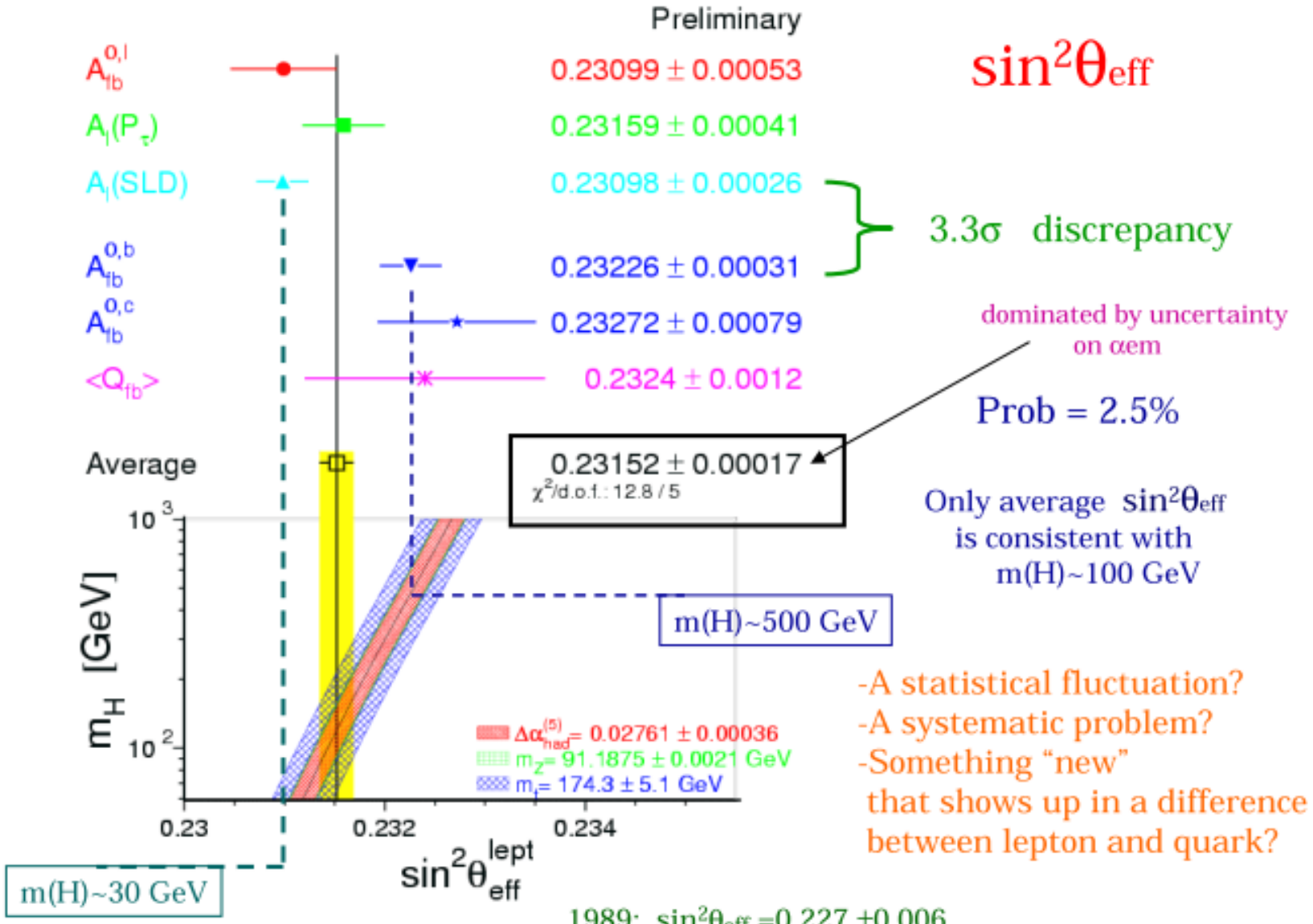




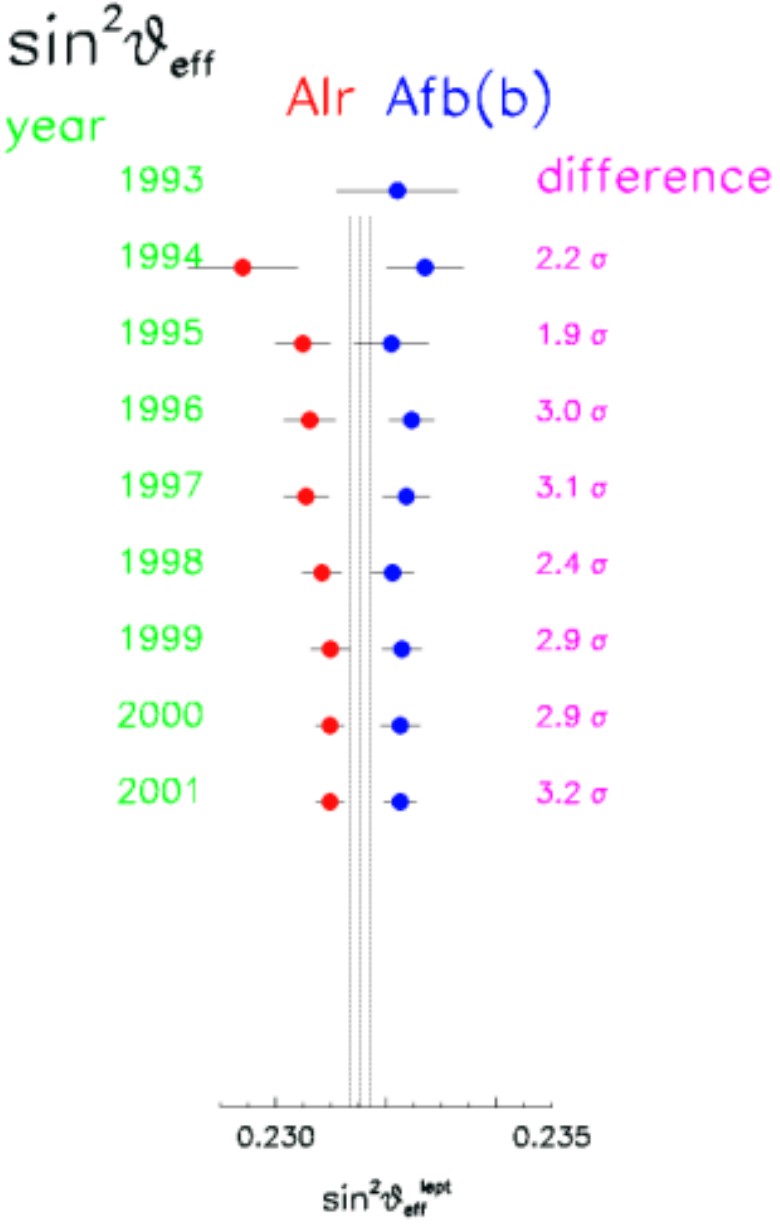


"CC" = two central electrons, "CF" = one central and one forward electron

Credit: Chiara Mariotti



Credit: Chiara Mariotti



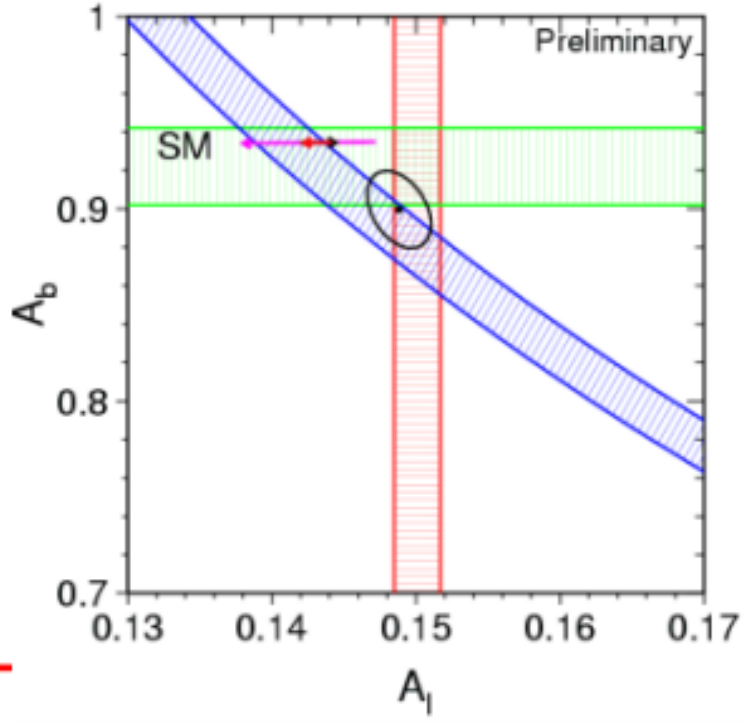
This difference is small but it is there since the "beginning".
First was thought as a LEP-SLD difference, now as

lepton vs quark

difference

Since Ae (SLD) = Ae(LEP)

Ab (SLD) = Ab(LEP)

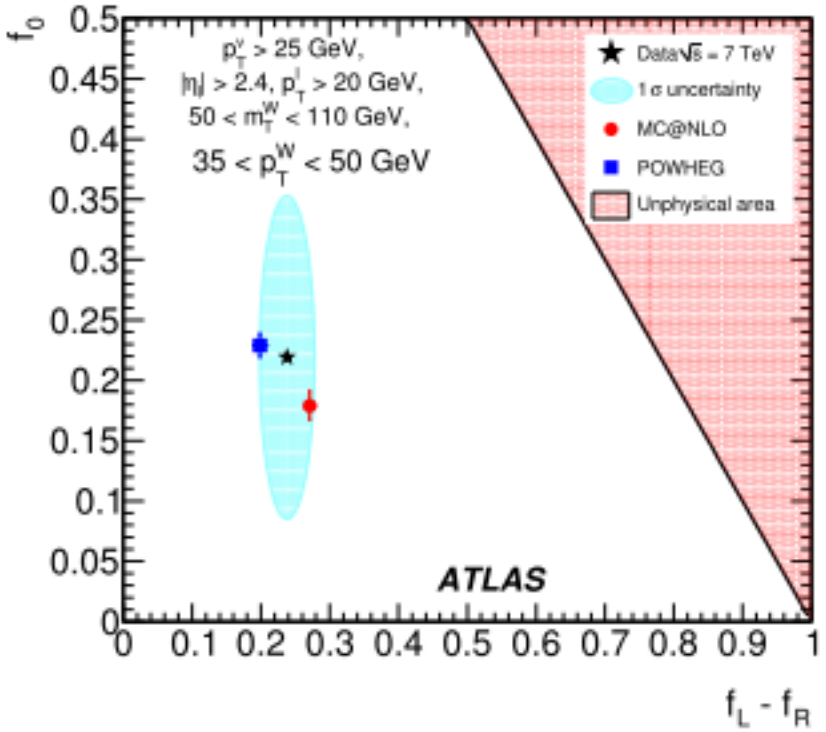


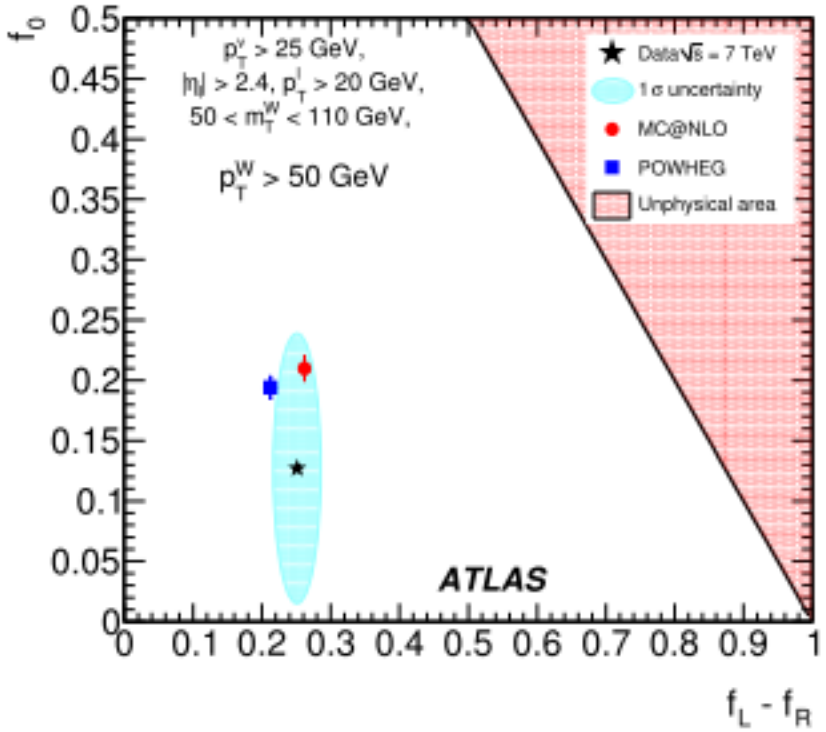
24

W polarization at high p_T

Eur. Phys. J. C72 (2012) 2001

- ★ Helicity fractions, f_0 and $f_L - f_R$, measured from angular distribution in transverse plane: $cos\theta_{2D} = \vec{p_T^{\ell *}} \cdot \vec{p_T^W} \ / \ |\vec{p_T^{\ell *}}||\vec{p_T^W}|$
  - ✓ Measurements done for $35 < p_T^W < 50\ GeV$ and $p_T^W > 50\ GeV$ regions





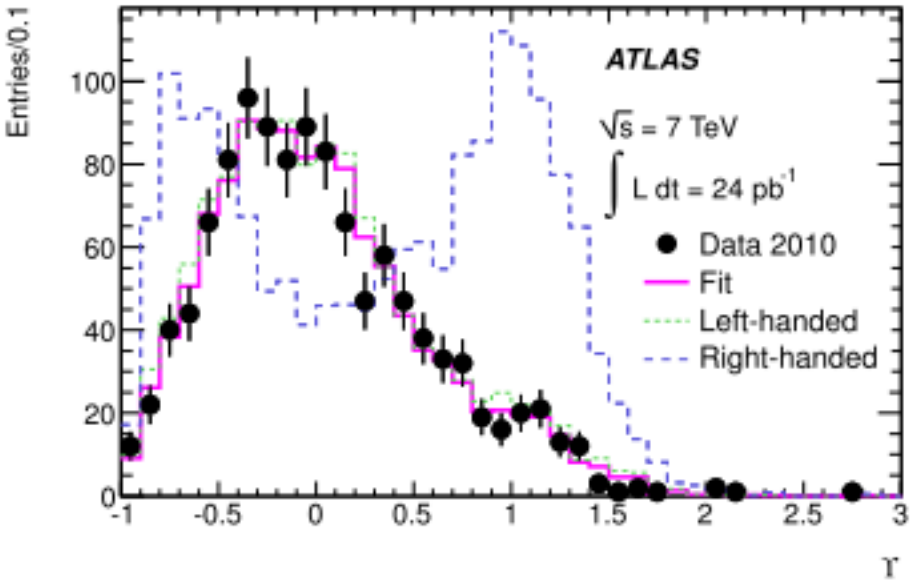
- ★ $f_L - f_R$ measured with 12–14% syst. uncertainty, dominated by hadronic recoil scale uncertainty (statistical uncertainty in 6–8% range)
- ★ Results compared to NLO QCD predictions from `MC@NLO`, `POWHEG` MCs

τ polarization in $W \to \tau\nu$ decays

Eur. Phys. J. C72 (2012) 2062

- ★ First measurement at hadron collider and first probe of helicity structure of $W \to \tau\nu$ coupling at high Q^2
  - ✓ Done in hadronic τ decay channels with single charged hadron
- ★ General method based on energy sharing of charged and neutral πs in τ decay relative to $p_T^{\tau,vis}$ ("charged asymmetry", Υ)
- ★ Systematic uncertainty dominated by τ and cluster energy calibrations

Source	$+\Delta P_\tau$	$-\Delta P_\tau$
Energy scale central	0.042	0.063
Energy scale forward	0.007	0.002
E_T^{miss} resolution	0.014	-
No FCal	0.003	-
τ identification	0.005	0.006
Trigger	0.007	0.006
MC model	0.020	0.020
W cross-section	0.005	0.005
Z cross-section	0.006	0.006
Combined	0.05	0.07



- ★ Measured value in agreement with SM within uncertainties (5 – 7%)

$P_\tau = -1.06 \pm 0.04\,(stat)^{+0.05}_{-0.07}\,(syst)$ (Bayesian 95% credibility interval $[-1, -0.91]$)