Electroweak precision measurements in CMS

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Moriond EW
La Thuile, Italy

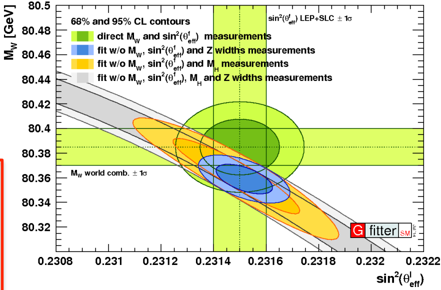
Overview of the Electroweak Sector

- Electroweak (EW) precision observables
  - $\alpha_{\text{em}}, \mathrm{G_F}, m_{\mathrm{W}}, m_{\mathrm{Z}}, \sin^2\theta_{\mathrm{W}}, m_h$
- Not independent but related through Standard Model (SM)

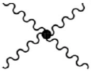
$$m_{\mathrm{W}}^2 \sin^2\theta_{\mathrm{W}} = \frac{\pi\alpha}{\sqrt{2}\mathrm{G_F}} \qquad \sin^2\theta_{\mathrm{W}} = 1 - \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2} \qquad \text{(Tree level)}$$

- Precision EW measurements
  - SM is over constrained with m_h
  - Testing the consistency of the SM
- Non-abelian Gauge structure
  - Are there anomalous couplings?

Eur. Phys. J. C 74, 3046 (2014)



- Focus of this talk:
  - $\sin^2\theta_{\mathrm{W}}$
  - EW production of same sign WW



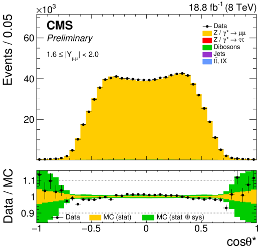
Dilepton production at the LHC

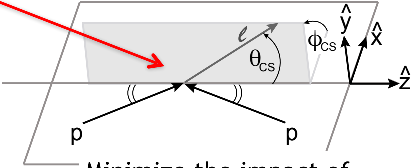
- Neutral current process: $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ **CMS-PAS-SMP-16-007**
- Z boson couplings are different for left and right-handed fermions
- Forward-backward asymmetry (A_{FB}) in the polar angle distribution of negatively charged lepton in the rest frame of di-lepton system
  - Defined with respect to the incoming quark

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta} = \frac{3}{8}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}\left\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + \boxed{A_4\cos\theta}\right\}$$

- A_{FB} defined in Collin-Soper (CS) frame $A_{\mathrm{FB}} = \dfrac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$

F: cosθ>0
B: cosθ<0





Minimize the impact of incoming quark transverse momentum

Effective weak mixing angle

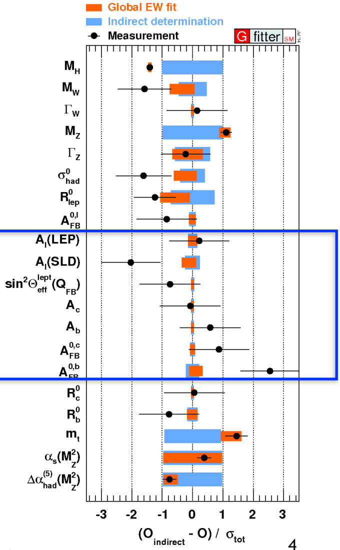
- A_{FB} is sensitive to $\sin^2\theta_W$ near Z peak
  - Product of vector and axial couplings
- Electroweak corrections:
  - Tree level couplings are replaced by effective couplings

$$\boxed{\sin^2\theta^f_{\text{eff}} = \kappa^f_Z \sin^2\theta_W}$$

$$g^f_A = \sqrt{\rho_f}\, t^f_{3L}$$

$$g^f_V = \sqrt{\rho_f}\,(t^f_{3L} - 2Q_f\kappa_f \sin^2\theta_W)$$

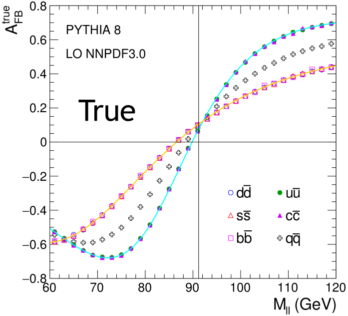
- Template fit to extract the $\sin^2\theta^\ell_{\text{eff}}$
- Large discrepancy (~3 standard deviations) between the two most precise LEP/SLD measurements

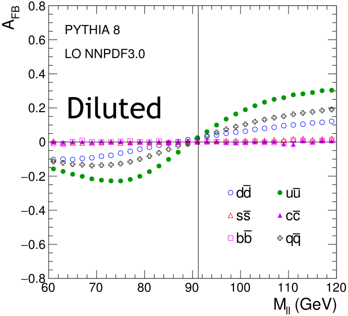


Eur. Phys. J. C 74, 3046 (2014)

Forward-backward Asymmetry

- A_{FB} measured as function of di-lepton mass in muon and electron final states (mass dependence from the Z/gamma* interference)
- Proton-proton collisions: where is the quark?
  - Direction of longitudinal boost of the di-lepton system in the laboratory frame chosen as the positive axis
  - Quark direction is not always along the positive axis
    - Dependence on PDF from large-x antiquarks

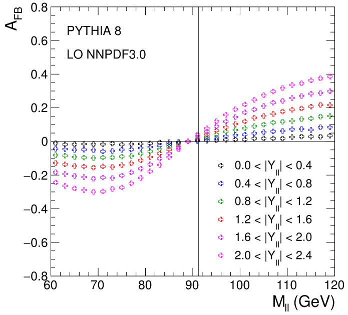


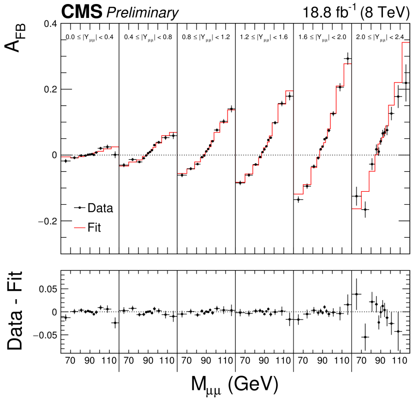


A_{FB} and $\sin^2\theta^{\ell}_{\mathrm{eff}}$

- Dilution strongly depends on rapidity->maximal at Y=0->A_{FB}=0
- A_{FB} is measured in 6 bins of rapidity and 12 bins of dilepton mass
- Extract $\sin^2\theta^{\ell}_{\mathrm{eff}}$ by fitting the measured A_{FB} with different templates
  - Angular event weighting->less sensitive to cosθ acceptance modeling
  - Precise lepton momentum calibration

Eur. Phys. J. C67, 321-334 (2010)





Statistical and systematic uncertainties

- Statistical uncertainties dominate

channel	statistical uncertainty
muon	0.00044
electron	0.00060
combined	0.00036

- Experimental uncertainties are small (dominated by limited number of simulated events)

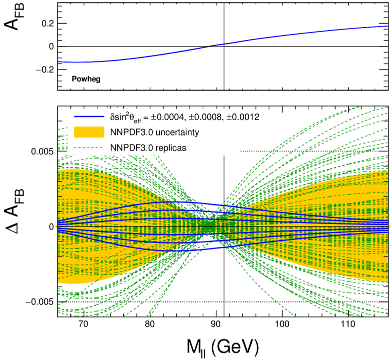
Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

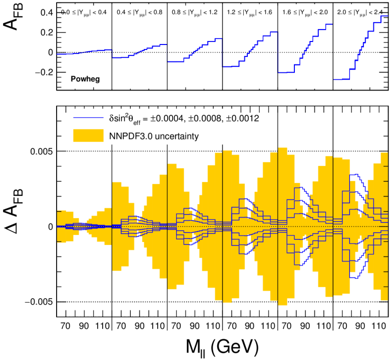
- Modeling uncertainties small compared to the statistical uncertainties
  - Dominated by QCD scale

model variation	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
QCD $\mu_{R/F}$ scale	0.00011	0.00013
POWHEG MiNLO Z+j vs NLO Z model	0.00009	0.00009
FSR model (PHOTOS vs PYTHIA)	0.00003	0.00005
UE tune	0.00003	0.00004
Electroweak ($\sin^2\theta_{\text{eff}}^{\text{lept}} - \sin^2\theta_{\text{eff}}^{\text{u,d}}$)	0.00001	0.00001
Total	0.00015	0.00017

PDF uncertainties

- Measured A_{FB} is sensitive to the PDFs
  - Different couplings of u and d-type quarks to Z boson
  - Size of the dilution effect (large-x antiquarks)
- PDF dependence is large at small and large masses, small near the peak

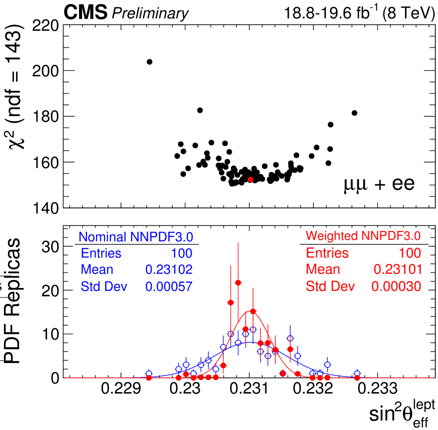




PDF uncertainties

- Bayesian χ^2 reweighing method used to constrain the PDFs
- Perform the $\sin^2\theta^{\ell}_{\mathrm{eff}}$ fit for each NNPDF3.0 replica
- Weight each replica by:

$$w_i = \frac{e^{-\frac{\chi^2_{\mathrm{min}}}{2}}}{\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{\chi^2_{\mathrm{min}}}{2}}},$$



- Consistent between electron/muon
- PDF uncertainties reduced by x2

Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

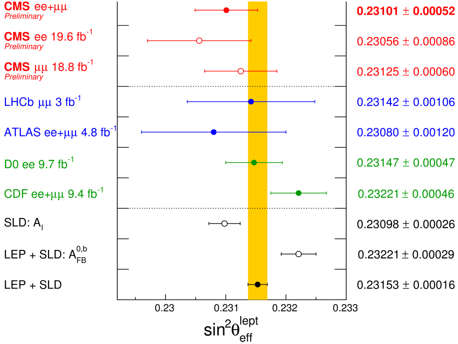
- Similar picture with Hessian PDF sets

Results

- Results are consistent with the mean value of LEP and SLD and other available measurements
  - Comparable to precision at the Tevatron!
  - Statistical uncertainties dominate

$$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} = 0.23101 \pm 0.00036(\mathrm{stat}) \pm 0.00018(\mathrm{syst}) \pm 0.00016(\mathrm{theory}) \pm 0.00030(\mathrm{pdf})$$

$$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} = 0.23101 \pm 0.00052.$$



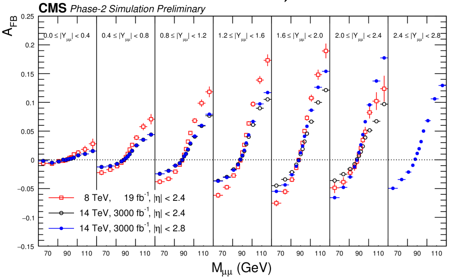
Future

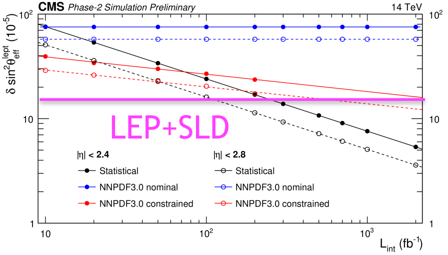
- What can we expect at the high-luminosity LHC
  - Negligible statistical uncertainties
  - PDF uncertainties further constrained with profiling
  - Extended lepton acceptance with the upgraded CMS detector

CMS-PAS-FTR-17-001

- Smaller A_{FB} at 14 TeV (less valence quark contribution)

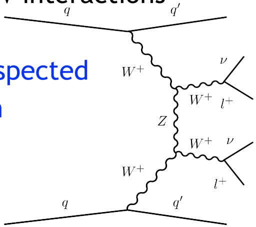
- Larger lepton |η| acceptance

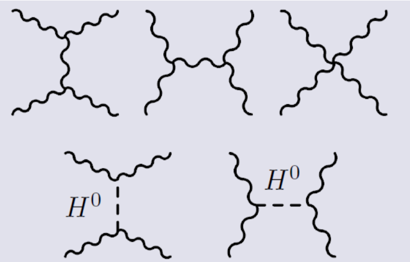


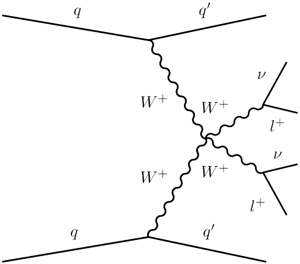


Gauge boson couplings

- Shift from precision observables to first measurements
- Probe the non-Abelian gauge structure of the EW interactions
- Vector boson scattering processes
  - What mechanism ensures the unitarity is respected
  - Is the 125 GeV Higgs boson the only solution
  - Characterized by VV and 2 jet final state



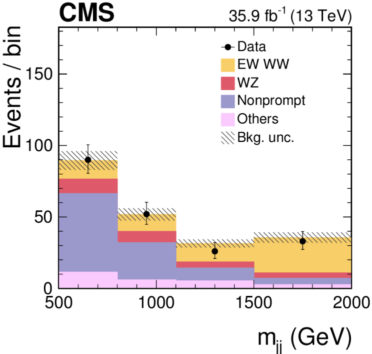


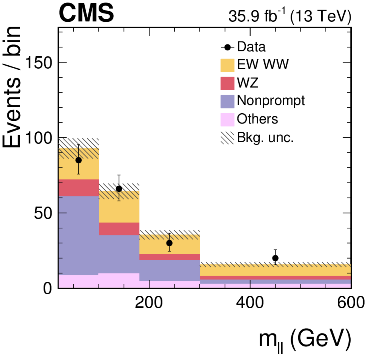


Vector boson scattering

- Events are selected by requiring 2 same-sign leptons and 2 jets with large pseudorapidity separation and large mass
- First observation of EW production of same-sign W boson pairs
  - Observed (expected) significance is 5.5 (5.7) standard deviations
  - Observed signal is consistent with SM predictions
  - Evidence by ATLAS and CMS in Run 1

PRL. 120, 081801 (2018)

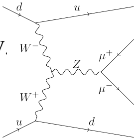




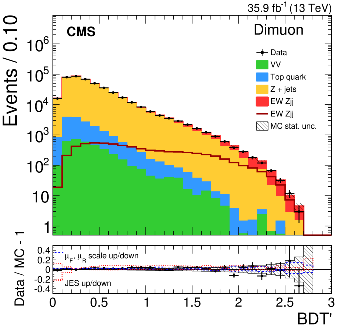
Electroweak Z+2jet production

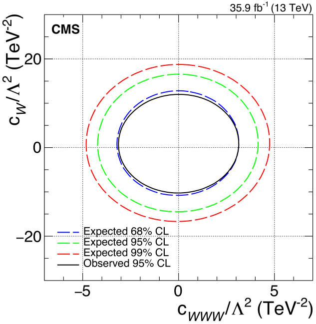
- Pure EW production of dileptons in association with two jets
- Measured cross section is in agreement with the leading order SM predictions $\sigma_{\text{EW}}(\ell\ell\text{jj}) = 552 \pm 19\,(\text{stat}) \pm 55\,(\text{syst})\,\text{fb}$

  $m_{\ell\ell} > 50\,\text{GeV}$, $m_{\text{jj}} > 120\,\text{GeV}$, and transverse momenta $p_{\text{Ti}} > 25\,\text{GeV}$.



- Best limits of anomalous triple gauge couplings

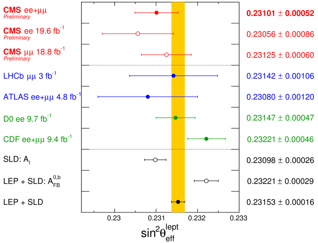




CMS-SMP-16-018
Submitted to Eur.Phys.J.C.

Summary

- Electroweak precision measurements with the CMS detector
- Precise measurement of the effective weak mixing angle
  - Comparable to precision at the Tevatron!
  - PDF and statistical uncertainties dominate
  - Experimental uncertainties are under control
- First observation of electroweak production of same sign W boson pairs
  - Observed (expected) significance is 5.5 (5.7) standard deviations
- Many more results to come



ADDITIONAL MATERIAL

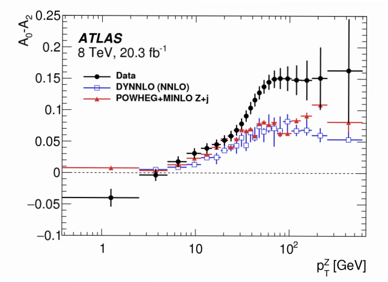
Angular coefficients

- Accurate modeling of QCD effects is crucial to perform the EW precision measurements
- Factorizing the Drell-Yan production cross section from the decay kinematics

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi$$
$$+\frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta$$
$$+A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}$$

CS frame

A_0-A_2 is non-zero for QCD calculations beyond NLO: Lam-Tung relation violated



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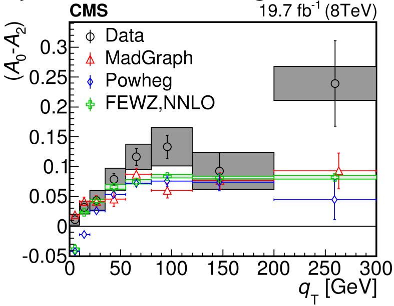

Phys. Lett. B 750 (2015) 154

Angular event weighting

- Observable: weighted A_{FB} (Eur. Phys. J. C67, (2010) 321) (also used by CDF measurement)
- For each event with cosθ=c, define two weights:

$$w_D = \frac{1}{2}\frac{c^2}{(1+c^2+h)^3}, \quad h = 0.5A_0(1-3c^2)$$

$$w_N = \frac{1}{2}\frac{|c|}{(1+c^2+h)^2}.$$

$$D_F = \sum_{c>0} w_D, D_B = \sum_{c<0} w_D.$$

$$N_F = \sum_{c>0} w_N, N_B = \sum_{c<0} w_N.$$

$$A_{FB} = \frac{3}{8}\frac{N_F - N_B}{D_F + D_B}$$

- **In 4π, Raw A_{FB} = Weighted A_{FB} = Weighted A_{FB} within lepton acceptance**

  => less sensitive to cosθ acceptance modeling
- Also, weighted A_{FB} yield smaller stat. uncertainty of extracted $\sin^2\theta_{eff}$

The slide is from:
https://indico.cern.ch/event/661916/contributions/2702568/attachments/1536039/2406301/171005_WmW.pdf