W and Z Production (inclusive, exclusive, and diboson) at CMS

PING TAN on behalf of the CMS collaboration

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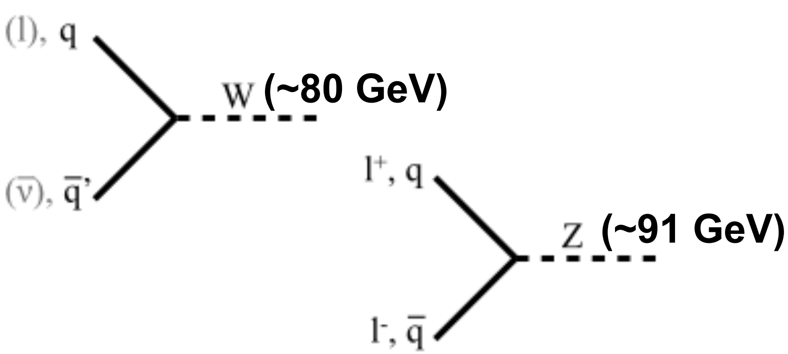
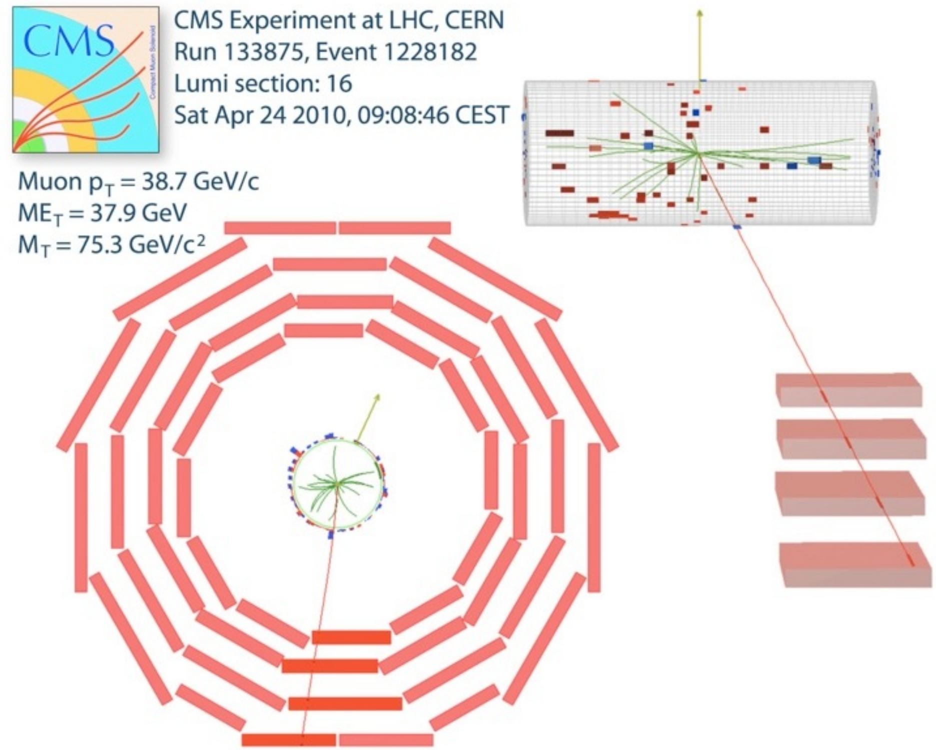
La Thuile 2016 - Aosta Valley, Italy, Mar. 6-12, 2016

Introduction

- Started with a handful of events at W/Z discoveries (UA1/UA2)
- Hadron collider:
  dominant production via quark anti-quark annihilation;
  clean leptonic final state





- **LHC is a W/Z factory**

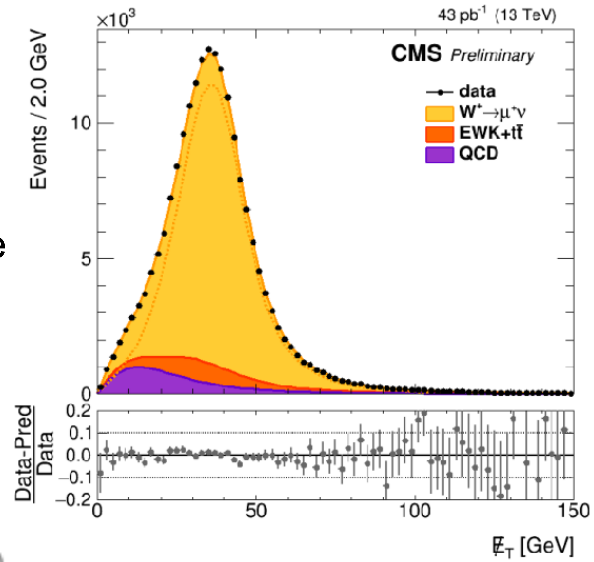
  → ~ 100 million W(μν)
  → ~ 10 million Z(μμ) (recorded by CMS in LHC Run I.)

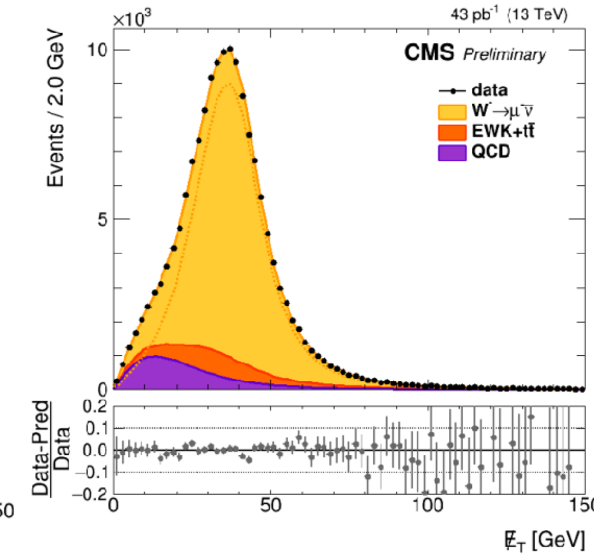
W: high p_T - lepton + Missing E_T
Z: two high p_T-leptons

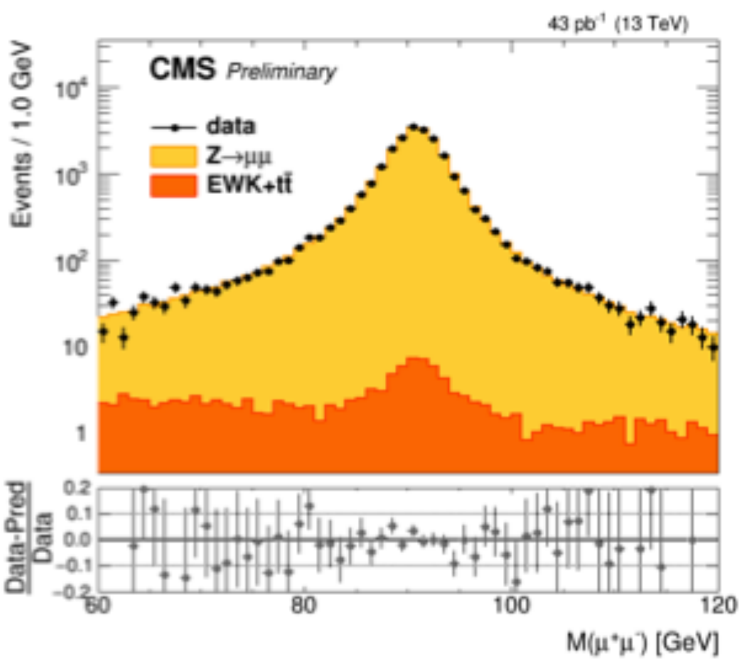
Inclusive W/Z production

- **Standard candles**
- Single lepton trigger

- W: signal extraction with fit to the missing transverse momentum: negative of vector sum of all reconstructed particles.





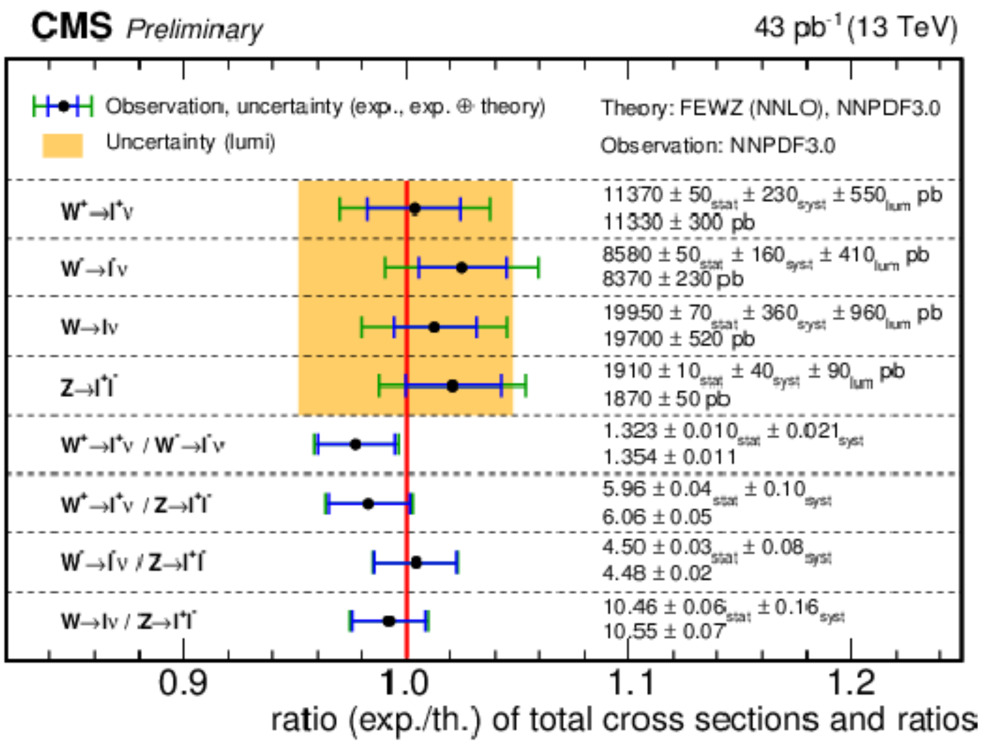


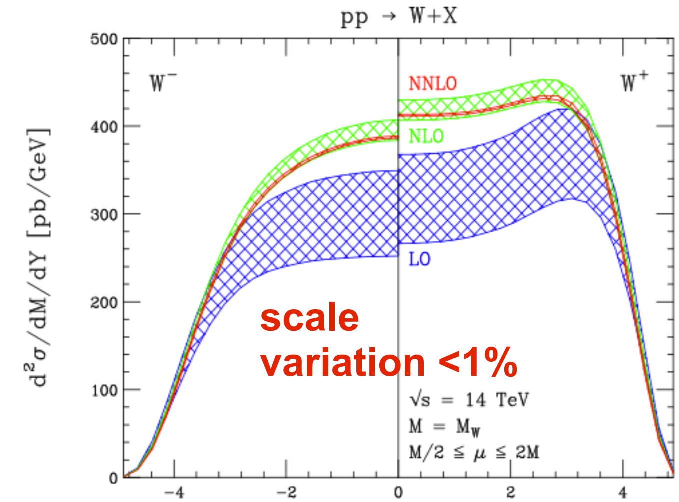
- Z: almost background free
- Counting events around Z-pole

- Both fiducial cross section and total cross section, different ratios, W/Z, etc.

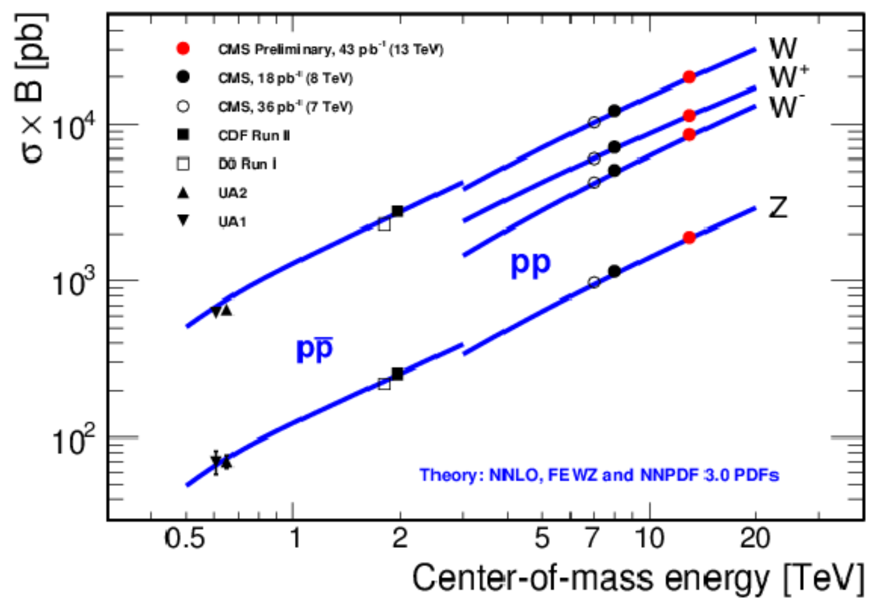
CMS-PAS-SMP-15-004

Inclusive W/Z production (cont.)





C. Anastasiou et. al., Phys. Rev. D69, 094008 (2004)

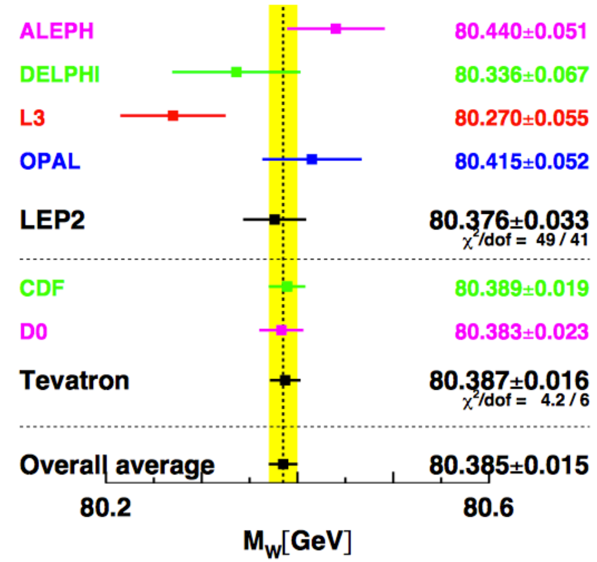


- With only 43 pb^{-1}, it can challenge the state-of-the-art theoretical predictions: <1% scale variation at NNLO.

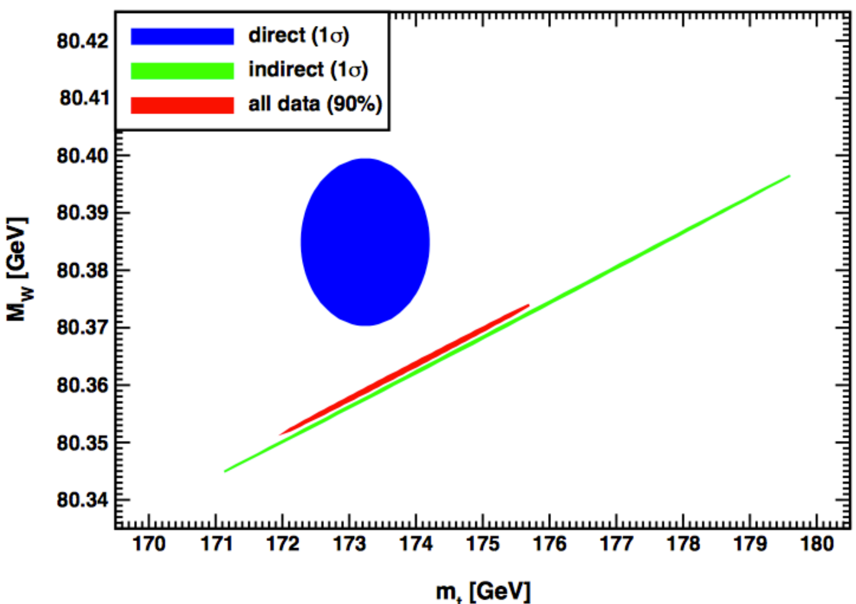
W mass

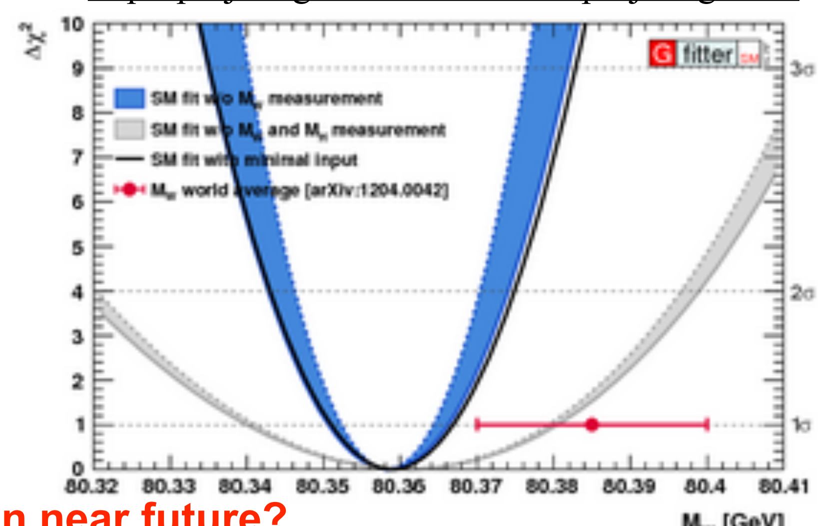
Many more high-precision W/Z measurements
→ Fundamental parameters: W mass, weak mixing angle
→ Unique inputs for PDF constraints
→ Test pQCD, …

Strong interplay between theoretical community and experiments, pushing the understanding of detector performance to extreme



http://project-gfitter.web.cern.ch/project-gfitter/



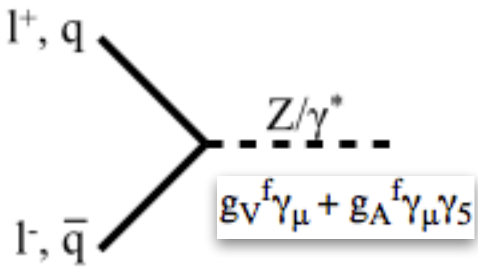


Reach 10 MeV precision in near future?

Forward-backward Asymmetry & Weak Mixing Angle

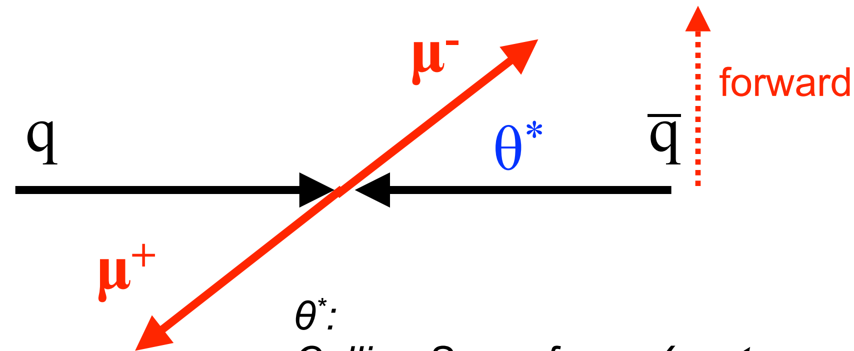
arXiv: 1601.04768

- Forward-backward asymmetry
- V-A structure in Z/γ^*-fermion couplings

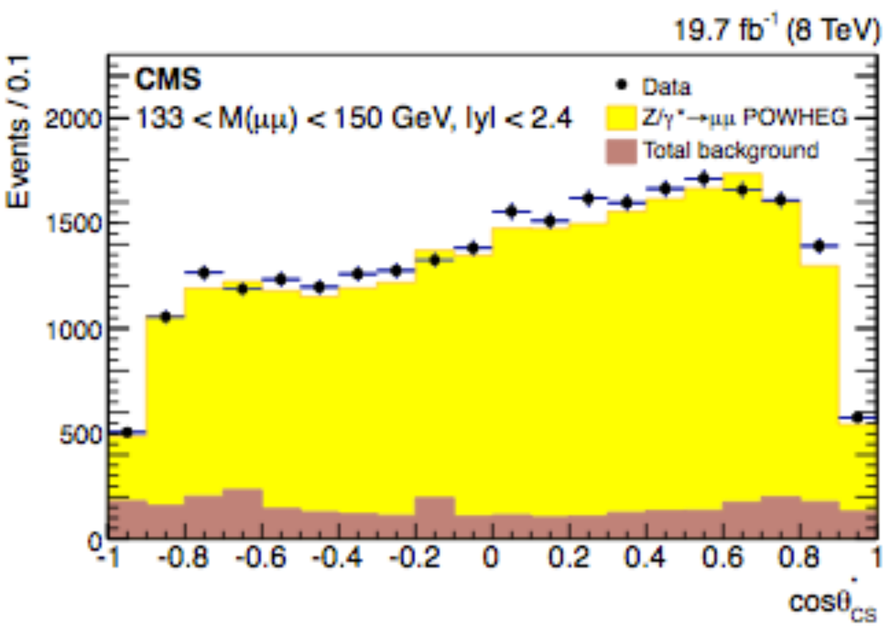


$$g_V{}^f\gamma_\mu + g_A{}^f\gamma_\mu\gamma_5$$

: $g_V{}^f = I_3 - 2Q_f \sin^2\theta_W$



θ^*:
Collins-Soper frame ***(w.r.t incoming quark)***



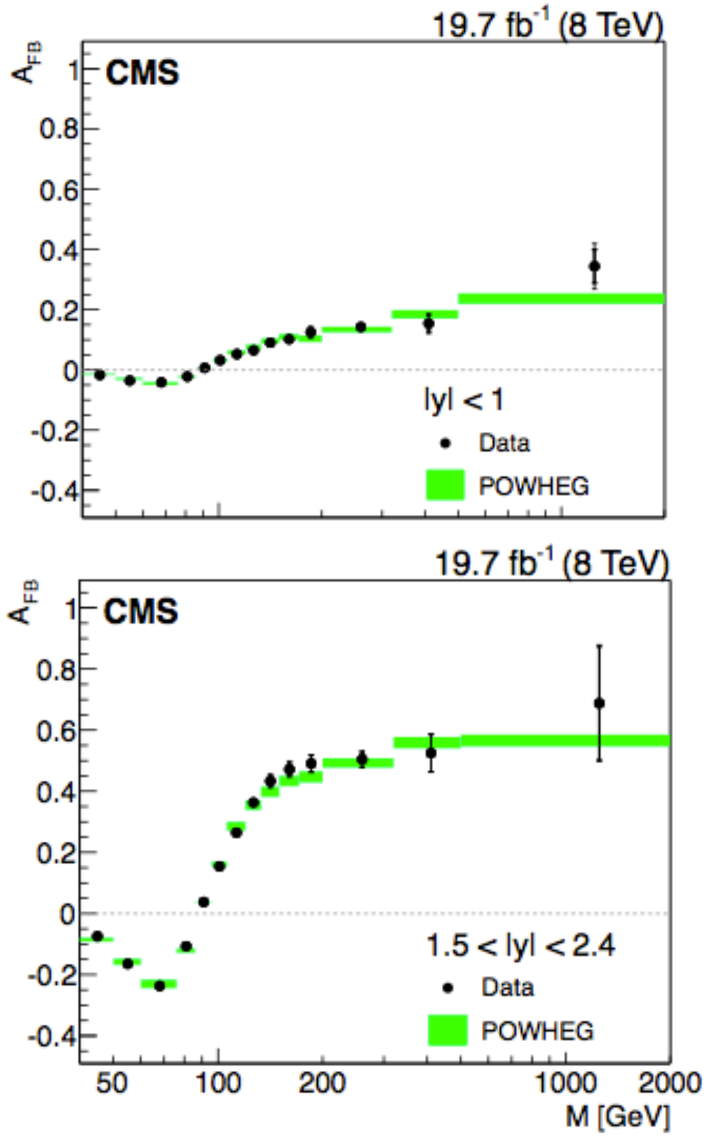
$$\frac{d\sigma}{d(\cos\theta^*)} = A(1+\cos^2\theta^*) + B\cos\theta^*$$

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

σ_F: $\cos(\theta^*)>0$

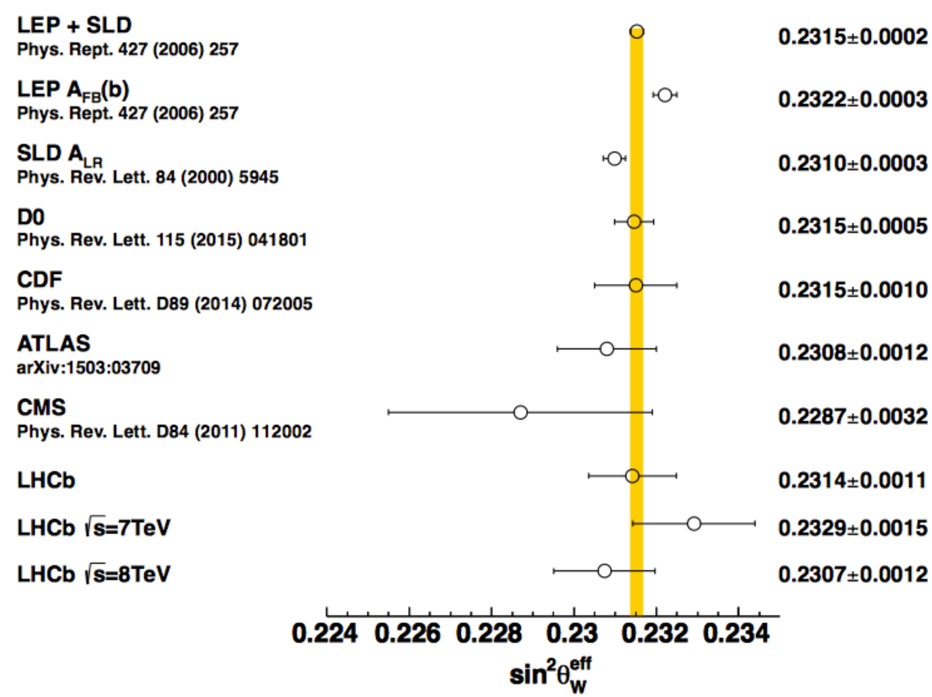
Observed $\cos(\theta^*)$ modified by acceptance, efficiency, and other detector effects

Forward-backward Asymmetry & Weak Mixing Angle



- Dilution (due to unknown incoming quark direction) is significant at LHC, particularly for ATLAS and CMS.
- Continued efforts to extract weak mixing angle in same dataset
  improved lepton calibration,
  several innovations (A. bodek et. al., Eur.Phys.J. C67 (2010) , arXiv:1507.02470, etc),
  explore optimal lepton identification,

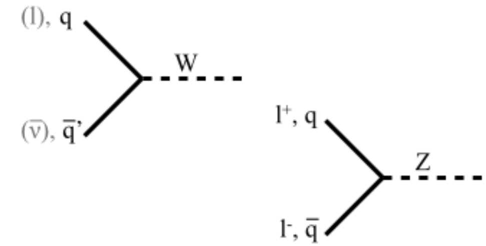
Expected statistical precision < 0.0004

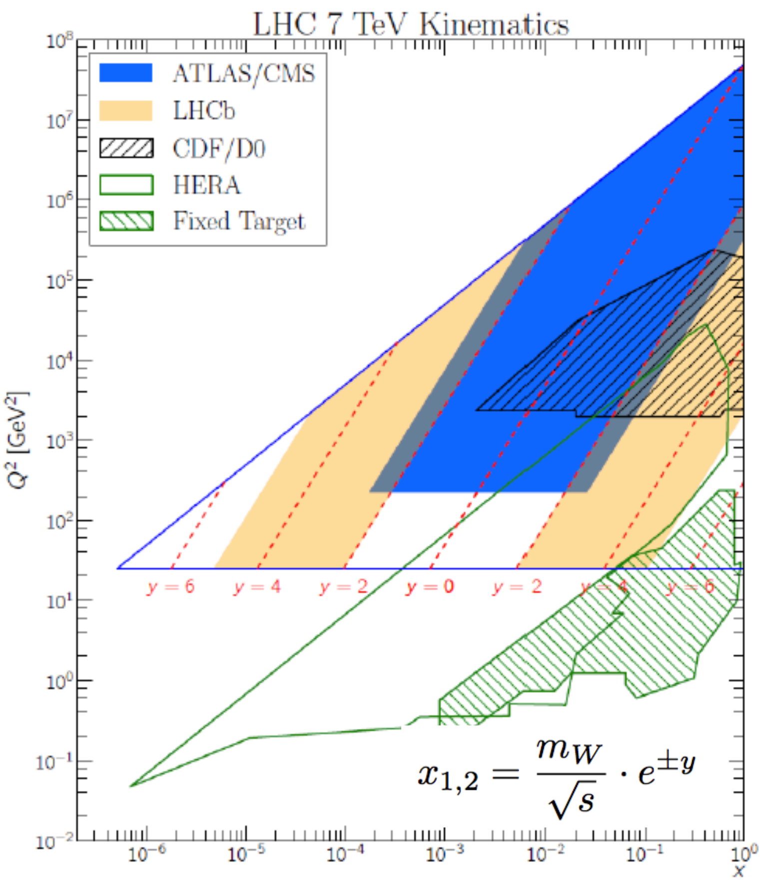


Constraining PDFs

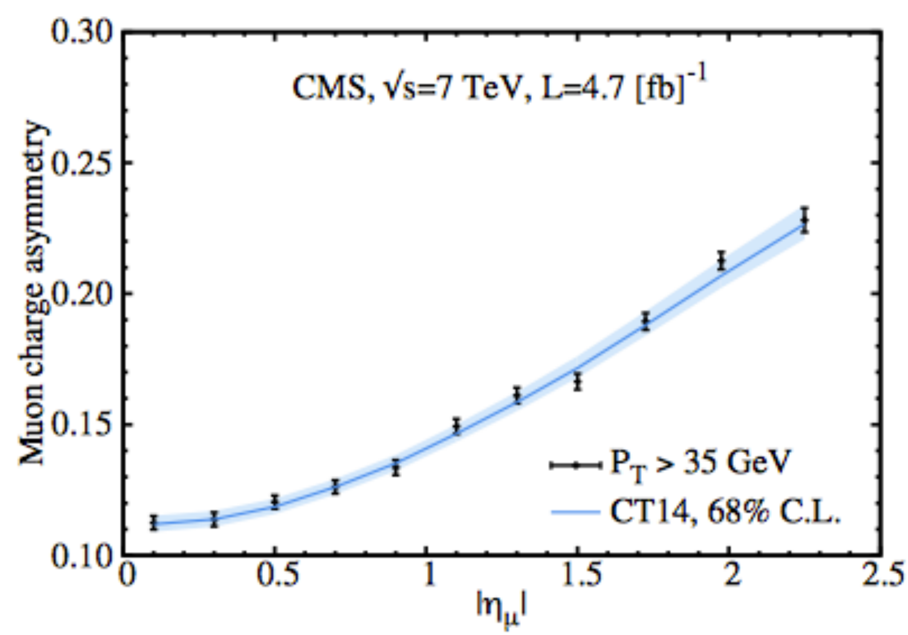
$$\sigma(pp \to X) = \sum_{a,b} \int dx_1 dx_2 \cdot f_a(x_1, Q^2) f_b(x_2, Q^2) \cdot \hat{\sigma}(q_a q_b \to X)$$

f_a, f_b*: PDF** ***hard interaction





- **Test high-precision perturbative QCD predictions at the NNLO:**
  $\alpha_S^2(Z) \sim \alpha(Z)$,
  photon-induced background,
- W charge asymmetry, Z-boson transverse momentum & rapidity

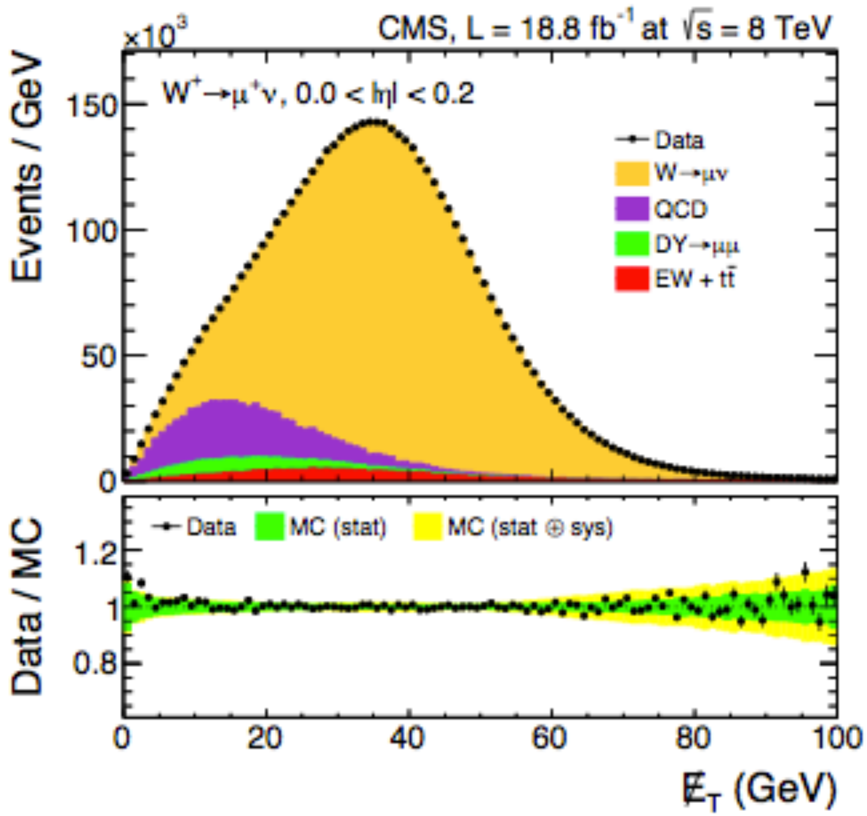


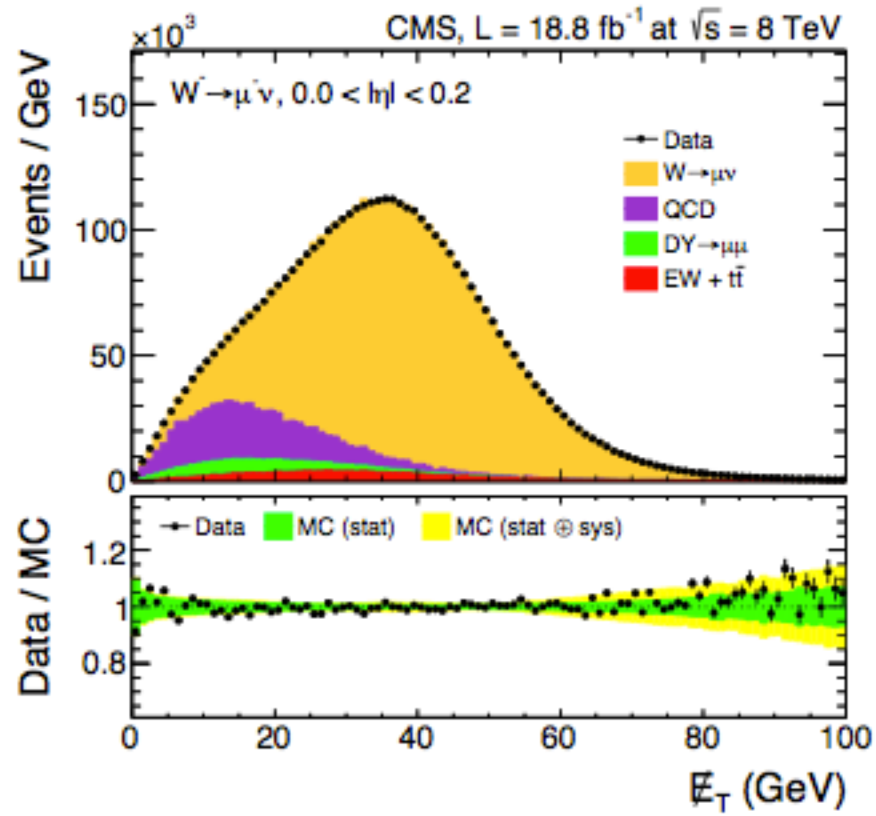
Constraining PDFs - W Differential Cross Section

- A measurement with ~100 M W candidates

arXiv: hep-ex/1603.01803

$$\sigma_\eta^\pm = \frac{1}{2\Delta\eta}\frac{N^\pm}{\epsilon^\pm\epsilon_{\mathrm{FSR}}^\pm\mathcal{L}_{\mathrm{int}}}$$

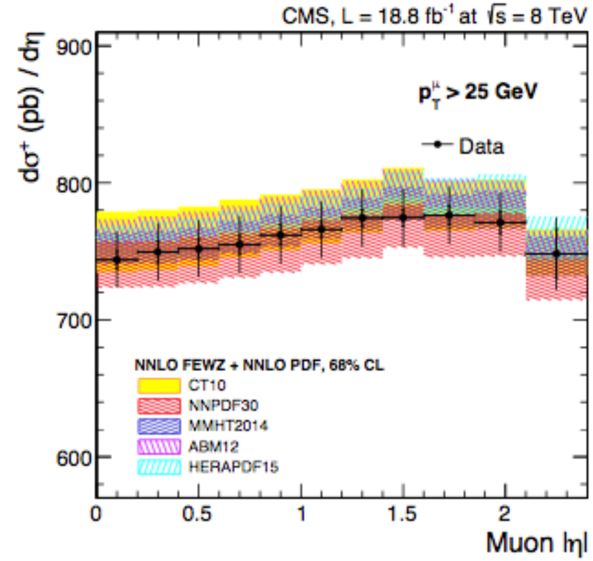


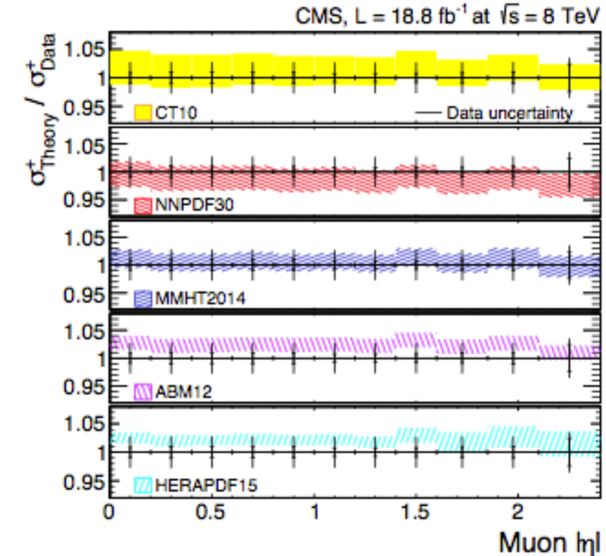


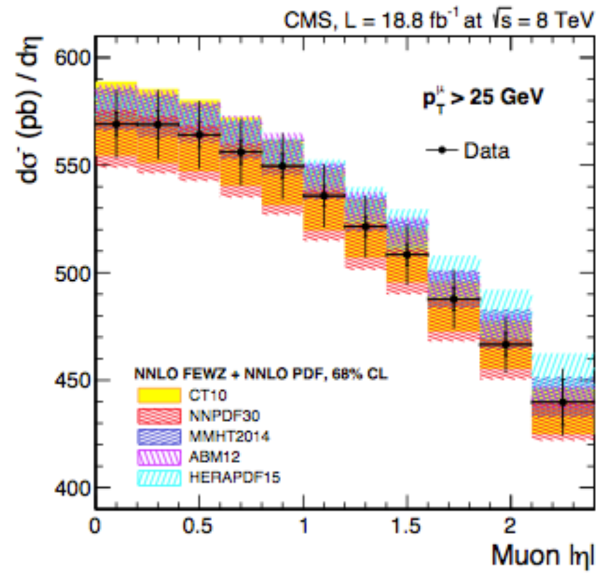
Constraining PDFs - W Charge Asymmetry

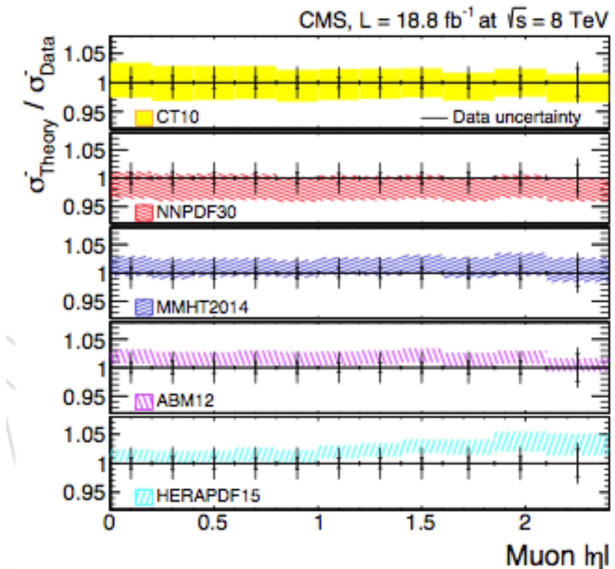
- A measurement with ~100 M W candidates
- Fiducial cross section (correct for final-state radiation)
- Total uncertainties are between 0.5-1.0% (excluding lumi. uncert. 2.6%)

$$\sigma_\eta^\pm = \frac{1}{2\Delta\eta}\frac{N^\pm}{\epsilon^\pm \epsilon^\pm_{\mathrm{FSR}} \mathcal{L}_{\mathrm{int}}}$$





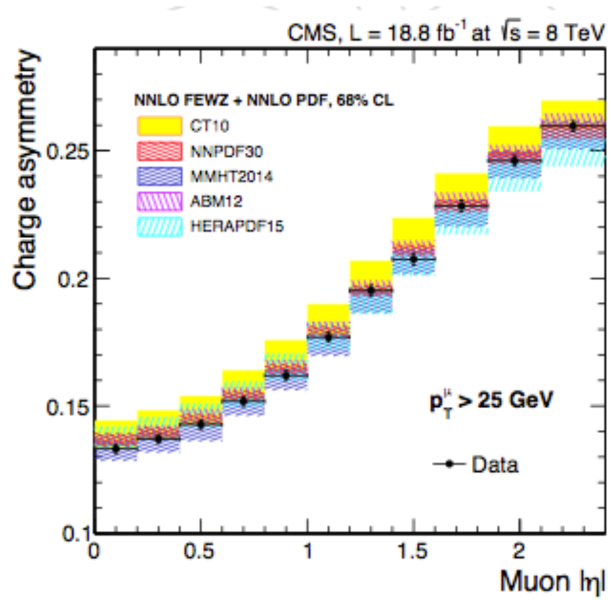


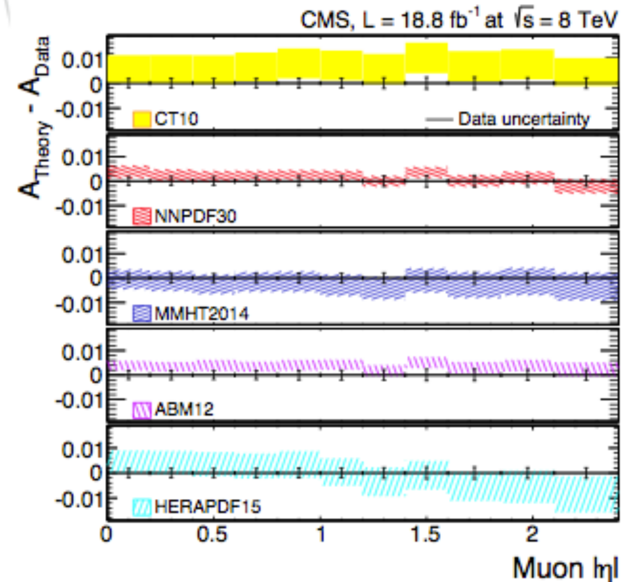


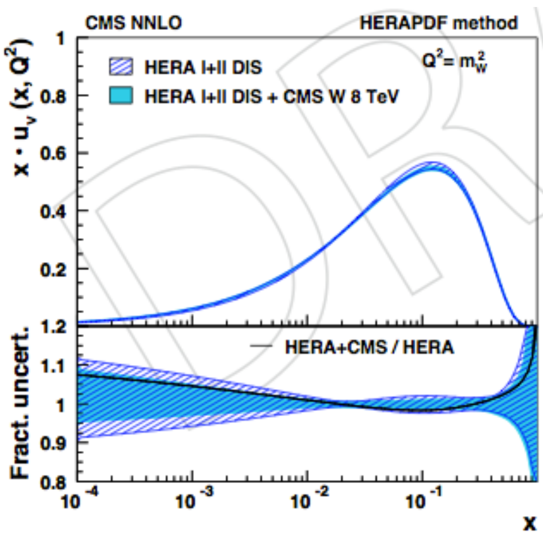
Constraining PDFs - W Differential Cross Section

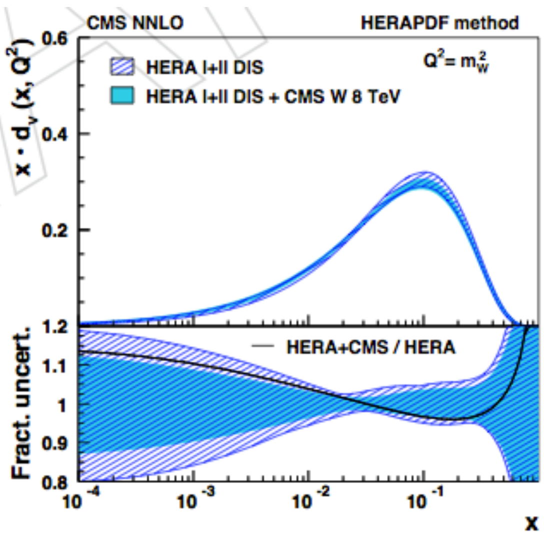
- A measurement with ~100 M W candidates
- Charge asymmetry: derived from cross section considering correlated and uncorrected sys. uncert.

$$\mathcal{A}(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$$









NNLO QCD analysis with charge asymmetry only

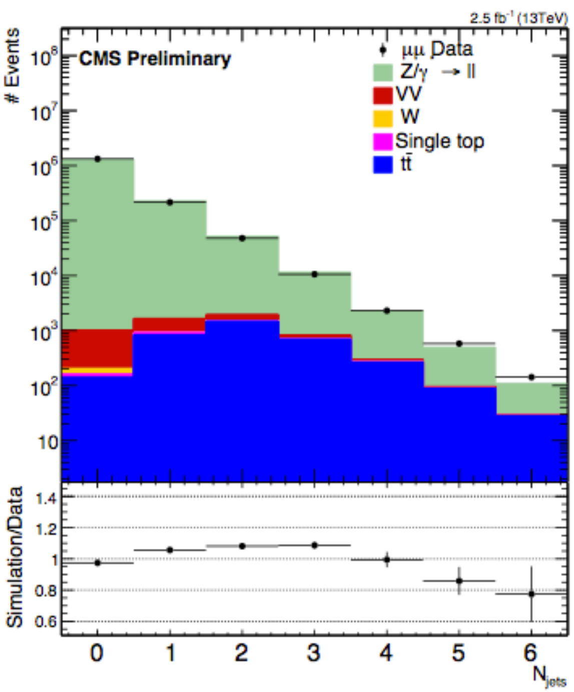
Z(μμ)+jets at 13 TeV

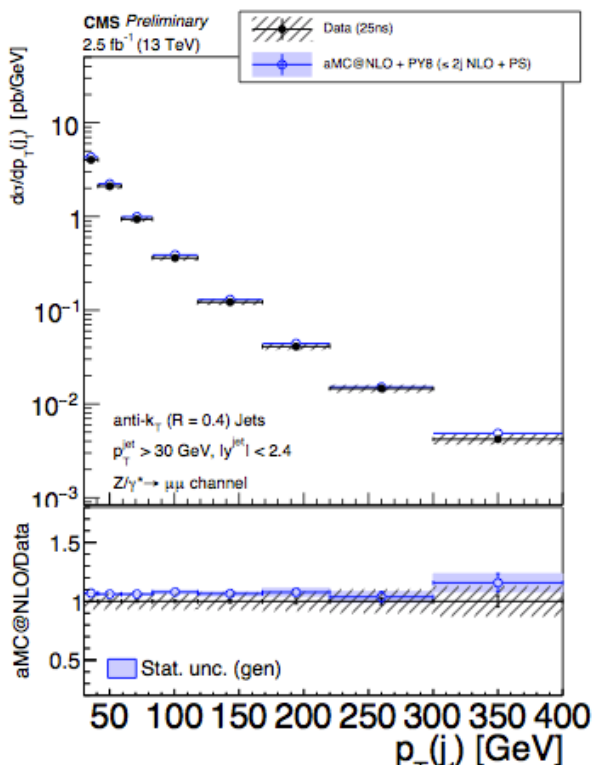
- Ideal testbed for pQCD and various MC tools

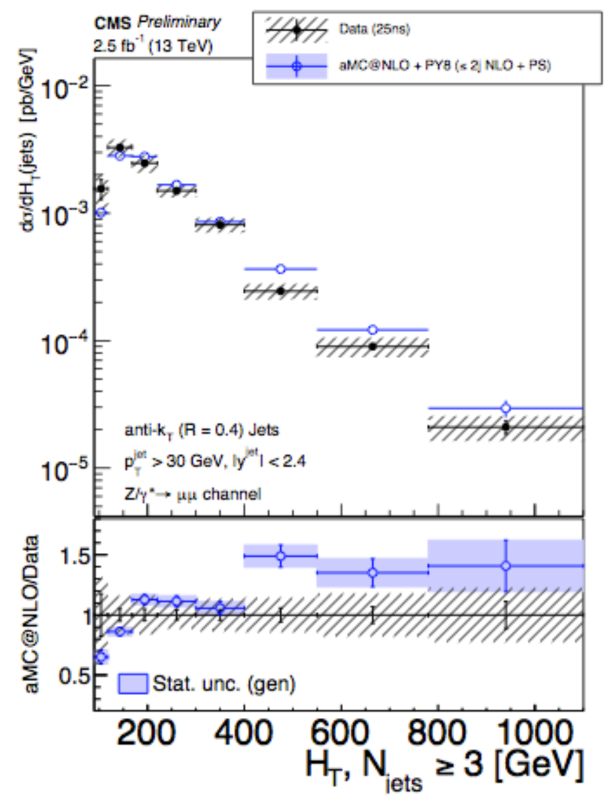
CMS-PAS-SMP-15-010

- Selection:
  muons pT>20 GeV, |η|<2.4; jets pT>30 GeV, |η|<2.4; +/-20 GeV mass window around Z pole.
- **ttbar background is significant at high jet multiplicity.**
- **Updated results with electron channels, W+jets, and many more are coming soon**

H_T: scalar sum of jet p_T

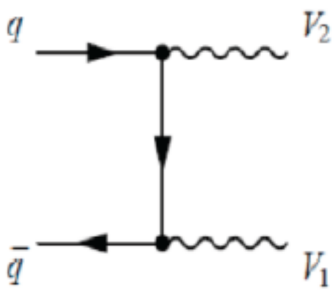


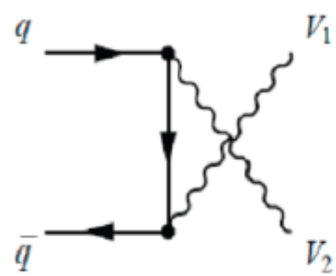


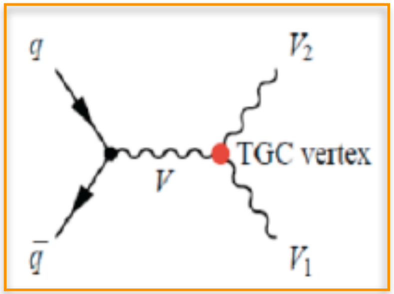


Diboson Physics

- Trilinear gauge couplings (TGC) determined by SM gauge structure, $SU(2)_L \times U(1)_Y$:
- Generalized triple gauge vertices, anomalous TGC (aTGC).
  predicted at 10^{-3} or less (SM)
- **Deviation of TGC → new physics**







Coupling	Parameters	Channel
WWγ	$\Delta\kappa_\gamma$, λ_γ	WW, Wγ
WWZ	Δg_1^Z, $\Delta\kappa_Z$, λ_Z	WW, WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
ZγZ	f_4^γ, f_5^γ	ZZ

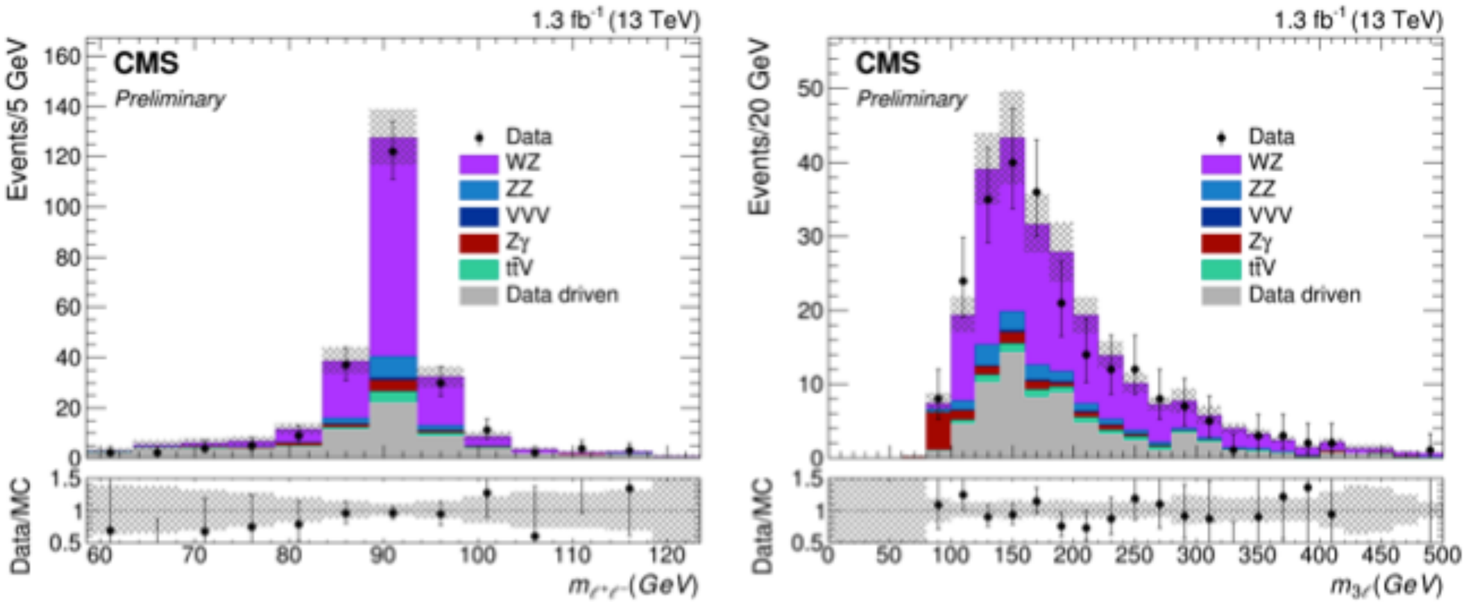
Allowed in SM

Forbidden at tree level

WZ Production Cross Section at 13 TeV

- ✦ Explore three decay modes: W→lν, Z→ll
- ✦ Including both electron and muon decays.
- ✦ Data-driven jet fake background

CMS-PAS-SMP-15-006



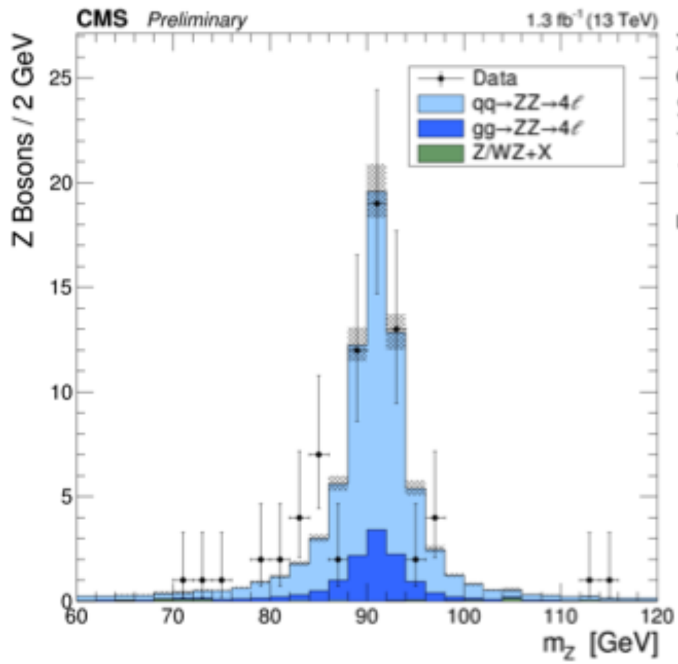
$$\sigma(\mathrm{pp} \to \mathrm{WZ}) = 36.8 \pm 4.6\,(\mathrm{stat})^{+8.1}_{-6.2}\,(\mathrm{syst}) \pm 0.6\,(\mathrm{theo}) \pm 1.7\,(\mathrm{lum})\,\mathrm{pb}$$

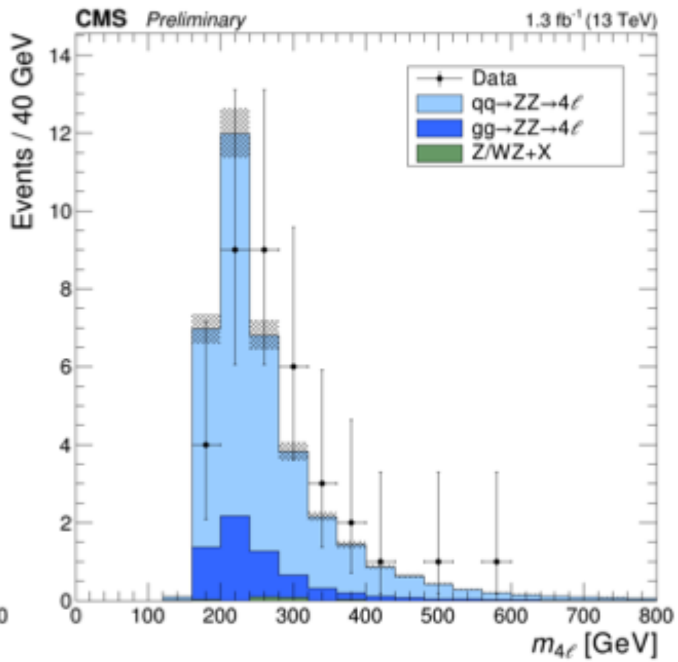
Consistent to NLO prediction of 42.7+1.6-0.8 pb (MCFM+nlo NNPDF3.0)

ZZ Production Cross Section at 13 TeV

- ZZ→llll, (l =e, μ)
  almost background free

CMS-PAS-SMP-15-005



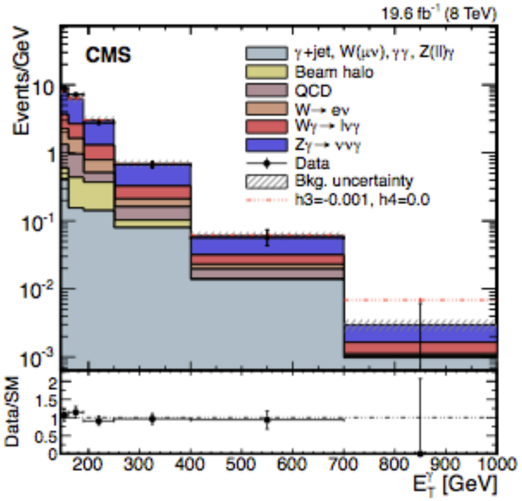


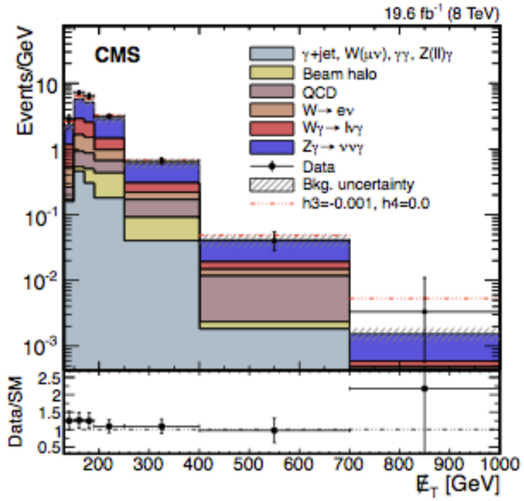
$$\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 16.7^{+2.9}_{-2.6}\,(\mathrm{stat})^{+0.7}_{-0.5}\,(\mathrm{syst}) \pm 0.3\,(\mathrm{theo}) \pm 0.8\,(\mathrm{lum})\,\mathrm{pb}$$

Consistent to NLO prediction of 16.7+0.7-0.5 pb (MCFM+nlo NNPDF3.0)

- **Improved results with full 2015 CMS data are coming soon**

Physics - Z(νν)γ Production

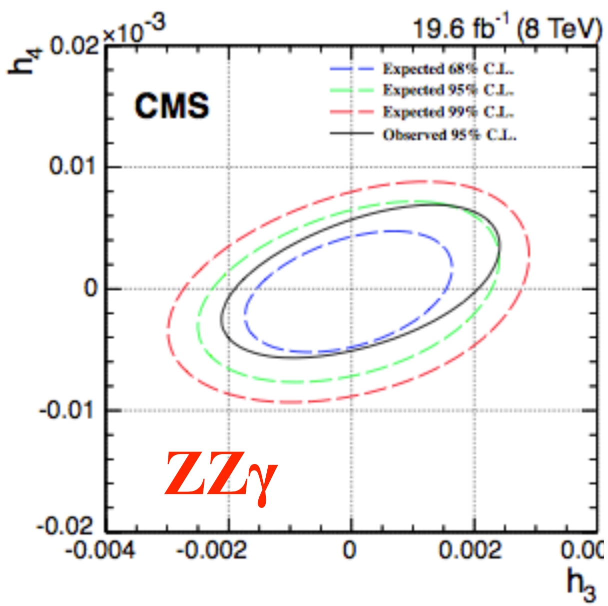


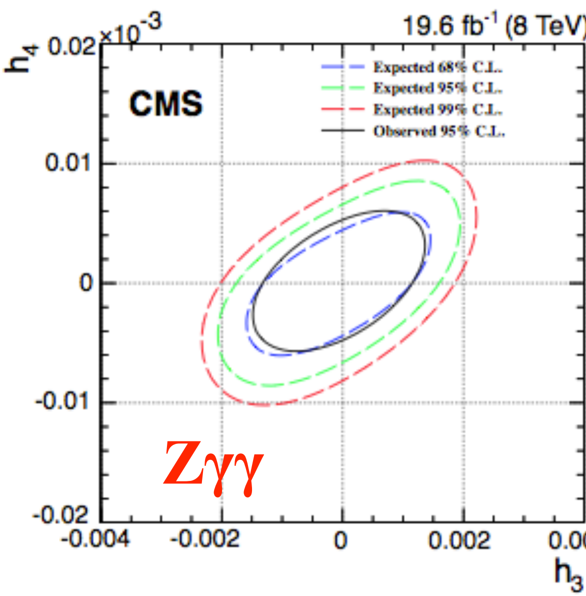


- Photon pT spectrum or MET are using as observables.
- Dominant background Wγ, W, jet fake, etc.

Coupling	Parameters	Channel
WWγ	$\Delta\kappa_\gamma$, λ_γ	WW, Wγ
WWZ	Δg_1^Z, $\Delta\kappa_Z$, λ_Z	WW, WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
ZγZ	f_4^γ, f_5^γ	ZZ

- Cross section is consistent to the SM prediction at NNLO: 50.0+2.4-2.2 pb
- Most stringent constraints to date on anomalous neutral tripple gauge couplings.



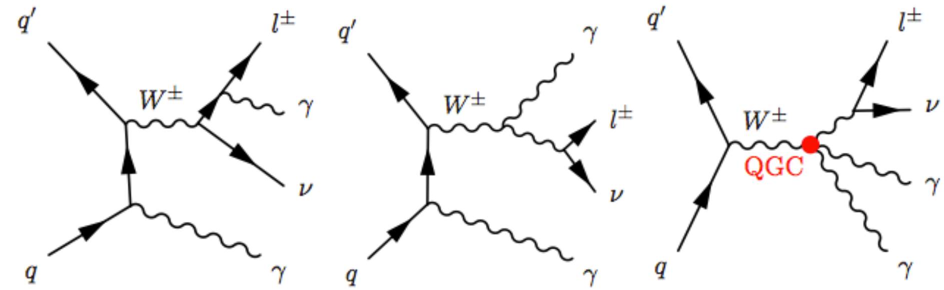


arXiv:1602.07152

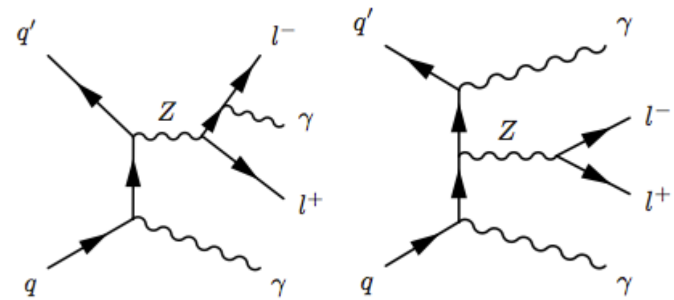
Triboson production - Quartic Gauge Coupling

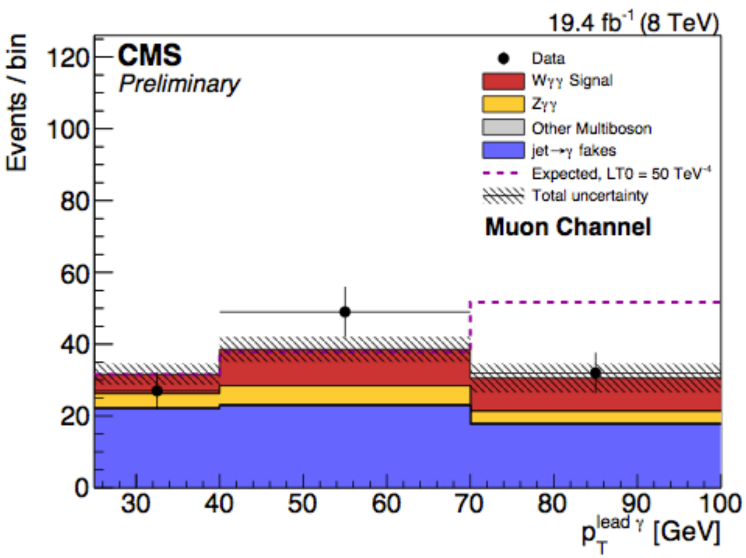
CMS-PAS-SMP-15-008

- WWWW, WWZZ, WWZγ, WWγγ allowed in SM
- Wγγ production diagrams at tree level



- Zγγ production diagrams at tree level





$$\sigma^{\text{fid}}_{W^{\pm}\gamma\gamma} \cdot \text{BR}\,(\text{W} \to \ell\nu) = 6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})\ \text{fb}$$

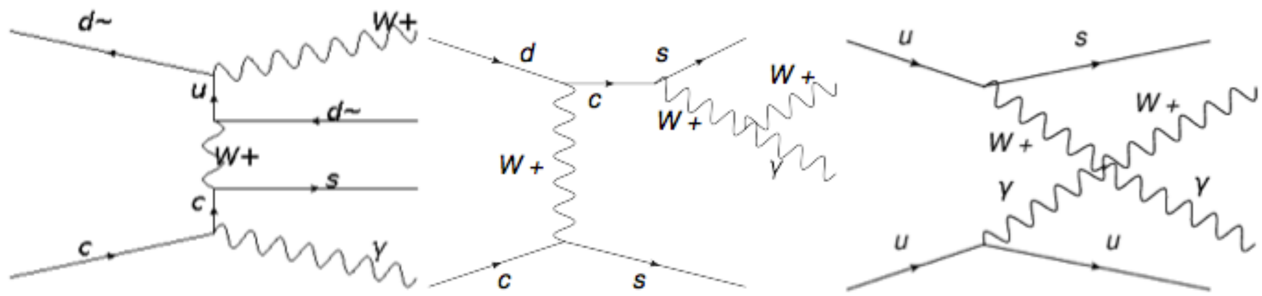
$$\sigma^{\text{fid}}_{Z\gamma\gamma} \cdot \text{BR}\,(\text{Z} \to \ell\ell) = 12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})\ \text{fb}$$

- **Cross section consistent to NLO predictions.**
- **No significant deviation of leading photon pT spectrum from SM.**

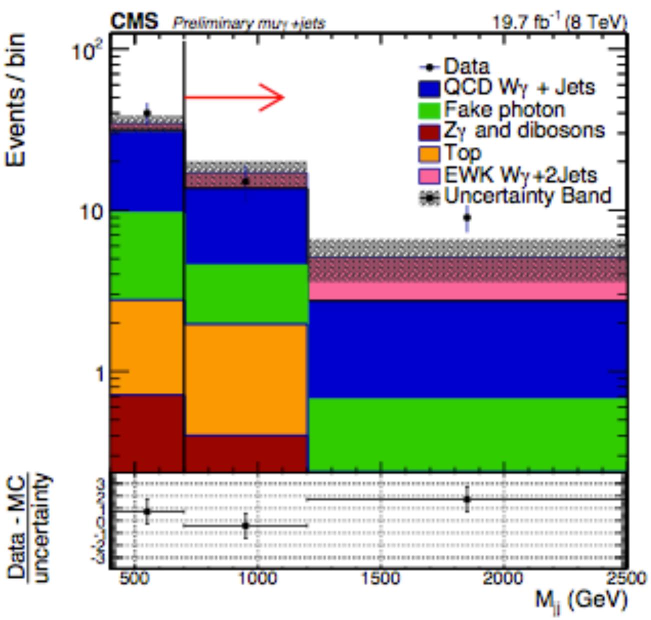
Electro-weak Induced Wγ

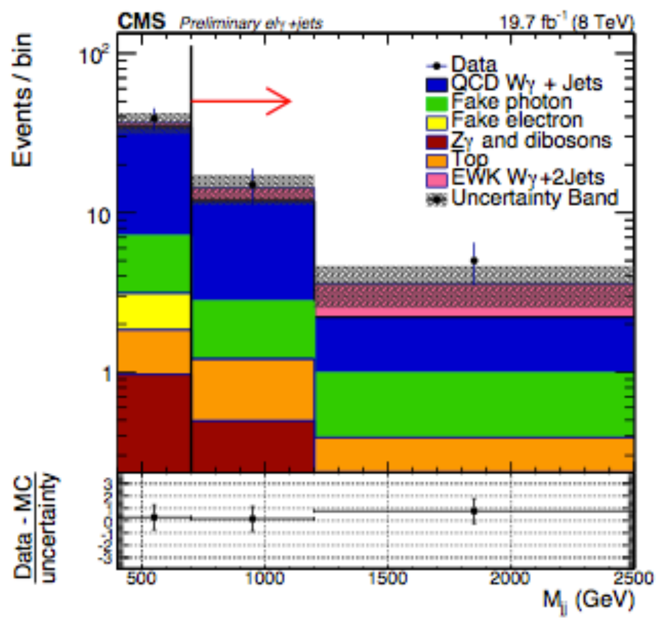
CMS-PAS-SMP-14-011

- Unique physics opportunity at LHC
- Vector-boson fusion signature: electro-weak induced Wγ production
- Disentangle interference between VBF(VBS) signature or tri-boson production by invariant mass of dijet system.



(a) Bremsstrahlung (b) With TGC (c) With QGC



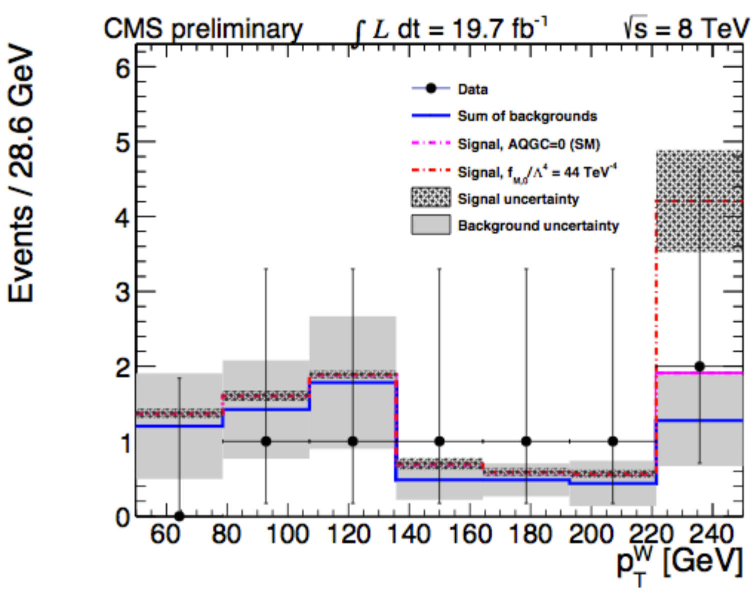


- Single lepton trigger
- Impose large m(jj) value, Zeppenfeld variable, and others to enhance electro-weak contribution.
- **The significance of the electro-weak Wγ component is at 2.7 sigma level.**

Electro-weak induced Wγ Production

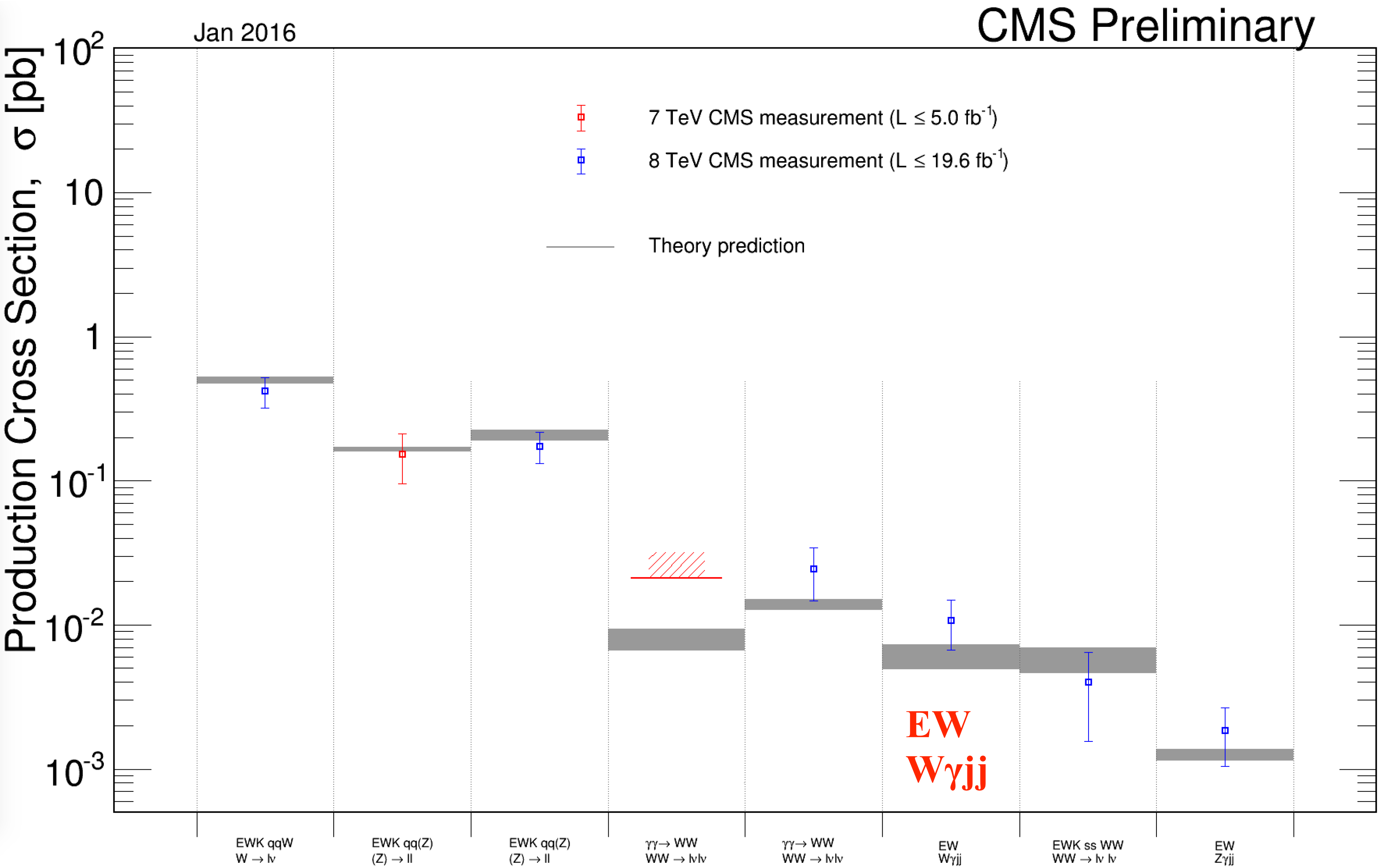
- Setting limits on dimension-8 aQGC parameters, taking an effective Lagrangian approach

$$
\begin{aligned}
\mathcal{L}_{AQGC} = \; & \frac{f_{M,0}}{\Lambda^4}\,\mathrm{Tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] + \frac{f_{M,1}}{\Lambda^4}\,\mathrm{Tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
+ \; & \frac{f_{M,2}}{\Lambda^4}\left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] + \frac{f_{M,3}}{\Lambda^4}\left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
+ \; & \frac{f_{M,4}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger\mathbf{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu} + \frac{f_{M,5}}{\Lambda^4} \times \frac{1}{2}\left[(D_\mu\Phi)^\dagger\mathbf{W}_{\beta\nu}D^\nu\Phi + (D^\nu\Phi)^\dagger\mathbf{W}_{\beta\nu}D_\mu\Phi\right] \times B^{\beta\mu} \\
+ \; & \frac{f_{M,6}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger\mathbf{W}_{\beta\nu}\mathbf{W}^{\beta\nu}D^\mu\Phi\right] + \frac{f_{M,7}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger\mathbf{W}_{\beta\nu}\mathbf{W}^{\beta\mu}D^\nu\Phi\right] \\
+ \; & \frac{f_{T,0}}{\Lambda^4}Tr\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] \times Tr\left[\mathbf{W}_{\alpha\beta}\mathbf{W}^{\alpha\beta}\right] + \frac{f_{T,1}}{\Lambda^4}Tr\left[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}\right] \times Tr\left[\mathbf{W}_{\mu\beta}\mathbf{W}^{\alpha\nu}\right] \\
+ \; & \frac{f_{T,2}}{\Lambda^4}Tr\left[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}\right] \times Tr\left[\mathbf{W}_{\beta\nu}\mathbf{W}^{\nu\alpha}\right] + \frac{f_{T,5}}{\Lambda^4}Tr\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
+ \; & \frac{f_{T,6}}{\Lambda^4}Tr\left[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} + \frac{f_{T,7}}{\Lambda^4}Tr\left[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}. \qquad (2)
\end{aligned}
$$



Observed Limits	Expected Limits
-77 (TeV^{-4}) < f_{M0}/Λ^4 < 74 (TeV^{-4})	-47 (TeV^{-4}) < f_{M0}/Λ^4 < 44 (TeV^{-4})
-125 (TeV^{-4}) < f_{M1}/Λ^4 < 129 (TeV^{-4})	-72 (TeV^{-4}) < f_{M1}/Λ^4 < 79 (TeV^{-4})
-26 (TeV^{-4}) < f_{M2}/Λ^4 < 26 (TeV^{-4})	-16 (TeV^{-4}) < f_{M2}/Λ^4 < 15 (TeV^{-4})
-43 (TeV^{-4}) < f_{M3}/Λ^4 < 44 (TeV^{-4})	-25 (TeV^{-4}) < f_{M3}/Λ^4 < 27 (TeV^{-4})
-40 (TeV^{-4}) < f_{M4}/Λ^4 < 40 (TeV^{-4})	-23 (TeV^{-4}) < f_{M4}/Λ^4 < 24 (TeV^{-4})
-65 (TeV^{-4}) < f_{M5}/Λ^4 < 65 (TeV^{-4})	-39 (TeV^{-4}) < f_{M5}/Λ^4 < 39 (TeV^{-4})
-129 (TeV^{-4}) < f_{M6}/Λ^4 < 129 (TeV^{-4})	-77 (TeV^{-4}) < f_{M6}/Λ^4 < 77 (TeV^{-4})
-164 (TeV^{-4}) < f_{M7}/Λ^4 < 162 (TeV^{-4})	-99 (TeV^{-4}) < f_{M7}/Λ^4 < 97 (TeV^{-4})
-5.4 (TeV^{-4}) < f_{T0}/Λ^4 < 5.6 (TeV^{-4})	-3.2 (TeV^{-4}) < f_{T0}/Λ^4 < 3.4 (TeV^{-4})
-3.7 (TeV^{-4}) < f_{T1}/Λ^4 < 4.0 (TeV^{-4})	-2.2 (TeV^{-4}) < f_{T1}/Λ^4 < 2.5 (TeV^{-4})
-11 (TeV^{-4}) < f_{T2}/Λ^4 < 12 (TeV^{-4})	-6.3 (TeV^{-4}) < f_{T2}/Λ^4 < 7.9 (TeV^{-4})
-3.8 (TeV^{-4}) < f_{T5}/Λ^4 < 3.8 (TeV^{-4})	-2.3 (TeV^{-4}) < f_{T5}/Λ^4 < 2.4 (TeV^{-4})
-2.8 (TeV^{-4}) < f_{T6}/Λ^4 < 3.0 (TeV^{-4})	-1.7 (TeV^{-4}) < f_{T6}/Λ^4 < 1.9 (TeV^{-4})
-7.3 (TeV^{-4}) < f_{T7}/Λ^4 < 7.7 (TeV^{-4})	-4.4 (TeV^{-4}) < f_{T7}/Λ^4 < 4.7 (TeV^{-4})

Summary of Electro-weak Induced Processes



Summary and Conclusion

- Thanks LHC's excellent performance
- CMS has collected high-quality data in LHC Run I and ongoing Run II
- Probe fundamental parameters in the SM:
  W mass with unprecedented precision,
  Approaching LEP/SLD precision on weak mixing angle,
  A whole class of precision measurements to constraint PDFs,
  Testing pQCD and MC tools in V+jets, …
- A wide range of measurements to explore the gauge structure of the SM and search for anomalies beyond the SM:
  diboson/tri-boson production,
  electro-weak induced diboson production
- Continuously explore W/Z sector at the energy frontier and hope to see deviations to the SM