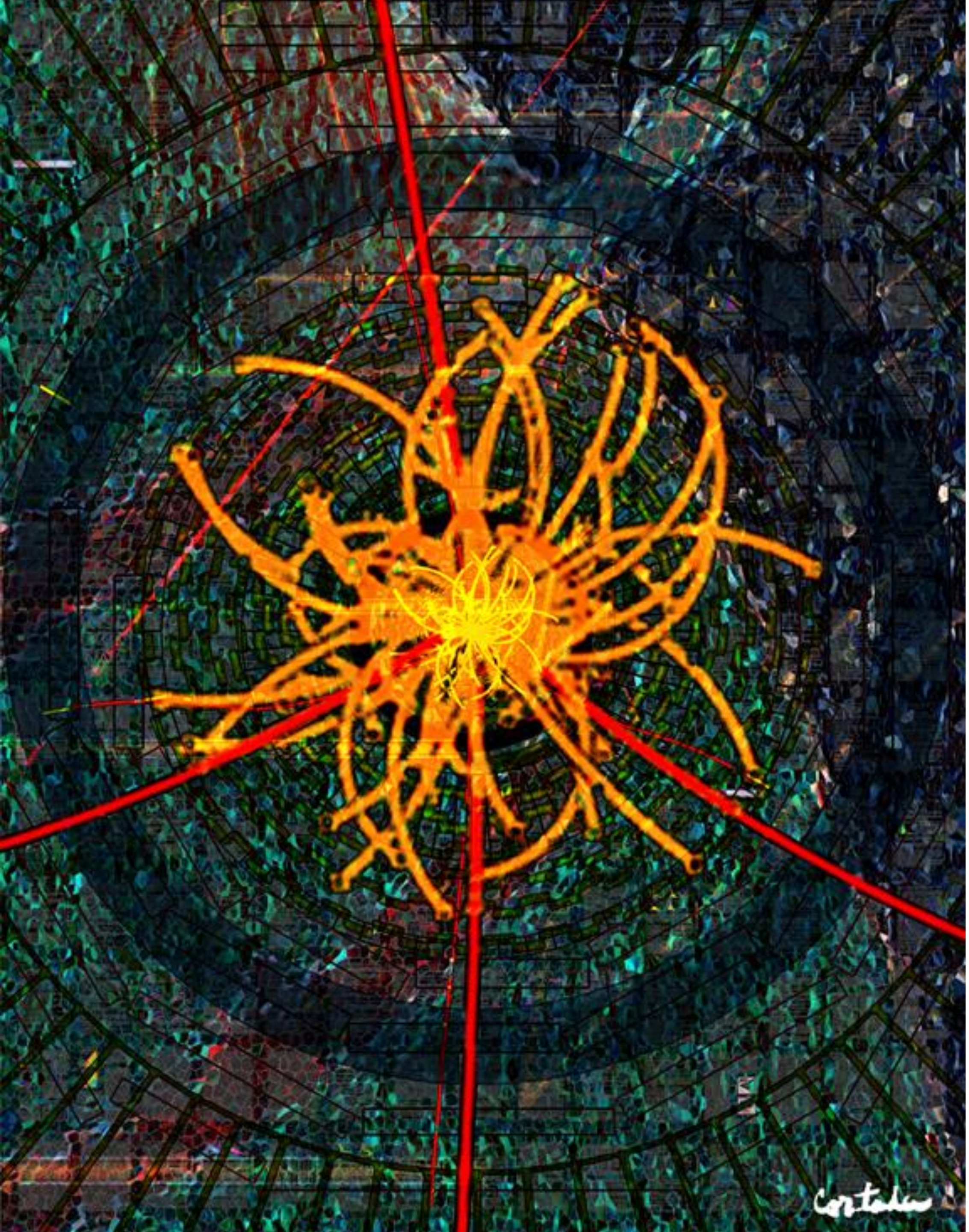


# Tests of the Electroweak Interactions at Hadron Colliders

Aspen Winter Conference

January 19, 2014

Jeffrey Berryhill (Fermilab)

On behalf of ATLAS, CDF, CMS, and DØ collaborations

Digital art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz) "In search of the Higgs boson: H -> ZZ"

# Outline

- Z and Drell-Yan Physics
  - Cross sections
  - $Sin^2\theta_{eff}$ & prospects
- W Physics
  - W mass
  - W asymmetry and PDFs
- Diboson Physics and Triple Gauge Couplings
  - Dimension 6 gauge boson effective field theory (EFT)
  - Observation of vector boson fusion production of the Z
  - Diboson cross sections
  - Triple gauge couplings
- Tribosons, VBS, and Quartic Gauge Couplings
  - Dim 8 gauge boson EFT
  - Triboson production and vector boson scattering results
  - VBS prospects for 13 TeV

Links for complete set of results:

CMS public electroweak results

ATLAS public electroweak results

CDF public electroweak results

D0 public electroweak results

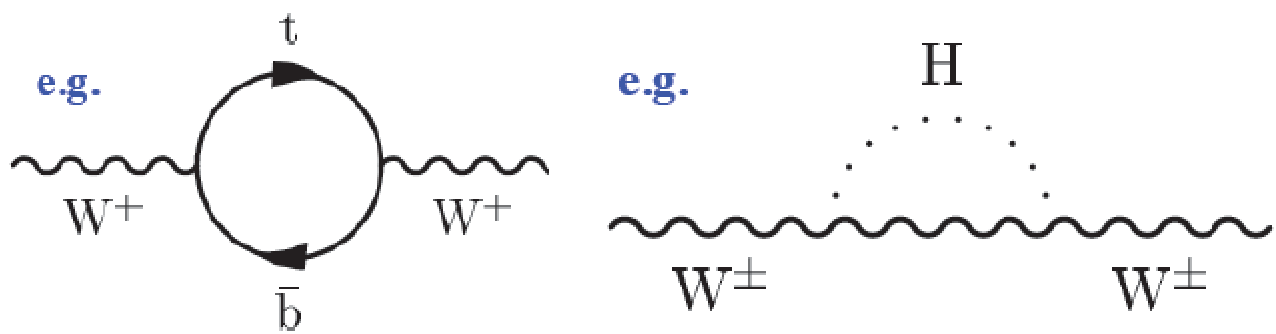
# State of the Electroweak Theory: Precision Frontier

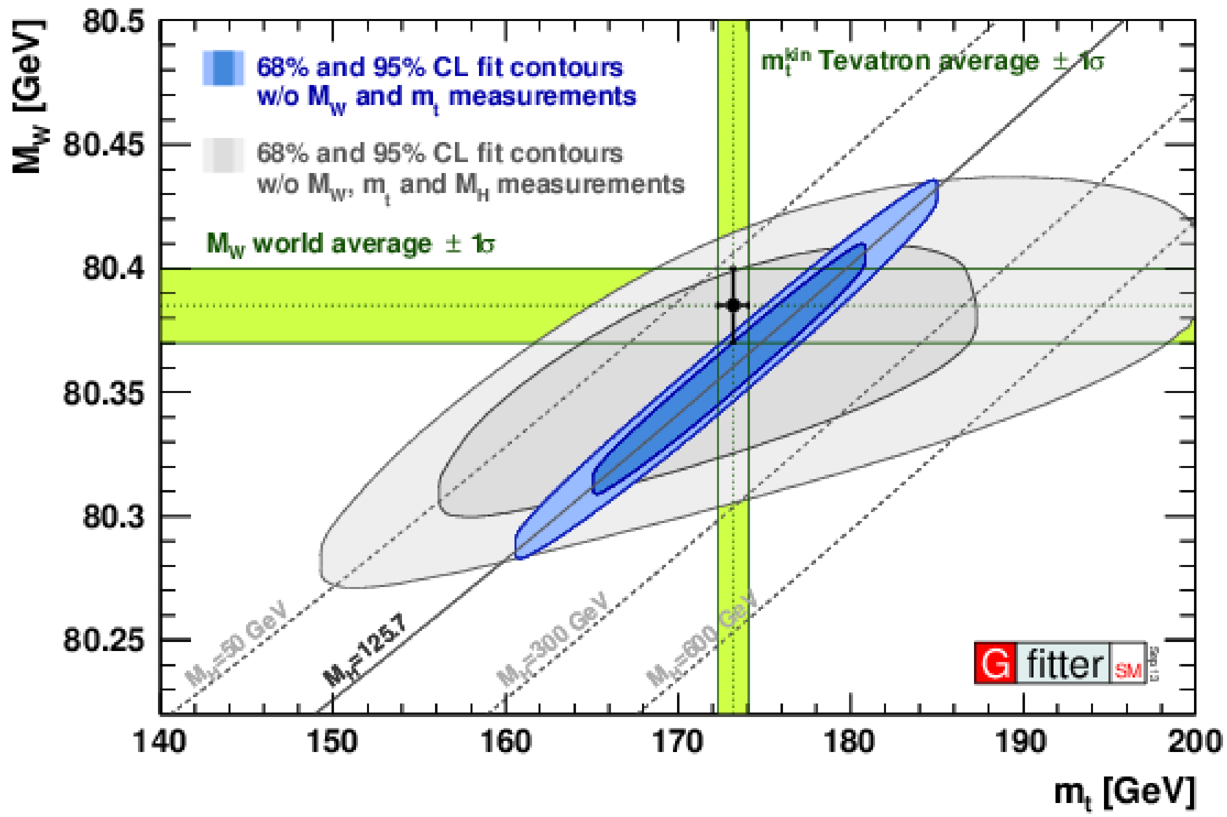
Radiative corrections to precision EWK **measurements of W, Z sensitive to Mt, MH**

SM-like Higgs discovery at ~125.7 GeV is compatible with global EWK data at 1.3 sigma (p = 0.18)

**Indirect constraints are now superior** to some of the most precise direct W, Z measurements

**Can EWK experiment catch up?**



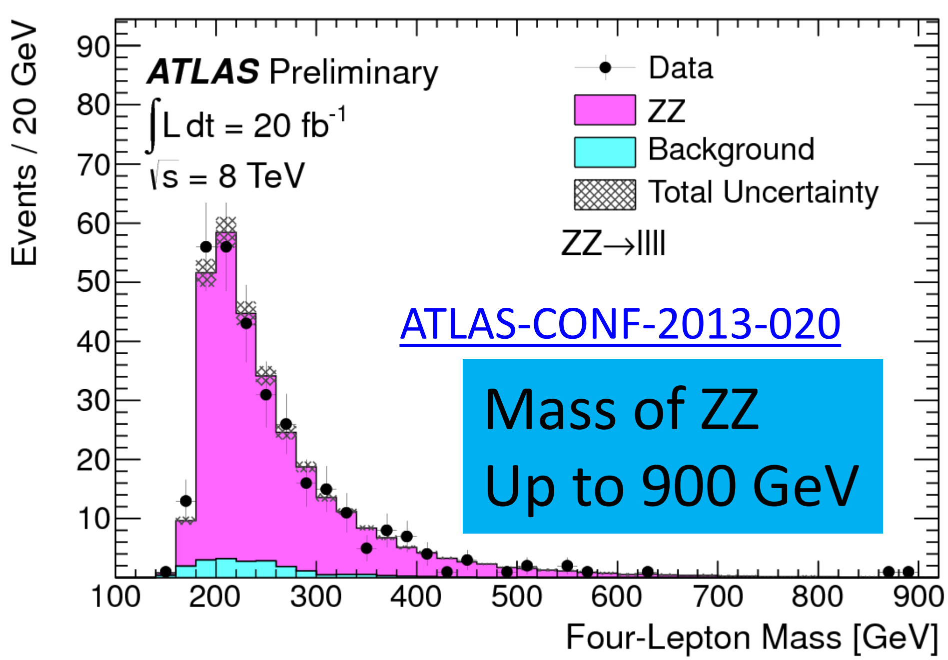

http://project-gfitter.web.cern.ch/project-gfitter/

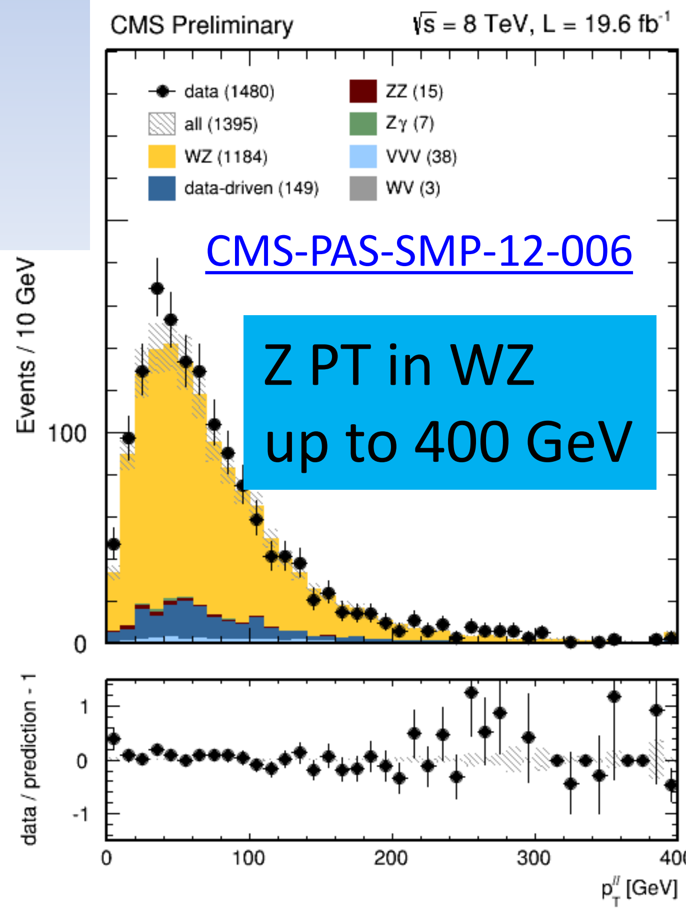
# State of the Electroweak Theory: Energy Frontier

The **successful LHC Run 1 is now providing TeV-scale tests** of single and multiple electroweak boson production

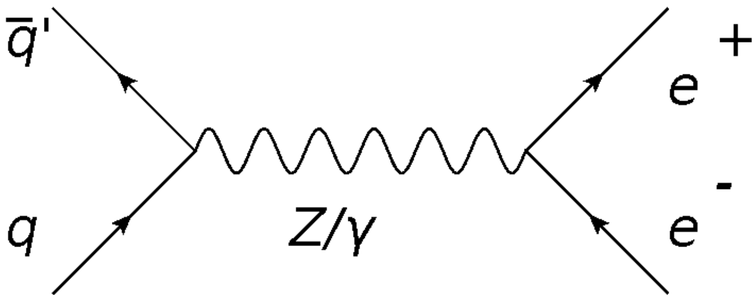
Details of electroweak symmetry breaking induce O(1) effects **in vector boson scattering at the TeV scale**

Multiboson production will be a fertile area of testing electroweak interactions **for the lifetime of LHC and beyond.**



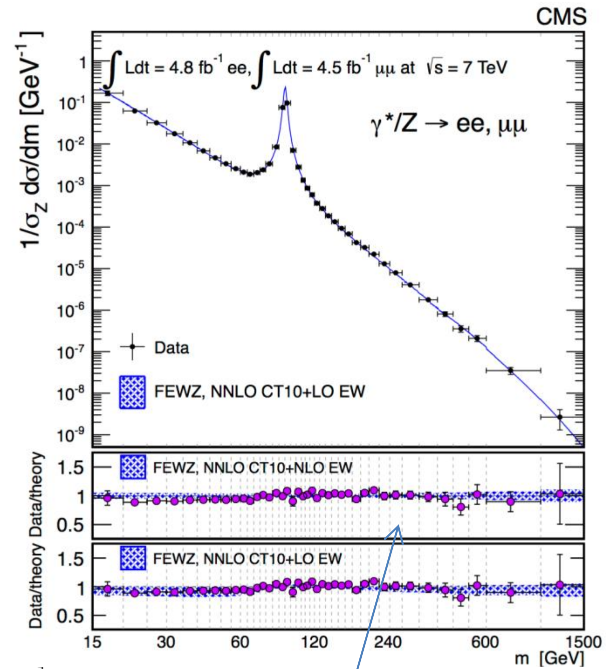
# Z and Drell-Yan Physics



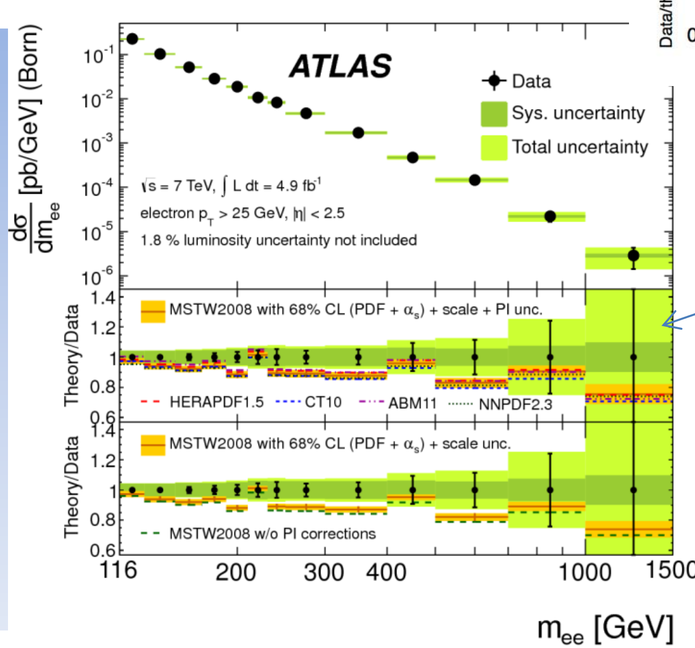

Digital art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz) "In search of the Higgs boson: H -> tautau"

# Drell-Yan Cross Section at LHC

- Differential cross section vs. dilepton mass measured at 7 TeV, from 15-1500 GeV in mass.
- 1M events/fb/experiment at 7 TeV!
- ee, mumu in agreement with each other and with the Standard Model



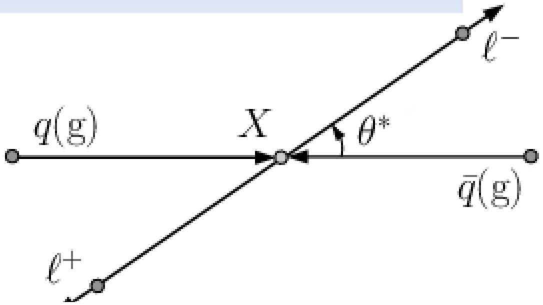

- NNLO QCD corrections are important at low mass (mostly boosted events)
- NLO EWK corrections and photon-induced production now relevant at all masses. Photon PDF (NNPDF 2.3) is now needed!




**FEWZ 3 NNLO QCD + NLO EWK + γγ→*l+l-***

# Weak mixing angle at LHC

- In the dilepton CM, lepton angle with respect to axis of quark momentum is sensitive to interference effects: vector with axial-vector Z couplings, Z with photon, or Z with new physics



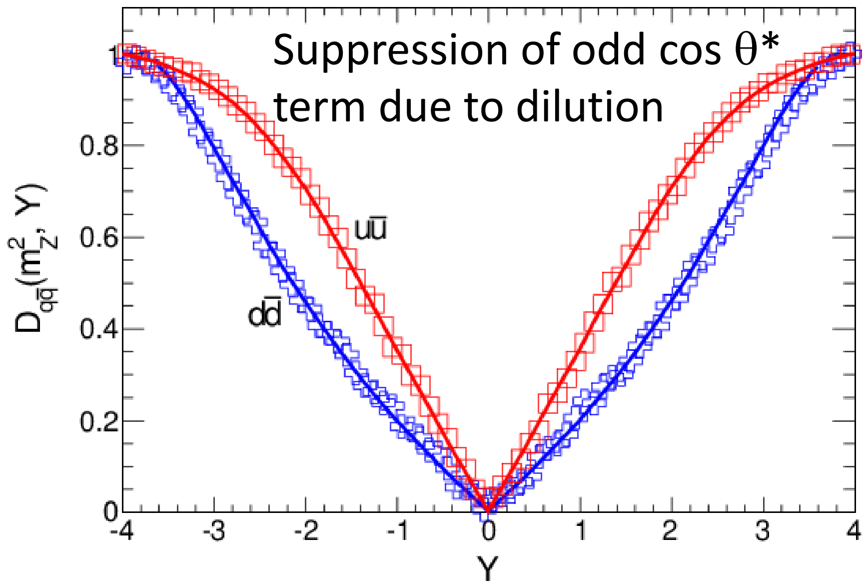

$$\hat\sigma_{q\bar q}(\hat s,\cos\theta^*;\theta_W) \propto \frac{3(\rho_V^{q\bar q\to\gamma})^2(\rho_V^{\gamma\to\ell\ell})^2}{2\hat s}\times(1+\cos^2\theta^*) + \frac{3}{2}\frac{\hat s}{(\hat s-m_Z^2)^2+m_Z^2\Gamma_Z^2} \times[((\rho_V^{q\bar q\to Z})^2+(\rho_A^{q\bar q\to Z})^2)((\rho_V^{Z\to\ell\ell})^2+(\rho_A^{Z\to\ell\ell})^2)(1+\cos^2\theta^*)+8\rho_V^{q\bar q\to Z}\rho_A^{q\bar q\to Z}\rho_V^{Z\to\ell\ell}\rho_A^{Z\to\ell\ell}\cos\theta^*] + \frac{3(\hat s-m_Z^2)\rho_V^{q\bar q\to\gamma}\rho_V^{\gamma\to\ell\ell}}{(\hat s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\times[\rho_V^{q\bar q\to Z}\rho_V^{Z\to\ell\ell}(1+\cos^2\theta^*)+2\rho_A^{q\bar q\to Z}\rho_A^{Z\to\ell\ell}\cos\theta^*].$$

V-A int. ~ $\sin^2\theta_{eff}$ -1/4

Z-photon int.

- This relation is diluted in real proton collisions, where a Collins-Soper frame choice of cos θ* axis is weakly correlated with real quark axis.

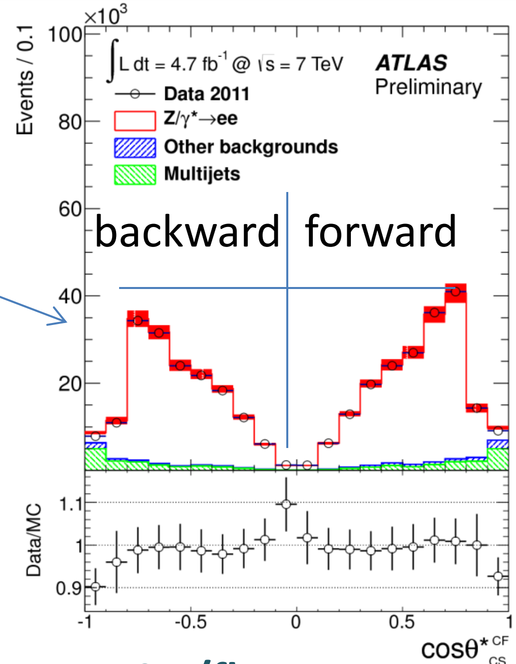
- Forward dilepton production has stronger correlation of Collins-Soper cos θ* with quark-level cos θ* → higher statistical power per event

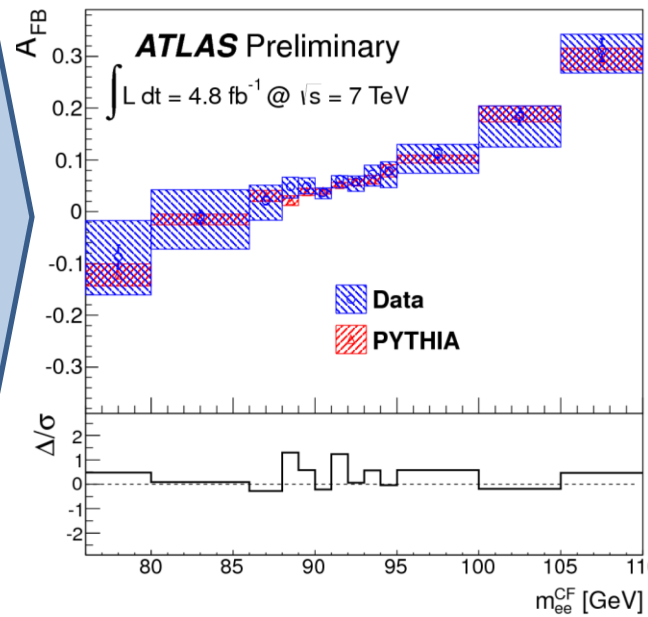


# Weak mixing angle at LHC

ATLAS-CONF-2013-043

- Select central dilepton pairs, **and also central-forward electrons** with full 7 TeV dataset
- Raw AFB = Count forward/backward abundance in CS frame
- AFB in good agreement with PYTHIA * PHOZPR NNLO K-factor (MSTWNNLO2008)
- Test AFB vs. mass for min. chi$^2$ against templates of varying $\sin^2\theta_W$
- 1.8σ lower than LEP+SLD average



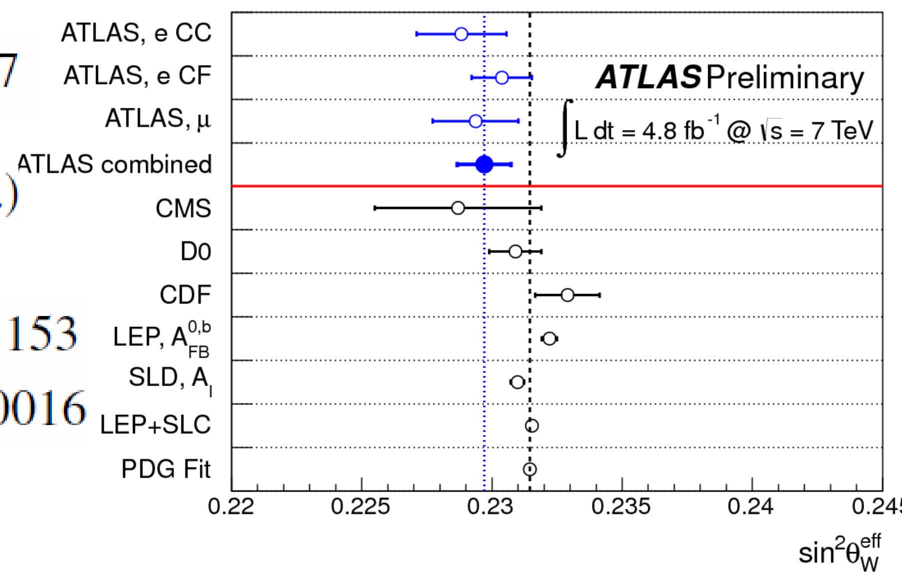




**ATLAS 5/fb**

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

**LEP + SLD**

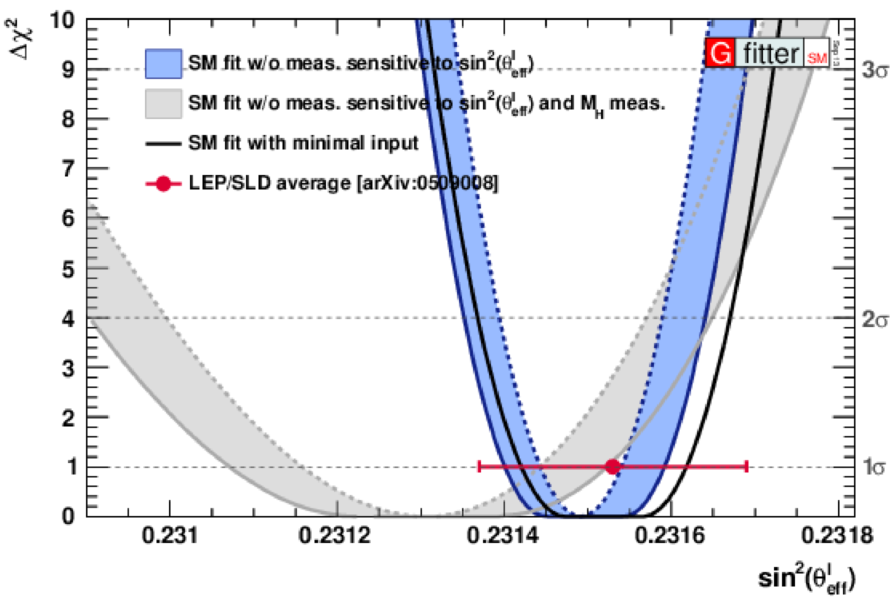
$$\sin^2\theta_W^{eff} = 0.23153 \pm 0.00016$$



# Weak-mixing angle prospects for Run 2

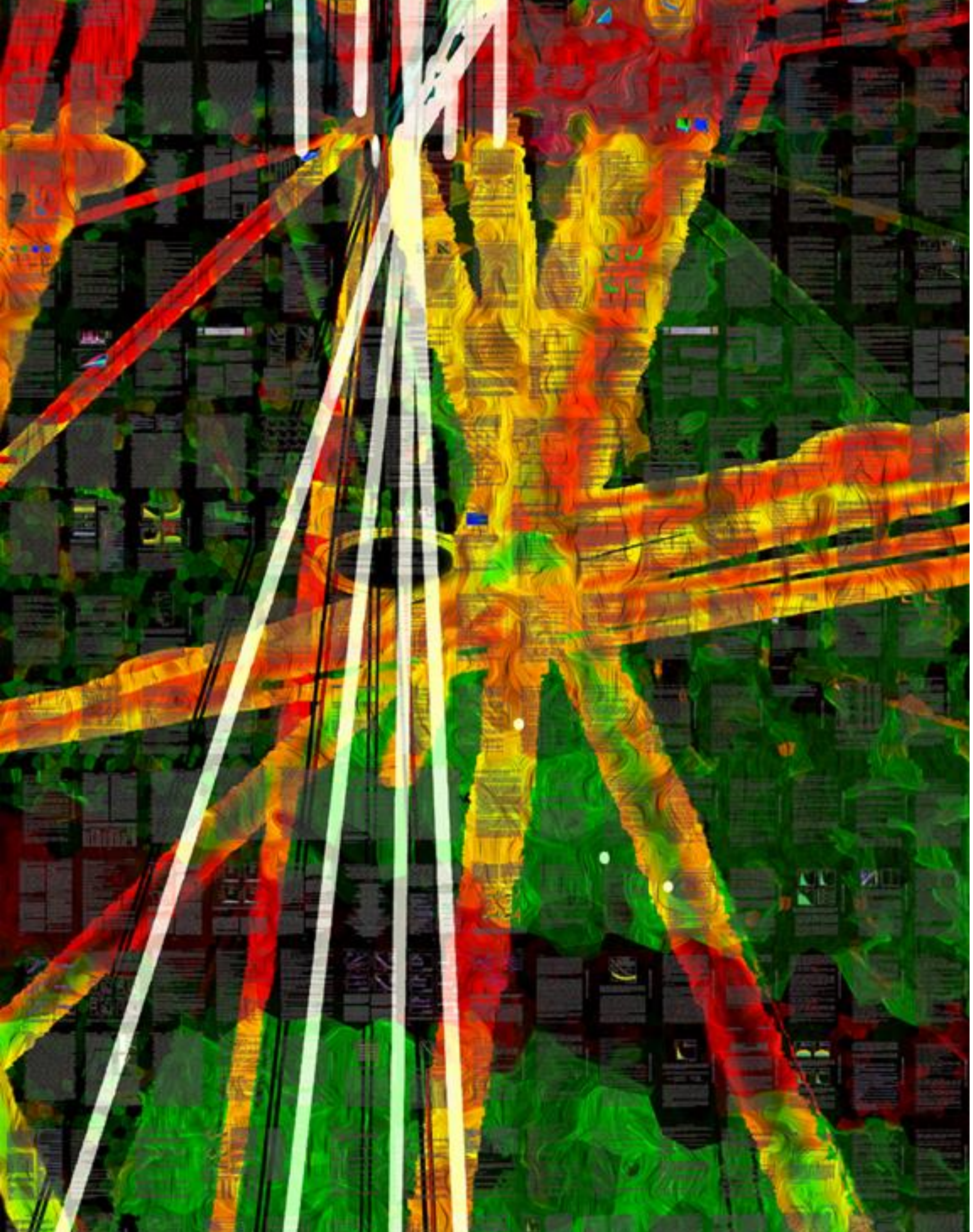
- Need a 6X better measurement to achieve world-average precision
- Statistical error hits this target with ~20/fb @ 13-14 TeV
- **PDF uncertainty is biggest concern**, needs >5-10X improvement over pre-LHC PDFs from LHC data
- Lepton energy scale must also improve >5X
- Gfitter: Next 2X in world direct precision (1.6E-4) will match indirect precision (1.0E-4)

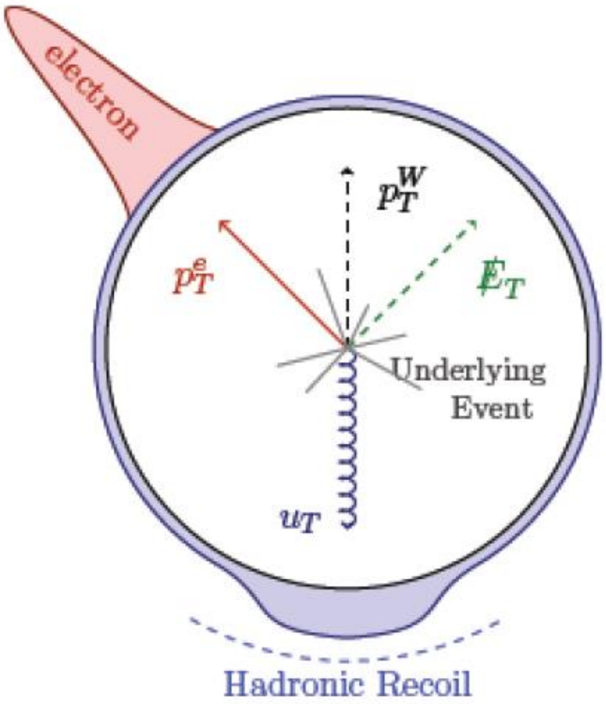
| Uncertainty source | CC electrons ($10^{-4}$) | CF electrons ($10^{-4}$) | Muons ($10^{-4}$) | Combined ($10^{-4}$) |
|---|---|---|---|---|
| PDF | 9 | 5 | 9 | 7 |
| MC statistics | 9 | 5 | 9 | 4 |
| Electron energy scale | 4 | 6 | – | 4 |
| Electron energy smearing | 4 | 5 | – | 3 |
| Muon energy scale | – | – | 5 | 2 |
| Higher-order corrections | 3 | 1 | 3 | 2 |
| Other sources | 1 | 1 | 2 | 2 |




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

# W Physics



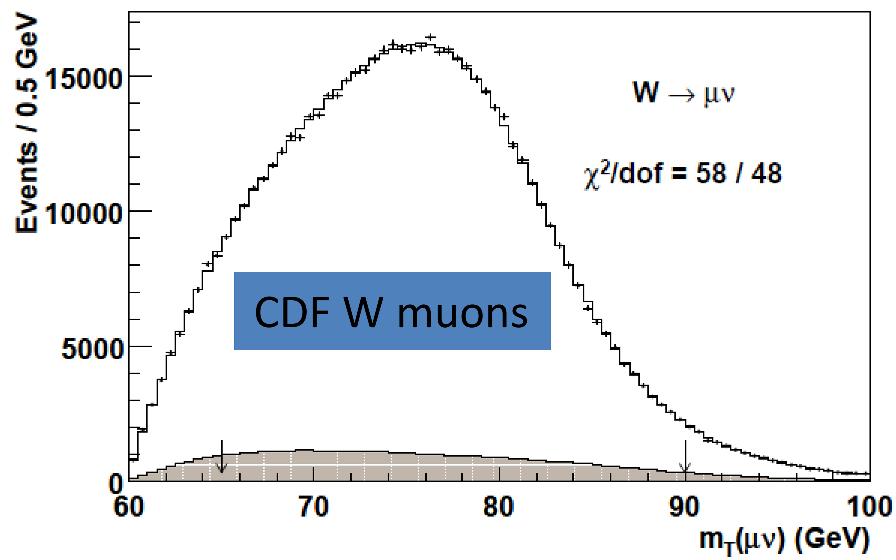



Digital art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz) "In search of the Higgs boson: H -> bottom bottom"

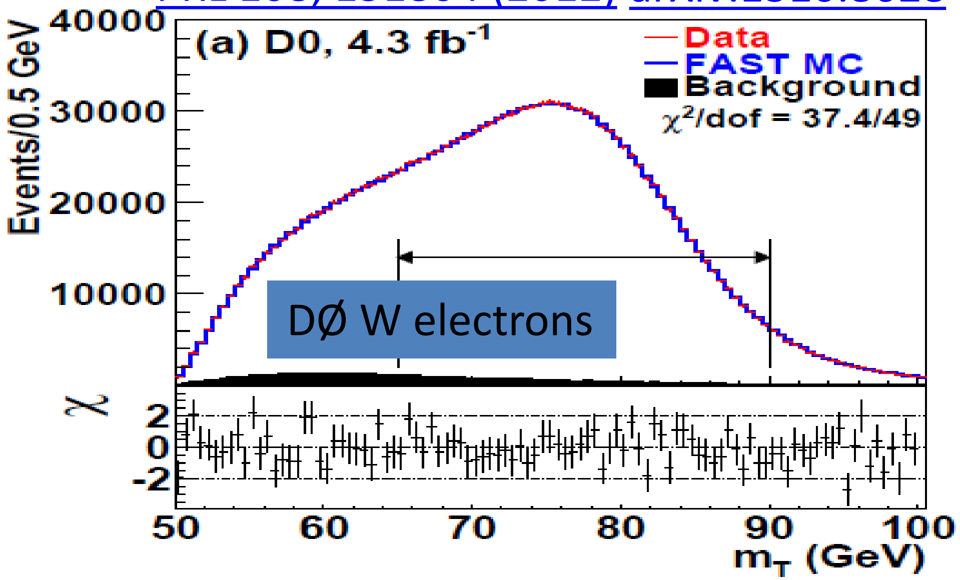
# Status of Tevatron W mass

- CDF and DØ have world's most precise measurements based on 20% and 50% of their data → 1.1M and 1.7M Ws, resp.
- MT is the most sensitive single variable, lepton PT and MET used also
- **Precision lepton response (0.01%) and recoil models (1%)** built up from Z dileptons, Z mass reproduced to 6X LEP precision
- MW precision:
    - CDF 19 MeV,
    - DØ 23 MeV,
    - LEP2 33 MeV

PRL 108, 151803 (2012) arXiv:1311.0894




PRL 108, 151804 (2012) arXiv:1310.8628



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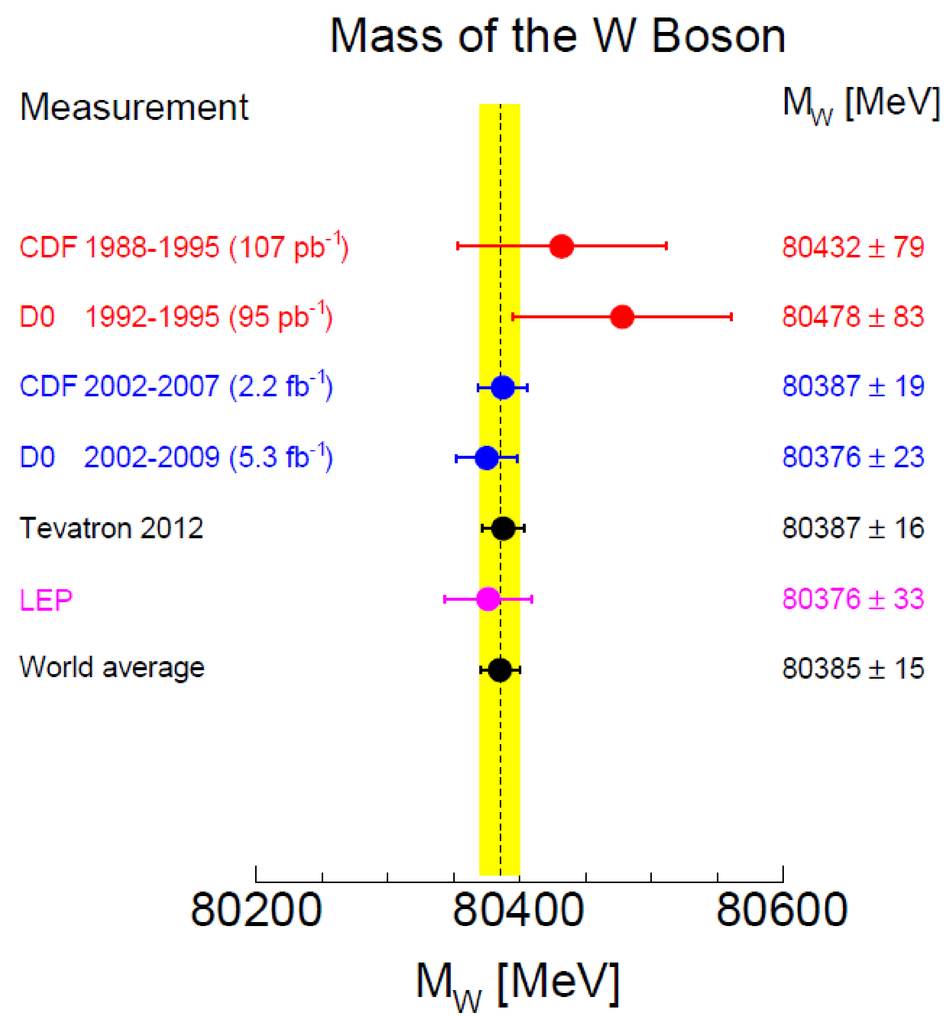
- Precision lepton response (0.01%) and recoil models (1%) built up from Z dileptons, Z mass reproduced to 6X LEP precision
- **MW precision:**
  - **CDF 19 MeV,**
  - **DØ 23 MeV,**
  - **LEP2 33 MeV**
  - **2012 world average: 15 MeV**

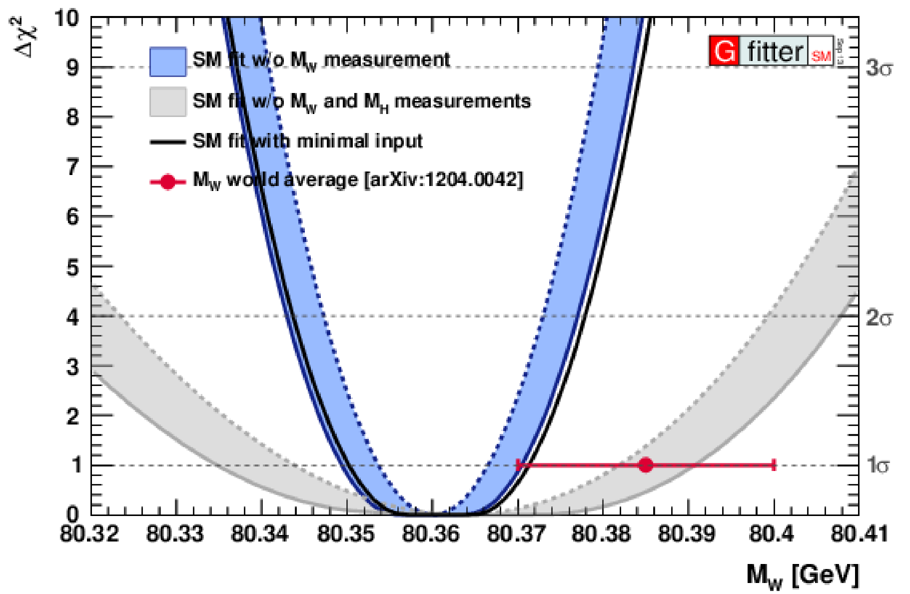


# Prospects for Tevatron W mass

- Largest single uncertainties are **stat. and PDF syst.**
- **2X PDF improvement** and incremental improvement elsewhere results in **9 MeV projected final Tevatron precision**
- <10 MeV precision is well motivated to **further confront indirect precision (11 MeV)**

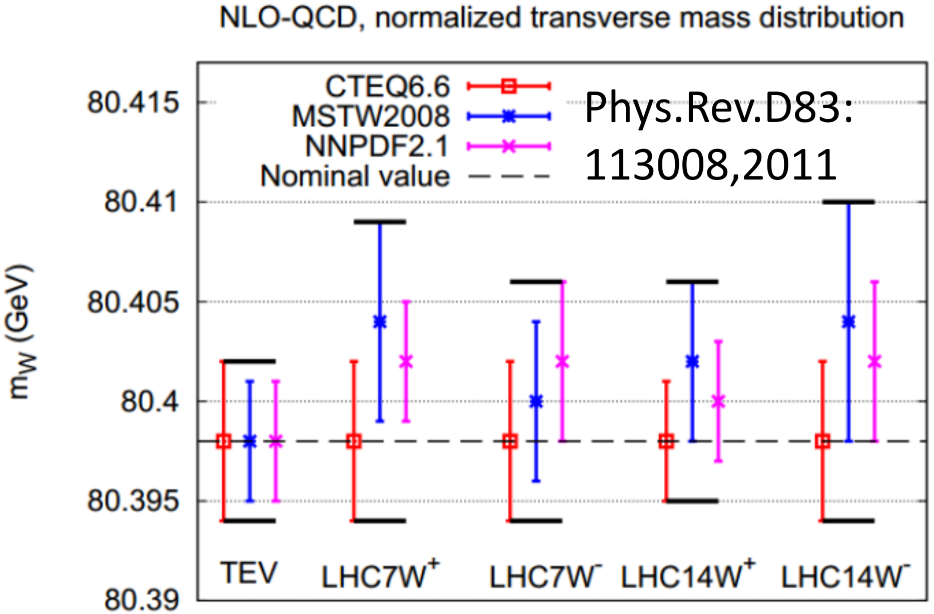
arxiv:1310.6708

| $\Delta M_W$ [MeV] | CDF | D0 | combined | projected combined |
|---|---|---|---|---|
| $\mathcal{L}[\text{fb}^{-1}]$ | 2.2 | 4.3 (+1.1) | 7.6 | 20 |
| PDF | 10 | 11 | 10 | 5 |
| QED rad. | 4 | 7 | 4 | 3 |
| $p_T(W)$ model | 5 | 2 | 2 | 2 |
| other systematics | 10 | 18 | 9 | 4 |
| $W$ statistics | 12 | 13 | 9 | 5 |
| Total | 19 | 26 (23) | 16 | 9 |



# Prospects for LHC W mass

- The LHC has excellent detectors and semi-infinite statistics and thus has a good *a priori* prospect for a <10-MeV measurement
- Biggest three obstacles to surmount:
  - PDFs: sea quarks play a much stronger role than the Tevatron. What are the limiting d.o.f. and can they be measured in situ? Need at least 2X better PDFs.
  - Momentum scale: "vanilla" determination is not competitive. Identify limiting factors (FSR).
  - Recoil model/MET: Can a precision model be constructed with higher pileup data? With usable MET resolution?




| $\Delta M_W$ [MeV] | LHC | | |
|---|---|---|---|
| $\sqrt{s}$ [TeV] | 8 | 14 | 14 |
| $\mathcal{L}[\text{fb}^{-1}]$ | 20 | 300 | 3000 |
| PDF | 10 | 5 | 3 |
| QED rad. | 4 | 3 | 2 |
| $p_T(W)$ model | 2 | 1 | 1 |
| other systematics | 10 | 5 | 3 |
| $W$ statistics | 1 | 0.2 | 0 |
| Total | 15 | 8 | 5 |

arxiv:1310.6708

# W charge asymmetry

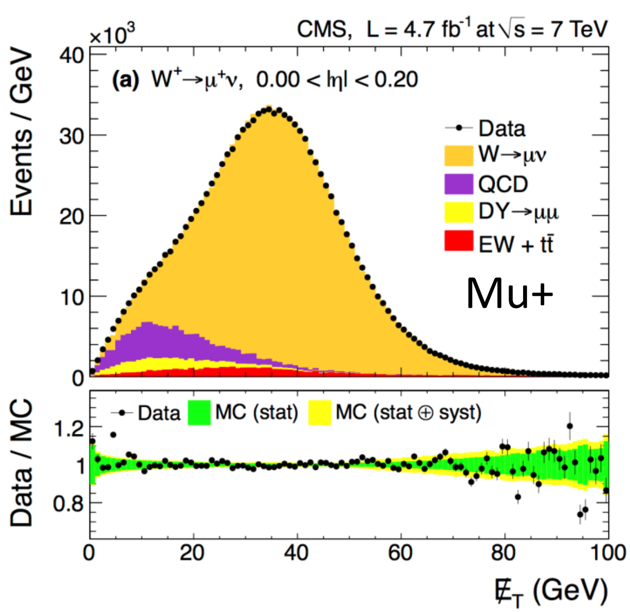
arXiv:1312.6283

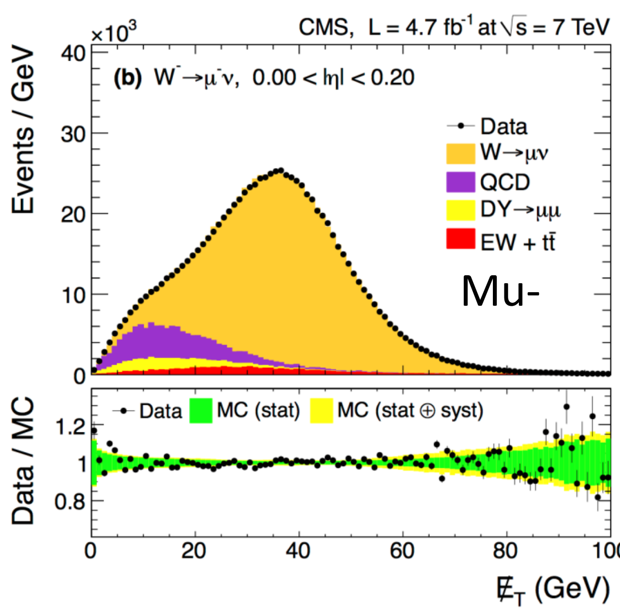
- At 7 TeV, ~4M W muon candidates produced per /fb with high purity and efficiency, for PT > 25 GeV and |η| < 2.4

- Differential W charge asymmetry precisely probes u/d ratio vs. x, strong constraint on PDFs and hence precision electroweak measurements

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$

- Recent CMS measurement can precisely extract a clean W asymmetry using ~20 million W candidates!

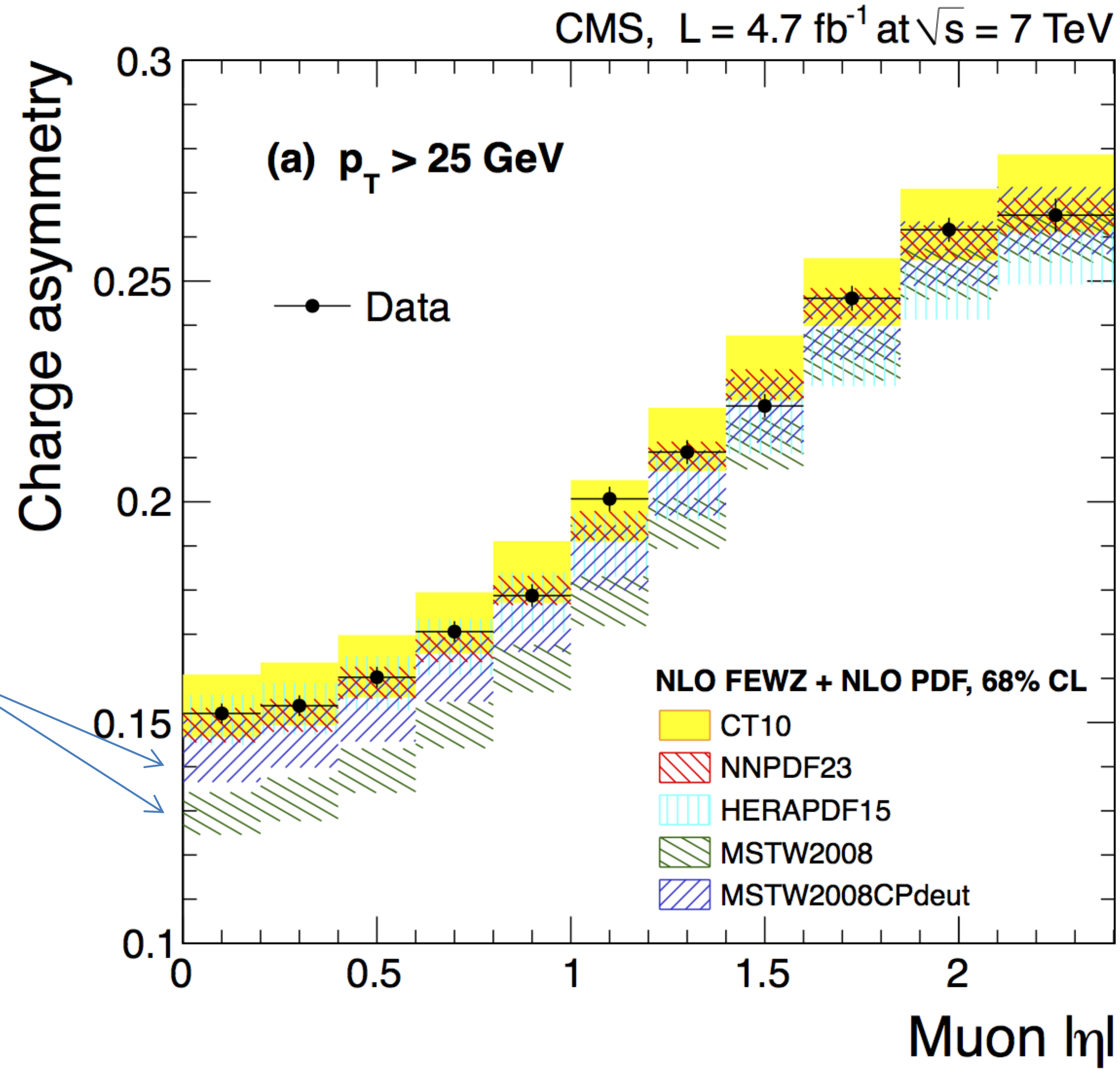


# W charge asymmetry

arXiv:1312.6283

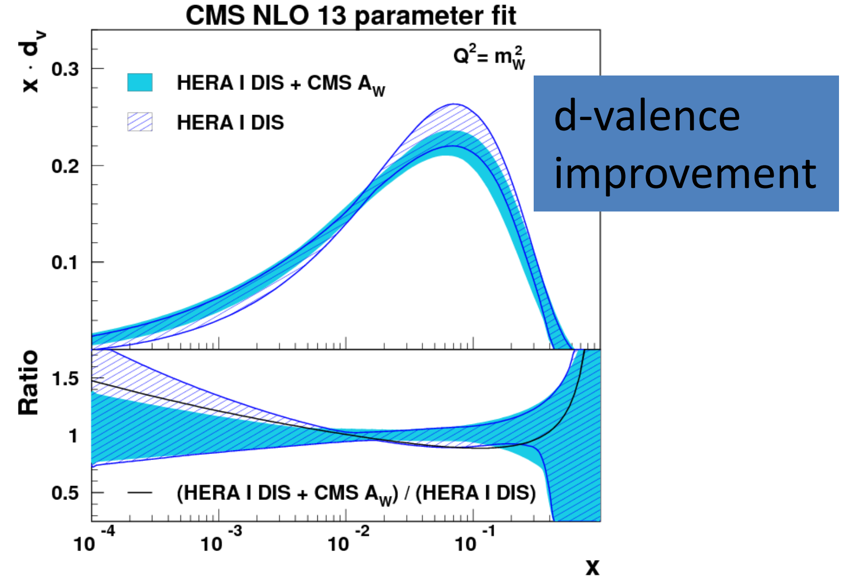
- Measured in 11 bins of η, for PT > 25 GeV and |η| < 2.4
- Asymmetry measured to 0.1% absolute per bin, with only small inter-bin correlations
- Disagreement with original MSTW2008 led to reformulation of valence x-dependence
- Has obvious constraining power for all PDF families

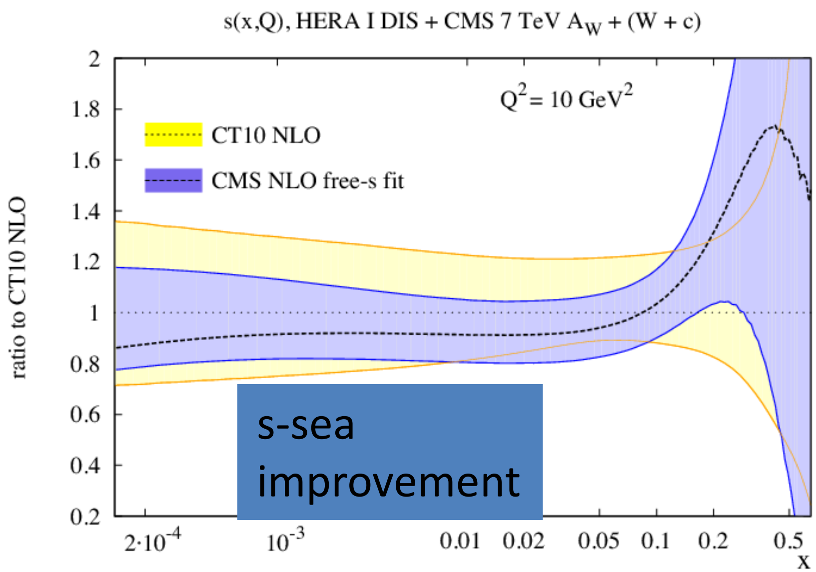


# W charge asymmetry

arXiv:1312.6283

- Using HERA fitter framework, CMS W asymmetry is combined with HERA DIS to exhibit valence PDF improvement
- Using HERA DIS, CMS AW, and CMS W+c, fit for strange quark PDF is in agreement with and comparable to fixed-target neutrino constraints (CT10)!

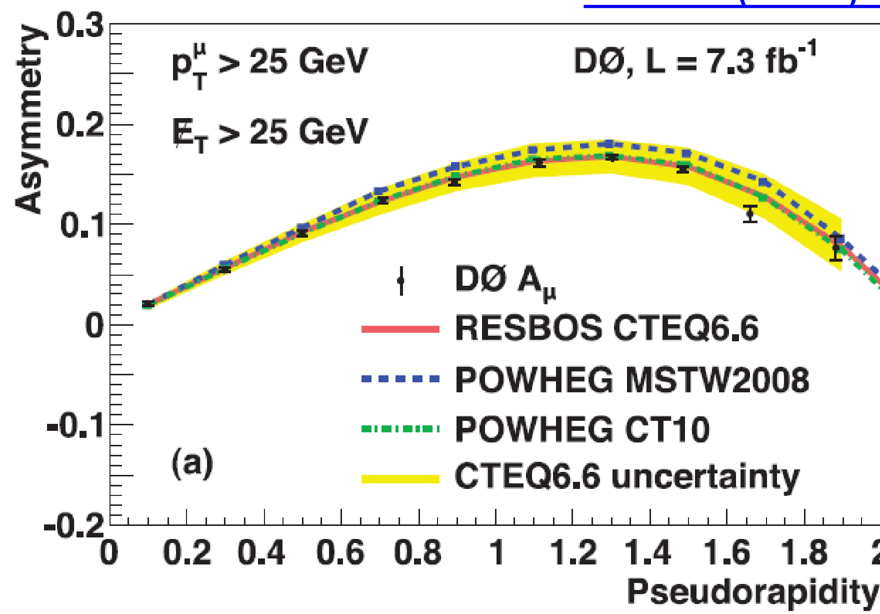


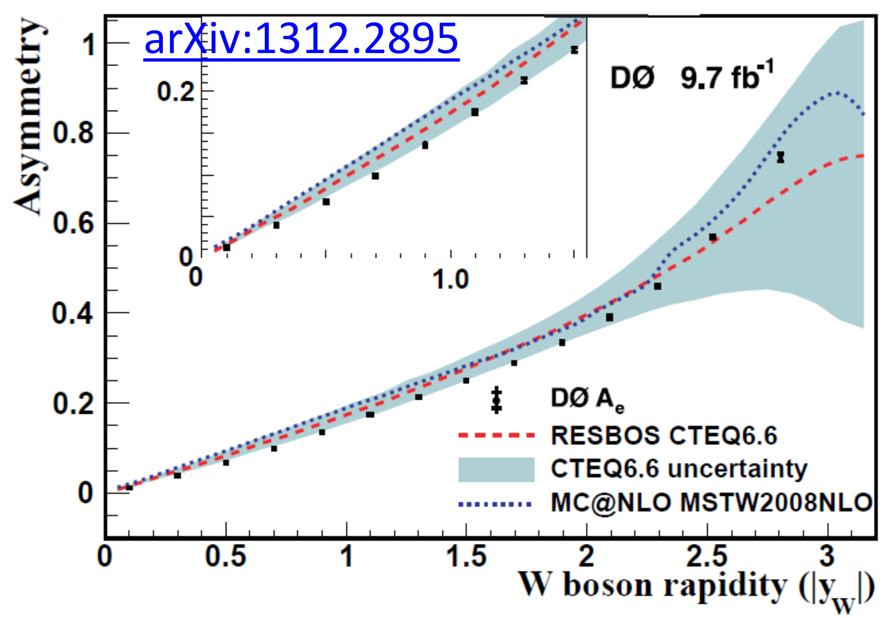
# W charge asymmetry

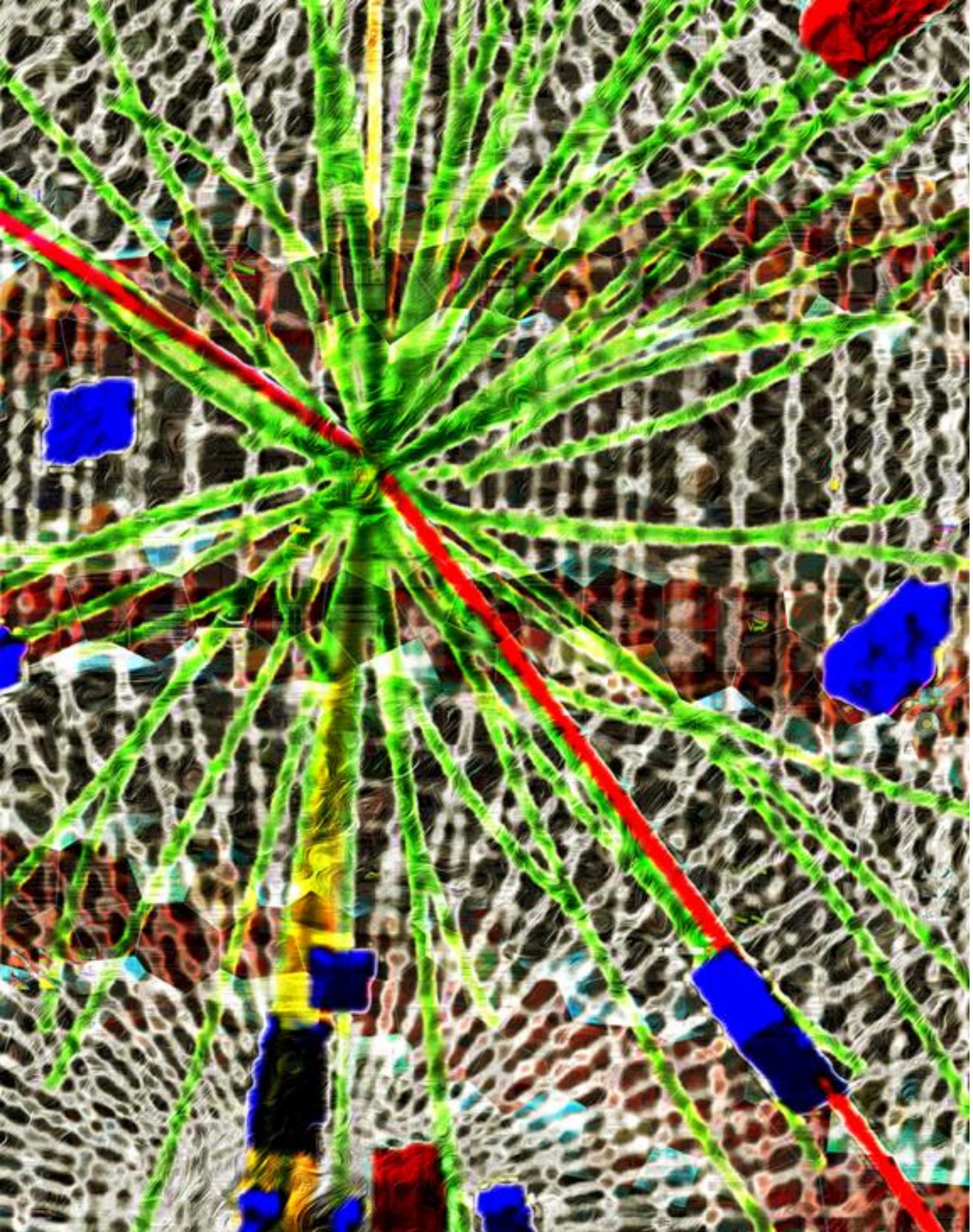
PRD 88 (2013) 091102

- Tevatron has only exploited a fraction of their data until recently.
- DØ muon rapidity asymmetry also has clear constraining power
- DØ W rapidity asymmetry uses electron and MET to estimate W rapidity directly (higher correlation with PDFs)
- Implications still being understood!

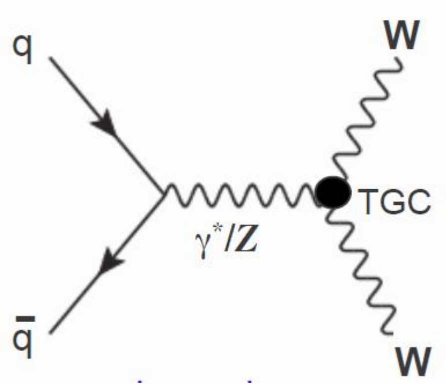



arXiv:1312.2895





# Diboson Physics and Triple Gauge Couplings




Digital art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz) "In search of the Higgs boson: H -> gamma gamma"

# Effective Field Theory and Boson Interactions

- For generic new physics effects descended from some high energy scale $\Lambda$, explore **operator product expansion with Wilson coefficients c_i**
- Lowest dimension operators (dim 6, i.e. n=2) most important (assumes we are in perturbative regime for OPE).
- Before EWSB, 5 gauge boson interaction terms respect gauge invariance (3 CP even + 2 CP odd)
- After EWSB, induces trilinear VVV', VV'H, and quartic interactions with correlated coefficients.
- At dim 6, expect WW$\gamma$, WWZ interactions (ZZZ or ZZ$\gamma$ are dim >=8) with 3 independent CP-even parameters ($g_1$, $\kappa$, $\lambda$)

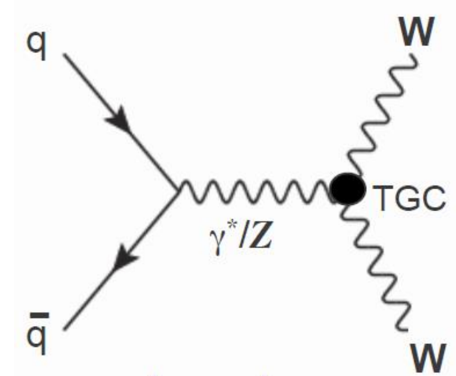
UNBROKEN

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

$$\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu] \\
\mathcal{O}_W &= (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \\
\mathcal{O}_B &= (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) \\
\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu} W^{\nu\rho} W_\rho^\mu] \\
\mathcal{O}_{\tilde{W}} &= (D_\mu \Phi)^\dagger \tilde{W}^{\mu\nu} (D_\nu \Phi)
\end{aligned}$$

BROKEN

$$\begin{aligned}
\mathcal{L} = \; & i g_{WWV} \Big( g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \\
& \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \\
& + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \Big)
\end{aligned}$$

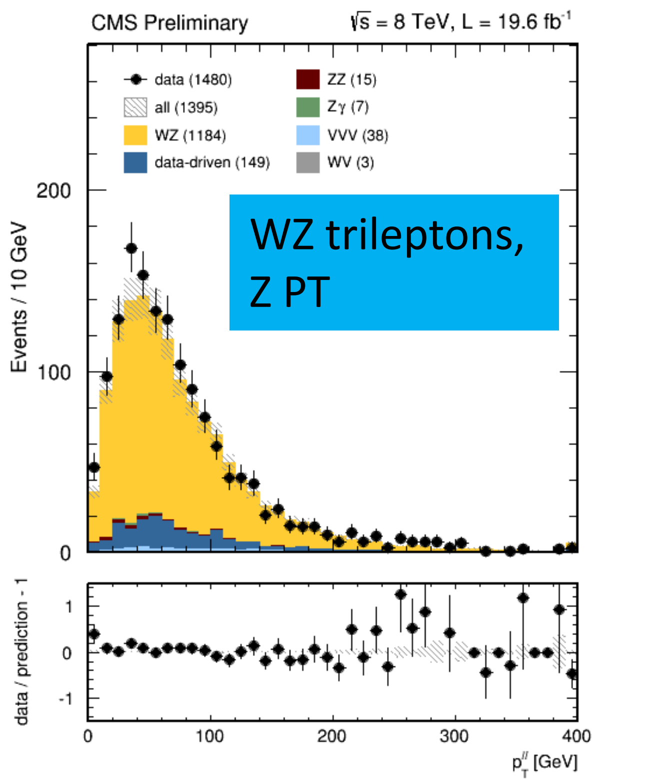


# WZ and Wγ Production

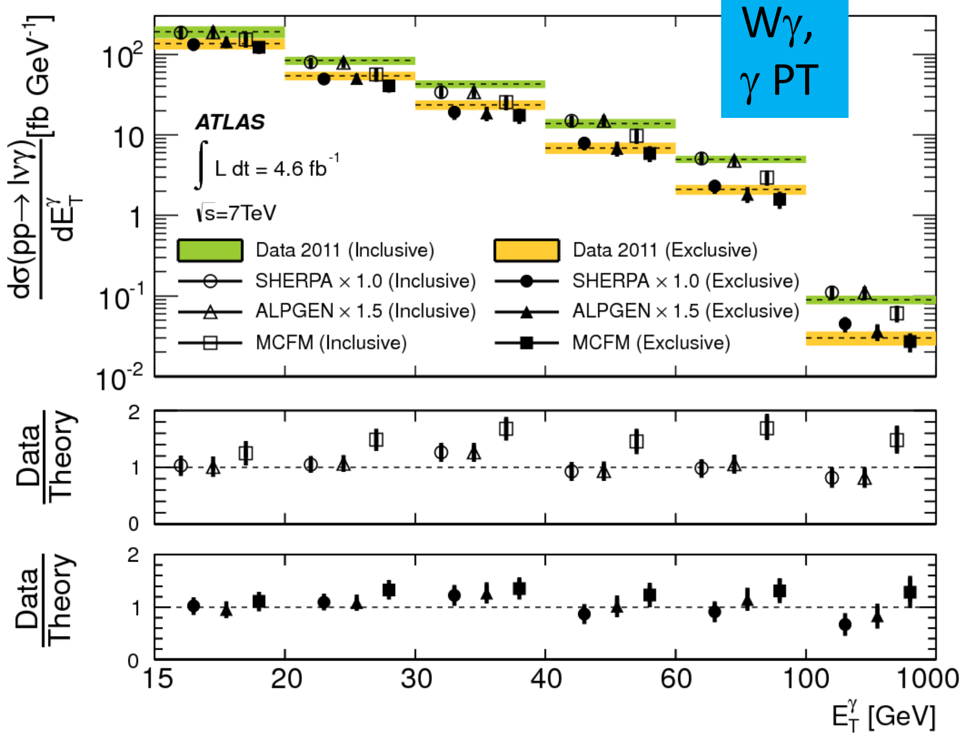
PRD 87, 112003 (2013)

CMS-PAS-SMP-12-006

- LHC has thousands of high purity trilepton WZ candidates, tens of thousands of Wγ
- Photon and lepton fakes are the predominant background
- No evidence of new physics in high PT tails




WZ trileptons, Z PT




Wγ, γ PT

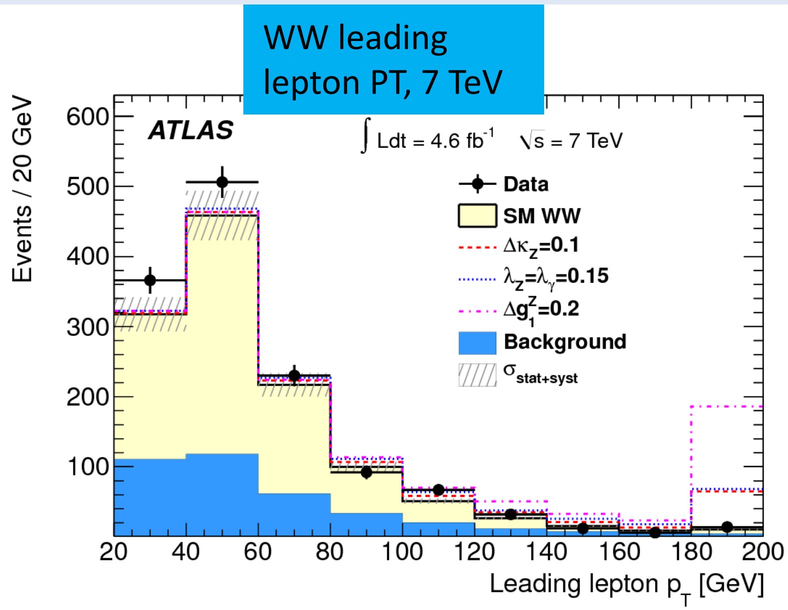
# WW Production

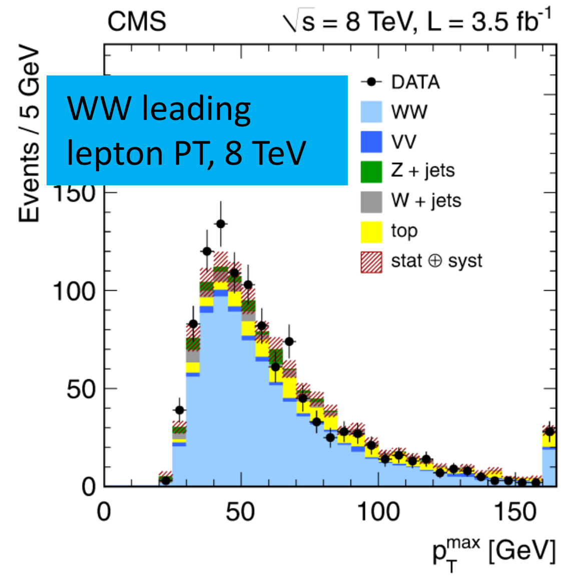
PRD 87, 112001 (2013)

Phys. Lett. B 721 (2013) 190–211

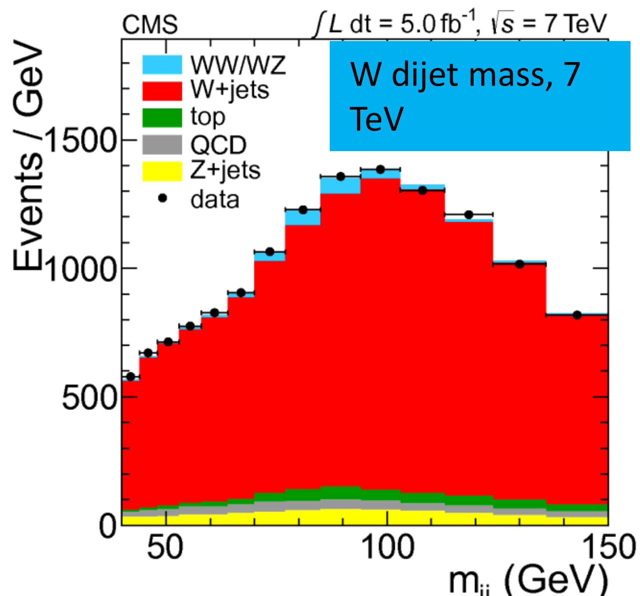
Eur.Phys.J. C73 (2013) 2283

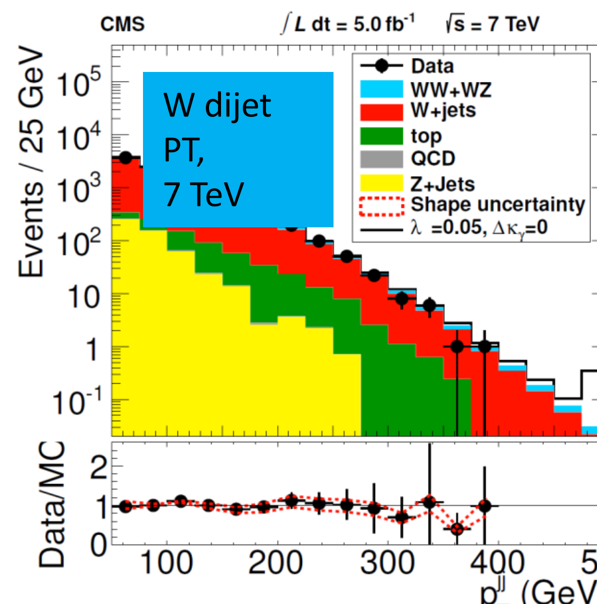
- Thousands of candidates in dilepton channel
- Leading lepton PT shows no anomalous contribution



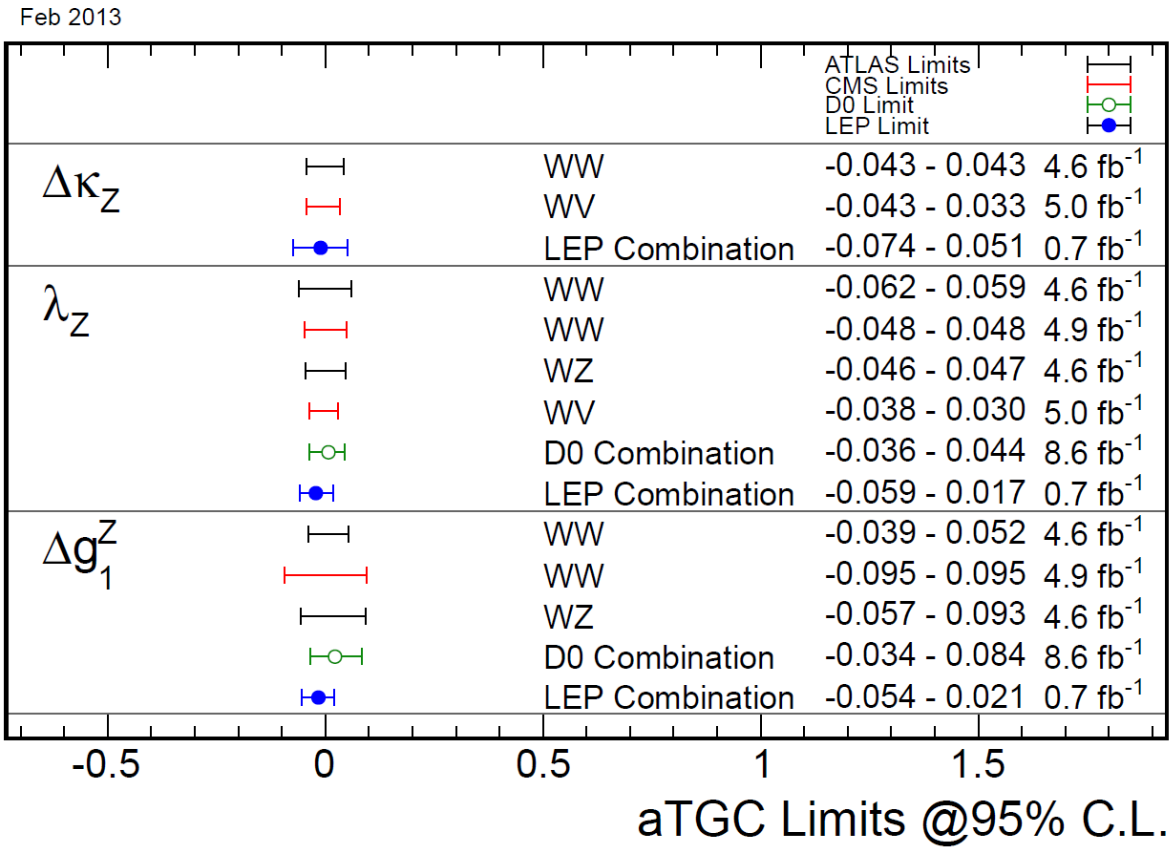

- Significant diboson signal in semileptonic channel
- Higher BR and low background at high PT gives superior TGC constraint



# Charged aTGCs: World Summary

- Best single LHC 7 TeV measurements equal LEP2 or Tevatron combinations
- Semileptonic WW gives the best information on κ and λ, leptonic WW and WZ better for g.
- LHC 8 TeV will provide 2-3X better constraints, eclipsing LEP2
- W magnetic moment constrained to 1% level, electric quadrupole moment to 0.01% level

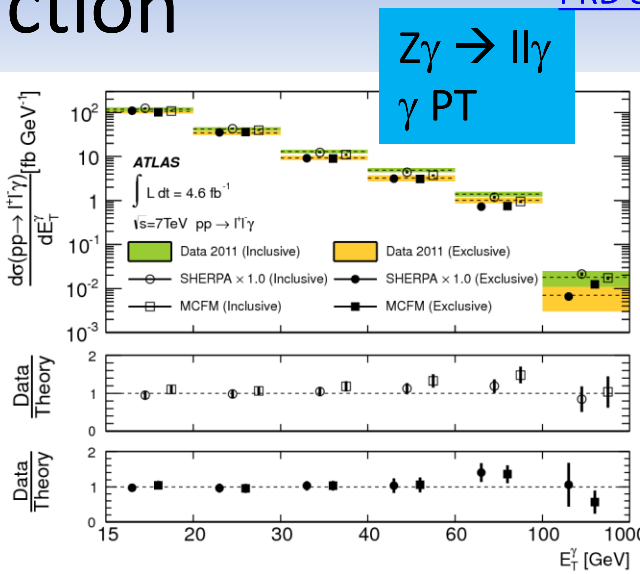


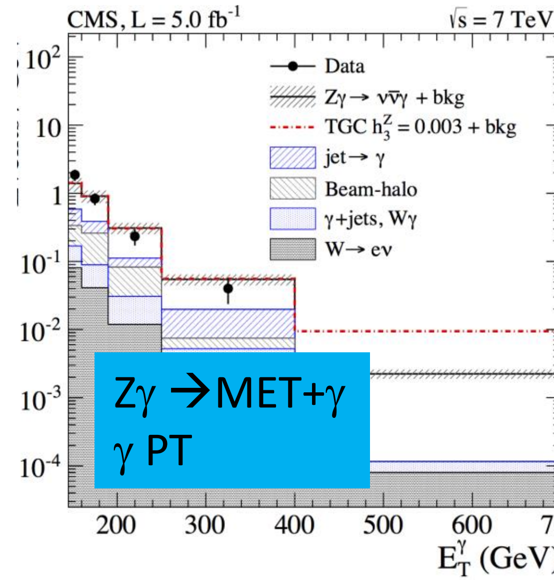
# Zγ and ZZ Production

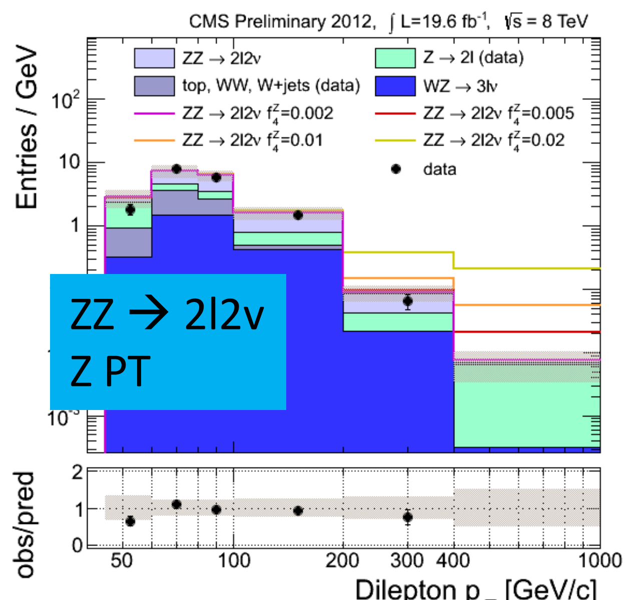
ATLAS-CONF-2013-020 CMS-PAS-SMP-12-016

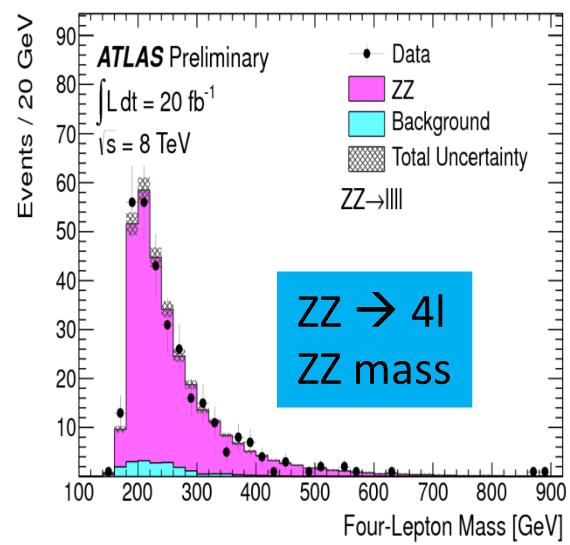
PRD 87, 112003 (2013) JHEP 10 (2013) 164

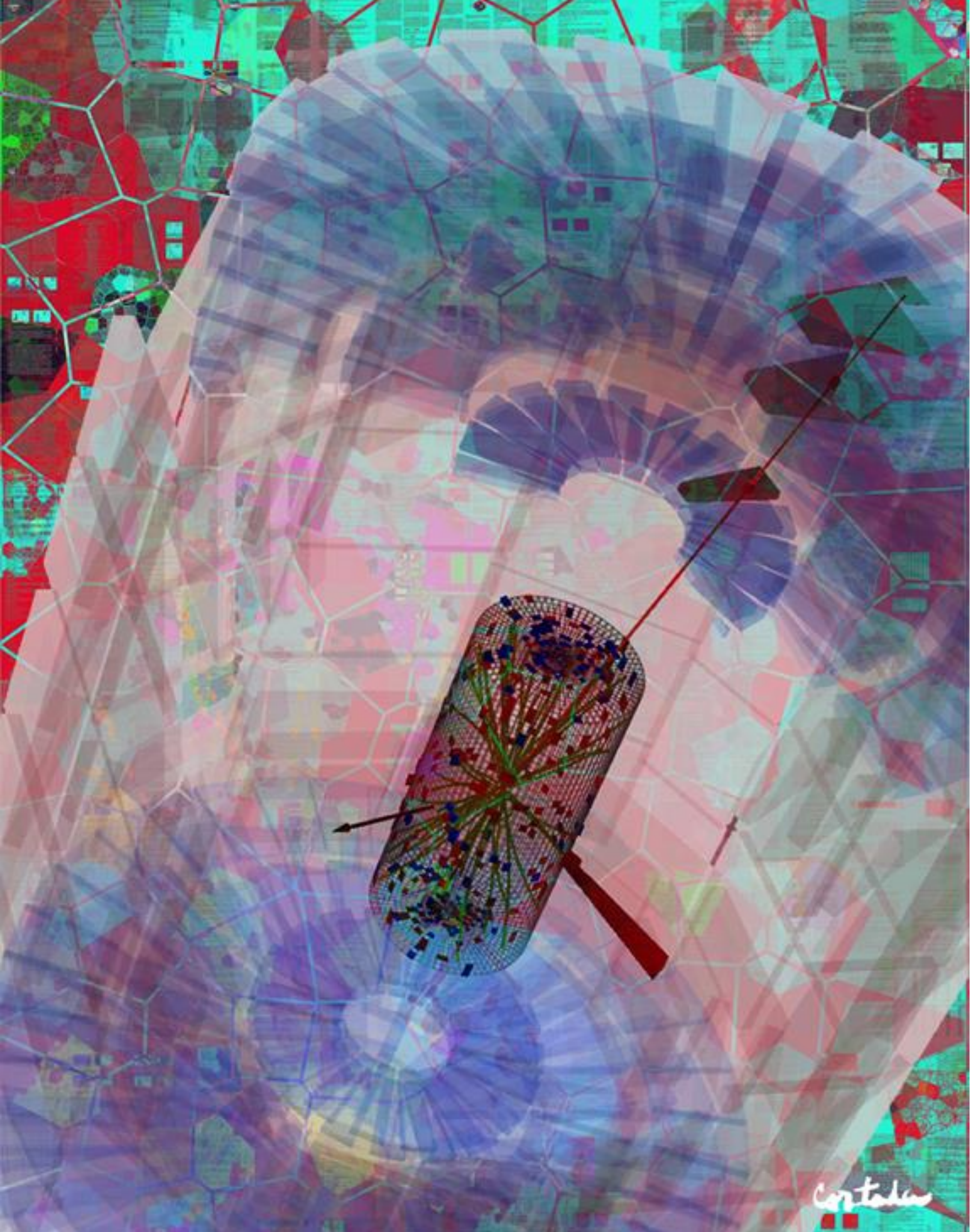
- Thousands of dilepton-photon events at 7 TeV agree with SM
- MET-photon channel: Higher BR and low background at high PT gives superior TGC constraint
- ~200 ZZ to 2l2v candidates observed at 8 TeV
- ~300 ZZ to 4-lepton candidates observed at 8 TeV/experiment



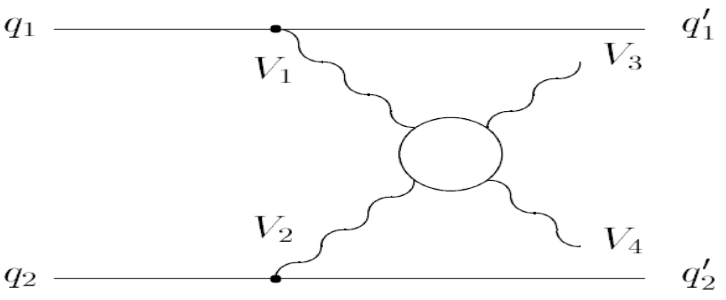





# Tribosons, VBS, and Quartic Gauge Couplings




Digital art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz) "In search of the Higgs boson: H -> WW"

# Effective Field Theory Revisited

- **SM has 4 EW quartic interactions (QGCs)**: WWWW, WWZZ, WWγγ, and WWZγ
- Dim 6 OPE has QGC correlated with TGC→dibosons dominate their constraints
- **19 new quartic terms become relevant at Dim 8** with various contributions to 4 boson interactions. Neutral 4 boson vertices can be non-zero (ZZZZ, ZZZγ, ZZγγ, Zγγγ).

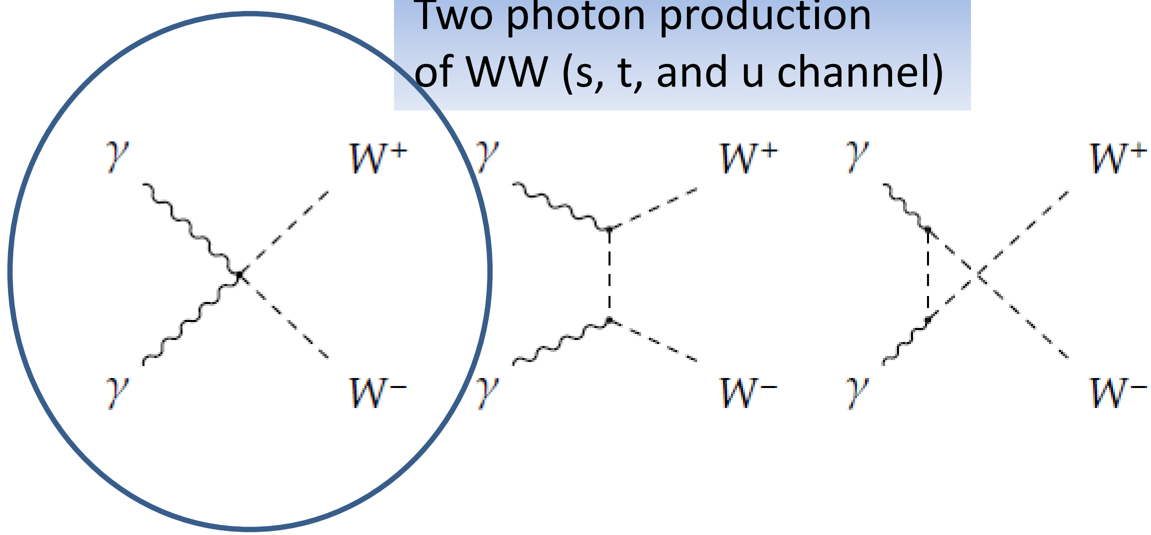
| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA |
|---|---|---|---|---|---|---|---|---|
| $\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$ | X | X | X | O | O | O | O | O |
| $\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$ ,$\mathcal{L}_{M,7}$ | X | X | X | X | X | X | X | O |
| $\mathcal{L}_{M,2}$ ,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$ ,$\mathcal{L}_{M,5}$ | O | X | X | X | X | X | X | O |
| $\mathcal{L}_{T,0}$ ,$\mathcal{L}_{T,1}$ ,$\mathcal{L}_{T,2}$ | X | X | X | X | X | X | X | X |
| $\mathcal{L}_{T,5}$ ,$\mathcal{L}_{T,6}$ ,$\mathcal{L}_{T,7}$ | O | X | X | X | X | X | X | X |
| $\mathcal{L}_{T,9}$ ,$\mathcal{L}_{T,9}$ | O | O | X | O | O | X | X | X |

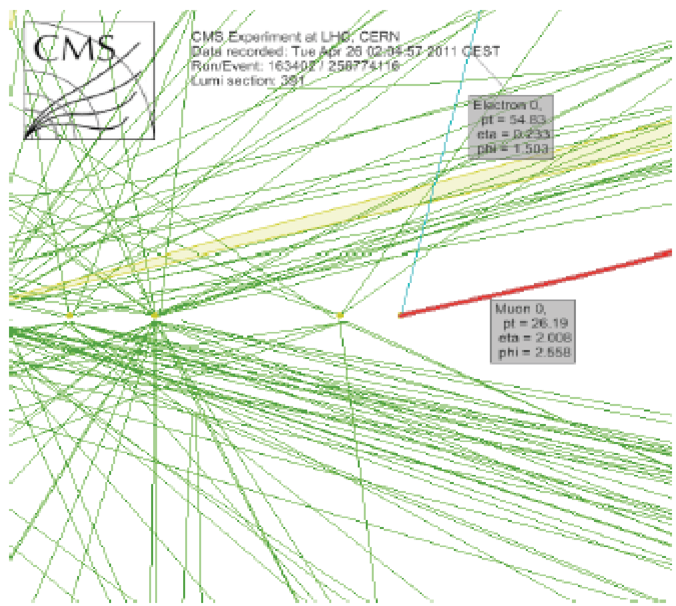
# WW QGC via two-photon production

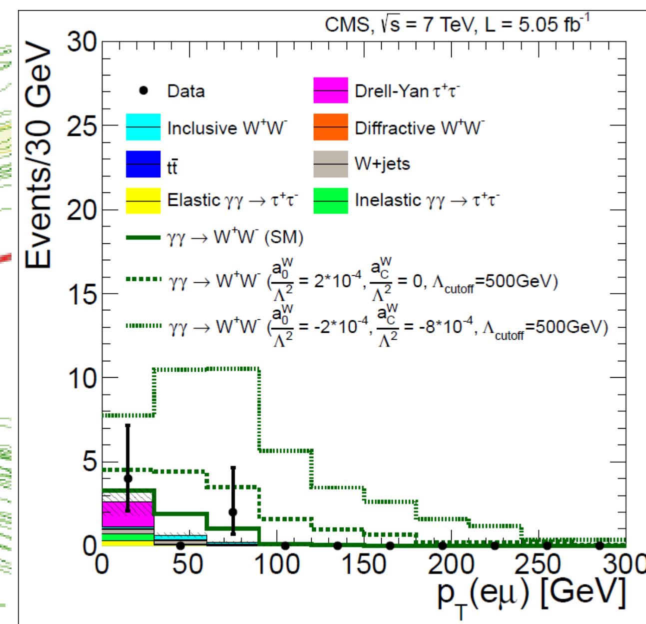
- First search for photon-photon scattering production of WW
- $WW\gamma\gamma$ quartic gauge coupling one of the amplitudes
- Two eμ events observed **with no UE present**
- First quartic gauge coupling limits at LHC; $WW\gamma\gamma$ limit two orders better than LEP or Tevatron!
- Forward proton tagging in Run 2 will improve sensitivity further

JHEP 1307 (2013) 116

Two photon production of WW (s, t, and u channel)



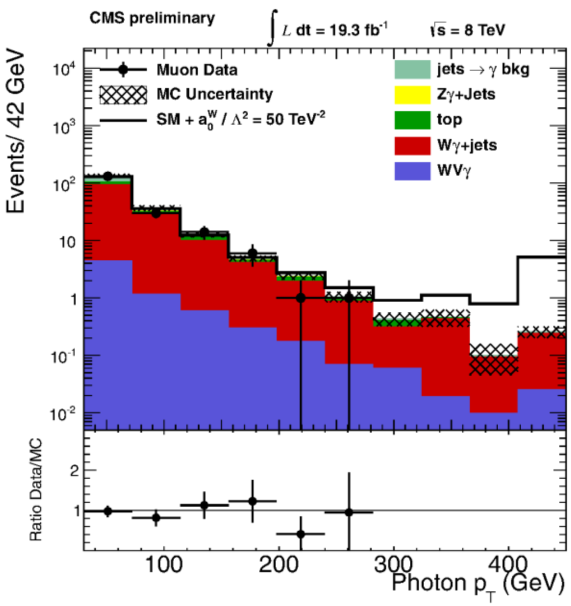



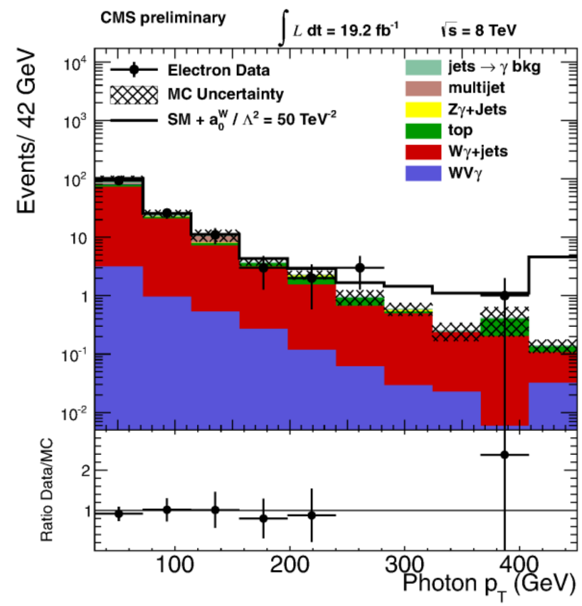



CMS-PAS-SMP-13-009

# Triboson search in WWγ and WZγ

- Photon PT exhibits no anomalous high PT tail
- Cross section UL on SM triboson rate is 3.4XSM (<241 fb)




$$-21 < a_0^W/\Lambda^2 < 20\,\mathrm{TeV}^{-2},$$
$$-34 < a_C^W/\Lambda^2 < 32\,\mathrm{TeV}^{-2},$$
$$-25 < f_{T,0}/\Lambda^4 < 24\,\mathrm{TeV}^{-4},$$
$$-12 < \kappa_0^W/\Lambda^2 < 10\,\mathrm{TeV}^{-2},\ \text{and}$$
$$-18 < \kappa_C^W/\Lambda^2 < 17\,\mathrm{TeV}^{-2}.$$

| Process | muon channel number of events | electron channel number of events |
|---|---|---|
| W γ +jets | 136.9 ± 3.5 ± 9.2 ± 0.0 | 101.6 ± 2.9 ± 8.0 ± 0.0 |
| WV+jet, jet -> γ | 33.1 ± 1.3 ± 4.6 ± 0.0 | 21.3 ± 1.0 ± 3.1 ± 0.0 |
| MC $t\bar{t}\gamma$ | 12.5 ± 0.8 ± 2.9 ± 0.5 | 9.1 ± 0.7 ± 2.1 ± 0.4 |
| MC single top | 2.8 ± 0.8 ± 0.2 ± 0.1 | 1.7 ± 0.6 ± 0.1 ± 0.1 |
| MC Z γ +jets | 1.7 ± 0.1 ± 0.1 ± 0.1 | 1.5 ± 0.1 ± 0.1 ± 0.1 |
| multijets | < 0.2± 0.0 ± 0.1 ± 0.0 | 7.2 ± 3.6 ± 3.6 ± 0.0 |
| SM WW γ | 6.3 ± 0.1 ± 1.5 ± 0.3 | 4.7 ± 0.1 ± 1.1 ± 0.2 |
| SM WZ γ | 0.6 ± 0.0 ± 0.1 ± 0.0 | 0.5 ± 0.0 ± 0.1 ± 0.0 |
| Total predicted | 193.9 ± 3.9 ± 10.8 ± 1.0 | 147.6 ± 4.8 ± 9.6 ± 0.7 |
| Data | 183 | 139 |

# Towards VBS: VBF Z production

CMS-PAS-FSQ-12-035

Comprehensive study of Z+forward dijet production at 7 and 8 TeV.

VBF Z one of the interfering amplitudes

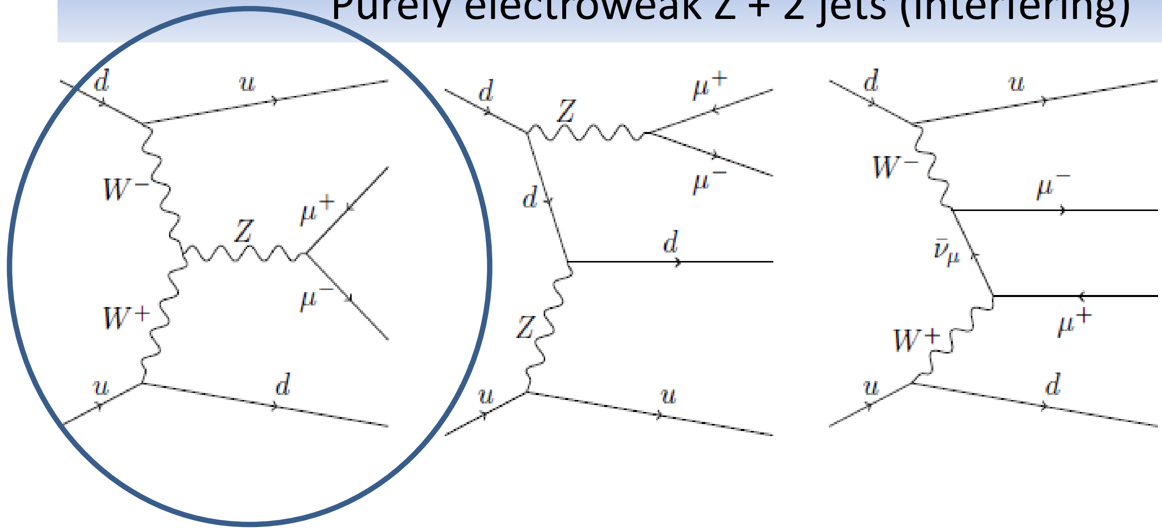
Z+2jet events selected with "VBF topology": large dijet mass, large dijet Δy

Small S/B enhanced with BDT selection exploiting all Z+2jet kinematics

**5 sigma signal for electroweak Z+jet production observed, fully consistent with SM**

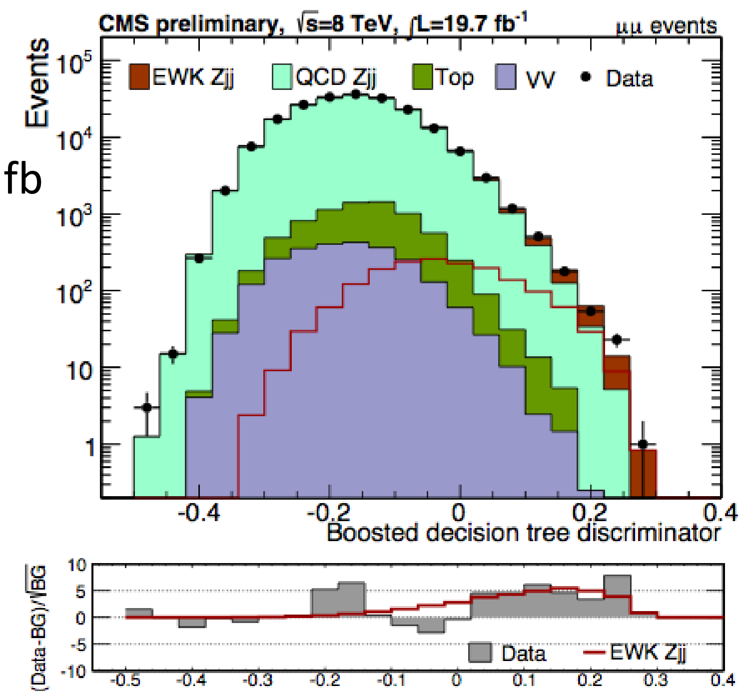
TGC potential under study

Purely electroweak Z + 2 jets (interfering)



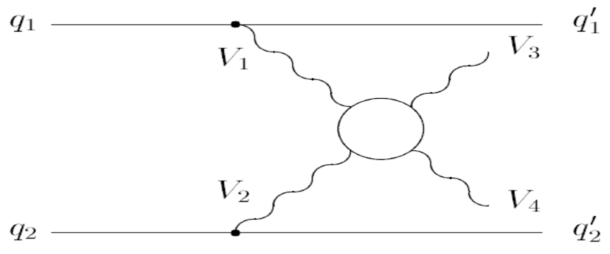
σEWK = 226 ± 26 stat ± 35 syst fb

σVBFNLO = 239 fb



# Towards VBS: VV projections

ATLAS-PHYS-PUB-2013-006



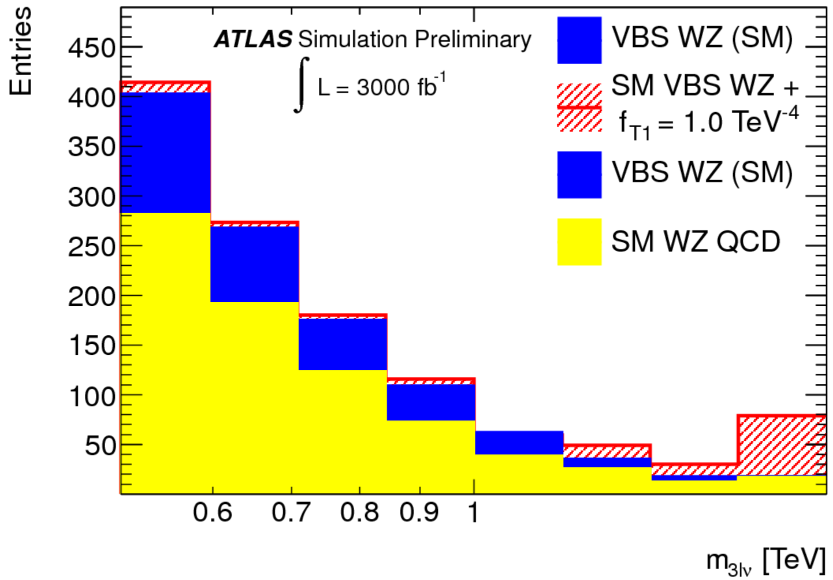

Snowmass study to understand VBS potential of Run2+

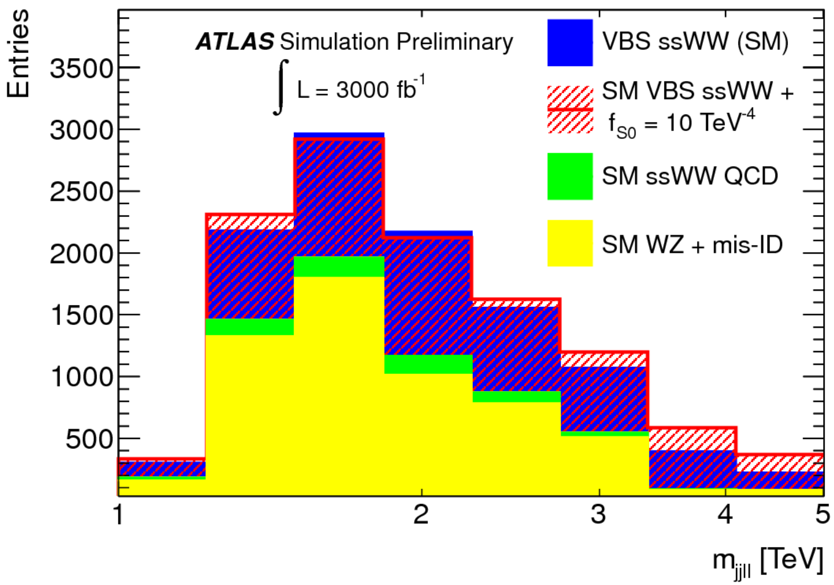
Select 3 lepton or same-sign dilepton events with "VBF dijet" (dijet mass > 1 TeV )

**Several modes expected to be observed with < 300/fb**

**5 sigma anomalous dim 8 production at the 1 TeV scale possible in Phase 1**

| Parameter | dimension | channel | $\Lambda_{UV}$ [TeV] | 300 fb$^{-1}$ | |
|---|---|---|---|---|---|
| | | | | $5\sigma$ | 95% CL |
| $c_{\phi W}/\Lambda^2$ | 6 | $ZZ$ | 1.9 | 34 TeV$^{-2}$ | 20 TeV$^{-2}$ |
| $f_{S0}/\Lambda^4$ | 8 | $W^\pm W^\pm$ | 2.0 | 10 TeV$^{-4}$ | 6.8 TeV$^{-4}$ |
| $f_{T1}/\Lambda^4$ | 8 | $WZ$ | 3.7 | 1.3 TeV$^{-4}$ | 0.7 TeV$^{-4}$ |
| $f_{T8}/\Lambda^4$ | 8 | $Z\gamma\gamma$ | 12 | 0.9 TeV$^{-4}$ | 0.5 TeV$^{-4}$ |
| $f_{T9}/\Lambda^4$ | 8 | $Z\gamma\gamma$ | 13 | 2.0 TeV$^{-4}$ | 0.9 TeV$^{-4}$ |



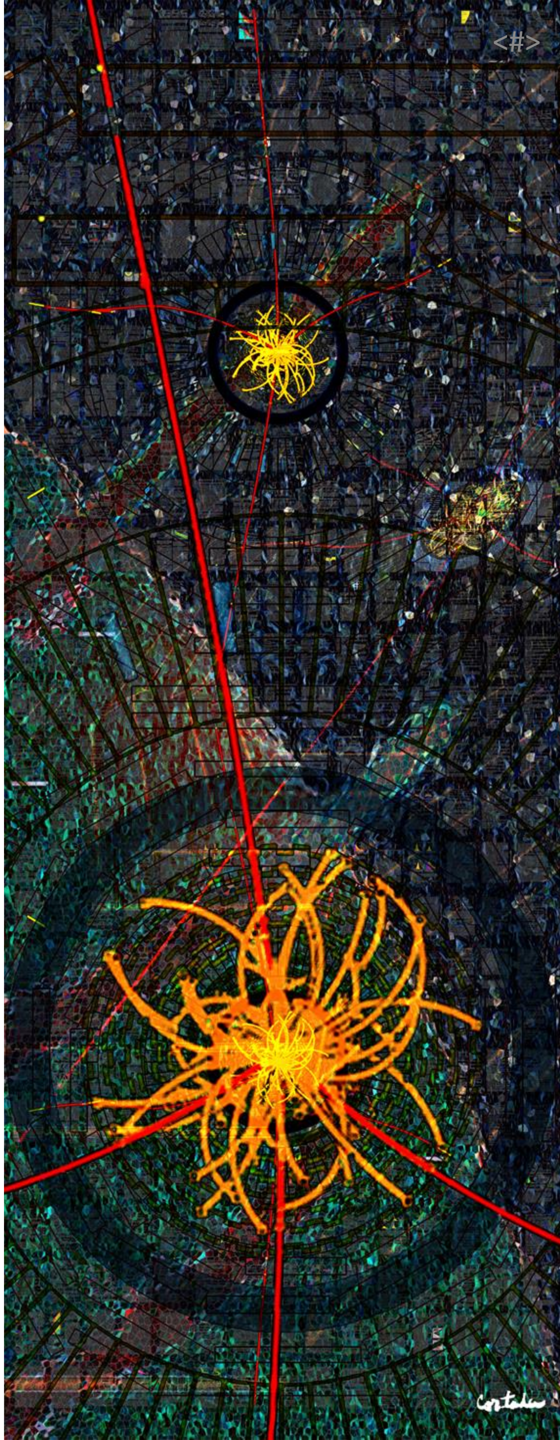



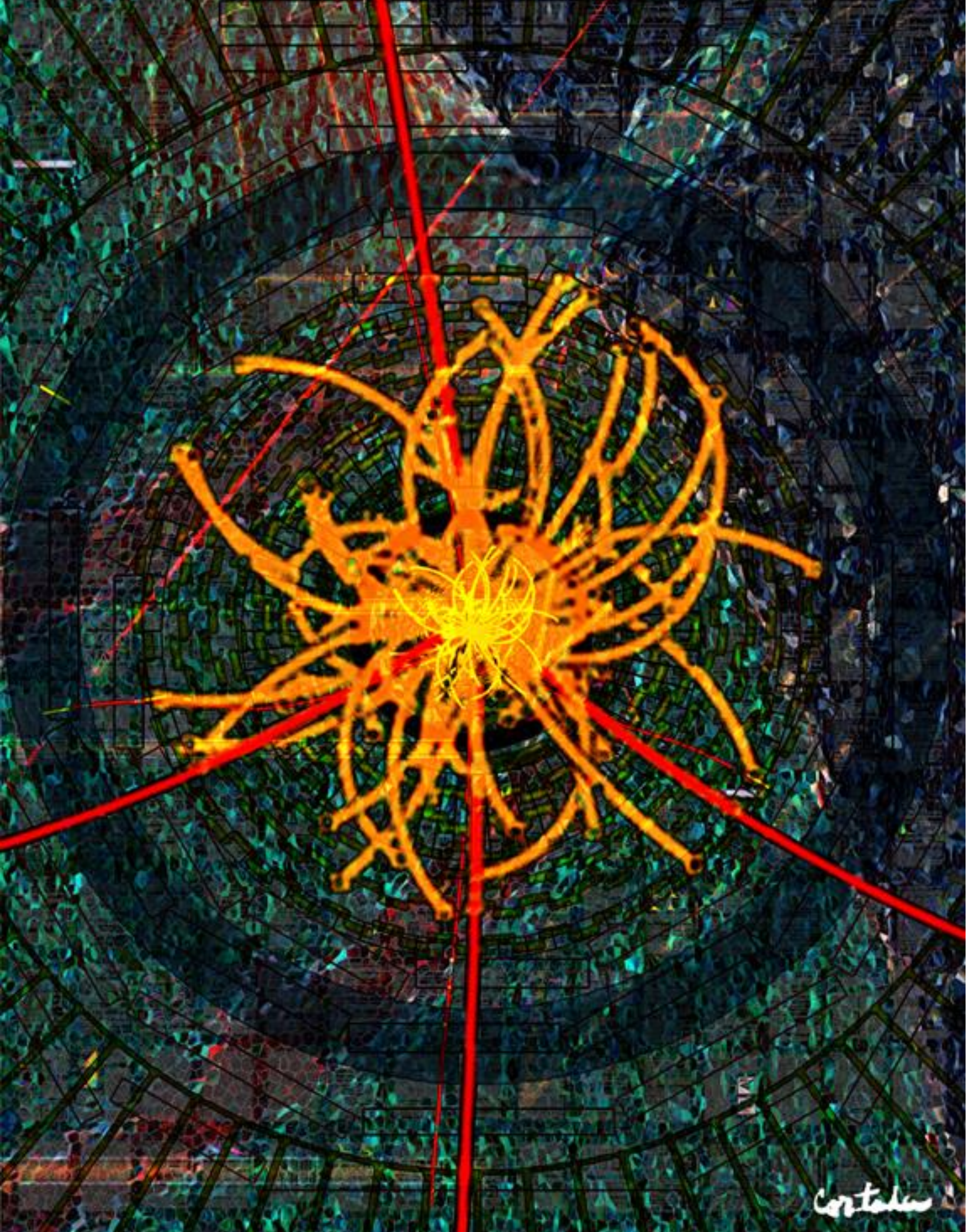
# Summary

- W and Z physics at the LHC and Tevatron provide precision tests of PDFs and NNLO QCD + NLO EWK calculations, with future potential to further refine the precision electroweak sector as well.

- The LHC is now the leading laboratory for exploring the gauge boson self-interactions.

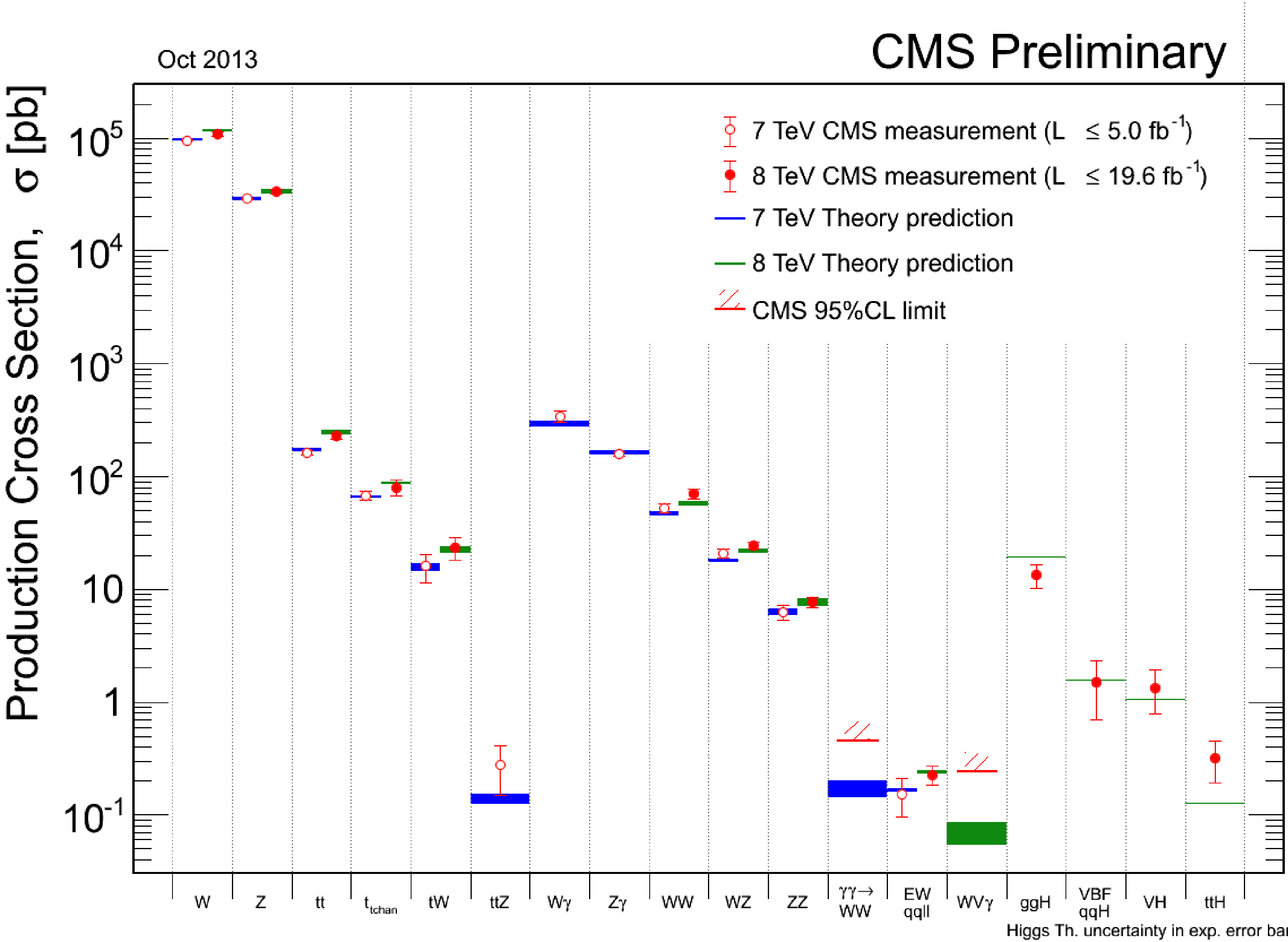
- Now poised to explore vector boson scattering phenomena and directly test electroweak symmetry breaking.



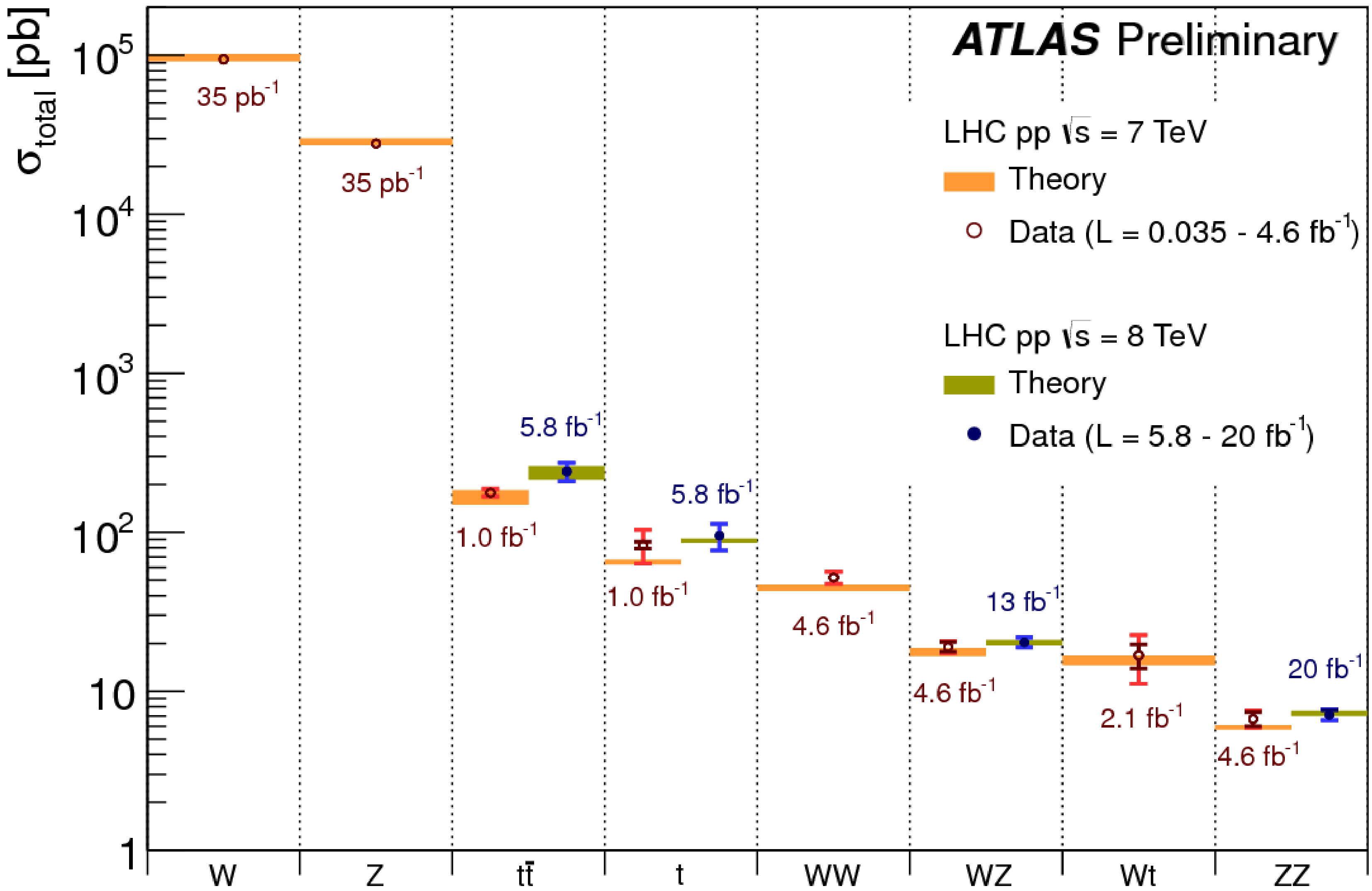


# Backups

# CMS Electroweak Cross Section Summary

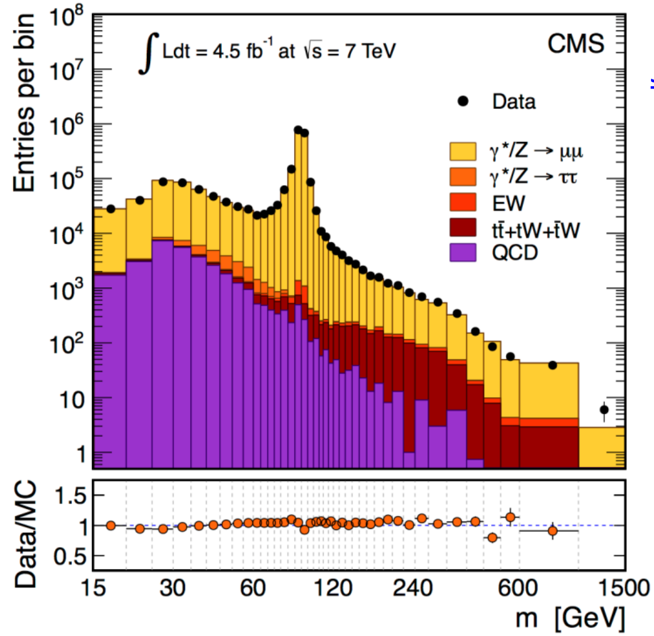


# ATLAS Electroweak Cross Section Summary



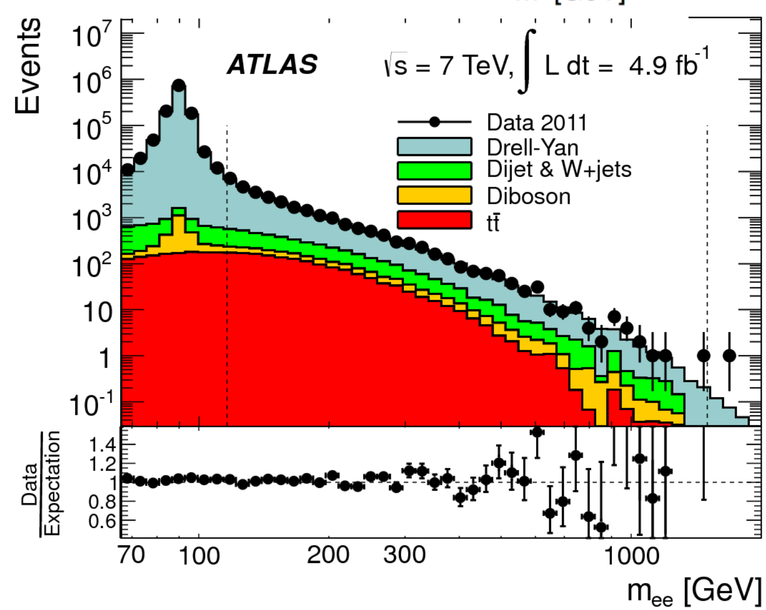
# Drell-Yan Cross Section at LHC

- Z/Drell-Yan production at the 7 TeV LHC gives us 1M dilepton events/fb with high efficiency and purity
- Efficiency estimated in situ using “tag-and-probe” methods
- Small backgrounds estimated from emu, same-sign, and lepton+jet control samples




J. High Energy Phys. 12 (2013) 30

**7 TeV dilepton spectrum extending to 1500 GeV in dilepton mass**




Phys. Lett. B 725 (2013) 223

# Z and Drell-Yan Production at LHC

- ATLAS systematic uncertainties for high mass DY(ee) cross section

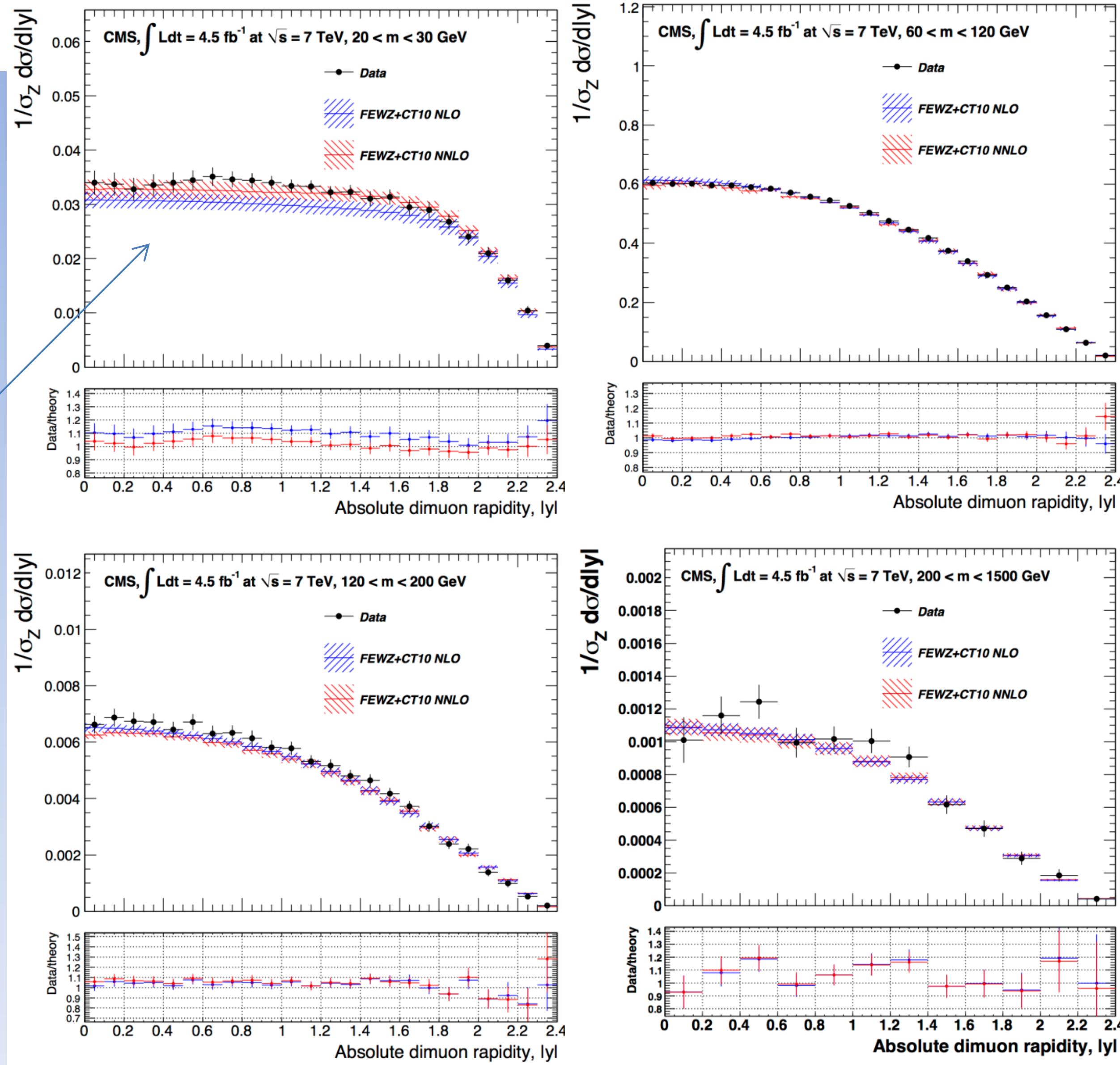
| Source of uncertainty | Uncertainty [%] in $m_{ee}$ bin 116–130 GeV | 1000–1500 GeV |
|---|---|---|
| Total background estimate (Stat.) | 0.1 | 7.6 |
| Total background estimate (Syst.) | 1.3 | 3.1 |
| Electron energy scale & resolution | 2.1 | 3.3 |
| Electron identification | 2.3 | 2.5 |
| Electron reconstruction | 1.6 | 1.7 |
| Bin-by-bin correction | 1.5 | 1.5 |
| Trigger efficiency | 0.8 | 0.8 |
| MC statistics ($C_{\mathrm{DY}}$ stat.) | 0.7 | 0.4 |
| MC modelling | 0.2 | 0.3 |
| Theoretical uncertainty | 0.3 | 0.4 |
| Total systematic uncertainty | 4.2 | 9.8 |
| Luminosity uncertainty | 1.8 | 1.8 |
| Data statistical uncertainty | 1.1 | 50 |

Table 1: Summary of systematic uncertainties on the cross-section measurement, shown for the lowest and highest bin in $m_{ee}$. For some sources the lowest or highest uncertainty may lie in an intermediate bin. The data statistical uncertainties are also given for comparison.

# Drell-Yan cross section at LHC

J. High Energy Phys. 12 (2013) 30

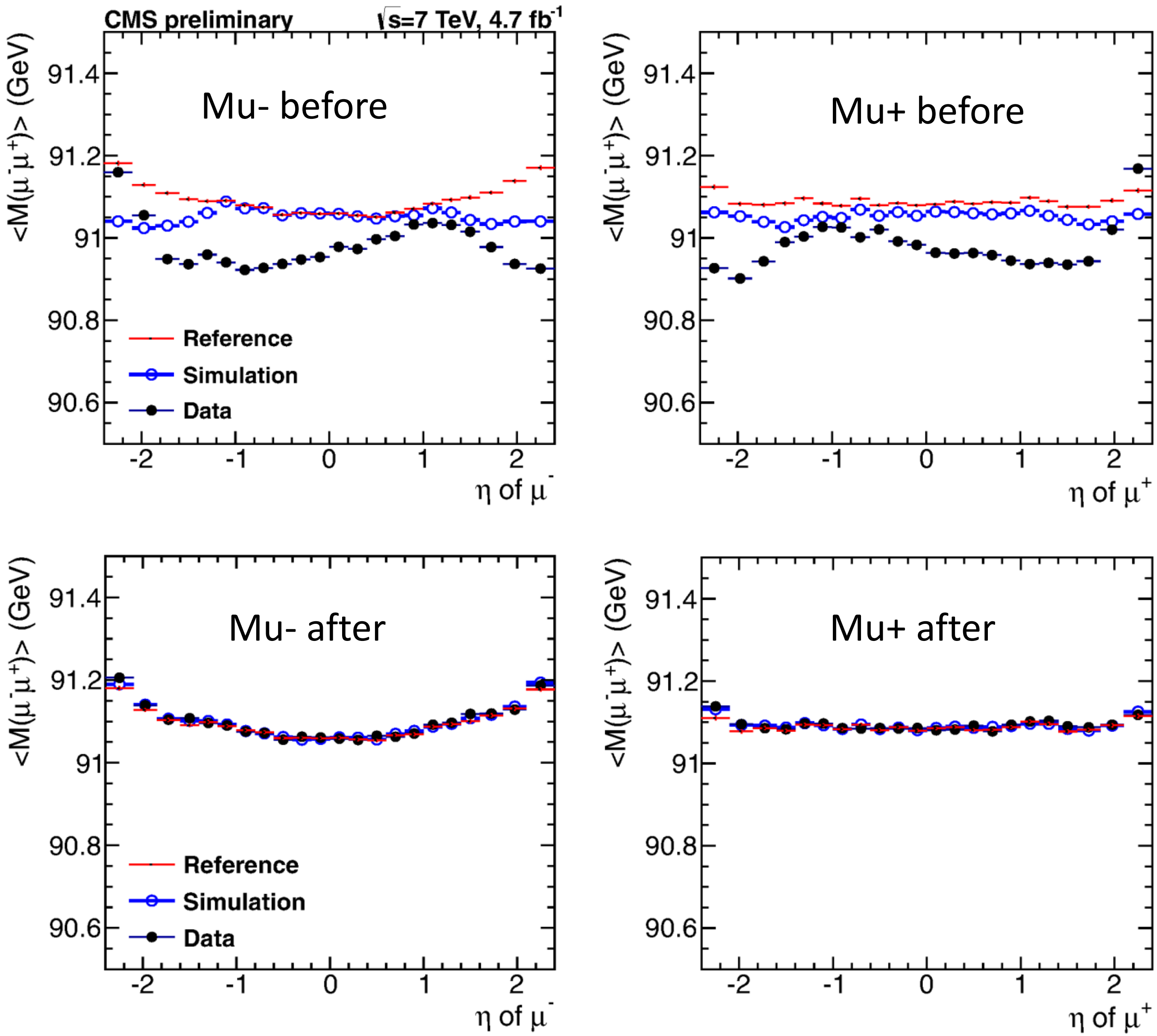
- Double-differential cross section in M and y measured for the first time at LHC (dimuons only)
- Unfolded to the pre-FSR "Born level"
- NNLO QCD effects are visible at low mass
- **Expected to have an impact on sea quark PDFs**
- Combined with W data, could constrain strange quark PDF, à la ATLAS (*Phys.Rev.Lett. 109 (2012) 012001*) with 2010 data.



# W charge asymmetry

CMS-PAS-SMP-12-021

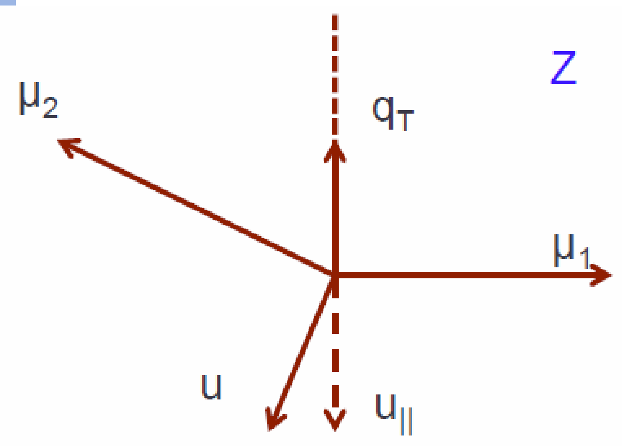
- Precise W counting requires sharp knowledge of muon PT acceptance
- Curvature of Z muons are calibrated against reference <1/PT> as a function of charge and $\eta$, $\phi$
- Curvature corrected further to match expected MZ. Iteratively converges to final calibration
- Afterwards, $\eta$, $\phi$ closely match MC generator reference

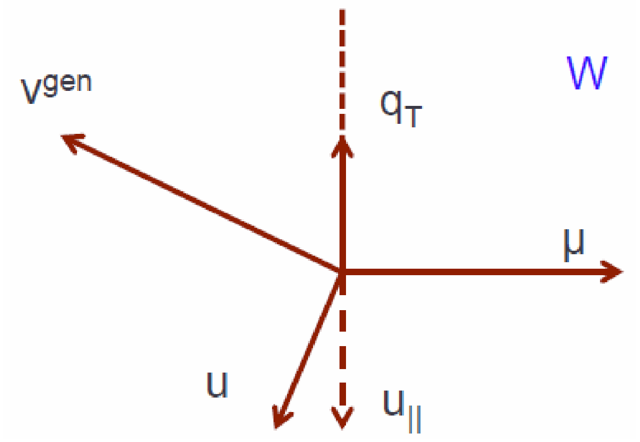


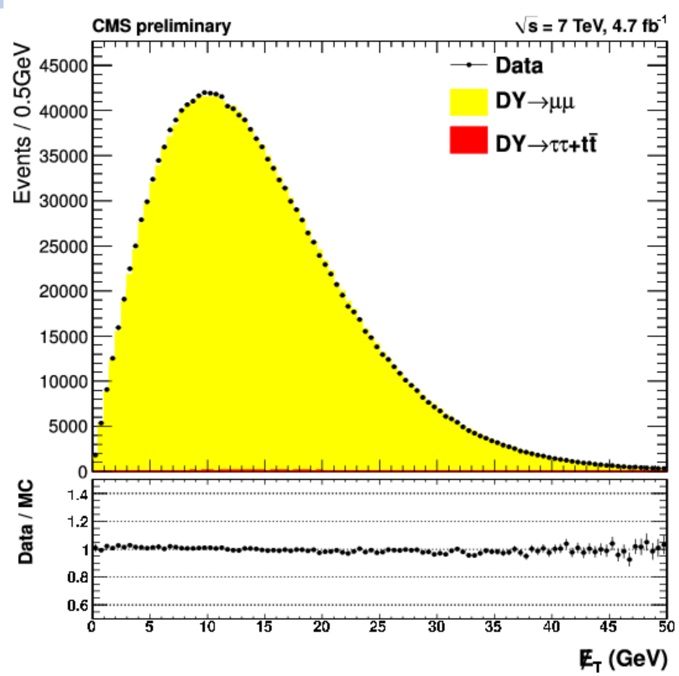
# W charge asymmetry

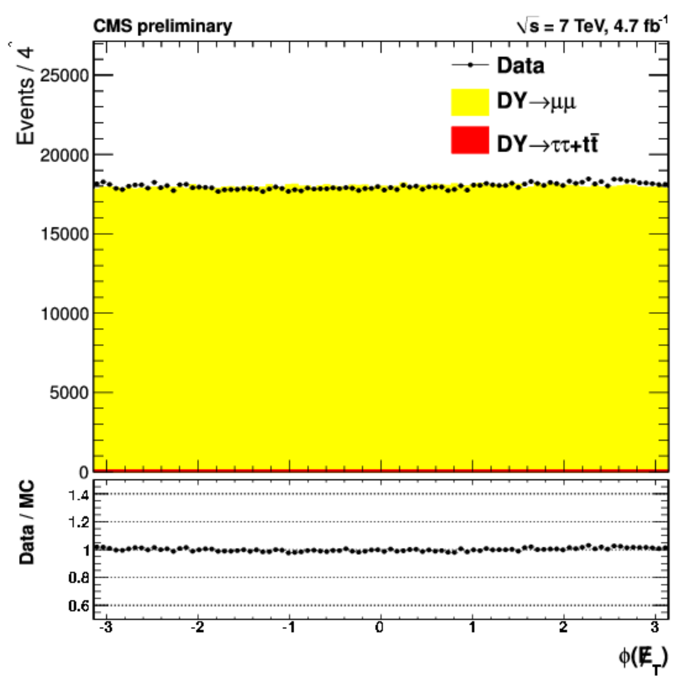
CMS-PAS-SMP-12-021

- Signal-background separation requires precision W recoil model
- Recoil u(perp) and u(para) mean and width measured in Z sample vs. Nvtx, η(jet), qT
- Z/Drell-Yan "MET" and "MET ϕ" precisely recovered after data/MC corrections of recoil model
- W recoil model receives same data/MC scalings of u



# W+charm cross section

arXiv:1310.1138

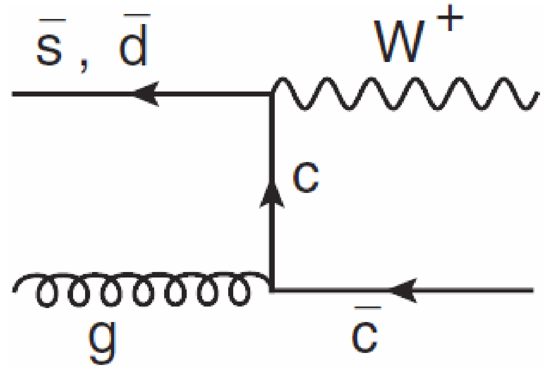
Leading order W+c directly probes **strange quark PDF**

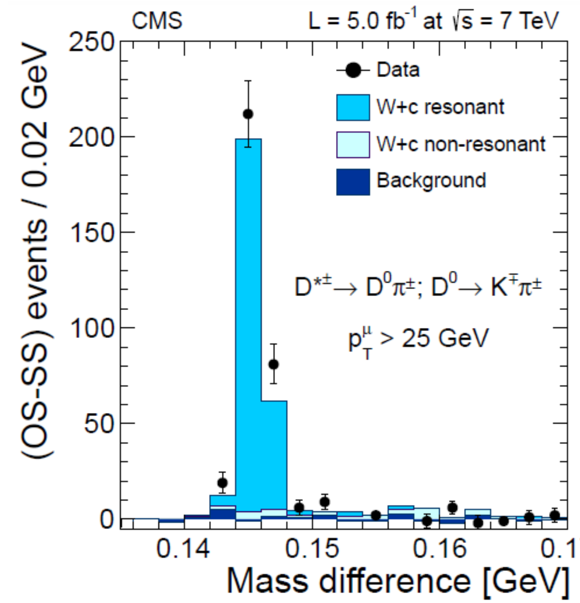
Strange and anti-strange probed independently by W+, W-

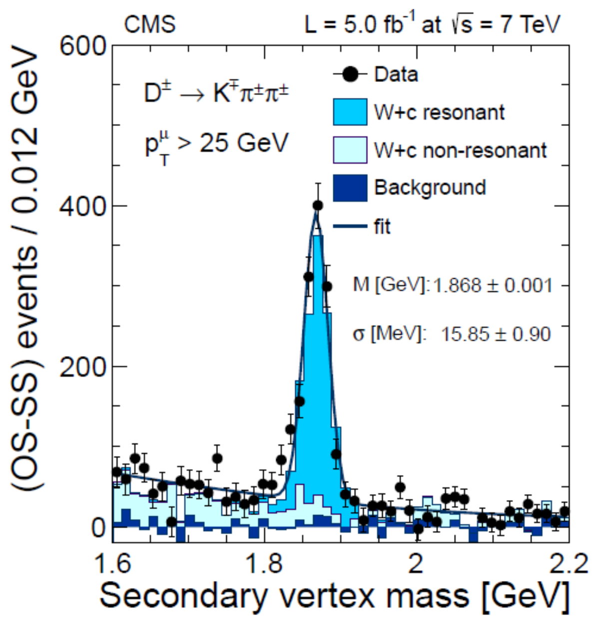
**W and c are opposite sign**

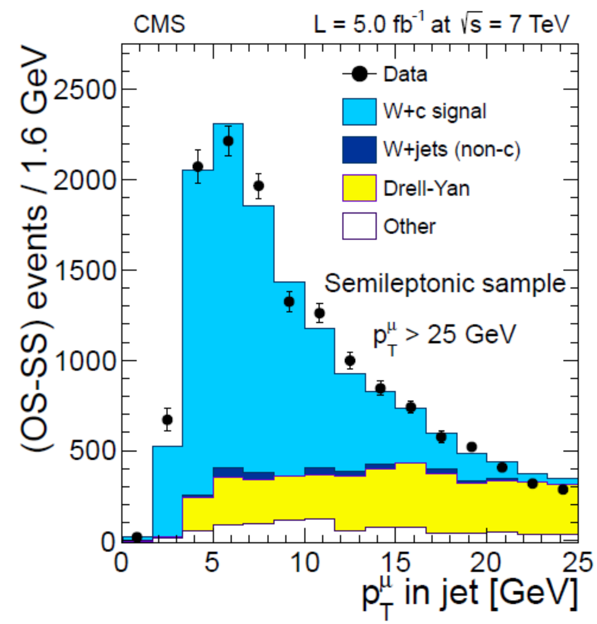
Higher-order W+cc, W+bb, top are **same-sign/opposite-sign symmetric**→subtract with same-sign data

(semi-)exclusive **charm hadron reconstruction** gives high-purity, self-charge-tagged W+c samples



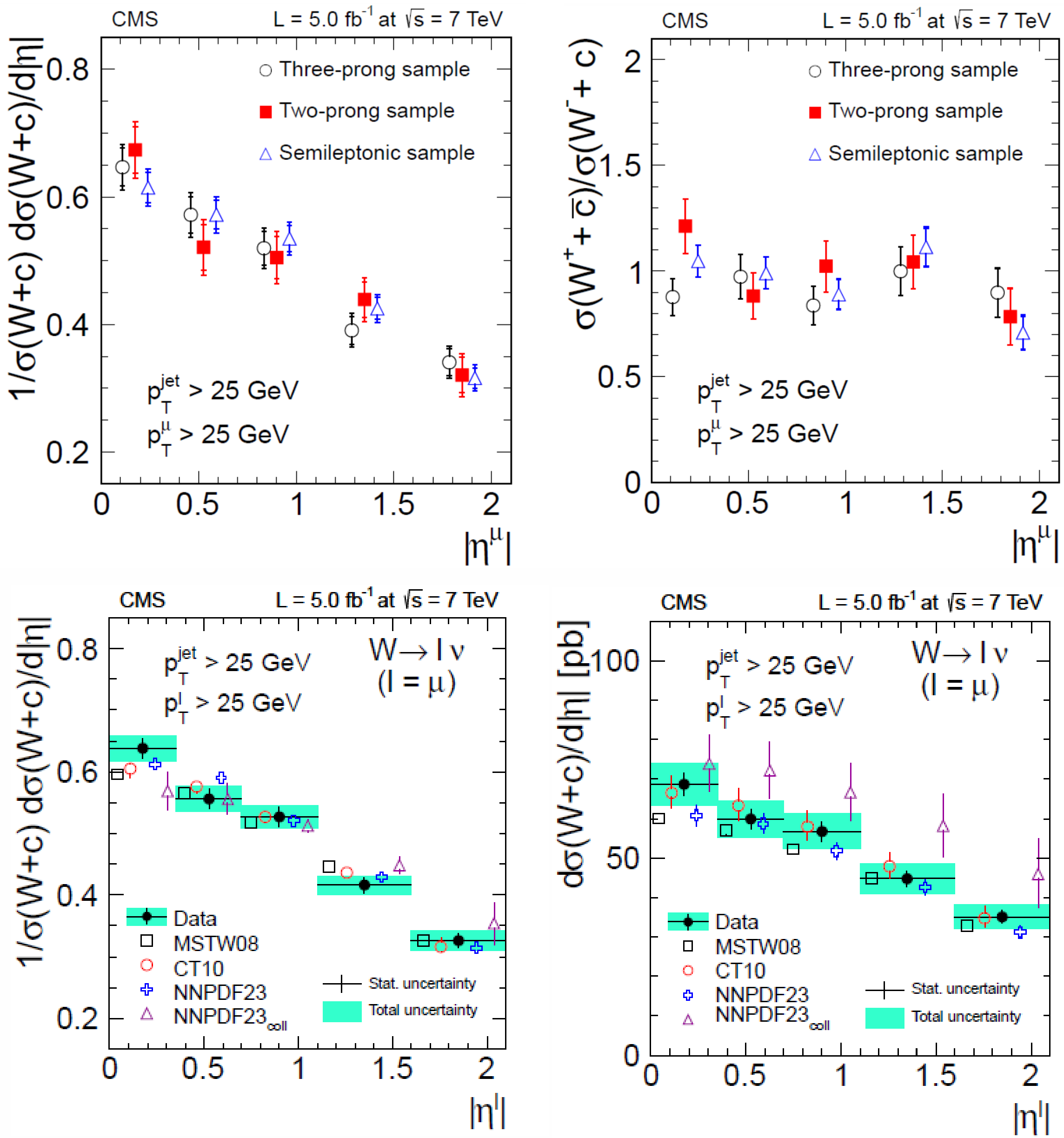



# W+charm cross section

arXiv:1310.1138

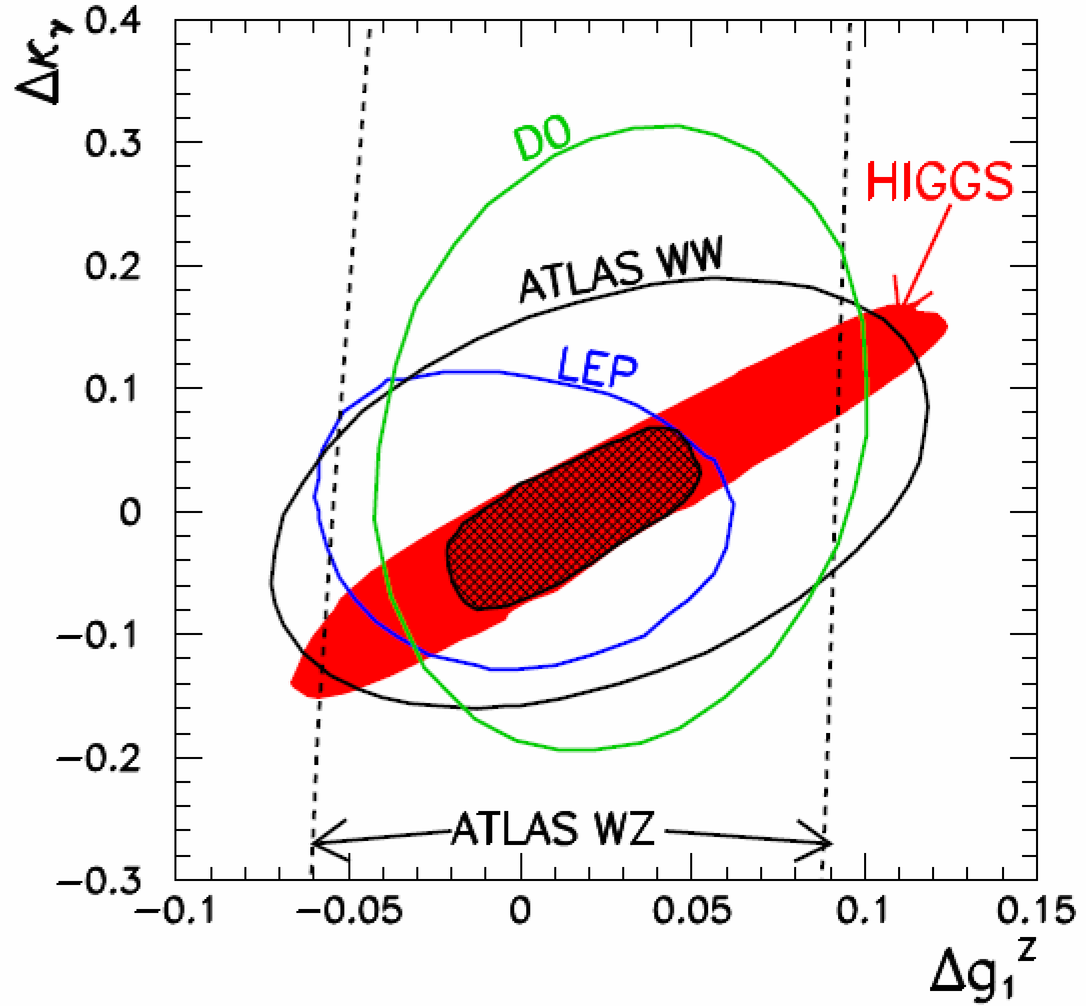
- Measure cross section and charged ratio vs lepton |η|
- Consistent across three different hadron reco methods
- Leading syst. are JES, charm branching fractions
- Consistent with NLO MCFM predictions



# Charged aTGCs: World Summary

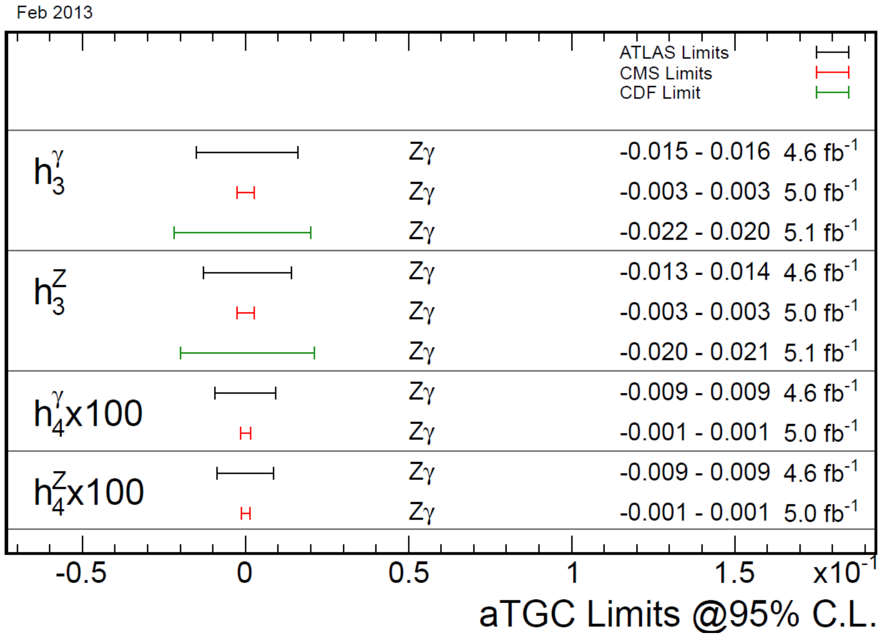
arXiv:1304.1151

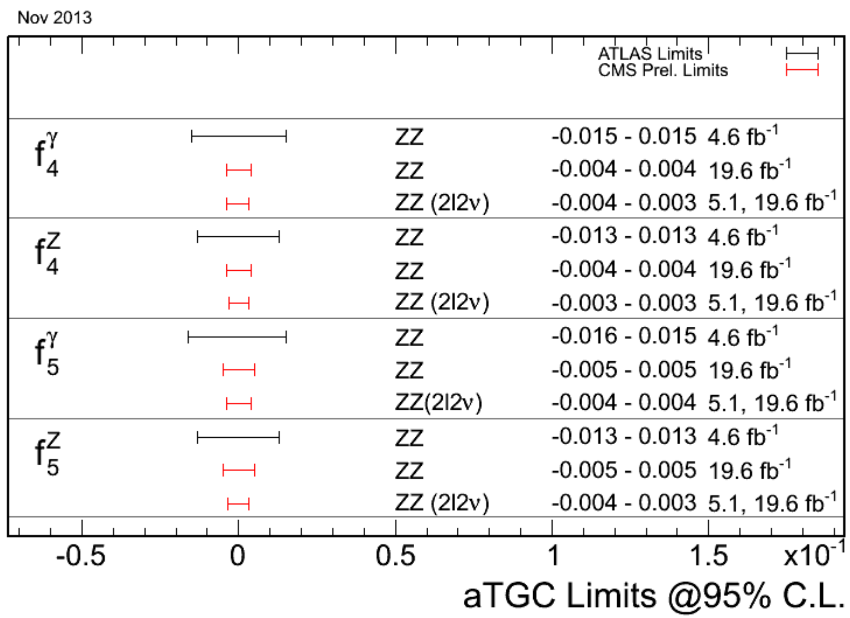
- HVV' operators are also induced by dim 6 anomalous interactions → Higgs σBR's also constrain aTGCs!
- Full 8 TeV Higgs data has better constraining power than 7 TeV dibosons. 8 TeV dibosons should catch up.
- Full Run 1 analysis should combine Higgs and diboson data in a consistent, multi-dimensionally correlated way



# Neutral aTGCs: World Summary

- 7 TeV Zγ (ννγ) world-leading in ZZγ/Zγγ sensitivity

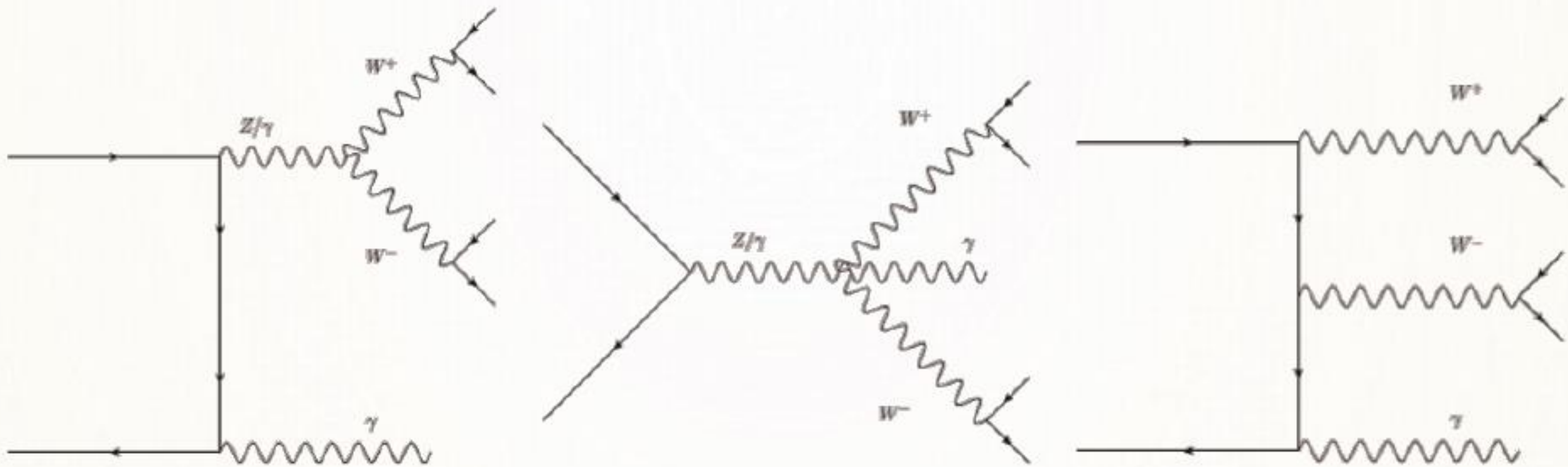



- New CMS 8 TeV ZZ (2l2ν) result world-leading in ZZZ sensitivity

# Triboson search in WWγ and WZγ

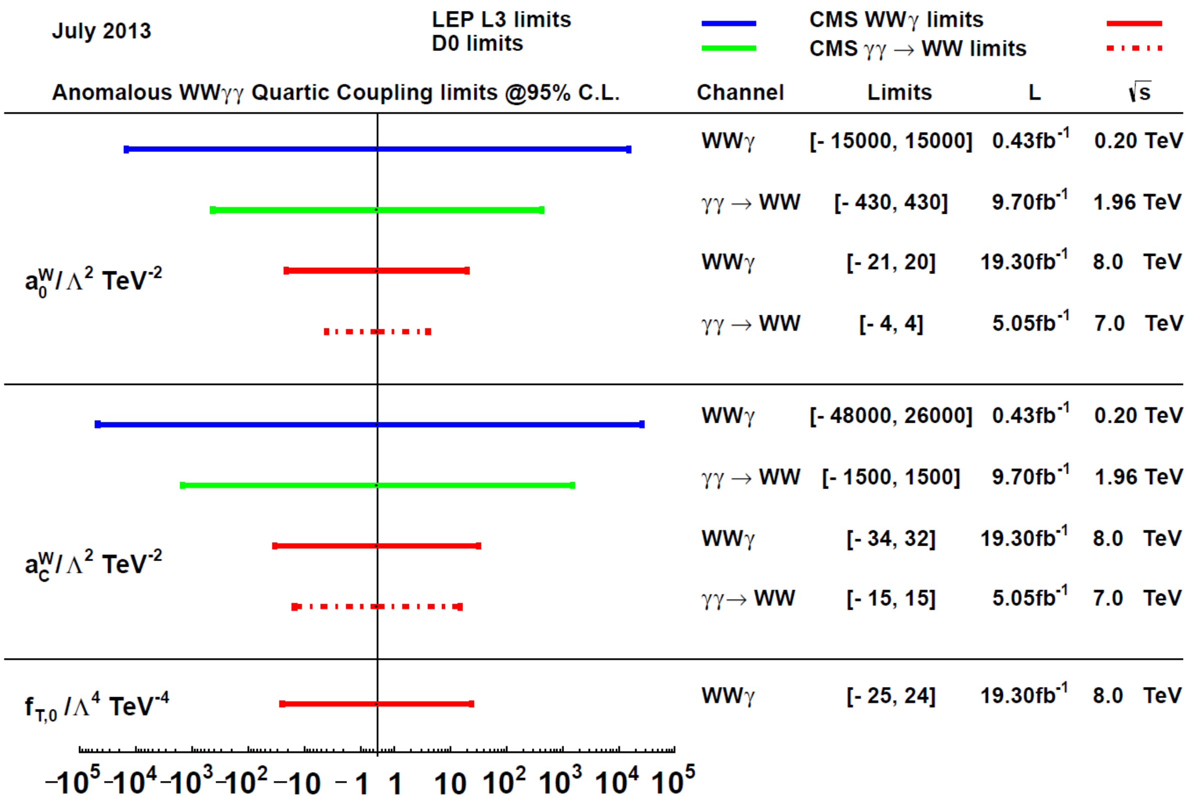
- Triboson final state is an admixture of QGC, TGC, and double radiative events




$$\mathcal{L}_{aQGC} = \frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_C^W}{4g^2}\mathcal{W}_c^\gamma + \sum_i \kappa_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}.$$

# Quartic Gauge Couplings: World Summary

- WWγγ constraint is now dominated by CMS exclusive WW production result.
- WWZγ explored for the first time ($f_{T,0}$).
- Present limits do not correspond to meaningfully high energy scales or perturbative, unitary coupling regime.



# Effective Field Theory Revisited

Dim 6

- Which Operators contribute to which Vertices ?

| | $\mathcal{O}_{WWW}$ | $\mathcal{O}_{WW}$ | $\mathcal{O}_{W}$ | $\mathcal{O}_{BB}$ | $\mathcal{O}_{B}$ | $\mathcal{O}_{\tilde{B}}$ | $\mathcal{O}_{\tilde{B}B}$ | $\mathcal{O}_{\tilde{W}W}$ | $\mathcal{O}_{\tilde{W}WW}$ | $\mathcal{O}_{\tilde{D}W}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| WWZ | × | | × | | × | × | | | × | × |
| WWA | × | | × | | × | × | | | × | × |
| ZZH | | × | × | × | | × | × | × | | |
| WWH | | × | × | | | | | × | | |
| AAH | | × | | × | | | × | × | | |
| AZH | | × | × | × | × | × | × | × | | |
| WWWW | × | | × | | | | | | × | × |
| WWZZ | × | | × | | | | | | × | × |
| WWAA | × | | | | | | | | × | × |
| WWAZ | × | | × | | | | | | × | × |
| WWHH | | × | × | | | | | × | | |
| ZZHH | | × | × | × | × | × | × | × | | |
| AZHH | | × | × | × | × | × | × | × | | |
| AAHH | | × | | × | | | × | × | | |

# Triboson search in WWγ and WZγ

- Dim 6 and Dim 8 operators will exhibit a high PT tail for the photon
- Can interpret results in both dim 6 (k's) and dim 8 (f's) picture.

$$\frac{f_{M,0}}{\Lambda^4} = -\frac{g^4}{M_W^2}\frac{\kappa_0^w}{\Lambda^2},$$

$$\frac{f_{M,2}}{\Lambda^4} = -\frac{g^2 g'^2}{2M_W^2}\frac{\kappa_0^b}{\Lambda^2},$$

$$\frac{f_{M,1}}{\Lambda^4} = \frac{g^4}{M_W^2}\frac{\kappa_c^w}{\Lambda^2},$$

$$\frac{f_{M,3}}{\Lambda^4} = \frac{g^2 g'^2}{2M_W^2}\frac{\kappa_c^b}{\Lambda^2}.$$