DIBOSON AND EWK PHYSICS AT CMS

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On behalf of the CMS collaboration

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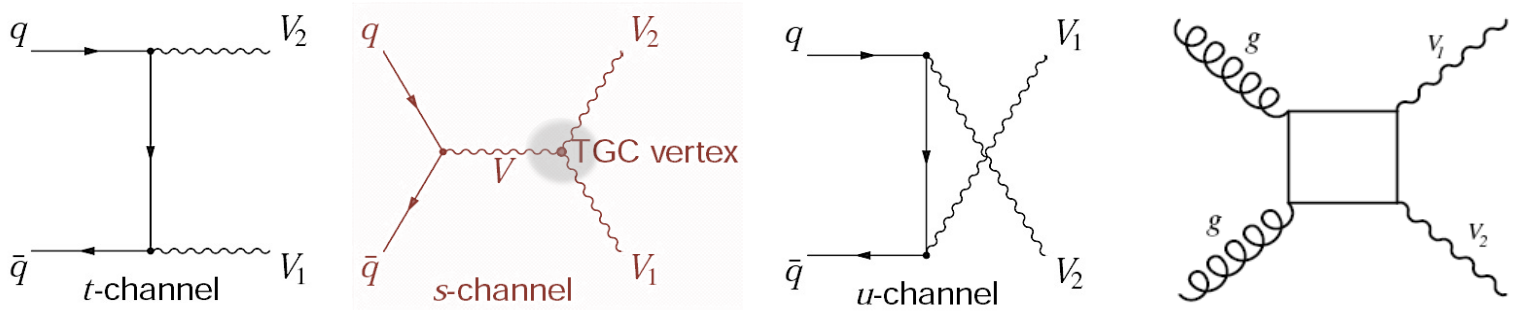
Outline

- **The talk will be focus on latest results from CMS**
- **Diboson production:**
  - **γγ production** at 7 TeV, SMP-13-001
  - **ZZ→4l** at 8 TeV, SMP-13-005
  - **ZZ→2l2ν** at 7 and 8 TeV, SMP-12-016
  - **WZ→3lν** at 7 and 8 TeV, SMP-12-006
  - **VZ→2l2b** at 8 TeV, SMP-13-011
  - **VWγ→lνjjγ** at 8 TeV, SMP-13-009
- **Search for anomalous couplings**
- **Selected electroweak results**
  - **VBF Z production** at 8TeV, FSQ-12-035
  - **Muon charge asymmetry** at 7 TeV, arXiv:1312.6283
  - **V+jets cross section** at 7 TeV
  - **PDF constraints**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Diboson production

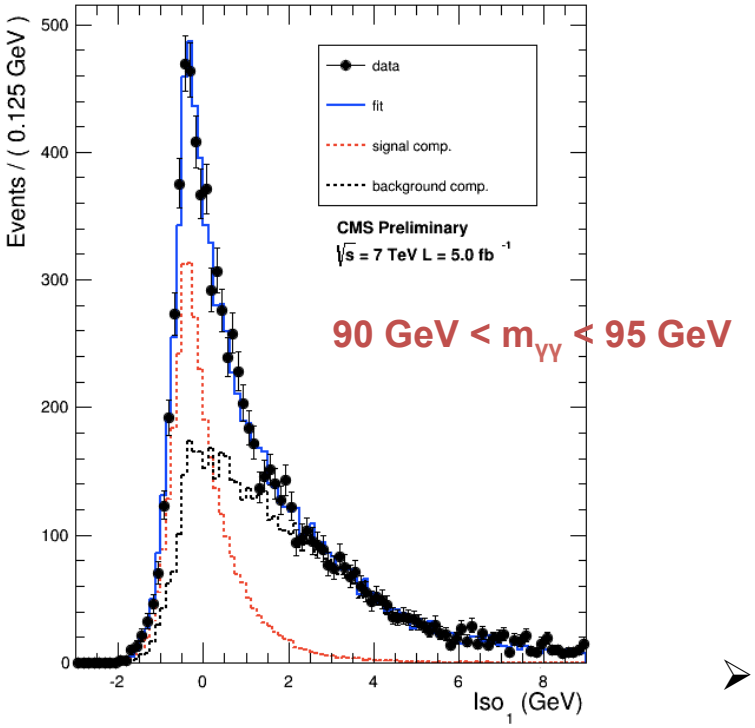
- **Feynman diagram: V_1, V_2, V = Z, W , γ ➔ $\gamma\gamma$, WZ, ZZ**



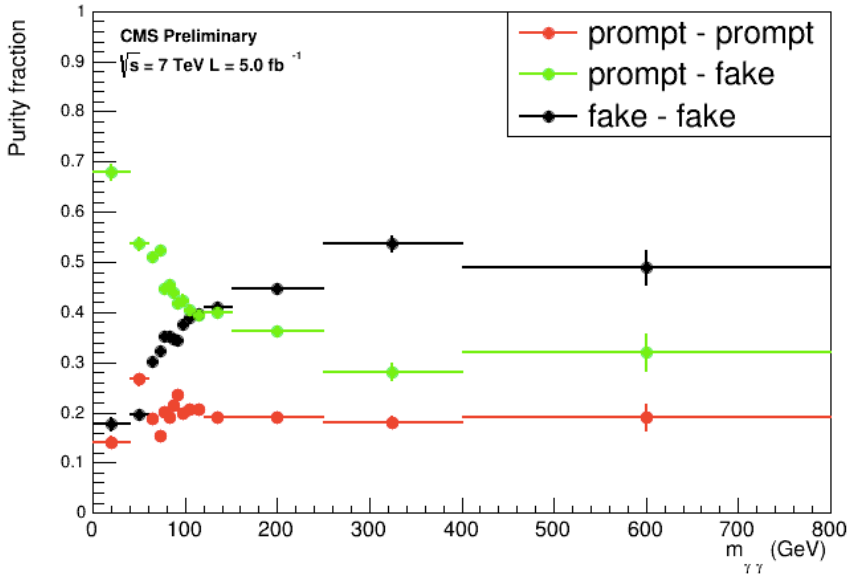
- **Cross section available at NLO QCD for WZ and ZZ, and NNLO for $\gamma\gamma$**
  - Gluon-gluon enters at NLO (~5% correction)
- **Fundamental test of Standard Model**
  - Test of gauge structure of the Standard Model
- **Irreducible background for Higgs boson measurements and BSM searches**
  - Precise knowledge of cross sections and kinematical distributions are important
- **Probe for new physics**
  - Search for Anomalous Triple Gauge Couplings (TGC) and Quartic Gauge Coupling (QGC): indirect search for tree or loop effect of massive new particles

Diphoton cross-section

- **SMP-13-001, 5.0fb-1 at 7 TeV**
- **Differential cross-section** measured as a function of $M_{\gamma\gamma}$, $P_{T,\gamma\gamma}$, $\Delta\Phi_{(\gamma1,\gamma2)}$, $\cos(\theta^*)$
- **Kinematical range:** $|\eta_\gamma|<2.5$, $E_{T,\gamma1}>40$, $E_{T,\gamma2}>25$ GeV, $\Delta R_{(\gamma1,\gamma2)}>0.45$
- Main background is from jets mis-id as a γ (fake)
  - Data-driven approach to extract the prompt diphoton yield based on particle-flow photon isolation template: ~10% systematic uncertainties



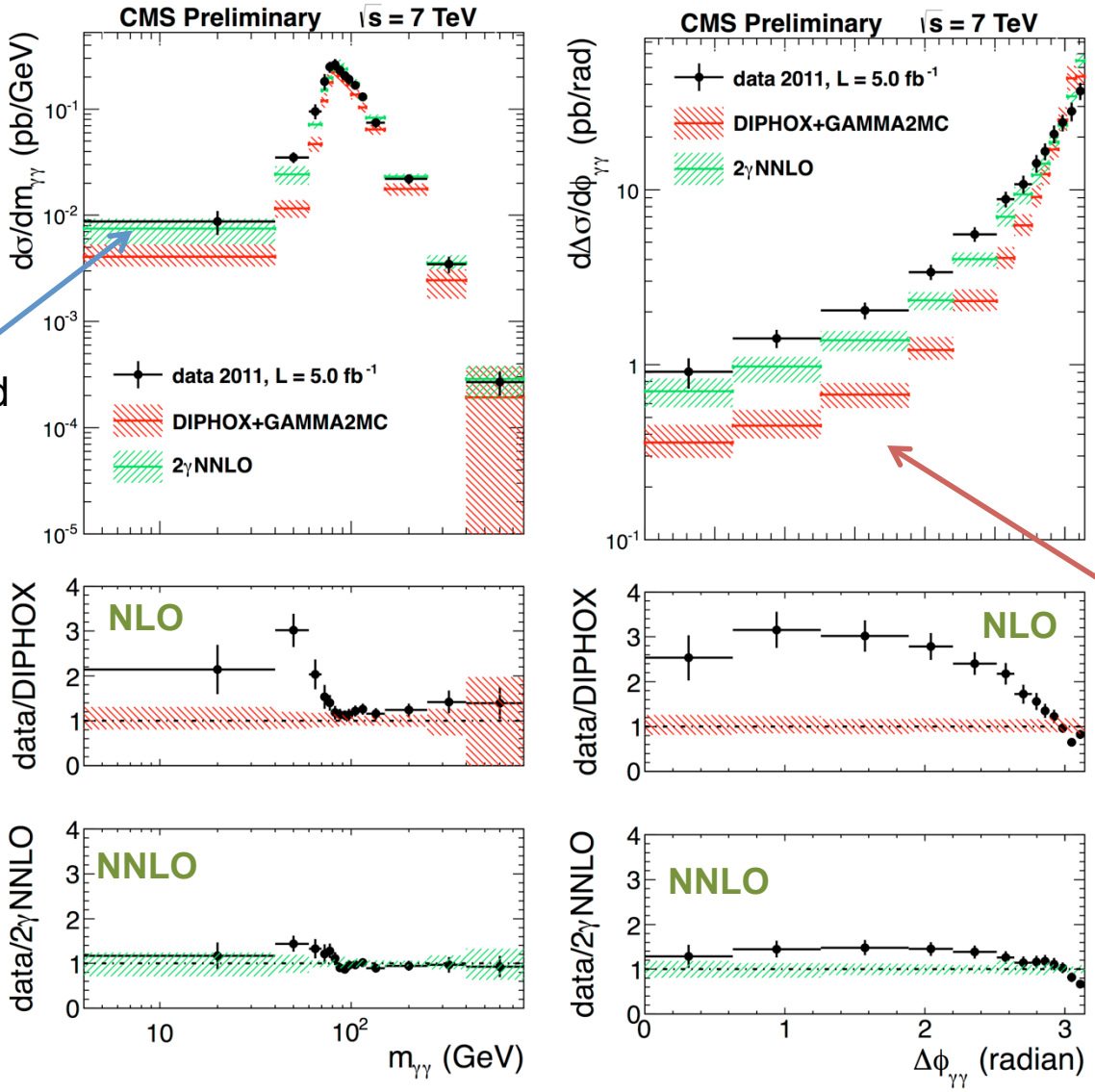
Uncertainties are statistical only.



➢ **Main systematic from data-driven templates**

Diphoton cross-section

SMP-13-001

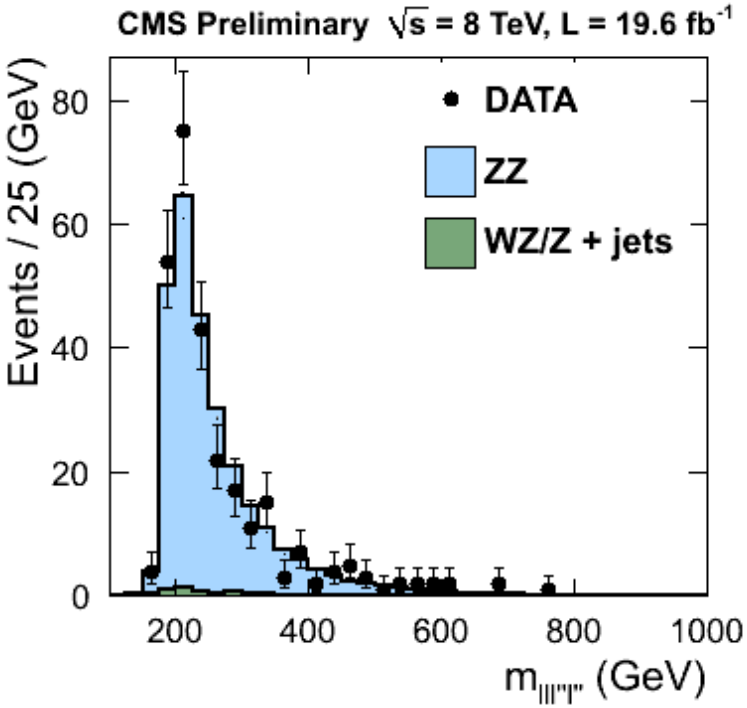


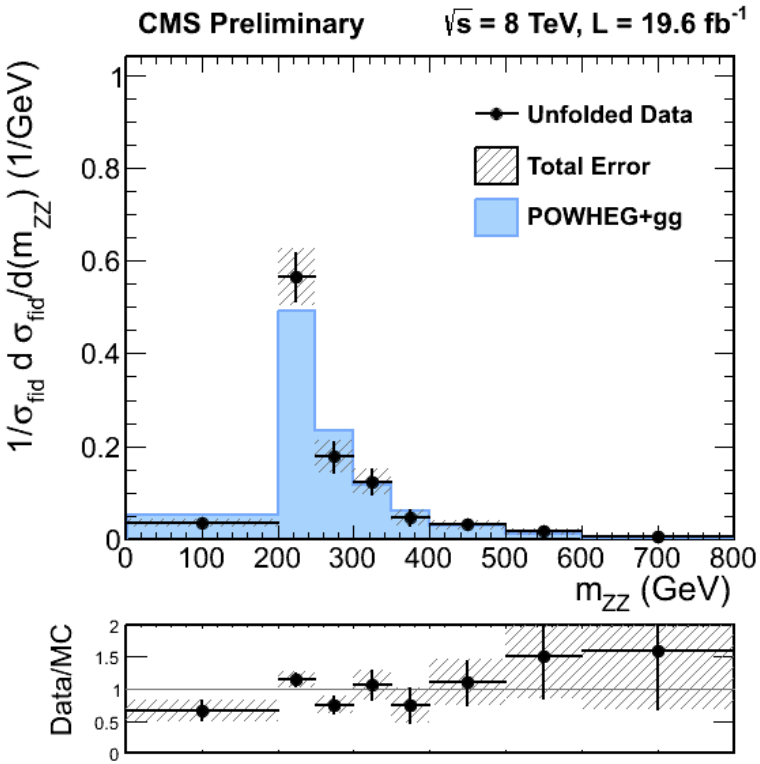
NNLO enhanced region

- **NNLO** predictions improve a lot the data/ MC agreement
- **Still an excess in data at low ΔΦ** (sensitive to missing higher order QCD effects)

ZZ→4l cross section

- **SMP-13-005, 19.6fb-1 at 8 TeV**
- Inclusive and differential cross section measurement in the channel to 4l (including one Z to taus)
- Main backgrounds (significant only in llττ): Z +jets (jet faking a lepton), WZ, top





8 TeV

Data σ = 7.7 $^{+0.5}_{-0.5}$ (stat.) $^{+0.5}_{-0.4}$ (sys.) ± 0.4 (theo.) ± 0.3 (lumi.) pb

MCFM@NLO 7.7 ± 0.6 pb

➢ **Main systematic from data-driven background**

ZZ→2l 2ν

- **SMP-12-016, 4.9fb-1 at 7 TeV and 19.6fb-1 at 8 TeV**
- Inclusive cross section measurement in the channel to 2l 2ν
- Main backgrounds estimated from control samples in data: DY, top, WW
- Cross-section measured using a reduced MET variable

7 TeV

Data $\sigma = 5.0\ ^{+1.5}_{-1.4}\,(\text{stat})\ ^{+1.3}_{-1.0}\,(\text{syst}) \pm 0.2\,(\text{lumi})$ pb

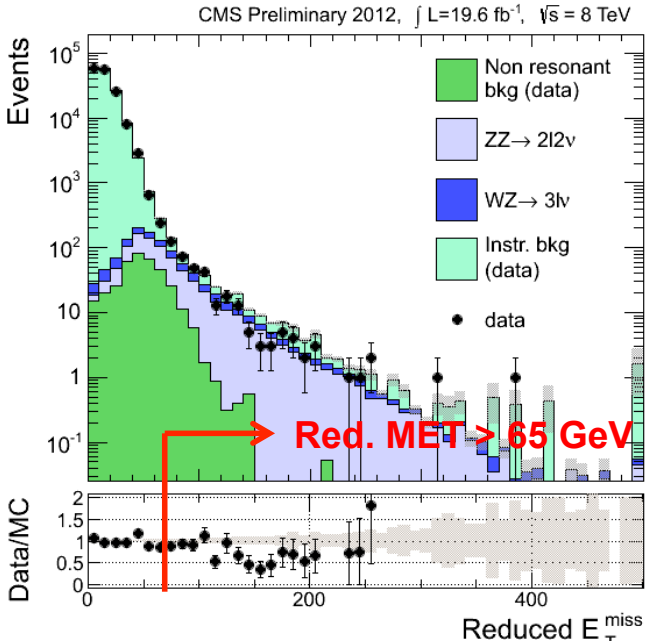
MCFM NLO $\sigma = 6.5 \pm 0.3$ pb

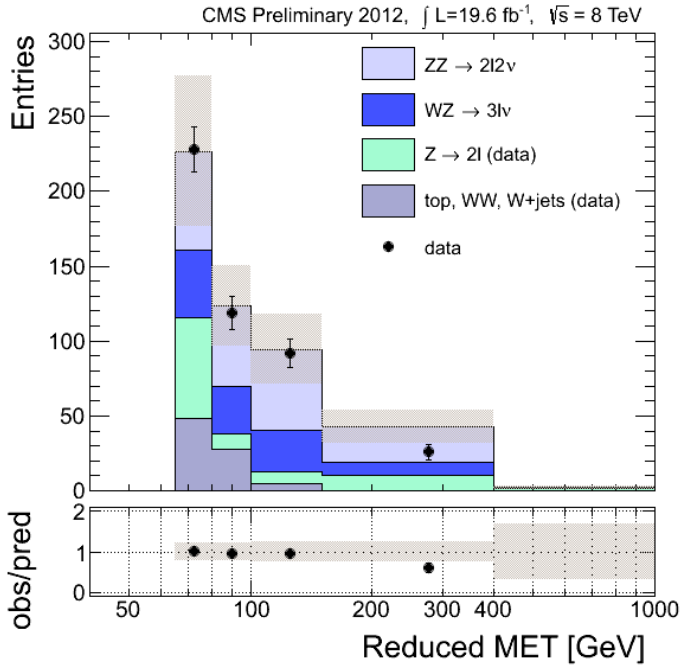
8 TeV

Data $\sigma = 6.8\ ^{+0.8}_{-0.8}\,(\text{stat})\ ^{+1.8}_{-1.4}\,(\text{syst}) \pm 0.3\,(\text{lumi})$ pb

MCFM NLO $\sigma = 7.7 \pm 0.6$ pb

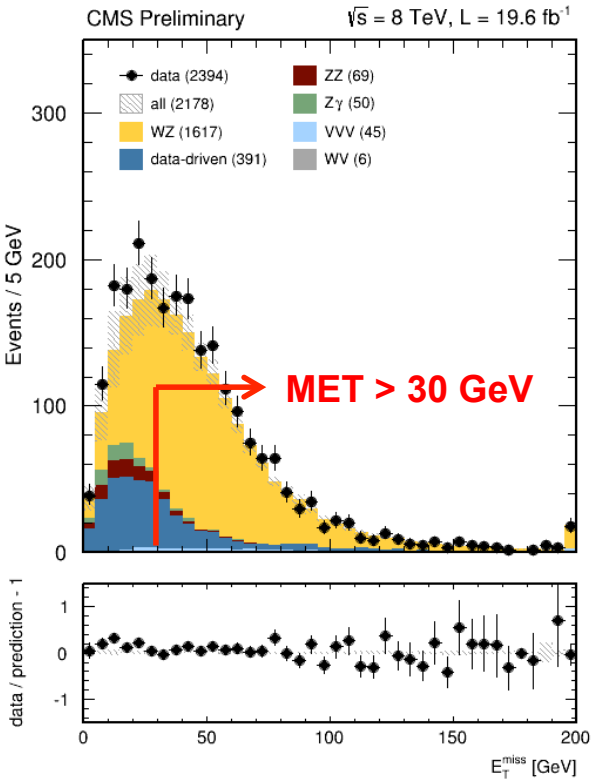
➢ **Main systematic from data-driven templates**

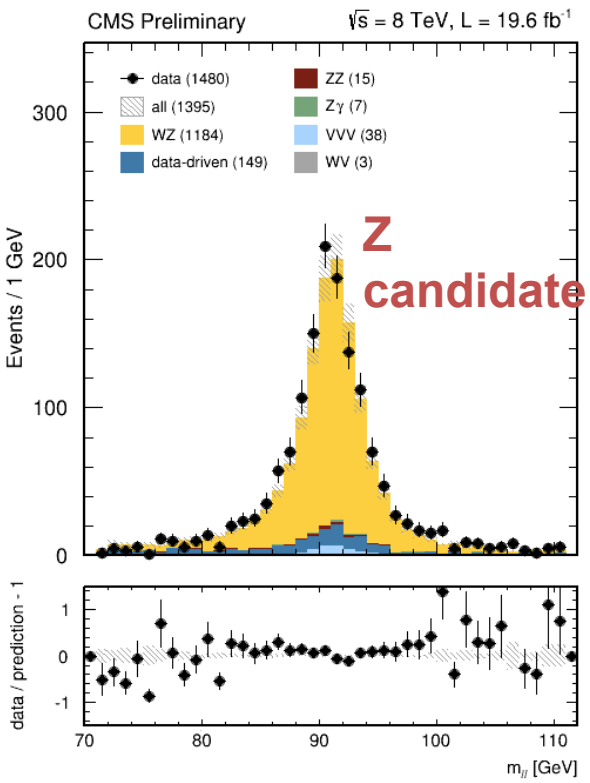


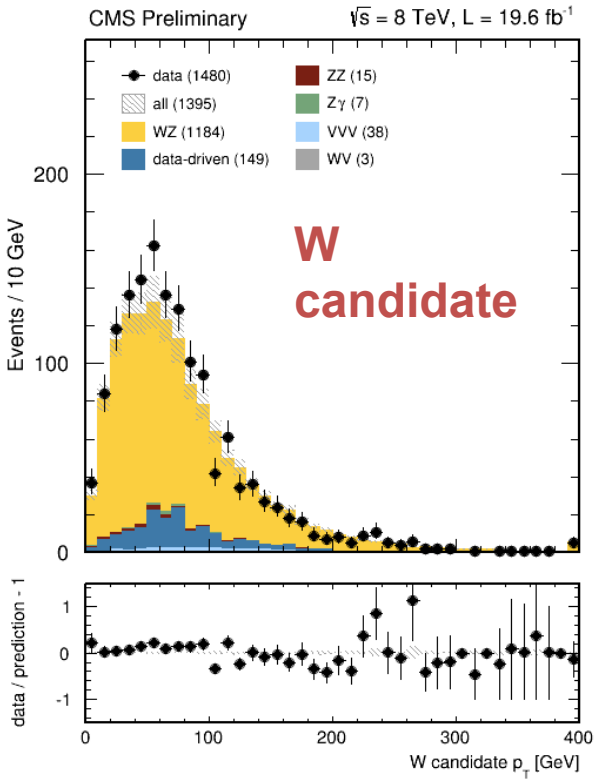


WZ→3lν cross section

- **SMP-12-006, 4.9fb-1 at 7 TeV and 19.6fb-1 at 8 TeV**
- Inclusive cross section in 3 leptons + MET, measured with 4 final states: eee, eeμ, eμμ, μμμ
- Main backgrounds Z+jet /top estimated from data (inverting lepton isolation), ZZ (from MC)







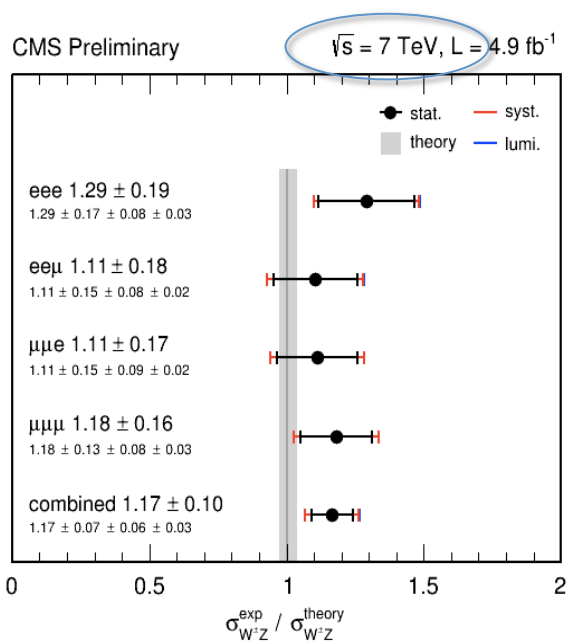
WZ→3lν cross section

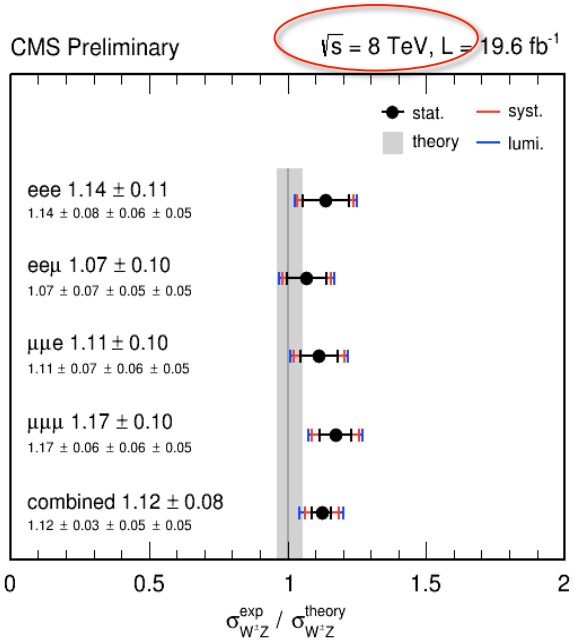
- **Systematic limited: ~6%** (mainly from Z+jet/top background estimate and MET)
- **Cross-sections consistently compatible within ~1σ with the SM (MCFM@NLO) predictions**
- W^+Z/W^-Z ratios are compatible with NLO predictions. Help to constrains u/d PDF ratio

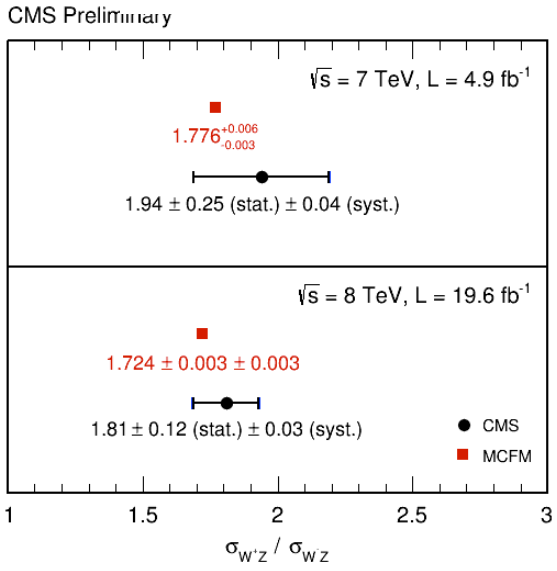
7 TeV: Data σ= 20.76 ± 1.32 (stat.) ± 1.13 (syst.) ± 0.46 (lumi.) pb

8 TeV: Data σ= 24.61 ± 0.76 (stat.) ± 1.13 (syst.) ± 1.08 (lumi.) pb

$$\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}} = \frac{N_S^+}{N_S^-} \cdot \frac{(\mathcal{A}\cdot\varepsilon)^-}{(\mathcal{A}\cdot\varepsilon)^+}$$

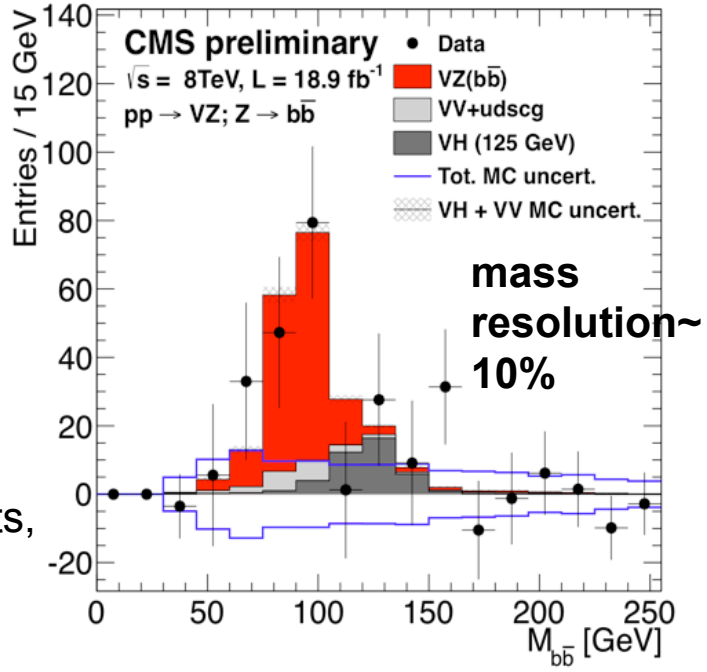


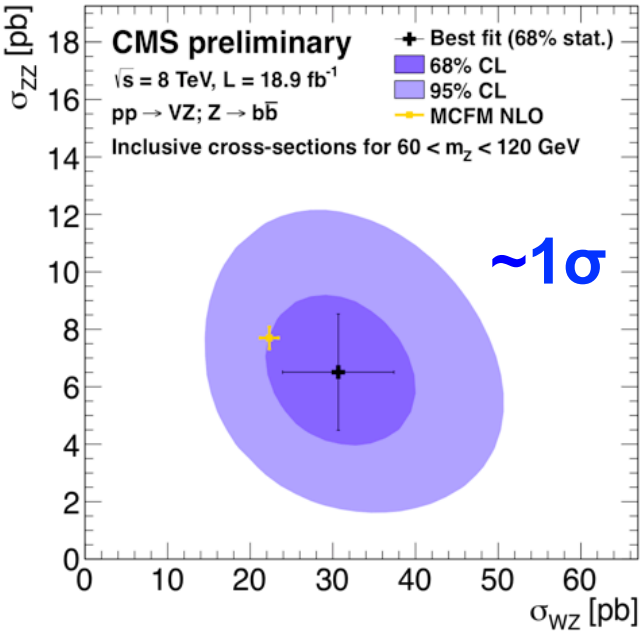




VZ(2b) cross section

- **SMP-13-011, 18.9fb-1 at 8 TeV**
- Inclusive cross section measurement of VZ(bb) (V=W,Z) in final state: 2l2b, lvbb, vvbb (l=e,μ)
- Main backgrounds: Zbb, Wbb, ttbar
- **Multivariate analysis:**
  - Use lepton and jet kinematics, b-tagging and MET information, m(jj)
  - Use 3 "staggered" BDT, trained against ttbar, W/Z+jets, and all background





Observed significance of 6.3σ (exp. 5.9σ)

pp→WZ

σ = 30.7 ± 9.3(stat.) ± 7.1(syst.) ± 4.1(theo.) ± 1.0 (lumi.) pb *(MCFM 22.3 ± 1.1 pb)*

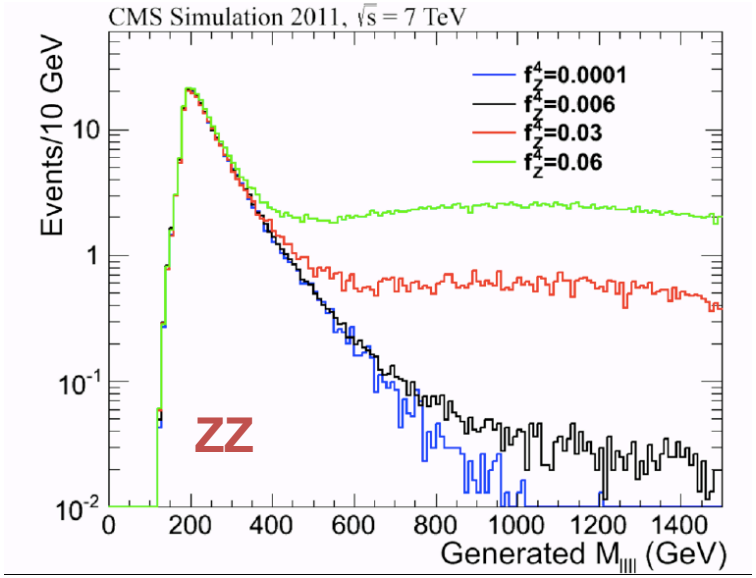
pp→ZZ

σ = 6.5 ± 1.7(stat.) ± 1.0(syst.) ± 0.9(theo.) ± 0.2 (lumi.) pb *(MCFM 7.7 ± 0.6 pb)*

➢ **Main systematic from background estimation and theory**

Anomalous Triple Gauge Couplings (aTGC)

- **No neutral TGCs at tree level in SM**
- New Physics shows up through virtual effects: modification to TGCs wrt to SM
  - Increase of cross section at high invariant mass and high transverse momentum!
- **Results based on effective lagrangian approach**
  - The expected number of signal events can be written as a function of the SM cross section plus some aTGC parameters
  - Additional constraints can be imposed to reduce the number of parameters, i.e. charged couplings use “LEP parametrization”

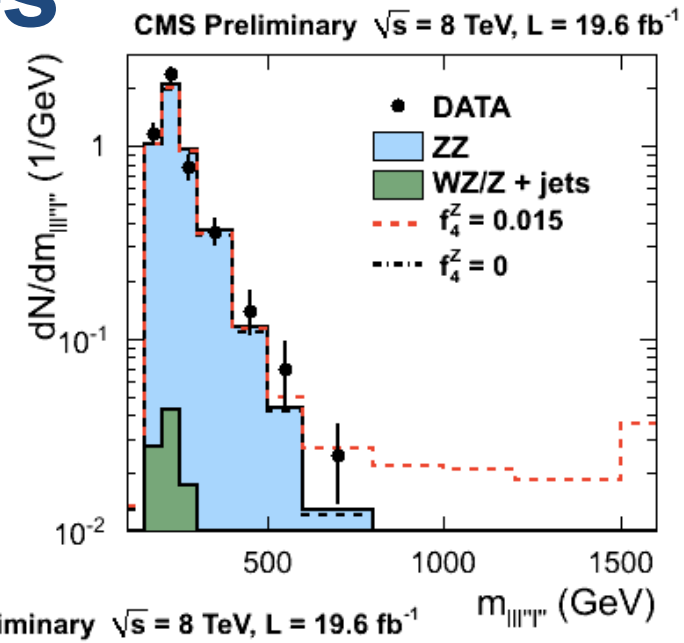


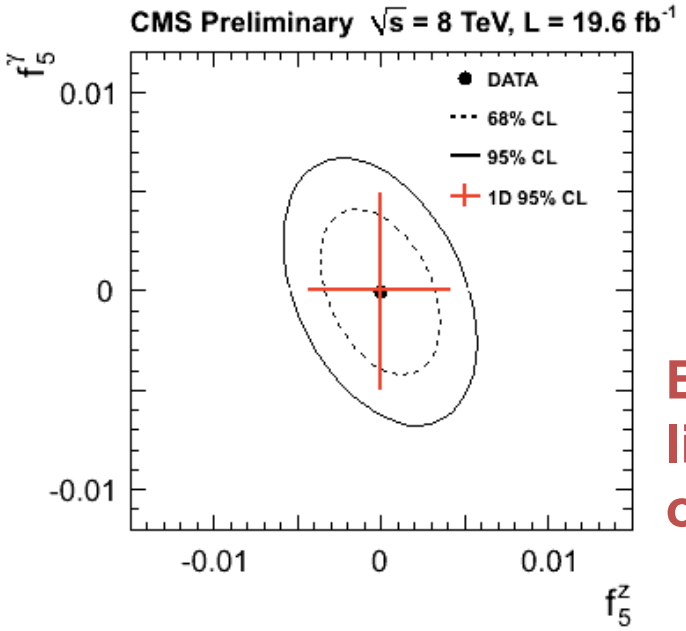
➢ ***No form factors used***

coupling	parameters	channel	
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, Wγ	Charged couplins
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ	Charged couplins
$ZZ\gamma$	h_3^Z, h_4^Z	Zγ	Neutral couplins
$Z\gamma\gamma$	h_3^γ, h_4^γ	Zγ	Neutral couplins
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ	Neutral couplins
ZZZ	f_{40}^γ, f_{50}^γ	ZZ	Neutral couplins

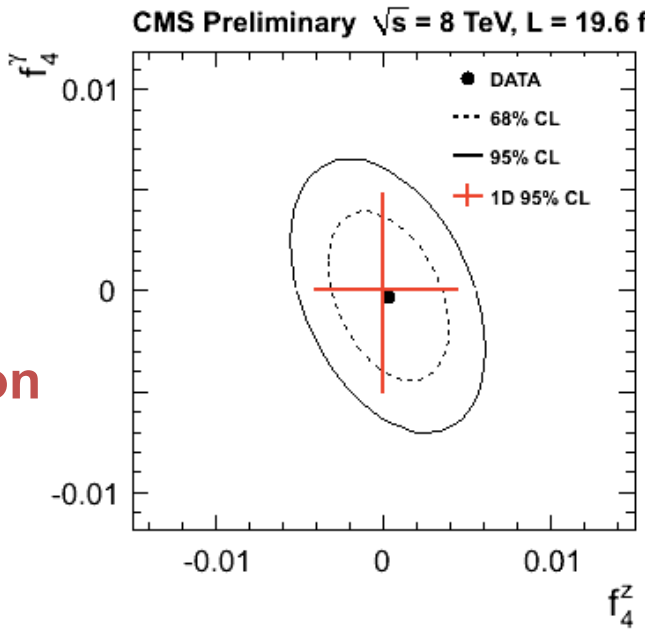
ZZ → 4l aTGC searches

- **SMP-13-005, 19.6fb-1 at 8 TeV**
- Search for anomalous vertices **ZZγ and ZZZ**
- Search performed for looking excess in data at high ZZ invariant mass
- **Results improved 7 TeV results by a factor ~2.5**





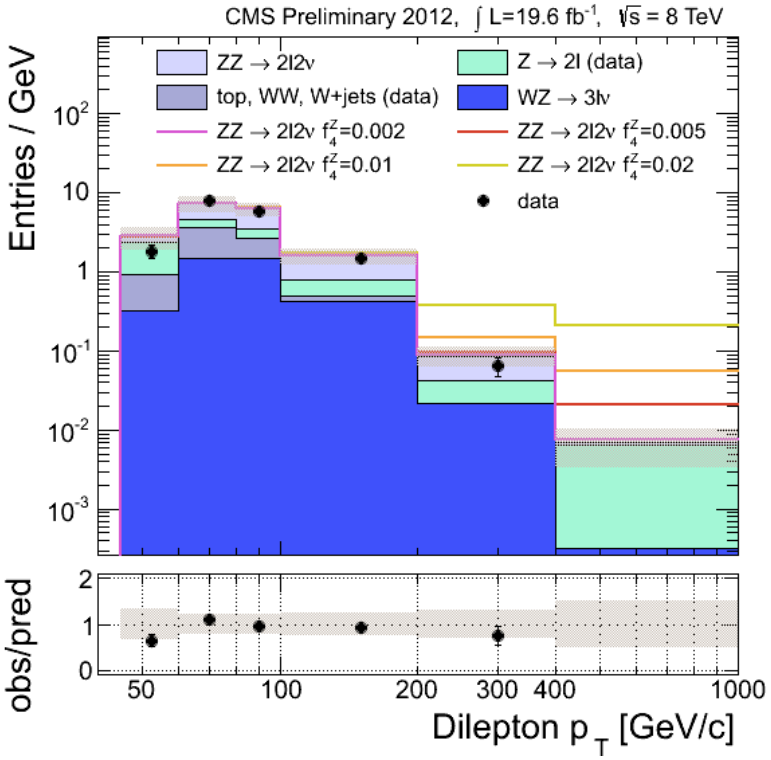
Exclusion limits on f^{V}_{5}

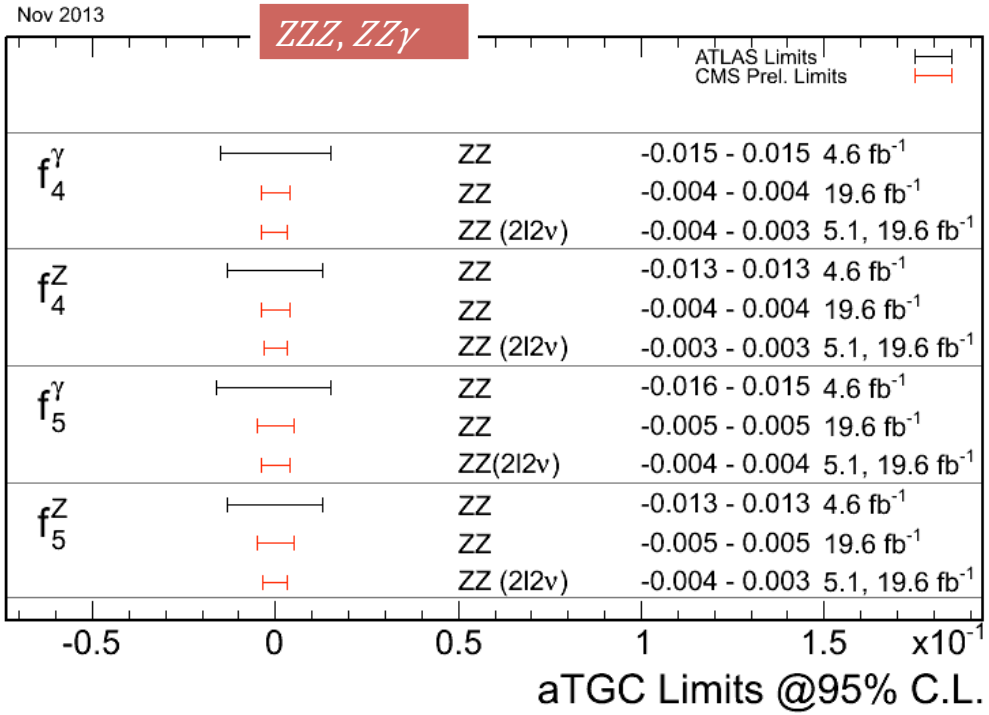


Exclusion limits on f^{V}_{4}

ZZ→2l2ν aTGC searches

- **SMP-12-016, 4.9fb-1 at 7 TeV and 19.6fb-1 at 8 TeV**
- Search for anomalous vertices **ZZγ** and **ZZZ**
- Search performed for looking excess in data using Z p_T
- **Results with ZZ(2l2ν) are ~25% better than ZZ(4l) results**

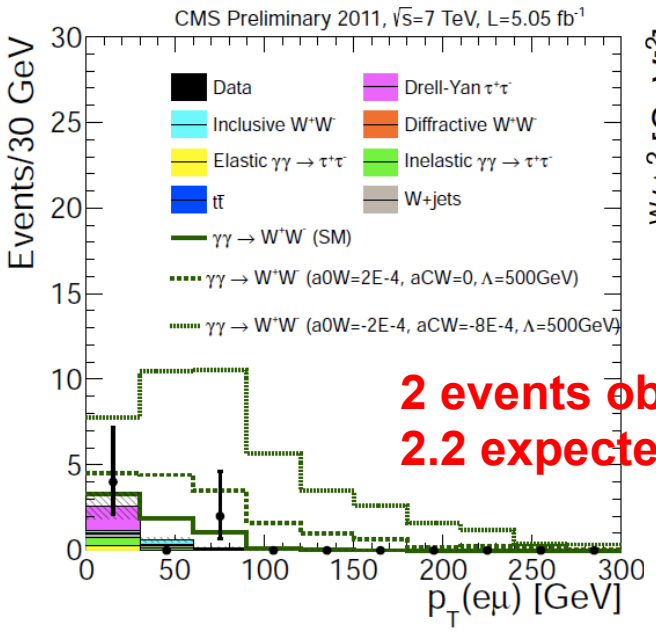


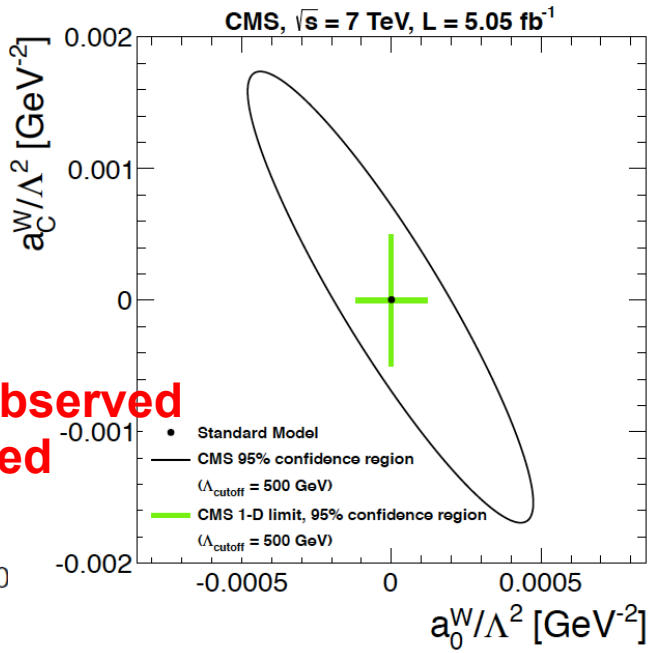


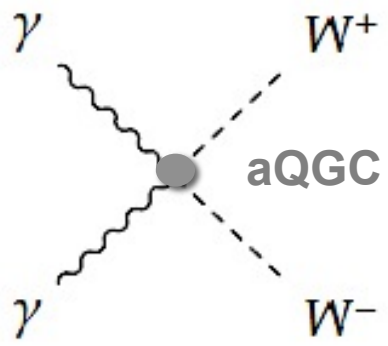
Triboson and quartic gauge coupling

- **No neutral QGCs in the SM**
- **Quartic couplings are accessible via triboson and vector boson scattering**
  - **aQGC parametrized with effective field theory approach:** associated to dimension 6 $a_0^W, a_C^W, k_0^W, k_C^W, f_{T,0}$ or dimension 8 $f_{M,i}$ effective operators

➢ First measurement of aQGC at LHC done with CMS:
$pp \to p^{(*)}\gamma\gamma\, p^{(*)} \to p^{(*)}$ WW $p^{(*)}$ at 7 TeV analysis





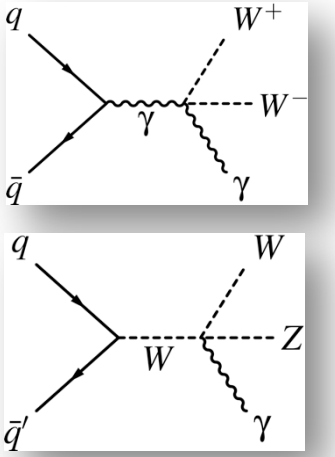


JHEP 1307 (2013) 116

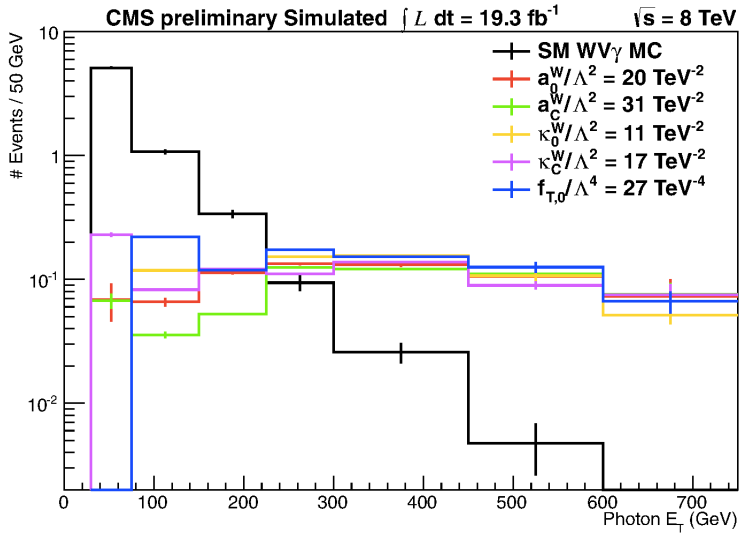
Sensitivity exceeds LEP experiments !

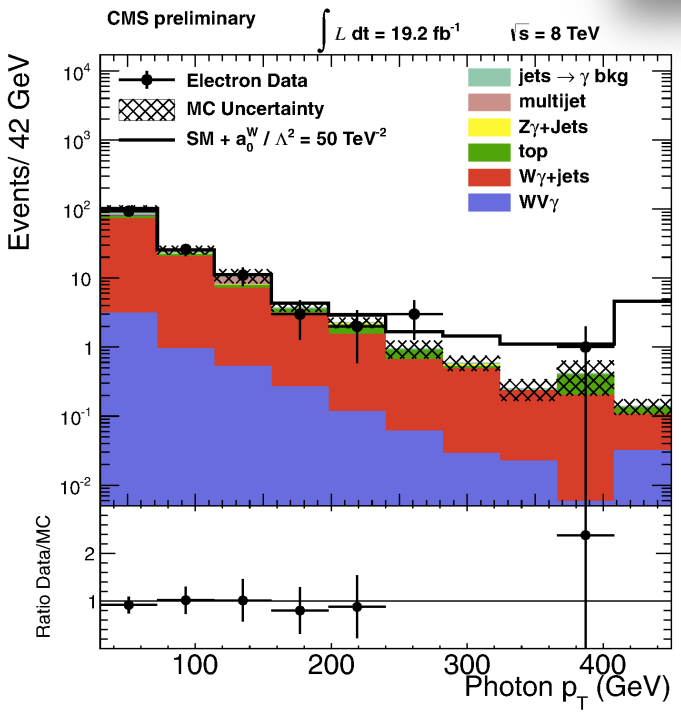
WVγ with semi-leptonic decay

- **SMP-13-009, 19.3fb-1 at 8 TeV**
- Search triboson WWγ and WZγ production in the final state: lν+jj+γ
- Main backgrounds from Wγ+jets (normalized in data M_{jj} sideband), fake photons (invert photon isolation)
- **Measured inclusive cross section at 8 TeV is < 3.4 x SM@NLO at 95% CL:** will have the sensitivity at 14 TeV.



➢ Set limit on **aQGC using photon pT**

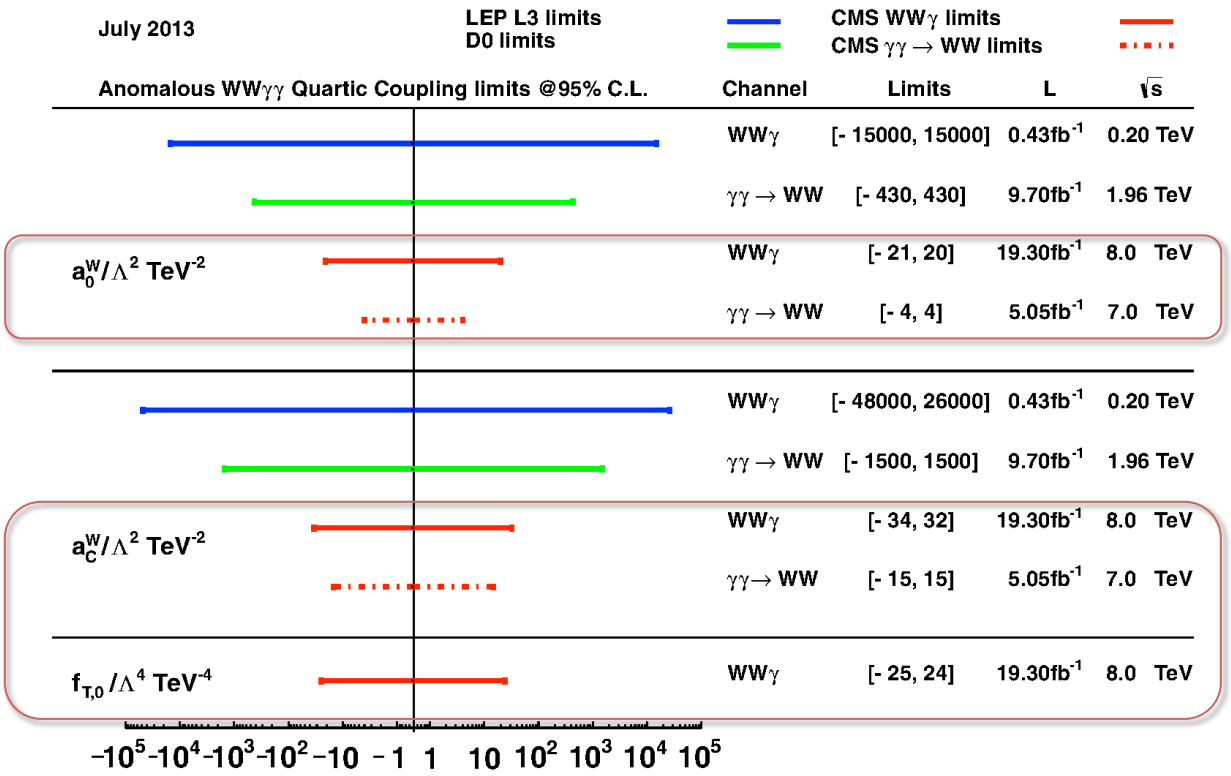




Electron channel

WVγ with semi-leptonic decay

- **Set limits aQGC modeled with Effective Field Theory**
- **WWγγ** and **WWZγ** vertices are tested
  - Limits on a_0^W, a_C^W are 4x better with γγ→WW than with VWγ
  - **First ever limits on $f_{T,0}$ and k_0^W,k_C^W**

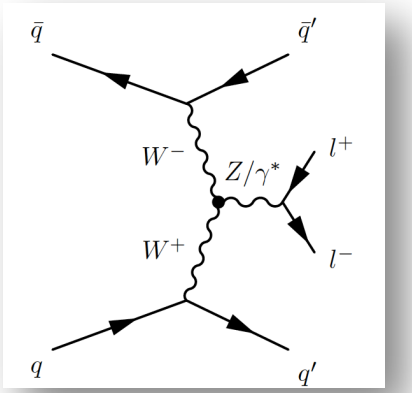


➢ Limits set w/o form-factors

Selected EWK results

- **EWK physics plays a significant role in understanding the EWSB**
- **W and Z decays are special final states:**
  - They are used to understand and calibrate the detector response (trigger, identification, resolution, efficiencies)
  - They are dominant signal and/or background in many searches for new particles
  - Provide powerful constraints for nonperturbative part (PDFs, tunes)

EWK Z production



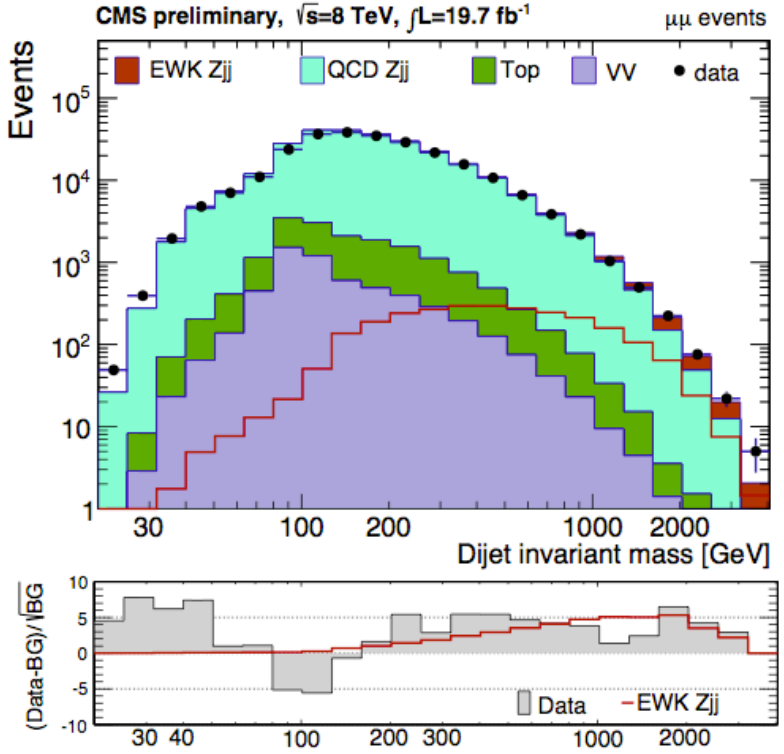
- **FSQ-12-035, 19.7 fb-1 at 8 TeV**
- Electroweak production cross section of a Z-boson with two foward/backward jets in the di-lepton Z decay channels (μ,e)
- Dominant background from standard DY production
- Small S/B enhanced with BDT selection exploiting all Z+2jet kinematics
- Probe Triple gauge coupling: WWZ

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

σ(μμ+ee) = 226 ± 26 (stat.) ± 35 (syst.) ± 27 (th.) ± 3 (lum.)fb

VBFNLO = 239 fb

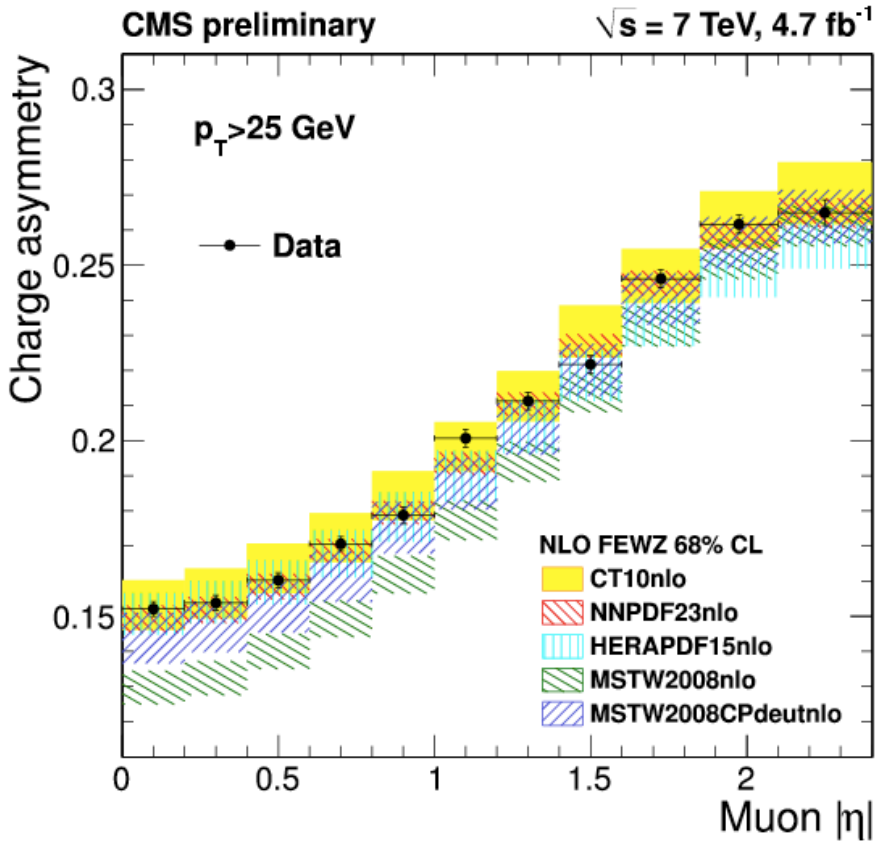
➢ **Main systematic from theory and JER**



Muon charge asymmetry

- **arXiv:1312.6283 , 4.7fb-1 at 7 TeV**
- Measurement of W muon charge asymmetry vs |η|:
  - performed by fitting **MET templates** in bins of muon η
- Backgrounds: estimated from MC after data/MC correction
- Measured to ~1%. Many uncertainties cancel in ratio.
- Sensitive to parton density functions in the proton: constrains u/d PDF ratio

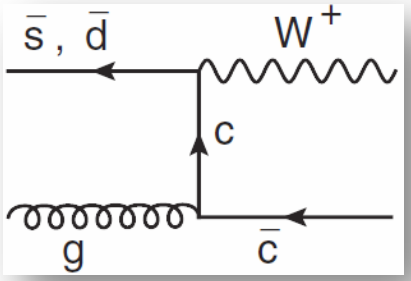
$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\overline{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\overline{\nu})}$$



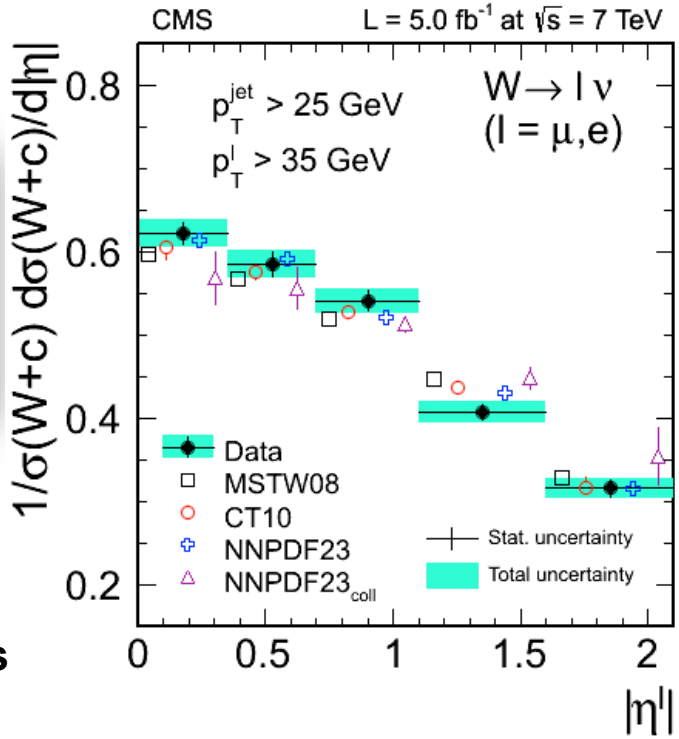
- **The experimental uncertainties are smaller than the current PDF uncertainties**
- **It can be used to significantly improve the determination of PDFs in future fits.**

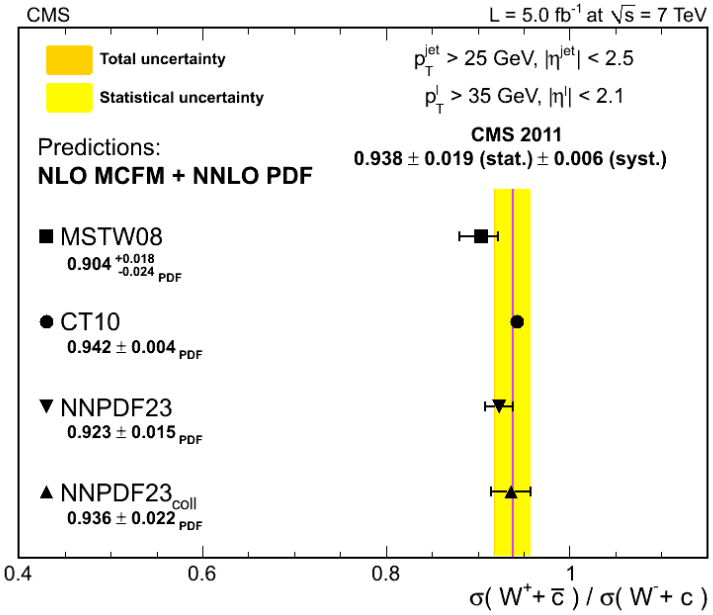
V+jets cross sections

- **W+bb cross section,** arXiv:1312.6608, 5.0 fb-1 at 7 TeV
- **Z+b jets cross section**, arXiv:1402.1521, 5.0 fb-1 at 7 TeV
- **W+c cross section,** arXiv:1310.1138, 5.0 fb-1 at 7 TeV
  - Leading order W+c directly probes **strange quark PDF**
  - Measurement of inclusive and differential cross section in the W→lν channel
  - c-jet identified by D-Meson/semi- leptonic decays



➢ **Main systematic from JES and c branching fractions**

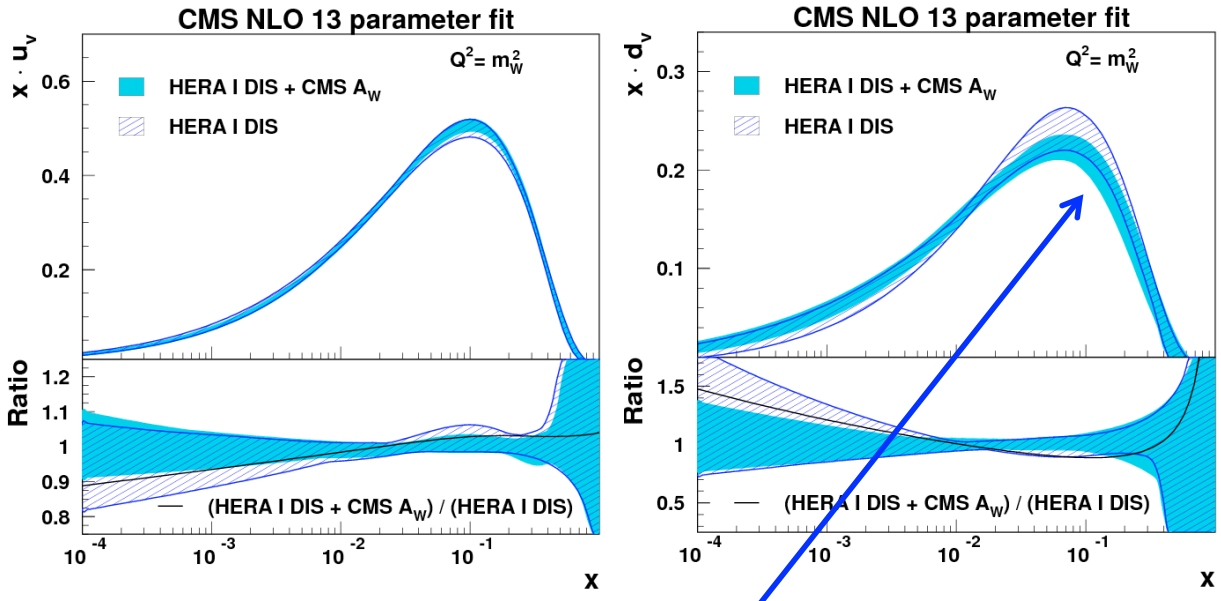




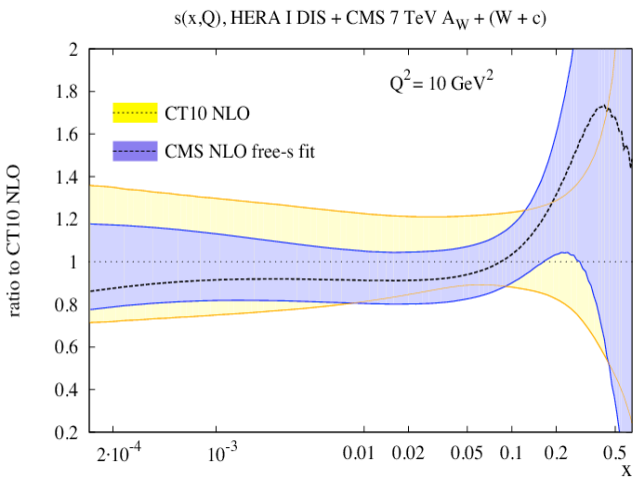
PDF constraints

- **CMS have carried out a NLO QCD analysis to explore PDF constraints**
- Use HERA inclusive deep inelastic scattering (DIS), CMS *W* asymmetry & CMS *W+c* data
  - The muon charge asymmetry in W-boson production imposes strong constraints on the valence-quark distributions
  - the W+charm process is directly sensitive to the strange-quark distribution

➢ **Valence quark distributions**



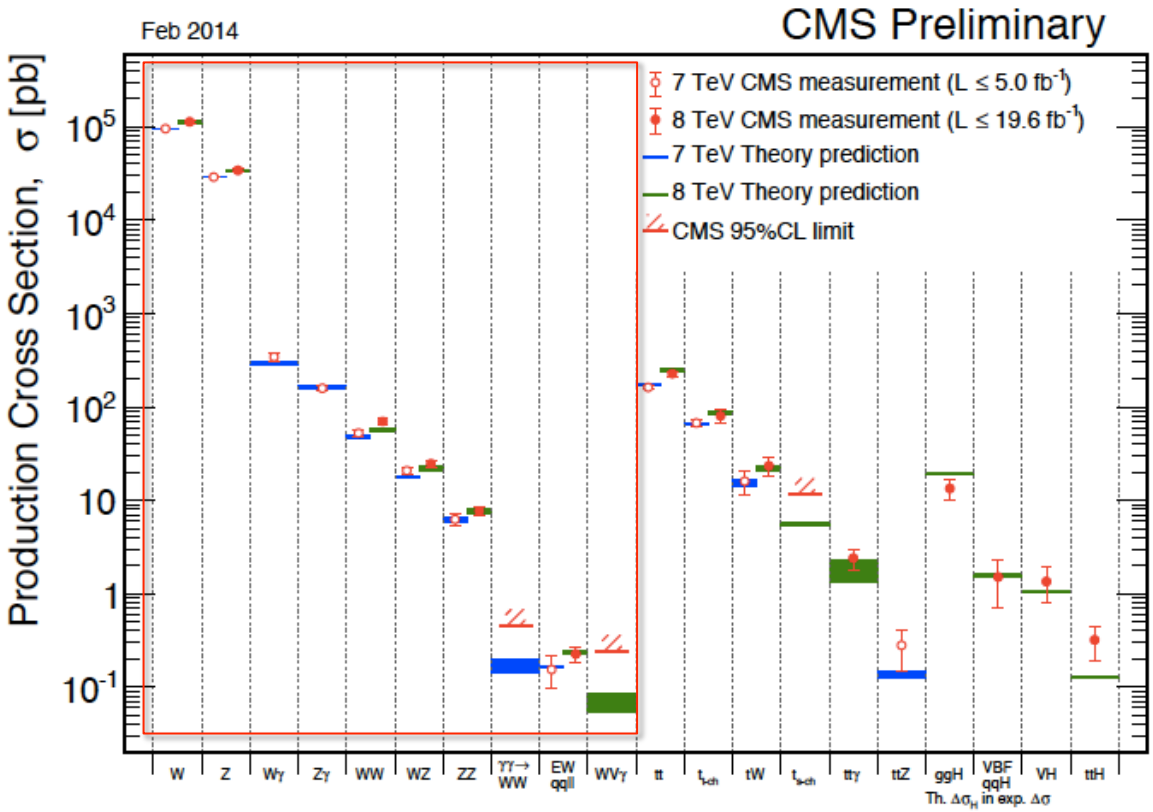
➢ **Strange sea**



Notice that $xd_v(x)$ is reduced.

Summary

- **Impressive amount of EWK results from the LHC**
  - Precise test of the Standard Model at TeV scale
  - Agreement with theory across orders of magnitude
  - **Starting to set serious constraints on PDFs**



- The LHC is now the leading laboratory for exploring the gauge boson self-interactions.
- **Limits set on anomalous triple/quartic gauge couplings.**
  - **No evidence for new physics yet**
- **Still analysis to be updated with the full 8TeV data**
  - More results with improved precision expected soon, stay tuned!

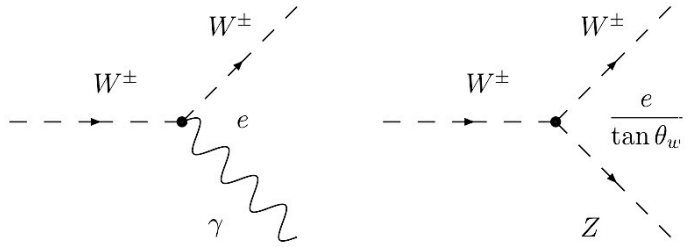
Backup material

Gauge Self-Couplings in the EWK sector

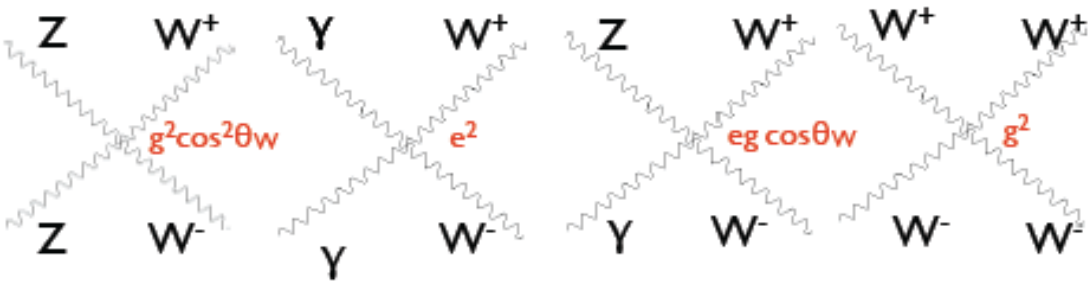
- SU(2)xU(1) symmetry leads to several gauge bosons self-interactions in the electroweak sector of the SM, following fromthe Gauge coupling interaction term in the EWK lagrangian:

$$\mathcal{L}_{\mathrm{GC}} = \frac{1}{2} g_2 (\partial_\mu W^i_\nu - \partial_\nu W^i_\mu) \varepsilon_{ijk} W^{j\mu} W^{k\nu} - \frac{1}{4} g_2^2 \varepsilon_{ijk} \varepsilon_{imn} W^j_\mu W^k_\nu W^{m\mu} W^{n\nu}$$

Triple Gauge Couplings



Quartic Gauge Couplings



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Cross section measurements

Cut & Count in most cases

Dominant contributions always data-driven

$$\sigma = \frac{N_{selected} - N_{background}}{A \cdot \epsilon \cdot \int \mathcal{L} dt}$$

- Determined from MC wrt to target measurement phase space (inclusive or reduced)
- Correction factor applied to account for data/MC efficiency differences

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aTGC parameterizations

- Charged couplings: WWV (V=Z,γ)

$$L/g_{WWV} = ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{*\mu}V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2}W^*_{\rho\mu}W^\mu_\nu V^{\nu\rho}$$

  - 5 parameters: $\Delta g_1^Z (=g_1^Z-1), \Delta\kappa_Z (=\kappa_Z-1), \Delta\kappa_\gamma (=\kappa_\gamma-1, \lambda_Z, \lambda_\gamma$
  - Additional constraints may be imposed: used in CMS measurements

LEP scenario	$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot tan^2\theta_w$ and $\lambda_Z = \lambda_\gamma = \lambda$	3 free parameters
HISZ scenario	$\Delta\kappa_z = \Delta g_1^z(\cos^2\theta_w - \sin^2\theta_w)$, $\Delta\kappa_\gamma = 2\Delta g_1^Z \cos^2\theta_w$ and $\lambda_Z = \lambda_\gamma$	2 free parameters
Equal coupling scenario	$\Delta g_1^Z = \Delta g_1^\gamma = 0$ $\Delta\kappa_Z = \Delta\kappa_\gamma$ and $\lambda_Z = \lambda_\gamma = \lambda$	2 free parameters

- Neutral couplings: ZZV (V=Z,γ)

$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

  - 4 parameters: $f_4^Z, f_4^\gamma, f_5^Z, f_5^\gamma$

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aQGC parameterizations

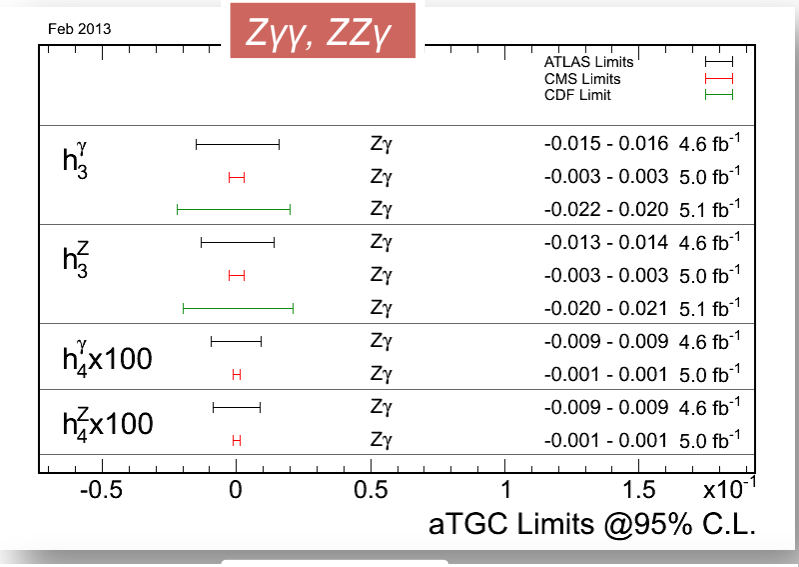
- Effective lagrangians parameterize low energy effects of BSM physics:

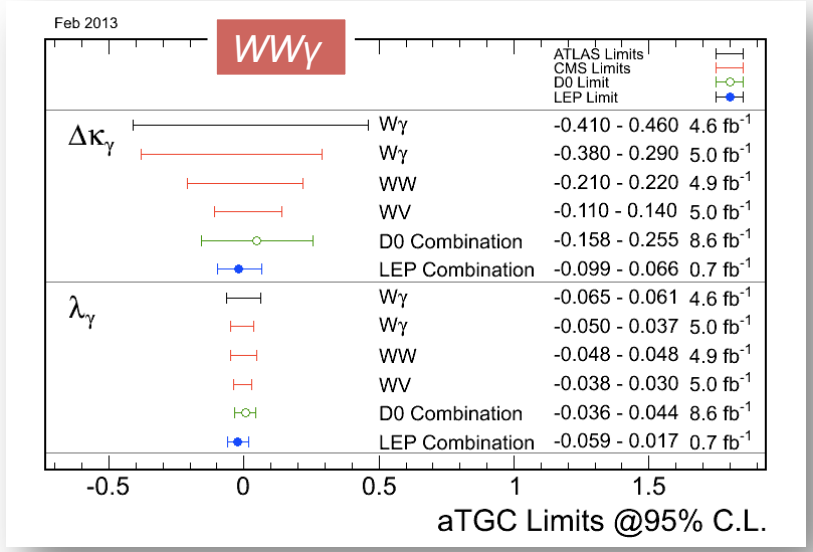
$$L = L_{SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

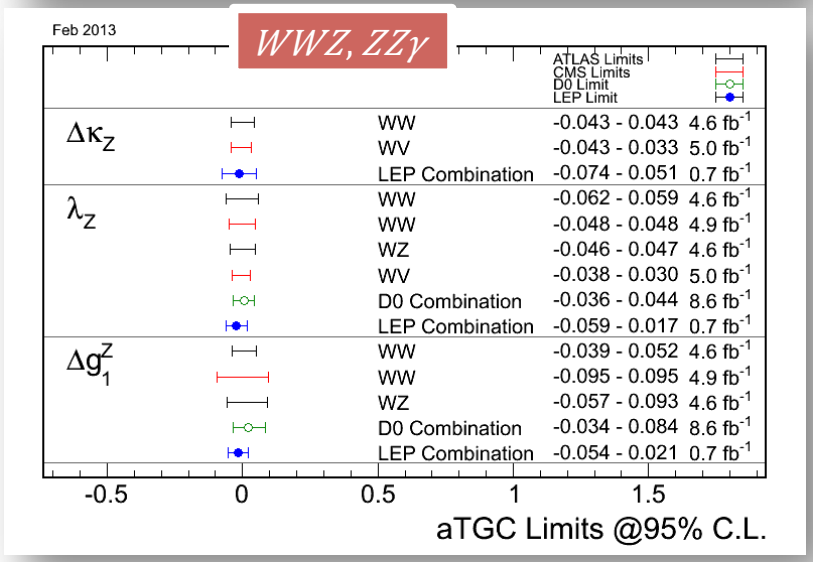
- Different realizations for quartic interactions:
- Nonlinear realization of $SU(2)_L xU(1)$:
  - lowest order genuine quartic interaction: dimension 6
- Linear realization:
  - lowest order genuine quartic interaction: dimension 8

Other aTGC summary

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

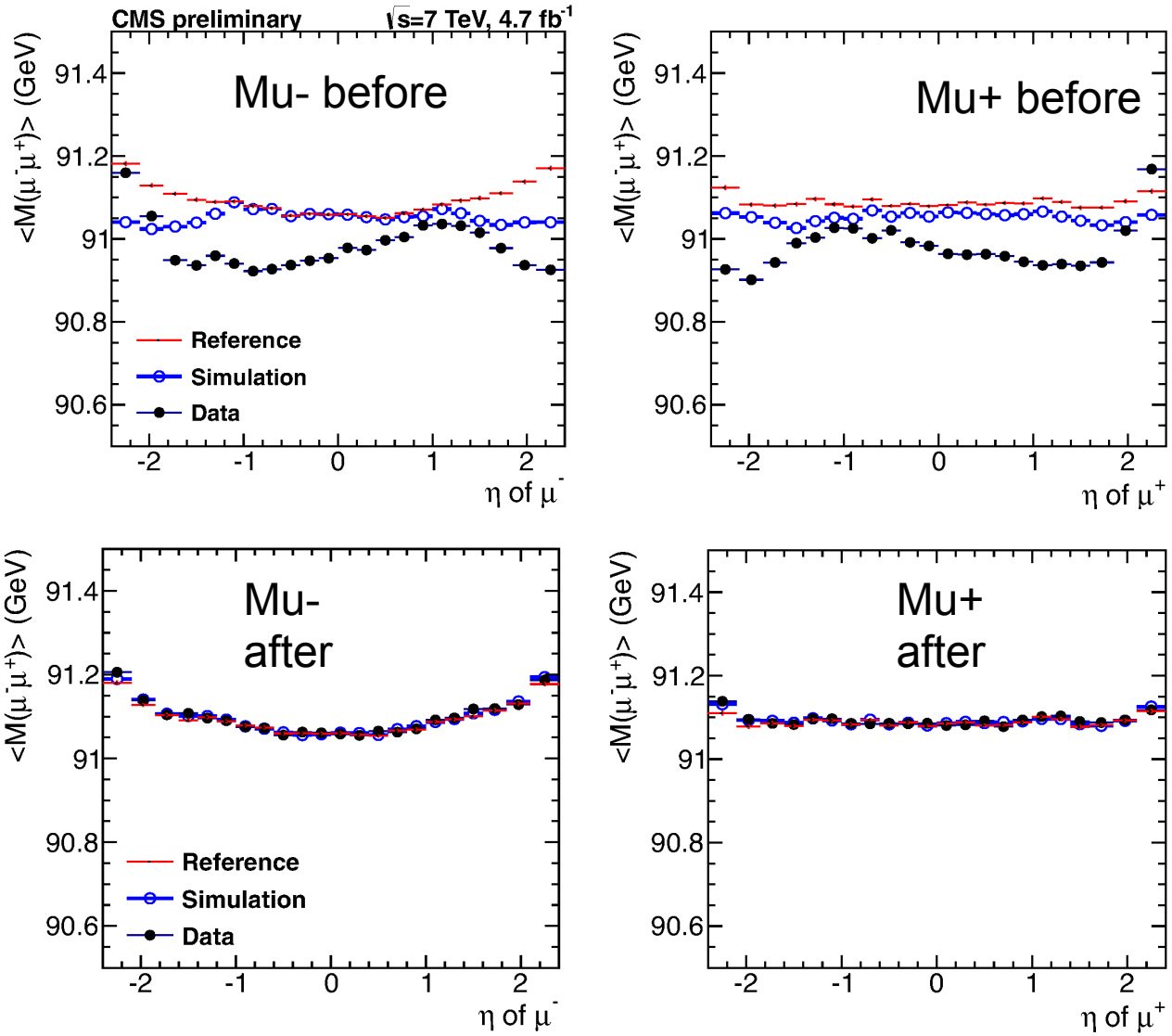






- **TGCs consistent with the SM**
- 8 TeV data not included yet on these results

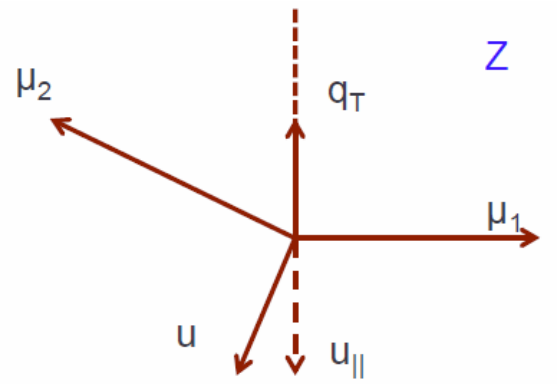
Muon charge asymmetry

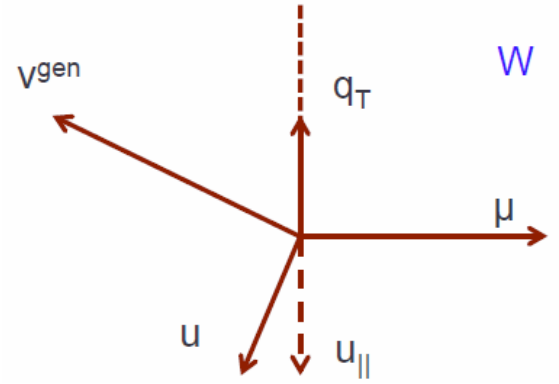


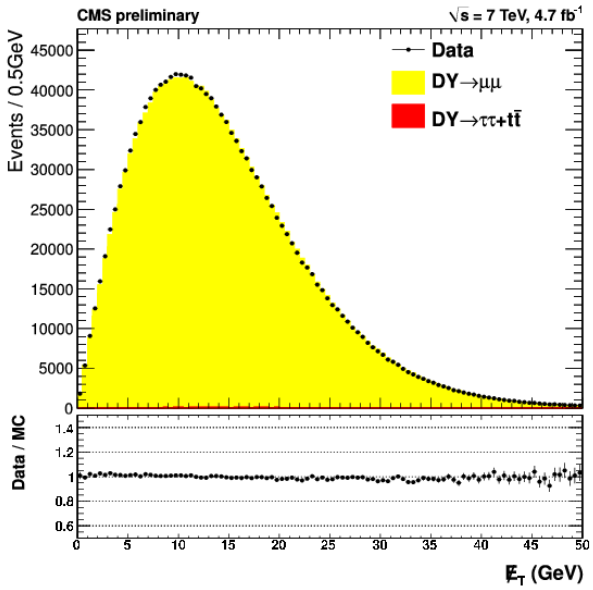
SMP-12-021

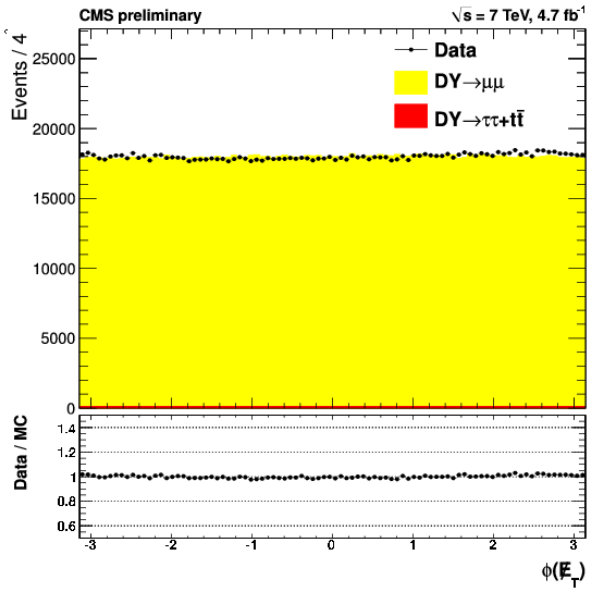
- Correcting residual data/MC difference of tracker misalignment and magnetic field map
- **Dimuon mass scale corrected** as a function of muon charge, η, Φ

Muon charge asymmetry







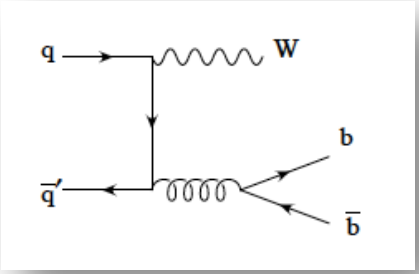


SMP-12-021

- Missing transverse energy (MET) corrected using hadronic recoil in Z→μμ events
- Z/Drell-Yan “MET” and “MET ϕ” precisely recovered after data/MC corrections of recoil model

W+bb cross section

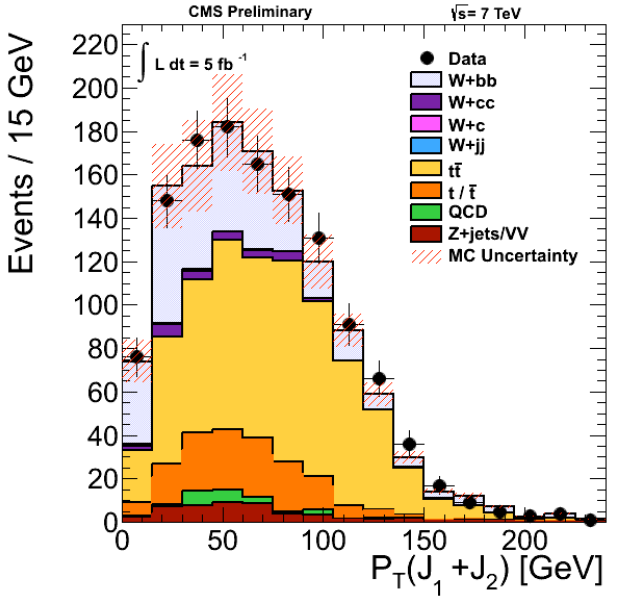
- **arXiv:1312.6608, 5.0 fb-1 at 7 TeV**
- Exclusive W + 2 central b-jets cross section measured
- Complementary phase space wrt W+b
- Analysis double tags events to remove W+c and constrains top contribution from high jet multiplicity region
- Major background to H→bb analysis
- Measurement is in agreement with the MCFM prediction within uncertainties

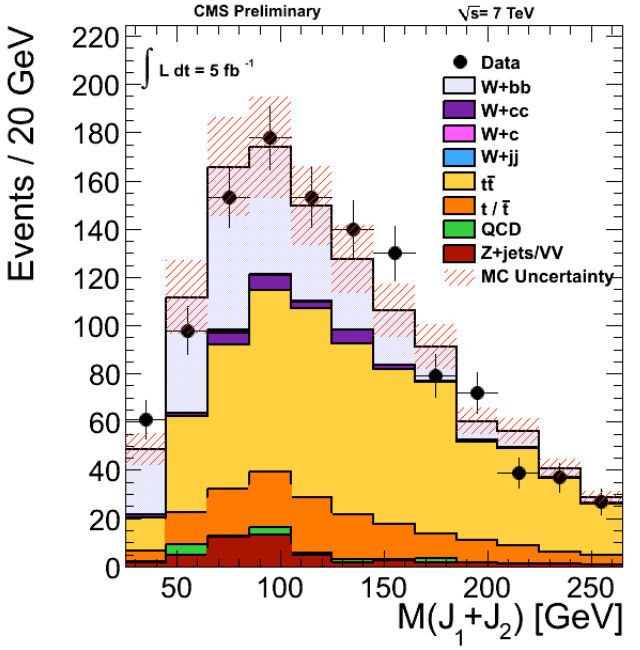


σ(W+bb)

Data (CMS) 0.53 ± 0.05 (stat) ± 0.1 (sys) pb

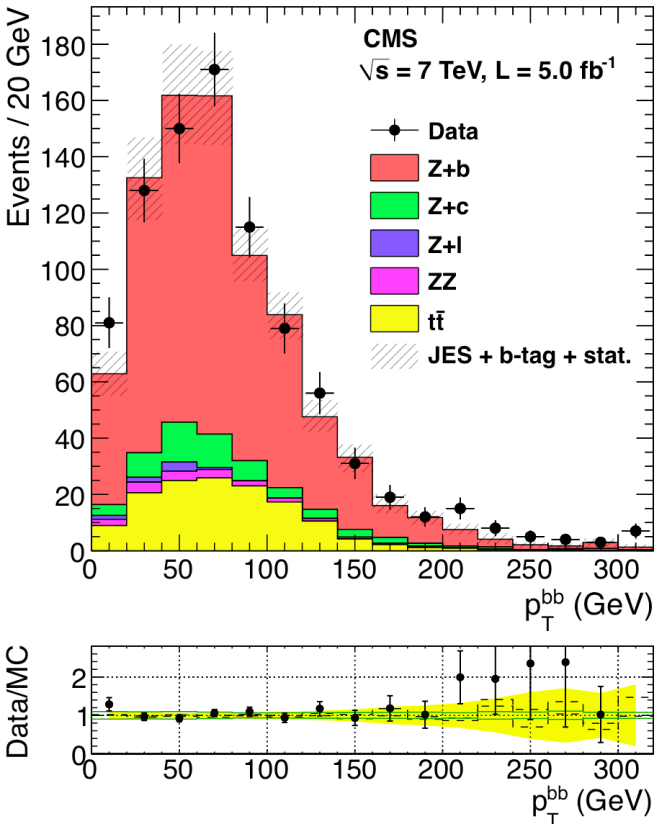
MCFM (MSTW08NNLO) 0.52 ± 0.03 pb





Z+ b jets cross sections

- **arXiv:1402.1521, 5.0 fb-1 at 7 TeV**
- Measurement of the production cross sections for a Z boson and one or more b jets
  - b-tagged Jets with p_T>25 GeV, |η|<2.4 in Z events
- Most important kinematical observables compared to ME+PS generator (MadGraph), in both the 4F and 5F schemes



Cross section	$\mu\mu$	ee
σ_{Z+1b} (pb)	$3.52 \pm 0.03 \pm 0.22$	$3.51 \pm 0.04 \pm 0.23$
σ_{Z+2b} (pb)	$0.38 \pm 0.02 \pm 0.07$	$0.32 \pm 0.02 \pm 0.06$
σ_{Z+b} (pb)	$3.91 \pm 0.04 \pm 0.23$	$3.84 \pm 0.04 \pm 0.24$
$\sigma_{Z+b/Z+j}$ (%)	$5.23 \pm 0.04 \pm 0.24$	$5.08 \pm 0.05 \pm 0.24$

- **Z + bb cross section 10% higher than tree-level prediction by Madgraph 5F rescaled by k = 1.23**
- **Some tensions in the description of the event dynamics**