Measurements of WV Boson Production and Limits on Charged aTGCs at CMS

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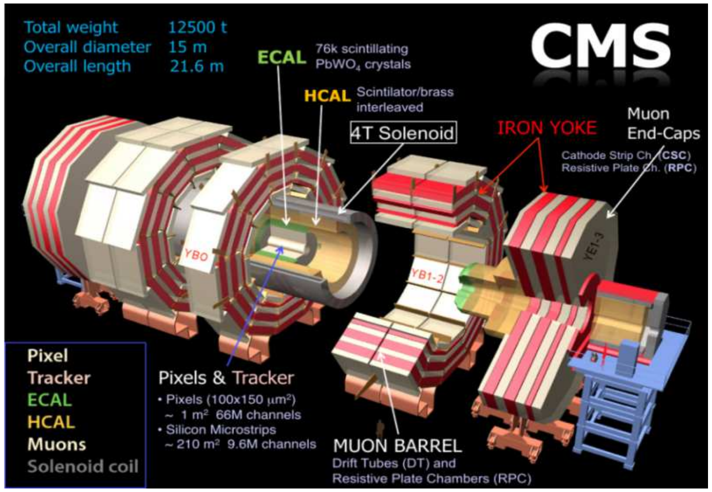
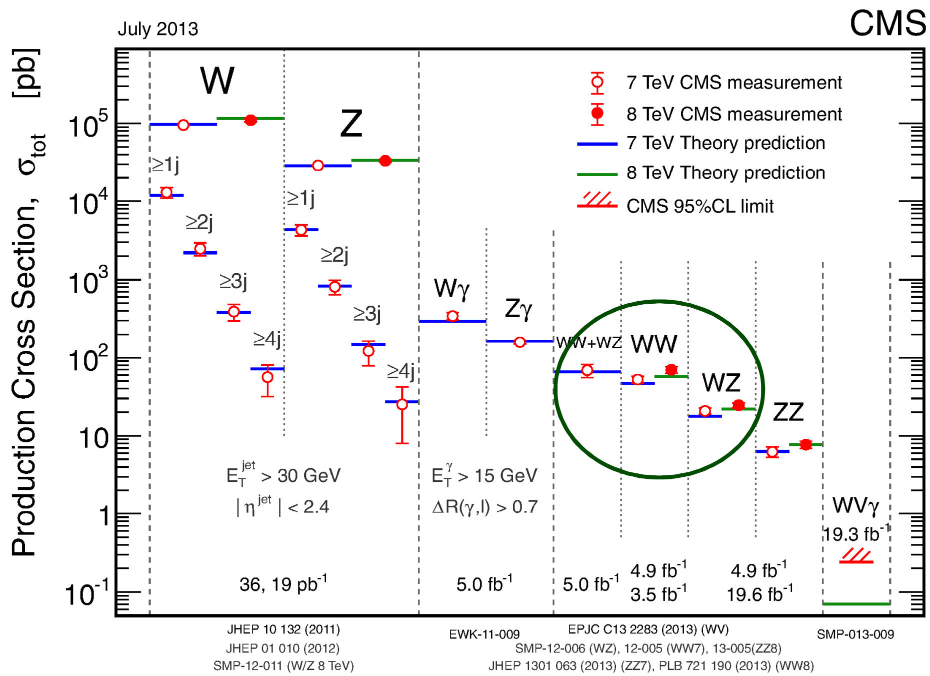


Motivation

❖ Why Measure Charged Vector Boson Gauge Couplings ?

- Verify the consistency of SM by performing the Vector Boson coupling measurements in several channels
- Understand backgrounds for other measurements (e.g. Higgs)
- Search for New Physics



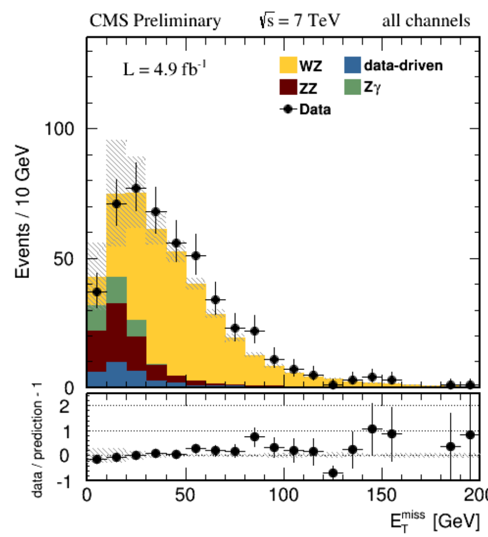
❖ **This presentation will focus on analyses of WZ → *lνll*, WW → *lνlν* and WV → *lνjj* final states**

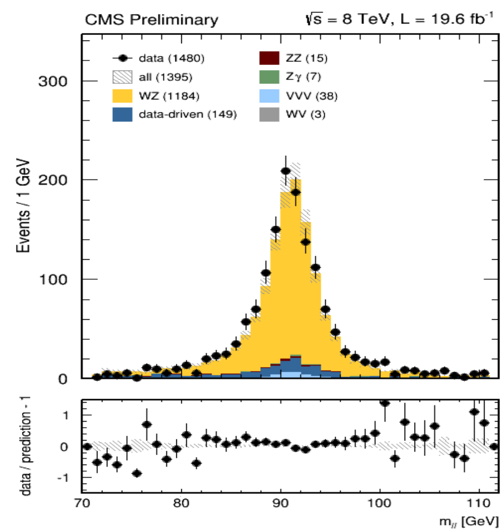
WZ → *lνll* Analysis

❖ **Reconstruct WZ → *lνll* final states with *l*=μ, e**

- **Z reconstruction:**
  - p_T^{l1}>20 GeV, p_T^{l2}>10 GeV
  - 71 < m_{l+l-} < 111GeV (& closest to the Z mass)
- **W reconstruction:**
  - p_T^{l}>20 GeV, MET>30 GeV
- **Backgrounds:**
  - Non Peaking - no Z boson (e.g. tt)
  - Prompt Lepton - real Z and an isolated lepton(-like) object (e.g. ZZ, Zγ).
  - Fake Lepton - real Z plus a jet faking a lepton
- **Estimate the Fake Lepton background from sideband regions in the data**

❖ **High Purity Signal Extracted**



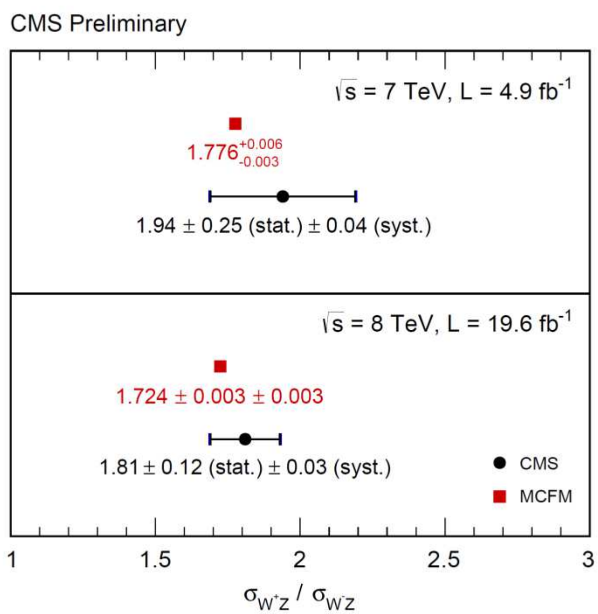


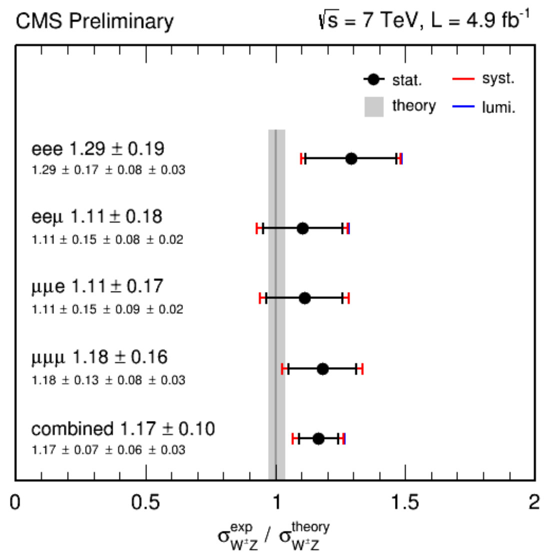
sample	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Z+jets	9.8 ± 4.4	16.9 ± 6.0	14.5 ± 5.4	13.8 ± 4.5
top	1.4 ± 0.4	2.7 ± 0.3	6.2 ± 0.7	9.1 ± 1.0
ZZ	2.4 ± 0.1	3.1 ± 0.1	3.9 ± 0.1	5.8 ± 0.1
Zγ	2.4 ± 0.9	0.4 ± 0.4	3.8 ± 1.2	0
WV	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	2.2 ± 0.7
VVV	6.1 ± 0.3	7.9 ± 0.3	10.4 ± 0.4	13.4 ± 0.4
WZ	193.9 ± 1.4	245.8 ± 1.6	315.9 ± 1.9	428.0 ± 2.2
total MC	216.0 ± 4.7	277.0 ± 6.3	354.9 ± 6.0	472.3 ± 5.2
data-driven	14.8 ± 1.4	27.1 ± 2.9	47.9 ± 3.4	59.0 ± 4.6
data	235	288	400	557

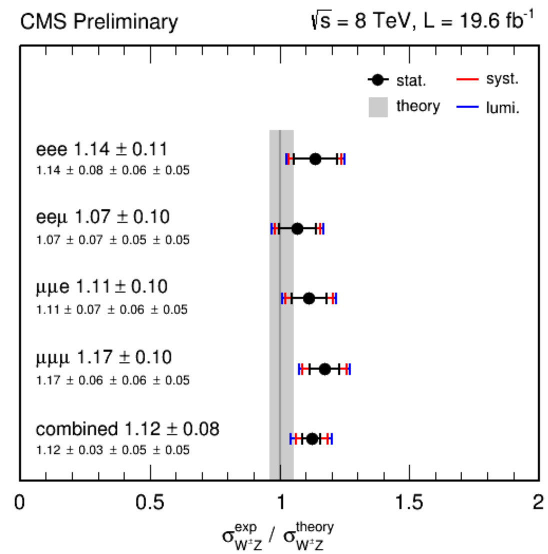
WZ → *lνll* Cross Section Measurement

➢ Assess the systematic uncertainties, with the largest contributions originating from MET energy & resolution and data-driven background estimates.

❖ Subtract the expected background events from the total and compute σ







❖ $\sigma = 20.8 \pm 1.3(\text{stat.}) \pm 1.1\ (\text{syst.}) \pm 0.5(\text{lumi.})$ pb @7TeV

❖ $\sigma = 24.6 \pm 0.8(\text{stat.}) \pm 1.1\ (\text{syst.}) \pm 1.1(\text{lumi.})$ pb @8TeV

➢ Consistent with NLO predictions: $17.8^{+0.7}_{-0.5}$ & $21.9^{+1.2}_{-0.88}$

➢ The W^+Z production cross section is expected to be a factor of 1.72 (1.78@7TeV) larger than σ_{W-Z}

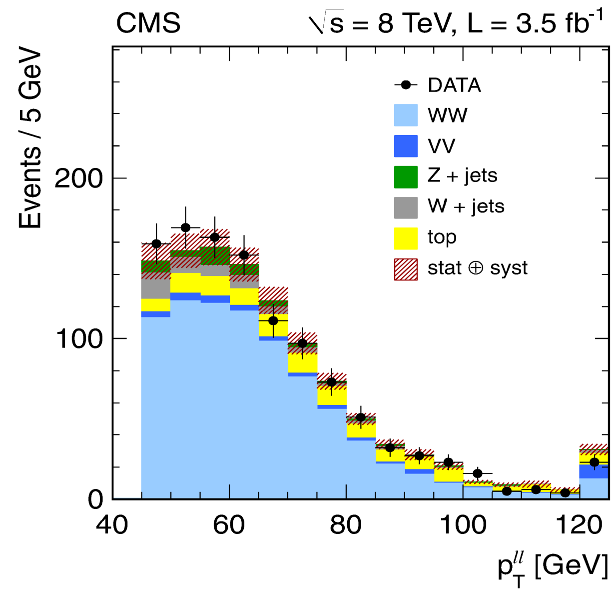
❖ $\sigma_{W+Z}/\sigma_{W-Z} = 1.94 \pm 0.25(\text{stat.}) \pm 0.04(\text{syst.})$ @7TeV and $\sigma_{W+Z}/\sigma_{W-Z} = 1.81 \pm 0.12(\text{stat.}) \pm 0.03(\text{syst.})$ @8TeV, consistent with the theory expectations

WW → *lνlν* Analysis

- Identify two central ($|\eta_\mu|<2.4$, $|\eta_e|<2.5$), oppositely charged leptons with $p_T>20$GeV
- Background Reduction:
  - Top - remove events with jet $p_T>30$GeV and apply top-quark-tagging techniques.
  - Drell Yan – require MET>45 GeV (>20 GeV in the μe channel). Reduce further by applying jet separation, Z mass window and dilepton p_T cuts.
  - Diboson - remove events with third lepton $p_T>10$GeV
  - Wγ - reject photon-conversion electrons
- Top, Drell Yan, W+Jets backgrounds and Wγ scale are determined from data control regions
- Systematics - dominated by jet veto efficiency and uncertainty in background estimation

- σ=52.4 ± 2.0 (stat.) ± 4.5 (syst.) ± 1.2 (lumi.) pb @7TeV
- σ=69.9 ± 2.8 (stat.) ± 5.6 (syst.) ± 3.1 (lumi.) pb @8TeV, 3.5fb^{-1}

- Consistent with the Standard Model prediction of 47.0 ± 2.0 pb and $57.3^{+2.3}_{-1.6}$ pb.



Channel	$\ell'\nu\ell''\nu$
W^+W^-	684 ± 50
$t\bar{t}$ and tW	132 ± 23
W+jets	60 ± 22
WZ and ZZ	27 ± 3
Z/γ^*+jets	43 ± 12
$W\gamma^{(*)}$	14 ± 5
Total background	275 ± 35
Signal + background	959 ± 60
Data	1111

Charged Vector Boson Triple Gauge Couplings

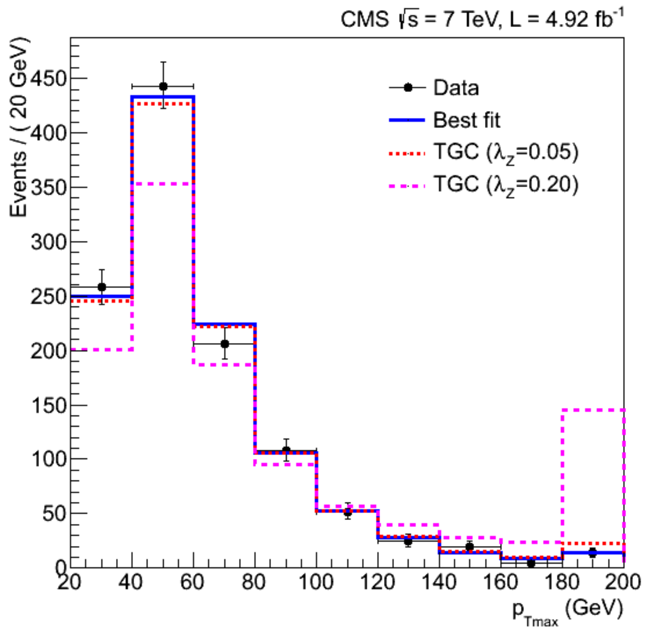
❖ **Extend the Electro-Weak Lagrangian**

$$\begin{aligned}\frac{\mathcal{L}_{eff}^{VWW}}{g_{VWW}} &= ig_1^V\left(W_{\mu\nu}^* W^\mu V^\nu - W_\mu^* V_\nu W^{\mu\nu}\right) + i\kappa_V W_\mu^* W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda,\mu}^* W_\nu^\mu V^{\nu\lambda} \\ &- g_4^V W_\mu^* W_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) + g_5^V \epsilon^{\mu\nu\lambda\rho}\left(W_\mu^* \partial_\lambda W_\nu - \partial_\lambda W_\mu^* W_\nu\right) V_\rho \\ &+ i\tilde{\kappa}_V W_\mu^* W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^* W_\nu^\mu \tilde{V}^{\nu\lambda}\end{aligned}$$

- **Lorentz invariant**
- **V=Z, γ**

- **Require that C and P be conserved separately: $g_4^V=g_5^V=\tilde{\kappa}_V=\tilde{\lambda}_V=0$**
- **EM gauge invariance: $g_1^\gamma=1$**
- **Redefine: $g_1^Z=1+\Delta g_1^Z$, $\kappa_V=1+\Delta\kappa_V$**
- **aTGCs: $\Delta g_1^Z\neq0$, $\Delta\kappa_V\neq0$, $\lambda_V\neq0$ for any of the five couplings represents a deviation from the SM**
  - **New particles present at tree level**
  - **Loop effects of heavy particles**
  - **Non-abelian structure of the gauge sector**
- **Assuming the presence of a Higgs doublet, SU(2)xU(1) gauge invariance and considering up to dimension 6 operators:**
  - **$\lambda_Z=\lambda_\gamma=\lambda$**
  - **$\Delta\kappa_Z=\Delta g_1^Z-\Delta\kappa_\gamma{*}\tan^2\theta_w$**

WW → *lνlν* aTGC Measurement



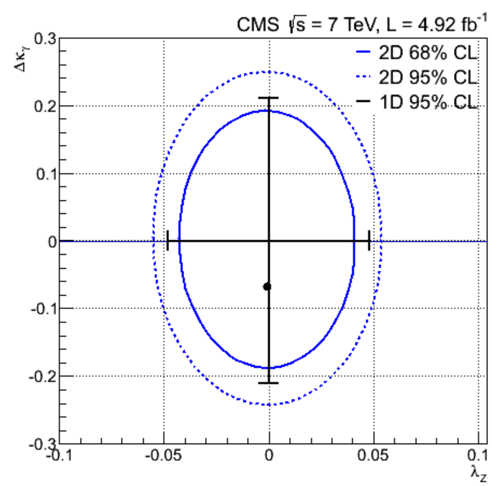
- Use the leading lepton p_T spectrum
- Quadratic dependence of the cross-section on aTGCs
- Interpolate using MCFM NLO
- aTGC presence would enhance the yield at high p_T values
- Incorporate the systematic uncertainties into the likelihood function by introducing nuisance parameters with Gaussian constraints.

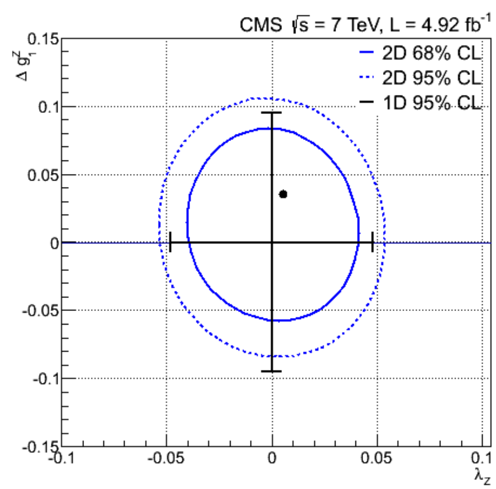
❖ **1D 95% CL limits:**

$-0.048 < \lambda_z < 0.048$

$-0.095 < \Delta g_1^z < 0.095$

$-0.22 < \Delta\kappa_\gamma < 0.22$

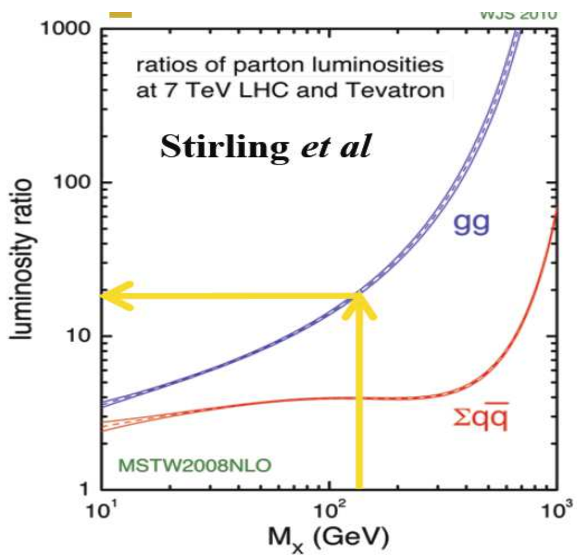




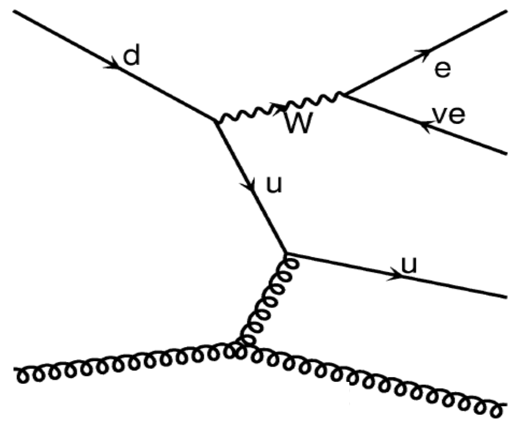
WV → *lνjj* Challenges

❖ **Vast majority of events originate from the W+jets background**

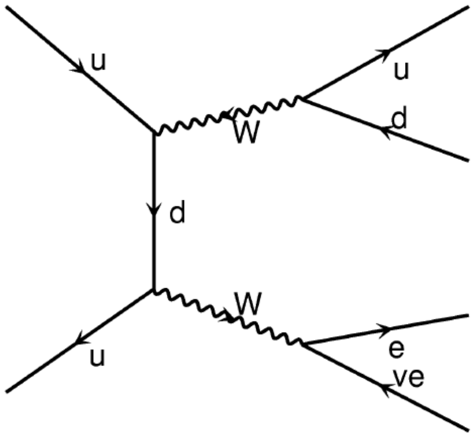
- **The production is dominated by quark-gluon scattering (vs. q-$\bar{q}$ at the Tevatron)**
- **σ_{W+jets}=3x10^{4}pb @NLO**



W+jj production via quark-gluon scattering



WW production via q-q̄ annihilation



- **WW+WZ production is dominated by quark-antiquark collisions**
  - **W vs Z mass difference ~resolution of the detector, thus the reconstructed signal is WW+WZ**
    - **σ_{WW+WZ}≈70pb (mainly WW ~70%)**

❖ **The Signal to Background ratio is much worse at the LHC and stronger cuts as well as improved analysis techniques are needed**

WV → *lνjj* Advantages

❖ **Why study the diboson production in the WW+WZ semileptonic channel ?**

Q. Why do you rob banks?

A. Because, that's where the money is.

- John Dillinger

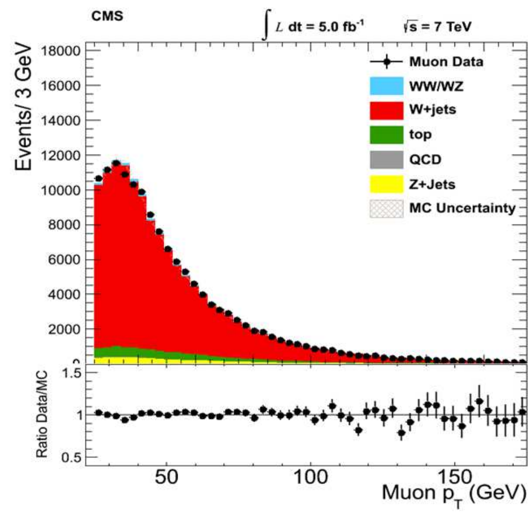
❖ **Higher Standard Model and Potential New Physics Signal Production Rates**

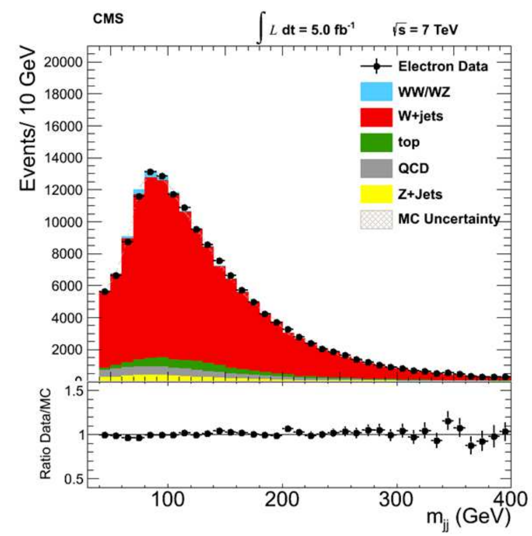
- **Serves as a precursor to other analyses with hadronic final states**
  - **Complimentary final states (e.g. W(→ jj)+γ, V(→ jj)+Z(→MET)) - high event counts**
  - **Merged high p_T jets - enhanced aTGC contribution**
  - **aQGC & Vector Boson Fusion - first signatures**
- **Current WV → *lνjj* Analysis Goals:**
  - **Confirm the WV signal in the semi-leptonic events at CMS**
  - **Set limits on Anomalous Triple Gauge couplings**

WV → *lvjj* Analysis

- Select central μ (p_T>25GeV), *e* (p_T>35GeV), MET (>25, 30GeV) and reconstruct the leptonic W (m_T>30, 50GeV)
- Reconstruct exactly two (PU corrected) AK5 jets (p_T>35GeV, |η|<2.6)
- Object level cuts to remove additional leptons, poorly reconstructed or b-jets
- Implement quality cuts to enhance S/B:
  - Dijet p_T^{jj}>20GeV, $|\Delta\eta_{jj}|$<1.5
  - Reduce the W+jets background by removing low p_T V candidates and jets with a high degree of separation
- Backgrounds:
  - W+Jets (σ=3.1x10^4pb) - Dominant background
  - Z+Jets (σ=3.0x10^3pb) - smaller σ and one lepton misID'd
  - ttbar (σ=163pb) -two real W's and two b-jets; reduced by anti-btagging or used as a control sample
  - Single Top (σ=85pb) - one (leptonic) W and a b-jet, reduced by anti-btagging
  - QCD/Multijet - shape taken from the Data sideband with inverted isolation and yield from MET fit

❖ Reasonable agreement between data and MC, but higher precision needed to extract WV





WV → *lνjj* M_{jj} Spectrum Fit

- Unbinned maximum likelihood for $40 < M_{jj} < 150$ GeV
- Shape templates taken from Monte Carlo (and multijet sideband)
- Two separate fits for muon and electron event yields (combine when evaluating the cross-section)

  - The background contributions are free to float subject to Gaussian constraints.

Yield Constraints

Process	Shape	Constraint on normalization
Diboson (WW+WZ)	sim.	Unconstrained
W+jets	sim.	31314 pb ± 5% (NLO)
$t\bar{t}$	sim.	163 pb ±7% (NLO)
Single top	sim.	85 pb ±5% (NNLO)
Drell-Yan+jets	sim.	3.05 nb ±4.3% (NNLO)
Multijet	data	E_T^{miss} fit in data

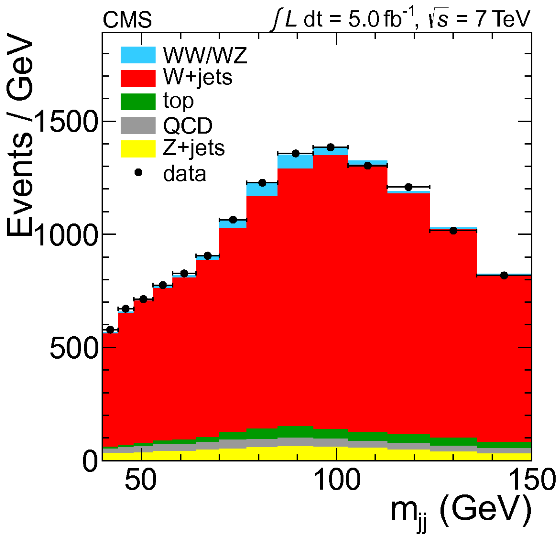
- W+jets shape is a combination of:
  - Default (MADGRAPH) MC
  - Either Matrix Element - Parton Shower Matching Up (μ=2μ_0) or Matching Down (μ=0.5μ_0) MC
  - Either Factorization Scale Up (q'=2q_0) or Scale Down (q'=0.5q_0) MC
- The choice of Up or Down Sample is based on the best fit to the Data
- The relative fractions (α,β) are free to vary in the fit (empirical model):

$$\mathcal{F}_{\mathrm{W+jets}} = \alpha \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q'^2) + \beta \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu'^2, q_0^2) + (1-\alpha-\beta) \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q_0^2)$$

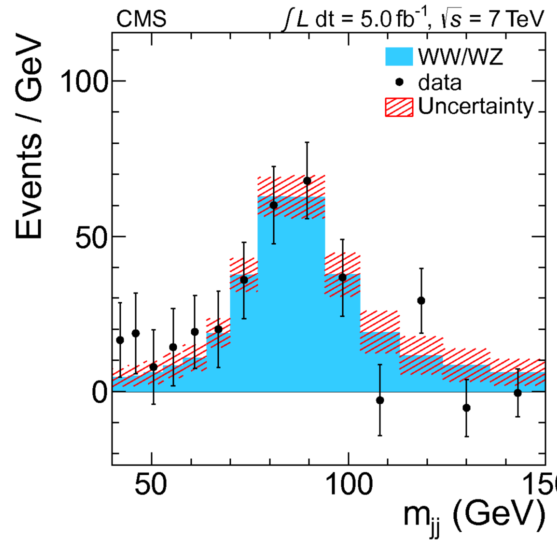
- Diboson contribution is free to float during the fit

WV → *lνjj* Cross Section

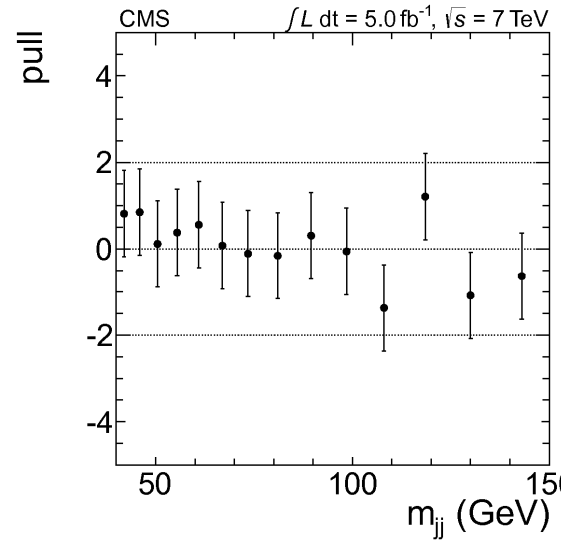
Mjj Fit Result



All SM backgrounds, except WW+WZ subtracted



Normalized Residual: [Data - Fit]/FitUncertainty



- ➢ **We extract 2682±482 WW+WZ events out of 1.15x10^5 (4.3σ using profile likelihood ratio)**

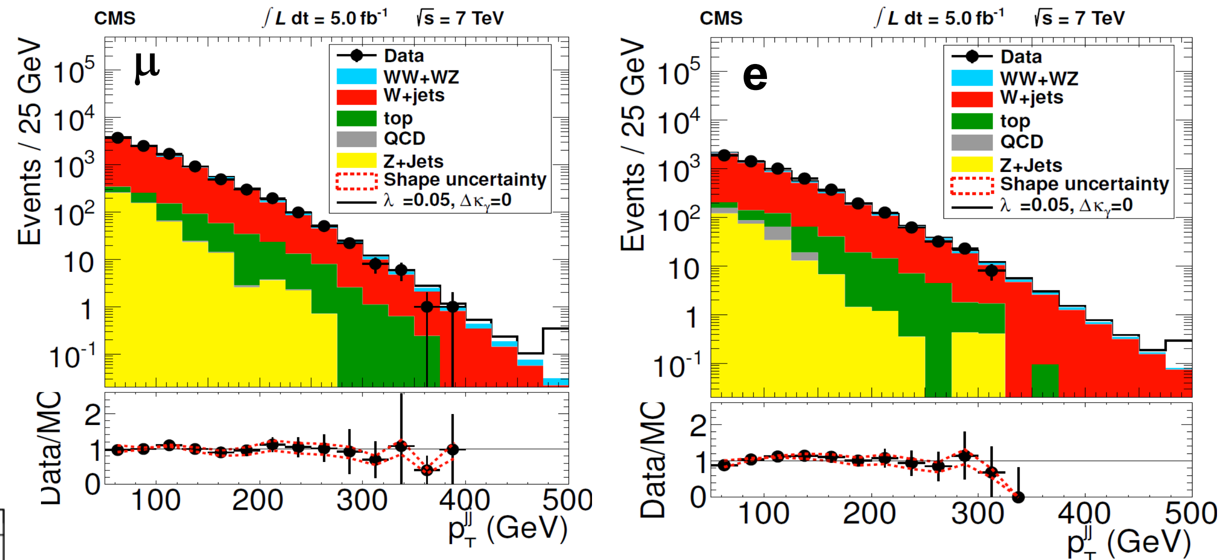
❖ Systematics:

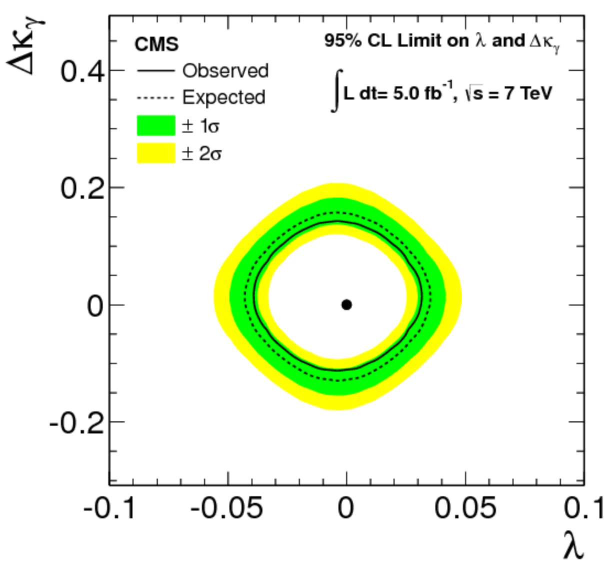
- ➢ **Potential Fit Bias - verified to be small by performing pseudo experiments and corrected for based on the resulting pull distributions.**
- ➢ **W+jets shape and uncertainties due to the choice of ME-PS matching and Factorization/Renormalization scale - covered by the empirical model**
- ➢ **Uncertainties due to JES, JER, MET resolution, trigger efficiency, lepton reconstruction & selection efficiency, choice of parton PDF, jet veto and luminosity are included**

❖ **σ(pp→WW+WZ) = 68.9 ± 8.7 (stat.) ± 9.7 (syst.) ± 1.5 (lum.) pb, consistent with NLO expectation of 65.6 ± 2.2 pb.**

WV → *lνjj* aTGC Measurement

- Use the hadronic V→jj p_T distributions
- Place a $75 < m_{jj} < 95$ GeV cut to enhance signal purity
- Normalize the backgrounds based on fit results





- aTGC dependence is modeled by reweighting SM Diboson MC to MCFM predictions
- Systematics are accounted for and CL_S is used to set limits
- Δg_1^Z is taken to be 0 and $\Delta\kappa_\gamma$ vs λ limits are produced

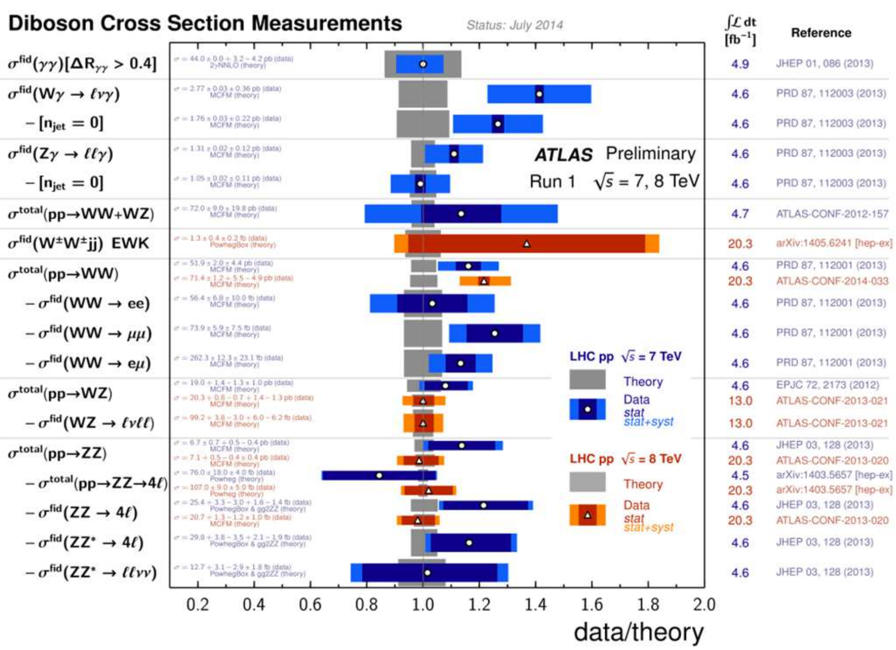
❖ 1D (95% CL) Limits:

❖ $-0.038 < \lambda_Z < 0.030$, $-0.111 < \Delta\kappa_\gamma < 0.142$

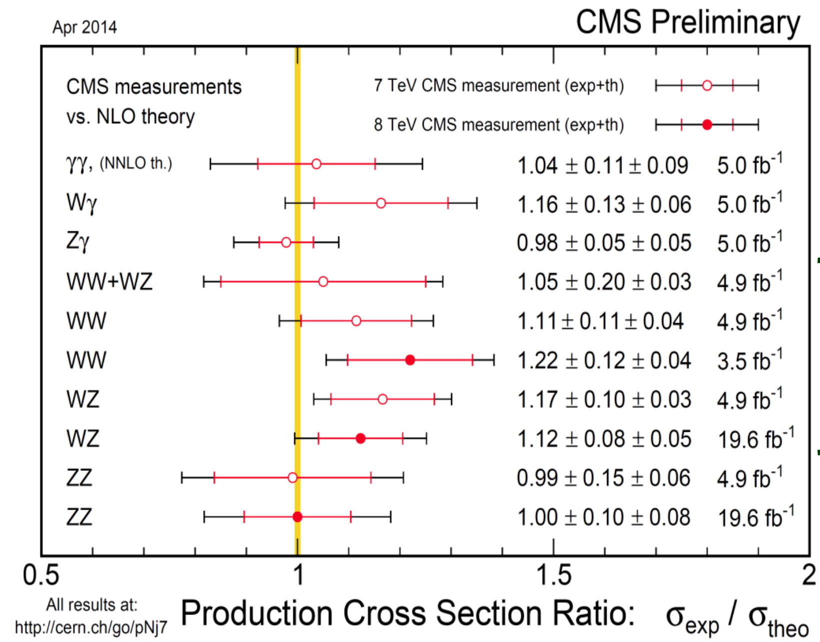
Diboson Cross-Sections at The LHC

➢ **Compare the ratios of $\sigma_{Measured}/\sigma_{Predicted}$**

ATLAS



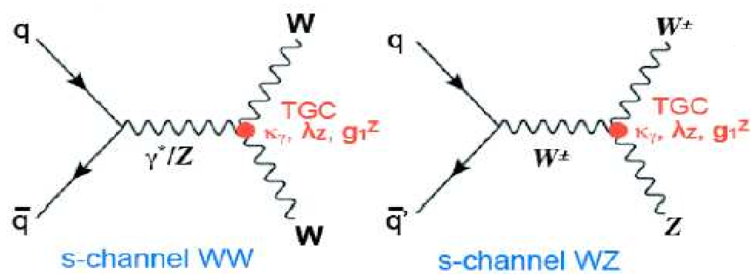
CMS



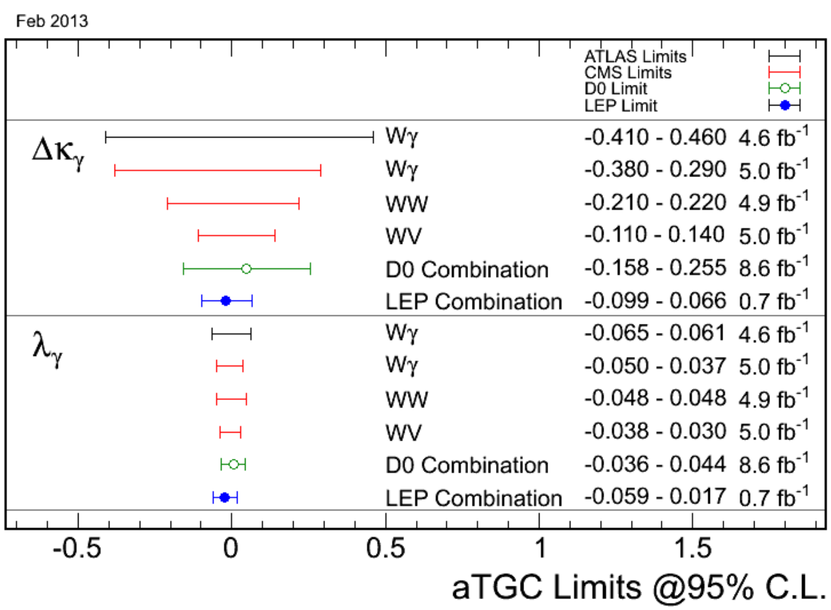
➢ **Excesses in the measured cross-sections are generally observed**

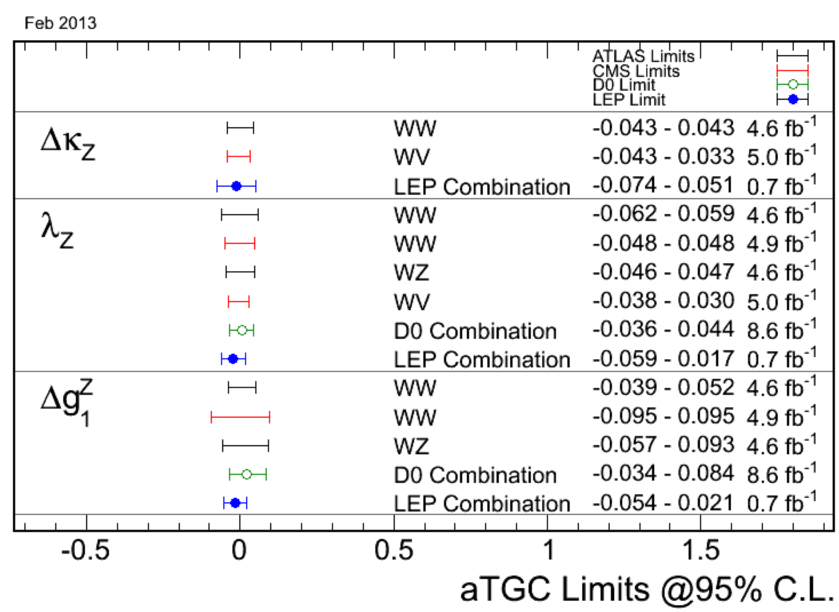
➢ **Measurements are within 3σ of the theory predictions**

Charged aTGCs Summary



- New physics would manifest itself as an enhancement in the s-channel WV production
- More prevalent at high p_T's
- Generally stronger limits in channels with higher event counts





❖ **CMS sets either competitive or strongest limits to date**

Summary

❖ Cross Section Measurements

- Implemented selections and extracted the signal for WZ → *lνll*, WW → *lνlν*, WV → *lνjj* processes
- Excesses observed for several channels, but no evidence for physics beyond SM

❖ Anomalous Triple Gauge Couplings

- Are expected to modify the spectrum at high p_T values
- Increased signal yield and aTGC discriminating ability in the semileptonic channel
- No evidence of anomalous interactions between the charged vector bosons
- Limits set by CMS are either competitive or the strongest to date

❖ Future Projections

- Relative strength of the anomalous signal will go up with increased energy
- Analyses to include merged jets, extensions to similar semileptonic final states and VBF topologies

Backup

Effective Field Theory and aTGCs

- **Express the Lagrangian as an effective theory of the Standard Model**

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

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

$$\begin{aligned}
g_1^Z &= 1 + c_W\frac{m_Z^2}{2\Lambda^2} \\
\kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\
\kappa_Z &= 1 + (c_W - c_B\tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2} \\
g_4^V &= g_5^V = 0 \\
\tilde{\kappa}_\gamma &= c_{\tilde{W}}\frac{m_W^2}{2\Lambda^2} \\
\tilde{\kappa}_Z &= -c_{\tilde{W}}\tan^2\theta_W\frac{m_W^2}{2\Lambda^2} \\
\tilde{\lambda}_\gamma &= \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g^2m_W^2}{2\Lambda^2}
\end{aligned}$$

- **Expansion in powers of $1/\Lambda^2$ (a high energy scale where new physics comes into effect), rather than $1/m_W^2$**
- **3 CP even and 2 CP odd parameters prior to EWSB**
- **The parameters in the default formalism can be expressed in terms of the EFT coefficients**

References

❖ WZ $\rightarrow l\nu ll$

- CMS-PAS-SMP-12-006 (**http://cds.cern.ch/record/1564318?ln=en**)

❖ WW $\rightarrow l\nu l\nu$

- **7TeV** - Eur.Phys.J. C73 (2013) 2610 (http://arxiv.org/abs/1306.1126)
- **8TeV** - Phys. Lett. B 721 (2013) 190–211 (http://arxiv.org/abs/1301.4698)

❖ WV $\rightarrow l\nu jj$

- Eur.Phys.J. C73 (2013) 2283 (**http://arxiv.org/abs/1210.7544**)

❖ CMS Combinations

- **https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP**
- **https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC**

❖ EFT and aTGCs

- Effective Field Theory: A Modern Approach to Anomalous Couplings (http://arxiv.org/abs/1205.4231)