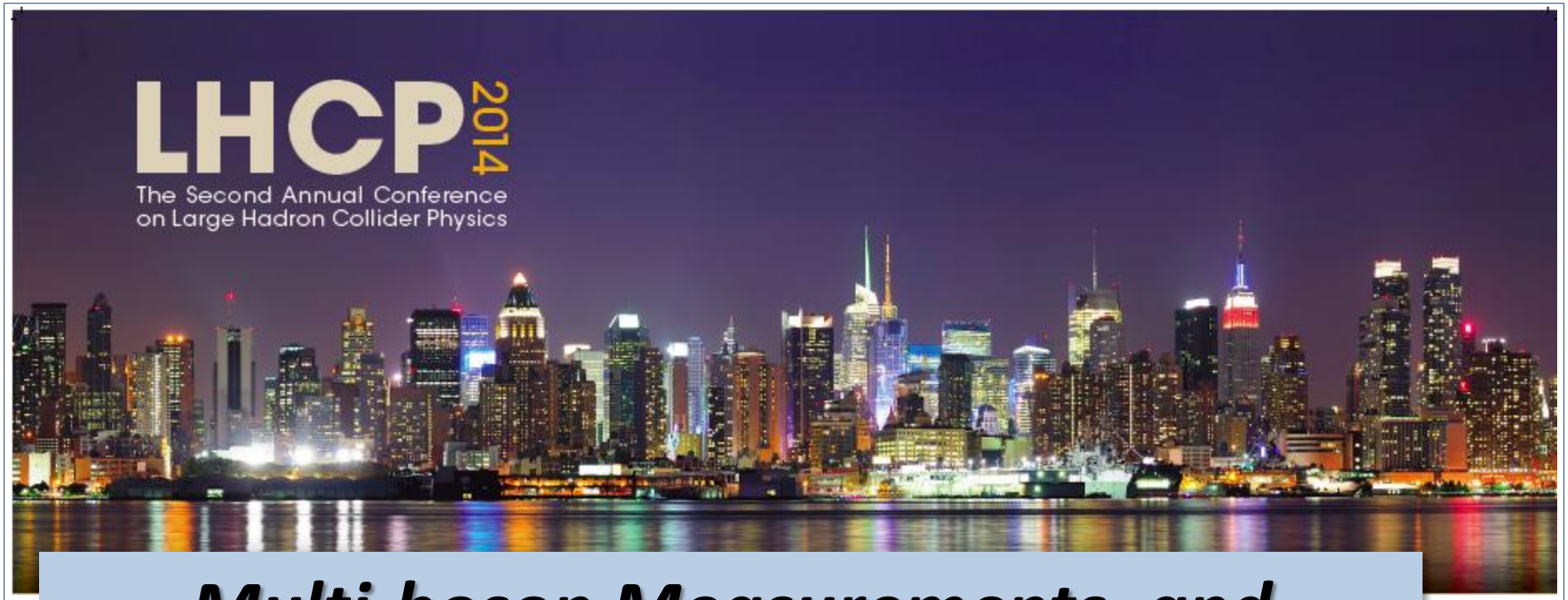



# *Multi-boson Measurements, and Triple and Quartic Gauge Couplings with the CMS*

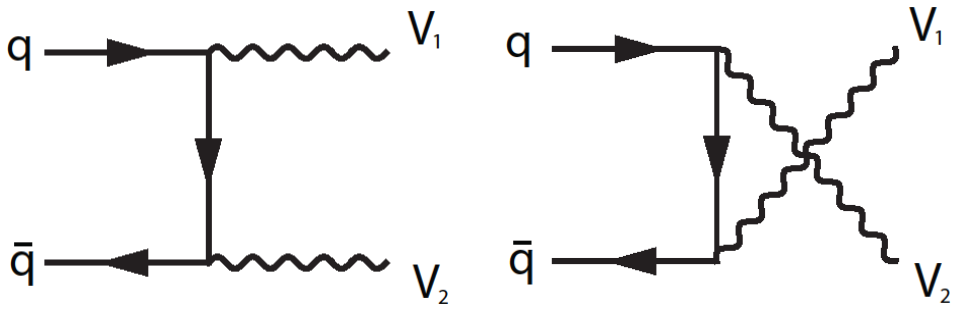
*Jordan Damgov*
*on behalf of*
*The CMS collaboration*

# Overview

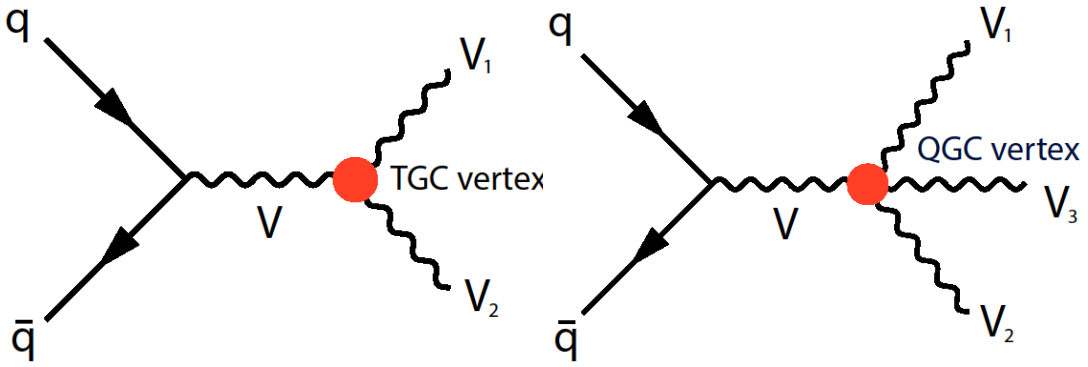
❖ Test of the standard model

❖ Irreducible back ground to new physics searches and Higgs boson analyses

- Cross section results
  - Wγ, Zγ production
  - WW/WZ production
  - ZZ production
  - exclusive γγ -> WW
  - WVγ production




- **aTGC** results
- **aQGC** results



7 TeV

# Zγ->llγ / Wγ->lνγ

EWK-11-009

*Signature **Zγ->llν**:*

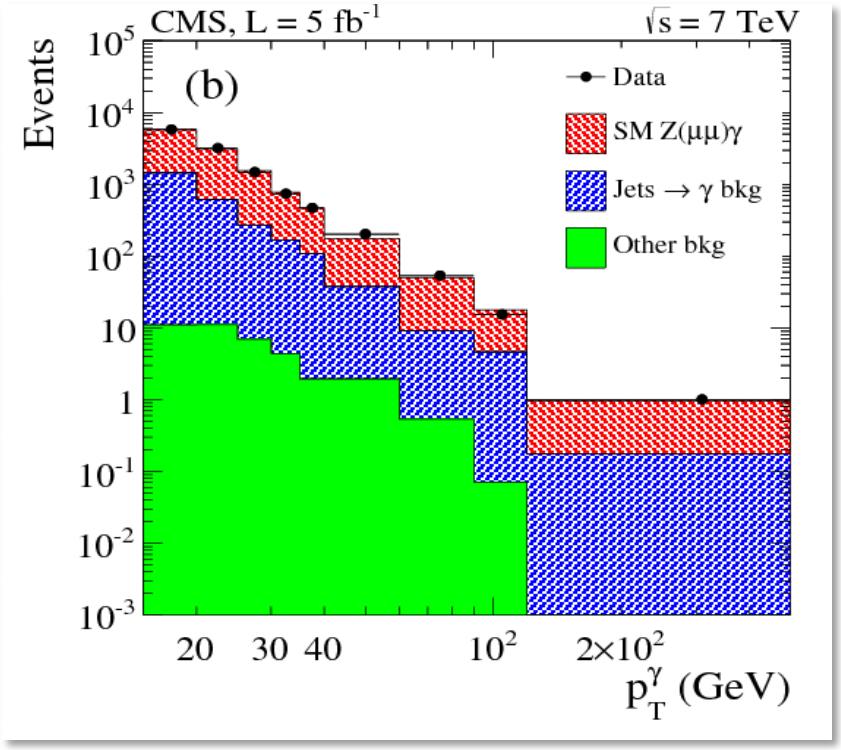
two leptons + γ

*Event selection:*

$p_T^l > 20$ GeV, $|\eta^l|<2.5(2.4)$, l=e(μ)

$p_T^\gamma > 15$ GeV, $|\eta^\gamma|<2.5$

$\Delta R(l,\gamma)>0.7$, $m_{ll} > 50$ GeV




*Signature **Wγ->lνγ** :*

Single lepton + $E_t^{miss}$ + γ

*Event selection:*

$p_T^l > 35$ GeV, $|\eta^l|<2.5(2,1)$, l=e(μ)

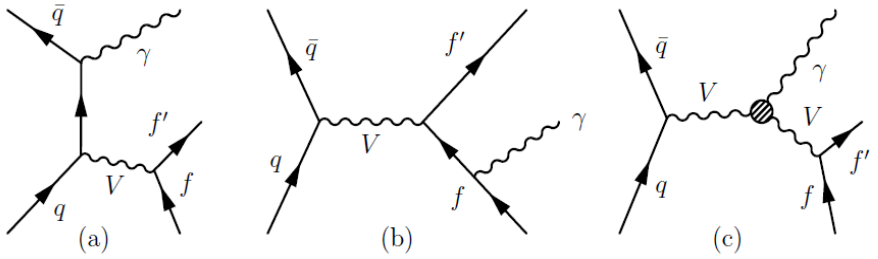
$p_T^\gamma > 15$ GeV, $|\eta^\gamma|<2.5$

$\Delta R(l,\gamma)>0.7$, $M_T^W>70$ GeV

only one lepton

*Background:*

Jets mimicking photons is dominant background. Using data-driven methods to estimate most of them.

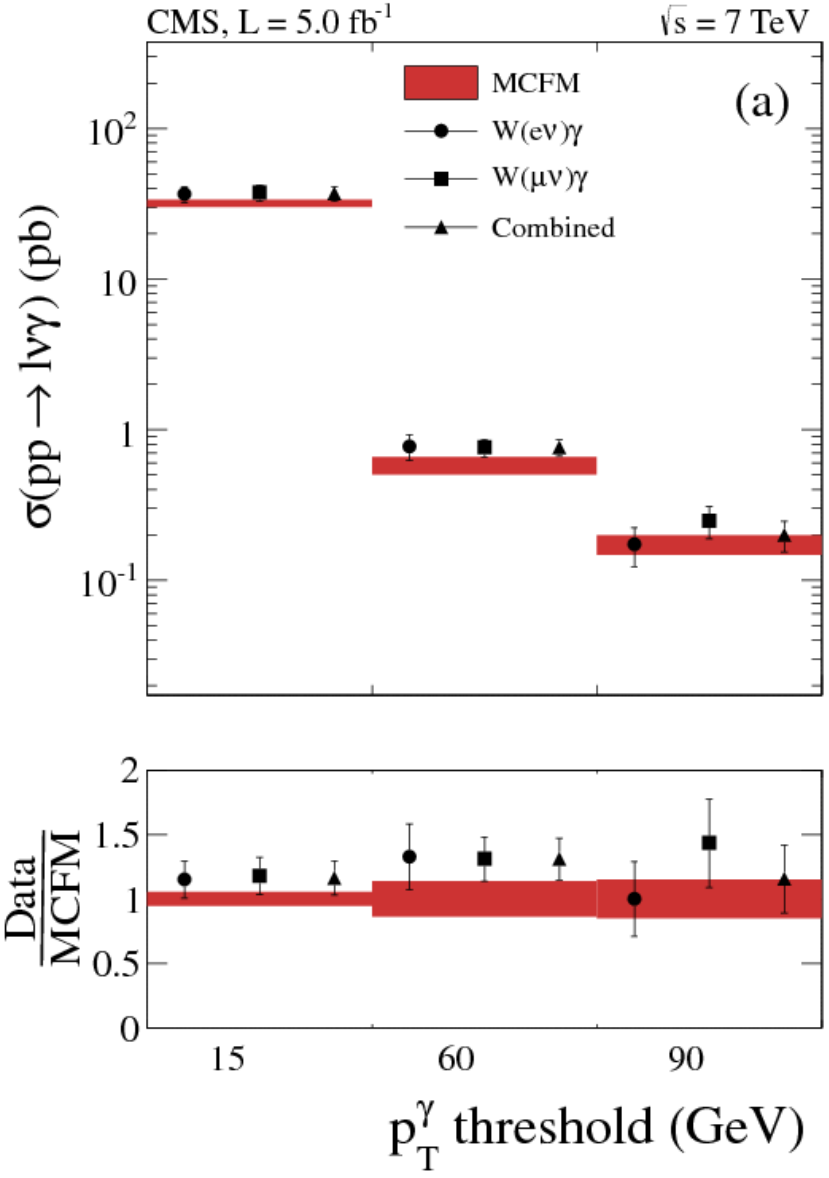


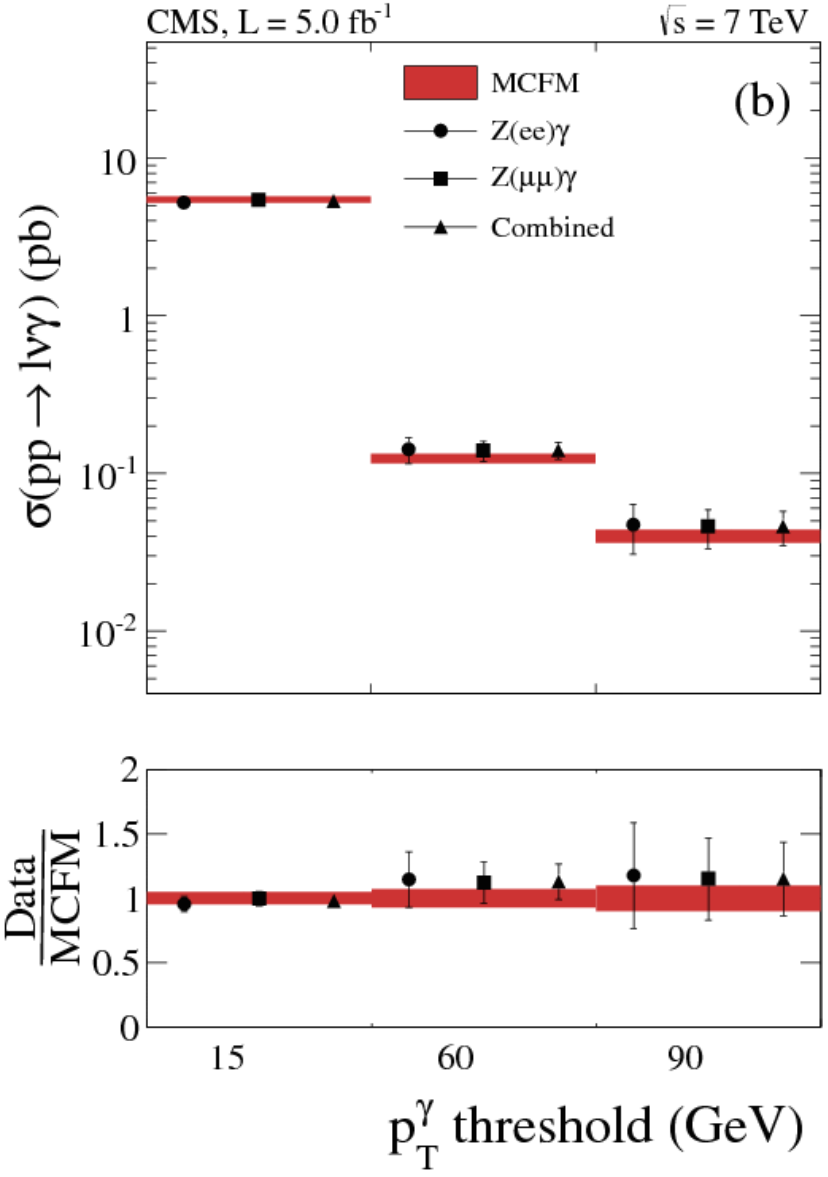

ISR FSR TGC

7 TeV

# Wγ / Zγ cross section

EWK-11-009



7 TeV

# Zγ->νν̄γ

SMP-12-020

Signature:

$E_t^{miss}$ + γ

Event selection:

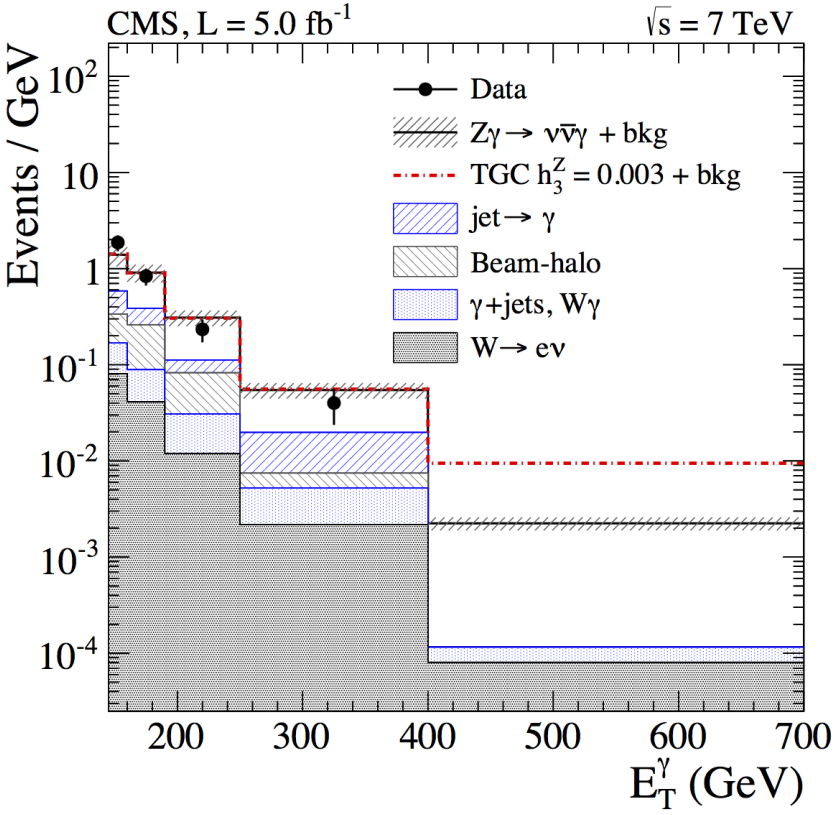
$p_T^{\gamma} > 145$ GeV, $|\eta^{\gamma}| < 1.4$

$E_t^{miss} > 130$ GeV,

$p_T^{jets} < 40$ GeV, $p_T^{tracks} < 20$ GeV

✓Large instrumental and non-collision backgrounds – estimated with data-driven methods

| Source | Estimate |
|---|---|
| Misidentified jets | $11.2 \pm 2.8$ |
| Beam-gas processes | $11.1 \pm 5.6$ |
| Misidentified electrons | $3.5 \pm 1.5$ |
| $W\gamma$ | $3.3 \pm 1.0$ |
| $\gamma\gamma$ | $0.6 \pm 0.3$ |
| $\gamma$+jet | $0.5 \pm 0.2$ |
| Total | $30.2 \pm 6.5$ |
| $Z\gamma \to \nu\nu\gamma$ (NLO) | $45.3 \pm 6.9$ |
| data | 73 |




Measured cross section ($p_T^{\gamma}$>145GeV,$|\eta^{\gamma}|$<1.4):

**21.3 ± 4.2 (stat.) ± 4.3 (syst.) ± 0.5 (lumi.) fb**

Theoretical(BAUR) cross section:

**21.9 ± 1.1 fb**

8 TeV

# ZZ->lll'l'

SMP-13-005

*Signature*:

Four leptons $l^-l^+l^-'l^+'$, l=e,μ, l'= l=e,μ,τ

Include Z->ττ for the second candidate

*Event selection:*

$p_T^l$ > 20(10) GeV, leading(other) lepton(s)

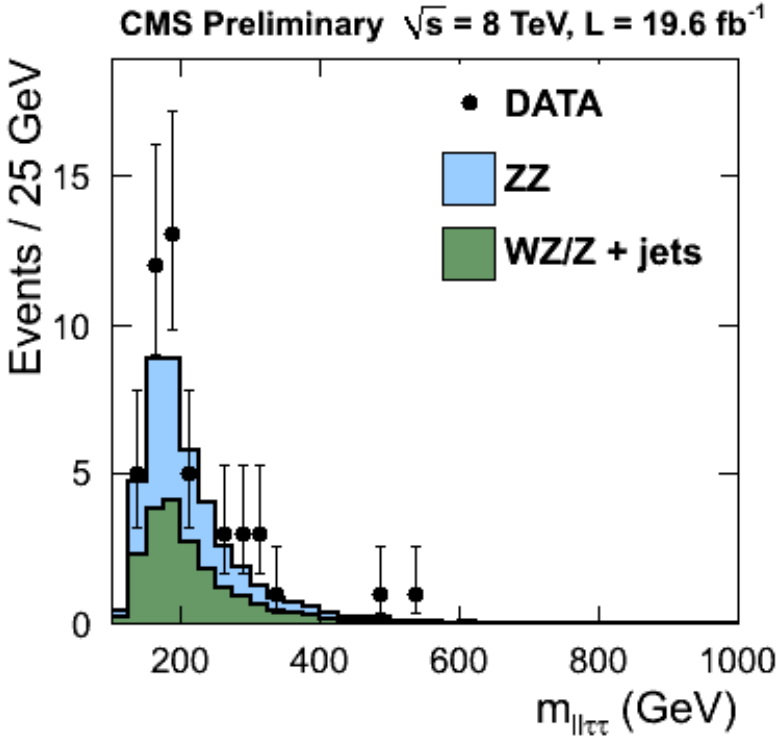
$|\eta^l|$<2.5(2.4), l=e(μ)

60< $m_{ll}$ < 120 GeV (each pair)

20/30 < $m_{\tau\tau}$<90 GeV (eμ/other)

*Background:*

Jet is misidentified as lepton in WZ/Z+jets and tt. Data driven estimate – control region with relaxed isolation.




| Decay channel | $N_{ZZ}^{exp}$ | Background | Total expected | Observed |
|---|---|---|---|---|
| μμμμ | 77.32 ± 0.29 ± 10.08 | 1.19 ± 0.36 ± 0.48 | 78.51 ± 0.49 ± 10.09 | 75 |
| eeee | 55.28 ± 0.25 ± 7.64 | 2.16 ± 0.26 ± 0.88 | 57.44 ± 0.37 ± 7.69 | 54 |
| μμee | 136.09 ± 0.59 ± 17.50 | 2.35 ± 0.34 ± 0.93 | 138.44 ± 0.70 ± 17.52 | 148 |
| Total ℓℓττ | 22.65 ± 0.05 ± 2.94 | 19.51 ± 2.15 ± 5.85 | 42.16 ± 2.28 ± 6.87 | 47 |

Measured cross section pp->ZZ:

**7.7 ± 0.5 (stat.) $^{+0.5}_{-0.4}$(syst .)**

**± 0.4 (theo.) ± 0.3 (lumi.) pb**

Theoretical cross section :

**7.7 ± 0.6 pb** (MCFM, qq(NLO),gg(LO))

8 TeV

# ZZ->2l2ν

SMP-12-016

*Signature:*

Two opposite charge leptons + $E_t^{miss}$

*Event selection:*

$p_T^l > 20$ GeV, l=e,μ

$(m_{ll} - 91) < 7.5$ GeV

di-lepton $p_T > 45$ GeV

b-tag veto for jet with $p_T > 20$ GeV

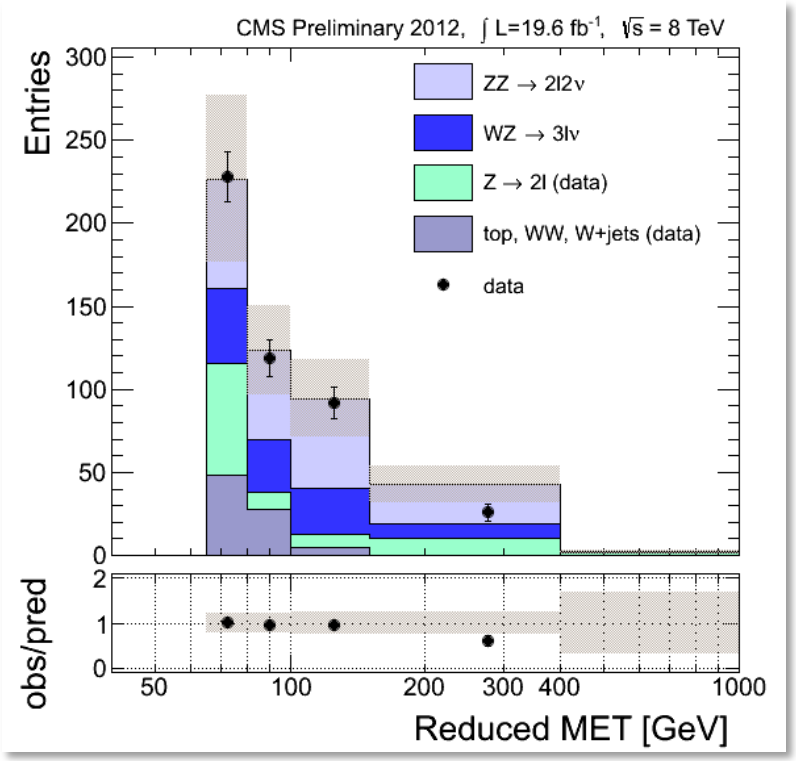
no jets with $p_T > 30$ GeV, lepton veto

reduced – $E_t^{miss} > 65$ GeV

$\Delta\varphi(E_t^{miss}, l) > 0.2$, $\Delta\varphi(E_t^{miss}, jet) > 0.5$

*Background:*

WZ, Z+jets, WW, top




pp -> ZZ -> 2l2ν cross sections at 7 and 8 TeV

| Channel | $\sigma$ [fb] 7 TeV | 8 TeV |
|---|---|---|
| $ee$ | $284^{+101}_{-90}$ (stat) $^{+75}_{-64}$ (syst) $\pm 10$ (lumi) | $224^{+48}_{-45}$ (stat) $^{+71}_{-50}$ (syst) $\pm 9$ (lumi) |
| $\mu\mu$ | $135^{+69}_{-62}$ (stat) $^{+56}_{-57}$ (syst) $\pm 5$ (lumi) | $305^{+43}_{-41}$ (stat) $^{+88}_{-66}$ (syst) $\pm 13$ (lumi) |
| Combined | $192^{+57}_{-52}$ (stat) $^{+51}_{-40}$ (syst) $\pm 7$ (lumi) | $261^{+32}_{-31}$ (stat) $^{+71}_{-52}$ (syst) $\pm 11$ (lumi) |

Measured pp->ZZ cross section:

**$6.8 \pm 0.8$ (stat) $^{+1.8}_{-1.4}$ (syst) $\pm 0.3$ (lumi) pb**

Theoretical cross section :

**$7.7 \pm 0.6$ pb** (MCFM, qq(NLO),gg(LO))

8 TeV

# WW->2l2ν

SMP-12-024

*Signature:*

Two opposite charge leptons + $E_t^{miss}$

*Event selection:*

$p_T^l$ > 20 GeV, 3rd l veto >10 GeV

no jets with $p_T$ > 30 GeV

$E_t^{miss}$ > 45/45/20 GeV (ee, μμ,eμ)

$m_{ll}$-$m_Z$ > 15 GeV (ee, μμ)

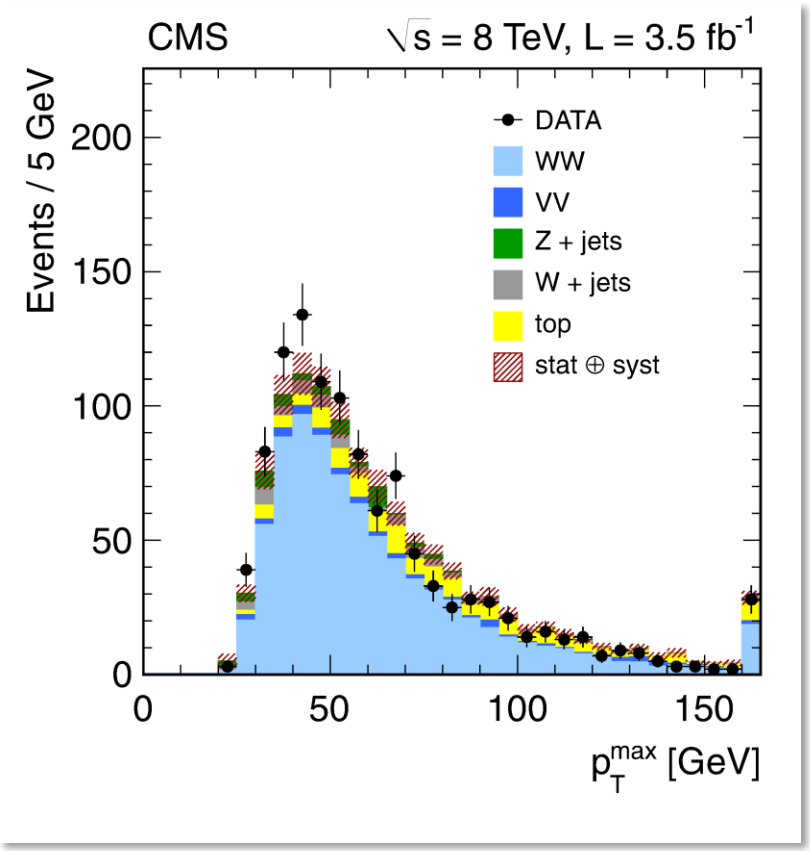
$m_{ll}$>12 GeV (ee, μμ)

di-lepton $p_T$ > 45 GeV

*Background:*

V+jets, Top, VV

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




Measured cross section

**69.9±2.8(stat)±5.6(syst)±3.1(lum) pb.**

**SM: $\sigma_{WW}$(NLO) = $57.3^{+2.3}_{-1.6}$pb**

(Higgs contribution @ mH125 GeV: +4%)

7 TeV 8 TeV

# WZ->3lv

SMP-12-006

*Signature:*

Two opposite charge leptons + 3rd l+ $E_t^{miss}$

*Event selection:*

Z reconstruction:

$p_T^l > 20$ (10) GeV

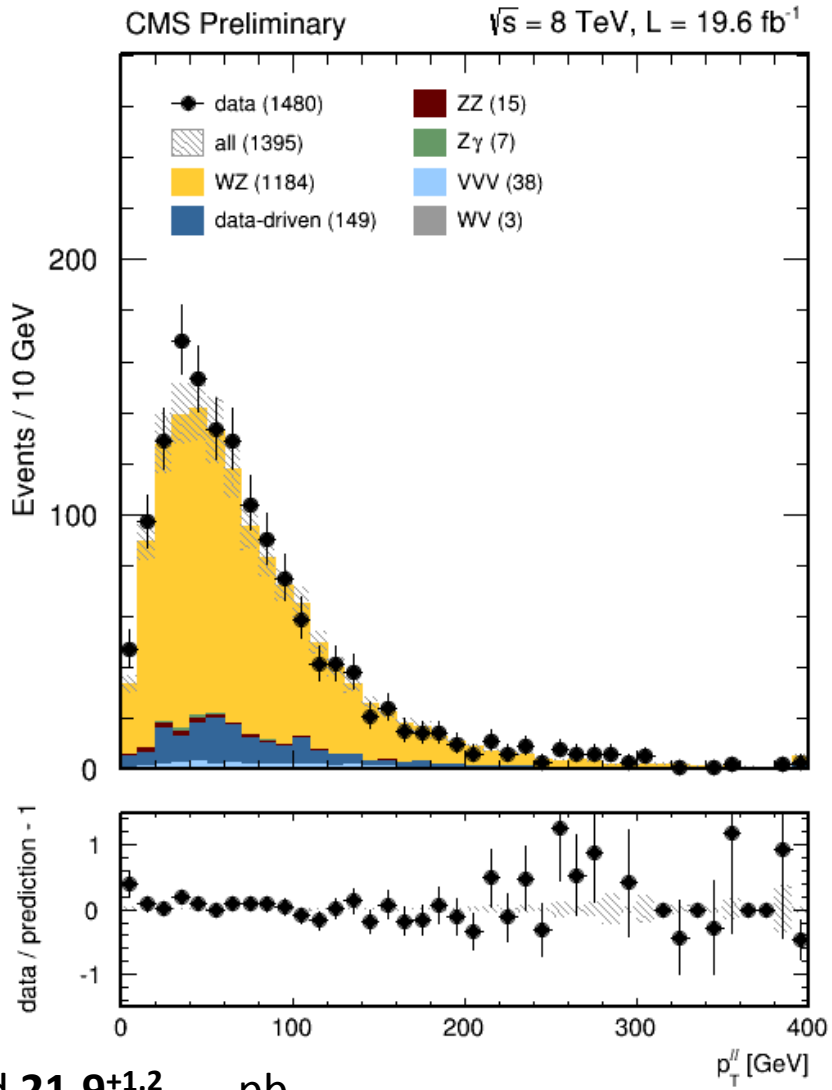
$71 < m_{ll} < 111$ GeV (and closest to $m_Z$)

W reconstruction:

$p_T^l > 20$ GeV, $E_t^{miss} > 30$ GeV

*Background:*

- Fake lepton - real Z plus a jet faking a lepton – the dominant background-
  - Non Peaking - no Z boson (e.g. tt)
  - Prompt Lepton - real Z and an isolated lepton(-like) object (e.g. ZZ, Z).




Measured pp->WZ cross section:

**20.8 ± 1.3(stat.) ± 1.1 (syst.) ± 0.5(lumi.) pb @7TeV**

**24.6 ± 0.8(stat.) ± 1.1 (syst.) ± 1.1(lumi.) pb@8TeV**

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

7 TeV

# WV->lvjj

SMP-12-015

*Signature:*

lepton + $E_t^{miss}$ + jets

one W boson decays leptonically (l = e,m)

the other boson (W or Z) decays hadronically (jj)

*Event selection:*

$p_T^l$ > 35(25) GeV, l=e(μ)

$|\eta^l|$<2.5(2.1), l=e(μ)

$M_T^W$> 50(30) GeV, l=e(μ)

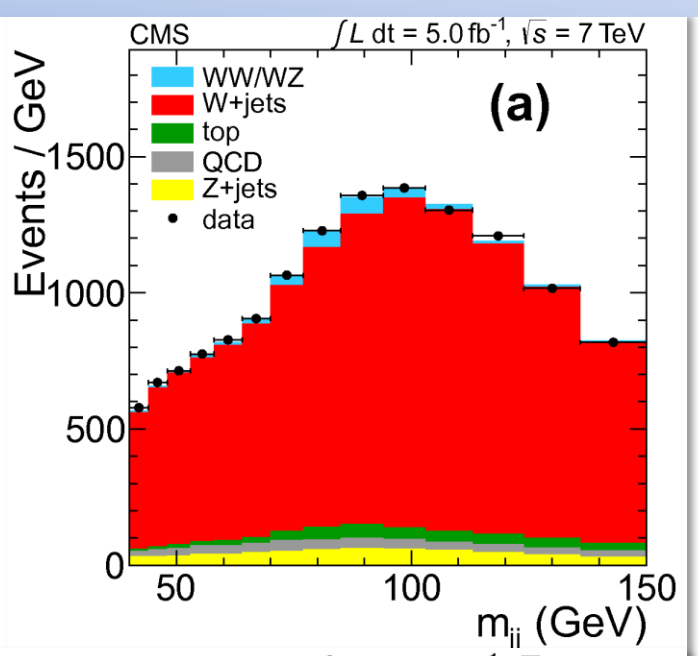
$E_T^{miss}$ > 30(25) GeV, l=e(μ)

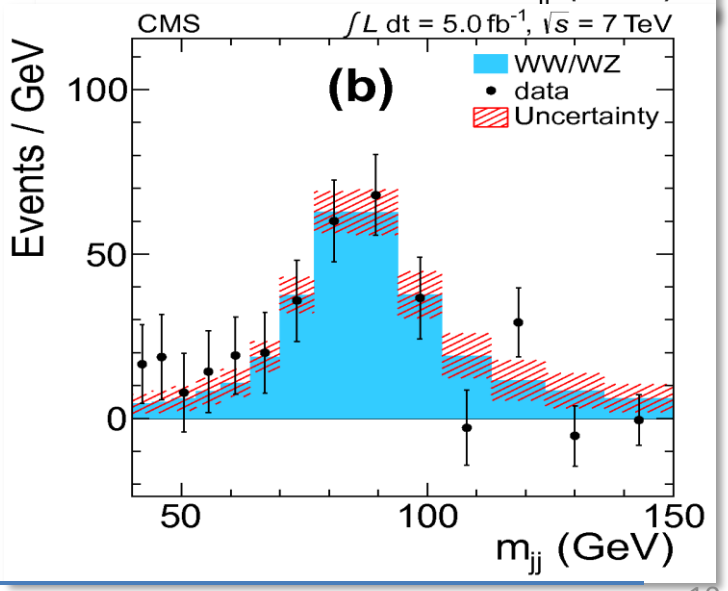
$p_T^{jet}$ > 35 GeV, $|\eta^{jet}|$<2.6, jet b-tag veto

*Background:*

W+jets(dominant), top, Z+jets,

jet -> l misidentification.




Measured cross section pp -> WW and pp-> WZ

**68.9 ± 8.7 (stat.) ± 9.7 (syst.) ± 1.5 (lum.) pb**

SM (NLO): **65.6 ± 2.2 pb**

8 TeV

# VZ->Vbb

SMP-13-011

*Signature:*

Two b-jets+ $E_t^{miss}$ + 0,1,2 leptons

*Event selection:*

2 b-jets ($|\eta|<2.5$), $m_{jj}<250$ GeV

0l($Z \rightarrow \nu\nu$): $E_T^{miss} > 100$ GeV

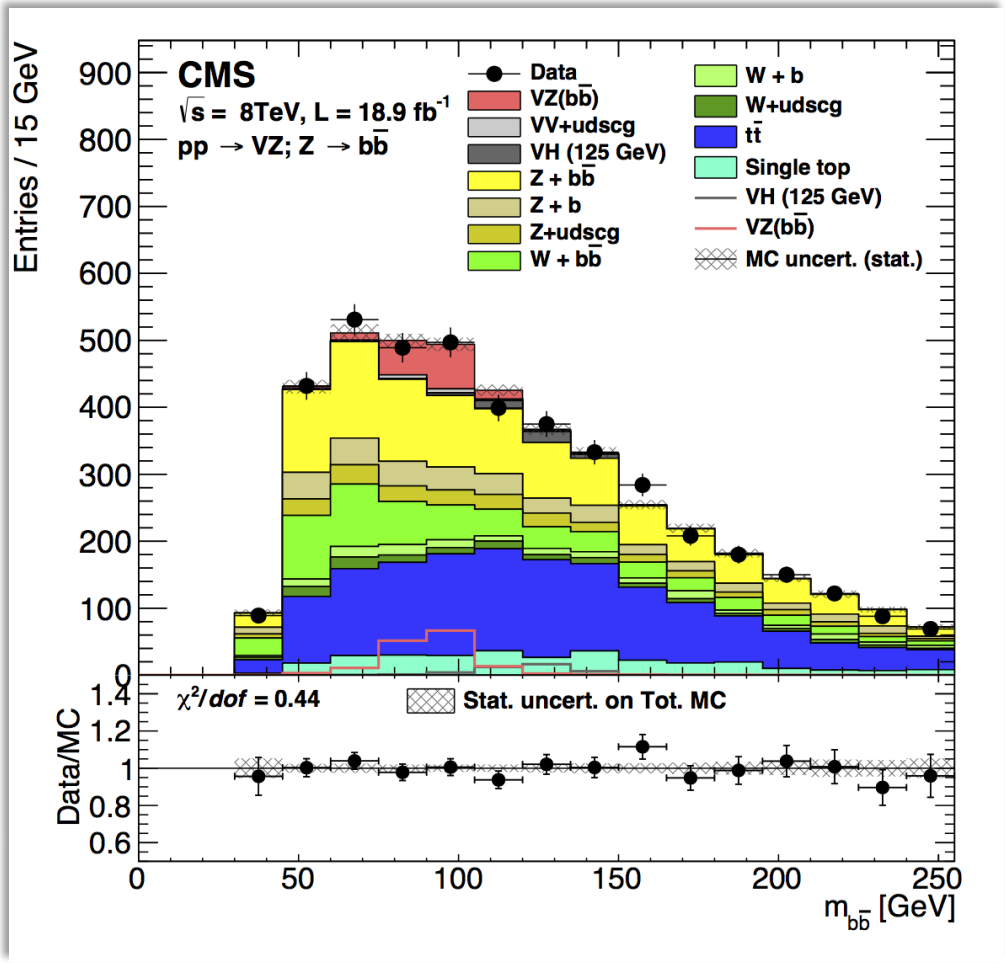
1l($W \rightarrow l\nu$): $E_T^{miss} > 45$ GeV

2l($Z \rightarrow ll$): 75GeV < $m_{ll}$< 105 GeV

Fit of multivariate discriminant/ $m_{jj}$

*Background:*

V+j, top, VH




Measured cross section **pp → WZ**

**30.7 ± 9.3(stat.) ± 7.1(syst.) ± 4.1(theo.) ± 1.0(lumi.) pb**

Measured cross section **pp → ZZ**

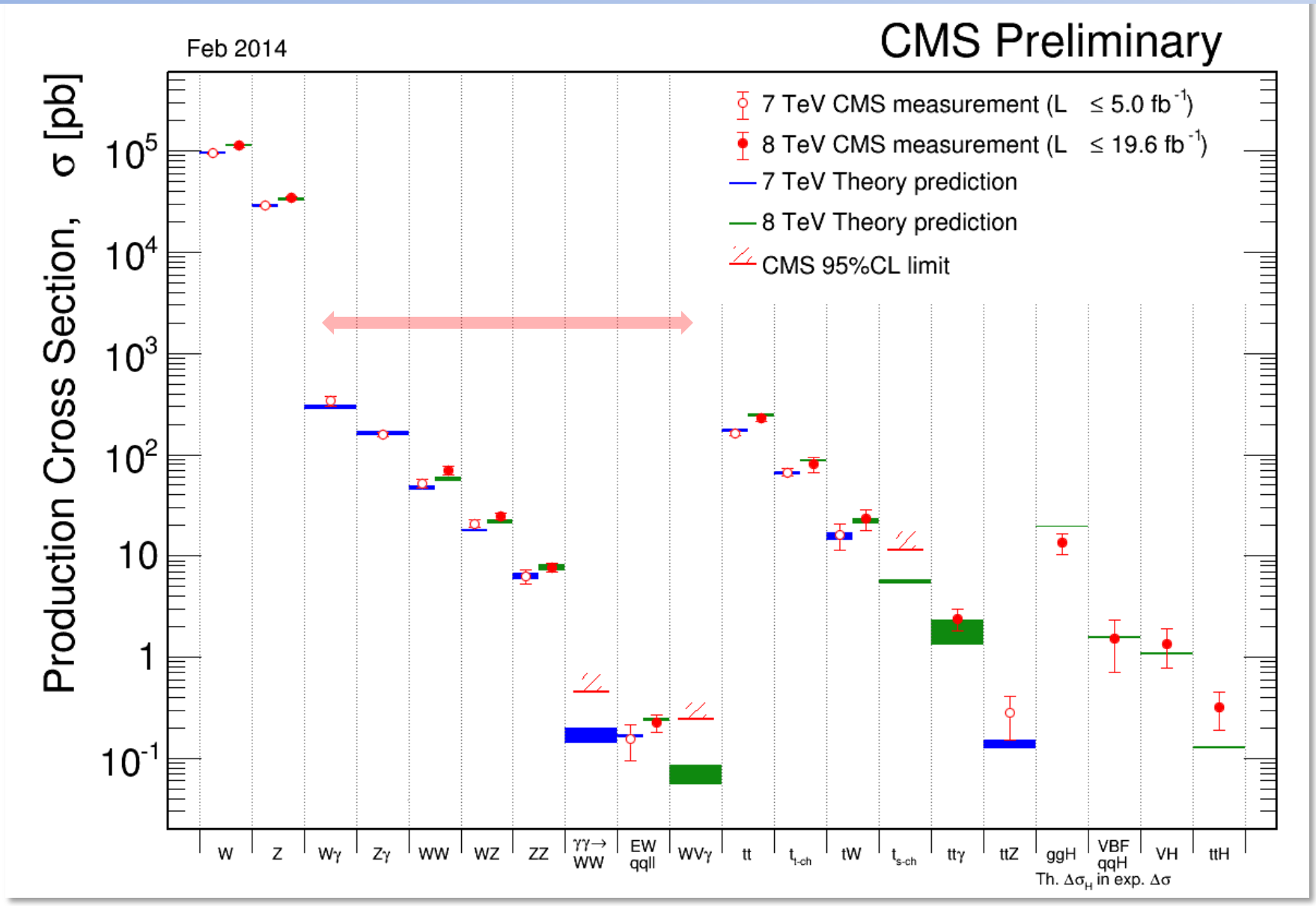
**6.5 ± 1.7(stat.) ± 1.0(syst.) ± 0.9(theo.) ± 0.2(lumi.) pb**

SM (NLO, 60 <$m_Z$< 120 GeV),

**$\sigma_{ZZ}$= 7.7 ±0.4 pb,**

**$\sigma_{WZ}$= 22.3 ±1.1 pb**

# Multi-boson Production cross section



# Triple Gauge Couplings

❖ Predicted by the Gauge structure of the Standard Model

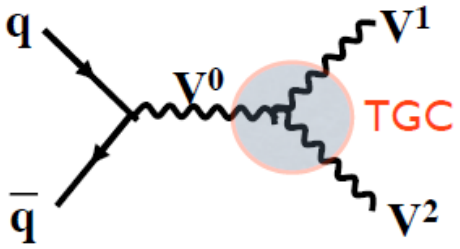
❖Neutral TGC (ZZZ, ZZγ, Zγγ) are forbidden at tree level by the SM

❖SM predictions: $\lambda_\gamma=\lambda_Z=0$, $g_1^Z=\kappa_\gamma=\kappa_Z=1$

❖aTGC modeled using an effective Lagrangian depending on few parameters

❖aTGC modify ***total cross sections*** and ***kinematics***

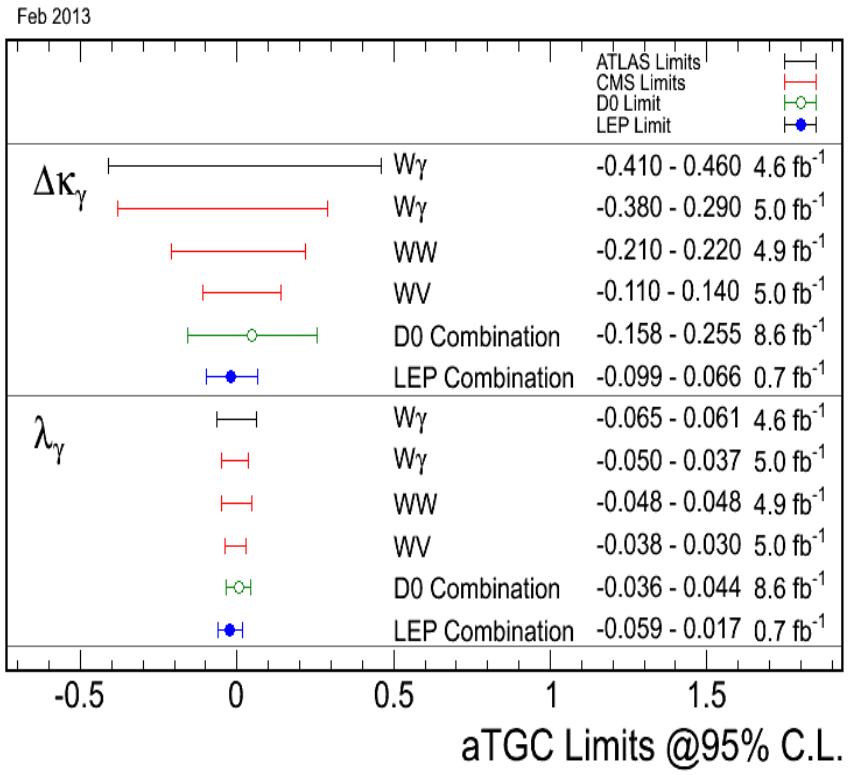
❖aTGC sensitivity to $M^{VV'}$, $p_T^V$, etc...

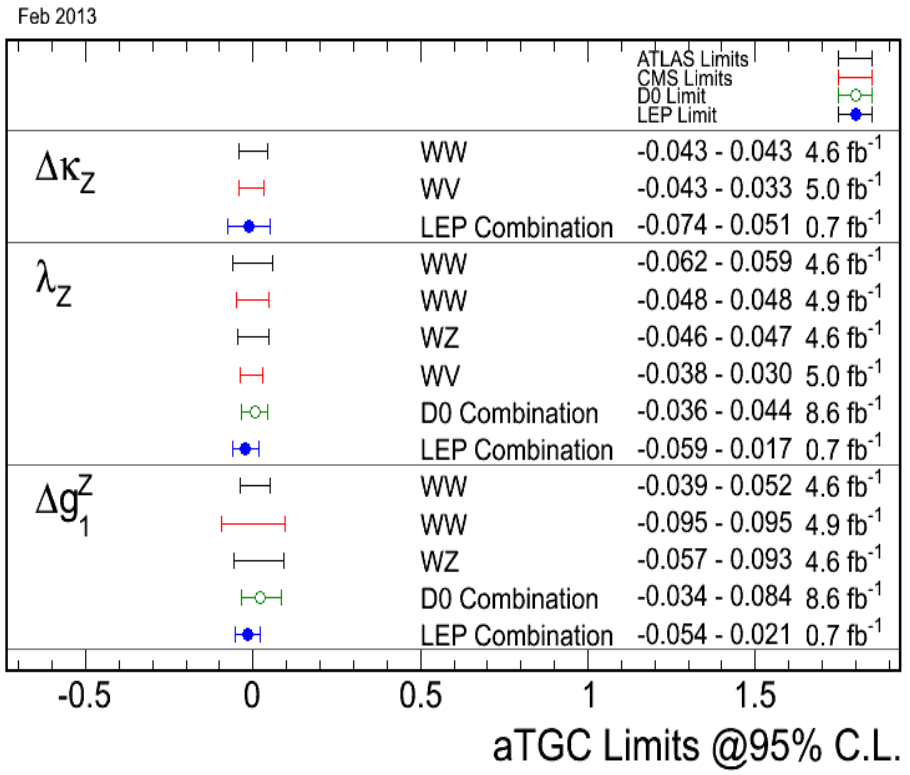



| Coupling | Parameters | Channel |
|---|---|---|
| WWγ | $\Delta\kappa_\gamma$, $\lambda_\gamma$ | WW, Wγ |
| WWZ | $\Delta g_1^Z$, $\Delta\kappa_Z$, $\lambda_Z$ | WW, WZ |
| ZZγ | $h_3^Z$, $h_4^Z$ | Zγ |
| Zγγ | $h_3^\gamma$, $h_4^\gamma$ | Zγ |
| ZZZ | $f_4^Z$, $f_5^Z$ | ZZ |
| ZγZ | $f_4^\gamma$, $f_5^\gamma$ | ZZ |

# Charged aTGC limits

✓ Comparison with other measurements from LHC, LEP and Tevatron

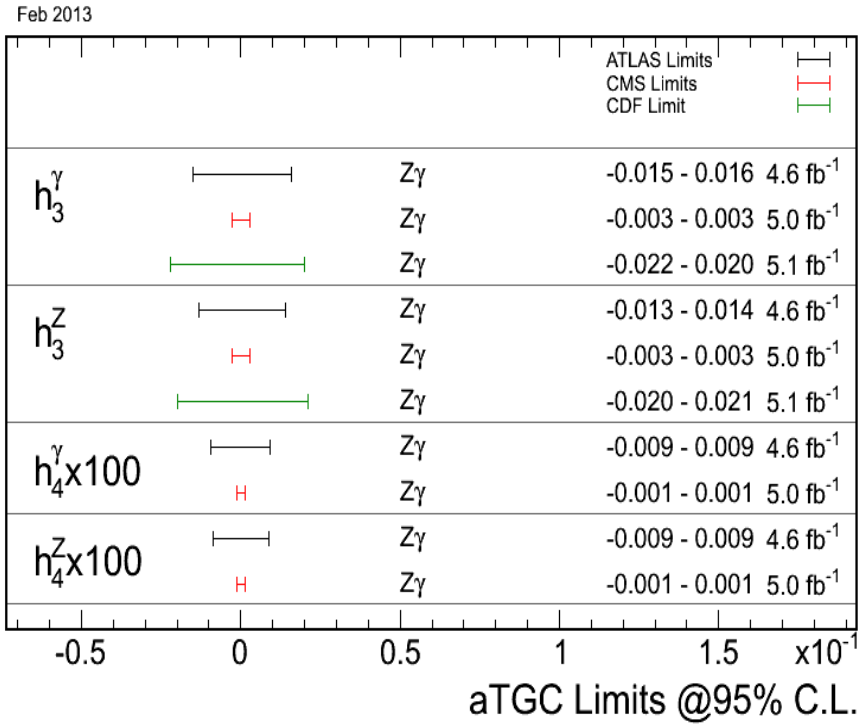


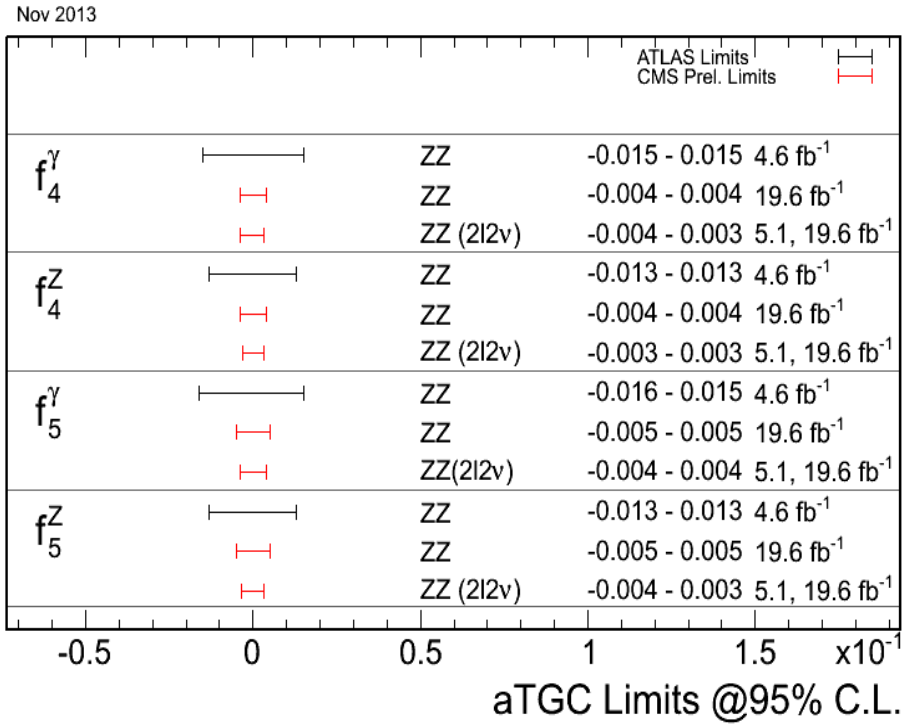




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

# Neutral aTGC limits

✓ Comparison with other measurements from LHC and Tevatron




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

7 TeV

# γγ->WW

FSQ-12-010

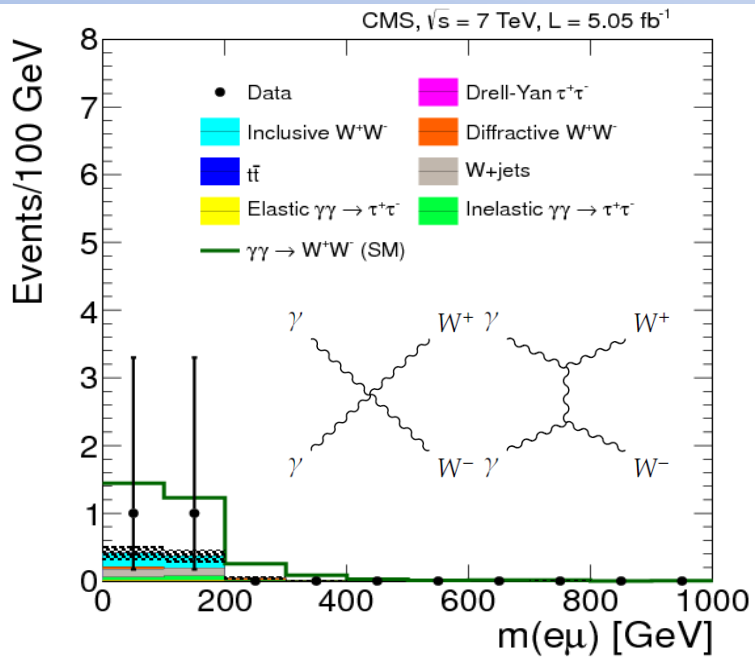
- ✓ pp→ γγ(→ WW)p*p* with forward scattered protons escaping detection. Protons stay intact, or dissociate into an undetected low-mass system
- ✓ Reconstruct a vertex with WW→$\mu^+e^-$ or $\mu^-e^+$(opposite flavor)
- ✓ lepton $p_T$>20GeV, |η|<2.4,
- ✓ $m_{ll}$>20GeV, $p_T^{ll}$>30GeV
- ✓ no extra tracks from the μe vertex.

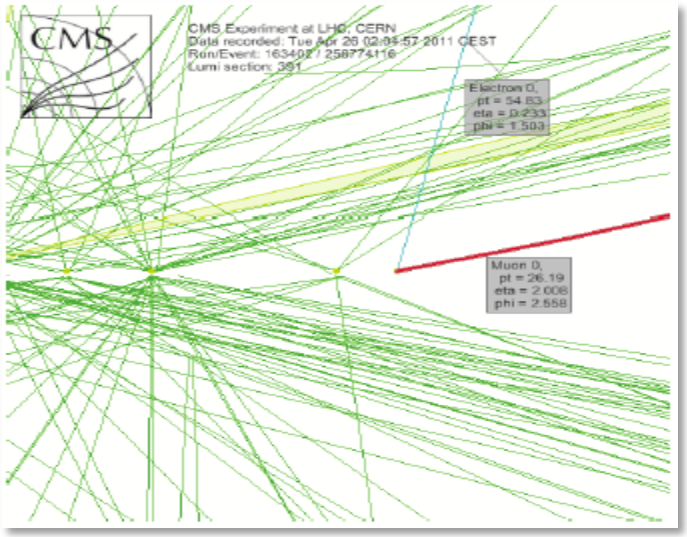
*Backgrounds:*

Inclusive $W^+W^-$, Drell-Yan to ττ, γγ → ττ.

The SM expectation is **2.2 ± 0.4 signal** and **0.84 ± 0.15 background** events.
*Two signal events are observed*

Measured cross section: $\mathbf{2.2^{+3.3}_{-2.0}}$ **fb**
SM: **3.8 ± 0.9**



8 TeV

# WVγ -> lνjjγ

SMP-13-009

*Signature:*

lepton + $E_t^{miss}$ + jets + γ

One W boson decays leptonically (l = e,m)

The other boson (W or Z) decays hadronically (jj)

*Event selection:*

$p_T^{\gamma} > 30$ GeV, $|\eta^{\gamma}|<1.44$

$p_T^{l} > 30(25)$ GeV, l=e(μ)

$|\eta^{l}|<2.5(2.1)$, l=e(μ)

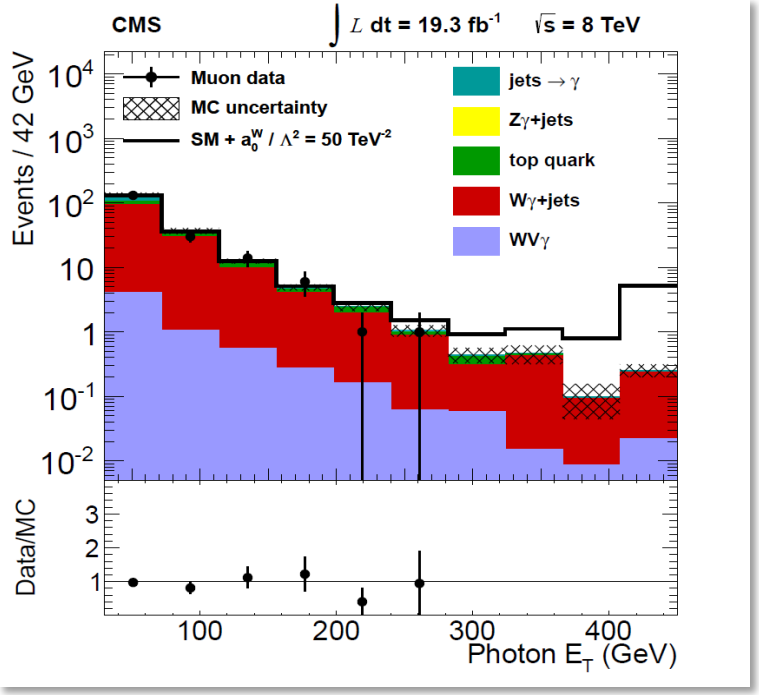
$M_T^{W} > 30$ GeV, $E_T^{miss} > 35$ GeV, $70<m_{jj}<120$ GeV

$p_T^{jets} > 30$ GeV, $|\eta^{jet}|<2.4$, jet b-tag veto

*Background:*

Wγ +jets(dominant), top, Zγ +jets,

jet->γ misidentification.




Limit on SM cross section at 95% CL ($p_T^{\gamma} > 30$ GeV, $|\eta^{\gamma}|<1.44$): **311 fb**

SM (NLO): **91.6 ± 21.7 fb**

| Process | Muon channel number of events | Electron channel number of events |
|---|---|---|
| SM $WW\gamma$ | $6.6 \pm 1.5$ | $5.0 \pm 1.1$ |
| SM $WZ\gamma$ | $0.6 \pm 0.1$ | $0.5 \pm 0.1$ |
| $W\gamma$ + jets | $136.9 \pm 10.5$ | $101.6 \pm 8.5$ |
| $WV$ + jet, jet → γ | $33.1 \pm 4.8$ | $21.3 \pm 3.3$ |
| MC $t\bar{t}\gamma$ | $12.5 \pm 3.0$ | $9.1 \pm 2.2$ |
| MC single top quark | $2.8 \pm 0.8$ | $1.7 \pm 0.6$ |
| MC $Z\gamma$ + jets | $1.7 \pm 0.1$ | $1.5 \pm 0.1$ |
| Multijets | — | $7.2 \pm 5.1$ |
| Total prediction | $194.2 \pm 11.5$ | $147.9 \pm 10.7$ |
| Data | 183 | 139 |

# Anomalous Quartic Gauge Couplings

- Effective lagrangian parameterizes low energy effects of BSM physics

- Different realizations for quartic interactions
  - ❖ nonlinear realization of $SU(2)_L xU(1)$ - lowest order genuine quartic interaction: dimension 6 (arXiv:hep-ph/0310141)
  - ❖linear realization - lowest order genuine quartic interaction: dimension 8 (arXiv:hep-ph/0606118)
- Parameters conversion from the nonlinear realization to the linear realization. The linear realization has parameters with no analog in the nonlinear realization

Variety of parameters available that modify quartic couplings.

| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA | AAAA |
|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$ | X | X | X | O | 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 | 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 | O |
| $\mathcal{L}_{T,0}$ ,$\mathcal{L}_{T,1}$ ,$\mathcal{L}_{T,2}$ | X | 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 | X |
| $\mathcal{L}_{T,9}$ ,$\mathcal{L}_{T,9}$ | O | O | X | O | O | X | X | X | X |

*http://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling*

# AQGC limits

❖ The γγ → WW analysis interprets the results in terms of LEP-like "dimension-6" γγWW AQGC's.

$$-4.0\times10^{-6} < a_0^W/\Lambda^2 < 4.0\times10^{-6}\,\mathrm{GeV}^{-2}\ (a_C^W/\Lambda^2 = 0, \text{no form factor}),$$
$$-1.5\times10^{-5} < a_C^W/\Lambda^2 < 1.5\times10^{-5}\,\mathrm{GeV}^{-2}\ (a_0^W/\Lambda^2 = 0, \text{no form factor}).$$

❖ The WVγ results are Interpreted in terms of both dimension-6 and dimension-8 (linear) anomalous *WWγγ and WWZγ couplings*

| Observed limits | Expected limits |
|---|---|
| $-21 < a_0^W/\Lambda^2 < 20\,\mathrm{TeV}^{-2}$ | $-24 < a_0^W/\Lambda^2 < 23\,\mathrm{TeV}^{-2}$ |
| $-34 < a_C^W/\Lambda^2 < 32\,\mathrm{TeV}^{-2}$ | $-37 < a_C^W/\Lambda^2 < 34\,\mathrm{TeV}^{-2}$ |
| $-25 < f_{T,0}/\Lambda^4 < 24\,\mathrm{TeV}^{-4}$ | $-27 < f_{T,0}/\Lambda^4 < 27\,\mathrm{TeV}^{-4}$ |
| $-12 < \kappa_0^W/\Lambda^2 < 10\,\mathrm{TeV}^{-2}$ | $-12 < \kappa_0^W/\Lambda^2 < 12\,\mathrm{TeV}^{-2}$ |
| $-18 < \kappa_C^W/\Lambda^2 < 17\,\mathrm{TeV}^{-2}$ | $-19 < \kappa_C^W/\Lambda^2 < 18\,\mathrm{TeV}^{-2}$ |

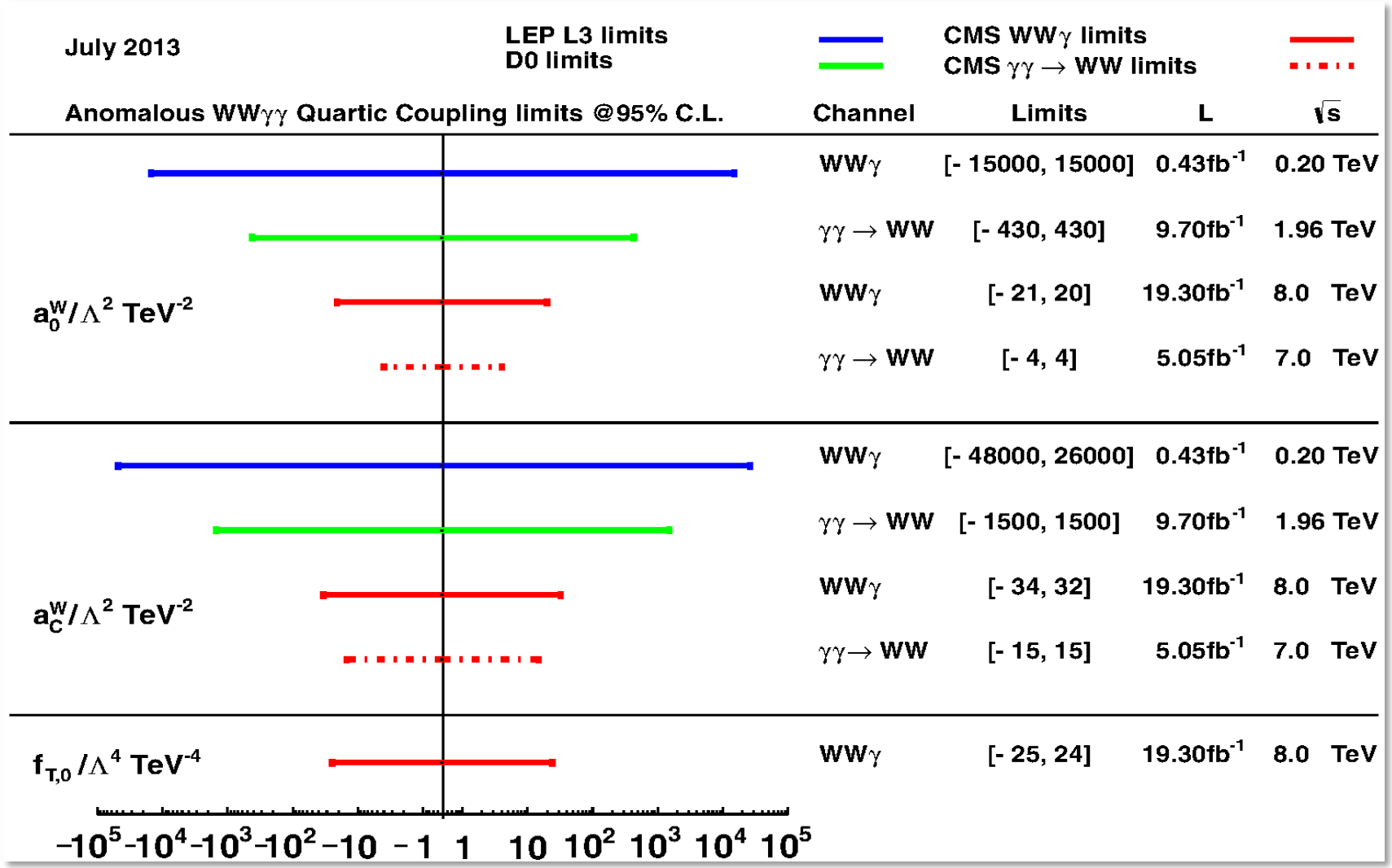
First limits on CP-conserving *WWZγ* couplings $k_c^W$, $k_0^W$

| Observed limits ($\mathrm{TeV}^{-4}$) | Expected limits ($\mathrm{TeV}^{-4}$) |
|---|---|
| $-77 < f_{M,0}/\Lambda^4 < 81$ | $-89 < f_{M,0}/\Lambda^4 < 93$ |
| $-131 < f_{M,1}/\Lambda^4 < 123$ | $-143 < f_{M,1}/\Lambda^4 < 131$ |
| $-39 < f_{M,2}/\Lambda^4 < 40$ | $-44 < f_{M,2}/\Lambda^4 < 46$ |
| $-66 < f_{M,3}/\Lambda^4 < 62$ | $-71 < f_{M,3}/\Lambda^4 < 66$ |

Translation of the limits on WWγγ a0W and aCW (dimension-6) to limits on $f_{M,I}$ (dimension-8).

# AQGC – WWγγ limits comparison

*Orders of magnitude better than LEP and Tevatron limits on WWγγ.*



# Summary

- Processes with multible bosons in final state has been studied
  - ✓Production cross section have been measured and is found to be in agreement with the standard model prediction
  - ✓Contribution from anomalous triple and quartic gauge coupling is not observed – limits are set