

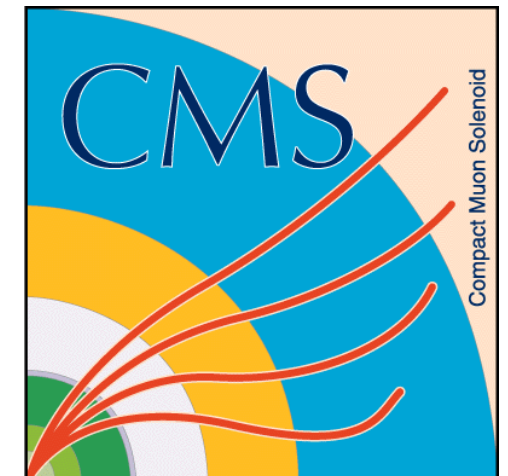
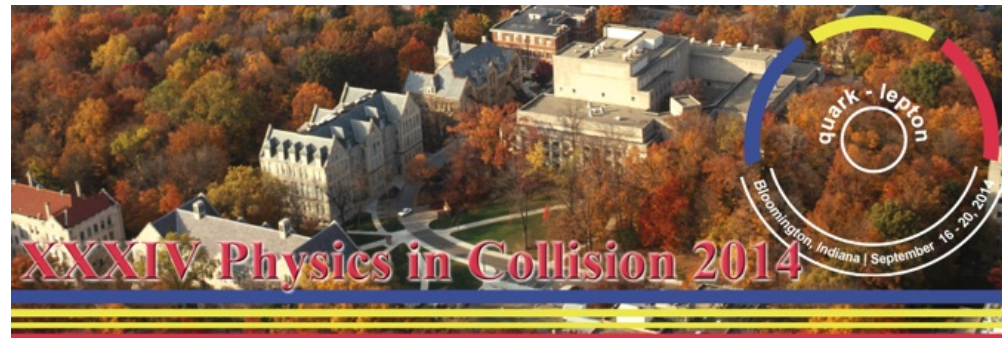
Electroweak Measurements with Multiple Gauge Boson Interactions

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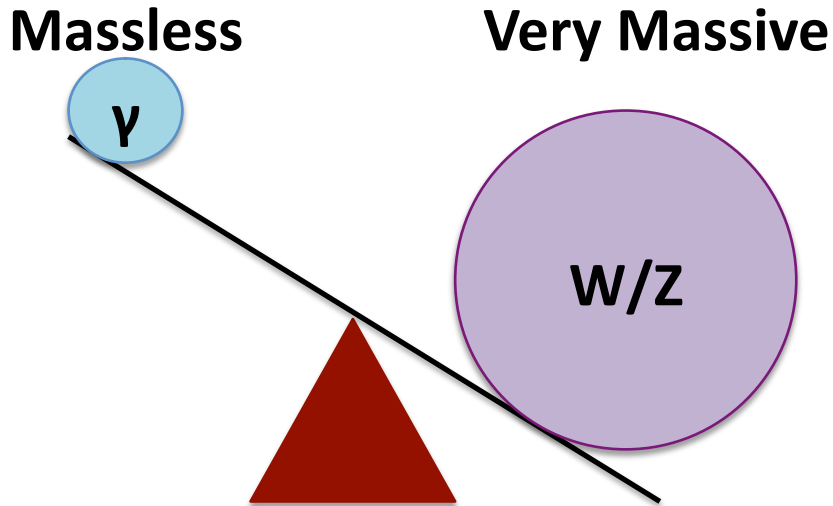
on behalf of the ATLAS and CMS Collaborations

Physics in Collision Conference, Sept. 17, 2014



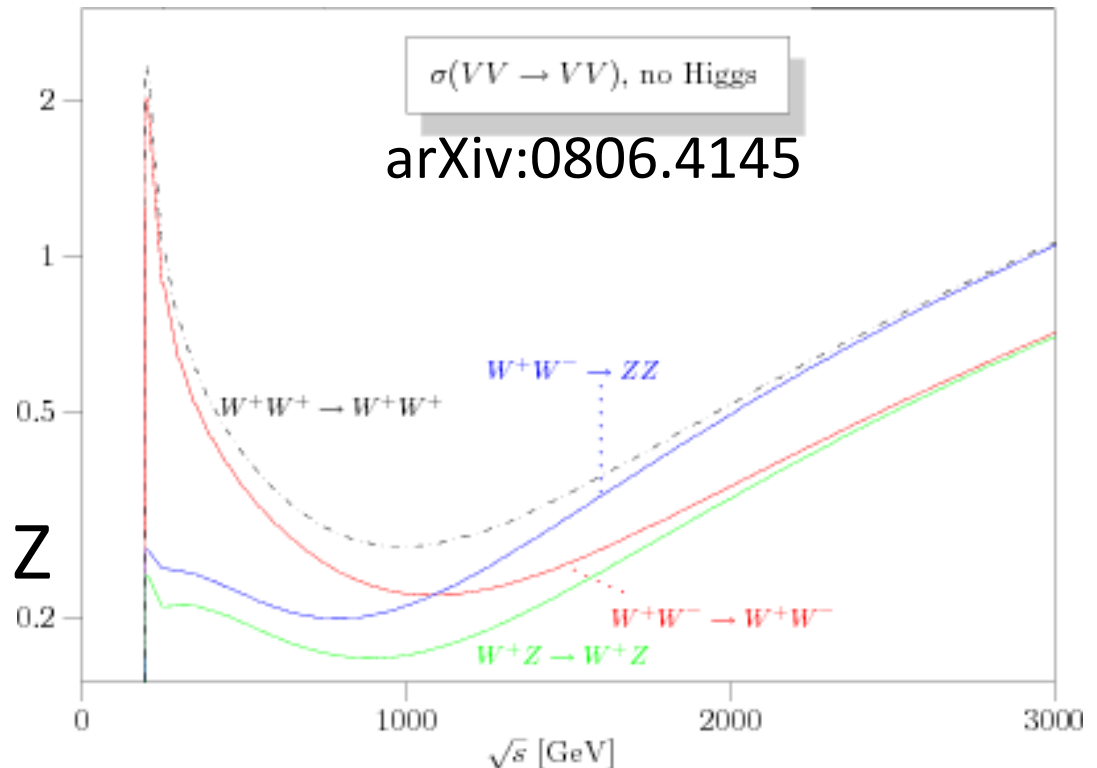
Motivation

- Standard Model (w/o Higgs) is gauge theory that predicts forces mediated by massless vector bosons



Electroweak symmetry broken in nature!

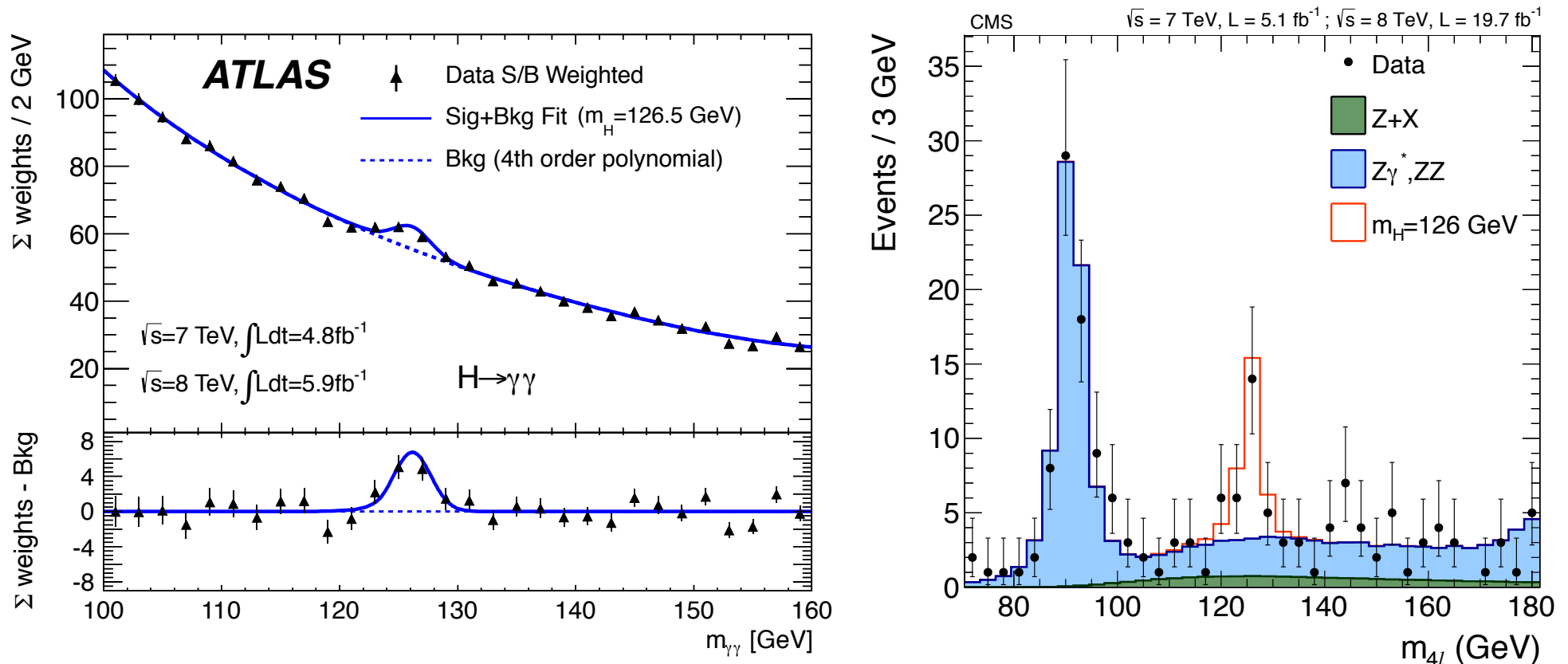
- Without new physics, unitarity violation in vector boson scattering (VBS) for massive W and Z



Experimental Approaches I

Test Favorite Theory

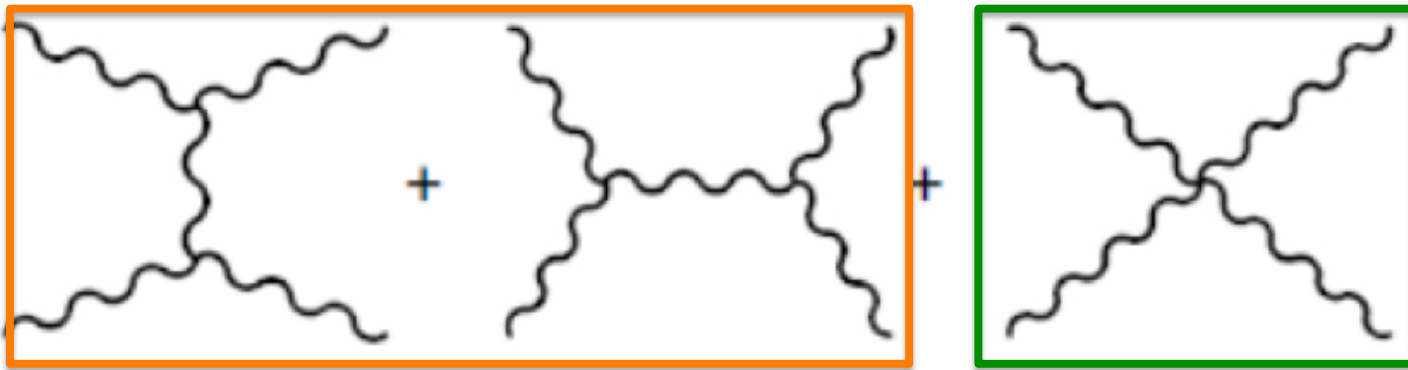
- Look for new particle(s) at low energy
- Drawback: may never find anything
- However, worked out pretty well in 2012



Experimental Approaches II

Measure EW Boson Interactions

- Two types of couplings in VBS diagrams: **triple gauge couplings (TGCs)** and **quartic gauge couplings (QGCs)**



- SM amplitude (without Higgs) grows as s/v^2
- Look for evidence of these couplings deviating from the SM values

aTGCs/aQGCs

Parameterization

- **Anomalous Couplings**
 - Simply add deviation from SM coupling to Lagrangian

$$\mathcal{K}_Z W_\mu^\dagger W_\nu Z^{\mu\nu} \rightarrow (\mathcal{K}_Z^{SM} + \Delta\mathcal{K}_Z) W_\mu^\dagger W_\nu Z^{\mu\nu}$$

- **Effective Field Theory**
 - Add higher dimension operators suppressed by energy scale for new physics

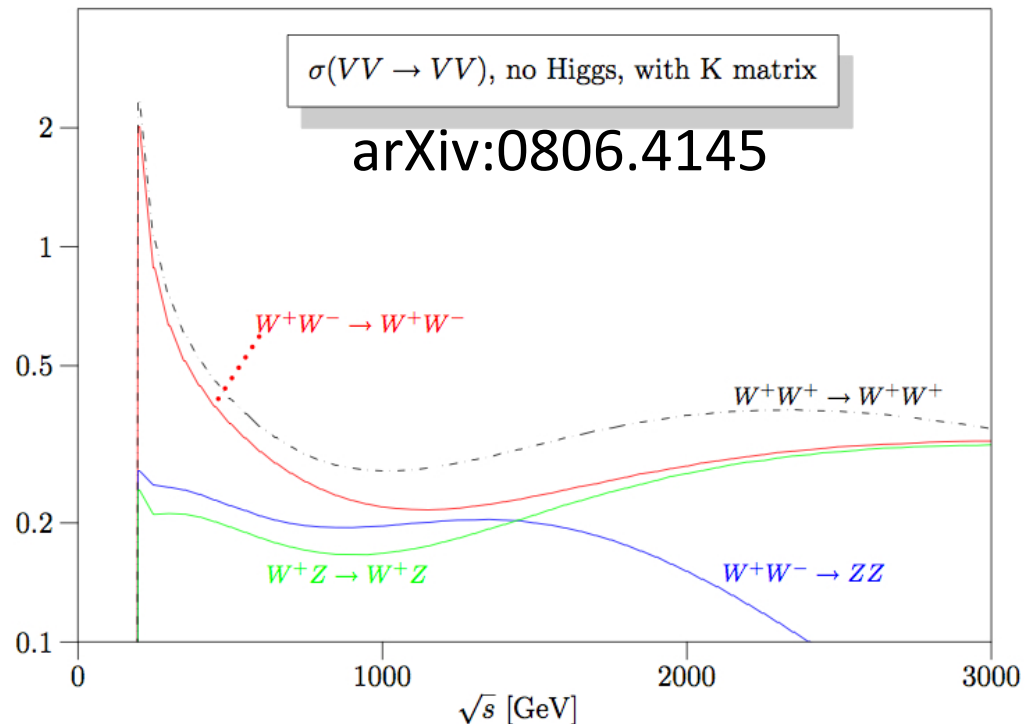
$$\frac{\mathcal{C}_W}{\Lambda^2} (D_\mu \varphi)^\dagger W^{\mu\nu} (D_\nu \varphi)$$

Unitarization

- **Form Factor**
 - Coupling decreases with s above a cutoff energy

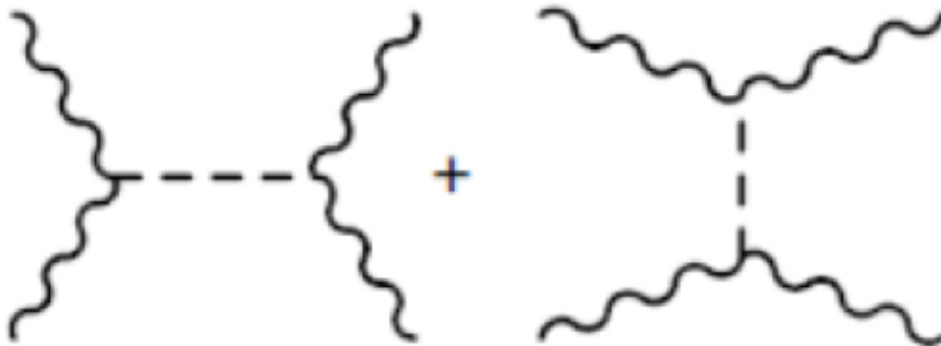
$$a = a_0 (1 + s/\Lambda^2)^{-n}$$

- **K-matrix**



But Higgs was found. Problem solved?

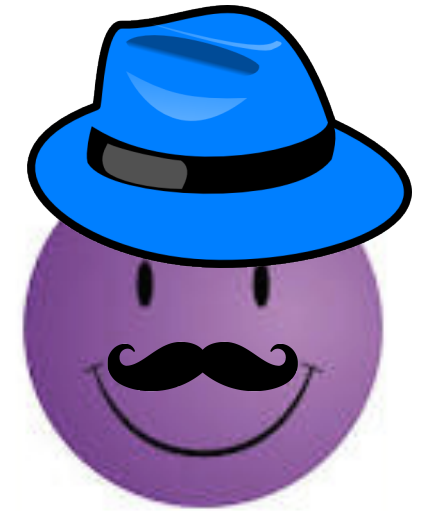
- Higgs diagrams in VBS cancel term that grows with E_{CM}



SM Higgs

LHC Higgs?

- Higgs couplings not yet precisely measured



- **Any difference in EW couplings requires new physics to avoid unitarity violation in VBS**

Agenda

- **Measurements sensitive to aTGCs**
 - EW Zjj^* ATLAS/CMS, 8 TeV
 - $WW^*/WZ^\dagger/ZZ^{*\dagger}$ ATLAS/CMS, 8 TeV
 - $W\gamma^\dagger/Z\gamma^{*\dagger}$ ATLAS/CMS, 7 TeV
- **Measurements sensitive to aQGCs**
 - $\gamma\gamma \rightarrow WW$ CMS, 7 TeV
 - $WW\gamma/WZ\gamma$ CMS, 8 TeV
 - Same-sign $WW^{*\dagger}$ ATLAS/CMS, 8 TeV
- References for all measurements listed in extra slides

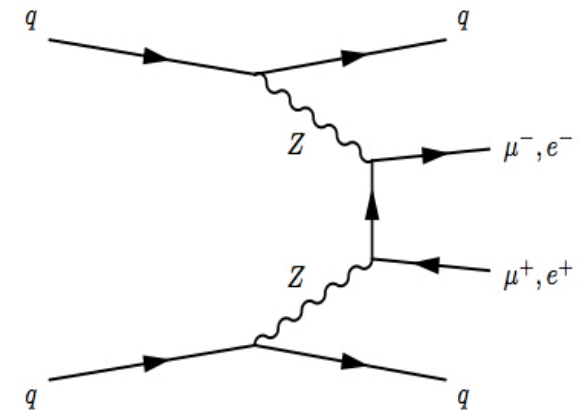
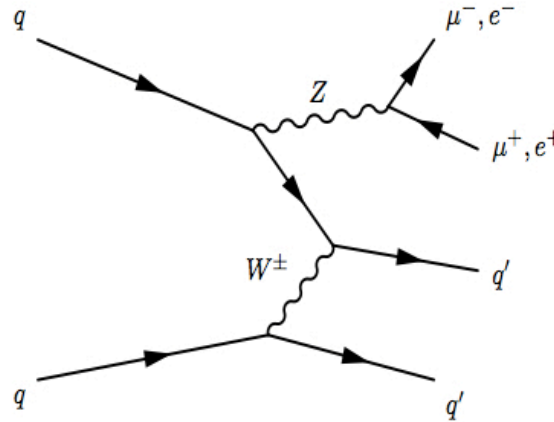
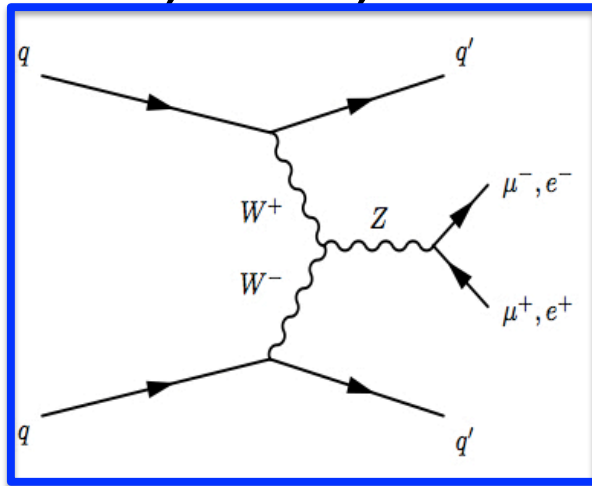
*ATLAS analysis shown

†CMS analysis shown

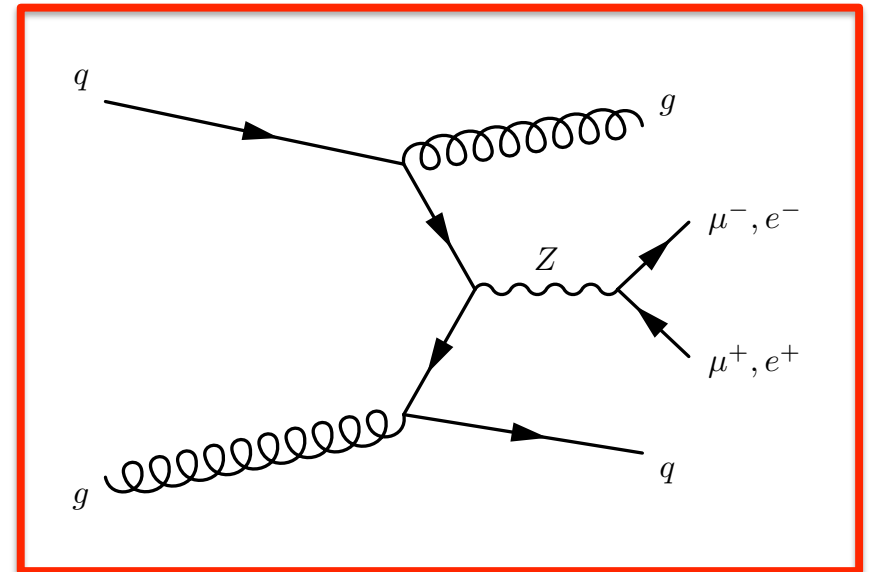
ATLAS, 8 TeV, 20.3 fb⁻¹

EW Z(-->ll)jj

arXiv:1401.7610



- Sensitivity to WWZ coupling from VBF process
- Not the dominant production mechanism
 - Rate to get two jets from QCD interactions much higher



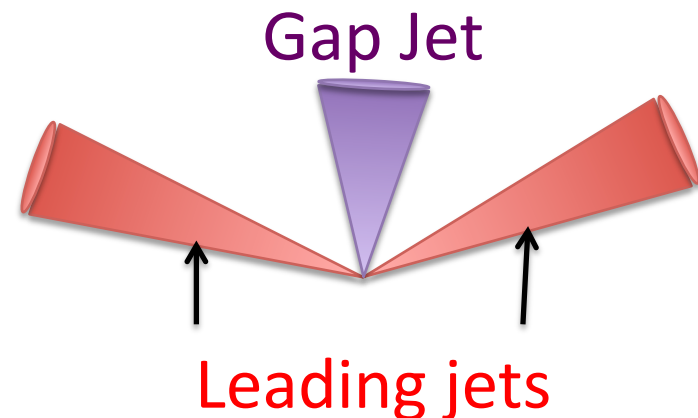
- Select events with kinematics characteristic of VBF
 - 2 high-momentum jets w/ large rapidity gap
- Five regions defined to measure total/EW cross section

Event Selection

Zjj production accounts for 96-99% of events in analysis regions

| Region | Cuts | Measurement | % EW Zjj |
|------------|---|--|----------|
| Baseline | 2 leptons + 2 jets | Incl. xsec | 1.1 |
| High p_T | $p_T^{j1} > 85 \text{ GeV}$, $p_T^{j2} > 75 \text{ GeV}$ | Incl. xsec | 2.1 |
| High mass | $m_{jj} > 1 \text{ TeV}$ | Incl. xsec | 12 |
| Search | $p_T^{\ell} > 20 \text{ GeV}$, $m_{jj} > 250 \text{ GeV}$, $N_{\text{jet}}^{\text{gap}} = 0$, $p_T^{\text{balance}} < 0.15$ | EW xsec | 4.0 |
| Control | Same as search except $N_{\text{jet}}^{\text{gap}} \geq 1$ and 3 rd jet included in p_T^{balance} | Incl. xsec, constrain bkg shape in search region | 1.4 |

$$p_T^{\text{balance}} = \left| \sum_{\ell, j} \vec{p}_T \right| / \sum_{\ell, j} |\vec{p}_T|$$

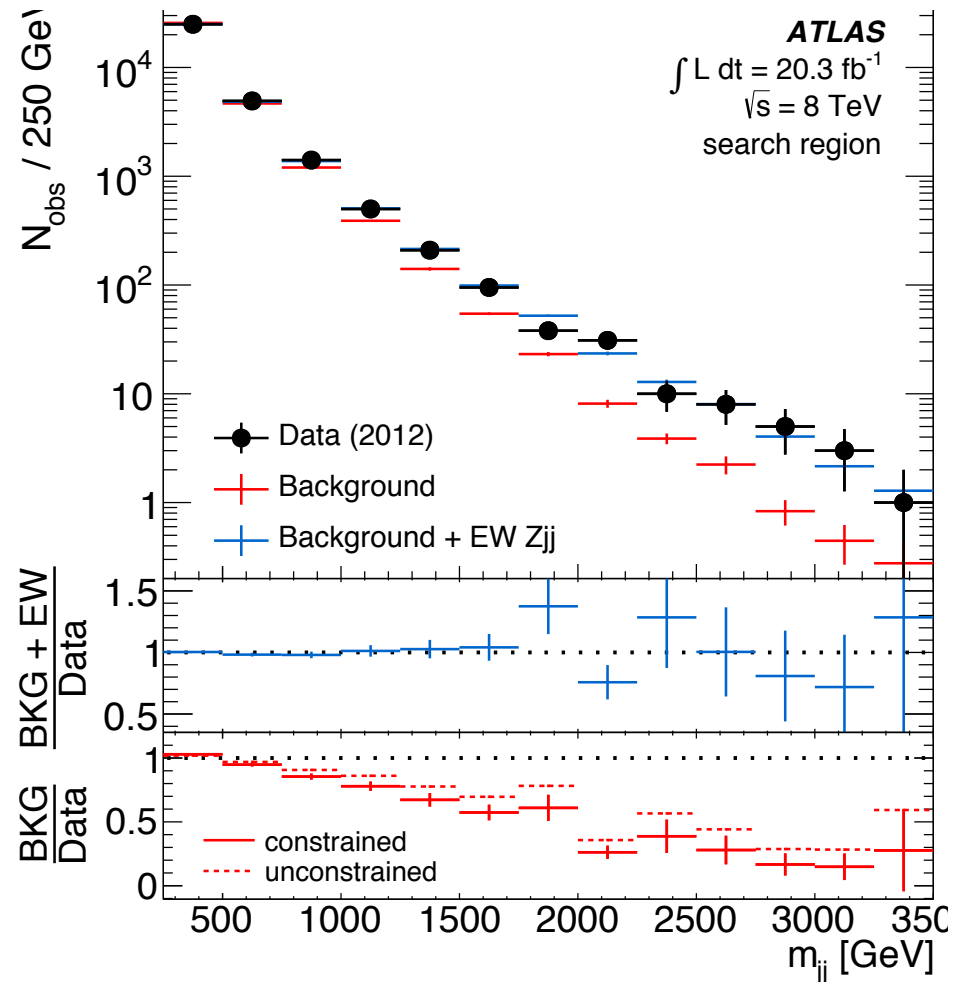
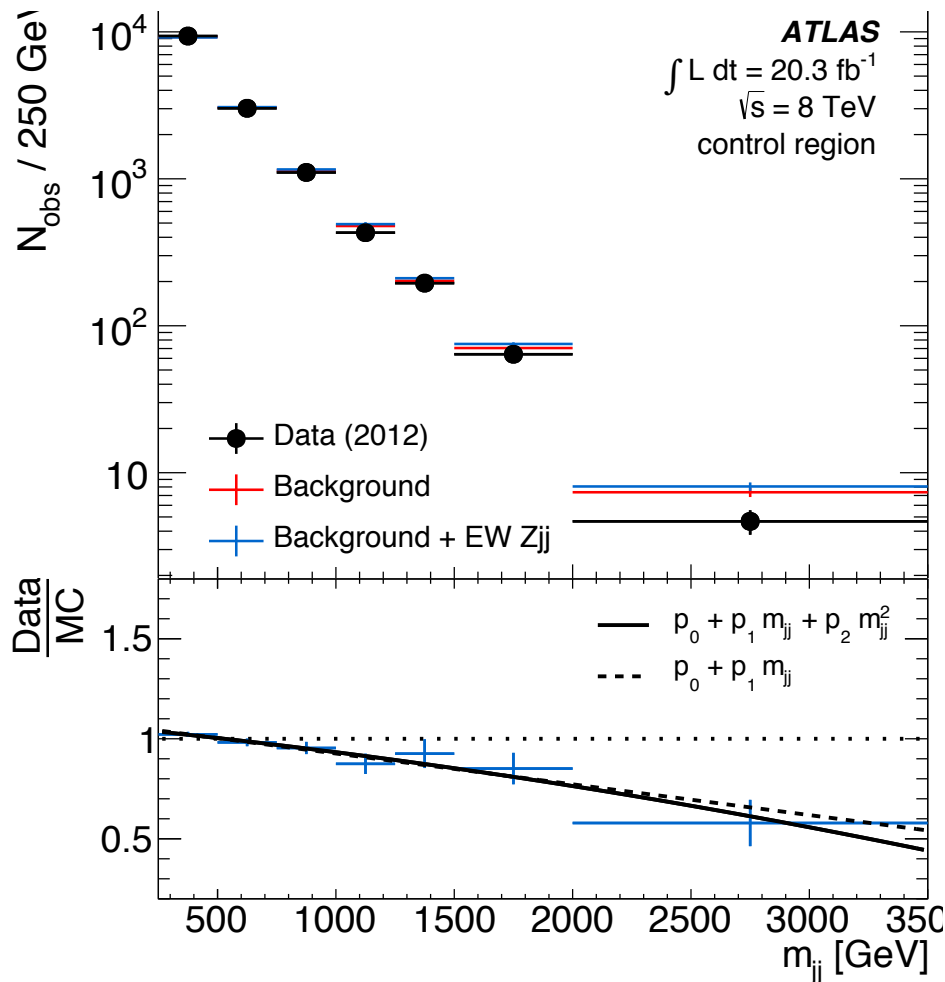


EW Cross Section Measurement

Fit for number of EW events using MC templates for signal and background

$$\sigma_{EW}^{fid} = \frac{N_{EW}}{L \times \epsilon}$$

Background template shape constrained using control region



Results

- **Observed EW Zjj production with significance $> 5\sigma$**

$$\sigma_{EW}^{m_{jj} > 250 \text{ GeV}} = 54.7 \pm 4.6 \text{ (stat)} \begin{matrix} +9.8 \\ -10.4 \end{matrix} \text{ (syst)} \pm 1.5 \text{ (lumi)} \text{ fb}$$

$$\sigma_{EW}^{m_{jj} > 1 \text{ TeV}} = 10.7 \pm 0.9 \text{ (stat)} \pm 1.9 \text{ (syst)} \pm 0.3 \text{ (lumi)} \text{ fb}$$

- **Measured fiducial cross sections agree with SM predictions of $46 \text{ fb} \pm 1$ and $9.4 +0.3/-0.4 \text{ fb}$**
- Fitted number of EW events in $m_{jj} > 1 \text{ TeV}$ region used to set limits on aTGCs
 - aTGC parameters varied with and without form factor
 - Limits determined by profile likelihood test

| aTGC | $\Lambda = 6 \text{ TeV}$ (obs) | $\Lambda = 6 \text{ TeV}$ (exp) | $\Lambda = \infty$ (obs) | $\Lambda = \infty$ (exp) |
|------------------|---------------------------------|---------------------------------|--------------------------|--------------------------|
| $\Delta g_{1,Z}$ | $[-0.65, 0.33]$ | $[-0.58, 0.27]$ | $[-0.50, 0.26]$ | $[-0.45, 0.22]$ |
| λ_Z | $[-0.22, 0.19]$ | $[-0.19, 0.16]$ | $[-0.15, 0.13]$ | $[-0.14, 0.11]$ |

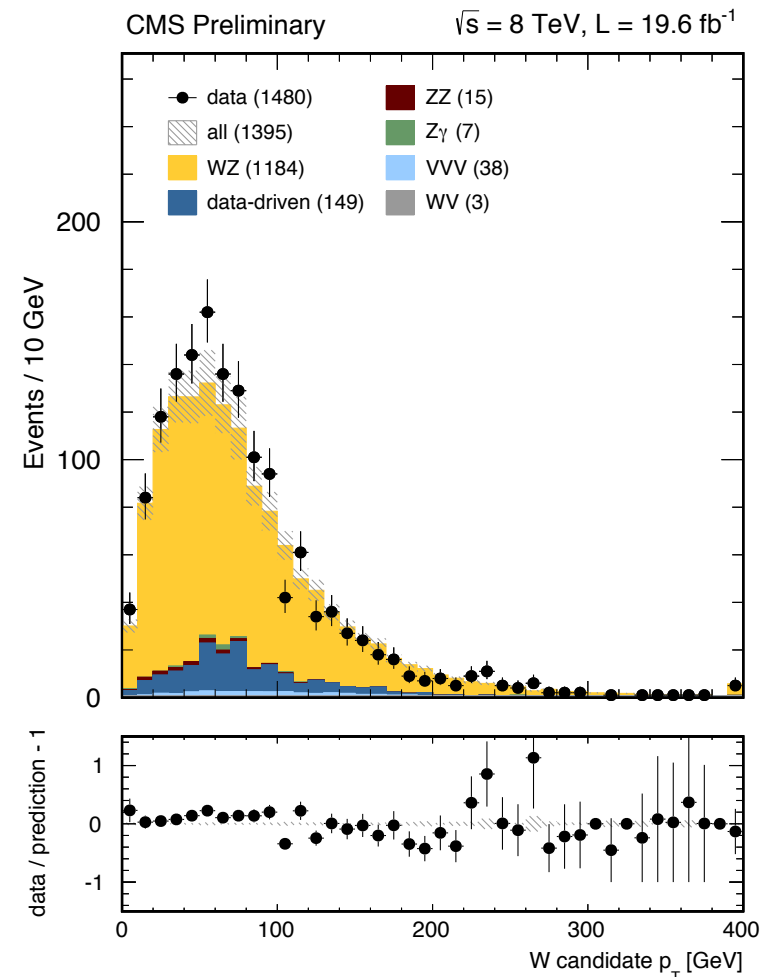
CMS, 8 TeV, 19.6 fb⁻¹

$WZ \rightarrow 3\ell$

CMS-PAS-SMP-12-006

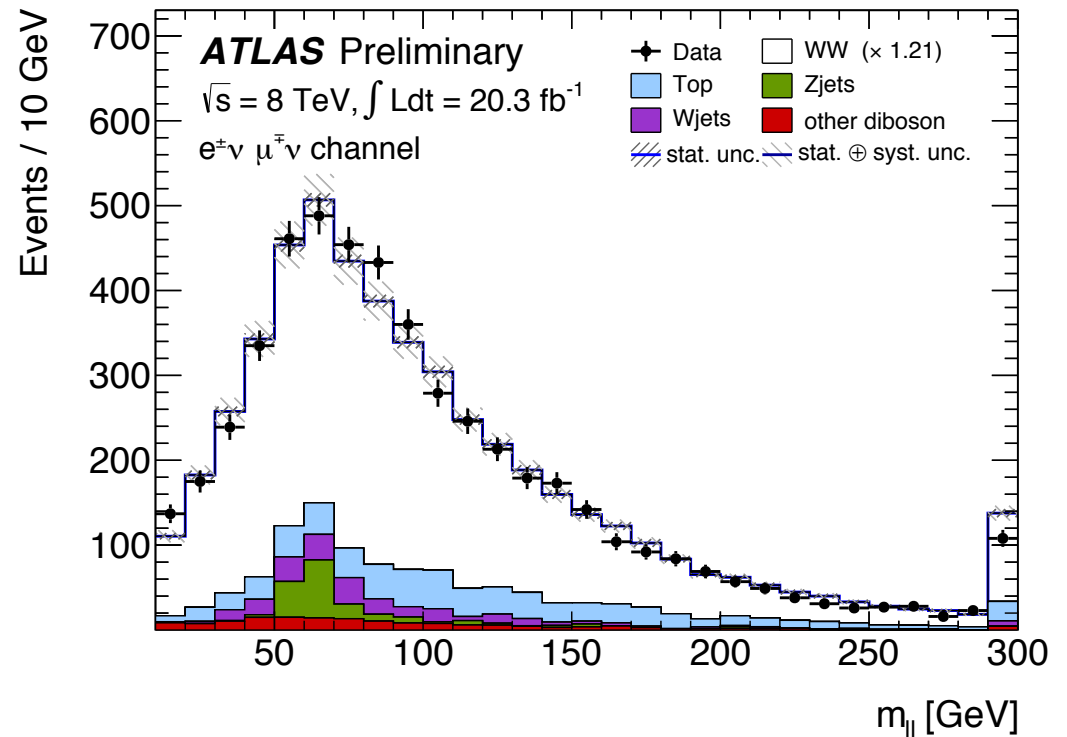
- Sensitive to WWZ coupling
- **Select events with 3 isolated leptons, Z candidate**
 - **clean signal, low background**
- **Main background from non-prompt leptons**
 - **Estimate from data events with non-isolated leptons**
- Cross section from event yield in signal region
- +/- ratio also measured

| | |
|---------------------------------------|---|
| $\sigma(W+Z)/\sigma(W-Z)$ observed | 1.81 ± 0.12 (stat) ± 0.03 (syst) |
| SM $\sigma(W+Z)/\sigma(W-Z)$ | 1.724 ± 0.003 |



ATLAS, 8 TeV, 20.3 fb⁻¹ $WW \rightarrow 2\ell 2\nu$ ATLAS-CONF-2014-033

- Sensitive to WWZ and WW γ couplings
- **Higher rate than WZ, but also higher backgrounds**
 - Select events with 2 leptons and large E_T^{miss}
 - Suppress backgrounds with jet veto, Z veto
- **Main background from top**
 - Estimated from CR w/o jet veto and large $\Sigma |\mathbf{p}_T|$ of leptons and jets
- Likelihood fit to event counts in signal region

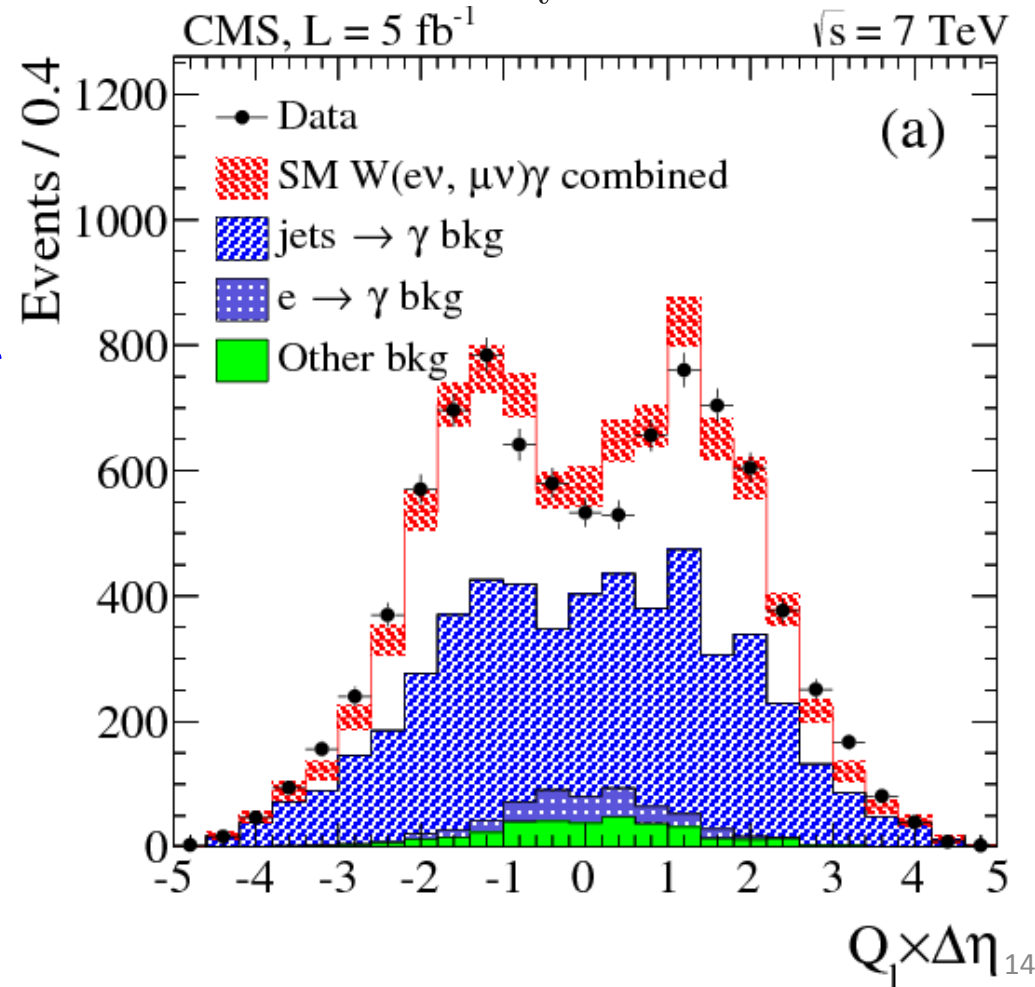
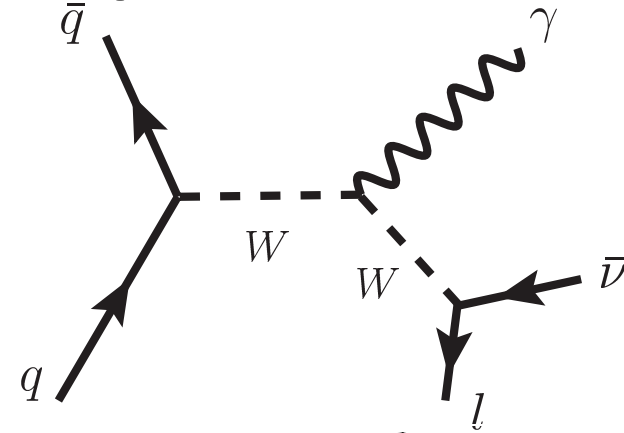


CMS, 7 TeV, 5.0 fb⁻¹

$$W(\rightarrow e\nu)\gamma$$

arXiv:1308.6832

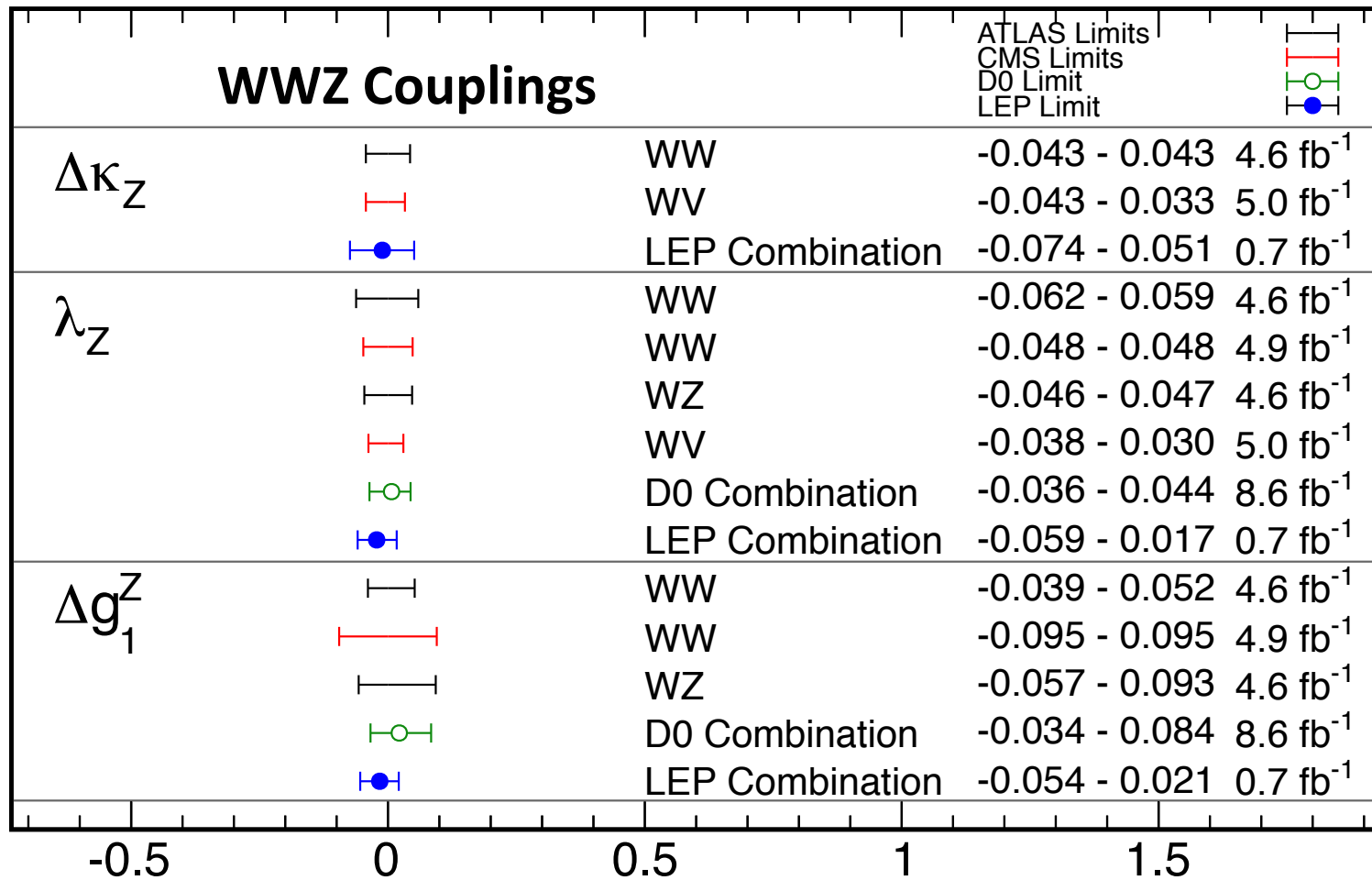
- Sensitive to $WW\gamma$ coupling
- Direct access to one of the bosons from TGV
- **Backgrounds**
 - **Jet \rightarrow photon, template fit to shower width**
 - **Electron \rightarrow photon, estimated from pixel hit CR**
- Cross section calculated from observed event yield
- aTGC limits from E_T^γ distribution



aTGC Limits I

Limits from LHC beginning to improve on previous limits from Tevatron, LEP.

Feb 2013



WW γ limits in extra slides.

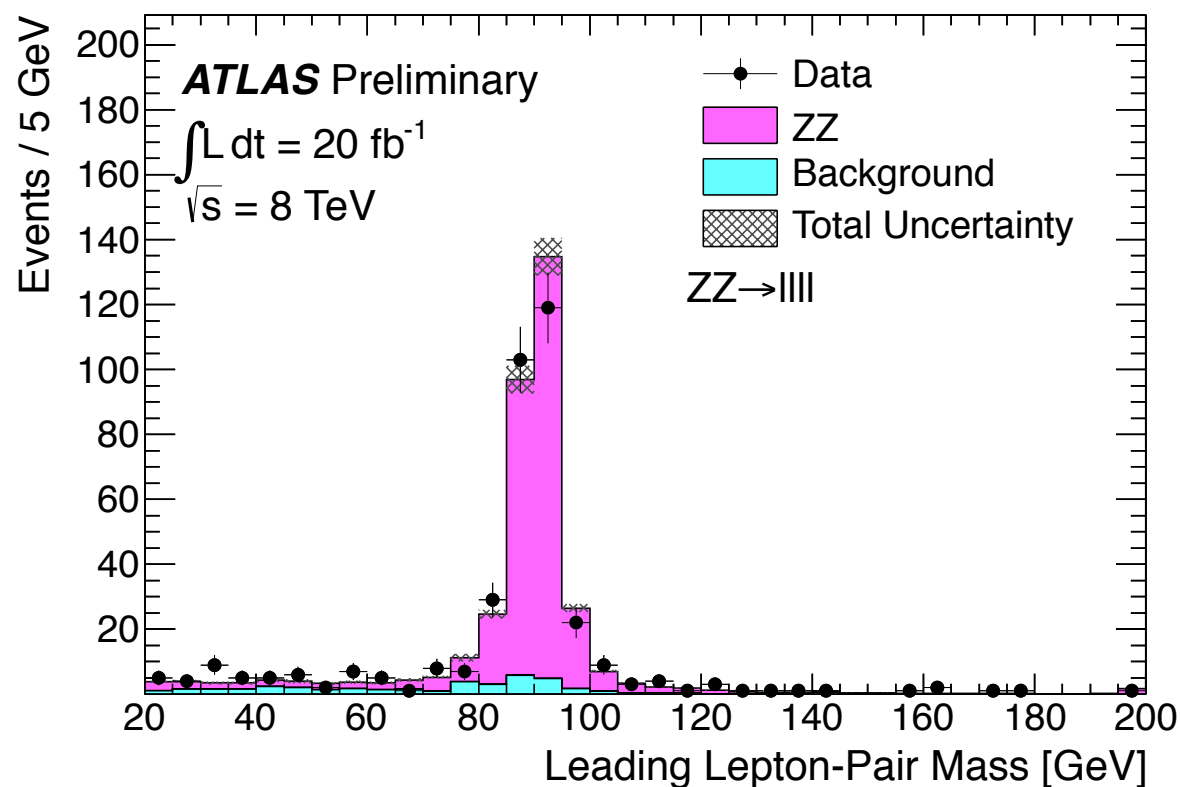
aTGC Limits @95% C.L.

ATLAS, 8 TeV, 20.3 fb⁻¹

$ZZ \rightarrow 4\ell$

ATLAS-CONF-2013-020

- Sensitive to ZZZ and $ZZ\gamma$ couplings
- **Select 4 leptons, with 2 SF OS pairs near Z mass**
 - **Very low background, can completely reconstruct diboson system**
- Small background from non-prompt leptons
 - Estimated from data



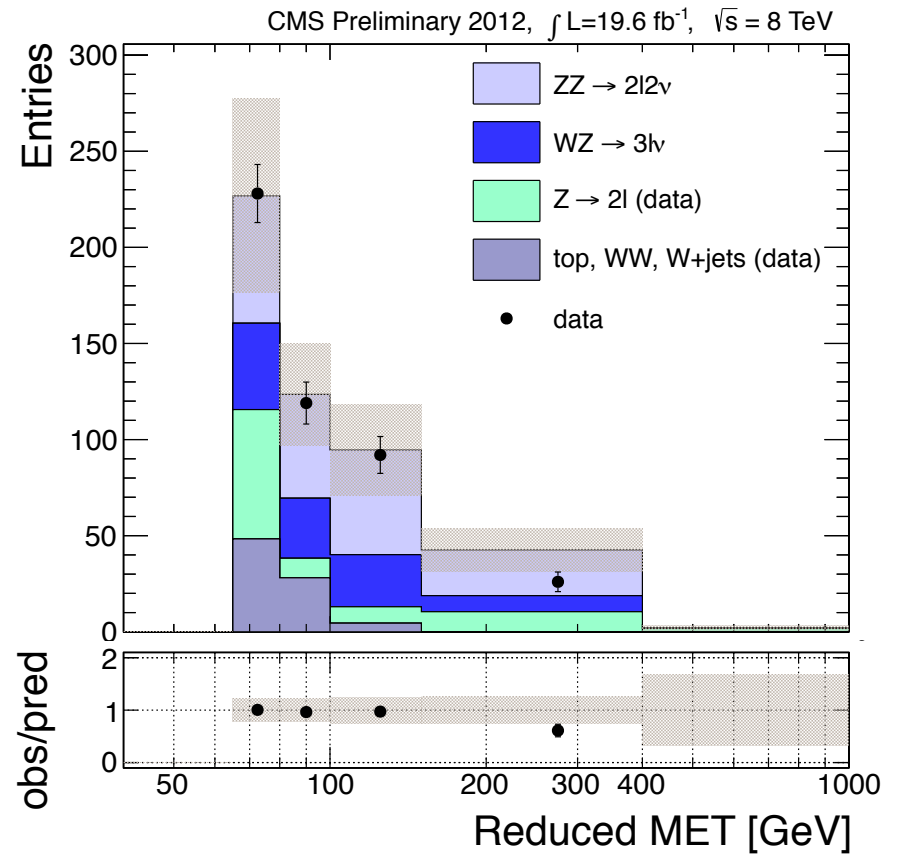
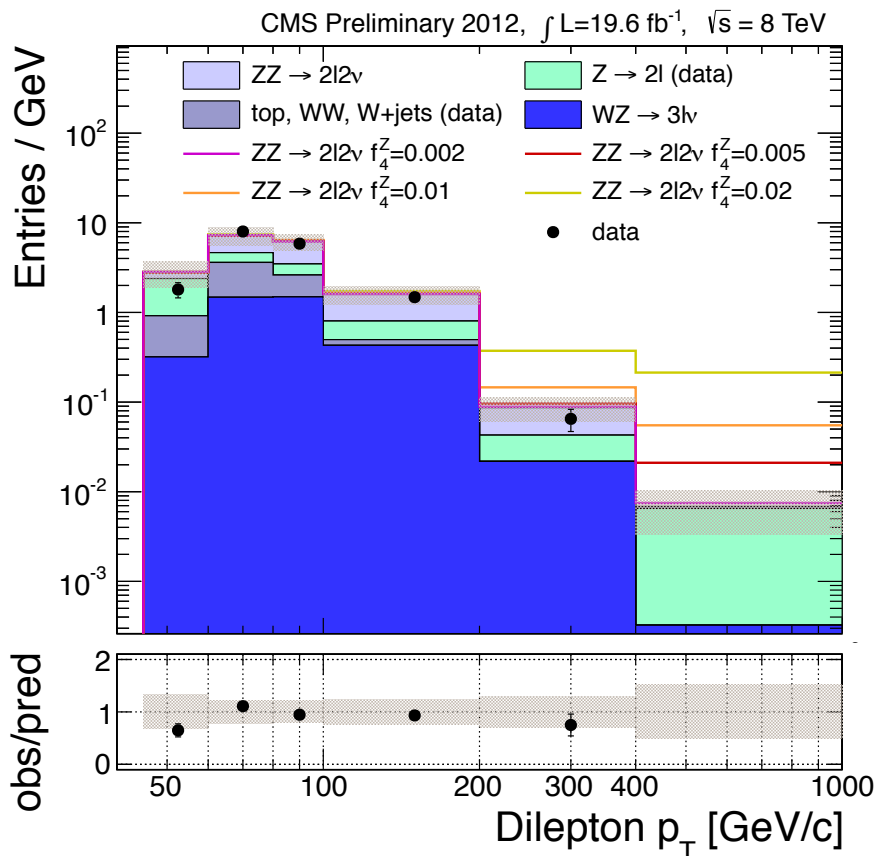
CMS, 8 TeV, 19.6 fb⁻¹

$ZZ \rightarrow 2\ell 2\nu$

CMS-PAS-SMP-12-016

Much higher branching fraction,
but also higher backgrounds

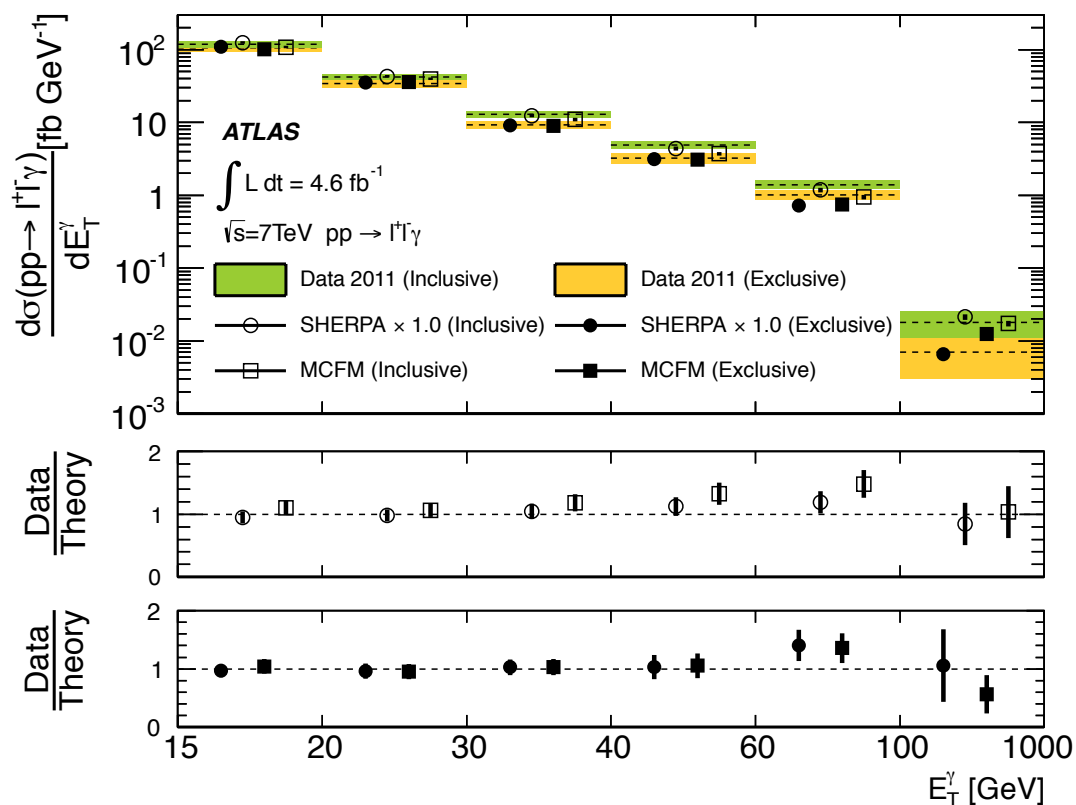
Fit to reduced E_T^{miss} distribution
for cross section



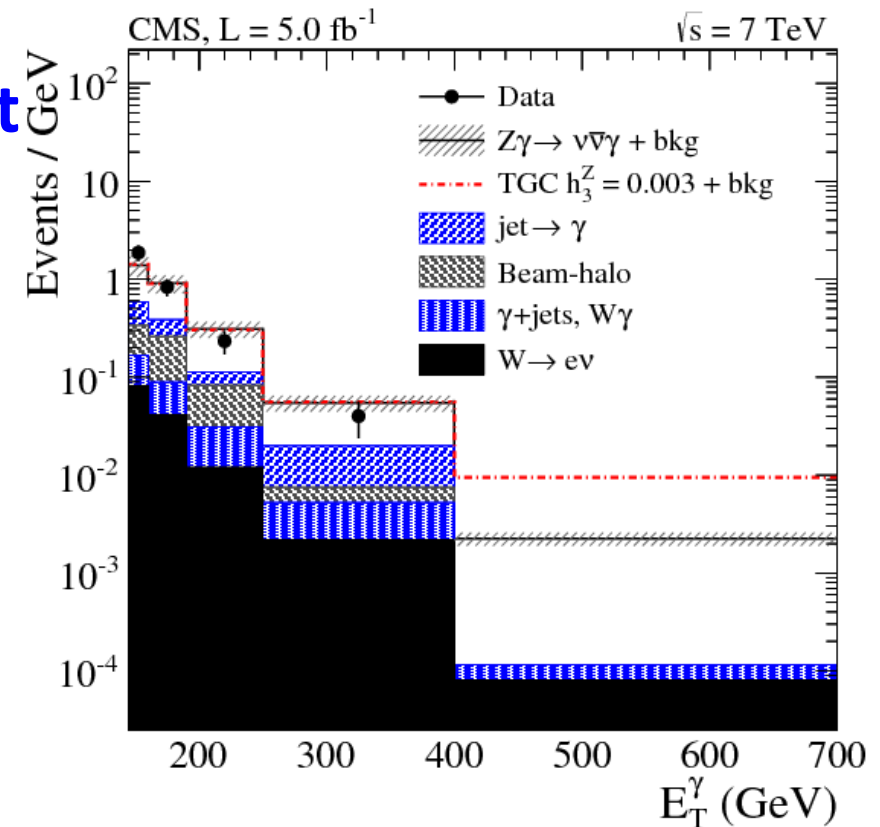
Z+jets estimated from γ +jets, top/
WW from $e\mu$ events, and WZ from
MC

Profile likelihood test using dilepton
 p_T distribution for aTGC limits

- Sensitive to ZZ γ and Z $\gamma\gamma$ couplings
- **Main background from non-prompt photons, estimated using non-isolated photons**
- Likelihood fit to event yield
 - $E_T^\gamma > 15$ GeV for xsec
 - $E_T^\gamma > 100$ GeV for aTGC lim.
- Differential cross sections also measured



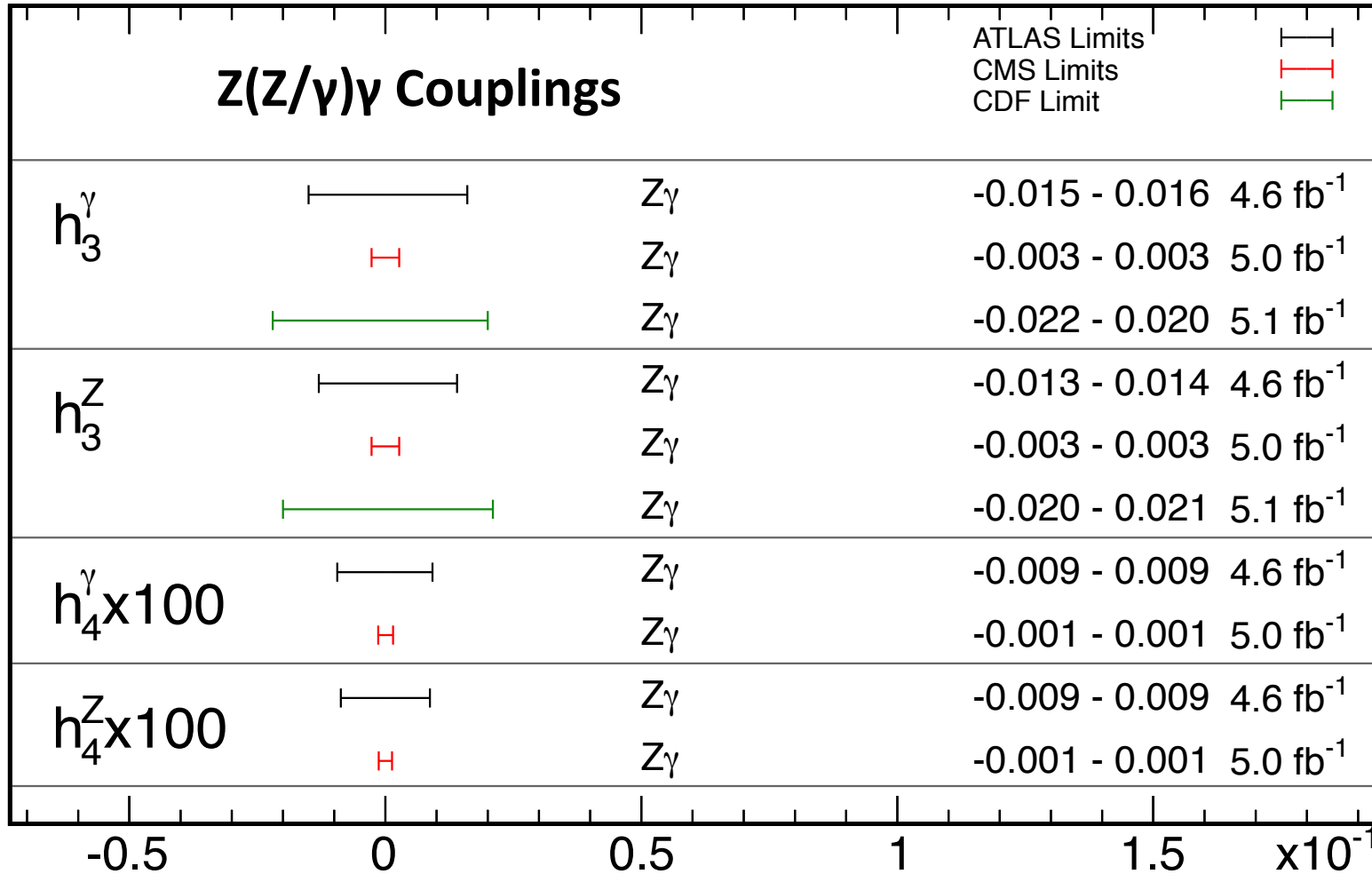
- Higher rate, lots of instrumental background
- **Veto events w/ high-p_T track (20 GeV) or jet (40 GeV)**
- **Backgrounds**
 - Misidentified jets, fake factor estimate
 - Beam halo, estimated from sample w/o timing requirement
 - Misidentified electron, estimated from pixel hit CR
- Likelihood test using E_T^γ distribution for aTGC limits



aTGC Limits II

Improvement on previous limits on neutral couplings from Tevatron

Feb 2013



ZZ(Z/γ) limits in extra slides.

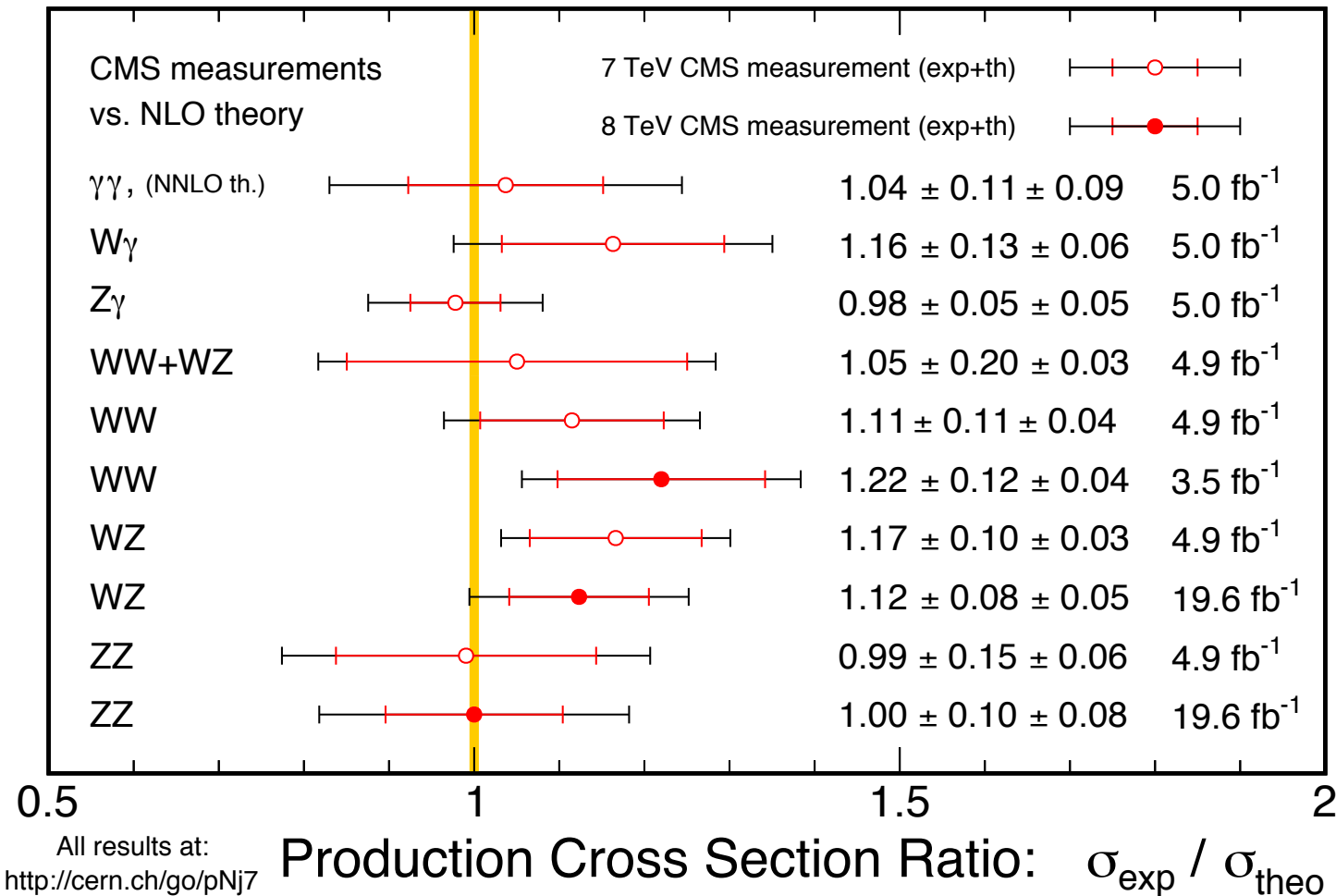
aTGC Limits @95% C.L.

Measured Cross Sections

Good overall agreement with SM

Apr 2014

CMS Preliminary



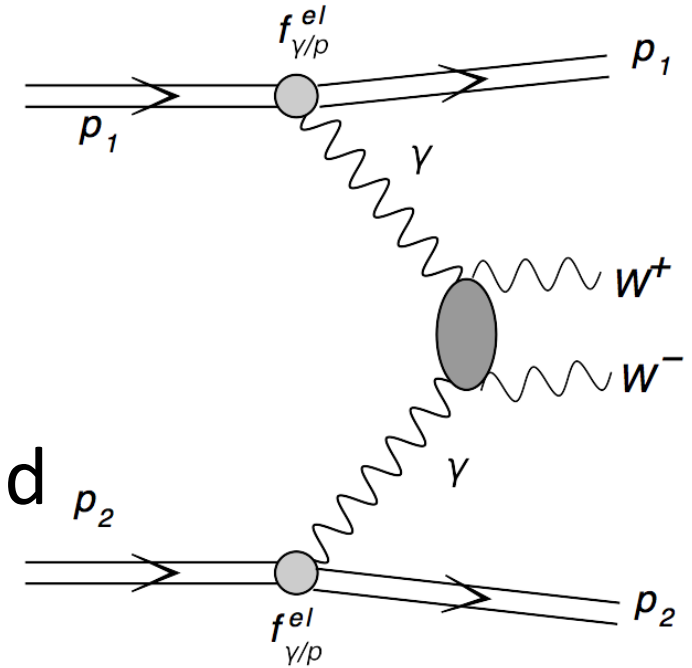
Similar results seen by ATLAS (summary plot in extra slides).

CMS, 7 TeV, 5.1 fb⁻¹

$\gamma\gamma \rightarrow WW$

arXiv:1305.5596

- Protons scatter at small angle and escape undetected
 - Leads to sparse event with only W decay products
- ee/ $\mu\mu$ events have large background from $\gamma\gamma \rightarrow \ell\ell$ and Drell-Yan
- Event Selection
 - 1 electron and 1 muon of opposite charge with $p_T > 20$ GeV
 - $m_{\ell\ell} > 20$ GeV and dilepton $p_T > 30$ GeV
 - No other tracks matched to primary vertex



Background Estimation

- Background from inclusive WW production, W +jets $\gamma\gamma \rightarrow \tau\tau$, and Drell-Yan $\tau\tau$ production
 - W +jets estimated from data sample with one lepton failing ID criteria
 - Others estimated from MC

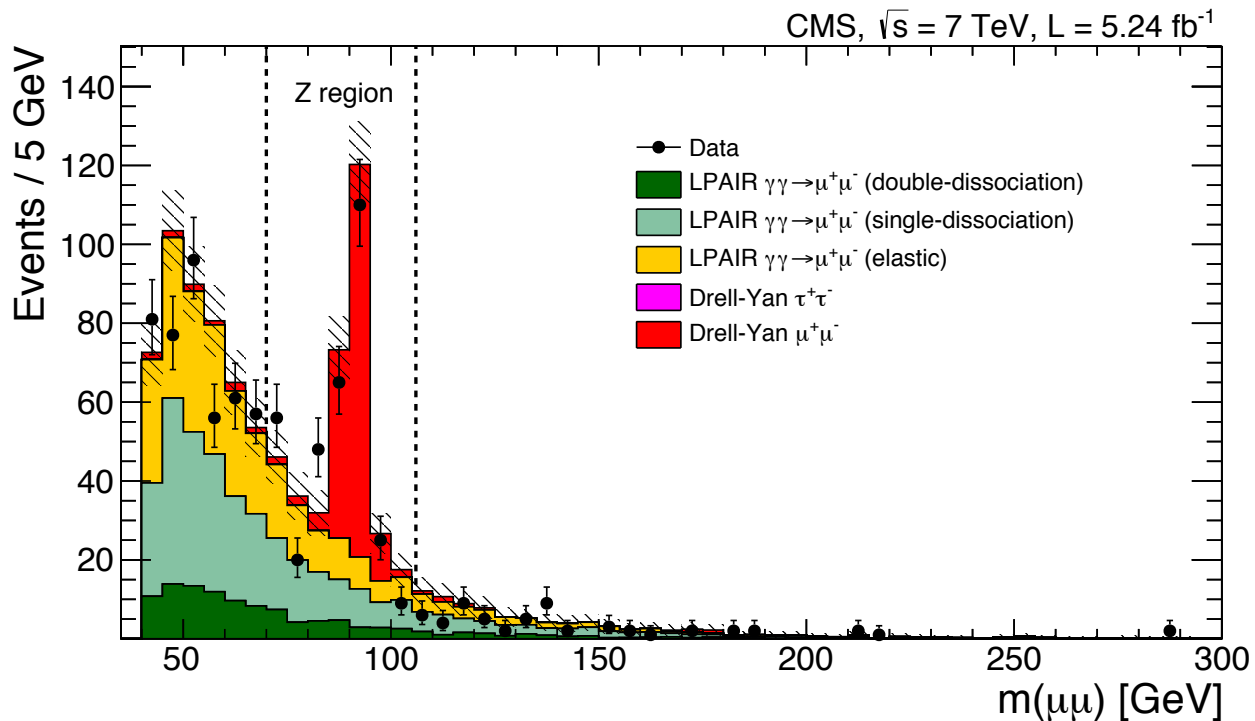
| Region | Background process | $N_{\text{extra tracks}}$ | $p_T(\mu^\pm e^\mp)$ |
|--------|---|---|----------------------|
| 1 | Inclusive W^+W^- | $1 \leq N_{\text{extra tracks}} \leq 6$ | $>30 \text{ GeV}$ |
| 2 | Inclusive Drell-Yan $\tau^+\tau^-$ | $1 \leq N_{\text{extra tracks}} \leq 6$ | $<30 \text{ GeV}$ |
| 3 | $\gamma\gamma \rightarrow \tau^+\tau^-$ | $N_{\text{extra tracks}} = 0$ | $<30 \text{ GeV}$ |

- **Checked in control regions defined by inverting track multiplicity and dilepton p_T cuts**

| Region | Background process | Data | Sum of backgrounds | $\gamma\gamma \rightarrow W^+W^-$ signal |
|--------|---|------|--------------------|--|
| 1 | Inclusive W^+W^- | 43 | 46.2 ± 1.7 | 1.0 |
| 2 | Inclusive Drell-Yan $\tau^+\tau^-$ | 182 | 256.7 ± 10.1 | 0.3 |
| 3 | $\gamma\gamma \rightarrow \tau^+\tau^-$ | 4 | 2.6 ± 0.8 | 0.7 |

$\gamma\gamma$ “Luminosity” Correction

- $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow \tau\tau$ predictions corrected for rate of $\gamma\gamma$ interactions in which one or both protons dissociate
- Corr. factor from $\gamma\gamma \rightarrow \mu\mu$ events with $m_{\ell\ell} > 160$ GeV

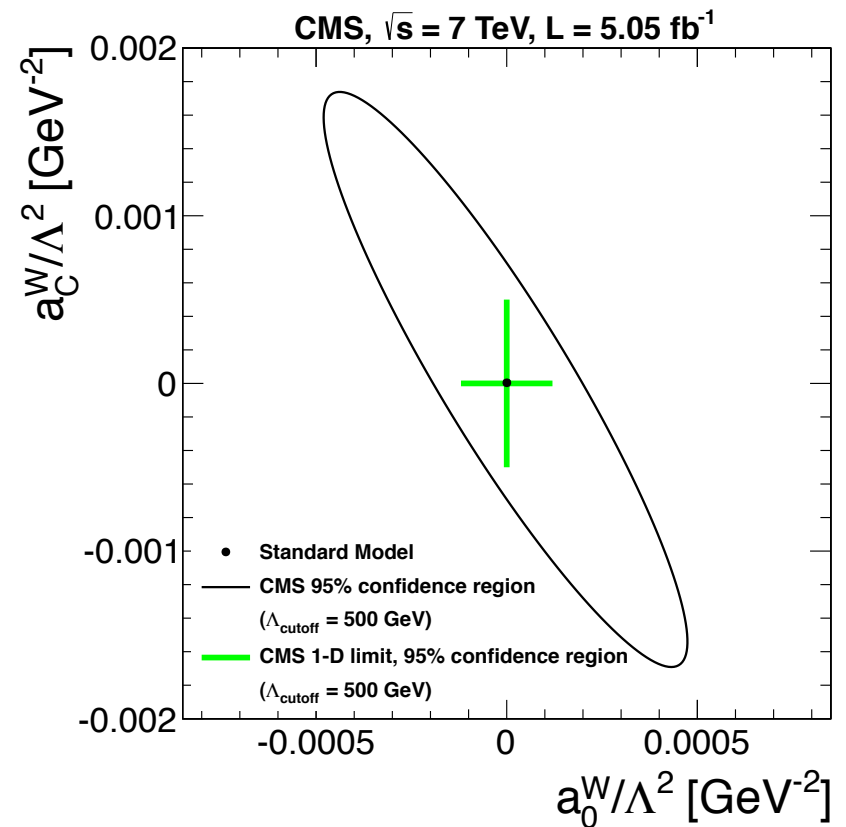
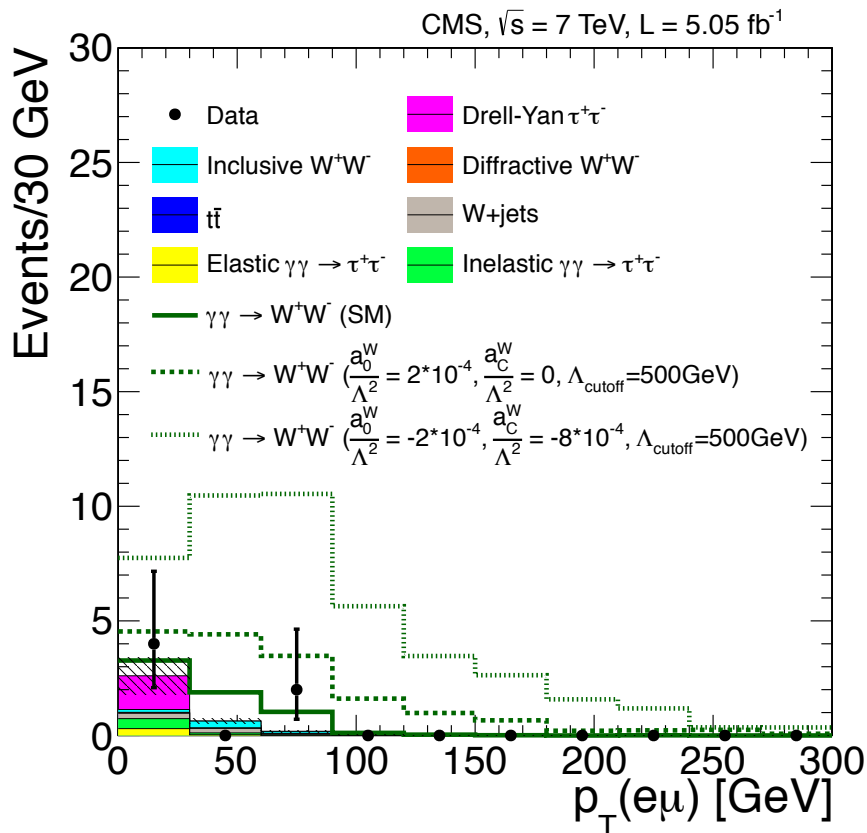


$$F = \frac{N_{data} - N_{DY}}{N_{elastic}} = 3.23 \pm 0.53$$

- **Final prediction is 2.2 ± 0.4 signal events and 0.84 ± 0.15 background events**

Results

- 2 events observed in agreement with SM prediction
- **Cross sections > 2.6 times SM prediction of 4.0 ± 0.7 fb excluded at 95% CL**
- Event yield for dilepton $p_T > 100$ GeV used to set limits set on anomalous $\gamma\gamma WW$ couplings



- Leptonically decaying W and hadronically decaying V(=W,Z) gives signature of $\ell jj\gamma + E_T^{\text{miss}}$

- W selection**

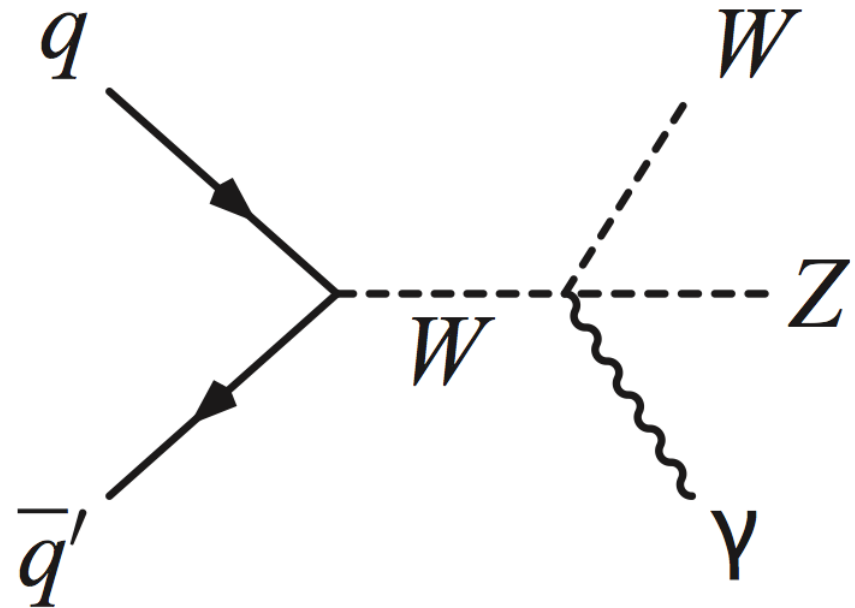
- 1 muon with $p_T > 25$ GeV or 1 electron with $p_T > 30$ GeV
- $E_T^{\text{miss}} > 35$ GeV and $m_T(\ell, E_T^{\text{miss}}) > 30$ GeV

- V selection**

- 2 jets with $p_T > 30$ GeV and failing b-jet identification
- $70 \text{ GeV} < m_{jj} < 100 \text{ GeV}$ and $|\Delta\eta_{jj}| < 1.4$

- γ selection**

- Central photon with $E_T > 30$ GeV



Backgrounds

- $W\gamma$ +jets
 - Shape from MC
 - Normalization from fit to m_{jj} sidebands
- Jets misidentified as photons
 - Estimated using non-isolated photons
- $t\bar{t}\gamma$, single top, $Z\gamma$ +jets

– MC estimate

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

- Multijet

– Fit to E_T^{miss}
distribution

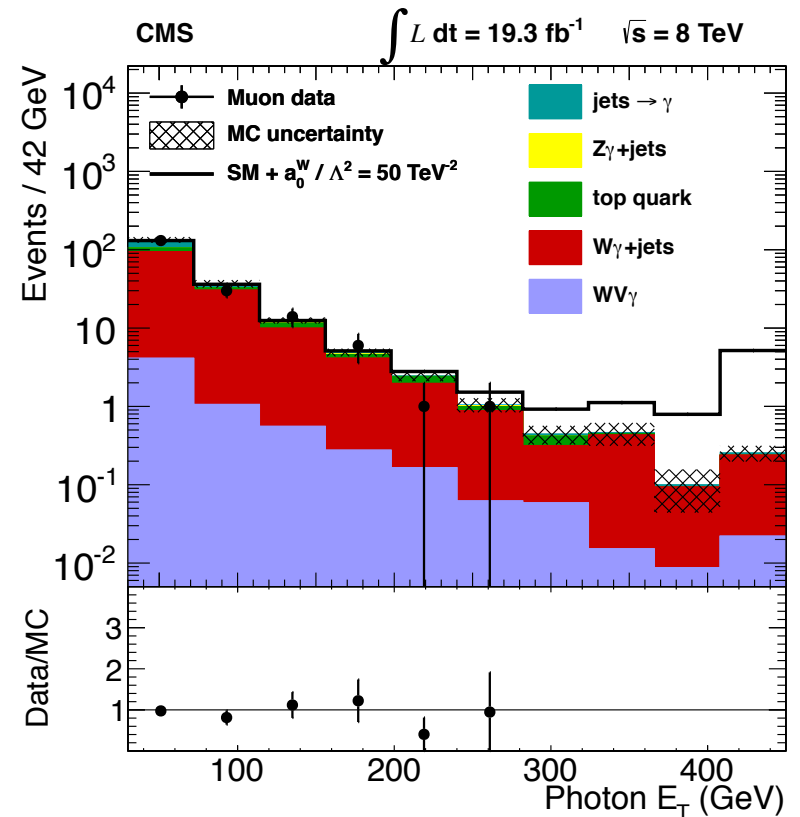
Results

- Slight deficit observed, but in agreement with SM

| | | |
|------------------|------------------|------------------|
| Total prediction | 194.2 ± 11.5 | 147.9 ± 10.7 |
| Data | 183 | 139 |

- Cross sections above 3.4 times SM value of 91.6 ± 21.7 fb excluded at 95% CL**
- Likelihood test using photon E_T distribution used for aQGC limits
- Limits set on several parameters affecting $WW\gamma\gamma$ and $WWZ\gamma$**

| Observed Limits | |
|-----------------------------|---|
| -21 (TeV^{-2}) | $< a_0^W / \Lambda^2 < 20$ (TeV^{-2}) |
| -34 (TeV^{-2}) | $< a_C^W / \Lambda^2 < 32$ (TeV^{-2}) |
| -25 (TeV^{-4}) | $< f_{T,0} / \Lambda^4 < 24$ (TeV^{-4}) |
| -12 (TeV^{-2}) | $< \kappa_0^W / \Lambda^2 < 10$ (TeV^{-2}) |
| -18 (TeV^{-2}) | $< \kappa^W / \Lambda^2 < 17$ (TeV^{-2}) |



- **WW selections**

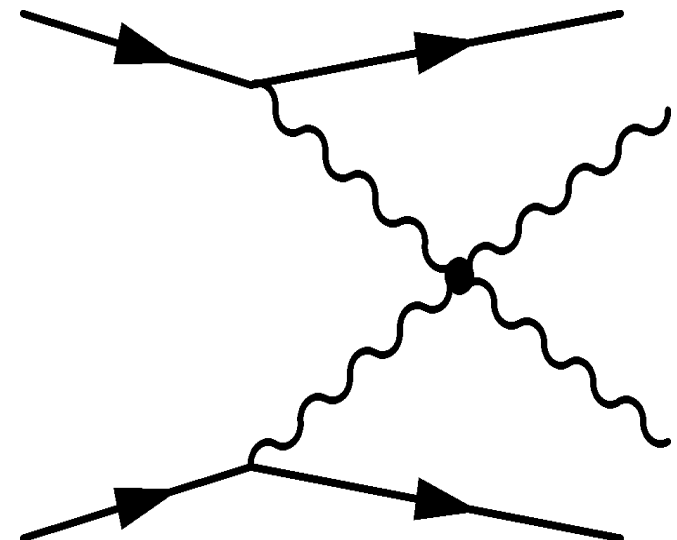
- 2 isolated same-sign leptons w/ $p_T > 25$ GeV
- $E_T^{\text{miss}} > 40$ GeV

- **Background targeted selections**

- 3rd lepton veto: WZ
- $|m_{ee} - m_Z| > 10$ GeV: charge mis-ID
- b-jet veto: non-prompt leptons

- VBS selections

- ≥ 2 jets w/ $p_T > 30$ GeV



- $m_{jj} > 500$ GeV

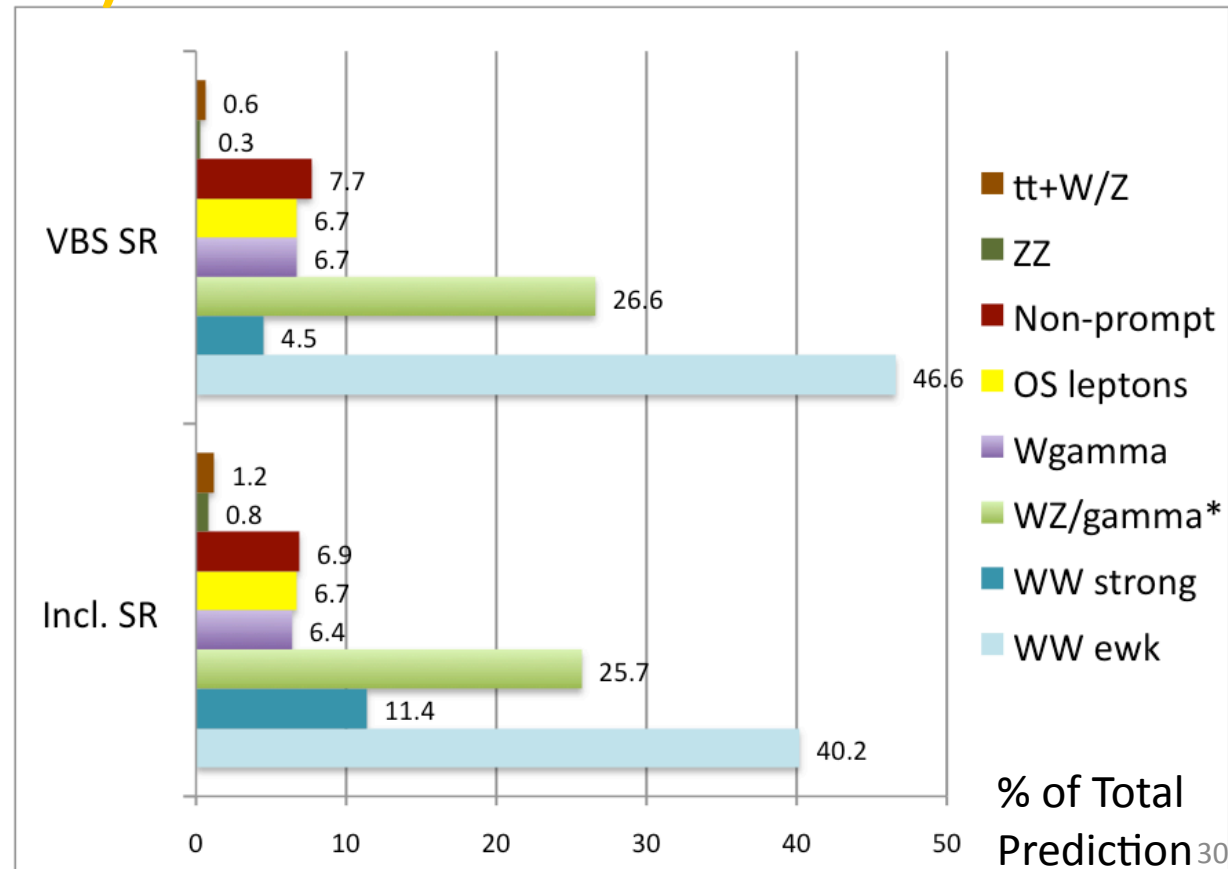
Inclusive SR – $W^\pm W^\pm jj$ ewk+strong

- $|\Delta y_{jj}| > 2.4$

VBS SR – $W^\pm W^\pm jj$ ewk only

Signal and Background Overview

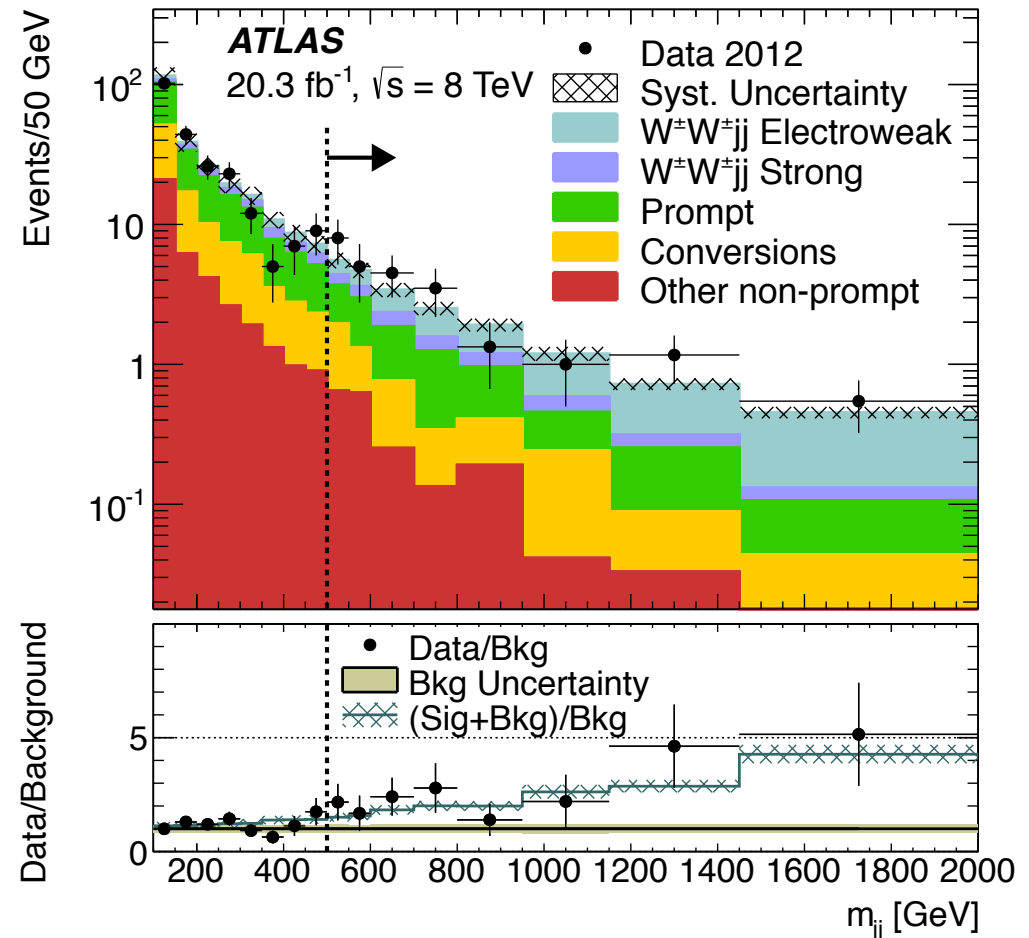
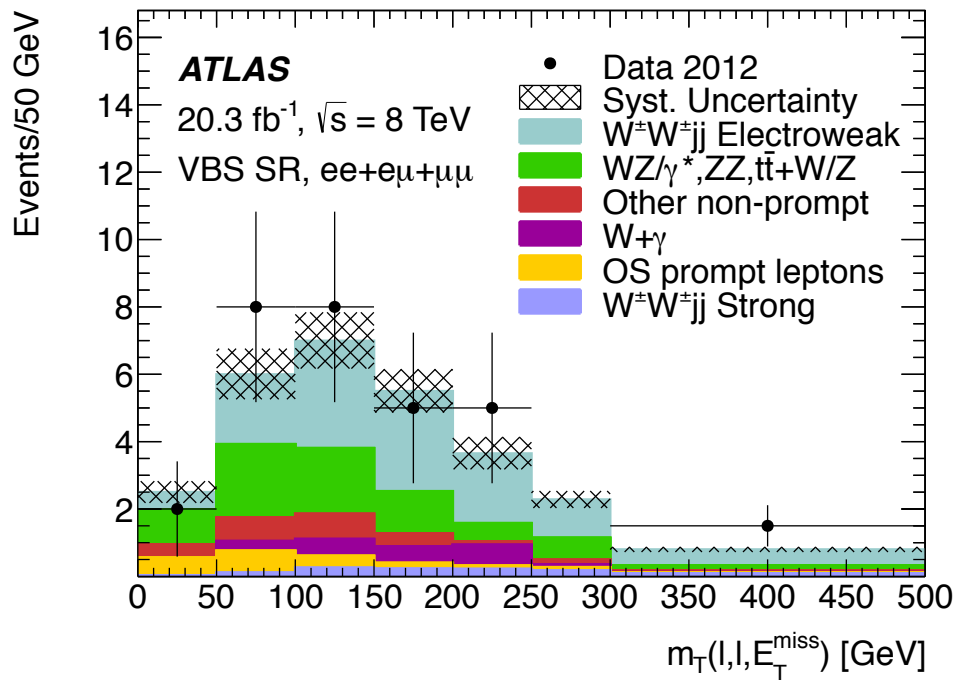
- $W^\pm W^\pm$ signal: MC estimate
- Prompt background
 - WZ/γ^* (and ZZ , $tt+W/Z$, DPI): MC estimate
- Conversions
 - OS leptons (Charge mis-ID): estimated from OS data
 - $W+\gamma$: MC estimate
- Other non-prompt
 - Leptons from hadron decays: fake factor estimate



Results

Observe excess of events consistent with $W^\pm W^\pm jj$ production

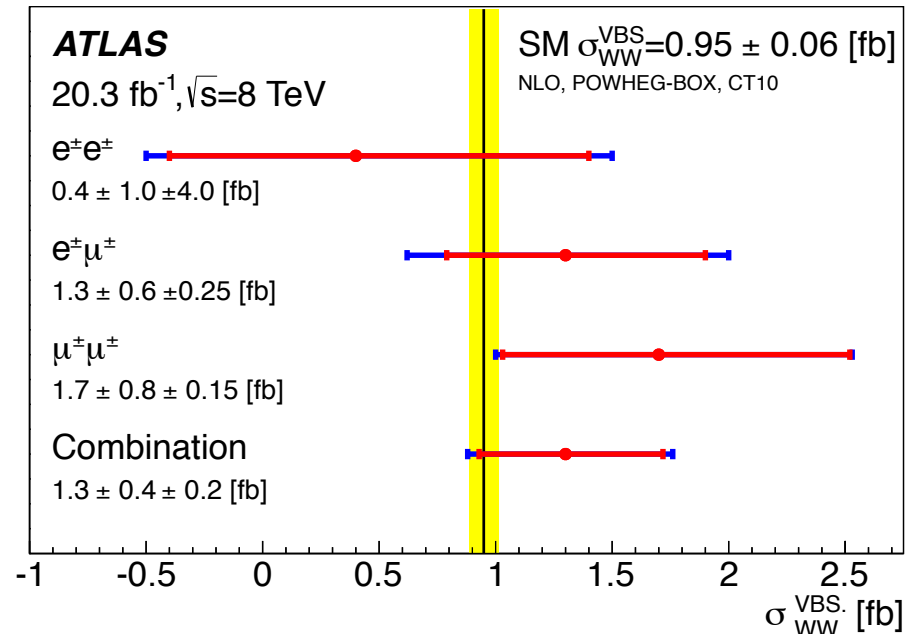
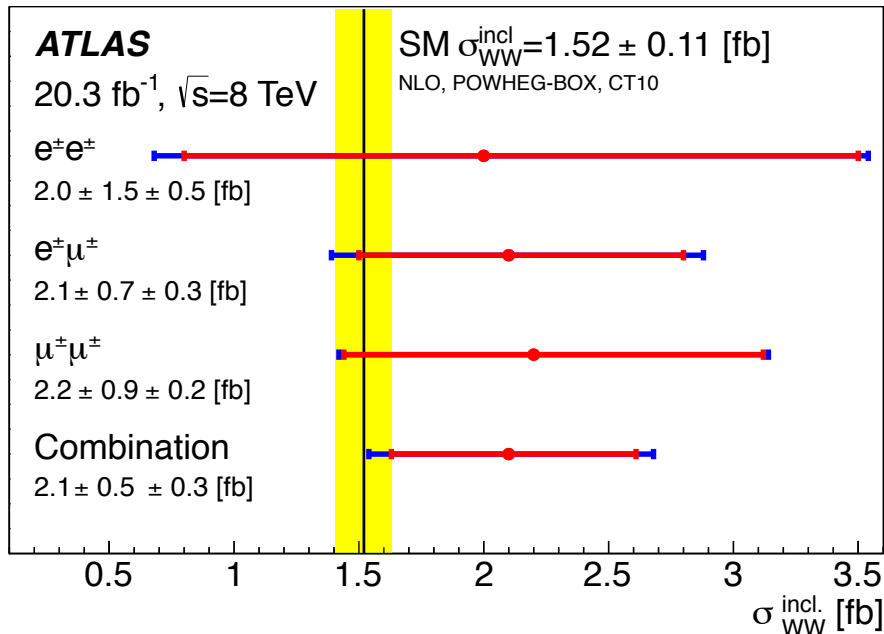
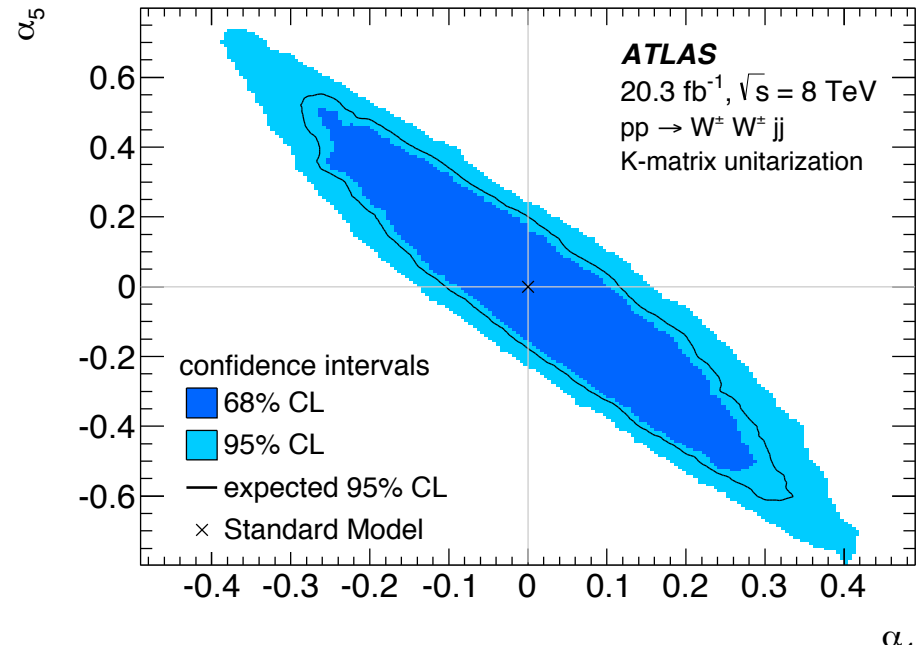
Significance of excess is 4.5σ for inclusive process and 3.6σ for EW production



Results

Profile likelihood using event yields in inclusive (VBS) region used for inclusive (EW) cross section

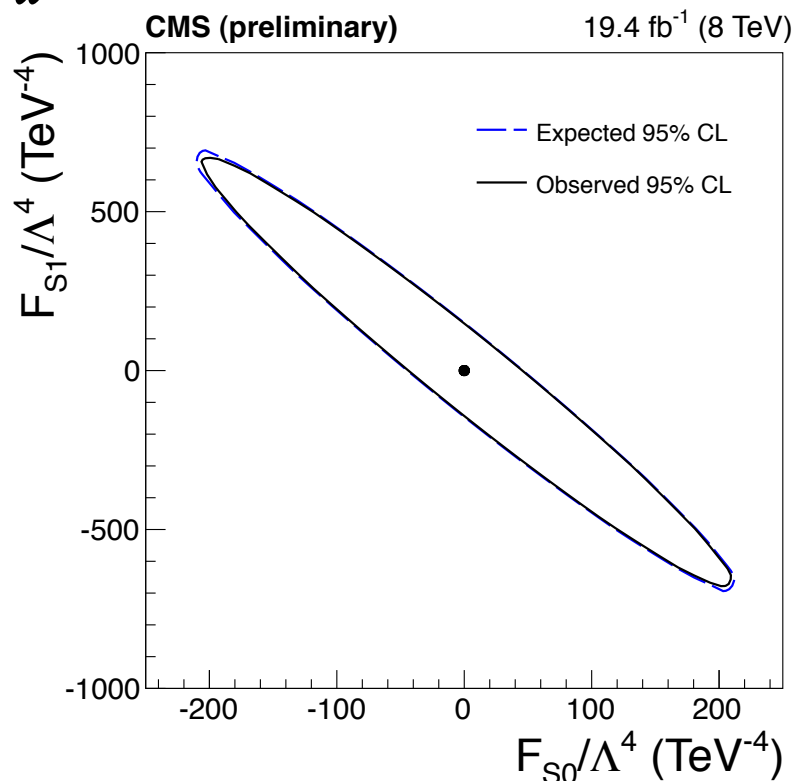
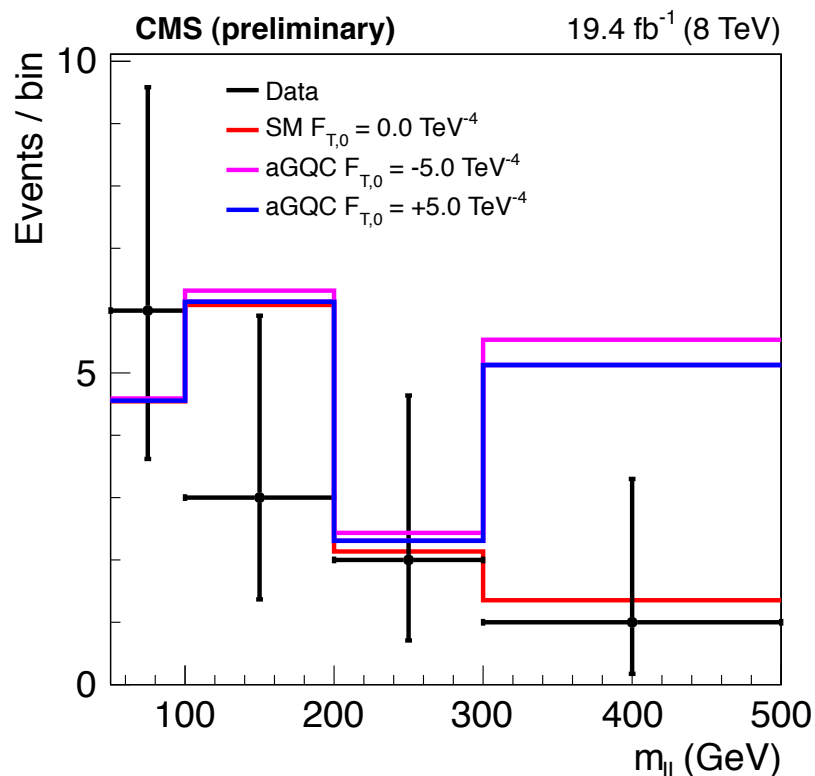
Cross sections in agreement with SM, so aQGC limits set using event yield in VBS region



| | Data | W [±] W [±] jj | Total bkg. | Non-prompt | WZ | VVV | Wrong sign | WW DPS |
|-------------------------------|------|----------------------------------|------------|------------|-----------|-----------|------------|-----------|
| W [±] W [±] | 12 | 8.8 ± 0.2 | 5.7 ± 0.8 | 4.2 ± 0.8 | 1.0 ± 0.1 | 0.3 ± 0.1 | 0.1 ± 0.08 | 0.1 ± 0.1 |
| W ⁺ W ⁺ | 10 | 7.0 ± 0.2 | 3.1 ± 0.6 | 2.1 ± 0.6 | 0.6 ± 0.1 | 0.2 ± 0.1 | 0.1 ± 0.08 | 0.1 ± 0.1 |
| W ⁻ W ⁻ | 2 | 1.8 ± 0.1 | 2.6 ± 0.6 | 2.1 ± 0.5 | 0.4 ± 0.1 | 0.1 ± 0.1 | — | — |

Excess with significance of 2σ for inclusive production and 1.9σ for EW production

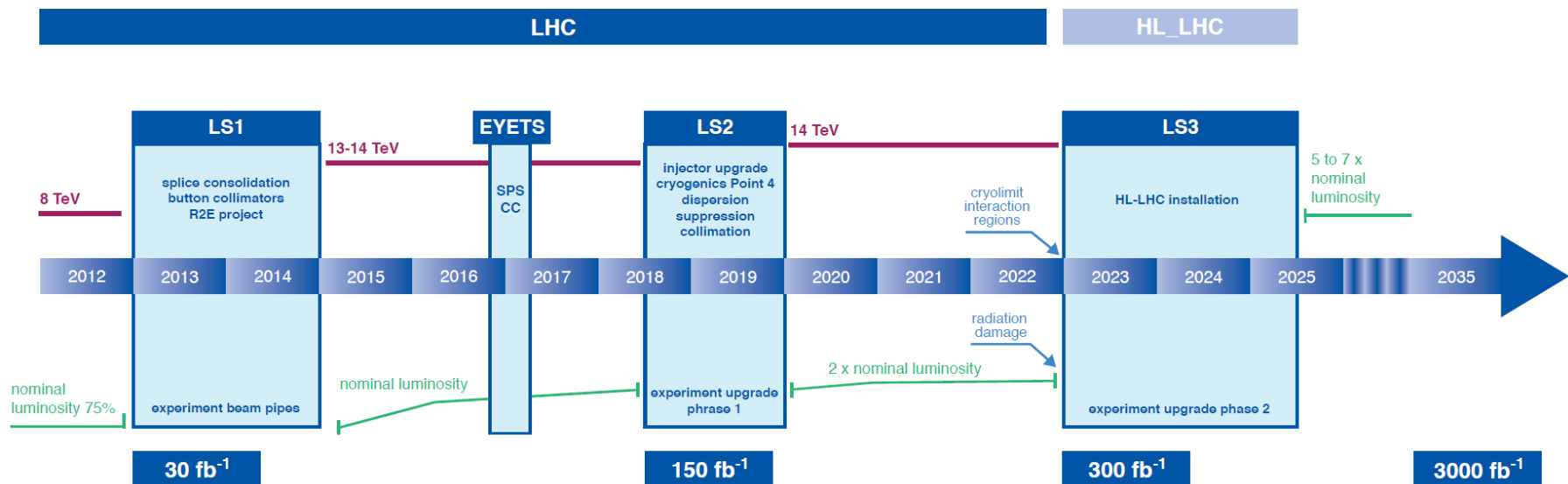
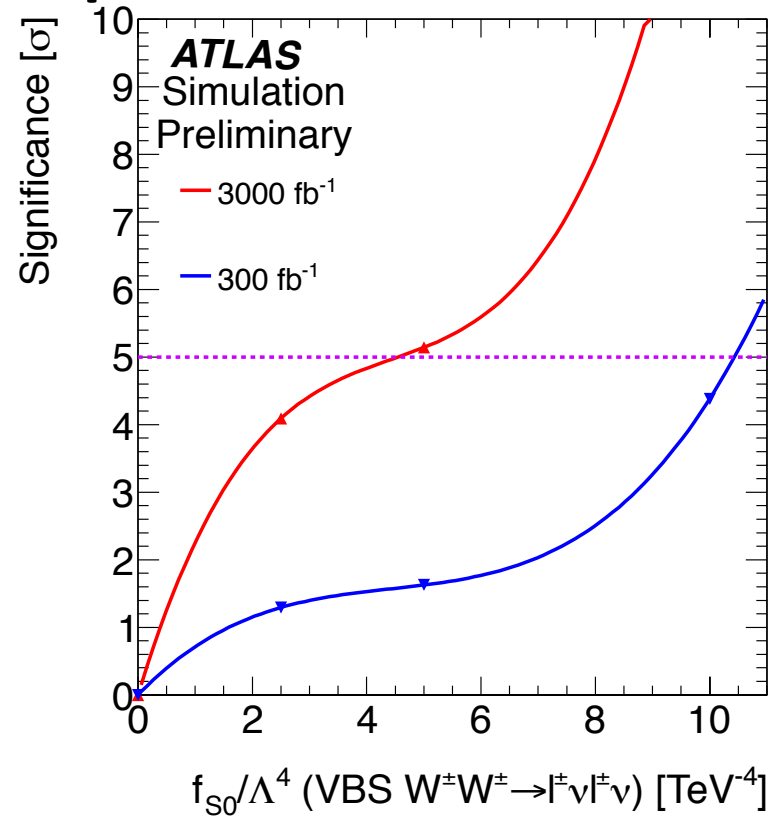
Limits on aQGCs set using m_{ℓℓ} distribution



Future Prospects

New run at 13-14 TeV set to begin in 2015

Expect factor of 3-4 improvement in sensitivity to anomalous couplings



Conclusions

- Wide array of measurements sensitive to EW gauge boson interactions performed at LHC
- **Includes evidence/observation of EW processes not previously measured at hadron colliders**
- **Have again confirmed SM predictions**
- **But new run at ~twice the energy is almost here**

Backup

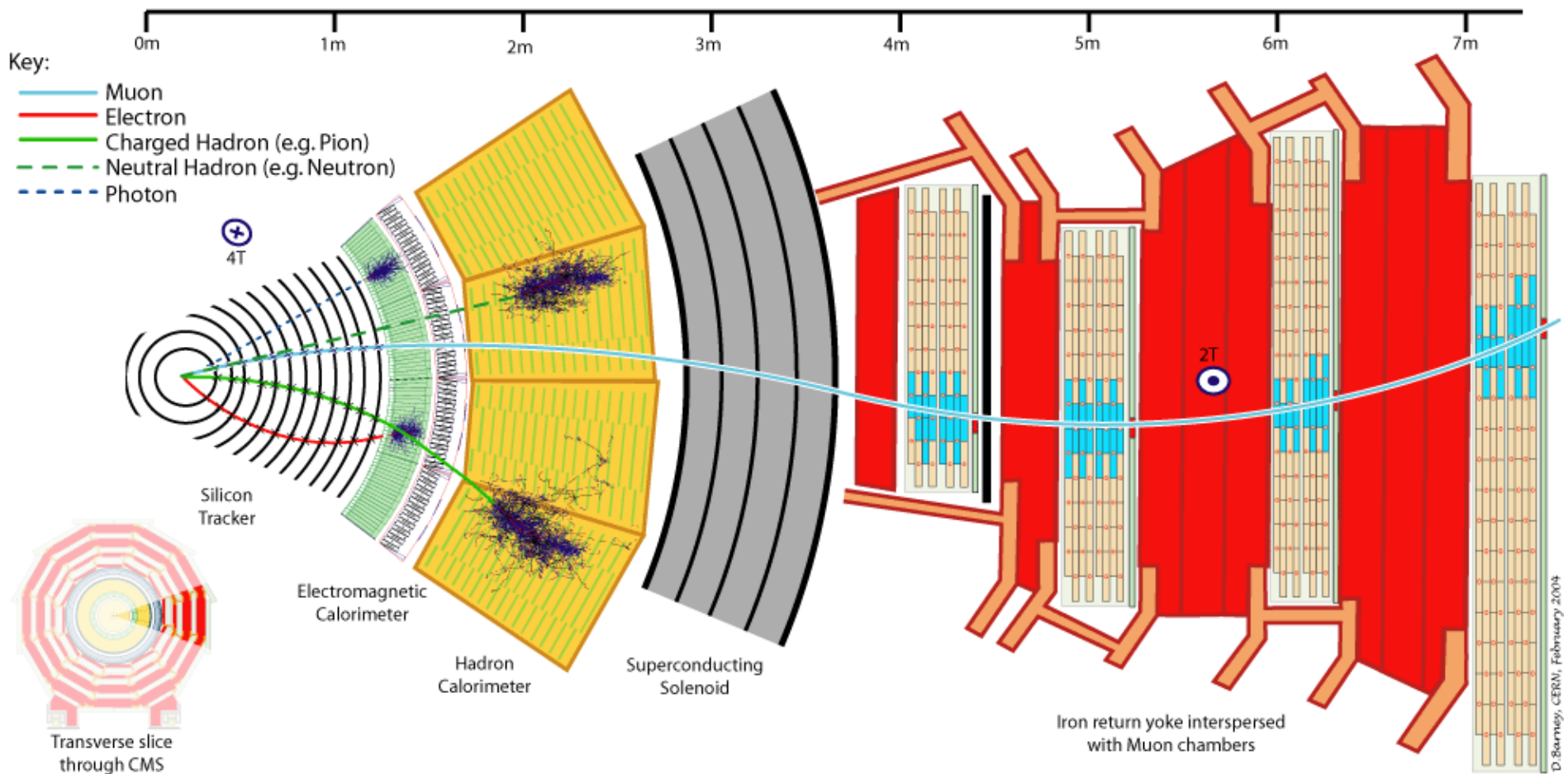
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- ZZ->2l2v: CMS-PAS-SMP-12-016. <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12016>

References

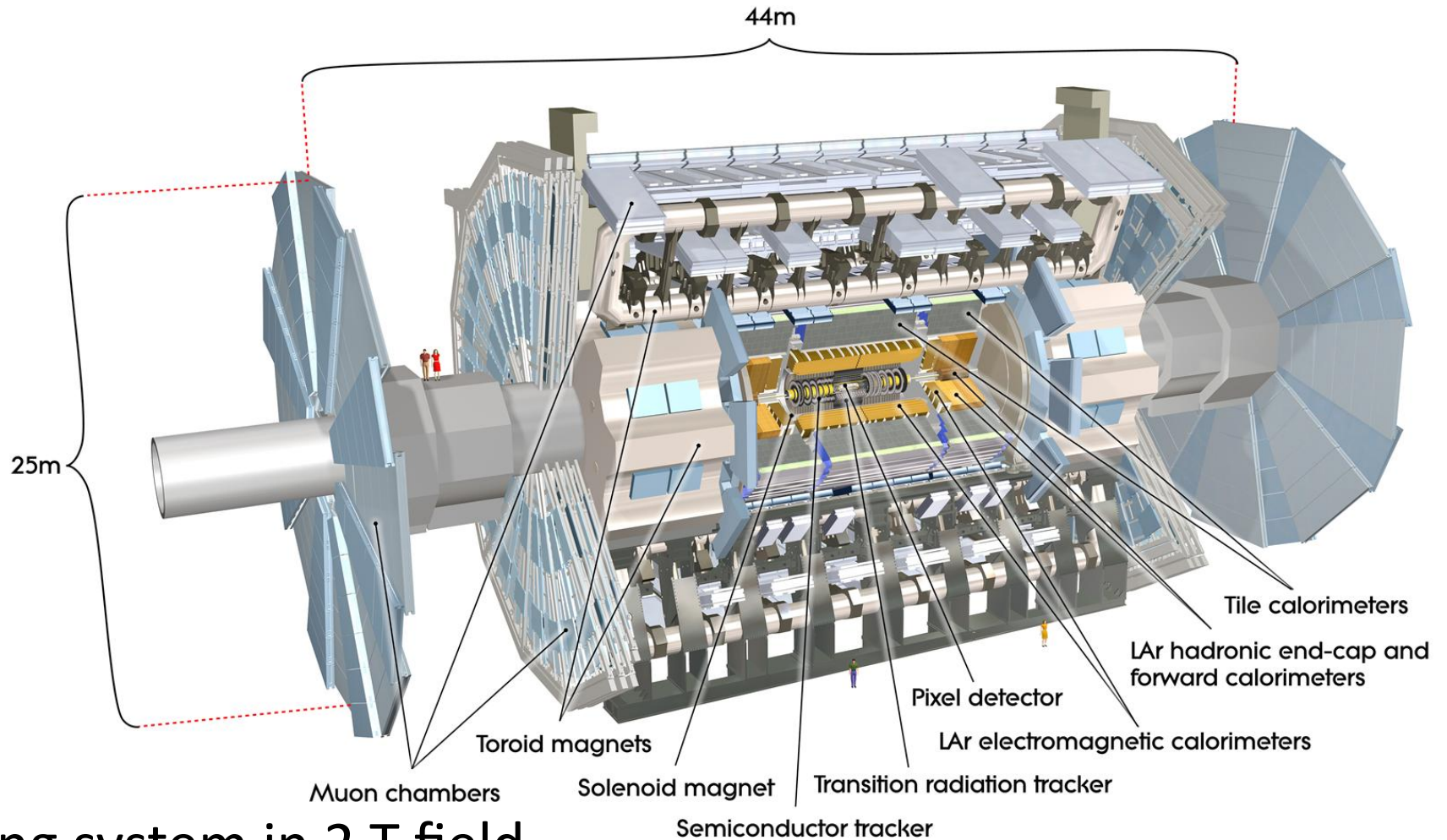
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CMS Detector



Tracking system in 4 T field generated by solenoid
Lead tungstate crystal EM calorimeter
Brass-scintillator hadronic calorimeter
Muon chambers flux-return yoke of solenoid

ATLAS Detector



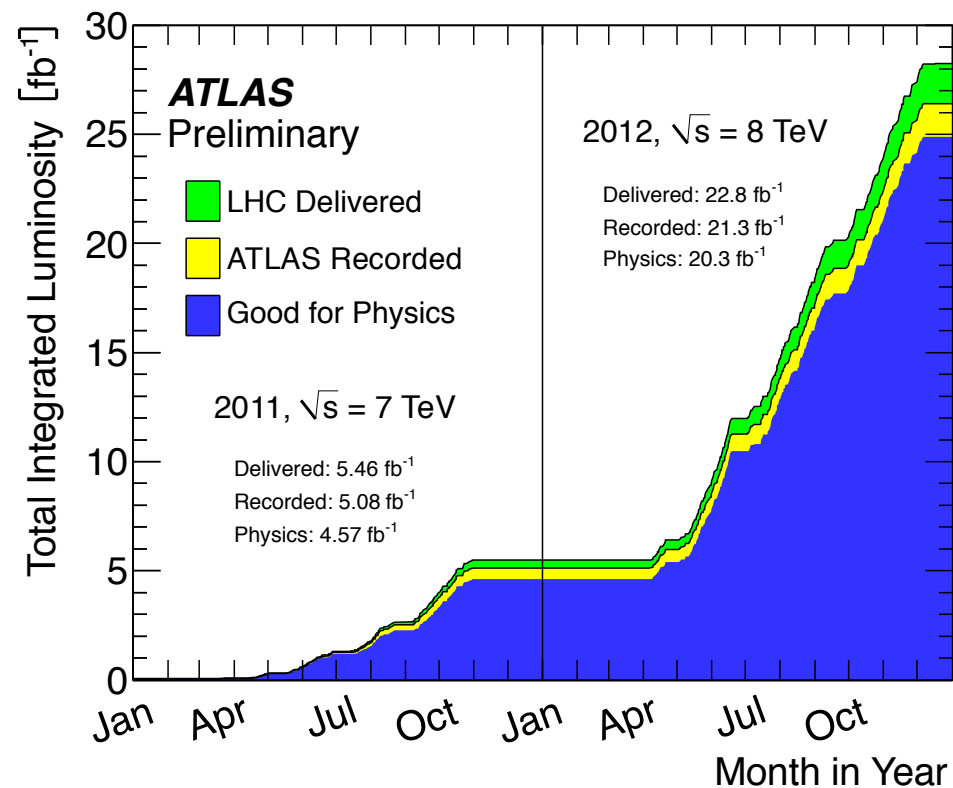
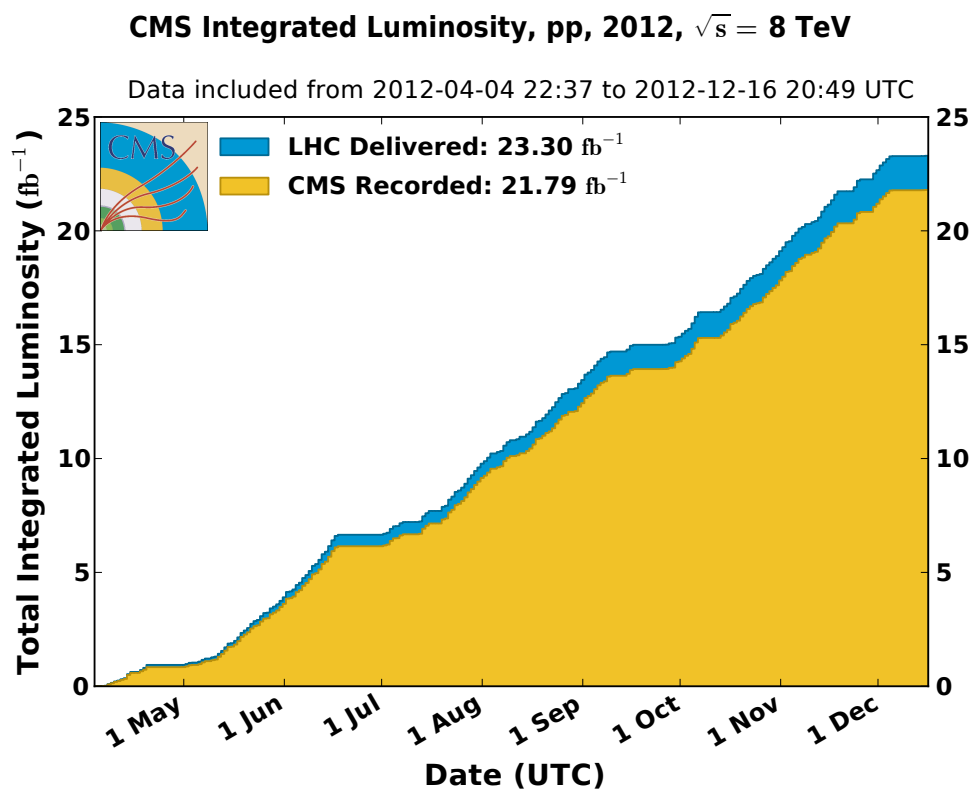
Tracking system in 2 T field

Liquid argon EM calorimeter

Steel-scintillator hadronic calorimeter

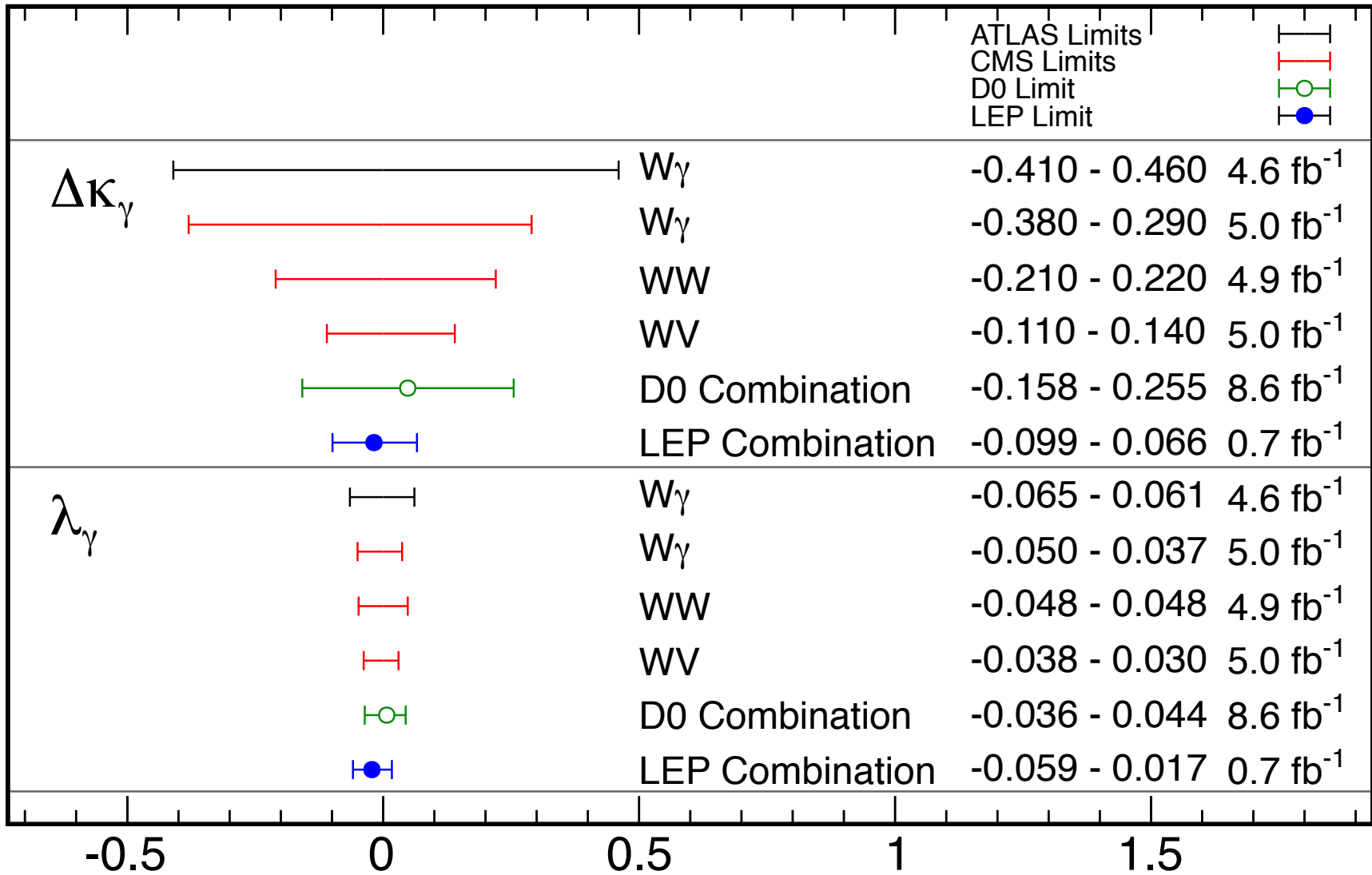
Muon chambers in toroidal field

Detector Performance



WW γ Limits

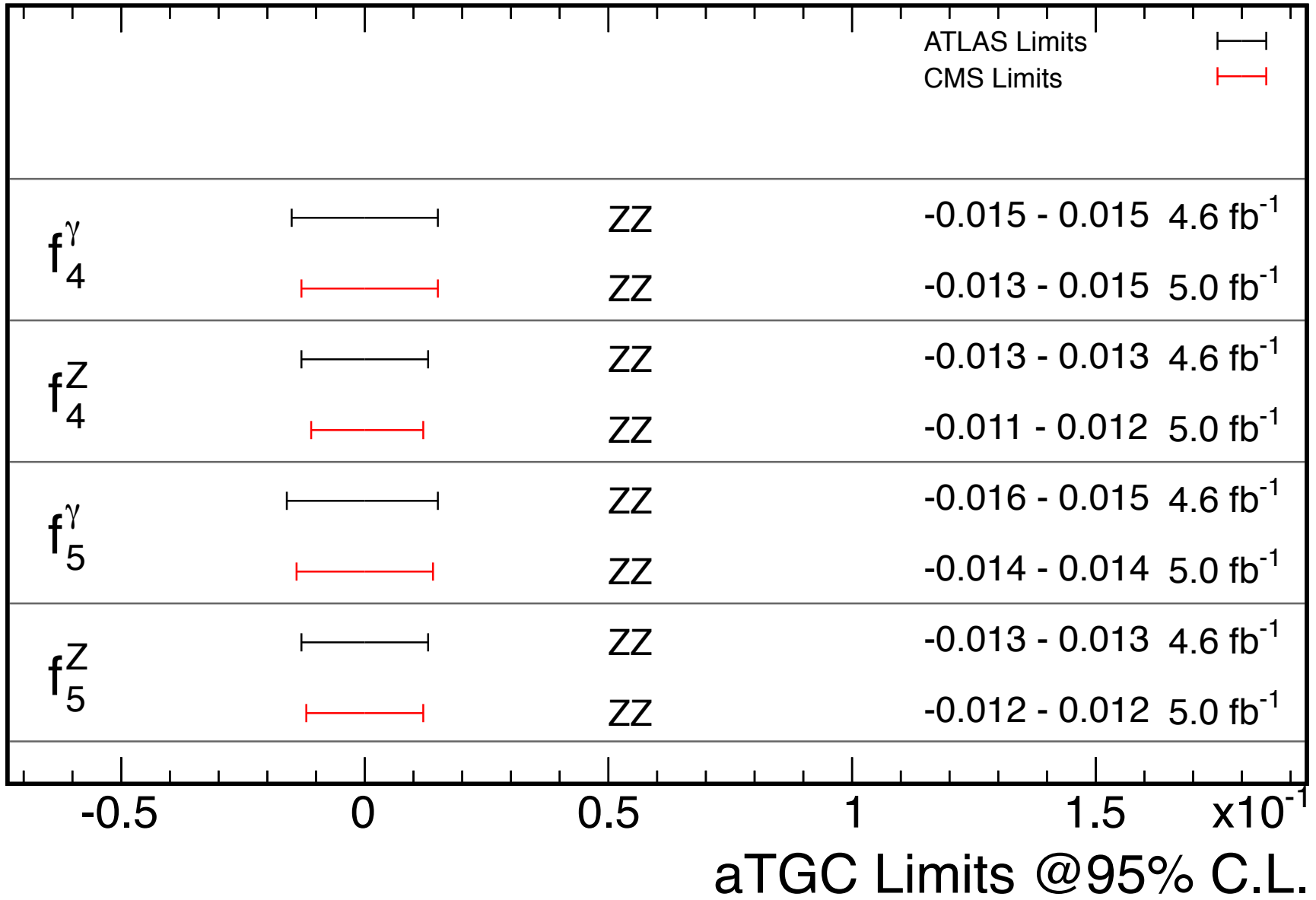
Feb 2013



aTGC Limits @95% C.L.

ZZ(Z/γ) Limits

Feb 2013



ATLAS Diboson Cross Sections

Diboson Cross Section Measurements

Status: July 2014

$\int \mathcal{L} dt$
[fb⁻¹]

Reference

