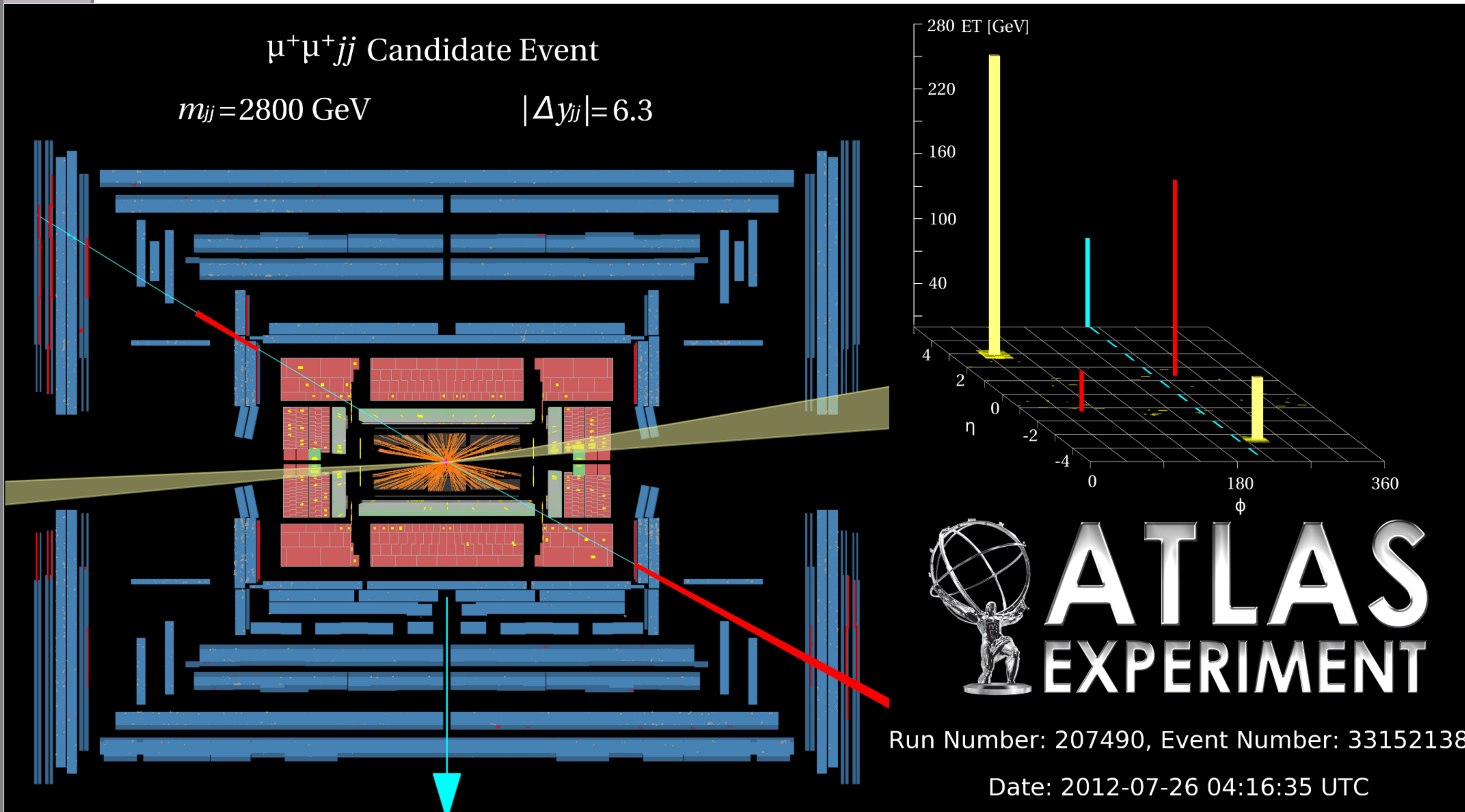
ATLAS VBS ssWW Candidate Event



Electroweak Measurements at the LHC

K. Einsweiler, LBL   *Lepton-Photon 2015*

on behalf of the ATLAS and CMS Collaborations

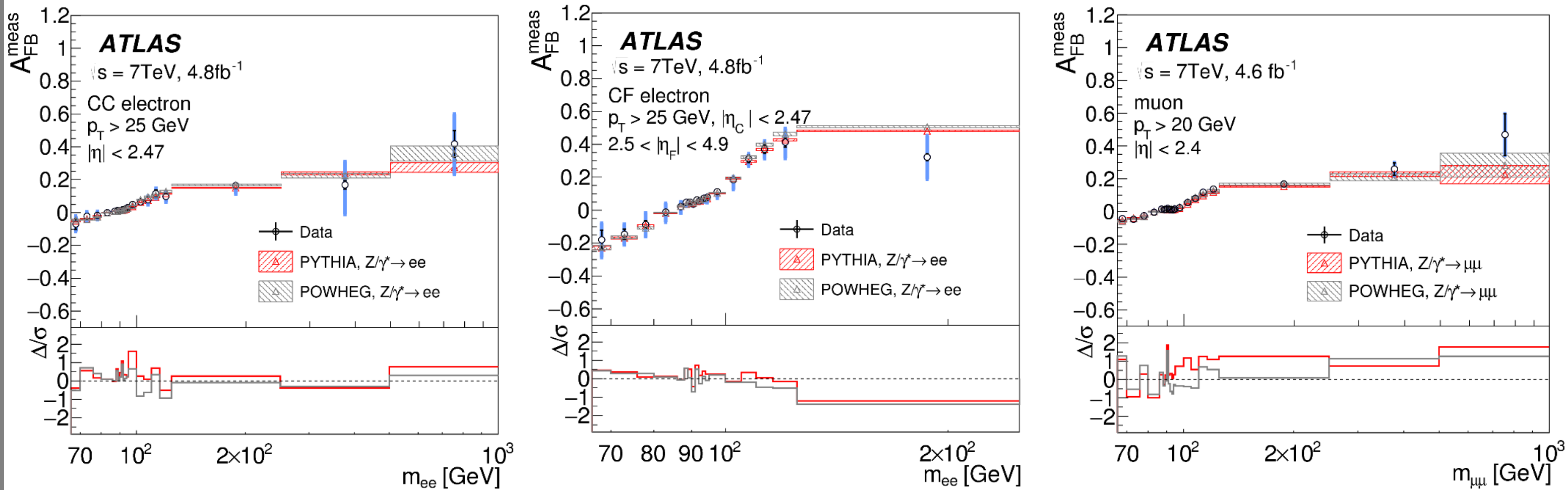
Electroweak Measurements at the LHC

- Summarize LHC Run 1 measurements in Electroweak area
- Scope includes EWK observables and processes:
  - Z A_{fb} and m(W) results (here Tevatron still has advantages)
  - VBF/VBS results (Observation and Evidence !)
  - Di-boson and Tri-boson results (many new results => aTGC/aQGC)
- Show only 8 TeV results unless 7 TeV results are unique !
- Many Electroweak results still to appear in coming (many) months…
  - Run 1 statistics far beyond Tevatron => precise and complex analyses, requiring substantial investment to complete.
  - Combinations of results, especially anomalous coupling limits, across ATLAS/CMS are still to come.

Z → ll Forward/Backward Asymmetry A_{fb} (ATLAS)

[ATLAS A_{fb}]

- ATLAS result from 7 TeV sample currently most precise value from LHC. Convert to $\sin^2\theta_{eff}$ EWK observable, and also derive value for A_μ (best measurement from SLD 0.142 ± 0.015 => re-measure, but must assume SM value for A_q).
- Use muons with $|\eta| < 2.4$. Use electrons with $|\eta| < 2.5$ (C) and $2.5 < |\eta| < 4.9$ (F) – use only CC and CF combinations to control backgrounds.
- Use measured distributions to extract results. Provide unfolded distributions w/wo dilution corrections as well. Use Pythia6 LO generator to extract EWK parameters, use Powheg as cross-check for NLO effects.



$Z \rightarrow ll$ Forward/Backward Asymmetry A_{fb} (ATLAS)

- Results, systematics, and comparisons to other measurements:

	$\sin^2\theta_{\text{eff}}^{\text{lept}}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2307 \pm 0.0015$
El. combined	$0.2308 \pm 0.0006(\text{stat.}) \pm 0.0007(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2308 \pm 0.0013$
Combined	$0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2308 \pm 0.0012$

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

- Measure $A_\mu = 0.153 \pm 0.007$ (stat) ± 0.009 (syst) $= 0.153 \pm 0.012$

$Z \rightarrow ll$ Forward/Backward Asymmetry A_{fb} (ATLAS)

	$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	Δ/σ (wrt LEP+SLC)	Δ/σ (wrt ATLAS)
ATLAS	0.2308 ± 0.0012	-0.6	–
CMS [6]	0.2287 ± 0.0032	-0.9	-0.6
D0 [5]	0.23146 ± 0.00047	-0.1	0.5
CDF [4]	0.2315 ± 0.0010	-0.03	0.4
LEP, $A_{\text{FB}}^{0,b}$ [3]	0.23221 ± 0.00029	–	1.2
LEP, $A_{\text{FB}}^{0,l}$ [3]	0.23099 ± 0.00053	–	-0.1
SLC, A_{LR} [3]	0.23098 ± 0.00026	–	-0.1
LEP+SLC [3]	0.23153 ± 0.00016	–	0.6
PDG global fit [46]	0.23146 ± 0.00012	-0.4	0.6

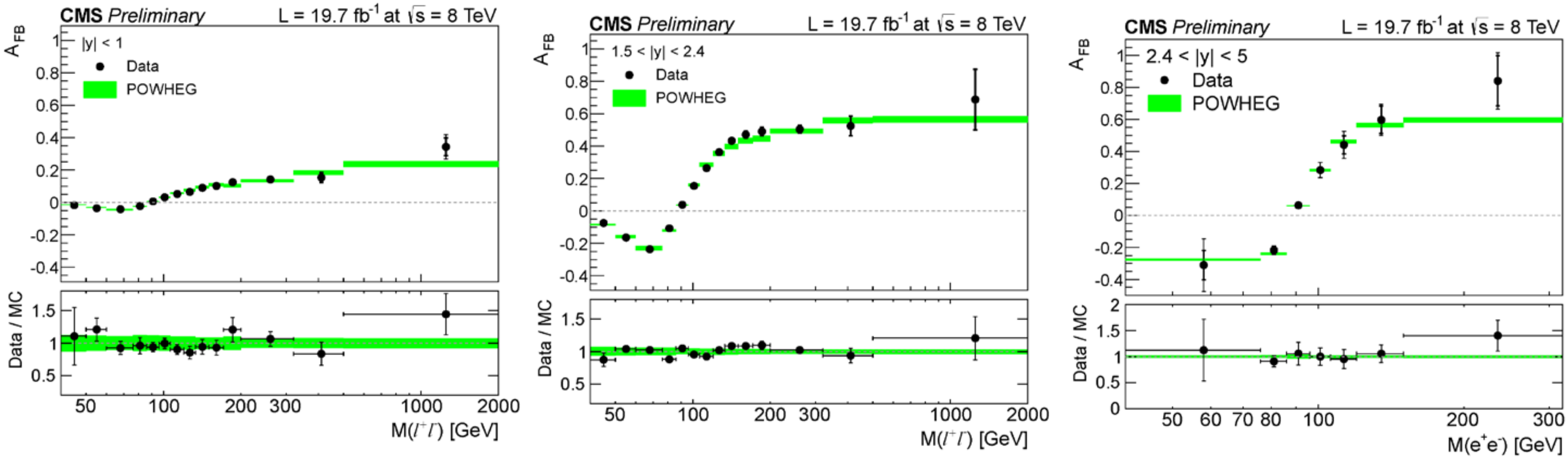
- LHC not yet competitive – Tevatron results approaching LEP/SLD ($p\bar{p}$ has much smaller dilution !), and CDF (μ)/D0 (e) published one channel without combination – could gain another factor 2 with both channels/expt and overall combination ?

- Need more statistics for LHC (7 TeV only), but more important, need to develop combined fitting with PDFs and/or alternate multi-dimensional fitting strategies.

CMS-SMP-14-004

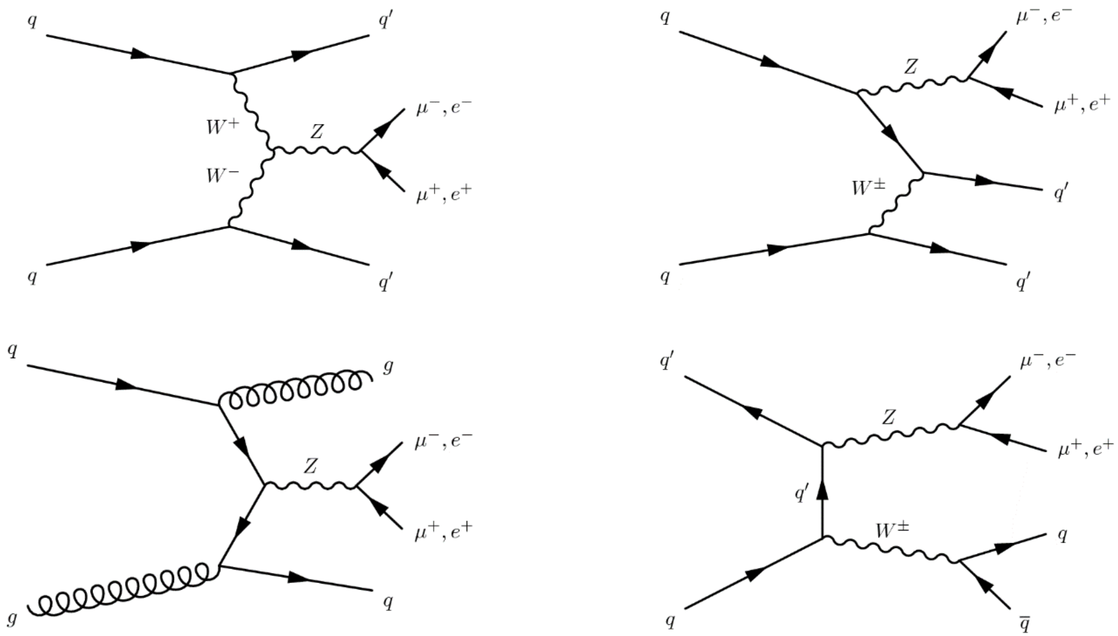
Z → ll Forward/Backward Asymmetry A_{fb} (CMS)

- Preliminary CMS analysis using full 8 TeV data sample (no measurement of $\sin^2\theta_{eff}$ yet).
- Results below show several of 4/5 η-bins for μ/e final states. Comparison with Powheg looks very promising – excellent agreement between data/MC.
- Full Run 1 samples will take analysis to next level – still too early to forecast ultimate limits of measurements at LHC (but 30x statistics through Run 3 !)



Electroweak Production of W and Z: VBF Z

- Very complex and detailed analyses from both ATLAS and CMS. First result from ATLAS, demonstrated significance above 5σ => observation of VBF production.
- Many careful comparisons of physics-sensitive distributions demonstrate excellent agreement data/MC – will be “VBF reference analysis”.
- Physics: Z+2-jet final state, separate “EWK” (t-channel exchange of W/Z) and “non-EWK” contributions. EWK dominantly VBF + Z-bremsstrahlung diagrams:



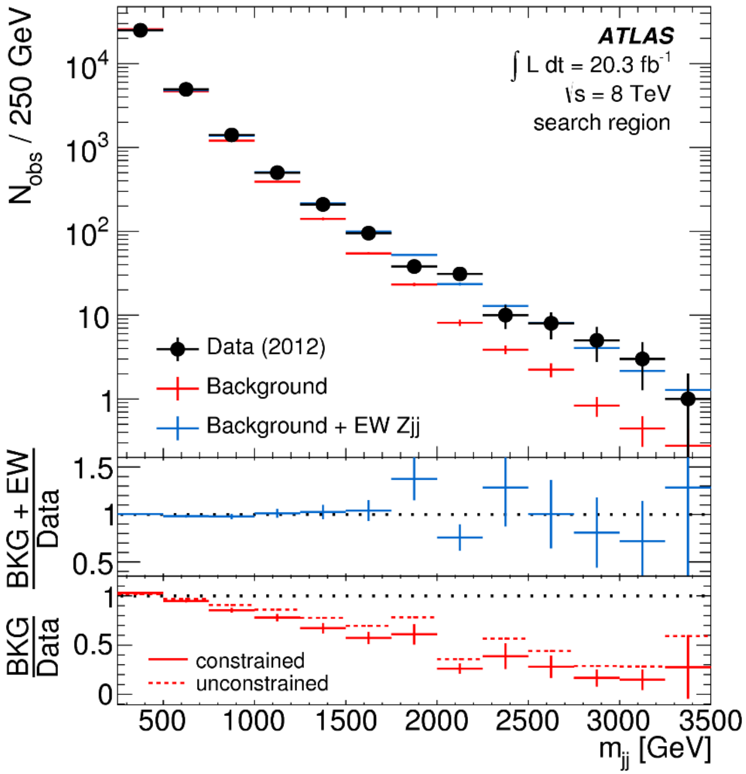
EWK

Typical non-EWK (BKG)

ATLAS VBF Z

Electroweak Production of W and Z: VBF Z (ATLAS)

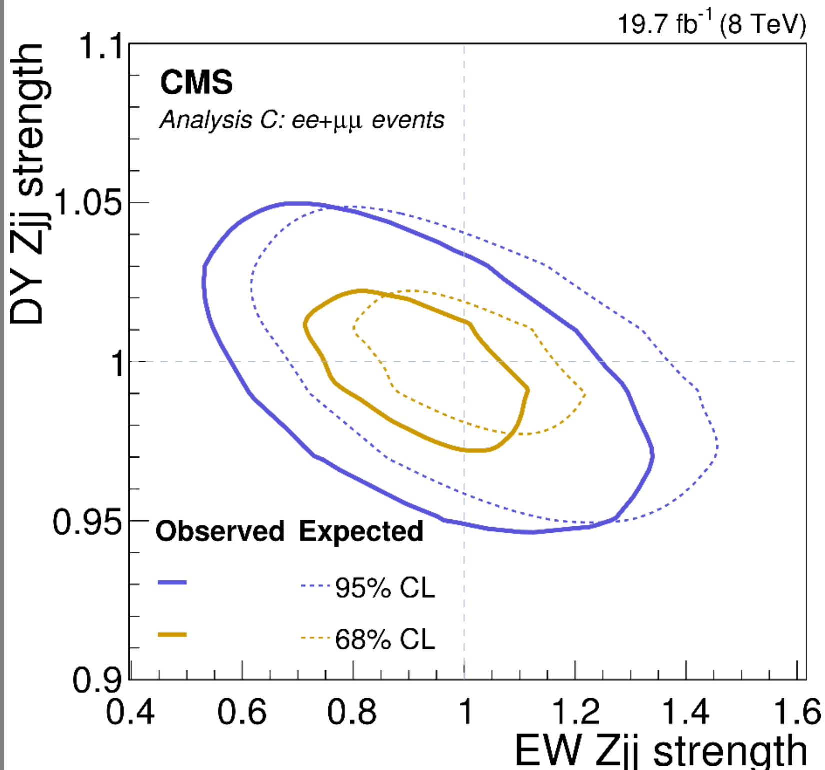
- ATLAS analysis defines 5 fiducial regions for Z+2-jet final states (baseline, high-mass, search, control, high-P_T), 2 for EWK (m(jj) > 250 and m(jj) > 1000 GeV).
- Analysis is cut-based, uses MC templates and control regions to extract signal. Both Sherpa (LO multi-leg) and Powheg (NLO) used for signal modeling.



- The "search" region (plot, m(jj) > 250 GeV): EWK is 5% of total Z+jets signal.
- $\sigma_{EWK} = 54.7 \pm 4.6\text{(stat)}\ ^{+9.8}_{-10.4}\text{(syst)} \pm 1\text{ (lumi)}$
- $\sigma_{Powheg} = 46.1 \pm 1.0$ fb
- Similar agreement for m(jj) > 1000 GeV region
- Significance estimated using Toys for search and control regions.
- Extract aTGC limits (compare to others)…

Electroweak Production of W and Z: VBF Z (CMS)

- CMS analysis uses 3 different multi-variate analyses (MVAs), including different variables in the boosted decision trees (BDTs), and different background estimation techniques.
- Madgraph+Pythia used for signal modeling. Developed a q/g separator for VBF jets, and find that this increases the sensitivity by only 5%.

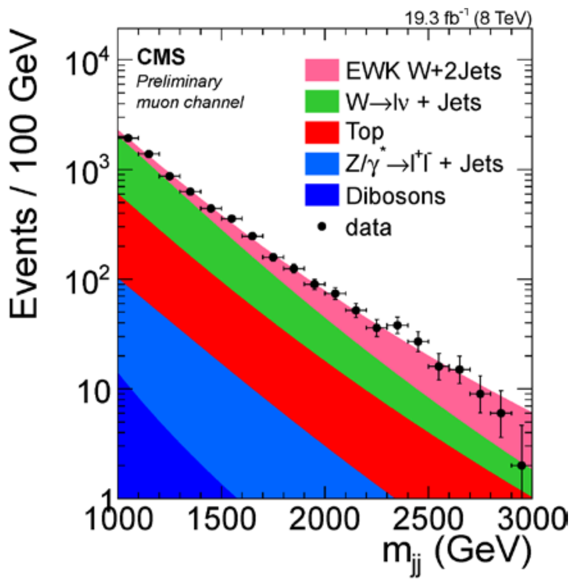


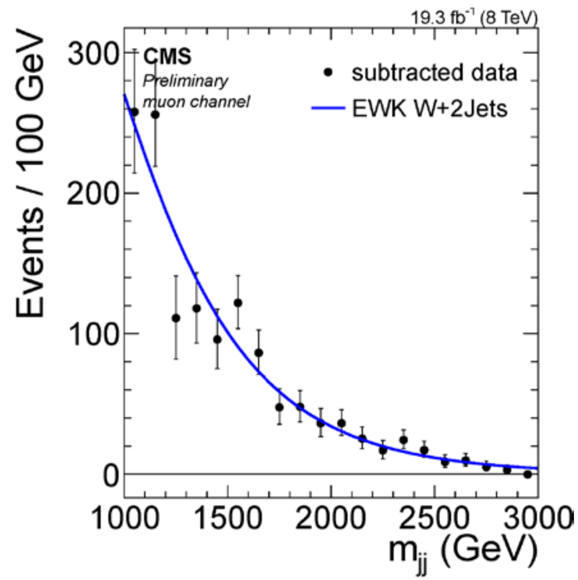
- σ_{Fid} = 174 ± 15 (stat) ± 40 (syst) fb
- σ_{LO} = 208 ± 15 fb
- Figure shows EWK versus QCD signal strength in data and MC => excellent agreement with expectations.

CMS-SMP-13-012

Electroweak Production of W and Z: VBF W (CMS)

- CMS uses MVA, and after cutting on the BDT discriminant, a likelihood fit is performed to the m(jj) distribution to extract the signal. The data/MC agreement for distribution of BDT discriminant values not ideal => systematic.
- Madgraph+Pythia used for signal modeling.





Muon channel before/after background subtraction

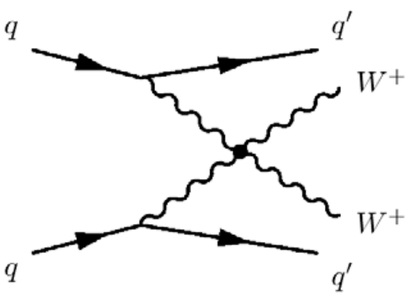
Electron channel looks very similar

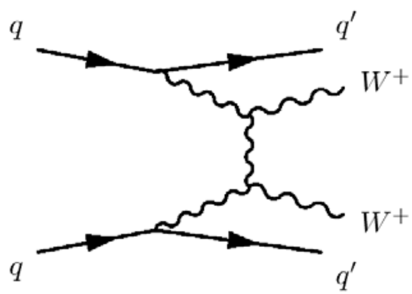
Event category	Measured cross section
μjj	0.43 ± 0.04 (stat.) ± 0.10 (syst.) ± 0.01 (lumi.) pb
ejj	0.41 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb
combined μjj and ejj	0.42 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb

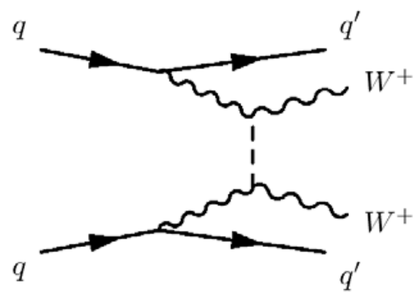
Predicted:
$\sigma = 0.50 \pm 0.03$ pb

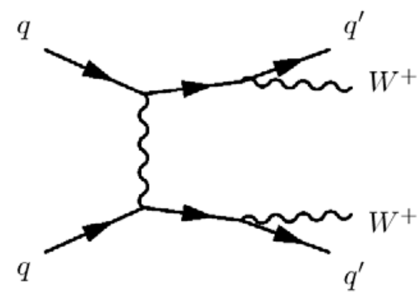
Electroweak Production of W and Z: VBS ssWW (ATLAS)

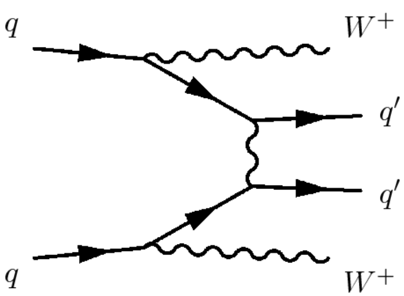
- First evidence for Vector-Boson Scattering based on use of same-sign WW final state (QCD and EWK contributions roughly same size). First result from ATLAS, demonstrated above 3σ => evidence for VBS production.
- Physics: same-sign dilepton+2-jet+MET final state, separate "EWK" (O(α_{EW}^6) diagrams) and "QCD" (O($\alpha_s^2\alpha_{EW}^4$) diagrams) contributions. Below = 5 VBS EWK diagrams (EWK includes non-VBS too, such as VH, VVV, and others):







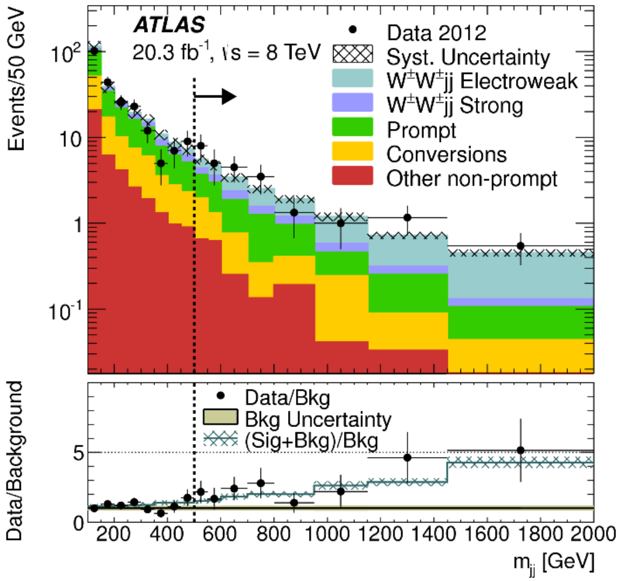


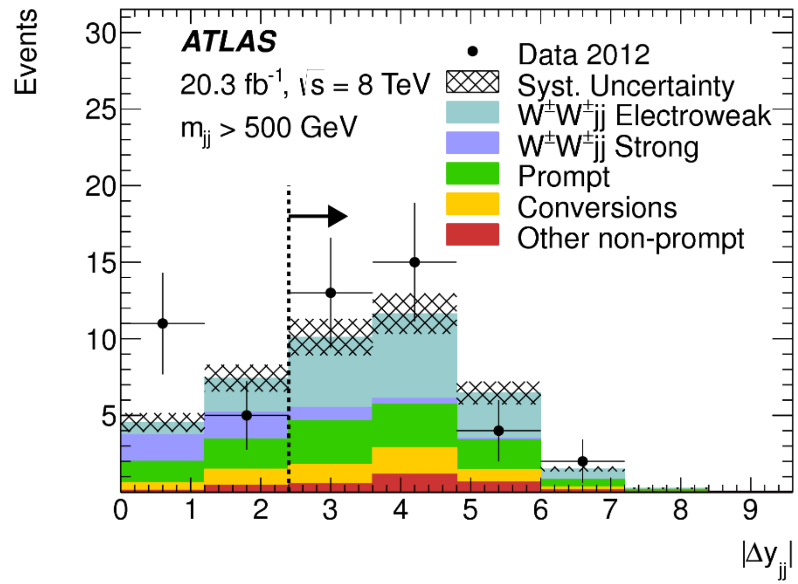


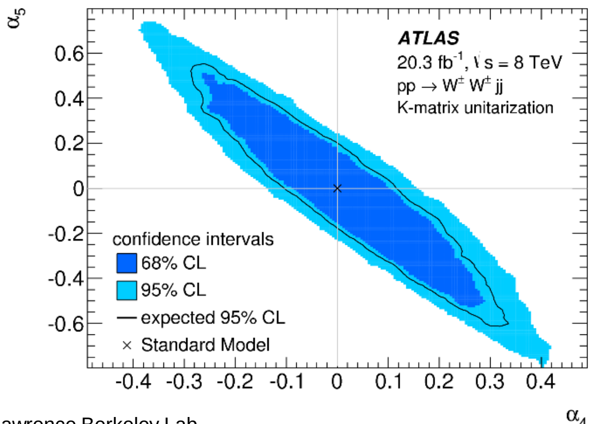
- ATLAS Signal modeling: Sherpa with Powheg for NLO normalization
- Two analyses: "inclusive ssWW" and "VBS EWK" (subset)
- σ(incl) = 2.1 ± 0.5 (stat) ± 0.3 (syst) fb; σ(pred) = 1.52 ± 0.11 fb
- σ(EWK) = 1.3 ± 0.4 (stat) ± 0.2 (syst) fb; σ(pred) = 0.95 ± 0.06 fb

Electroweak Production of W and Z: VBS ssWW (ATLAS)

- Results: left = "inclusive" (right of vert line), right = "EWK" (right of vert line).





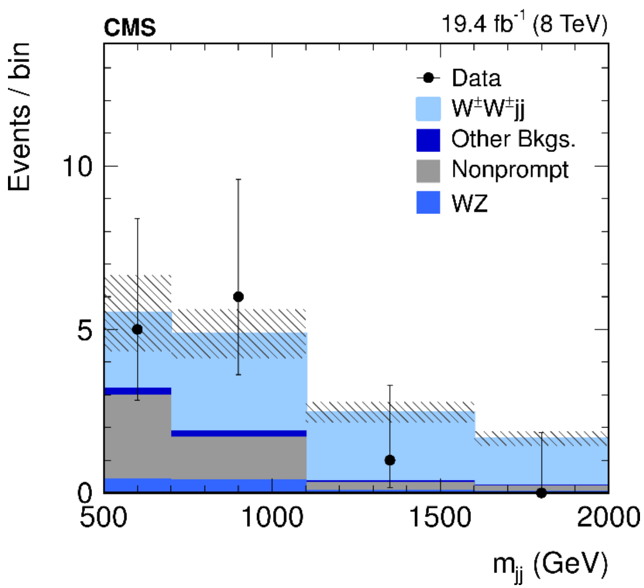


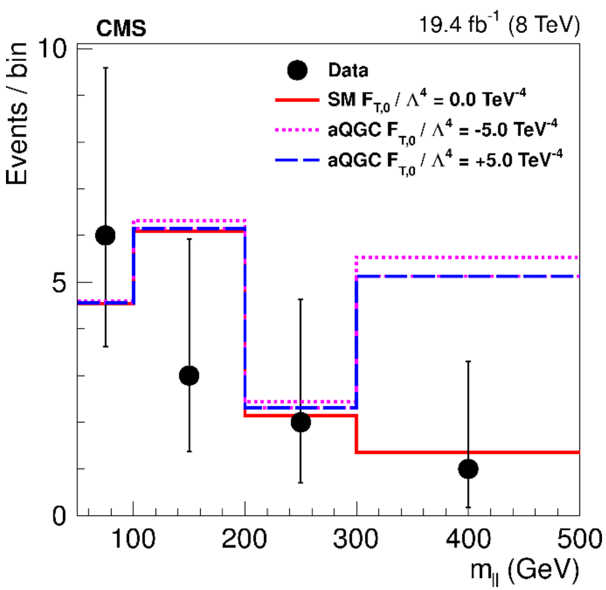
- Set first limits on aQGC parameters relevant for WWWW couplings: α_4 and α_5
- Use WHIZARD and K-matrix regularization and set limits using data in "EWK" analysis region.

CMS VBS ssWW

Electroweak Production of W and Z: VBS ssWW (CMS)

- Signal modeling uses Madgraph (norm to VBFNLO). Event selection for signal region very similar to ATLAS: m(jj) > 500 GeV and |Δη(jj)| > 2.5.





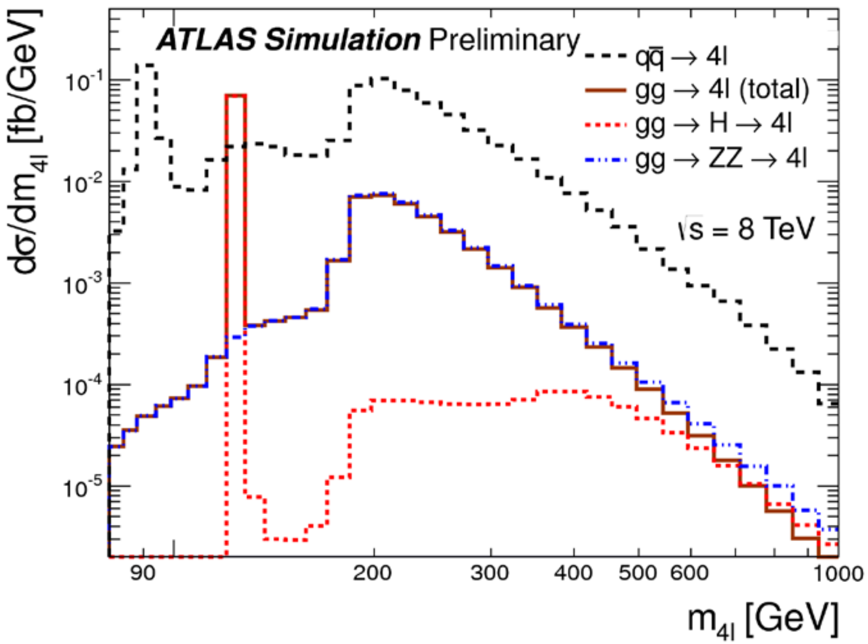
Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

- Good data/MC agreement for fiducial cross-section (also in WZ control region). Signif obs (exp) = 2.0σ (3.1σ)
- Set limits on all 9 relevant aQGC parameters (m(ll) most sensitive variable) one at a time (see table).

ATLAS-CONF-2015-031

Di-boson production: Inclusive 4-lepton Production (ATLAS)

- Measure m(4l) and P_T(4l) spectra for kinematic range 80 < m(4l) < 1000 GeV. This is relevant region for measuring off-shell Higgs production ("Higgs width").
- Find 476 events with 26.2 ± 3.6 events estimated background in 8 TeV data.
- Use Bayesian unfolding for m(4l) and P_T(4l) distributions. Signal modeling uses Powheg. Use three background control regions optimized for ee+ll and $\mu\mu$+ll.



Contributions shown in plot:

- $q\bar{q} \rightarrow$ 4-leptons (MCFM NLO)
- $gg \rightarrow H \rightarrow$ 4-leptons (MCFM LO * K(NNLO))
- $gg \rightarrow ZZ \rightarrow$ 4-leptons (MCFM LO)

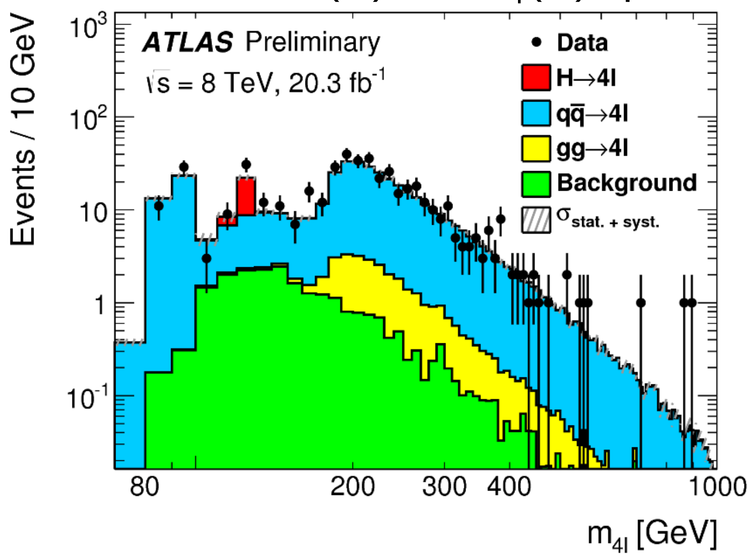
- σ(comb) = 73 ± 4 (stat) ± 4 (syst) ± 2 (lumi) fb
- σ(exp) = 65 ± 4 fb

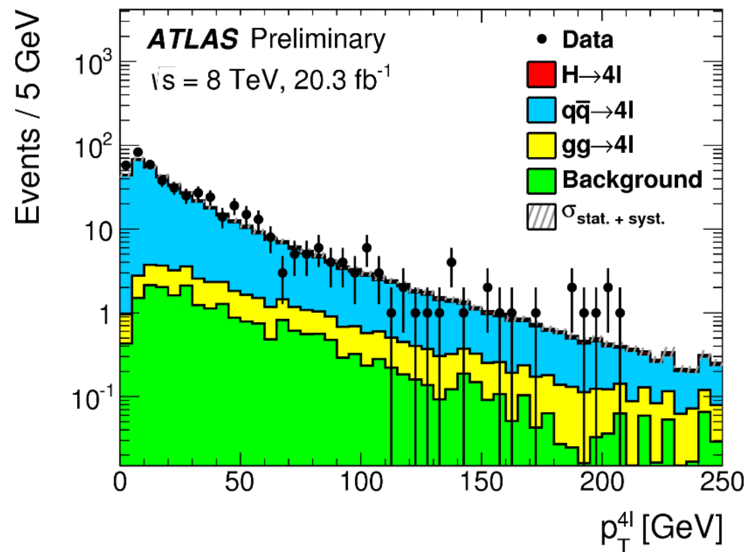
- On-shell Higgs signal compatible with μ = 1.44 from dedicated Higgs properties analysis.

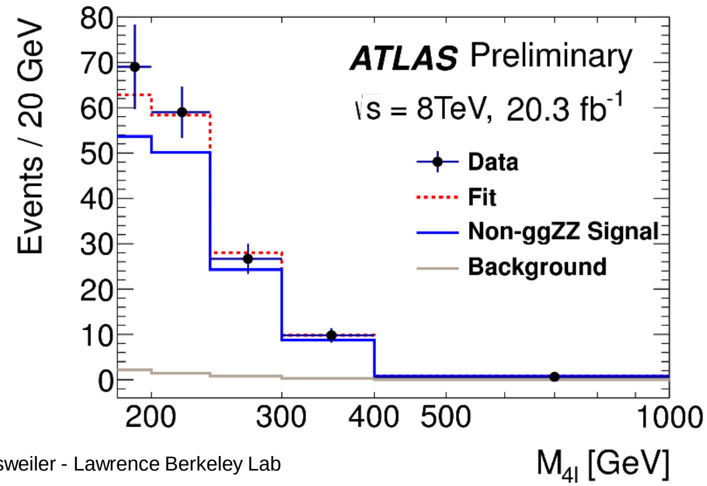
- Enhancement in $gg \rightarrow H^* \rightarrow ZZ$ at several hundred GeV is driven by $Z_L Z_L$ couplings.

Di-boson production: Inclusive 4-lepton Production (ATLAS)

- Measure m(4l) and P_T(4l) spectra for kinematic range 80 < m(4l) < 1000 GeV.





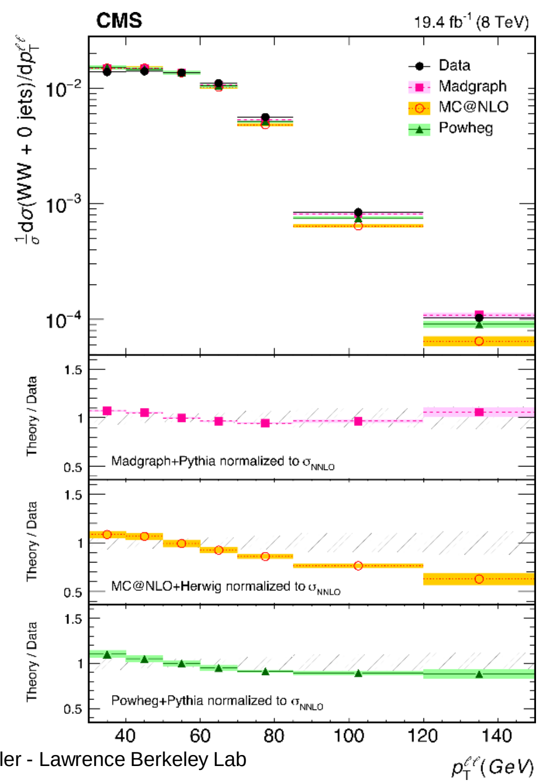


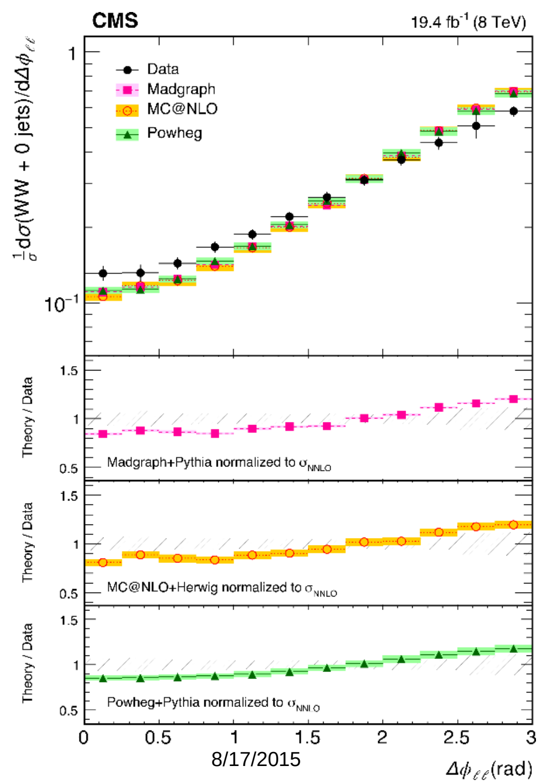
- For region m(4l) > 180 GeV, extract gg → ZZ rate by subtracting other contributions.
- Measure $\mu_{gg} = \sigma(\text{data})/\sigma_{MC}(\text{LO})$. Theory expectation for gg continuum/interference K ~2-3.
- μ_{gg} = 2.4 ± 1.0 (stat) ± 0.5 (exp) ± 0.8 (theo)

[CMS WW](#)

Di-boson production: W^+W^- Production (CMS)

- Remove contribution from H → WW (~8% effect)
- Signal model: for $q\bar{q}$ → WW use Powheg (check with Madgraph, MC@NLO). For gg → WW use GG2WW, then normalize sum to pp → WW (NNLO) calculation.
- Include dedicated resummation calculations to predict impact of n(jet) binning.
- Measure in 4 categories: 0-jet, 1-jet, SF (same-flavor), DF (different flavor).

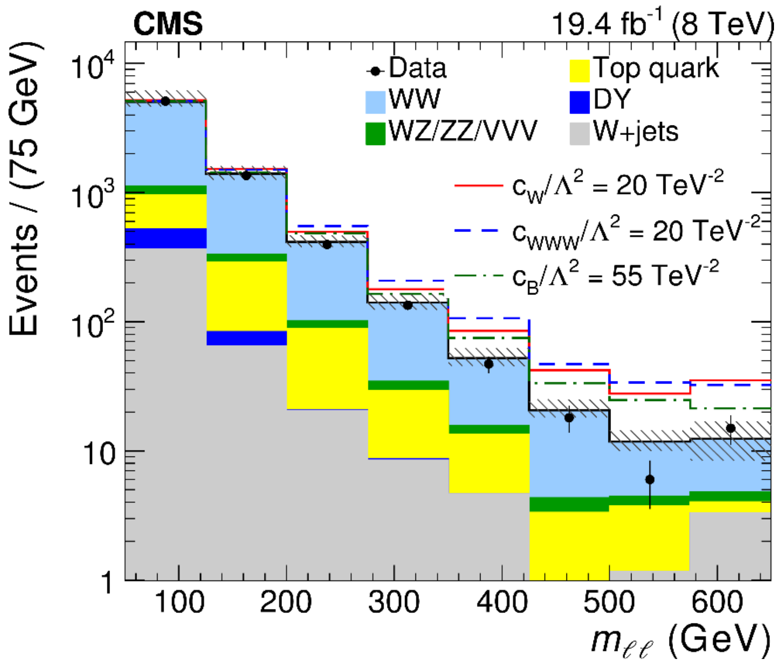




- Evaluate impact of change in P_T(jet) cut over range 20, 25, 30 GeV => data and MC track well.
- Unfold distributions and compare data and MC.
- Observe for some variables (e.g. P_T(ll) and $\Delta\phi$(ll) shown here), there are significant shape differences.

Di-boson production: W^+W^- Production (CMS)

- Measure σ(fid) = 60.1 ± 0.9 (stat) ± 3.2 (exp) ± 3.1 (theo) ± 1.6 (lumi) pb
- Theory σ(NNLO) = 59.8 ± 1.2 pb
- Good agreement (expt ± 8%), but NNLO calculations are really necessary.
- Evaluate aTGC anomalous couplings using Madgraph:



Coupling constant	This result (TeV^{-2})	Its 95% CL interval (TeV^{-2})	World average (TeV^{-2})
c_{WWW}/Λ^2	$0.1^{+3.2}_{-3.2}$	$[-5.7, 5.9]$	-5.5 ± 4.8 (from λ_γ)
c_W/Λ^2	$-3.6^{+5.0}_{-4.5}$	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$ (from g_1^Z)
c_B/Λ^2	$-3.2^{+15.0}_{-14.5}$	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$ (from κ_γ and g_1^Z)

- Summarize results in tables later…

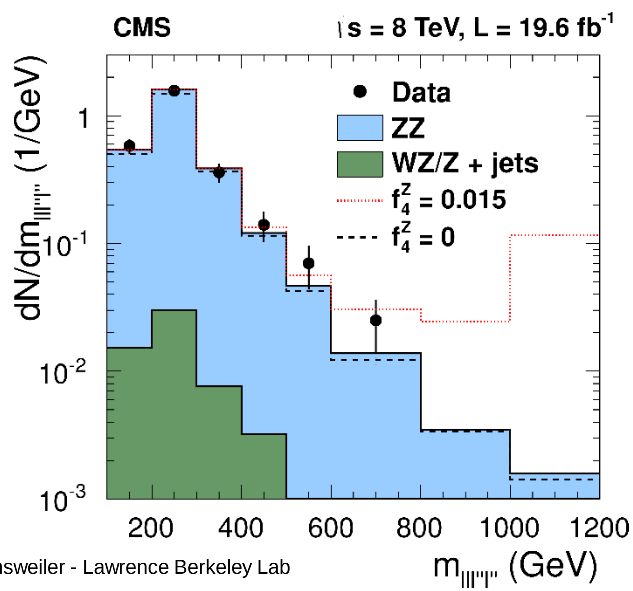
[CMS ZZ 4l](#)

Di-boson production: ZZ Production (CMS)

4-Lepton Final State:

- Include ee, $\mu\mu$, $\tau_l\tau_l$, $\tau_l\tau_h$ (τ final states included in σ not differential distributions).
- Measure ZZ total cross-section in each channel, and compare to theoretical value, calculated with NLO $q\bar{q} \to ZZ$ plus LO $gg \to ZZ$ = 7.7 ± 0.6 pb.
- Excellent agreement !
- Produce unfolded distributions of key variables (P_T(ZZ), m(ZZ))

Decay channel	Total cross section, pb
$4e$	$7.2\,^{+1.0}_{-0.9}\,(\text{stat.})\,^{+0.6}_{-0.5}\,(\text{syst.}) \pm 0.4\,(\text{th.}) \pm 0.2\,(\text{lum.})$
4μ	$7.3\,^{+0.8}_{-0.8}\,(\text{stat.})\,^{+0.6}_{-0.5}\,(\text{syst.}) \pm 0.4\,(\text{th.}) \pm 0.2\,(\text{lum.})$
$2e2\mu$	$8.1\,^{+0.7}_{-0.6}\,(\text{stat.})\,^{+0.6}_{-0.5}\,(\text{syst.}) \pm 0.4\,(\text{th.}) \pm 0.2\,(\text{lum.})$
$\ell\ell\tau\tau$	$7.7\,^{+2.1}_{-1.9}\,(\text{stat.})\,^{+2.0}_{-1.8}\,(\text{syst.}) \pm 0.4\,(\text{th.}) \pm 0.2\,(\text{lum.})$
Combined	$7.7 \pm 0.5\,(\text{stat.})\,^{+0.5}_{-0.4}\,(\text{syst.}) \pm 0.4\,(\text{th.}) \pm 0.2\,(\text{lum.})$



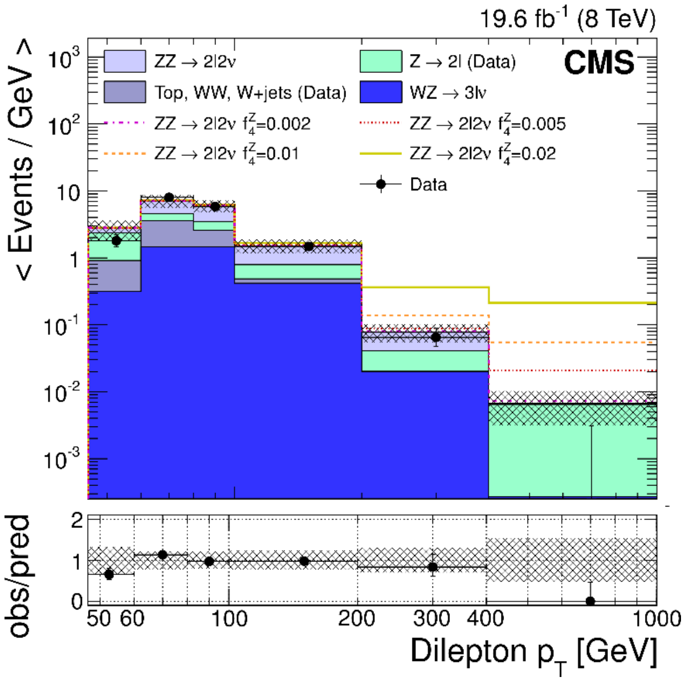
- Evaluate aTGC limits - sensitivity indicated in plot on left.
- Summarize results in tables later…

CMS ZZ 2l2ν

Di-boson production: ZZ Production (CMS)

2-Lepton 2-Neutrino Final State:

- Include ee, μμ final states with P_T(ll) > 45 GeV and reduced MET > 65 GeV.
- Measure ZZ total cross-section in each channel, and compare to theoretical value, calculated with NLO MCFM and including NLO EWK corrections.
- Good agreement !



Channel	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
ee	99^{+35}_{-31} (stat) $^{+27}_{-22}$ (syst) ± 3 (lumi)	80^{+17}_{-16} (stat) $^{+25}_{-18}$ (syst) ± 3 (lumi)
$\mu\mu$	48^{+24}_{-21} (stat) $^{+20}_{-19}$ (syst) ± 2 (lumi)	97^{+14}_{-14} (stat) $^{+29}_{-22}$ (syst) ± 4 (lumi)
Combined	67^{+20}_{-18} (stat) $^{+18}_{-14}$ (syst) ± 2 (lumi)	88^{+11}_{-10} (stat) $^{+24}_{-18}$ (syst) ± 4 (lumi)
Theory	79^{+4}_{-3} (theo)	97^{+4}_{-3} (theo)

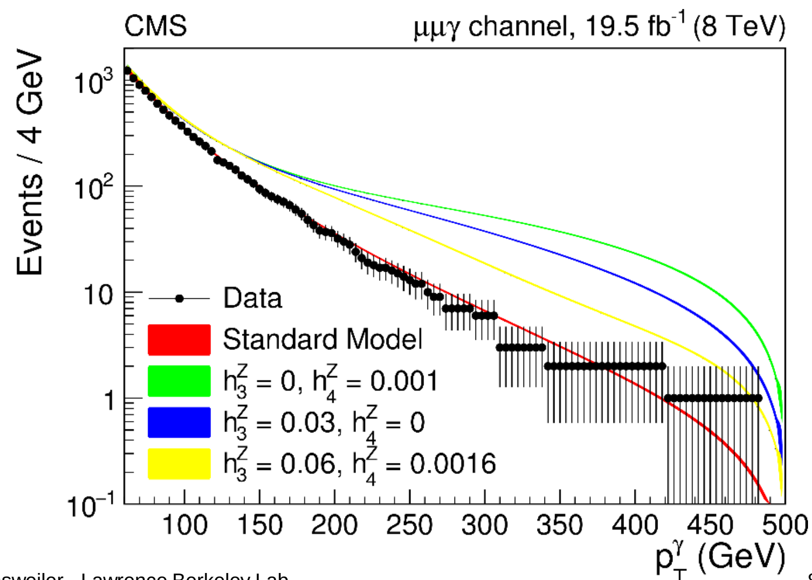
- Evaluate aTGC limits - sensitivity indicated in plot on left.
- Summarize results in tables later…

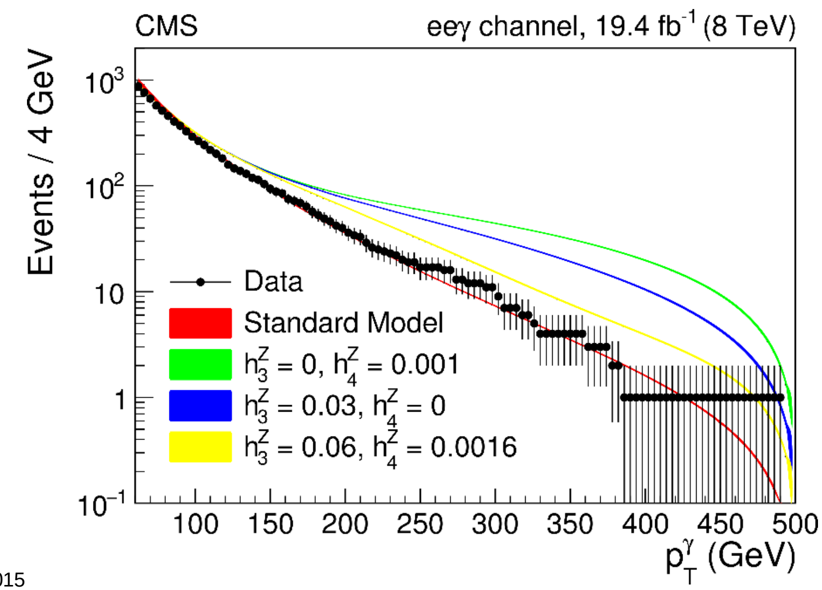
CMS Zγ 2l

Di-boson production: Zγ Production (CMS)

2-Lepton Final State:

- Require $\Delta R(l\gamma) > 0.7$ to suppress FSR. $P_T(\gamma) > 15$ GeV, use highest P_T photon.
- Signal modeling: use Sherpa multi-leg LO with MCFM NLO normalization. Evaluate impact of higher order QCD: compare data/MC for both NNLO and Sherpa, with both inclusive and exclusive (no jets with $P_T(j) > 30$ GeV) analyses.
- Excellent agreement in $P_T(\gamma)$ shapes and total cross-section. Not true for inclusive distributions with MCFM NLO => need NNLO
- Extract limits on aTGC => no signs of excess. Cumulative distributions shown:



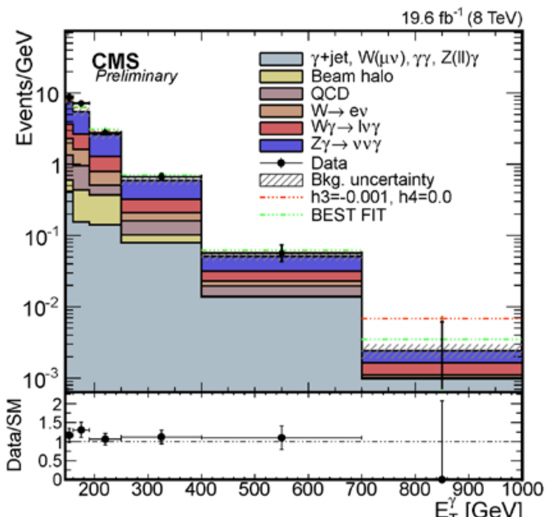


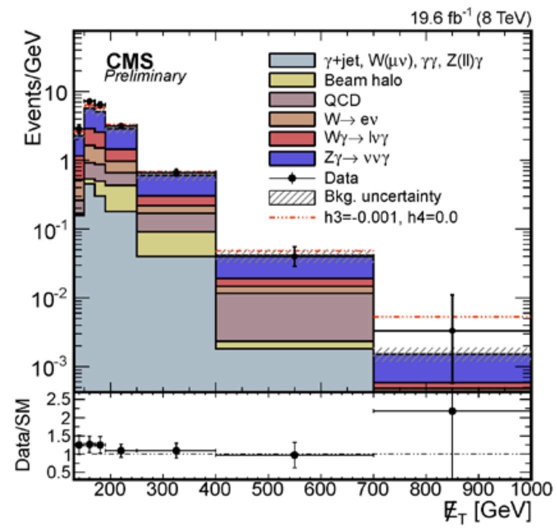
Di-boson production: Zγ Production (CMS)

2-Neutrino Final State:

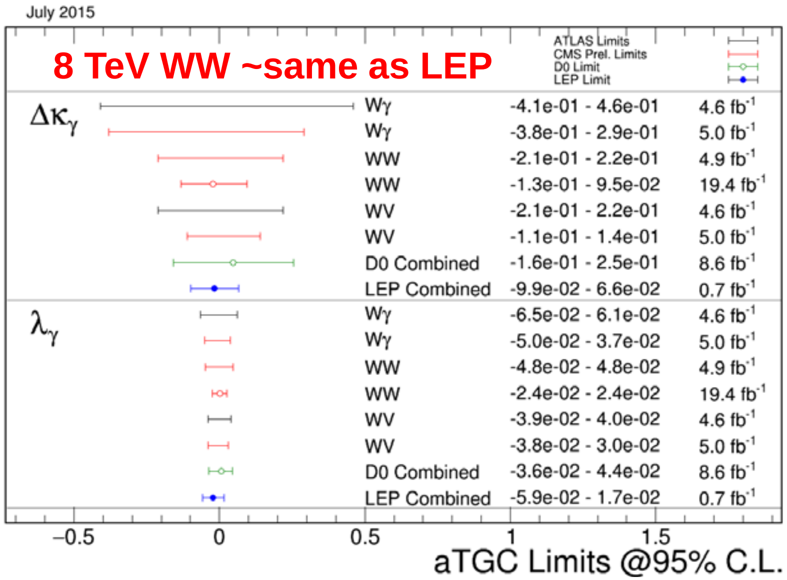
- BR(νν) is 3xBR(ll), and acceptance ~100% for Z -> νν at large P_T(Z).
- Require E_T(γ) > 145 GeV and E_T(miss) > 140 GeV for aTGC sensitivity.
- Extract cross-section 52.7 ± 6.9 fb, predicted (NNLO) 50.0 ± 2.3 fb.
- Good agreement in E_T(γ) shapes and total cross-section. Leads to most sensitive limits on Zγγ and ZZγ aTGC parameters.

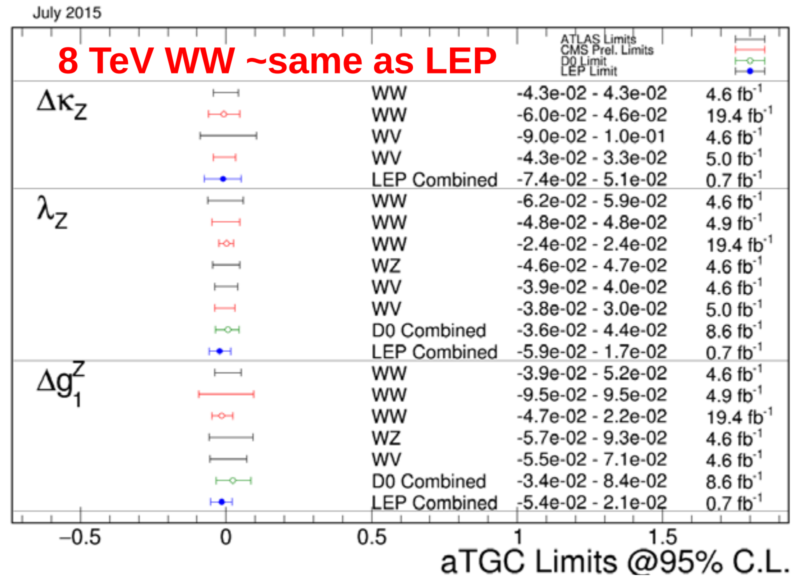
Coupling	h_3 Lower limit 10^{-3}	h_3 Upper Limit 10^{-3}	h_4 Lower limit 10^{-6}	h_4 Upper Limit 10^{-6}
$Z\gamma\gamma$	-1.12	0.95	-3.80	4.35
$ZZ\gamma$	-1.50	1.64	-3.96	4.59

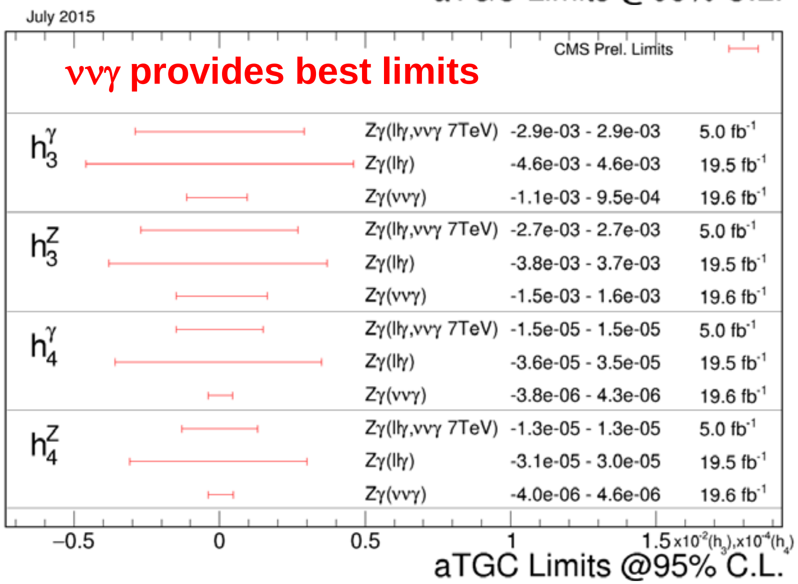


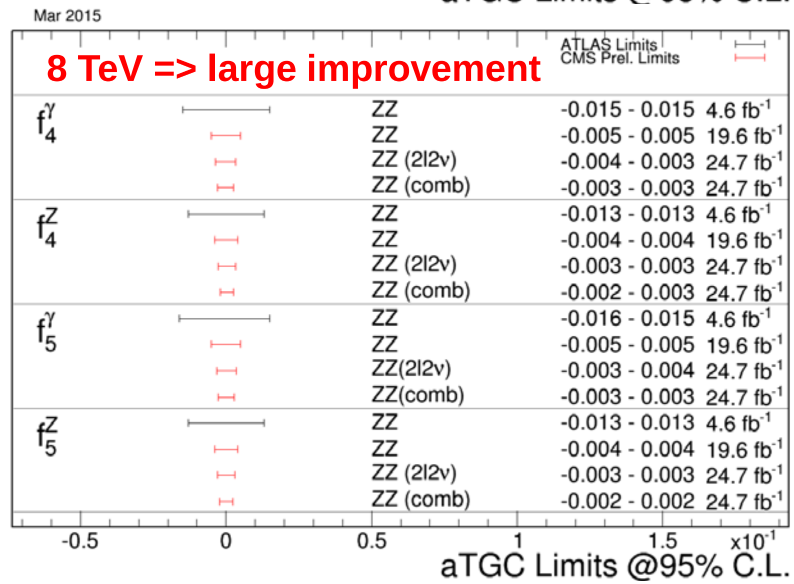


Summary of aTGC limits (compiled by CMS)





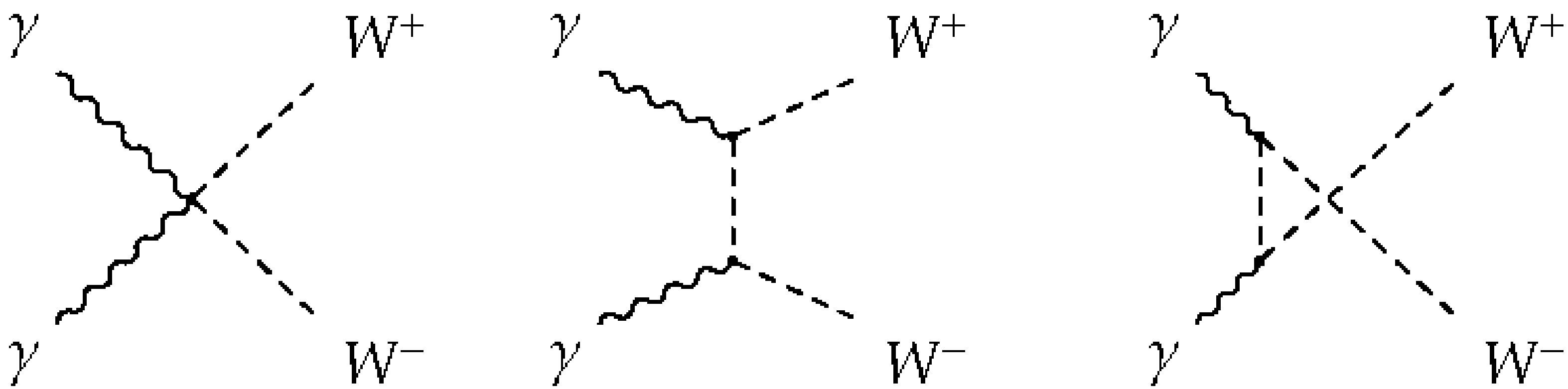




[CMS-FSQ-13-008]

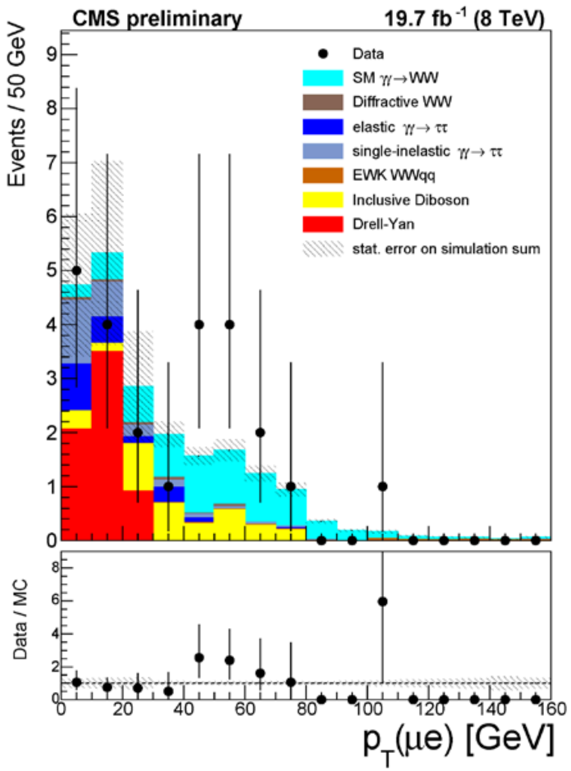
Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production (CMS)

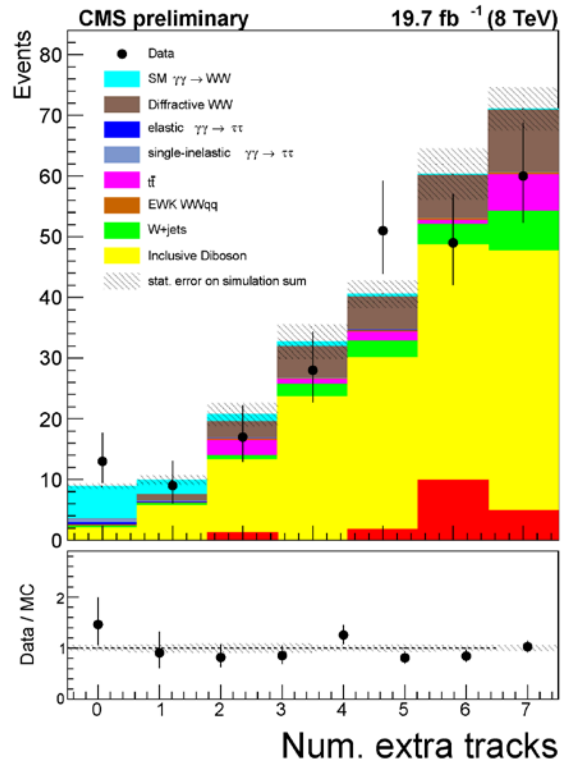
- Use $e\mu$ dilepton final states to establish first evidence for process at 3.6σ (exp 2.4σ).
- Sensitive to aQGC, signature is $e\mu$ tracks pointing to a common primary vertex, with NO other tracks since this process has no underlying event (no color flow).
- Use $\gamma\gamma \rightarrow ee$, $\mu\mu$ exclusive processes as control regions ($P_T(ll) \sim 0$), characterize elastic versus proton dissociation contributions, also use sidebands in $P_T(ll)$ plus number of extra tracks at vertex to characterize additional mis-associated tracks.
- Use Pompyt to estimate diffractive WW production => very small.



Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production (CMS)

- Measure $\sigma(p^* \mu e\ p^*) = 12.3\ ^{+5.5}_{-4.4}$ fb (includes elastic and p dissociation), SM prediction is 6.9 ± 0.6 fb.
- Compatible, although observed cross-section is factor 1.9 larger than expected.
- Derive limits on dim 6 and dim 8 aQGC (see summary later).





CMS WVγ

WWγ/WZγ (WVγ) Production (CMS)

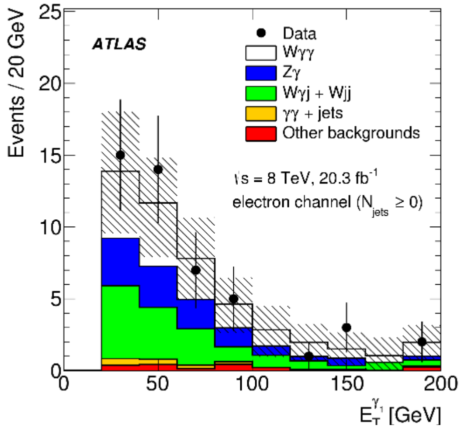
- CMS performed a search for this process with lνjjγ final state, $E_T(\gamma) > 10$ GeV.
- Signal is modeled by Madgraph. Set limits on dim 6 aQGC – limits significantly poorer than for exclusive $\gamma\gamma \rightarrow WW$ process.

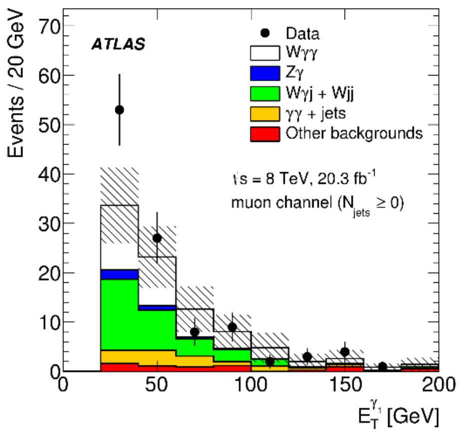
$$-21 < a_0^W/\Lambda^2 < 20\,\text{TeV}^{-2},$$
$$-34 < a_C^W/\Lambda^2 < 32\,\text{TeV}^{-2},$$
$$-25 < f_{T,0}/\Lambda^4 < 24\,\text{TeV}^{-4},$$
$$-12 < \kappa_0^W/\Lambda^2 < 10\,\text{TeV}^{-2},$$
$$-18 < \kappa_C^W/\Lambda^2 < 17\,\text{TeV}^{-2}.$$

Evidence for Wγγ Production (ATLAS)

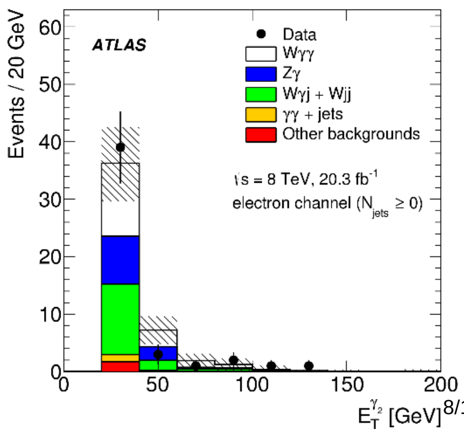
- ATLAS performed a search for this process with $l\nu\gamma\gamma$ final state, $E_T(\gamma)$ > 20 GeV.
- Signal is modeled by Sherpa. Extract inclusive and exclusive (no jets with P_T > 30 GeV) fiducial cross-sections.
- Significance is more than 3σ for inclusive (and cross-section is 1.9σ larger than expected).

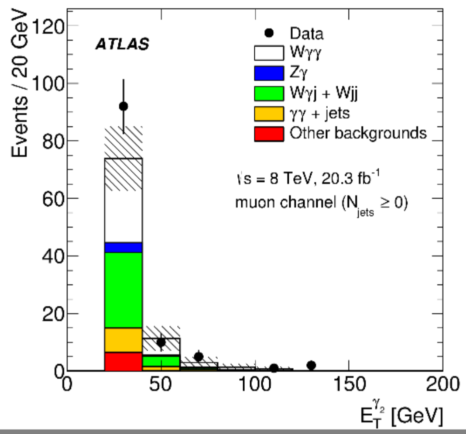
Leading γ E_T distribution





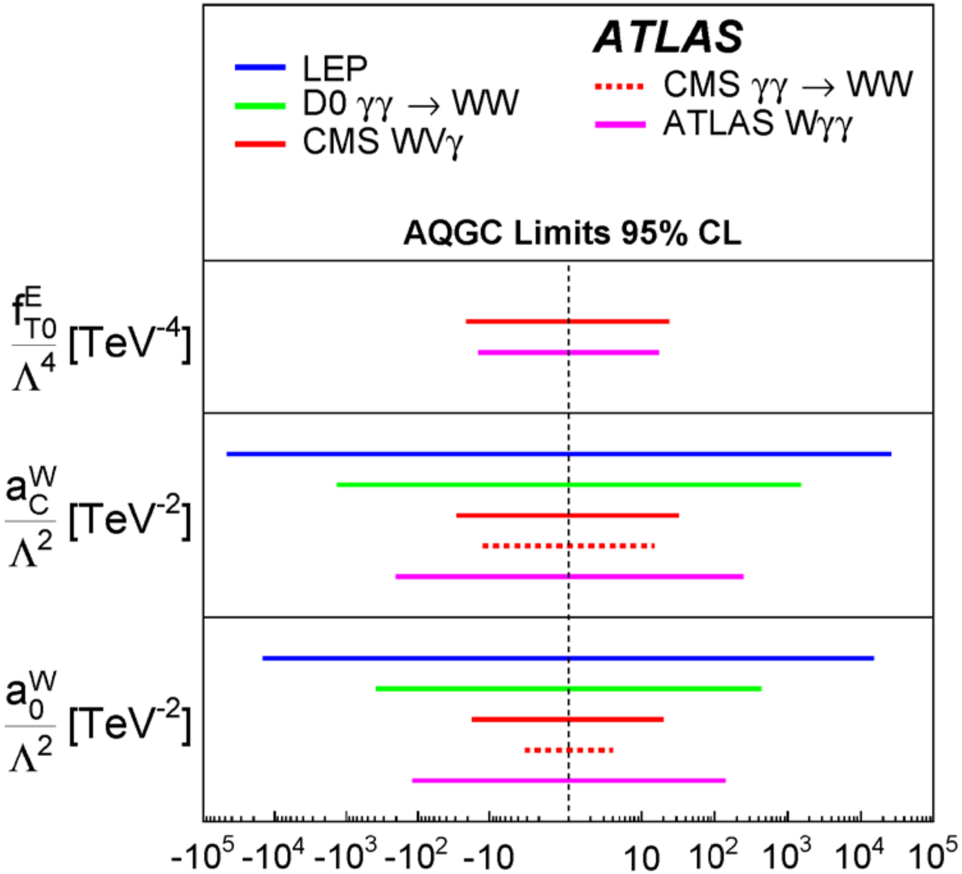
Sub-leading γ E_T distribution





Summary of aQGC Limits (compiled by ATLAS)

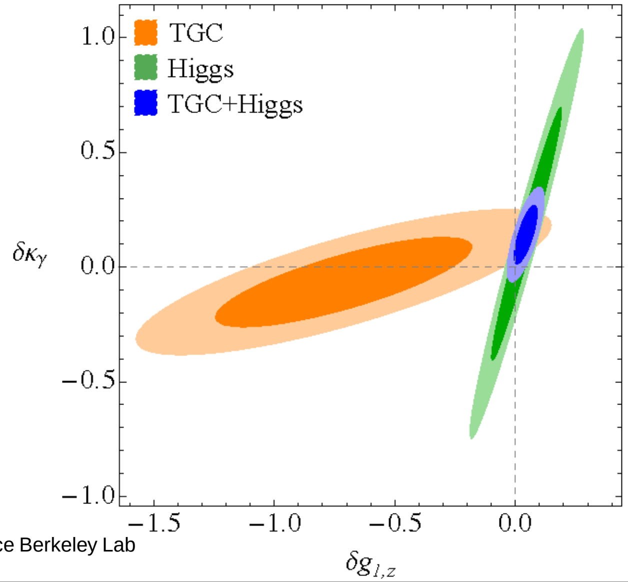
- Compilation from LEP, Tevatron, and three relevant analyses shown in this talk.



- Note in this figure, ATLAS results have been converted to the same convention (Eboli et al.) as for CMS (multiply by g^4), and the ATLAS results with "n=0" (no FF) are used.
- Different channels have differing sensitivities. All limits are better than LEP and Tevatron results.

Overall Summary

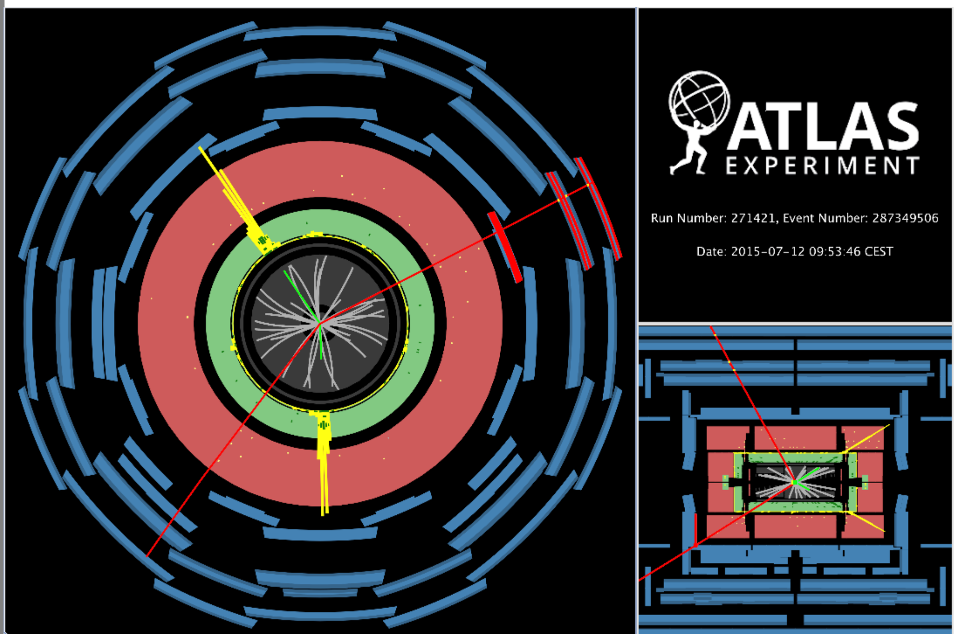
- Run 1 has produced huge range of EWK results, including observation/evidence for VBF, VBS, and tri-boson production.
- Many results still to come, and significant effort will be required to combine results. From 7 TeV, m(W) is most interesting, while from 8 TeV, need full matrix of results from both experiments – channels like WV, WZ, Wγ, and WWW still missing.
- Will be some time (Winter conferences 2017 ?) before Run 2 data will take over from Run 1 in the EWK area => continue efforts with Run 1 data !
- Re-interpretation in global EFT framework will be very useful to allow synthesis with wide range of other results (e.g. Higgs couplings !). Example shown here from recent preprint of Falkowski et al. hep-ph 1508.00581:

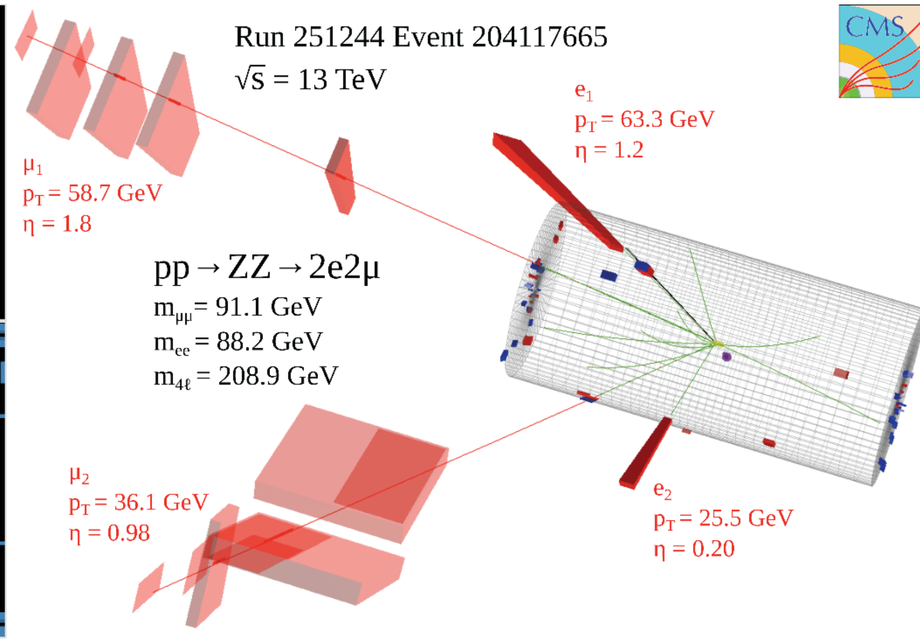


- Note in this figure, compare LEP WW TGC results and LHC Higgs coupling results – ellipses almost orthogonal in this plane => significant reduction in limits when combined through common EFT approach…

Electroweak Physics and Run 2

- Below are some of the first di-boson events from ATLAS (left) and CMS (right) for Run 2. Both are 2e2μ events with two oppositely charged SF lepton pairs in the Z mass window => early ZZ candidates !





Run 2 Electroweak physics has started !