Electroweak Measurements at LHC

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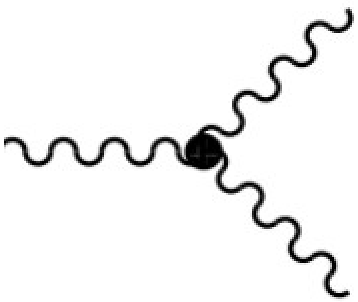
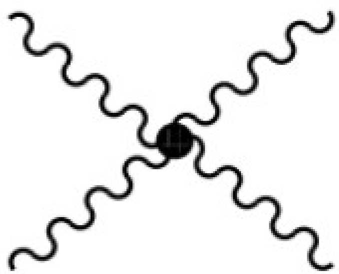
On Behalf of the ATLAS and CMS Collaboration

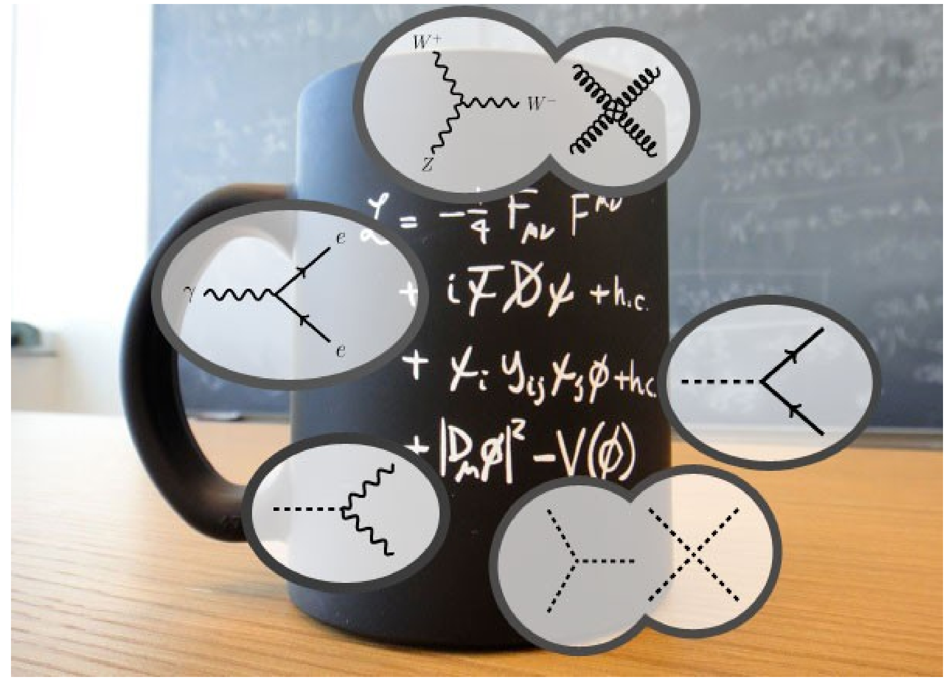
LHCP, September 2nd, 2015

Introduction

- Electroweak sector of the SM based on SU(2)xU(1) gauge group, that is non-Abelian
  - → **Triple and quartic gauge self-coupling**







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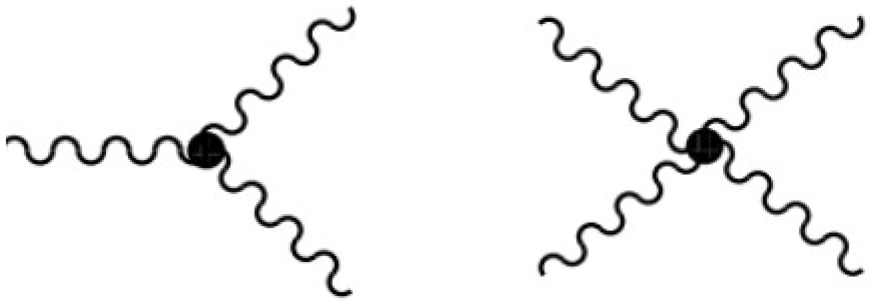

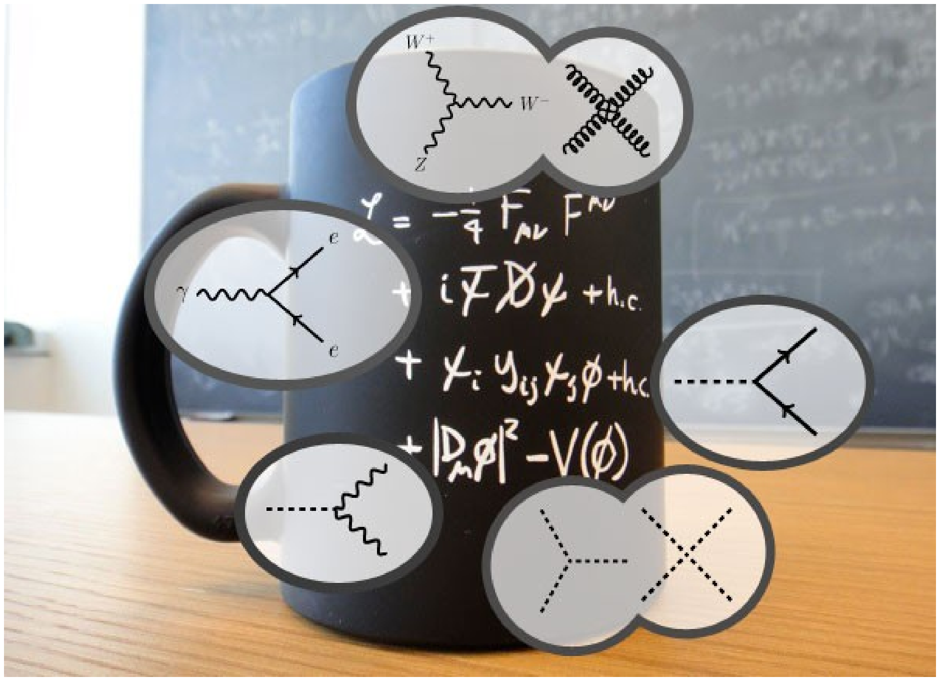

<u>EWK program @LHC in Run 1</u>

- Reached unprecedented precisions
- Observed new processes
- Accessed unexplored corners of phase-space

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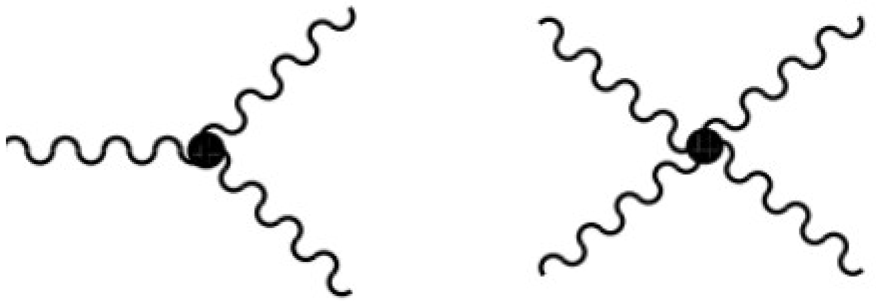
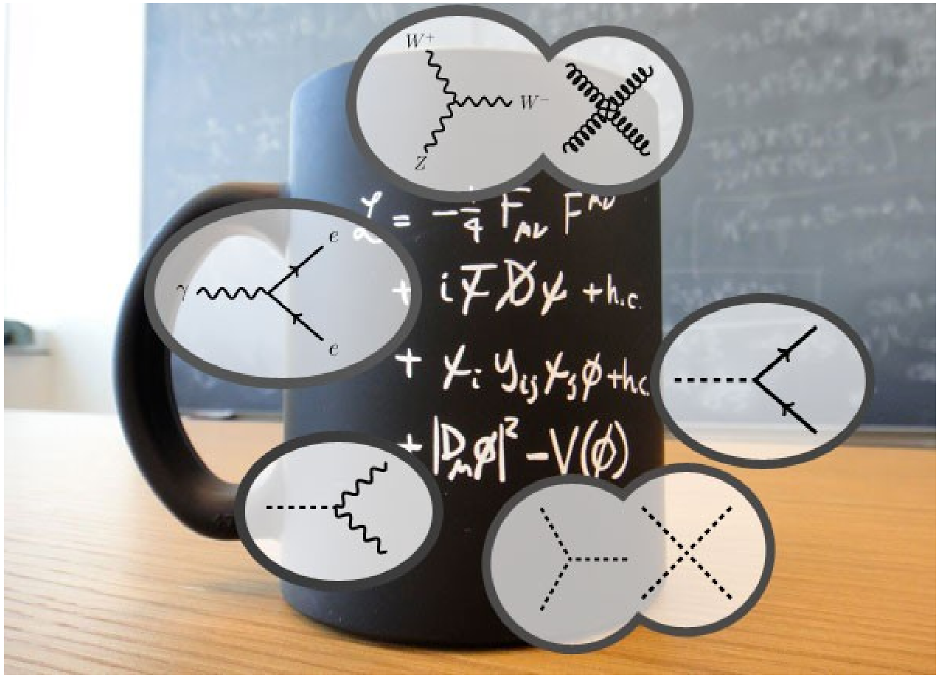




EWK program @LHC in Run 1

- Reached unprecedented precisions
- Observed new processes
- Accessed unexplored corners of phase-space

Measurements require complex analyses (syst. limited)

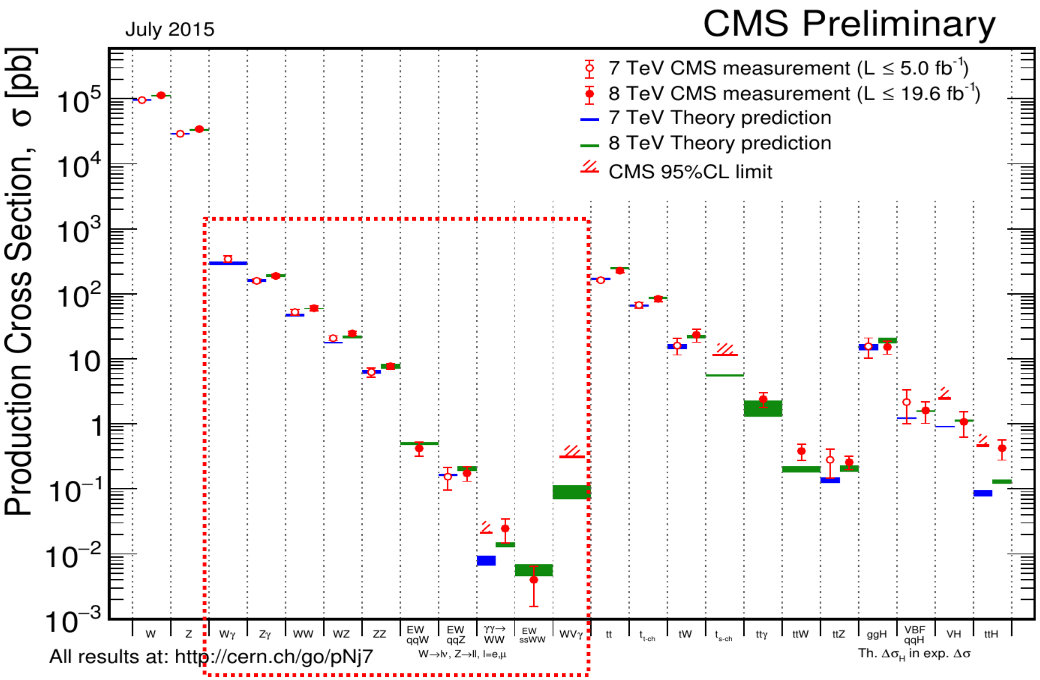
Run 1 more to offer before Run 2 takes over

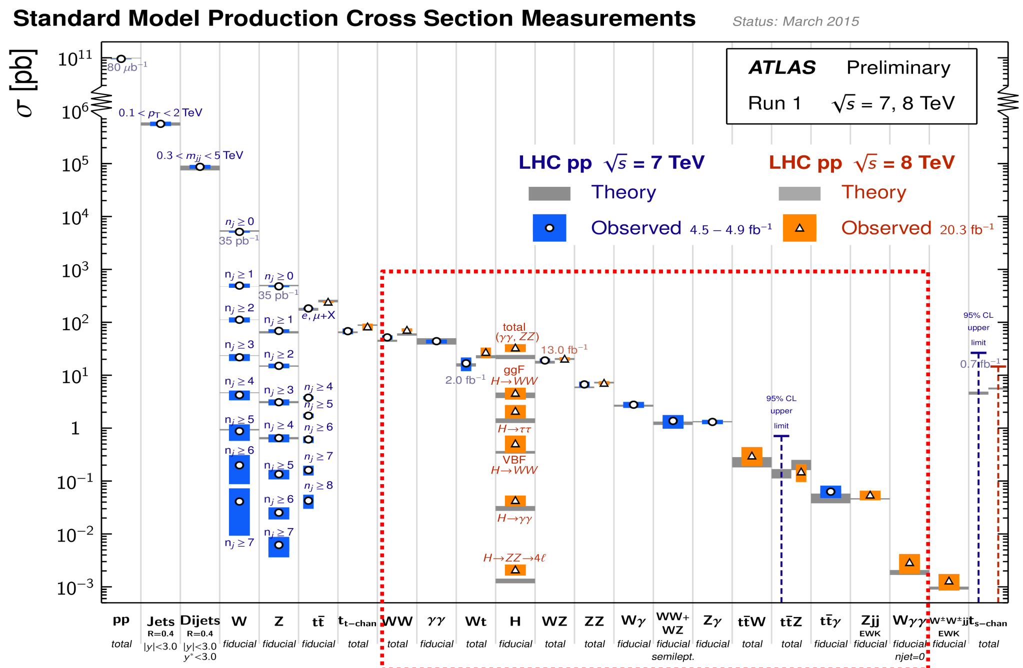
Challenge also for theorists

Experimental results need precise predictions to be correctly interpreted

Outline Of The Talk

ATLAS and CMS Summary Of Cross Section Measurements

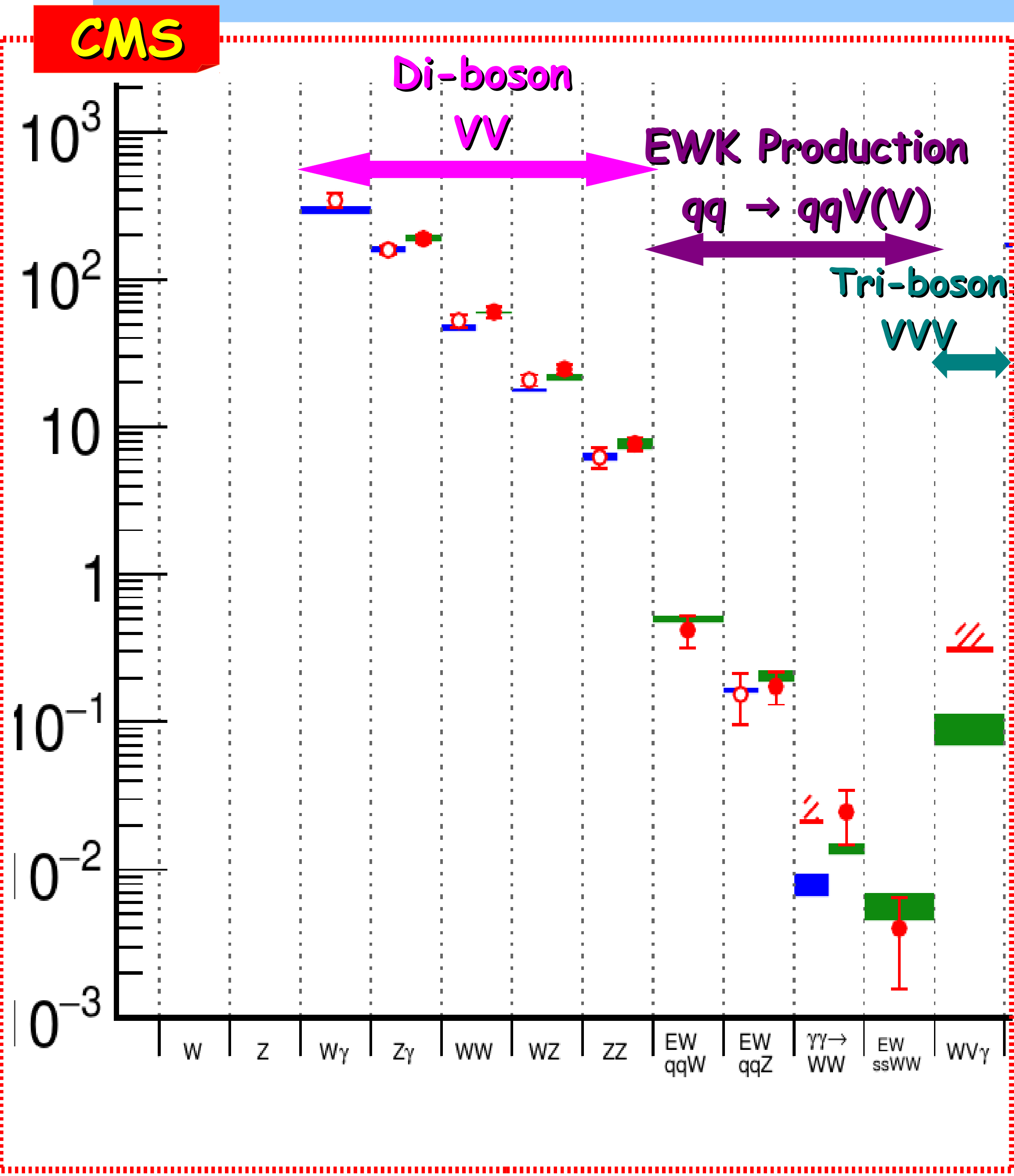


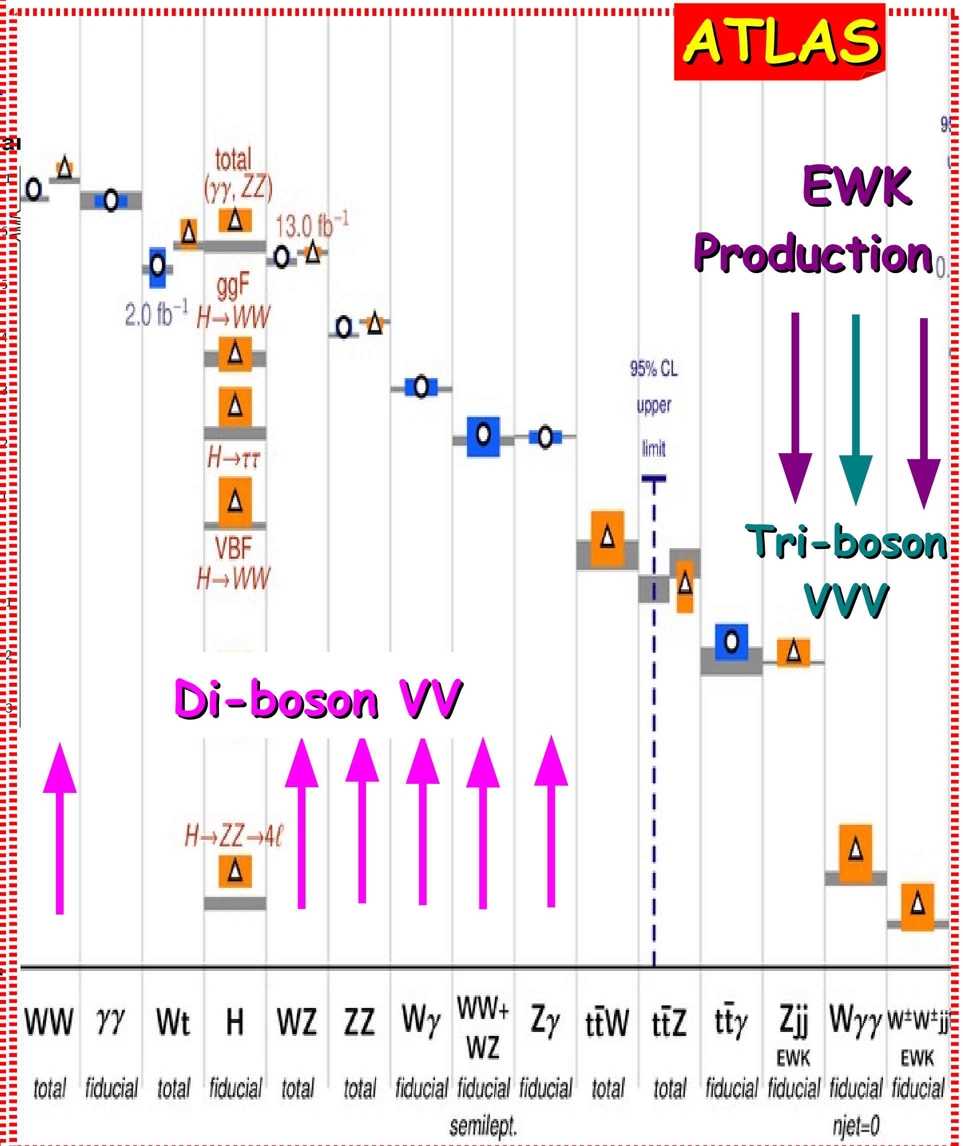


Need a zoom in...

Outline Of The Talk

Disclaimer: only the more recent 8 TeV results in this talk





Diboson Measurements

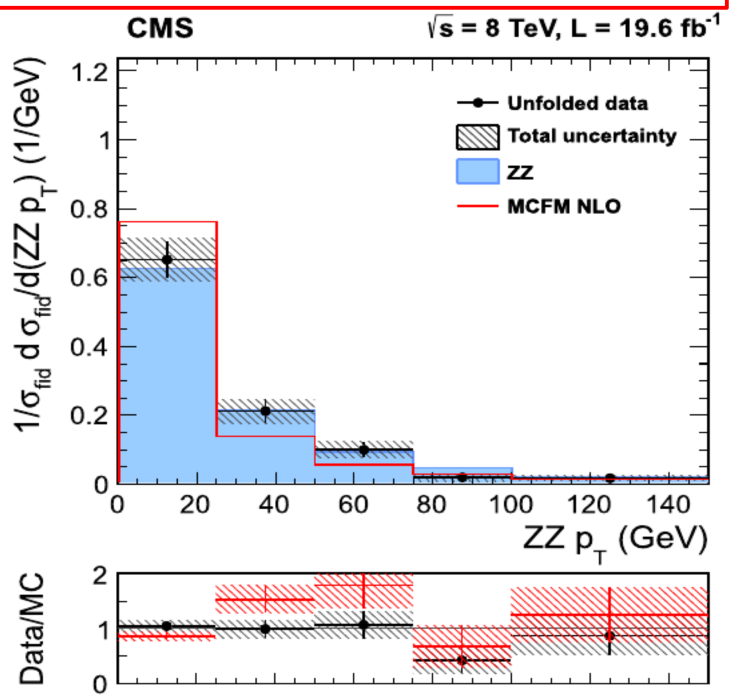
PLB 740 (2015) 250 and CMS PAS SMP-12-016

ZZ Production

CMS

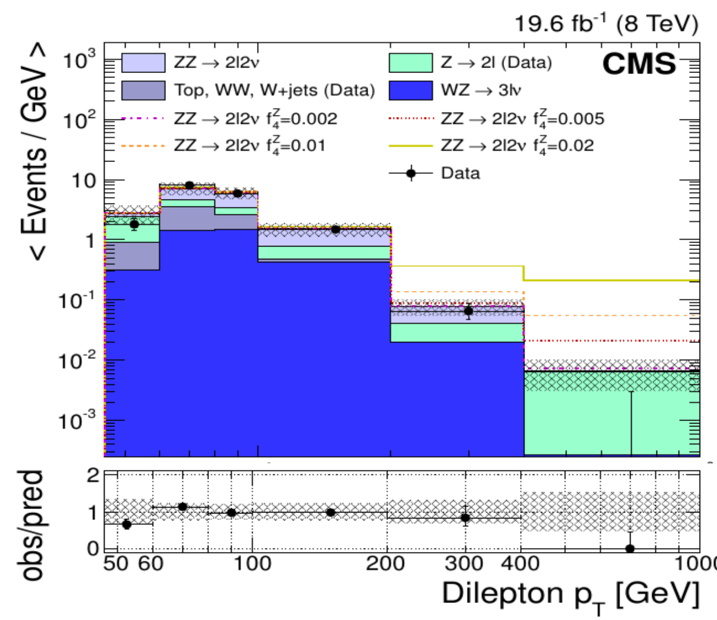
- ZZ → 4l with 2 on-shell Z ($60<m_Z<120$)
  - l=e, μ, τ (τ only in σ, not differential)
  - FSR γ recovery for better m_Z resolution
- Total σ compared with NLO qq → ZZ and LO gg → ZZ
- Stat/Syst/Theory error all O(6-7%)

$$\sigma(pp \rightarrow ZZ \rightarrow 4l) = 7.7 \pm 0.8 \text{ pb}$$
$$\sigma^{MC} = 7.7 \pm 0.6 \text{ pb}$$



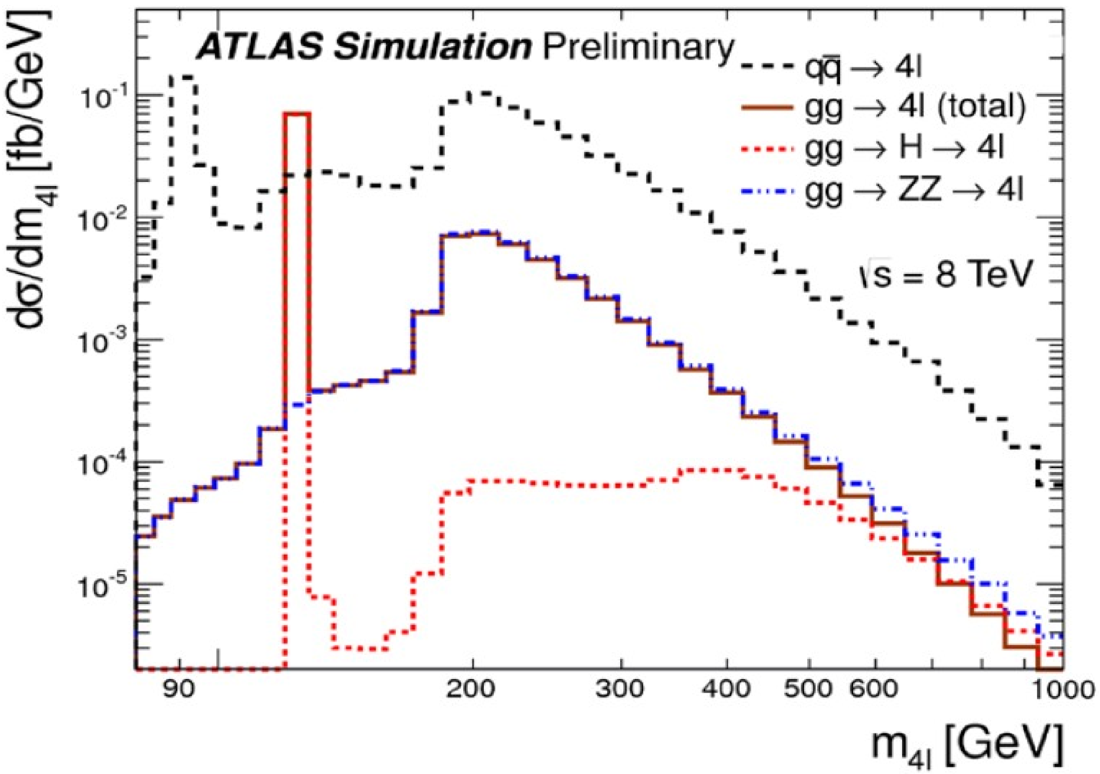
- Measurement recently also in the channel ZZ → llνν
  - $P_T(ll)$ > 45 GeV and MET > 65 GeV
  - l=e, μ
- Predictions with MCFM (NLO)

$$\sigma(8\text{ TeV}) = 6.9 \pm 0.8(\text{stat.})^{+1.8}_{-1.4}(\text{syst.}) \pm 0.3(\text{lumi.}) \text{ pb}$$
$$\sigma^{MC} = 7.42^{+0.37}_{-0.24} \text{ pb}$$
$$\sigma(7\text{ TeV}) = 5.2^{+1.5}_{-1.4}(\text{stat.})^{+1.4}_{-1.1}(\text{syst.}) \pm 0.2(\text{lumi.}) \text{ pb}$$
$$\sigma^{MC} = 6.46^{+0.30}_{-0.21} \text{ pb}$$



4l differential measurement

- Measure differential σ in m(4l) and P_T(4l) for inclusive 4l ($80<m_{4l}<1000$ GeV)
  - Relaxed m(ll) requirement: 12 < m(34) < 120 GeV
  - Very rich physics: resonant Z- and H-bosons, continuum ZZ productions from qq, qg and gg initial states (plus interference). Background very low
  - Theory predictions available at different level of corrections



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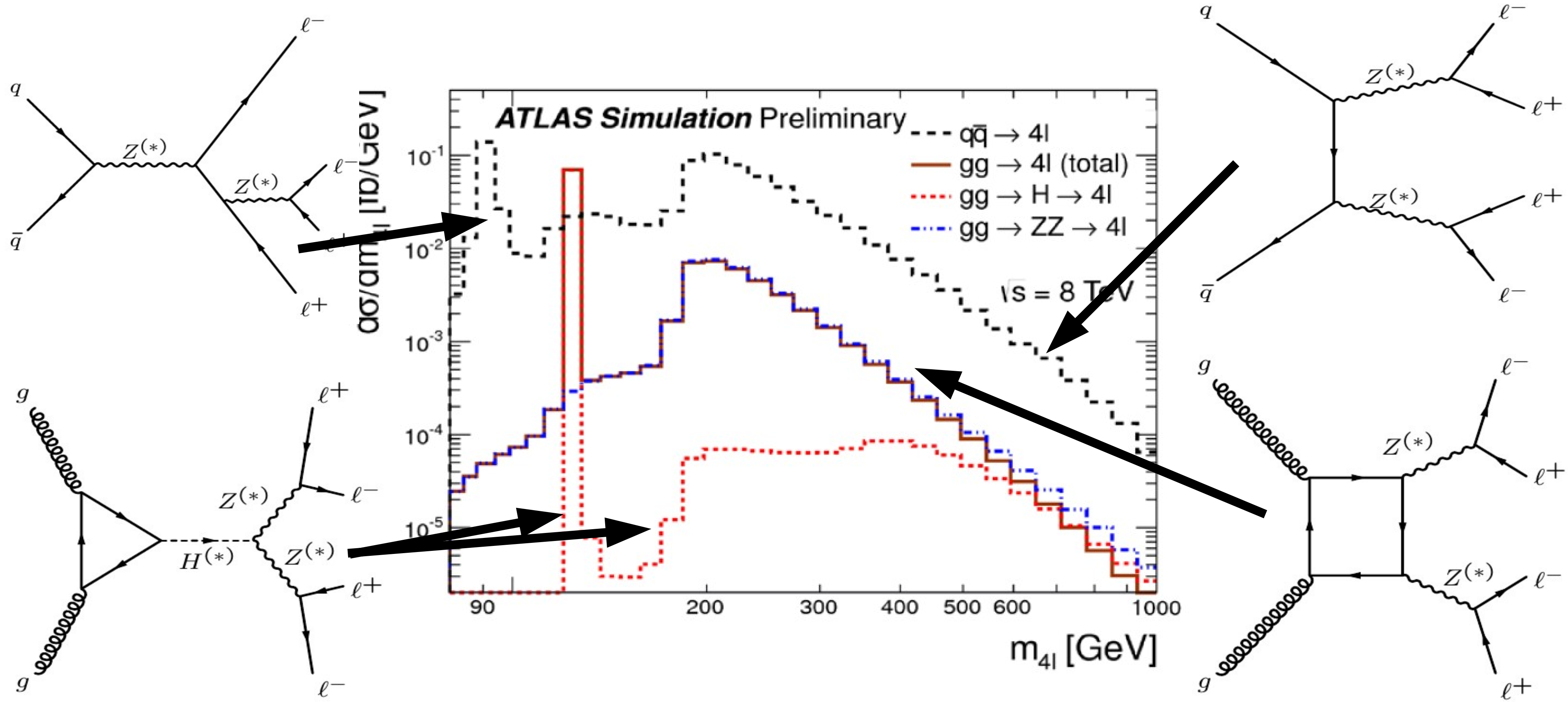

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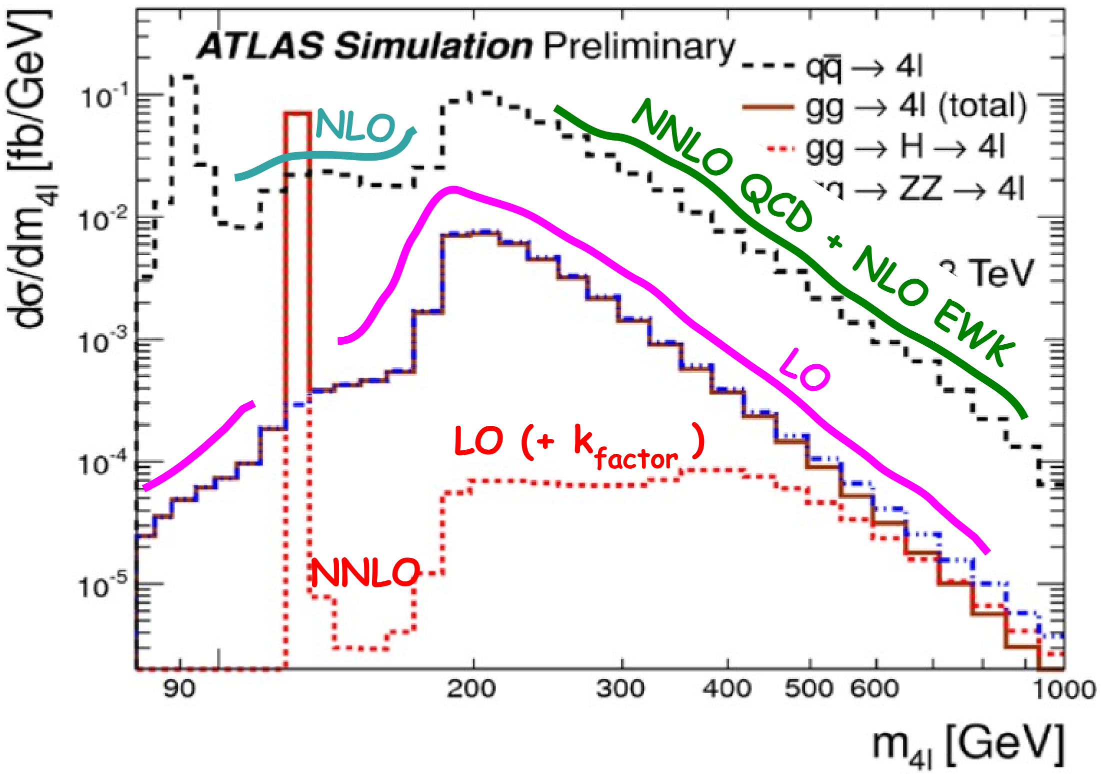
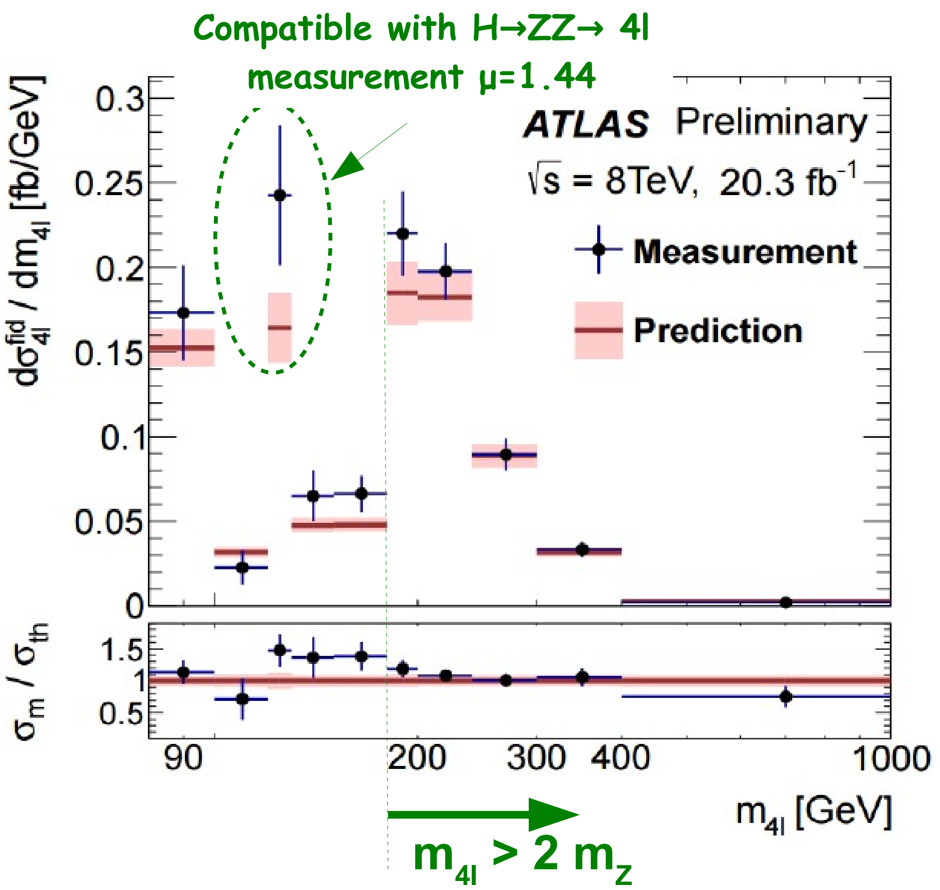


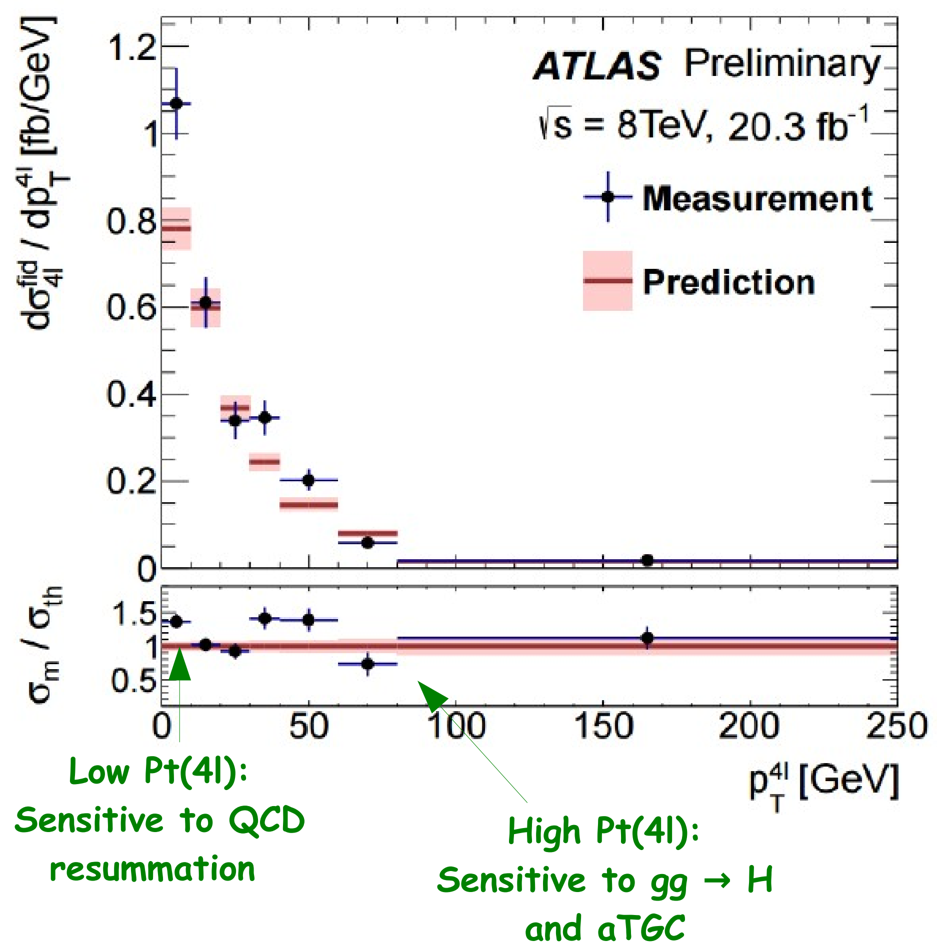
- SM Predictions:
  - qq → ZZ: Powheg (NLO)
  - On-shell H (ggF, VBF): Powheg (NLO)
  - gg → ZZ : MCFM (LO)
- Higher Order Corrections:
  - H → 4l and on-shell qq → ZZ: NNLO QCD + NLO EWK

4l differential measurement

- m(4l) unfolded measurement
  - NNLO normalization AND shape for $m_{4l} > 2\ m_Z$
- Slight excess for off-shell ZZ*region

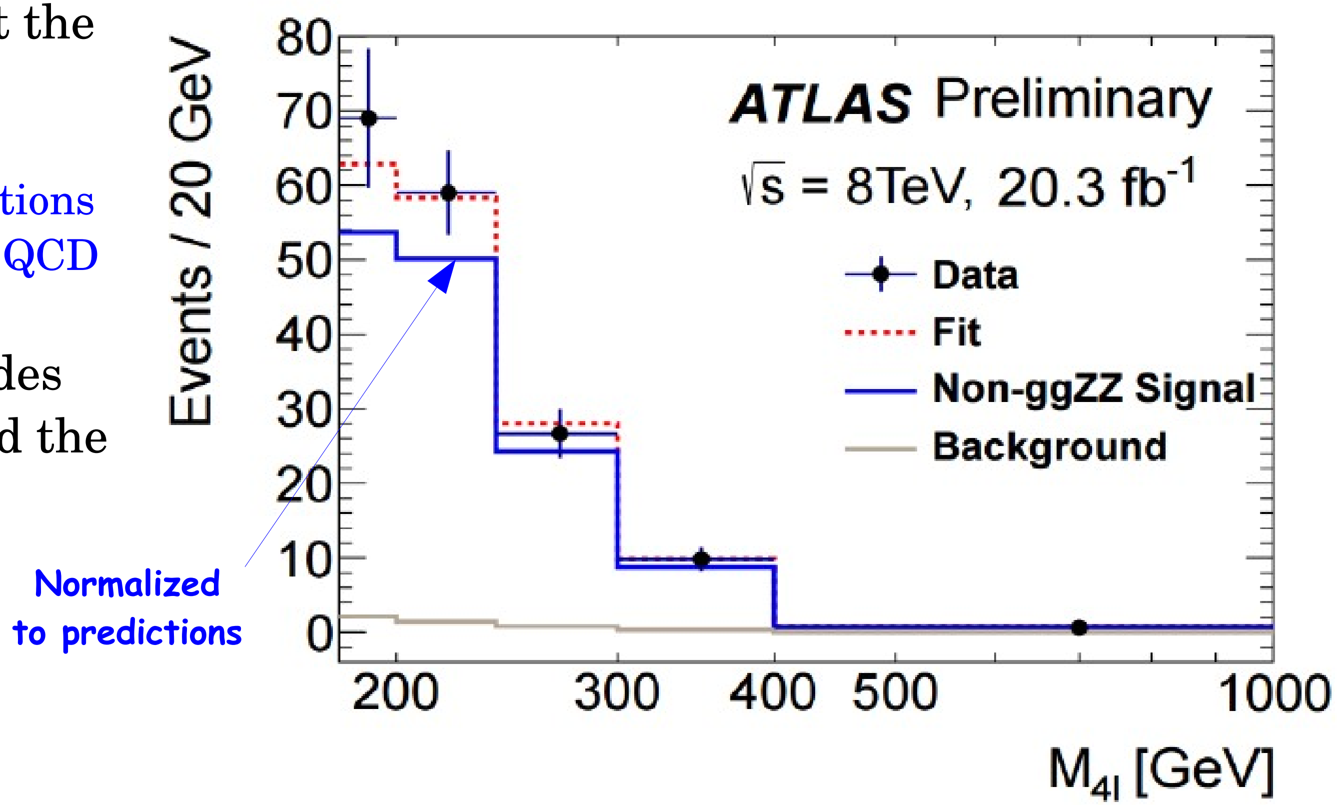
- P_T(4l) unfolded measurement
  - @NLO for the qq production
- Low P_T modeling affected by gluon resummation





4l differential measurement

- For m(4l)> 180 GeV extract the gg → ZZ contributions
  - Non-ggZZ signal (qq → ZZ) subtracted from MC predictions with m_{4l}-dependent NNLO QCD + NLO EWK corrections
- gg → ZZ contribution includes off-shell Higgs, gg → ZZ and the interference



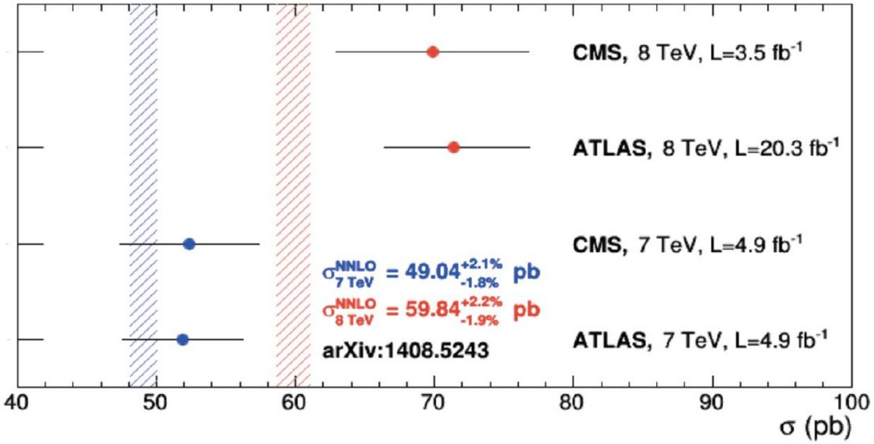
- Derived signal strength w.r.t. current LO prediction
  - $\mu_{gg} = \sigma(\text{data})/\sigma(\text{MC})$

$$\mu_{gg} = 2.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.8(\text{th.})$$

Note: k-factor for off-shell Higgs and interference ~ 3.

WW Production

- Excess of WW production from both ATLAS and CMS with early measurements at 8 TeV



WW Production

CMS

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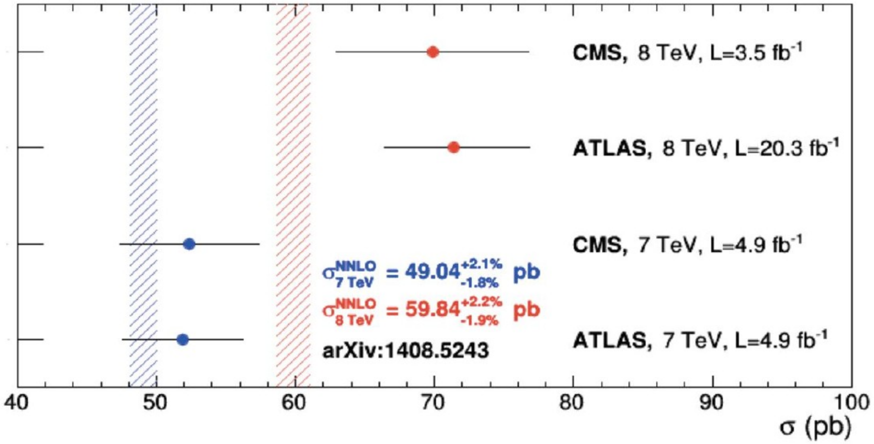


- Recent update from CMS with full 8 TeV dataset and few improvements
  - H → WW included in bkg. (8%)
  - NNLO calculations (7% higher)
  - WW P_t resummation reweighting
  - Madgraph (LO) → Powheg (NLO)
- Measurement done in the 0-jet, 1-jet, same flavor, opposite flavor bin

- Inclusive CMS WW cross section:

$$\sigma^{data} = 60.1 \pm 4.8 \text{ pb}$$
$$\sigma^{NNLO} = 59.8^{+1.3}_{-1.1} \text{ pb}$$

- Good agreement in individual channels:

W^+W^- production cross section (pb.)	
$59.7 \pm 1.1\,(\text{stat.}) \pm 3.3\,(\text{exp.}) \pm 3.5\,(\text{th.}) \pm 1.6\,(\text{lum.})$	0j DF
$64.3 \pm 2.1\,(\text{stat.}) \pm 4.6\,(\text{exp.}) \pm 4.3\,(\text{th.}) \pm 1.7\,(\text{lum.})$	0j SF
$59.1 \pm 2.8\,(\text{stat.}) \pm 6.0\,(\text{exp.}) \pm 6.2\,(\text{th.}) \pm 1.6\,(\text{lum.})$	1j DF
$65.1 \pm 5.5\,(\text{stat.}) \pm 8.3\,(\text{exp.}) \pm 8.0\,(\text{th.}) \pm 1.7\,(\text{lum.})$	1j SF

- CMS cross section in fiducial region,
  - 0-jet WW → eμνν, $p_T(l) > 20$ GeV
  - Jet veto at different P_T threshold

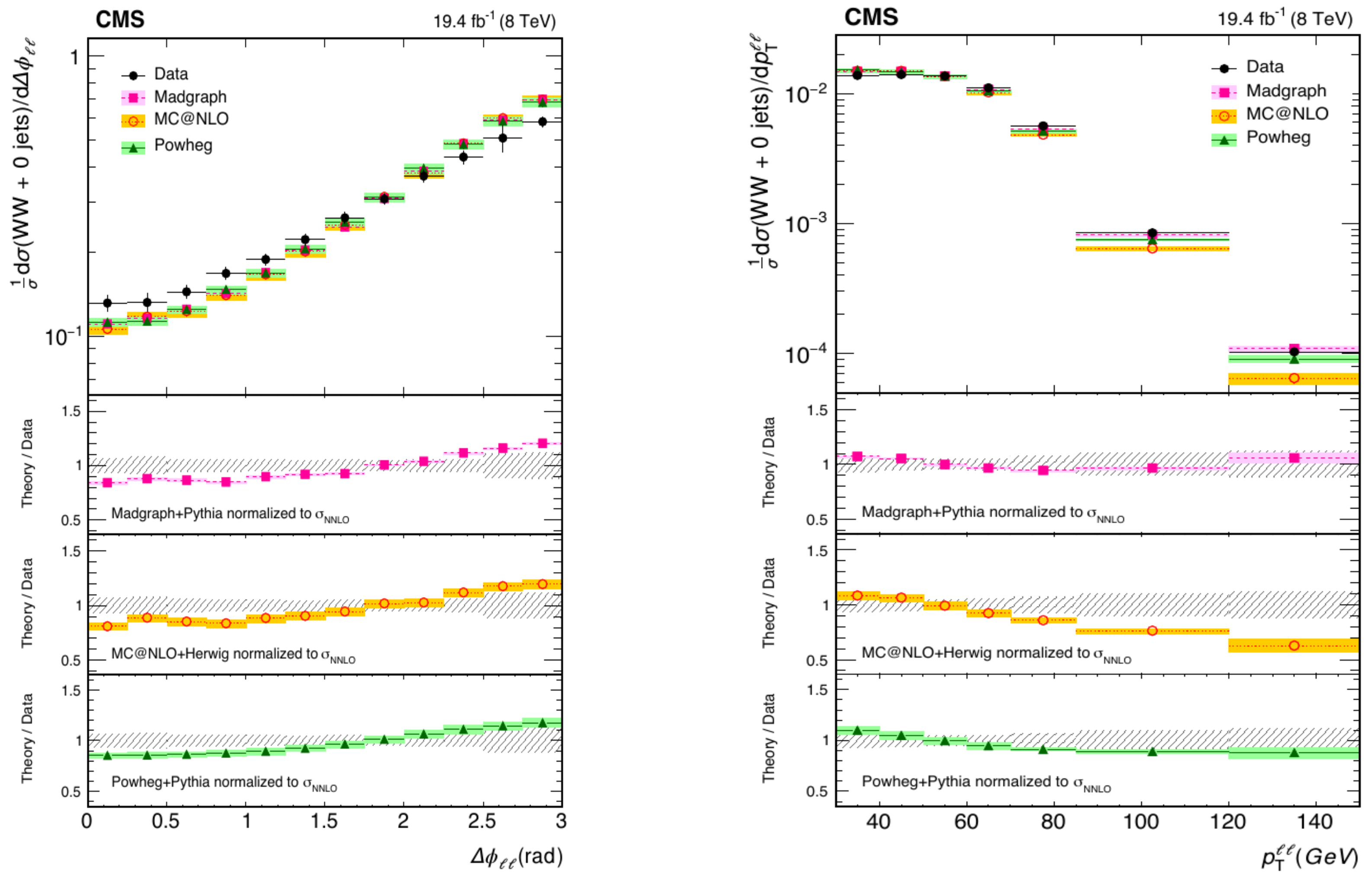
$$\sigma^{data} = 0.273 \pm 0.019 \text{ pb}$$
$$[\sigma^{MC} = 0.274 \pm 0.001 \text{ pb}]$$

[P_T(jet)> 30 GeV]

New CMS cross section results accounting for P_T(WW) resummation in good agreement with NNLO predictions

WW Production

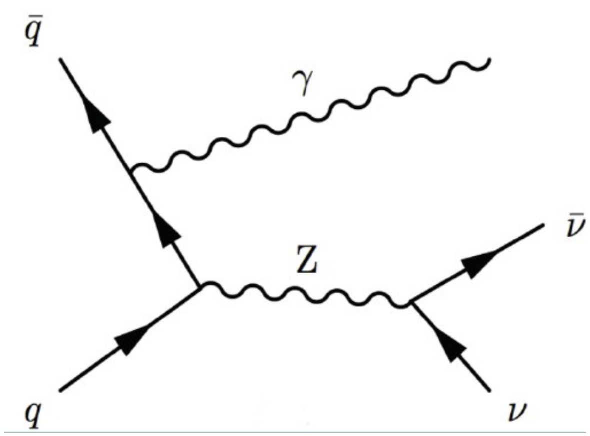
Differential measurements and comparison with different MC all normalized with NNLO prediction → observe still some significant shape discrepancies

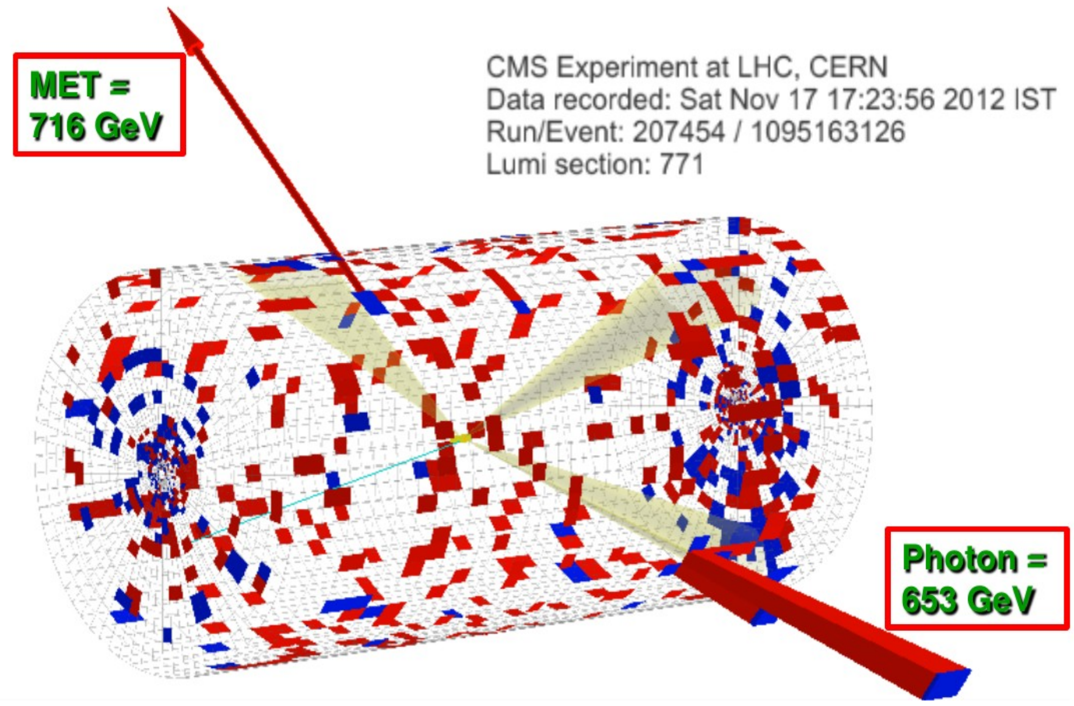


Z γ Production @8TeV

CMS

- High statistic diboson measurement at 8 TeV, no s-channel in SM (Zγγ Vertex)
  - Di-Lepton channel: isolated photons with $P_T > 15$ GeV in barrel/endcap ECAL, ΔR (l, γ)>0.7
    - Main background: DY + jets (→ γ), data-driven estimate
  - Z → νν+γ channel: isolated photons with $P_T > 145$ GeV in barrel ECAL only, $|\eta|<1.44$
    - Main background: W+ γ (16%), W → eν (7%)





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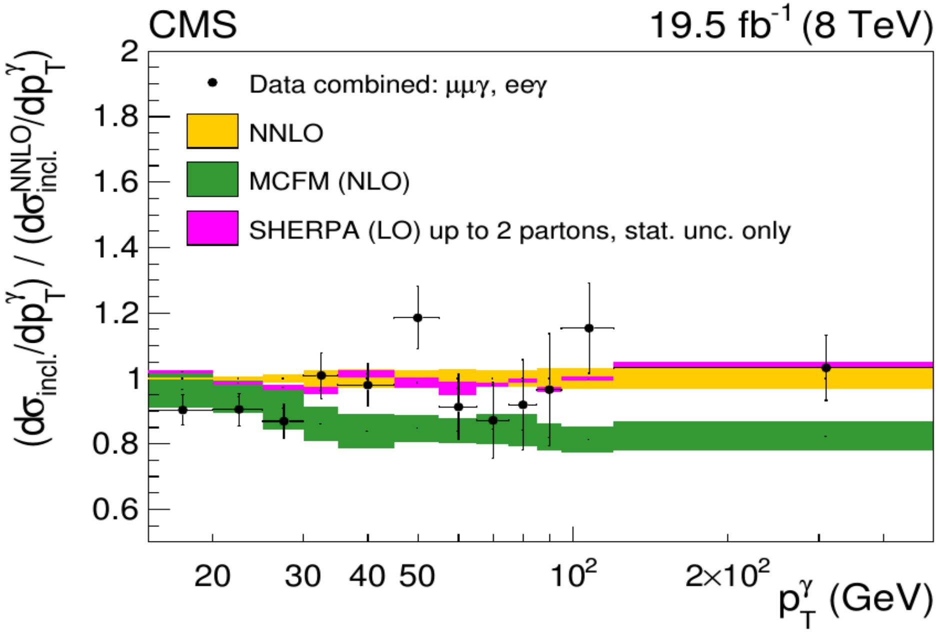
    - Main background: DY + jets (→ γ), data-driven estimate
  - $Z \rightarrow \nu\nu + \gamma$ channel: isolated photons with $P_T > 145$ GeV in barrel ECAL only, $|\eta| < 1.44$
    - Main background: W+ γ (16%), W → eν (7%)
- Cross section measurements for both channels agree well with NNLO predictions

- Neutrino channel fiducial (γ : $P_T > 145$ GeV, $|\eta| < 1.44$)

$$\sigma^{data} = 52.7 \pm 2.1(\text{stat.})6.4(\text{syst.}) \pm 1.4(\text{lumi.})\ \text{fb} \quad [\sigma^{NNLO} = 50.0^{+2.4}_{-2.2}\ \text{fb}]$$

- For lepton channel also differential measurements in $P_T(\gamma)$
  - NNLO/NLO k-factor important at high Pt
  - Sherpa (after global rescaling to NNLO) describes well the P_T shape of the photon

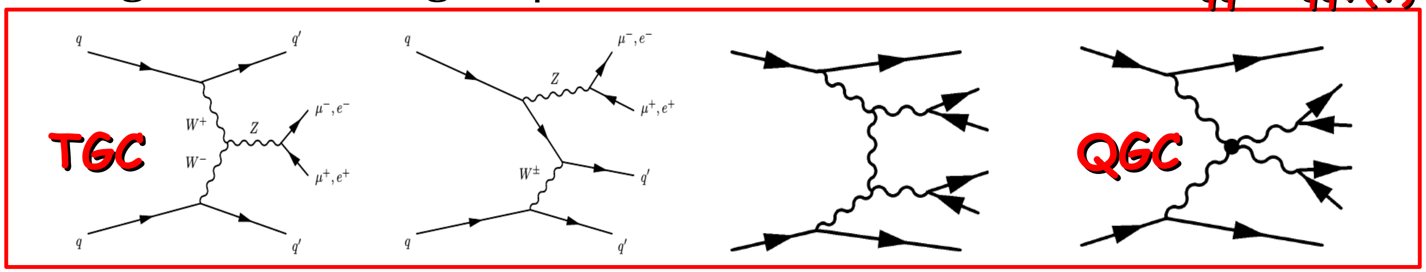


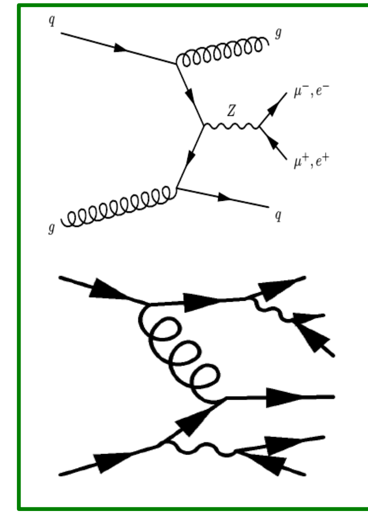
Vector Boson Scattering and Tri-boson Production

(Di-)Boson Electroweak Production

- (Di-)Boson production in association with dijet dominated by $O(\alpha_S^2)$ QCD corrections to inclusive V(V) production
- Rarer contribution from EWK processes qq → qqV(V) with t-channel exchange of color-singlet γ/W/Z or VBS

qq → qqV(V)





(V)V+2j

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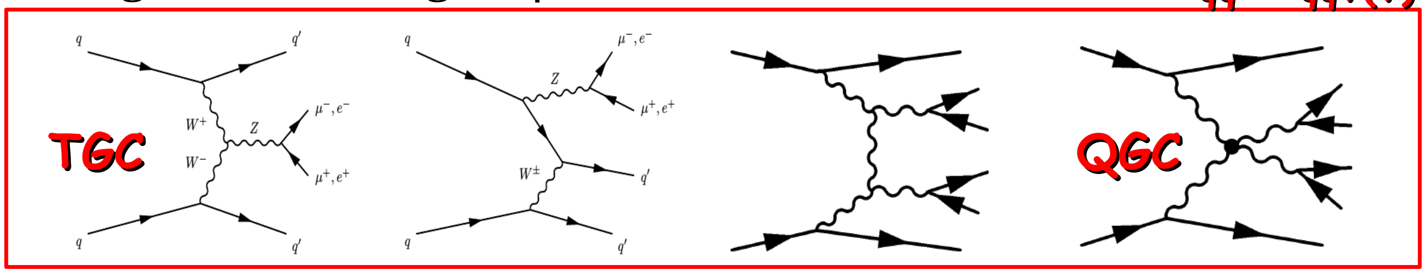
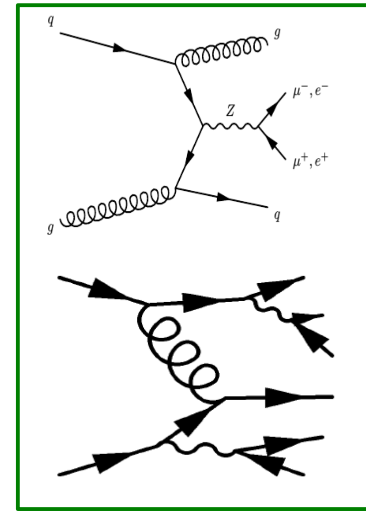
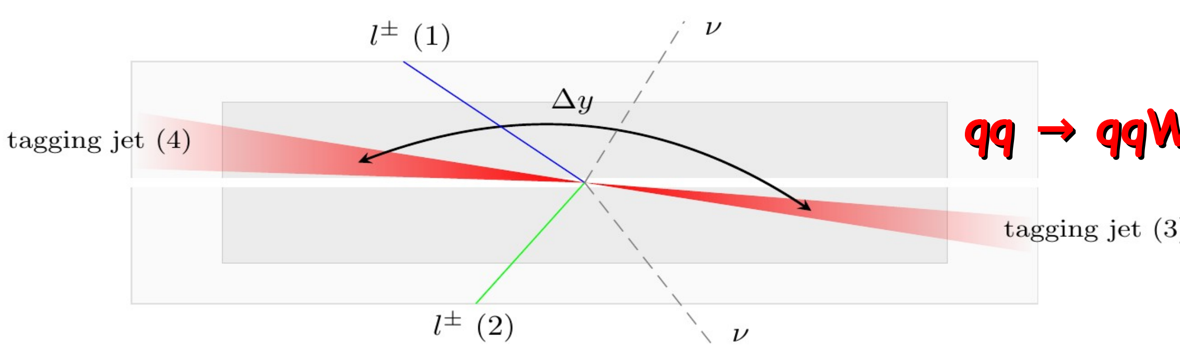


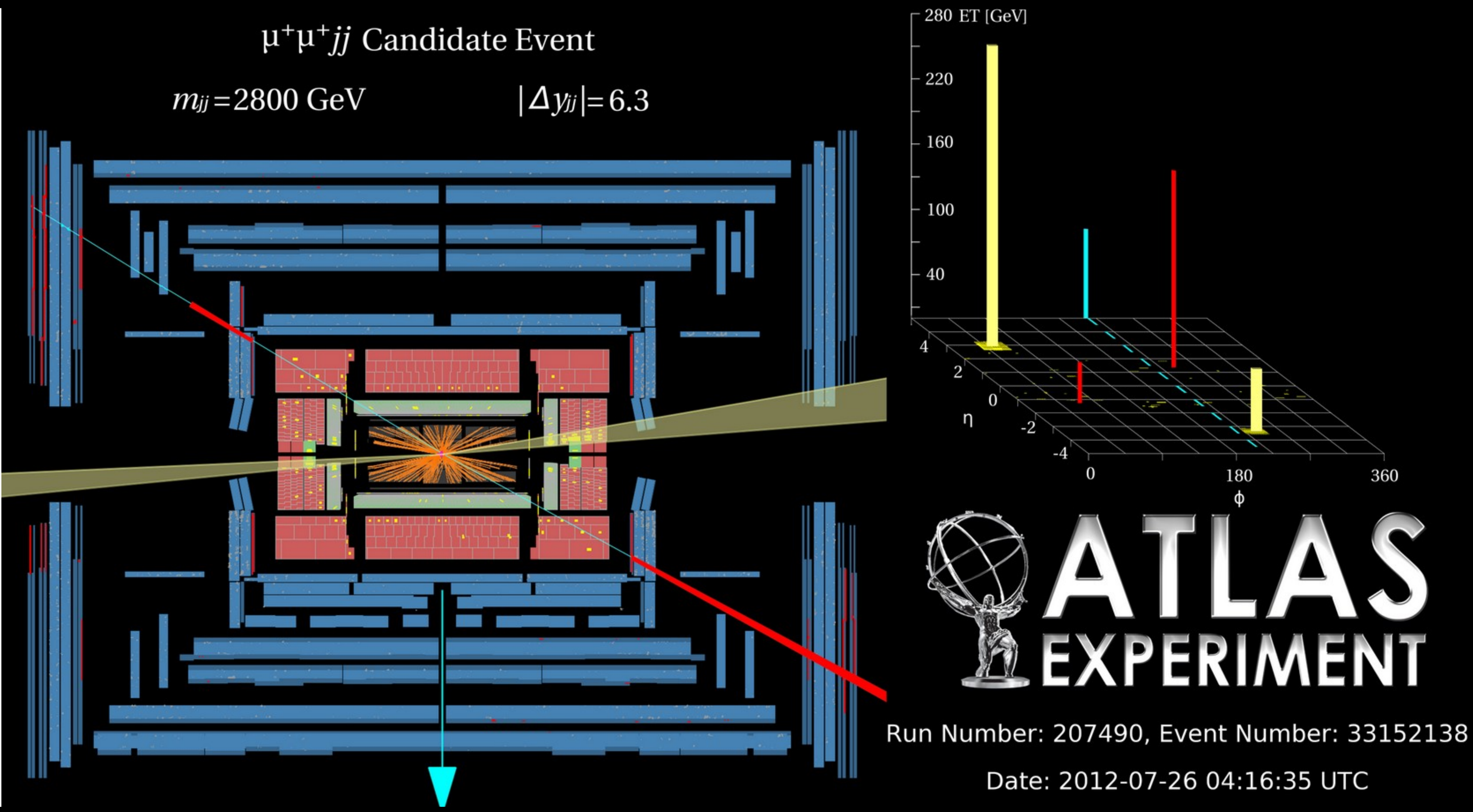


(V)V+2j

- Peculiar signature of EWK production and phase space:
  - Presence of two high energetic hadronic (quark) jets with wide rapidity separation
  - Suppressed hadronic activity “between” the two jets (central region)
  - High m(jj) region (> 500 GeV or more) enriched in EWK production
- Signal extraction allows detailed tests of EWK production modeling, connected with (quartic)triple gauge coupling
  - Strong (V)V+ 2jets production dominating and not well modeled by MC
- EWK production of W and Z measured by ATLAS and CMS (see S. Farry talk)



qq → qqWW


$\mu^+\mu^+jj$ Candidate Event
m_{jj} = 2800 GeV
$|\Delta y_{jj}|$ = 6.3
280 ET [GeV]
220
160
100
40
4
2
0
-2
-4
η
0
180
360
ϕ
ATLAS
EXPERIMENT
Run Number: 207490, Event Number: 33152138
Date: 2012-07-26 04:16:35 UTC

EWK WW Production

- $V_L V_L \rightarrow V_L V_L$ scattering linked to the mechanism responsible for the EWSB
  - The SM Higgs boson cancels increase for large *s* preserving unitarity
- WW scattering essential to experimentally probe the nature of the EWSB
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  - Observed (Expected) Significance: **ATLAS 3.6σ (2.8σ), CMS 1.9σ (2.9σ)**

PRL 114 (2015) 051801 [CMS], PRL 113 (2014) 0141803 [ATLAS]

Same Sign WW Production

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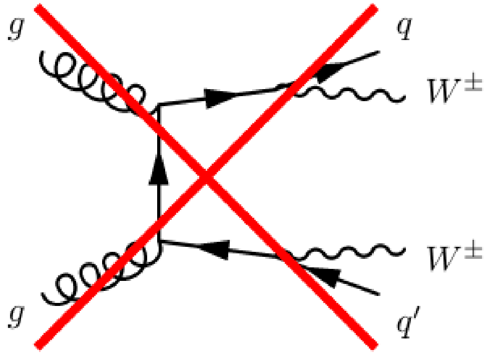
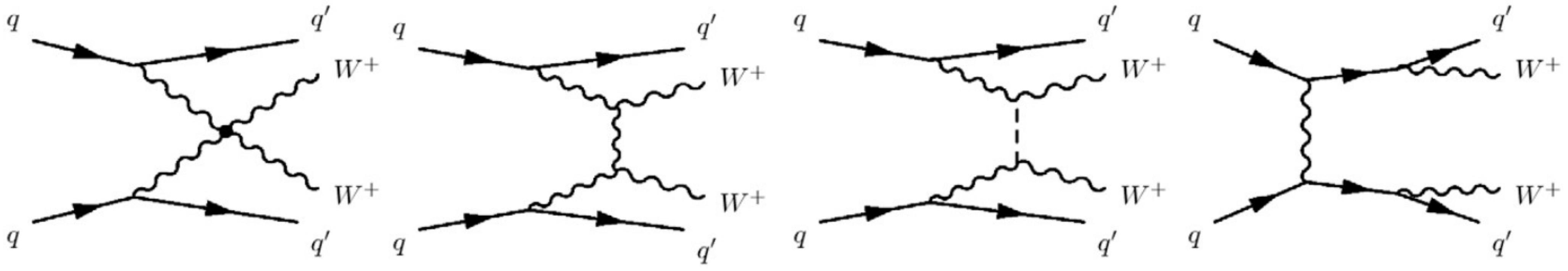
  - Observed (Expected) Significance: **ATLAS 3.6σ (2.8σ), CMS 1.9σ (2.9σ)**
- Experimental Signature:
  - Dilepton + MET + 2jets
  - Combination of "EWK" and "QCD" ($O(\alpha_S^2 \alpha_{EW}^4)$)
- Same sign channel needed:
  - To suppress huge tt background
  - To suppress "QCD" (no gg initial state)
    - "EWK"/"QCD" ~ 1:1
  - Charge flip (e-channel), WZ → 3l and non-prompt leptons main background
  - Quark/gluon tagging for VBS jets by CMS

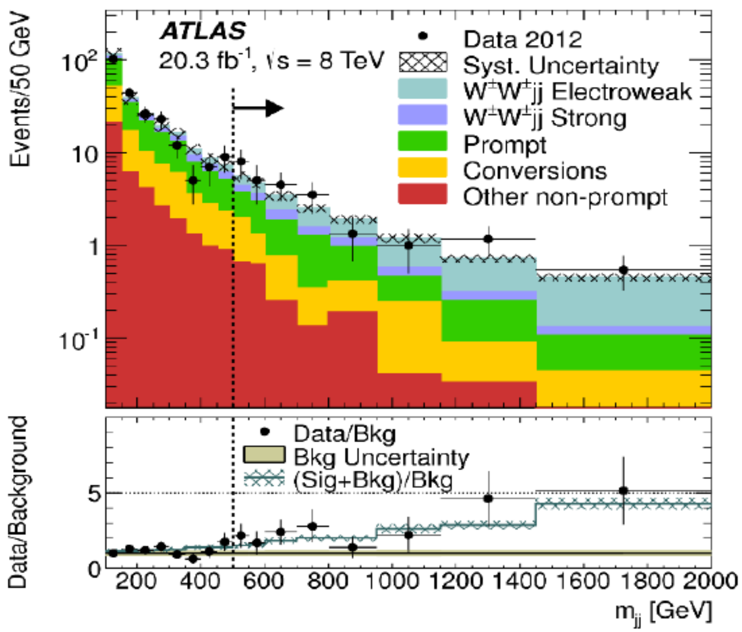


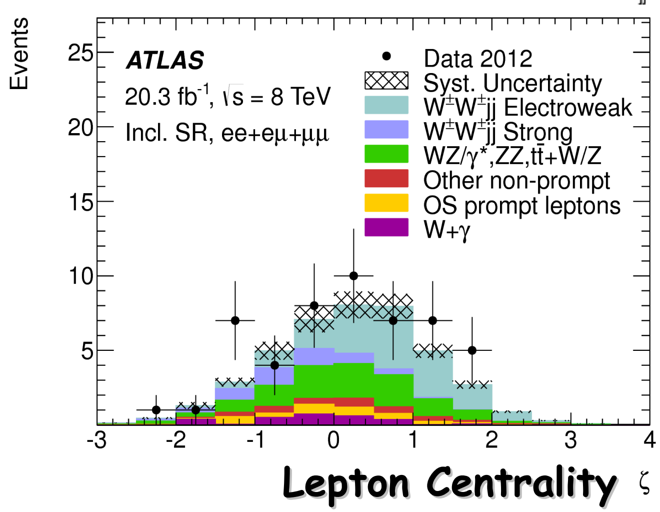
Typical "EWK" contributions



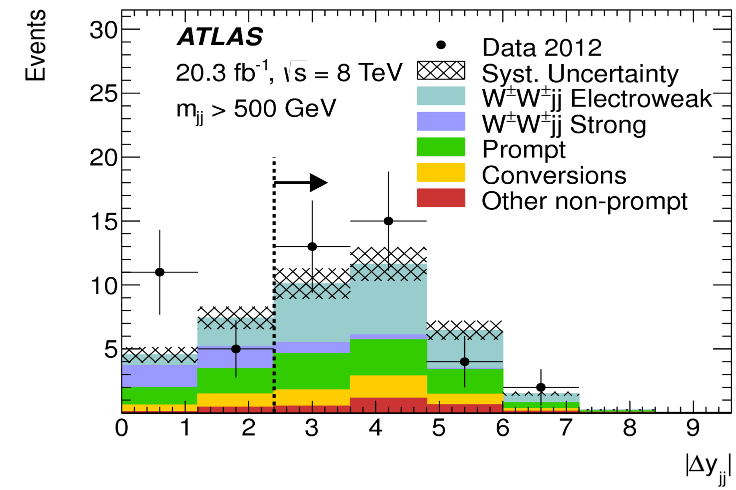
ssWW Production

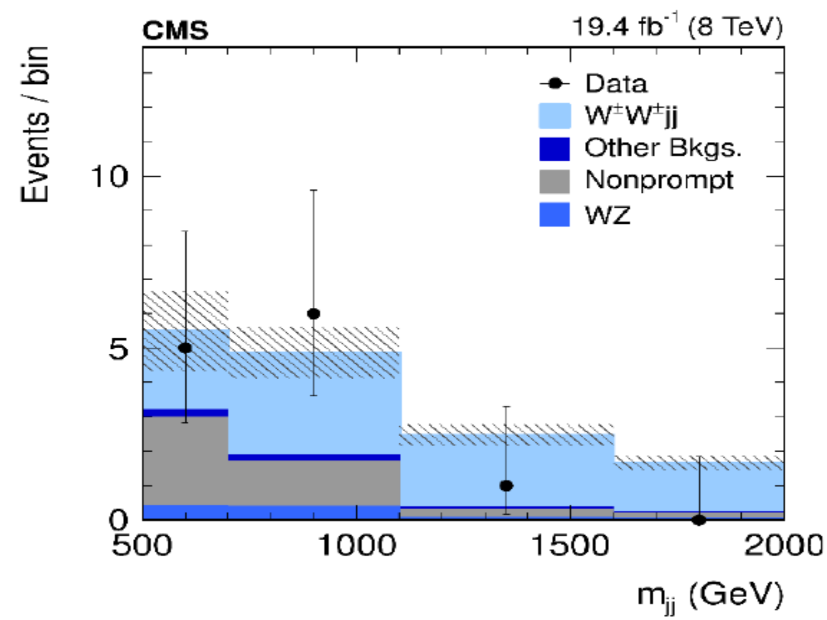
- ATLAS measured also “EWK+QCD” in m_{jj}> 500 GeV region





- Sensitivity to EWK increases in phase space with m_{jj}>500 and |Δη|>2.5

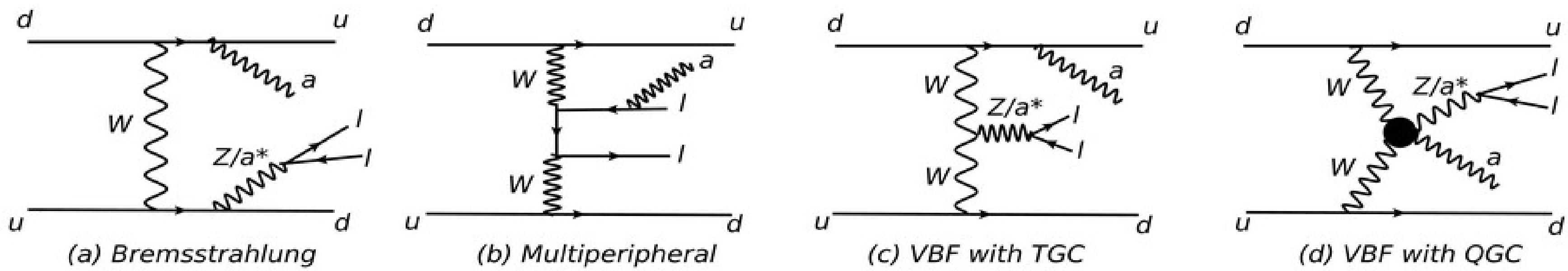




Off-Press from CMS

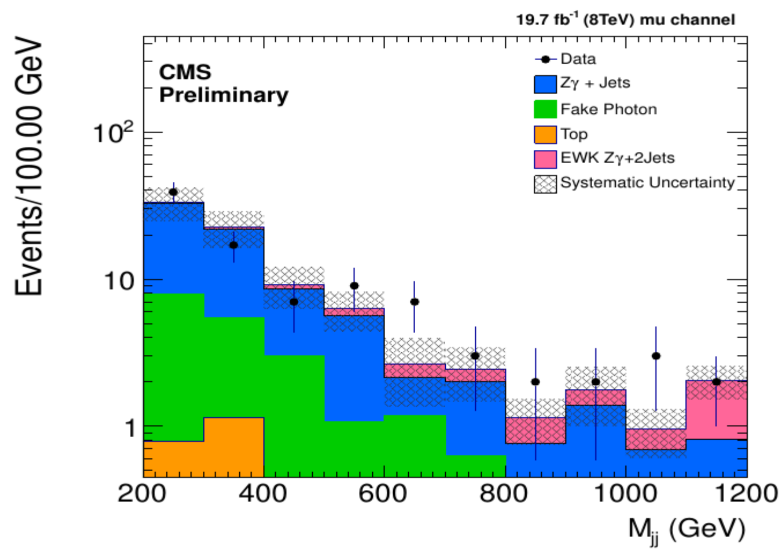
CMS PAS SMP-14-18 [CMS]

Z γ Electroweak Production



Evidence of: qq → qqZγ ($l^+ l^- \gamma$ j j)

- (Relatively) High VV EWK cross section
- Final state can be fully reconstructed
  - m(Zγ) related to the VBS scale
- Significant strong production: Z γ + 2j
  - Modeled from control region and subtracted



- Cross Section Phase Space:
  - 2 lep. + 1 γ P_T> 20 GeV (|η(γ)|<1.44)
  - 70 < m(ll) < 110 GeV
  - M_{jj} > 400 GeV and |Δη(jj)|>2.5

$$\sigma^{EWK} = 1.86^{+0.89}_{-0.75}(\text{stat.})^{+0.41}_{-0.27}(\text{syst.}) \pm 0.05(\text{lumi.})\ \text{fb}$$

$$\sigma^{MC} = 1.26 \pm 0.11(\text{scale}) \pm 0.05(\text{PDF})\text{fb}$$

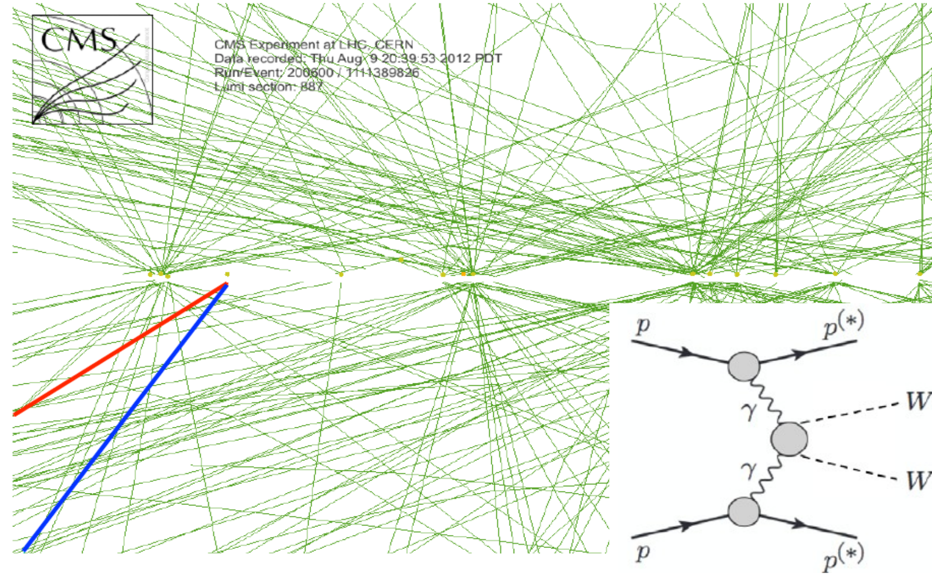
- Dedicated phase space for aQGC

- In an EWK enriched phase space:
  - Observed (exp.) significance: **3.0σ (2.1σ)**

Exclusive γγ → WW Production

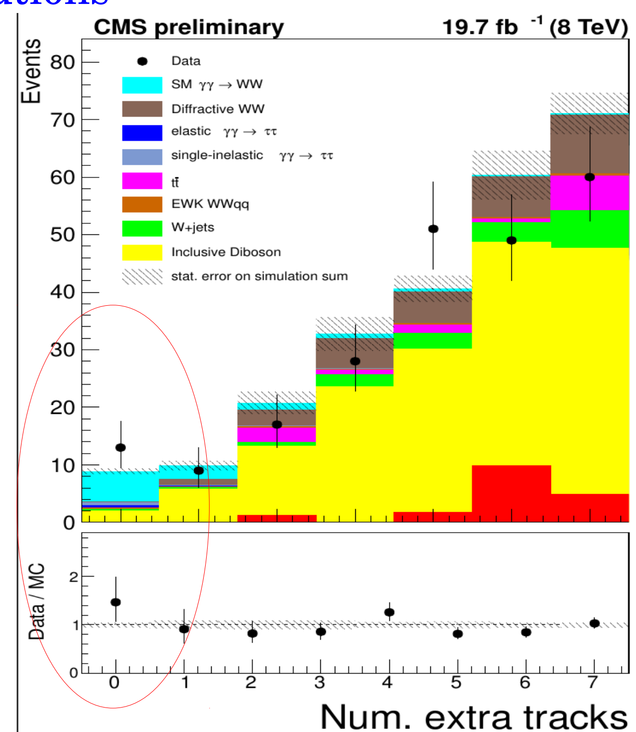
CMS

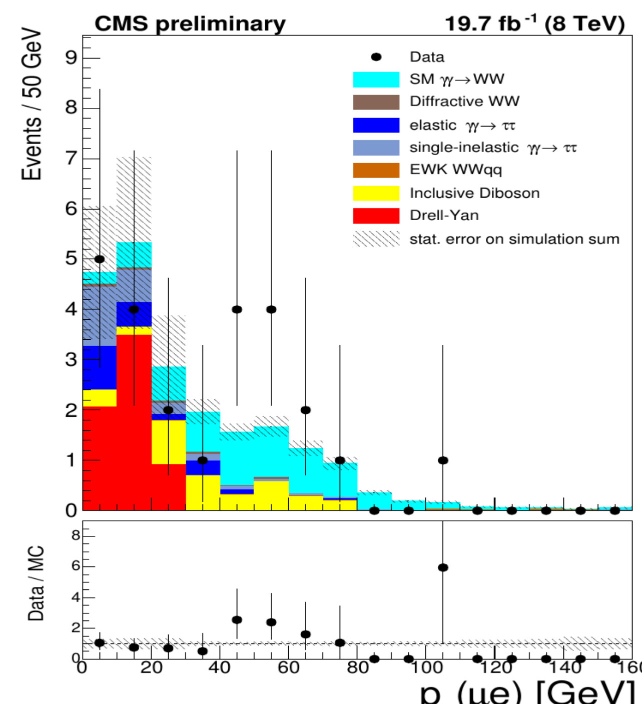
- Probing the γγWW vertex with exclusive production
- Key signature:
  - 2 lepton tracks from same primary vertex and no other charge particles
- eμ channel to suppress DY and γγ → l+l- exclusive process
  - γγ → ee, μμ used as control sample at $P_T(ll) \sim 0$ to study charged track veto and characterize to correct for non-elastic contributions



- Results:
  - Signal region: m(eμ)>20 GeV and p_T(eμ)> 30 GeV
  - 5.3±0.1 (3.5±0.5) signal (background) expected
  - 13 data events observed (1.2σ above exp.)

$$\sigma(pp \to p^{*}WWp^{*} \to p^{*}e\mu\nu\nu p^{*}) = 12.3^{+5.5}_{-4.4}\ \text{fb}$$





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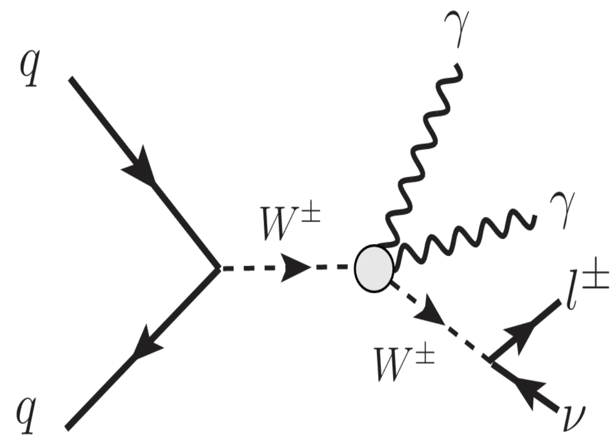
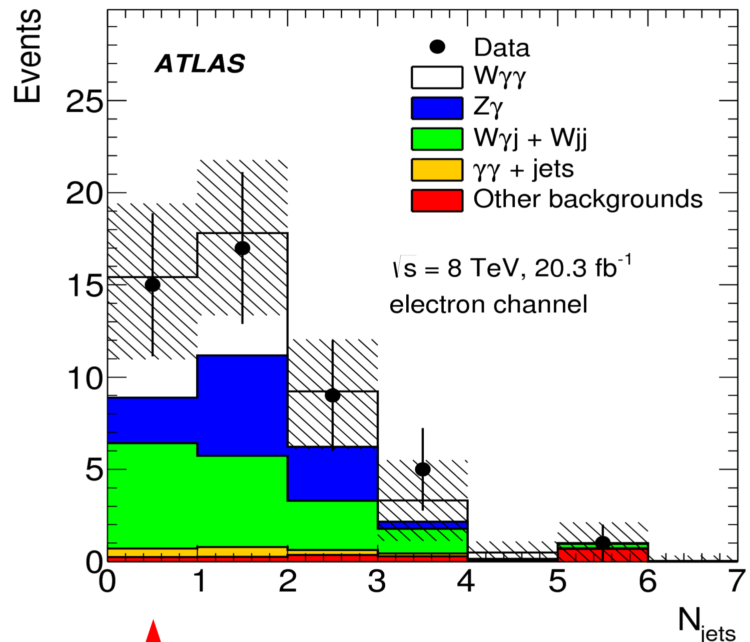
ATLAS

Wγγ Production

- First evidence of tri-boson production
  - Sensitive to (anomalous) quartic coupling
- Signature:
  - Lepton+MET, and 2 photons
    - $E_T(\gamma) > 15$ GeV and isolated
  - Main contribution from W + 2 (1) ISR γ
- Background:
  - Jet→γ [Wγ +jets] and e→γ [Z(e"γ")γ]
- Results:
  - Measurements in inclusive ($N_{jet} \geq 0$) and exclusive region ($N_{jet} = 0$)
  - Significance >3σ (combined)
  - Stat/syst unc.: 20%/20% (inclusive region)
  - Upwards fluctuation w.r.t. NLO predictions
    - 1.9σ compatibility for the inclusive measurement

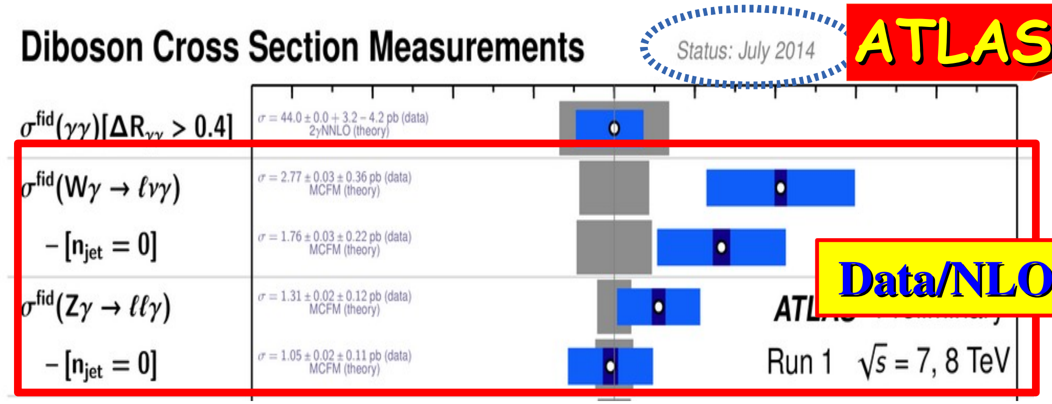




$\sigma = 6.1^{+1.1}_{-1.0}(\text{stat.}) \pm 1.2(\text{syst.}) \pm 0.2(\text{lumi.})$ pb $[2.90 \pm 0.16\ (NLO)]$	Inclusive Region
$\sigma = 2.9^{+0.8}_{-0.7}(\text{stat.})^{+1.0}_{-0.9}(\text{syst.}) \pm 0.1(\text{lumi.})$ pb $[1.88 \pm 0.20\ (NLO)]$	Exclusive Region

Intermezzo: NNLO Vγ Predictions

- Wγ cross section at 7 TeV showed significant disagreement with NLO SM predictions (similar findings from CMS)
  - One of the motivation for the exclusive (N_{jet} = 0) measurement, to suppress high order radiation
  - Less pronounced effect on Zγ



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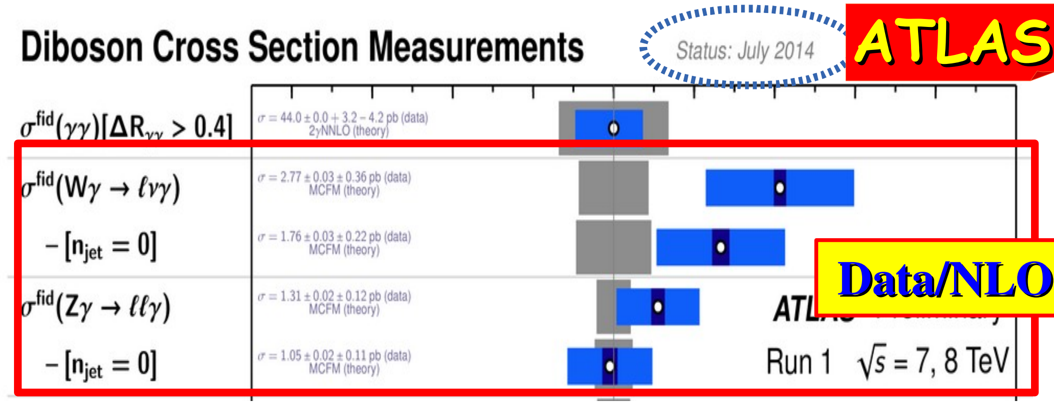
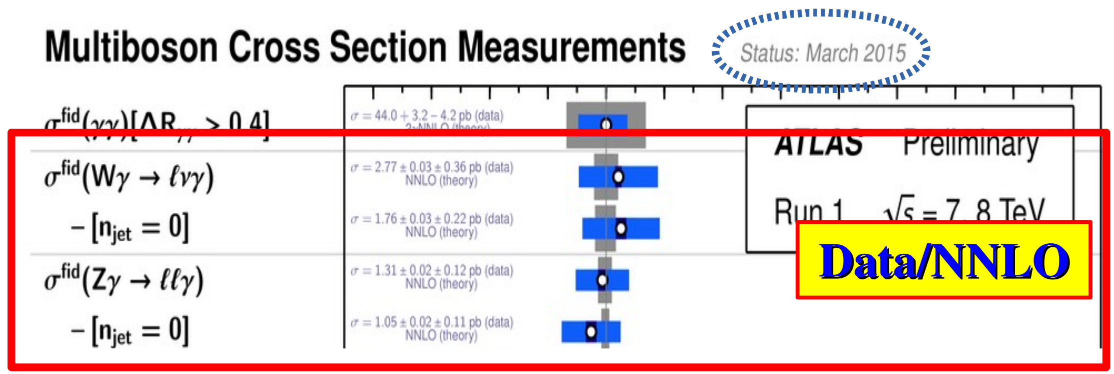


- Recently Wγ and Zγ x-sec calculation made available
  - Grazzini, Kallweit, Rathlev **(arXiv1504.0133)**
  - Re-checked with published ATLAS 7 TeV data → tension disappeared
  - K (NNLO/NLO) ~ 1.2
    - NLO scale uncertainties did not cover for it!

Talk yesterday



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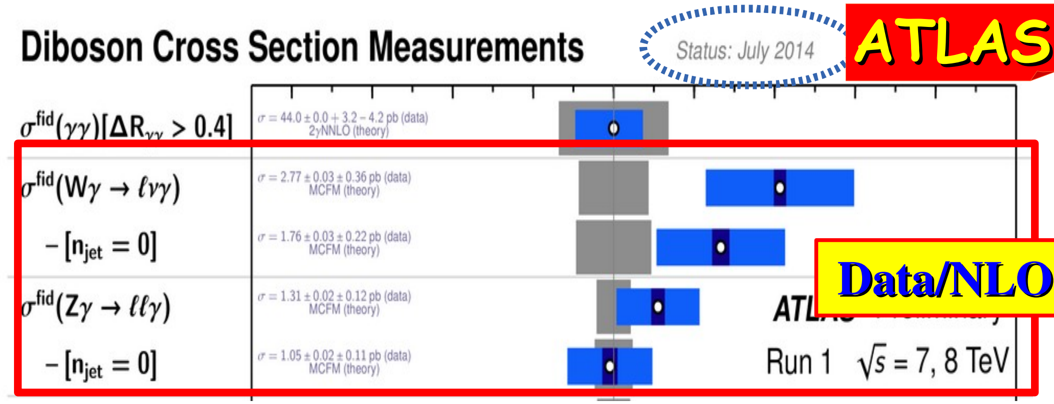

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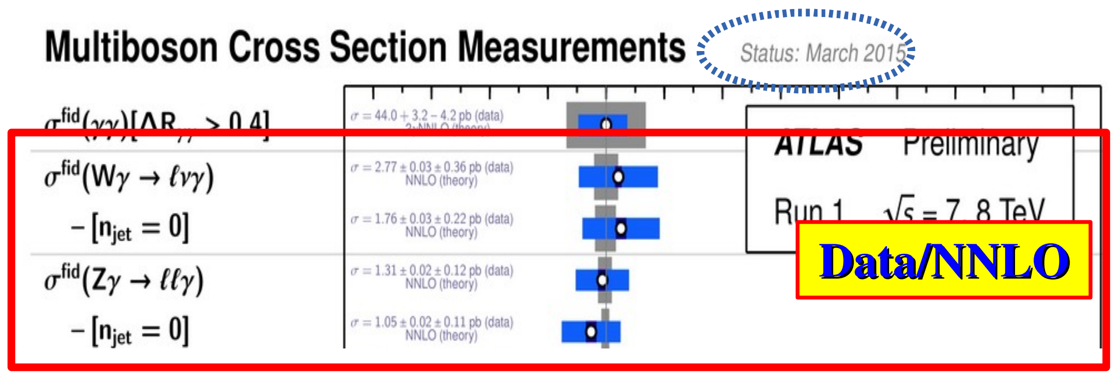
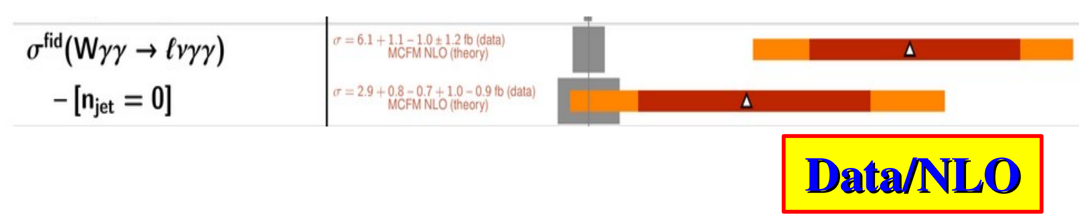


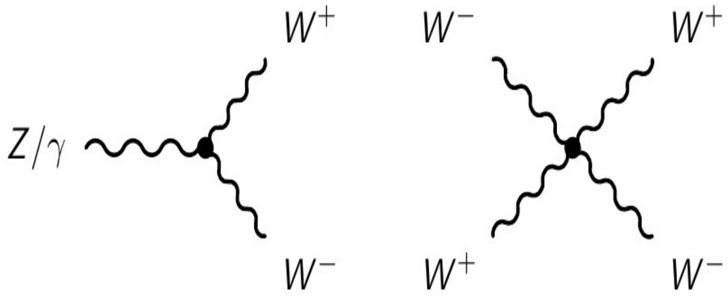
- Possibly we are seeing the same thing in Wγγ
  - Need NNLO predictions!



Anomalous Gauge Coupling

Anomalous Gauge Boson Couplings

- Self couplings of gauge bosons consequence of the non-Abelian nature of the EWK theory and fixed in SM
- BSM effects can manifest as deviation from the predicted SM couplings
  - How to quantify the deviations? Or constrain them?



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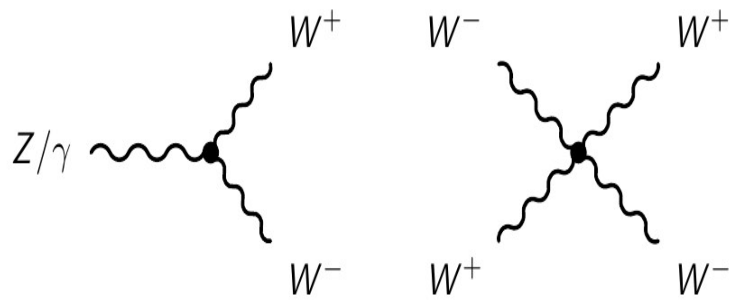


- Different model independent parametrizations of BSM on the market
  - Effective Lagrangian, for example for aTGC:

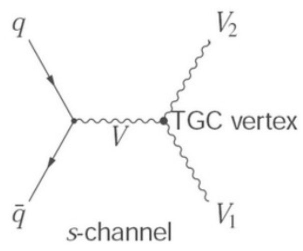
$$\mathcal{L}_{WWV} = i g_{WWV}\Big(g_1^V \left(W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu} \right) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} \Big)$$

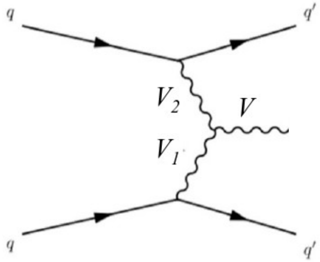
  - Effect field theory (EFT) approach, scale of new physics Λ large far from accessible energy ($s << \Lambda^2$). Adding new operators at higher dimension. SM restored for $\Lambda \rightarrow \infty$
    - Similar to Fermi approach for β-decay, G_F coupling for $s << M_W$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Anomalous Gauge Boson Couplings

- Diboson and VBF Boson production sensitive to ATGC





coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta k_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta k_Z,\ \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

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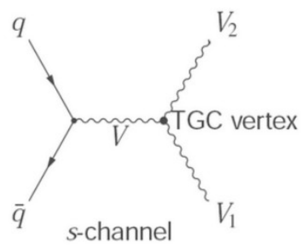

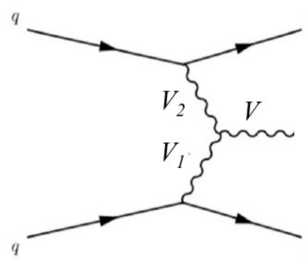

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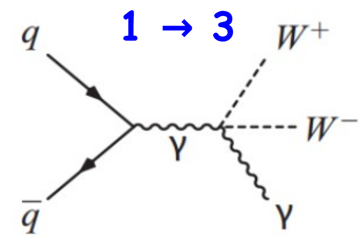
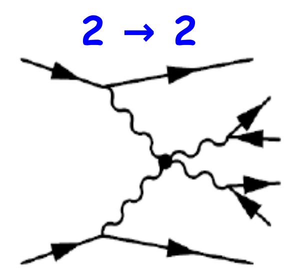
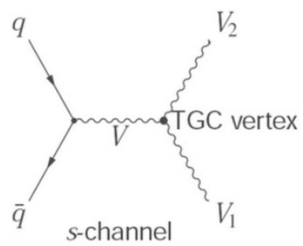


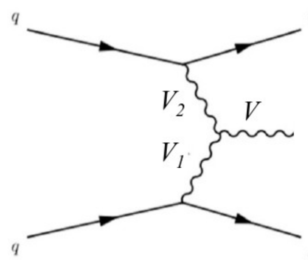


	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$			X			X	X	X	X

Anomalous Gauge Boson Couplings

- Diboson and VBF Boson production sensitive to ATGC





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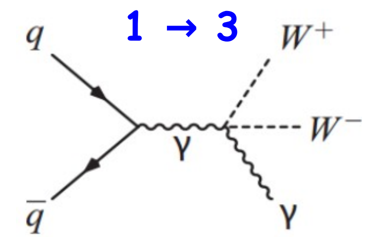
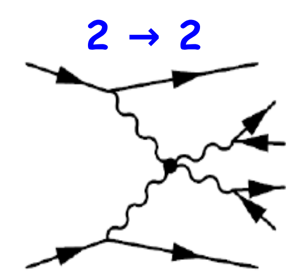




	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

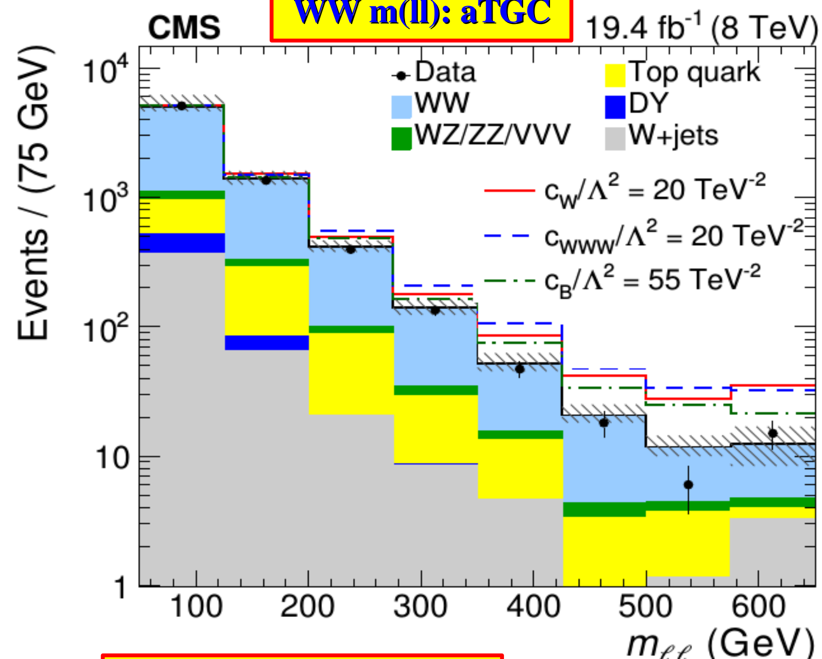
- Unitarity problem: AT(Q)GC will violate unitarity at some scale
  - Form Factor or K-matrix method
    - Choice arbitrary and introduce model dependence
  - Not unitarize ($\Lambda_{FF} = \infty$)
    - Limits "over-sensitive" and argued to be "unphysical"

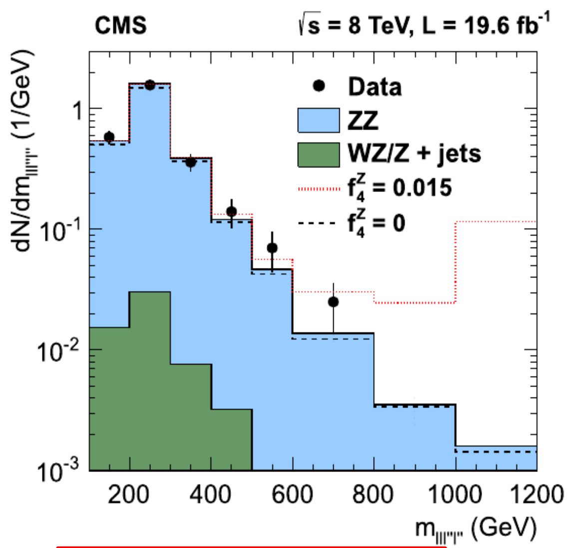
$$\mathcal{F}(s) = (1 + \hat{s}/\Lambda_{\rm FF}^2)^{-n}$$

AGC Signature

- AGC expected to be stronger at high s-hat
  - Search target observables related to the s-hat of the event, like m_{VV}, m_{ll} $P_T(VV)$, $P_T(V)$
- Binned fit for a single observable
  - Binning/selection may be optimized for AGC
  - Sensitivity mostly from the last bins
  - Limited by signal statistics, and background unc.
  - Channels with higher BR usually have higher sensitivity, i.e. ZZ→llνν, γZ(→νν), WγV(→qq)
- Different processes have different sensitivity for various AGC parameters
  - Limits depends on parametrization choice (i.e. Λ)

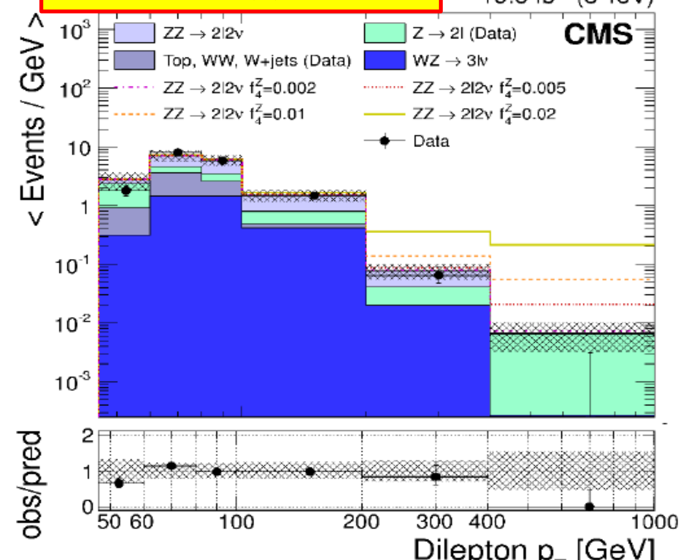
WW m(ll): aTGC





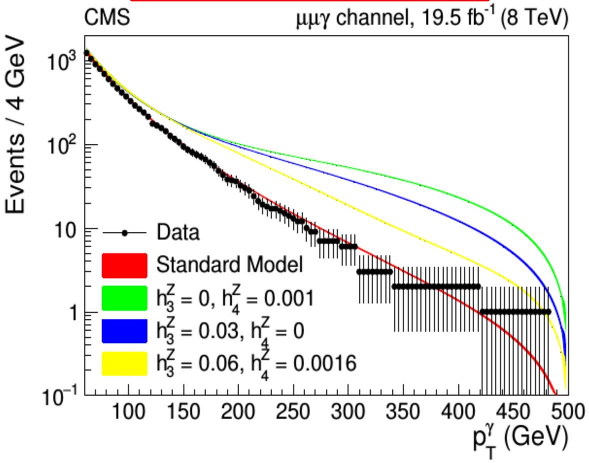
ZZ→llll m(4l): aNTGC

ZZ→llνν Pt(ll): aNTGC

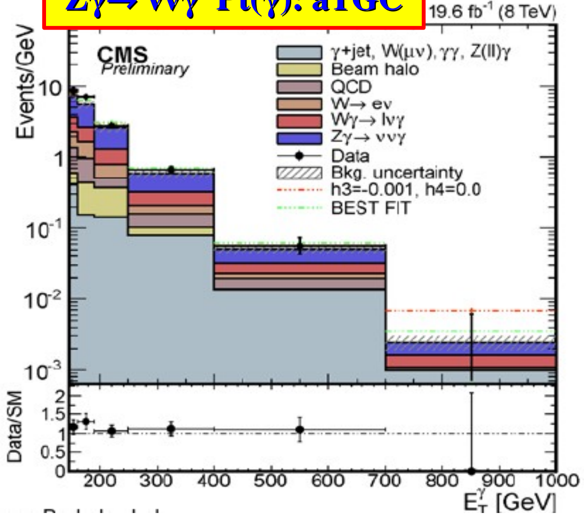


AGC Signature

Zγ→llγ Pt(γ): aTGC

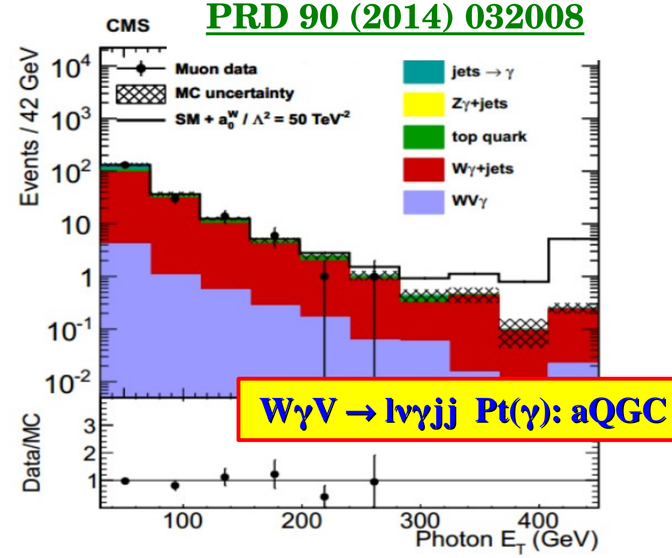


Zγ→ ννγ Pt(γ): aTGC

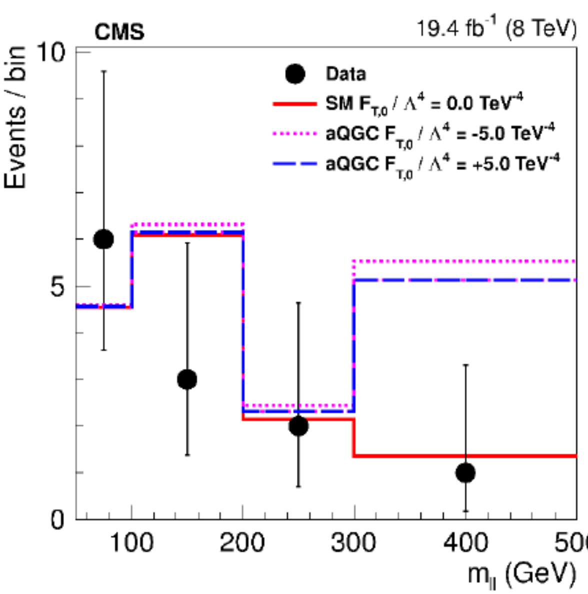


PRD 90 (2014) 032008

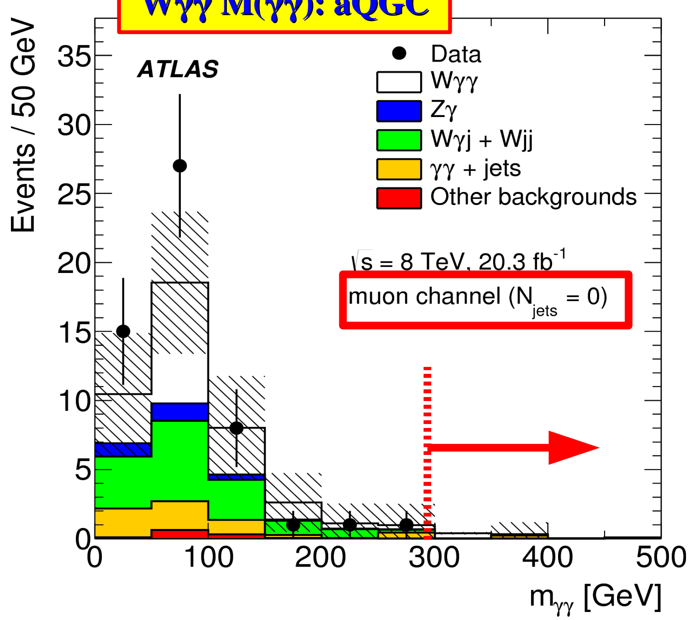
WγV → lνγjj Pt(γ): aQGC



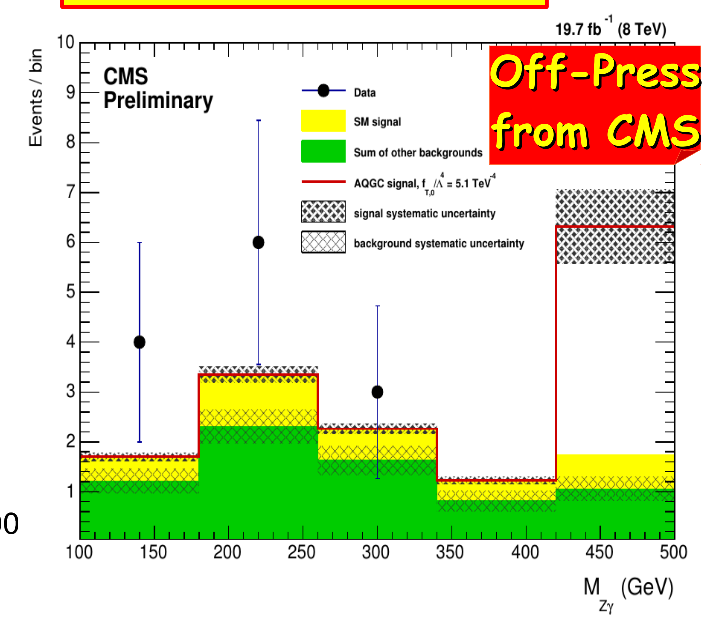
VBS ssWW M(ll): aQGC



Wγγ M(γγ): aQGC

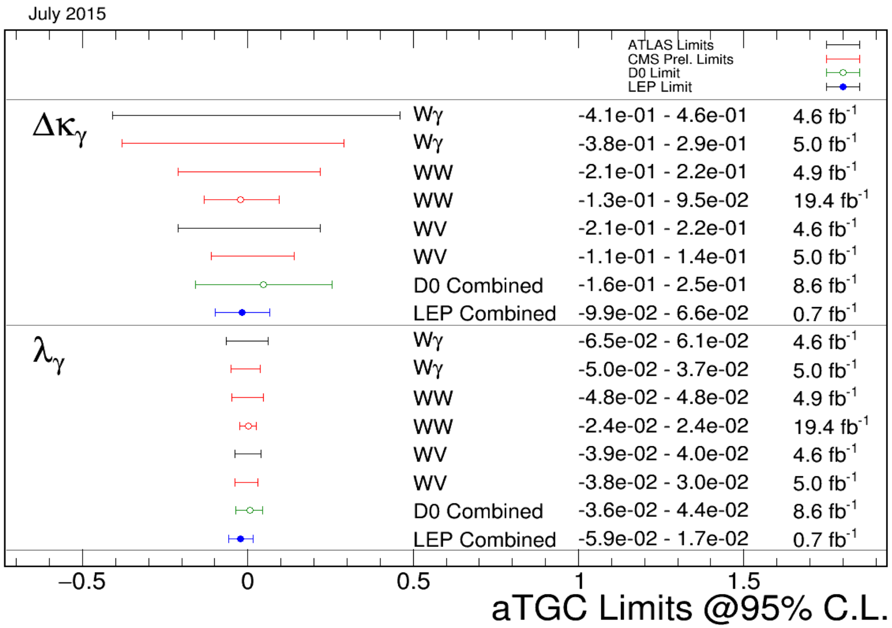


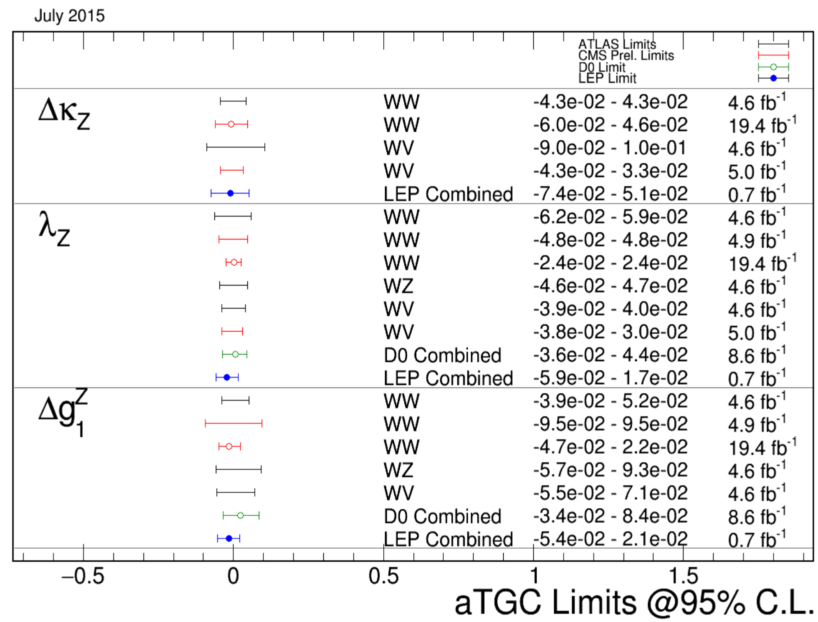
VBS Zγ→llγjj M(lγ): aQGC



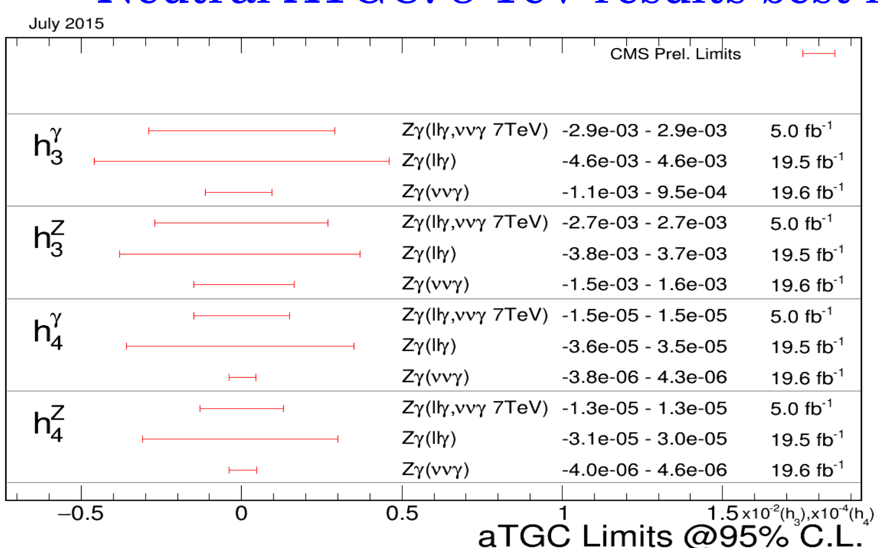
Summary aTGC

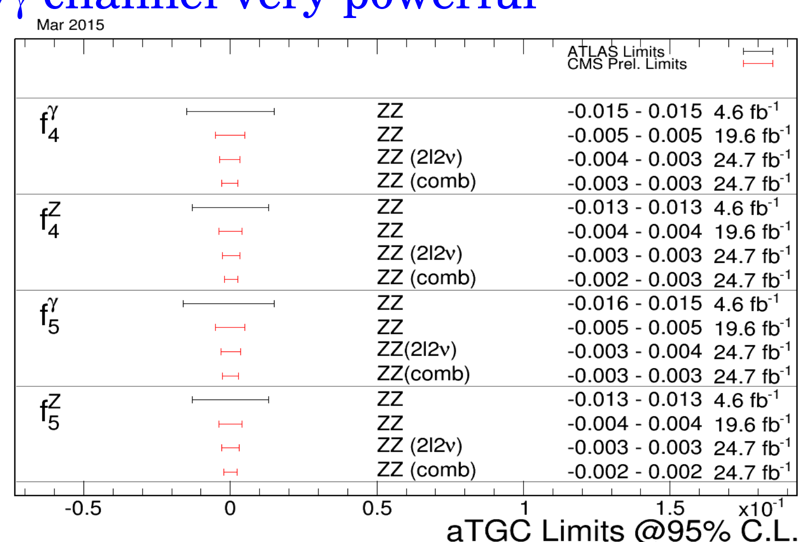
Charged ATGC: Only one analysis at 8 TeV so far (WW), best limit ~ to LEP





Neutral ATGC: 8 TeV results best limit, ννγ channel very powerful

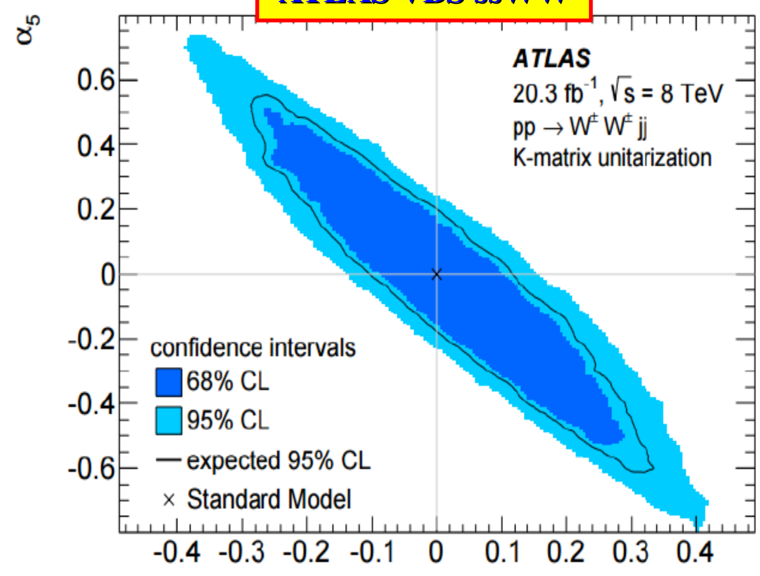


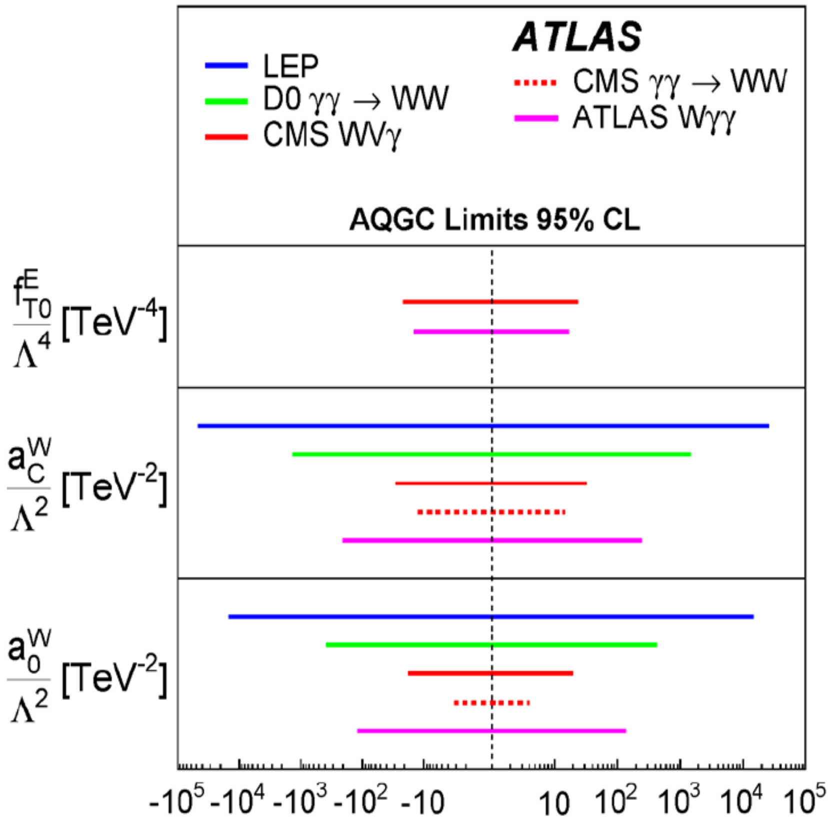


Summary aQGC

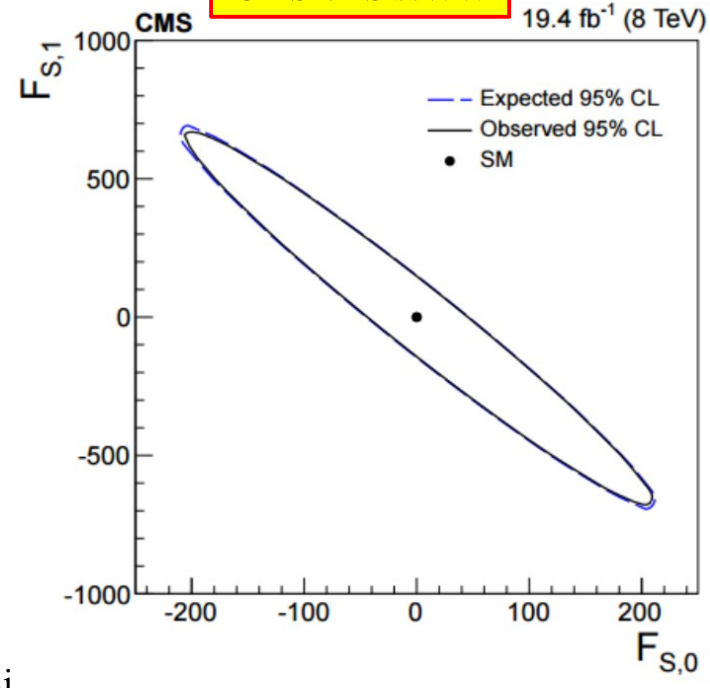
- $W\gamma\gamma$ aQGC more sensitive to f_{T0} than f_{Mi}
  - Limit on dim-8 operators f_{M2}, f_{M3} transformed to dim-6 a_C, a_0 operators for comparison
  - Non-unitarized limit shown, for comparison
- AQGC limit from ssWW reported as non-unitarized dim-8 operators (CMS) and unitarized K-matrix formalism (ATLAS)

ATLAS VBS ssWW



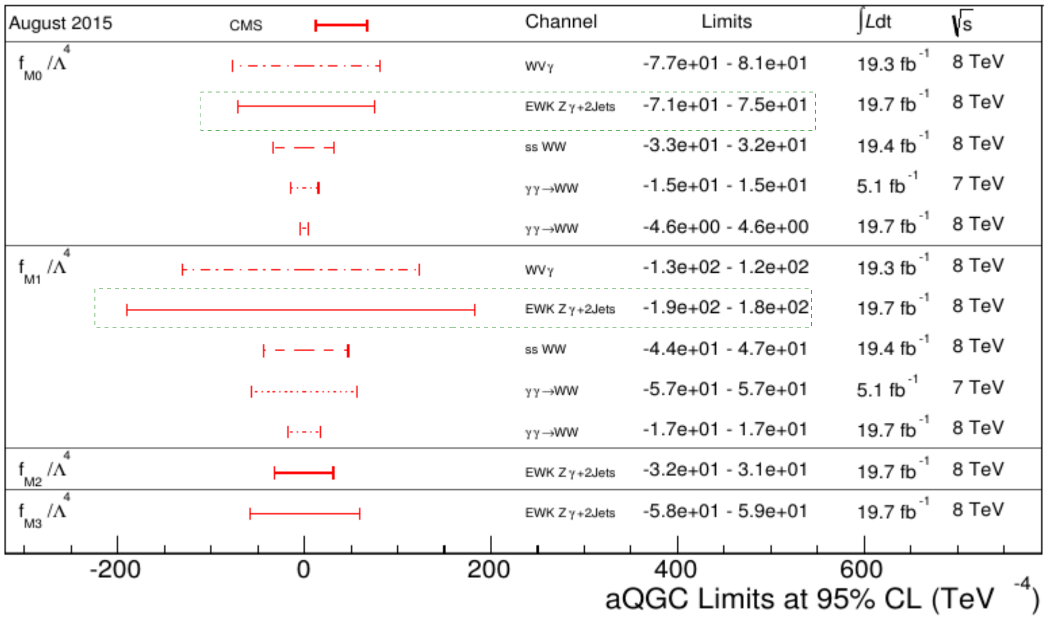


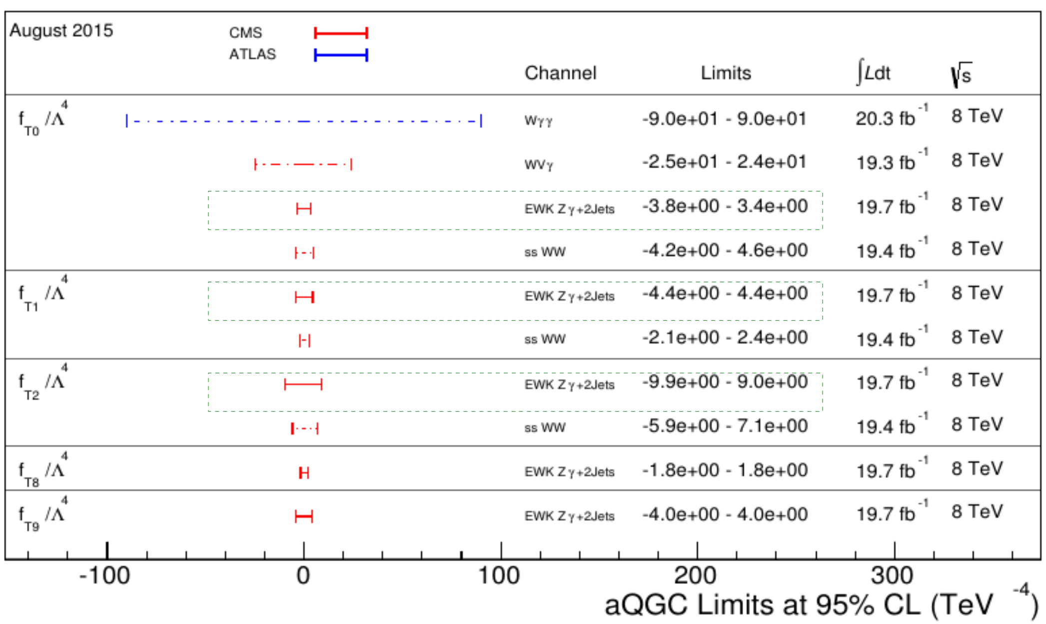
CMS VBS ssWW



Summary aQGC

Off-Press from CMS





New aQGC limits on dim-8 operators from EWK Zγ (non-unitarized)

Some of them competitive with the limits from ssWW

Summary

- Triple Gauge Coupling
  - Inclusive dibosons is now approaching precision physics, need adequate theory predictions
  - Single boson electroweak production ($qq \rightarrow qqV$) experimentally established
- Quartic Gauge Coupling
  - Tri-boson final states start to be experimentally accessible ($W\gamma\gamma$), more to come in Run 2
  - Vector Boson Scattering new frontier to complete the understanding of the EWSB
- Anomalous Gauge Coupling
  - Better and better limits, need a more uniform model independent parametrization and interpretation of the constraint provided by a very wide range of data
  - Boson couplings g/W/Z now have another player: H. “Unification” with the Higgs-sector? Via EFT?
- **Run 1 data still has more to offer**

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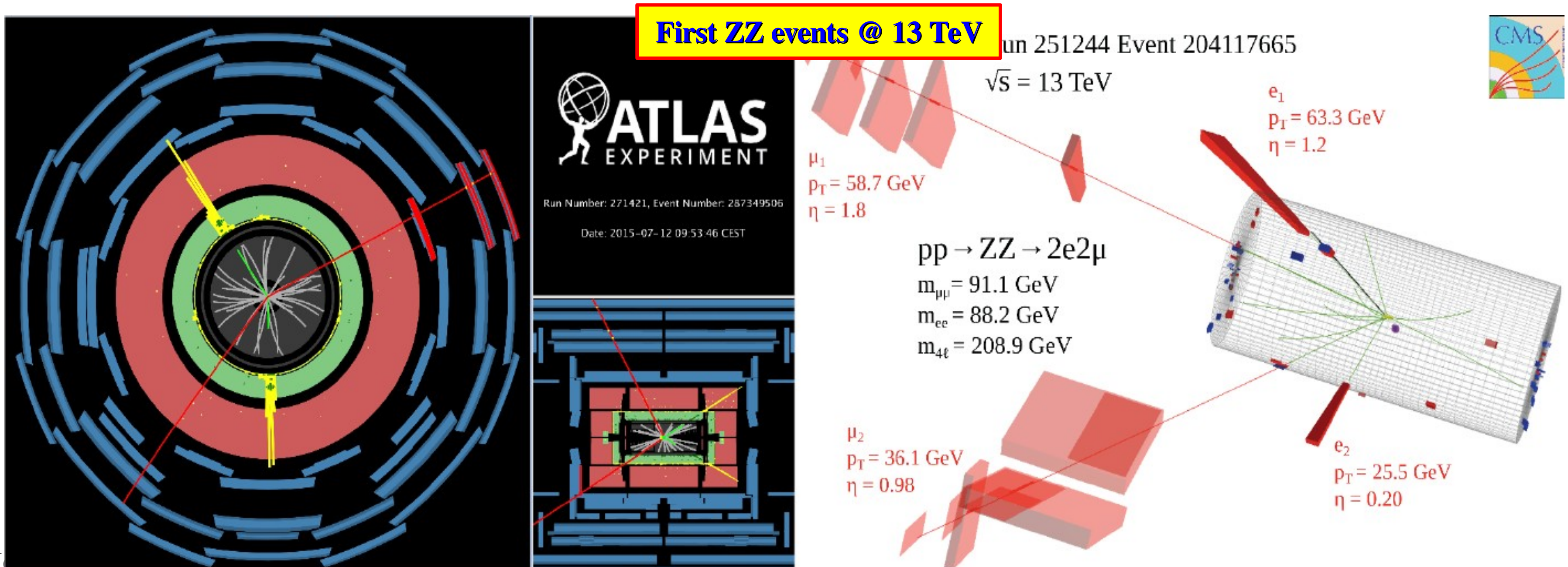
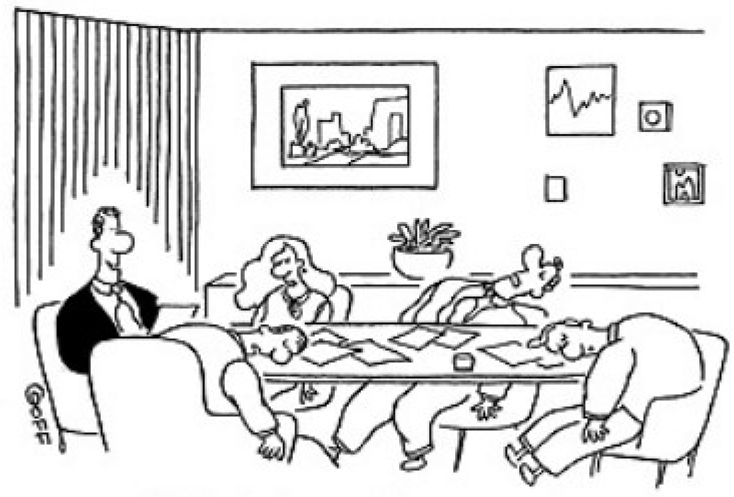
- **Run 1 data still has more to offer, and Run 2 data are knocking on our door!**



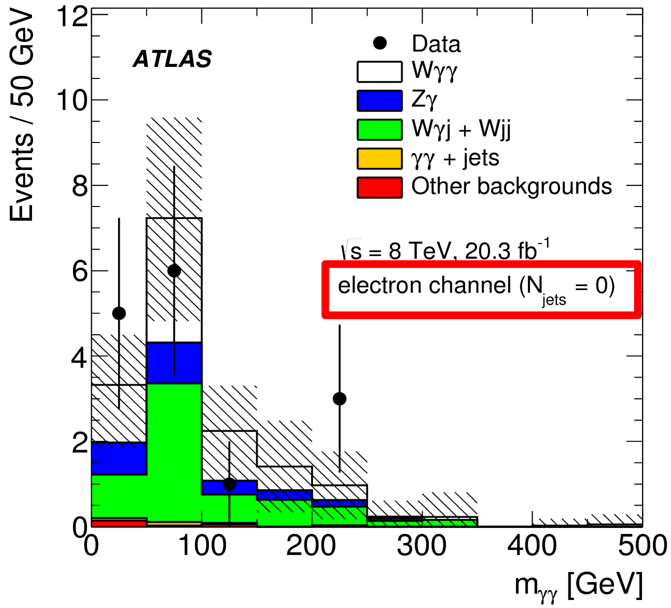


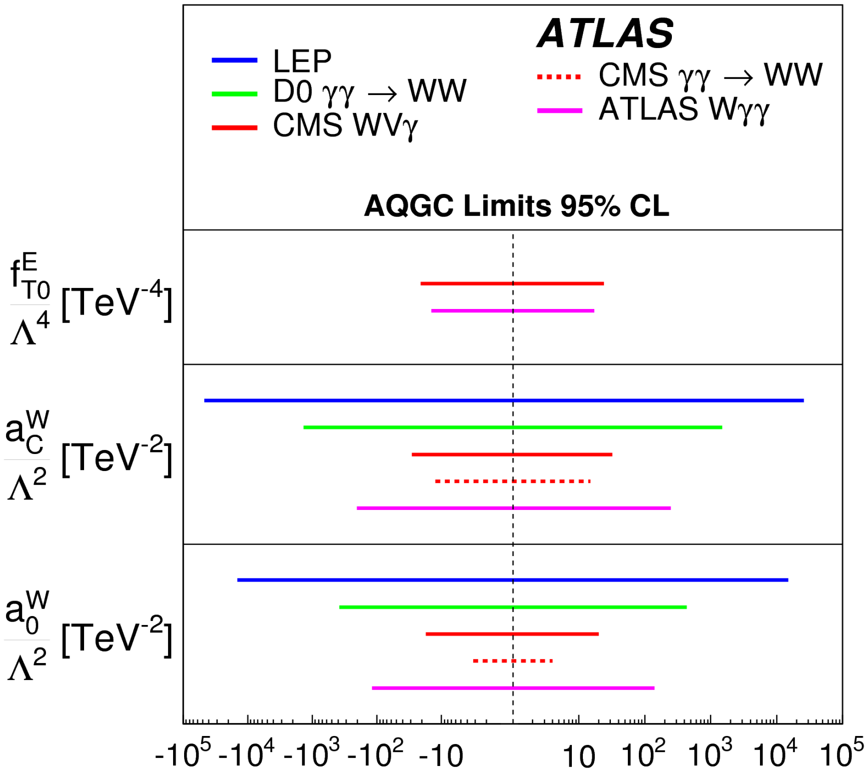
Thank You

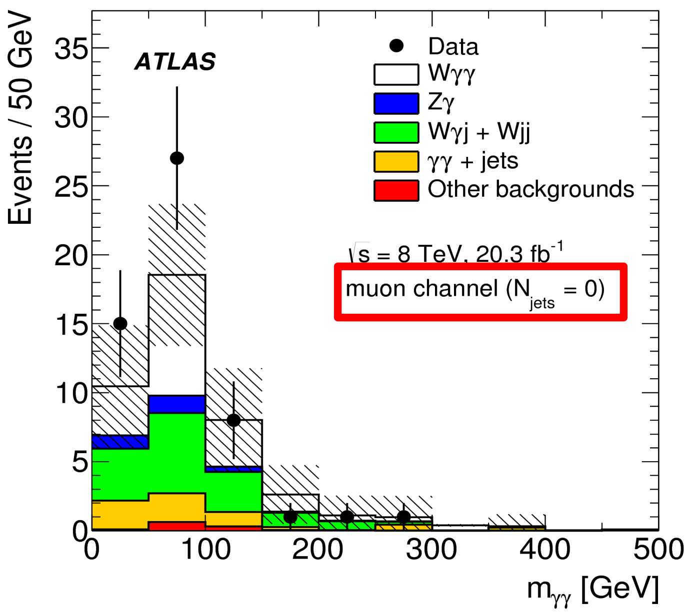
Backup

Wγγ Production

- Search for aQGC coupling in exclusive region and with $m_{\gamma\gamma} > 300$ GeV
- Effective field theory approach
  - Up to dim8 operators
- Highest sensitivity for T0 operators
  - Λ_{FF}=500 GeV for f_{T0}







Other Relevant Talks

Tuesday September 1

- Vector boson pair production at hadron colliders at NNLO QCD 20'
  - Speaker: Stefan Kallweit (University of Mainz)
- VBS & anomalous couplings - ZZjj production in the POWHEG-BOX 20'
  - Alexander Karlberg (University of Oxford (GB))
- Diboson and triboson production with photons 20'
  - Shu Li (Duke University (US))
- Production of heavy vector boson pairs (WW, WZ, ZZ) 20'
  - Riccardo Bellan (Universita e INFN Torino (IT))
- Vector boson scattering 20'
  - Linda Finco (Universita e INFN Torino (IT))

Friday September 4

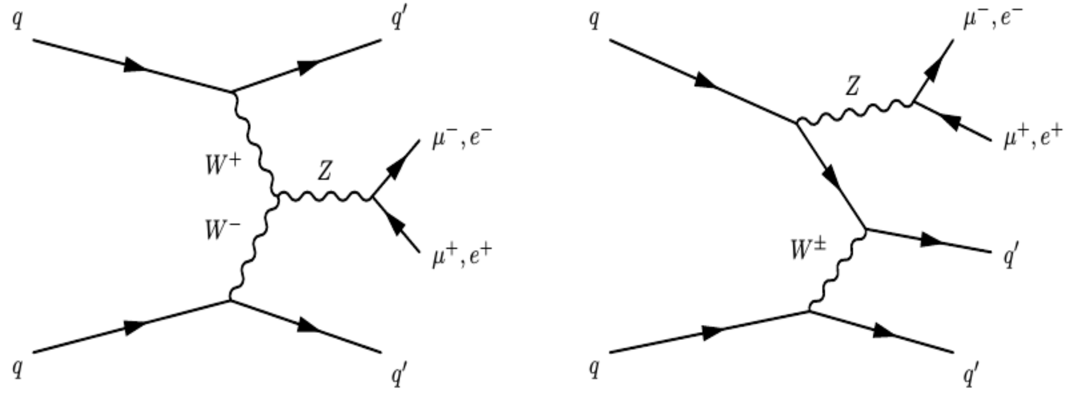
- NNLO Mixed QCD-EW corrections to Drell-Yan processes in the resonance region 18'
  - Christian Schwinn (Freiburg University)
- ATLAS/CMS Forward-backward asymmetries and sin2theta 18'
  - Anna Di Ciaccio (Universita e INFN Roma Tor Vergata (IT))
- Forward-backward asymmetries and sin2theta 18'
  - Siqi Yang (Univ. of Science and Technology of China, Hefei)
- W boson mass 18'
  - Oliver Stelzer-Chilton (TRIUMF (CA))

Electroweak Production of Single Boson (aka Vector Boson Fusion)

W and Z Electroweak Production

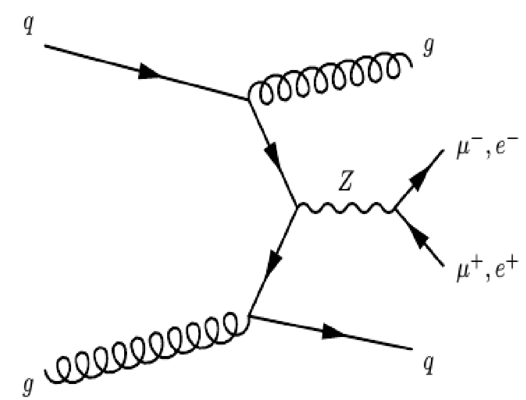
- Production of W and Z bosons (V) in association with dijet (Vjj) dominated by $O(\alpha_S^2)$ QCD corrections to inclusive V production
- Rarer contribution from EWK processes qq → qqV with t-channel exchange of color-singlet γ/W/Z
- Peculiar signature of EWK boson production exploited to distinguish from strong $O(\alpha_S^2)$ QCD production
  - Presence of two high energetic hadronic (quark) jets with wide rapidity separation
  - Suppressed hadronic activity “between” the two jets (central region)
- Signal extraction allows detailed tests of EWK-production modeling

EWK qq → qqZ production



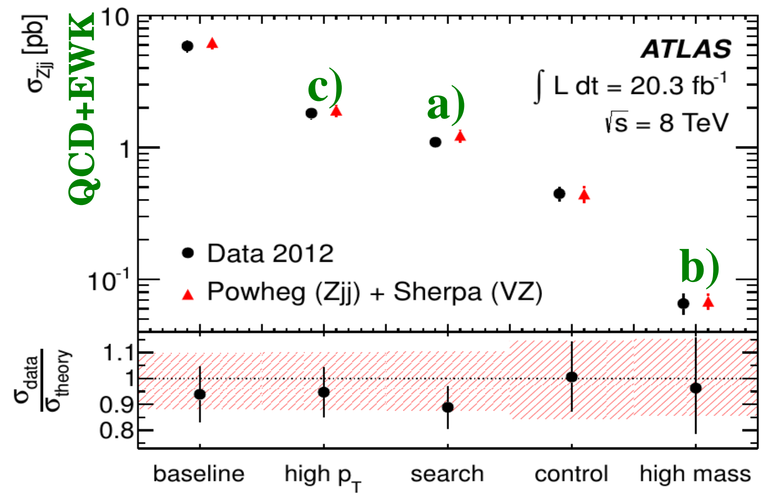
(a) vector boson fusion (b) Z-boson bremsstrahlung

Strong Zjj production

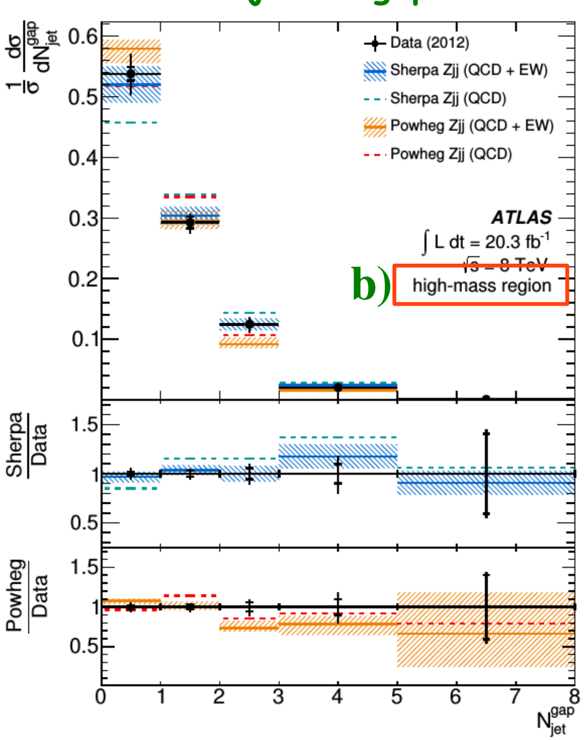


Z Electroweak Production

- ATLAS analysis uses 5 fiducial regions, 3 with high EWK/"strong" ratio [JHEP04 (2014) 031]
  - a) m_{jj}> 250 GeV + no jet in jj gap + low P_T(Zjj) [4%]
  - b) m_{jj}> 1 TeV [12%]
  - c) harder cut on jets [2.1%]
- CMS: 3 multi-variate analyses [EPJC (2015) 75:66]
  - including q/g likelihood discriminator
  - For xsec: m_{jj}> 200 GeV + Z between jets + low P_T(Zjj)



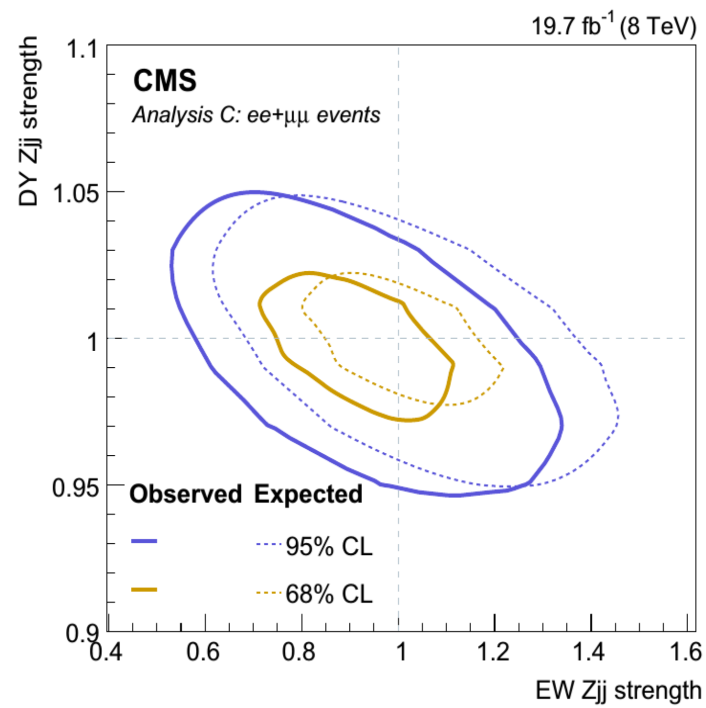
N. jets in gap



- Strong Zjj production poorly modeled in these regions
  - → data-corrections from control regions
- Signal model (NLO) from Sherpa/Powheg [ATLAS] or Madgraph+Phytia [CMS]

$\sigma^{fid} = 174 \pm 42$ fb
[$\sigma^{LO} = 208 \pm 15$ fb] **CMS**

$\sigma^{fid} = 54.7 \pm 11$ fb **ATLAS**
[$\sigma^{Powheg} = 46.1 \pm 1.0$ fb]

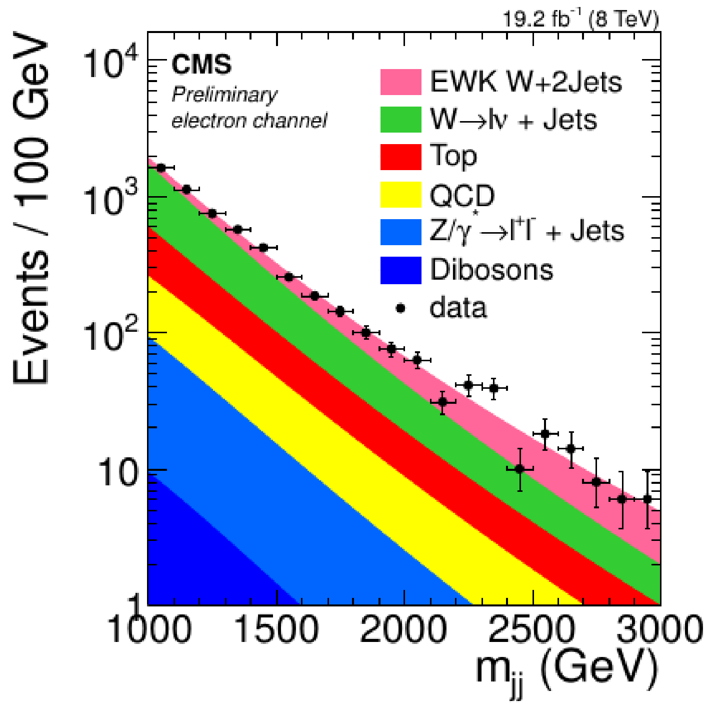


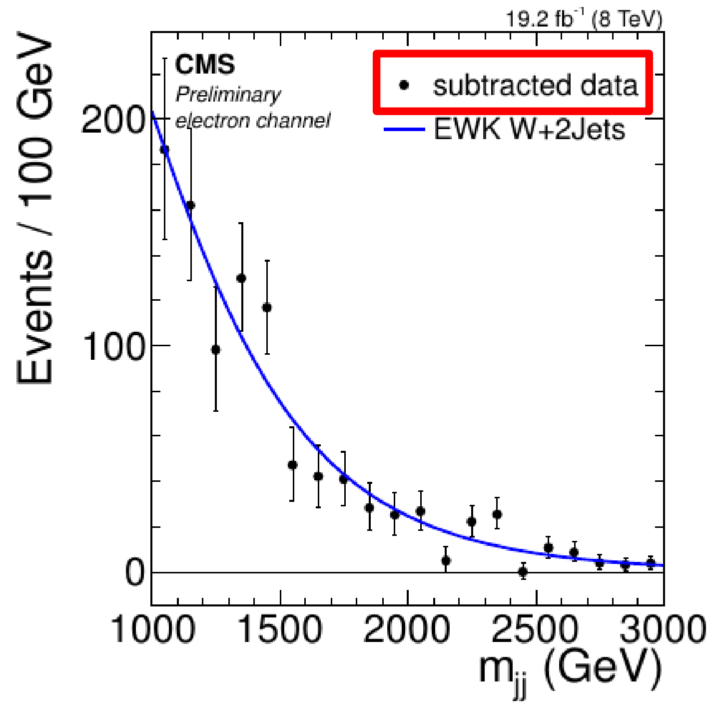
a)

W Electroweak Production

CMS

- Boosted Decision Tree (BDT) discriminant employed to select events, then fit m_{jj} for EWK, strong production, and other background (mainly top)
  - m_{jj} shape for the EWK Wjj fixed with functional form from MC, normalization floating
  - Strong Wjj shape fit to data (MC not reliable), normalization from control region
- Madgraph+Phytia for signal model





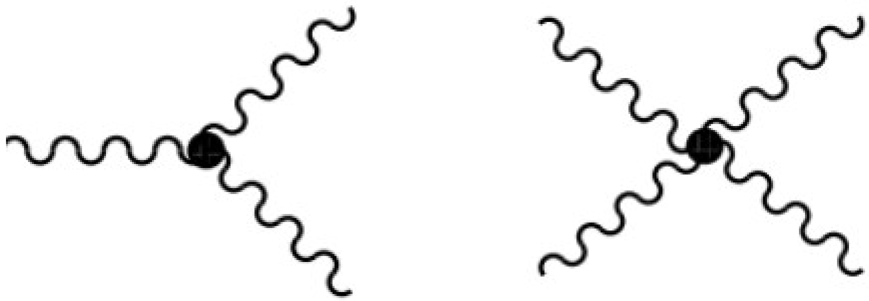
Electron Channel

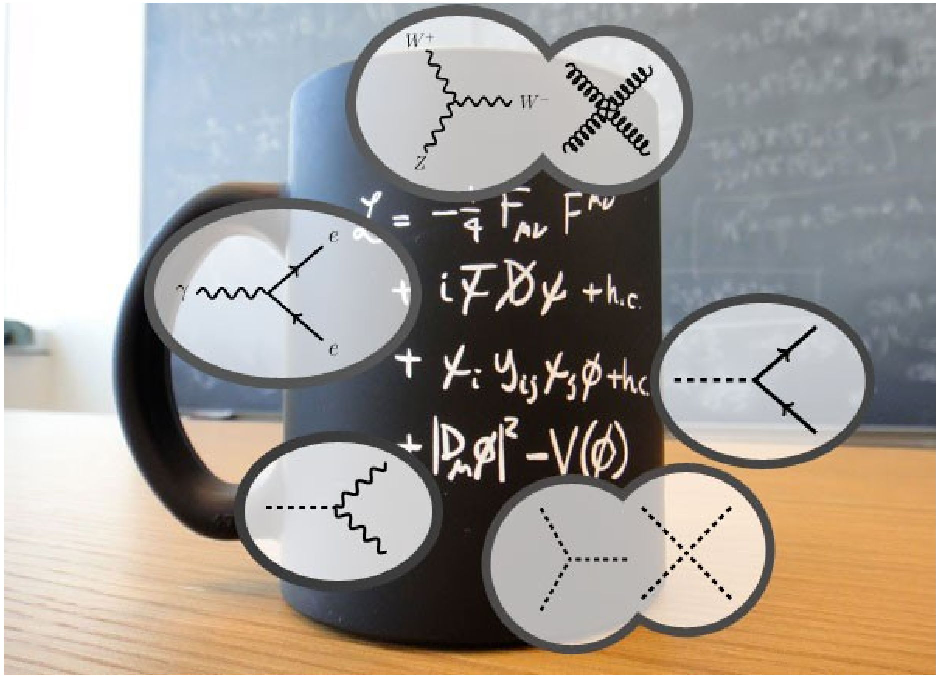
$$\sigma^{fid} = 0.42 \pm 0.04(\text{stat.}) \pm 0.09(\text{syst.}) \pm 0.01(\text{lumi.})\ \text{pb}$$
$$[\sigma^{\text{Madgraph}} = 0.50 \pm 0.03\ \text{pb}]$$

- Main Systematics
  - Strong Wjj shape and normalization
  - Strong/EWK interference

Introduction

- Electroweak sector of the SM based on SU(2)xU(1) gauge group, that is non-Abelian
  - **→ Triple and quartic gauge self-coupling**





EWK program @LHC in Run 1

- Reached unprecedented precisions
- Observed new processes
- Accessed unexplored corners of phase-space

- Measurements require complex analyses (syst. Limited)
  - Run 1 more to offer before Run 2 takes over
- Challenge also for theorists
  - Experimental results need precise predictions be correctly interpreted

Introduction

- The Run 1 Electroweak physics program has been providing a huge amount of tests for the SM predictions with measurements of processes never observed before, with unprecedented precisions, and in previously unexplored corners of phase space.

- These measurements require complex analyses either because systematically limited, or because of the complex final state/topology of the signal, or because of the tiny signal to be extracted from large background.
  - Still more to extract from the Run 1 data before Run 2 takes over

- Summary of more recent 8 TeV results using di-boson and tri-boson final state
  - Cross section (inclusive and differential) on fiducial regions (close to experimental phase-space); Combination of channel for maximum sensitivity
  - VBF and VBS production modes
  - Search for anomalous triple/quartic gauge couplings

- Challenge also for theorists, many experimental results need higher order corrections (in both α_S and α_{EWK}) to be correctly interpreted, for many processes still not available