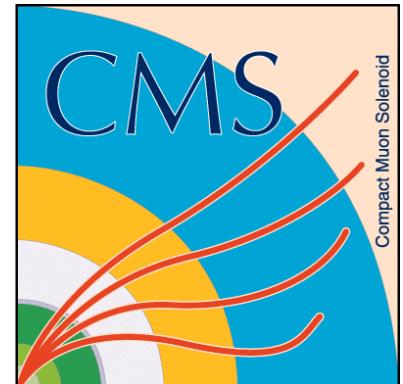




Production of heavy vector boson pairs: WW , WZ , ZZ



Riccardo Bellan
Università di Torino and INFN

On behalf of the **ATLAS** and **CMS** Collaborations

LHCP2015: The Third Annual Conference on Large Hadron Collider Physics

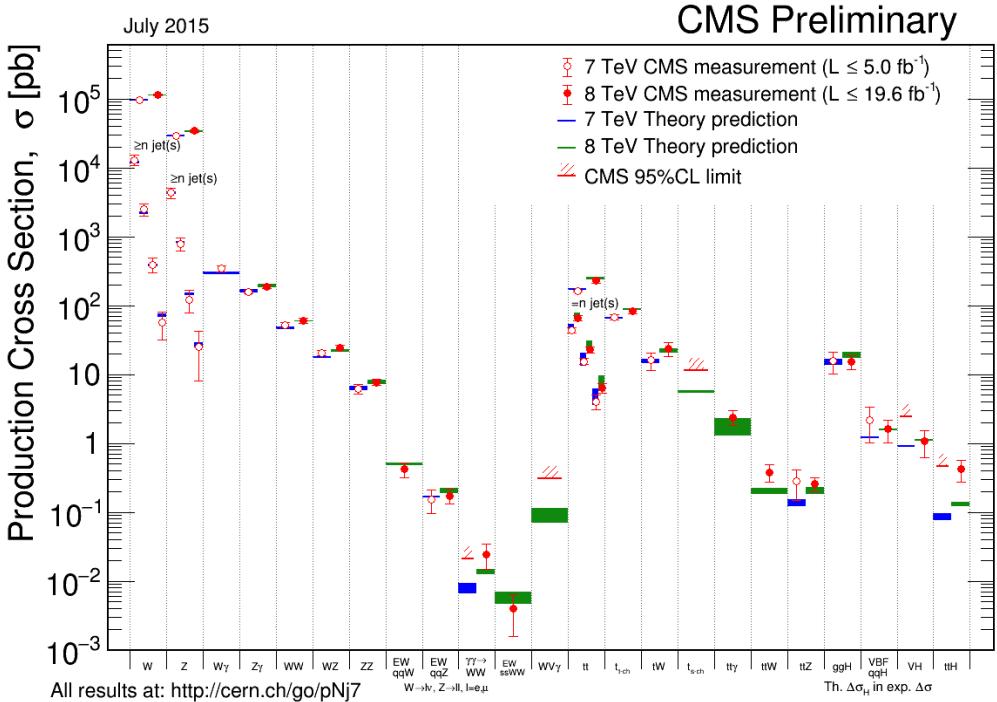
St. Petersburg, Russia, 31 August – 5 September, 2015
Standard Model Electroweak Physics Session



Stairway to Heaven or Highway to Hell?



- Standard Model cross sections successfully tested over **8 order of magnitude**
- We discovered a **Higgs boson**
- *Still* we have to understand in detail the **Electroweak Symmetry Breaking Mechanism** (*and if there is new physics beyond the SM*)



It is crucial to deeply understand the final states **mediated by heavy gauge boson pair production**: do we **master** them, using our NⁿLO computations?

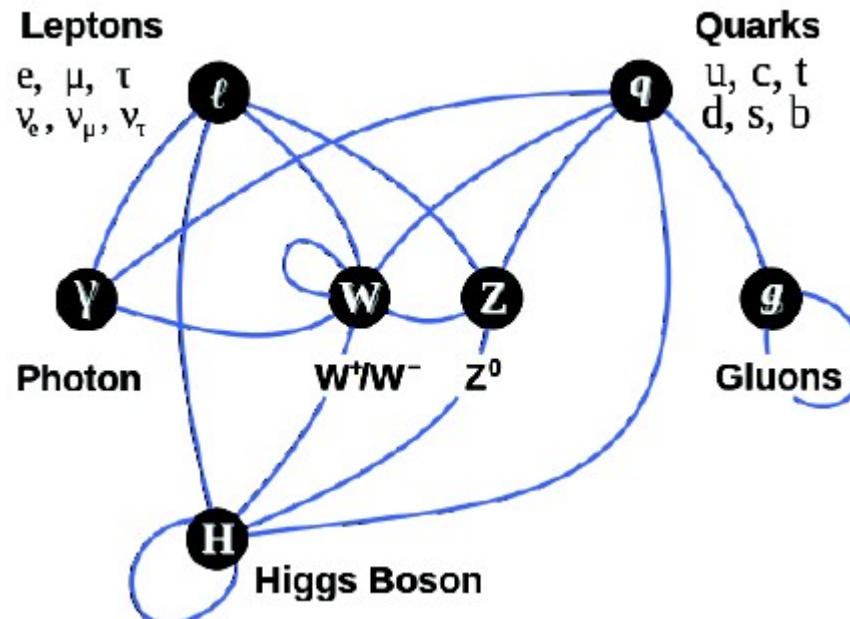
Measure with high precision the differential cross sections

Measure exclusive multi boson production mechanisms, such as VV scattering and QGC mediated

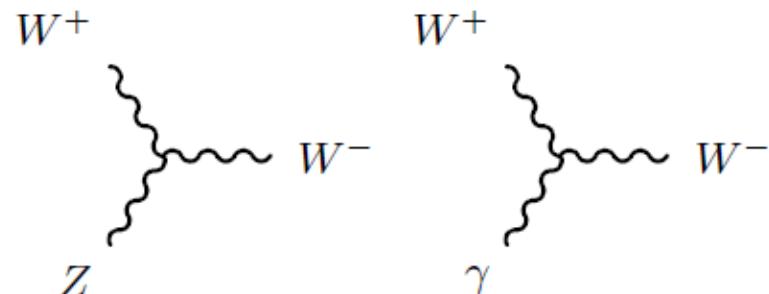
Investigate the high VV mass region



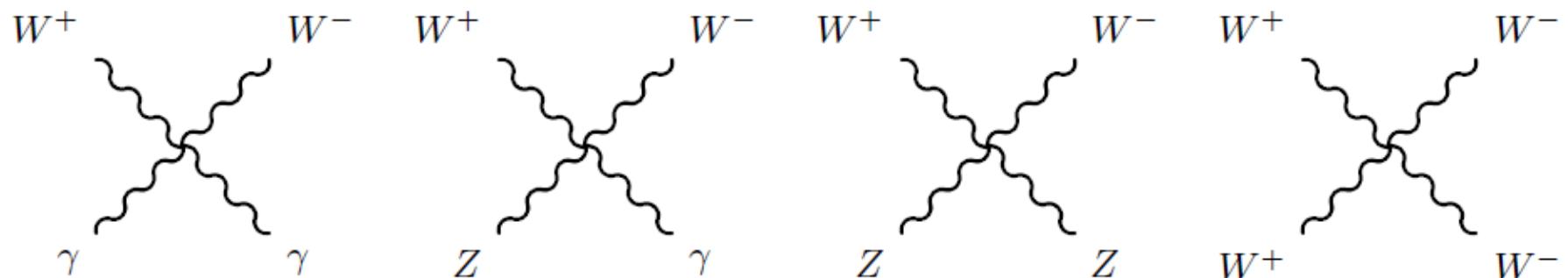
What Interesting EW Features can the VV Production Probe?



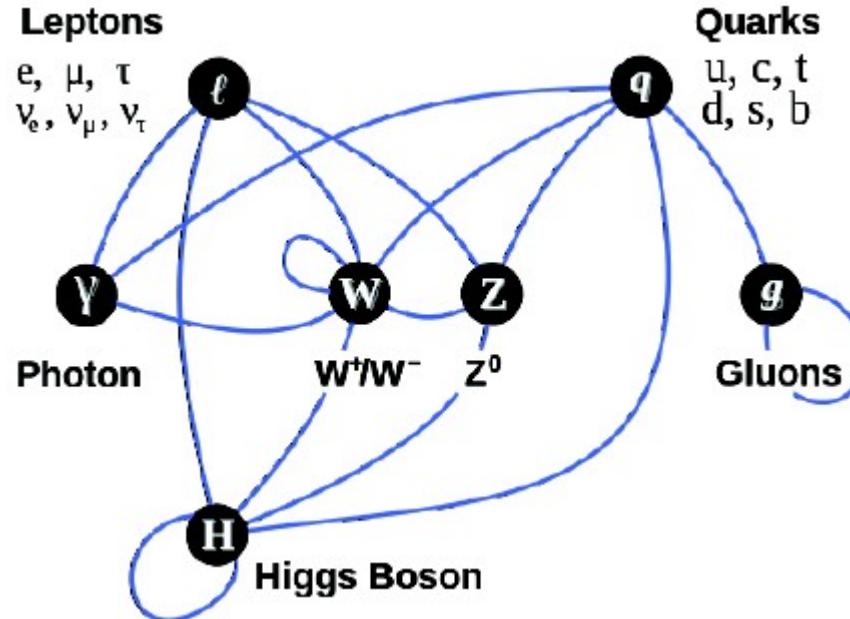
- **Triple gauge couplings (TGC)**



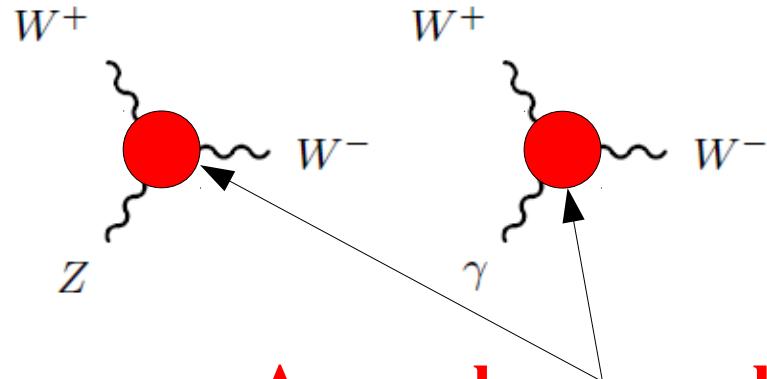
- **Quartic gauge couplings (QGC)**



What Interesting EW Features can the VV Production Probe?

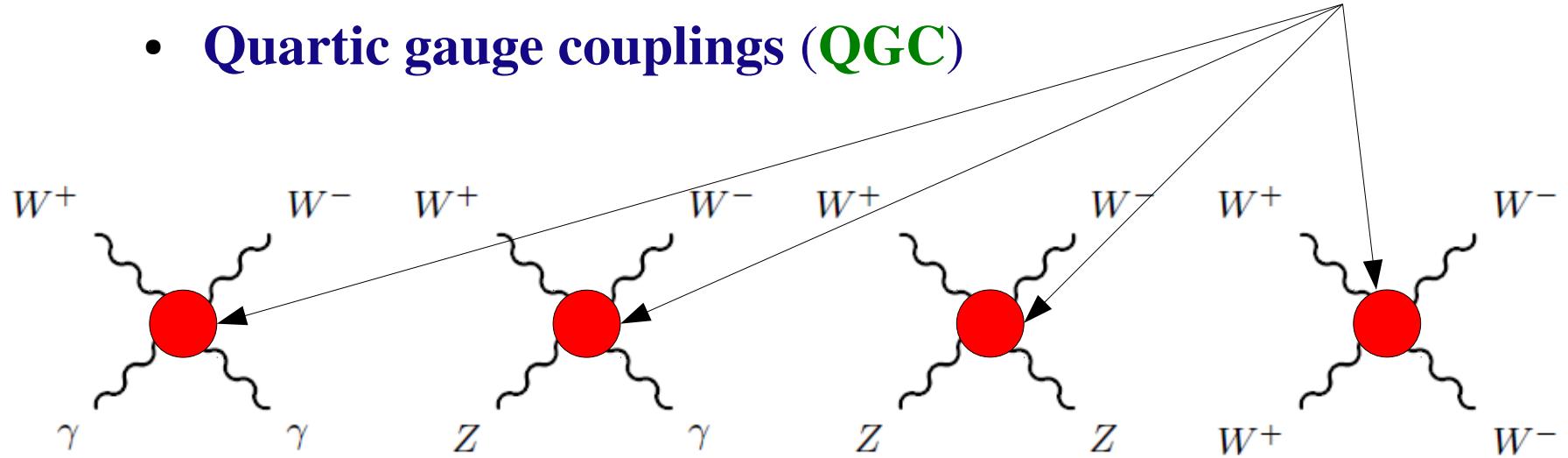


- **Triple gauge couplings (TGC)**



**Anomalous couplings
+ what forbidden in SM**

- **Quartic gauge couplings (QGC)**





ATLAS & CMS Multi-Boson Analyses



ZZ , WZ and WW production can be investigated in a plethora of final states, that sometime link together the different VV production mechanisms:

4ℓ	$3\ell 1\nu$	$\ell^\pm \ell^\pm 2\nu$	$2\ell 2\nu$	$2\ell b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\nu 2j$
ZZ	WZ	$W^\pm W^\pm$	WW	ZZ	WZ	WW
			ZZ			WZ

ATLAS and CMS explored all this final states, summing up 7 and 8 TeV runs



ATLAS & CMS Multi-Boson Analyses



7 TeV

ATLAS

ZZ **4 ℓ +2 ℓ 2 ν** JHEP 03 (2013) 128

WZ **3 ℓ 1 ν** EPJC (2012) 72:2173
 ℓ νjj JHEP 01 (2015) 049

WW **2 ℓ 2 ν** PRD 87, 112001
2 ℓ 2 ν PRD 91, 052005 (w/ $t\bar{t}$ and $Z \rightarrow \tau\tau$)
 ℓ νjj JHEP 01 (2015) 049

CMS

4 ℓ JHEP 01 (2013) 063
2 ℓ 2 ν arXiv.1503.05467 sub EPJC

3 ℓ 1 ν CMS-PAS-SMP-12-006
 ℓ ν2j EPJC 73 (2013) 2283
2 ℓ 2 ν EPJC 73 (2013) 2610
 ℓ ν2j EPJC 73 (2013) 2283

8 TeV

ATLAS

ZZ **4 ℓ** ATLAS-CONF-2013-020
4 ℓ ATLAS-CONF-2015-031

WZ **3 ℓ 1 ν** ATLAS-CONF-2013-021

WW **2 ℓ 2 ν** ATLAS-CONF-2014-033

W $^\pm$ W $^\pm$ **$\ell^\pm\ell^\pm 2\nu$** PRL 113, 141803

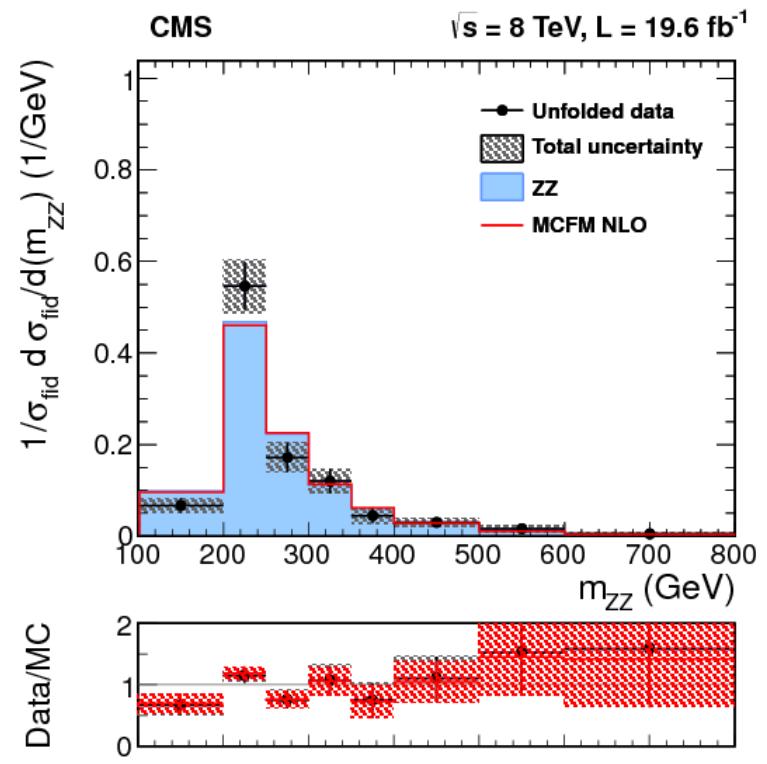
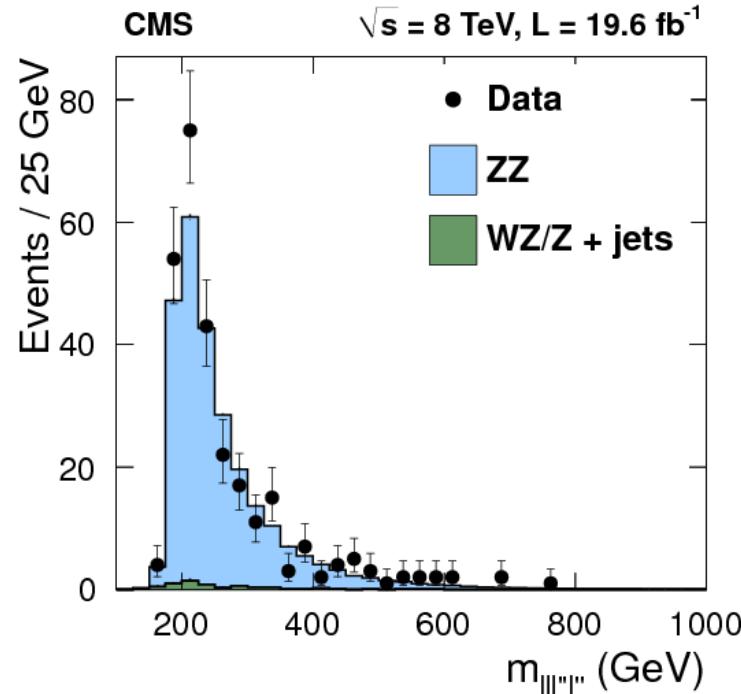
CMS

4 ℓ PLB 740 (2015) 250
2 ℓ 2 ν arXiv.1503.05467
2 ℓ /2 ν b \bar{b} EPJC 74 (2014) 2973
3 ℓ 1 ν CMS-PAS-SMP-12-006
 ℓ νb \bar{b} EPJC 74 (2014) 2973
2 ℓ 2 ν arXiv.1507.03268 sub EPJC
 $\ell^\pm\ell^\pm 2\nu$ PRL 114 (2015) 051801

$ZZ \rightarrow 4l$ On-shell Analysis

ATLAS-CONF-2013-020; CMS: PLB 740 (2015) 250, arXiv.1503.05467

- Select charged leptons to pair into **two on-shell Z**, w/ a mass between [66 – 116] GeV (ATLAS) or [60 – 120] GeV (CMS).
- **Irreducible background** from genuine 4 lepton processes ($t\bar{t}Z$, WWZ , $t\bar{t}WW$) estimated with **MC** → they are pretty *rare*.
- **Reducible background** from jets faking leptons estimated from **data**. Main sources of this kind are: DY, $t\bar{t}$ bar, WZ .

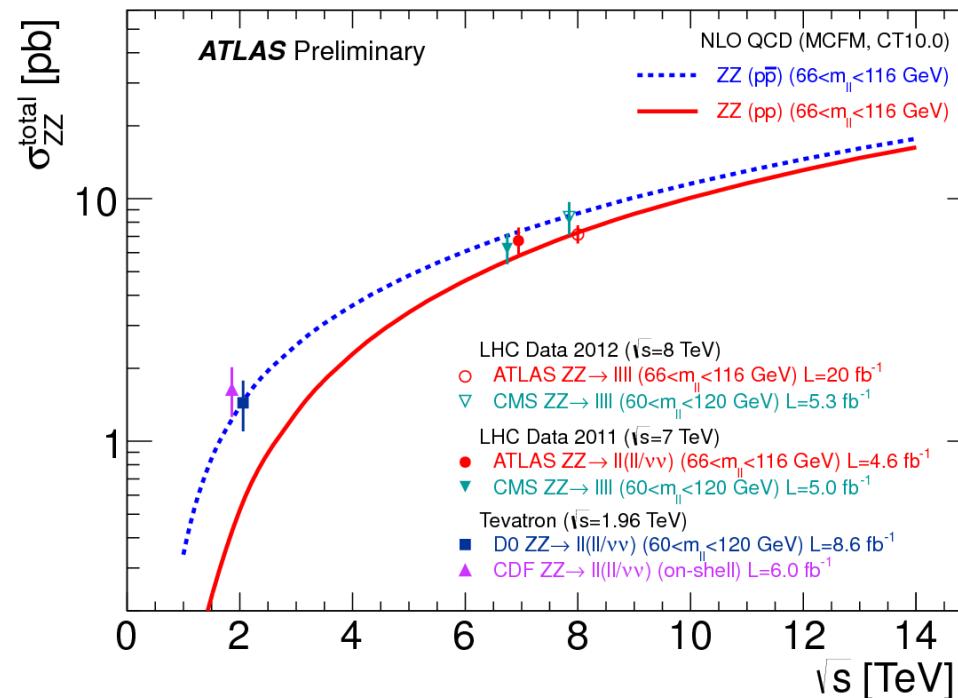




ZZ → 4l On-shell Analysis

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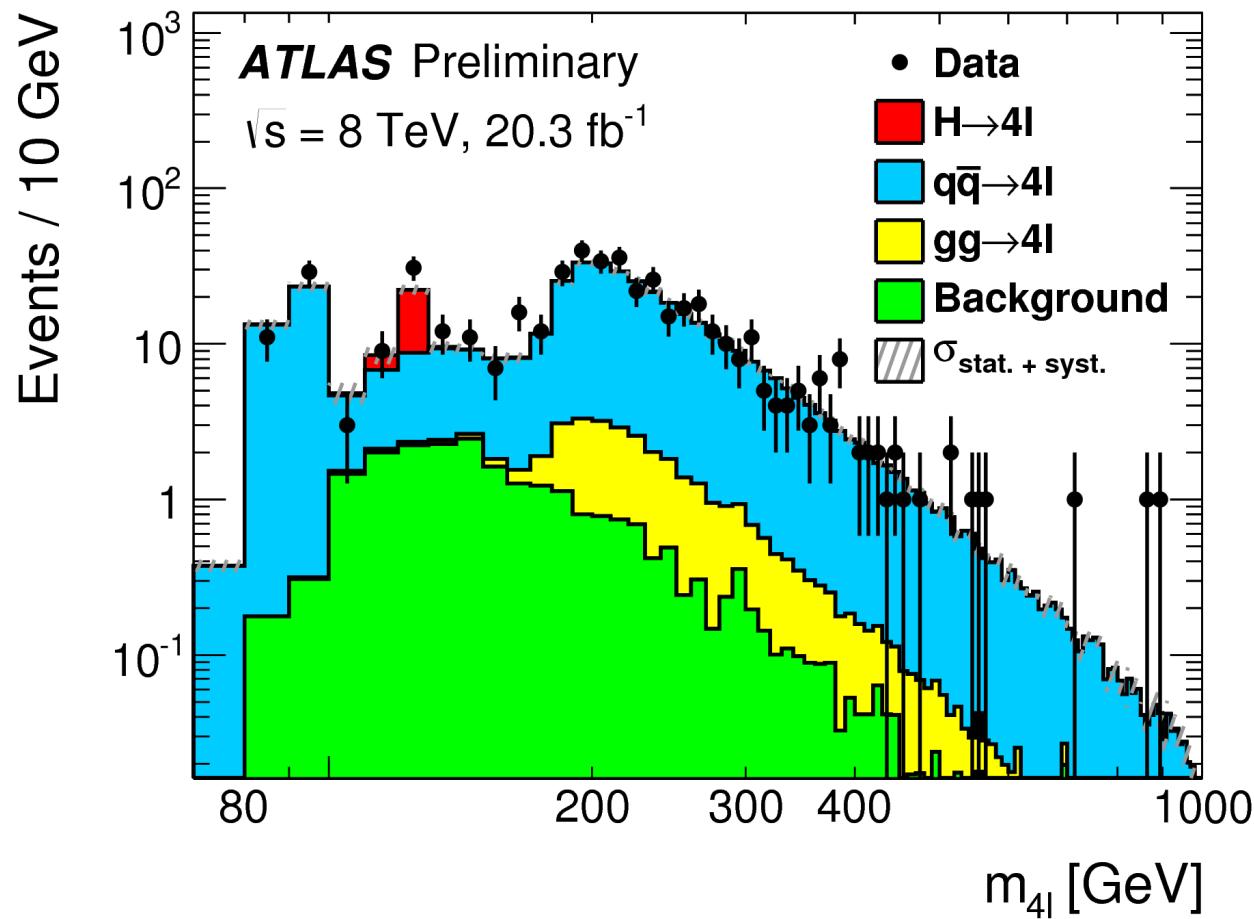
4 charged leptons final state: a ZZ Off-Shell Analysis



ATLAS-CONF-2015-031

- Relax the requirement on the second Z boson in the event

Lepton selection	
Muons:	$p_T > 6 \text{ GeV}, \eta < 2.7$
Electrons:	$p_T > 7 \text{ GeV}, \eta < 2.5$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $ m_Z - m_{\ell\ell} $
Subleading pair:	The remaining SFOS with the largest $m_{\ell\ell}$
For both pairs:	$p_T^{\ell^+\ell^-} > 2 \text{ GeV}$
Event selection	
Lepton $p_T^{\ell_1, \ell_2, \ell_3}$:	$> 20, 15, 10(8 \text{ if } \mu) \text{ GeV}$
Mass requirements:	$50 < m_{12} < 120 \text{ GeV}$ $12 < m_{34} < 120 \text{ GeV}$
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1 \text{ (0.2)}$ for same- (different-) flavour leptons
J/ ψ veto:	$m(\ell_i^+, \ell_j^-) > 5 \text{ GeV}$
4 ℓ mass range:	$80 < m_{4\ell} < 1000 \text{ GeV}$



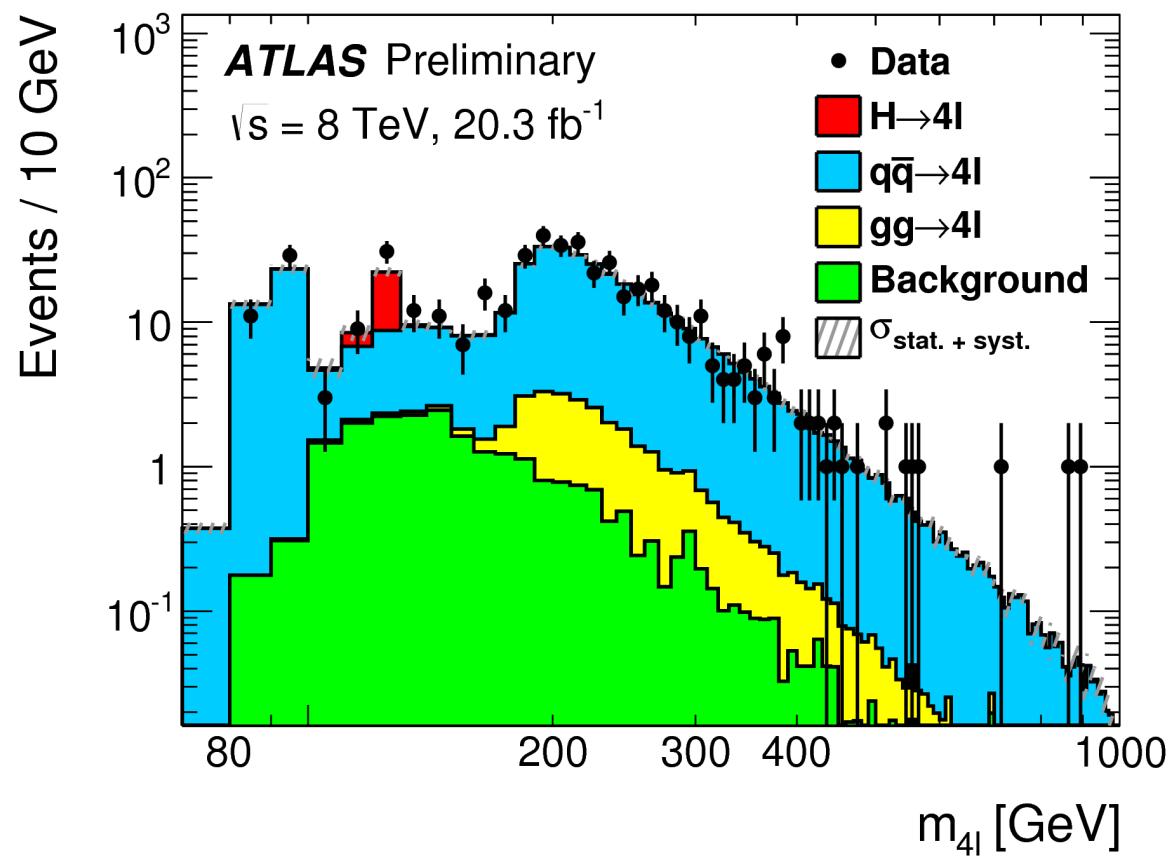


4 charged leptons final state: a ZZ Off-Shell Analysis



ATLAS-CONF-2015-031

- Relax the requirement on the second Z boson in the event



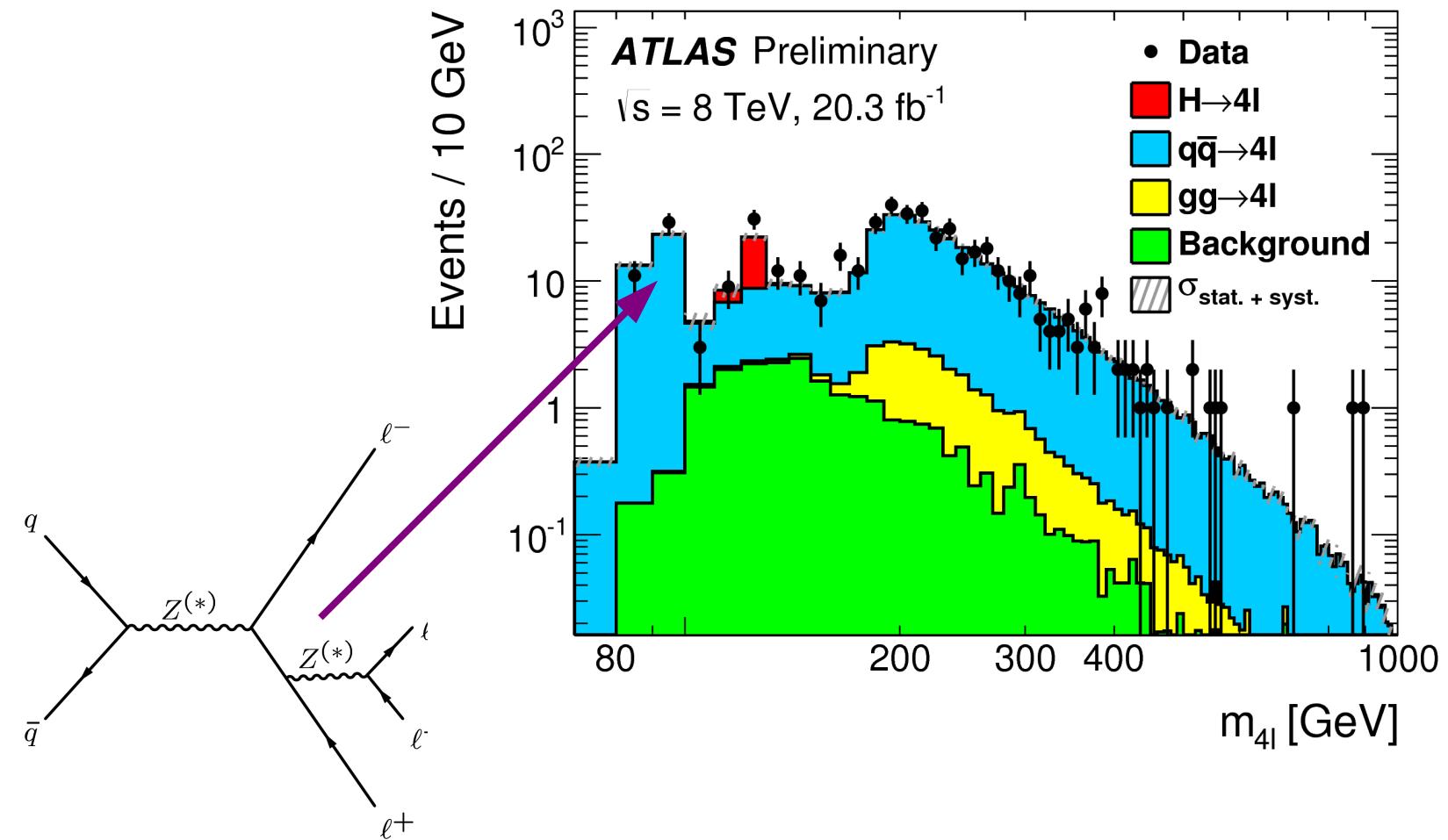


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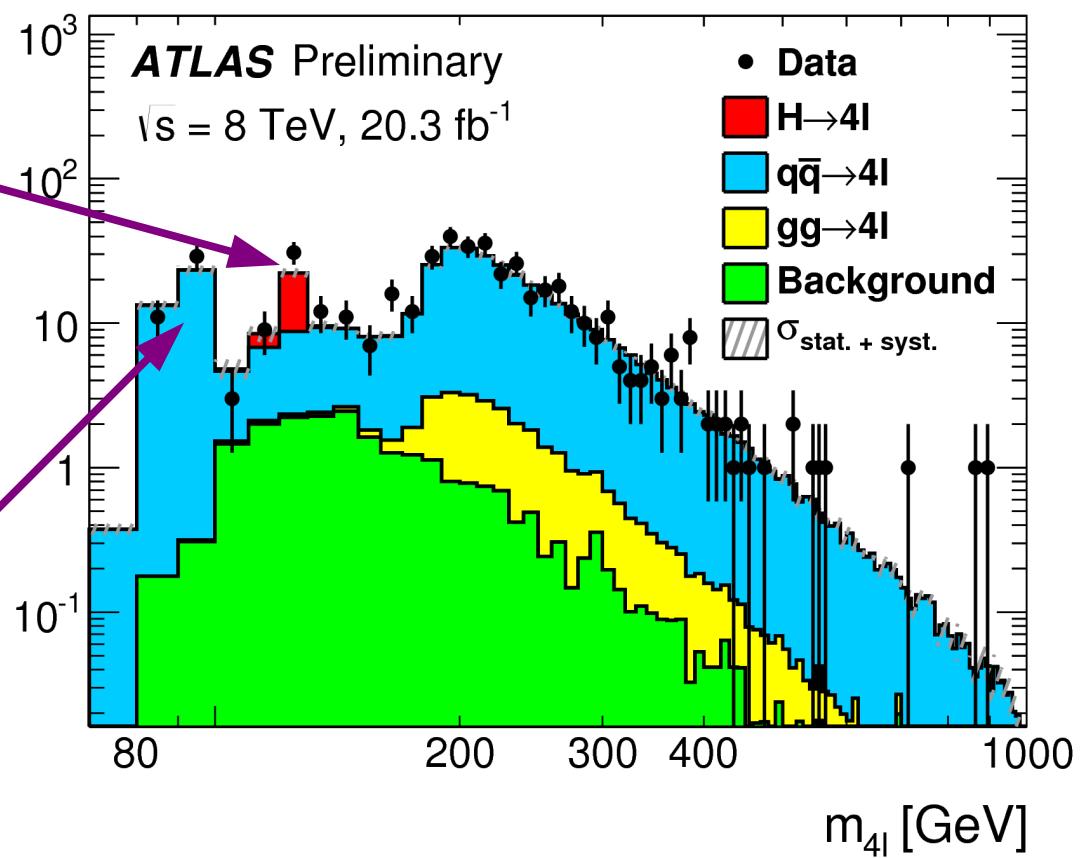
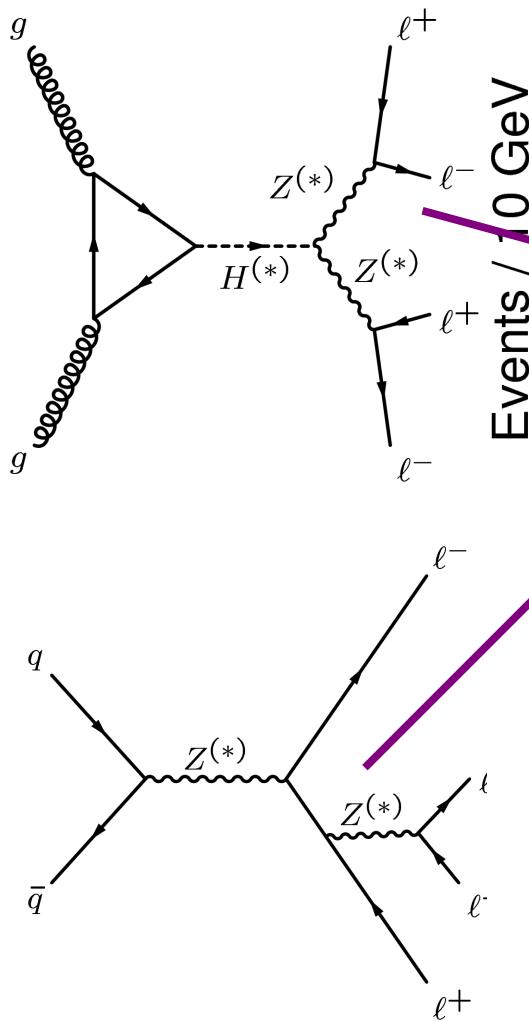


4 charged leptons final state: a ZZ Off-Shell Analysis



ATLAS-CONF-2015-031

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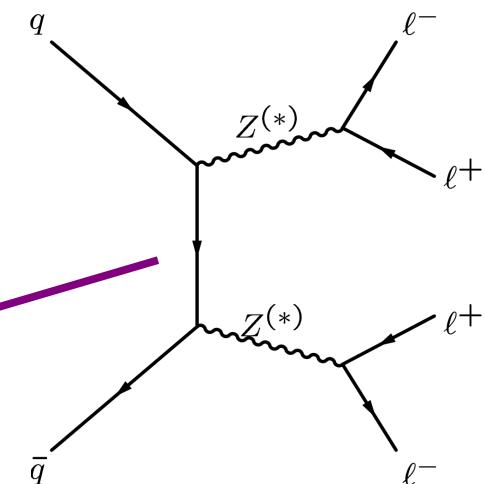
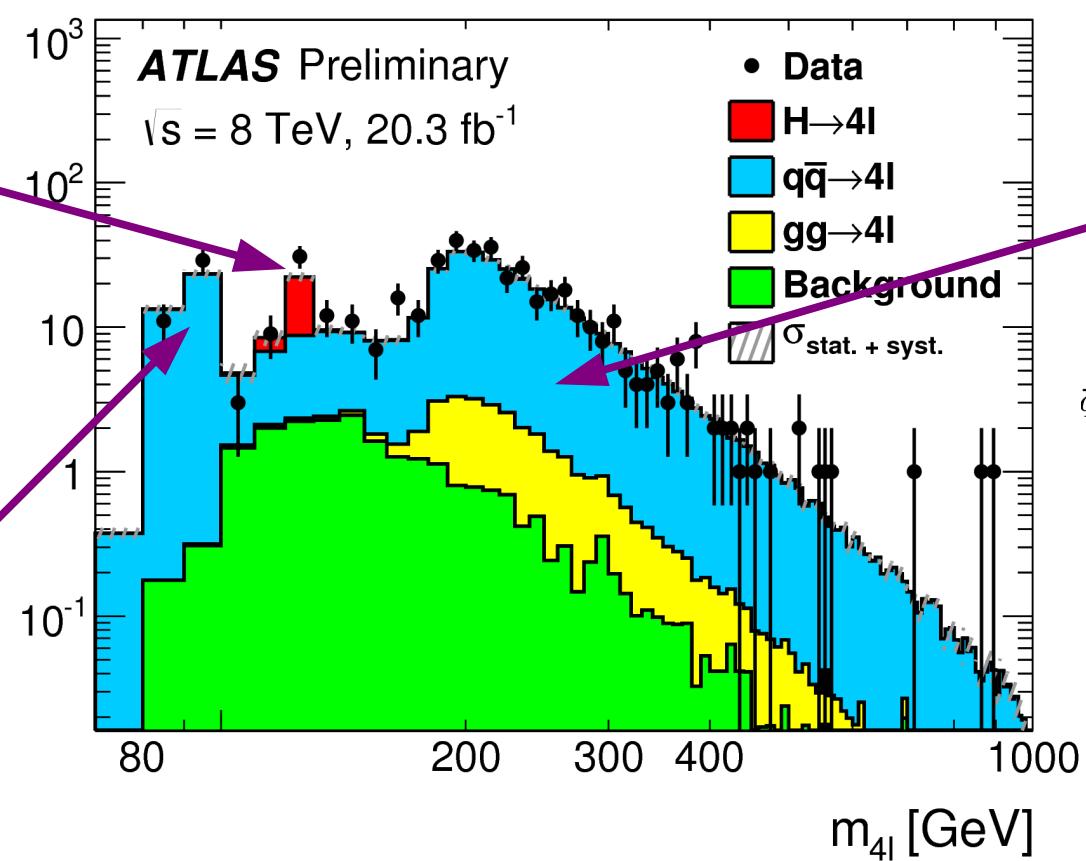
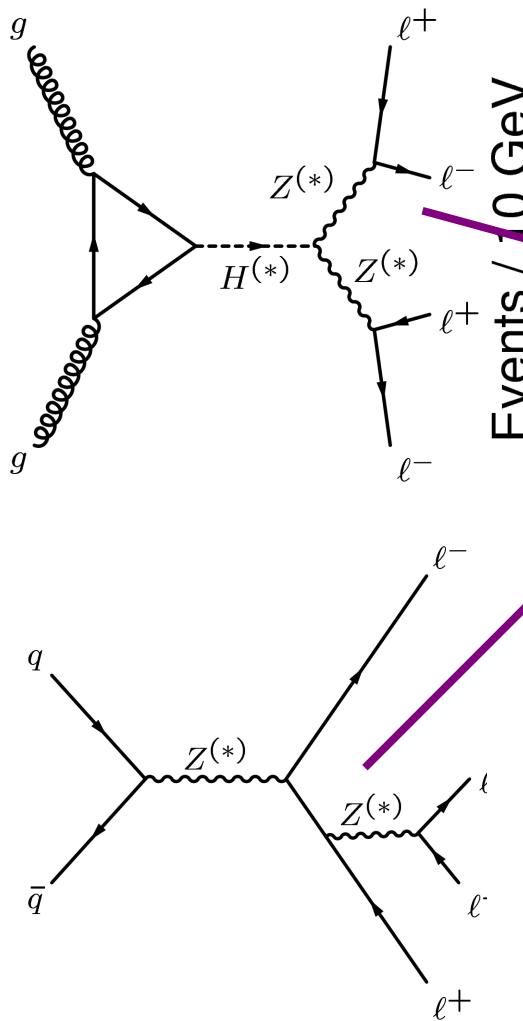


4 charged leptons final state: a ZZ Off-Shell Analysis



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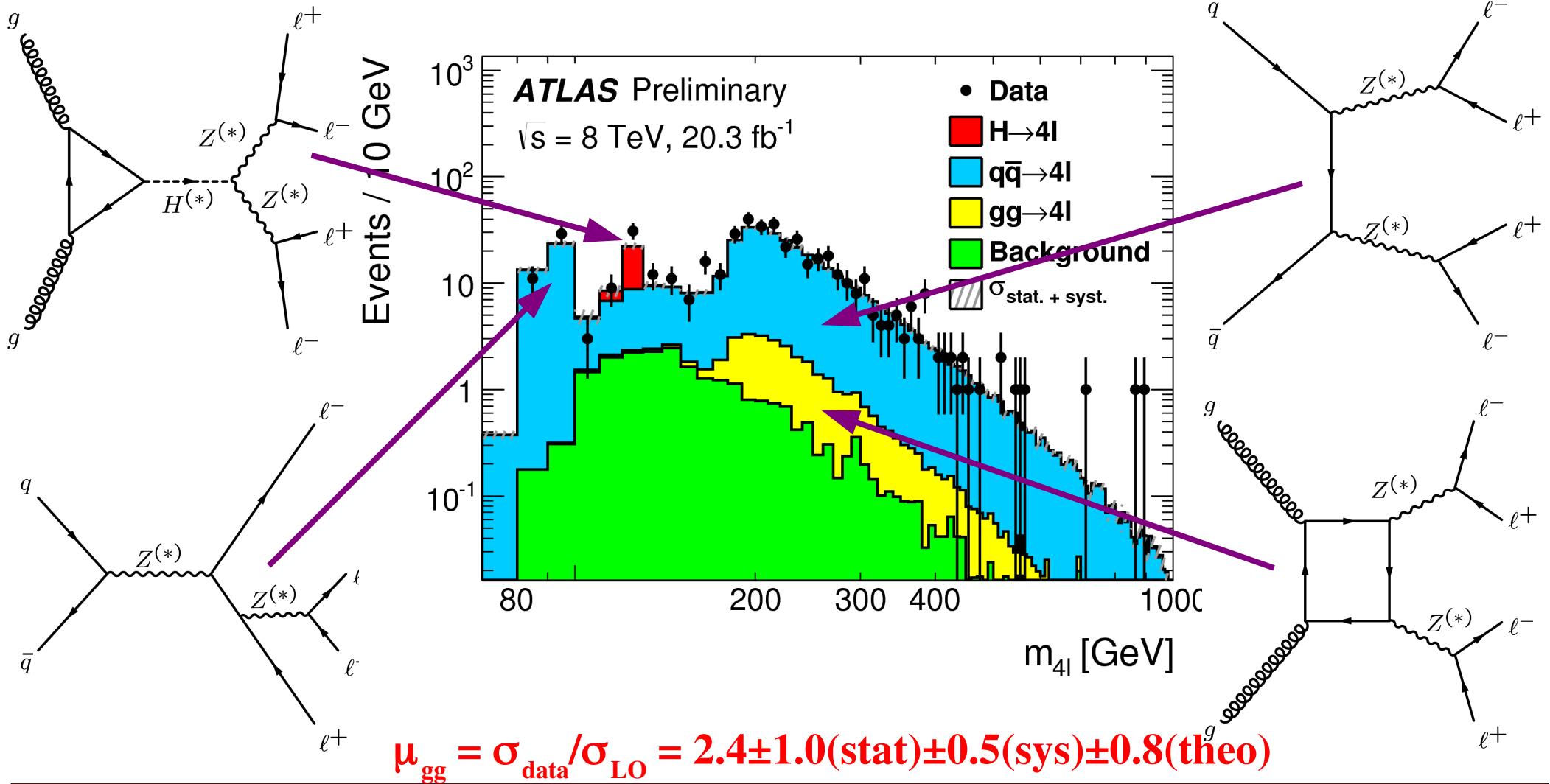


4 charged leptons final state: a ZZ Off-Shell Analysis



ATLAS-CONF-2015-031

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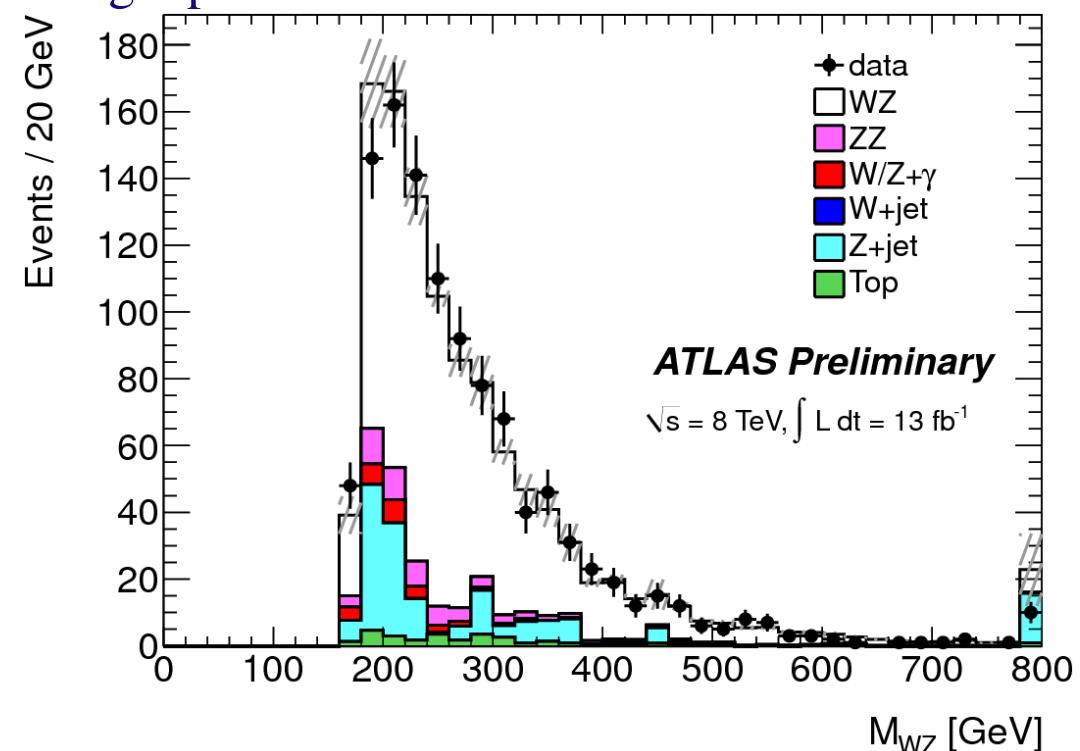
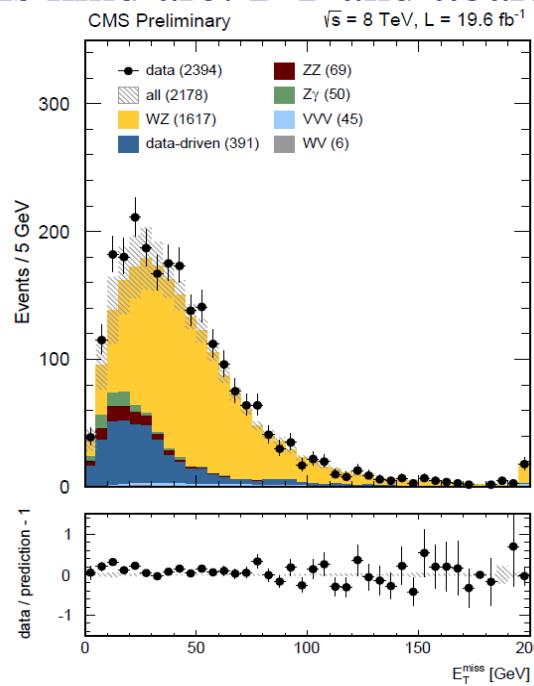




WZ $\rightarrow 3\ell 1\nu$

ATLAS-CONF-2013-021; CMS-PAS-SMP-12-006

- Select charged leptons to pair into one on-shell Z, typically w/ a mass between 10 – 20 GeV around the m_Z , plus an additional isolated high- p_T lepton. Missing E_T must be greater than few ten of GeV, similarly for $m_{T,W}$ (if required, as in ATLAS).
- **Irreducible background** from $ZZ \rightarrow 4$ leptons, where a lepton is not identified, or from $Z/W + \gamma$. These contributions are estimated with **Simulation**.
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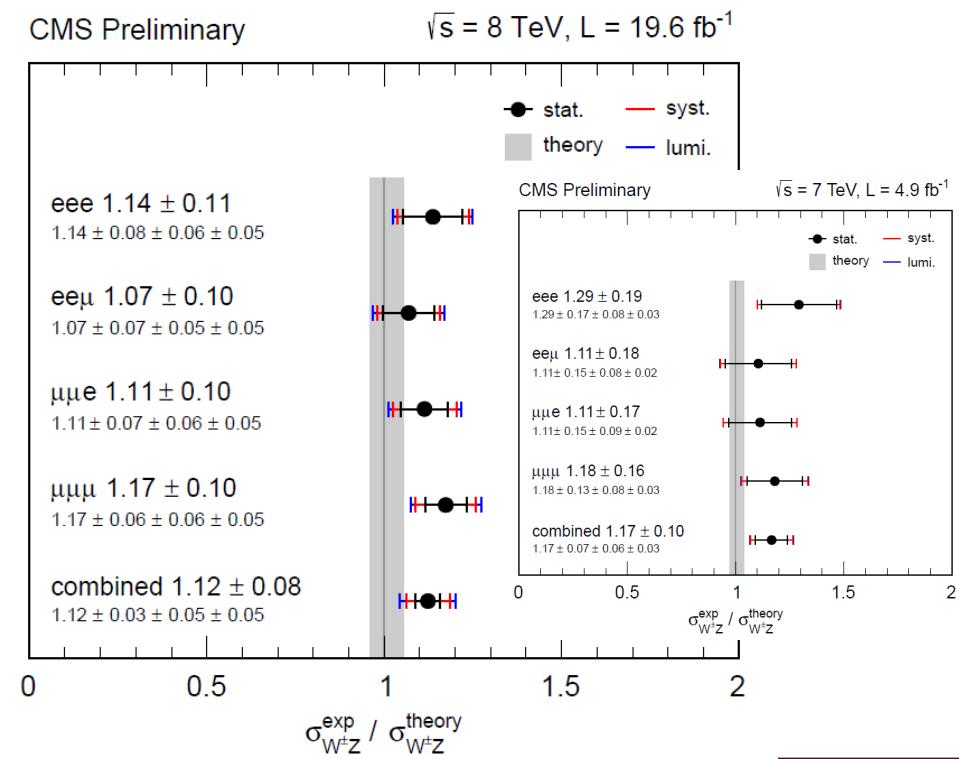
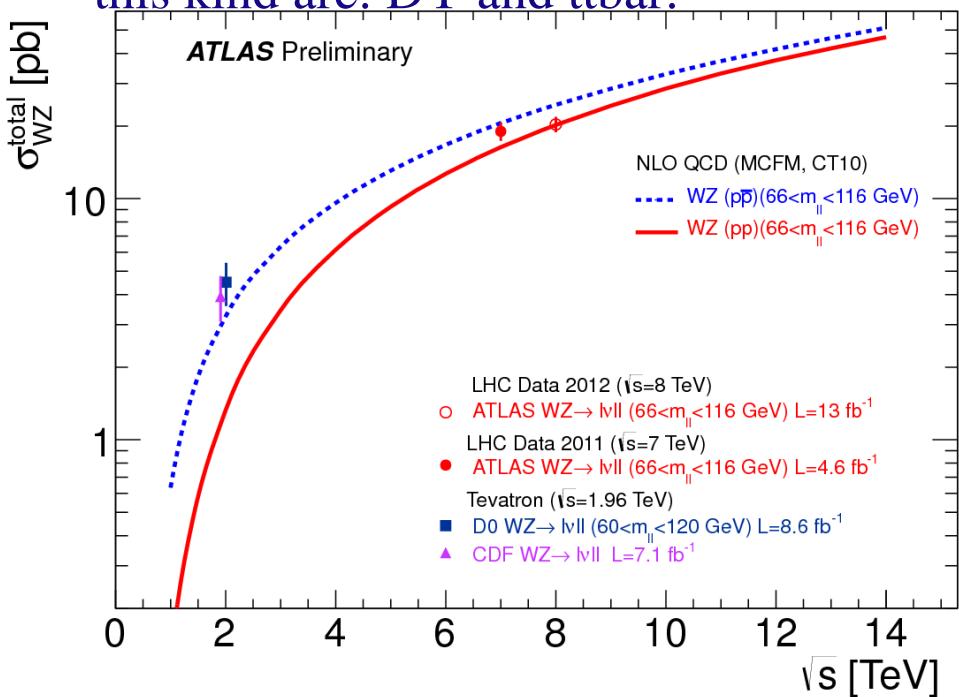


WZ \rightarrow 3 ℓ 1 ν

ATLAS-CONF-2013-021; CMS-PAS-SMP-12-006



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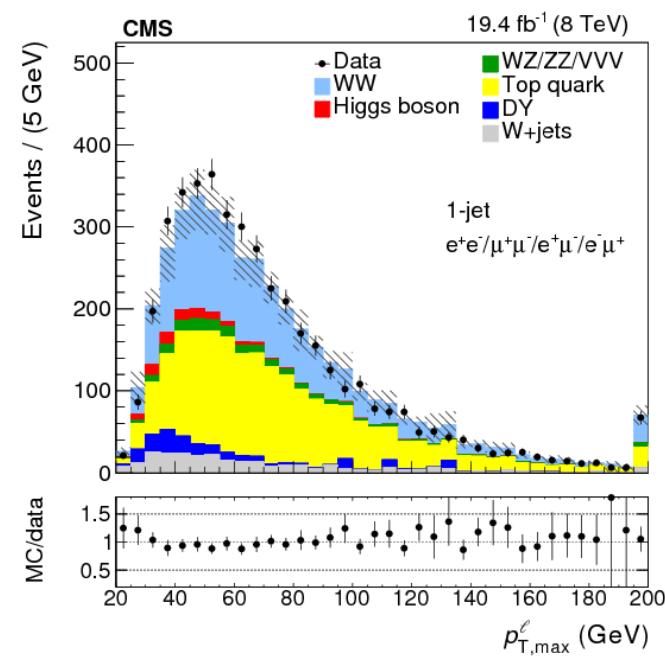
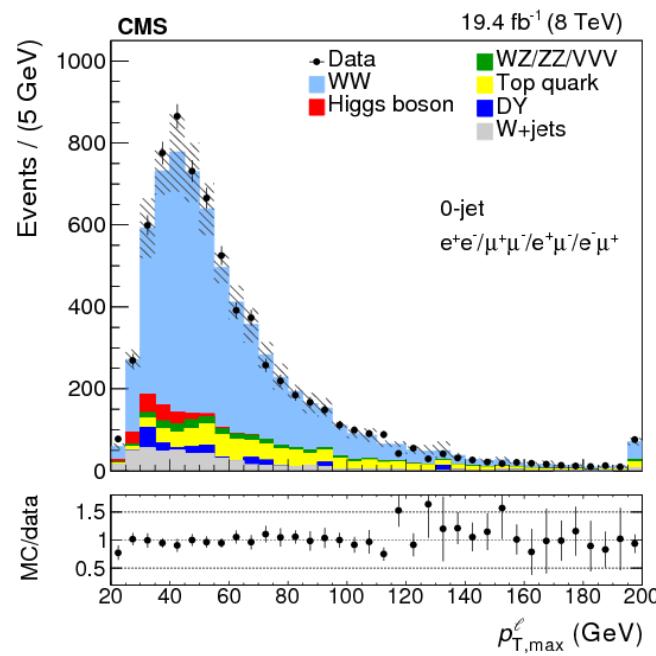
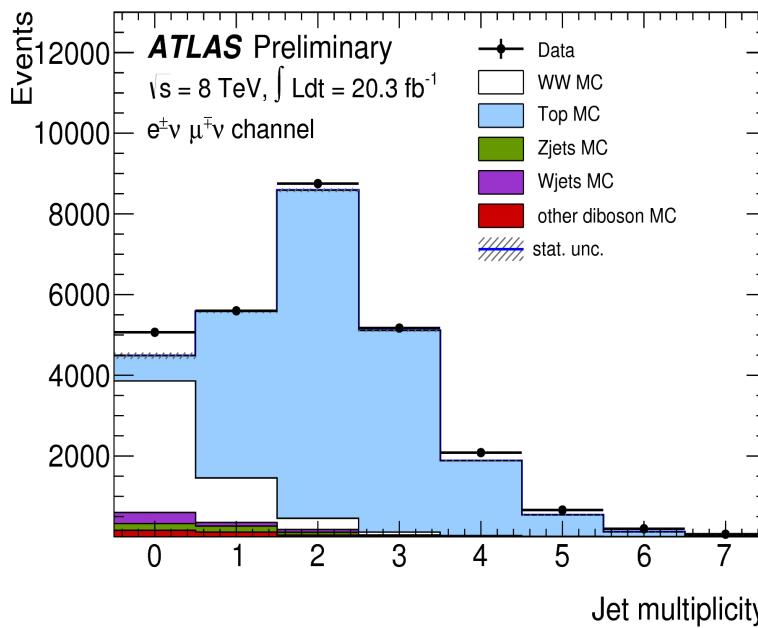




WW $\rightarrow 2\ell 2\nu$

ATLAS-CONF-2014-033; CMS: arXiv.1507.03268

- Require 2 isolate high- p_T leptons of **opposite charge** (outside the m_Z mass window, if of same flavour). Veto additional leptons, cut on quantities such as $p_T^{\ell\ell}$, $m_{\ell\ell}$, missing E_T (or its projection), missing track p_T , jet b-tagging, **Either jet veto or 0-1 jet categorization.**
- Background from **ttbar** and **W+jets** is measured with **data**, **DY** with **MC normalized to data**, while **W γ** , **W γ^*** , **WZ**, **ZZ** and **VVV** are estimated from **simulation**.

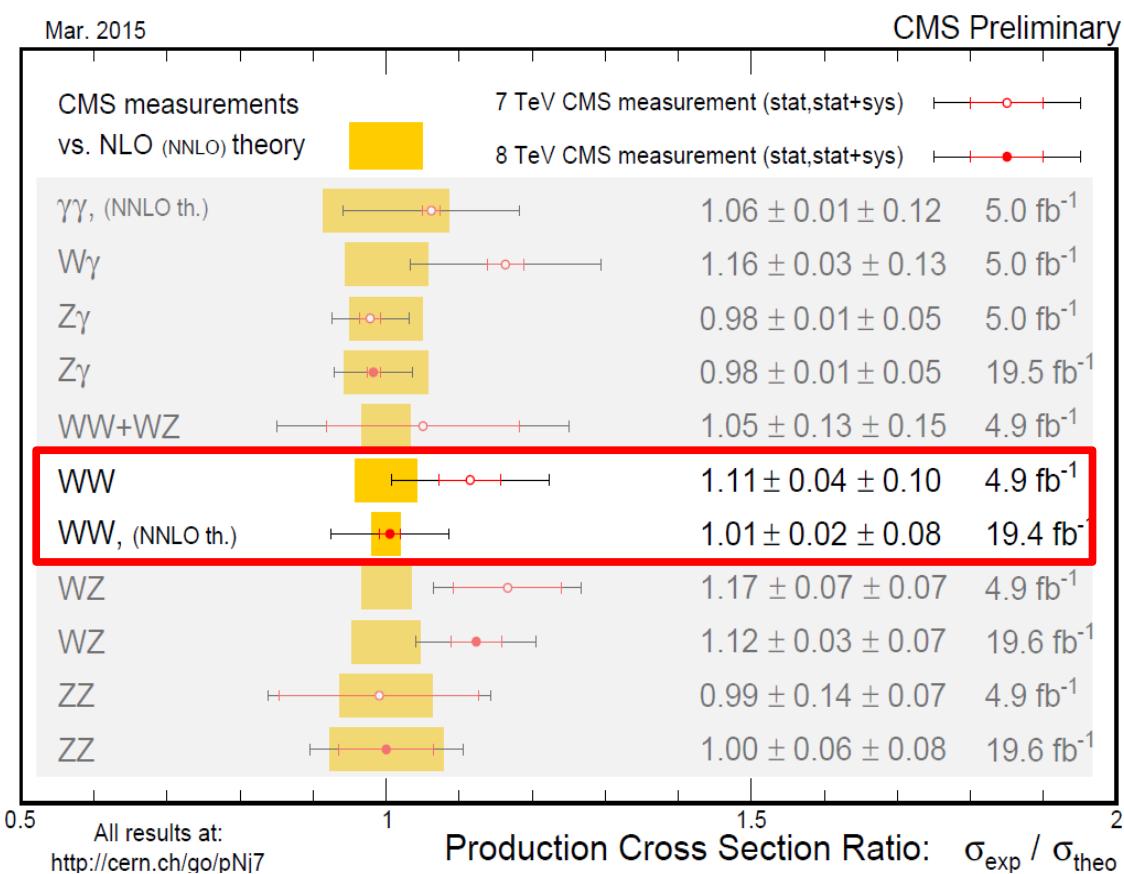
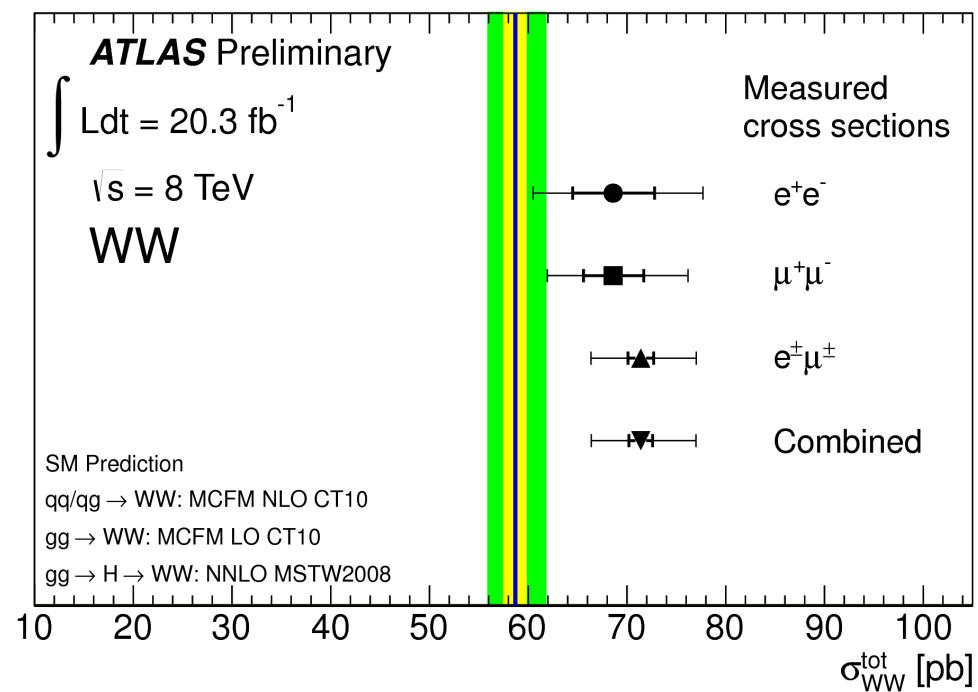




WW $\rightarrow 2\ell 2\nu$: Cross Section

ATLAS-CONF-2014-033; CMS: arXiv.1507.03268

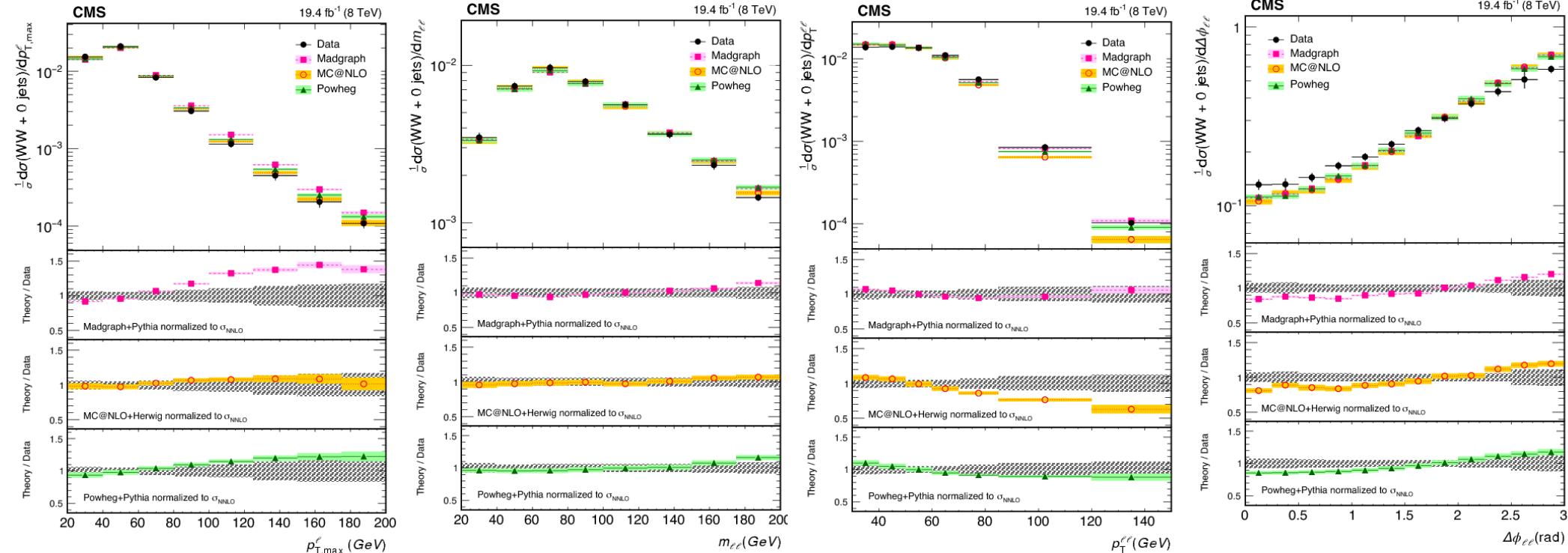
- **ATLAS:** $71.4 \pm 1.2(\text{stat})^{+5.0}_{-4.4}(\text{sys})^{+2.2}_{-2.1}(\text{lumi}) \text{ pb}$
- **CMS:** $60.1 \pm 0.9(\text{stat}) \pm 3.2(\text{exp}) \pm 3.1(\text{theo}) \pm 1.6(\text{lumi}) \text{ pb}$
- **Predicted by SM:** $59.8^{+1.3}_{-1.1} \text{ pb}$





WW → 2ℓ2ν – Unfolded Distributions

CMS: arXiv.1507.03268



- Data and theory in good agreement for the m_{ll} and the p_T^{ll} distributions, MC@NLO predicts a **softer p_T^{ll} spectrum** compared with the data events.
- In case of the $p_T^{l,\text{max}}$, the **MadGraph** prediction shows an **excess of events** in the tail of the distribution compared to data, while **POWHEG** shows a **reasonable agreement** and **MC@NLO** shows a **good agreement**.
- **Differences in the shape** of the $\Delta\phi(l,l)$ for the **three generators** compared to the data.



Other WW Production Analyses

- ATLAS and CMS made two beautiful analyses aiming to observe the **first evidence of $W^\pm W^\pm jj$** (ATLAS&CMS) and **$WZjj$** (CMS) produced via **Electroweak processes!**
 - ATLAS: PRL 113 (2014) 141803, CMS: 114 (2015) 051801
- Production of **WW via photon-photon scattering**
 - CMS: JHEP 1307 (2013) 116

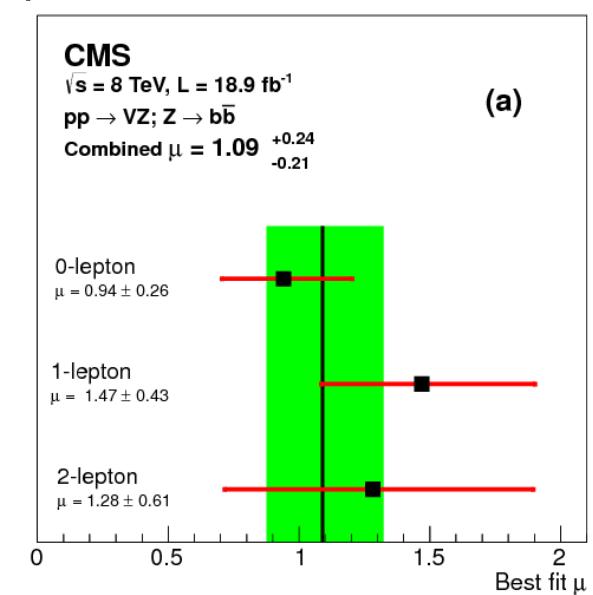
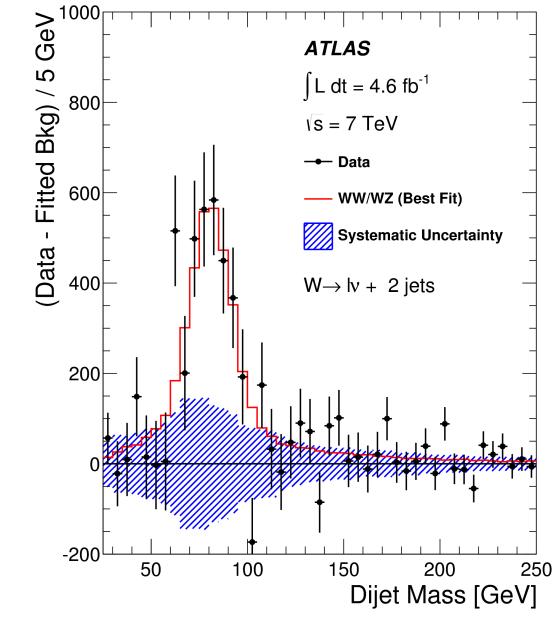
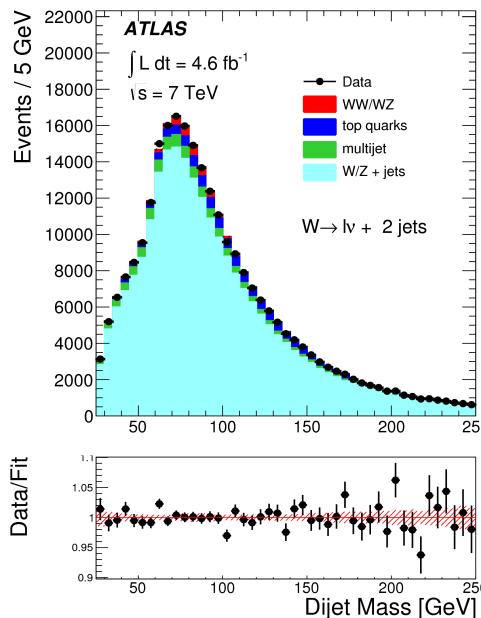
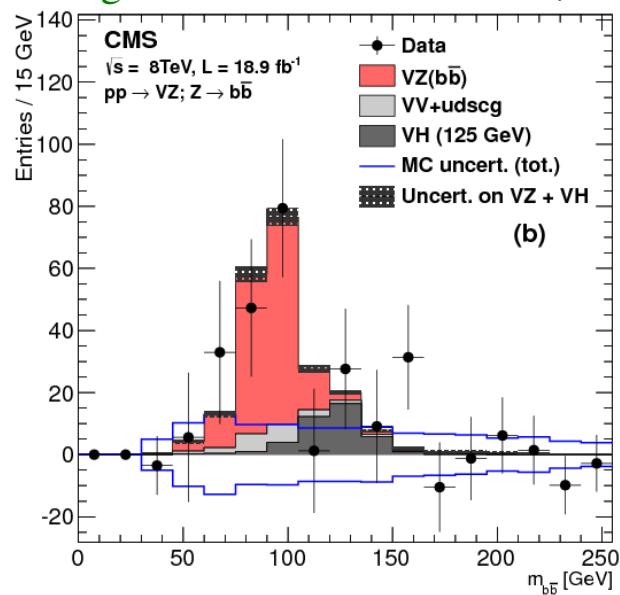
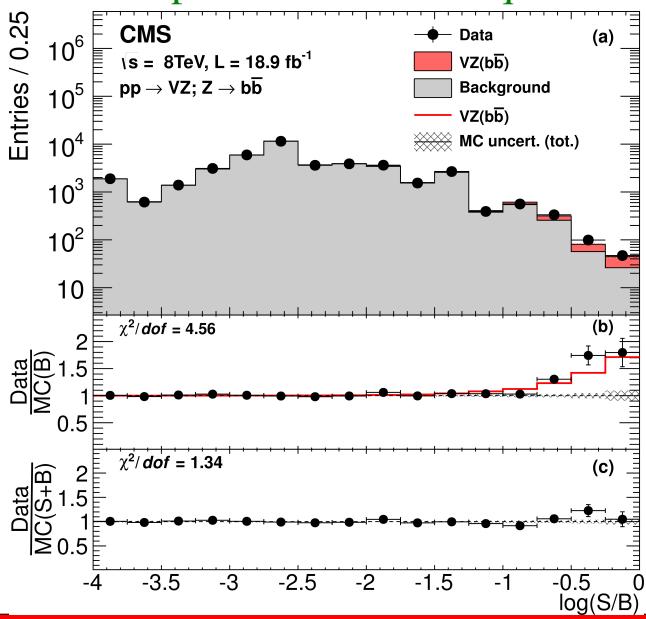
There is a dedicated talk on these analyses (cfr. Linda Finco's)



Hadronic Decays of V: $W/Z \rightarrow jj; Z \rightarrow b\bar{b}$

ATLAS: JHEP 01 (2015) 049; CMS: EPJC 73 (2013) 2283, EPJC 74 (2014) 2973

- Low S/B, but signal can be clearly extracted
- WV, where $W/Z \rightarrow jj$, analyses done by ATLAS and CMS @ 7 TeV
 - The inclusive jj analyses uses m_{jj} template fit
- CMS studied also the VZ production where $Z \rightarrow b\bar{b}$ (@ 8 TeV)
 - CRs used to normalize the simulation, then exploit a BDT technique to extract the signal





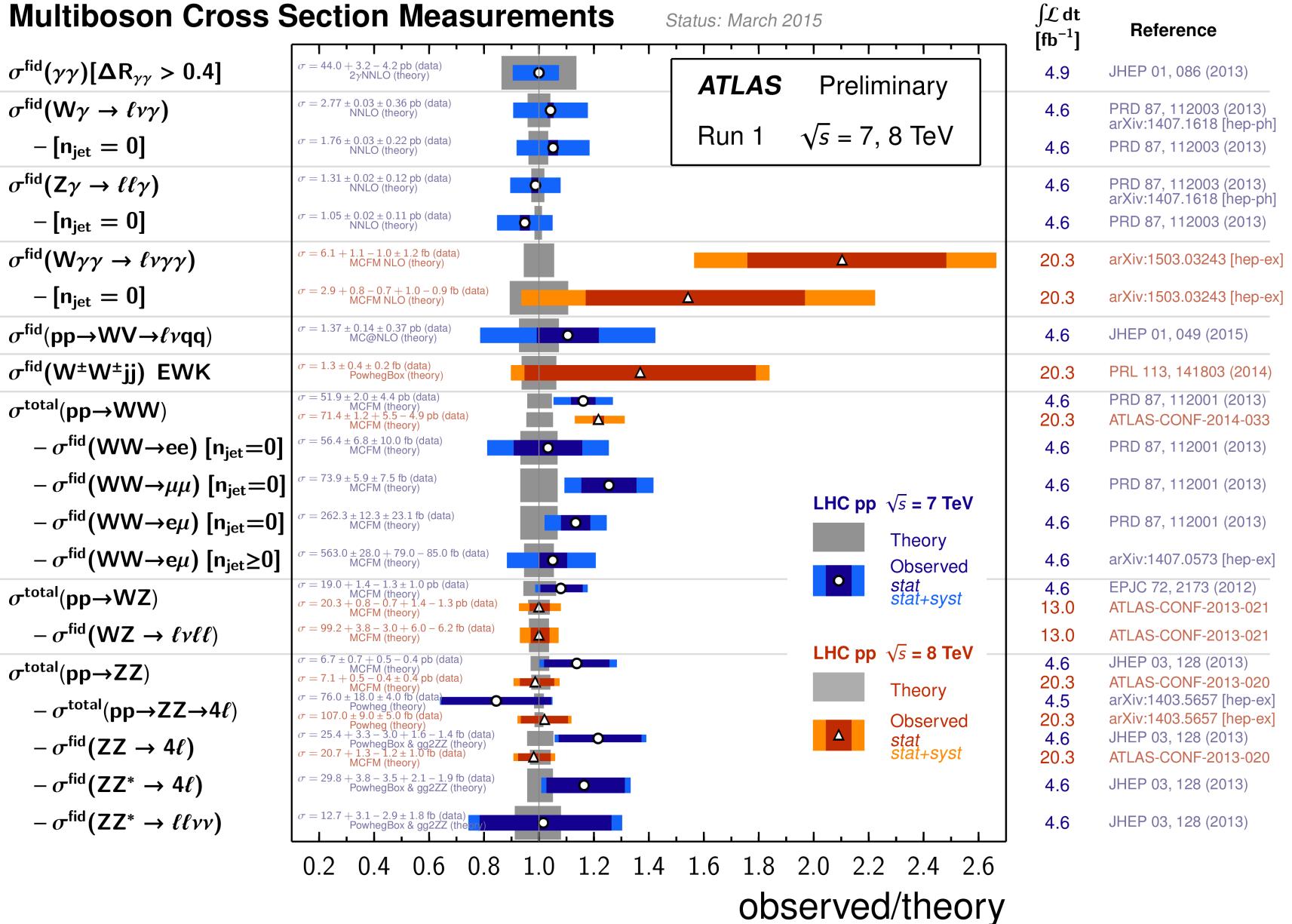
ATLAS Multi-Boson Summary

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/>



Multiboson Cross Section Measurements

Status: March 2015



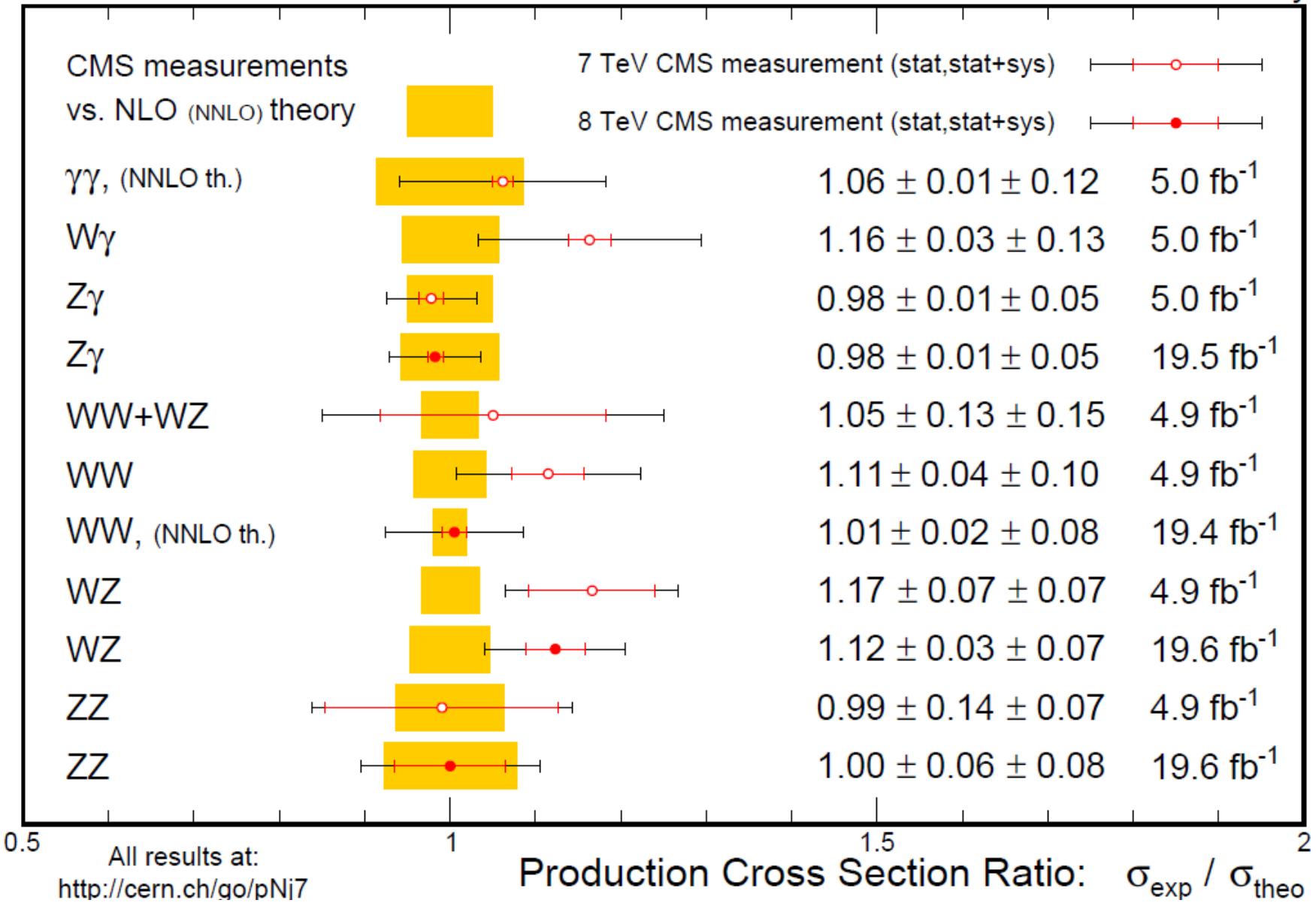


CMS Multi-Boson Summary

<http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html>

Mar. 2015

CMS Preliminary



All results at:
<http://cern.ch/go/pNj7>



Anomalous Vector Boson Couplings

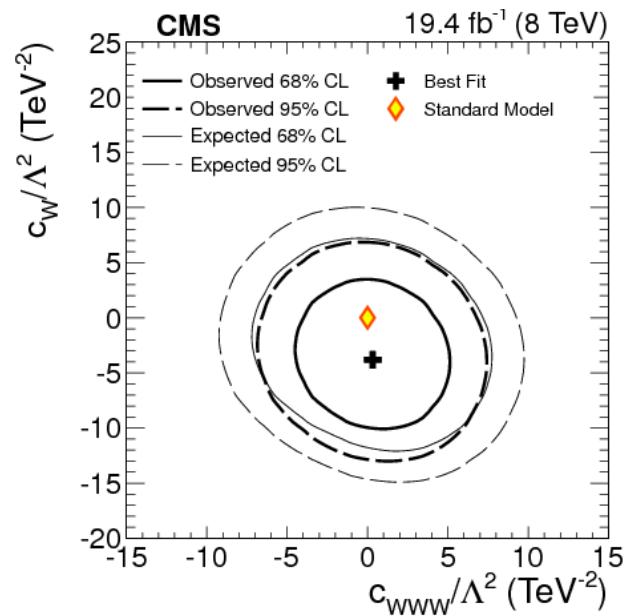
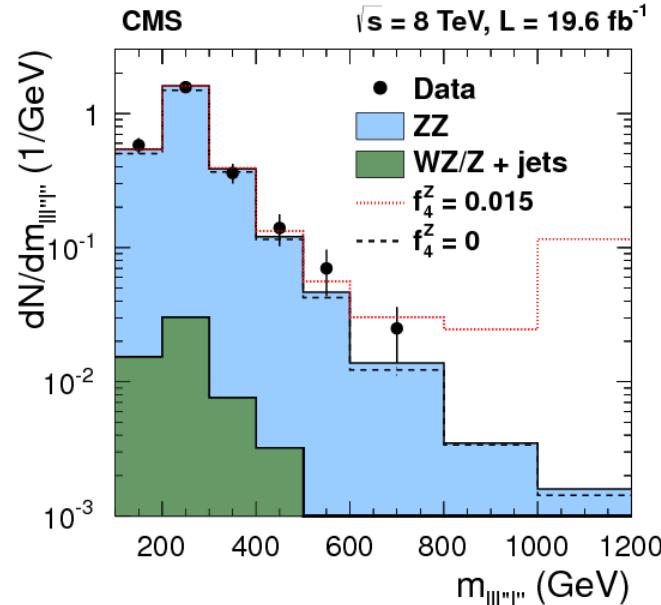
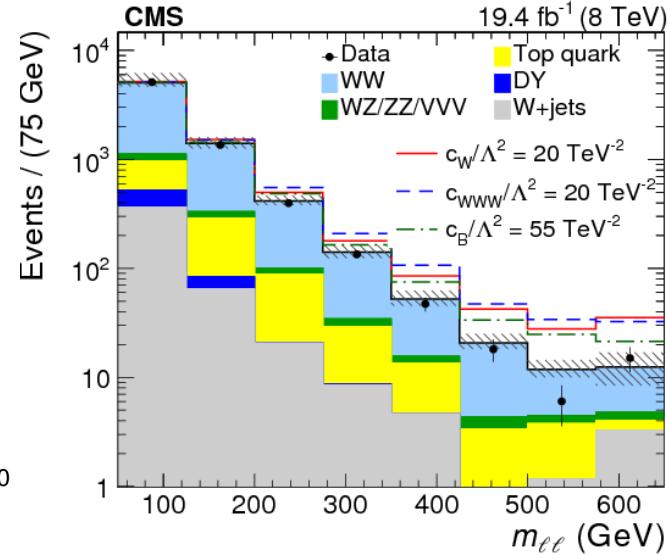
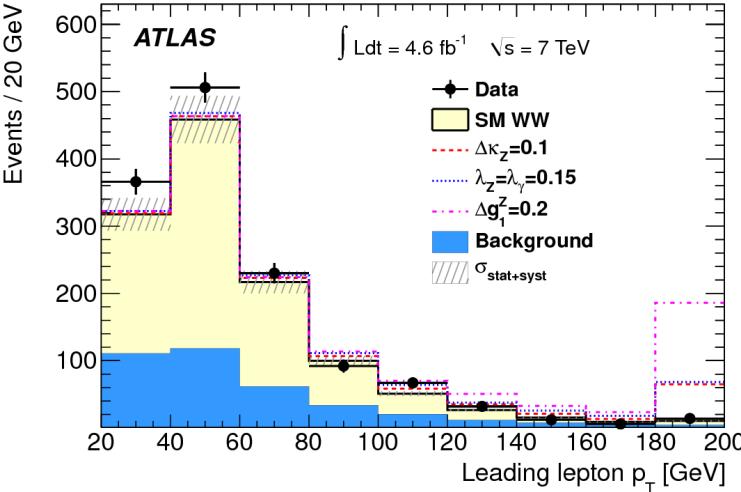


- Search for **new physics** *while doing EW measurements*
- Look for deviations from SM in tail of distributions (m_{vv} , m_{ll} , m_{jj} , $p_{T,v}$, ...)
- Parametrize the new physics **adding terms to the SM lagrangian**
- Several possibilities:
 - **Effective vertex approach** [Nucl.Phys.B282(1987)253] → used in **ZZ** analysis.
 - **Effective lagrangian approach** [Phys.Rev.D41(1990)2113] → used in **WV** analyses.
 - **Effective field theory approach** [Phys.Rev.D48(1993)2182] → used in **WW**, **VBS** and triboson analyses.
- Parameters are usually varied **one-by-one** or at most **two-by-two**, as there is **little correlation among them**.



Testing Anomalous Couplings

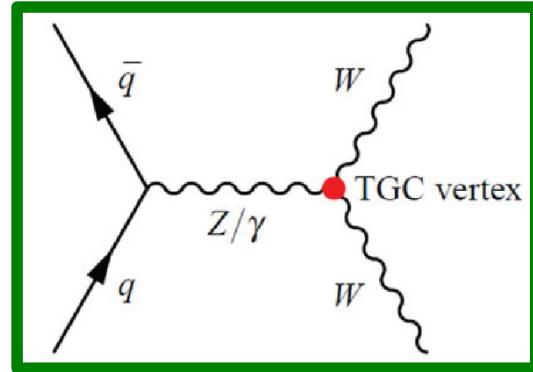
ATLAS: PRD 87, 112001, CMS: arXiv.1507.03268 , PLB 740 (2015) 250



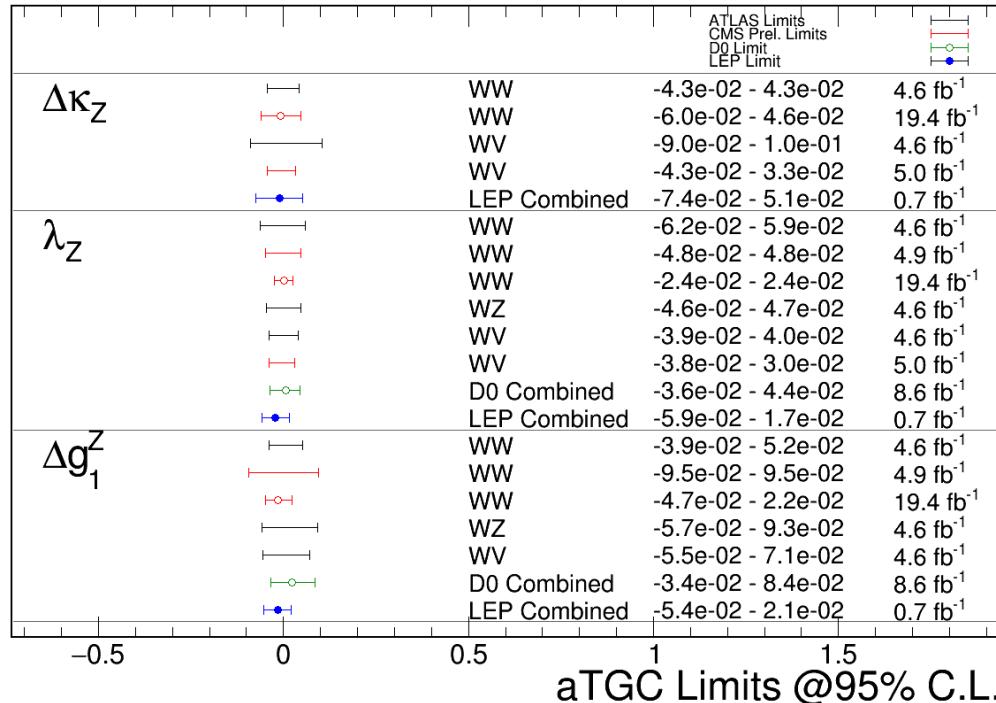
- No significant deviation w.r.t. SM are observed
- Couplings are measured (or limits are set) by performing **binned fit in single sensitive observable**
 - Limiting factors: observed **statistics** in the tail (primary) and systematic and statistical uncertainty on the **signal model** (secondary)



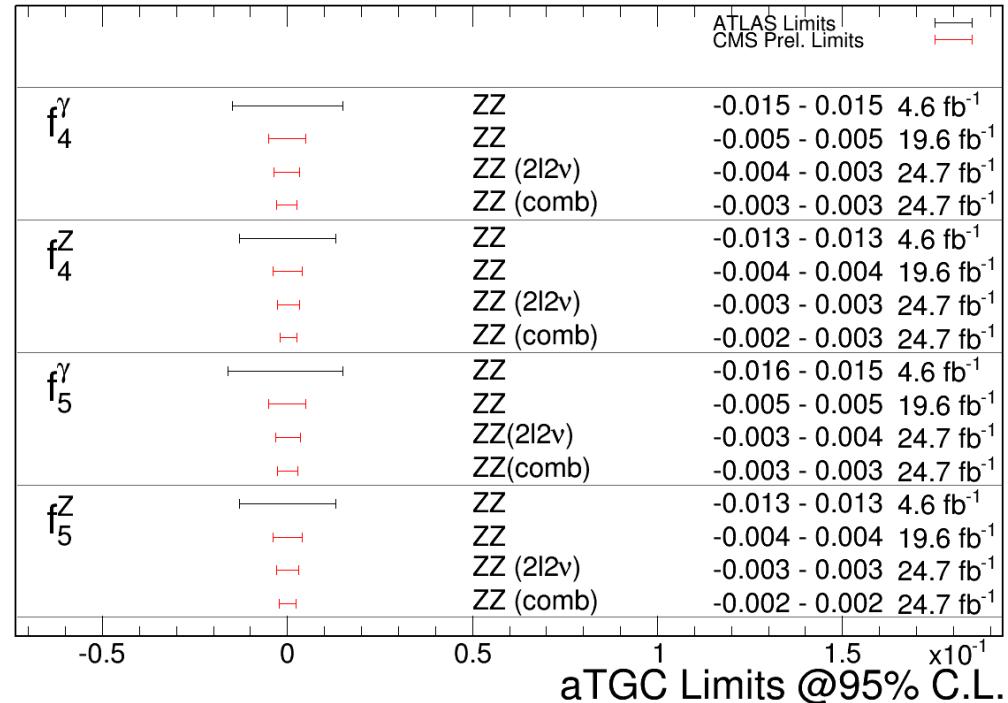
Anomalous Couplings Summary



July 2015



Mar 2015





Conclusions

- We discovered a Higgs boson, yet **the comprehension of the Electroweak Symmetry Breaking is not completed**
→ **Understanding the Multi-boson production is the key point!**
 - Complementary to Higgs boson properties studies and high mass searches
- **Several analyses on 7 and 8 TeV data** explored the multi-boson final states setting limits on possible deviation from the Standard Model predictions
 - (Not discussed here, but **first** Vector Boson scattering processes observed at LHC)

**Time of multi-boson production is coming, the NEW FRONTIER will be:
VV + jets, Vector Boson Scattering and triboson production**

→ **they will be ones of the hot topic of LHC Run II!**

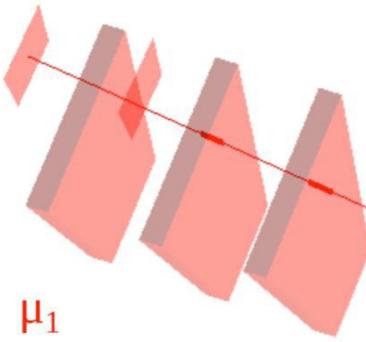
Details on results can be found in the public pages of the two experiments:

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/>

<http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html>



Exciting Moments Ahead of Us!!



μ_1
 $p_T = 58.7 \text{ GeV}$
 $\eta = 1.8$

Run 251244 Event 204117665

$\sqrt{s} = 13 \text{ TeV}$

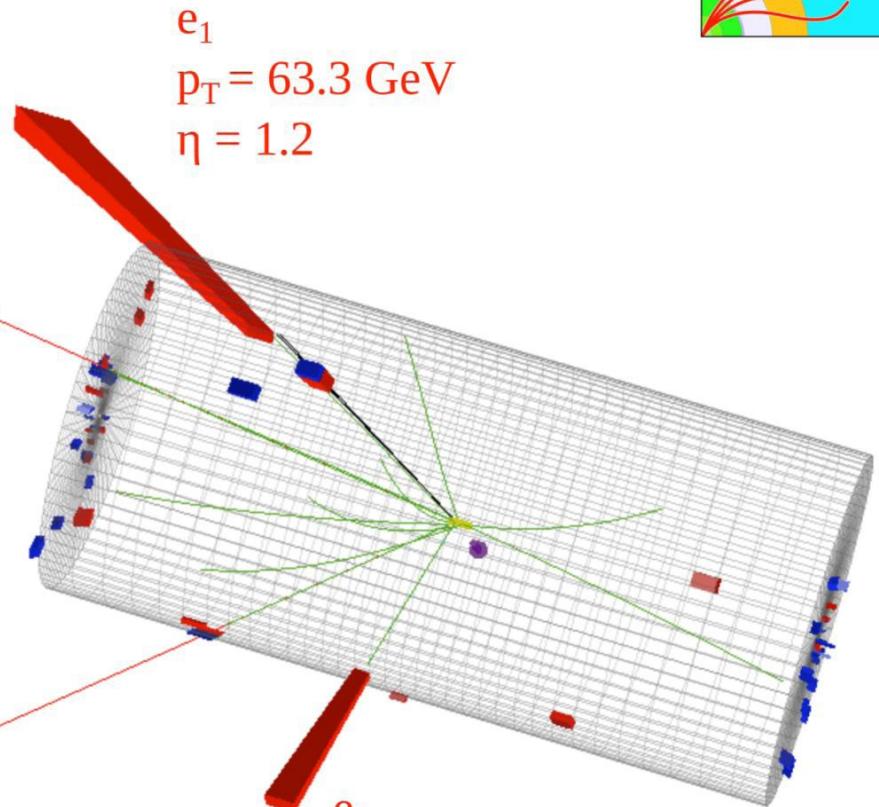
$pp \rightarrow ZZ \rightarrow 2e2\mu$

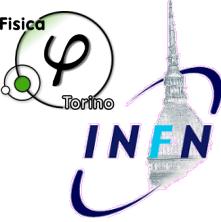
$m_{\mu\mu} = 91.1 \text{ GeV}$

$m_{ee} = 88.2 \text{ GeV}$

$m_{4\ell} = 208.9 \text{ GeV}$

μ_2
 $p_T = 36.1 \text{ GeV}$
 $\eta = 0.98$

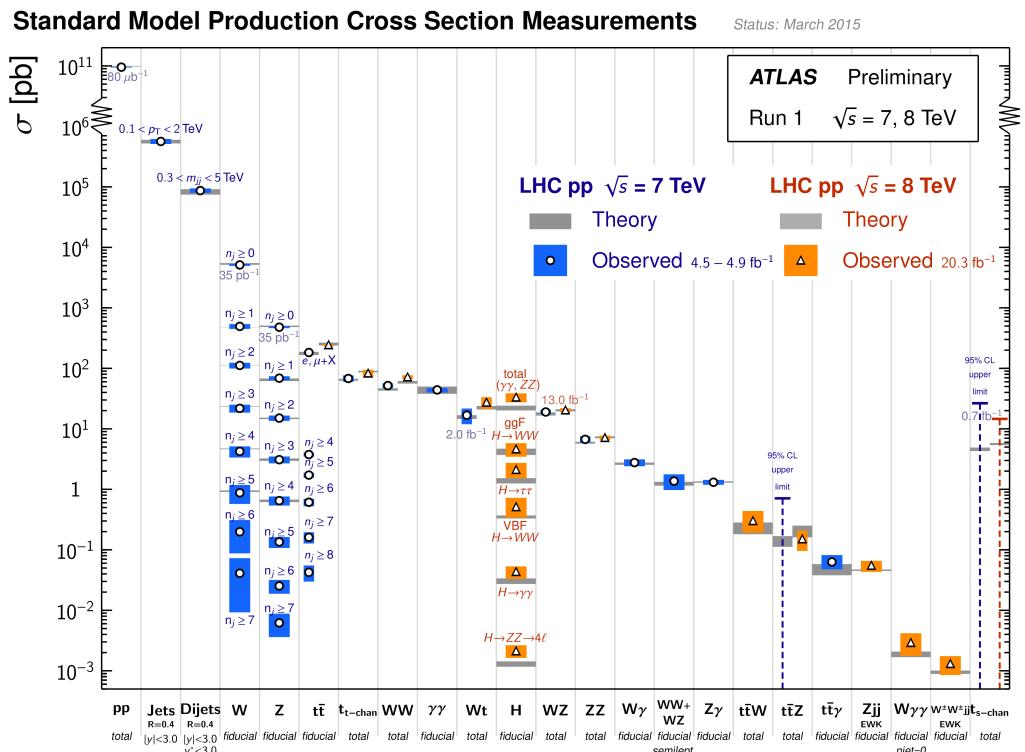
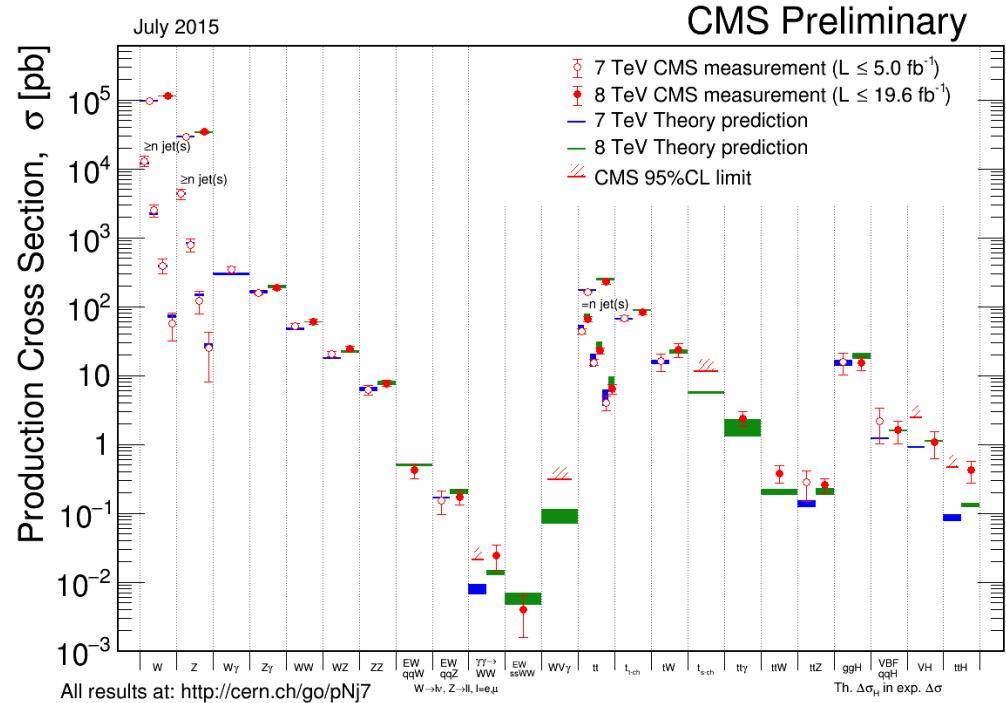




More Material



Stairways to Heaven?





WW @ 8 TeV CMS

Variable	Different-flavor	Same-flavor
Opposite-sign charge requirement	Applied	Applied
p_T^ℓ [GeV]	>20	>20
$\min(\text{proj. } E_T^{\text{miss}}, \text{proj. track } E_T^{\text{miss}})$ [GeV]	>20	>20
DY MVA	—	>0.88 in 0-jet (>0.84 in 1-jet)
$ m_{\ell\ell} - m_Z $ [GeV]	—	>15
$p_T^{\ell\ell}$ [GeV]	>30	>45
$m_{\ell\ell}$ [GeV]	>12	>12
Additional leptons ($p_T^\ell > 10$ GeV)	veto	veto
Top-quark veto	applied	applied
Number of reconstructed jets	<2	<2

Source	Uncertainty (%)
Statistical uncertainty	1.5
Lepton efficiency	3.8
Lepton momentum scale	0.5
Jet energy scale	1.7
E_T^{miss} resolution	0.7
$t\bar{t}+tW$ normalization	2.2
W+jets normalization	1.3
$Z/\gamma^* \rightarrow \ell^+\ell^-$ normalization	0.6
$Z/\gamma^* \rightarrow \tau^+\tau^-$ normalization	0.2
$W\gamma$ normalization	0.3
$W\gamma^*$ normalization	0.4
VV normalization	3.0
$H \rightarrow W^+W^-$ normalization	0.8
Jet counting theory model	4.3
PDFs	1.2
MC statistical uncertainty	0.9
Integrated luminosity	2.6
Total uncertainty	7.9

p_T^{jet} (GeV)	$\sigma_{\text{zero-jet}}$ measured (pb)	$\sigma_{\text{zero-jet}}$ predicted (pb)
>20	$36.2 \pm 0.6 \text{ (stat)} \pm 2.1 \text{ (exp)} \pm 1.1 \text{ (theo)} \pm 0.9 \text{ (lumi)}$	$36.7 \pm 0.1 \text{ (stat)}$
>25	$40.8 \pm 0.7 \text{ (stat)} \pm 2.3 \text{ (exp)} \pm 1.3 \text{ (theo)} \pm 1.1 \text{ (lumi)}$	$40.9 \pm 0.1 \text{ (stat)}$
>30	$44.0 \pm 0.7 \text{ (stat)} \pm 2.5 \text{ (exp)} \pm 1.4 \text{ (theo)} \pm 1.1 \text{ (lumi)}$	$43.9 \pm 0.1 \text{ (stat)}$

Event category	W^+W^- production cross section (pb)	
zero-jet category	Different-flavor	$59.7 \pm 1.1 \text{ (stat)} \pm 3.3 \text{ (exp)} \pm 3.5 \text{ (theo)} \pm 1.6 \text{ (lumi)}$
	Same-flavor	$64.3 \pm 2.1 \text{ (stat)} \pm 4.6 \text{ (exp)} \pm 4.3 \text{ (theo)} \pm 1.7 \text{ (lumi)}$
one-jet category	Different-flavor	$59.1 \pm 2.8 \text{ (stat)} \pm 6.0 \text{ (exp)} \pm 6.2 \text{ (theo)} \pm 1.6 \text{ (lumi)}$
	Same-flavor	$65.1 \pm 5.5 \text{ (stat)} \pm 8.3 \text{ (exp)} \pm 8.0 \text{ (theo)} \pm 1.7 \text{ (lumi)}$



Why VV Scattering

In the symmetry breaking (EWSB) mechanism the **W** and **Z** bosons get their **masses** and acquire a **longitudinal degree of polarization**.

The mechanism responsible for the EWSB has to **regulate the $V_L V_L \rightarrow V_L V_L$ cross section** such that the unitarity is preserved above $m_{VV} \sim 1\text{-}2 \text{ TeV}$

VV scattering is the key process to probe EWSB and high energy vector boson scattering will play a central role:

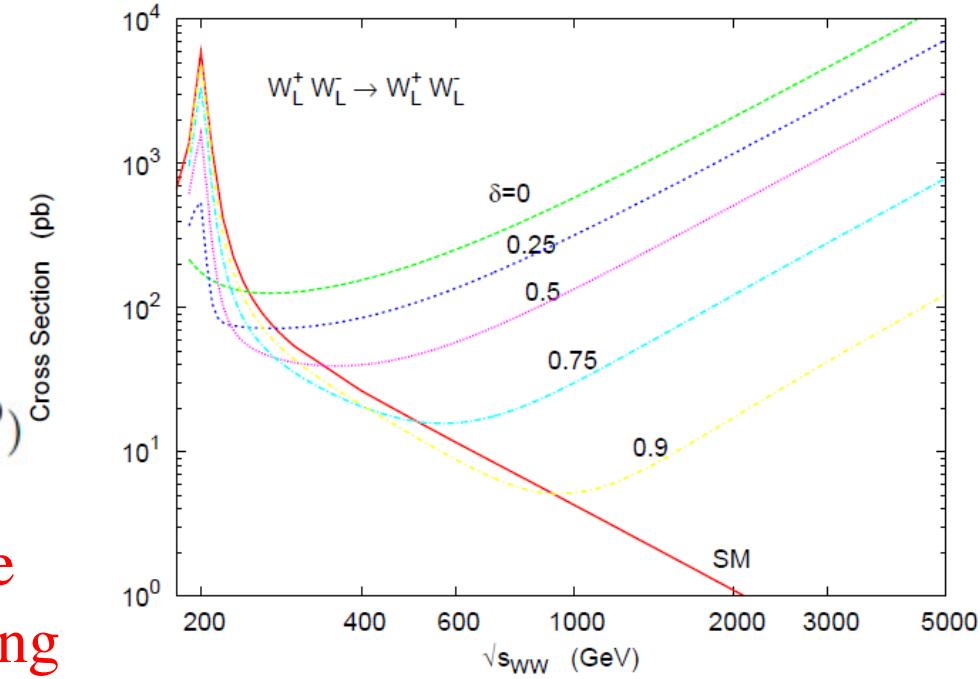
- both as a **test of the Higgs boson nature**
 - If the discovered Higgs boson contributes **fully to the EWSB**, then most probably the interaction among longitudinal weak bosons would remain **weak** at high energy
- and as a **model independent research** of alternative theory to explain EWSB
 - if the 125.5 GeV Higgs boson is only **partially responsible for the EWSB**, then the VV interaction could get **strong** at high energy.
- Also **TGC** and **QGC** processes may carry **new physics phenomena**

The Higgs Job

- If the cancellation of the **Higgs diagrams** is not complete, then we expect a **g_{HWW} coupling smaller than the SM.**
- The **$W_L W_L$ will keep growing with \sqrt{s}** , up to the new resonance, or more generally to the **new physics scale Λ .**
- Suppose the Higgs-WW coupling is **$\sqrt{\delta}$ of the SM value**. then the amplitudes become

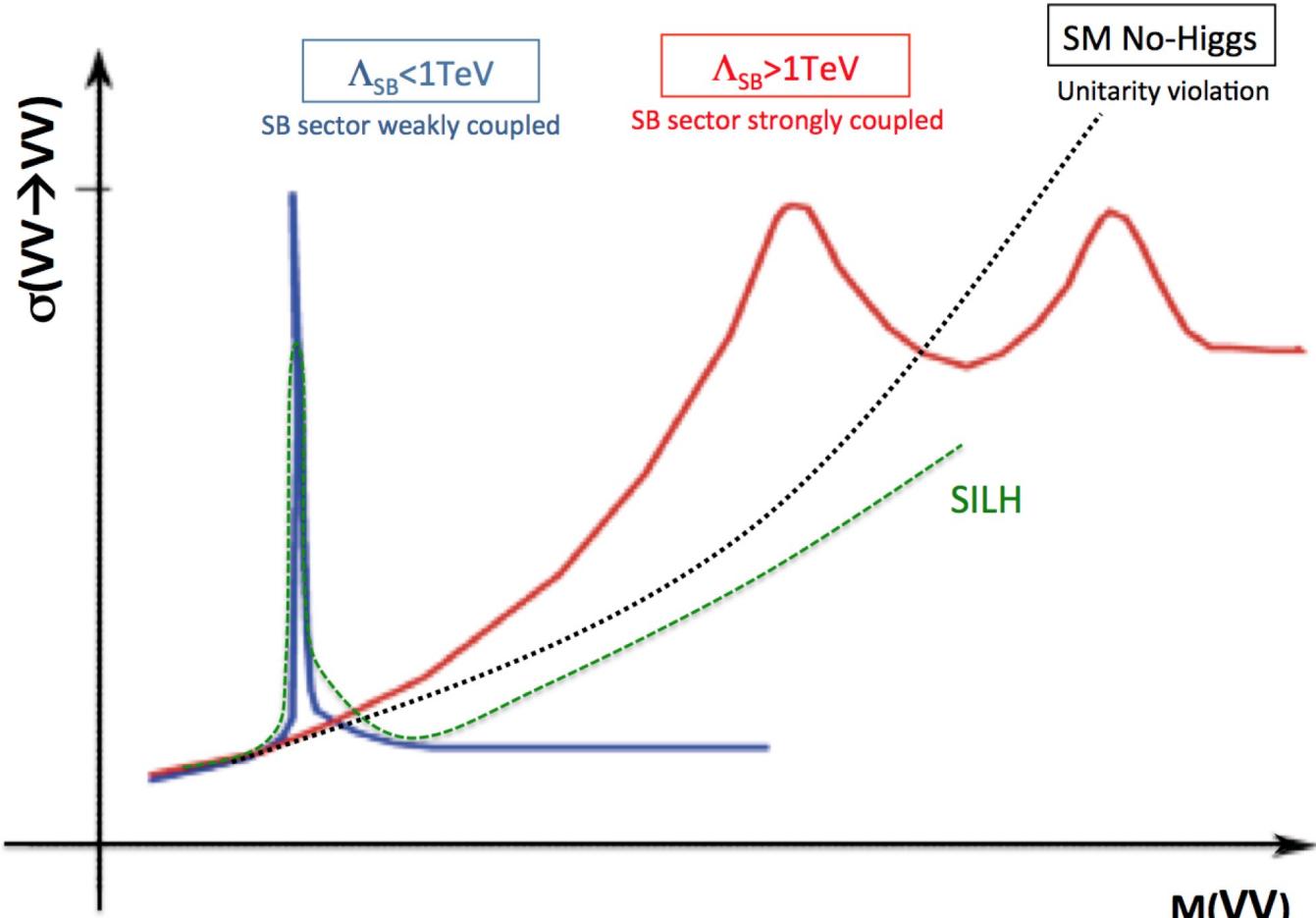
$$\begin{aligned} i\mathcal{M}^{\text{gauge}} &= -i \frac{g^2}{4m_W^2} u + \mathcal{O}((E/m_W)^0) \\ i\mathcal{M}^{\text{higgs}} &= i \frac{g^2}{4m_W^2} u \delta + \mathcal{O}((E/m_W)^0) \\ i\mathcal{M}^{\text{all}} &= -i \frac{g^2}{4m_W^2} u(1 - \delta) + \mathcal{O}((E/m_W)^0) \end{aligned}$$

Measure with high precision both the HVV coupling and the $V_L V_L$ scattering



Cheung, Chiang, Yuan

VV Scattering to test the EWSB



SILH :

$$g_h \rightarrow g_h / \sqrt{1 + \xi c_H}, \xi = v^2 / f^2$$

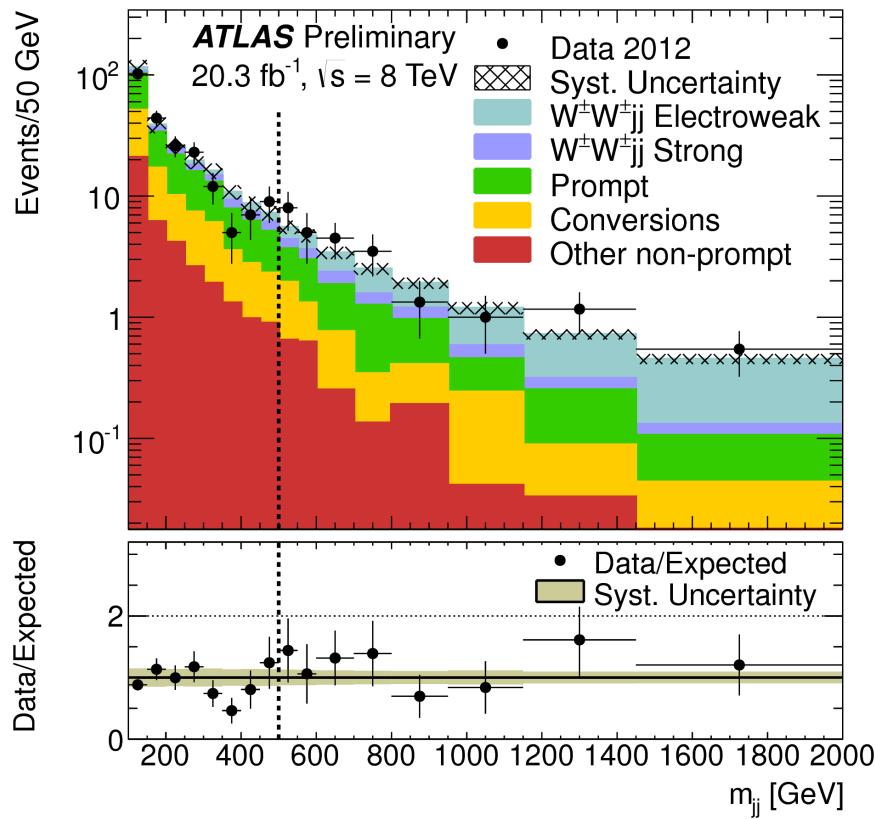
Higgs a pseudo Goldstone Boson of a new strong sector

Both a light Higgs and Bosons strongly coupled

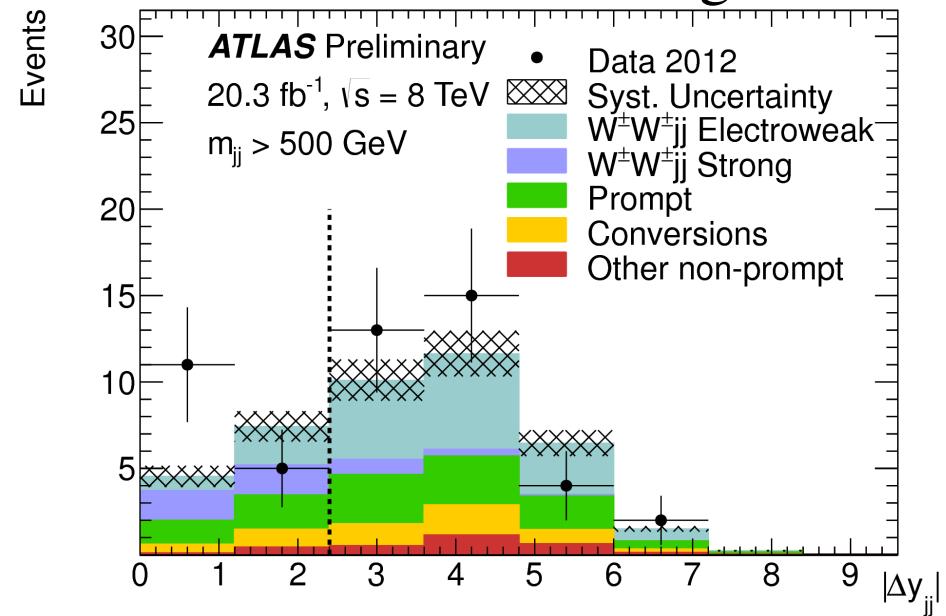
$$\text{Modified higgs coupling } h \rightarrow h / \sqrt{1 + \xi c_H}, \xi = v^2 / f^2$$

SILH Giudice et al arXiv:hep-ph/0703164v2

Inclusive (QCD+EW) region



VBS enriched region



Measured cross section in *fiducial region*

Incl: $\sigma_{\text{fid}} = 2.1 \pm 0.5 \text{ (stat)} \pm 0.3 \text{ (sys)} \text{ fb}$

VBS: $\sigma_{\text{fid}} = 1.3 \pm 0.4 \text{ (stat)} \pm 0.2 \text{ (sys)} \text{ fb}$

	Inclusive Region			VBS Region		
	e $^\pm$ e $^\pm$	e $^\pm$ μ $^\pm$	μ $^\pm$ μ $^\pm$	e $^\pm$ e $^\pm$	e $^\pm$ μ $^\pm$	μ $^\pm$ μ $^\pm$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
W $^\pm$ W $^\pm$ jj Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
W $^\pm$ W $^\pm$ jj Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total signal	4.0 ± 0.4	11.4 ± 1.2	6.3 ± 0.7	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

Significances

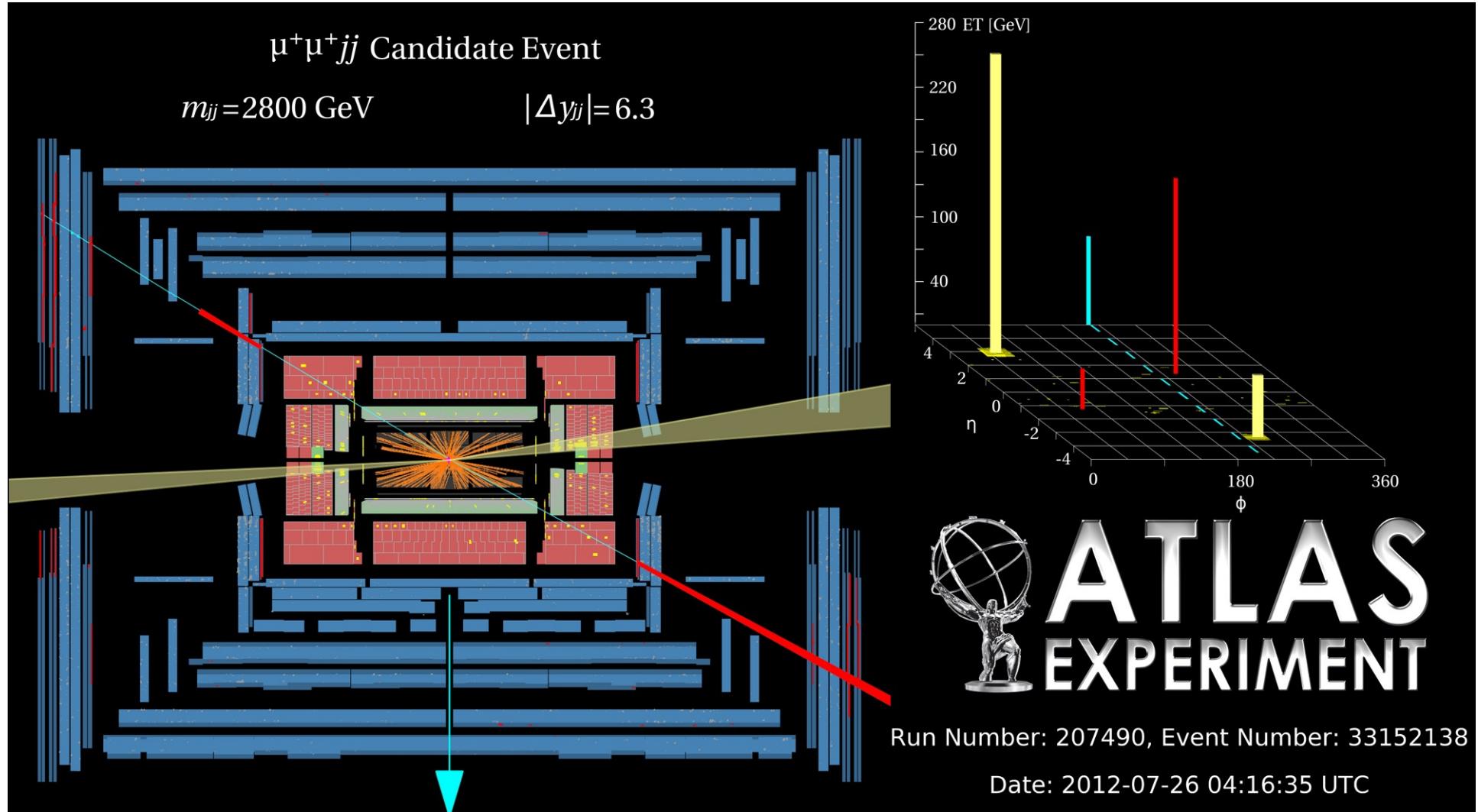
EW+QCD: 4.5 (3.4)

VBS: 3.6 (2.8)
(predicted values)



pp \rightarrow W $^\pm$ W $^\pm$ jj \rightarrow $\mu^\pm\mu^\pm\nu\nu$ jj Candidate

ATLAS-CONF-2014-013



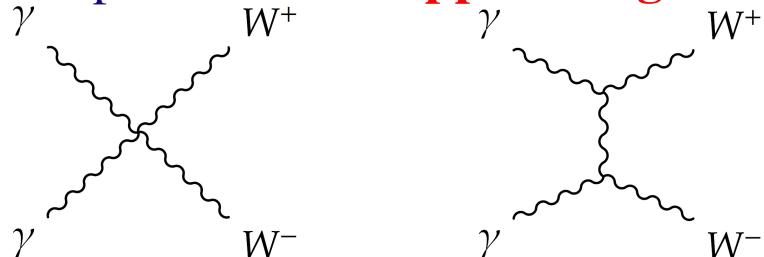


$$pp \rightarrow p^{(*)}\gamma\gamma p^{(*)} \rightarrow p^{(*)}W^\pm W^\mp p^{(*)} \rightarrow p^{(*)}e^\pm\mu^\mp p^{(*)}$$

CMS: JHEP 1307 (2013) 116



- Look for production of **opposite sign W bosons**, produced via **$\gamma\text{-}\gamma$ interaction**



- Search done reconstructing events with **2 different flavour and opposite sign lepton** and... *no other tracks* coming from the 2-leptons common vertex

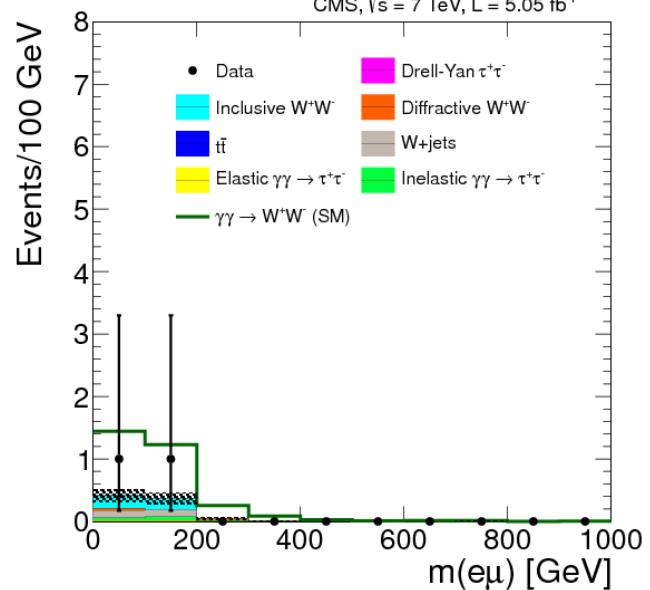
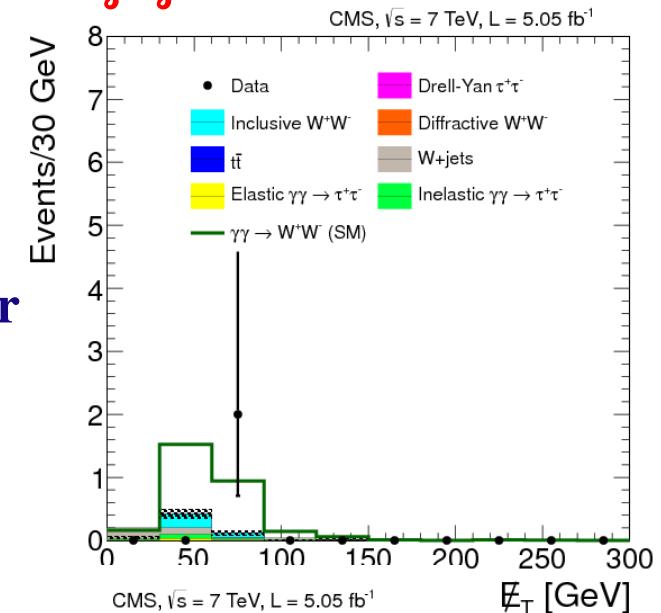
- $p_T(e^\pm\mu^\mp) > 30 \text{ GeV}$ ($>100 \text{ GeV}$ for aQGC study)

- **2 events found passing all criteria**, against a prediction of 0.84 ± 0.13 background events (2.2 ± 0.5 is the SM prediction for the signal)

Measured cross-section:

$$\sigma(pp \rightarrow p^{(*)}e^\pm\mu^\mp p^{(*)}) = 2.1^{+3.1}_{-1.9} \text{ fb (1.1 } \sigma)$$

$$\sigma(pp \rightarrow p^{(*)}e^\pm\mu^\mp p^{(*)}) < 8.4 \text{ fb (95 \% CL)}$$





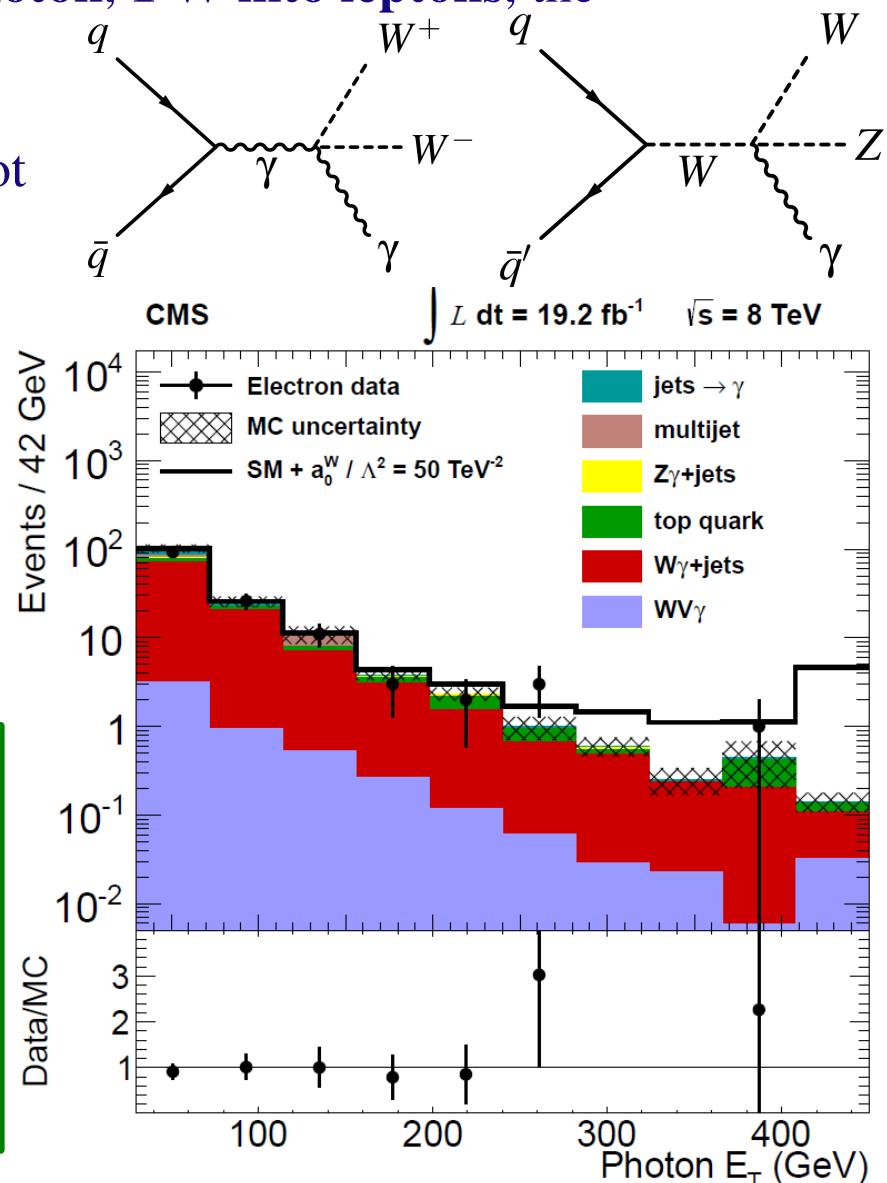
$pp \rightarrow W^+W^-\gamma / W^\pm Z\gamma \rightarrow l\nu jj\gamma$

CMS: CMS-PAS-SMP-13-009 (sub PRD)



- Process with production of **3 vector bosons**: **1 photon**, **1 W into leptons**, the other **W decays hadronically**: sensitive to QGC
- Only 1 high p_T isolated **lepton** $ME_T > 35$ GeV, not pointing towards leading-jet, $M_T^W > 30$ GeV
- 2 close-by central **jets** with $p_T > 30$ GeV, anti-b-tagged, with m_{jj} in the $m_{W/Z}$ window
- 1 central high p_T isolated **photon** ($p_T > 30$ GeV)
- **Best observable for QGC: photon p_T**

Predicted number of events: **$193.9 \pm 3.9 \pm 10.8 \pm 1.0$**
($147.6 \pm 4.8 \pm 9.6 \pm 0.7$) in the μ (e) channel.
Expected # signal events: **6.9 ± 1.5 (5.2 ± 1.1)**
Observed: **183** (**139**) events
Cross section upper limit: **241 fb @ 95% C.L.**
($3.4 \times$ SM cross section)

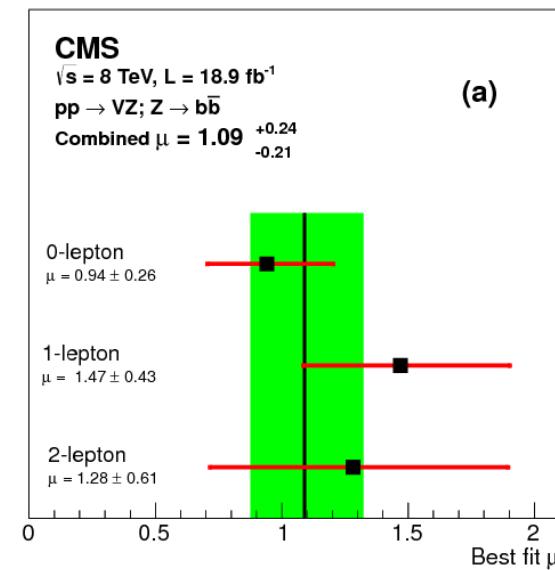
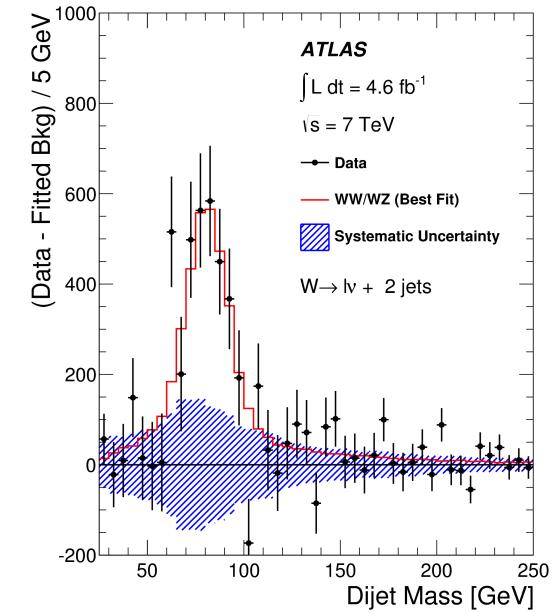
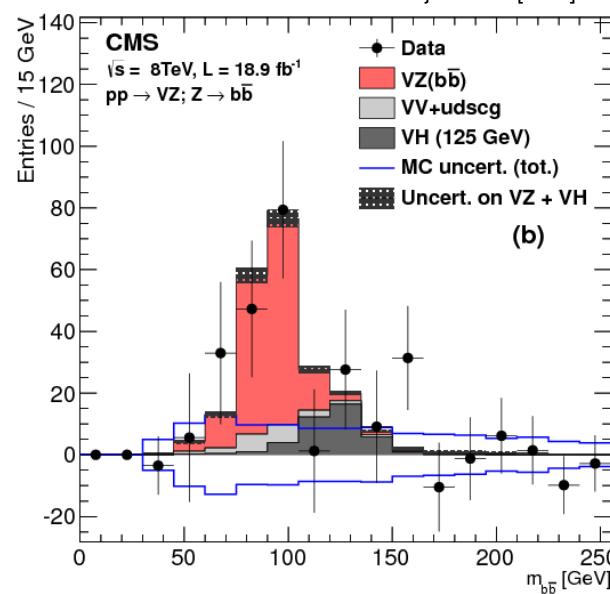
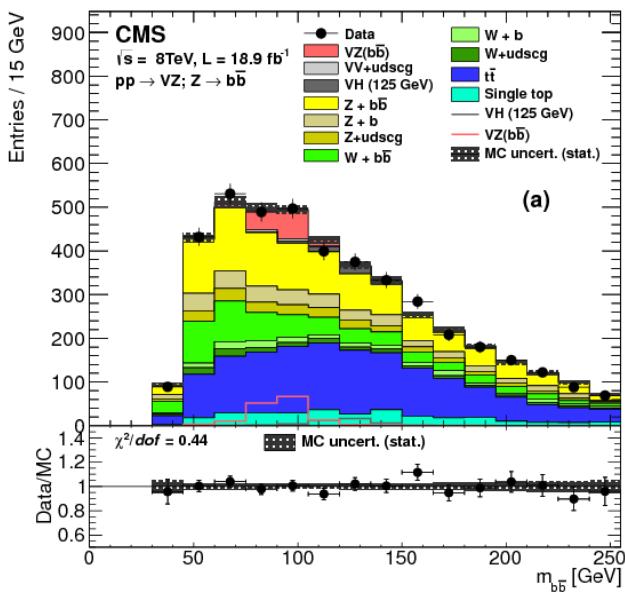




Hadronic Decays of V: $W/Z \rightarrow jj; Z \rightarrow b\bar{b}$

ATLAS: JHEP 01 (2015) 049; CMS: EPJC 73 (2013) 2283, EPJC 74 (2014) 2973

- Low S/B, but signal can be clearly extracted
- The jj analysis make use of template fit, while $b\bar{b}$ one uses CRs to normalize the simulation
- $b\bar{b}$ analysis exploit BDT technique





Anomalous Quartic Gauge Couplings Modelling

- Extension of the SM Lagrangian by introducing additional **dimension-8 (or 6) operators**:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \dots$$

desideratum: $\Lambda \sim 1\text{-}2 \text{ TeV}$

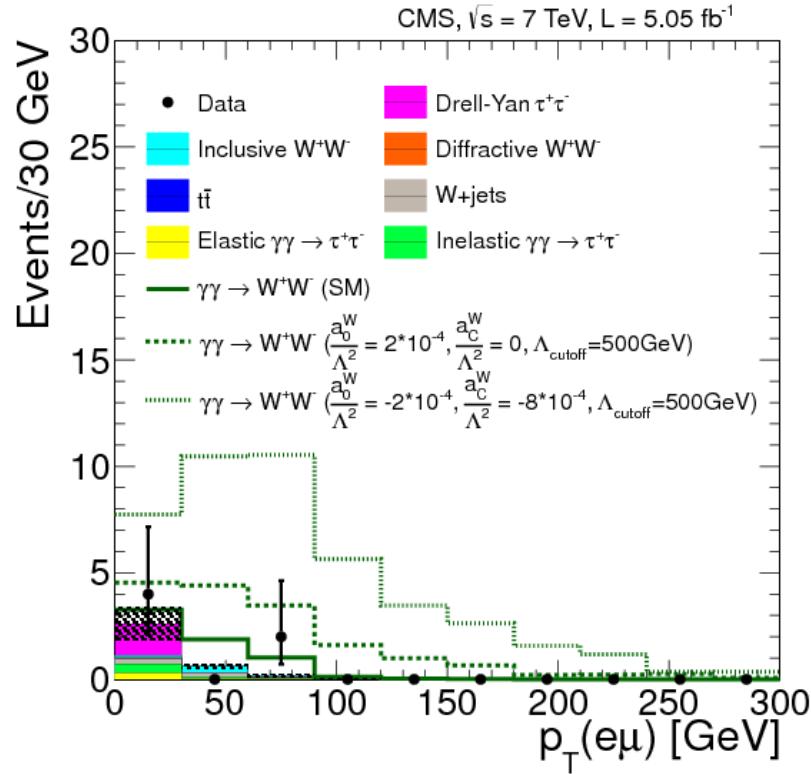
- Effective field theory** is useful as a methodology for studying possible new physics effects from massive particles that are **not directly detectable**.

- Underlying assumption: scale **Λ is large compared with the experimentally-accessible energy**
- These operators have **coefficients of inverse powers of mass (Λ)**, and hence are suppressed if this mass is large compared with the experimentally-accessible energy
- Limit:** Λ so large that the effect is comparable to missing higher order corrections from SM
- An effective field theory is the **low-energy approximation of the new physics**
- coefficients in **dimension-6** (i.e. c_i/Λ^2) (e.g., hep-ph/9908254), **may affects 3 boson vertices too**:
 - $C_{\phi W}/\Lambda^2$ (**VBFNLO**), a_0^W/Λ^2 , a_c^W/Λ^2 (**CALCHEP**)...
- coefficients in **dimension-8** (i.e. c_i/Λ^4) (e.g., hep-ph/0606118), **modifies 4 boson vertices only**:
 - $f_{S,0}/\Lambda^4$, $f_{T,0}/\Lambda^4$...

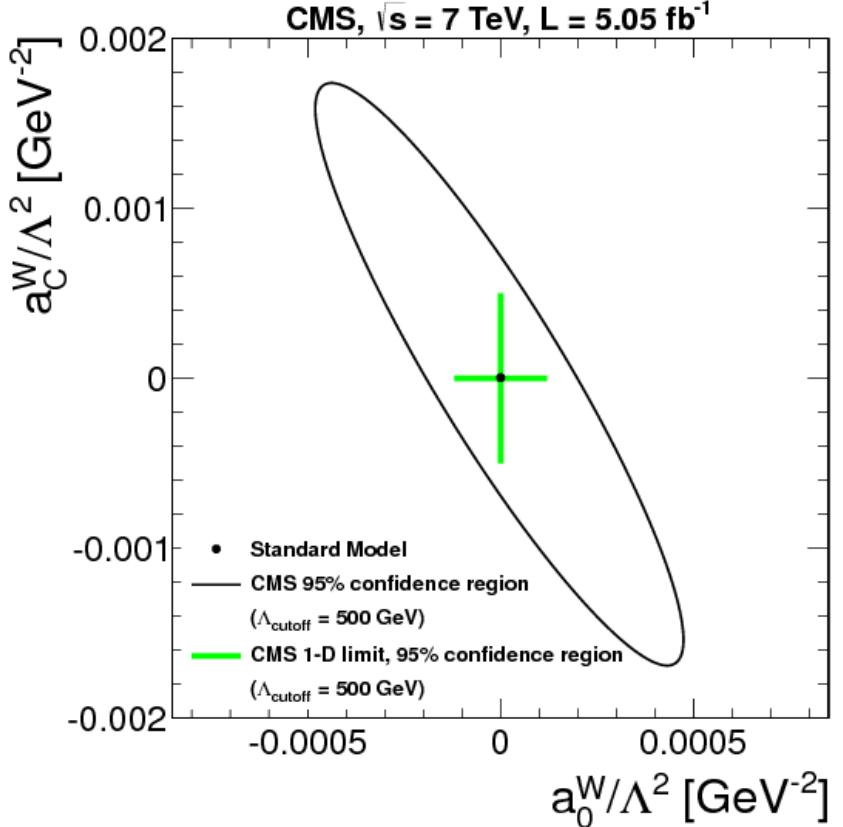
Limits on Anomalous QGC

$pp \rightarrow p^{(*)}\gamma\gamma p^{(*)} \rightarrow p^{(*)}W^\pm W^\mp p^{(*)} \rightarrow p^{(*)}e^\pm\mu^\mp p^{(*)}$

- Sensitive to $\gamma\gamma WW$ vertex



CMS: JHEP 1307 (2013) 116



- For aQGC study, limit the search region to $p_T(e\mu) > 100$ GeV
 - Cross section limit w.r.t. Standard model prediction < 1.9 fb @ 95% CL**
 - No deviation from SM TGC assumed ($\lambda_y = 0$)**



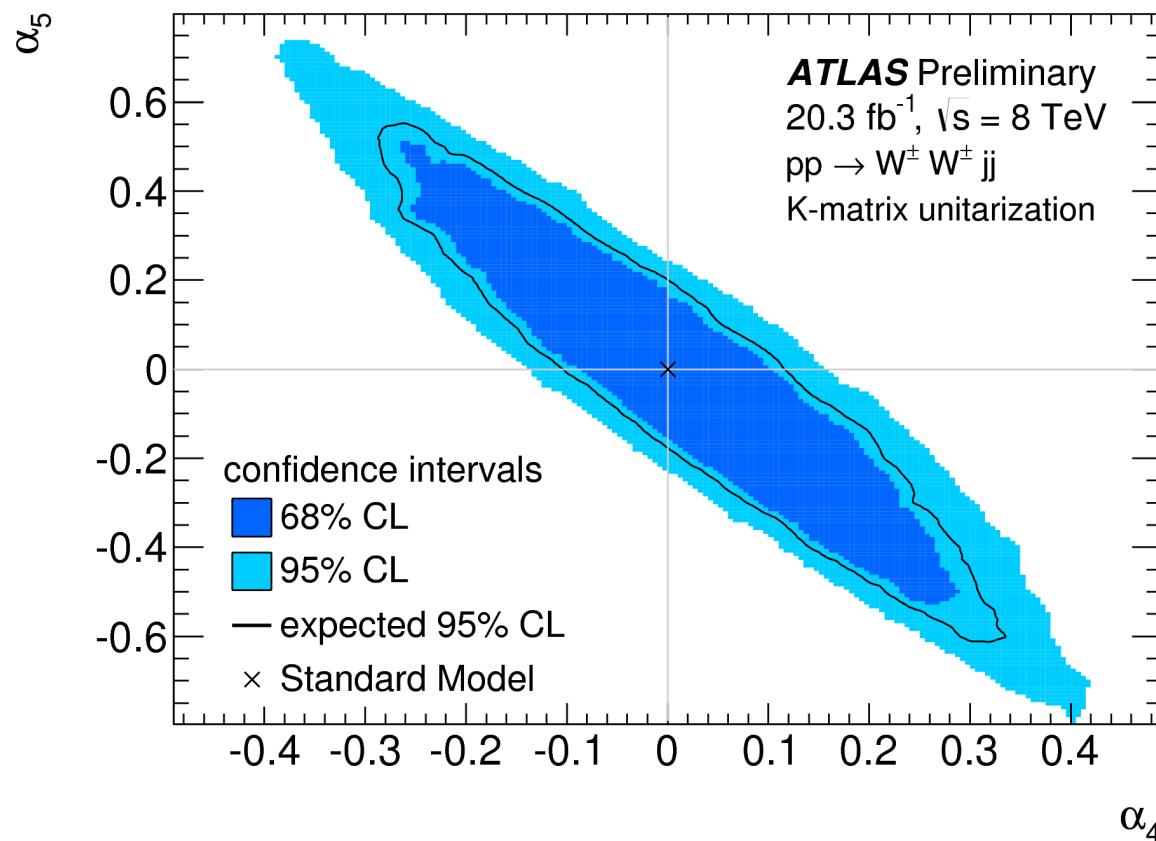
pp \rightarrow W $^\pm$ W $^\pm$ jj \rightarrow l $^\pm$ l $^\pm$ vvjj

ATLAS-CONF-2014-013



- Channel sensitive to **WWWW** vertex
- Placed limits on *EW chiral approach* to aQGC modelling (α_4 and α_5)
- **New physics scale** in **WWWW** couplings set to be **above 600 GeV**

arXiv:1307.8170





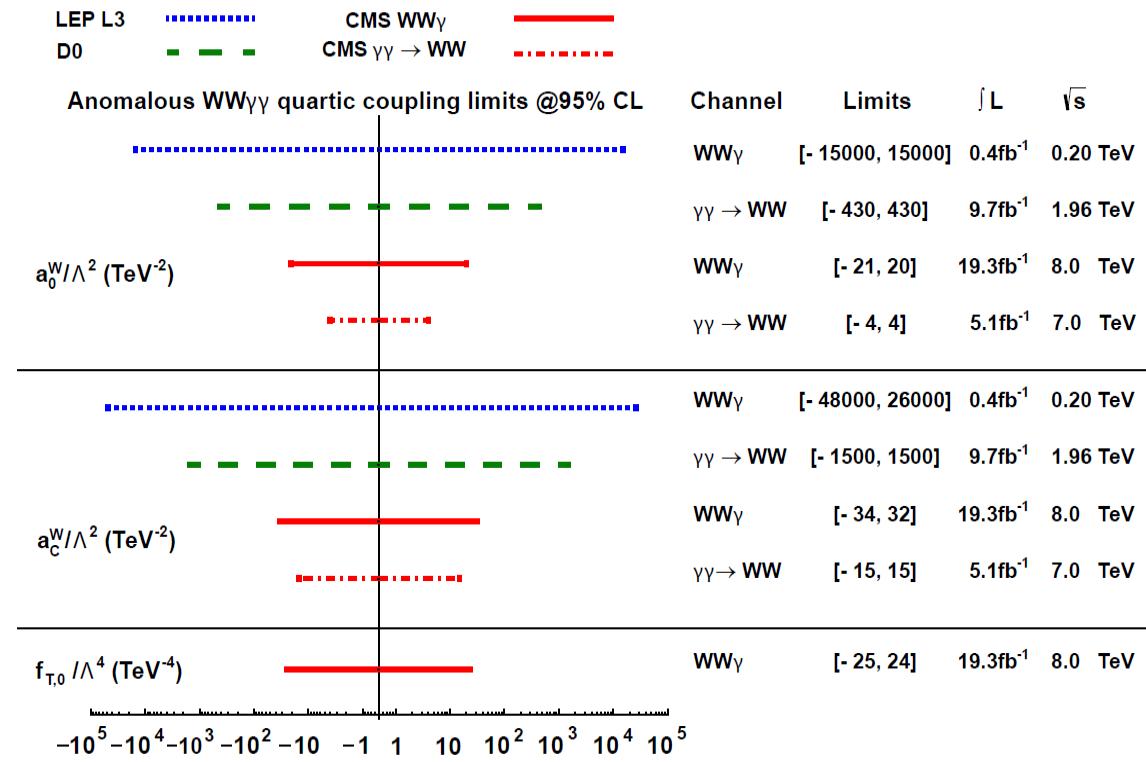
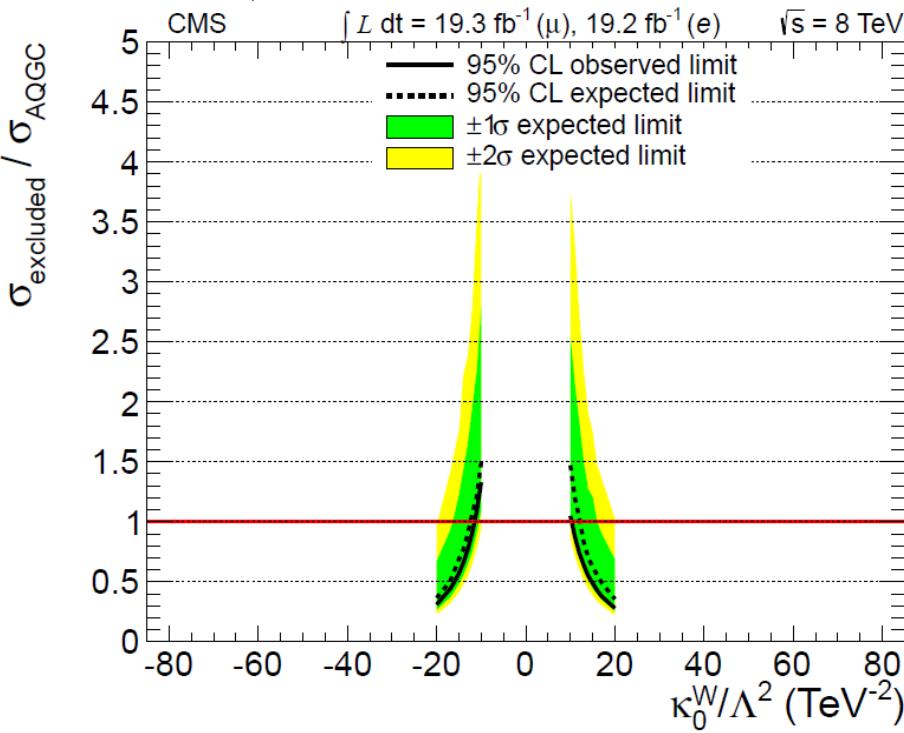
$pp \rightarrow W^+W^-\gamma / W^\pm Z\gamma \rightarrow l\nu jj\gamma$

CMS: CMS-PAS-SMP-13-009 (sub PRD)

- Sensitive to $WW\gamma\gamma$ and $WWZ\gamma$ vertices

$$\mathcal{L}_{aQGC} = \frac{a_0^W}{4g^2} \mathcal{W}_0^\gamma + \frac{a_C^W}{4g^2} \mathcal{W}_c^\gamma + \sum_i \kappa_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}$$

- First two terms affect $WW\gamma\gamma$, the 3rd one $WWZ\gamma$, $f_{T,0}/\Lambda^4$ both
- Exclusion limits are also translated on 8-dimensions operators $f_{M,0/1/2/3}/\Lambda^4$ ($f_{T,0}/\Lambda^4$ already part of the parametrization above)





Future Projections

- Several final states investigated by both Collaborations (ATLAS-PHYS-PUB-2013-006 and CMS-PAS-FTR-13-006) for $\sqrt{s} = 14 \text{ TeV}$ and two luminosity scenarios, 300 fb^{-1} and 3000 fb^{-1} :
 - $\text{pp} \rightarrow \text{ZZqq} \rightarrow 4\text{ljj}$ (VBS)
 - $\text{pp} \rightarrow \text{WZqq} \rightarrow 3\text{l}\nu\text{jj}$ (VBS)
 - $\text{pp} \rightarrow \text{W}^\pm\text{W}^\pm\text{qq} \rightarrow \text{l}^\pm\nu\text{l}^\pm\nu\text{jj}$ (VBS)
 - $\text{pp} \rightarrow \text{Z}\gamma\gamma \rightarrow \text{l}\nu\gamma\gamma$ (QGC)
- Results interpreted in terms of **Effective Lagrangian**, to estimate the sensitivity to new physics.



pp \rightarrow ZZqq \rightarrow 4ljj - VBS @ 14 TeV

ATLAS-PHYS-PUB-2013-006

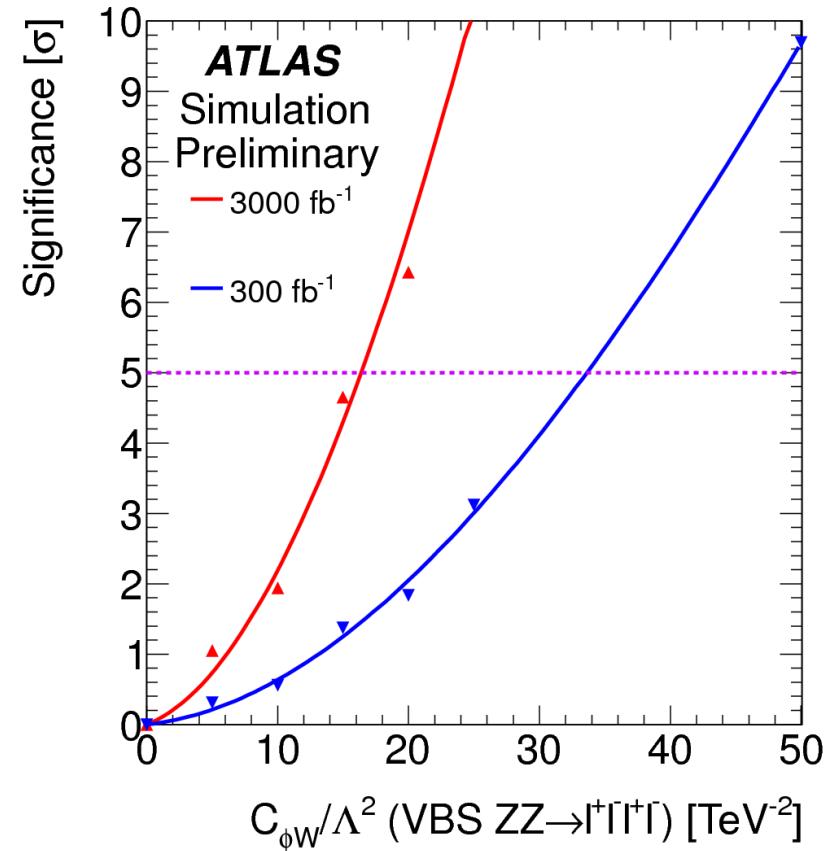
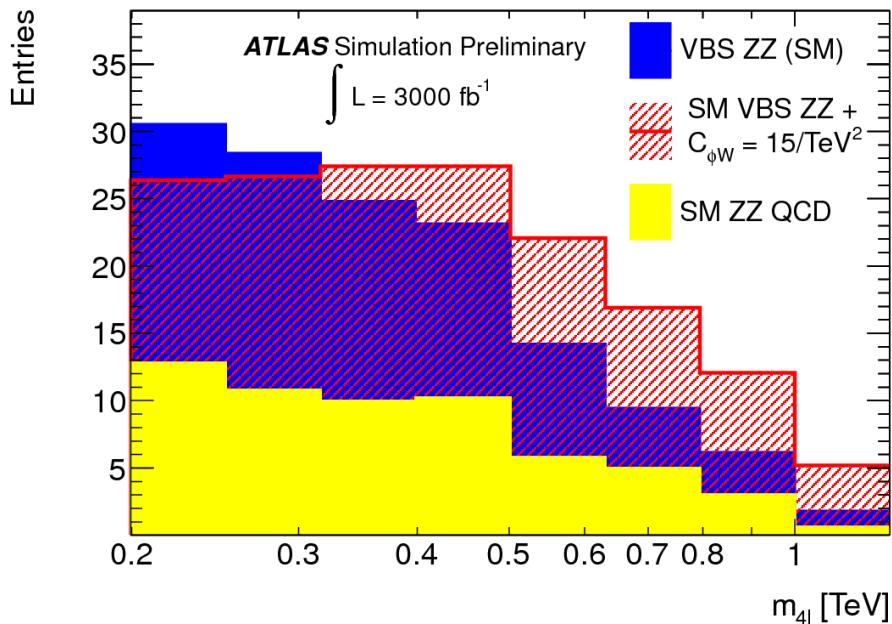


- Standard VBS cuts:

- 4 leptons with $p_T > 25$ GeV, 2 jets with $p_T > 50$ GeV and $M(jj) > 1000$ GeV

- New physics parametrized as

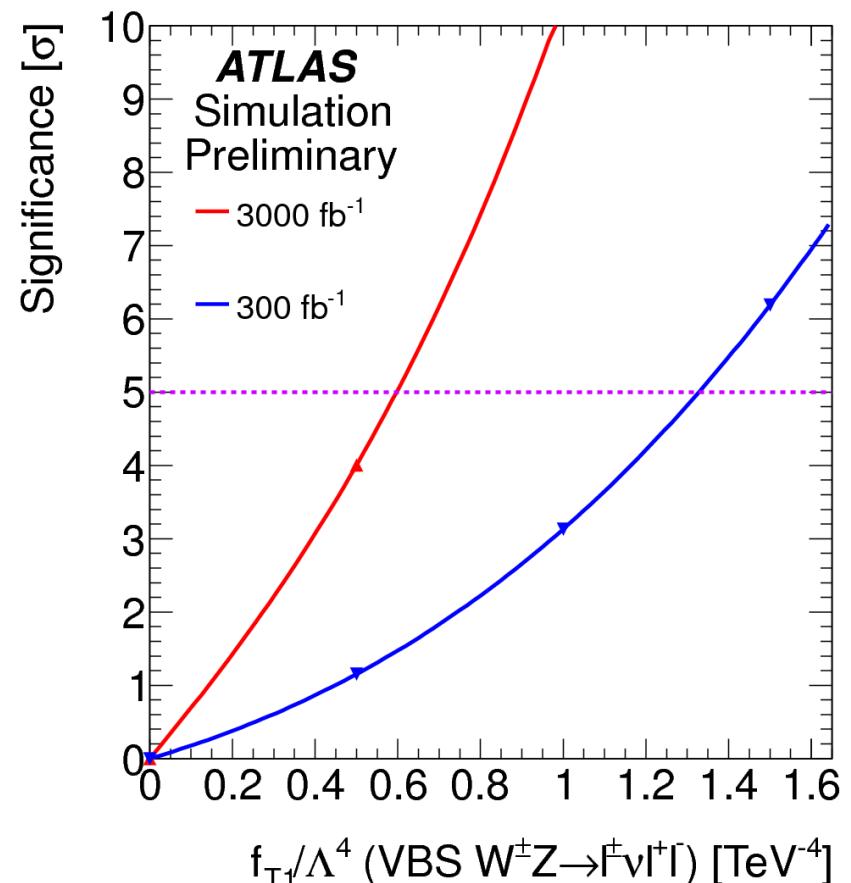
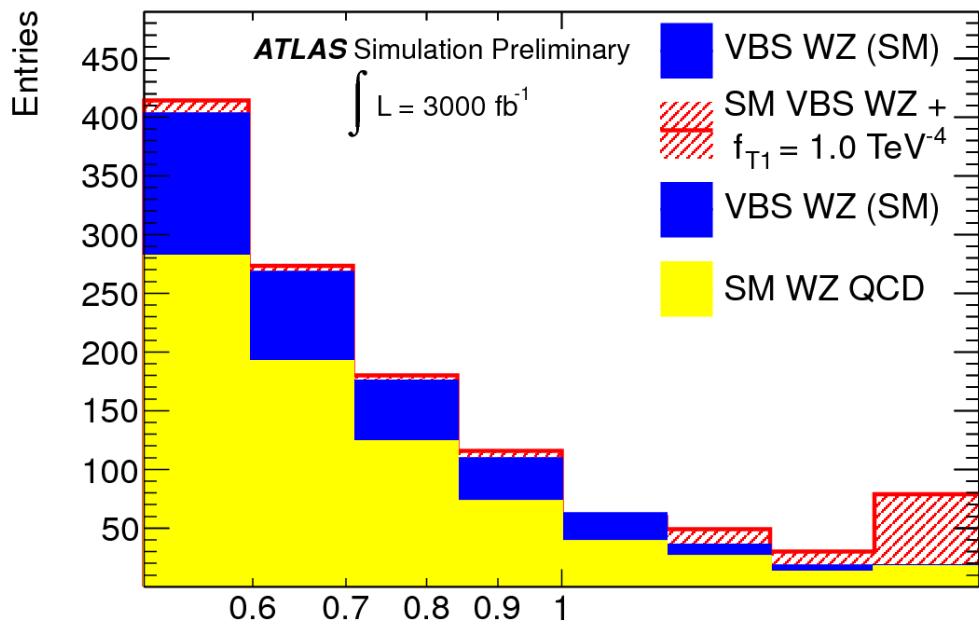
$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \text{Tr}(W^{\mu\nu} W_{\mu\nu}) \phi^\dagger \phi$$



- Significance of 5 sigma (300 fb^{-1})

$$\rightarrow C_{\phi W}/\Lambda^2 \sim 35 \text{ TeV}^{-4}$$

- Standard VBS cuts:
 - 3 leptons with $p_T > 25$ GeV, 2 jets with $p_T > 50$ GeV and $M(jj) > 1000$ GeV
- New physics parametrized as $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \text{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \text{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$



- Significance of 5 sigma (300 fb^{-1})
 $\rightarrow f_{T1}/\Lambda^4 \sim 1.3 \text{ TeV}^{-4}$

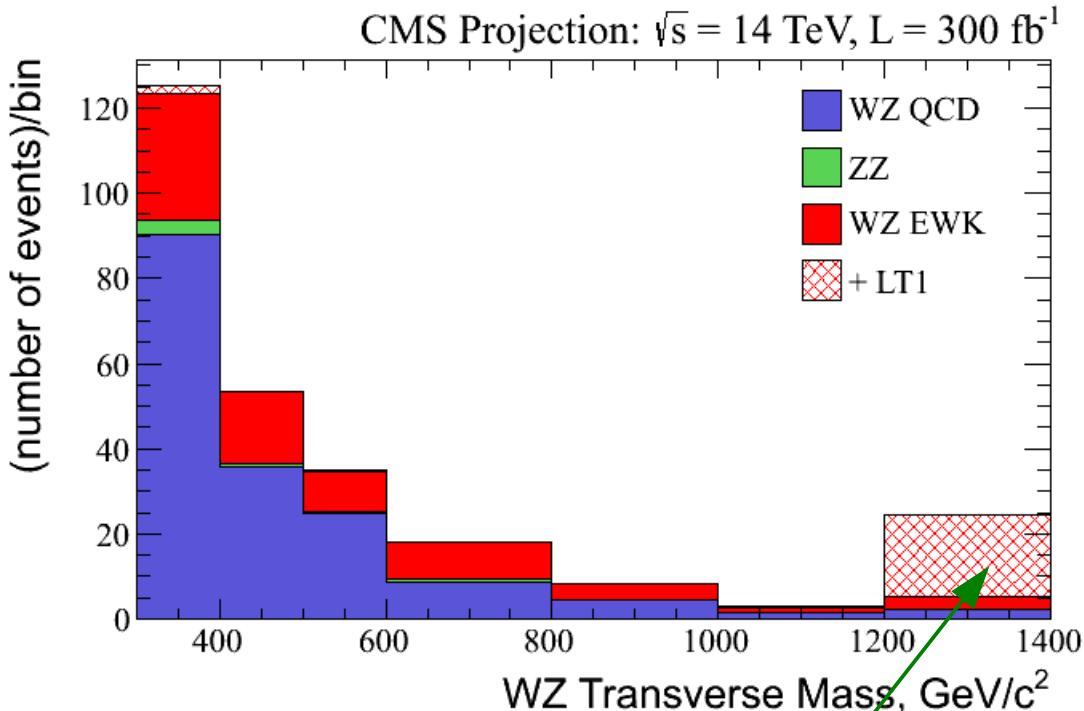


pp \rightarrow WZqq \rightarrow 3lvjj - VBS @ 14 TeV

CMS-PAS-FTR-13-006



- 300 fb^{-1} (*Phase 1*) with **50 pile-up** event and **current detector**
- 3000 fb^{-1} (*Phase 2*) with **140 pile-up** events and with the **detector upgrade** (new tracker and Ecal, mu-detection down to $\eta < 4$)
- **Typical VBF/VBS cuts:**
 - Lepton $p_T > 20 \text{ GeV}$, jet $p_T > 50 \text{ GeV}$, $\Delta\eta(j,j) > 4$, $M(jj) > 600 \text{ GeV}$



Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

Additional contribution
from aQGC with
 $f_{T1}/\Lambda^4 = 1 \text{ TeV}^{-4}$.



pp \rightarrow W $^\pm$ W $^\pm$ qq \rightarrow l $^\pm$ v l $^\pm$ v jj - VBS @ 14 TeV

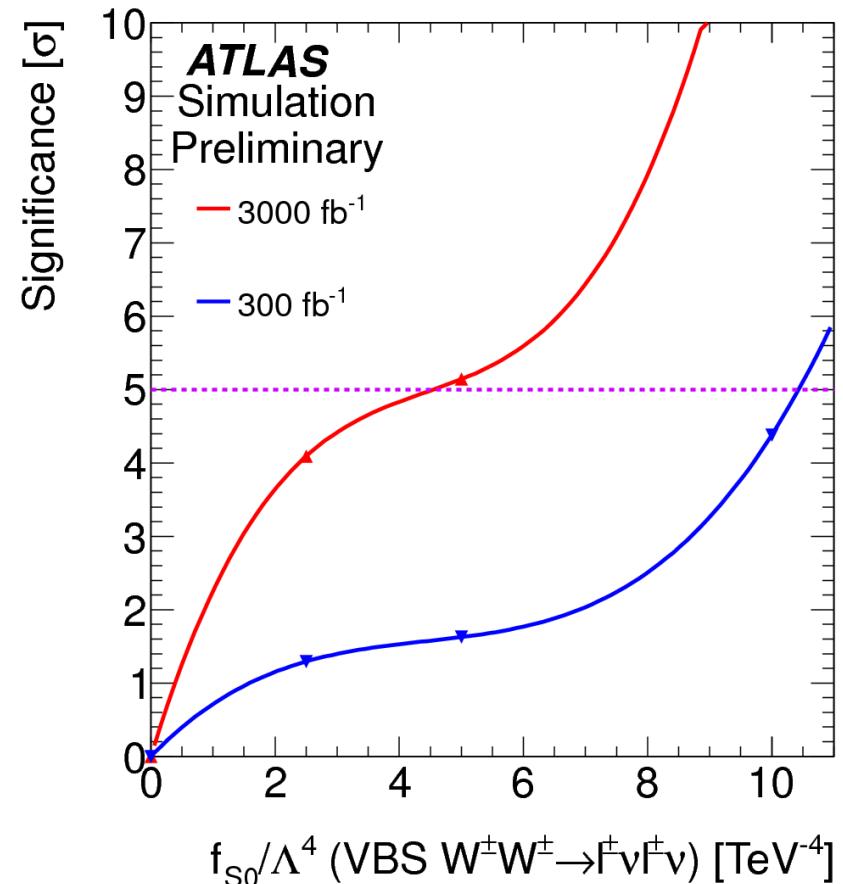
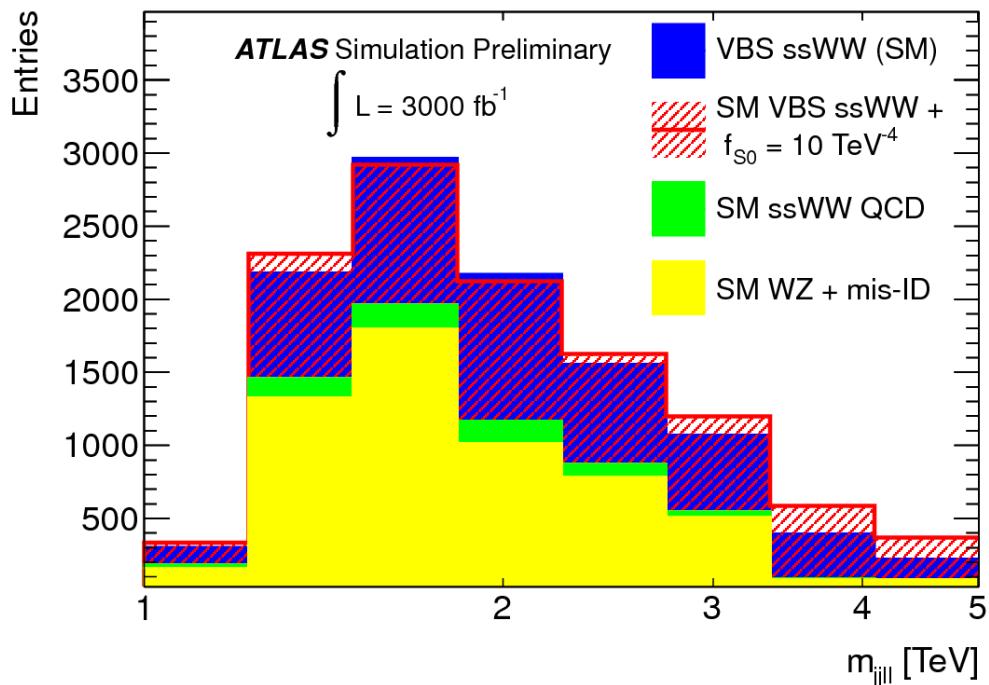
ATLAS-PHYS-PUB-2013-006



- Standard VBS cuts:

- 2 leptons with $p_T > 25$ GeV, 2 jets with $p_T > 50$ GeV and $M(jj) > 1000$ GeV

- New physics parametrized as $\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4} [(D_\mu \phi)^\dagger D_\nu \phi] \times [(D^\mu \phi)^\dagger D^\nu \phi]$



- Significance of 5 sigma (300 fb^{-1})

$$\rightarrow f_{S0}/\Lambda^4 \sim 10 \text{ TeV}^{-4}$$



Final States and their Cross-sections

- Needs to simulate all $2 \rightarrow 6$ processes at least at the order $\mathcal{O}(\alpha_{EW}^6)$
- **Large interference** among same order diagrams
- **Signal has to be defined a posteriori**, using kinematic cuts
- Cross Sections for $\sqrt{s} = 14$ TeV from Phantom Monte Carlo Generator:
full simulation of $2 \rightarrow 6$ @ $\mathcal{O}(\alpha_{EW}^6) + \mathcal{O}(\alpha_{EW}^4 \alpha_{QCD}^2)$

arXiv:0801.3359

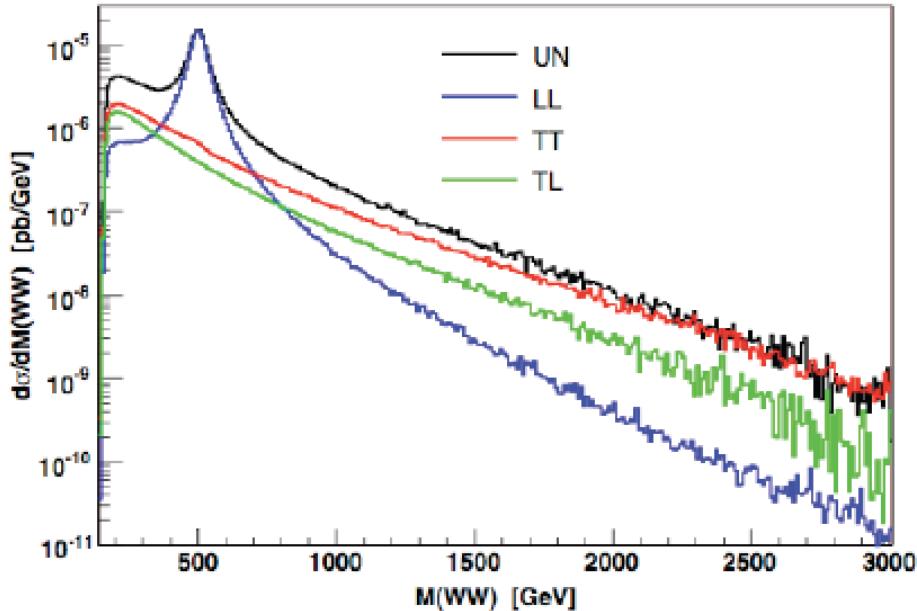
	qqqqμν/eν				qqqqqμμ/ee			
	no-Higgs		500 GeV		no-Higgs		500 GeV	
	σ (pb)	perc.						
total	0.689	100%	0.718	100%	0.0305	100%	0.0350	100%
signal	0.158	23%	0.184	26%	0.0125	41%	0.0165	47%
top	0.495	72%	0.494	69%	0.0137	45%	0.0137	39%
non resonant	0.020	3%	0.023	3%	0.0030	10%	0.0035	10%
three bosons	0.016	2%	0.017	2%	0.0012	4%	0.0014	4%

	qqμμμμ/eeee				qqμμμν				qqμ $^\pm$ νμ $^\pm$ ν			
	no-Higgs		500 GeV		no-Higgs		500 GeV		no-Higgs		500 GeV	
	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.						
total	0.180	100%	0.310	100%	4.182	100%	4.152	100%	4.29	100%	4.16	100%
signal	0.120	66.4%	0.229	74.1%	1.317	31.5%	1.281	30.8%	3.26	76%	3.11	75%
top	0	0%	0	0%	1.817	43.5%	1.828	44.01%	0	0%	0	0%
non resonant	0.0364	20.2%	0.0533	17.2%	0.673	16.1%	0.651	15.7%	0.47	11%	0.46	11%
three bosons	0.0241	13.4%	0.0268	8.66%	0.375	8.9%	0.392	9.5%	0.56	13%	0.58	14%

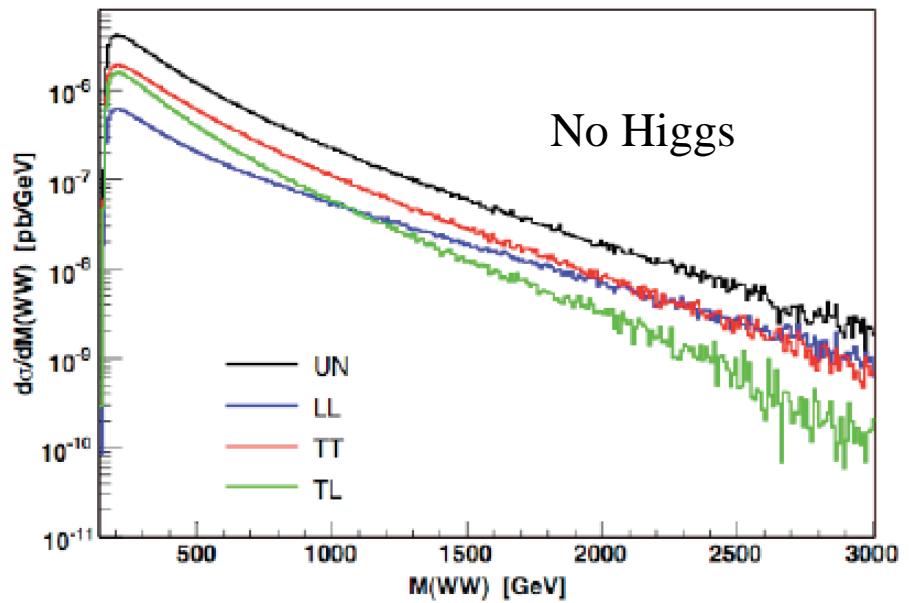
Scattering of Polarized Vector Bosons

Accomando et al: hep-ph/0512219

$ud \rightarrow ud W^+W^- \rightarrow ud \mu^+ \nu c s \bar{s}$



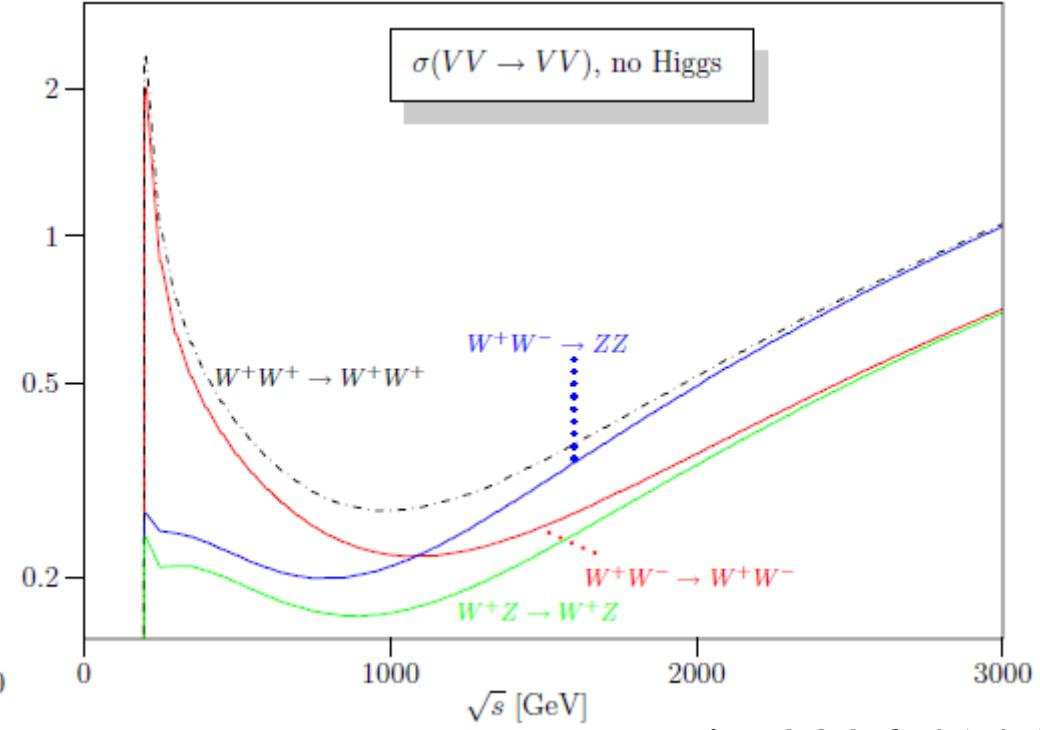
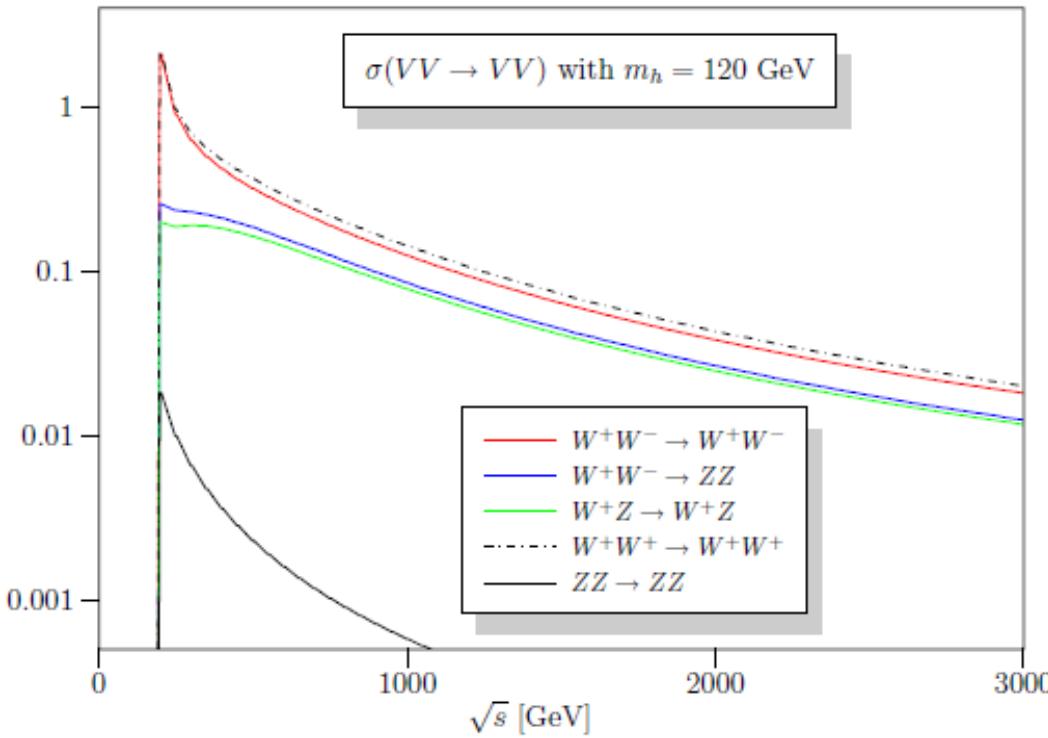
$ud \rightarrow ud W^+W^- \rightarrow ud \mu^+ \nu c s \bar{s}$



- The VL are coupled to the Higgs and they are the ones sensitive to the EWSB.
- The behavior of the LL cross section only can give information on the scale at which the symmetry breaks.
- At large $M(VV)$ the TT cross section is of the same order as the LL (in the no-Higgs case)

If there is a new resonance at a scale Λ , the LL cross section will not decrease until Λ .
 Experimentally we should enhance LL wrt TT and measure XS at the highest $M(VV)$

- The cross section decreases rapidly at high invariant masses due to PDF – Hard life for LHC @14 TeV !
- The invariant VV mass is the equivalent of the CM energy of the elastic VV scattering

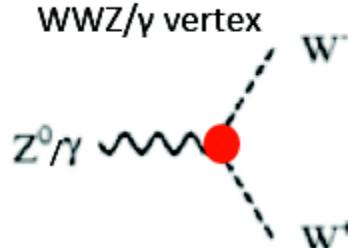


arxiv:0806.4145



Anomalous Couplings Parametrization

Phys. Rev. D48 (1993) 2182



Nucl. Phys. B282 (1987) 253
Phys. Rev. D41 (1990) 2113

EFFECTIVE LAGRANGIAN PARAMETRIZATION

allow the couplings of SM operators to vary +
add higher order operators that respect
symmetries

(Hagiwara et al., Nucl.Phys.B282:253,1987)

$$\begin{aligned} \Gamma_{WWV}^{\alpha\beta\mu} &= (1 + \Delta g_V^\mu)[(q_1 - q_2)^\mu g^{\alpha\beta} - q_1^\beta g^{\mu\alpha} + q_2^\alpha g^{\mu\beta}] \\ &+ (1 + \Delta \kappa_V)[q_2^\alpha g^{\mu\beta} - q_1^\beta g^{\mu\alpha}] \\ &+ \frac{\lambda_V}{m_W^2} (q_1 - q_2)^\mu \left[\frac{s}{2} g^{\alpha\beta} - q_2^\alpha q_1^\beta \right] \\ &+ i g_5^V \epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho \end{aligned}$$

Assumptions (14->3 independent parameters):

Electromagnetic gauge invariance, C and P conservation,
Lagrangian SU(2)XU(1) invariant

$$\Delta g_1^Z = \Delta \kappa_Z + \tan^2 \theta_W \Delta \kappa_\gamma \quad \Delta g_1^Z = g_1^Z - 1, \quad \Delta \kappa_{\gamma,Z} = \kappa_{\gamma,Z} - 1$$

valid for $\sqrt{s} \ll \Lambda$

SU(3)xSU(2)xU(1) invariance by construction

Λ is large, of the order of the scale of New Physics

terms suppressed by $\propto \frac{\sqrt{s}}{\Lambda}$

only the first terms are relevant

O_i are operator of (energy) "dimension n"

c_i are adimensional couplings of order ~ 1

allows systematic calculation of higher order corrections

Translation between
two approaches:

$$\begin{aligned} g_1^Z &= 1 + c_W \frac{m_Z^2}{2\Lambda^2} \\ \kappa_\gamma &= 1 + (c_W + c_B) \frac{m_W^2}{2\Lambda^2} \\ \kappa_Z &= 1 + (c_W - c_B \tan^2 \theta_W) \frac{m_W^2}{2\Lambda^2} \\ \lambda_\gamma &= \lambda_Z = c_{WWW} \frac{3g^2 m_W^2}{2\Lambda^2} \end{aligned}$$

EFFECTIVE FIELD THEORY PARAMETRIZATION

infinite sum of (non-renormalizable) Lagrangians:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

Assumptions (5->3 independent parameters):
CP conservation

$$\mathcal{O}_{WWW} = \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu]$$

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$$

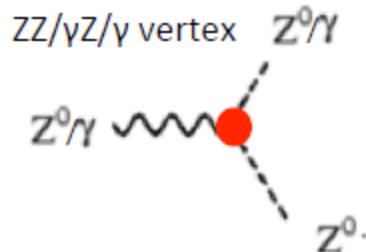
$$\mathcal{O}_B = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

'HISZ' parametrization

channel	couplings	parametrization	parameters	Dimensionality of operator
WW	ZWW, γWW	Effective Lagrangian	Δκ	dim4
	ZWW, γWW		λ	dim6
	ZWW	Effective field theory	Δg ¹ _Z	dim4
	ZWW, γWW		c _{WWW} /Λ ²	dim6
			c _B /Λ ²	dim6
			c _W /Λ ²	dim6



Anomalous Couplings Parametrization



EFFECTIVE VERTEX PARAMETRIZATION

add higher order operators that respect symmetries

Nucl. Phys. B282 (1987) 253

Assumptions Z γ channel: CP conservation

(Hagiwara et al., Nucl.Phys.B282 (1987) 253 (+ missing "i" factor))

$$\begin{aligned} \Gamma_{Z\gamma V}^{\alpha\beta\mu} = & i e \frac{q_V^2 - m_V^2}{m_Z^2} \{ h_1^V (q_\gamma^\mu g^{\alpha\beta} - q_\gamma^\alpha g^{\beta\mu}) \\ & + h_2^V \frac{q_V^\alpha}{m_Z^2} (q_\gamma q_V g^{\beta\mu} - q_\gamma^\mu q_V^\beta) \\ & + h_3^V \epsilon^{\alpha\beta\mu\rho} q_{\gamma\rho} \\ & + h_4^V \frac{q_V^\alpha}{m_Z^2} \epsilon^{\mu\beta\rho\sigma} q_{V\rho} q_{\gamma\sigma} \} \end{aligned}$$

Assumptions ZZ channel: Electromagnetic gauge invariance

(Hagiwara et al., Nucl.Phys.B282:253,1987)

$$\begin{aligned} \Gamma_{Z_1 Z_2 V}^{\alpha\beta\mu} = & i e \frac{q_V^2 - m_V^2}{m_Z^2} \{ f_4^V (q_V^\alpha g^{\beta\mu} + q_V^\beta g^{\mu\alpha}) \\ & + f_5^V \epsilon^{\alpha\beta\mu\rho} (q_{Z_1\rho} - q_{Z_2\rho}) \} \end{aligned}$$

channel	couplings	parametrization	parameters	Dimensionality of operator
Z γ	ZZ γ , γ Z γ	Effective vertex	h_3	dim6
ZZ	ZZZ, γ ZZ		h_4	dim8
			f_4	dim6
			f_5	dim6