Triboson, VV scattering and Quartic Gauge Couplings Measurements

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

DIS 2014: ***XXII International Workshop on Deep-Inelastic Scattering and Related Subjects***

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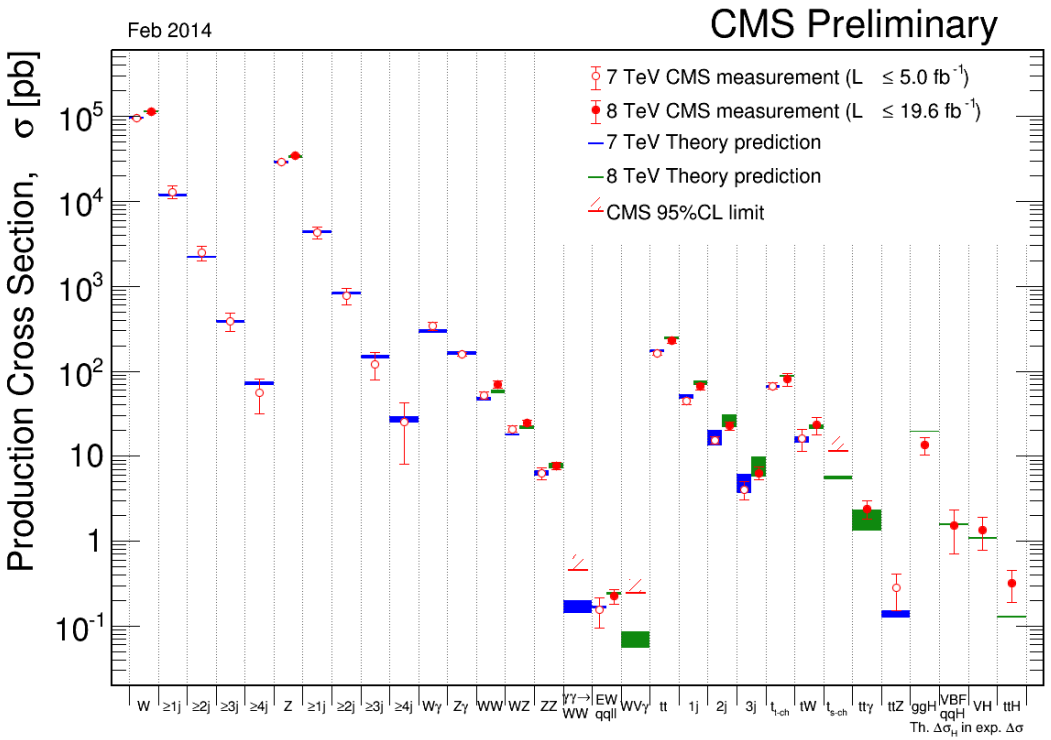
Electroweak Physics and Beyond the Standard Model Session

Stairways to Heaven?

- Standard Model cross sections successfully tested over **6 order of magnitude**
- We **discovered** a new particle: **a Higgs boson**
- ***Still*** we have to understand **the nature of this Higgs boson** and if there is **new physics beyond the SM**



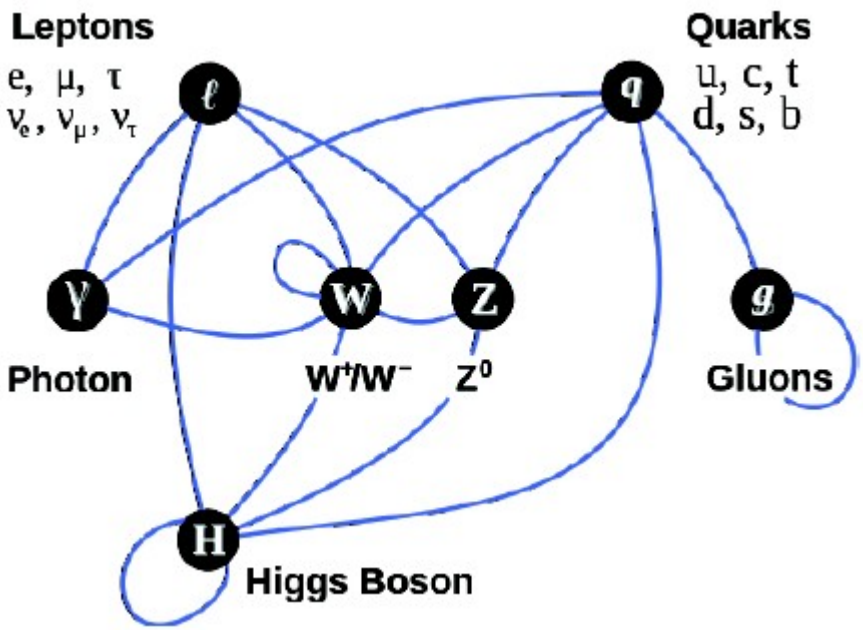
Is it the ***sole*** **Higgs boson**? Is it ***really*** **doing the Higgs boson job**?

→ Keep investigating the **high mass region**

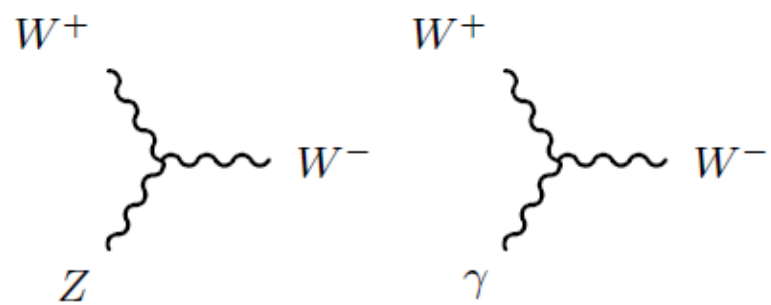
→ Measure with **high precision** (% level) **the properties** of the ***125.5 GeV boson***

→ Measure the **EW vector boson interactions**, establishing if this Higgs boson really can make **unitarity-preserving** the **VV scattering amplitude** at all energies

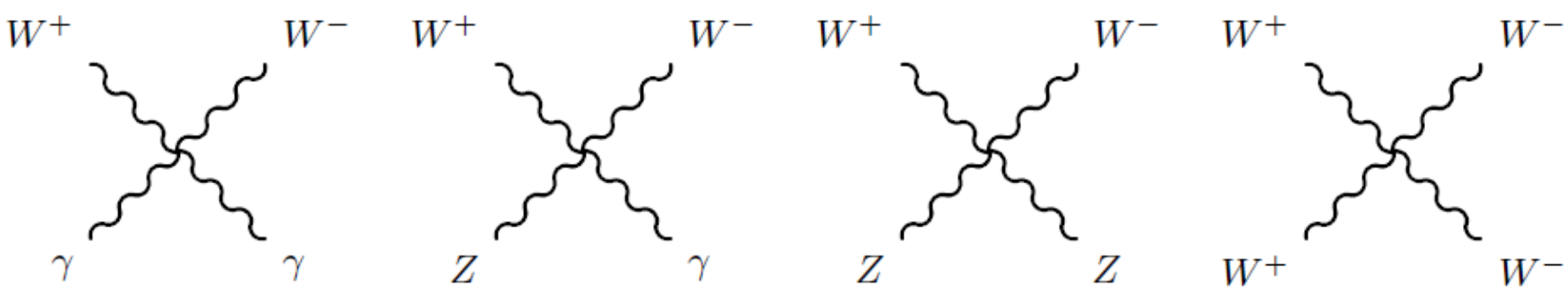
What's Still Need to be Studied in the EW Sector?



- **Vector boson self-interactions**
- **Triple gauge couplings** (TGC)



- **Quartic gauge couplings** (QGC)



- **Higgs self-interaction** (not presented here)

Vector Bosons' Interactions Studies

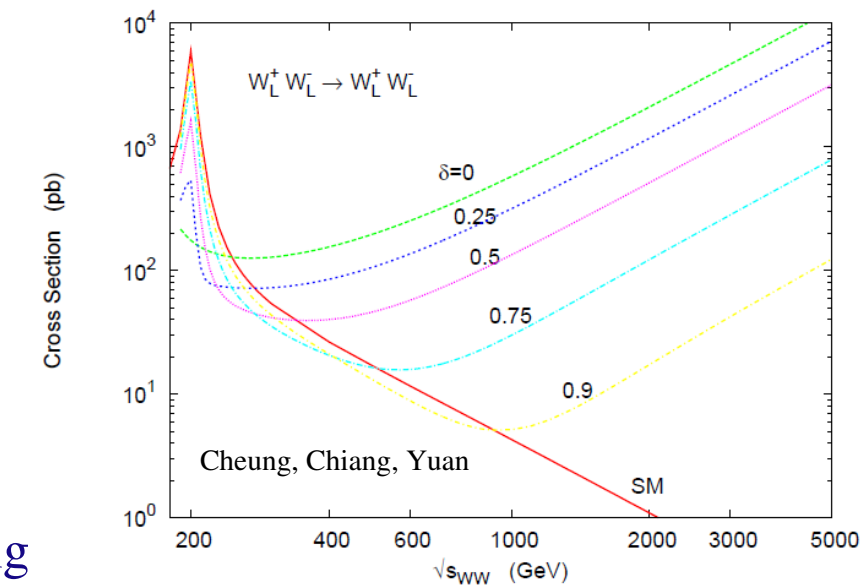
VV scattering is the key process to probe Electroweak Symmetry Breaking (EWSB) and high energy vector boson scattering will play a central role:

- 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.

$$i\mathcal{M}^{\text{gauge}} = -i\frac{g^2}{4m_W^2}\,u + \mathcal{O}((E/m_W)^0)$$

$$i\mathcal{M}^{\text{higgs}} = i\frac{g^2}{4m_W^2}\,u\,\delta + \mathcal{O}((E/m_W)^0)$$

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

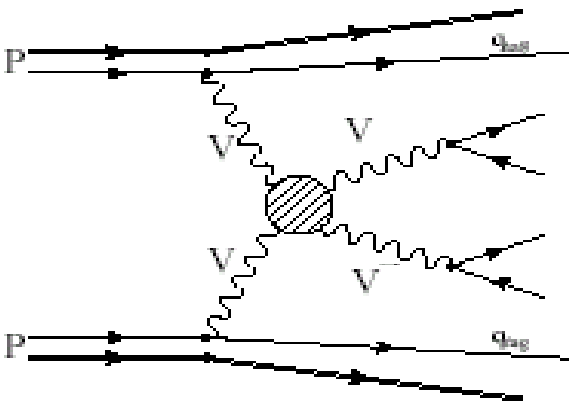


TGC and **QGC** processes (contained in VV scattering amplitudes, but *not only* produced in that processes) may carry **new physics phenomena**

Vector Bosons' Interactions Studies

- Studies made by ATLAS, CMS and several theorist indicates that **order of 100 fb^{-1} @ 14 TeV are needed to investigate sufficiently deeply these processes**.
- However, with the collected data at **7-8 TeV we can already start** to sniff some of the interactions aforementioned.
- Different way to explore them:
  - **Mono-boson produced in VV scattering** (triple gauge couplings)
  - **Di-boson produced in VV scattering** (full set of diagrams, depending on the chosen final state)
  - **Di-boson produced inclusively** (sensitive to triple gauge couplings, not covered here, see *E.-S. Protopapadaki's talk*)
  - **Multi-boson final state, namely triboson** (sensitive to quartic gauge couplings), not produced via VV scattering

Vector Boson Scattering Topology



- Two very energetic jets in the forward-backward region
- Large $\Delta\eta(j,j)$ with rapidity gap between the jets
- large m_{jj} and m_{6f}

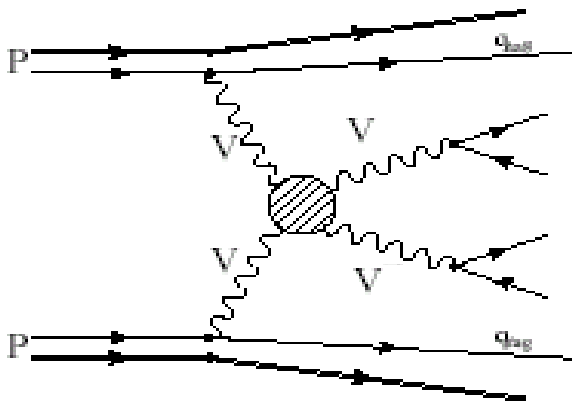
Interesting final states

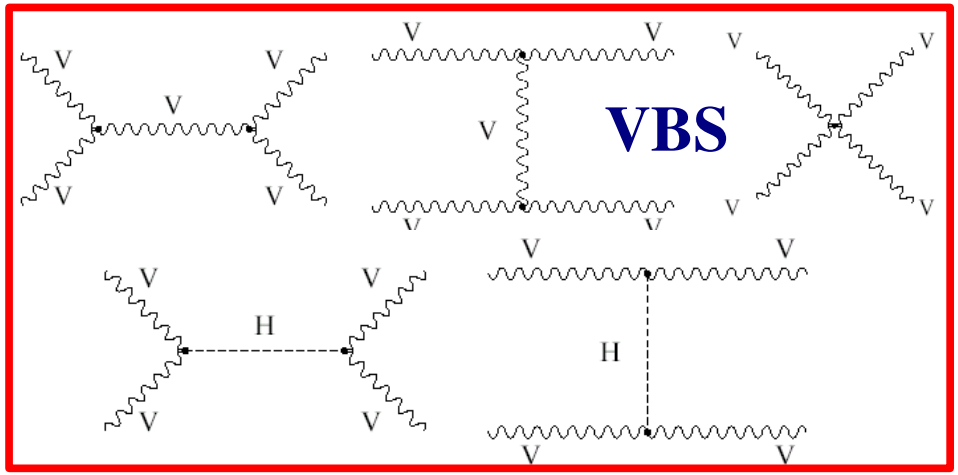
- **$pp \to W^{\pm}W^{\pm}qq \to l^{\pm}\nu l^{\pm}\nu\ 2j$**, most sensitive to SM deviations
- **$pp \to W^{\pm}W^{\mp}qq \to l^{\pm}\nu l^{\mp}\nu\ 2j$**, quite large cross-section, ttbar is nasty
- **$pp \to WZqq \to 3l\ \nu\ 2j$**, clean, interesting for no-Higgs scenarios
- **$pp \to ZZqq \to 4l\ 2j$**, very clean, low cross-section
- **$pp \to ZZqq \to 2l\ 2\nu\ 2j$**, clean, a bit more difficult but not low cross-section
- **$pp \to ZW/Zqq \to 2l\ 4j$**
- **$pp \to WW/Zqq \to l\ \nu\ 4j$**

largest cross section, but V+jets is an issue

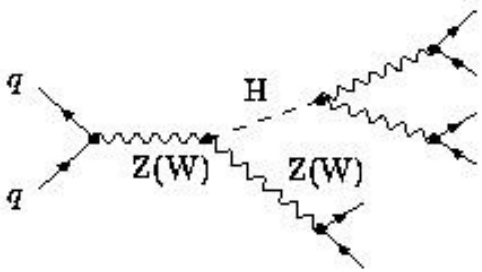
- **$pp \to Zqq \to 2l\ 2j$**, $\mathcal{O}(\alpha_{EW}^4)$ but similar topology as the process above

pp → VVqq → 6f Processes

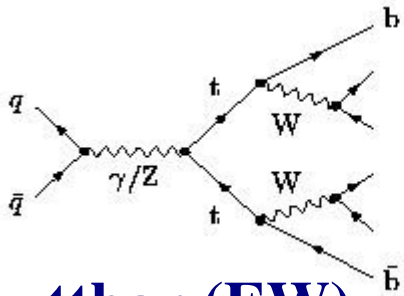




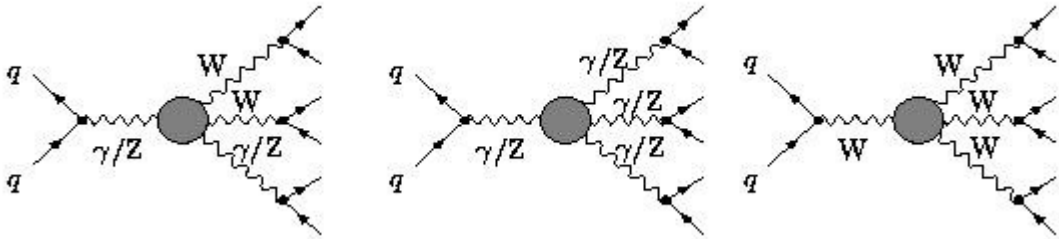
$\mathcal{O}(\alpha_{EW}^{6})$



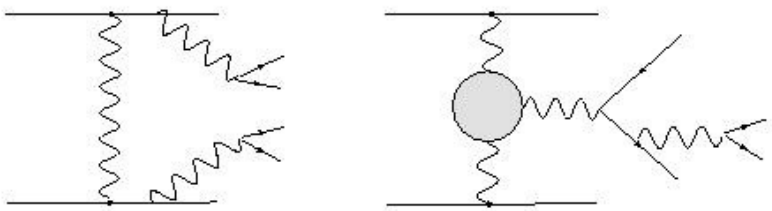
Higgs-strahlung



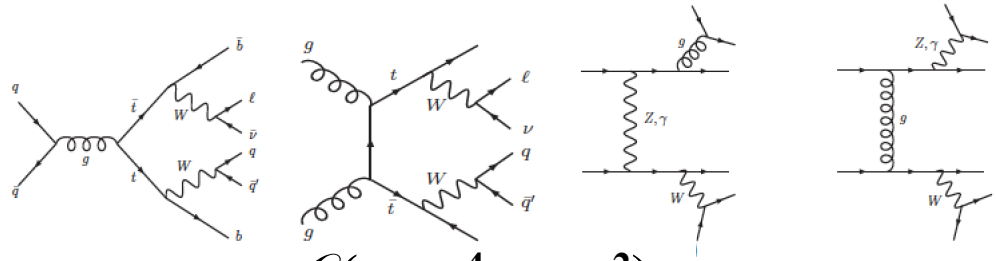
ttbar (EW)



TGC and QGC



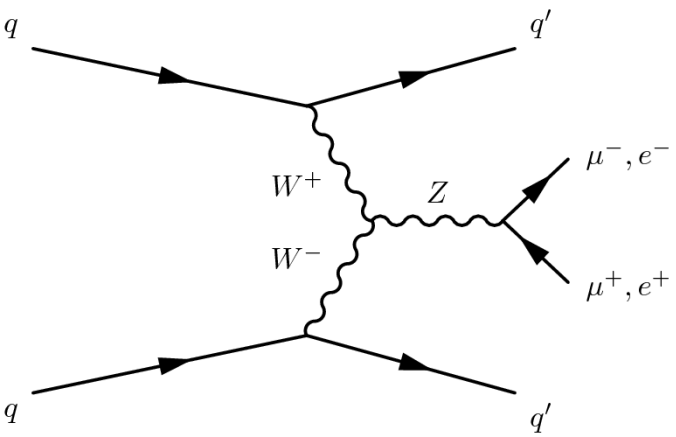
Non-resonant

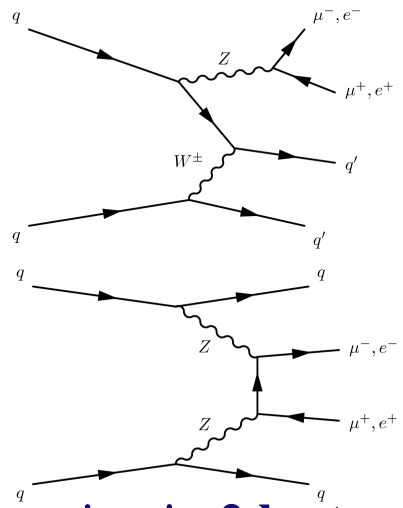


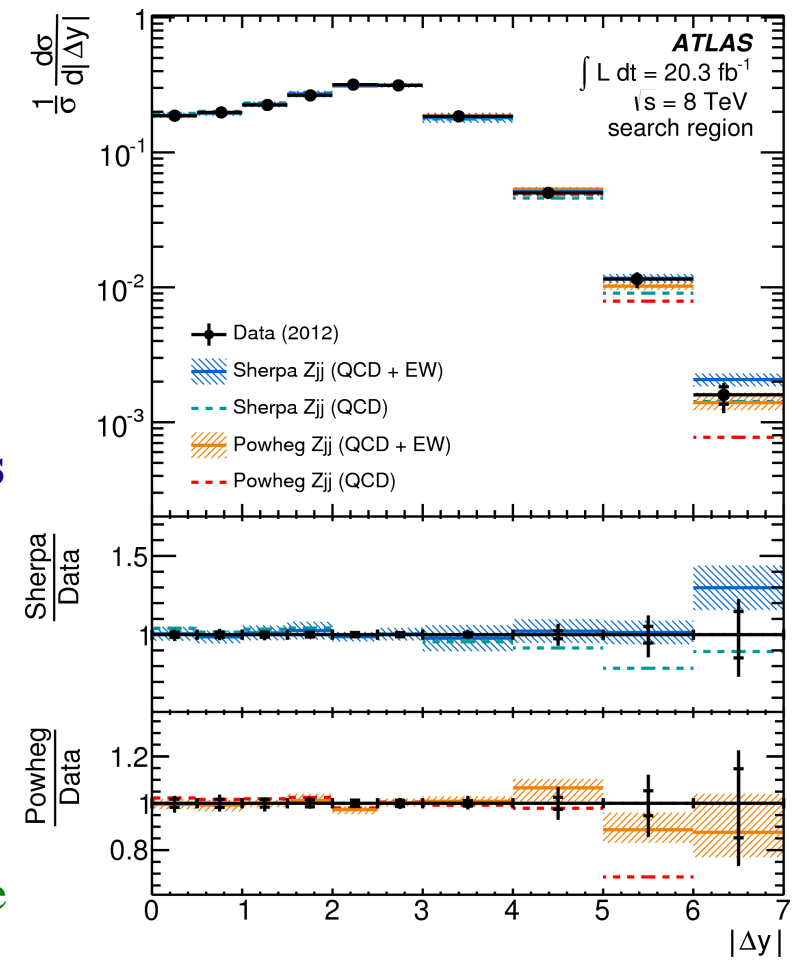
$\mathcal{O}(\alpha_{EW}^{4}\alpha_{QCD}^{2})$

$pp \rightarrow Z\, j_F j_B$

CMS: PAS-FSQ-12-035, ATLAS: JHEP 04 (2014) 031



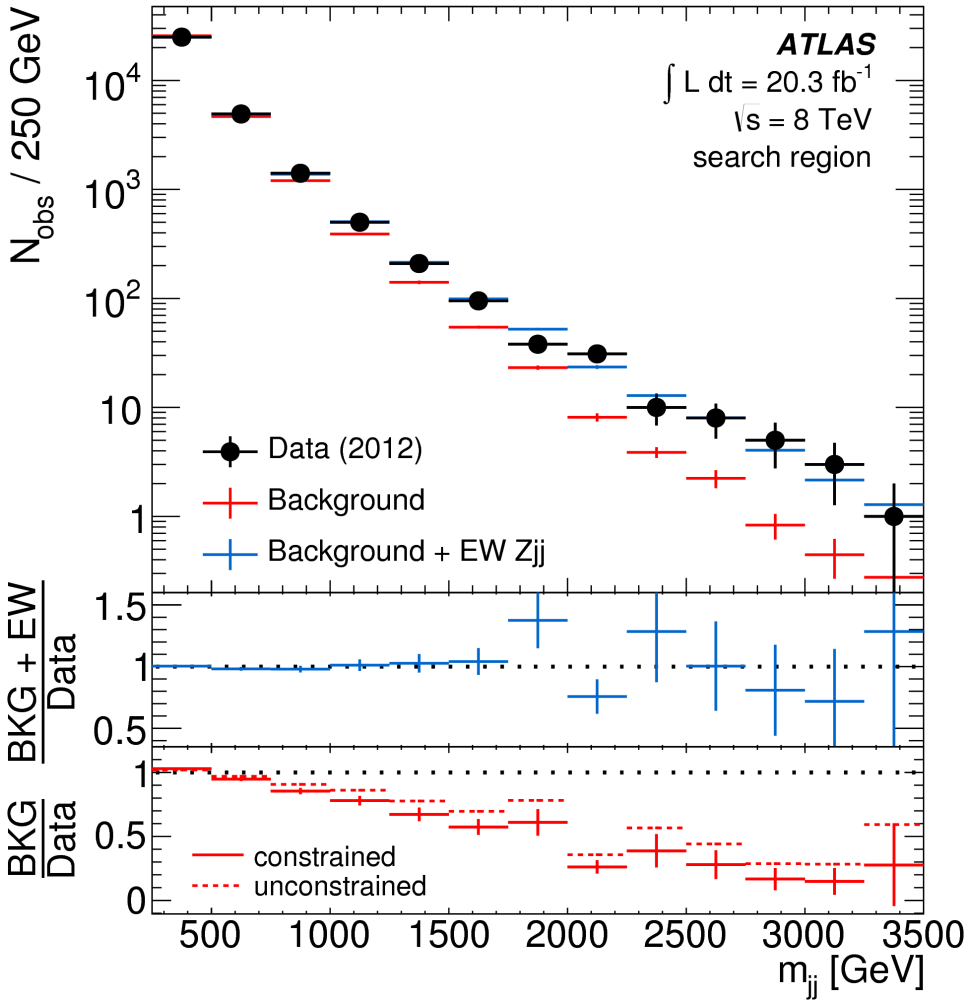


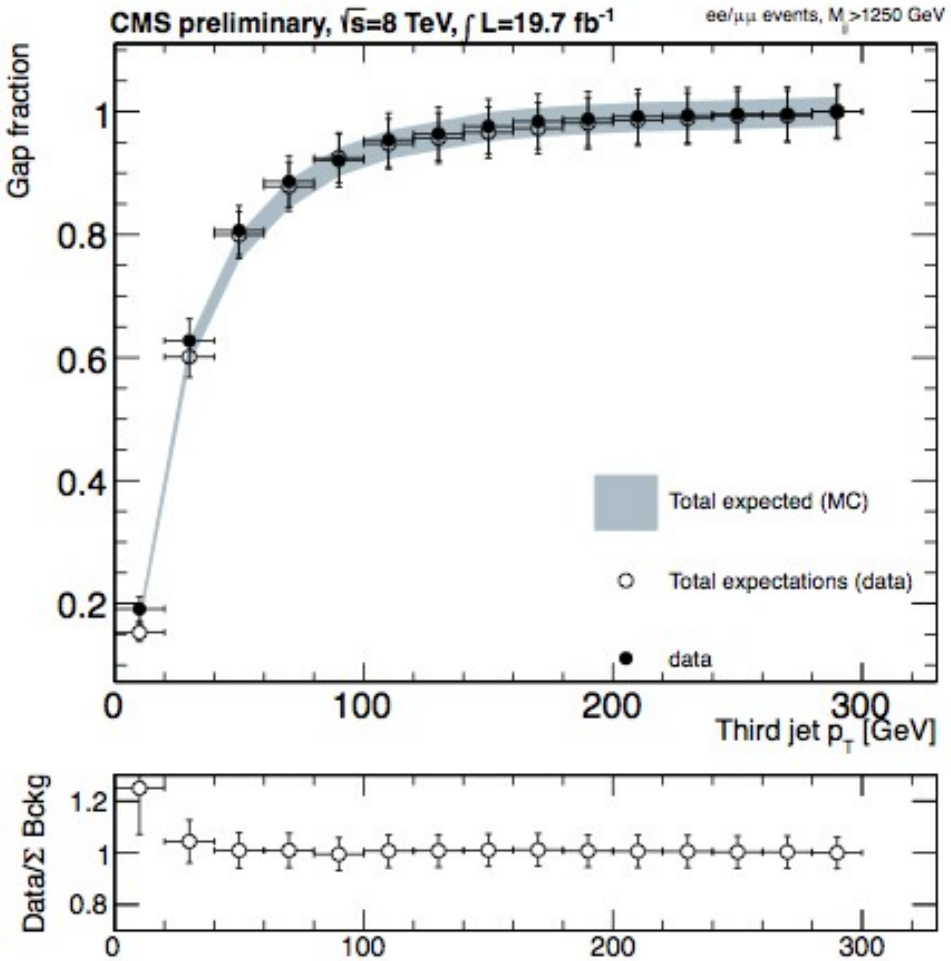


- Search for a single **Z** boson decaying in **2 leptons plus 2 tag jets** well separated in (pseudo-)rapidity, with high p_T and large jj mass
- **Exchange of colourless particle** between the 2 initial state quarks results in a hadronic activity **rapidity gap**
  - Possibility of **vetoing jets in the central** (defined by the two leading jets) region (done in ATLAS analysis)
  - CMS analysis studies the **3rd jet distribution** too
  - Several phase space regions with different EW and strong Zjj production composition investigated by the ATLAS Collaboration

$pp \rightarrow Z\, j_F j_B$

CMS: PAS-FSQ-12-035, ATLAS: JHEP 04 (2014) 031



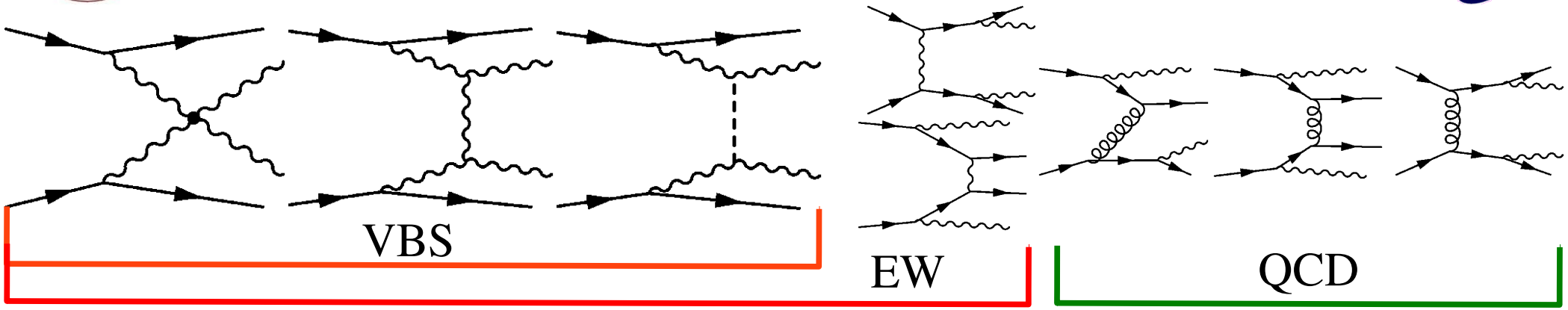


For $m_{ll} > 50$ GeV, $m_{jj} > 120$ GeV, jet $p_T > 25$ GeV $|\eta_j|$, $\Delta r(j,j) > 0.5$

CMS @ 8 TeV Measured a cross section of **226 ± 26 (stat) ± 35 (sys) fb** (prediction at NLO: 239 fb).

$pp \rightarrow W^{\pm}W^{\pm}jj \rightarrow l^{\pm}l^{\pm}\nu\nu jj$

ATLAS-CONF-2014-013

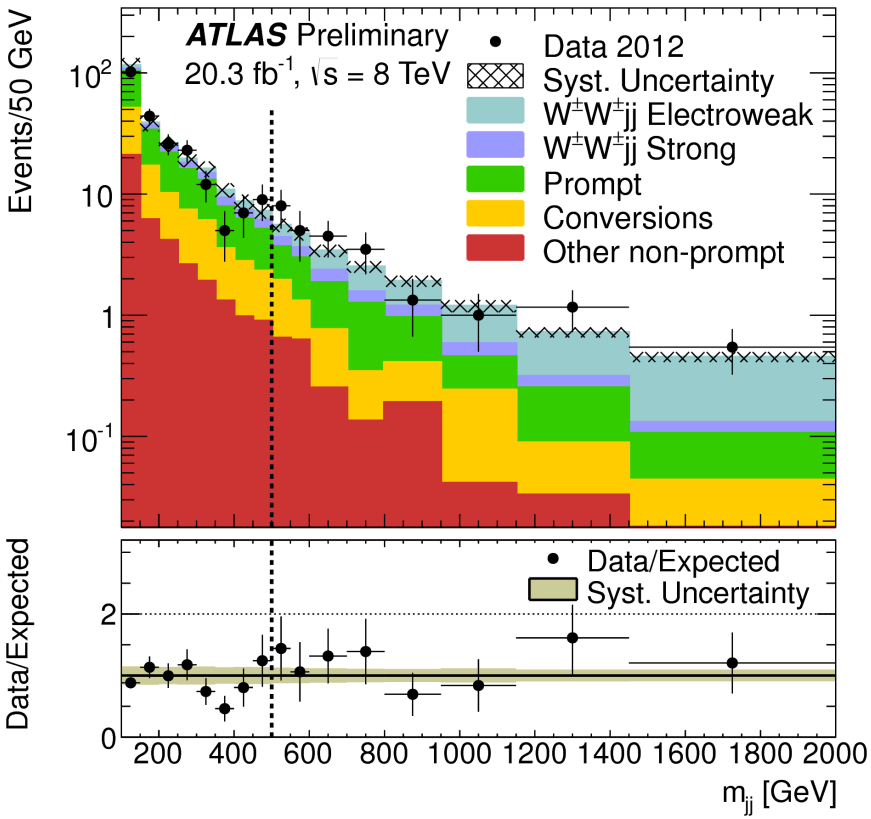


- The analysis aims to measure the **QCD+EW** production and **EW** production separately, looking at two different search regions
- **Inclusive analysis**:
  - Exactly 2 high p_T same-sign central leptons, $m_{ll} > 20$ GeV
  - Missing E_T from W decays
  - 2 jets ($p_T > 30$ GeV) with large m_{jj} (> 500 GeV) and with b-tag veto
- **EW analysis**:
  - Require also $|\Delta y(j,j)| > 2.4$ (VBS contribution enhanced)

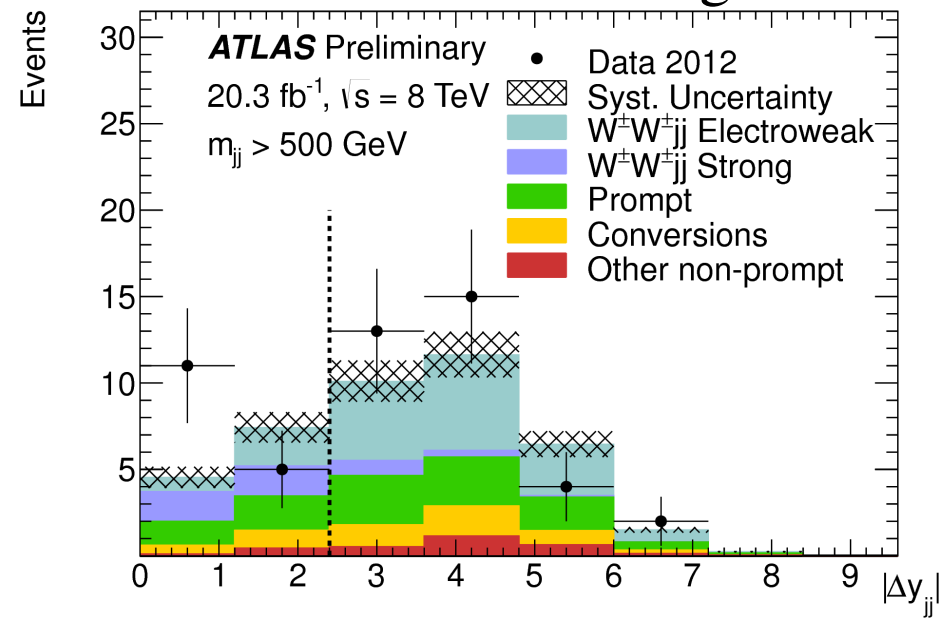
$pp \to W^{\pm}W^{\pm}jj \to l^{\pm}l^{\pm}\nu\nu jj$

ATLAS-CONF-2014-013

Inclusive (QCD+EW) region



VBS enriched region



Measured cross section in ***fiducial region***

Incl: σ_{fid} = 2.1 ± 0.5 (stat) ± 0.3 (sys) fb

VBS: σ_{fid} = 1.3 ± 0.4 (stat) ± 0.2 (sys) fb

	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
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

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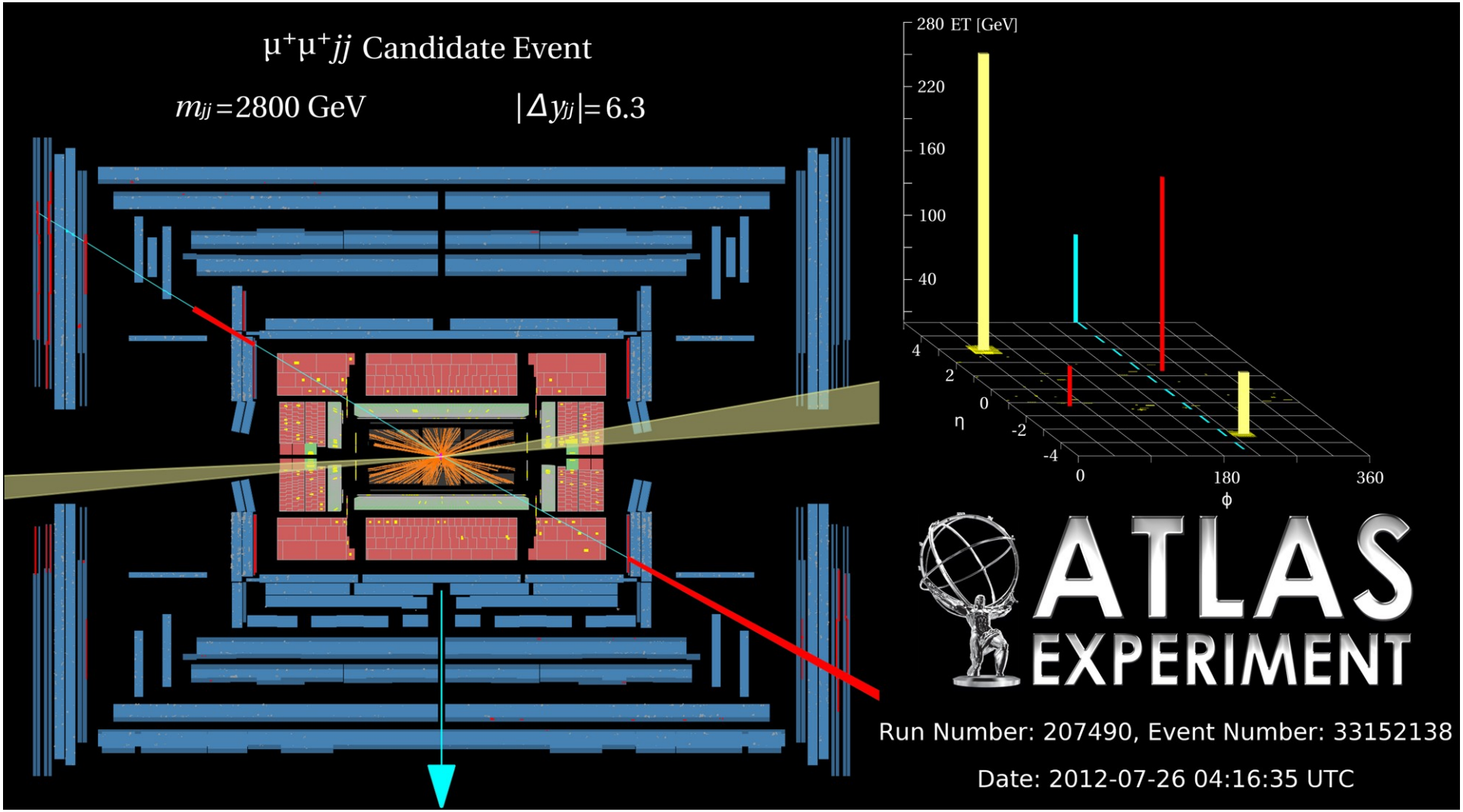
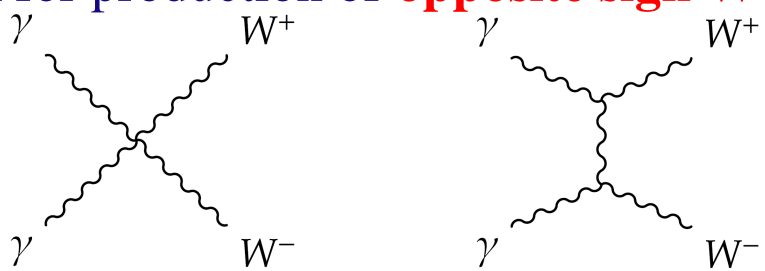


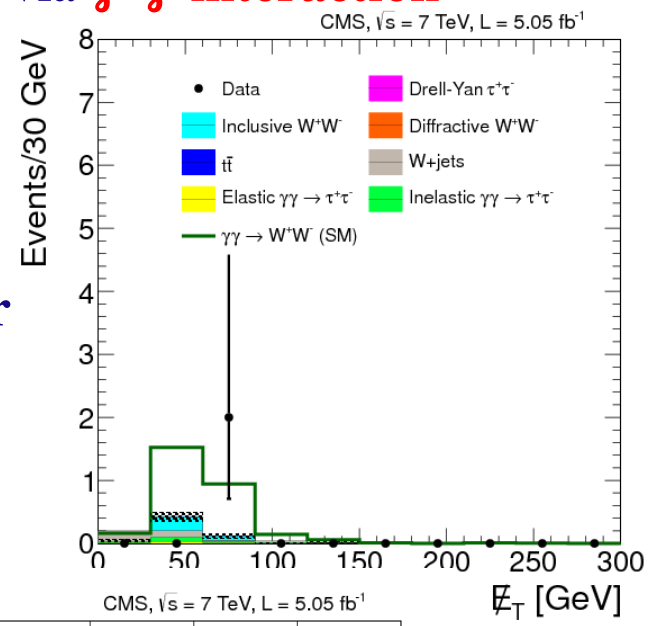
$pp \to p^{(*)}\gamma\gamma p^{(*)} \to p(*)W^{\pm}W^{\mp}p(*) \to p(*)e^{\pm}\mu^{\mp}p(*)$

CMS: JHEP 1307 (2013) 116

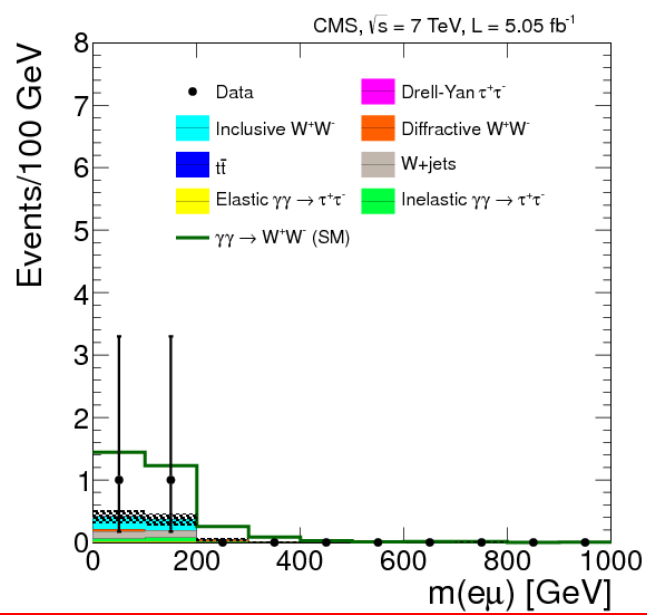
- Look for production of **opposite sign W** bosons, produced via **γ-γ interaction**



- Search done reconstructing events with **2 different flavour and opposite sign lepton** and... *no other tracks* coming from the 2-leptons common vertex
  - $p_T(e^{\pm}\mu^{\mp}) > 30$ GeV (>100 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)



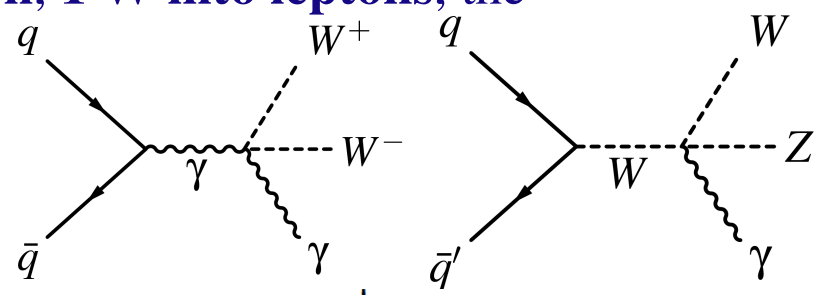
Measured cross-section:

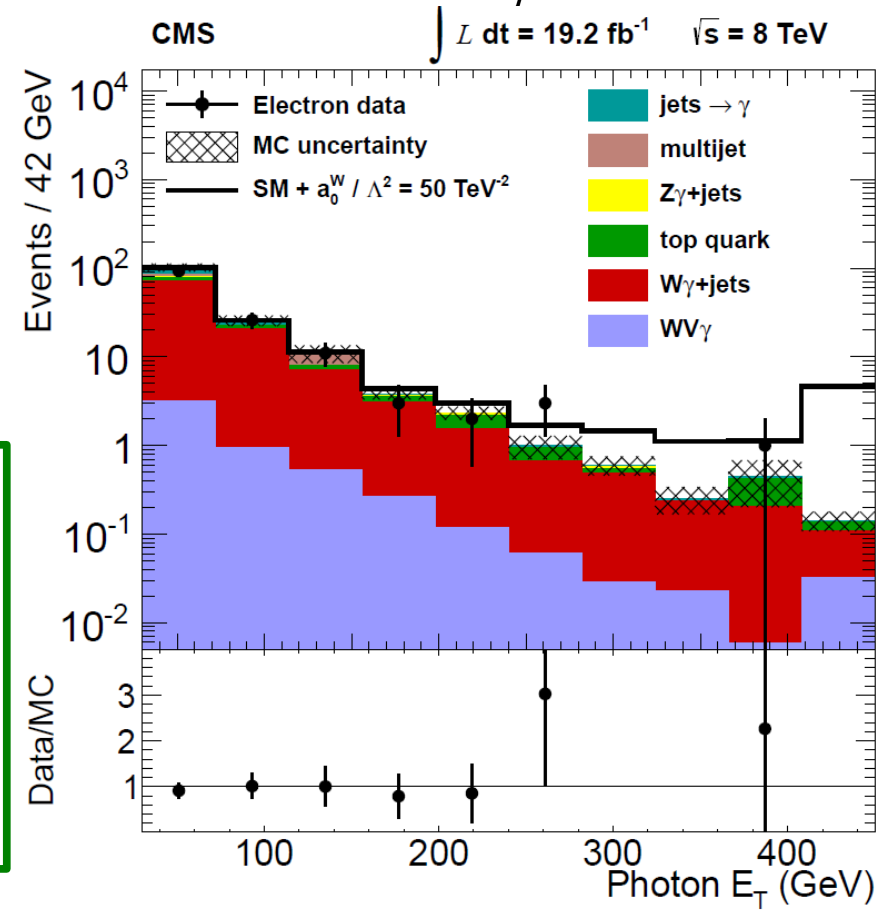
- $\sigma(pp \to p^{(*)}e^{\pm}\mu^{\mp}p^{(*)}) = 2.1^{+3.1}_{-1.9}$ fb (1.1 σ)
- $\sigma(pp \to p^{(*)}e^{\pm}\mu^{\mp}p^{(*)}) < 8.4$ fb (95 % CL)

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

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 ± 3.9 ± 10.8 ± 1.0** (**147.6 ± 4.8 ± 9.6 ± 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 x SM cross section**)

Anomalous Quartic Gauge Couplings Modelling

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

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

desideratum: Λ ~ 1-2 TeV

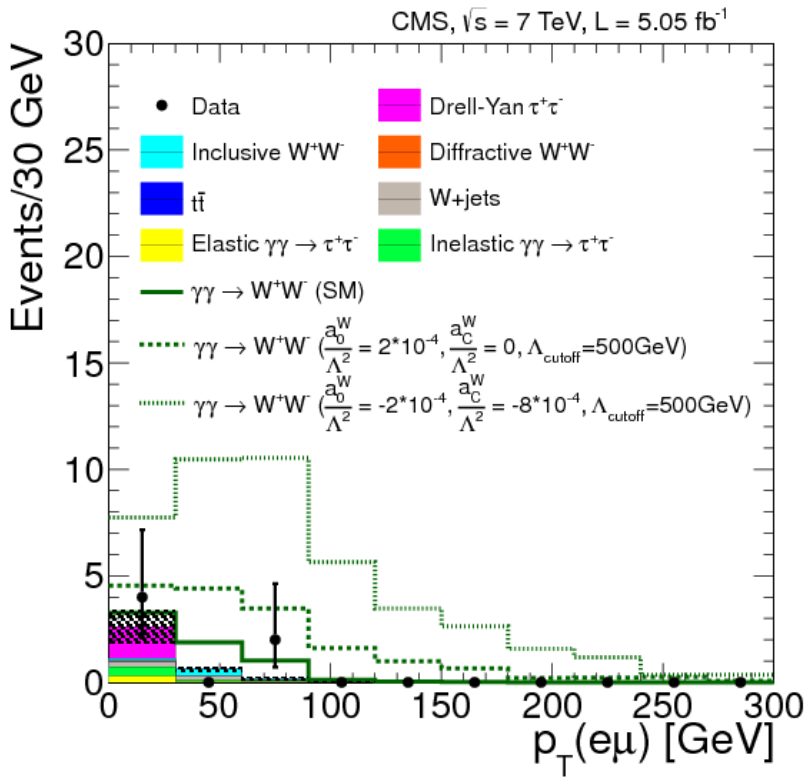
- **Effective field theory** is useful as a methodology for studying possible new physics effects from massive particles that are **not directly detectable**.
  - Underlying assumption: scale **Λ is large compared with the experimentally-accessible energy**
  - These operators have **coefficients of 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**:
  - **$f_{S,0}/\Lambda^4$, $f_{T,0}/\Lambda^4$…**

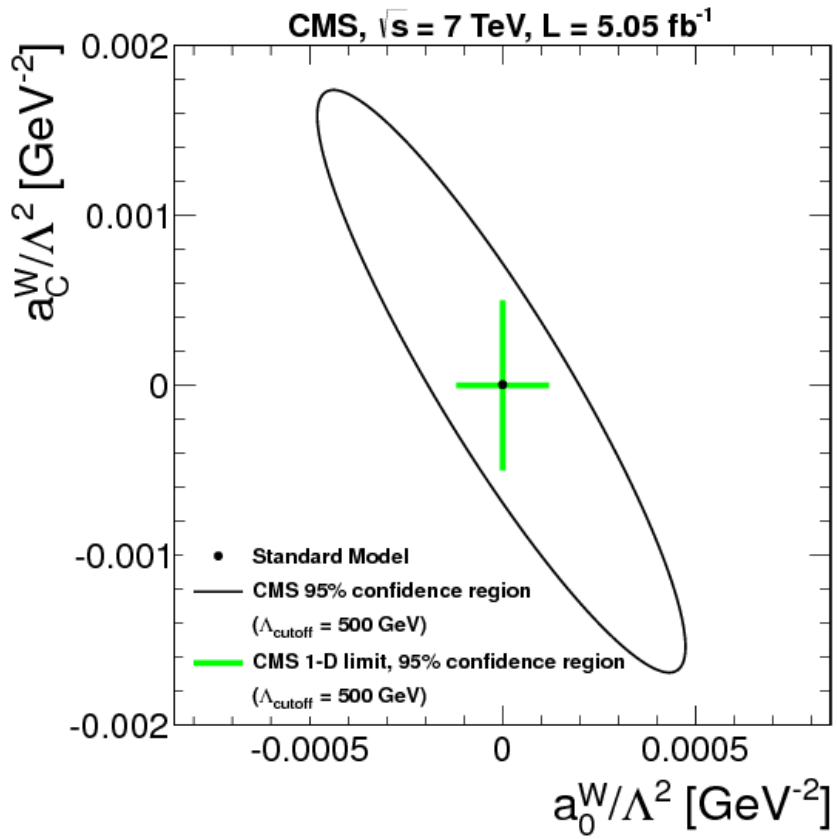
Limits on Anomalous QGC

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

- Sensitive to **$\gamma\gamma$WW** vertex

CMS: JHEP 1307 (2013) 116





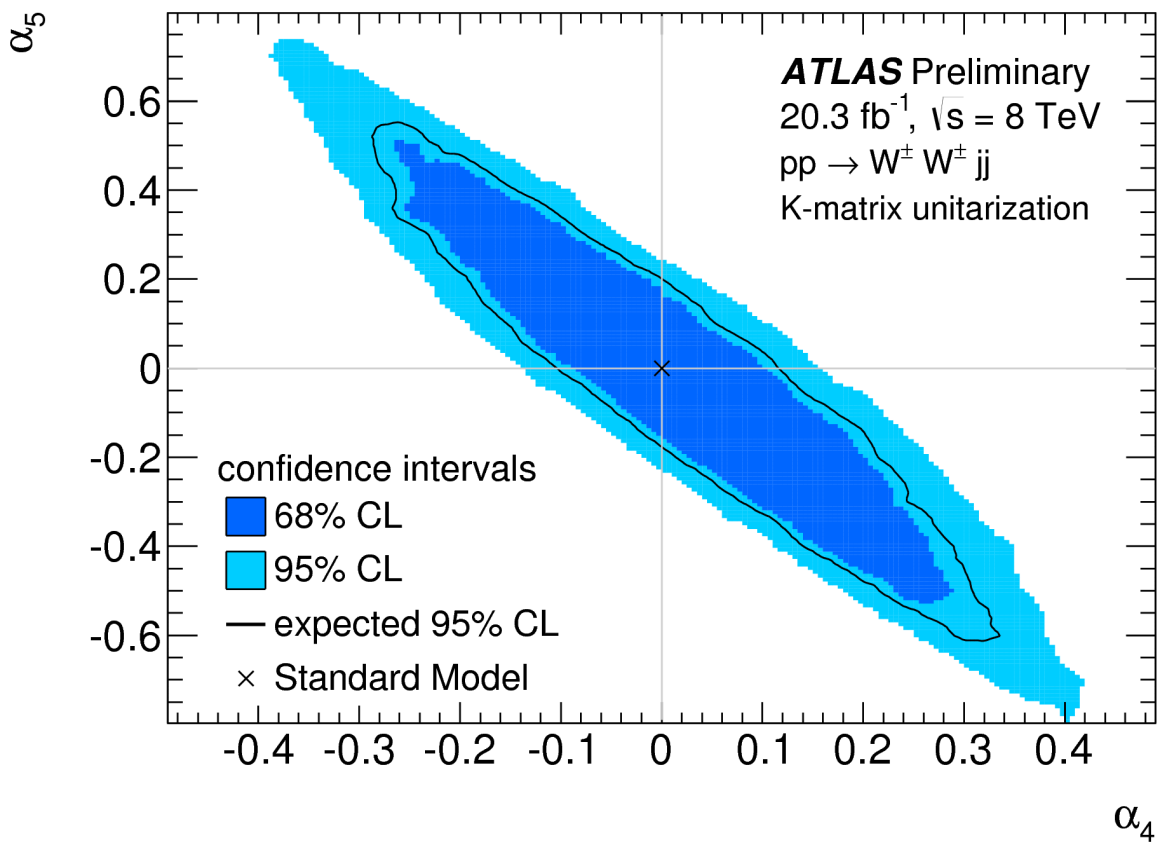
- For aQGC study, limit the search region to $p_T(e\mu) > 100$ GeV
  - **Cross section limit w.r.t. Standard model prediction < 1.9 fb @ 95% CL**
  - **No deviation from SM TGC assumed ($\lambda_\gamma = 0$)**

$pp \rightarrow W^{\pm}W^{\pm}jj \rightarrow l^{\pm}l^{\pm}\nu\nu jj$

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



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

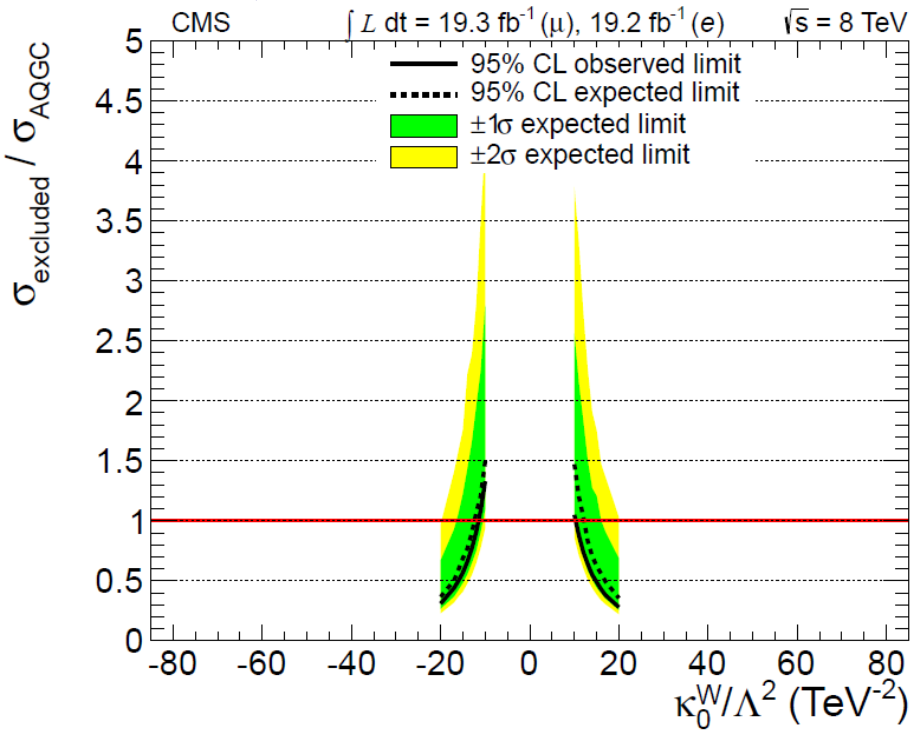
CMS: CMS-PAS-SMP-13-009 (sub PRD)

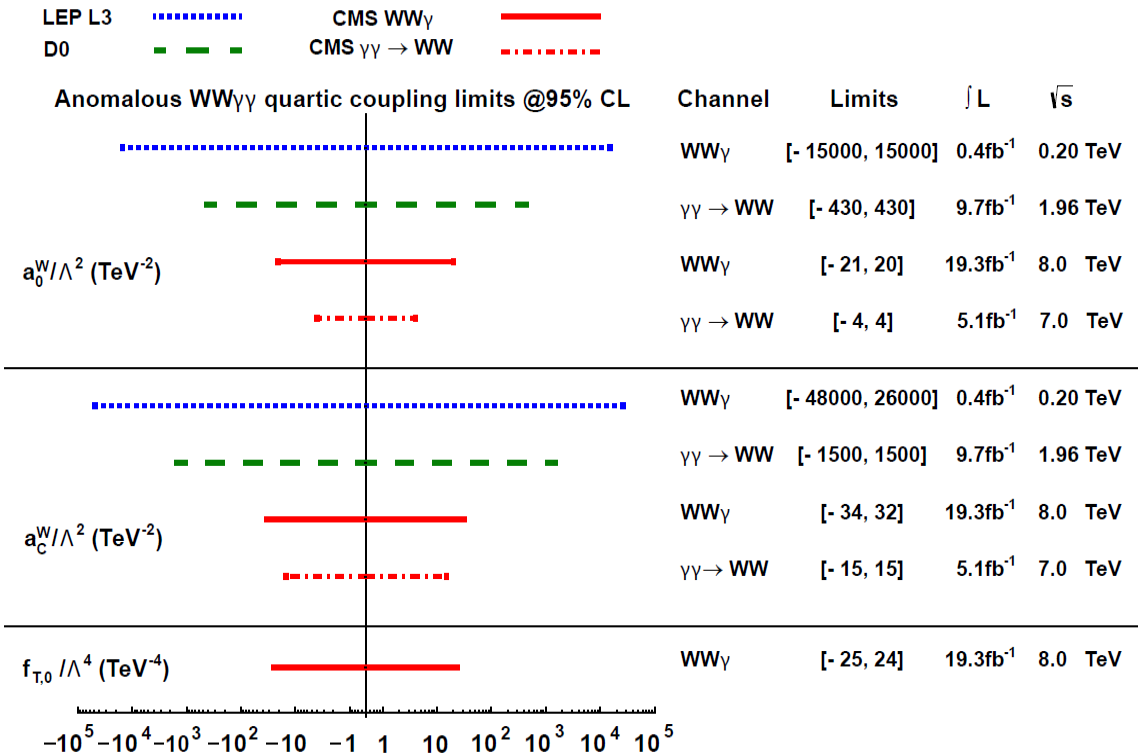
- Sensitive to **WWγγ** and **WWZγ** vertices

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

- First two terms affect **WWγγ**, the 3rd one **WWZγ**, $f_{T,0}/\Lambda^4$ **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)





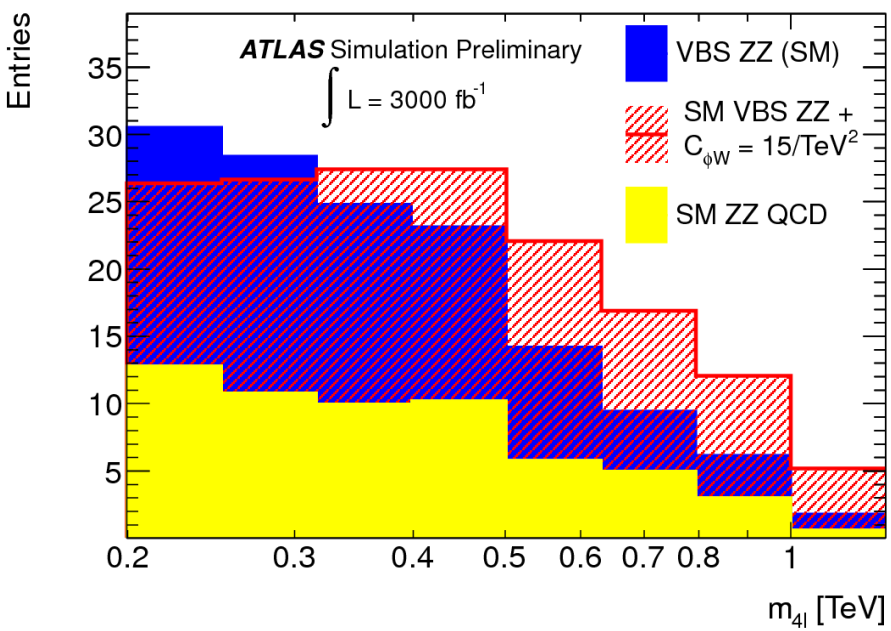
Future Projections

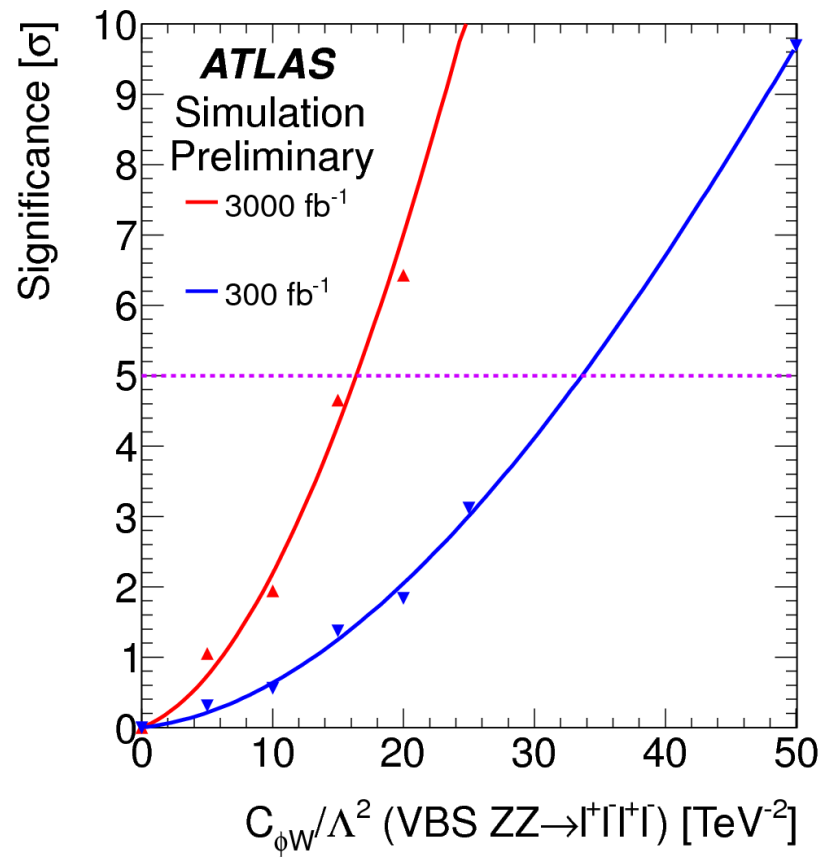
- Several final states investigated by both Collaborations (ATLAS-PHYS-PUB-2013-006 and CMS-PAS-FTR-13-006) for **$\sqrt{s}$ = 14 TeV** and two luminosity scenarios, **300 fb^{-1}** and **3000 fb^{-1}**:
  - $pp \rightarrow ZZqq \rightarrow 4ljj$ (VBS)
  - $pp \rightarrow WZqq \rightarrow 3l\nu jj$ (VBS)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

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



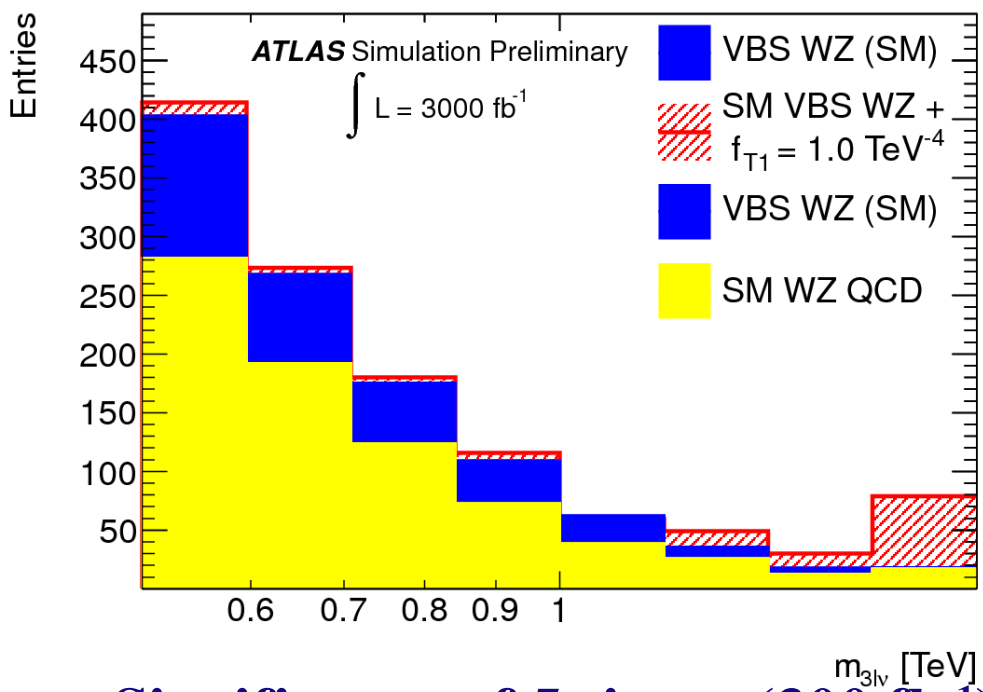


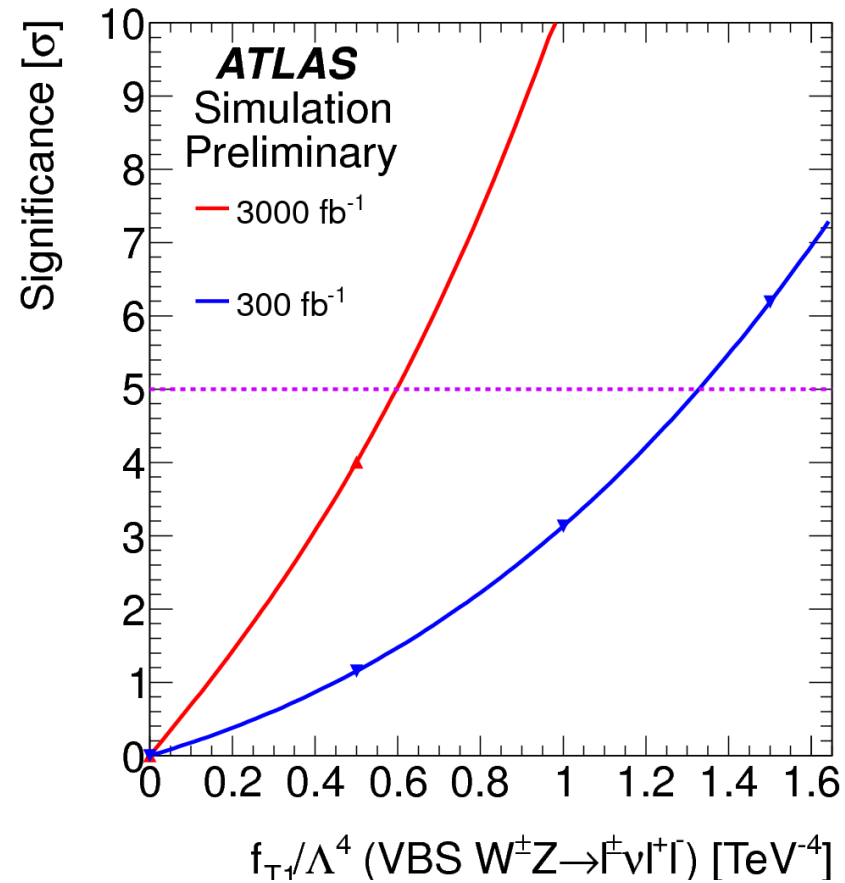
- **Significance of 5 sigma (300 fb^{-1})**
  → $C_{\phi W}/\Lambda^2$ ~ 35 TeV^{-4}

pp → WZqq → 3lνjj - VBS @ 14 TeV

ATLAS-PHYS-PUB-2013-006

- **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 $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$





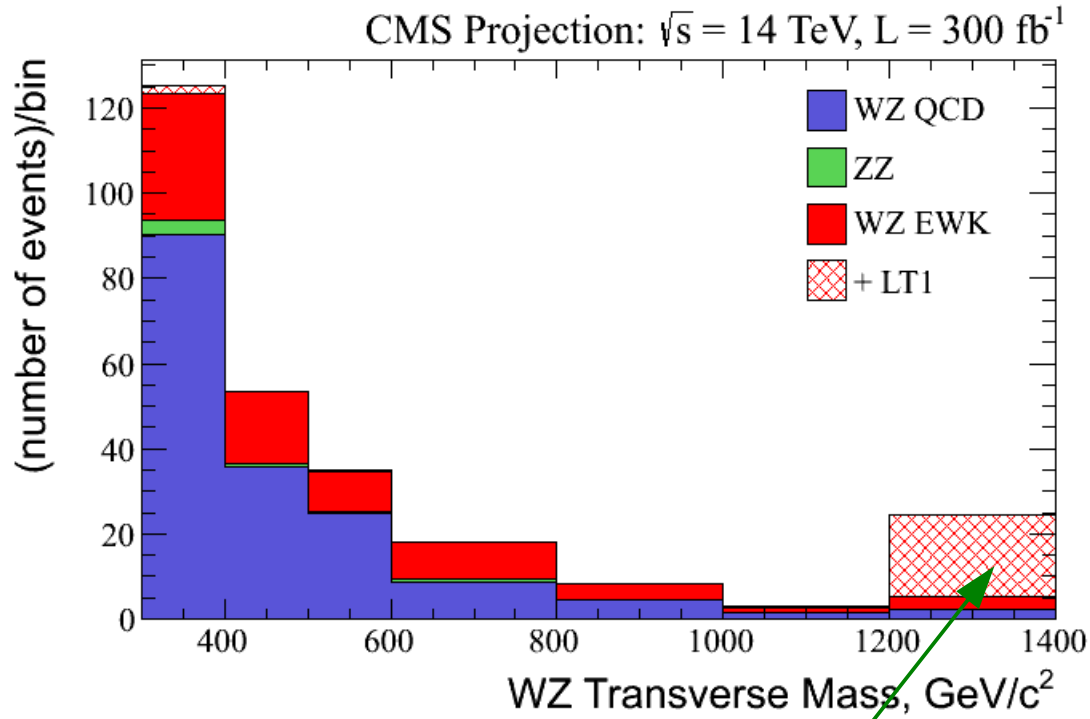
- **Significance of 5 sigma (300 fb^{-1})**

  → f_{T1}/Λ^4 ~ 1.3 TeV^{-4}

pp → WZqq → 3lνjj - 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 upgrad** (new tracker and Ecal, mu-detection down to $\eta < 4$)
- **Typical VBF/VBS cuts**:
  - Lepton $p_T > 20$ GeV, jet $p_T > 50$ GeV, $\Delta\eta(j,j) > 4$, $M(jj) > 600$ GeV



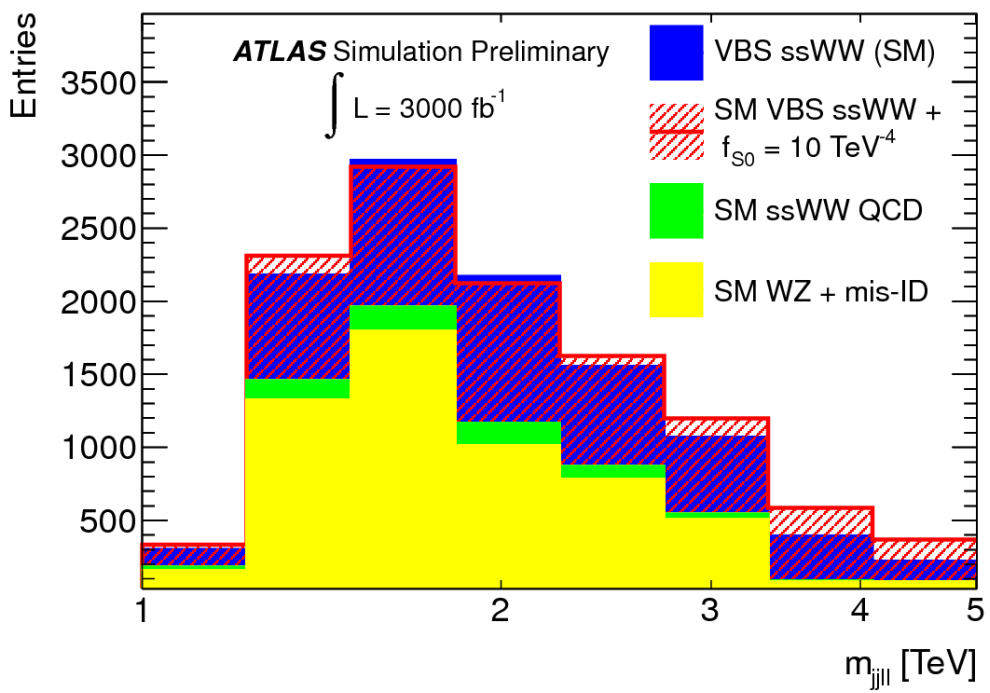
Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

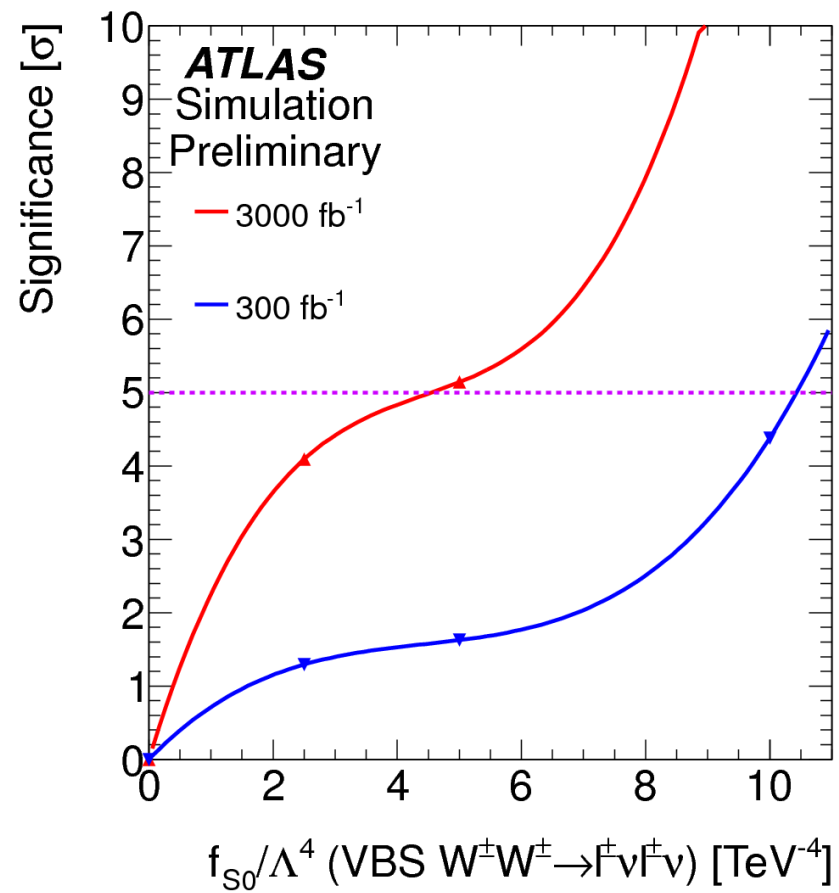
Additional contribution from aQGC with $f_{T1}/\Lambda^4 = 1$ TeV^{-4}.

$pp \rightarrow W^{\pm}W^{\pm}qq \rightarrow l^{\pm}\nu l^{\pm}\nu jj$ - 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}/Λ^4 ~ 10 TeV^{-4}**

pp → Zγγ → llγγ - QGC @ 14 TeV

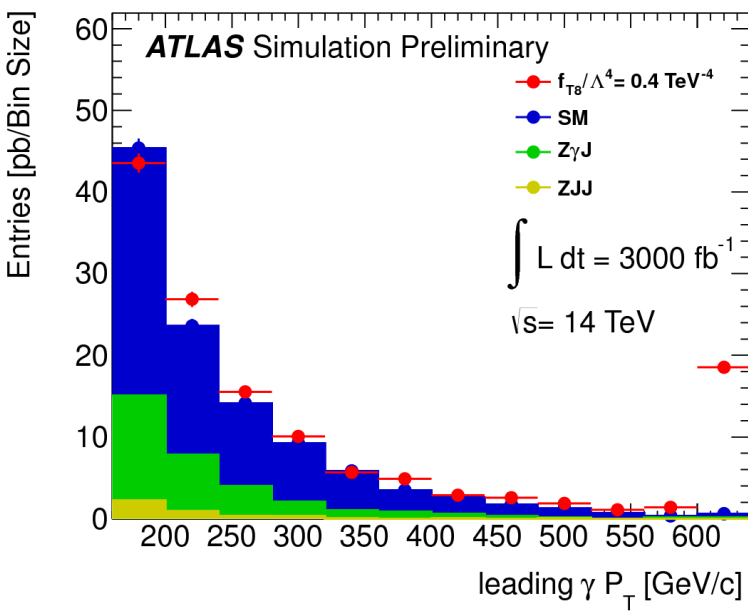
ATLAS-PHYS-PUB-2013-006

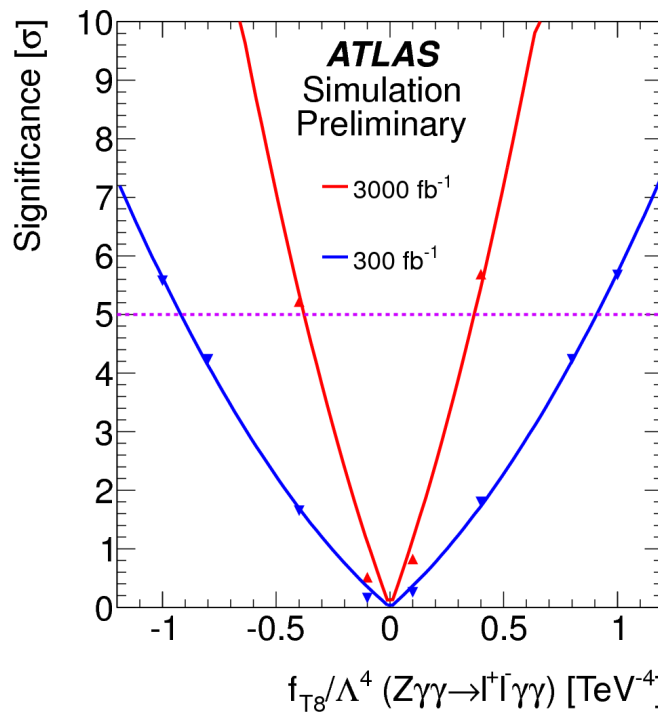
- **2 leptons** with p_T > 25 GeV (1 above 160 GeV), **2 γ** with p_T > 25 GeV (1 above 160 GeV), leptons and photons needs to be well separated
- New physics parametrized as

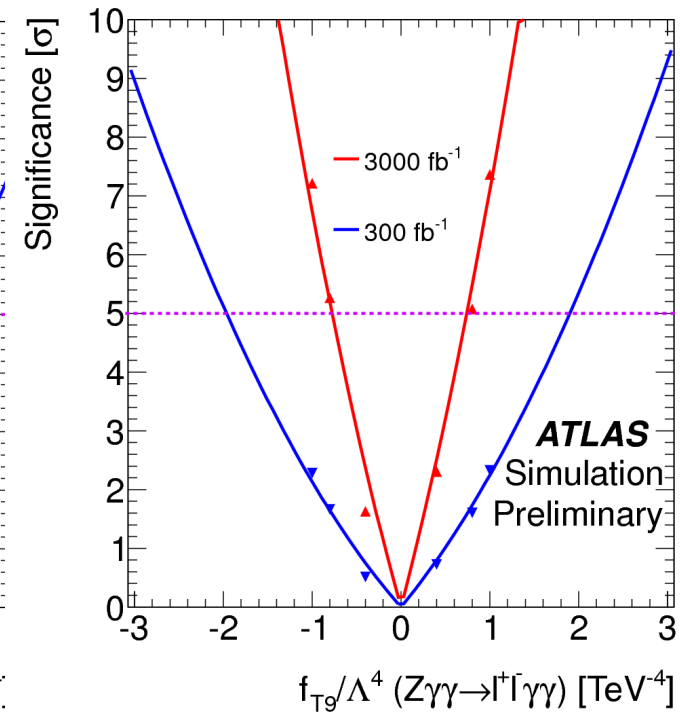
$$\mathcal{L}_{T,8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$

- **Leading γ p_T is the observable**







Conclusions

- We discovered a Higgs boson, yet **the comprehension of the Electroweak Symmetry Breaking <u>is not completed</u>**

  → Need to test the boson self-couplings vertices

  - **Complementary** to Higgs boson properties studies and high mass searches

- **Several analyses on 7 and 8 TeV data** started to explore the multi-boson final states, **setting limits on possible deviation from the Standard Model predictions**

- **First Vector Boson scattering processes observed at LHC**

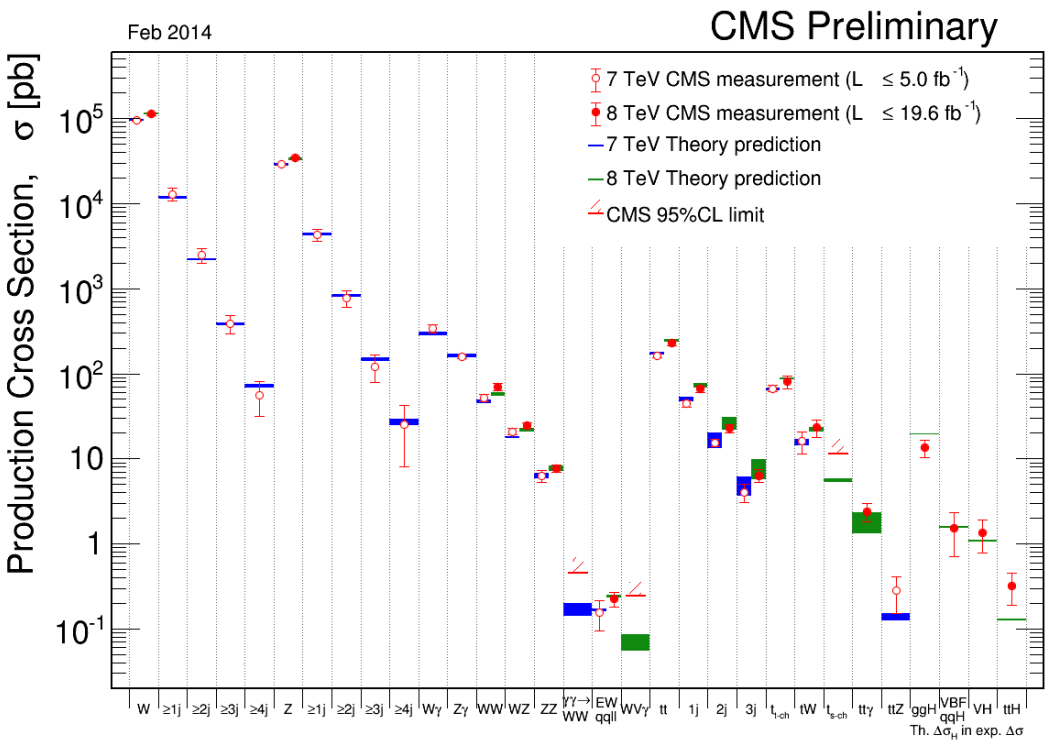
Time of Vector Boson Scattering and mutli-boson production is coming

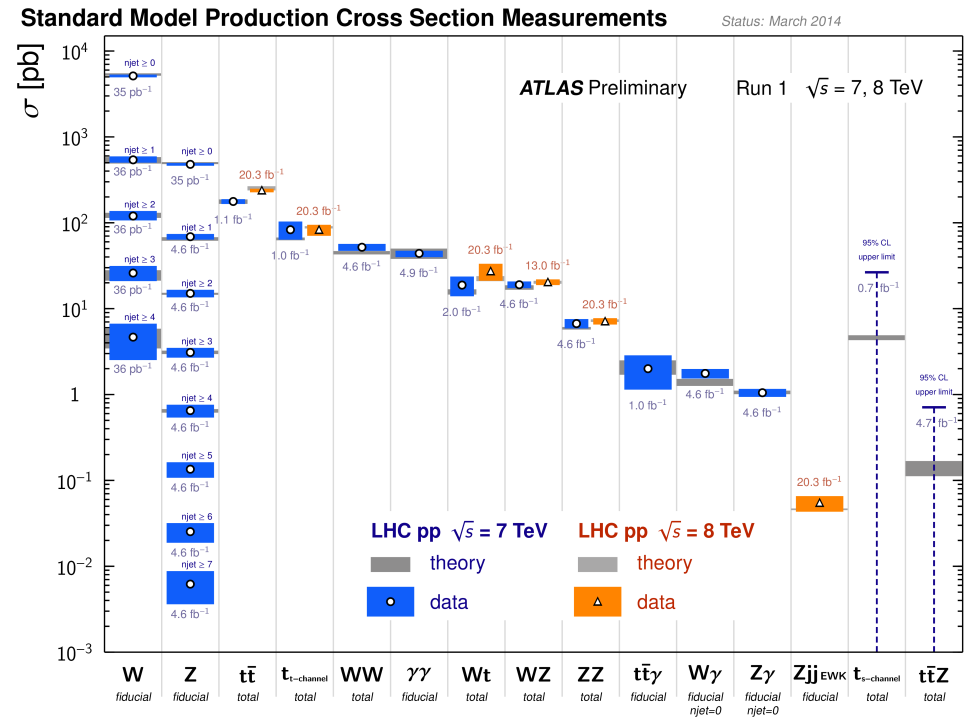
→ it will be one of the hot topic of LHC Run II

Details on results can be found in the public pages of the two experiments:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
https://twiki.cern.ch/twiki/bin/view/CMSPublic/

More Material

Stairways to Heaven?





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 $m_{VV} \sim$ 1-2 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**

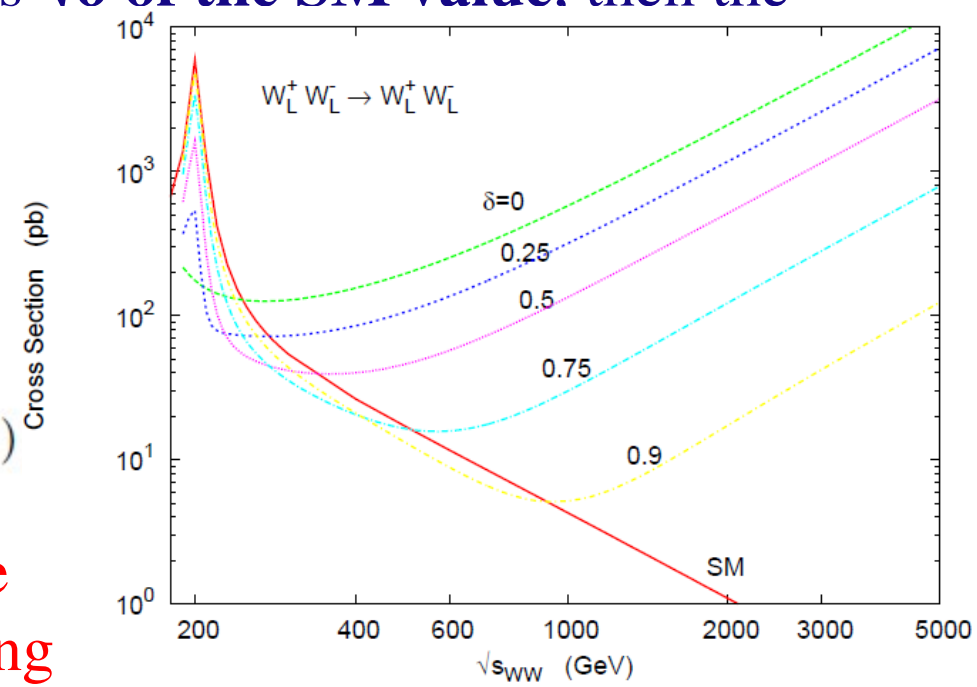
The Higgs Job

- 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 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

$$i\mathcal{M}^{\text{gauge}} = -i\frac{g^2}{4m_W^2}\, u + \mathcal{O}((E/m_W)^0)$$

$$i\mathcal{M}^{\text{higgs}} = i\frac{g^2}{4m_W^2}\, u\,\delta + \mathcal{O}((E/m_W)^0)$$

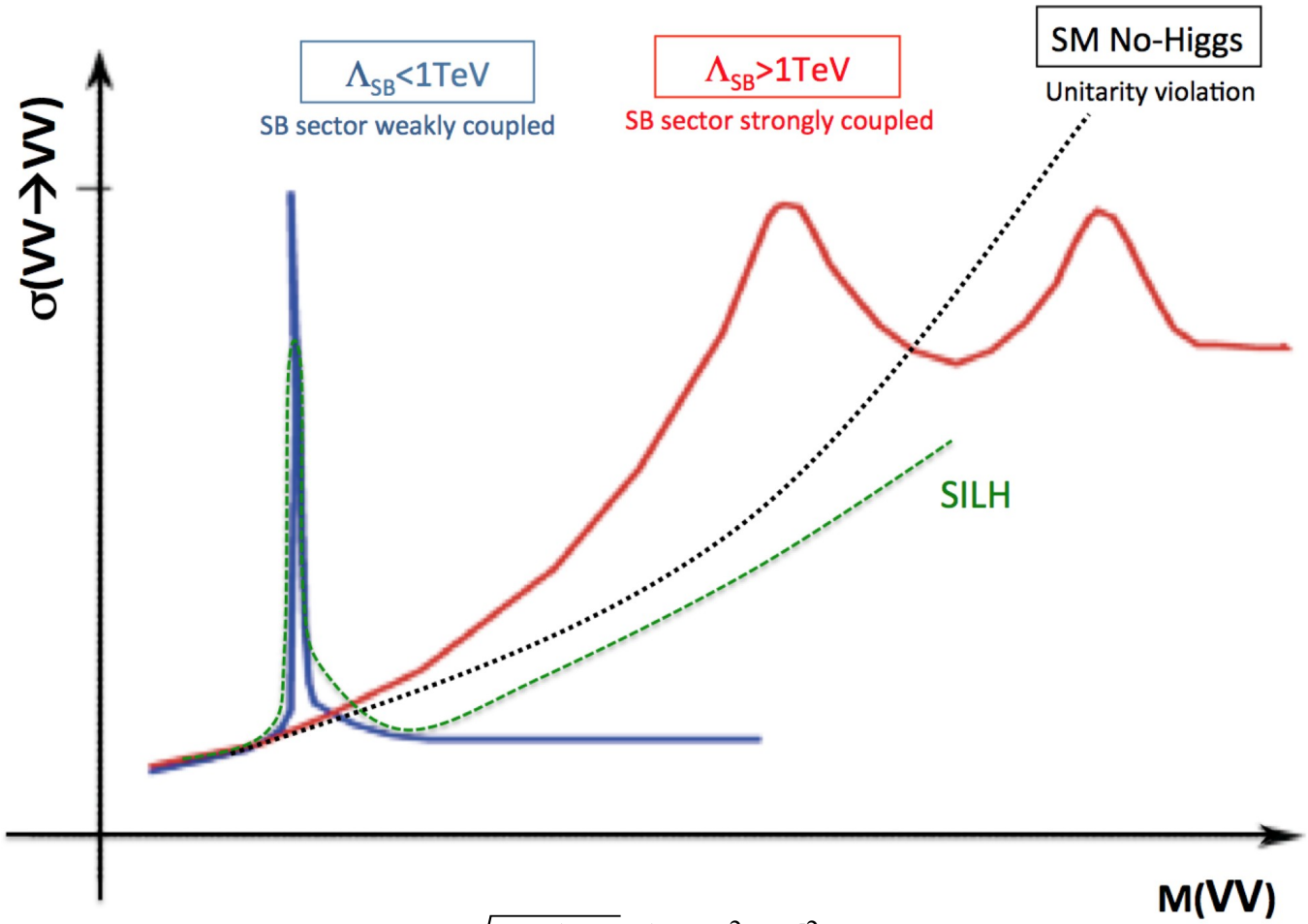
$$i\mathcal{M}^{\text{all}} = -i\frac{g^2}{4m_W^2} u(1-\delta) + \mathcal{O}((E/m_W)^0)$$



Cheung, Chiang, Yuan

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

VV Scattering to test the EWSB



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

SILH :

Higgs a pseudo Goldstone Boson of a new strong sector

Both a light Higgs and Bosons strongly coupled

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

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

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

arXiv:0801.3359

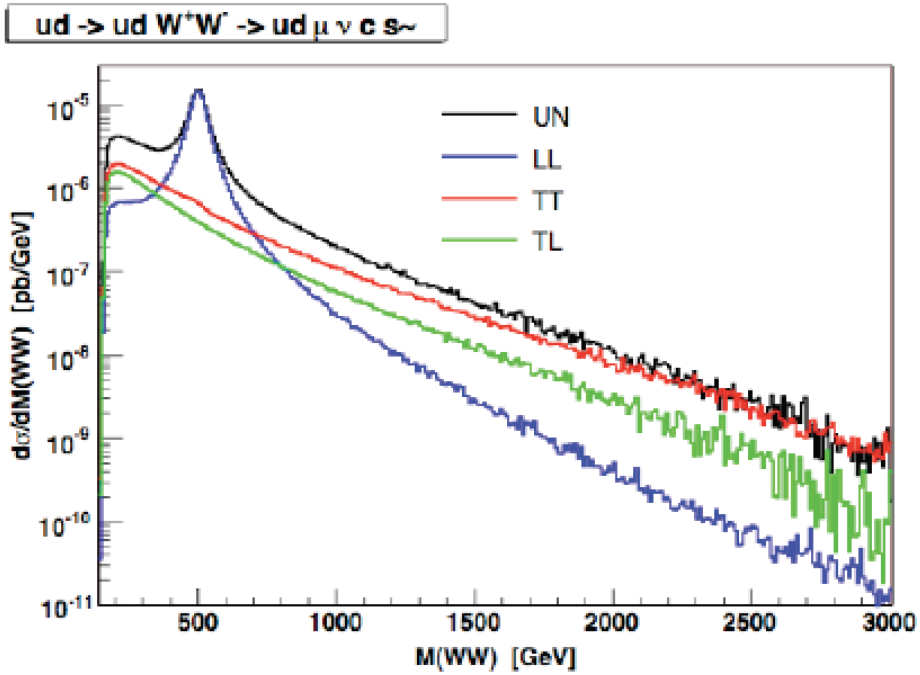
- Cross Sections for $\sqrt{s}$ = 14 TeV from Phantom Monte Carlo Generator:
  full simulation of $2 \rightarrow 6$ @ $\mathcal{O}(\alpha_{EW}^6) + \mathcal{O}(\alpha_{EW}^4 \alpha_{QCD}^2)$

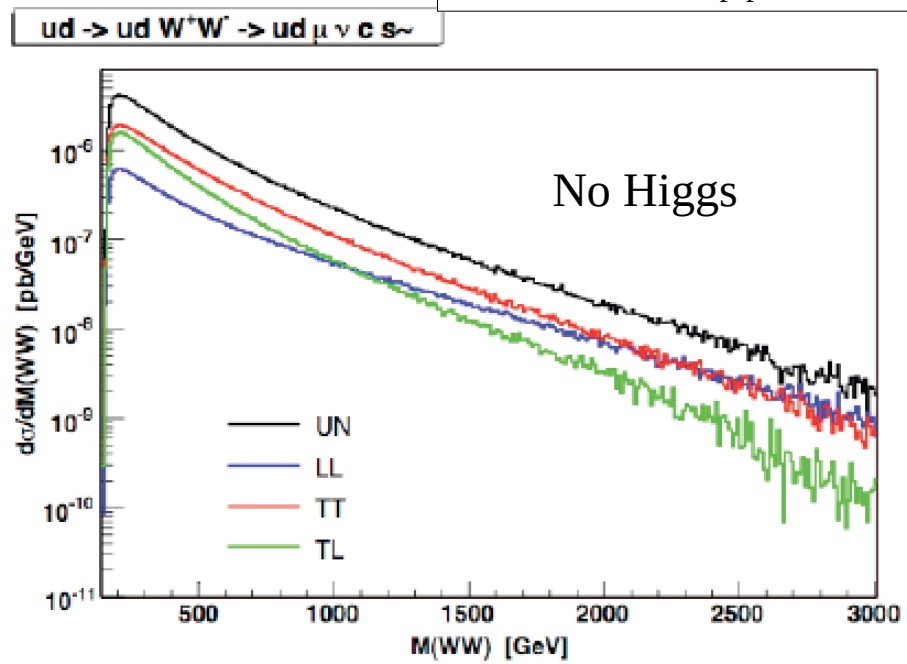
	$qqqq\mu\nu/e\nu$				$qqqq\mu\mu/ee$			
	no-Higgs		500 GeV		no-Higgs		500 GeV	
	σ (pb)	perc.	σ (pb)	perc.	σ (pb)	perc.	σ (pb)	perc.
total	0.689	100%	0.718	100%	0.0305	100%	0.0350	100%
signal	0.158	23%	0.184	26%	0.0125	41%	0.0165	47%
top	0.495	72%	0.494	69%	0.0137	45%	0.0137	39%
non resonant	0.020	3%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

	$qq\mu\mu\mu\mu/eeee$				$qq\mu\mu\mu\nu$				$qq\mu^{\pm}\nu\mu^{\pm}\nu$			
	no-Higgs		500 GeV		no-Higgs		500 GeV		no-Higgs		500 GeV	
	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.	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

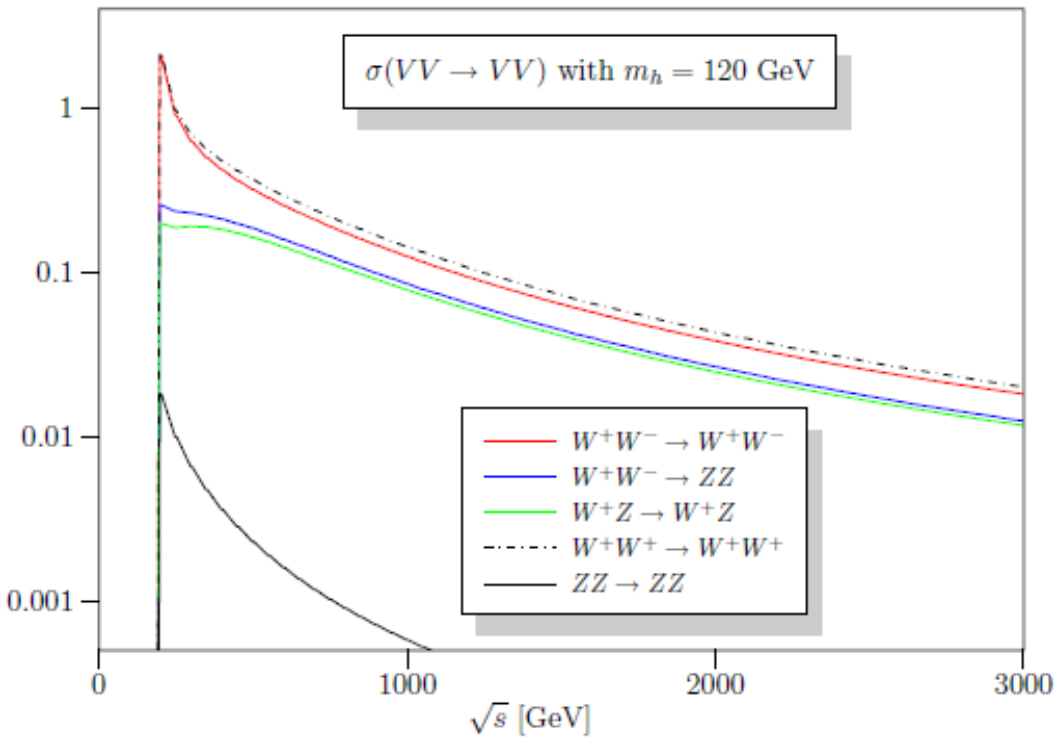


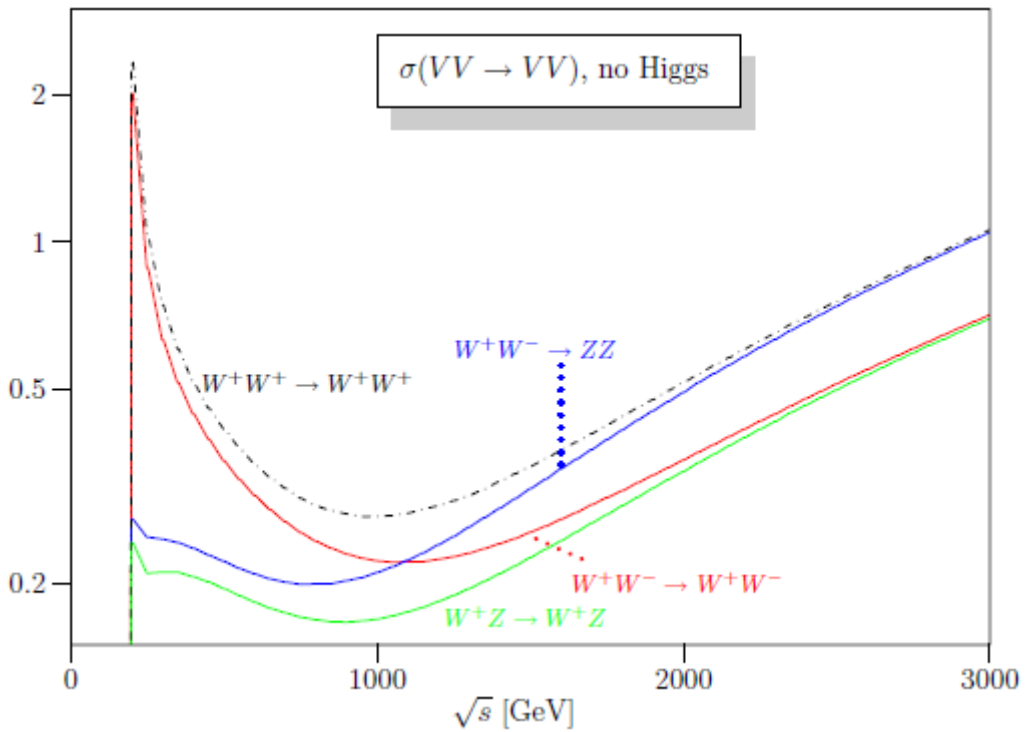


- The VL are coupled to the Higgs and they are the ones sensitive to the EWSB.
- The behavior of the LL cross section only can give information on the scale at which the symmetry breaks.
- At large M(VV) the TT cross section is of the same order as the LL (in the no-Higgs case)

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

$pp \rightarrow Z\, j_F j_B$

ATLAS: JHEP 04 (2014) 031

Fiducial region for the cross-section measurement:

- Leptons: $|\eta| < 2.47$, $p_T > 25$ GeV
- Dileptons: $81 \leq m_{ll} \leq 101$ GeV, $p_T > 20$ GeV
- Jets: $|y| < 4.4$, $p_{T,j1} > 55$ GeV, $p_{T,j2} > 45$ GeV, $\Delta R(j,l) \geq 0.3$
- Dijet: $m_{jj} > 250$ GeV
- Number of additional jets = 0
- $p_T^{balance} < 0.15$
  - $p_T^{balance} = |\mathbf{p}_{T,l1} + \mathbf{p}_{T,l2} + \mathbf{p}_{T,j1} + \mathbf{p}_{T,j2}| \,/\, (|\mathbf{p}_{T,l1}| + |\mathbf{p}_{T,l2}| + |\mathbf{p}_{T,j1}| + |\mathbf{p}_{T,j2}|)$

Cross-section measurement (at 5 σ level):

- $\boldsymbol{\sigma_{EW} = 54.7 \pm 4.6\ (stat)\ ^{+9.8}_{-10.4}\ (sys) \pm 1.5\ (lumi)\ fb}$