Vector Boson Scattering at LHC

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On behalf of the CMS and Atlas Collaborations

The Third Annual Large Hadron Collider Physics Conference

Outline and References

- Theoretic **Introduction** and **Motivations**
- **Current State** at LHC (Run I)
  - $\gamma\gamma$-Production of W^+W^-

    CMS: JHEP 1307 (2013) 116
  - Z + F/B jets

    CMS: Eur. Phys. J. C 75 (2015) 66, JHEP 10 (2013) 101 **Atlas**: JHEP 04 (2014) 031
  - W + F/B jets

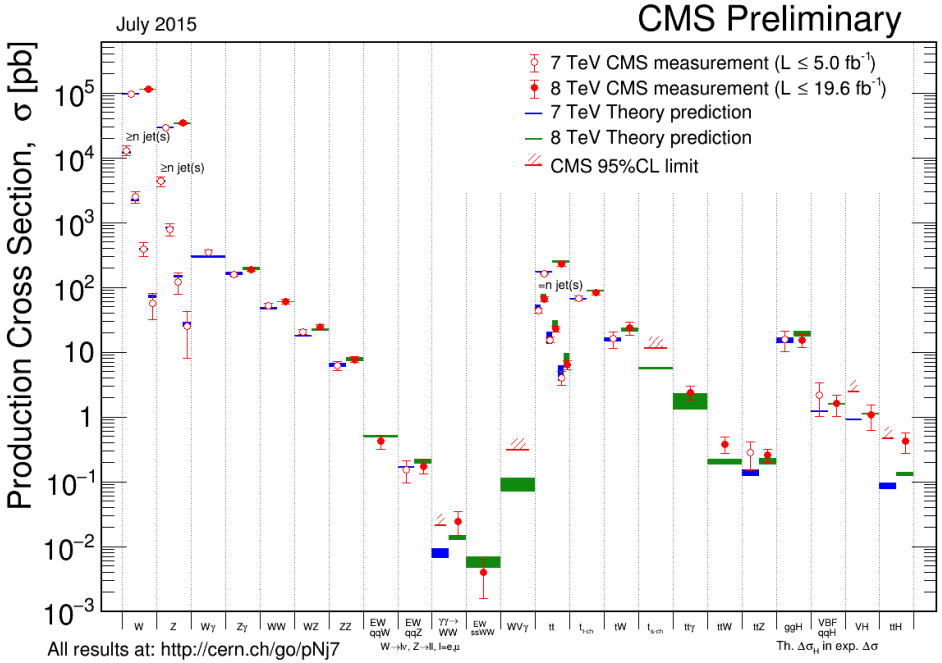
    CMS: CMS-PAS-SMP-13-012
  - $W^{\pm}W^{\pm}$ + 2 jets

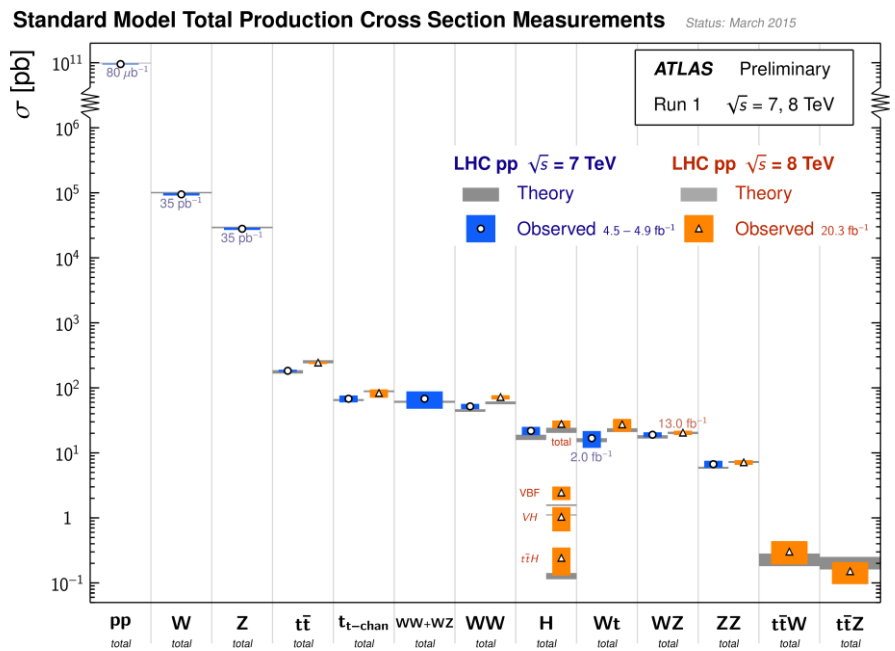
    CMS: Phys. Rev. Lett. 114 (2015) 05180 **Atlas**: Phys. Rev. Lett. 113 (2014) 141803
- **Future Projections** (Run III, HL-LHC)

  CMS: CMS-PAS-FTR-13-006 **Atlas**: ATL-PHYS-PUB-2013-006

General Remarks

Precise SM Measurements



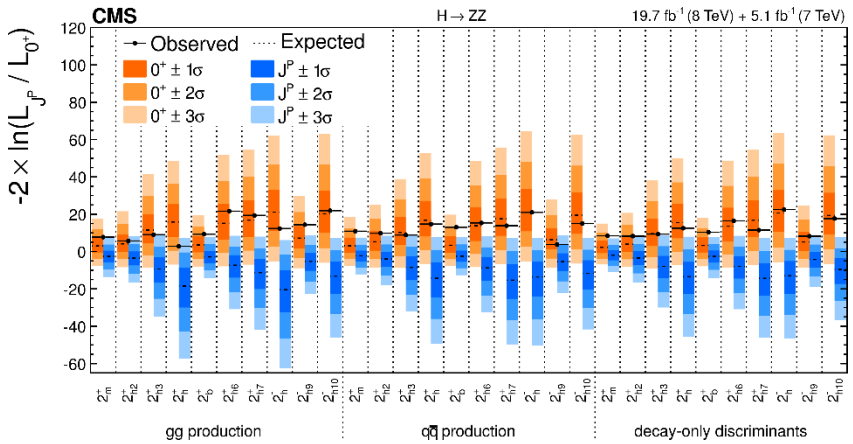


Good understanding of the detectors + accurate theory predictions

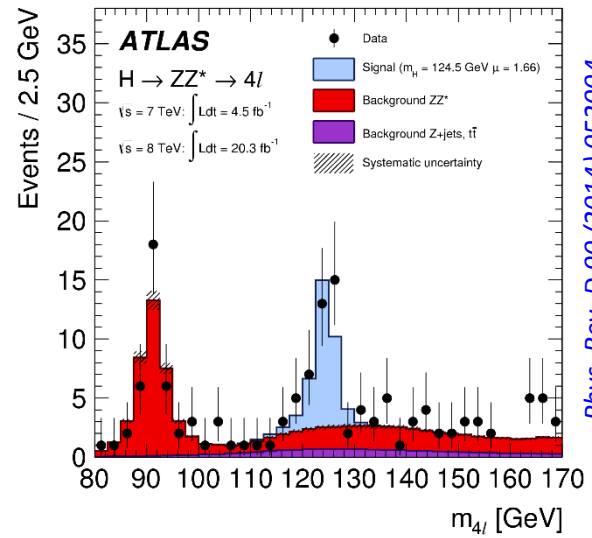
➡ **Precise measurements** of the Standard Model processes over many orders of magnitude

Still, a lot to be done…

In July 2012 a new particle was discovered: the **Higgs boson**



Phys. Rev. D 92 (2015) 012004



Phys. Rev. D 90 (2014) 052004

Open issues:

understand the **nature of this Higgs boson** and if there is **new physics beyond the SM**

How?

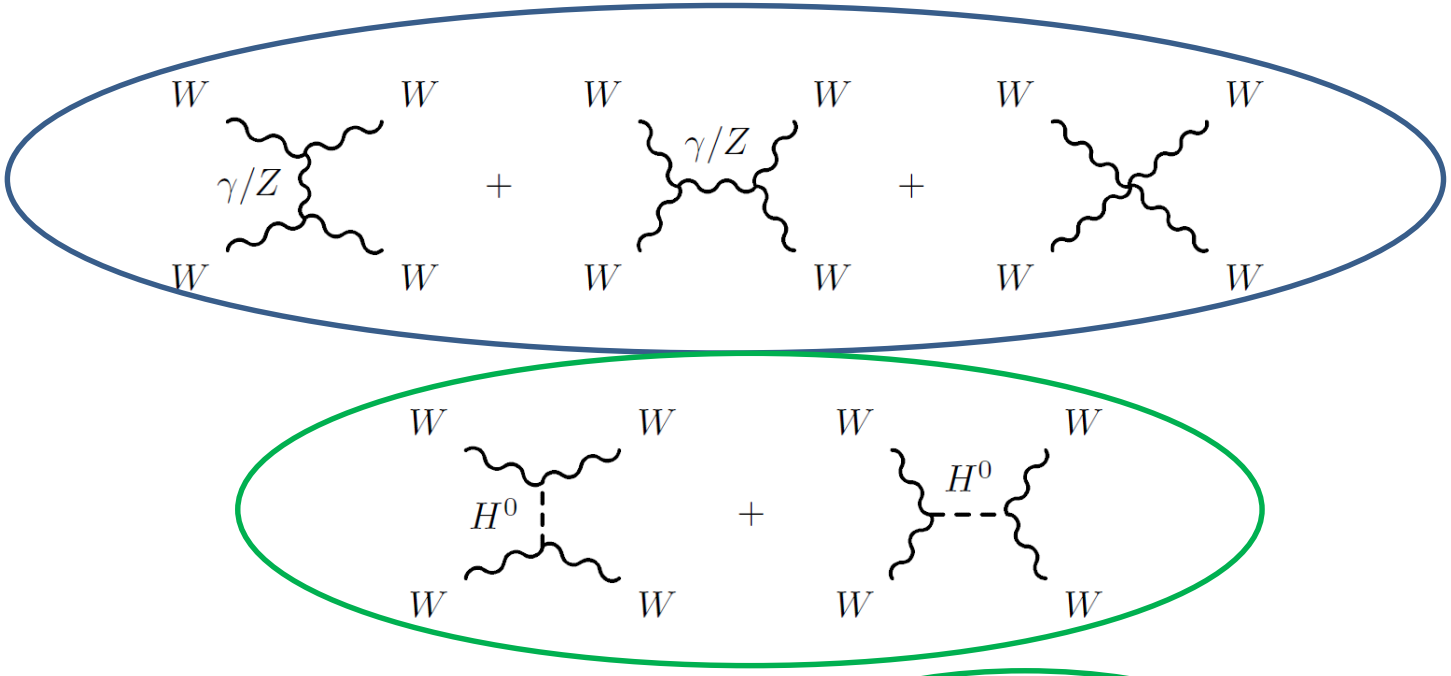
- keep searching for **new particles** (more Higgs bosons, sparticles, something new…)
- measure with high precision **its properties** to the %level
- measure the Higgs other important role: **unitarization of the VV scattering**

The Role of the SM Higgs Boson

The Higgs mechanism explains how the elementary particles get mass

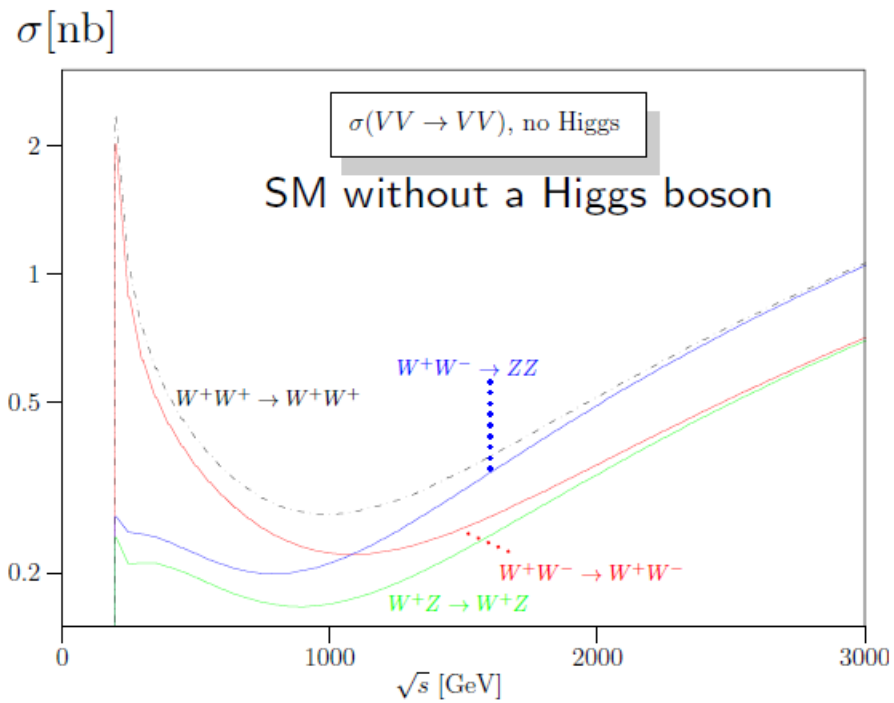
➡ The W and Z acquire the longitudinal degree of freedom (W_L, Z_L)

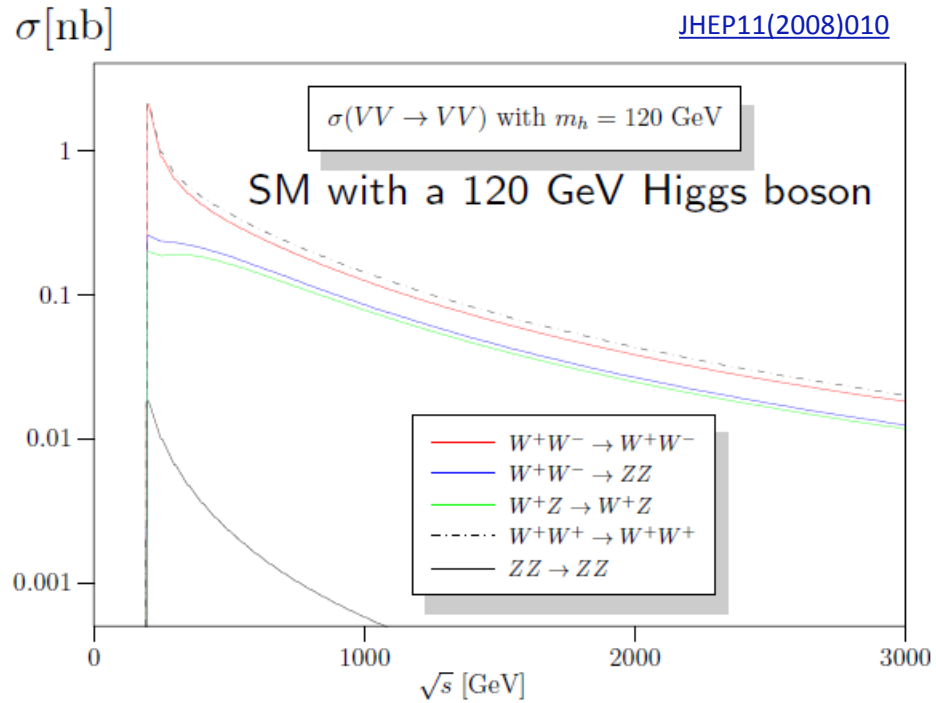
Without the Higgs, $V_L V_L \rightarrow V_L V_L$ would break unitarity (for $\sqrt{s}$ > 1.2 TeV)



$$\sigma_{V_L V_L \rightarrow V_L V_L} \propto \left[-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2} \right]$$

The Vector Boson Scattering





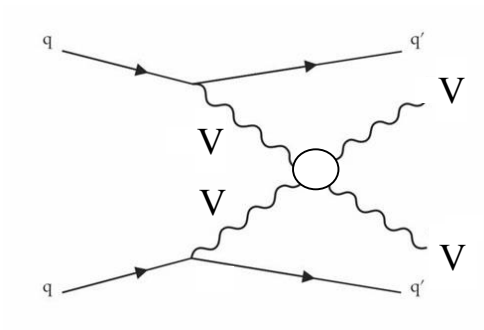
JHEP11(2008)010

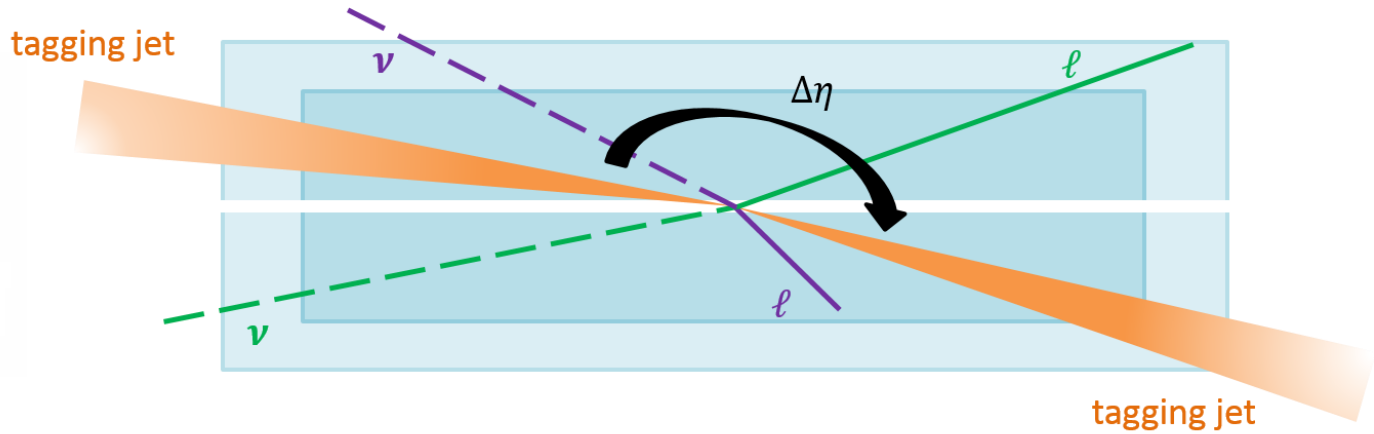
High energy vector boson scattering plays a **central role**:

- test of the **nature of the Higgs** boson
- main experimental grounds to the understanding of which **alternative theory** is at work.

➡ If the discovered Higgs boson is only partially responsible for EWSB, then $V_L V_L$ cross section will keep growing with s, up to the new physics scale Λ

VBS Signal Topology





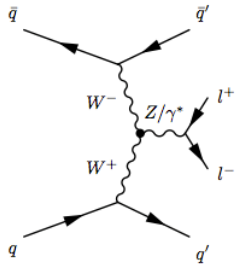
Main features:

- Energetic jets in the forward and backward directions
- Large rapidity separation $\boldsymbol{\Delta y_{jj}}$ ($\boldsymbol{\Delta \eta_{jj}}$)
- Large invariant mass of the two tagging jets $\boldsymbol{m_{jj}}$
- VV decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (no extra jets between tagging jets)

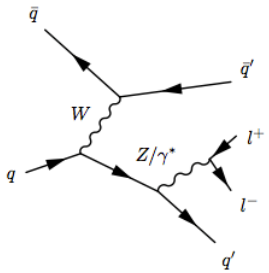
Current State

Z + F/B jets (8 TeV)

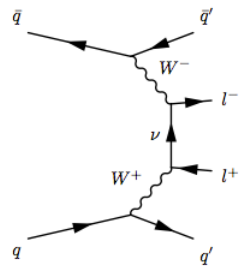
VBF

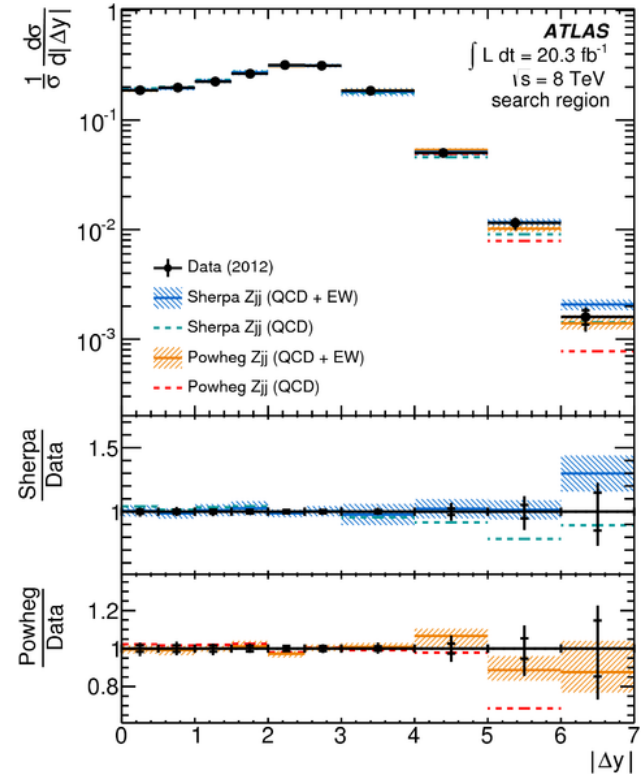


Bremsstrahlung



Non-resonant



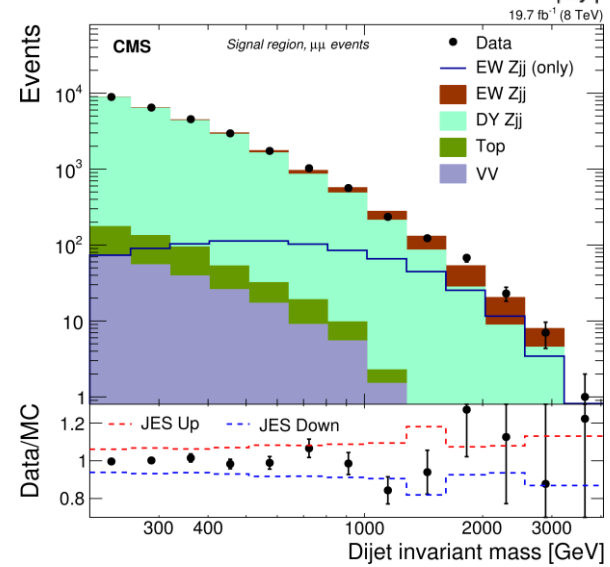


IMPORTANT BENCHMARK

- Comparable σ and topology to VBF production of Higgs
- Sensitivity to new physics in WWZ coupling
- Use it to refine forward jet selection

SIGNAL:

- Single $\boldsymbol{Z}$ **boson** decaying into 2 leptons ($Z \to ee, \mu\mu$)
- **Two high energy jets**, with large $\Delta\boldsymbol{\eta_{jj}}$ and $\boldsymbol{m_{jj}}$



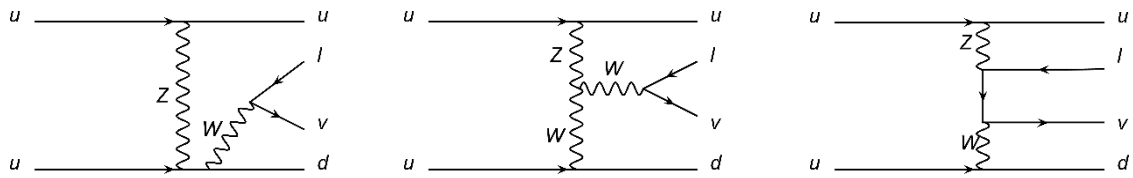
CMS: σ = 226 ± 26 (stat) ± 35 (syst) fb
(σ_{exp}= 239 fb)

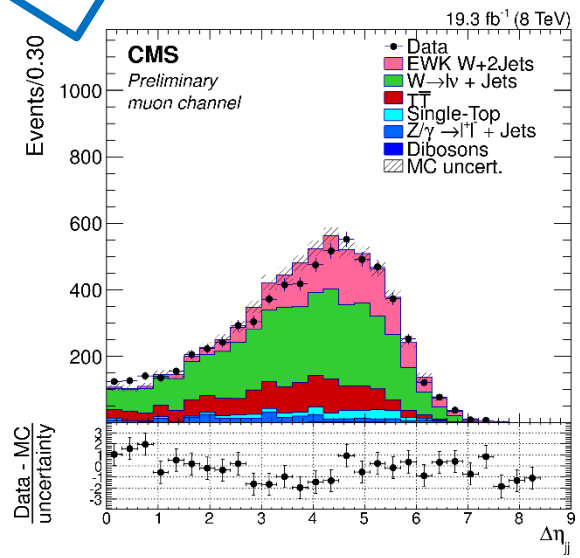
Atlas: σ = 54.7 ± 4.6 (stat) $^{+9.8}_{-10.4}$ (syst) ± 1.3 (lumi) fb
(σ_{exp}= 46.1 fb)

W + F/B jets (8 TeV)

NEW

VBF **Bremsstrahlung** **Non-resonant**



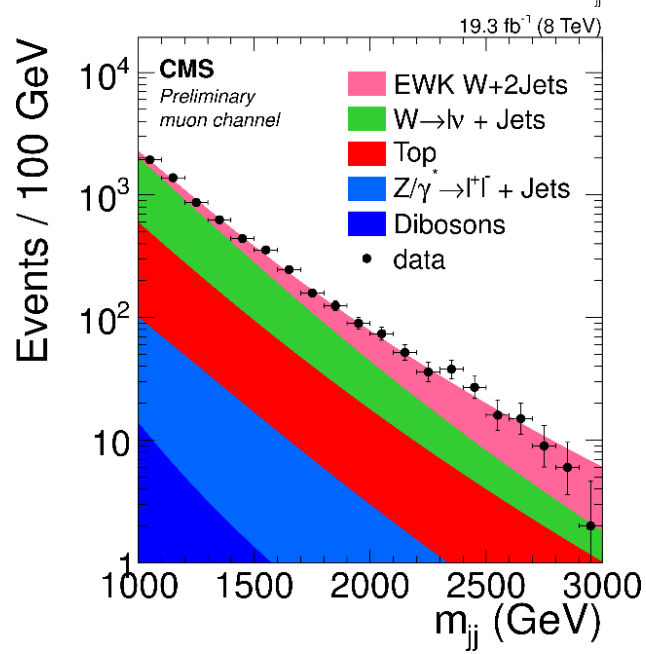


IMPORTANT BENCHMARK

- Comparable σ and topology to VBF production of Higgs
- Test of the SM predictions
- Use it to refine forward jet selection

SIGNAL:

- Single isolated lepton from ***W* boson** decay (W → $e\nu$, $\mu\nu$)
- Significant **missing E_T** due to the neutrino
- **Two high energy jets**, with large $\Delta\eta_{jj}$ and m_{jj}

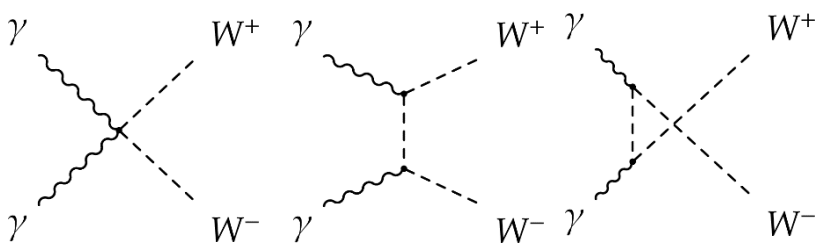


With p_T^{jet1}> 60 GeV p_T^{jet2}> 50 GeV $|\eta^{jet}|$< 4.7 m_{jj} > 1 TeV

σ_{fid} = 0.42 ± 0.04 (stat) ± 0.09 (syst) ± 0.01 (lumi) pb

(σ_{exp}= 0.50 ± 0.02 (scale) ± 0.02 (PDF) pb)

$\gamma\gamma$-Production of W^+W^- (7 TeV)



IMPORTANT BENCHMARK

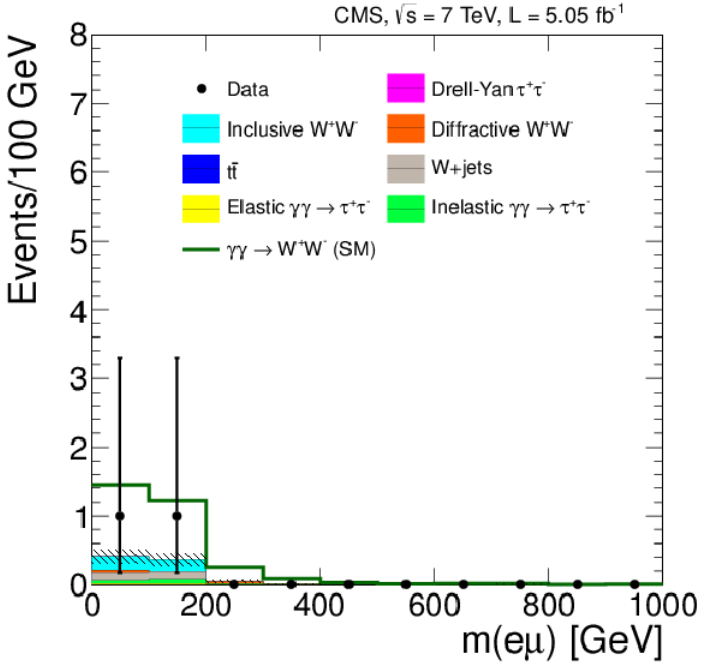
- Sensitivity to SM deviations
- First $VV \to VV$ analysis at LHC

SIGNAL: $\boldsymbol{pp \to p^{(*)}\gamma\gamma p^{(*)} \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e^{\mp}\mu^{\pm}p^{(*)}}$

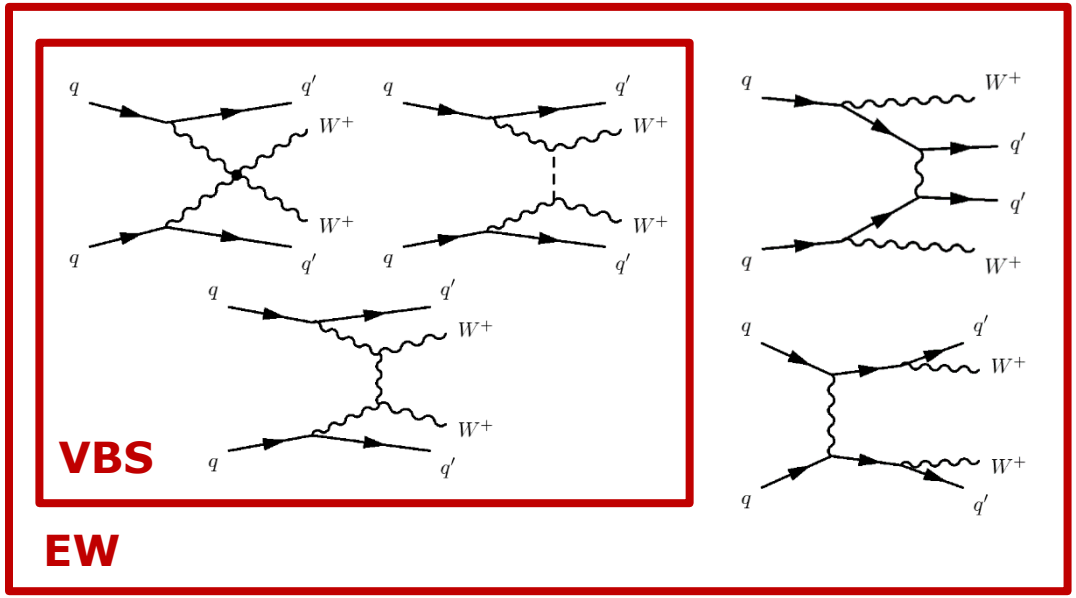
- 2 high p_T isolated leptons, with opposite charge and different flavour μe
- 0 extra tracks from primary vertex
- $p_T(e^{\mp}\mu^{\pm}) > 30$ GeV and $\mathrm{m}(e^{\mp}\mu^{\pm}) > 30$ GeV

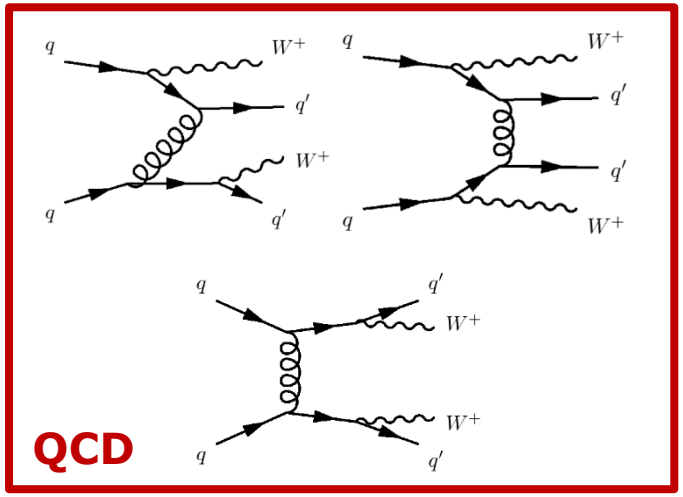
- **2 events observed** passing all criteria:
  2.2 ± 0.4 signal and 0.84 ± 0.15 background expected

- **Measured cross section**:
  $\sigma = 2.2\ ^{+3.3}_{-2.0}$ (stat) fb (predicted $\sigma = 4.0 \pm 0.7$ fb)
  Upper Limit $\sigma < 10.6$ fb at 95% C.L.



VBS in $W^{\pm}W^{\pm}$ + 2 jets Channel (8 TeV)





TWO DIFFERENT SEARCH REGIONS:

Inclusive Analysis – QCD + EW PRODUCTION (Atlas and CMS):

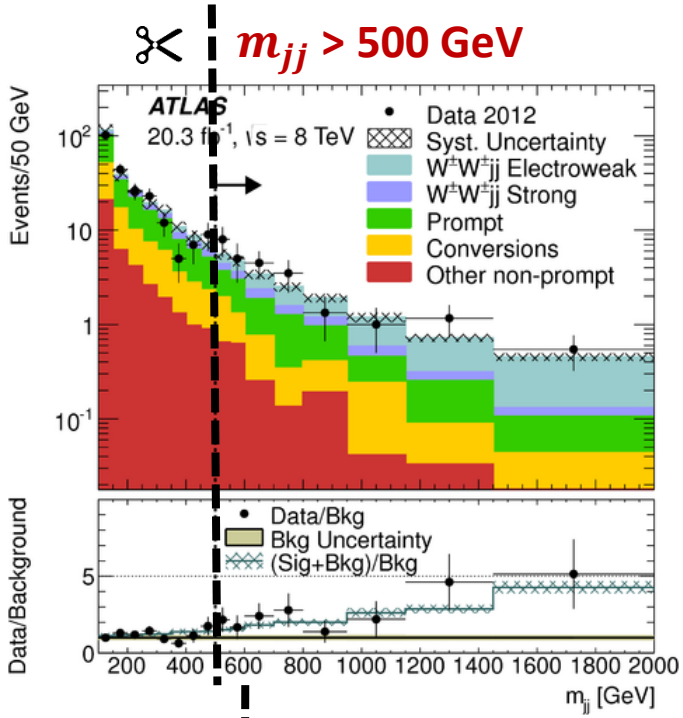
- 2 same-sign leptons with p_T > 25(20) GeV, $|\eta|$ < 2.5, $m_{\ell\ell}$ > 20(50) GeV
- Missing energy from W decay (E_T > 40 GeV)
- 2 jets with $p_T(E_T)$ > 30 GeV and m_{jj}> 500 GeV

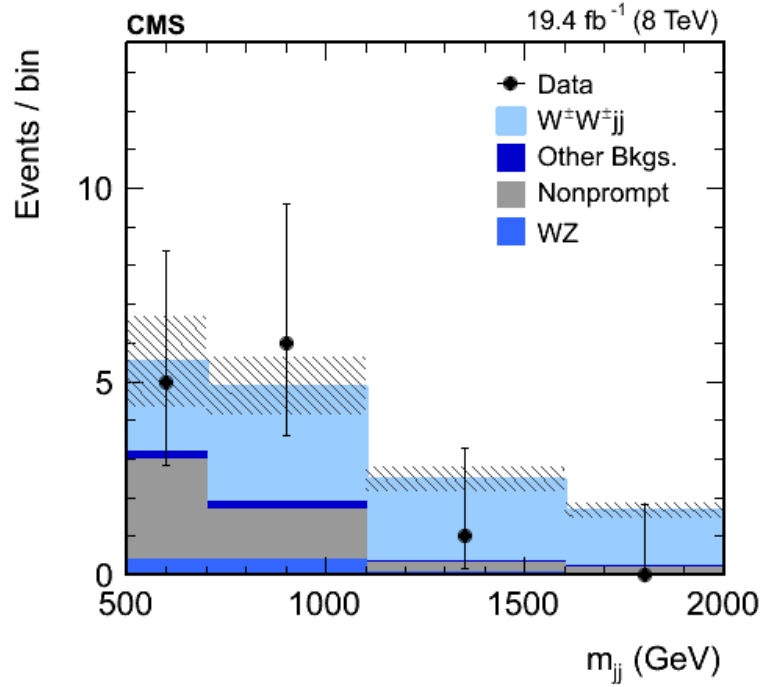
VBS Analysis – EW PRODUCTION (Atlas)

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

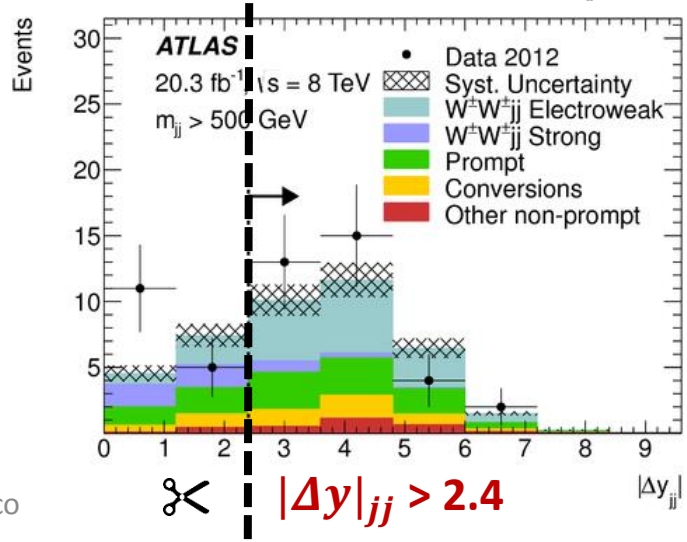
VBS in $W^{\pm}W^{\pm}$ + 2 jets Channel (8 TeV)

QCD + EW





EW



Cross sections

QCD+EW Region:

σ^{fid} = 2.1 ± 0.5 (stat) ± 0.3 (syst) fb (**Atlas**)

(σ_{exp} = 1.52 ± 0.11 fb)

σ^{fid}_{ext} = $4.0^{+2.4}_{-2.0}$ (stat) $^{+1.1}_{-1.0}$ (syst) fb (**CMS**)

(σ_{exp} = 5.8 ± 1.2 fb)

EW Region:

σ^{fid} = 1.3 ± 0.4 (stat) ±0.2 (syst) fb (**Atlas**)

(σ_{exp} = 0.95 ± 0.06 fb)

Anomalous Quartic Gauge Coupling

- SM may considered as a low-energy effective theory of a more complete but unknown theory
- **Extension** of the **SM Lagrangian** by introducing higher-dimension operators:

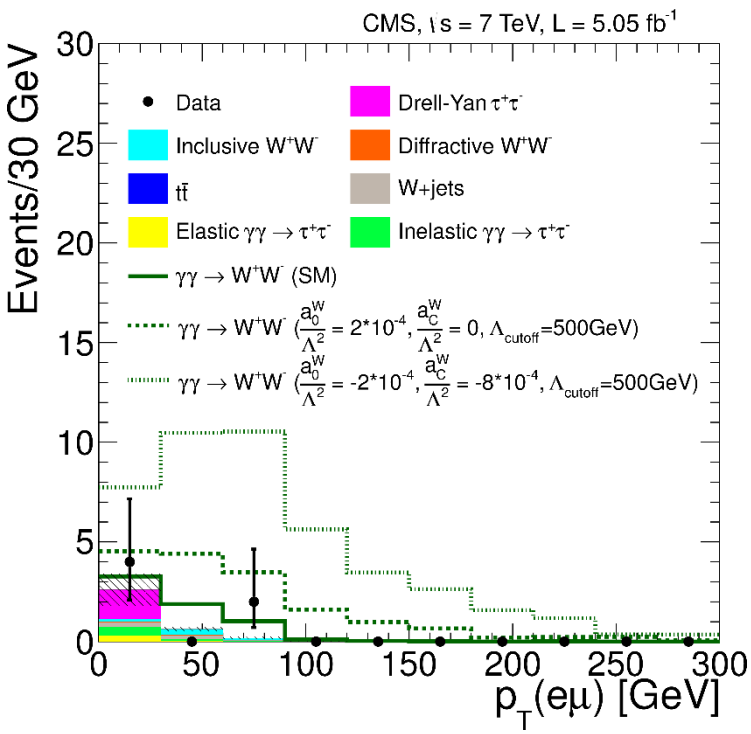
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \boxed{\sum_{\dim d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}}$$

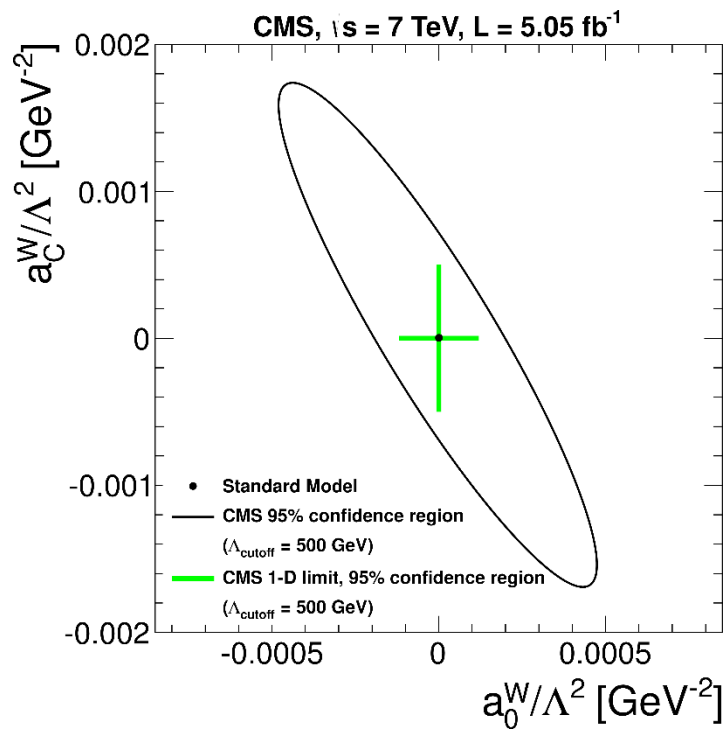
  - Λ is the **energy scale of new physics** and it is large compared with the experimentally accessible energy
  - Operator **coefficients** are **proportional to inverse powers** of mass (Λ)
  - **Dimension 6** operators ($\sim \frac{1}{\Lambda^2}$) may affect **3 boson vertices** too
  - **Dimension 8** operators ($\sim \frac{1}{\Lambda^4}$) modify **4 boson vertices** only
- **Effective field theory** is useful as a methodology for studying possible **new physics** effects from massive particles not directly detectable
- New physics in EW sector modifies gauge boson self-interactions
  - VBS could still be strong and differ from SM predictions

➡ Anomalous **enhancement** of the **cross section** at high energy

$\gamma\gamma$-Production of W^+W^- (7 TeV)

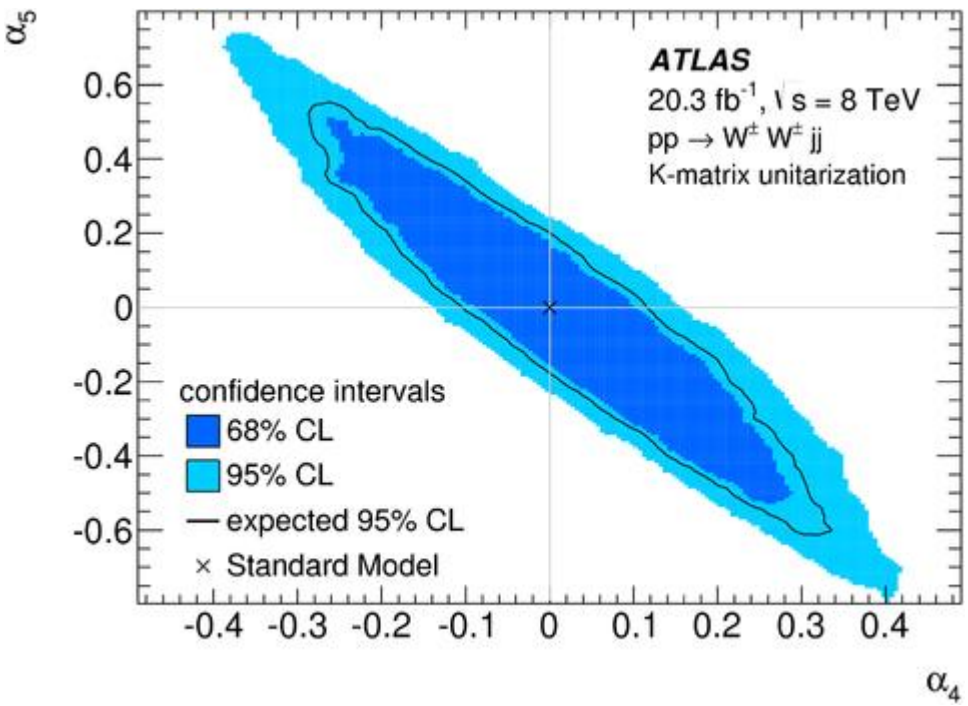
- Channel sensitive to $\boldsymbol{\gamma\gamma WW}$ vertex
- For aQGC study, limit the search region to $p_T(e^{\mp}\mu^{\pm})$ > 100 GeV
  - Cross section limit w.r.t. SM prediction < 1.9 fb at 95% C.L.
  - No deviation from SM TGC assumed

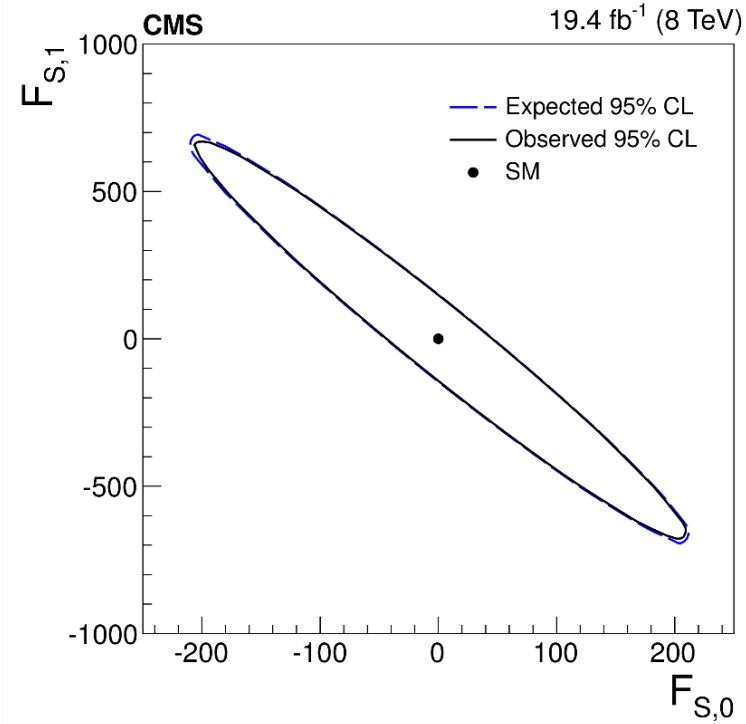




VBS in $W^{\pm}W^{\pm}$ + 2 jets Channel (8 TeV)

- Channel sensitive to $\boldsymbol{WWWW}$ vertex
- aQGC modelling:
  - **Atlas**: limits on EW chiral approach, using α_4 and α_5
  - **CMS**: limits on EFT approach, using $F_{S,0}$ and $F_{S,1}$





scale of new physics: Λ > 500 - 650 GeV

Future Perspectives

VBS Studies at High Luminosity

- **Several final states** investigated by both Collaborations at **14 TeV**
  - $pp \to ZZqq \to 4\ell jj$ (VBS)
  - $pp \to WZqq \to 3\ell\nu jj$ (VBS)
  - $pp \to W^{\pm}W^{\pm}qq \to \ell^{\pm}\ell^{\pm}\nu\nu jj$ (VBS)
  - $pp \to Z\gamma\gamma \to \ell\ell\gamma\gamma$ (QGC)
- **Two** different **scenarios**
  - $\mathcal{L}$ = 300 fb^{-1} (at the end of Run III)
  - $\mathcal{L}$ = 3000 fb^{-1} (HL-LHC)
- Results interpreted in terms of **Effective Lagrangian**, to estimate the sensitivity to new physics

VBS in ZZ + 2 jets Channel (14 TeV)

Standard VBS selection:

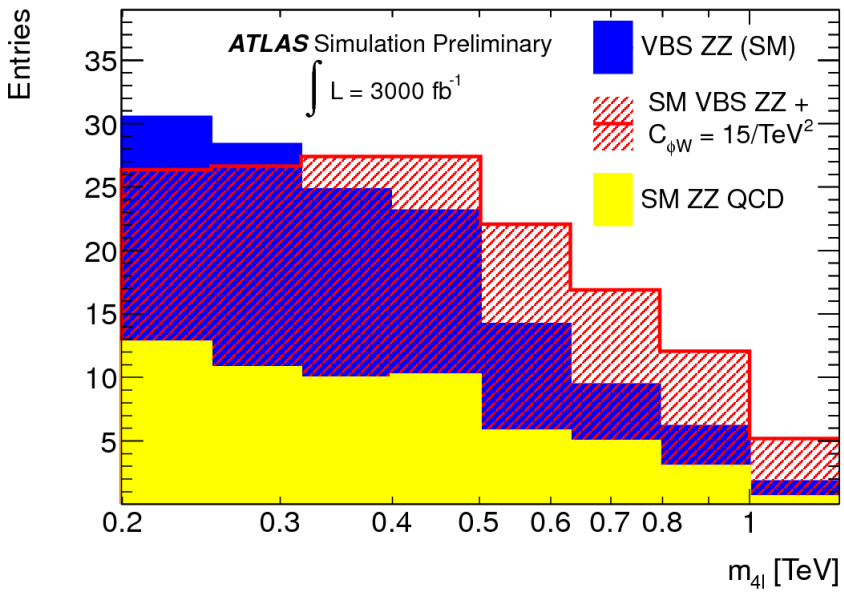
- 4 leptons with p_T > 25 GeV
- 2 jets with p_T > 50 GeV and m_{jj}> 1 TeV

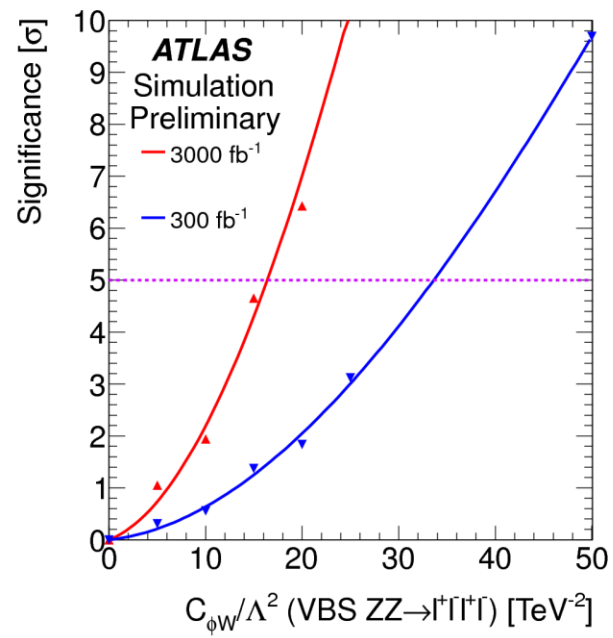
Sensitive to **dimension-6 operator**: $\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} Tr(W^{\mu\nu} W_{\mu\nu}) \phi^\dagger \phi$

Significance of 5σ:

$c_{\phi W}/\Lambda^2 \sim$ 35 TeV^{-2} (300 fb^{-1})

$c_{\phi W}/\Lambda^2 \sim$ 16 TeV^{-2} (3000 fb^{-1})





VBS in WZ + 2 jets Channel (14 TeV)

Standard VBS selection:

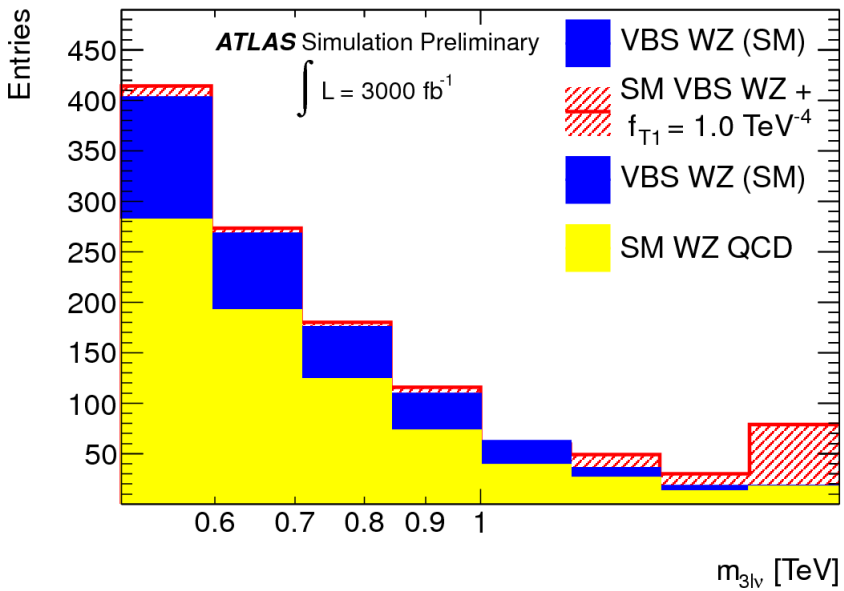
- 3 leptons with p_T > 25 GeV
- 2 jets with p_T > 50 GeV and m_{jj}> 1 TeV

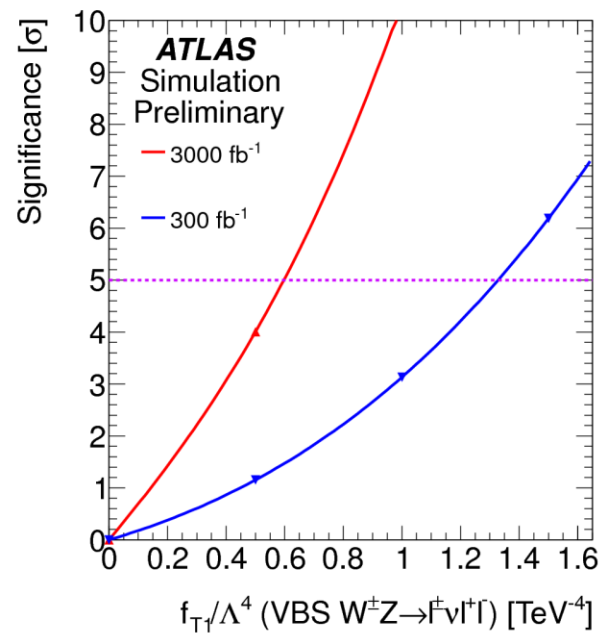
Sensitive to **dimension-8 operator**: $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} Tr(\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}) \times Tr(\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu})$

Significance of 5σ:

$f_{T1}/\Lambda^4 \sim$ 1.3 TeV^{-4} (300 fb^{-1})

$f_{T1}/\Lambda^4 \sim$ 0.6 TeV^{-4} (3000 fb^{-1})





VBS in WZ + 2 jets Channel (14 TeV)

Standard VBS selection:

- 3 leptons with p_T > 20 GeV
- 2 jets with p_T > 50 GeV, m_{jj}> 600 GeV and $\Delta\eta_{jj}$ > 4

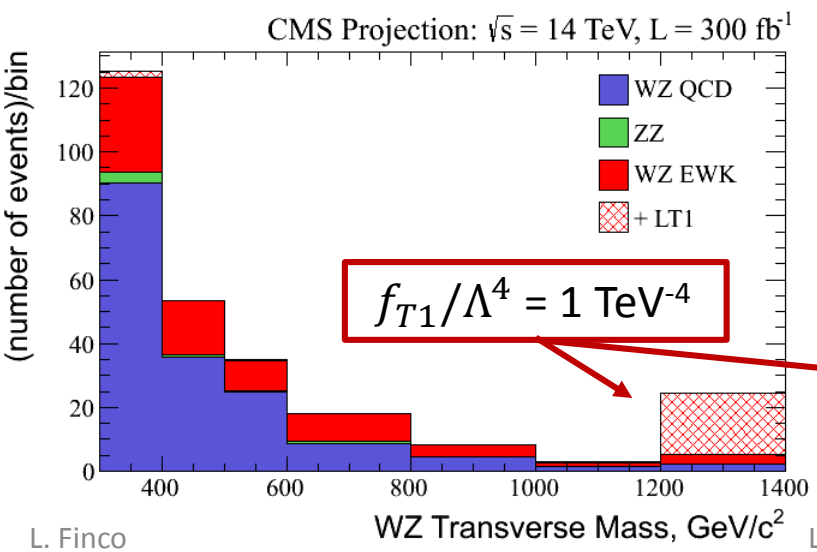
Sensitive to **dimension-8 operator**: $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} Tr(\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}) \times Tr(\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu})$

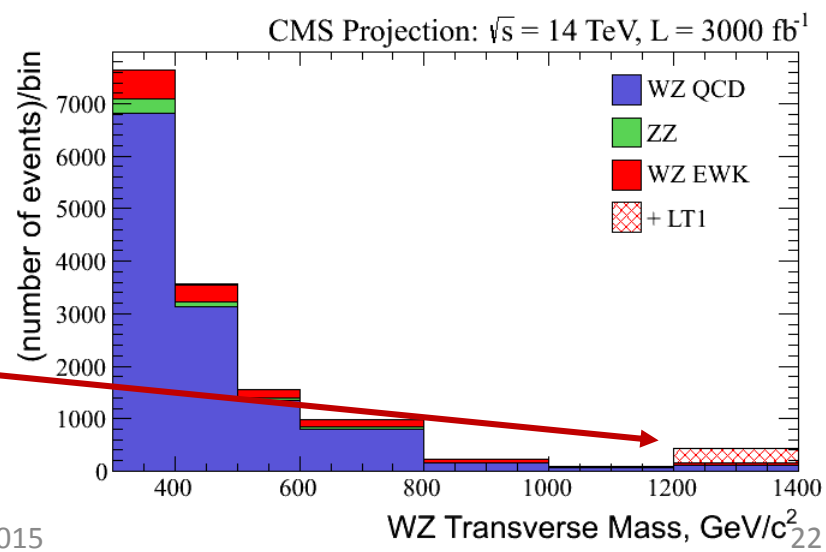
SM EW scattering discovery: 75 fb^{-1} for 3σ and 185 fb^{-1} for 5σ (m_{jj}> 1.2 TeV)

Significance of 3σ(5σ):

$f_{T1}/\Lambda^4 \sim$ 0.8(1.0) TeV^{-4} (300 fb^{-1})

$f_{T1}/\Lambda^4 \sim$ 0.45(0.55) TeV^{-4} (3000 fb^{-1})





VBS in $W^{\pm}W^{\pm}$ + 2 jets Channel (14 TeV)

Standard VBS selection:

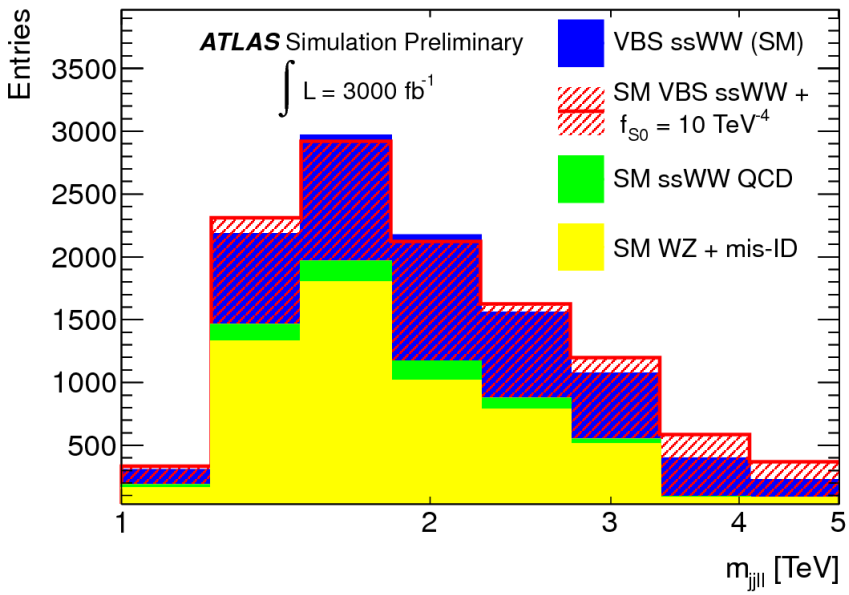
- 2 leptons with p_T > 25 GeV
- 2 jets with p_T > 50 GeV and m_{jj}> 1 TeV

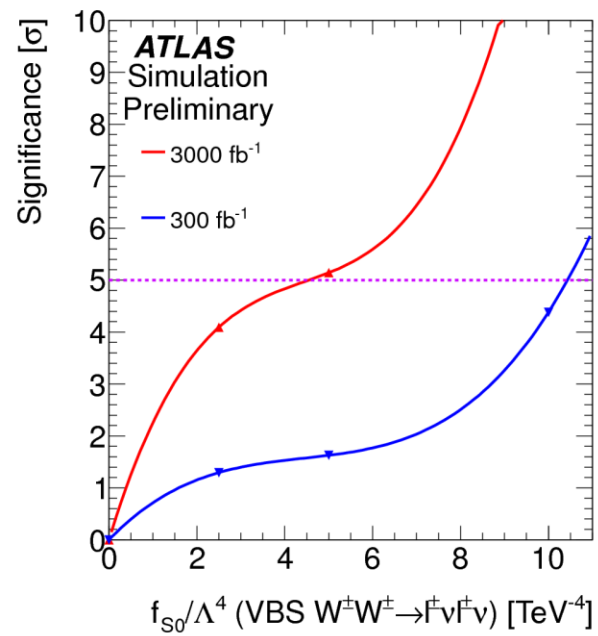
Sensitive to **dimension-8 operator**: $\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4}\left[\left(D_\mu\phi\right)^\dagger D_\nu\phi\right] \times \left[\left(D^\mu\phi\right)^\dagger D^\nu\phi\right]$

Significance of 5σ:

$f_{S0}/\Lambda^4 \sim$ 10 TeV^{-4} (300 fb^{-1})

$f_{S0}/\Lambda^4 \sim$ 4.5 TeV^{-4} (3000 fb^{-1})





Conclusions

- VBS provides an **important test** of the **EW theory** and of the dynamics of EW symmetry breaking

  ➡ Still need to check if the 125 GeV **Higgs unitarizes** VBS processes **completely** or new physics will appear at high mass
- **7** and **8 TeV analyses** started to **investigate multi-boson** final states and **exclusion limits** on possible SM deviations are set
- **First evidence** for a **VBS** dominated process at LHC in the $W^{\pm}W^{\pm}jj$ channel
- **Studies at 13/14 TeV** will increase the understanding of VBS and QGC

Waiting for new data…

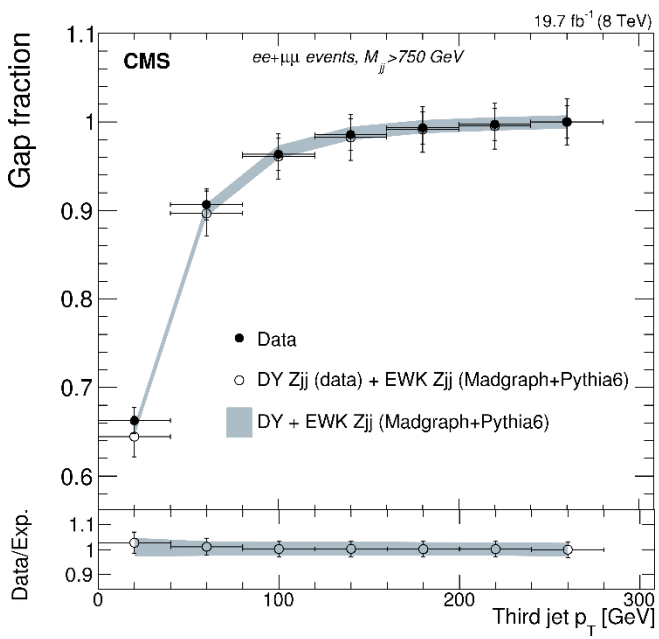
Backup

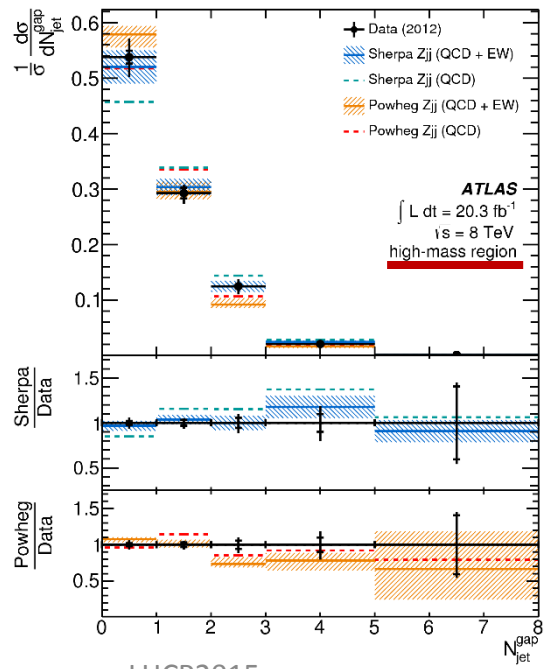
Z + F/B jets (8 TeV)

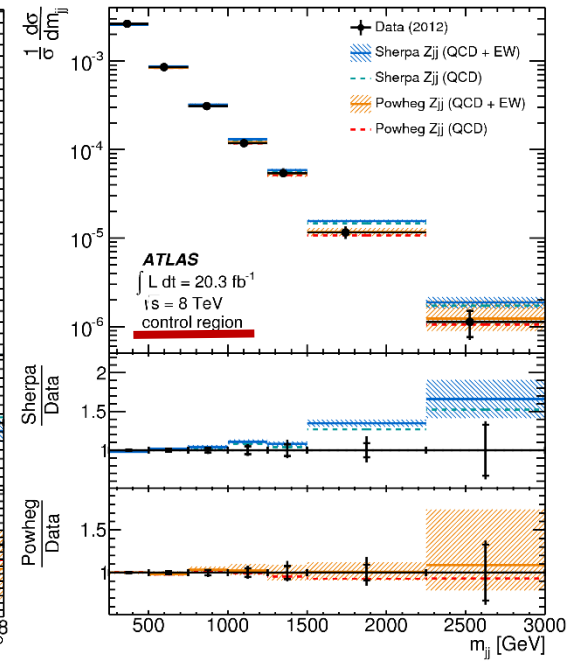
- Study of the **hadronic activity** in the rapidity interval between the jets

➡ **Rapidity gap** due to the exchange of colourless particle between the 2 initial quarks

- Possibility of **vetoing jets** in the central region (**Atlas**)
- Study of distributions related to the **3rd jet** (**CMS**)
- **Several phase space regions** with different EW and QCD Zjj contributions (**Atlas**)
- **Differential distributions** as a function of many observables sensitive to EW/QCD







VBS in $Z\gamma\gamma$ Channel (14 TeV)

Selection:

- 2 leptons with p_T > 25 GeV (one lepton with p_T > 160 GeV)
- 2 photons with p_T > 25 GeV (one photon with p_T > 160 GeV)
- leptons and photons well separated

Sensitive to **dimension-8 operator**: $\mathcal{L}_{T,8} = \frac{f_{T,8}}{\Lambda^4} B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$

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