Probing Electroweak Symmetry Breaking with Vector Boson Scattering

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Experiment-theory HEP seminar – November 13th 2019

Outline

- Introduction
- Challenges
- Experimental Results
- New Physics
- Conclusion

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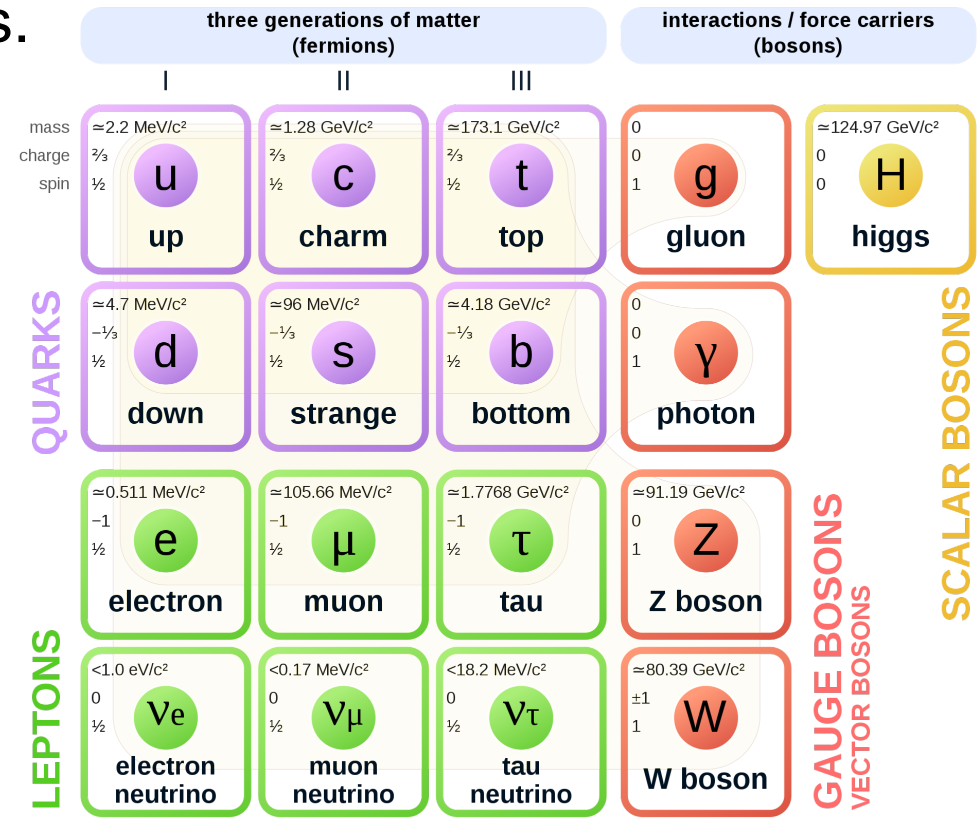
The Standard Model

- The SM is the model that describes all particles and their interactions.



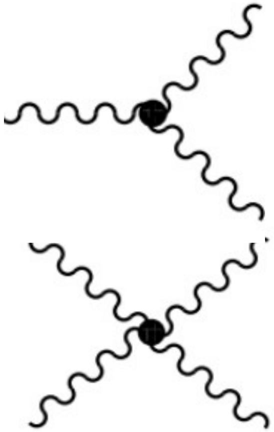
- There are 3 interactions:
  - Electromagnetism
  - Weak
  - Strong
  - Described by symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$

- The matter consists of 6 quarks and 6 leptons

- The last particle observed is the Higgs boson, consequence of the Electroweak Symmetry breaking (EWSB) mechanism. Started to be studied (mH, coupling, ...)

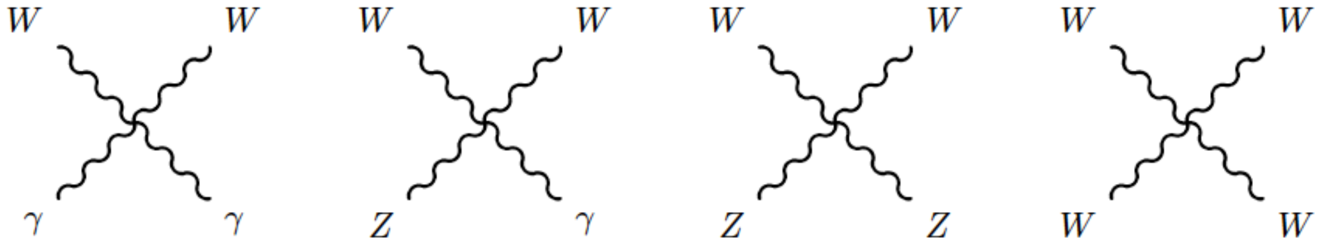
Electroweak theory

- Trilinear and Quartic Gauge boson couplings (TGC, QGC) are precisely determined by $SU(2)_L \times U(1)_Y$ gauge symmetry.
  - Neutral coupling forbidden.
  - TGC:
    - VBF and VV production.
  - QGC:
    - VBS and VVV production.
    - Allowed SM QGC vertex:



Studied at LEP, Tevatron and LHC.

Start to be accessible in LHC run2!

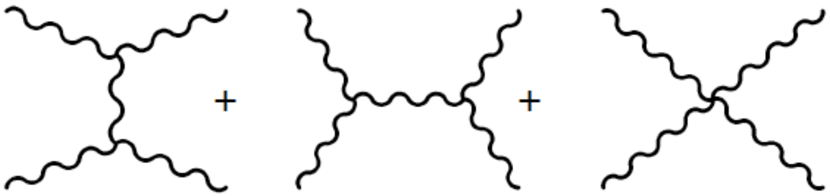


- Multiboson allow stringent test of EW theory, and model independent way to look for new physics at TeV scale!

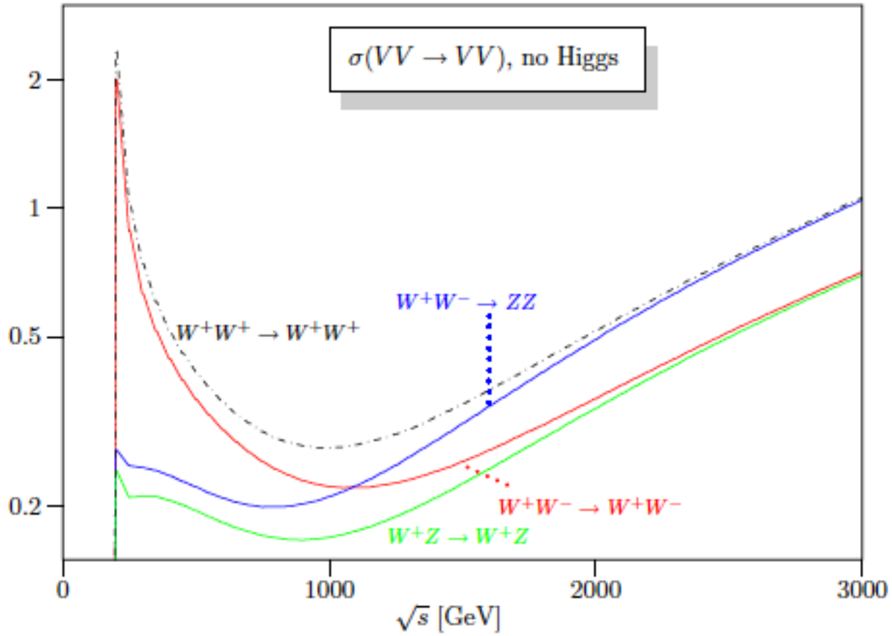
Why studying specifically VBS?

Arxiv:0806.4145

Let's consider the scattering of longitudinally polarized weak bosons: W^+W^-



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

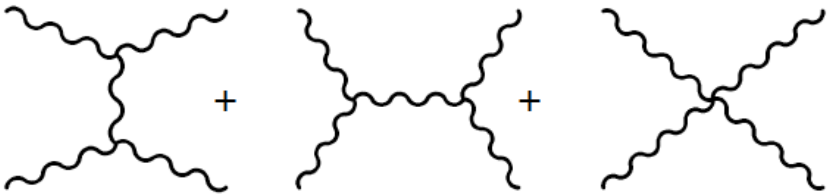


Without Higgs, the amplitude violate unitarity at high energy!

$V_L V_L$ scattering

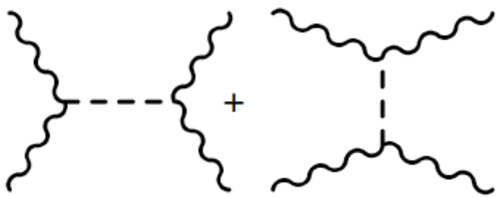
Arxiv:0806.4145

Let's consider the scattering of longitudinally polarized weak bosons: W^+W^-



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

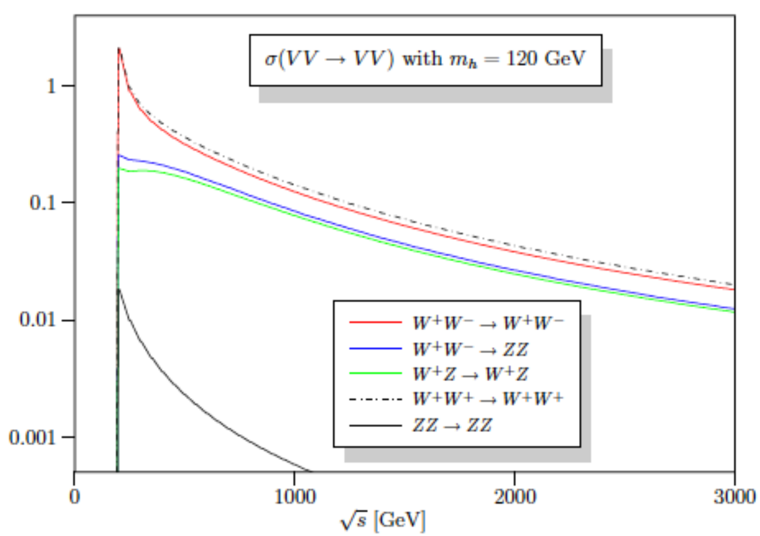
If there is a Higgs, destructive interference between Higgs and gauge boson scattering



$$\mathcal{M}^{Higgs} = \frac{g^2}{4m_W^2}$$

$$\Rightarrow \mathcal{M}^{tot} = \mathcal{O}((\frac{E}{m_W})^0)$$

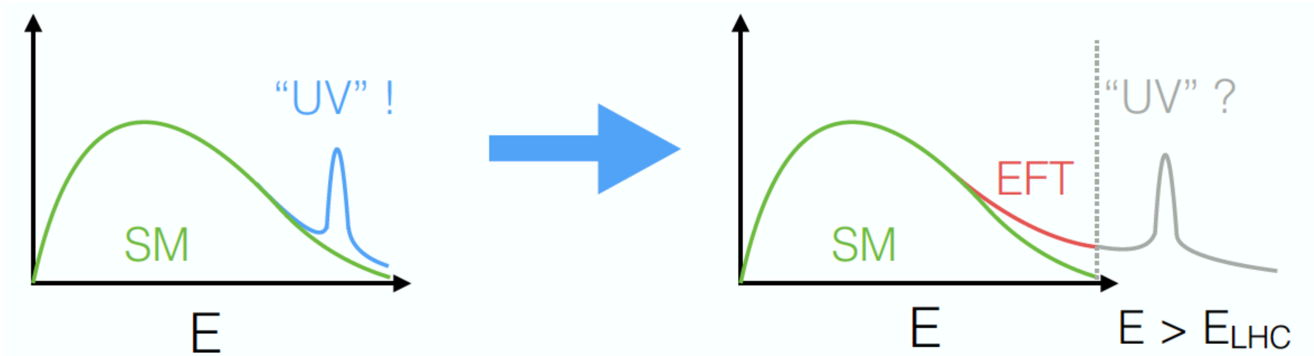
in the limit $s >> m_H^2, m_W^2$

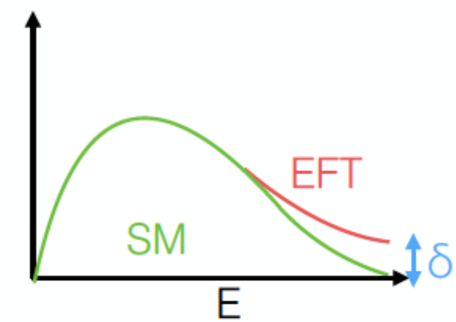


If the HVV coupling is not precisely given by its SM value: $2m_V^2/v$ then the unitarity is still violated, unless:

- **There are several (light) scalar resonances** where the sum of the coupling of all of them satisfy the SM value.
- **There are other new phenoma in VV scattering**.

New physics searches





- Use direct searches, look for resonance on falling background.
  - Model dependent approach..
  - If NP is out of the LHC reach, could we still observe it?

- Extend SM with Dim6 and Dim8 operators in Effective Field Theory (EFT):

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{(8)}$$

  - EFT model independent allow to recover deviation in distributions tails!
  - Provide limits on Dim8 operators with VBS.

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

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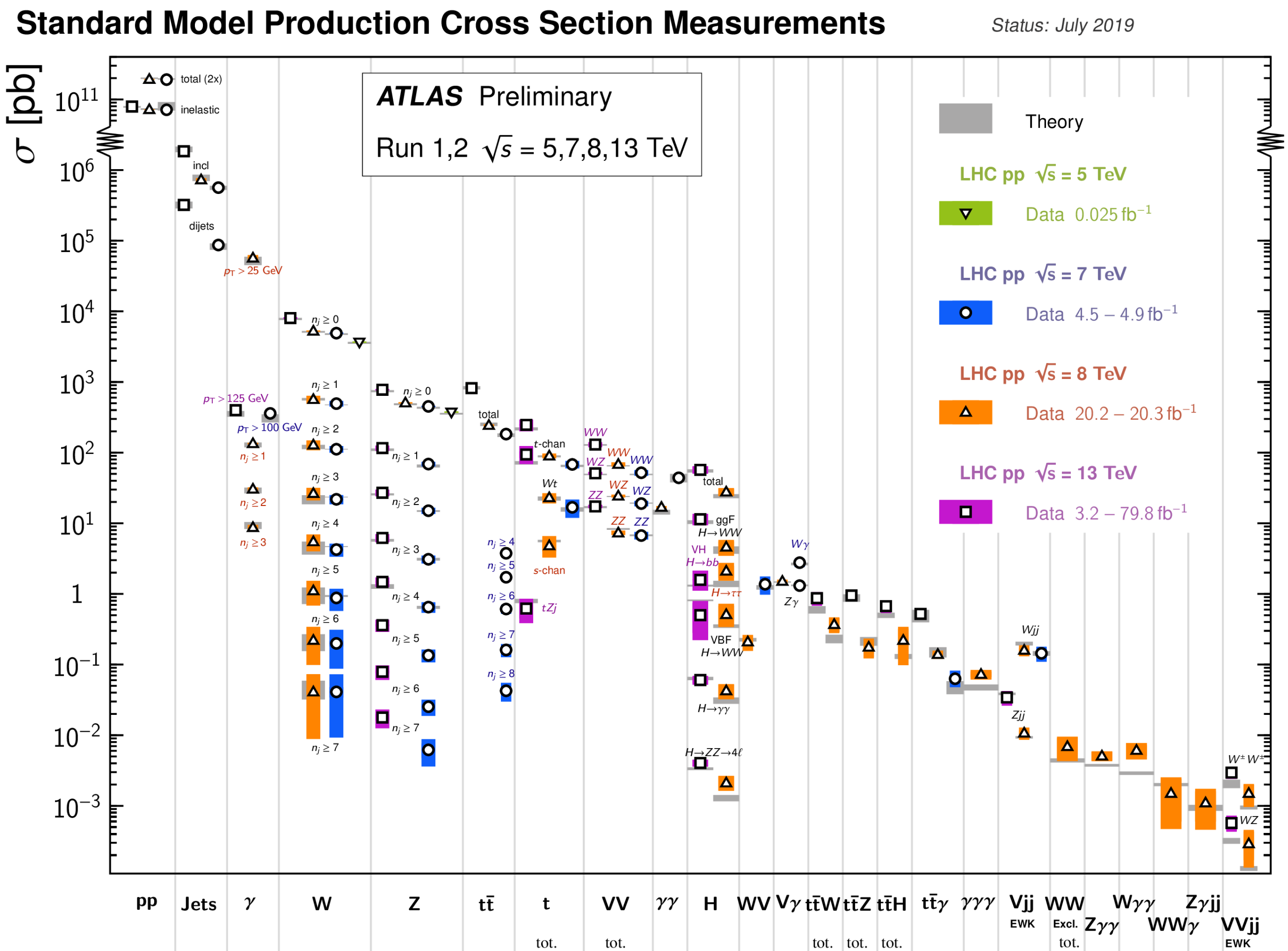
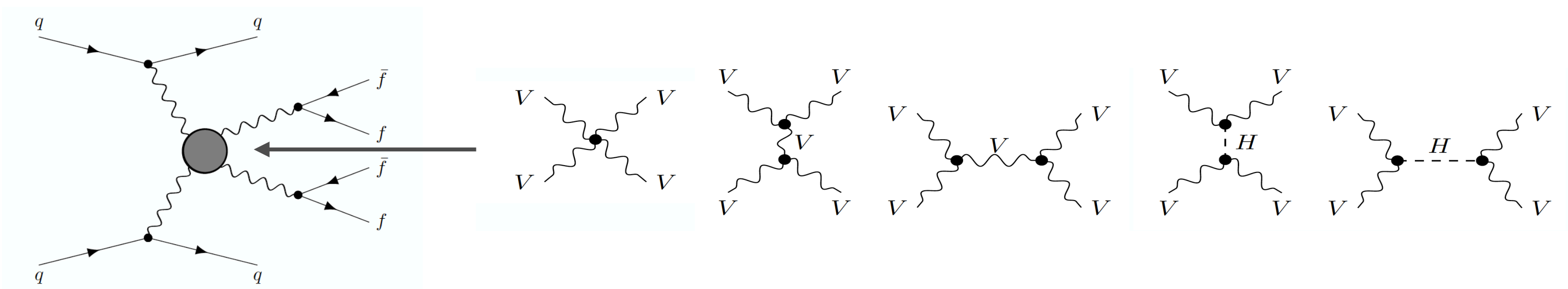


Classifying the VBS signal

Arxiv: 1610.08420

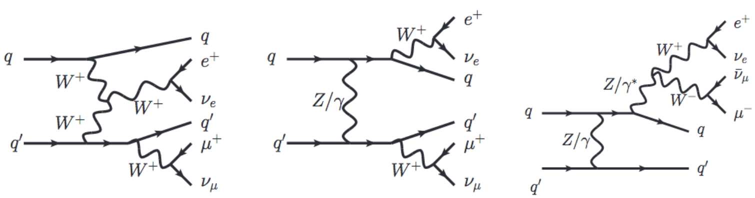
- VBS contains: quartic diagram, t-channel (H,V), s-channel (H,V)

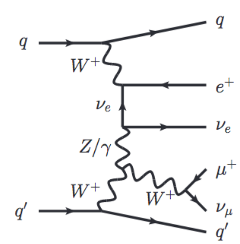


VBS

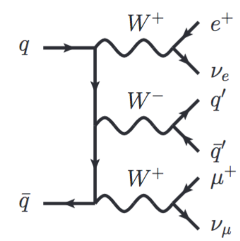
  - Alone do not form a gauge invariant ensemble. Need extra diagrams:

Resonant dibosons





Non-resonant



Tribosons

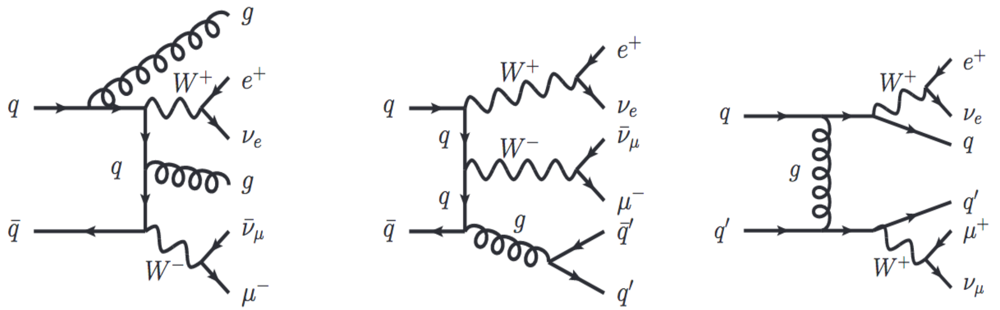
  - Possible to separate contributions using kinematic cuts.

- Together referred to Electroweak production, at LO order α^6_{EW}.

Main backgrounds to VBS

Arxiv: 1610.08420

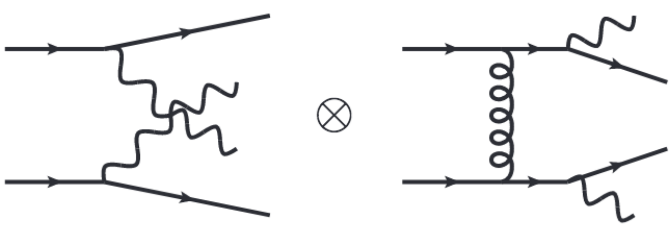
- Main backgrounds irreducible and order $\alpha^2_s\alpha^4_{EW}$



- Mostly contains gluons (emitted or exchanged).
  - Usually less energetic than electroweak diagrams

→They are referred to as QCD-induced backgrounds.

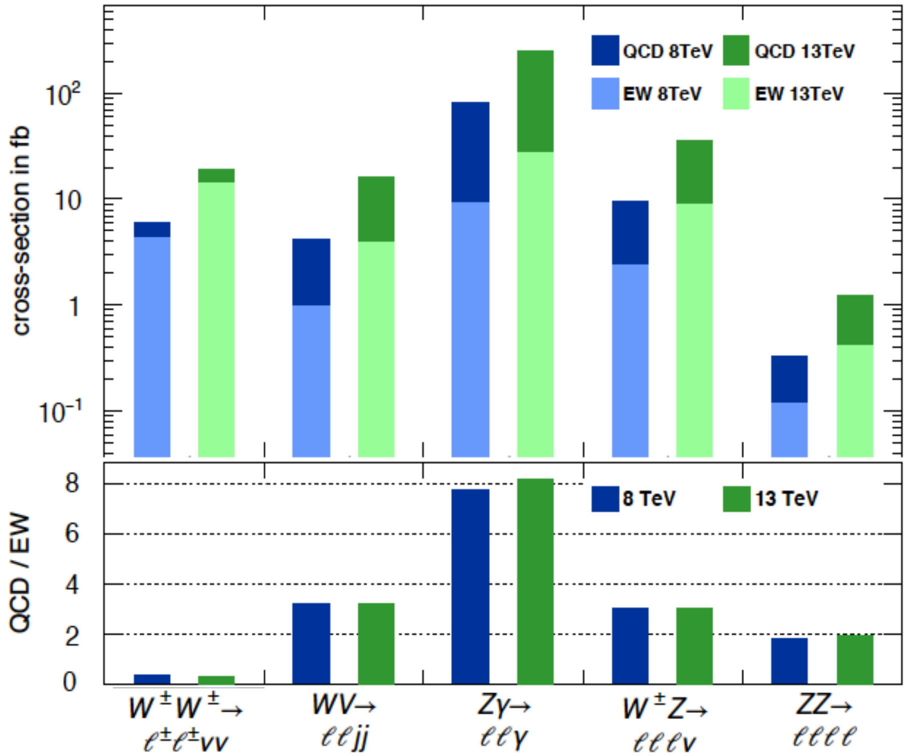
- Constructive interference between Electroweak signal and QCD-induced background order $\alpha_s\alpha^5_{EW}$



- Note that signal and backgrounds have all been computed to NLO QCD in the channel analyzed.

Cross sections @ LHC (8–13TeV)

CERN-THESIS-2014-105



LO Cross sections obtained with Sherpa 1.4

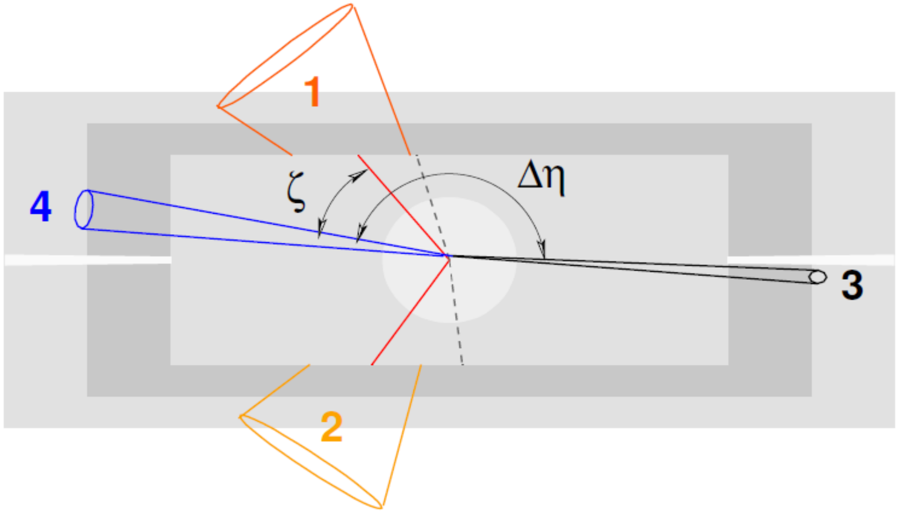
Cuts in "VBS-like" fiducial volume:

- Leptons: p_T>15 GeV, |η|<2.5
- Jets (N) ≥ 2, p_T>30 GeV, |η|<4.5 anti-k_T R=0.4
- m_{jj}>500 GeV
- If Z → ℓℓ in final state: Z window of 25GeV
- If photons in final state: pT > 15GeV, ΔR(γ,ℓ) > 0.1, ΔR(γ,j) > 0.1

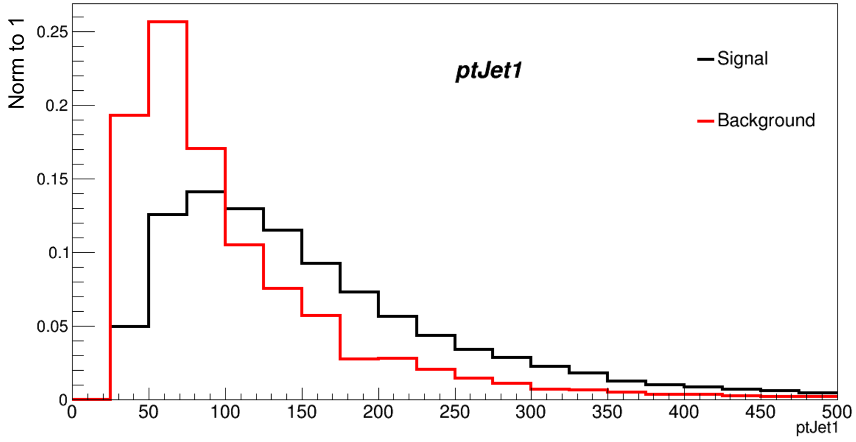
- Low signal cross section (o(fb)), vs high irreducible background!

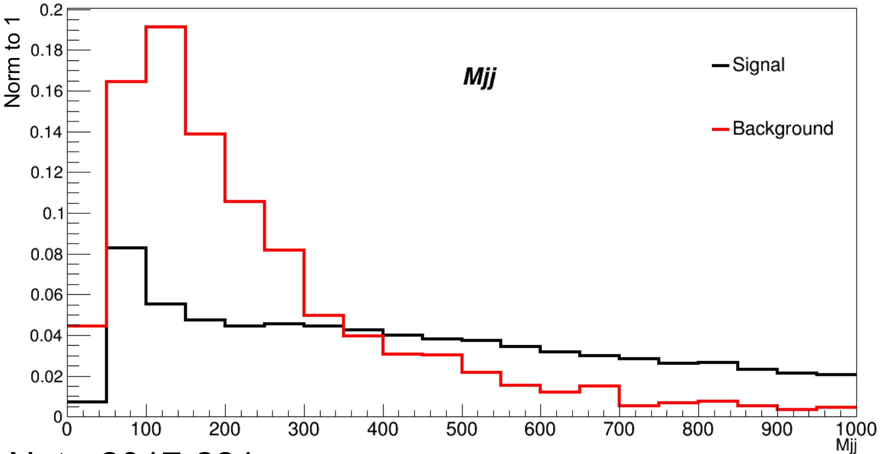
VBS topology

- Events with a very peculiar topology:
  - 2 jets (3,4) with:
    - Large p_T, ΔY, m_{jj}.
  - No or little color activity in between (~2 jets in the event).
  - Boson(s) decay products (1,2) are emitted in the di-jet rapidity gap.



Zɣjj events





CERN-STUDENTS-Note-2017-221

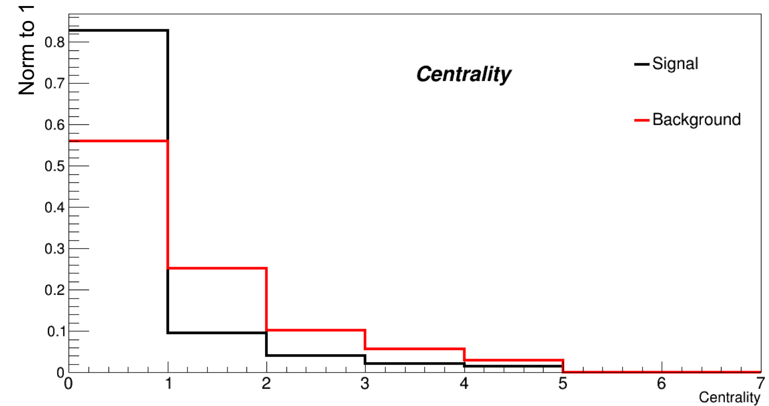
Tag VBS events

- Take advantage of this topology to tag the events.
- Use dedicated variables
  - Centrality:

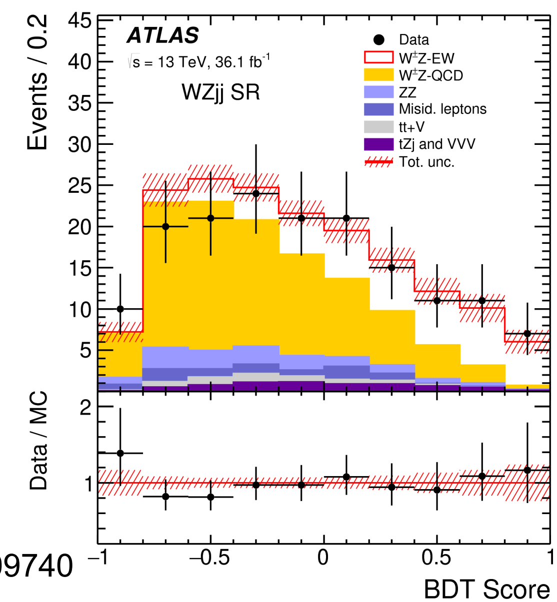
$$\zeta(\ell\ell\gamma) = \left|\frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{(y_{j_1} - y_{j_2})}\right|$$

- Most Higgs and VBS measurements employ multivariate approach.

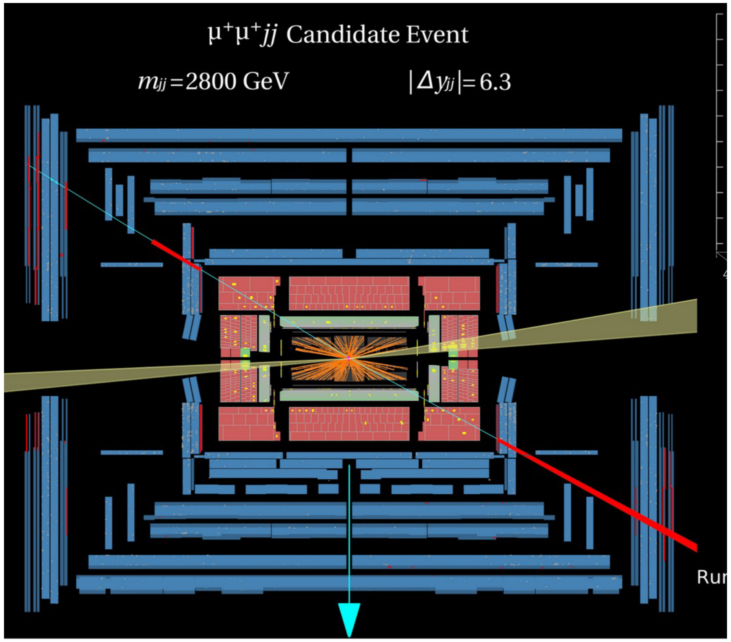
CERN-STUDENTS-Note-2017-221



Zγjj events



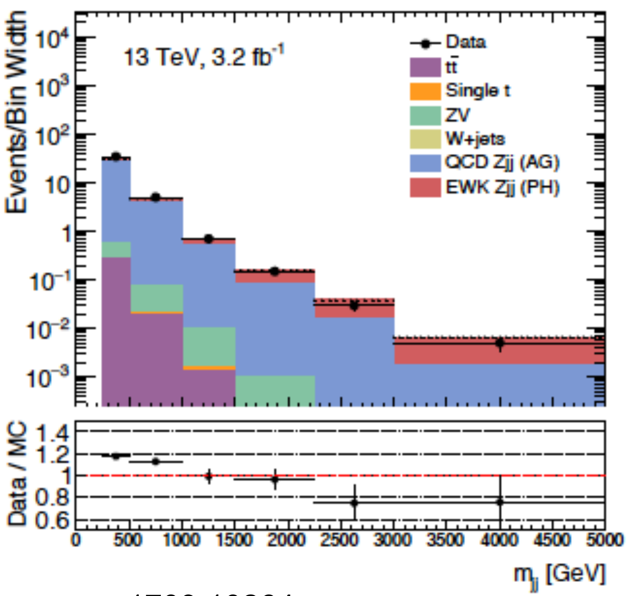
1812.09740



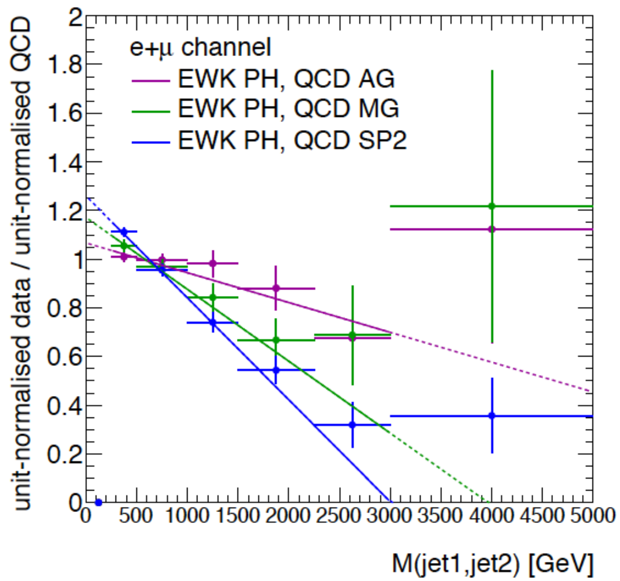
Mis-modelling in the VBF region

VBS analyses relies on proper modelling of:

- Jets in forward region.
- High m_{jj}, region (signal and backgrounds).

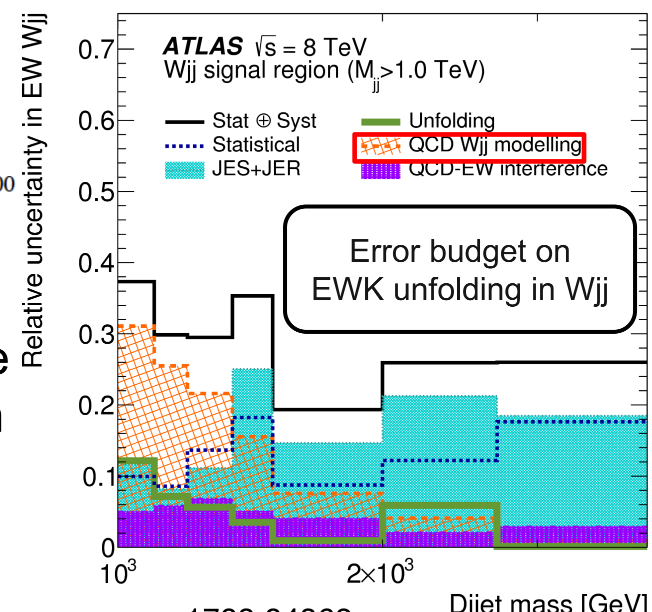


1709.10264



Known to misbehave, strategy consist most of the time to use a control region to constrain the shape of m_{jj}, and re-apply this correction to the search region.

- Nice opportunity to test the modelling of several MC generators!
- Only possible in VBF W/Z finale state because of the statistics available!



1703.04362

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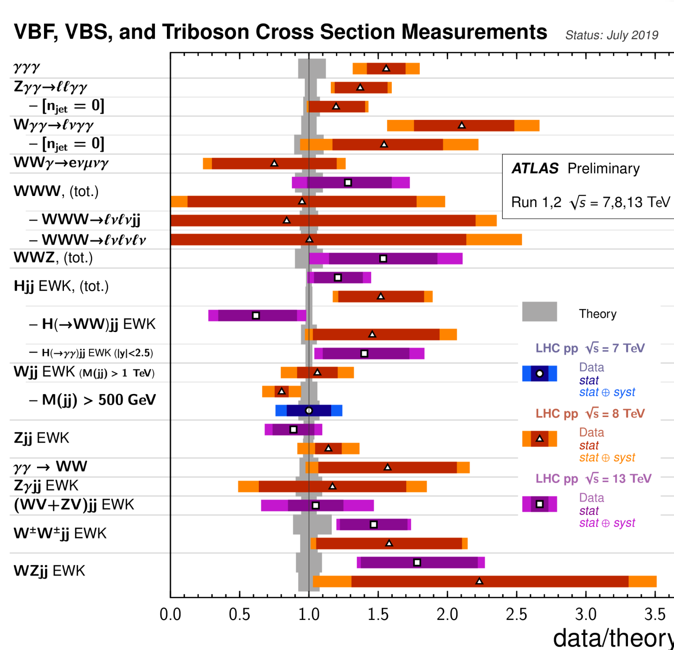
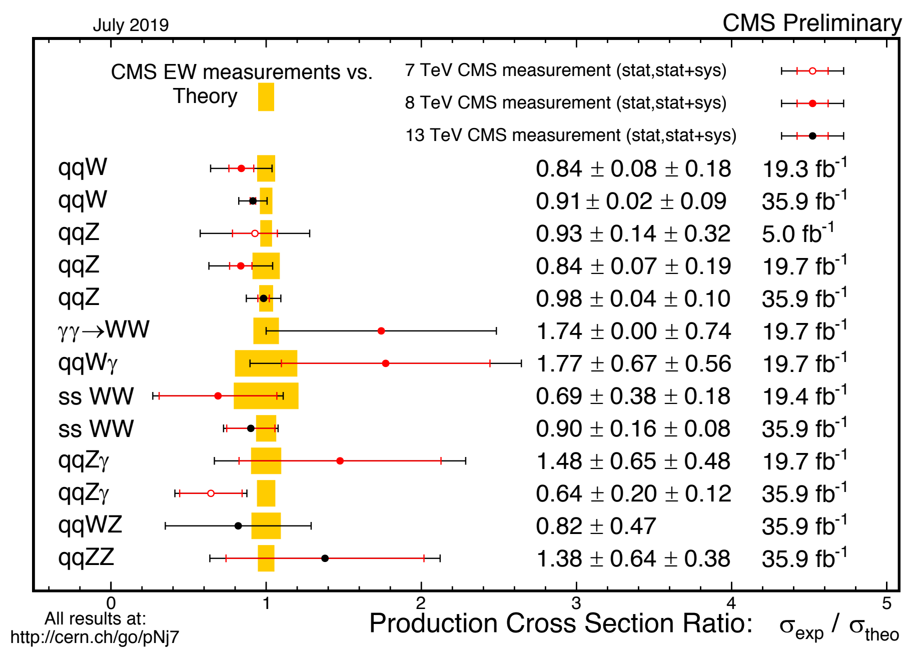




Summary of the main Run2 results

Best EW/QCD

>5σ observation

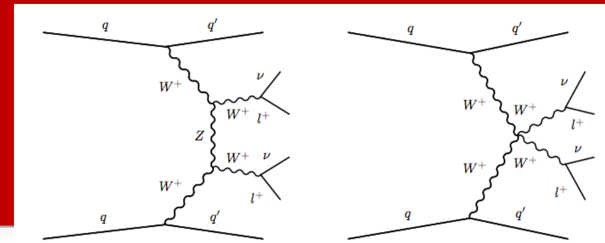
Channel	CMS	ATLAS
$W^{\pm}W^{\pm}jj$	1709.05822	1905.07714
$W^{\pm}Zjj$	1901.04060	1812.09740
ZZjj	1708.02812	ATLAS-CONF-2019-033
VVjj	1907.08354	1905.07714
$Z\gamma jj$	CMS-PAS-SMP-18-007	1910.09503

High purity

Best aQGC limits

High stat (EW and QCD) in leptonic channel

VBS $W^{\pm}W^{\pm}jj \rightarrow \ell\nu\ell\nu jj$



ATLAS: 1906.03203
CMS: 1709.05822

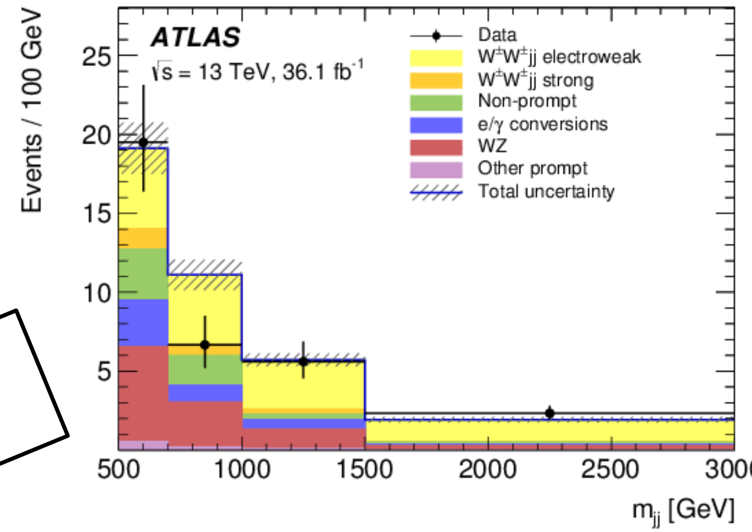
- **Selection:**
  - 2 same sign ℓ (e,μ).
  - 2 high p_T jets, with high m_{jj}.
  - Using 36 fb^{-1} of data (2015-2016).
- Fit different bin of m_{jj} in ATLAS, fit in 2D $m_{\ell\ell}$ vs m_{jj} in CMS.
- **Sensitivity**:
  ATLAS: 6.5 (4.6) σ,
  CMS: 5.5 (5.7) σ
- Measure cross section in fiducial space for EWK signal.

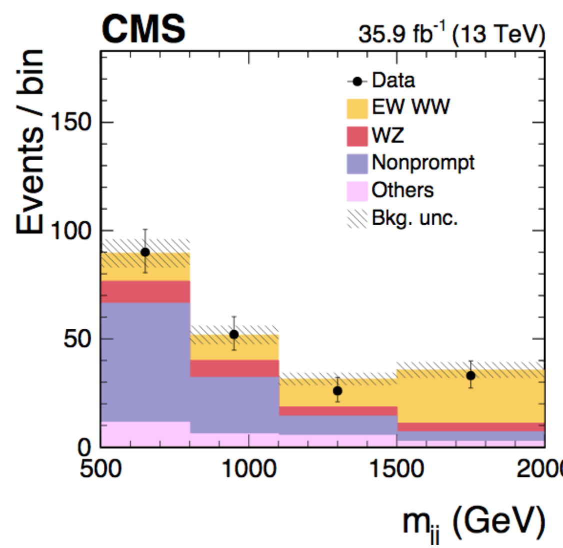
CMS: $\sigma^{fid}_{WW-EWK} = 3.83 \pm 0.77 \text{fb}$

Madgraph: $\sigma^{fid-LO}_{WW-EWK} = 4.25 \pm 0.27 \text{ fb}$

- CMS set limit on new physics.

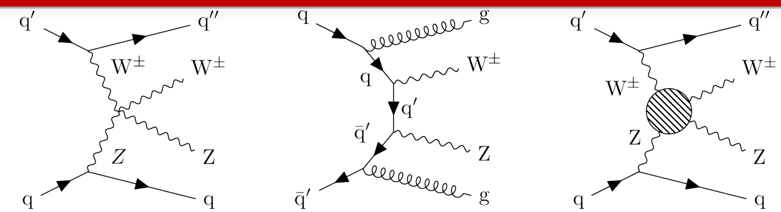
Observation for ATLAS and CMS!





VBS WZjj→ℓℓℓνjj

ATLAS: 1812.09740
CMS: 1901.04060



- **Selection:**
  - 3ℓ (e,μ) compatible with a Z and a W
  - 2 high p_T jets, with high m_{jj}.
  - Using 36 fb^{-1} of data (2015-2016).
- Use BDT approach in ATLAS, cut based approach for CMS fitting m_{jj}.
- **Sensitivity**:
  ATLAS: 5.3 (3.2) σ
  CMS: 2.2 (2.5) σ

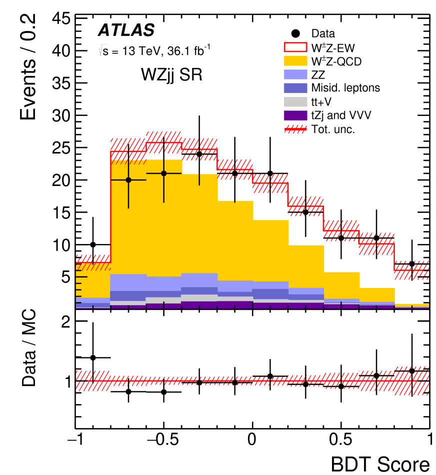
Observation for ATLAS!

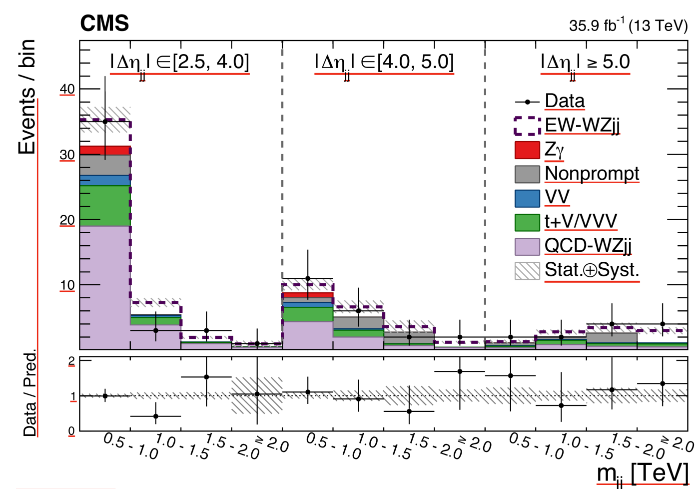
- Measure cross section in fiducial space for both EWK and QCD+EWK.

ATLAS: $\sigma^{fid}_{WZ-EWK} = 0.57^{+0.16}_{-0.14}\text{fb}$

Sherpa: $\sigma^{fid-LO}_{WZ-EWK} = 0.32 \pm 0.03(scale)\text{fb}$

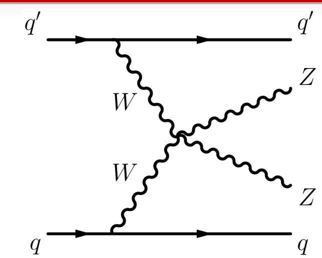
- CMS set limits on aQGC.





VBS ZZjj→ℓℓℓℓjj

ATLAS: ATLAS-CONF-2019-033
CMS: 1708.02812



- **Selection:**
  - 4ℓ (e,μ) compatible with 2 Z.
  - 2 high p_T jets, with high m_{jj}.
  - Using 36 fb^{-1} of data for CMS (2016), full run2 ATLAS!
    - ATLAS also measure signal with ℓℓvvjj.
- Use BDT approach in ATLAS and CMS.
- **Sensitivity**:
  ATLAS: 5.5 (3.9) σ,
  CMS: 2.7 (1.6) σ

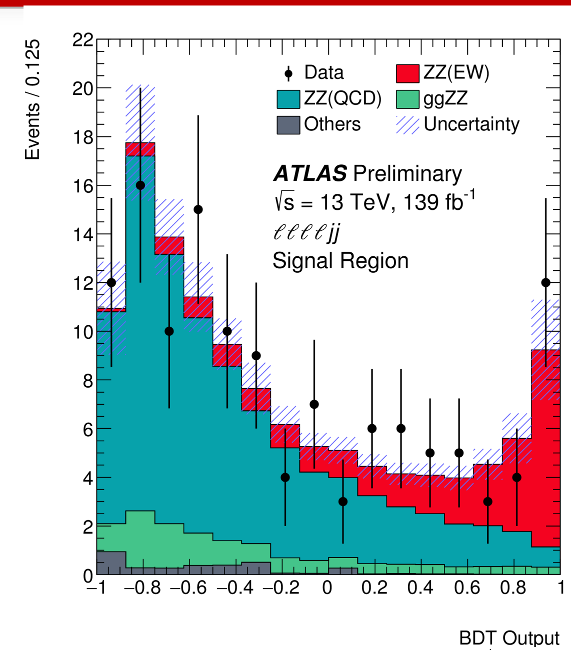
Observation for ATLAS!

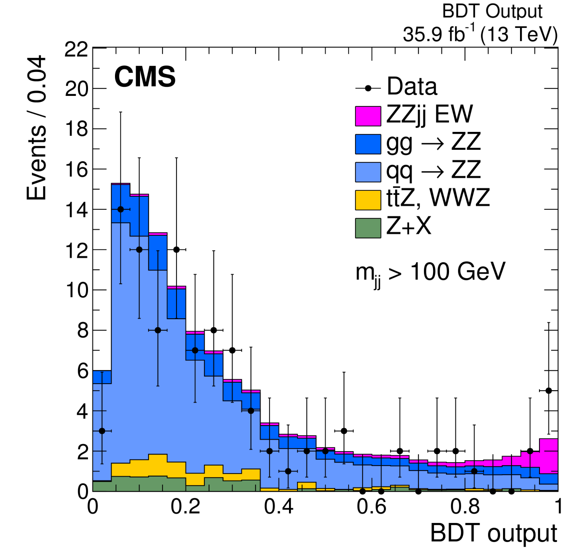
- Measure cross section in fiducial space for EWK

ATLAS: $\sigma^{fid}_{ZZ-EWK} = 0.82 \pm 0.21$ fb

Madgraph: $\sigma^{fid-LO}_{ZZ-EWK} = 0.61 \pm 0.03(scale)$fb

- CMS set limits on aQGCs.

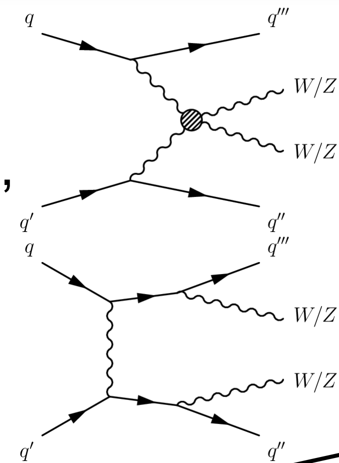


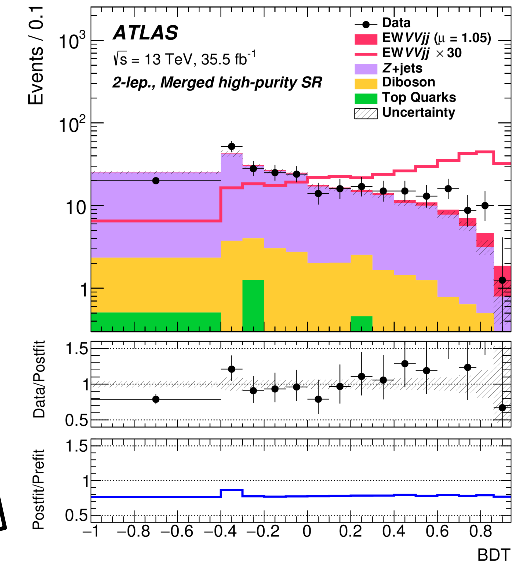


VBS VVjj→ℓνJjj or ℓℓJjj

ATLAS: 1905.07714
CMS: 1905.07445

- **Selection::**
  - 1 or 2 ℓ compatible with W or Z, 1 large R^{jet} compatible with W or Z, 2 high p_T jets with high m_{jj} .
    - Using 36 fb^{-1} of data (2015-2016).



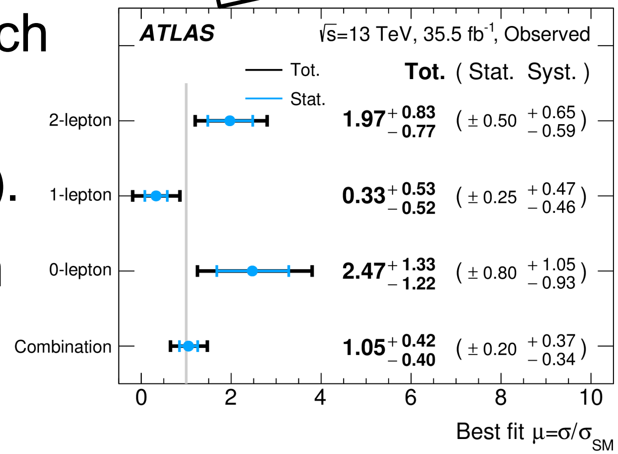


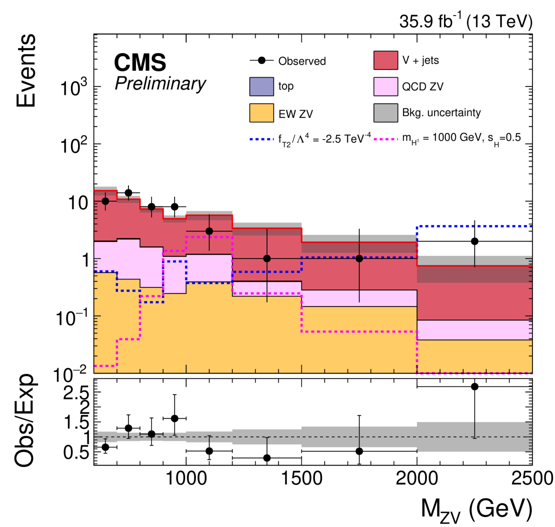
- CMS: Analysis not sensitive to SM coupling.
  - Set limit on aQGCs.

Some of the best aQGC limits!

- ATLAS: Uses BDT approach to extract SM signal.
  - Sensitivity: 2.7σ (2.5σ).
  - Measure cross section in fiducial space

$$\sigma^{fid}_{VV-EWK} = 45 \pm 17 \text{ fb}$$

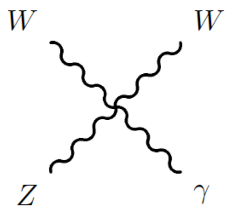


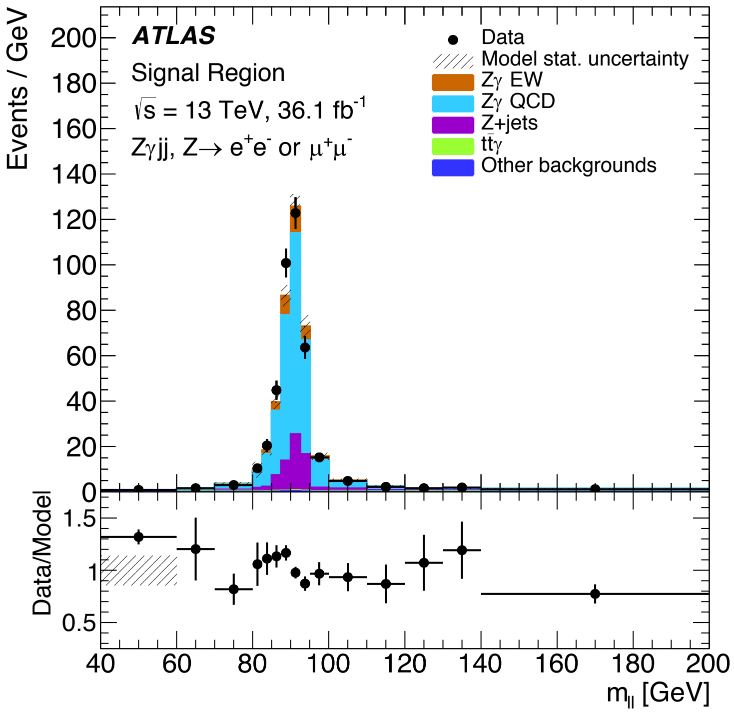


VBS Zɣjj→ℓℓɣjj

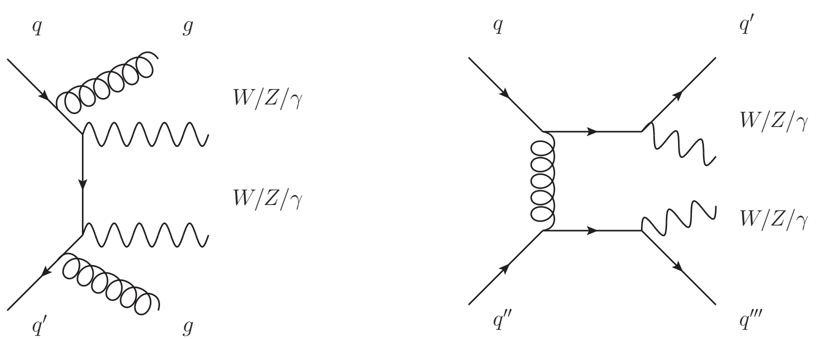
ATLAS: 1910.09503
CMS:CMS-PAS-SMP-18-007

- Zɣ sensitive to SM QGC vertex: WWZɣ.





- Large signal expected!
- Very large QCD background in this final state.

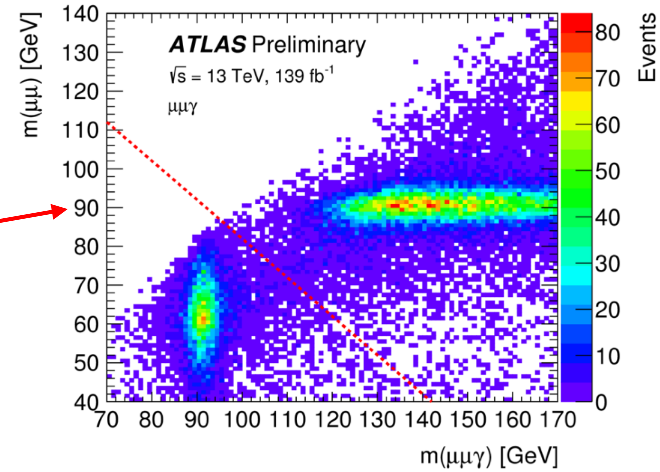


- High stat for signal and QCD, interesting to study modelling in VBS phase space.
- Analysis by both ATLAS and CMS with 36.1 fb-1 of data.
  - Will mostly develop the ATLAS analysis, but give point of comparisons with the CMS one.

VBS Zɣjj→ℓℓɣjj selection

	$\ell^+\ell^-\gamma jj$ preselection
Lepton	$p_T^\ell > 20$ GeV $\lvert\eta_\ell\rvert < 2.47(2.5)$ for $e(\mu)$ remove e if $\Delta R(e,\mu) < 0.1$ $N_\ell = 2$
Boson	$m_{\ell^+\ell^-} > 40$ GeV $m_{\ell^+\ell^-} + m_{\ell^+\ell^-\gamma} > 182$ GeV
Photon	$E_T^\gamma > 15$ GeV $\lvert\eta_\gamma\rvert < 2.37$ (excl. $1.37 < \lvert\eta_\gamma\rvert < 1.52$) remove γ if $\Delta R(\ell,\gamma) < 0.4$ $N_\gamma \geq 1$
b-jet	$p_T^{\text{jet}} > 25$ GeV , $\lvert\eta_{\text{jet}}\rvert < 2.5$
Jet	$p_T^{\text{jet}} > 50$ GeV , $\lvert\eta_{\text{jet}}\rvert < 4.5$ $N_{\text{Jets}} \geq 2$ remove jets if $\Delta R(\ell,\text{jet}) < 0.4$ OR $\Delta R(\gamma,\text{jet}) < 0.4$ $\lvert\Delta\eta_{jj}\rvert > 1.0$ $m_{jj} > 150$ GeV
b-CR	$\ell^+\ell^-\gamma jj$ preselection $\zeta(\ell\ell\gamma) < 5$ $\quad \zeta(\ell\ell\gamma) = \left\lvert\frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{(y_{j_1} - y_{j_2})}\right\rvert$ Nb−jet>0
Signal Region	$\ell^+\ell^-\gamma jj$ preselection $\zeta(\ell\ell\gamma) < 5$ Nb−jet=0

Remove FSR

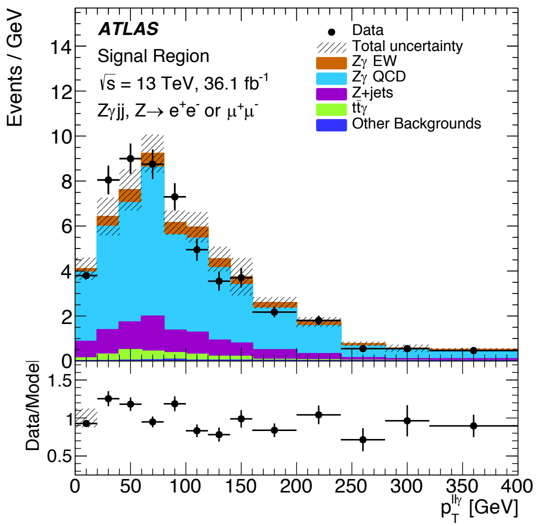


Differences wrt CMS:

- Higher ℓ and ɣ p_T threshold
- Different boson cuts ($70<m_{\ell\ell}<110$ GeV) and removal of FSR photons $m_{\ell\ell\gamma}>100$ GeV
- Lower jet p_T cut (50 vs 30 GeV)
- Lower $\Delta\eta_{jj}$ cut for ATLAS (1 vs 2.5)
- Lower dijet mass in SR (150 vs 500 GeV), and use CR (m_{jj} in 150-400 GeV) to constraint QCD.

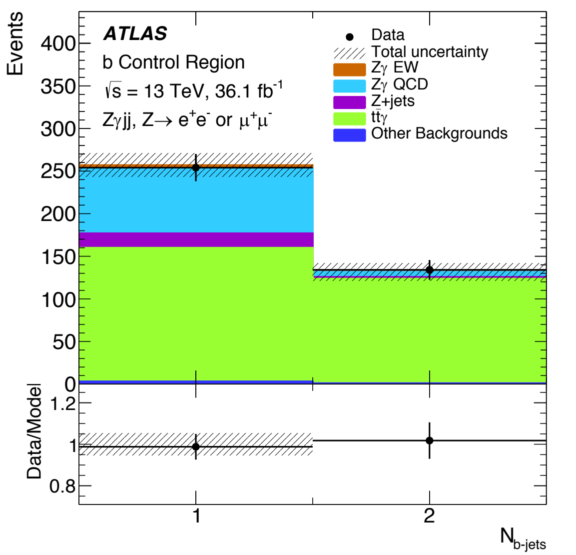
ATLAS bkg estimate Zɣjj→ℓℓɣjj

- **Zɣ QCD:**
  - Shape MC: Sherpa2.2 NLO 0,1j LO 2,3j
  - Normalization from data in the SR.



- **Z+jets:**
  - Shape from Data (revert photon identification).
  - Normalization using 2D sideband method in low m_{jj} region (<150 GeV), Extrapolation to SR using ratio Z+jet/Zɣ.

- **ttɣ:**
  - Shape from MC: aMC@NLO.
  - Normalization from dedicated CR (b-CR):
    - >=1 b-jet -> ~70% purity, 25% Zɣ QCD.



- **Other backgrounds:**
  - WZ, Wt.
  - ~0.5% in SR
  - From MC.

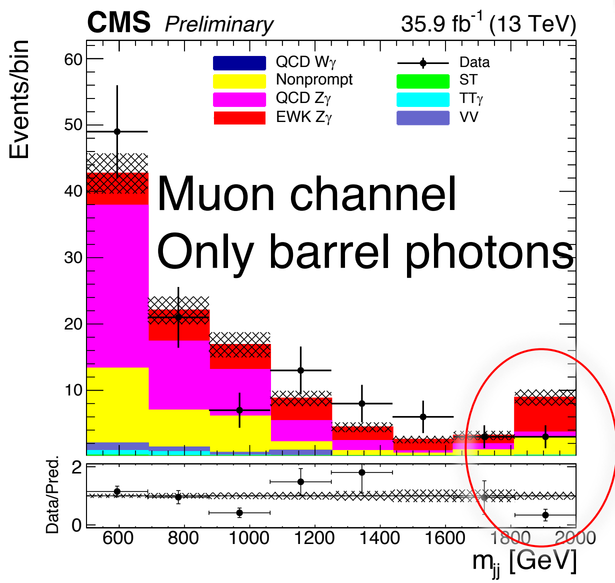
	SR		b-CR	
Data	1222		388	
Total expected	1222	±35	389	±19
$Z\gamma jj$−EW (signal)	104	±26	5	± 1
$Z\gamma jj$−QCD	864	±60	82	± 9
Z+jets	200	±40	19	± 4
$t\bar{t}+\gamma$	48	±10	280	±21
Other backgrounds	7	± 1	4	± 1

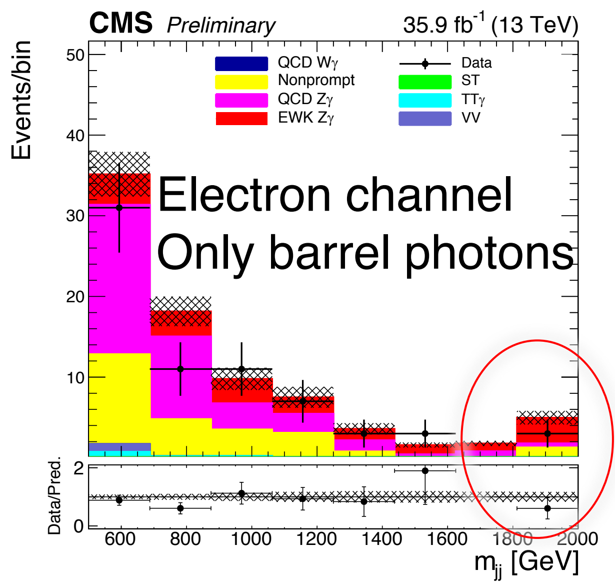
CMS bkg estimate Zɣjj→ℓℓɣjj

- **Zɣ QCD:**
  - Shape and Normalization MC: Madgraph NLO 0,1j, 2jLO
  - Constrained uncertainties in low m_{jj} region (150-400 GeV)
  - Observe disagreement in the High m_{jj} region (last bin contain overflow)

- **Z+jets:**
  - Shape and Normalization data-driven sideband estimate
  - Dominant uncertainties due to choice of isolation variable sideband, and non-closure.

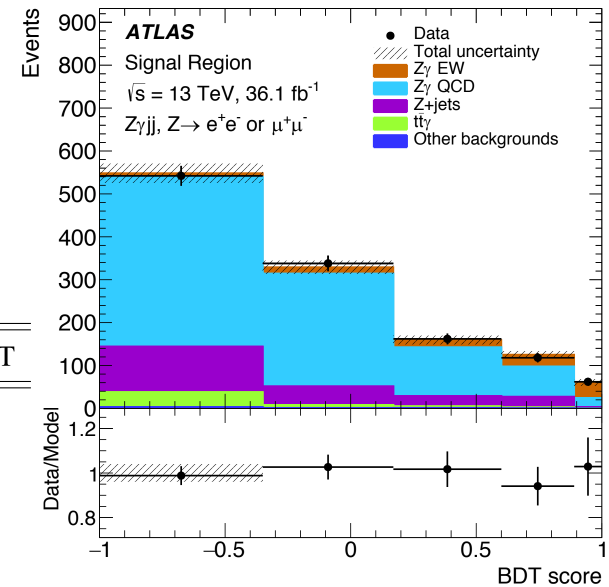
- **Other backgrounds:**
  - single top, ttɣ, diboson, taken from MC





ATLAS Signal extraction Zɣjj→ℓℓɣjj

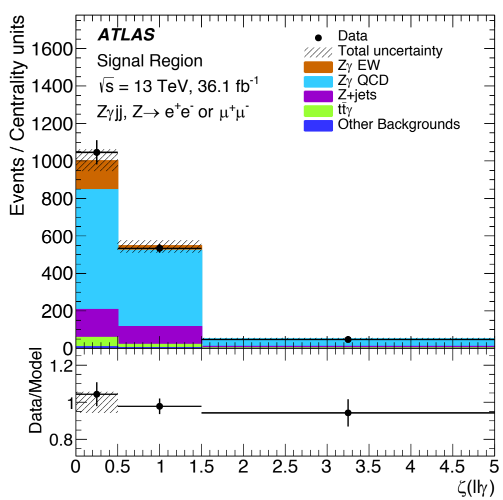
- In ATLAS construct BDT from 13 input variables.
  - Check that all are well modelled.
    - Except m_{jj}, disagreement at high mass same order as CMS disagreement.
    - Check that this has limited impact on signal.

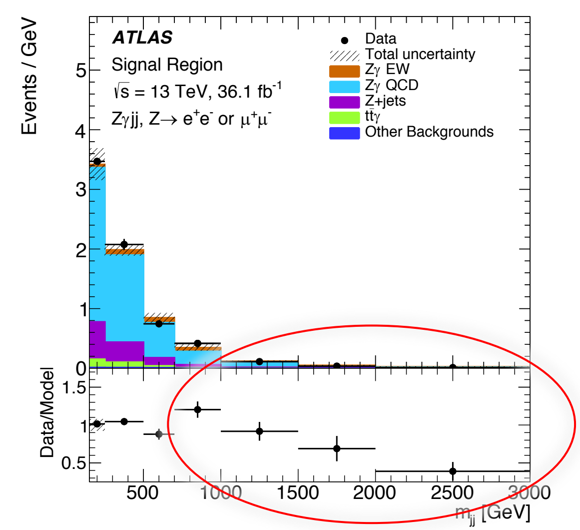


- Perform Maximum likelihood fit on BDT with electron and muon combined.
  - Fit simultaneously SR and b-CR.

Variable used in the BDT
m_{jj}
$\Delta\eta_{jj}$
$\zeta(\ell\ell\gamma)$
$m_{\ell\ell\gamma}$
$p_T^{\ell\ell\gamma}$
$m_{\ell\ell}$
$p_T^{\ell\ell}$
$p_T^{\text{lead lep}}$
$p_T^{\text{lead jet}}$
$\eta^{\text{lead jet}}$
$min\Delta R(\gamma, j)$
$\Delta\phi(\ell\ell\gamma, jj)$
$\Delta R(\ell\ell\gamma, jj)$

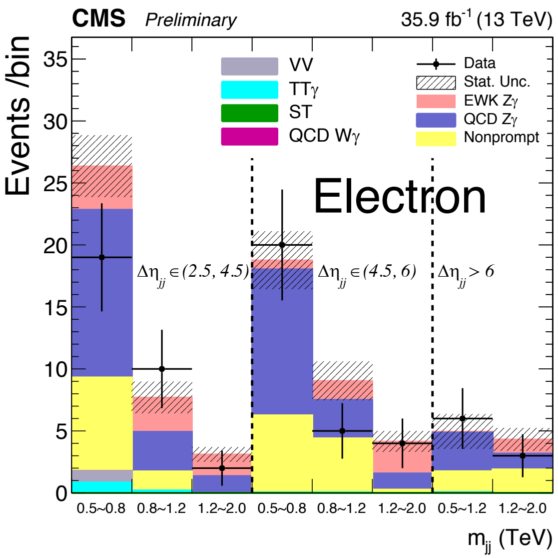
- Perform cross-check with cut-based analysis:
  - Split SR in low and high m_{jj} region (500 GeV)
  - Fit centrality





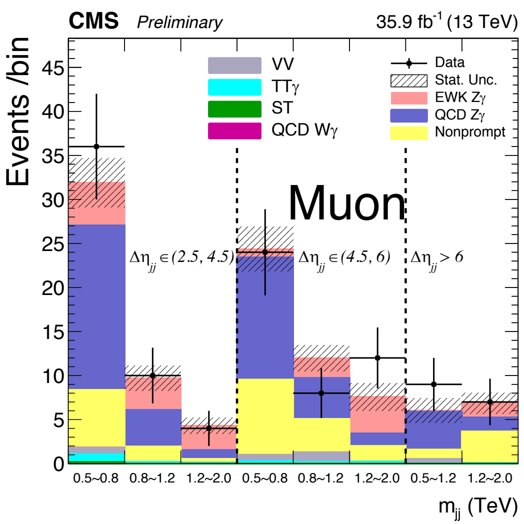
CMS Signal extraction Zɣjj→ℓℓɣjj

- In CMS uses distribution constructed from 2D m_{jj} vs $\Delta\eta_{jj}$:
  - 6 categories in signal region
  - Fit simultaneously SR/CR (low m_{jj}) to constrain Zɣ+2j QCD



- Yield of events in the SR:

	muon channel	electron channel
Nonprompt photon	47.6 ± 4.5	39.3 ± 4.0
Other background	7.4 ± 1.4	2.7 ± 0.8
QCD $Z\gamma$jj	62.9 ± 3.1	49.6 ± 2.7
EW $Z\gamma$jj	36.5 ± 0.7	25.4 ± 0.6
Total background	117.9 ± 5.6	91.6 ± 4.8
Data	172 ± 13	113 ± 11



~60 signal
~200 QCD backgrounds

Uncertainties Zɣjj→ℓℓɣjj

- **Source of errors in ATLAS:**
  - Statistical uncertainty.
  - Z+jet background.
  - Modelling uncertainty of the signal.
  - Jet uncertainties (JER/JES).
  - MC statistics.
  - Modelling of the QCD-background.

- **Source of errors In CMS:**
  - Z+jet backgrounds.
  - JES
  - Modelling of QCD background.

- **Interference** used by both analysis as a systematic uncertainty on template shape.

ATLAS

Source	Uncertainty [%]
Statistical	$^{+19}_{-18}$
$Z\gamma jj$–EW theory modelling	$^{+10}_{-6}$
$Z\gamma jj$–QCD theory modelling	±6
$t\bar{t}+\gamma$ theory modelling	±2
$Z\gamma jj$–EW and $Z\gamma jj$–QCD interference	$^{+3}_{-2}$
Jets	±8
Pile-up	±5
Electrons	±1
Muons	$^{+3}_{-2}$
Photons	±1
Electrons/photons energy scale	±1
b-tagging	±2
MC statistical uncertainties	±8
Other backgrounds normalisation (including Z+jets)	$^{+9}_{-8}$
Luminosity	±2
Total uncertainty	±26

uncertainties on EW fiducial cross-section

Source of systematic uncertainty	Relative uncertainty [%]
QCD $Z\gamma$ scale	5 - 25
EW $Z\gamma$ scale	2 - 14
JES	1 - 31
JER	1 - 13
Interference	4 - 8
Nonprompt photon	9 - 37
Integrated luminosity	2.5

CMS

Uncertainty on signal yield

Results Zɣjj→ℓℓɣjj

- **Sensitivity**:
  - ATLAS:
    - MVA: 4.1 (4.1) σ
    - cut-based: 2.9(2.7)σ
  - CMS:
    - Run2: 3.9 (5.2) σ
    - Run1+2: 4.7 (5.5) σ

Can claim evidence, but not observation!

Stay tune for full run2 analysis!

- Both analysis measure fiducial Zɣjj EWK cross section:

ATLAS

$$\sigma^{\text{fid.}}_{Z\gamma jj-\text{EW}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\,^{+1.0}_{-0.8}\,(\text{mod.})\text{ fb}$$
$$\sigma^{\text{fid., MadGraph}}_{Z\gamma jj-\text{EW}} = 7.75 \pm 0.03\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.40\,(\text{scale})\text{ fb}$$
$$\sigma^{\text{fid., Sherpa}}_{Z\gamma jj-\text{EW}} = 8.94 \pm 0.08\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.50\,(\text{scale})\text{ fb}$$

CMS

	Cross-section [fb]
$\sigma^{fid,obs}_{Z\gamma-EW}$	3.2 ±1.0 (stat) ±0.6 (syst) ±0.07 (lumi) = 3.2 ± 1.2
$\sigma^{fid,MadGraph}_{Z\gamma-EW}$	4.97 ± 0.14 (PDF + α_S) ± 0.25 (scale)

- Both analysis measure fiducial Zɣjj cross section:

ATLAS

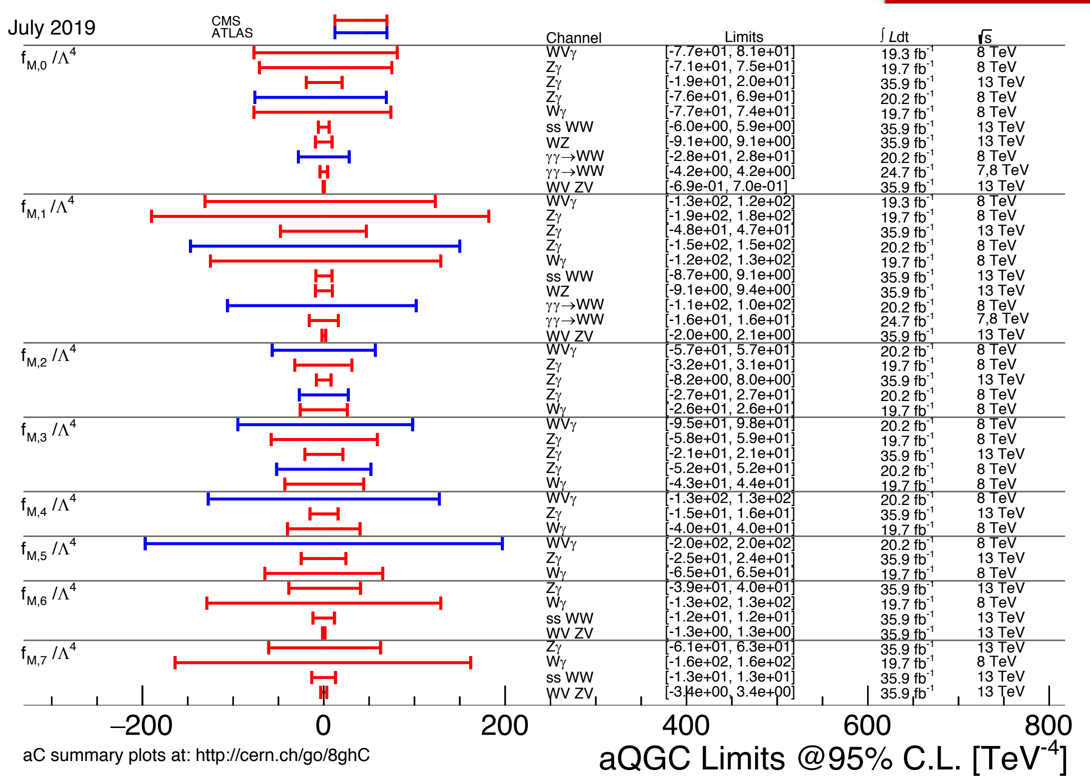
$$\sigma^{\text{fid.}}_{Z\gamma jj} = 71 \pm 2\,(\text{stat.})\,^{+9}_{-7}\,(\text{syst.})\,^{+21}_{-17}\,(\text{mod.})\text{ fb}$$
$$\sigma^{\text{fid., MadGraph+Sherpa}}_{Z\gamma jj} = 88.4 \pm 2.4\,(\text{stat.}) \pm 2.3\,(\text{PDF} + \alpha_S)^{+29.4}_{-19.1}\,(\text{scale})\text{ fb.}$$

CMS

	Cross-section [fb]
$\sigma^{fid,obs}_{Z\gamma jj}$	15.1 ± 1.2 (stat) ± 2.1 (sys) ± 0.4 (lumi) = 15.1 ± 2.4
$\sigma^{fid,MadGraph}_{Z\gamma jj}$	-

Outline

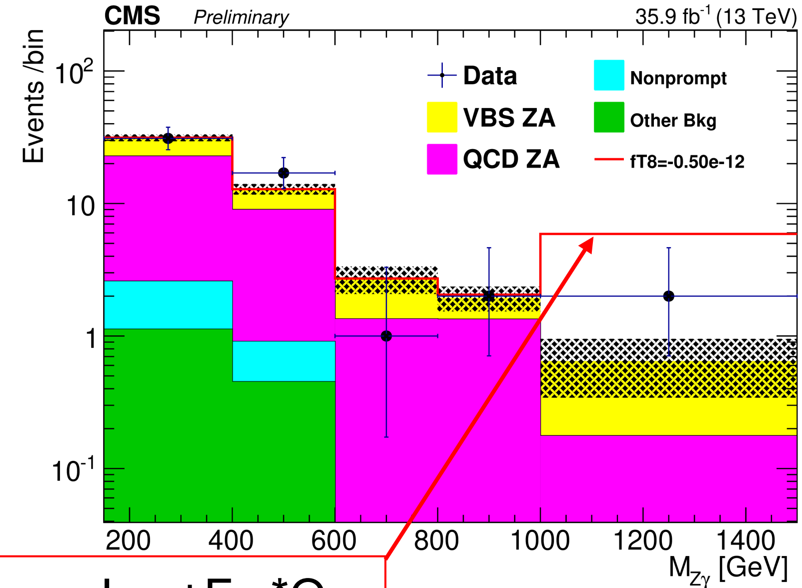
- Introduction
- Challenges
- Experimental Results
- **New Physics**



- Conclusion

EFT limits with Zγ VBS

- Look at the tail of the $M_{Z\gamma}$ distribution to find new physics.
- Use modeling of the analysis of Zγ EWK+QCD as background to search for signal.
- Generate EFT with Madgraph.
- Set limit on all parameters sensitive to Zγ coupling: (WWZγ, ZZZγ, ZZγγ, Zγγγ).



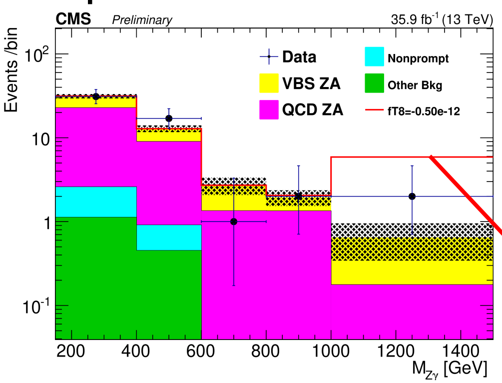
$L_{EFT} = L_{SM} + F_{T8} * O_{T8}$

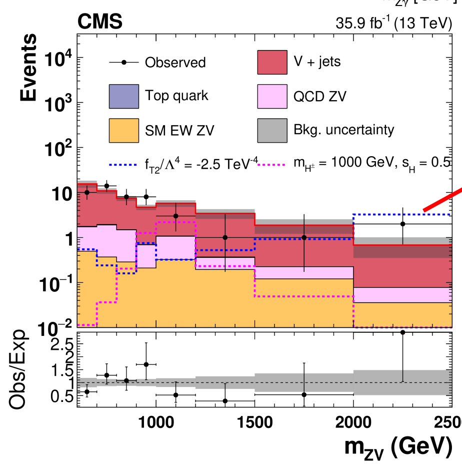
Observed Limits (TeV^{-4})	Expected Limits (TeV^{-4})
$-19.3 < F_{M,0}/\Lambda^4 < 20.2$	$-15.0 < F_{M,0}/\Lambda^4 < 15.1$
$-47.8 < F_{M,1}/\Lambda^4 < 46.9$	$-30.1 < F_{M,1}/\Lambda^4 < 30.0$
$-8.16 < F_{M,2}/\Lambda^4 < 8.04$	$-6.09 < F_{M,2}/\Lambda^4 < 6.06$
$-20.9 < F_{M,3}/\Lambda^4 < 21.1$	$-13.2 < F_{M,3}/\Lambda^4 < 13.3$
$-15.2 < F_{M,4}/\Lambda^4 < 15.8$	$-11.7 < F_{M,4}/\Lambda^4 < 11.7$
$-24.9 < F_{M,5}/\Lambda^4 < 24.4$	$-19.1 < F_{M,5}/\Lambda^4 < 18.2$
$-38.6 < F_{M,6}/\Lambda^4 < 40.5$	$-30.0 < F_{M,6}/\Lambda^4 < 30.1$
$-60.8 < F_{M,7}/\Lambda^4 < 62.6$	$-46.1 < F_{M,7}/\Lambda^4 < 46.3$
$-0.74 < F_{T,0}/\Lambda^4 < 0.69$	$-0.56 < F_{T,0}/\Lambda^4 < 0.51$
$-1.16 < F_{T,1}/\Lambda^4 < 1.15$	$-0.73 < F_{T,1}/\Lambda^4 < 0.72$
$-1.96 < F_{T,2}/\Lambda^4 < 1.85$	$-1.48 < F_{T,2}/\Lambda^4 < 1.37$
$-0.70 < F_{T,5}/\Lambda^4 < 0.74$	$-0.51 < F_{T,5}/\Lambda^4 < 0.57$
$-1.64 < F_{T,6}/\Lambda^4 < 1.67$	$-1.23 < F_{T,6}/\Lambda^4 < 1.26$
$-2.59 < F_{T,7}/\Lambda^4 < 2.80$	$-1.91 < F_{T,7}/\Lambda^4 < 2.12$
$-0.47 < F_{T,8}/\Lambda^4 < 0.47$	$-0.36 < F_{T,8}/\Lambda^4 < 0.36$
$-1.26 < F_{T,9}/\Lambda^4 < 1.27$	$-0.95 < F_{T,9}/\Lambda^4 < 0.95$

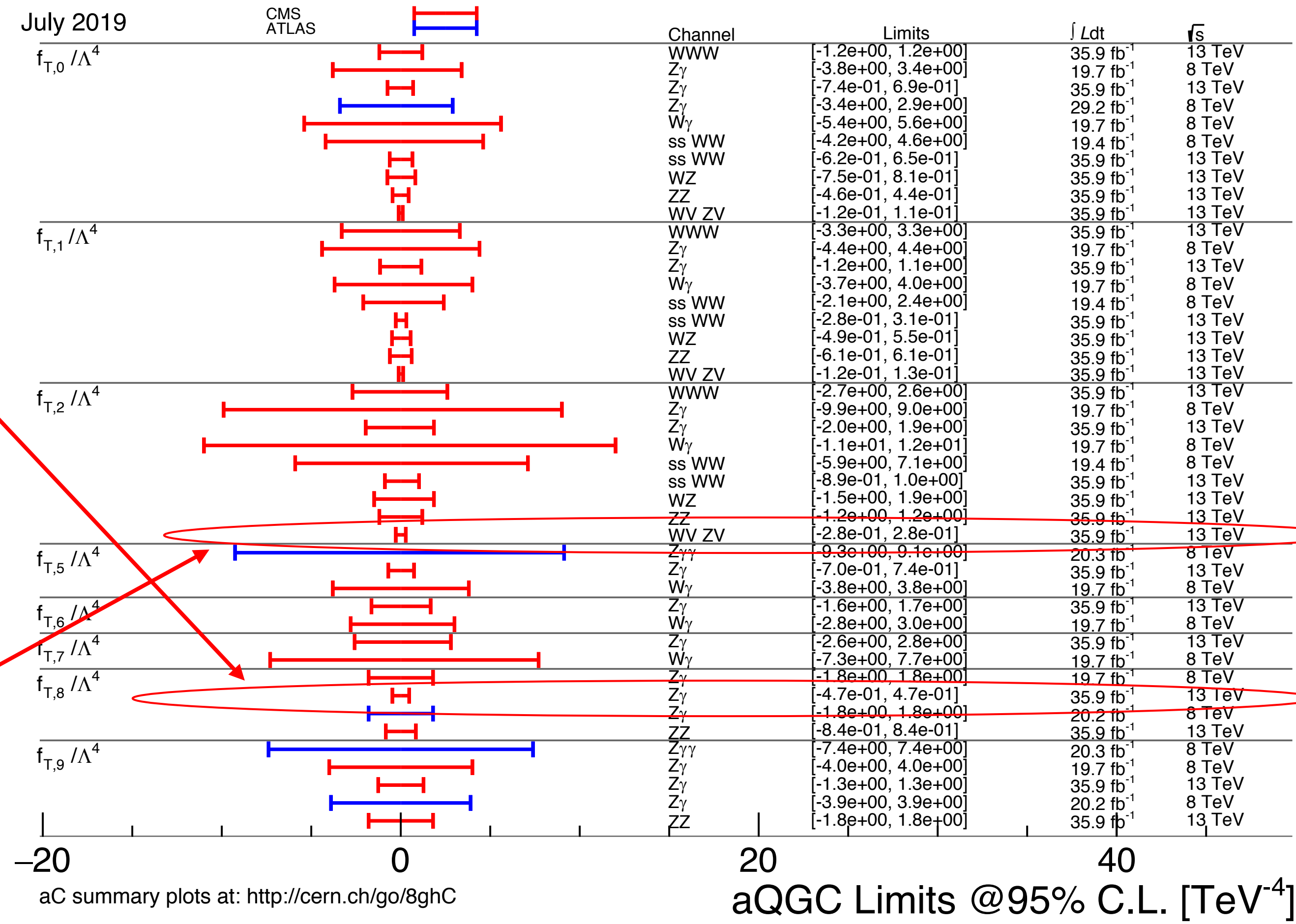
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,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

aQGC limits

Most stringent limit for this specific operator!







- Stringent limits are now set on all dim 8 operators F_S, F_M and F_T (here only show FT) using VBS and VVV channels.
- Combination of results will help improving these results in the future.

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Conclusions

- **VBS topology, very interesting to search for new physics!**
  - Although none observed...
  - Use EFT to interpret results!
- **Observation of 3 EWK final states achieved over the last years (WW,WZ,ZZ) with run2 data.**
  - More to come with full run2!
  - First observation of a process with QGC diagrams!
- **Lot of work still required to do precision measurement using VBS, and therefore probe EWSB.**
  - Need more data (3σ $V_L V_L$ polarization @HL-LHC).
  - Need better tuned MC calculations.
  - Need to improve on the experimental side (jets, ML,...).
- **Very interesting and active field of work!**