Results on VBS production for neutral diboson channels from ATLAS and CMS and constraints on aQGCs

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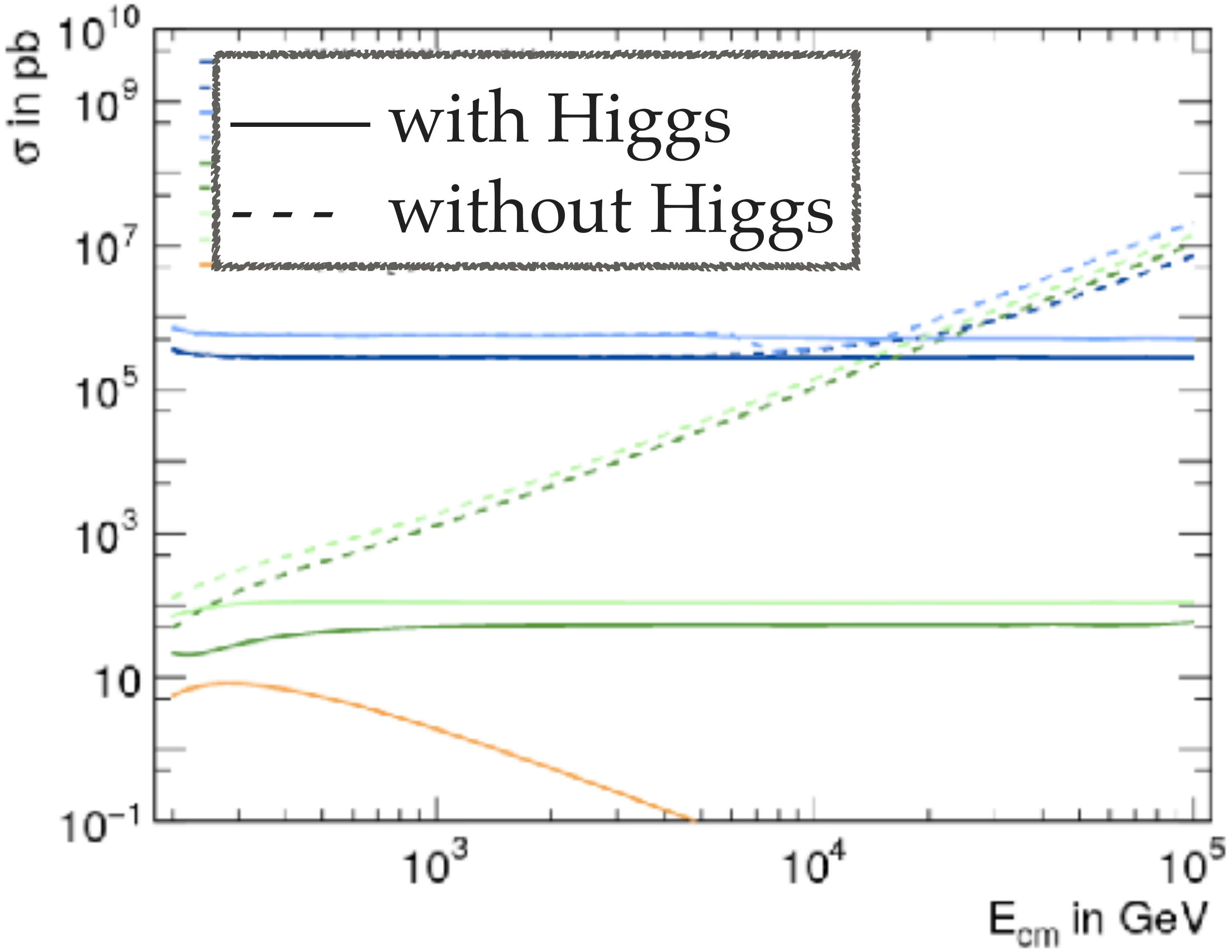
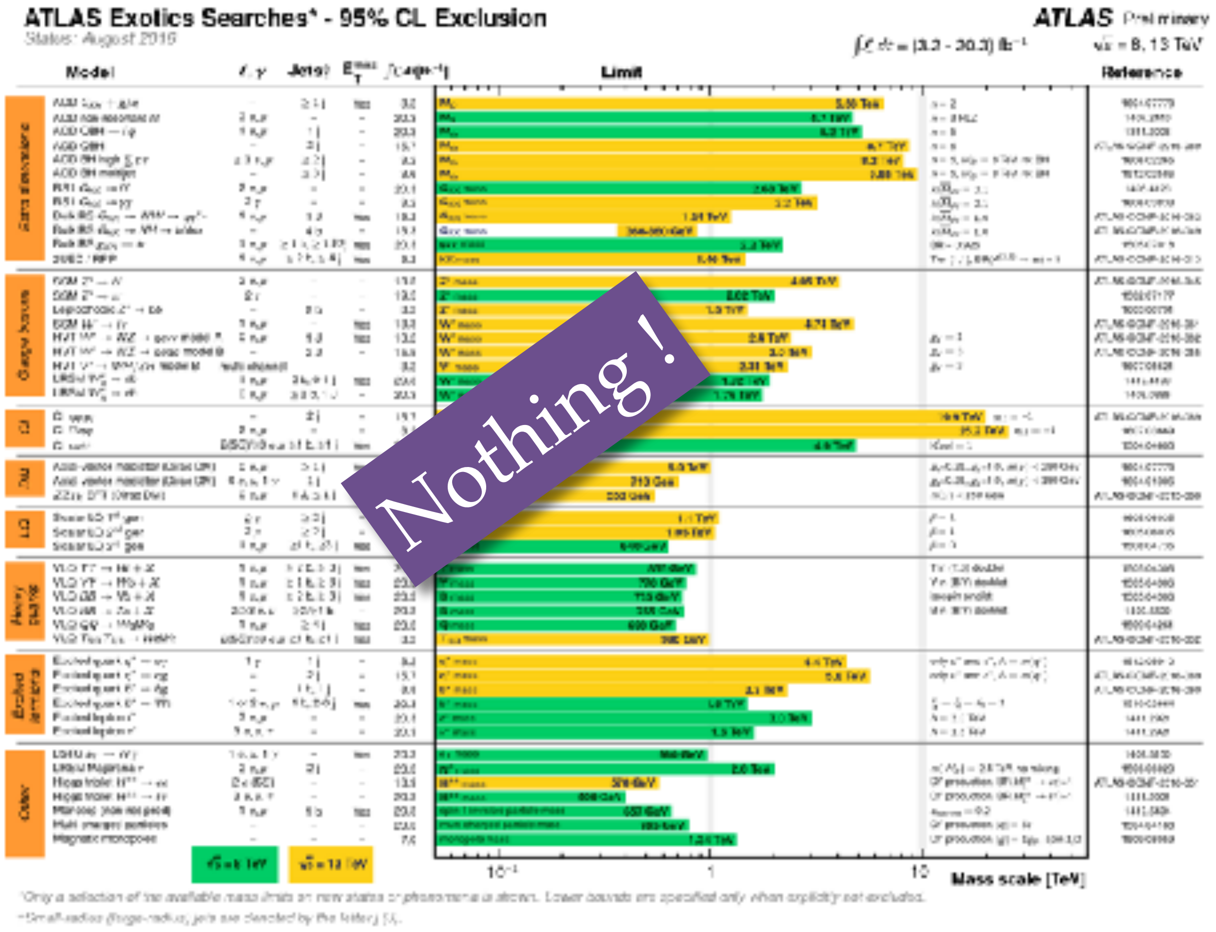
Introduction

- After Higgs discovery 5 years ago, no deviation found in its properties
- **Vector Boson Scattering (VBS) important test of electroweak sector and EW Symmetry Breaking**
    - Interaction with Higgs boson unitarizes the scattering amplitude -> is unitarization complete ?
    - **Complementary to Higgs boson property studies**




ATLAS Exotics Searches* - 95% CL Exclusion

ATLAS Preliminary

- Yet no sign of new physics with direct searches @LHC
- VBS allows **indirect search** by studying anomalous quartic gauge couplings (aQGC)

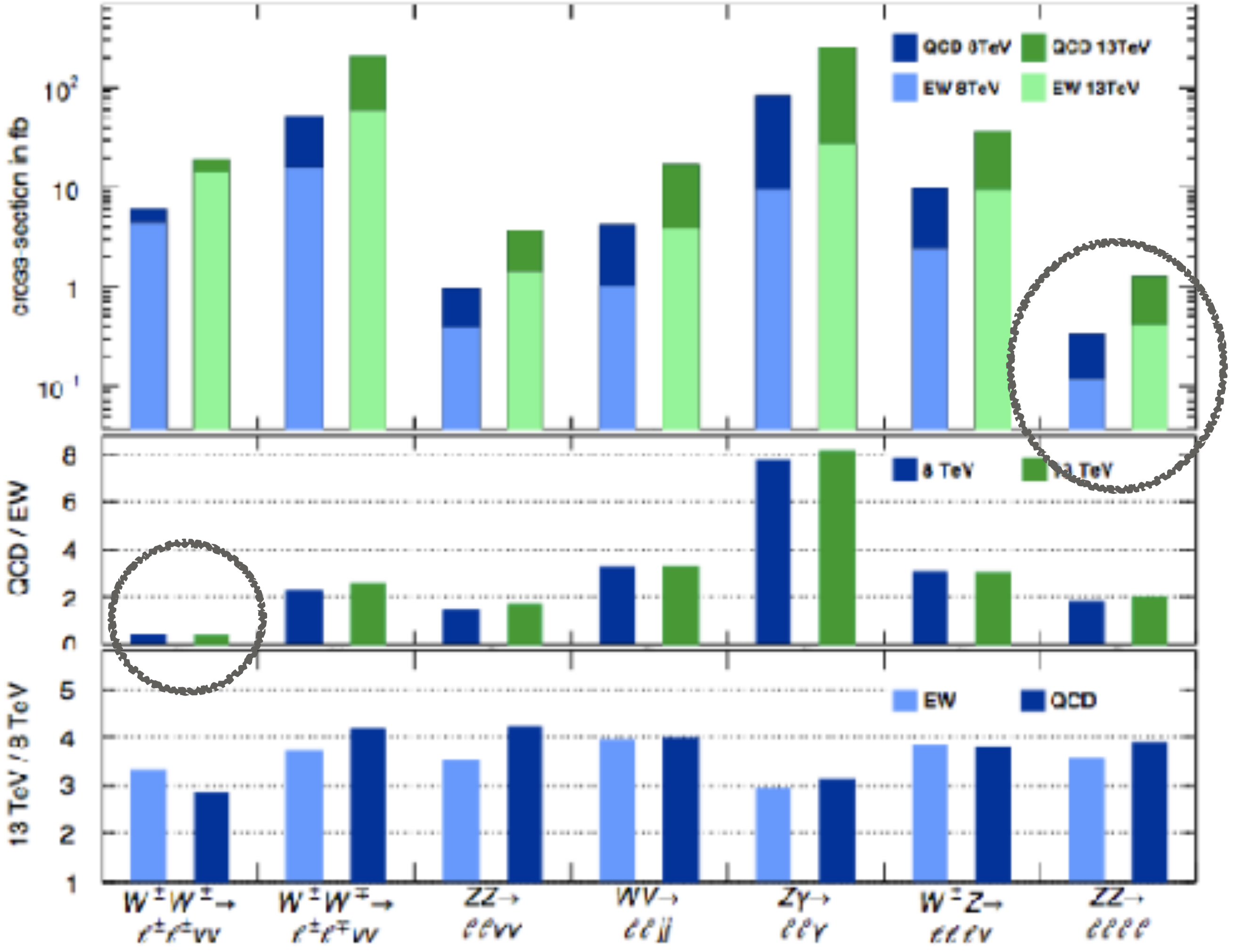
Introduction

- **Experimentally VBS is challenging**
  - very low rate ($\mathcal{O}$(fb))
  - large background, generally from strong production of same final state -> **scales as α^2_s / α^2**
  - large experimental and theory uncertainties
  - VBS observed only very recently !

- **What can help ?**
  - use of leptons / photons final states (clean channels, more limited backgrounds)
  - use of 13 TeV dataset : XS multiplied by a factor ~3-4
  - use of control regions to reduce systematic uncertainties
  - Topological selection to reduce QCD background

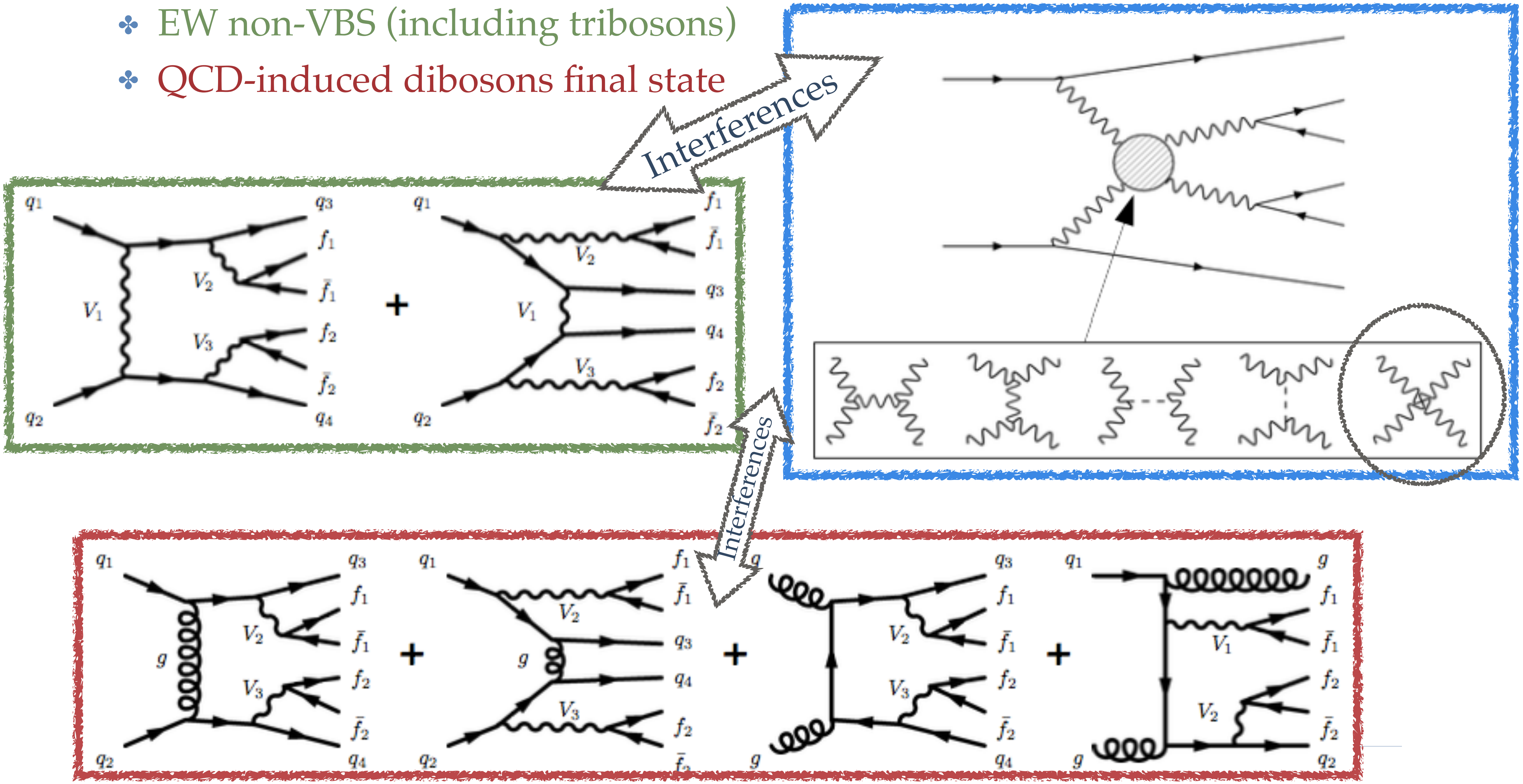
Best S/B !

Very small XS, but good S/B



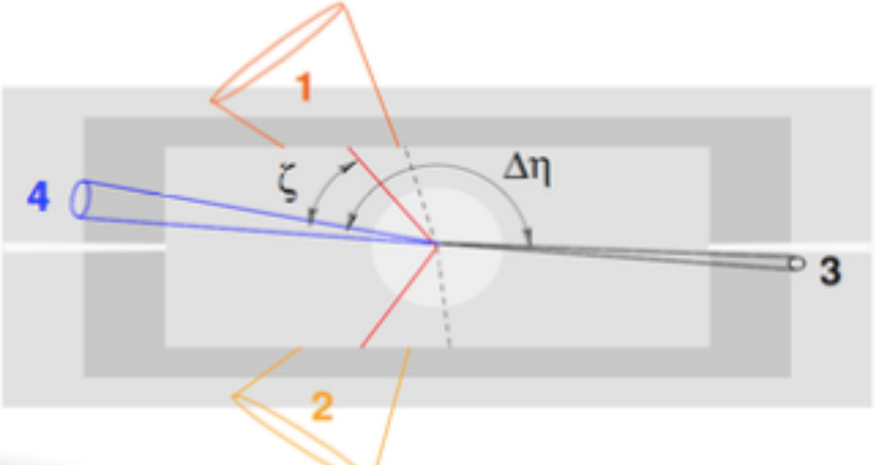
Phenomenology of VBS

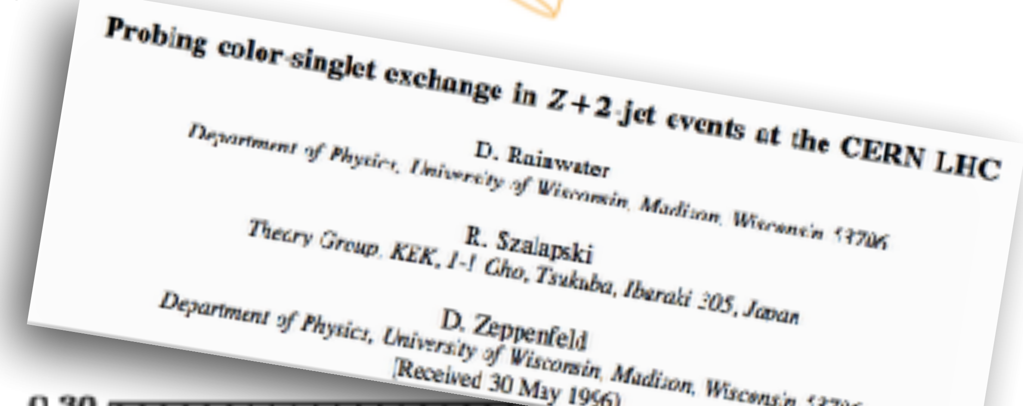
- As experimentalist, we cannot access pure VBS and pure quartic couplings
  - VBS with triple and **quartic** couplings
  - EW non-VBS (including tribosons)
  - QCD-induced dibosons final state



Phenomenology of VBS

- **VBS: has typical final states topology**
  1. Two hadronic jets in forward and backward regions with very high energy (*tagging jets*)
  2. Hadronic activity suppressed between the two jets (*rapidity gap*) due to absence of colour flow between interacting partons
  3. Two bosons produced ~back-to-back





Probing color-singlet exchange in $Z+2$-jet events at the CERN LHC

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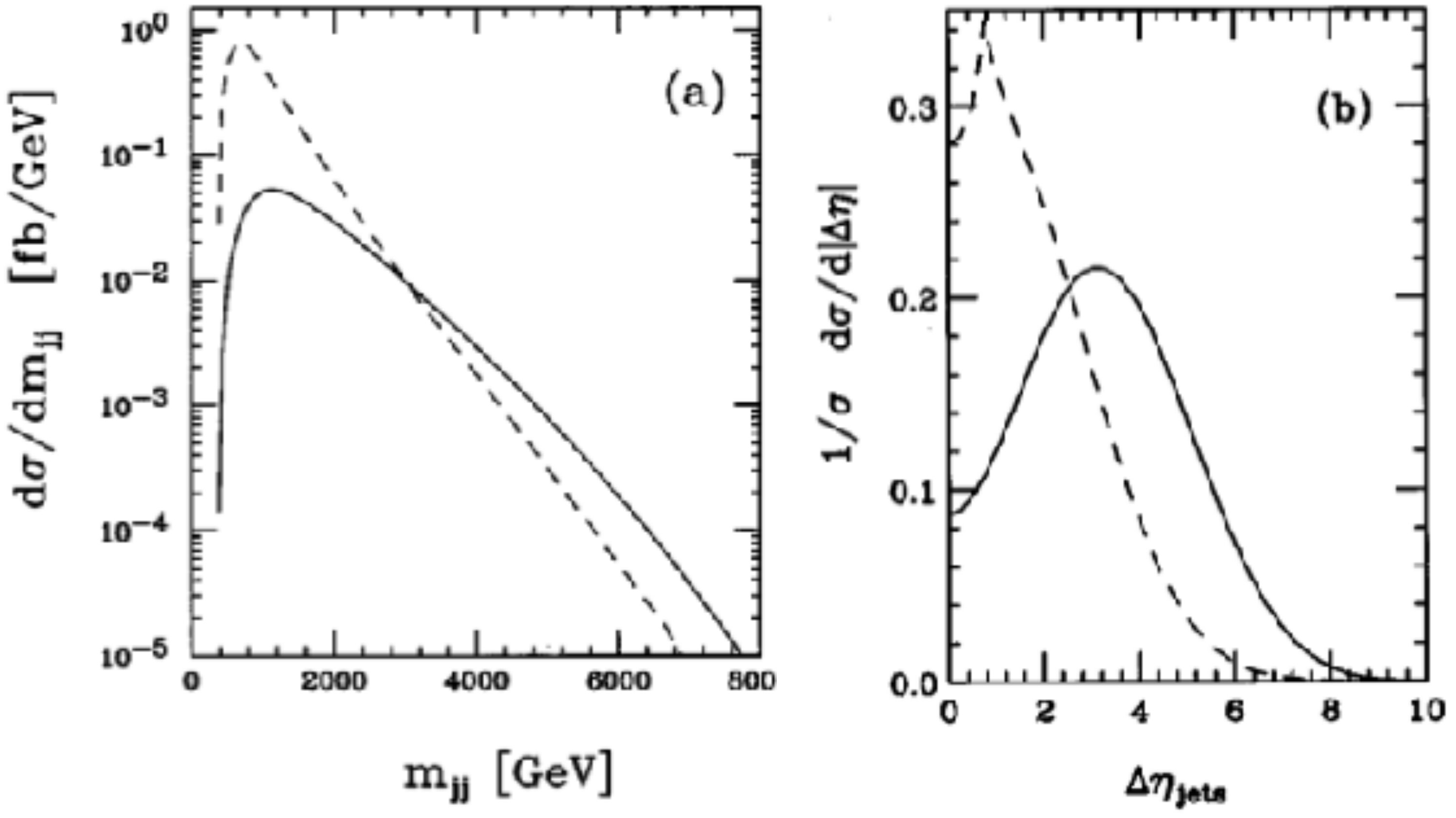
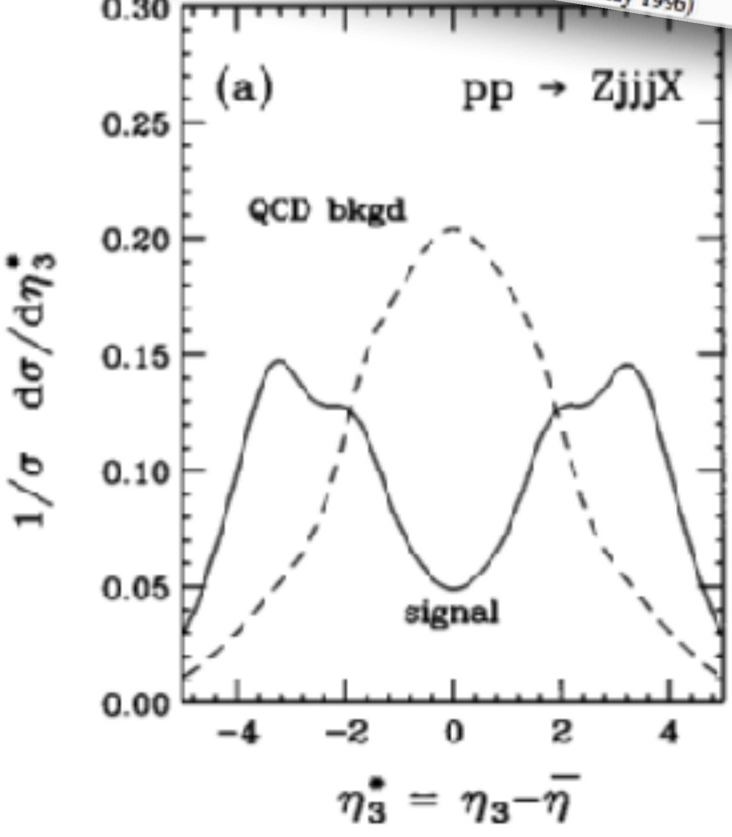
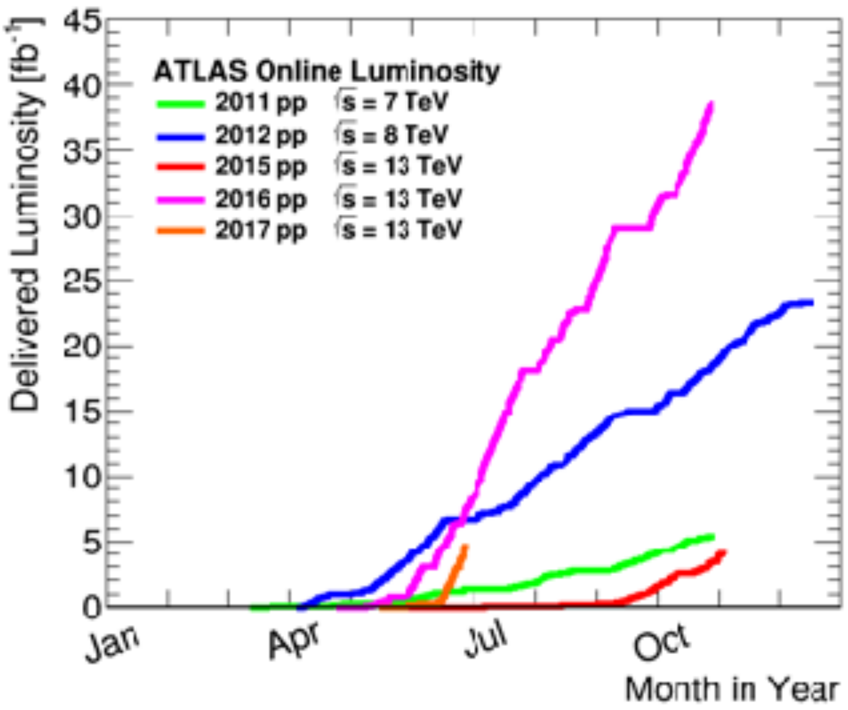




-> Zeppenfeld variable « centrality »

ATLAS and CMS VBS studies

- Datasets
  - ATLAS: 8 TeV (20.2 fb-1)
  - CMS: 8 TeV (19.7 fb-1) and 13 TeV (35.9 fb-1)



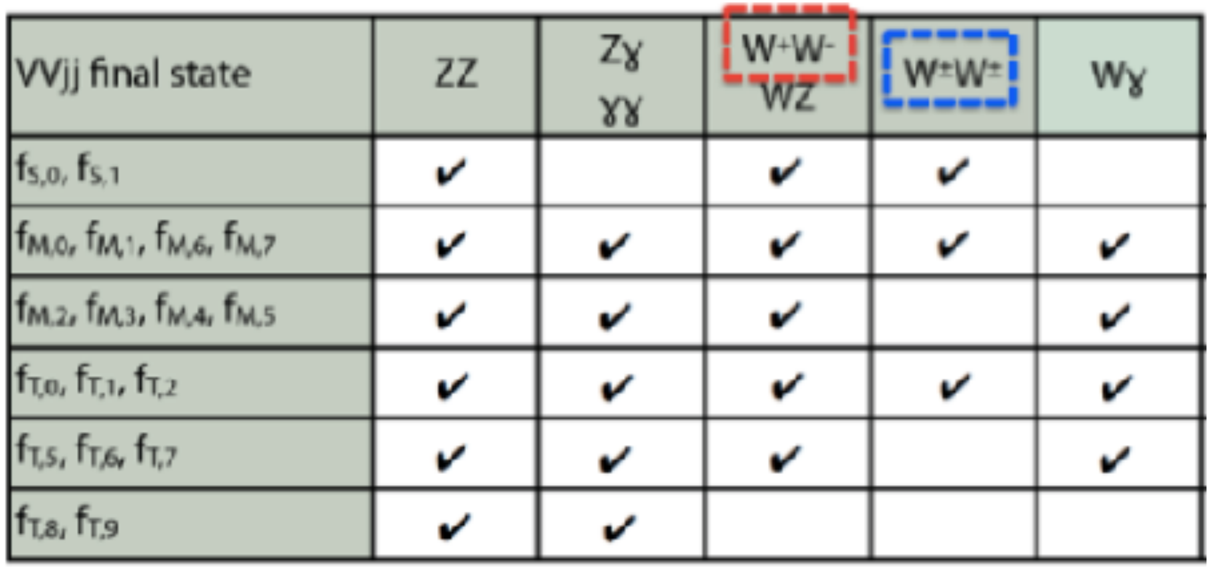
- Channels studied:

	ATLAS	CMS
$W^\pm W^\pm$ *Best EW/QCD*	8 TeV	8, **13 TeV**
$W^\pm Z$	8 TeV	-
$W\gamma$ *Largest XS*	-	8 TeV
WV semi-lept. *only access to aQGCs*	8 TeV	-
$Z\gamma$ *Low reduc. bkg*	8 TeV	8 TeV
ZZ	-	13 TeV

covered in Md Naimuddin's talk

covered in this talk

- **All possible VBS final states studied @ LHC**
  - except $\gamma\gamma$ and W^+W^-, difficult due to huge bkg.
  - **Can probe all operators of EFT !**



VVjj final state	ZZ	$Z\gamma$ $\gamma\gamma$	W^+W^- WZ	$W^\pm W^\pm$	$W\gamma$
$f_{S,0}$, $f_{S,1}$	✔		✔	✔	
$f_{M,0}$, $f_{M,1}$, $f_{M,6}$, $f_{M,7}$	✔	✔	✔	✔	✔
$f_{M,2}$, $f_{M,3}$, $f_{M,4}$, $f_{M,5}$	✔	✔	✔		✔
$f_{T,0}$, $f_{T,1}$, $f_{T,2}$	✔	✔	✔	✔	✔
$f_{T,5}$, $f_{T,6}$, $f_{T,7}$	✔	✔	✔		✔
$f_{T,8}$, $f_{T,9}$	✔	✔			

Anomalous quartic gauge couplings

- New physics could modify couplings between bosons, and allow neutral couplings ZZZγ, ZZ$\gamma\gamma$, Z$\gamma\gamma\gamma$ (forbidden in SM) -> aQGCs

- Presence of aQGC enhance EW XS at high-energy tails
    - use variable that carry the energy of the system: **transverse momentum or mass**

- **ATLAS and CMS common choice:** effective field theory (EFT) with higher order dimensions operators
    - Dim8 is lowest-**dimension** operators inducing only QGC without TGC vertices
    - VBS not competitive with dibosons/VBF for dim6 constraints.

- **Two approaches**
    - α_4 α_5: coefficients of the two linearly independent dim4 operators contributing to aQGCs (**ATLAS** WZ, ssWW, WV semilept.)
    - C,P conserving dim8 EFT operators that maintains SU(2)$_L$ x U(1)$_Y$ gauge symmetry of the type f$_i$/Λ_4 (**ATLAS** Zγ, **CMS** Zγ, Wγ, ssWW, ZZ)

Dim 8 operators

$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j$$

New physics scale

Anomalous quartic gauge couplings

- Dim8 operators: 3 types:
  - pure Higgs field (fS) pure longitudinal (cannot induce couplings with photons)
  - pure Field-strength tensor (fT) pure transverse
  - Mixed Higgs-field-strength (fM), mixed longitudinal-transverse

$$
\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}
$$

Not all independent !

$$
\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,3} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu} \\
\mathcal{L}_{T,4} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu} \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}
$$

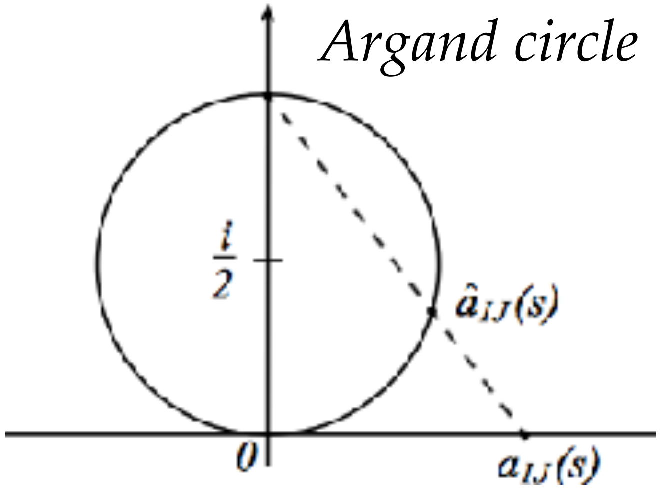
Only neutral couplings

Exemple of conversion to α_4,α_5 framework:

$$\frac{f_{S,0(1)}}{\Lambda^4} = \alpha_{4(5)} \times \frac{16}{v^4}\,,$$

for the WWZZ vertex

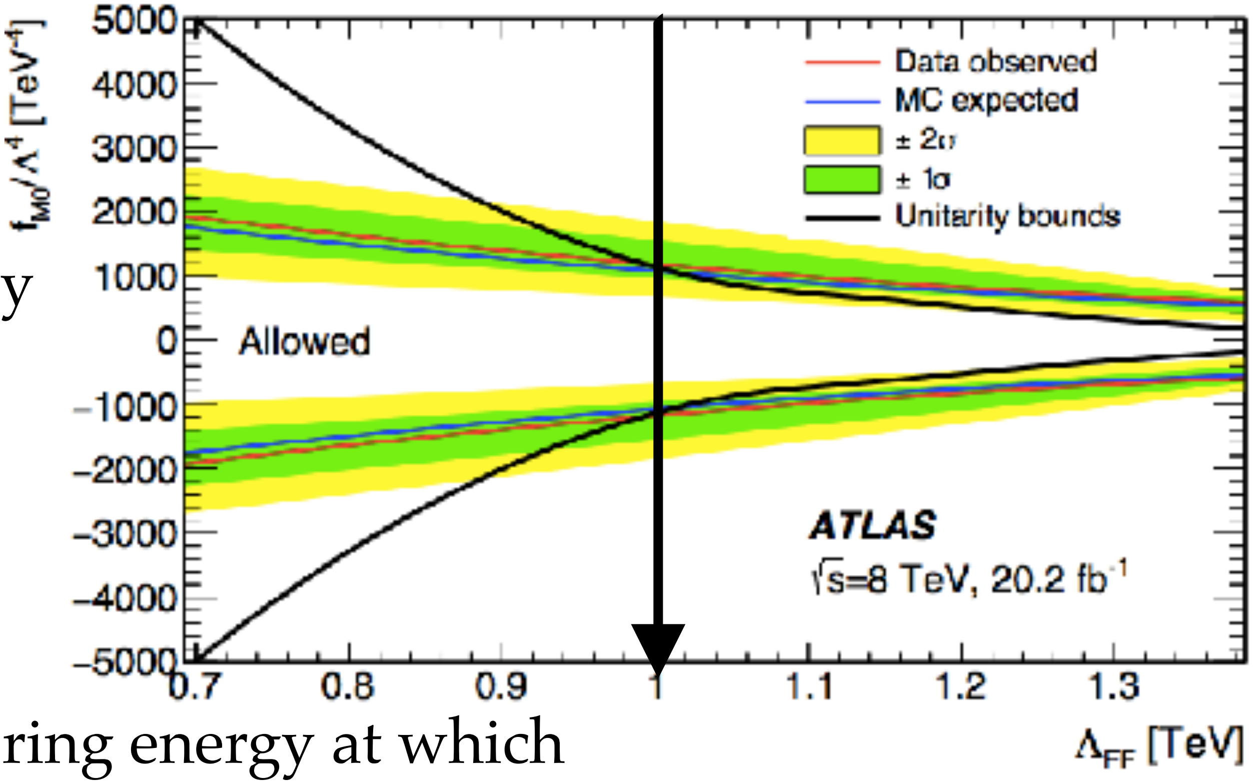
Unitarity



- Nonzero value in aQGCs lead to tree-level unitarity violation at high energy
- Could be unitarised with a form factor but depends on detailed structure of new physics -> we don't know it !
- In $\alpha_4\,\alpha_5$ framework, unitarisation done with **K-matrix method** (in WHIZARD) -> **ATLAS**
- In dim8 operators, two approaches
  1. **ATLAS**: use **form factor** to restore unitarity

$$f_i(\hat{s}) = f_i/(1+\hat{s}/\Lambda_{FF}^2)^n$$

n=2, Λ_{FF} cut-off scale



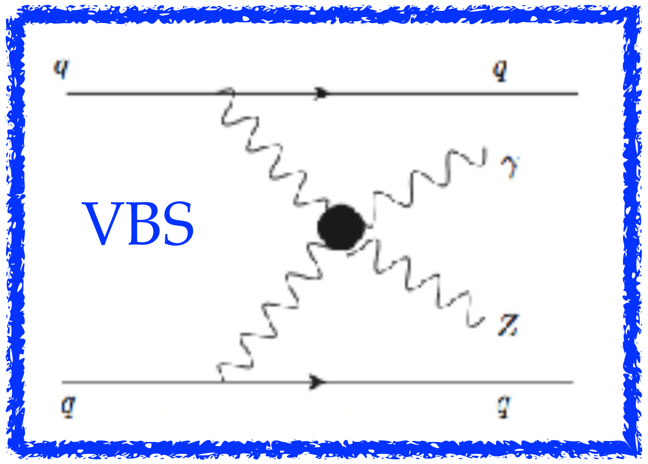
  2. **CMS**: provide only **validity bound** (scattering energy at which observed limit would violate unitarity, from VBFNLO) but don't use any form factor
     - Problem: many limits are set in the unitarity unsafe region !

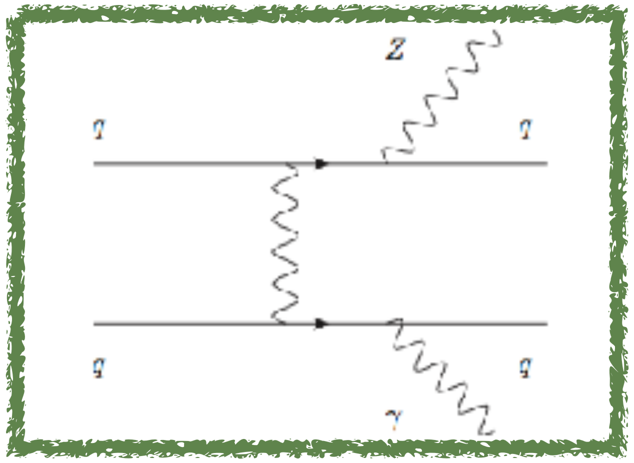
VBS $Z\gamma$+2j

ATLAS and CMS

Introduction

- Search for EW production of Zγ+2j
- **CMS** and **ATLAS**, with 8 TeV data (2012, 19.7 fb-1 and 20.2 fb-1)
    - CMS: Z->ee,μμ **Phys. Lett. B 770 (2017)**
    - ATLAS, Z->ee,μμ and Z->νν for aQGCs **JHEP 07 (2017) 107**
- **Interest:**
    - can probe T8 and T9 operators, experimentally accessible only via neutral boson final states
    - larger XS than ZZ, clean channel, relatively low instrumental background
- **Analysis strategy**
    - Measurement of total Zγjj cross section
    - Probing VBS with Z-> ee/μμ
    - Setting limits on aQGC with Z->ee/μμ/νν

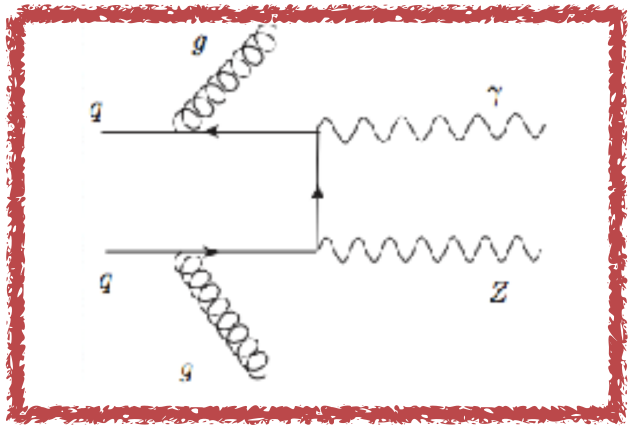




EW non VBS

QCD

Dominant background



Simulation and samples

- **Zγ+2j:**
  - CMS: LO MadGraph v5.1.3, matched to Parton shower based on MLM prescription.
    - 0-3 additional jets + NLO k-factor of 1.1 for $m_{jj}<400$ GeV for QCD.
  - ATLAS: LO Sherpa v1.4.5 (up to 3 add jets) and VBFNLO v2.7.1 for XS prediction

- **Interference EW/QCD**: treated as a systematic uncertainty:
  - CMS: from MadGraph, 18% of EW for $400<m_{jj}<800$ and 11% for $m_{jj}>800$ GeV
  - ATLAS: from MadGraph, ~7% of EW for $m_{jj}>500$ GeV

- **aQGCs:**
  - CMS: LO MadGraph v5.1.3
  - ATLAS: LO MadGraph (for efficiencies) and NLO VBFNLO (for XS prediction)

Baseline selection (charged lepton channels)

Objects	Particle- (Parton-) level selection
Leptons	$p_{\mathrm{T}}^{\ell} > 25$ GeV and $\lvert\eta^{\ell}\rvert < 2.5$ Dressed leptons, OS charge
Photon (kinematics)	$E_{\mathrm{T}}^{\gamma} > 15$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$ $\Delta R(\ell, \gamma) > 0.4$
Photon (isolation)	$E_{\mathrm{T}}^{\mathrm{iso}} < 0.5 \cdot E_{\mathrm{T}}^{\gamma}$ (no isolation)
FSR cut	$m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $m_{\ell\ell} > 40$ GeV
Particle jets (Outgoing partons) (j = jets) (p = outgoing quarks or gluons)	At least two jets (outgoing partons) $E_{\mathrm{T}}^{j(p)} > 30$ GeV, $\lvert\eta^{j(p)}\rvert < 4.5$ $\Delta R(\ell, j(p)) > 0.3$ $\Delta R(\gamma, j(p)) > 0.4$

ATLAS

+ m_{jj}>150 GeV

Remove triboson production ZγV(->jj)

CMS

Common selection
$p_{\mathrm{T}}^{\mathrm{j1,j2}} > 30\,\mathrm{GeV}$, $\lvert\eta^{\mathrm{j1,j2}}\rvert < 4.7$
$p_{\mathrm{T}}^{\ell1,\ell2} > 20\,\mathrm{GeV}$, $\lvert\eta^{\ell1,\ell2}\rvert < 2.4$
$\lvert\eta^{\gamma}\rvert < 1.4442$
$M_{\mathrm{jj}} > 150\,\mathrm{GeV}$
$70 < M_{\ell\ell} < 110\,\mathrm{GeV}$

+ $E_{T\gamma}$>20-25 GeV

Differences:

- lepton p_T (20/25 GeV)
- Photon E_T (20-25/15 GeV)
- photon η (<1.4 / <2.37)
- m_{ll} cut ([70,110] / >40 GeV + FSR cut)

Backgrounds

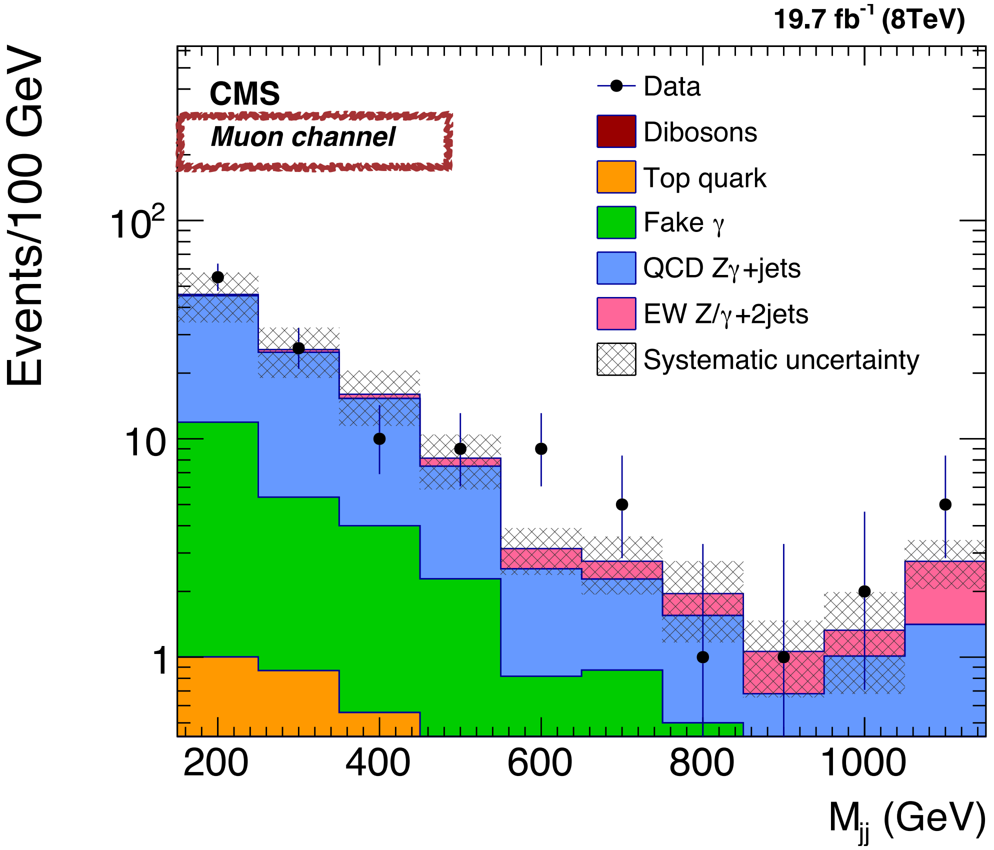
1. **QCD background dominant** in these analyses, yield validated (see later)

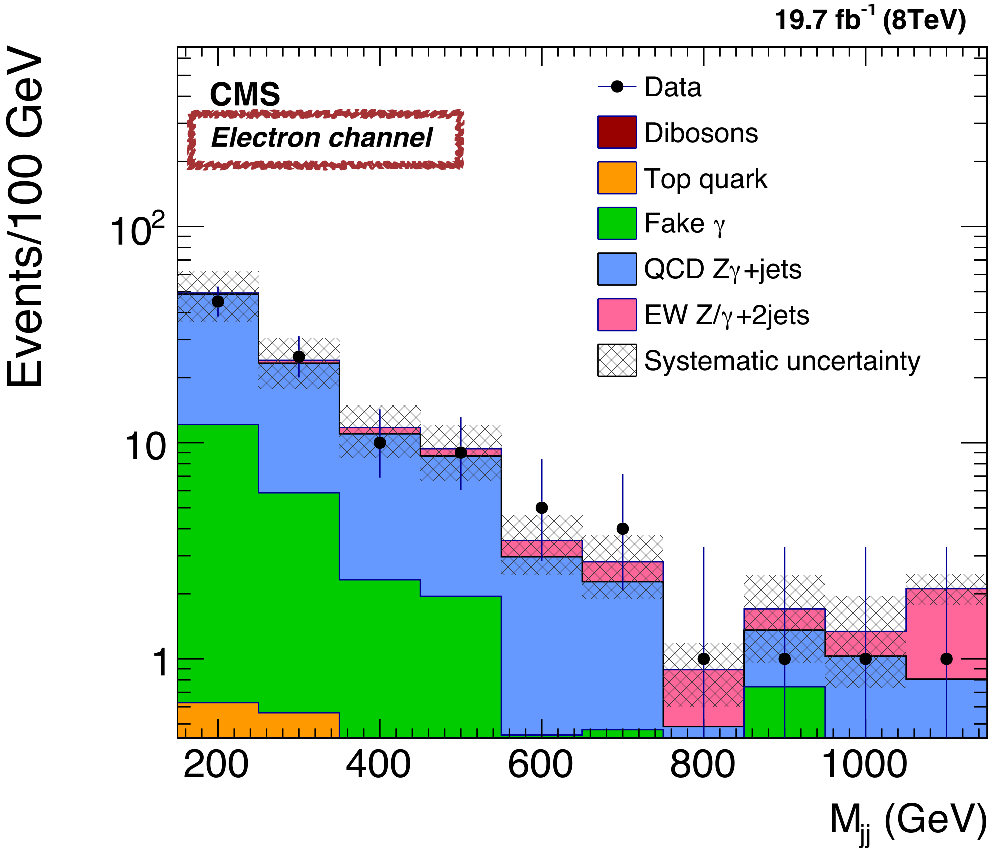
2. **Z+jets (jet faking photon):** extracted from data (not well modelled by MC) with a method based on identification quality and isolation of photon.
   - **ATLAS**: 3 control regions populated by events failing photon ID and/or isolation (ABCD method).
     - Shape of Z+jets found to be similar to Sherpa Zγjj (validated with Powheg and Alpgen)
     - Ratio of Z+jets/Zγjj extracted in region m_{jj}>100 GeV and used in other regions
     - **23 +/- 6% of QCD events**
   - **CMS**: select photon failing tight ID but passing looser requirements
     - get jets with similar kinematics than genuine photons
     - Calculate probability to get a fake photon in different $E_{T\gamma}$ regions -> **~30% of QCD**

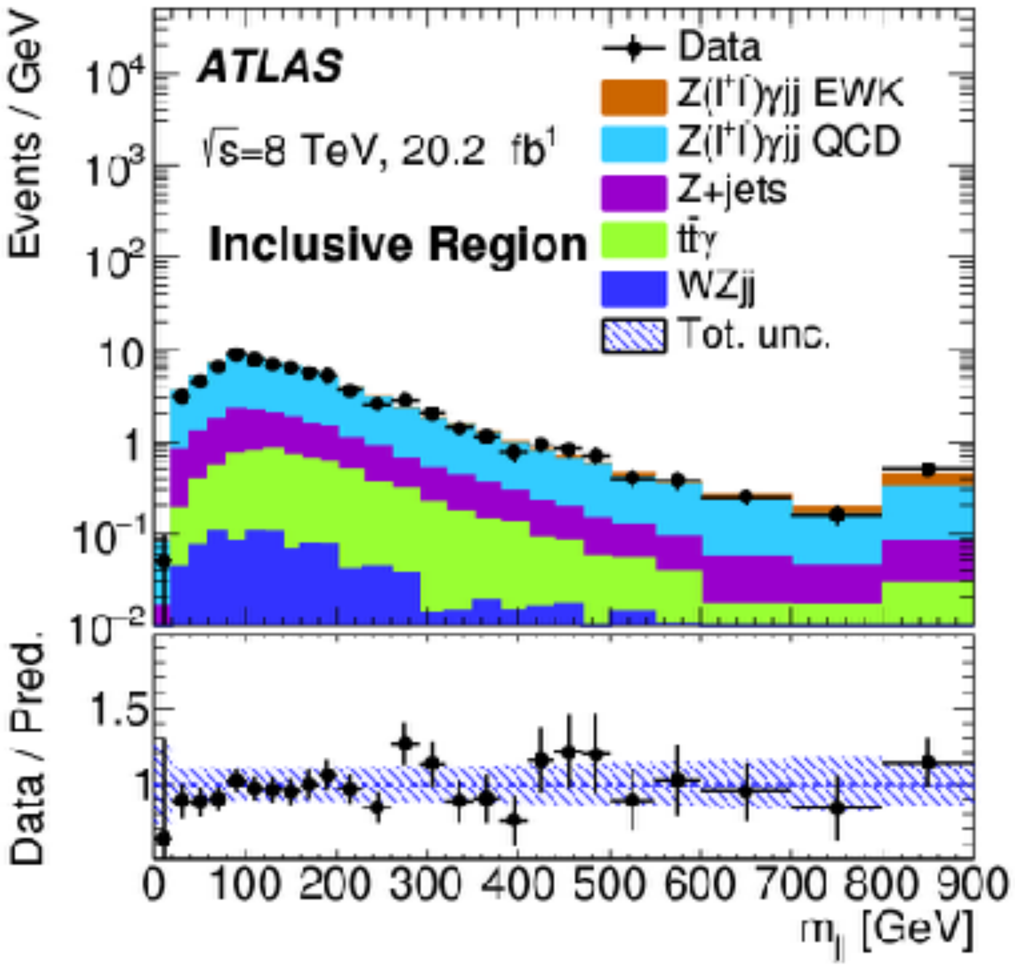
3. **ttbarγ background**: from simulation
   - **CMS**: Madgraph interfaced with Pythia (XS @ LO)
   - **ATLAS**: MadGraph5_aMC@NLO v5.2.1 , (XS @ NLO)

4. **Dibosons**: almost negligible in EW/aQGC regions, from simulation
   - **CMS**: consider WW, WZ, ZZ with Pythia
   - **ATLAS**: consider only WZ with Sherpa

Event yield and control plots







	Inclusive region $Z(\ell^+\ell^-)\gamma + \geq 2$ jets $e^+e^-\gamma jj$	 $\mu^+\mu^-\gamma jj$
Data	781	949
Z+jets bkg.	134 ± 36	154 ± 42
Other bkg. $(t\bar{t}\gamma,\ WZ)$	88 ± 17	91 ± 18
$N_{\text{data}} - N_{\text{bkg}}$	559 ± 46	704 ± 53
$N_{Z\gamma\ \text{QCD}}$ (SHERPA MC)	583 ± 41	671 ± 47
$N_{Z\gamma\ \text{EWK}}$ (SHERPA MC)	25.4 ± 1.5	27.3 ± 1.7
$N_{Z\gamma}$ (SHERPA MC)	608 ± 42	698 ± 49

Data properly described by simulation

Probing EW - CMS

- QCD/EW discriminant variables used to build an EW-enriched region, cuts optimised wrt expected significance
  - **~38%** of EW/QCD in this region in total (e+μ)
- Use 2-bins m_{jj} distribution : 400< m_{jj} <800 GeV and m_{jj} >800 GeV
- Combination of electron and muon channels
- Significance of **both EW and EW+QCD combined** Zγjj processes are measured
- EW fiducial cross-section also measured in fiducial region with a different selection

$400 < M_{jj} < 800\,\text{GeV}$	muon	electron
Fake photon from jet	3.4 ± 0.8	1.7 ± 0.5
Other background	0.1 ± 0.1	0.1 ± 0.1
QCD $Z\gamma jj$	4.8 ± 0.9	5.0 ± 1.0
EW $Z\gamma jj$	1.7 ± 0.1	1.8 ± 0.1
Total background	8.3 ± 1.2	6.8 ± 1.1
Data	13	8
$M_{jj} > 800\,\text{GeV}$	muon	electron
Fake photon from jet	0.4 ± 0.3	0.1 ± 0.1
Other background	0 ± 0	0 ± 0
QCD $Z\gamma jj$	0.4 ± 0.1	1.1 ± 0.2
EW $Z\gamma jj$	1.8 ± 0.1	1.8 ± 0.1
Total background	0.8 ± 0.3	1.2 ± 0.2
Data	5	2

EW signal measurement	Fiducial cross section
$p_T^{\gamma} > 25\,\text{GeV}$	$p_T^{\gamma} > 20\,\text{GeV}$
$\lvert\Delta\eta_{jj}\rvert > 1.6$	$\lvert\Delta\eta_{jj}\rvert > 2.5$
$\Delta R_{j\ell} > 0.3$, $\Delta R_{jj,\gamma j,\gamma\ell} > 0.5$	$\Delta R_{jj,\gamma j,\gamma\ell,j\ell} > 0.4$
$\lvert y_{Z\gamma} - (y_{j1} + y_{j2})/2\rvert < 1.2$	$M_{jj} > 400\,\text{GeV}$
$\Delta\phi_{Z\gamma,jj} > 2.0$ radians	
$M_{jj} > 400\,\text{GeV}$ with two divided regions	
$400 < M_{jj} < 800\,\text{GeV}$ and $M_{jj} > 800\,\text{GeV}$	

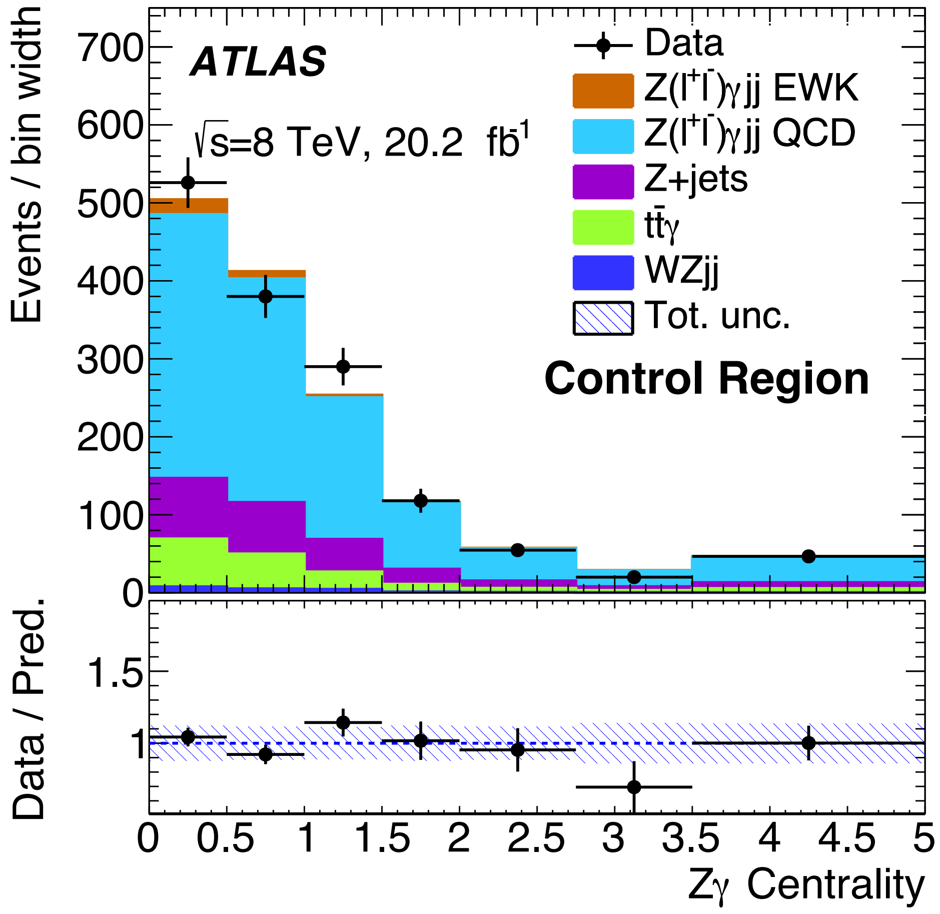
Minimum EW-enriched selection

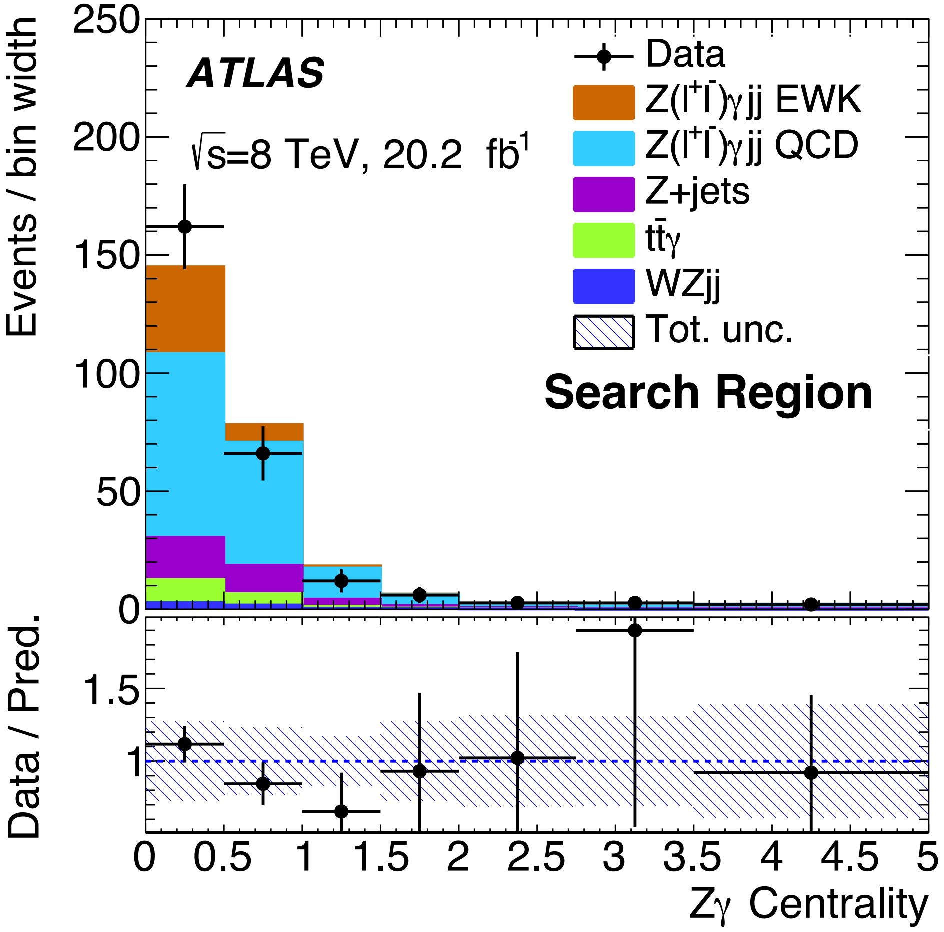
Probing EW - ATLAS

- EW-enriched region build by adding a cut m_{jj}>500 GeV on top of baseline selection (**~30% of EW/QCD**)
- QCD-enriched region (150< m_{jj} <500 GeV) build to validate the QCD modelling
- Centrality of Zγ system fitted using a template fit (**~44% of EW/QCD in first bin** !)
- All regions and channels (μ/e) are fitted simultaneously
- Cross-section of **both EW (in SR) and EW+QCD (in SR and CR)** Zγjj processes are measured

Centrality: $\zeta = \left| \frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}} \right|$ with $\bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2},$

	Control region		Search region	
	$150 < m_{jj} < 500$ GeV		$m_{jj} > 500$ GeV	
	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$
Data	362	421	58	72
Z+jets bkg.	57 ± 16	67 ± 18	8.5 ± 2.5	9.4 ± 2.7
Other bkg. ($t\bar{t}\gamma$, WZ)	47 ± 9	46 ± 9	5.8 ± 1.1	5.0 ± 1.0
$N_{\text{data}} - N_{\text{bkg}}$	258 ± 24	308 ± 27	44 ± 7	58 ± 8
$N_{Z\gamma\ \text{QCD}}$ (SHERPA MC)	249 ± 24	290 ± 26	37 ± 5	41 ± 5
$N_{Z\gamma\ \text{EWK}}$ (SHERPA MC)	8.6 ± 0.6	9.3 ± 0.6	11.2 ± 0.8	11.6 ± 0.7
$N_{Z\gamma}$ (SHERPA MC)	258 ± 25	299 ± 27	48 ± 6	53 ± 6





Validating modelling of QCD

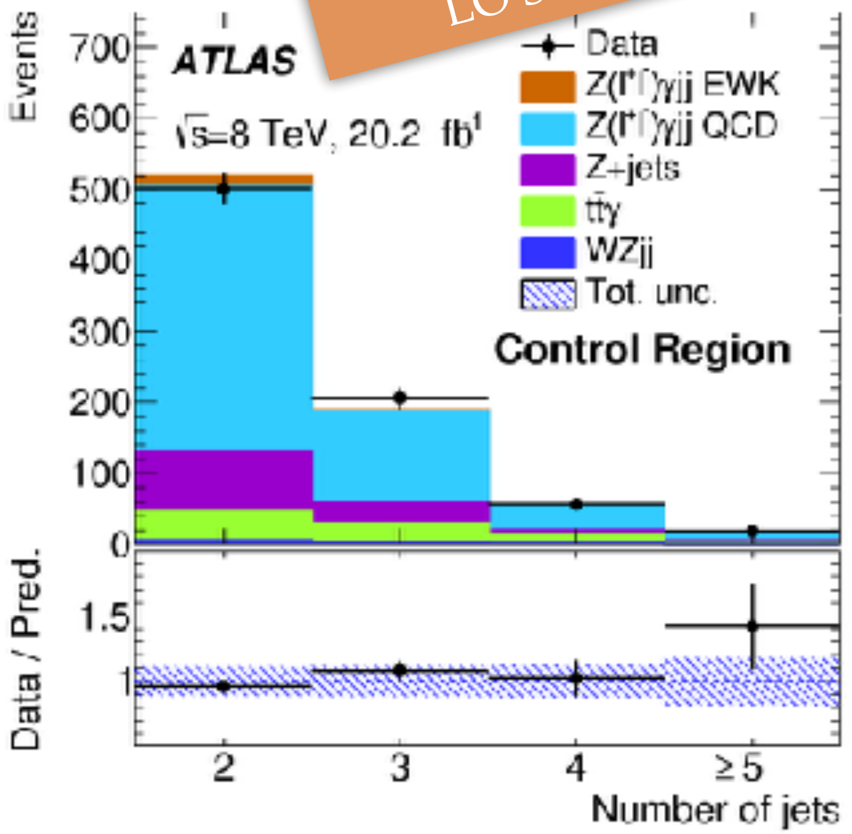
- QCD-enriched CR built to validate modelling of QCD background

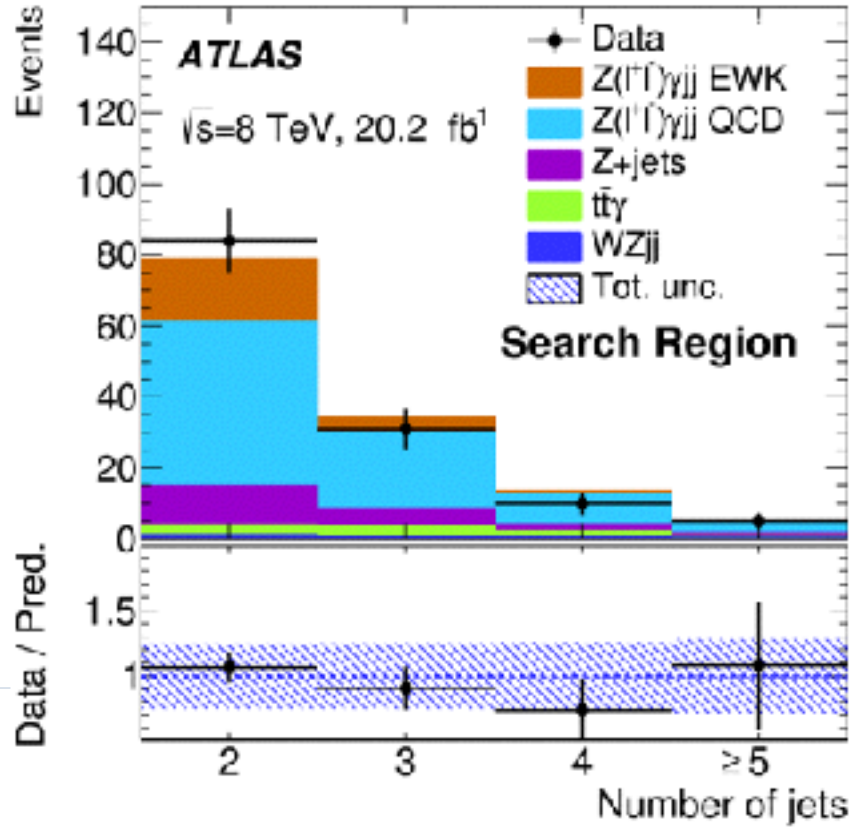
- Both CMS and ATLAS use shape from simulation

- **CMS**:
  - control region: 150< m_{jj} <400 (signal < 1%),
  - extract yield of QCD from data, well reproduced by simulation, **correction factor of: 1 +/- 0.22**
  - compatible with NLO QCD k-factor (1.1 for m_{jj} <400 GeV)

- **ATLAS**
  - control region: 150< m_{jj} <500 GeV (signal ~ 2%)
  - fit the QCD normalisation scale factor simultaneously in CR and SR
  - perfect agreement with Sherpa prediction within errors.
  - CR kept in fit because helps to reduce syst. on QCD: reduces total syst. unc. of EWK XS measurement in the SR from ~60% to 38%.

Good description of data by LO Sherpa v1.4.5

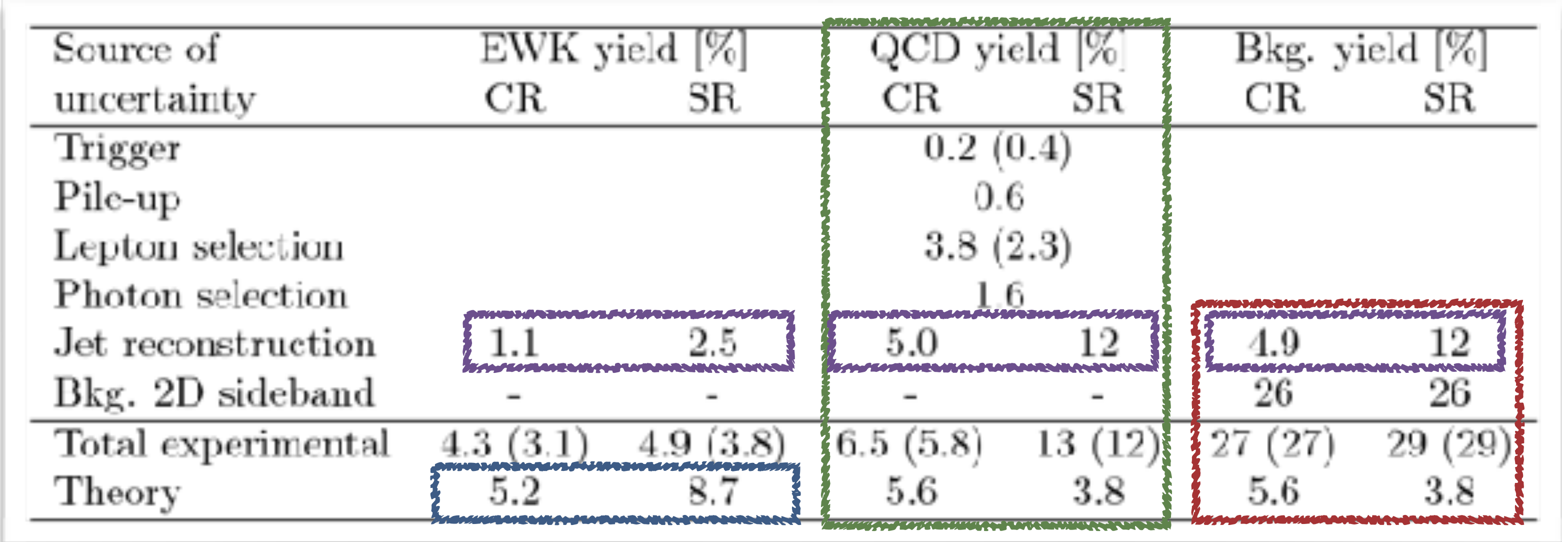




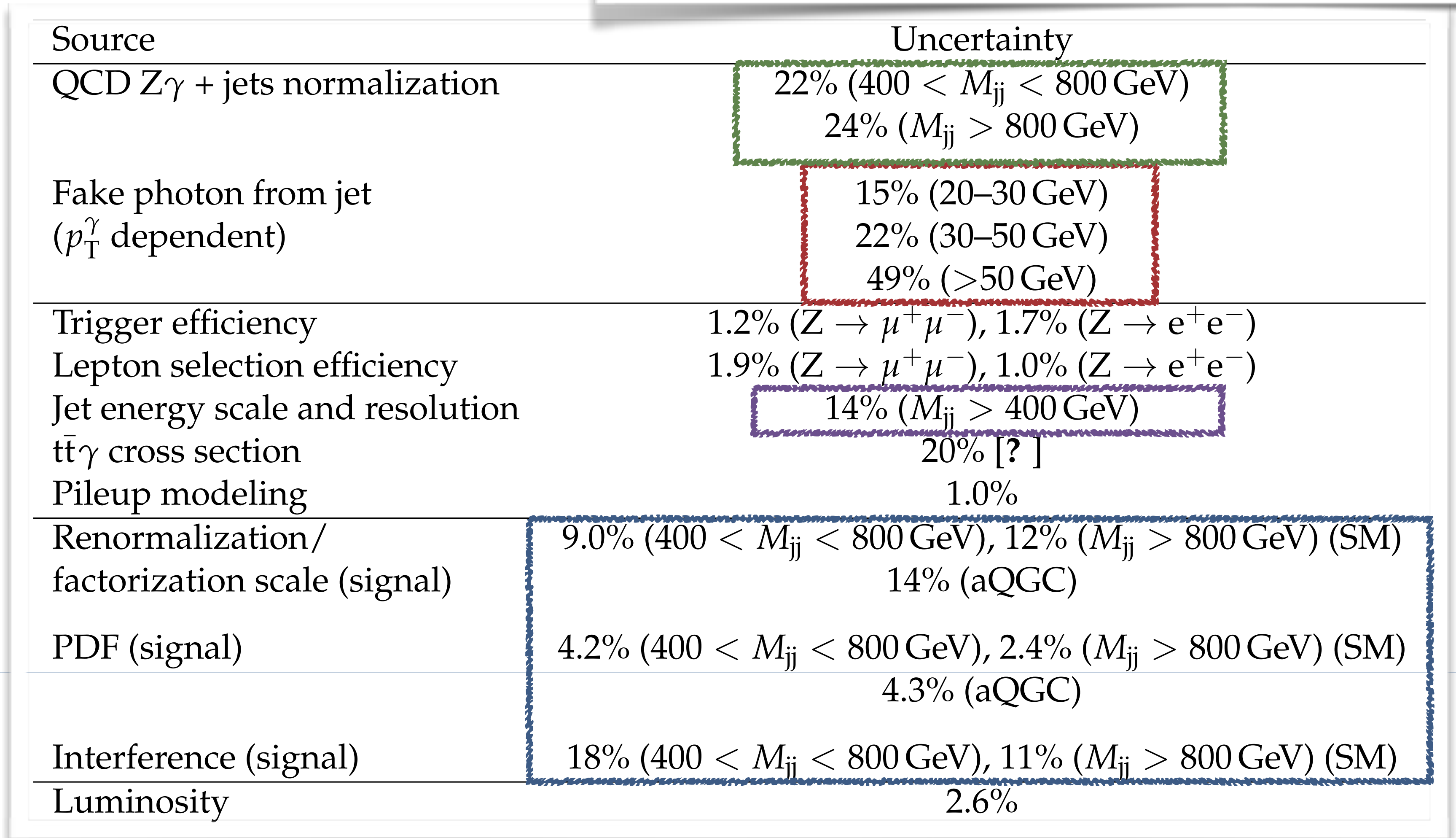
Systematics uncertainties

- Inputs systematics to the cross section/significance results
- Dominated by **jet energy scale uncertainties**, background normalisation (**QCD**, **others**) and by **theory uncertainties** (scales, pdf, interference)

ATLAS



Source of uncertainty	EWK yield [%] CR	EWK yield [%] SR	QCD yield [%] CR	QCD yield [%] SR	Bkg. yield [%] CR	Bkg. yield [%] SR
Trigger	0.2 (0.4)					
Pile-up	0.6					
Lepton selection	3.8 (2.3)					
Photon selection	1.6					
Jet reconstruction	1.1	2.5	5.0	12	4.9	12
Bkg. 2D sideband	-	-	-	-	26	26
Total experimental	4.3 (3.1)	4.9 (3.8)	6.5 (5.8)	13 (12)	27 (27)	29 (29)
Theory	5.2	8.7	5.6	3.8	5.6	3.8



Source	Uncertainty
QCD Zγ + jets normalization	22% ($400 < M_{jj} < 800$ GeV) 24% ($M_{jj} > 800$ GeV)
Fake photon from jet (p_T^γ dependent)	15% (20–30 GeV) 22% (30–50 GeV) 49% (>50 GeV)
Trigger efficiency	1.2% ($Z \to \mu^+\mu^-$), 1.7% ($Z \to e^+e^-$)
Lepton selection efficiency	1.9% ($Z \to \mu^+\mu^-$), 1.0% ($Z \to e^+e^-$)
Jet energy scale and resolution	14% ($M_{jj} > 400$ GeV)
$t\bar{t}\gamma$ cross section	20% [?]
Pileup modeling	1.0%
Renormalization/factorization scale (signal)	9.0% ($400 < M_{jj} < 800$ GeV), 12% ($M_{jj} > 800$ GeV) (SM) 14% (aQGC)
PDF (signal)	4.2% ($400 < M_{jj} < 800$ GeV), 2.4% ($M_{jj} > 800$ GeV) (SM) 4.3% (aQGC)
Interference (signal)	18% ($400 < M_{jj} < 800$ GeV), 11% ($M_{jj} > 800$ GeV) (SM)
Luminosity	2.6%

CMS

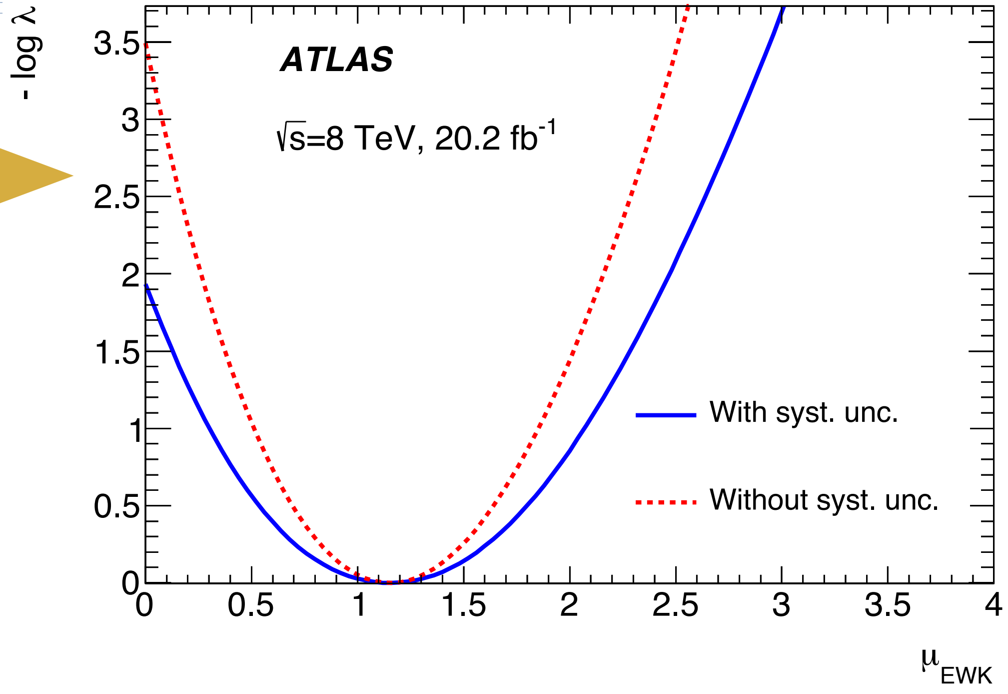
Results - CMS

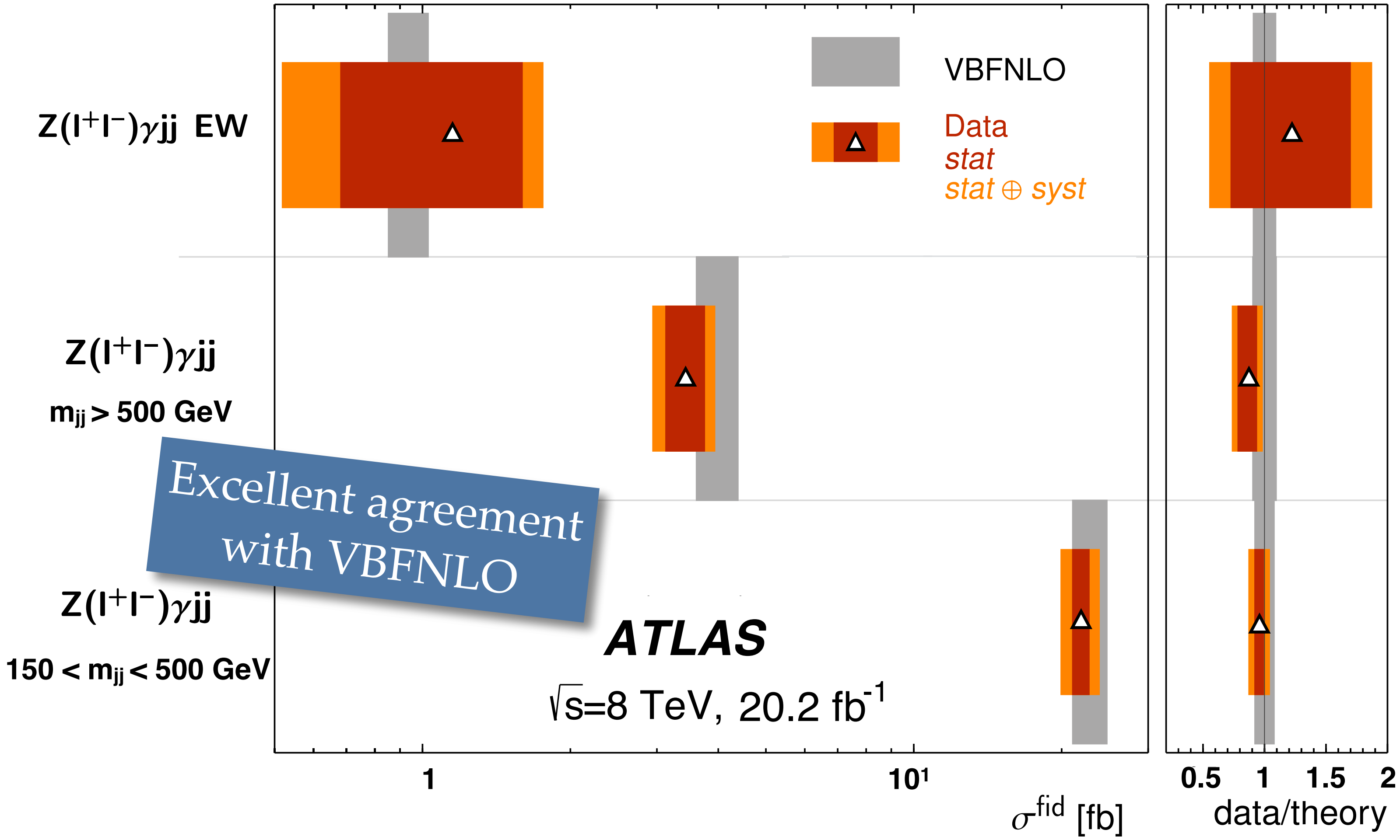
- EW signal significance with CL_s criterion, using 2 m_{jj} bins (400-800, >800 GeV)
- Significance for observing the EW signal (**EW region**)
  - **3.0 σ (2.1 σ expected)**
- Signal strength extracted with binned likelihood fit over 2 m_{jj} bins
  - $\mu = \sigma_{obs} / \sigma_{exp} = 1.5^{+0.9}_{-0.6}$
- Significance for observing EWK+QCD : 5.7σ (5.5σ expected)
- Cross section in **fiducial region**

Process type	Measured cross-section [fb]	Predicted cross-section [fb]
EWK	$1.86^{+0.90}_{-0.75}(\mathrm{stat})^{+0.34}_{-0.26}(\mathrm{syst}) \pm 0.05(\mathrm{lumi})$	$1.27 \pm 0.11(\mathrm{scale}) \pm 0.05(\mathrm{pdf})$
EWK+QCD	$5.94^{+1.53}_{-1.35}(\mathrm{stat})^{+0.43}_{-0.37}(\mathrm{syst}) \pm 0.13(\mathrm{lumi})$	$5.05 \pm 1.22(\mathrm{scale}) \pm 0.31(\mathrm{pdf})$

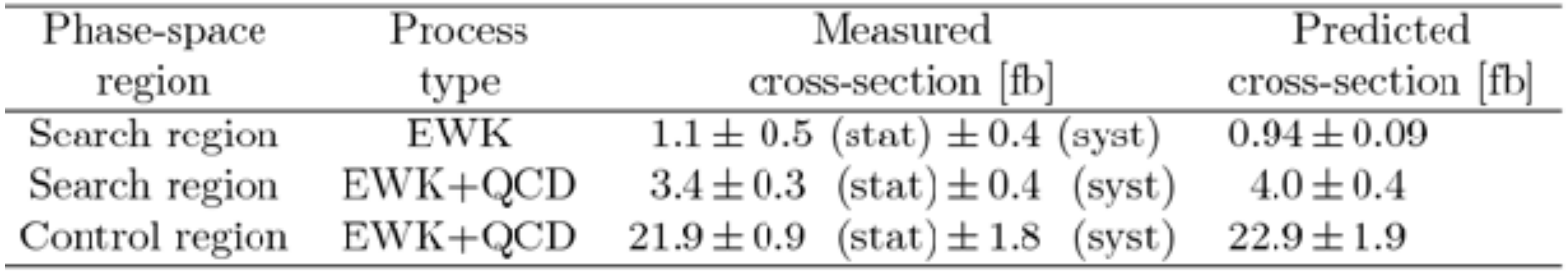
Results - ATLAS

- **Cross section measurements:**
  - Extended binned likelihood with parameter of interest $\mu = \sigma_{data} / \sigma_{MC}$
  - Significance for observing the EW signal: **2.0 σ (1.8 σ expected)**
  - Upper limit on cross section: **2.2 fb**



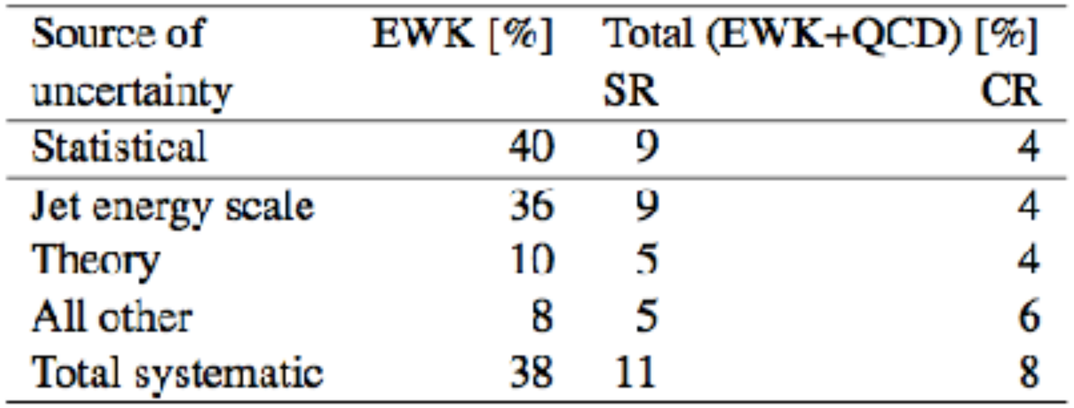


Excellent agreement with VBFNLO



Phase-space region	Process type	Measured cross-section [fb]	Predicted cross-section [fb]
Search region	EWK	1.1 ± 0.5 (stat) ± 0.4 (syst)	0.94 ± 0.09
Search region	EWK+QCD	3.4 ± 0.3 (stat) ± 0.4 (syst)	4.0 ± 0.4
Control region	EWK+QCD	21.9 ± 0.9 (stat) ± 1.8 (syst)	22.9 ± 1.9

- 3 measurements: EW only in SR, and QCD+EW in SR and CR
- Measurements compared with **VBFNLO v2.7.1** (4-10% unc.)

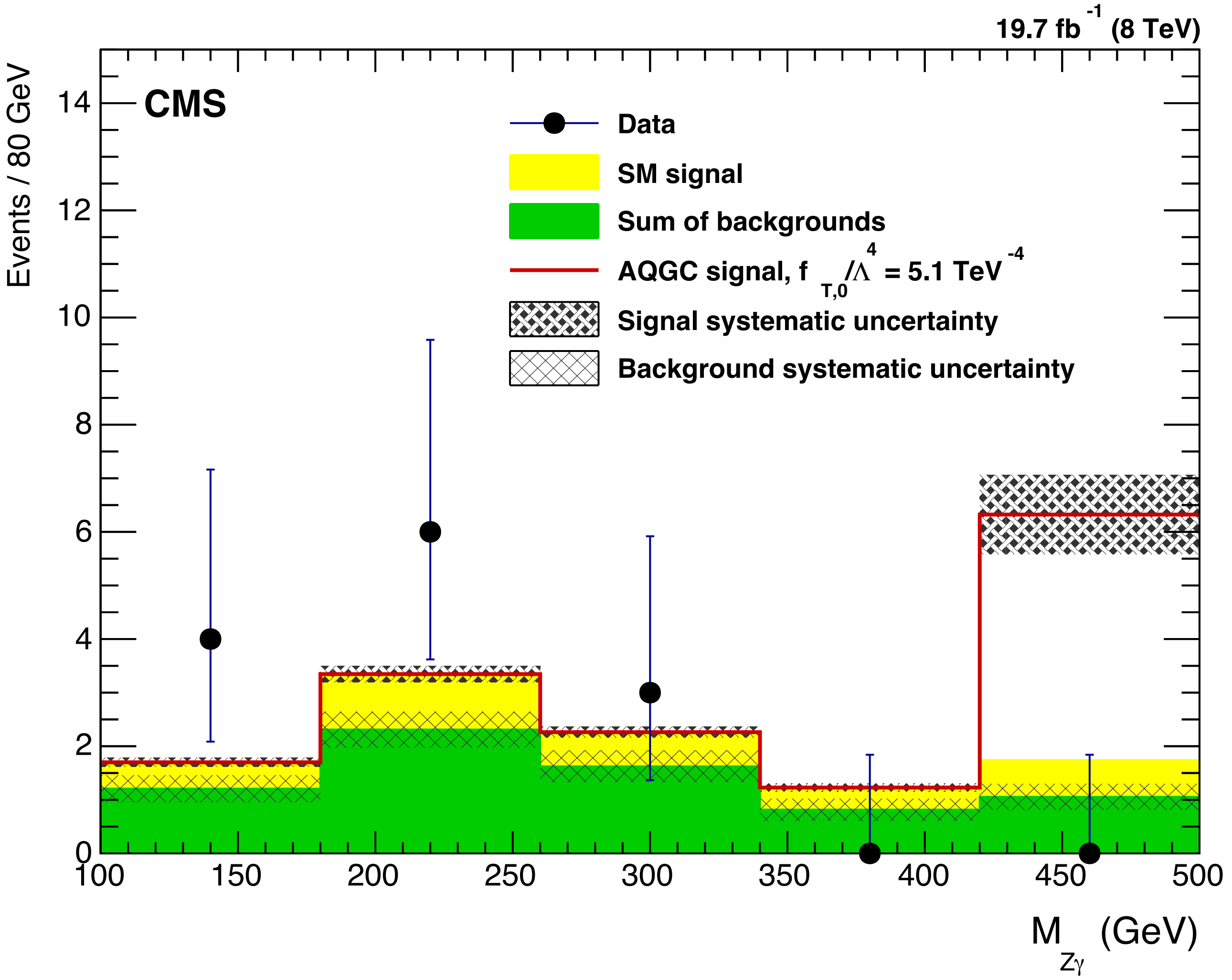


Source of uncertainty	EWK [%]	Total (EWK+QCD) [%] SR	CR
Statistical	40	9	4
Jet energy scale	36	9	4
Theory	10	5	4
All other	8	5	6
Total systematic	38	11	8

Unc. on the XS results dominated by stat. unc.(50%) and jet energy scale unc. (40%)

aQGC strategy and results - CMS

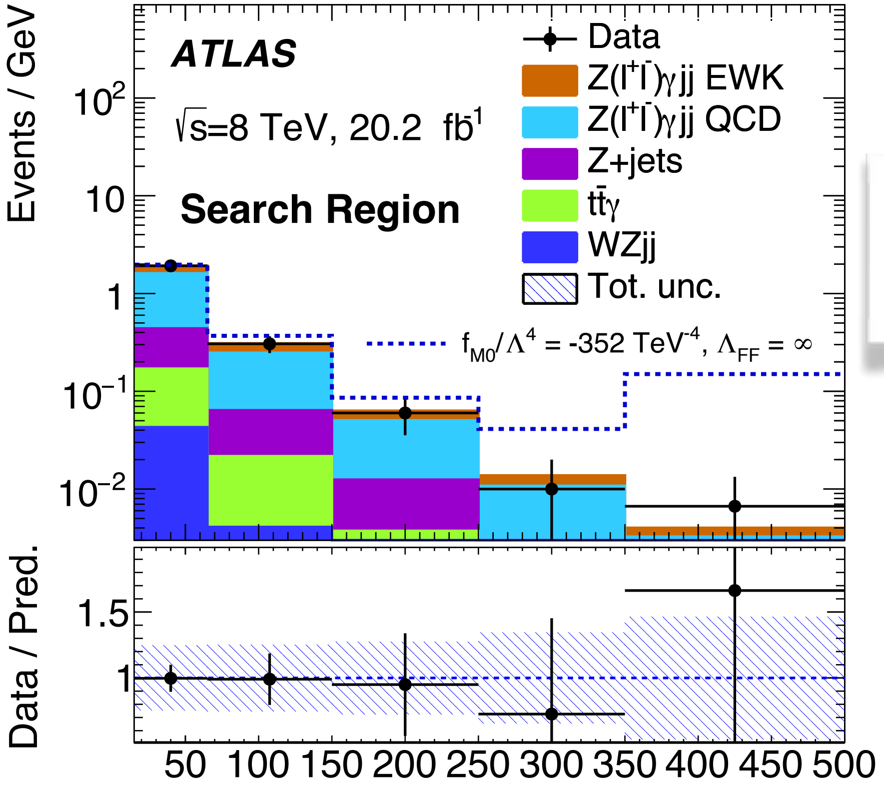
- On top of baseline region:
  - **$E_{T\gamma}$>60 GeV, ΔY>2.5, m_{jj}>400 GeV**
- Likelihood ratio test on $M_{Z\gamma}$ distribution
- EFT dim8, Lagrangian of aQGC implemented in MadGraph
- Each coupling varied over a set of discrete values, other parameters set to 0
- Unitarity bound checked with **VBFNLO**
  - no form factors introduced, limits on all aQGC parameters (except FT9) are set in the **unitary unsafe region**

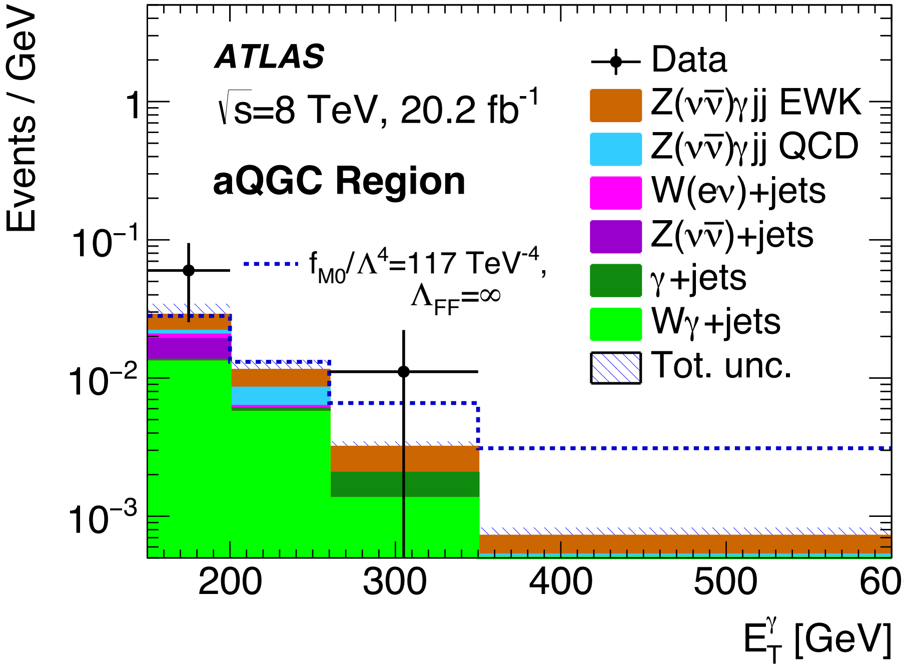


Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-71 < f_{M0}/\Lambda^4 < 75$	$-109 < f_{M0}/\Lambda^4 < 111$
$-190 < f_{M1}/\Lambda^4 < 182$	$-281 < f_{M1}/\Lambda^4 < 280$
$-32 < f_{M2}/\Lambda^4 < 31$	$-47 < f_{M2}/\Lambda^4 < 47$
$-58 < f_{M3}/\Lambda^4 < 59$	$-87 < f_{M3}/\Lambda^4 < 87$
$-3.8 < f_{T0}/\Lambda^4 < 3.4$	$-5.1 < f_{T0}/\Lambda^4 < 5.1$
$-4.4 < f_{T1}/\Lambda^4 < 4.4$	$-6.5 < f_{T1}/\Lambda^4 < 6.5$
$-9.9 < f_{T2}/\Lambda^4 < 9.0$	$-14.0 < f_{T2}/\Lambda^4 < 14.5$
$-1.8 < f_{T8}/\Lambda^4 < 1.8$	$-2.7 < f_{T8}/\Lambda^4 < 2.7$
$-4.0 < f_{T9}/\Lambda^4 < 4.0$	$-6.0 < f_{T9}/\Lambda^4 < 6.0$

aQGC strategy - ATLAS

- Three Z decays channels used : Z->ee/μμ/νν
- aQGC region:
  - Z->ee/μμ: $E_{T\gamma}$>250 GeV on top of SR





aQGC Z->νν selection

- $E_{T\text{miss}}$ > 100 GeV, 1γ p_T>150 GeV
- 2 jets with p_T>30 GeV,
- lepton veto (reduce Wγjj bkg), angular cuts (remove γ +jet bkg)
- centrality < 0.3 ; p_T balance < 0.1 ; m_{jj}> 600 GeV (to reduce QCD)

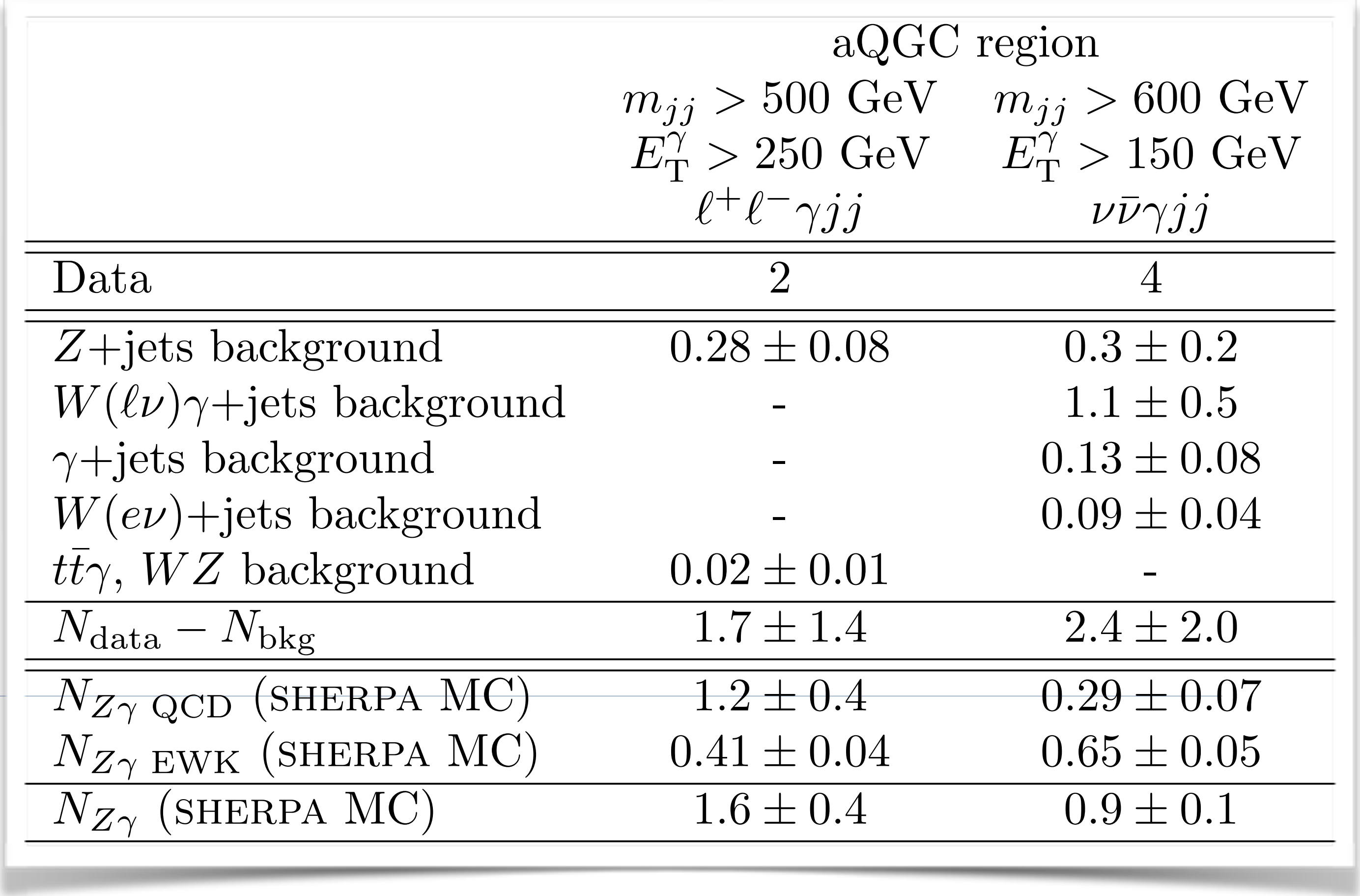
$$p_T^{\text{balance}} \equiv \frac{|\vec{p}_T^{\,\text{miss}} + \vec{p}_T^{\,\gamma} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}|}{E_T^{\text{miss}} + p_T^{\gamma} + p_T^{j_1} + p_T^{j_2}}$$

Main bkg in νν channel :

Wγ+jets (**59%**) norm. from data with 41% syst.

Z+jets (**15%**) 2D sideband method with 50% syst.

γ+jets (**7%**)



	aQGC region	
	$m_{jj} > 500$ GeV $E_T^\gamma > 250$ GeV $\ell^+\ell^-\gamma jj$	$m_{jj} > 600$ GeV $E_T^\gamma > 150$ GeV $\nu\bar{\nu}\gamma jj$
Data	2	4
Z+jets background	0.28 ± 0.08	0.3 ± 0.2
$W(\ell\nu)\gamma$+jets background	-	1.1 ± 0.5
γ+jets background	-	0.13 ± 0.08
$W(e\nu)$+jets background	-	0.09 ± 0.04
$t\bar{t}\gamma$, WZ background	0.02 ± 0.01	-
$N_{\text{data}} - N_{\text{bkg}}$	1.7 ± 1.4	2.4 ± 2.0
$N_{Z\gamma\ \text{QCD}}$ (SHERPA MC)	1.2 ± 0.4	0.29 ± 0.07
$N_{Z\gamma\ \text{EWK}}$ (SHERPA MC)	0.41 ± 0.04	0.65 ± 0.05
$N_{Z\gamma}$ (SHERPA MC)	1.6 ± 0.4	0.9 ± 0.1

aQGC results - ATLAS

- **Upper limit on cross section (log-likelihood fit, CL_s technique)** :
  - **1.06 fb** (0.99 exp.) ννγ and **1.03 fb** (1.01 fb exp.) ℓℓ-γ
- **Parametrisation**: parity conserving EFT Lagrangian with dim8 operators + Form factor (FF) to restore unitarity at very high √s
- One dim. profile likelihood fit -> 95%CL intervals
- Three channels are combined
- Best expected interval: ννγ, **improved by 10-30% when including ℓℓ-γ**
- Uncertainties dominated by QCD renormalization and factorization scale (~8%)
- Expected intervals are a factor ~2 better than CMS (without FF)

	95% CL intervals	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
$n = 0$	f_{T9}/Λ^4	$[-4.1, 4.2] \times 10^3$	$[-2.9, 3.0] \times 10^3$	
	f_{T8}/Λ^4	$[-1.9, 2.1] \times 10^3$	$[-1.2, 1.7] \times 10^3$	
	f_{T0}/Λ^4	$[-1.9, 1.6] \times 10^1$	$[-1.6, 1.3] \times 10^1$	
	f_{M0}/Λ^4	$[-1.6, 1.8] \times 10^2$	$[-1.4, 1.5] \times 10^2$	
	f_{M1}/Λ^4	$[-3.5, 3.4] \times 10^2$	$[-3.0, 2.9] \times 10^2$	
	f_{M2}/Λ^4	$[-8.9, 8.9] \times 10^2$	$[-7.5, 7.5] \times 10^2$	
	f_{M3}/Λ^4	$[-1.7, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	
$n = 2$	f_{T9}/Λ^4	$[-6.9, 6.9] \times 10^4$	$[-5.4, 5.3] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.5] \times 10^4$	0.7
	f_{T0}/Λ^4	$[-7.2, 6.1] \times 10^1$	$[-6.1, 5.0] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-8.8, 8.8] \times 10^2$	1.0
	f_{M1}/Λ^4	$[-1.6, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^4$	$[-9.2, 9.6] \times 10^3$	0.7
	f_{M3}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.4, 1.3] \times 10^4$	0.8

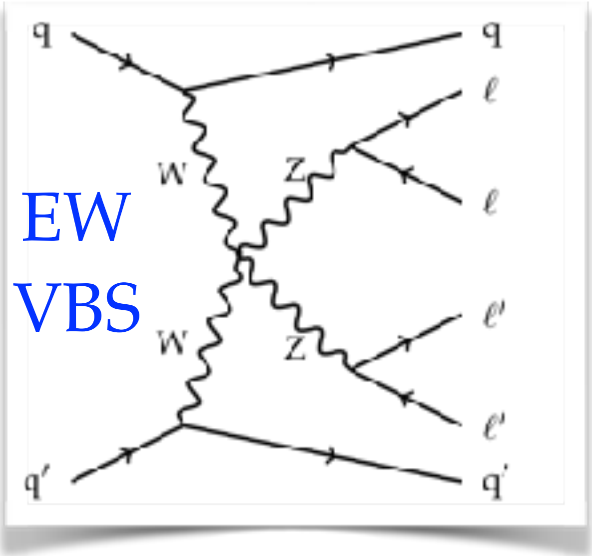
VBS ZZ+2j

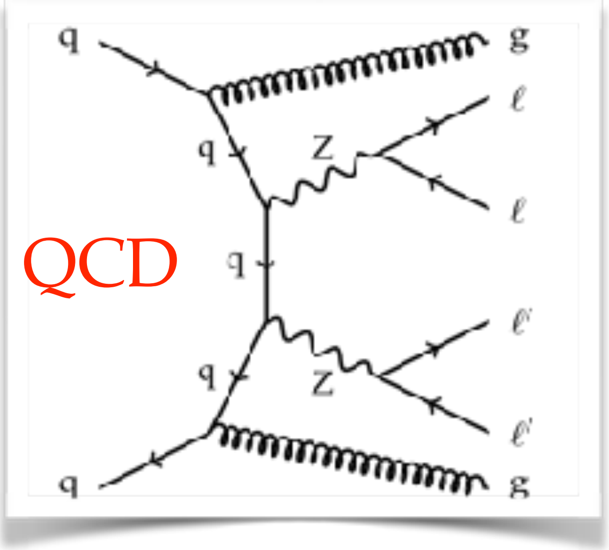
CMS

Introduction

arXiv:1708.02812

- Search for EW production of ZZ+2j fully leptonic decay of Z (electron and muons)
- CMS, 13 TeV data (2015 and 2016, 35.9 fb-1) , <pileup> ~23
- **Interests:**
  - Cross section very low (<1fb), but very clean channel, relatively less instrumental backgrounds than in other channels
  - Can probe T8 and T9 operators, experimentally accessible only via neutral boson final states
- **Analysis strategy**
  - Use a TMVA discriminant to extract the EW component, from a baseline region
  - Use this region to extract aQGC limits





Simulation and MC samples

- **ZZ+2j EWK**: MadGraph5_aMC @NLO (nominal) and Phantom @LO, include tribosons
- **ZZ+2j QCD**:
  - MadGraph5_aMC@NLO, up to 2 ongoing partons at born level, merging with FxFx scheme (scale 30 GeV). Leptonic decay: MadSpin
  - MCFM for gg->ZZjj (loop induced) and check with MadGraph5_aMC@NLO
- **Interference EWK/QCD**: <1% , neglected
- **aQGC**: LO Madgraph_aMC@NLO, ME reweighing to obtain grid for each of the 5 anomalous coupling constants

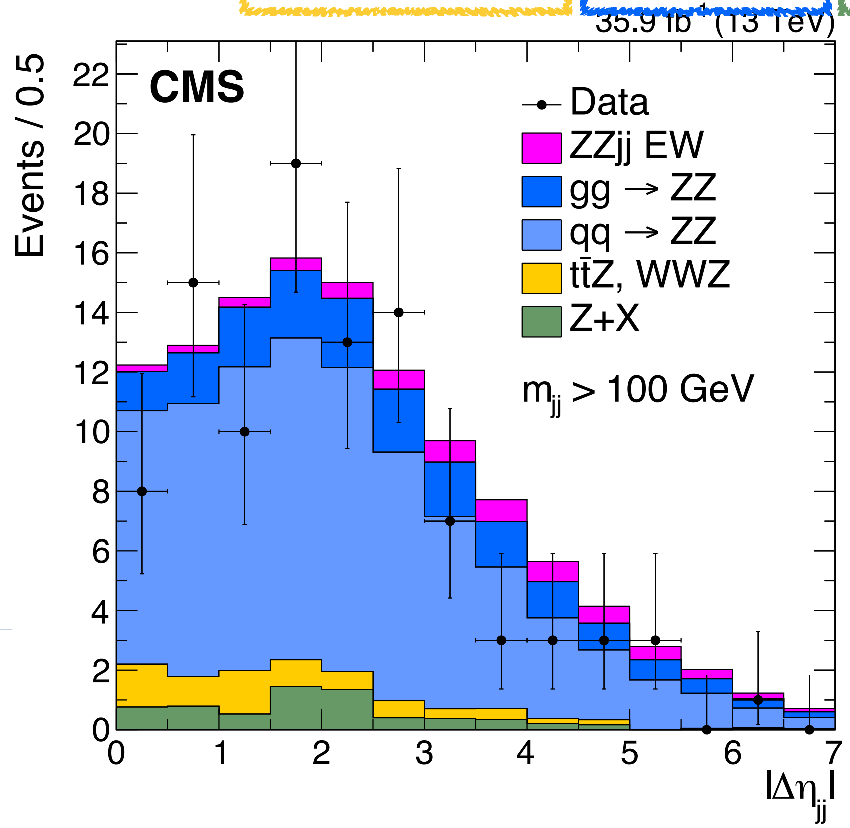
ZZ VBS - Selection

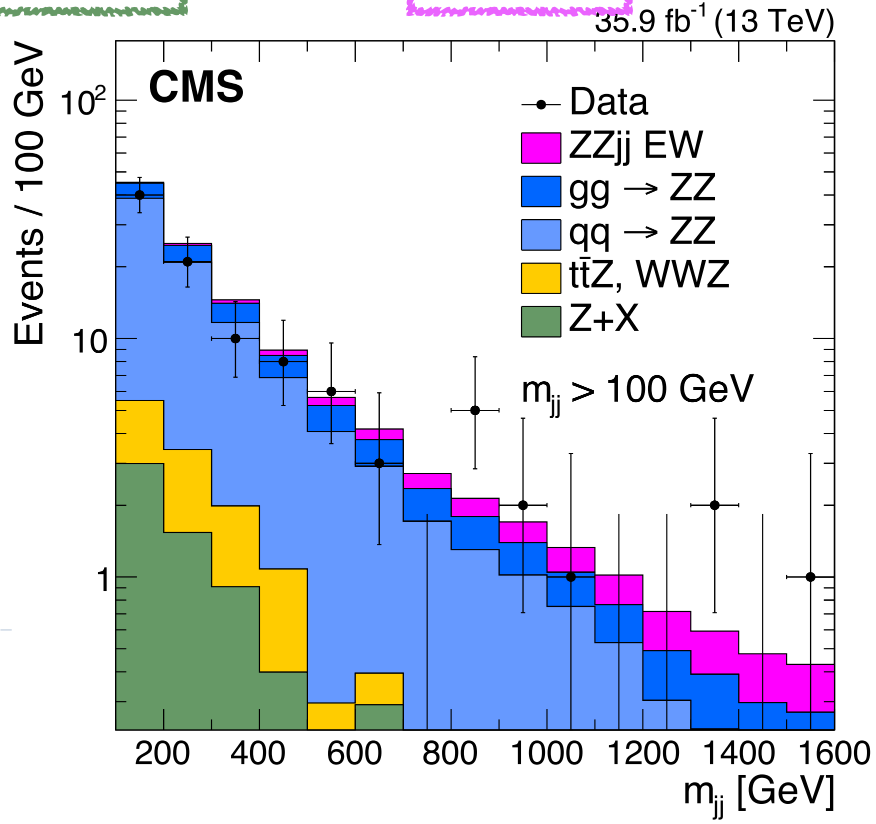
- **ZZ selection: 2 pairs of calibrated, isolated ID e/μ opposite charge**
  - p_{T1}>20 GeV (highest), p_{T2}>12 (10) GeV for e(μ) (second highest); ΔR(l1,l2)>0.02, ΔR(e,μ)>0.05.
  - m_{Z1}>40 GeV (for mass closest to m_Z) 60< m_{Z1}, m_{Z2}<120 GeV, m_{l+l-}>4 GeV (for all pairs)
  - In case more than one 4l candidate: candidate with m_{Z1} closest to m_Z chosen
- **Jets**: ΔR(l,j)>0.4, Loose ID, p_T>30 GeV η<4.7. Energy correction
- **ZZ+2j selection (used in analysis)**
  - >=2 jets, m_{jj}>100 —> **5% EW, 83% QCD**
- **QCD-enriched region (not used, just for check)**
  - m_{jj}<400 GeV | | ΔYjj<2.4
- **VBS-enriched region (not used, just for check)**
  - m_{jj}>400 GeV and ΔYjj>2.4

Backgrounds, event yields

- **QCD is the dominant background** in this analysis, yield checked while extracting EW
- **Irreducible bkg** (4 prompt and isolated leptons):
  - ttbarZ, WWZ, from MadGraph5_aMC@NLO (small)
- **Reducible bkg** (secondary leptons, jets misID as leptons)
  - Z+jets, ttbar, WZ+jets
  - Extracted with data-driven method with 2 control samples (ZZ selection with 1 and 2 leptons failing isolation and ID)
  - Bkg yield in SR obtained by weighting number of events in CR by lepton misID rate

Selection	$t\bar{t}Z$ and WWZ	QCD ZZjj	Z+X	Total bkg.	EW ZZjj	Total expected	Data
ZZjj	7.1 ± 0.8	97 ± 14	6.6 ± 2.5	111 ± 14	6.2 ± 0.7	117 ± 14	99
VBS signal-enriched	0.9 ± 0.2	19 ± 4	0.7 ± 0.3	20 ± 4	4 ± 0.5	25 ± 4	19
QCD-enriched	6.2	78	5.9	91	2.2	92	80





Probing EW

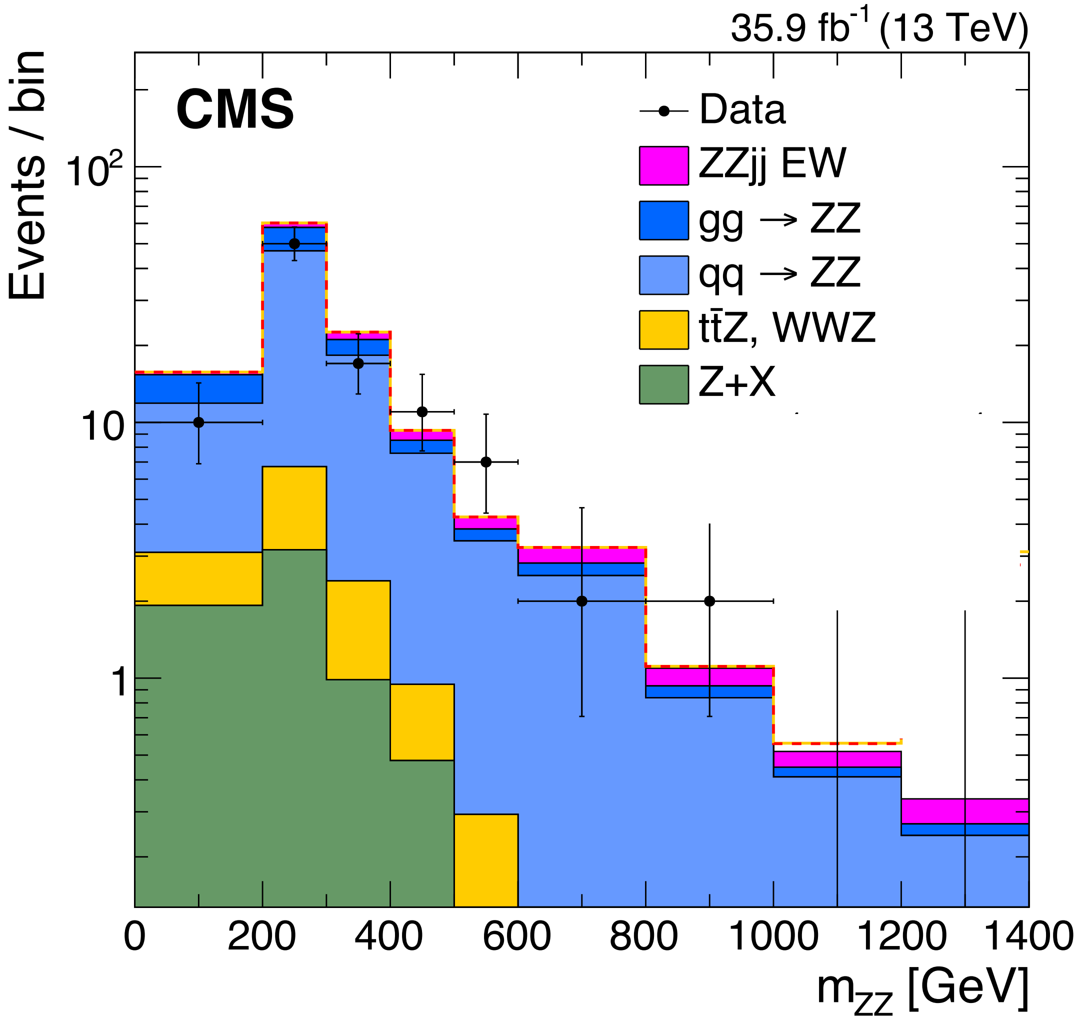
- Multivariate classifier used to separate signal and QCD using the following variables:
  - m_{jj}, ΔY_{jj}, m_{ZZ}
  - **Zeppenfeld variables of the 2 bosons**:

$$\eta^*_{Z_i} = \eta_{Z_i} - (\eta_{jet1} + \eta_{jet2})/2$$

  - $pT_{jj}/|pT_{j1}|+|pT_{j2}|$
  - **pT balance**:

$$p_T^{bal} = \frac{|p_T^{Z1}+p_T^{Z2}+p_T^{j1}+p_T^{j2}|}{|p_T^{Z1}|+|p_T^{Z2}|+|p_T^{j1}|+|p_T^{j2}|}$$

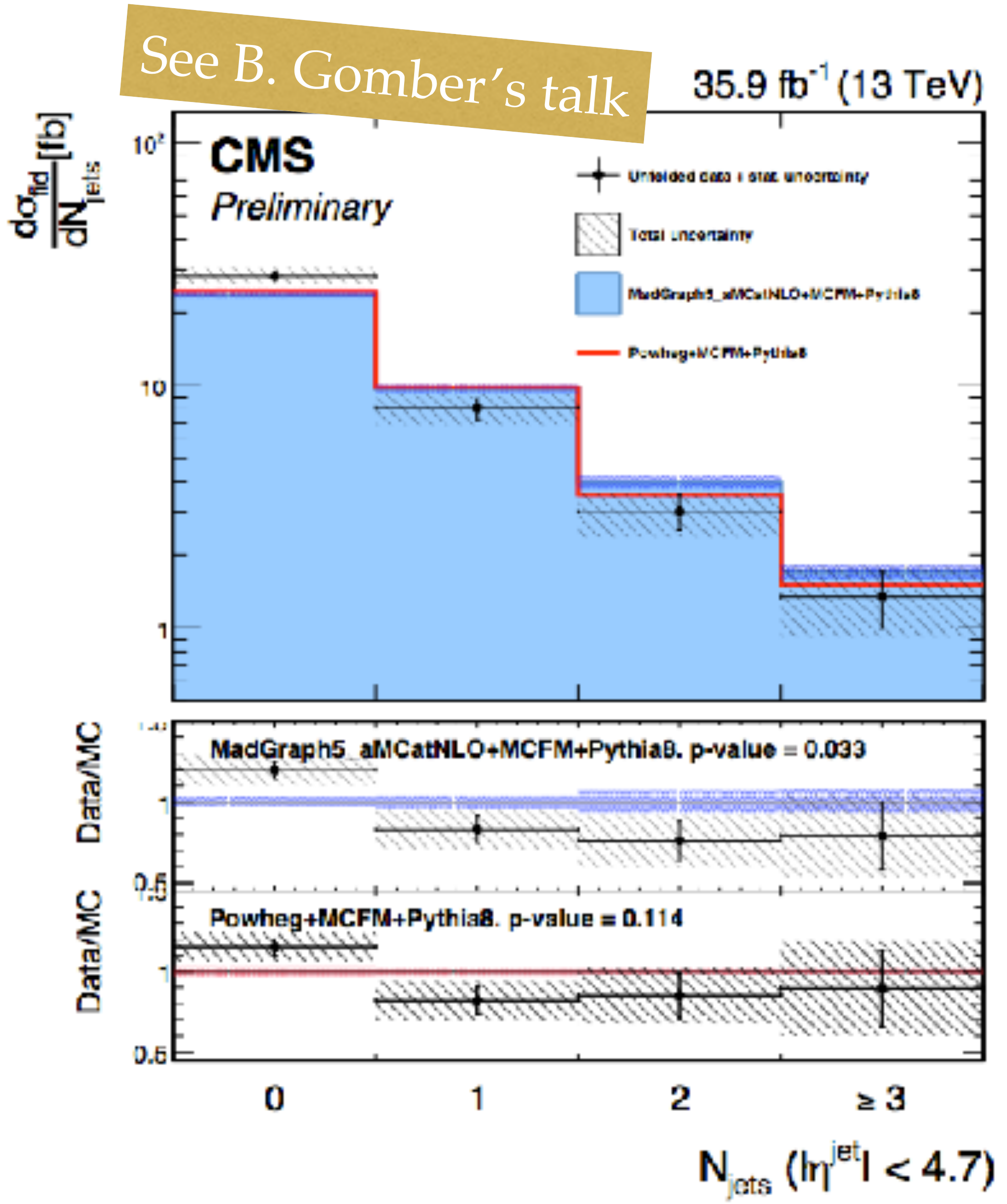
- BDT performance checked with a ME based approach: provides similar separation b/w signal and backgrounds



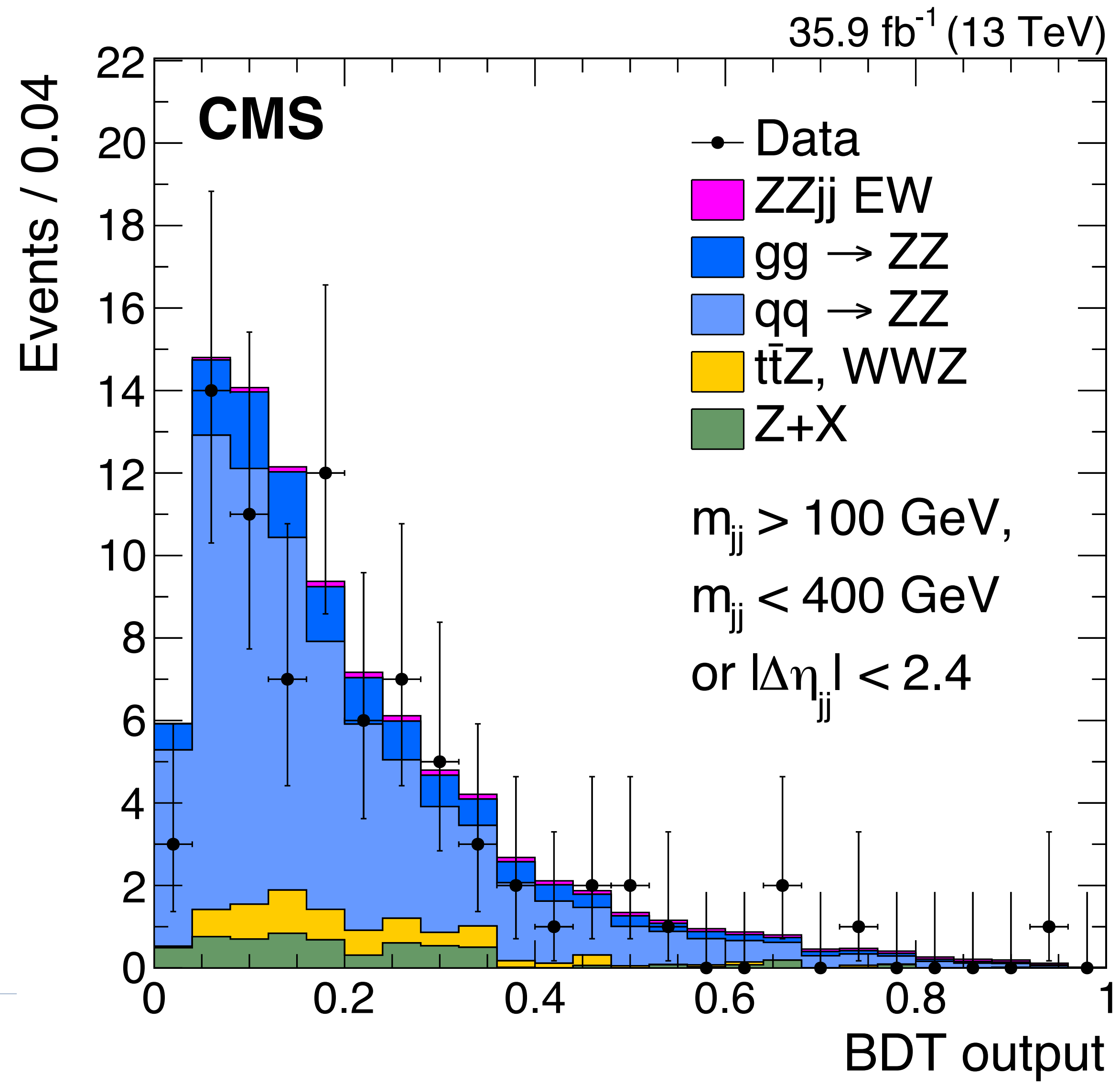
- Systematics
  - JES: 4-20% (low-high BDT score). JER: 8%
  - Leptons: 2-6%
  - Reducible bkg norm. : 40% (only yield)
  - Scales for QCD (EW): 10 (7)% ; PDF: 6-9%
  - **Propagated through the classifier** -> variation of MVA output, used in stat. analysis

Validating modelling of QCD

- Understanding of QCD production of ZZ pair and kinematic of associated jets crucial
    1. Dependence of the cross section on the jet multiplicity, important test of QCD corrections to ZZ production -> **overall good**, better with Powheg and in central region
    2. In the QCD-enriched region, check agreement of the BDT score between data and simulation -> **overall good agreement**



See B. Gomber's talk

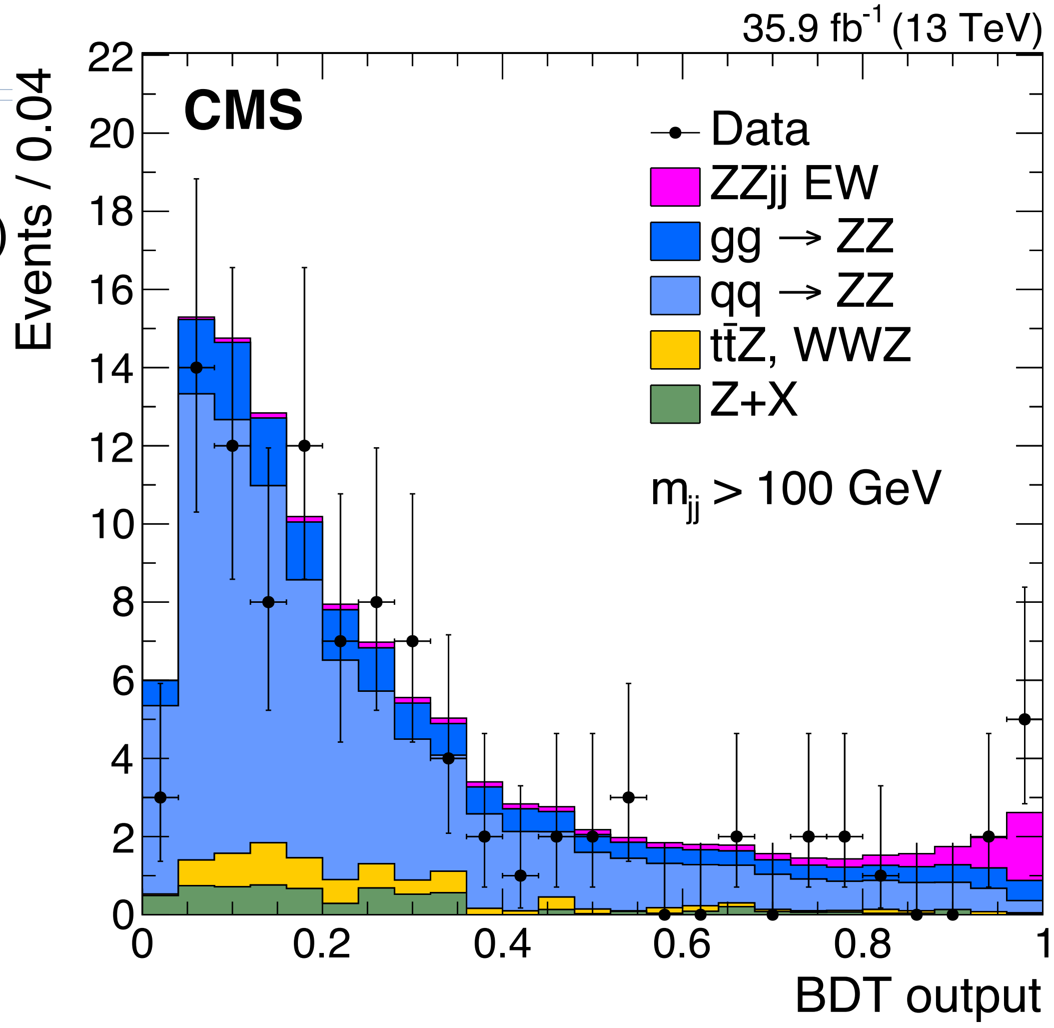


Results

- Full BDT spectrum fitted with max. likelihood template (signal and irreducible bkg from sim, reduc. bkg from data)
- Template shape and norm, vary within unc. (treated as NP in fit and profiled)

$$\mu = 1.39^{+0.72}_{-0.57}(\text{stat})^{+0.46}_{-0.31}(\text{syst}) = 1.39^{+0.86}_{-0.65}$$

- **Background-only hypothesis excluded with**
  - 1.6 σ expected
  - 2.7 σ observed



- **Fiducial cross section in fiducial volume**

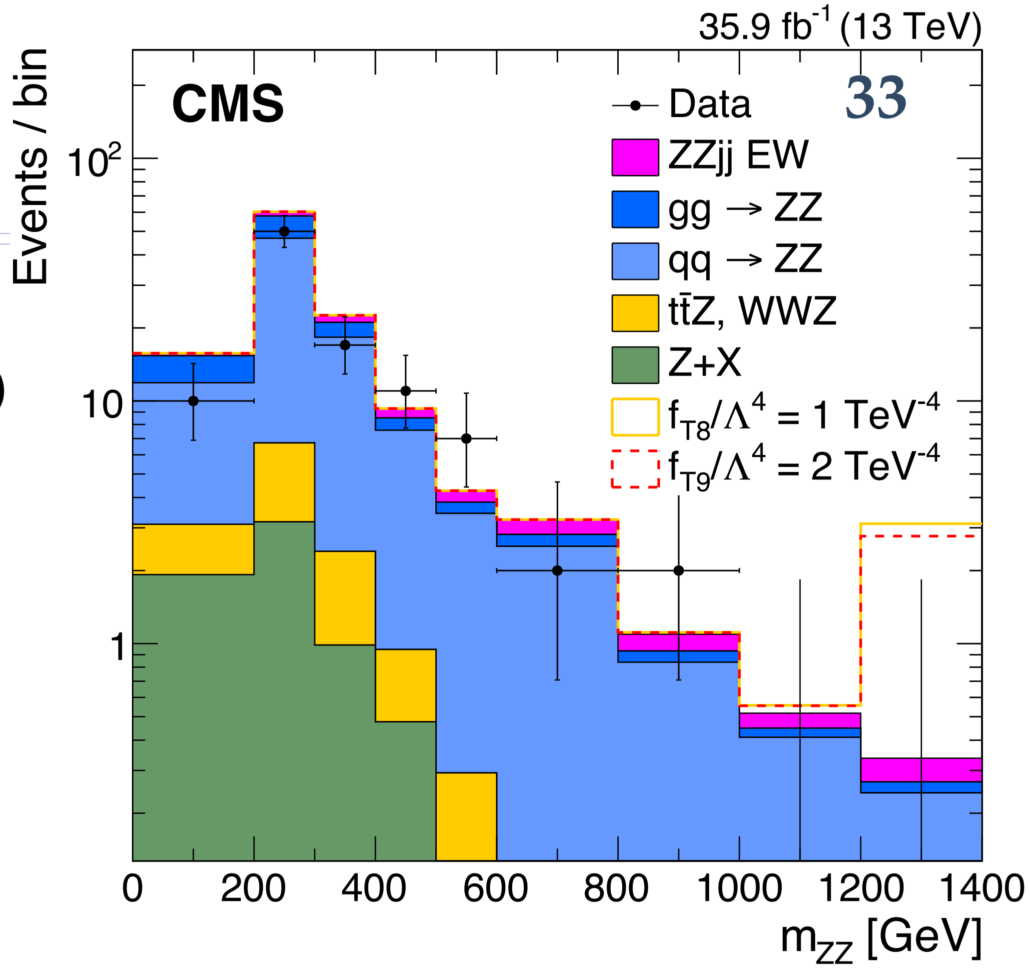
$$\sigma_{\text{fid}} = 0.40^{+0.21}_{-0.16}(\text{stat})^{+0.13}_{-0.09}(\text{syst})\ \text{fb}$$

0.29±0.03 fb expected

$p_T^e > 5$ GeV, $|\eta^e| < 2.5$
$p_T^\mu > 5$ GeV, $|\eta^\mu| < 2.5$
$p_T^{\ell_{3,4}} > 5$ GeV
$p_T^{\ell_1} > 20$ GeV , $p_T^{\ell_2} > 10$ GeV
$m_{\ell^+\ell^-} > 4$ GeV (any opposite-sign same-flavor pair)
$60 < m_{Z_1}, m_{Z_2} < 120$ GeV

+ m_{jj}> 100 GeV

aQGCs



- ZZjj can probe to all operators
  - in particular sensitive to T0,T1,T2 ($SU_L(2)$ gauge fields)
  - and T8 and T9 ($U_Y(1)$ field) -> experimentally accessible only with neutral boson final states
- m_{ZZ} used as a probe
- Quadratic increase of yields with anomalous couplings modelled with parabolic function
- Same statistic methodology as for EW signal strength
  - Wald Gaussian and Wilk's theorem to derive 95%CL limits
- Individual limits, setting other to zero, no form factor
- **Unitarity bound:** using VBFNLO framework)

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T_0}/Λ^4	-0.53	0.51	-0.46	0.44	0.6
f_{T_1}/Λ^4	-0.72	0.71	-0.61	0.61	0.6
f_{T_2}/Λ^4	-1.4	1.4	-1.2	1.2	0.6
f_{T_8}/Λ^4	-0.99	0.99	-0.84	0.84	2.8
f_{T_9}/Λ^4	-2.1	2.1	-1.8	1.8	2.9

Conclusions

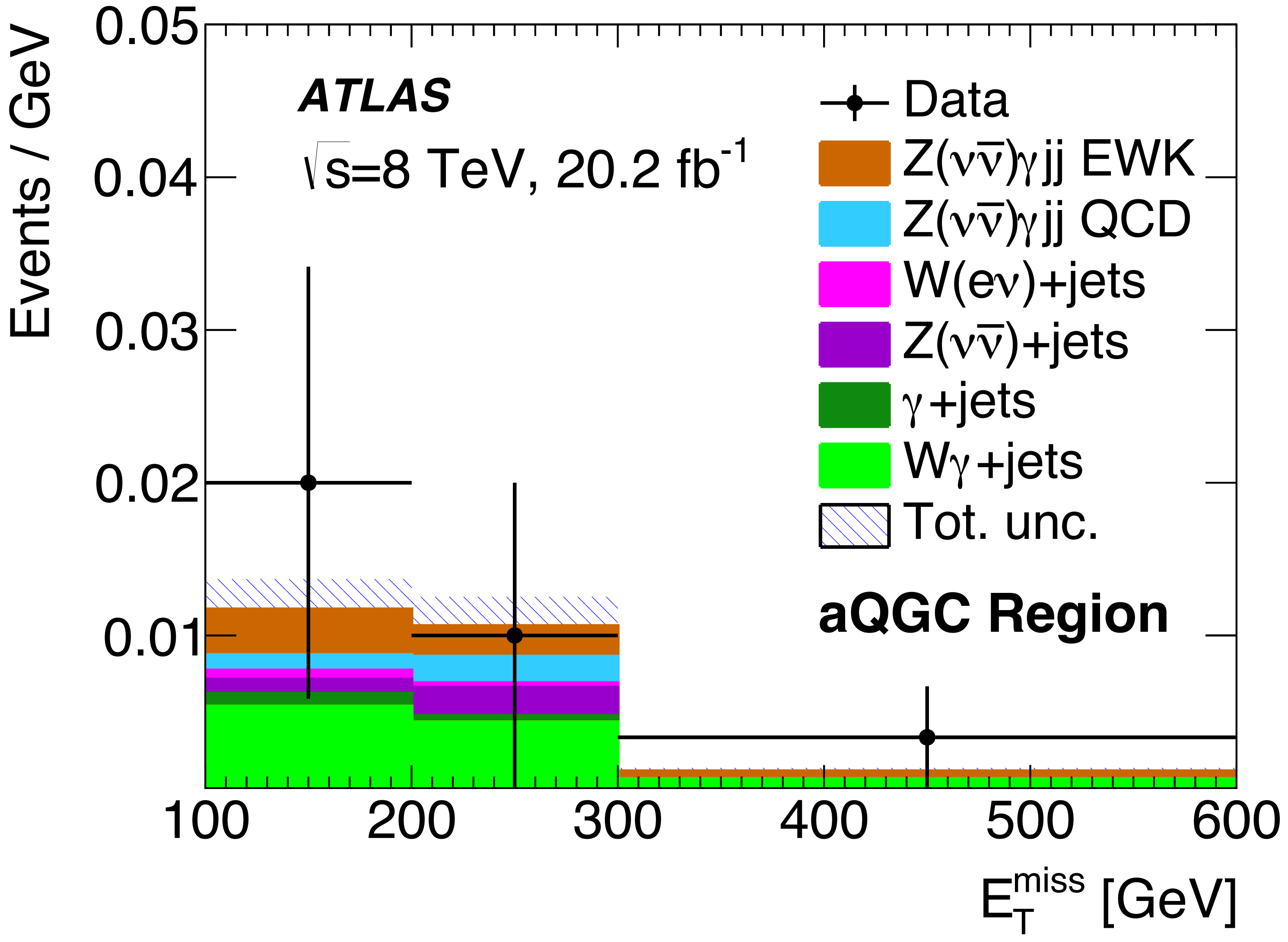
- Lot of information obtained from the study of neutral VBS final states (total QCD+EW cross section in several phase spaces, EW cross-section, validation of QCD modelling, …)
- In particular on the fT8 and ft9 operators of the EFT, most stringent limits set on them.
- Very small cross-sections !
- Study of 13 TeV ongoing, new results on Zγ and ZZ to come soon
  - will also allow to check dependence of XS with $\sqrt{s}$ for a given process

Back-up

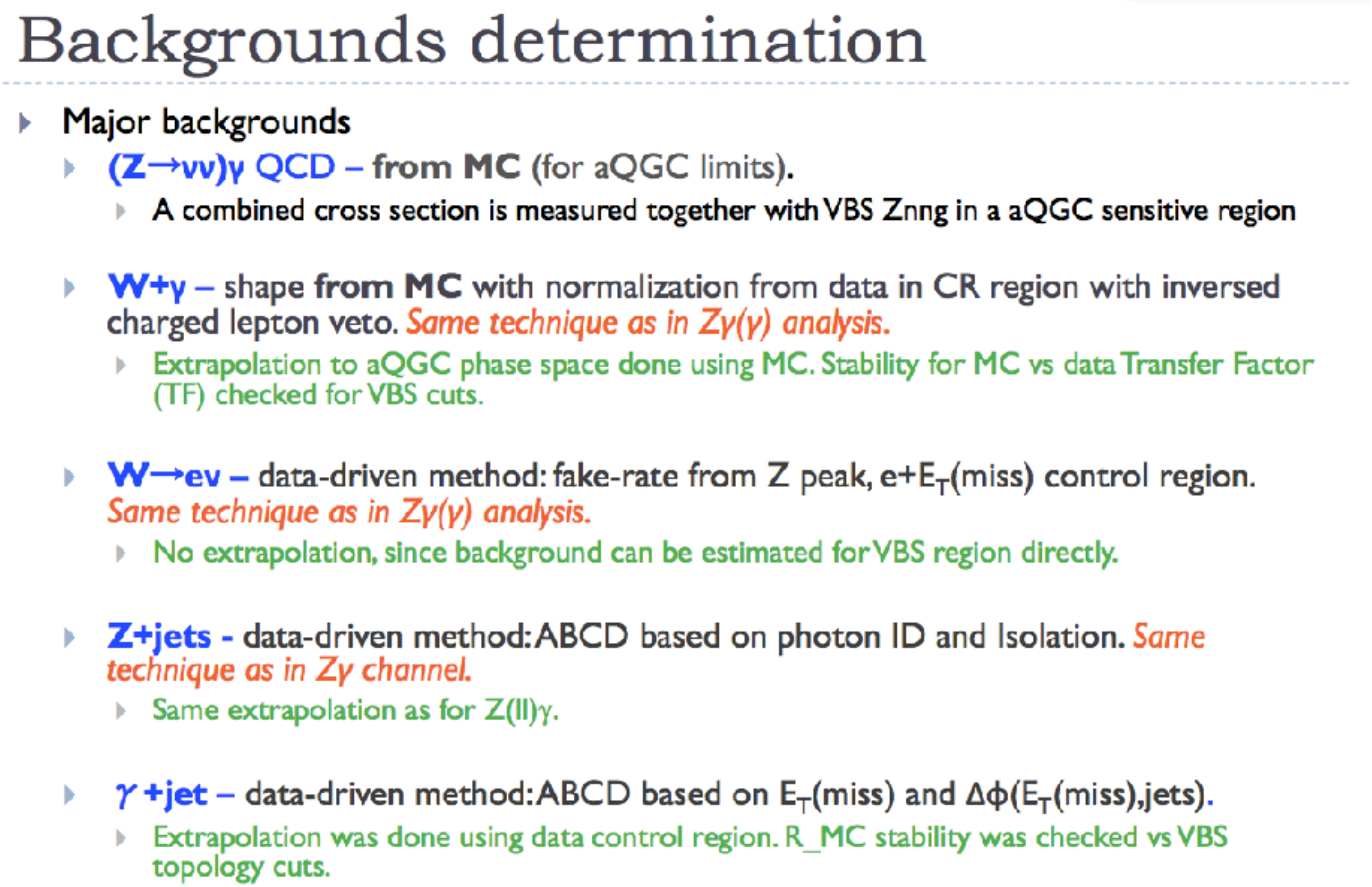
VBS Zγ: more details (νν channel)

Objects	Particle- (Parton-) level selection
Neutrinos	$E_{\mathrm{T}}^{\nu\bar{\nu}} > 100$ GeV
Photon (kinematics)	$E_{\mathrm{T}}^{\gamma} > 150$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$ $\Delta R(\ell, \gamma) > 0.4$
Photon (isolation)	$E_{\mathrm{T}}^{\mathrm{iso}} < 0.5 \cdot E_{\mathrm{T}}^{\gamma}$
Generator-level jets (Outgoing quarks) ($pp \to Z\gamma qq$)	At least two jets (quarks) $E_{\mathrm{T}}^{j(q)} > 30$ GeV, $\lvert\eta^{j(q)}\rvert < 4.5$ $\Delta R(\gamma, j(q)) > 0.4$
Event kinematic selection	$\lvert\Delta\phi(E_{\mathrm{T}}^{\nu\bar{\nu}}, \gamma jj(qq))\rvert > \frac{3\pi}{4}$ $\lvert\Delta\phi(E_{\mathrm{T}}^{\nu\bar{\nu}}, \gamma)\rvert > \frac{\pi}{2}$ $\lvert\Delta\phi(E_{\mathrm{T}}^{\nu\bar{\nu}}, j(q))\rvert > 1$ $E_{\mathrm{T}}^{\gamma} > 150$ GeV $\lvert\Delta y_{jj(qq)}\rvert > 2.5$ ζ_{γ} ¡ 0.3 $p_{\mathrm{T}}^{\mathrm{balance}} < 0.1$ $m_{jj(qq)} > 600$ GeV

VBS Zγ: more details (results)



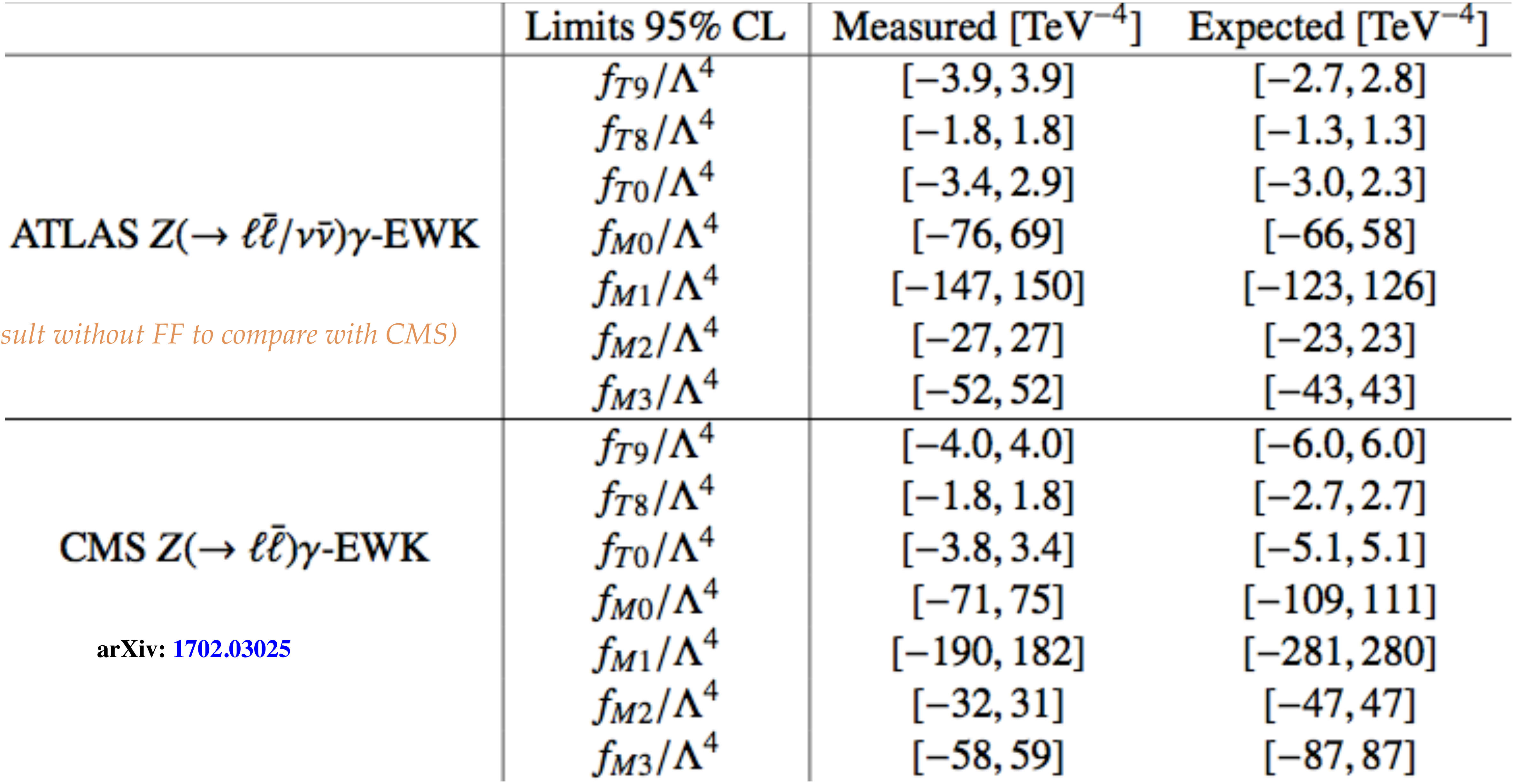
Zννg VBS



Backgrounds determination

- Major backgrounds
  - **(Z→νν)γ QCD – from MC** (for aQGC limits).
    - A combined cross section is measured together with VBS Znng in a aQGC sensitive region
  - **W+γ** – shape **from MC** with normalization from data in CR region with inversed charged lepton veto. *Same technique as in Zγ(γ) analysis.*
    - Extrapolation to aQGC phase space done using MC. Stability for MC vs data Transfer Factor (TF) checked for VBS cuts.
  - **W→eν** – data-driven method: fake-rate from Z peak, e+E_T(miss) control region. *Same technique as in Zγ(γ) analysis.*
    - No extrapolation, since background can be estimated for VBS region directly.
  - **Z+jets** - data-driven method: ABCD based on photon ID and Isolation. *Same technique as in Zγ channel.*
    - Same extrapolation as for Z(ll)γ.
  - **γ +jet** – data-driven method: ABCD based on E_T(miss) and Δϕ(E_T(miss),jets).
    - Extrapolation was done using data control region. R_MC stability was checked vs VBS topology cuts.

Comparison of ATLAS and CMS Zγ aQGC limits

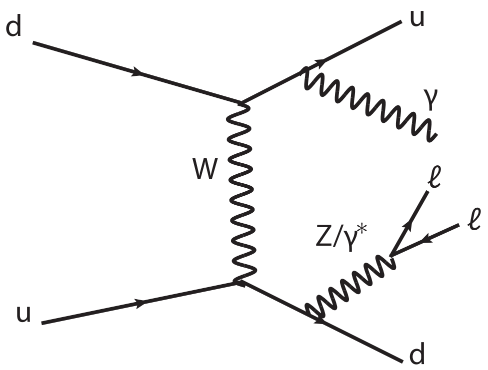


	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\to \ell\bar{\ell}/\nu\bar{\nu})\gamma$-EWK	f_{T9}/Λ^4	$[-3.9, 3.9]$	$[-2.7, 2.8]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-1.3, 1.3]$
	f_{T0}/Λ^4	$[-3.4, 2.9]$	$[-3.0, 2.3]$
	f_{M0}/Λ^4	$[-76, 69]$	$[-66, 58]$
	f_{M1}/Λ^4	$[-147, 150]$	$[-123, 126]$
	f_{M2}/Λ^4	$[-27, 27]$	$[-23, 23]$
	f_{M3}/Λ^4	$[-52, 52]$	$[-43, 43]$
CMS $Z(\to \ell\bar{\ell})\gamma$-EWK	f_{T9}/Λ^4	$[-4.0, 4.0]$	$[-6.0, 6.0]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-2.7, 2.7]$
	f_{T0}/Λ^4	$[-3.8, 3.4]$	$[-5.1, 5.1]$
	f_{M0}/Λ^4	$[-71, 75]$	$[-109, 111]$
	f_{M1}/Λ^4	$[-190, 182]$	$[-281, 280]$
	f_{M2}/Λ^4	$[-32, 31]$	$[-47, 47]$
	f_{M3}/Λ^4	$[-58, 59]$	$[-87, 87]$

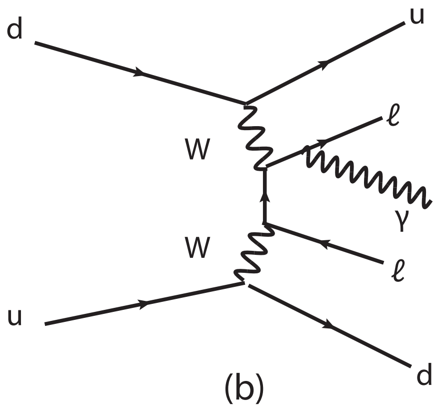
(result without FF to compare with CMS)

arXiv: 1702.03025

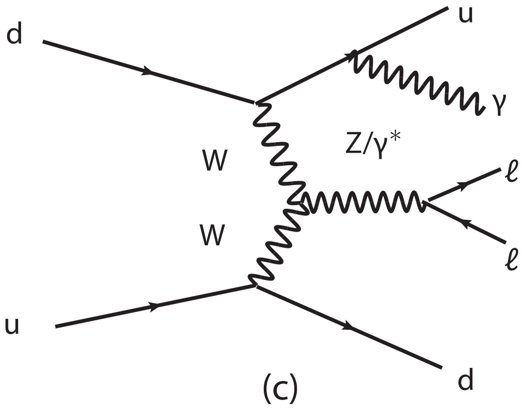
ZZ Feynman diagrams



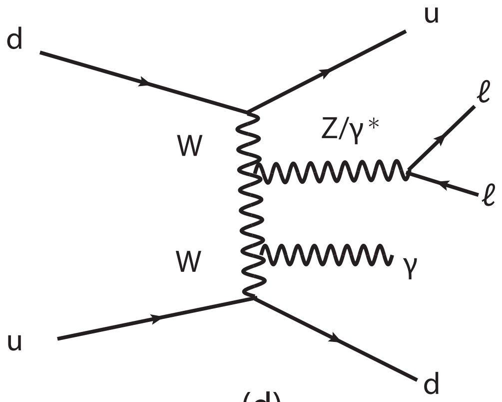
(a)



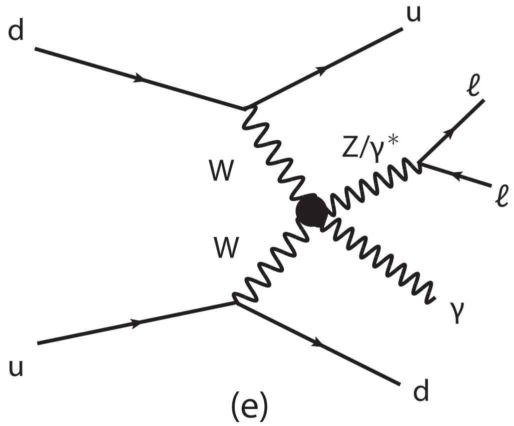
(b)



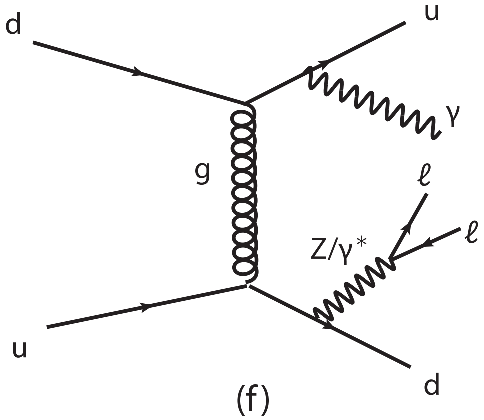
(c)



(d)

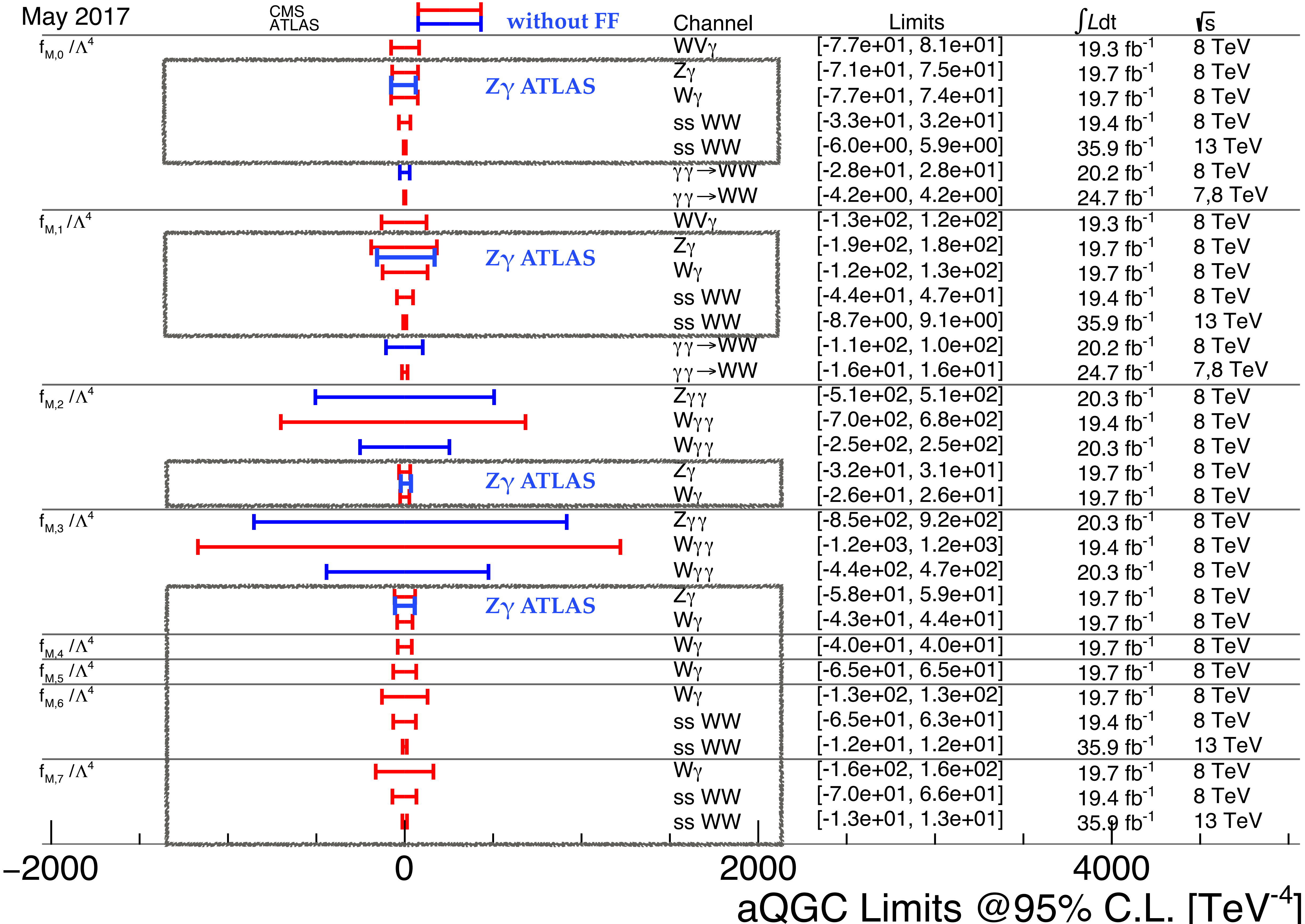


(e)



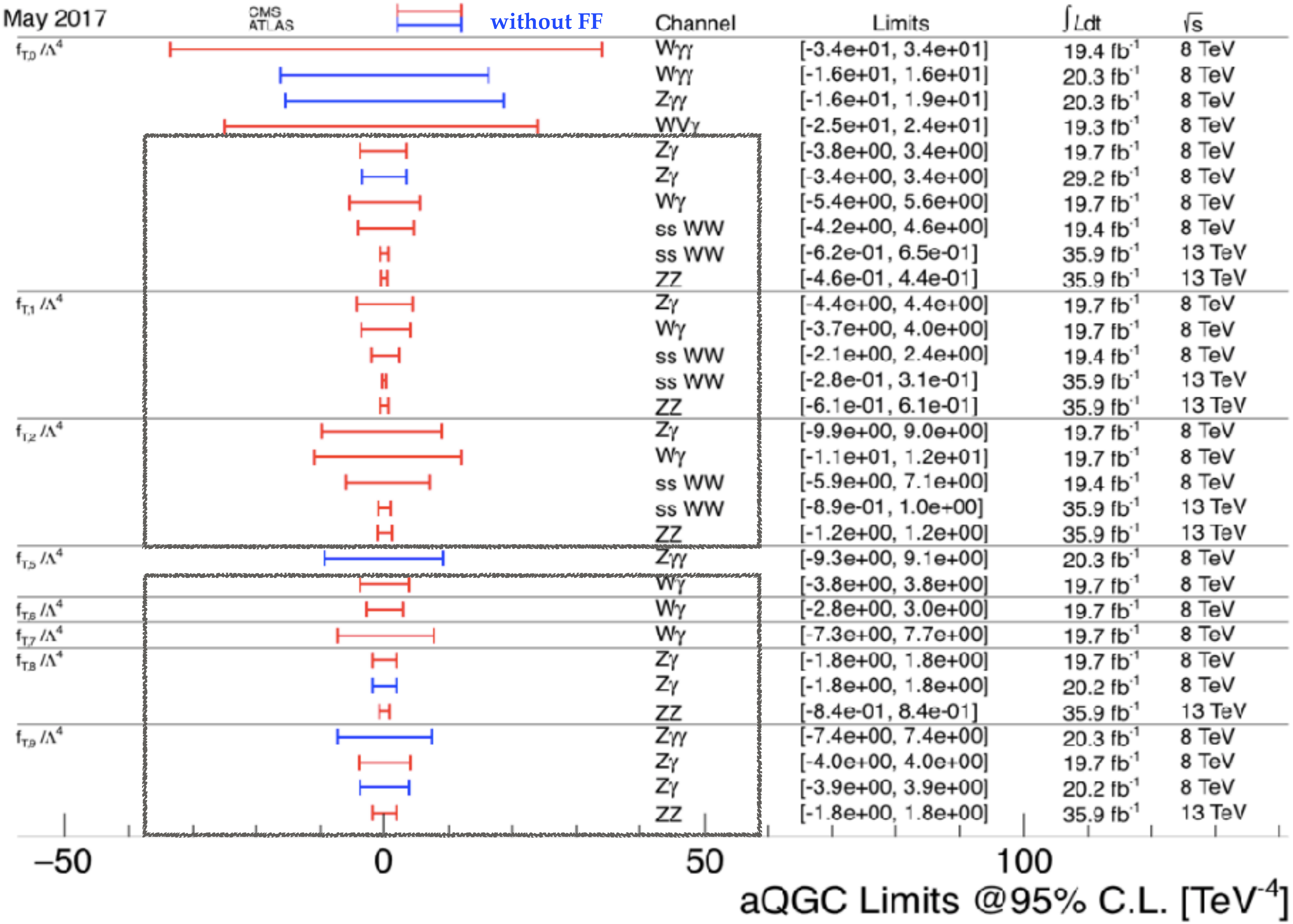
(f)

Comparisons of intervals for fM operators



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-3.3e+01, 3.2e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.0e+00, 5.9e+00]	35.9 fb^{-1}	13 TeV
	γγ→WW	[-2.8e+01, 2.8e+01]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.4e+01, 4.7e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.7e+00, 9.1e+00]	35.9 fb^{-1}	13 TeV
	γγ→WW	[-1.1e+02, 1.0e+02]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb^{-1}	7,8 TeV
$f_{M,2}/\Lambda^4$	Zγγ	[-5.1e+02, 5.1e+02]	20.3 fb^{-1}	8 TeV
	Wγγ	[-7.0e+02, 6.8e+02]	19.4 fb^{-1}	8 TeV
	Wγγ	[-2.5e+02, 2.5e+02]	20.3 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
$f_{M,3}/\Lambda^4$	Zγγ	[-8.5e+02, 9.2e+02]	20.3 fb^{-1}	8 TeV
	Wγγ	[-1.2e+03, 1.2e+03]	19.4 fb^{-1}	8 TeV
	Wγγ	[-4.4e+02, 4.7e+02]	20.3 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
$f_{M,4}/\Lambda^4$	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
$f_{M,5}/\Lambda^4$	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
$f_{M,6}/\Lambda^4$	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-6.5e+01, 6.3e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-1.2e+01, 1.2e+01]	35.9 fb^{-1}	13 TeV
$f_{M,7}/\Lambda^4$	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-7.0e+01, 6.6e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-1.3e+01, 1.3e+01]	35.9 fb^{-1}	13 TeV

Comparisons of intervals for fT operators



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	Wγγ	[-3.4e+01, 3.4e+01]	19.4 fb^{-1}	8 TeV
	Wγγ	[-1.6e+01, 1.6e+01]	20.3 fb^{-1}	8 TeV
	Zγγ	[-1.6e+01, 1.9e+01]	20.3 fb^{-1}	8 TeV
	WVγ	[-2.5e+01, 2.4e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.4e+00, 3.4e+00]	29.2 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-4.6e-01, 4.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-6.1e-01, 6.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb^{-1}	13 TeV
	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	Zγγ	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,6}/\Lambda^4$	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
$f_{T,7}/\Lambda^4$	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	Zγγ	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV