Experimental review of Vector Boson Scattering

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Monte-Carlo description of VBS - VBSCAN

16/11/2017

Nikhef

VBS CAN.

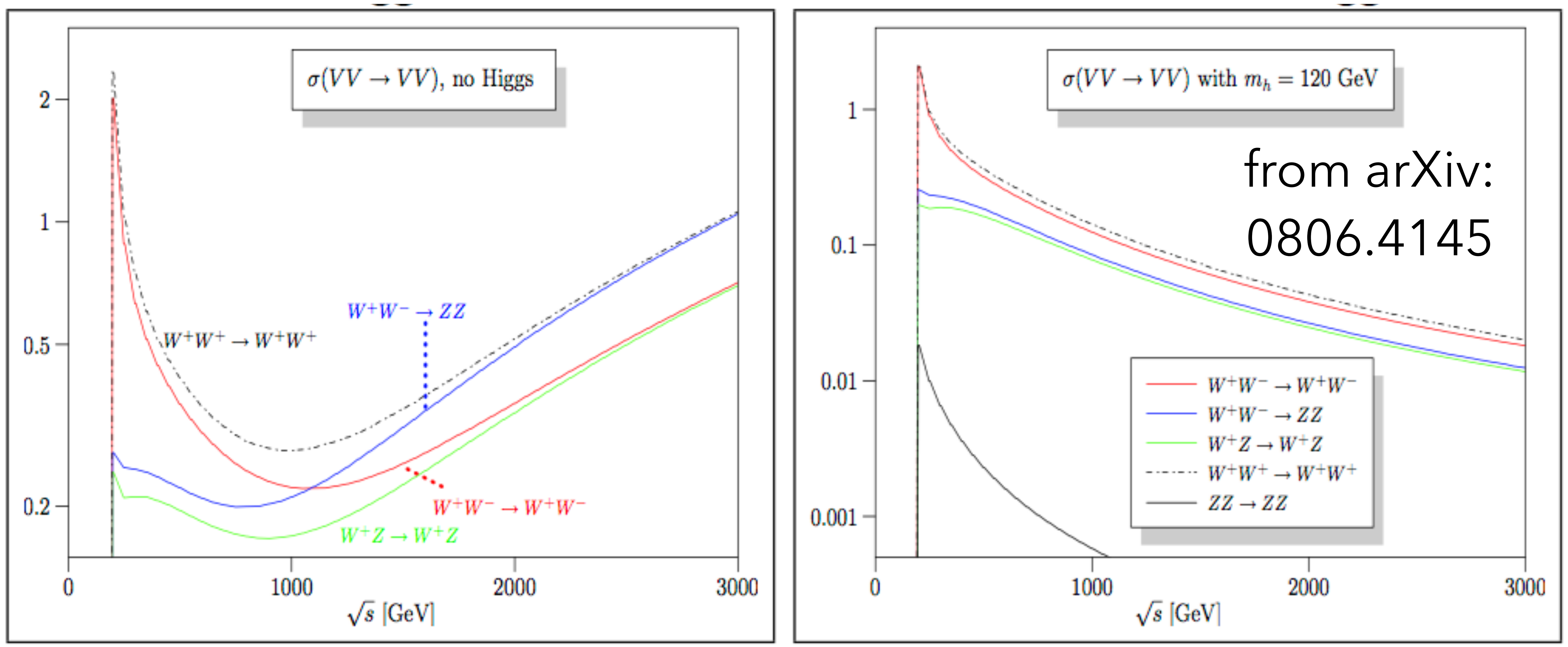
Introduction

Why are VBS studies important?

➡ Test of **electroweak sector** of the SM and of the **EW Symmetry Breaking**

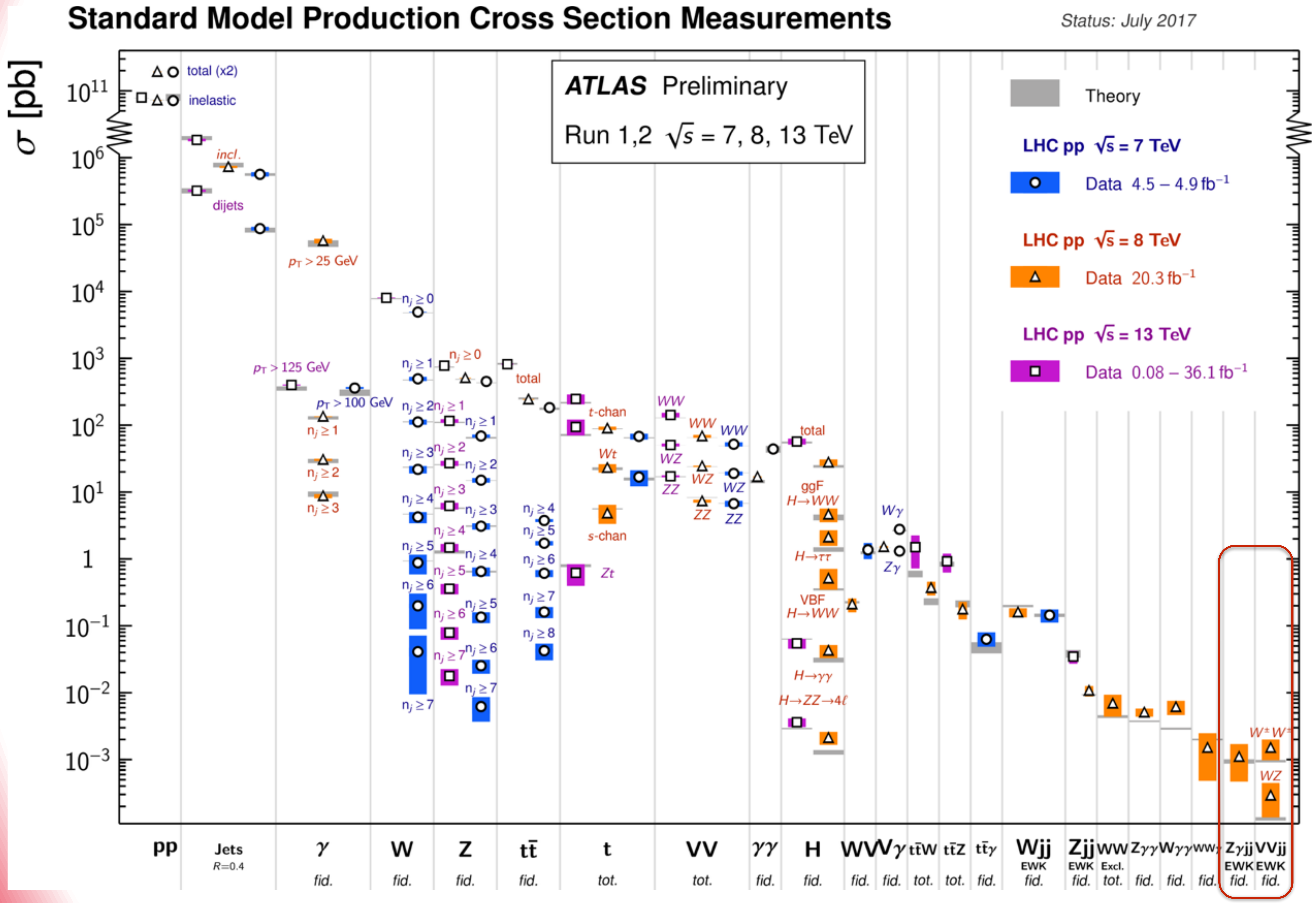
➡ Probing the role of the **Higgs mechanism in unitarization** of quartic coupling processes:

- the Higgs boson unitarizes the interactions of longitudinally polarized VBS
- Unitarity still violated in case of deviations of gHWW



➡ Sensitive to BSM physics allowing indirect searches by studying **anomalous triple and quartic gauge couplings** (aTGC, aQGC)

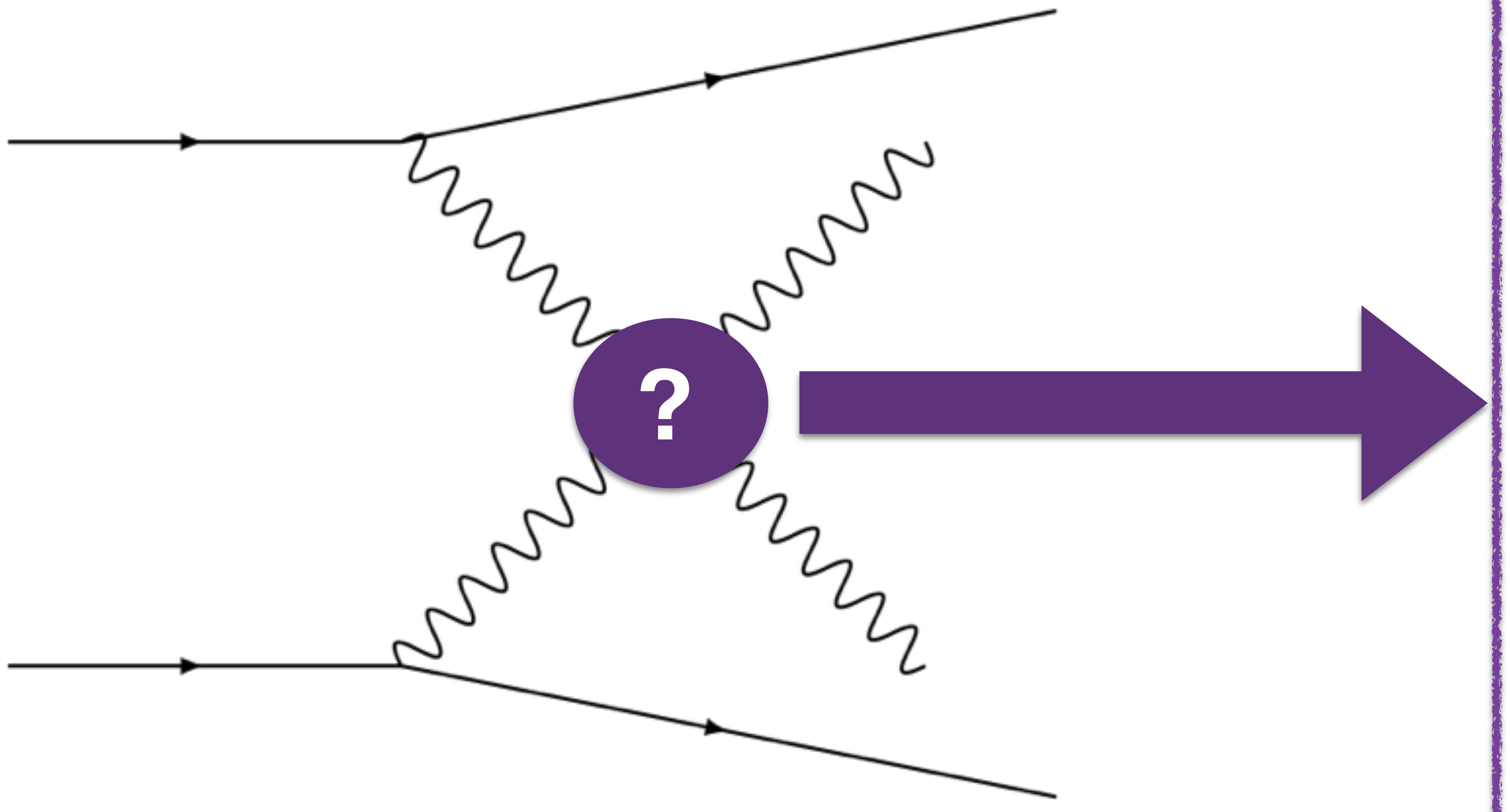
VBS Processes

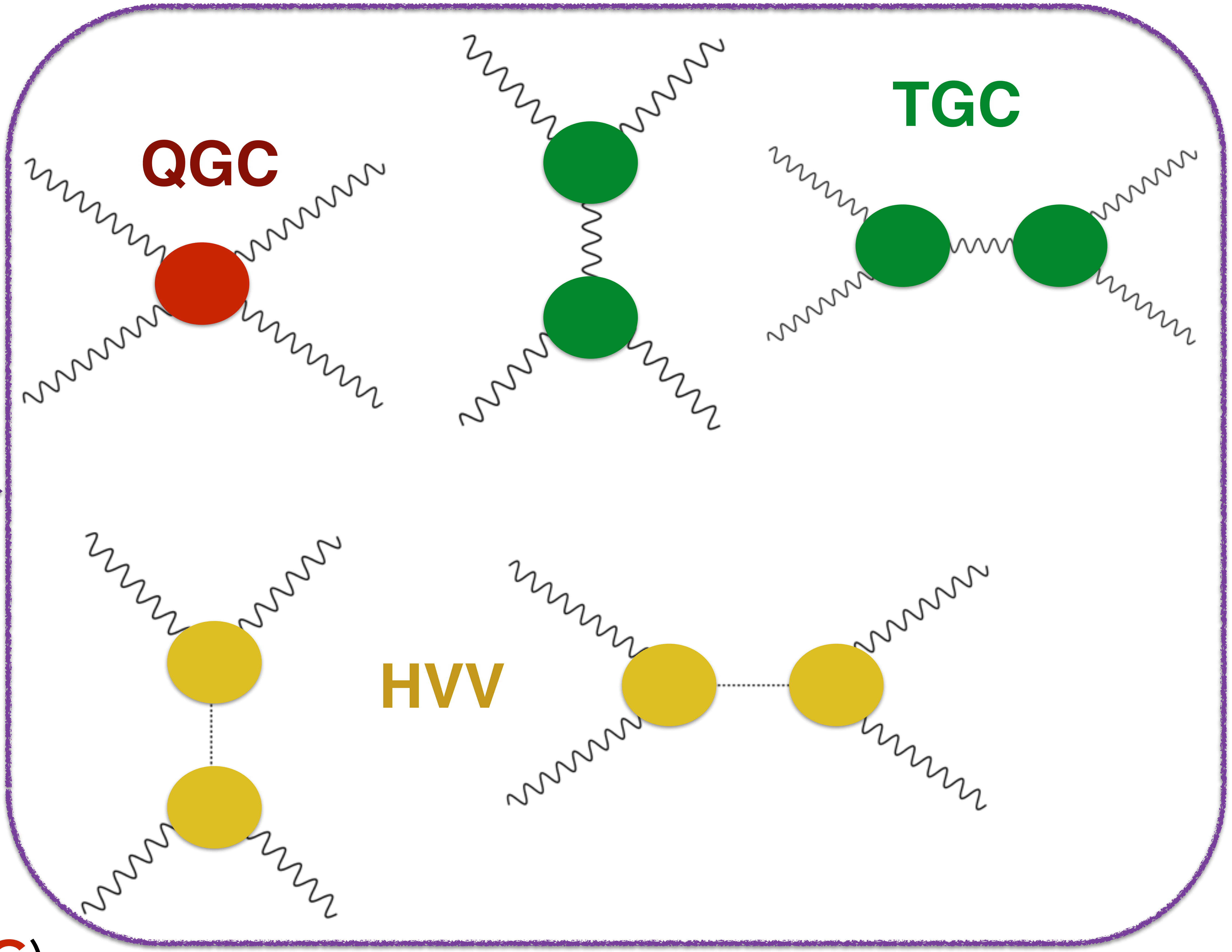


VBS, VBF and **tri-boson** are main processes to probe the QGC and TGC at LHC.

Rare processes, cross sections typically ~ 1 pb.

VBS Couplings





Vector Boson Scattering contains:

- Triple gauge boson vertices (TGC)
- Quartic gauge boson vertices (QGC)
- Interactions of the Higgs boson with the weak massive gauge bosons (HVV)

Anomalous quartic gauge couplings

The presence of **new physics** can alter the **couplings** between bosons

↓

The presence of **aQGC** enhances the **EW cross-section at high-energy tails**

Study Effective Field Theory scenarios with higher order dimensions operators

EFT can be translated to EW chiral Lagrangian approach and vice versa

Dimension 4	Dimension 6	Dimension 8
WWWW/WWZZ	WWZγ/WW$\gamma\gamma$	all VVVV
EW Chiral Lagrangian		effective operators
non linear representation		linear representation
$\alpha 4$, $\alpha 5$	$\frac{a_0}{\Lambda^2}, \frac{a_c}{\Lambda^2}$	$\frac{f_{S,i}}{\Lambda^4}, \frac{f_{T,i}}{\Lambda^4}, \frac{f_{M,i}}{\Lambda^4}$

→ Ex. translation dim4 ⇆ dim8 operators: $\boxed{\frac{f_{S,0(1)}}{\Lambda^4} = \alpha_{4(5)} \times \frac{16}{v^4}}$

Anomalous quartic gauge couplings

arXiv:1309.7890v1

Anomalous couplings are probed using **Effective Field Theory**

- Dimension 6 Operators → **Triple Gauge Couplings**
- Dimension 8 Operators → **Quartic Gauge Coupling**

Dim 6: TGC **Dim 8: QGC**

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

Pure Higgs field **Pure Field-strength tensor** **Mixed Higgs-field-strength**

Nonzero value in aQGCs lead to tree-level **unitarity violation** at high energy

➡**Form factors** of the form $\frac{1}{(1+\hat{s}/\Lambda_{\mathrm{FF}}^2)^2}$

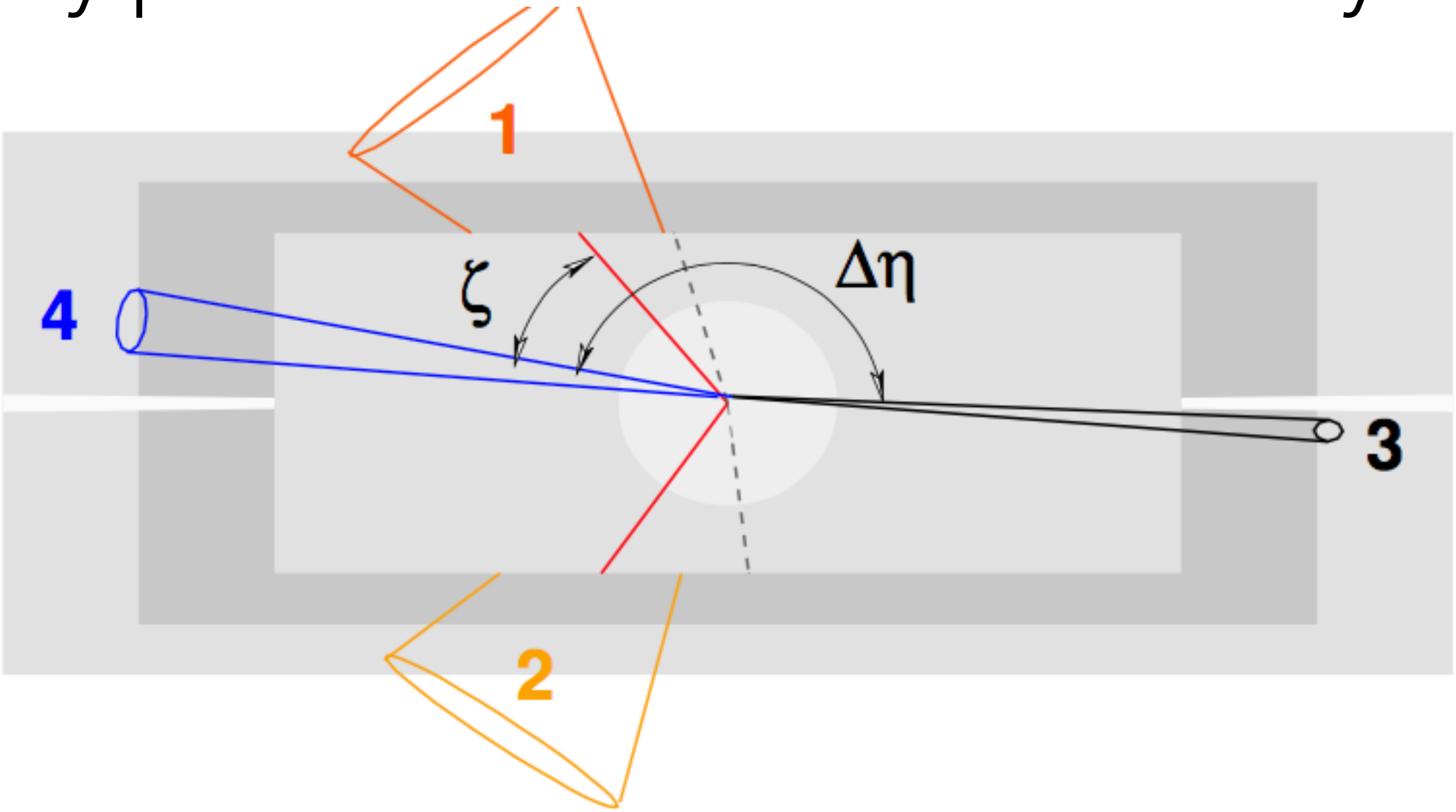
can be introduced to unitarize the high energy contribution (**ATLAS** approach).

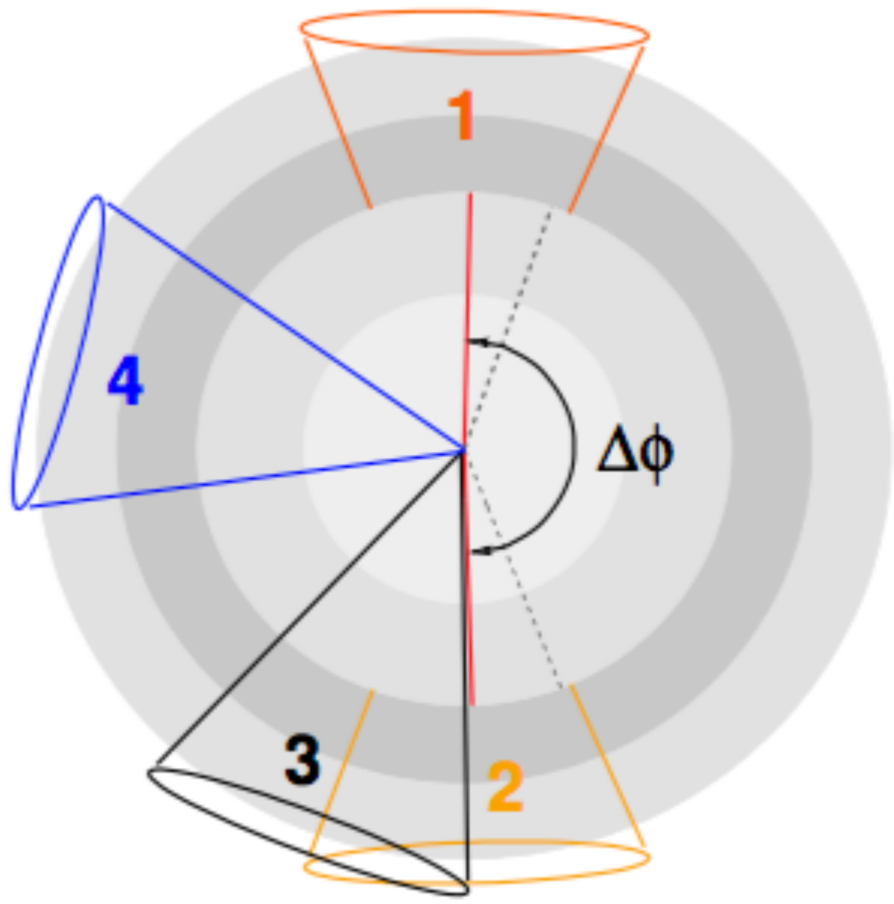
➡ Provide **only validity bound**: scattering energy at which observed limit would violate unitarity, (mainly from VBFNLO) but don't use any form factor (**CMS** approach)

VBS Signature

VBS has a characteristic final states topology

- Two highly energetic jets (3,4)
- Large invariant mass of di-jet system
- Large pseudo rapidity gap between jets
- No hadronic activity in the rapidity gap of the two tagging jets
- Decay products of the vector bosons lying between the tagging jets (1,2)





Analyses on VBS ATLAS+CMS

	ATLAS	CMS	Reference
W±W± +2jets	8 TeV	8, 13 TeV	arXiv:1611.02428v2 arXiv:1709.05822
Zγ +2 jets	8 TeV	8 TeV	arXiv:1705.01966v2 arXiv:1702.03025
Wγ + 2jets	-	8 TeV	arXiv:1612.09256
ZZ + 2jets	-	13 TeV	arXiv:1708.02812
WZ + 2jets	8 TeV		arxiv:1603.02151v1
WV semi-lept + 2jets	8 TeV		arxiv:1609.05122v2

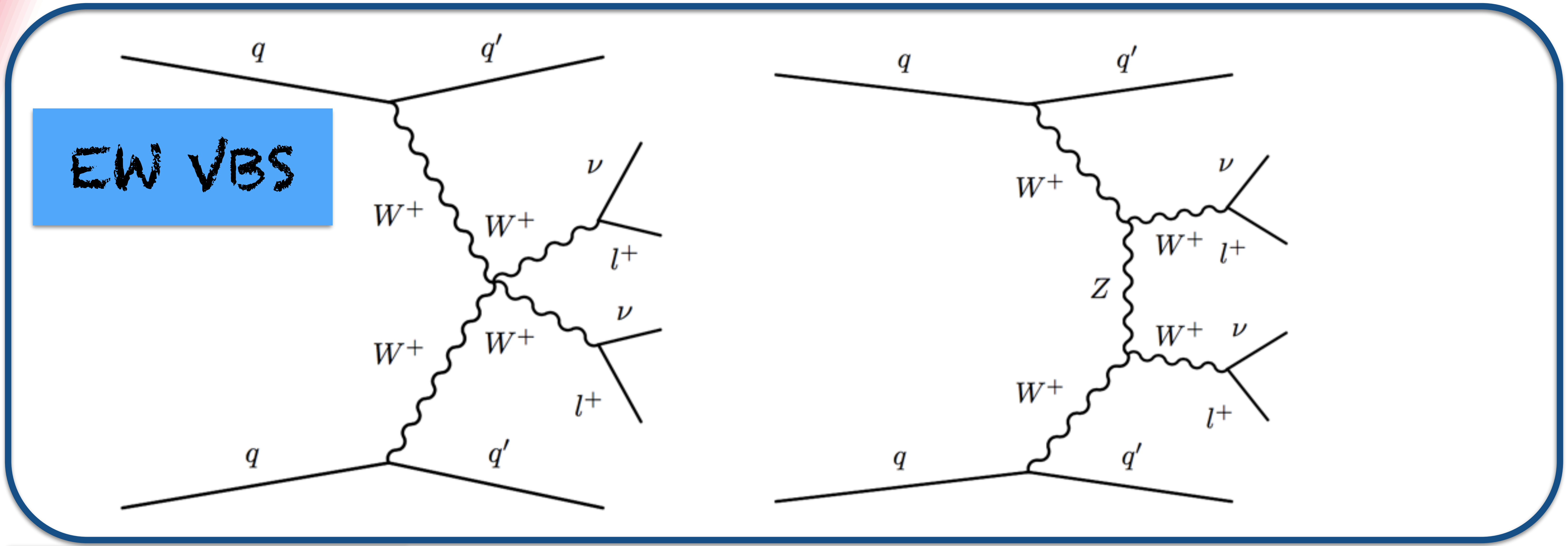
Datasets :

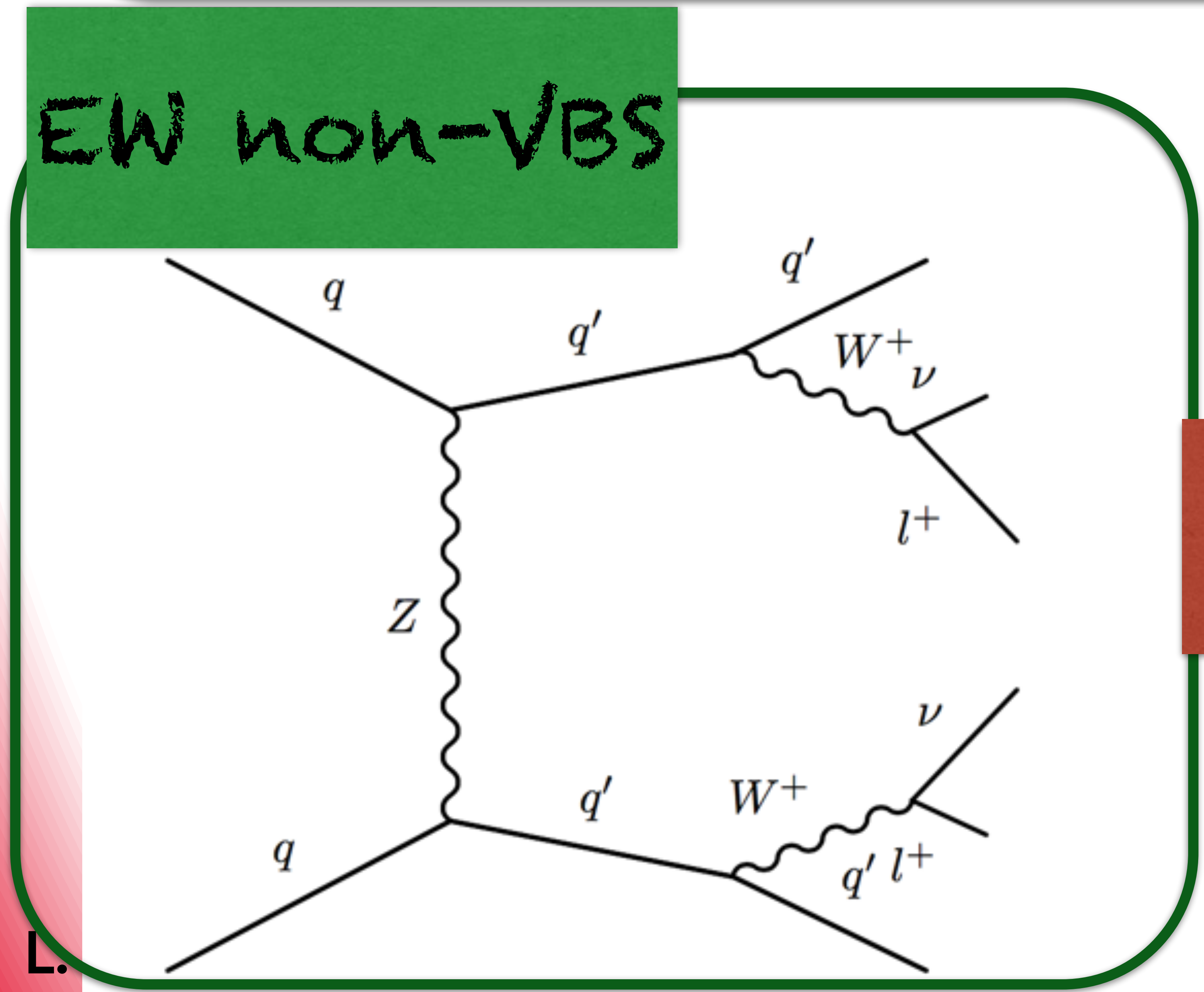
ATLAS: 8 TeV (20.2 fb-1)

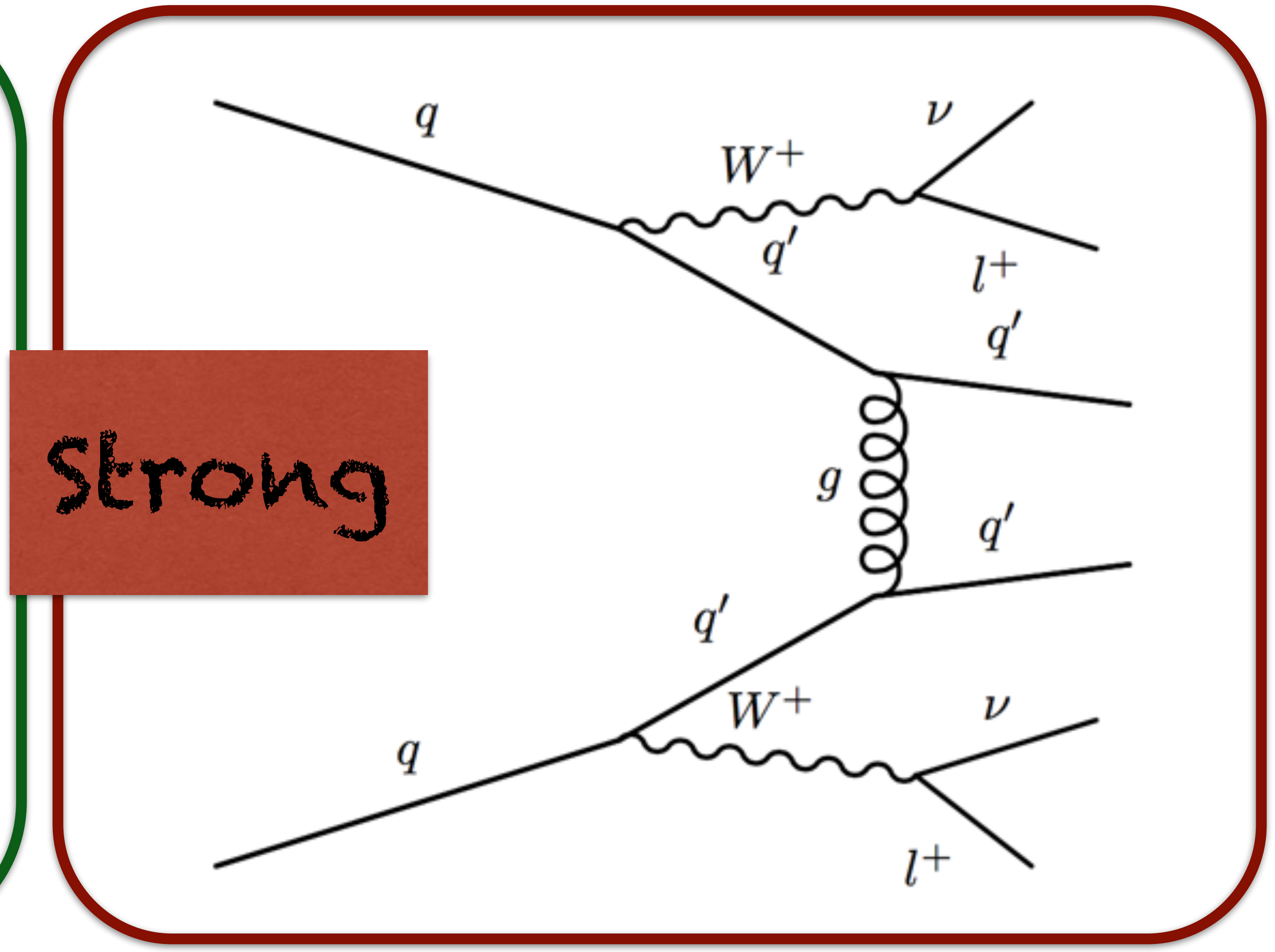
CMS: 8 TeV (19.7 fb-1) and 13 TeV (35.9 fb-1)

Vector Boson Scattering of same-charge W

Vector Boson Scattering of same-charge W







Main backgrounds:

- **Prompt bkg**: WZjj, ttV, ZZjj: estimated from MC

- **Non prompt bkg**: jets misidentified as leptons and leptons from hadron decays: estimated from the data

ssWWjj

ATLAS at 8 TeV

Two SR defined:

Inclusive SR: Both EW and QCD production as signal: defined requiring two leptons and at least two jets with mjj>500 GeV

VBS SR: EW only as signal: all inclusive SR cuts + |ΔYjj|>2.4

WWjj sample: LO Sherpa 1.4.5 QCD and EW

➡Cross section scaled to NLO (Powheg-Box)

➡ QCD /EW interference studied with dedicated samples, enhances the XS of 10.7% in the inclusive SR, 6.5 in the VBS SR

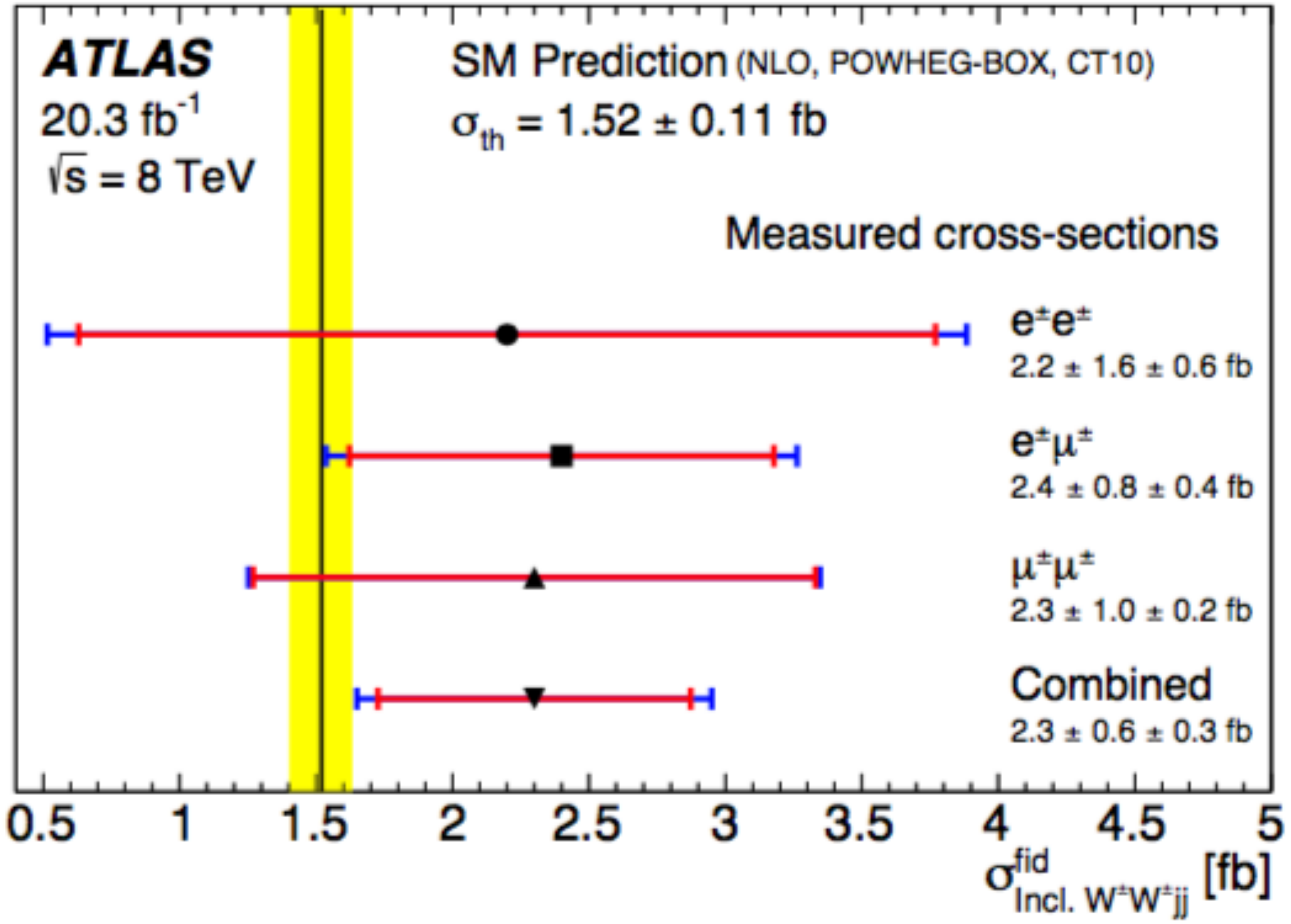
Main sources of uncertainty

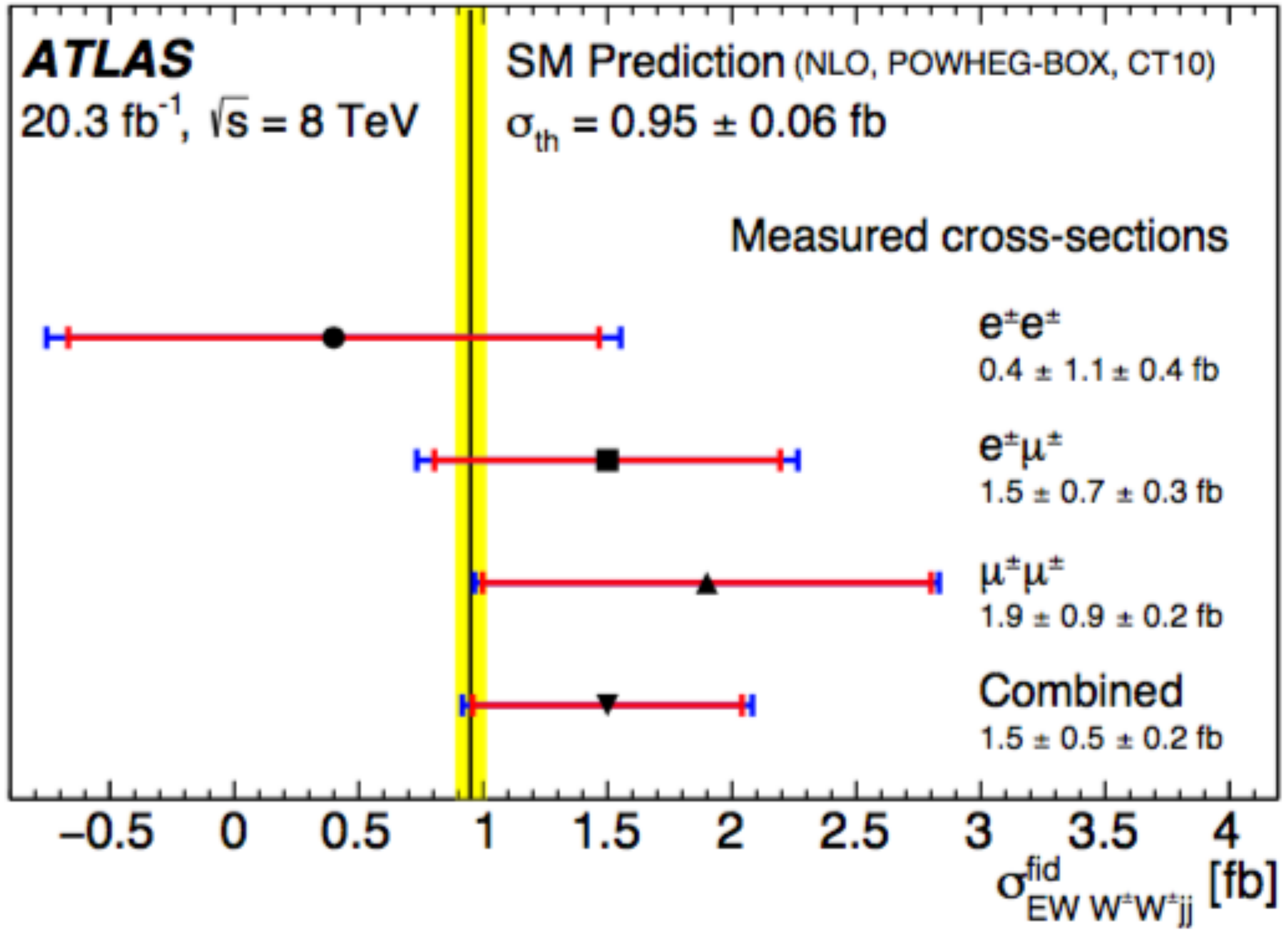
Source of uncertainty	$W^{\pm}W^{\pm}jj$-EW		$W^{\pm}W^{\pm}jj$-QCD	
	Inclusive	VBS	Inclusive	VBS
MC sample size	1%	2%	4%	8%
Showering model	2%	4%	3%	7%
Scale	2%	2%	12%	13%
PDF	2%	3%	2%	2%
Generator	5%	3%	5%	5%
Total uncertainty	6%	6%	14%	18%

Jet-related uncertainties are the main exp. uncertainties (up to 20% in the VBS SR)

ssWWjj - Fiducial cross section measurement

ATLAS at 8 TeV





Inclusive SR: $\sigma_{fid}(W^{\pm}W^{\pm}jj)$ =2.3 ± 0.6(stat.) ± 0.3(syst.) fb
significance of **4.5σ** (3.1σ expected).

VBS SR: $\sigma_{fid}(W^{\pm}W^{\pm}jj)$ = 1.5 ± 0.5(stat.) ± 0.2(syst.) fb
significance of **3.6σ** (2.3σ expected).

ssWWjj CMS at 13 TeV

Fiducial SR defined requiring two jets with $m_{jj}>500$ GeV and $|\Delta\eta_{jj}|>2.5$

WWjj Sample

LO Madgraph 5.2 QCD and EW

➡Interference between QCD and EW small in the SR and considered with a syst. uncertainty (up to 4.5%) . Estimated with PHANTOM 1.2.8

Main sources of uncertainty

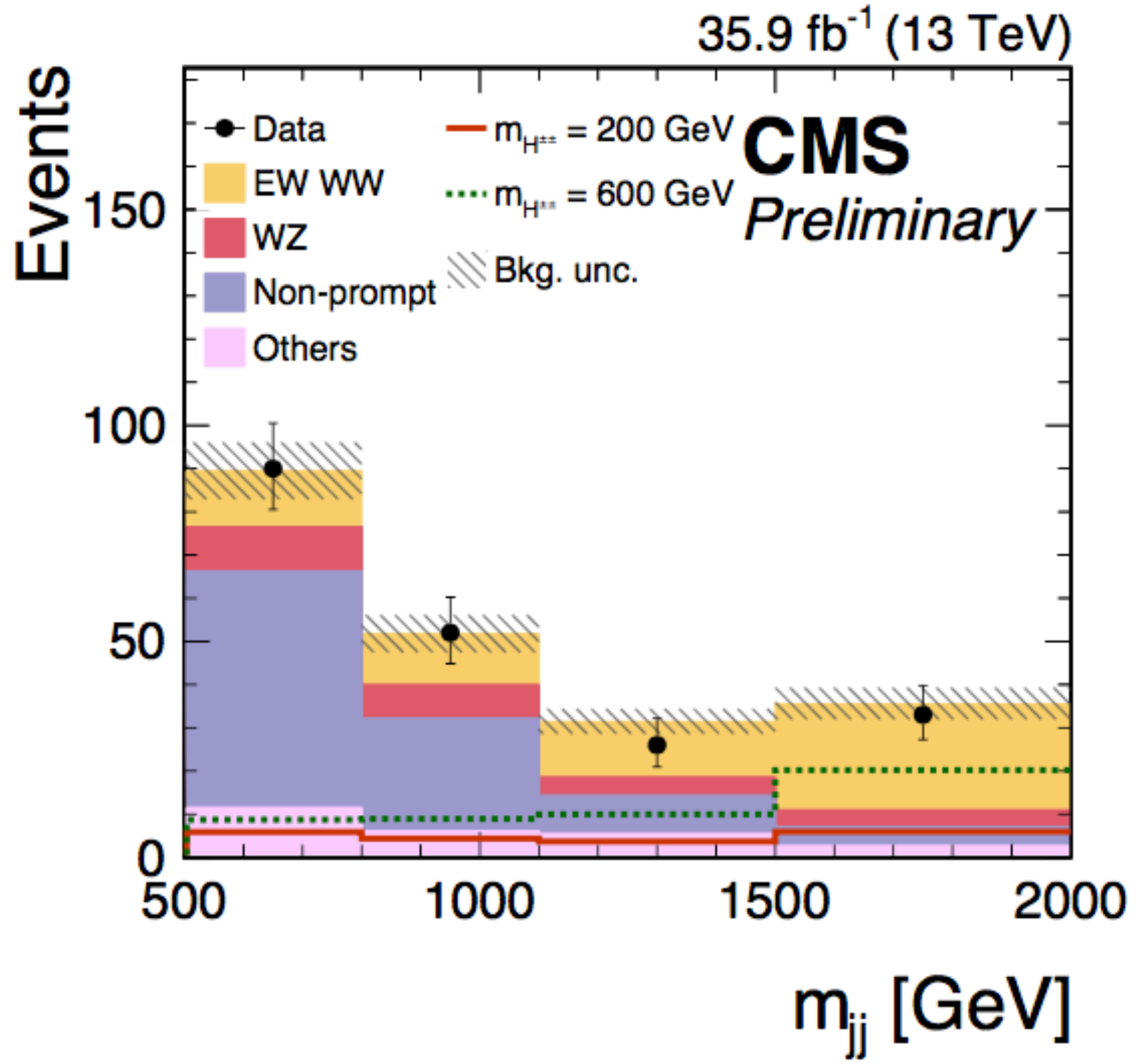
Main theory uncertainty: QCD scales in the WWjj sample: 13%

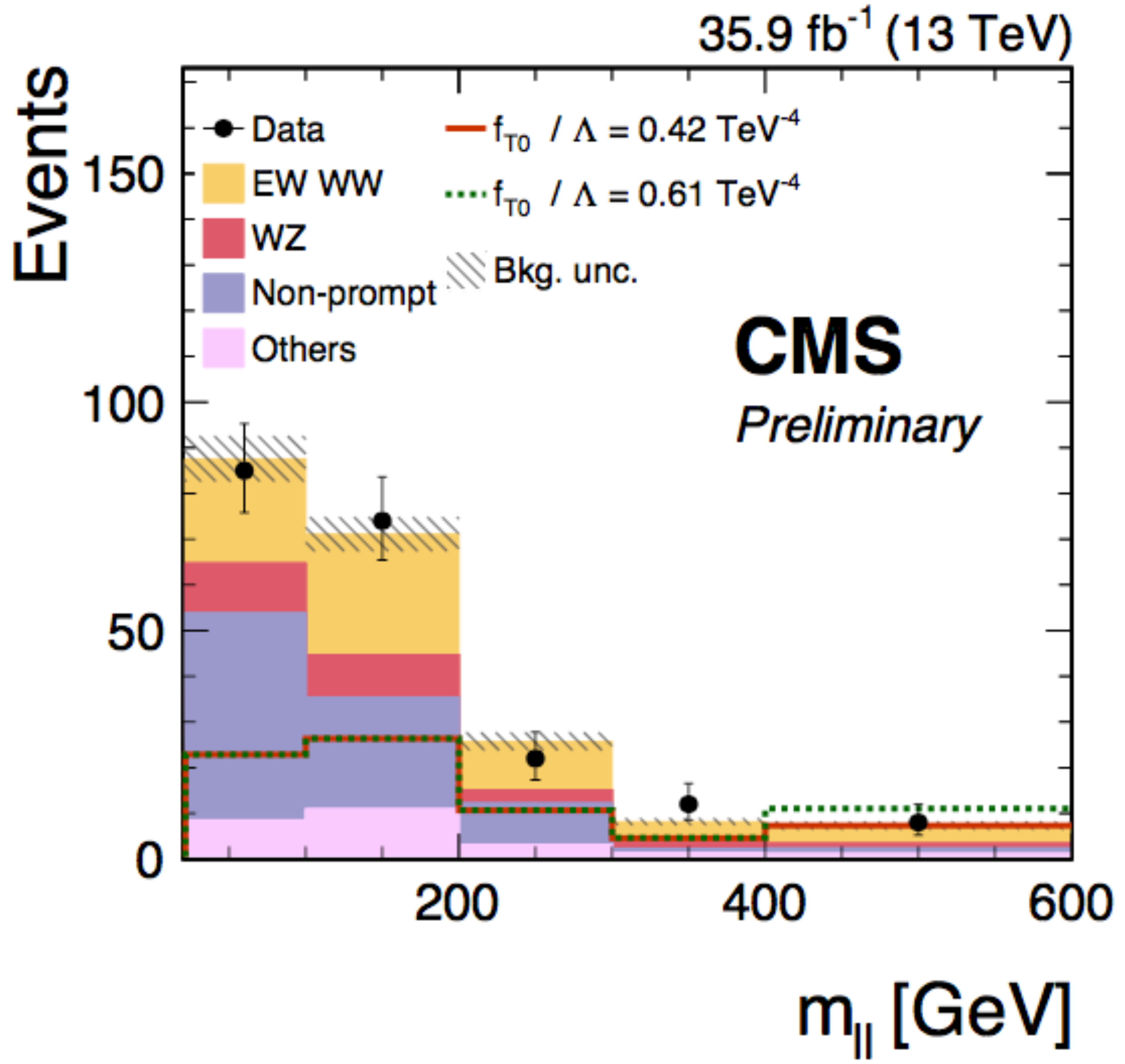
Other uncertainties: Jet-related uncertainties: 7%

Background uncertainties (DD, theory, extrapolation to SR): 20-40%

ssWWjj - Fiducial cross section measurement

CMS at 13 TeV Signal strength evaluated by 2D fit of m_{jj} and m_{ll} distributions





➡Observation at **5.5 standard deviations** (5.7 expected)

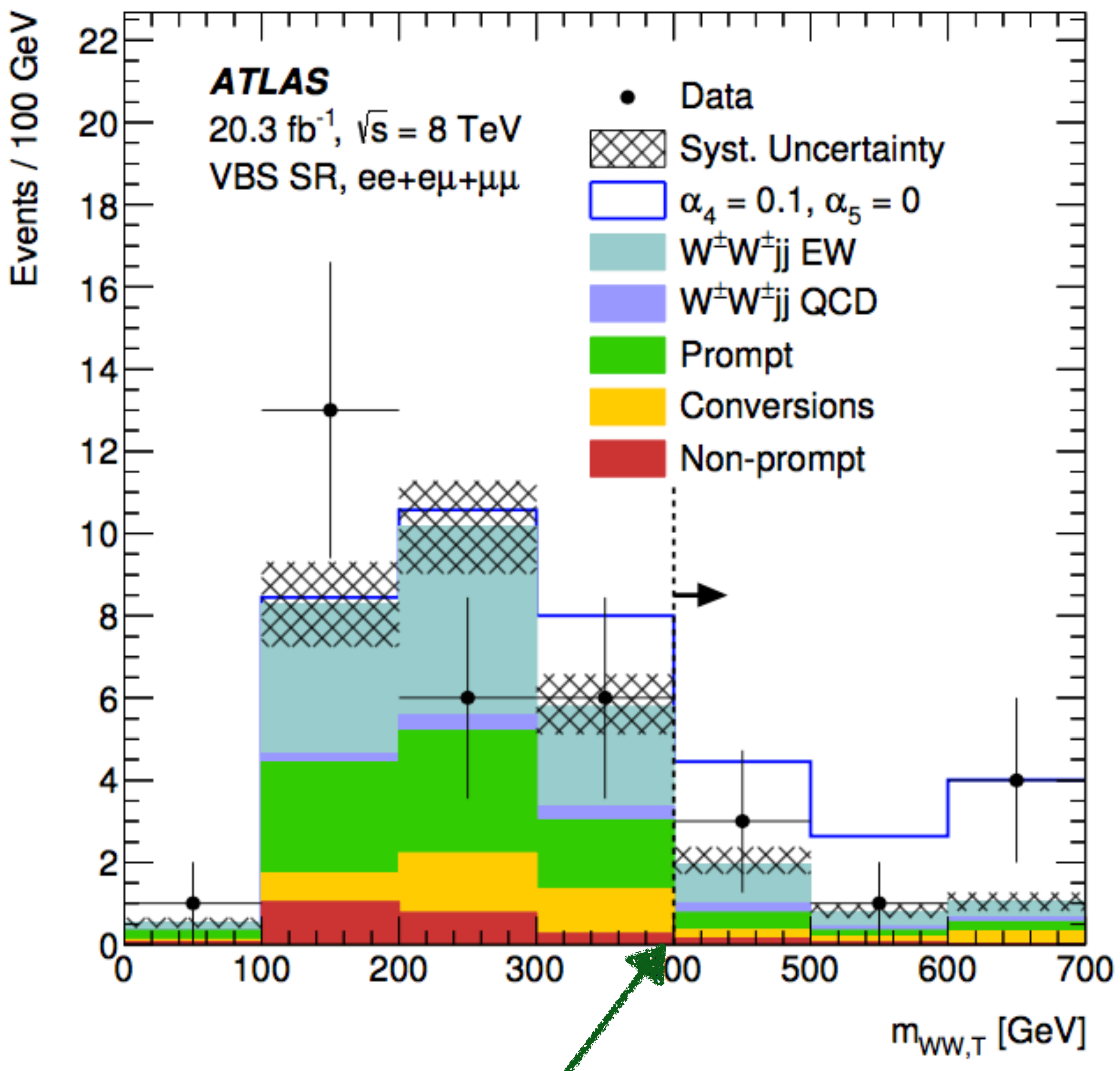
Fiducial XS: $\sigma_{fid}(W^{\pm}W^{\pm}jj)$ = 3.83±0.66(stat) ±0.35(syst) fb

In agreement with the SM expectation 4.25±0.21 fb (MG5 LO)

ssWWjj - aQGC

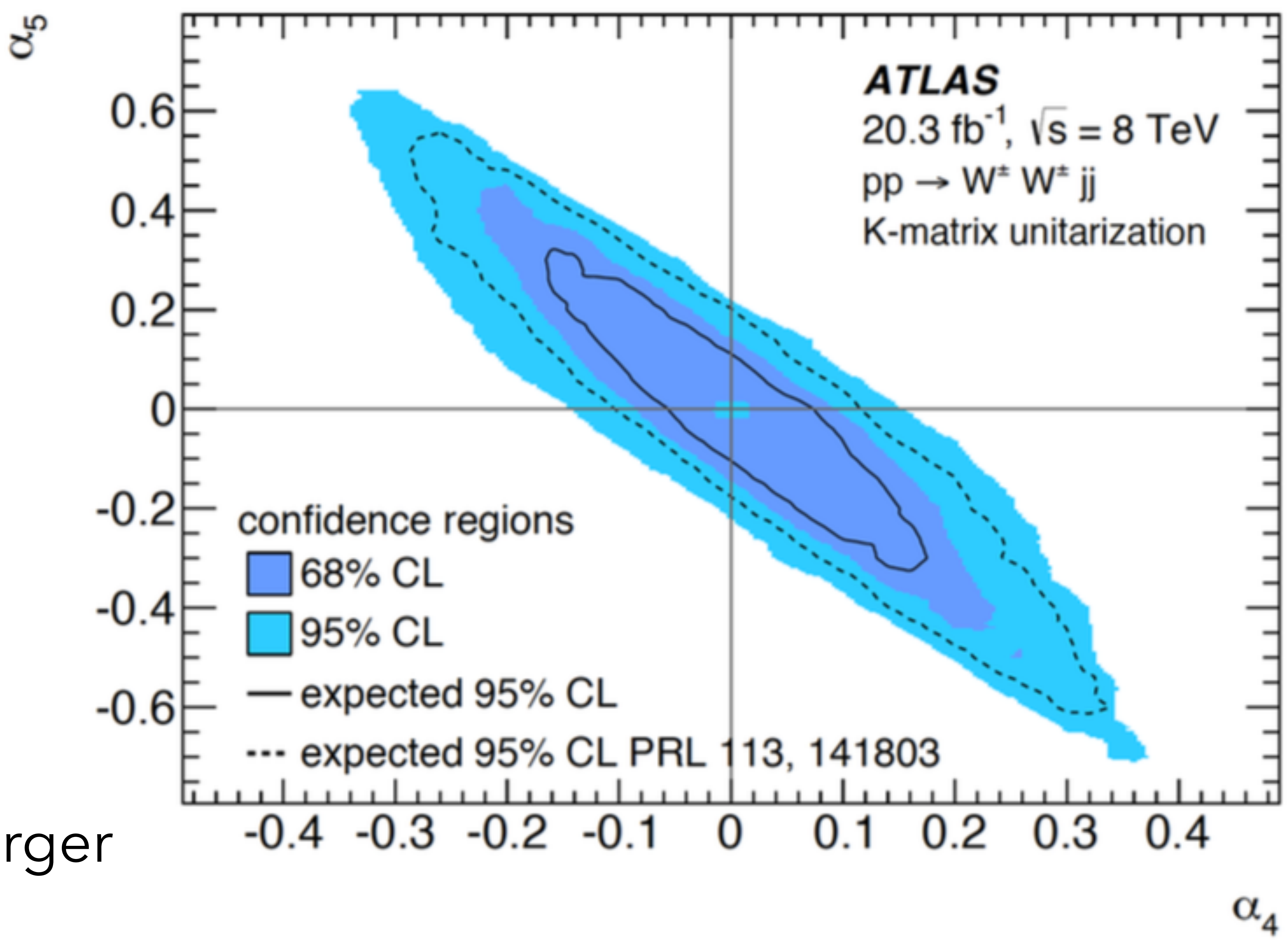
ATLAS at 8 TeV

Improved expected sensitivity to α4 and α5 is improved significantly selecting a phase-space region that is more sensitive to anomalous contributions to the WWWW vertex→ $m_{WW,T} = \sqrt{\left(\mathbf{P}_{\ell_1} + \mathbf{P}_{\ell_2} + \mathbf{P}_{E_T^{miss}}\right)^2}$ > 400 GeV.



Effects from new-physics processes are expected to be seen predominantly at larger mass scales

$-0.14 < \alpha 4 < 0.15$ and $-0.22 < \alpha 5 < 0.22$ (Observed 95% CL)
$-0.06 < \alpha 4 < 0.07$ and $-0.10 < \alpha 5 < 0.11$ (Expected 95% CL)



35% improvement in the expected aQGC sensitivity wrt the previous ATLAS result

ssWWjj - aQGC

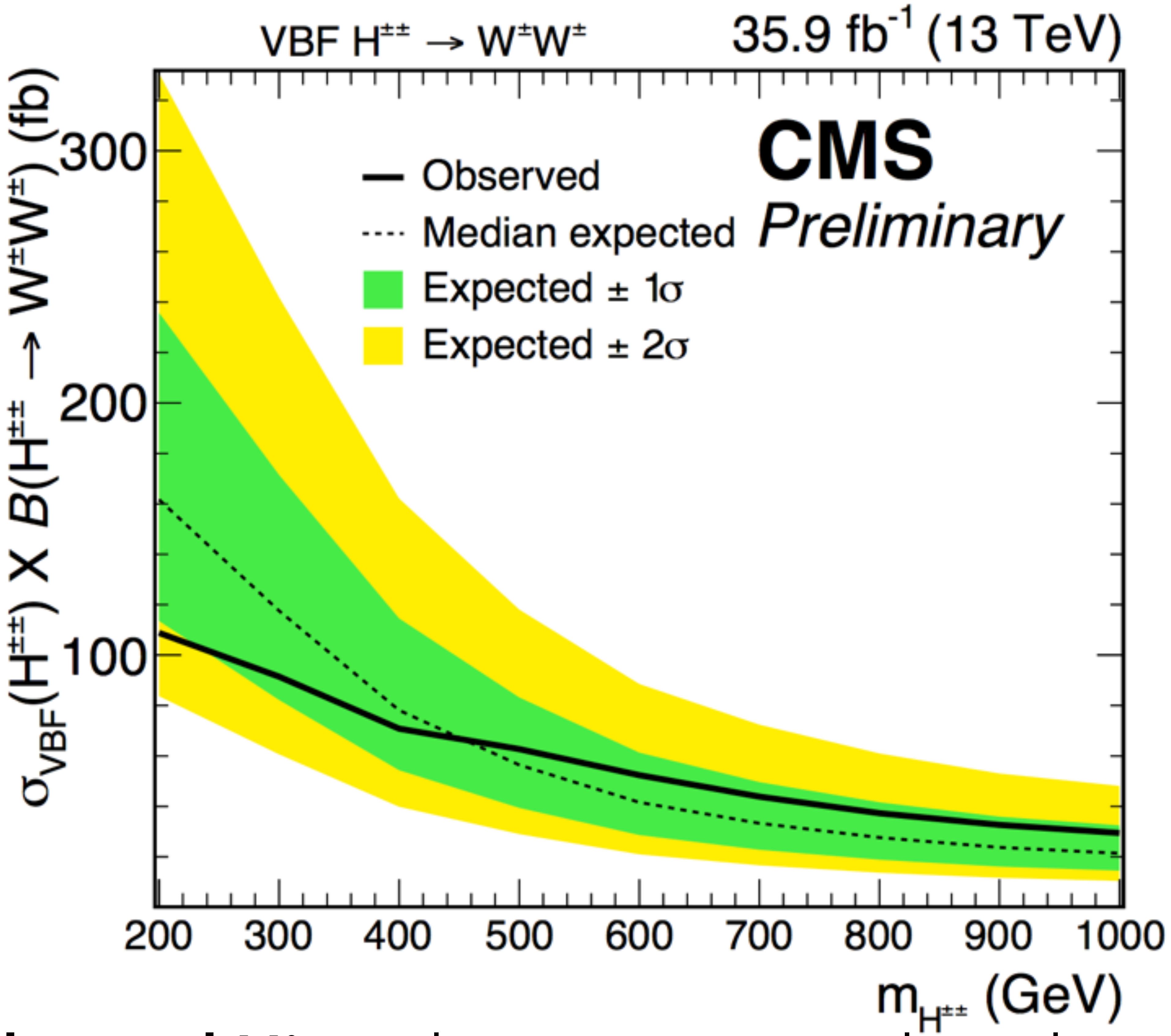
CMS at 13 TeV

Limits on nine independent CP-conserving **dimension-eight** effective operators to modify the quartic couplings

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})	Run-I limits (TeV^{-4})
f_{S0}/Λ	[-7.7, 7.7]	[-7.0, 7.2]	[-38 , 40] [11]
f_{S1}/Λ	[-21.6,21.8]	[-19.9,20.2]	[-118 , 120] [11]
f_{M0}/Λ	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6 , 4.6] [29]
f_{M1}/Λ	[-8.7 ,9.1]	[-7.9, 8.5]	[-17 , 17] [29]
f_{M6}/Λ	[-11.9,11.8]	[-11.1,11.0]	[-65 , 63] [11]
f_{M7}/Λ	[-13.3,12.9]	[-12.4,11.8]	[-70 , 66] [11]
f_{T0}/Λ	[-0.62,0.65]	[-0.58,0.61]	[-3.8 , 3.4] [30]
f_{T1}/Λ	[-0.28,0.31]	[-0.26,0.29]	[-1.9 , 2.2] [11]
f_{T2}/Λ	[-0.89,1.02]	[-0.80,0.95]	[-5.2 , 6.4] [11]

➡**95% CL limits on aQGC** using the the measured m_{ll} distributions.

➡ Greatly improved w.r.t. Run1



Doubly charged Higgs bosons are predicted in models containing a Higgs triplet field. (Georgi–Machacek model)

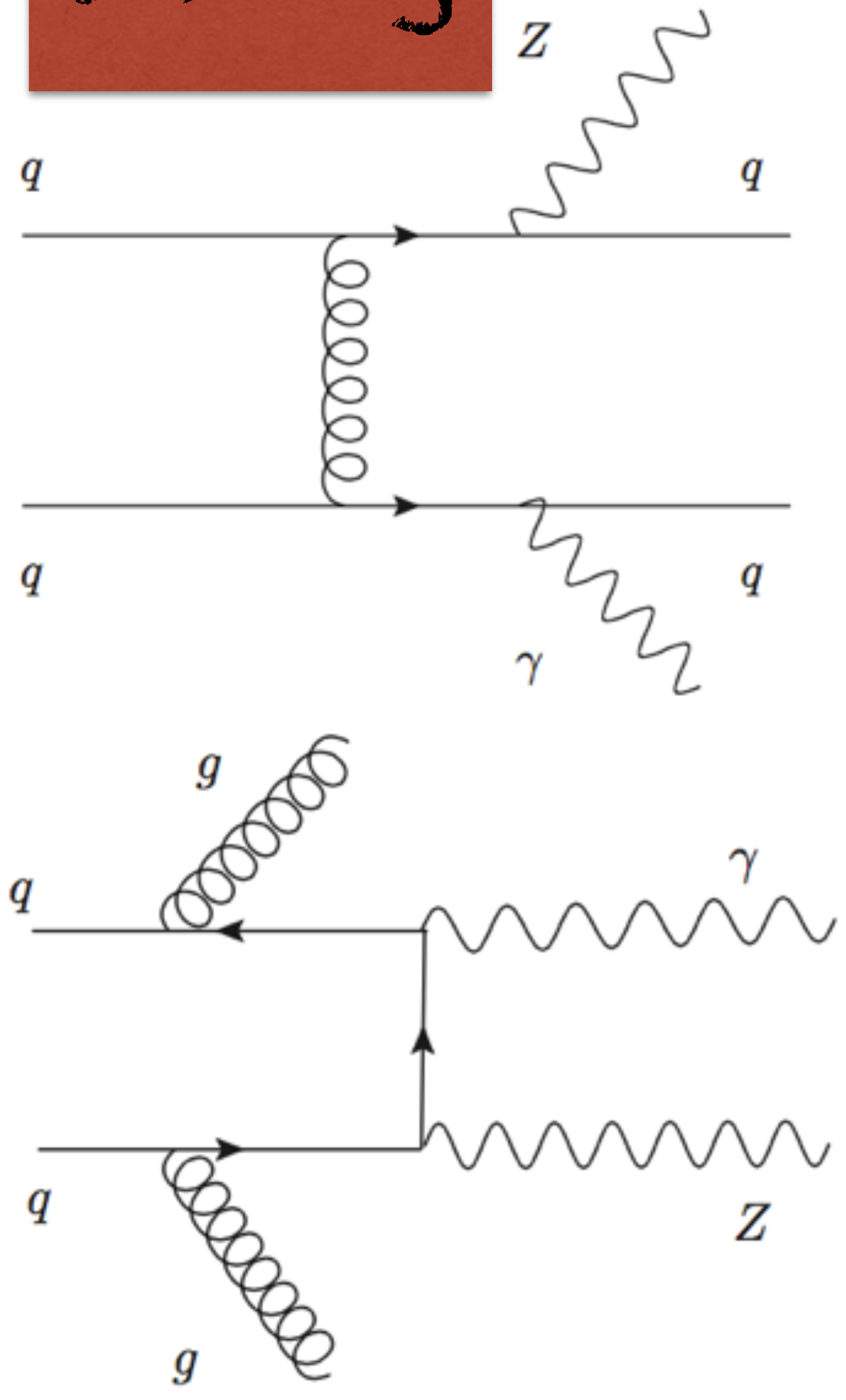
The selected same-sign events are used to constrain the parameters of such models

➡1st **limits** placed on $H^{\pm\pm} \to W^{\pm}W^{\pm}$ cross section using (m_{jj}, m_{ll}) 2D distributions

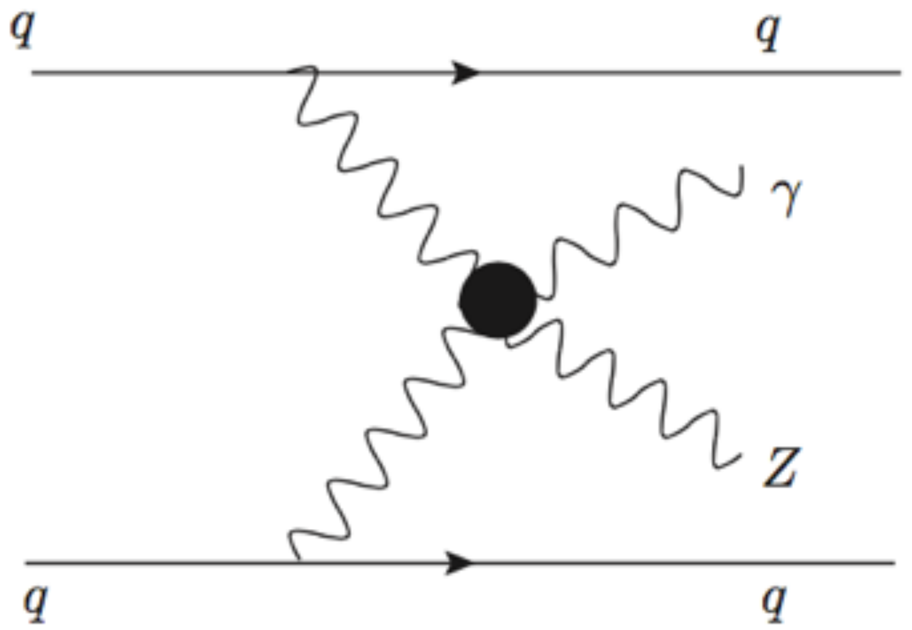
$Z\gamma$ + 2 jets final states

Zγ + 2jets

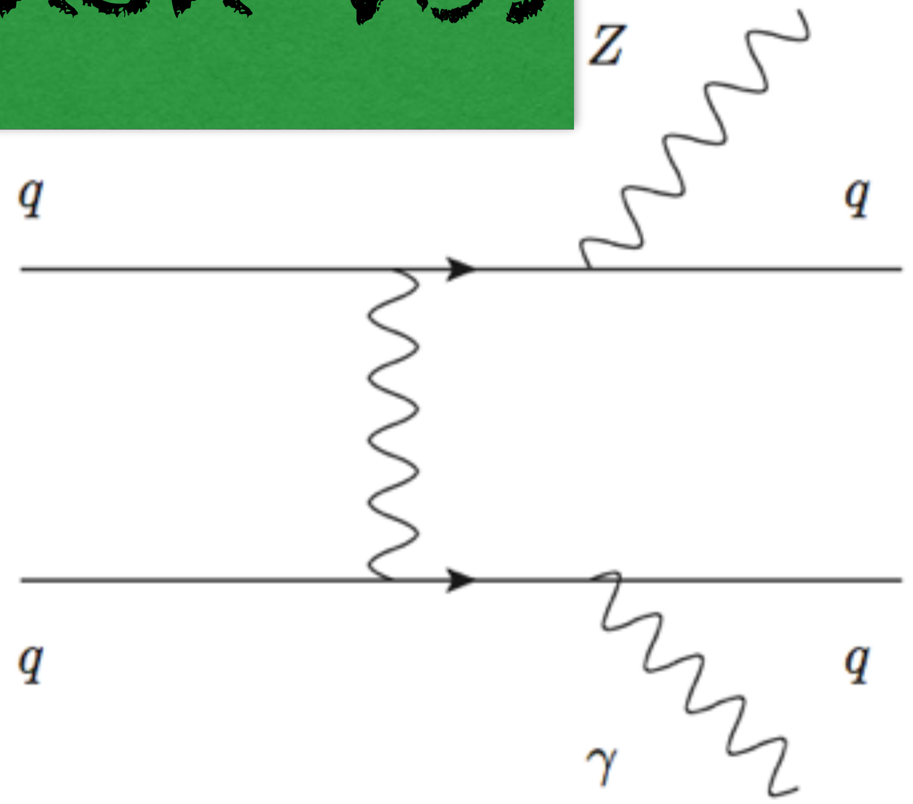
Strong

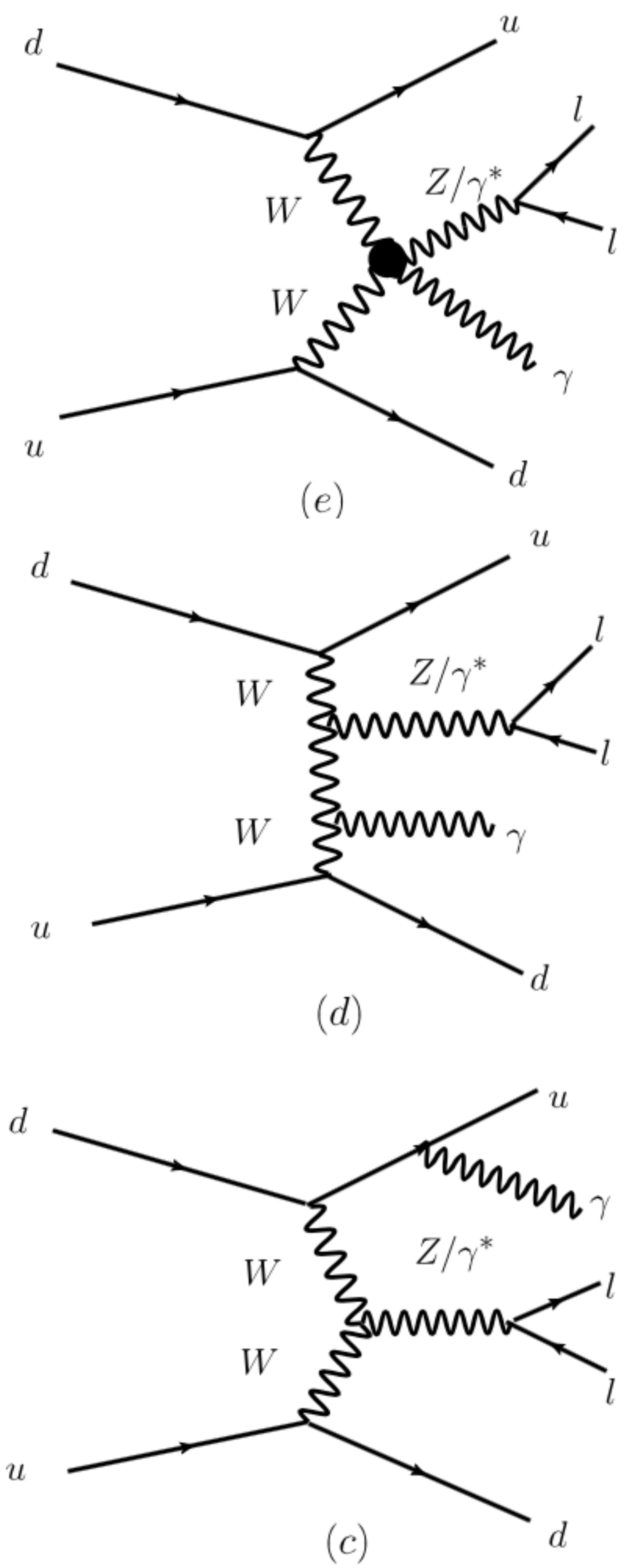


EW VBS



EW non-VBS





QGC

TGC

Main backgrounds:

QCD: from MC, yield validated
Z+jets (jet faking photon): extracted from data
ttbar γ: from simulation
Dibosons: almost negligible in SR, from MC

$Z\gamma$ + 2jets

ATLAS at 8 TeV

- **Inclusive signal region** with two leptons, two high-mass jets and a high energy photon.
  Channels: $\mu^+\mu^-\gamma jj$ and $e^+e^-\gamma jj$
- QCD production constrained with data in a CR requiring $150 < m_{jj} < 500\ GeV$
- **Search signal region** (VBS EW) $m_{jj} > 500\ GeV$

Zγjj Sample

Sherpa v1.4.5 at LO for both EWK and QCD EWK-QCD interference treated as system. uncertainty. Predicted from Madgraph to be less than 10% of the EWK XS in the Search Region

Sources of uncertainty

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

The contribution of the uncertainty in the η-intercalibration method of the JES is quite large, signal characterized by jets with high rapidity.

Sherpa modelling of the Zγ j j production processes and interference between the QCD and EWK processes

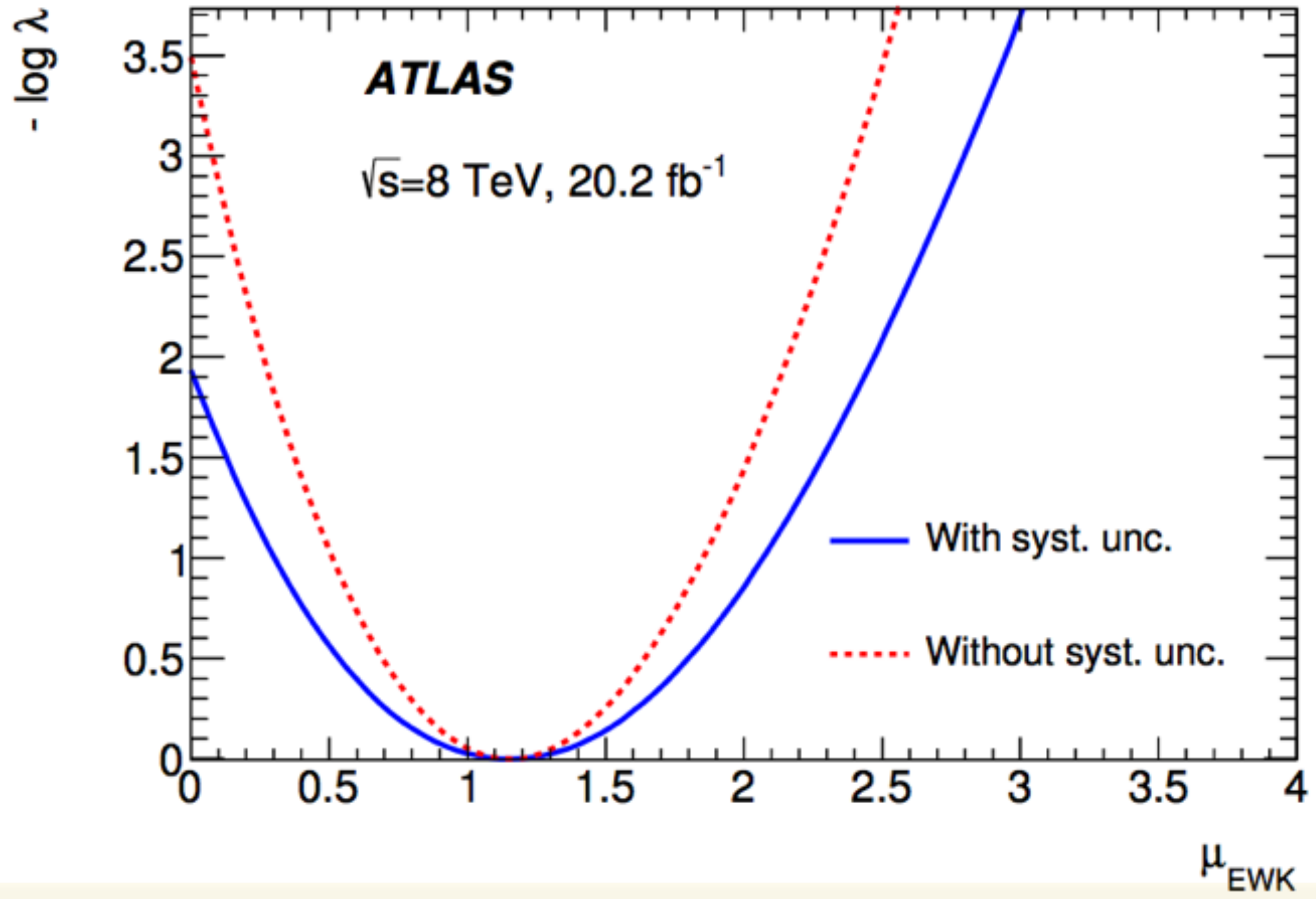
$Z\gamma$ + 2jets

ATLAS at 8 TeV

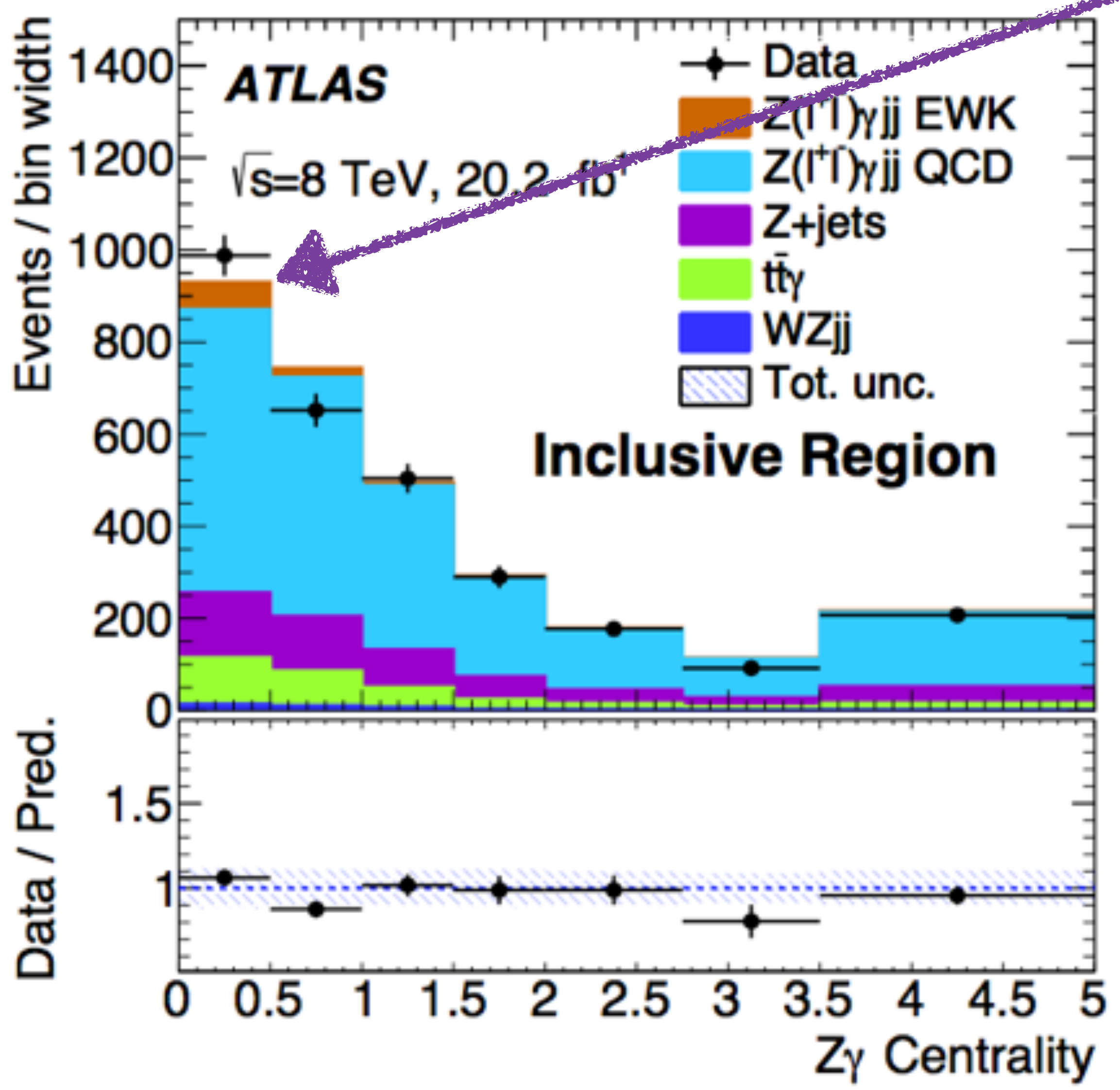
- **Inclusive signal region** with two leptons, two high-mass jets and a high energy photon.
  Channels: $\mu^+\mu^-\gamma jj$ and $e^+e^-\gamma jj$
- QCD production constrained with data in a CR requiring $150 < m_{jj} < 500\ GeV$
- **Search signal region** (VBS EW) $m_{jj} > 500\ GeV$

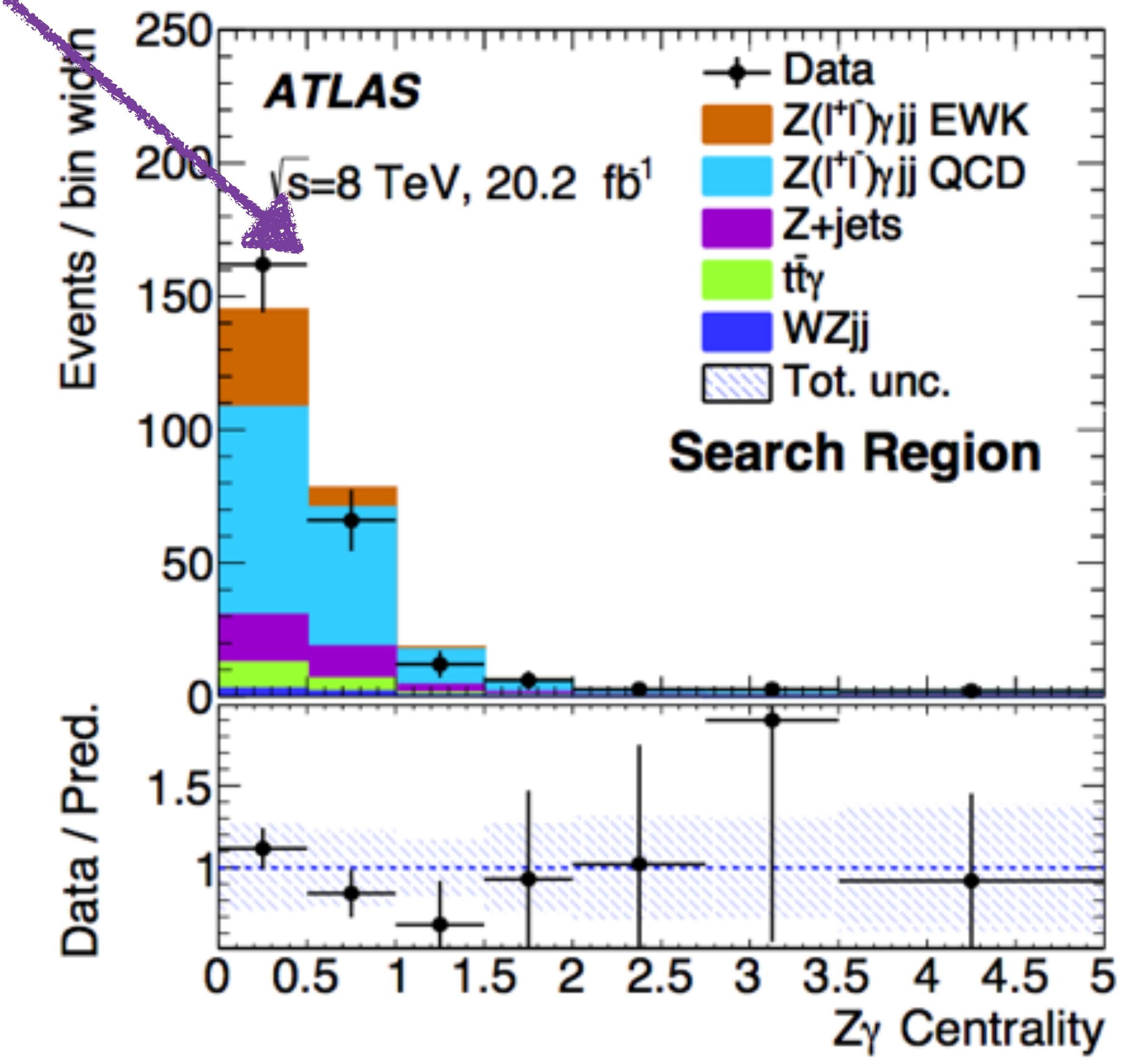
➡ **Likelihood fit over the $Z\gamma$ centrality:**

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



EW signal lower values of ζ





σ_{fid}(EWK)=1.1±0.5(stat)±0.4(syst) in agreement with the SM expectations σ_{VBFNLO}(EWK)=0.94±0.09

➡ Significance 2.0 σ (1.8 σ exp.)

$Z\gamma$ + 2jets - aQGC

ATLAS at 8 TeV

Two final states considered:

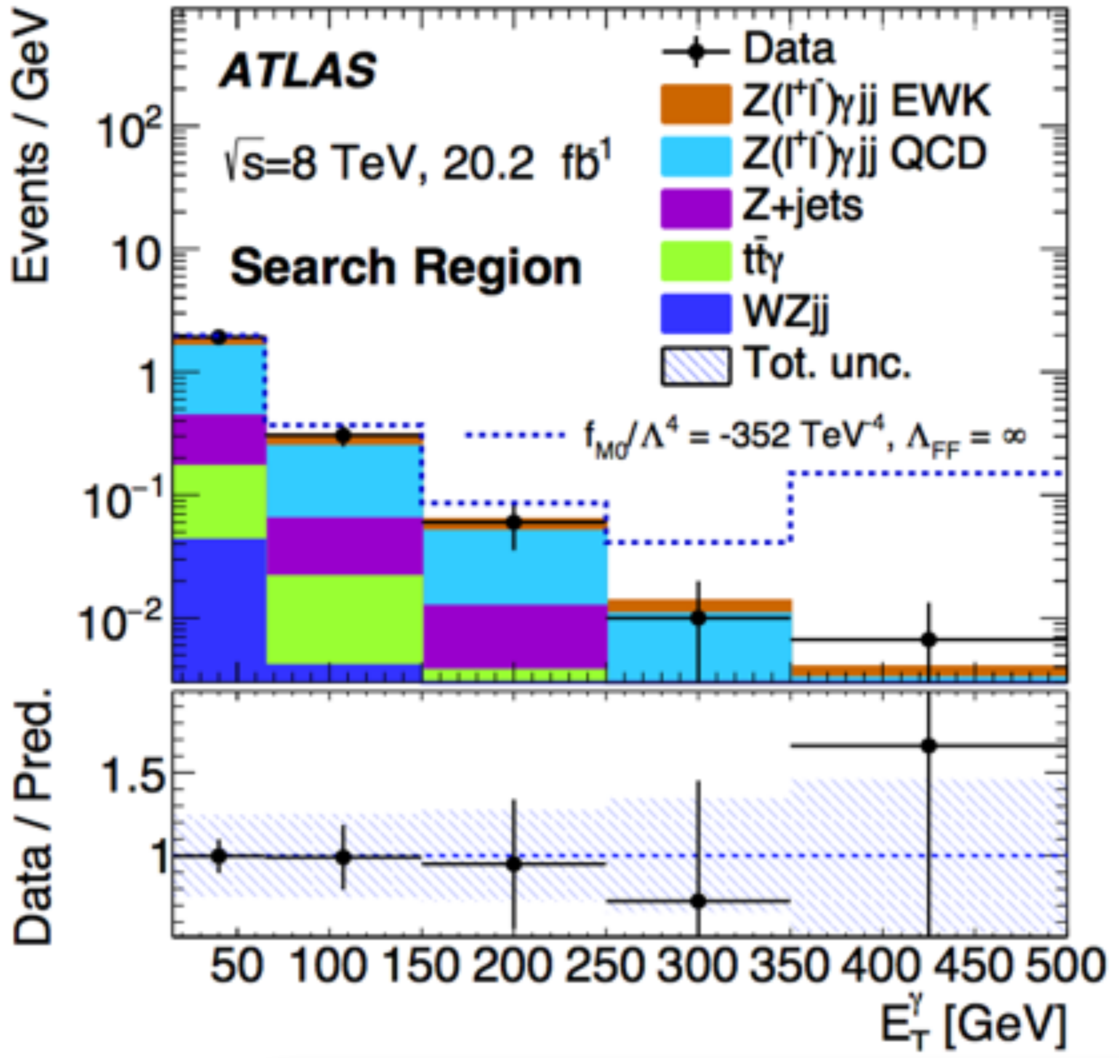
$\ell^+\ell^-\gamma jj$ and $\nu\bar{\nu}\gamma jj$

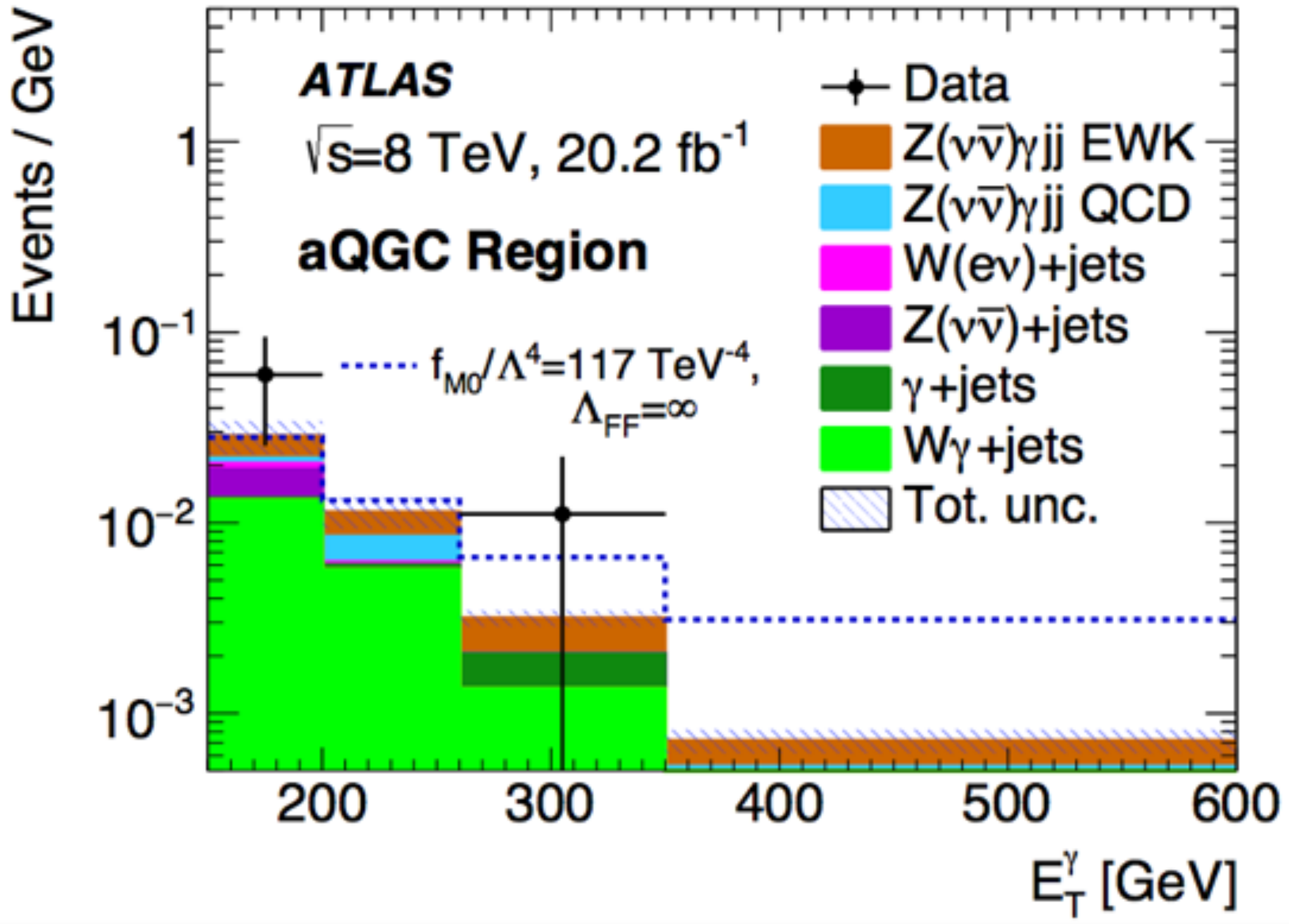
aQGC region	
$m_{jj} > 500$ GeV	$m_{jj} > 600$ GeV
$E_T^\gamma > 250$ GeV	$E_T^\gamma > 150$ GeV
$\ell^+\ell^-\gamma jj$	$\nu\bar{\nu}\gamma jj$

	95% CL intervals	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
	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	$[-1.9, 1.6] \times 10^1$	$[-1.6, 1.3] \times 10^1$	
$n = 0$	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	$[-1.7, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	
	$\boxed{f_{T9}/\Lambda^4}$	$[-6.9, 6.9] \times 10^4$	$[-5.4, 5.3] \times 10^4$	0.7
	$\boxed{f_{T8}/\Lambda^4}$	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.5] \times 10^4$	0.7
$n = 2$	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

n = 0→infinite FF scale: non-unitarized 95% CL intervals

accessible only via neutral QGC vertices





Upper limit on cross section (log-likelihood fit, CLs technique) :
1.06 fb (0.99 exp.) ννγ and 1.03 fb (1.01 fb exp.) llγ

One dim. 95%CL intervals on aQGC parameters

Best expected interval: ννγ (improved of 10-30% with including llγ)

Main uncertainties: QCD scales (~8%)

Expected intervals are a factor ~2 better than CMS (without Form Factors)

$Z\gamma$ + 2jets

CMS at 8 TeV

$Z\gamma jj$ Sample

Madgdaph at LO for both EWK and QCD with 0-3 additional jets + NLO k-factor of 1.1 for mjj<400 GeV for QCD

- MG5 matched to Parton shower based on MLM prescription

Dominated by the large stat uncertainty in the CR used for normalization

Sources of uncertainty

Summary of the major uncertainties.

Source	Uncertainty
QCD $Z\gamma$ + 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% [3]
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%

from MadGraph

$Z\gamma$ + 2jets

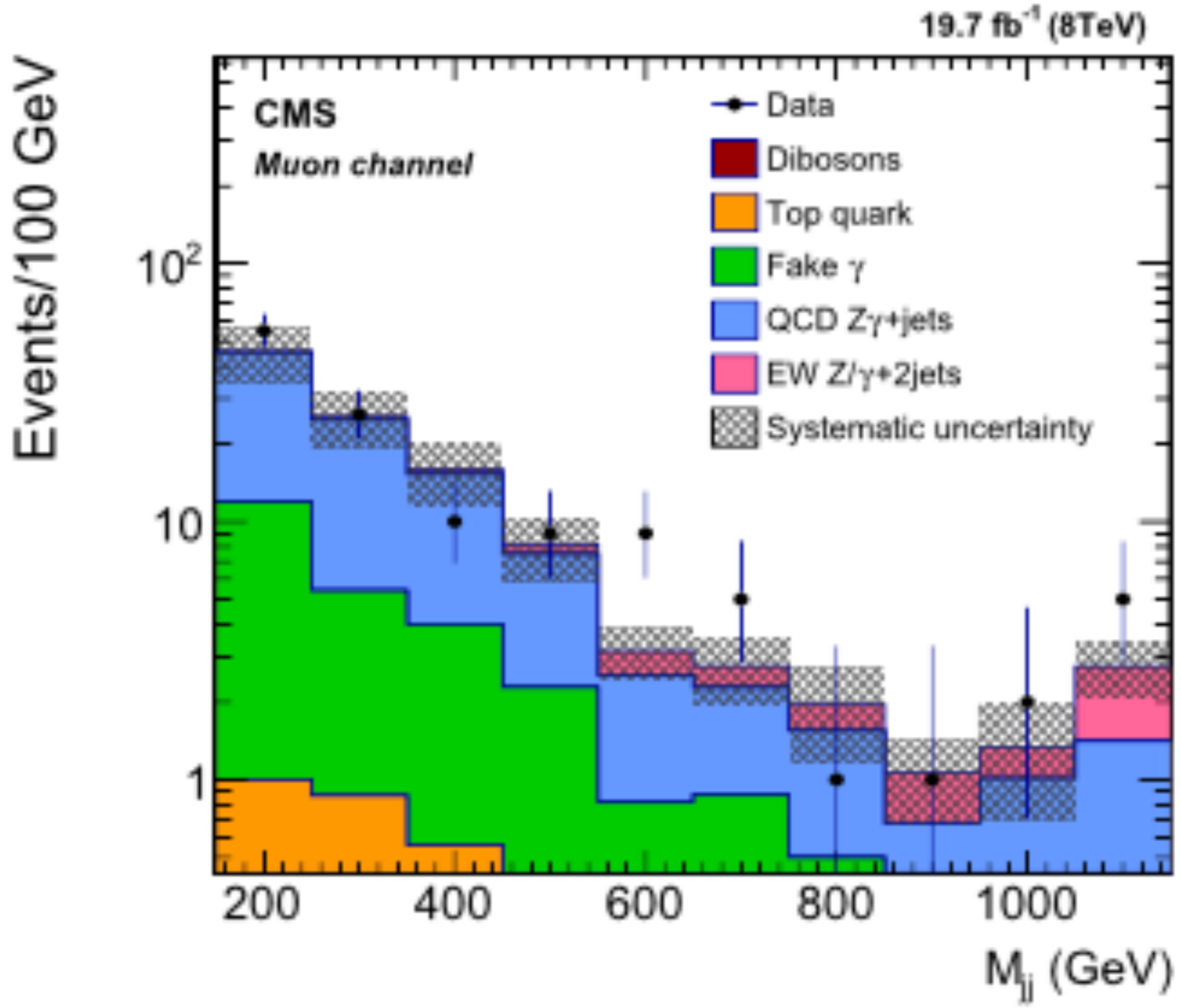
CMS at 8 TeV

QCD/EW discriminant variables used to build an EW-enriched region

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

EW SR: **Inclusive SR:**

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



EW signal significance with CL_s criterion, using 2 m_{jj} bins (400-800, >800 GeV)

σ_{fid}(EWK)=1.86±0.90(stat)±0.34(syst)±0.05(lumi) fb in agreement with the SM expectations $\sigma_{MG5(LO)}$ =1.27±0.11(scale)±0.05(PDF) fb
observed (exp.) significance of **3.0 σ (2.1 σ)**

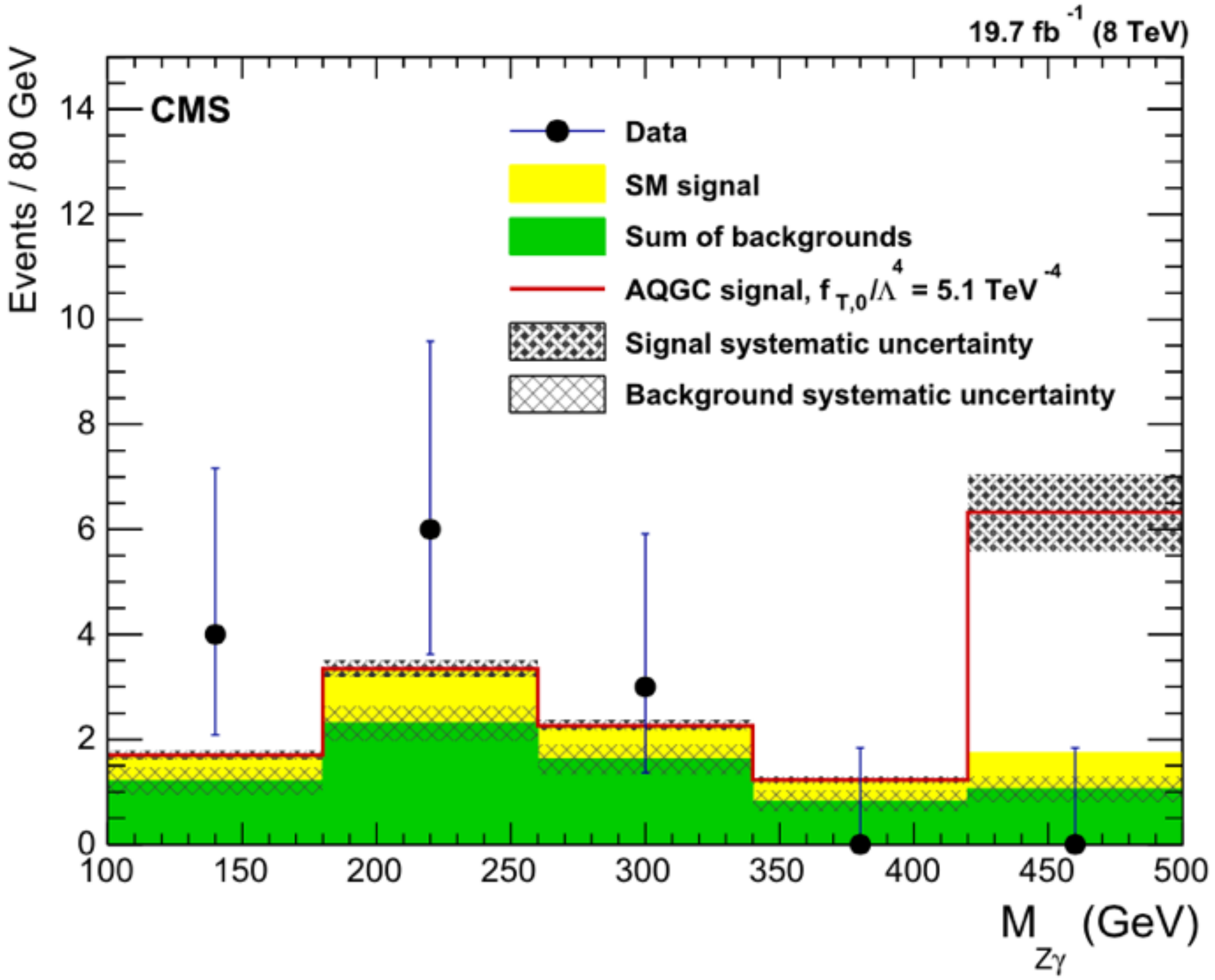
$Z\gamma$ + 2jets - aQGC

CMS at 8 TeV

- Baseline selection +

aQGC search
$p_T^{\gamma} > 60$ GeV
$\lvert\Delta\eta_{jj}\rvert > 2.5$
$\Delta R_{j\ell} > 0.3$, $\Delta R_{jj,\gamma j,\gamma\ell} > 0.5$
$M_{jj} > 400$ GeV

- Used shape of $M_{Z\gamma}$ distribution to extract limits on aQGC contributions



- The Lagrangian of the aQGCs is implemented in MadGraph.
- For each aQGC the unitarity bound has been checked with VBFNLO: the limits on all aQGC parameters are set in the unitary unsafe region (except for fT9)
- No form factors introduced

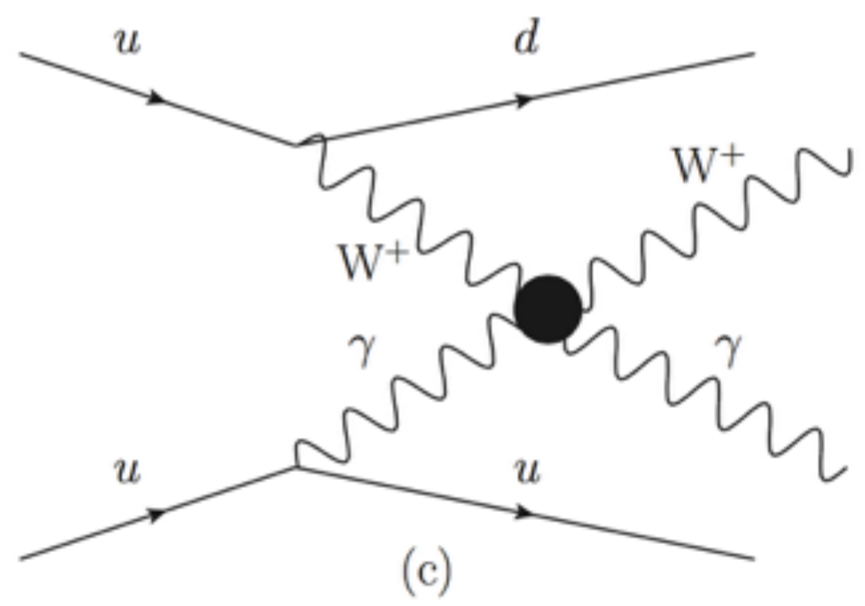
Observed and expected shape-based exclusion limits for each aQGC parameter at 95% CL, without a form factor applied.

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

$W\gamma$ + 2 jets final states

$W\gamma$ + 2jets

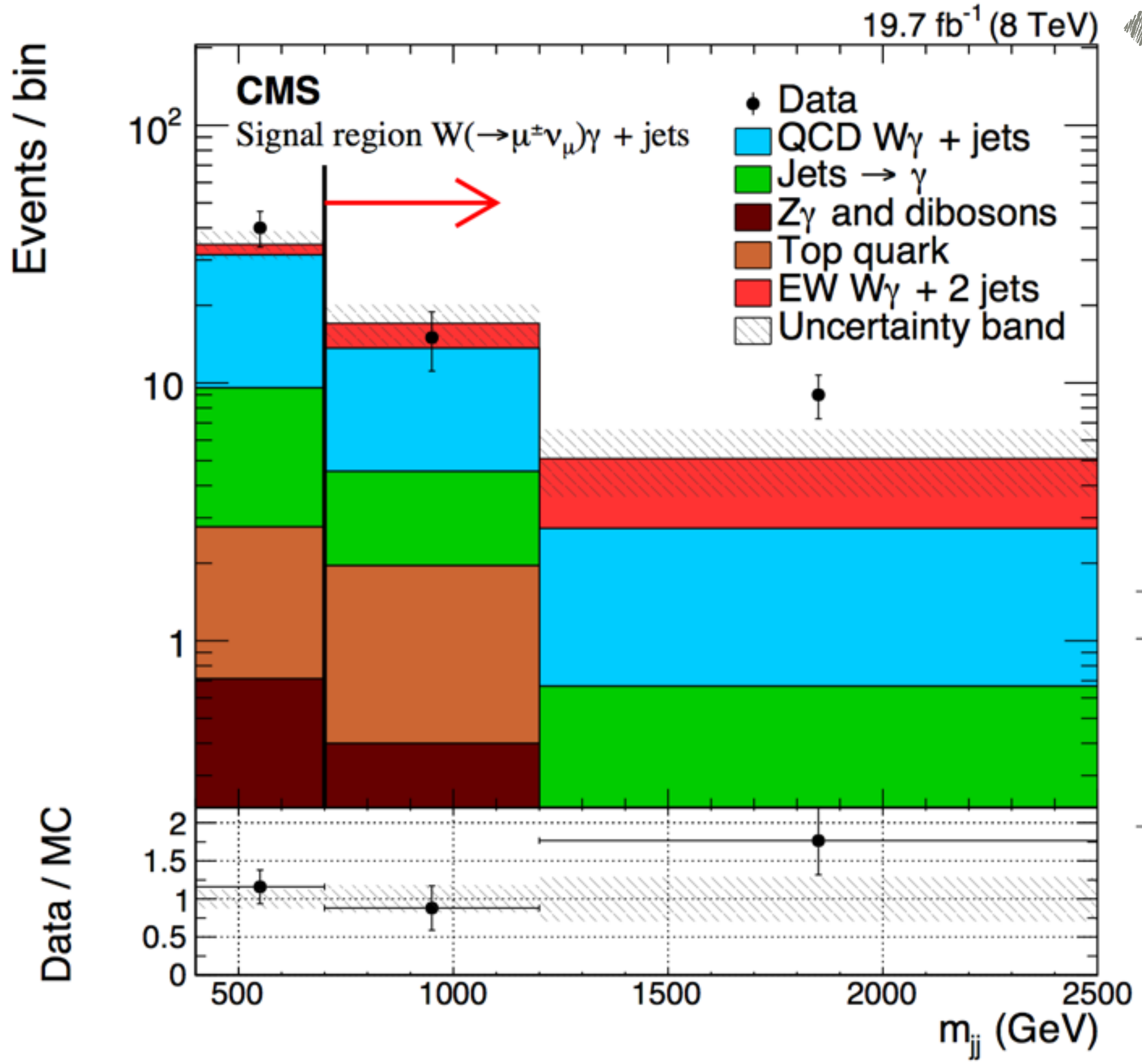
CMS at 8 TeV



- VBS channel with one of the **largest XS**
- **Main Backgrounds**: QCD $W\gamma jj$ production, jets mis-identified as photons or electrons (DD), $WV\gamma$ events with hadronically decaying V bosons, $Wt\gamma$

$W\gamma jj$ Sample

- EWK sample with MG5 LO, NLO QCD correction included with kfactor=1.2 (VBFNLO)
- QCD sample MG5 LO with MLM matching method, NLO correction included with kfactor =0.93
- Interference neglected



- QCD $W\gamma jj$ normalization from side-band $200 < m_{jj} < 400$ GeV

Search for EW $W\gamma jj$ on the binned m_{jj} distribution, $m_{jj} > 700$GeV

Items	EW measurement	EW+QCD measurement
Signal strength $\hat{\mu}_{sig}$	$1.78^{+0.99}_{-0.76}$	$0.99^{+0.21}_{-0.19}$
Observed (expected) significance	2.7 (1.5) standard deviations	7.7 (7.5) standard deviations
Theoretical cross section (fb)	6.1 ± 1.2 (scale) ± 0.2 (PDF)	23.5 ± 5.3 (scale) ± 0.8 (PDF)
Measured cross section (fb)	10.8 ± 4.1 (stat) ± 3.4 (syst) ± 0.3 (lumi)	23.2 ± 4.3 (stat) ± 1.7 (syst) ± 0.6 (lumi)

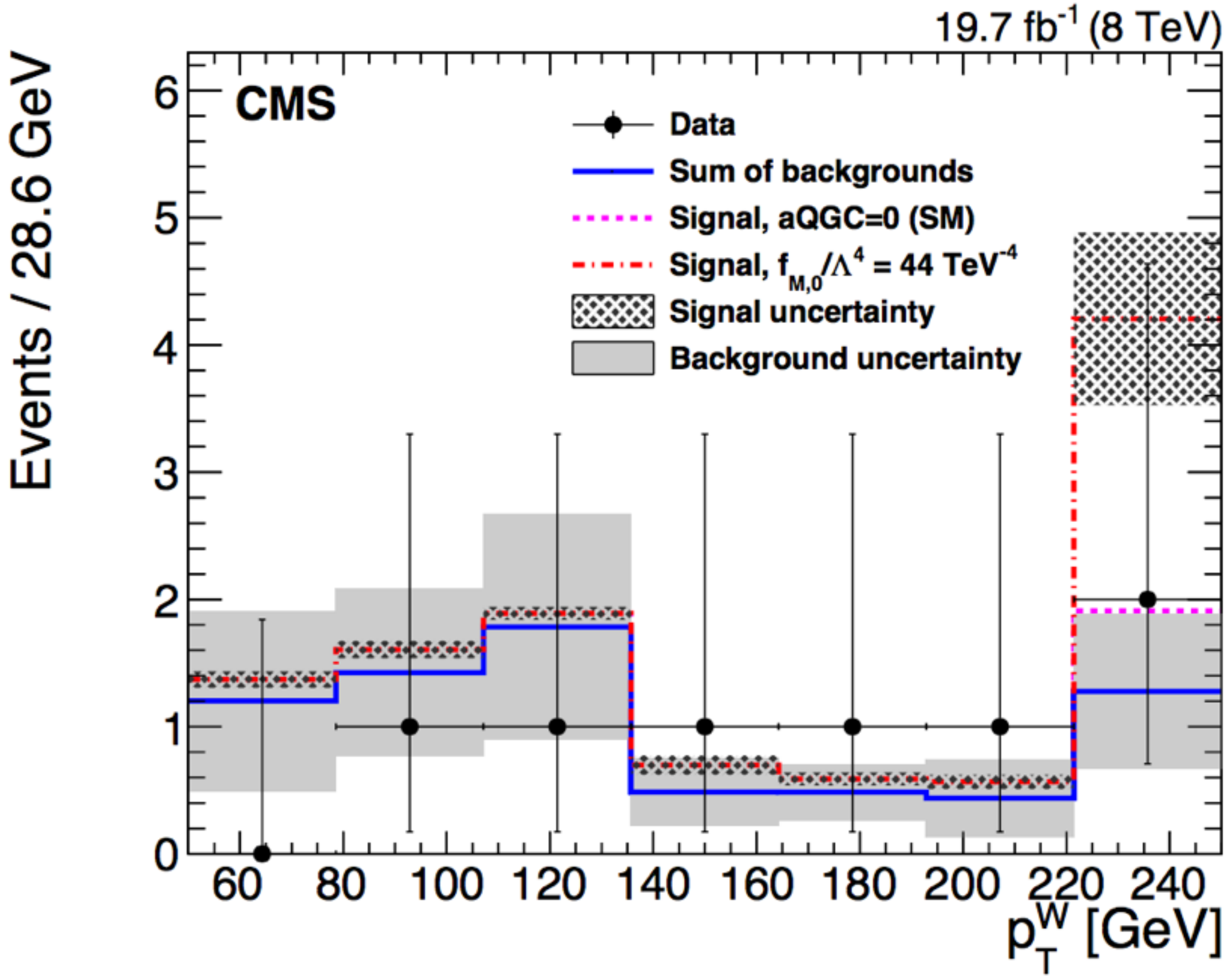
Consistent with the SM expectations

Wγ + 2jets - aQGC

CMS at 8 TeV

Main sources of uncertainty:
QCD scales EW Wγ (QCD) signal 20(30)%
Jet-uncertainties 12-31%
MisID jets as γ/l: 10-40%

- Presence of aQGC should enhance the XS at high energy tails
- Shape of p_T^W used to set limits
- Baseline selection + $|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 1.2$, $|\Delta\eta(j1, j2)| > 2.4$, $p_T^\gamma > 200\,\text{GeV}$.
- Search performed on each aQGC separately, while setting the others to the SM value



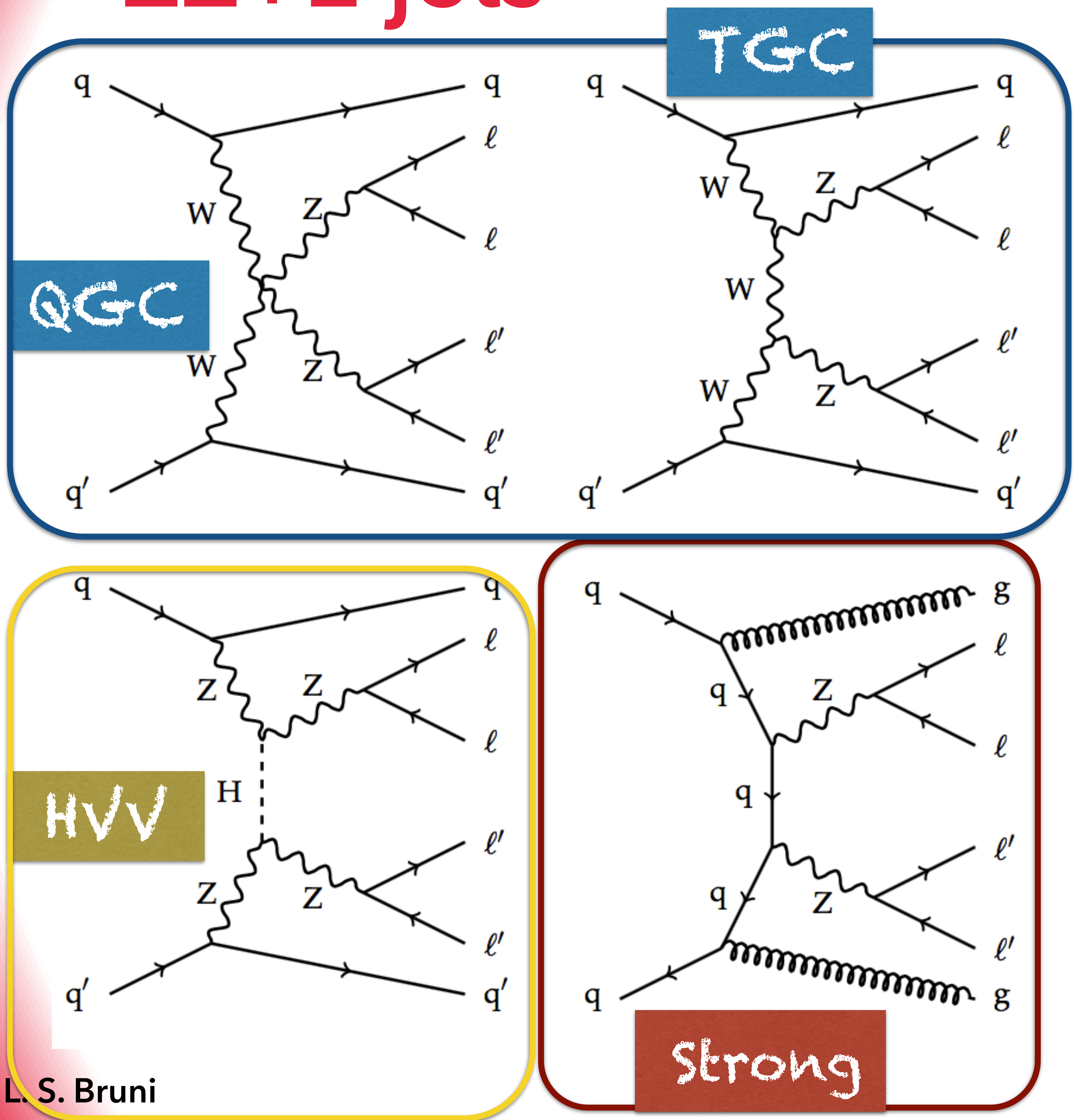
First limits set

Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-77 < f_{M,0}/\Lambda^4 < 74$	$-47 < f_{M,0}/\Lambda^4 < 44$
$-125 < f_{M,1}/\Lambda^4 < 129$	$-72 < f_{M,1}/\Lambda^4 < 79$
$-26 < f_{M,2}/\Lambda^4 < 26$	$-16 < f_{M,2}/\Lambda^4 < 15$
$-43 < f_{M,3}/\Lambda^4 < 44$	$-25 < f_{M,3}/\Lambda^4 < 27$
$-40 < f_{M,4}/\Lambda^4 < 40$	$-23 < f_{M,4}/\Lambda^4 < 24$
$-65 < f_{M,5}/\Lambda^4 < 65$	$-39 < f_{M,5}/\Lambda^4 < 39$
$-129 < f_{M,6}/\Lambda^4 < 129$	$-77 < f_{M,6}/\Lambda^4 < 77$
$-164 < f_{M,7}/\Lambda^4 < 162$	$-99 < f_{M,7}/\Lambda^4 < 97$
$-5.4 < f_{T,0}/\Lambda^4 < 5.6$	$-3.2 < f_{T,0}/\Lambda^4 < 3.4$
$-3.7 < f_{T,1}/\Lambda^4 < 4.0$	$-2.2 < f_{T,1}/\Lambda^4 < 2.5$
$-11 < f_{T,2}/\Lambda^4 < 12$	$-6.3 < f_{T,2}/\Lambda^4 < 7.9$
$-3.8 < f_{T,5}/\Lambda^4 < 3.8$	$-2.3 < f_{T,5}/\Lambda^4 < 2.4$
$-2.8 < f_{T,6}/\Lambda^4 < 3.0$	$-1.7 < f_{T,6}/\Lambda^4 < 1.9$
$-7.3 < f_{T,7}/\Lambda^4 < 7.7$	$-4.4 < f_{T,7}/\Lambda^4 < 4.7$

ZZ + 2 jets final states

ZZ+2 jets

CMS at 13 TeV



- Fully leptonic final state considered
- Low cross section but the clean final state results in a small reducible bkg

Main backgrounds:

- **QCD production**: from simulation, yields checked while extracting EW
- **Irriducible bkg** (4 prompt and isolated leptons): ttbarZ, WWZ, estimated with simulations
- **Reducible bkg** (secondary leptons, jets misID as leptons): Zjets, ttbar, WZjets, estimated from data

ZZjj Sample

MG5_aMC at LO for EWK, cross-checked with PHANTOM
MG5_aMC at NLO for QCD with 0,1,2 partons at born level with FxFx merging
interference evaluated at LO with MG5_aMC ~1% -> Neglected

ZZ+2 jets

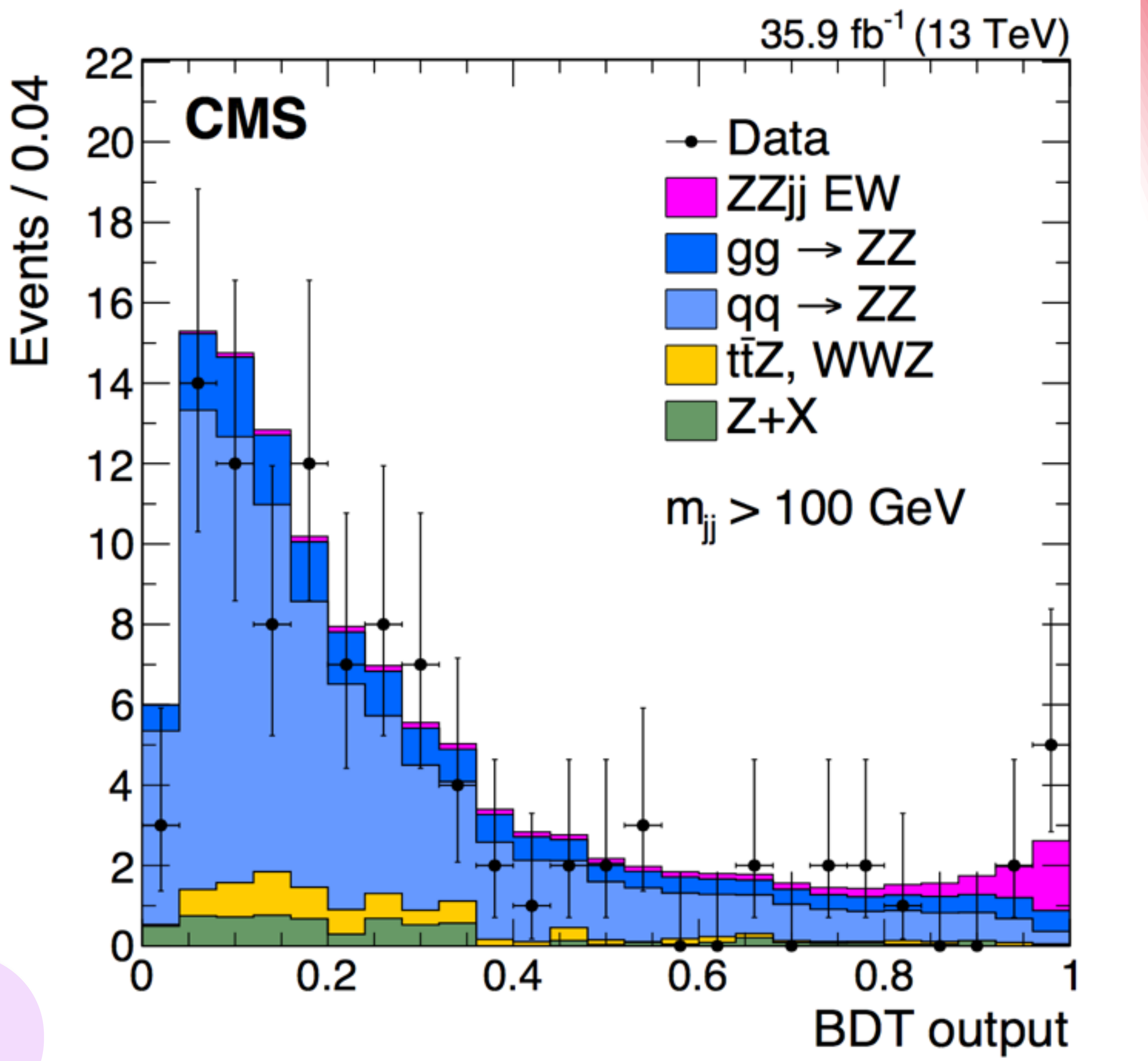
CMS at 13 TeV

Multivariate classifier is used to separate signal and QCD using a set of variables that can discriminate between QCD and EW production (as m_{jj}, ΔY_{jj}, m_{ZZ} …)

QCD bkg modeling validated by a QCD-enriched control region: $m_{jj} < 400$GeV or $|\Delta\eta_{jj}| < 2.4$

The BDT distribution is used to extract the significance of the EW signal by a **maximum-likelihood fit**

Main sources of systematics Scales for QCD (EW): 10 (7)%
JES 4/20% (low-high BDT score), JER 8%



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

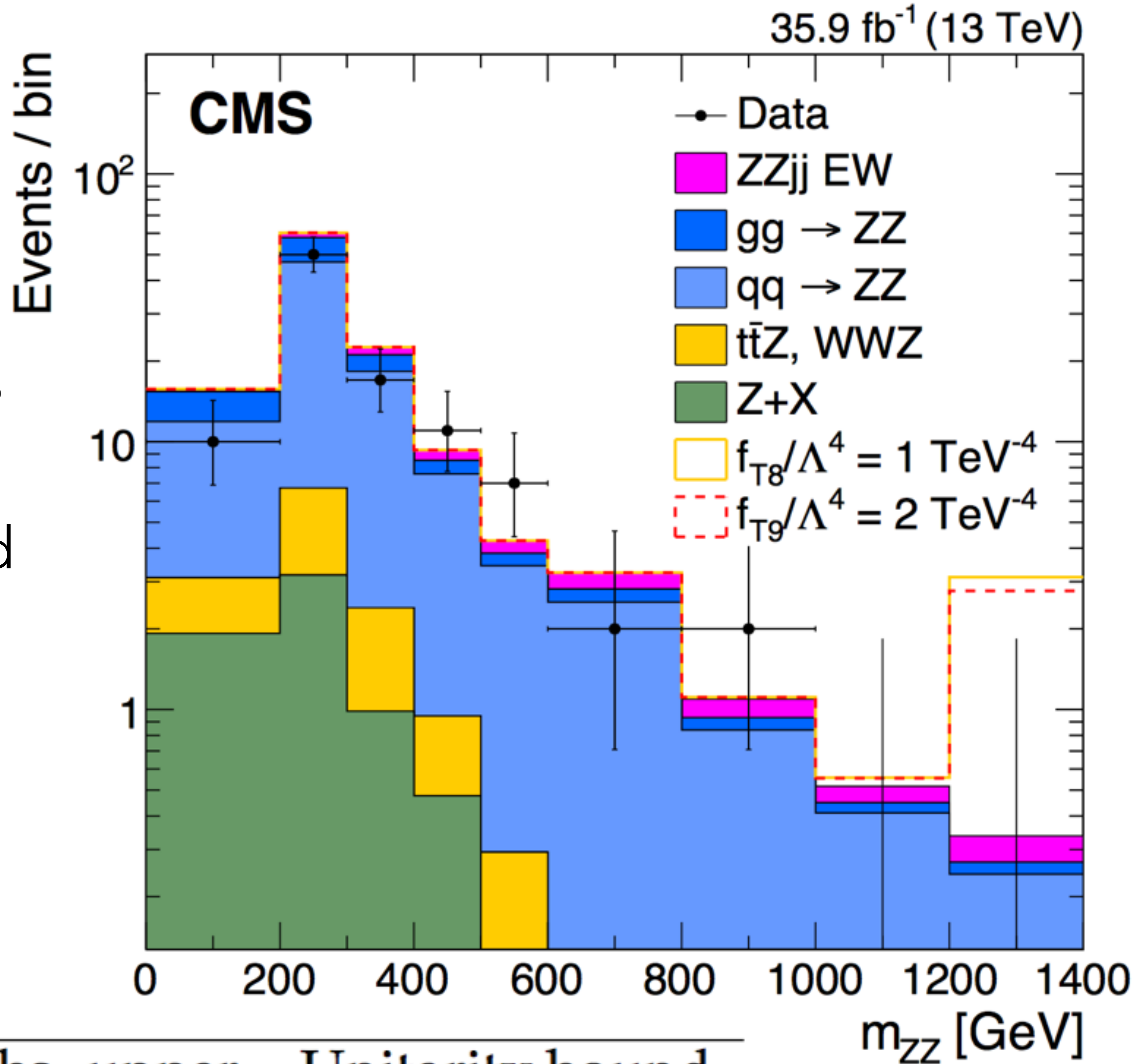
0.29±0.03 fb expected

Background-only hypothesis excluded with 1.6 σ expect. 2.7 σ observed

ZZ+2 jets - aQGC

CMS at 13TeV

- **M_{ZZ}** to constrain aQGC
- The increase of the yield exhibits a **quadratic dependence** on the anomalous coupling→ parabolic function is fitted to the per-mass bin yields: this allows an interpolation between the discrete coupling parameters of the simulated signals
- ZZjj sensitive in particular to operators
  - **T0**, **T1** and **T2** ($SU_L(2)$ gauge fileds)
  - **Neutral** current operators **T8** and **T9** ($U_Y(1)$ field)

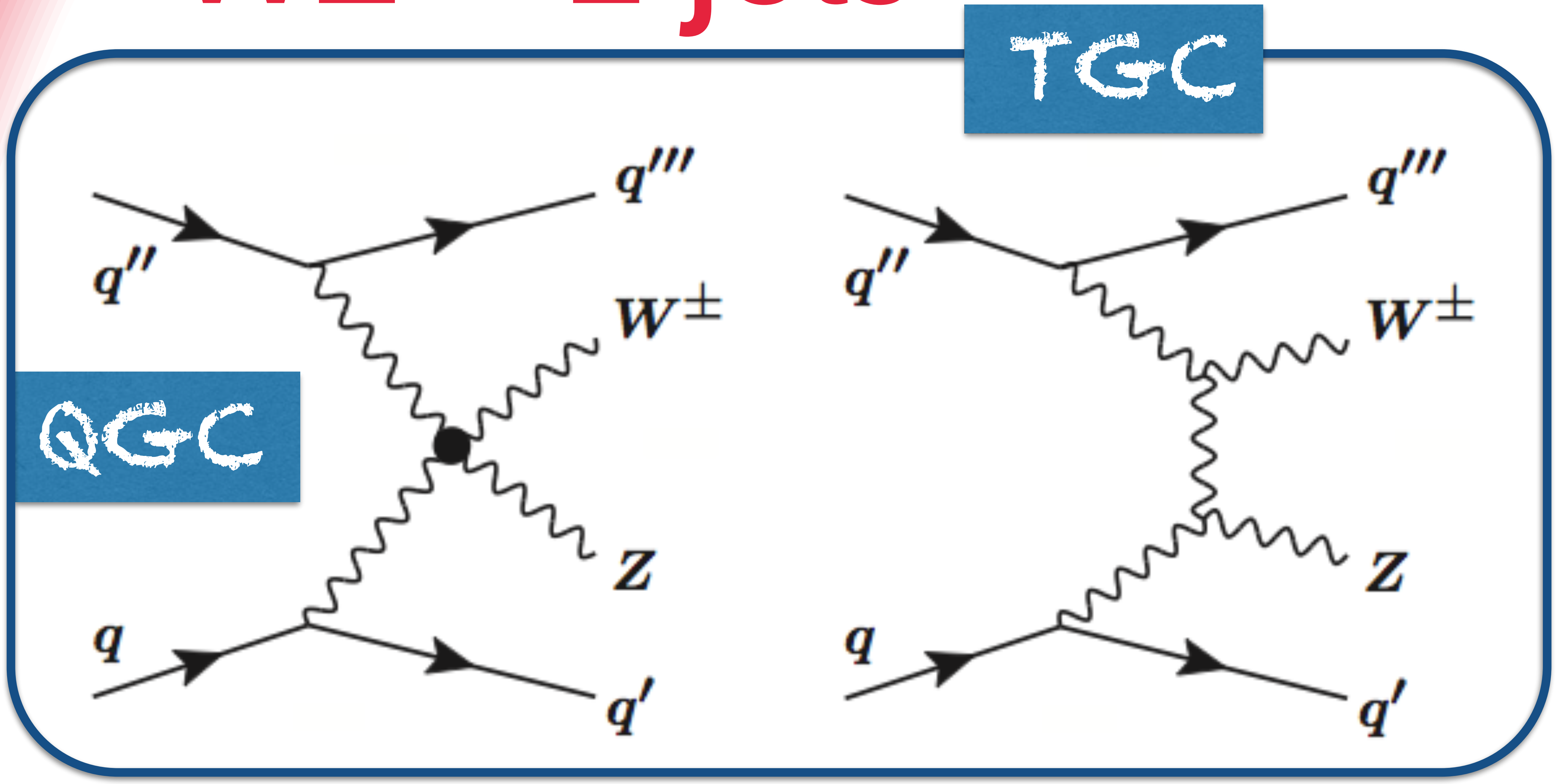


Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.53	0.51	−0.46	0.44	2.5
f_{T1}/Λ^4	−0.72	0.71	−0.61	0.61	2.3
f_{T2}/Λ^4	−1.4	1.4	−1.2	1.2	2.4
f_{T8}/Λ^4	−0.99	0.99	−0.84	0.84	2.8
f_{T9}/Λ^4	−2.1	2.1	−1.8	1.8	2.9

WZ + 2 jets

WZ + 2 jets

ATLAS at 8 TeV



Leptonic final state: $\ell\nu\ell\ell$

Bigger XS than ZZ, cleaner signature than WW

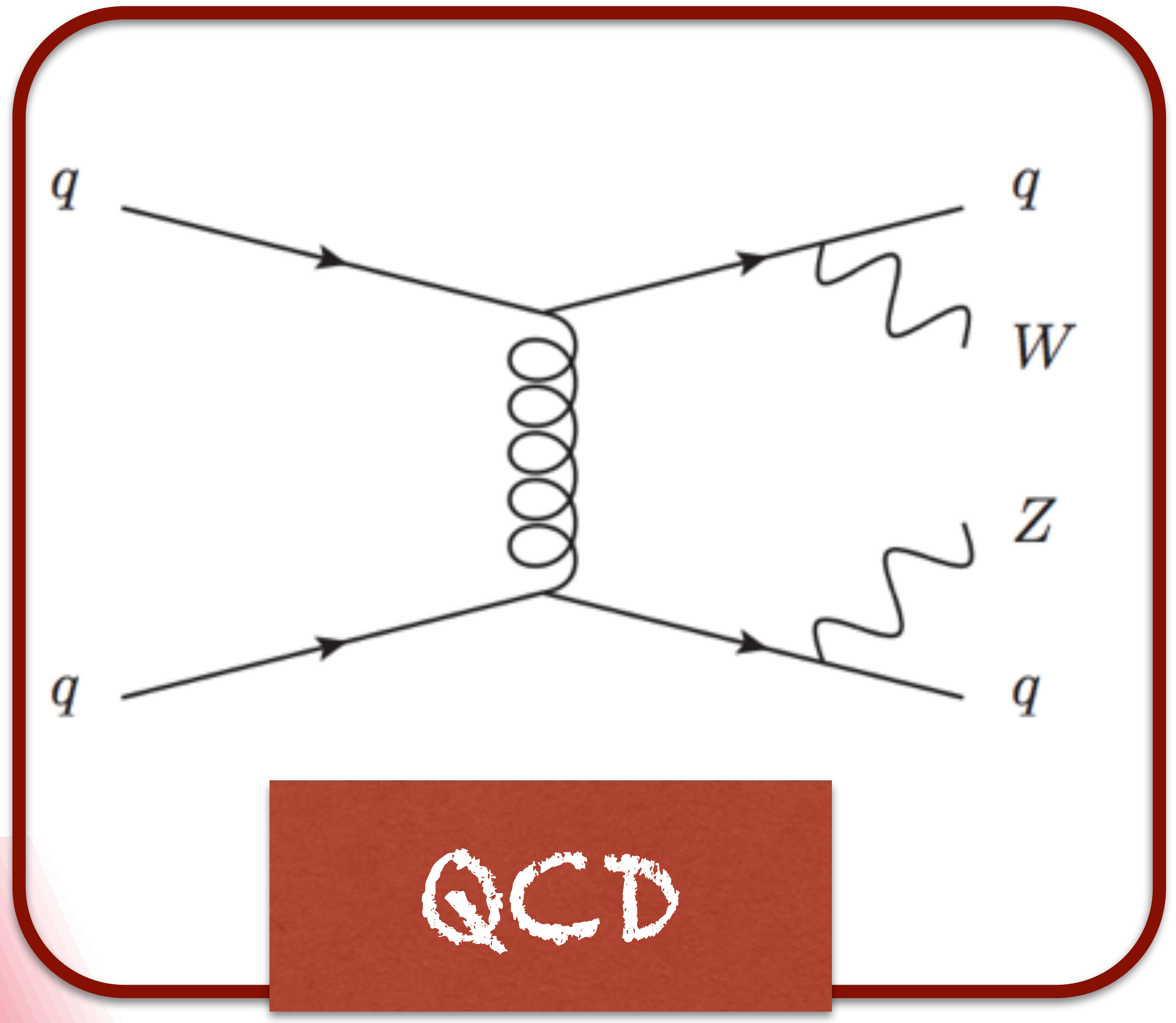
Main Backgrounds:

WZjj QCD (~70%), tZj (~10%), misID leptons, ZZ

WZjj Sample

Sherpa LO for both EW and QCD (matching CKKW)

Interference neglected



Variable	VBS
Lepton $\lvert\eta\rvert$	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	> 15, > 20
m_Z range [GeV]	$\lvert m_Z - m_Z^{PDG}\rvert < 10$
m_T^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	> 0.2, > 0.3
p_T two leading jets [GeV]	> 30
$\lvert\eta_j\rvert$ two leading jets	< 4.5
Jet multiplicity	≥ 2
m_{jj} [GeV]	> 500
$\Delta R(j, \ell)$	> 0.3
$\lvert\Delta\phi(W, Z)\rvert$	—
$\sum \lvert p_T^\ell\rvert$ [GeV]	—

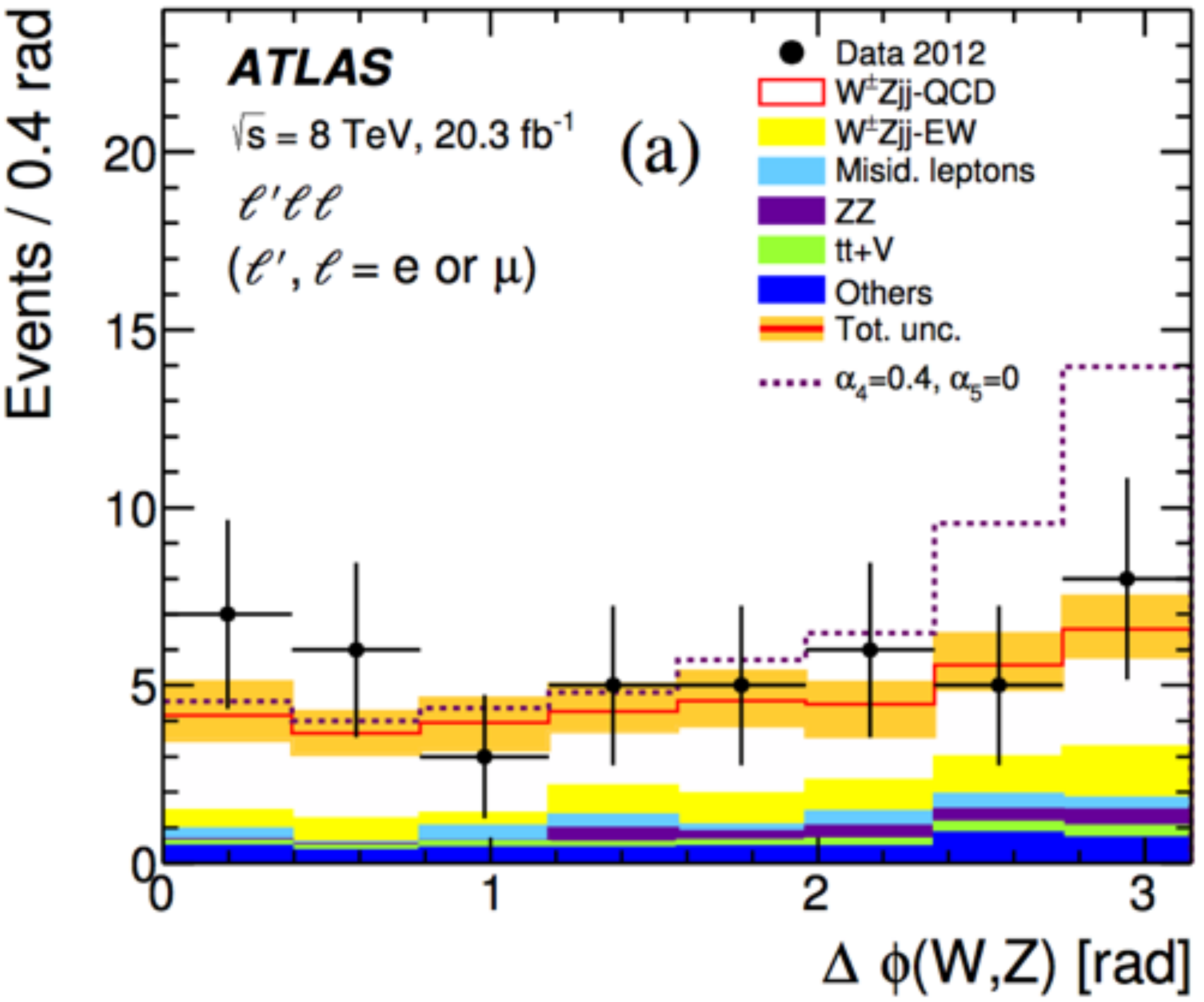
95% CL upper limit on $\sigma^{\text{fid.}}_{W^\pm Zjj\text{-EW}\to\ell'\nu\ell\ell}$ [fb]		
	VBS only	VBS + tZj
VBS phase space		
Observed	0.63	0.67
Expected	0.45	0.49
$\pm1\sigma$ Expected	[0.28 ; 0.62]	[0.33 ; 0.67]
$\pm2\sigma$ Expected	[0.08 ; 0.80]	[0.19 ; 0.84]

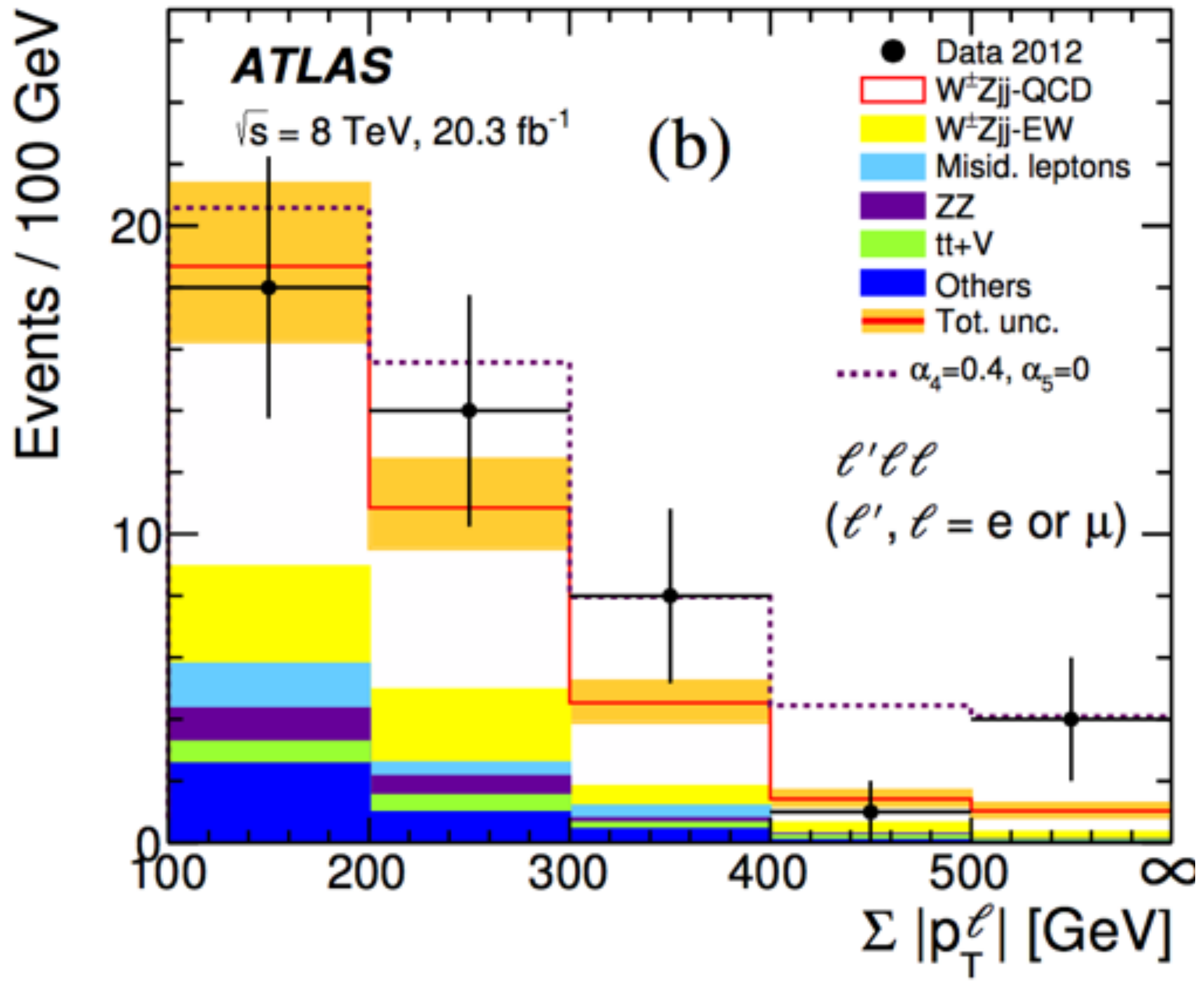
WZ + 2 jets -aQGC

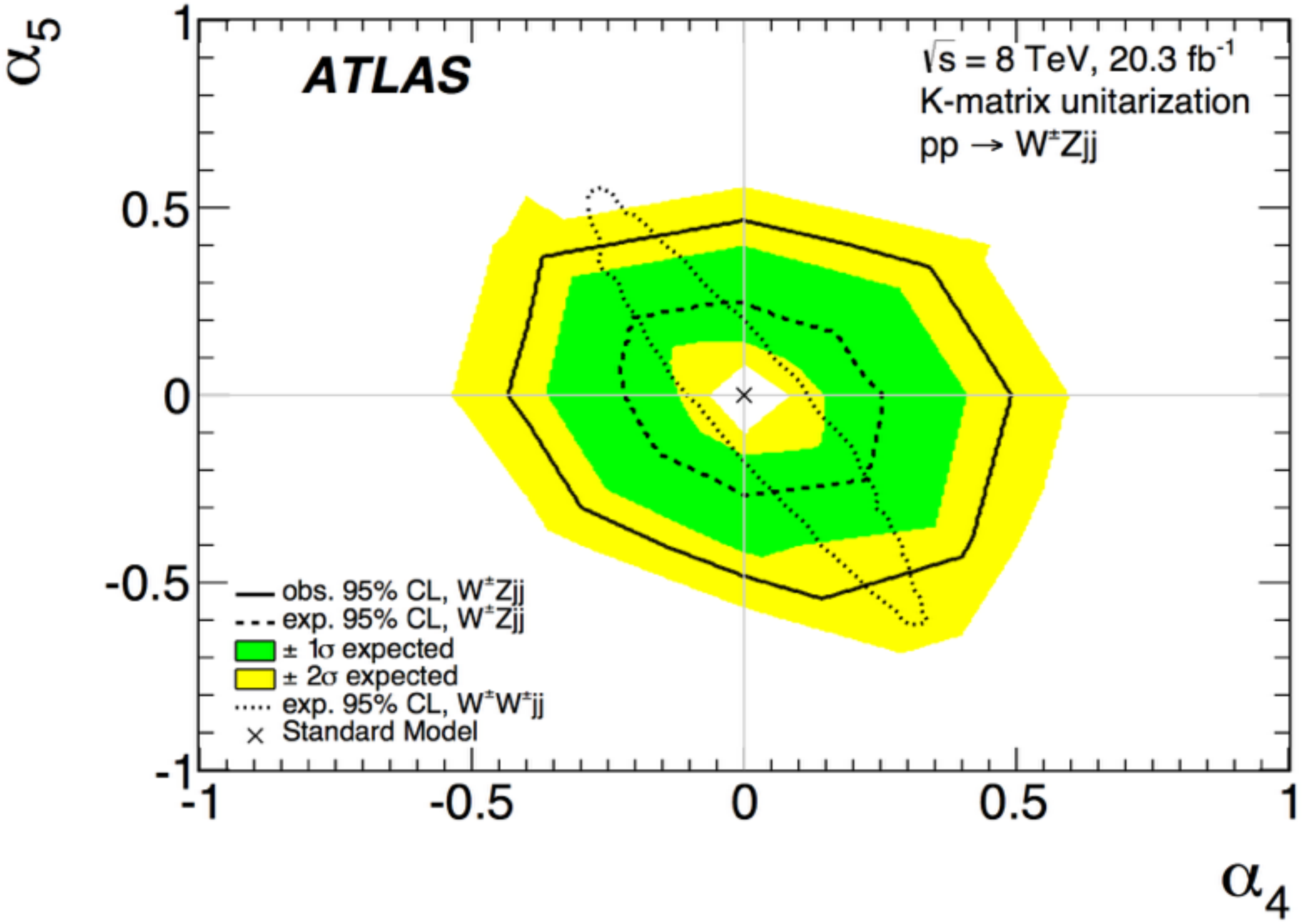
ATLAS at 8 TeV

VBS selection + $|\Delta\phi(W,Z)| > 2$, $\sum |p_T^\ell|$ [GeV] > 250

- Limits on dim4 opertarors **α4** and **α5** contributing to aQGC
- Whizard used to compute the ratio of the fiducial XS for different α4/α5 values to the SM XS (unitarization scheme included)
- Ratios multiplied by the SM fiducial XS estimated with Sherpa to obtain the predicted fiducial Xsec as a function of α4 and α5
- Distributions used to select events in the aQGC fiducial phase space



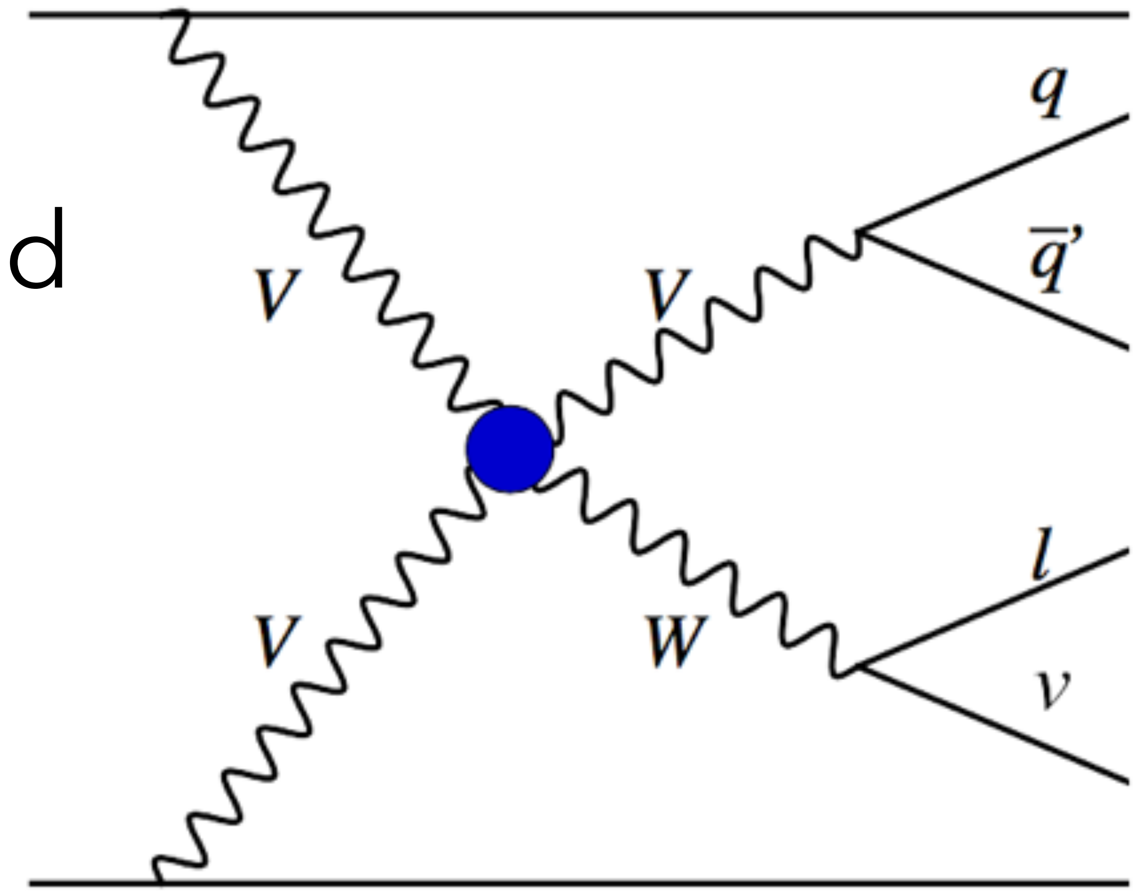




WV semi-leptonic

WV semi-leptonic

ATLAS at 8 TeV



- Search for VBS in the WVjj final state, where the W decays into leptons and the V (W/Z) into hadrons: larger BR than the leptonic channel, easier to reconstruct
- Channel with strong experimental **sensitivity to aQGC**

Main backgrounds: W-jets (MC, validated with data), ttbar, single top, di-boson (MC), multi-jet (DD)

WVjj EW Sample

Whizard +Pythia8 (LO)

Main sources of uncertainty

WVjj modelling: resolved (merged) 13 (29) %

Jet reconstruction: resolved (merged) 21(17) %

Selection Strategy

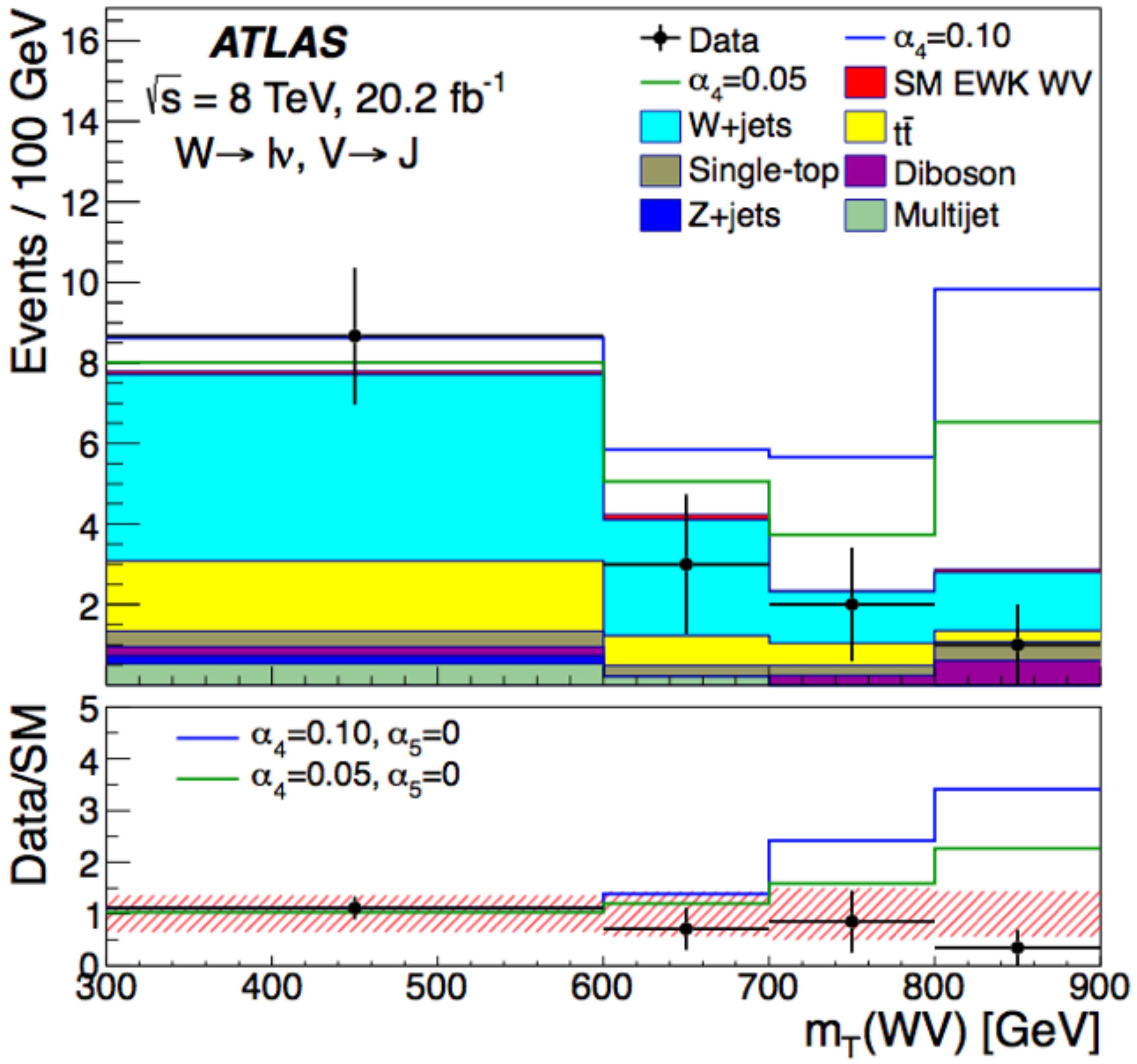
1) **Resolved selection**: reconstructs V_{had} as two small-R jets ($V \rightarrow jj$):
2) **Merged selection**: reconstructs V_{had} as a single large-R jet ($V \rightarrow J$):

improves the aQGC sensitivity

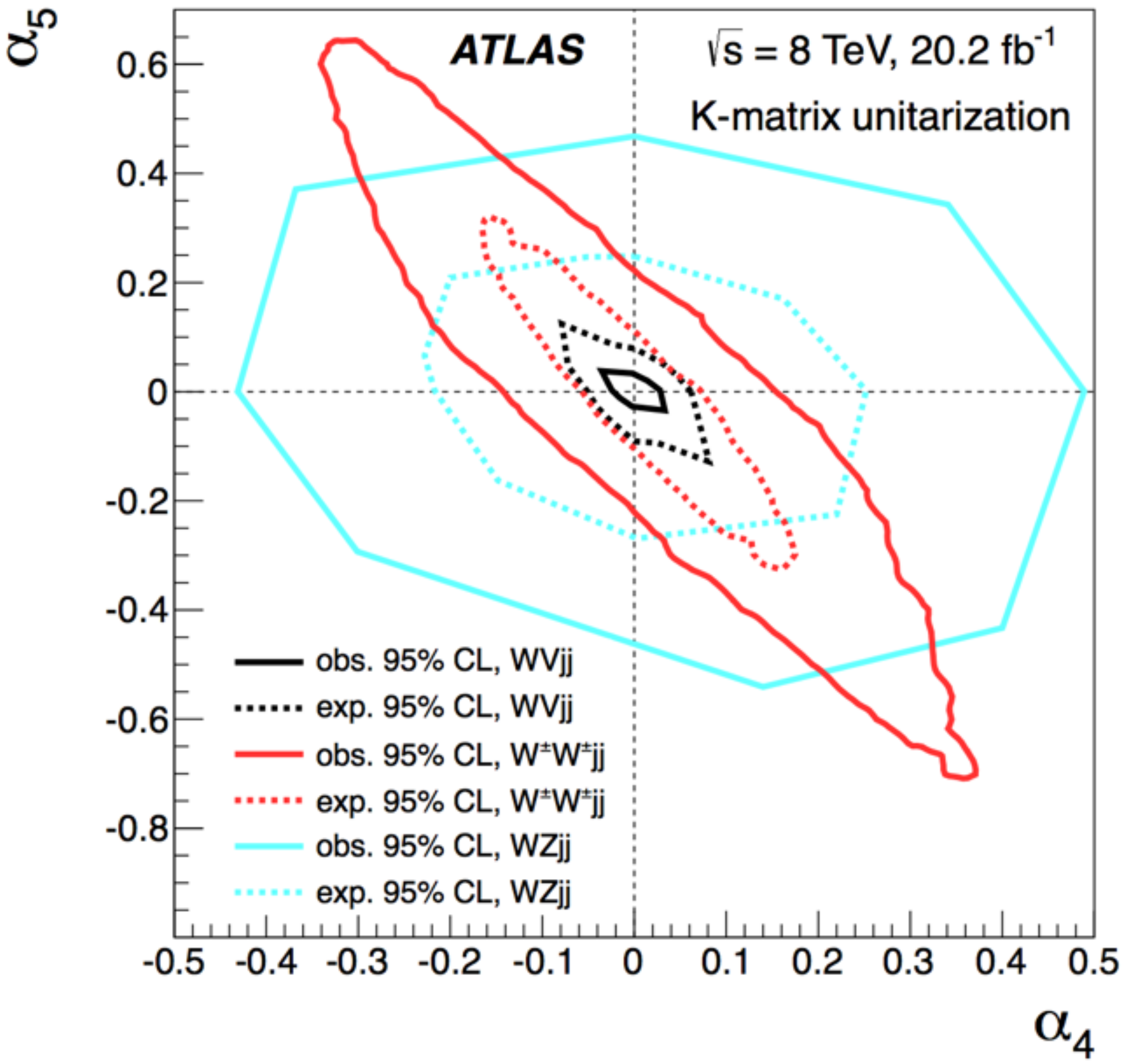
WV semi-leptonic

ATLAS at 8 TeV

- Search of aQGC performed studying m_T(WV)



- No evidence of aQGC→set 95% CL limits on dim-4 operators α4 and α5 with binned profile-likelihood fit to m_T(WV)



- **The observed CL are stronger than the expected!**

	Expected	Expected $\pm1\sigma$	Expected $\pm2\sigma$	Observed
lower limit, α_4	-0.060	$[-0.11, -0.030]$	$[-0.26, -0.015]$	-0.024
upper limit, α_4	0.062	$[0.034, 0.091]$	$[0.018, 0.20]$	0.030
lower limit, α_5	-0.084	$[-0.15, -0.034]$	$[-0.24, -0.018]$	-0.028
upper limit, α_5	0.080	$[0.039, 0.13]$	$[0.024, 0.23]$	0.033

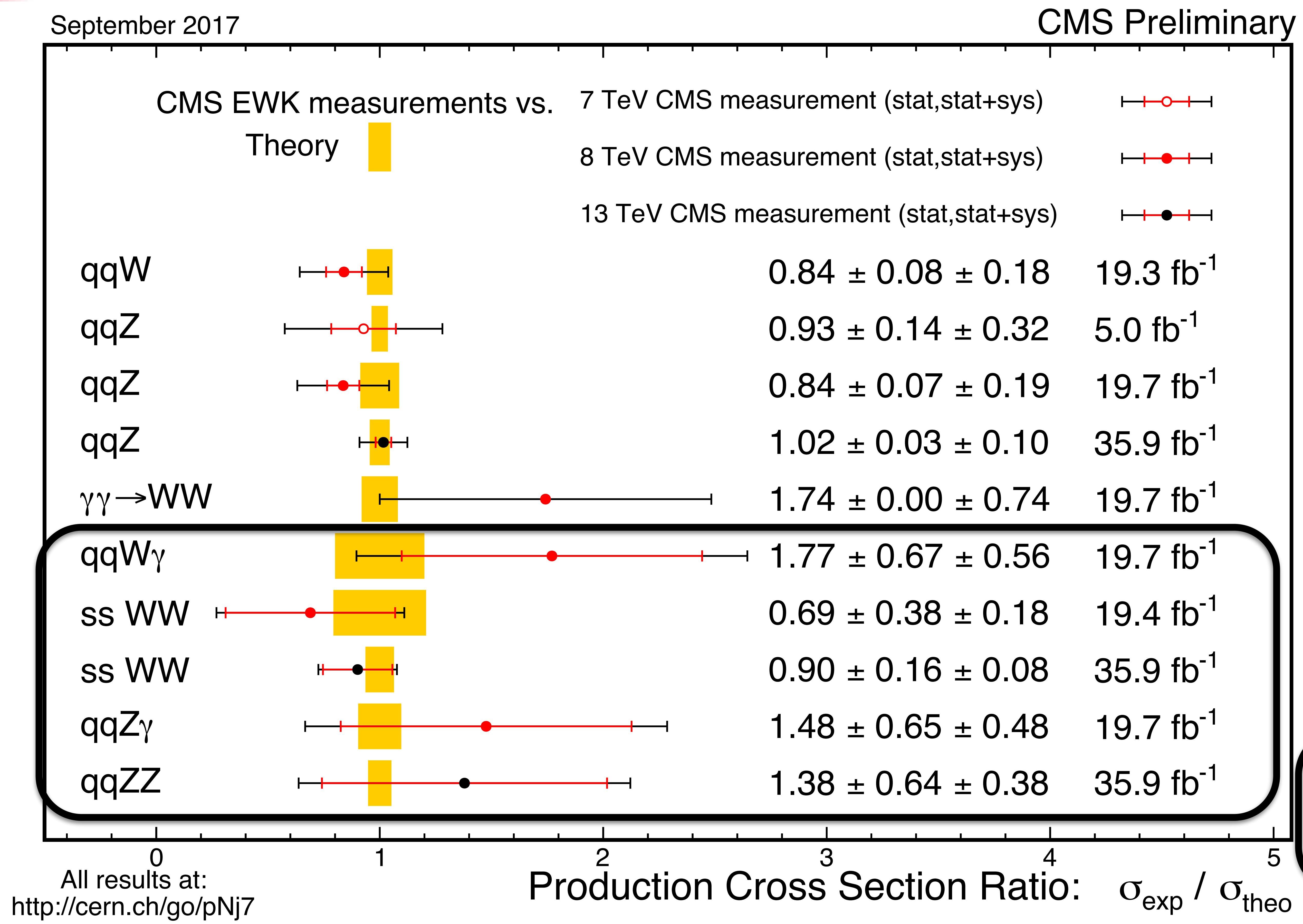
Observed confidence intervals are more stringent than existing ones from ssWW and WZ → lνll

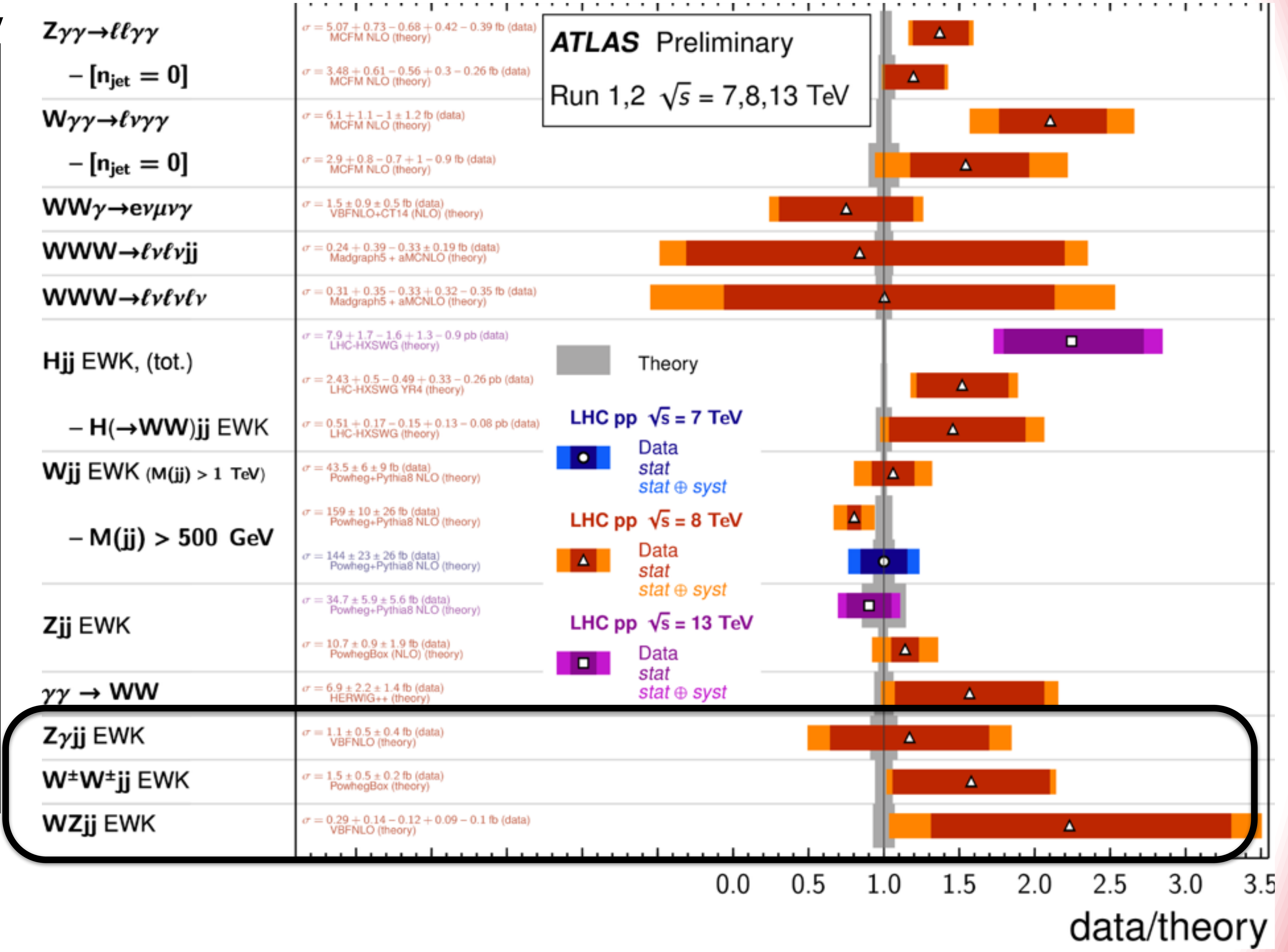
Summary

Summary - Simulations

	ssWW ATLAS	ssWW CMS	Zg ATLAS	Zg CMS	Wg CMS	ZZ CMS	WZ ATLAS	WV ATLAS
EW	Sherpa LO XS scaled NLO Powheg	Sherpa LO	Sherpa LO XS NLO: VBFNLO	MG5 LO kFactor 1.1 (mjj<400GeV)	MG5 LO kFactor 1.2 VBFNLO	MG5_aMC LO	Sherpa LO	Whizard LO
QCD	Sherpa LO	Sherpa LO	Sherpa LO	MG5 LO + matching MLM	MG5 LO + matching MLM	MG5_aMC NLO matching FxFx	Sherpa LO matching CKKM	Whizard LO
aQGC	Whizard LO	Sherpa LO	MG5 LO	MG5 LO	MG5 LO	MG5_aMC+ ME Reweighting	Whizard LO	Whizard LO
Interference	studied with dedicated samples 10.7(6.5)% in incl (SR)	syst. uncertainty (up to 4.5%) . Estimated with PHANTOM	syst. uncertainty. (~10%) Estimated with MG5	syst. uncertainty. (~11%) Estimated with MG5	Neglected	Neglected	Neglected	Neglected

Summary - Fiducial cross-section

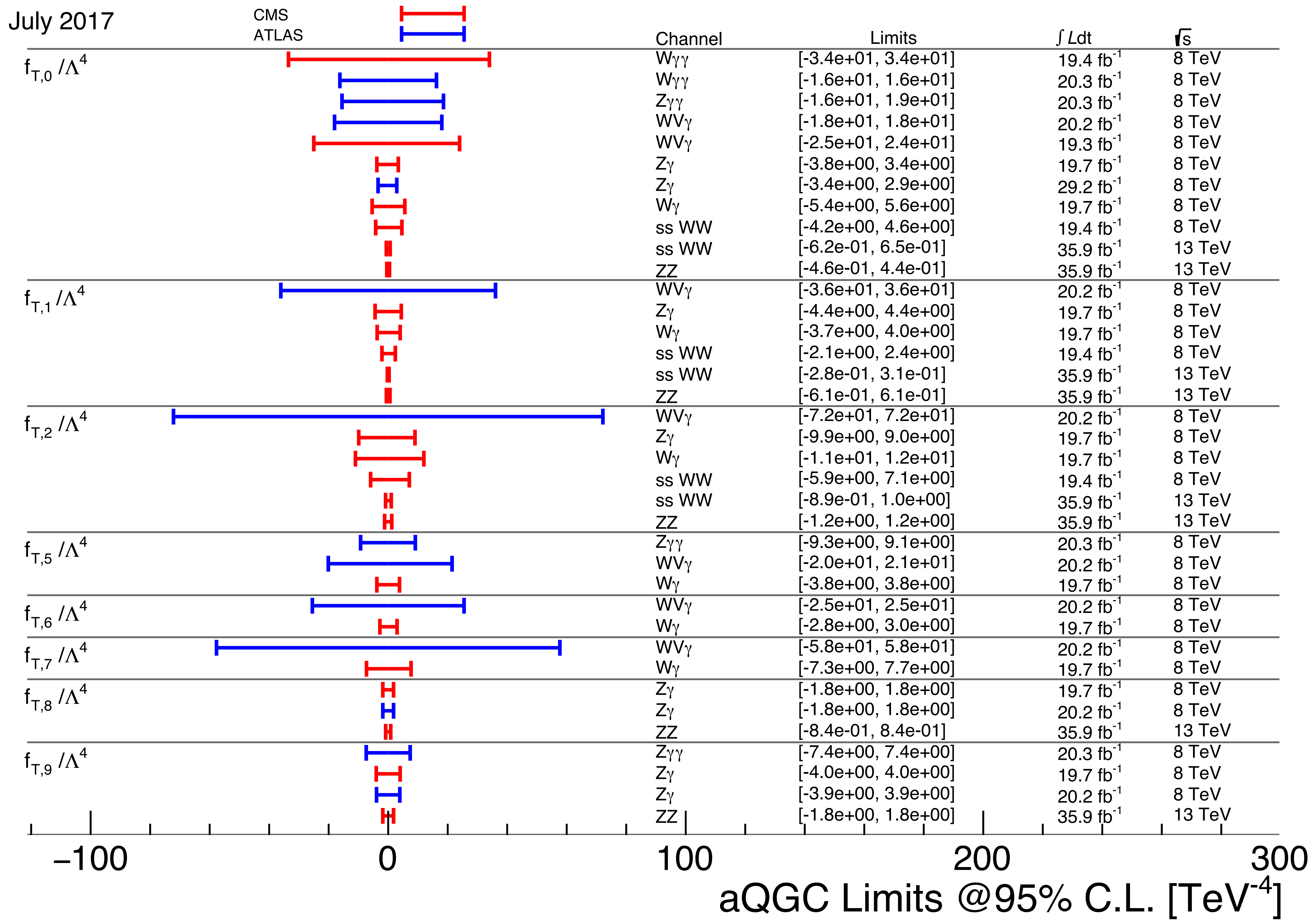


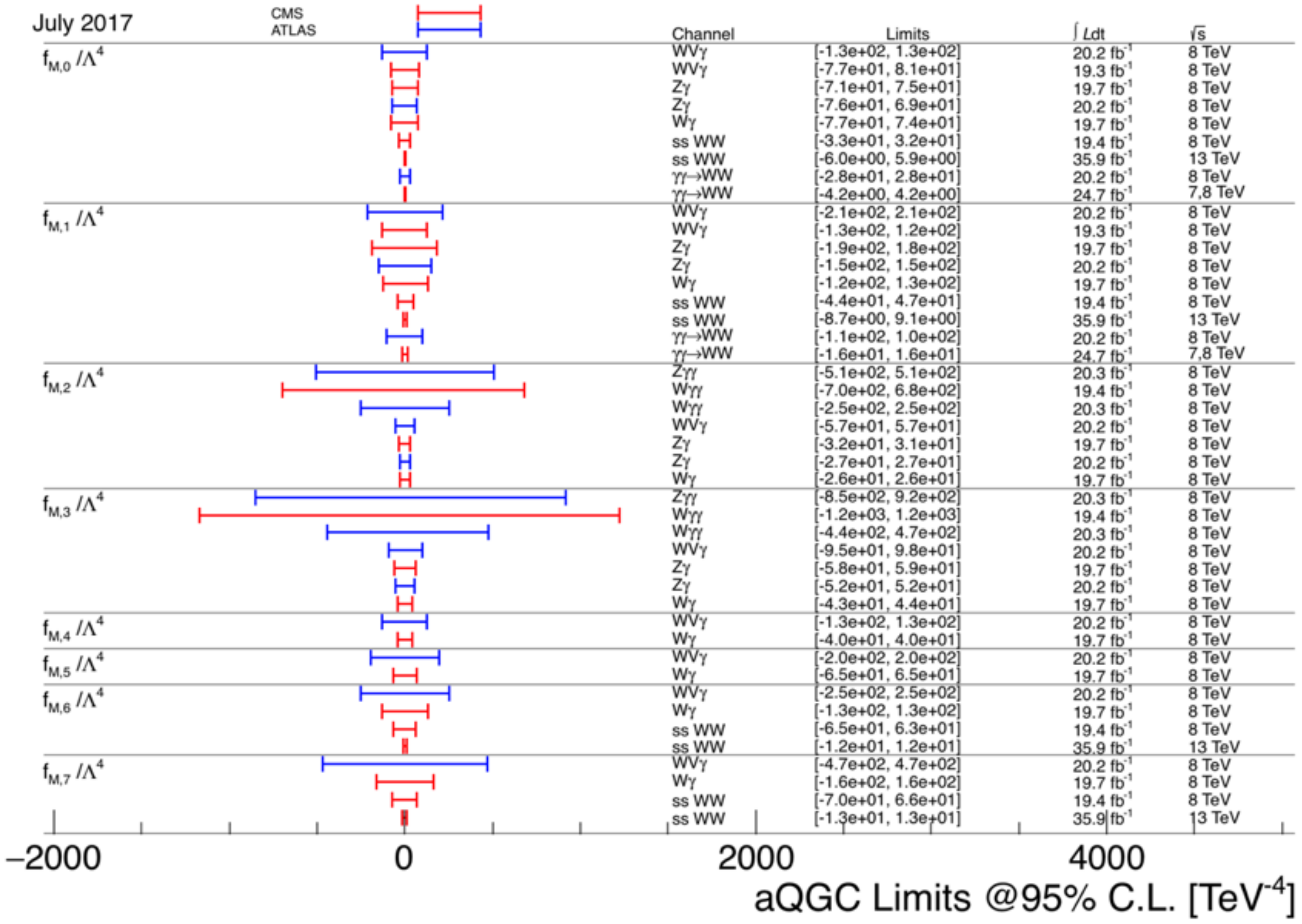


All recent measurements are statistic limited

Generally good agreement between experiment and theory

Summary - aQGC





- Constraints on aQGC also from diboson and triboson channels
- No deviations from the SM seen so far
- WV semi leptonic and $Z\gamma \to \nu\nu\gamma jj$ give more stringent limits than the fully leptonic channels

Conclusions

- Reviewed VBS analyses in ATLAS and CMS at 8 and 13 TeV:

$W^\pm W^\pm$ +2jets ,$Z\gamma$ +2 jets,$W\gamma$ + 2jets ,ZZ + 2jets, WZ + 2jets, WV semi-lept + 2jets

- Analyses still limited by **statistical uncertainties**, so far only $W^\pm W^\pm$ +2jets observed
- New physics could induce charged and neutral **aQGCs**
- The presence of aQGC enhances the EW cross-section at **high-energy tails** → discrimination with variables that carry the energy of the system like mT
- Stringent limits to constraint on EFT operators for aQGC have been set
- No deviations from the SM seen so far
- More exiting results at 13 TeV results expected soon!

Back-up

Dim 8 operators

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

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

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

ssWWjj

ATLAS theory uncertainties

Source of uncertainty	$W^{\pm}W^{\pm}jj$-EW		$W^{\pm}W^{\pm}jj$-QCD	
	Inclusive	VBS	Inclusive	VBS
MC sample size	1%	2%	4%	8%
Showering model	2%	4%	3%	7%
Scale	2%	2%	12%	13%
PDF	2%	3%	2%	2%
Generator	5%	3%	5%	5%
Total uncertainty	6%	6%	14%	18%

ATLAS

Signal Region		Selection Criteria
Inclusive	Lepton	Exactly two tight same-electric-charge leptons with $p_T > 25$ GeV
	Jet	At least two jets with $p_T > 30$ GeV and $\|\eta\| < 4.5$
	$m_{\ell\ell}$	$m_{\ell\ell} > 20$ GeV
	E_T^{miss}	$E_T^{miss} > 40$ GeV
	Z veto	$\|m_{\ell\ell} - m_Z\| > 10$ GeV (only for the $e^{\pm}e^{\pm}$ channel)
	Third-lepton veto	No third veto-lepton
	b-jet veto	No identified b-jets with $p_T > 30$ GeV and $\|\eta\| < 2.5$
	m_{jj}	$m_{jj} > 500$ GeV
VBS	Δy_{jj}	$\|\Delta y_{jj}\| > 2.4$
aQGC	$m_{WW,T}$	$m_{WW,T} > 400$ GeV

Relative Systematic Uncertainties $e^{\pm}e^{\pm}/e^{\pm}\mu^{\pm}/\mu^{\pm}\mu^{\pm}$ [%]

	Background Yield		Signal Yield	
	Inclusive SR	VBS SR	Inclusive SR	VBS SR
$W^{\pm}W^{\pm}jj$-EW cross-section			5	6
$W^{\pm}W^{\pm}jj$-QCD cross-section			3.1	–
$W^{\pm}Zjj$-EW cross-section	6/8/11	5/5/8		
$W^{\pm}Zjj$-QCD cross-section	–	0.9/1.5/2.6		
MC statistics	8/6/8	9/6/8	4/2.1/2.8	5/2.7/4
Luminosity	1.7/2.1/2.4	1.7/2.1/2.4	2.8	2.8
Trigger efficiency	0.1/0.2/0.4	0.1/0.2/0.4	0.1/0.3/0.5	0.1/0.3/0.5
Lepton reconstruction and identification	1.6/1.2/1.2	1.7/1.1/1.1	1.9/1.0/0.7	1.9/1.0/0.7
Jet-related uncertainties	11/13/13	13/20/20	6	5
E_T^{miss} reconstruction	2.2/2.4/1.8	2.9/3.2/1.4	1.1	1.1
b-tagging efficiency	1.0/1.1/1.0	0.8/0.9/0.7	0.6	0.6
Non-prompt	4/7/7	4/7/7		
Conversions	6/4/–	6/4/–		
$W\gamma$ cross-section	2.8/2.6/–	3.1/2.6/–		
Total	17/19/21	18/20/21	10/9/9	10/9/9

ssWWjj

CMS selection

- Only two leptons ($l = \mu, e$) of same charge with $p_{T1(2)} > 25(20)$ GeV $m_{ll} > 20$ GeV
- Two jets with $p_T > 30$ GeV, leading jets taken as tagging jets, $m_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 2.5$,
- max (z_l^*) < 0.75, where z_l^* = Zeppenfeld variable
- $E_T^{miss} > 40$ GeV (to reduce DY)
- b-jet veto (ttbar)
- $|m_{ll} - m_Z| > 15$ GeV (to reduce DY)

$Z\gamma$ + 2jets

ATLAS results without FF to compare with CMS

CMS results

Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
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	$[-52, 52]$	$[-43, 43]$
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	$[-58, 59]$	$[-87, 87]$

$W\gamma$ + 2jets

Baseline selection

Table 1: Summary of the baseline selection criteria.

Single-lepton (e, μ) trigger	$\lvert M_{e\gamma} - M_Z \rvert > 10\,\text{GeV}$ (electron channel)
Lepton, photon ID and isolation	$p_T^{j1} > 40\,\text{GeV}$, $p_T^{j2} > 30\,\text{GeV}$
Second lepton veto	$\lvert \eta^{j1} \rvert < 4.7$, $\lvert \eta^{j2} \rvert < 4.7$
Muon (electron) $p_T > 25\ (30)\,\text{GeV}$, $\lvert\eta\rvert < 2.1\ (2.4)$	$\lvert \Delta\phi_{j1,\vec{p}_T^{\text{miss}}} \rvert > 0.4$, $\lvert \Delta\phi_{j2,\vec{p}_T^{\text{miss}}} \rvert > 0.4\,\text{rad}$
Photon $p_T^{\gamma} > 22\,\text{GeV}$, $\lvert\eta\rvert < 1.44$	b quark jet veto for tag jets
W boson transverse mass $> 30\,\text{GeV}$	Dijet invariant mass $m_{jj} > 200\,\text{GeV}$
$\lvert \vec{p}_T^{\text{miss}} \rvert > 35\,\text{GeV}$	$\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{j\ell}, \Delta R_{\ell\gamma} > 0.5$

EW VBS selection: Baseline +

- $\lvert y_{W\gamma} - (y_{j1} + y_{j2})/2 \rvert < 0.6$;
- $\lvert \Delta\phi_{W\gamma,jj} \rvert > 2.6\,\text{rad}$;
- $m_{jj} > 700\,\text{GeV}$;
- $\lvert \Delta\eta(j1, j2) \rvert > 2.4$.