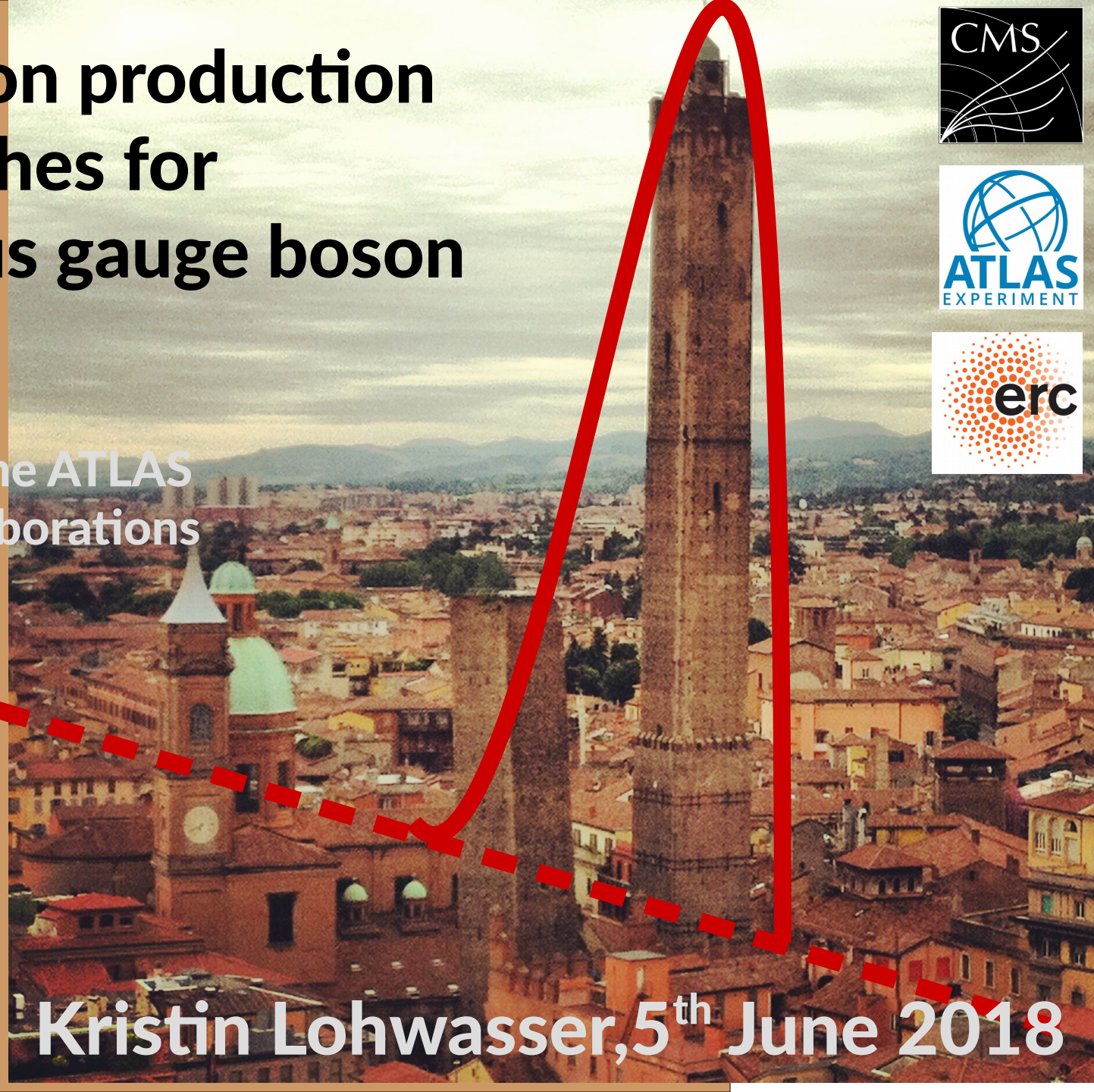
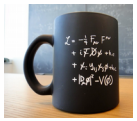
Multiboson production and searches for anomalous gauge boson couplings



On behalf of the ATLAS and CMS collaborations

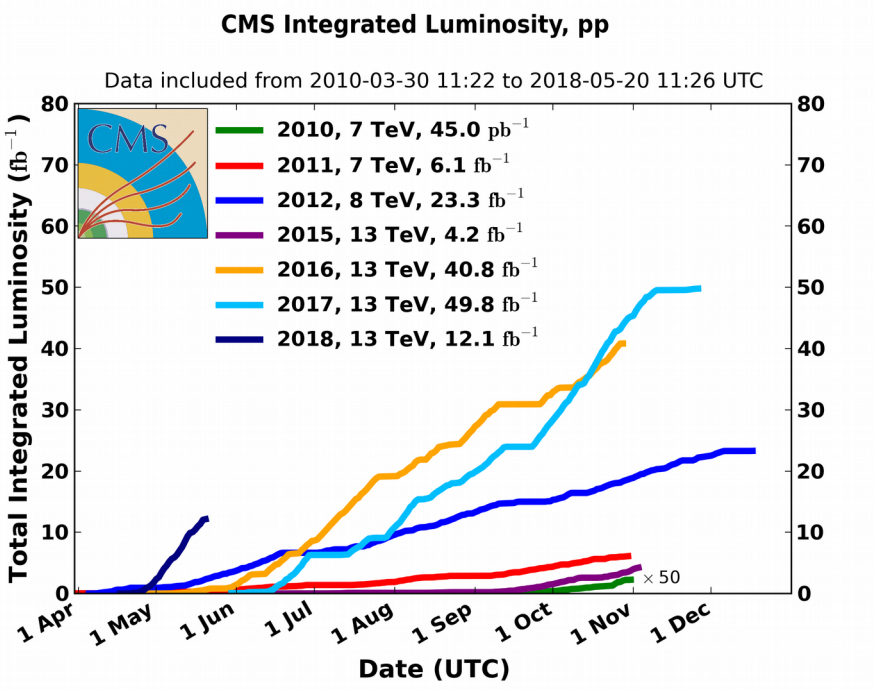
LHCP Kristin Lohwasser, 5th June 2018

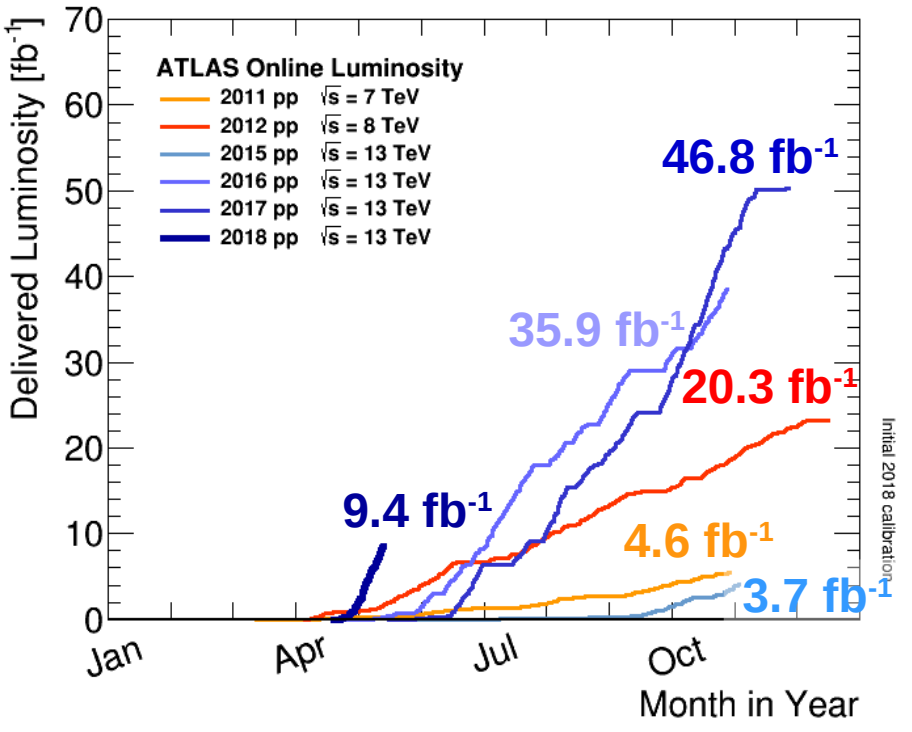
State of the Standard Model

> **More than 100 fb-1 collected by each experiment**
  - In high energy collisions since 2010
  - The **SM holds** 

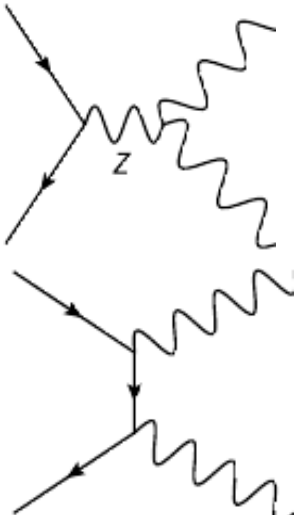
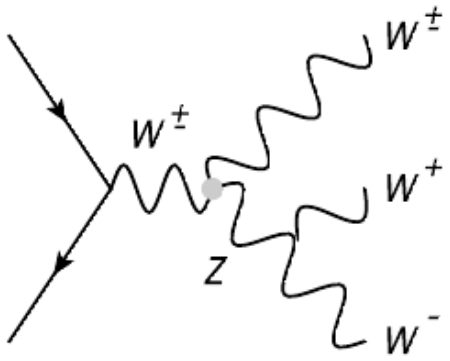
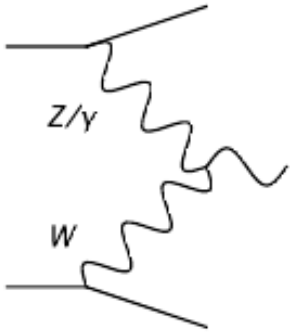
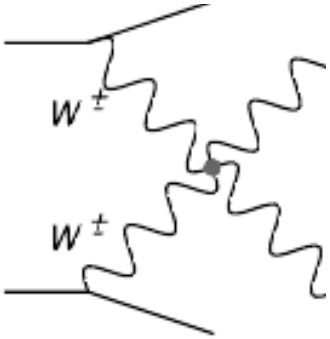
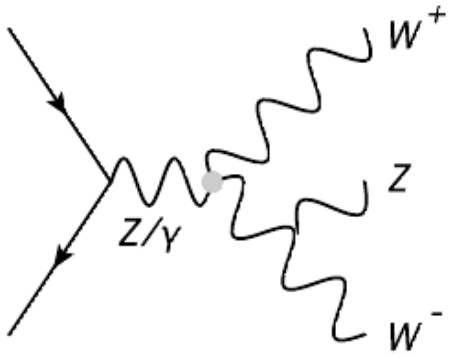
> **Measure rare SM-Processes: *Multiboson production***

> **Typical cross sections: O(fb) – O(10²pb)**
  - In 100 fb^{-1} expect: **100 – 10 million events** *(before detector)*
  - Some channels can be measured **for the first time**
  - Evaluate **new physics potential at high energy**





Multiboson interactions: Triple and quartic Gauge Couplings

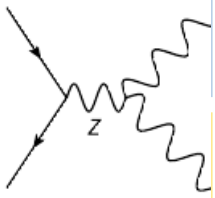
	Single boson	Multiboson	Triboson
Inclusive production	✗		 multilepton final state
Vector Boson Fusion or Scattering (VBF/VBS)	  two jets with large rapidity gap		

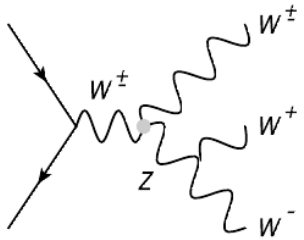
Multiboson interactions: Triple and quartic Gauge Couplings

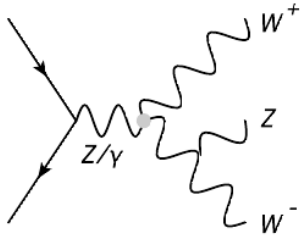
Inclusive production

Single boson	Multiboson	Triboson
7 TeV	$W\gamma$	WWZ
8 TeV	$Z\gamma$	WWW
13 TeV	WW	WZZ
not measured	WZ	$WW\gamma$
	ZZ	$WZ\gamma$
		$W\gamma\gamma$
		$\gamma\gamma\gamma$
		$ZZ\gamma$
		$Z\gamma\gamma$
		ZZZ

O(160 pb) → O(20 pb)





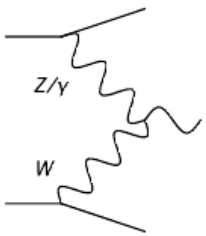


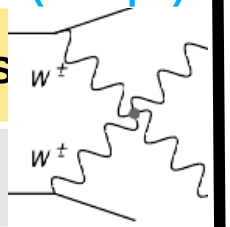
Vector Boson Fusion or Scattering (VBF/VBS)

W	WW_{VBS}	
Z	WZ_{VBS}	
γ not measured	ZZ_{VBS}	
	$Z\gamma_{VBS}$	
	$W\gamma_{VBS}$	

O(20 pb) - O(400 pb)

O(0.2 pb) - O(0.02 pb)





O(0.2 pb) → O(0.02 pb)

Excluding BR

Multiboson interactions: Triple and quartic Gauge Couplings

Inclusive production

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		$Z\gamma\gamma$
		ZZZ

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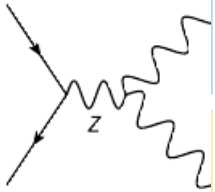

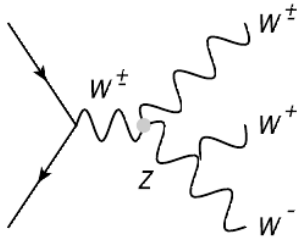

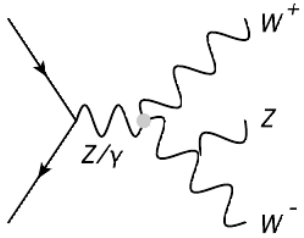

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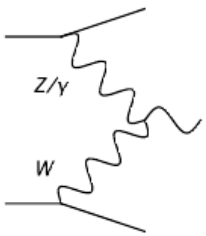
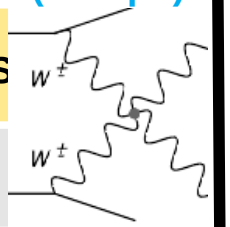
O(20 pb) - O(400 pb)

O(0.2 pb) - O(0.02 pb)





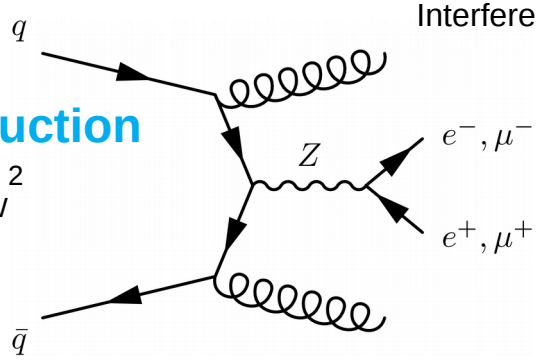
O(0.2 pb) → O(0.02 pb)

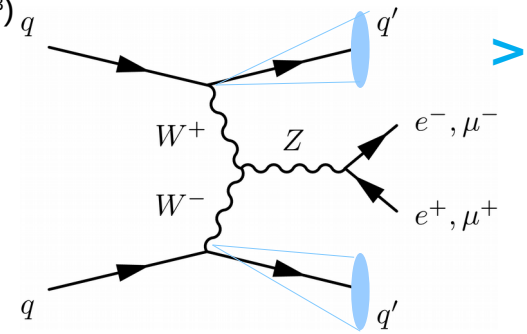
Electroweak Z production with two jets (VBF)

Interfere to small degree ($\alpha_s\alpha_w^3$)

> **QCD production**

$\alpha_s^2\alpha_w^2$





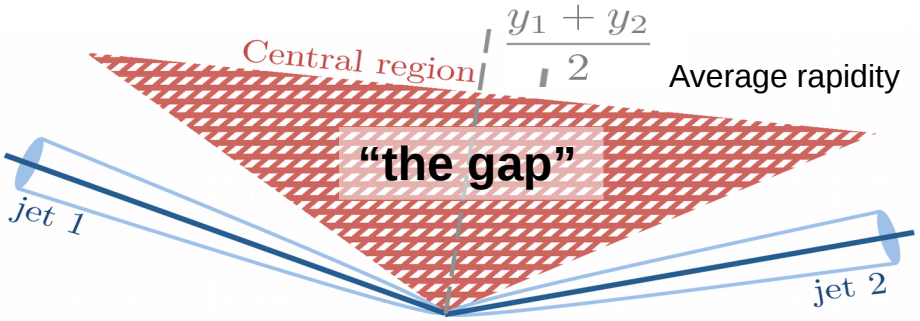
> **EWK production**

α_w^4

> **Standard candle for VBF processes, e.g. Higgs production or BSM particles**

> **Distinct kinematic signatures help to separate EWK production**

- Rapidity gap between high energy, low-momentum jets → large $\Delta\eta_{jj}, m_{jj}$
- No colour connection, low hadronic activity in gap



EWK-Z production: Large QCD background

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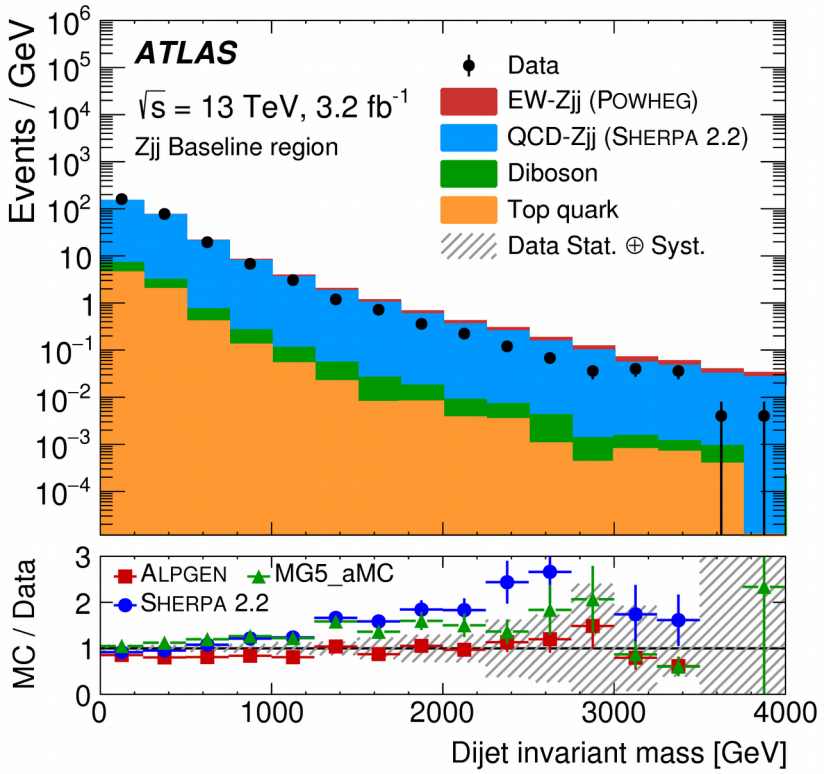
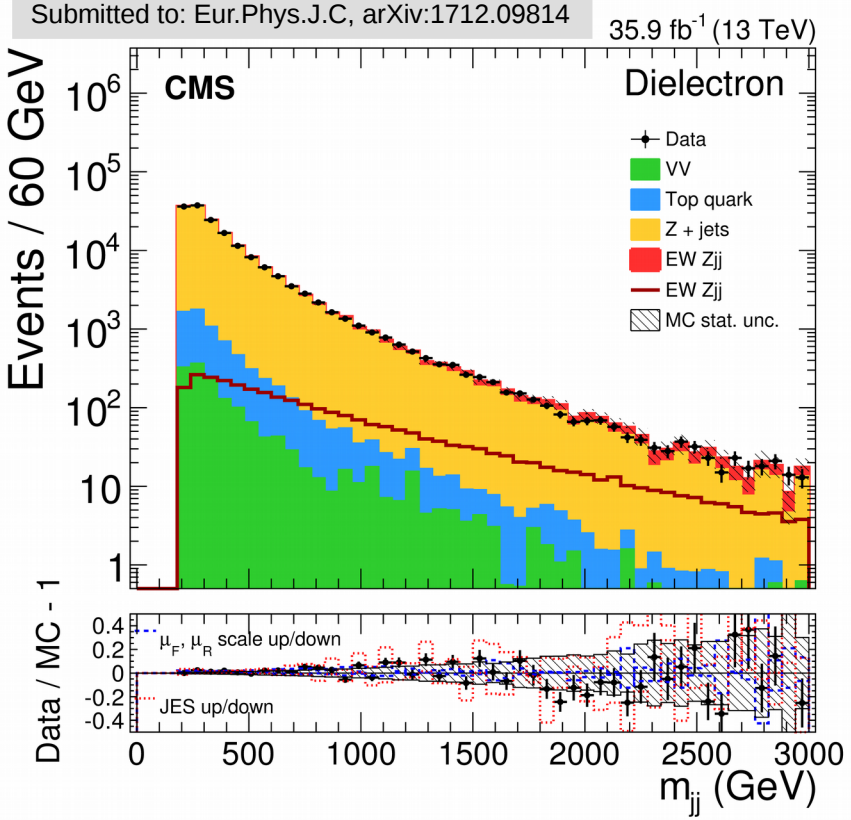


Submitted to: Eur.Phys.J.C, arXiv:1712.09814

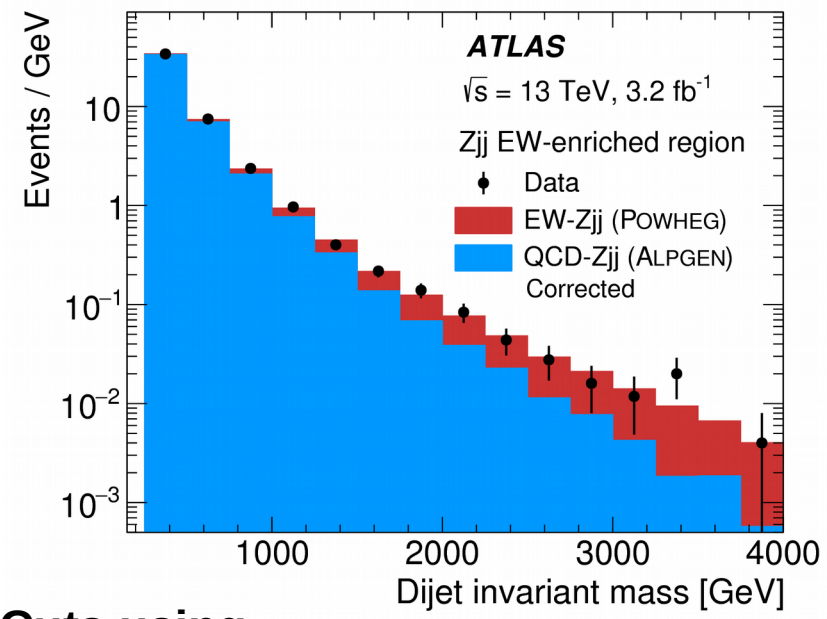


> **Largely dominated by DY Z +2 jets with some data-MC disagreement**
- ATLAS: slope correction from data control region
- CMS: attributed to interference (→large scale uncertainty), constrained in fit

> **Different strategy of EWK signal extraction:** Cuts (ATLAS) versus BDT (CMS)

EWK-Z production: Extraction of the signal

Physics Letters B 775 (2017) 206



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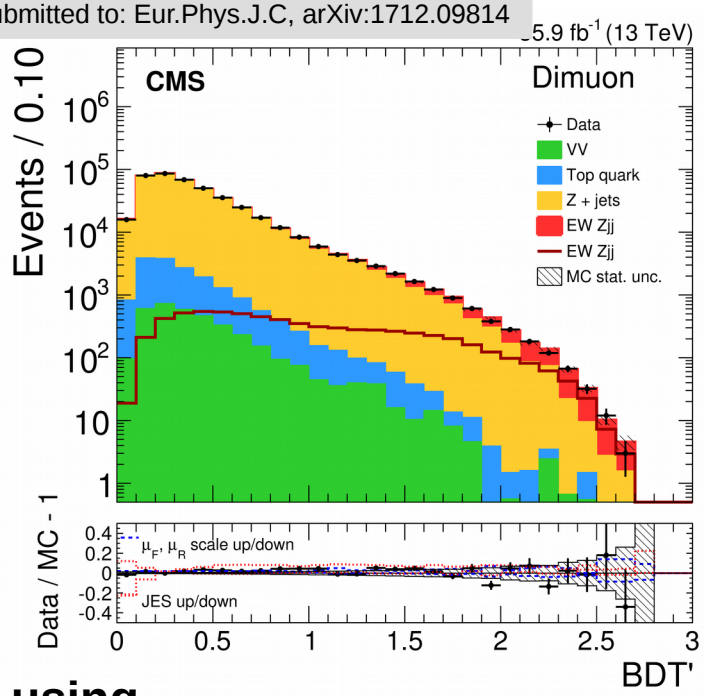


Cuts using

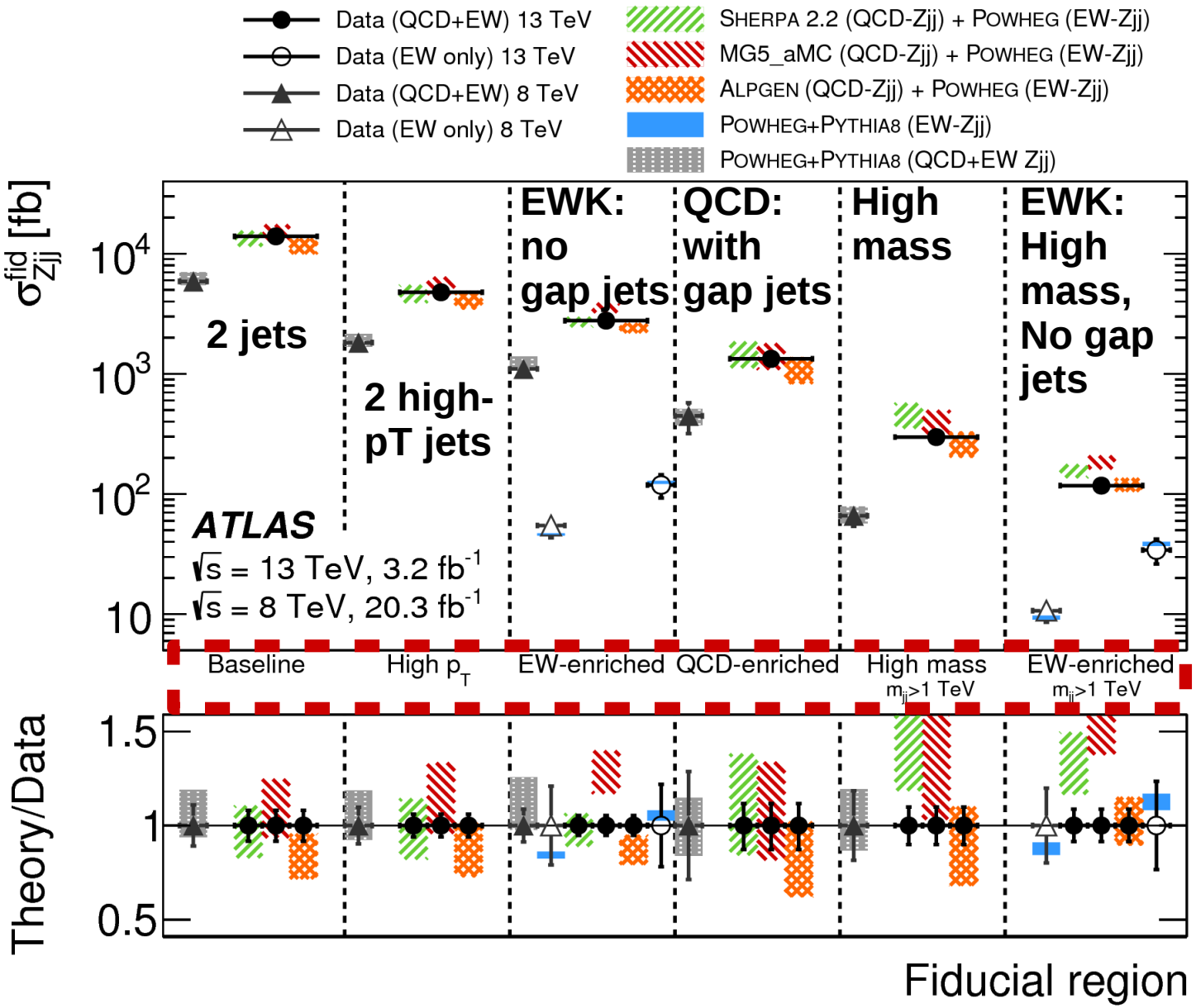
- Large m_{jj}
- $p_T^Z > 20$ GeV
- No jets within rapidity gap
- Well balanced system

$$|\Sigma p_T^i| / \Sigma |p_T^i| < 0.15$$

BDT using

- mjj, p_T^{jj}, $\Delta\eta_{jj}$
- pT balance system
- quark-gluon likelihood discriminant
- Ratio of y* (y_Z – average jet rapidities) compared to rapidity gap

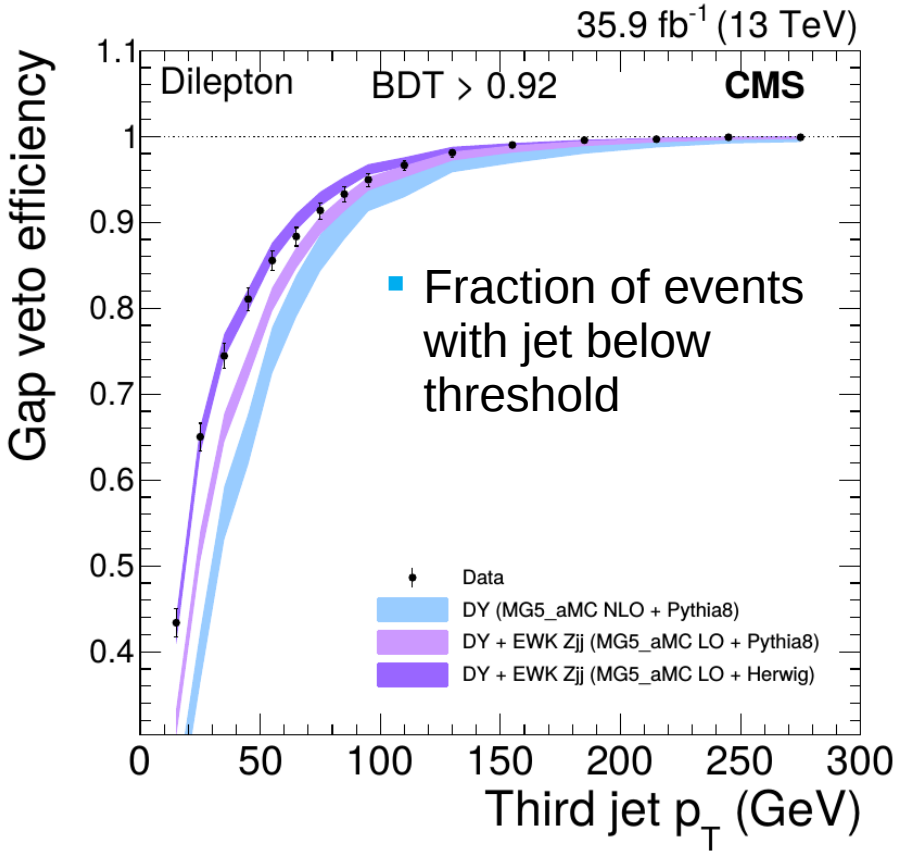
EWK-Z production: ATLAS study of fiducial regions



EWK-Z production: CMS study of gap activity

> Selection of region with equal EWK and QCD contributions (BDT>0.92)

- Study of gap activity using Particle Flow jets and soft tracks



- Fraction of events with jet below threshold

> Generally good agreement between data and prediction

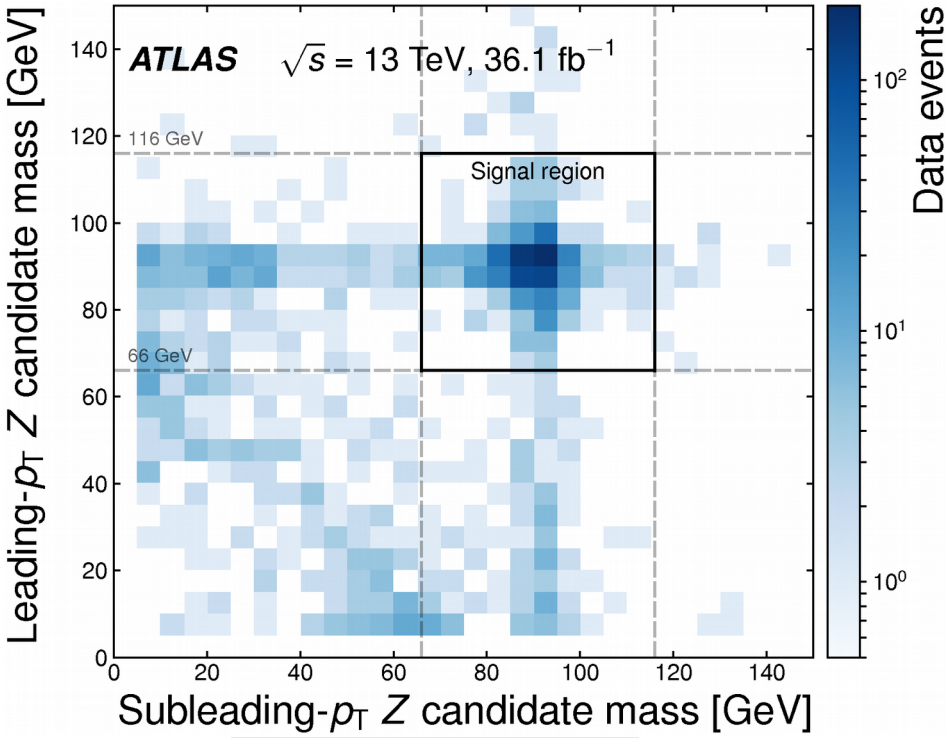
- ATLAS: emphasis on MC generators and calculations
  → **Powheg Pythia8 best**
- CMS: emphasis on Parton shower comparisons
  → **MG5 + Herwig best**

> Looking forward to more data and more investigations bringing these considerations together!

Differential measurement of ZZ production

> On-shell production of Z boson: *66-116 GeV* (ATLAS) vs *60-120 GeV* (CMS)

- Marginal differences in phase space (1.4-1.6% larger phase space for CMS)
- ATLAS: focus on on-shell region – CMS: includes study of lineshape and $Z \to 4\ell$ BR



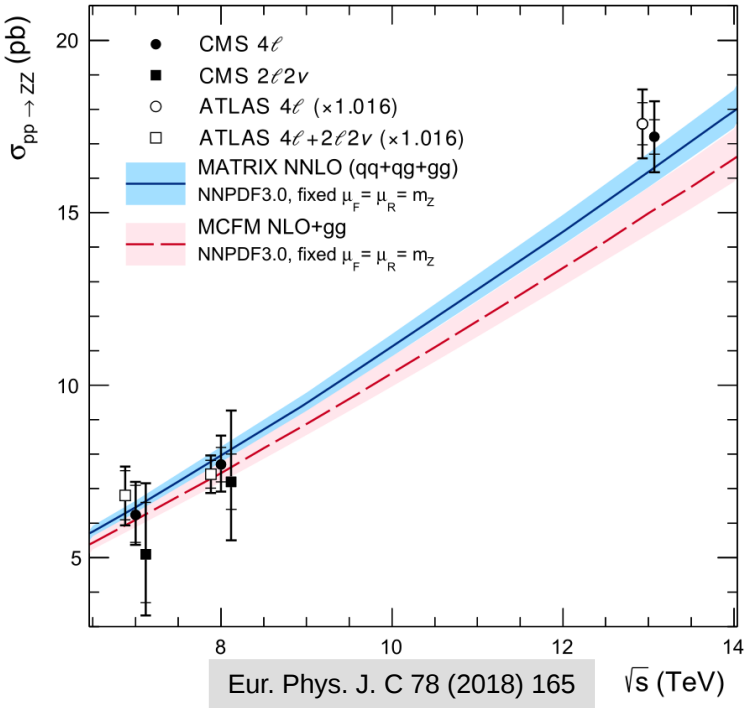
Phys. Rev. D 97 (2018) 032005

ZZ production: Total cross sections

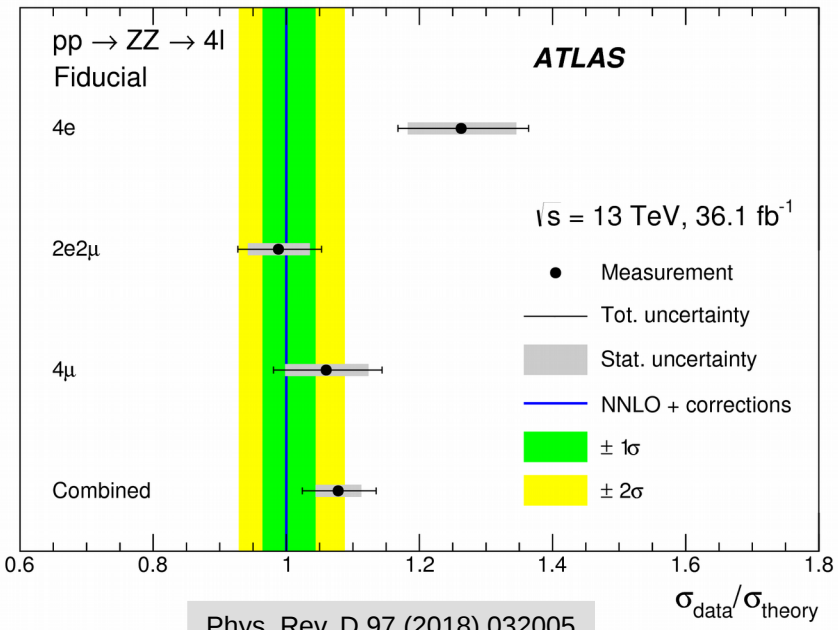
> ATLAS and CMS agree very well – NNLO calculation needed

- ATLAS: 46.2 +/- 1.5 (stat) +/- 1.15 (syst) +/- 1.5 (lumi) → theo: 42.9 +/- 1.7 pb
- CMS: 40.9 +/- 1.3 (stat) +/- 1.4 (syst) +/- 1.0 (lumi) → theo: 36.0 +/- 0.85 pb
  → **measurement starts to be systematics dominated**

- Excess for 4e (ATLAS, 2.5 σ) not confirmed by CMS (though also more 4e than expected)



Eur. Phys. J. C 78 (2018) 165

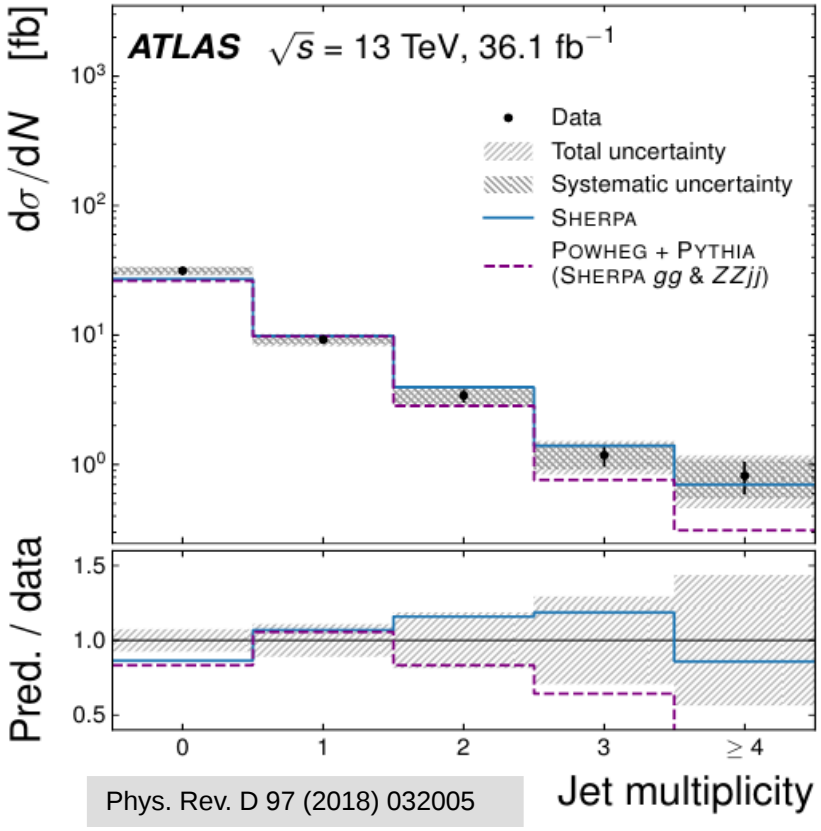


Phys. Rev. D 97 (2018) 032005

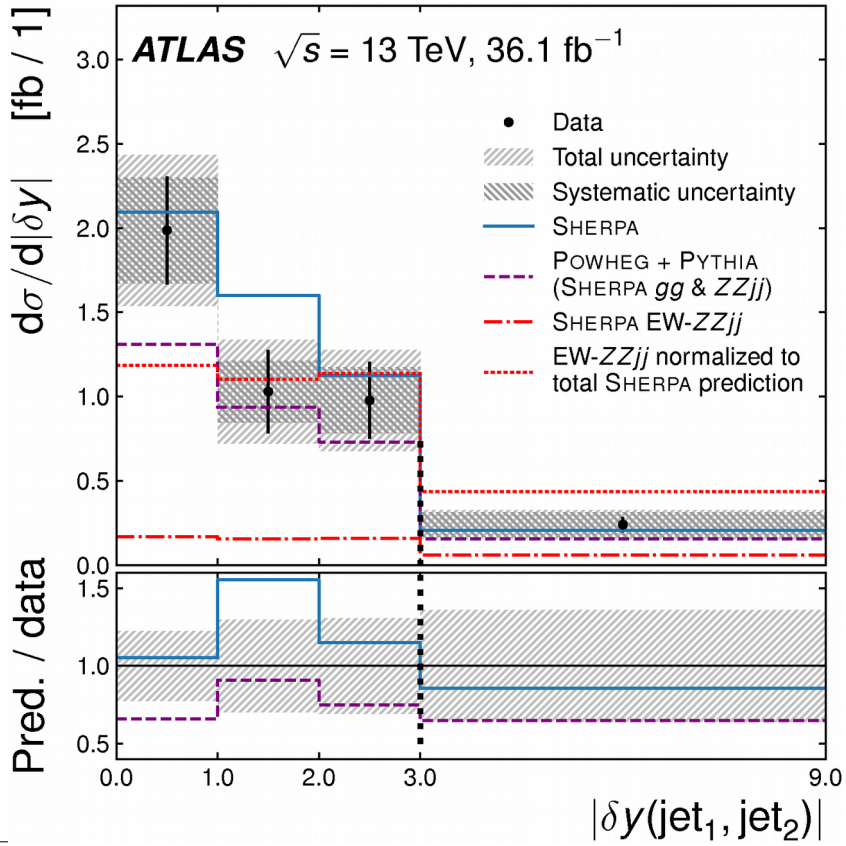
ZZ production: Differential distributions with ATLAS

> Reasonable agreement for various distributions with jets

- Important test with implications for other diboson production processes usually measured using jet vetos (→ e.g. WW)



Phys. Rev. D 97 (2018) 032005

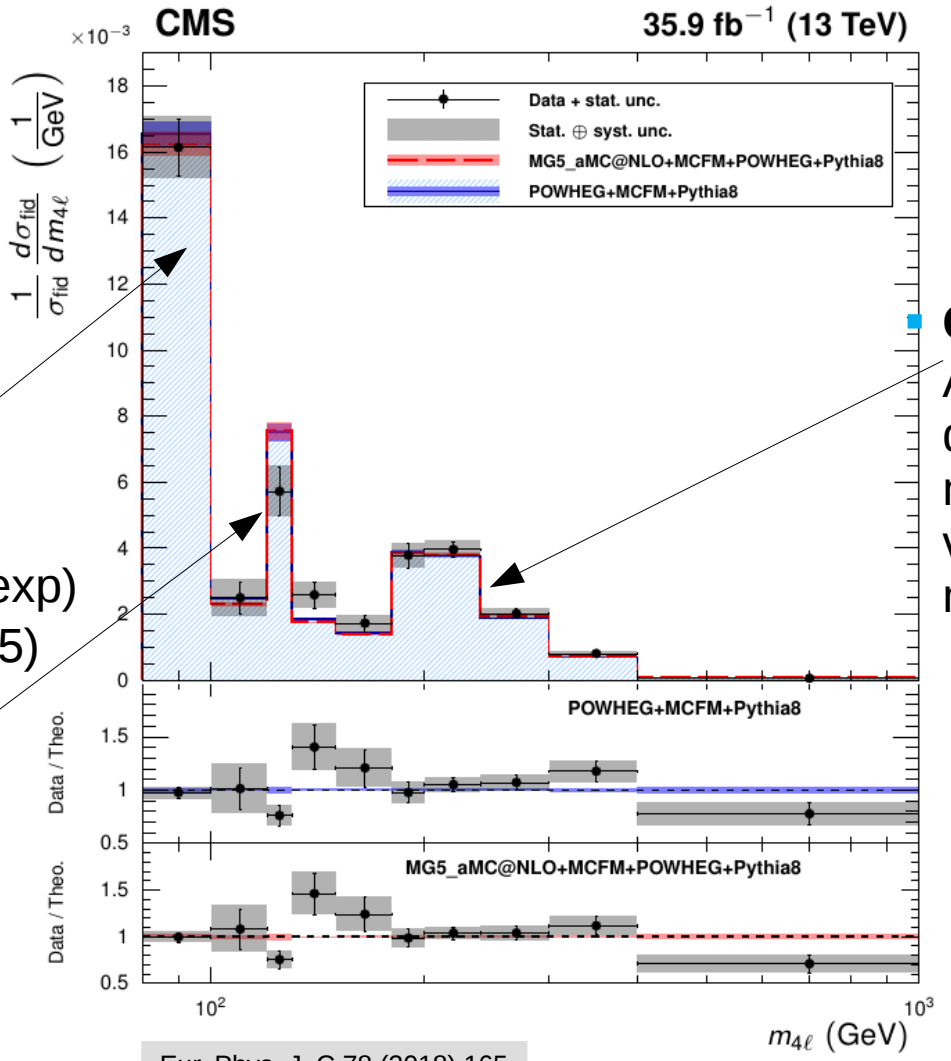


ZZ production: The lineshape with CMS

> M_{ZZ} lineshape well described

- **$Z \rightarrow 4\ell$**
  80<m(4ℓ)<100 GeV
  BR described
  well by theory
  $4.83 \pm 0.41 \times 10^{-6}$ (exp)
  4.6×10^{-6} (theo, MG5)

- **Higgs $\rightarrow 4\ell$**
  A visible peak in the spectrum



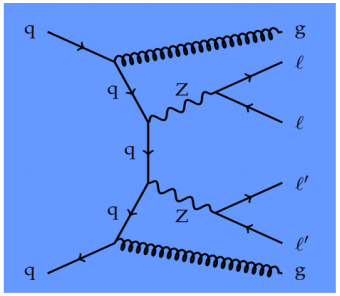
- **Continuum $ZZ \rightarrow 4\ell$**
  Above threshold differential measurement of key variables: pT(Z), m(ZZ), and others

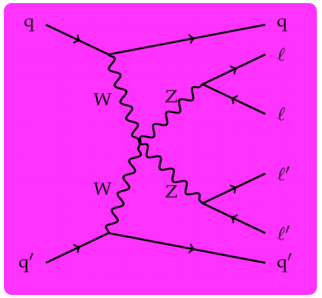
Eur. Phys. J. C 78 (2018) 165

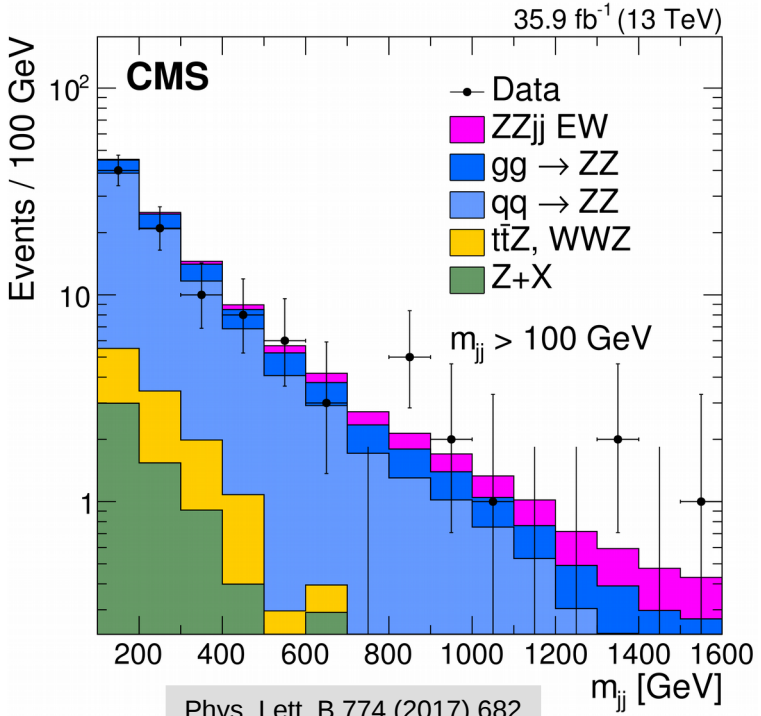
ZZ: Vector Boson Scattering

> Combining the kinematic signatures of EWK Zjj and ZZ production

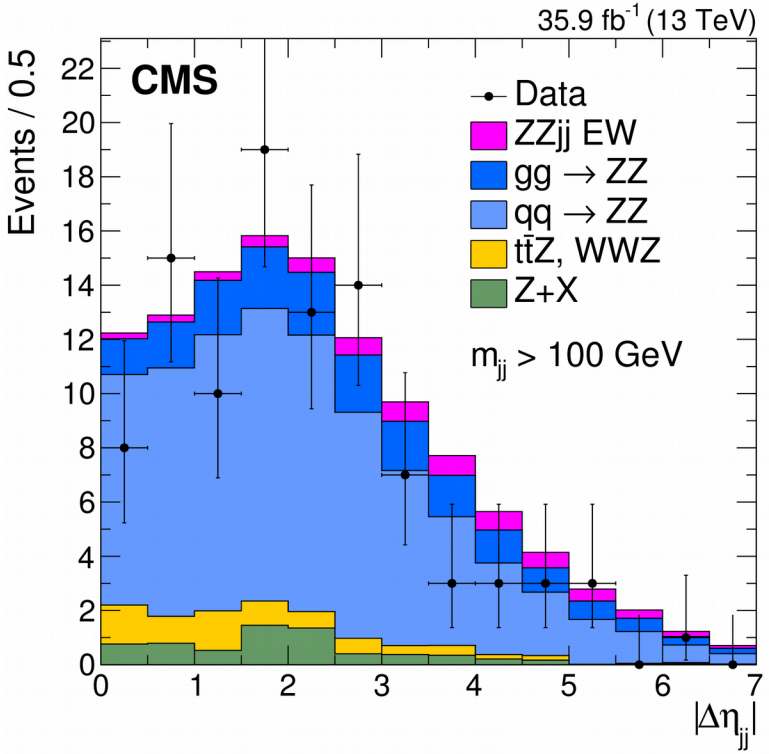
- Large invariant mass between tag jets
- Large rapidity gap
- 4 leptons (2 Z bosons)







Phys. Lett. B 774 (2017) 682

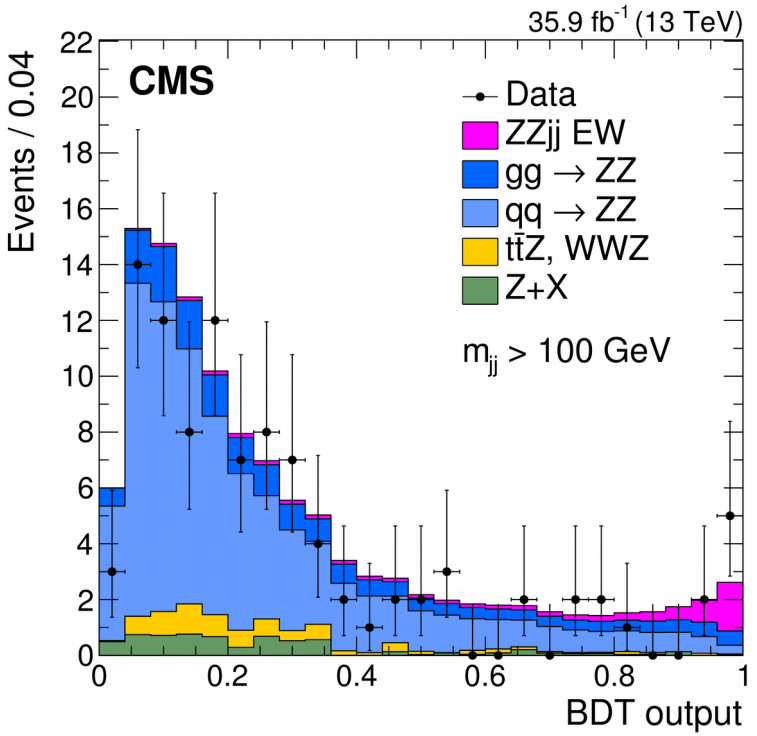


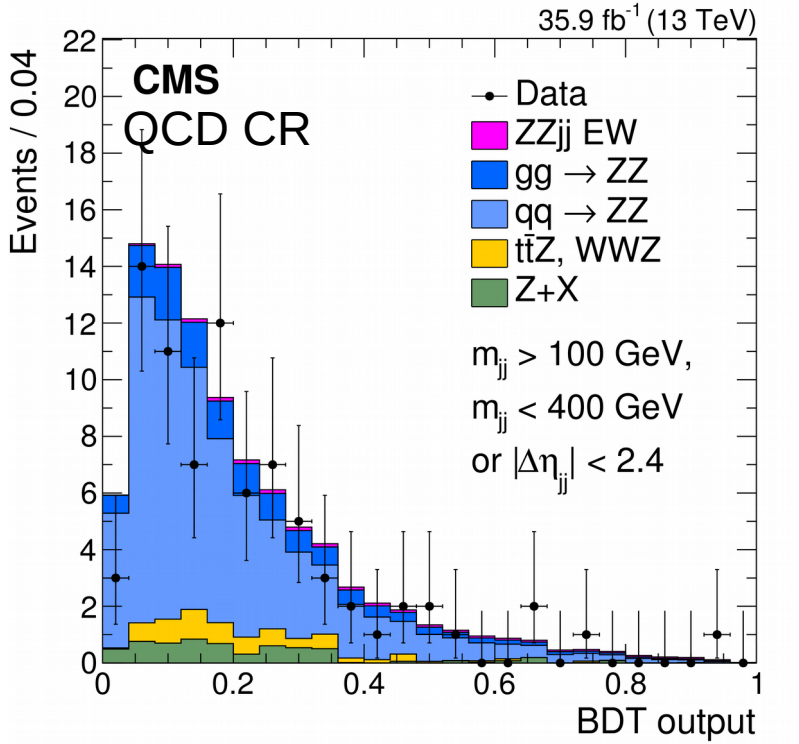
ZZ: *Almost* evidence for Vector Boson Scattering

> **Similar BDT training strategy used as for EWK Zjj (36 variables tested)**
  - mjj, p_T^{jj}, $\Delta\eta_{jj}$, m_{ZZ}, pT balance for tagging jets and hard scattering system (ZZ+jets)
  - Ratio of y* (y_z – average jet rapidities) compared to rapidity gap

> **Measured signal strength: 1.37 +/- 0.75 (stat. dominated)**

> **Observed significance 2.7 σ (expected: 1.6 σ)**



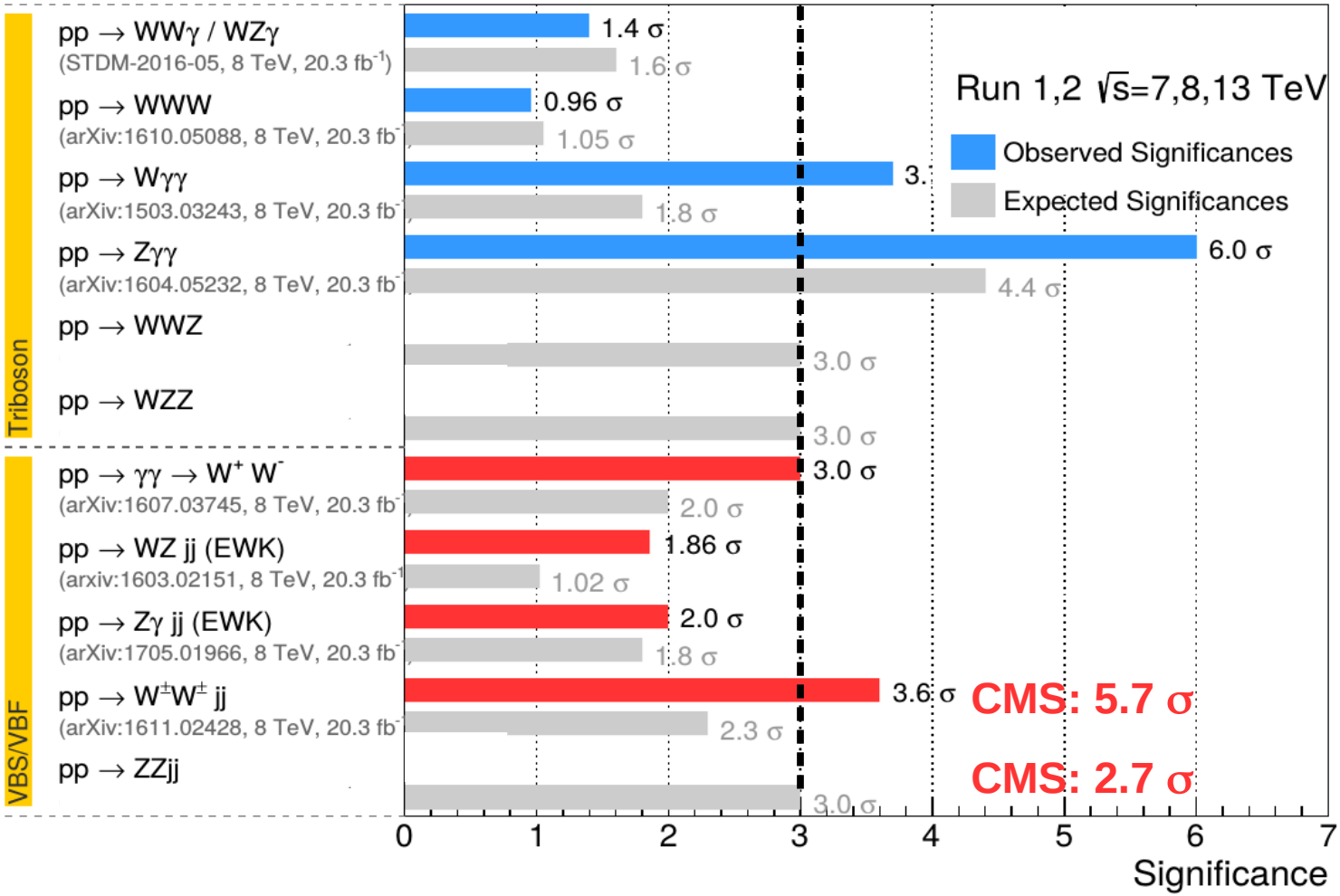


A preview of things to come

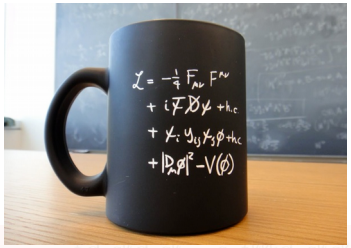
> Measured significance for rare processes based on ATLAS publications

- Disclaimer 1: partially just estimated from cross section limits (so are approximate)
- Disclaimer 2: expected significances are a rough estimate of what is possible for full Run-2

Plot by M. Schott, B. Lindquist and others



Multiboson processes beyond the SM



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d>4} \sum_{\rm i} \frac{c_{\rm i}^{d}}{\Lambda^{d-4}} \mathcal{O}_{\rm i}^{d}$$

Standard model

General extension: describes **new phenomena**
suppressed by **energy scale Λ (dimension d - 4)**

Coupling strength:
How strong is the interaction?

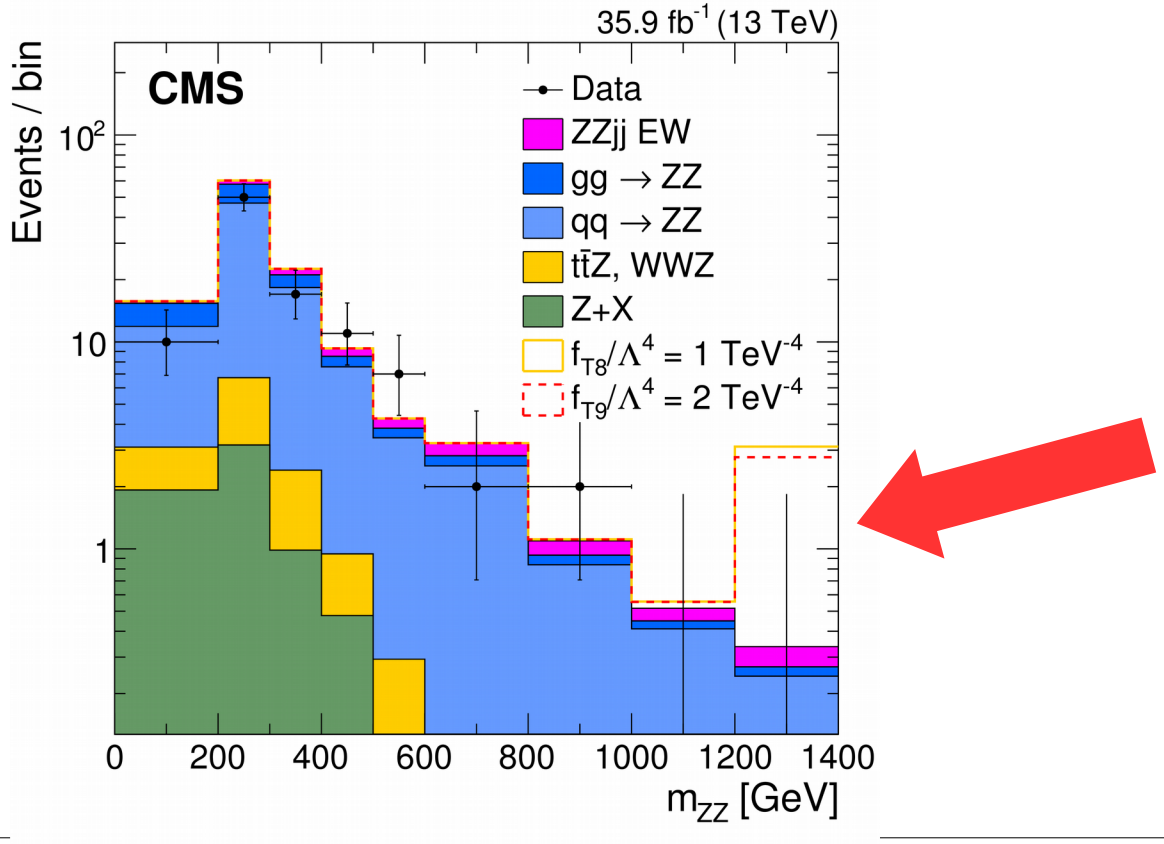
Operators: Which particles interact?

$d \leq 4 \rightarrow$ SM, d=5 $\rightarrow$ neutrino masses, $d \geq 6 \rightarrow$ Unknown phenomena

Shattering the Standard Model?

> Test for general SM extensions

- Strong dependence of cross section on EFT coefficients → Largest effects at high energies

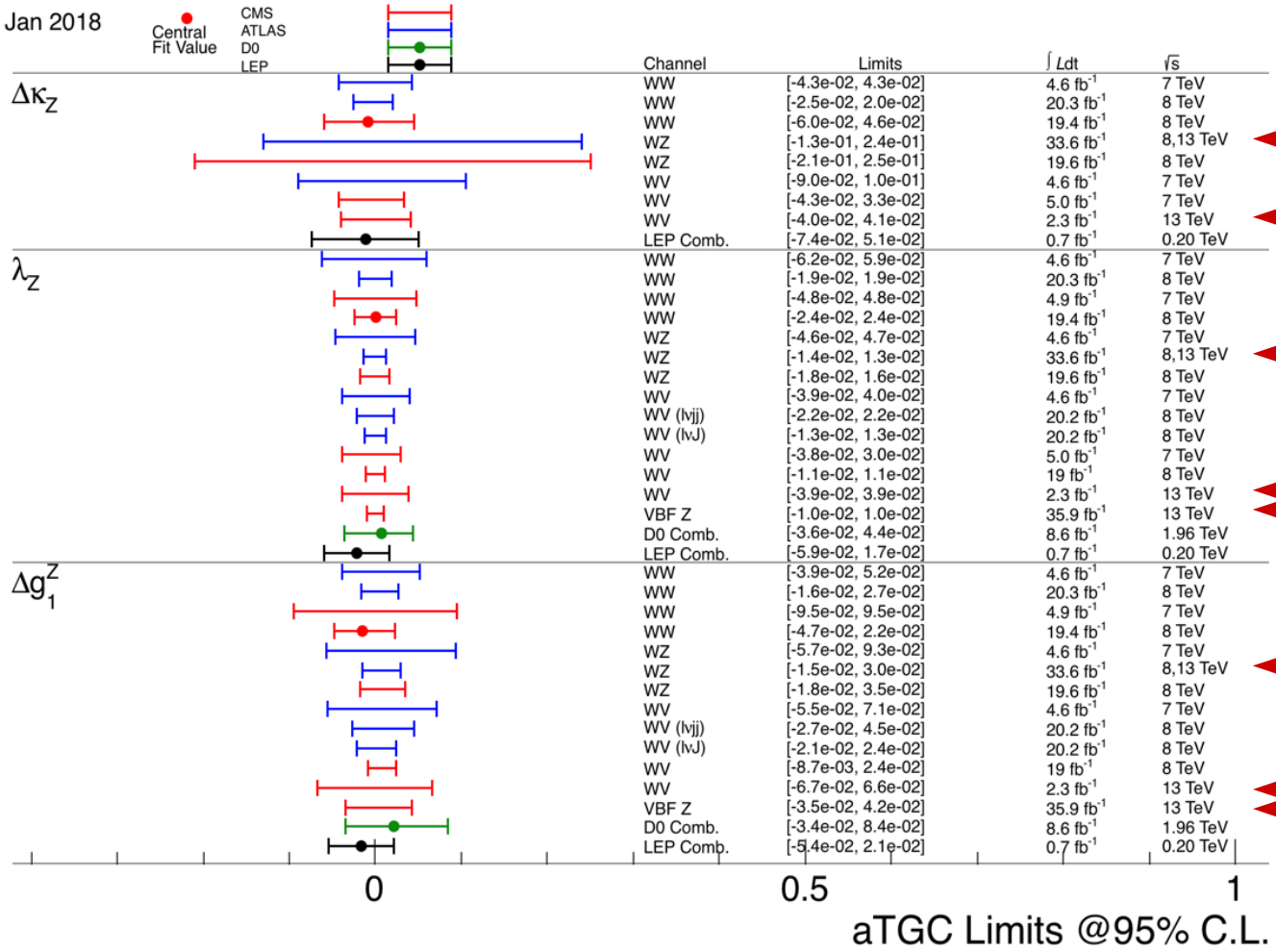


Shattering the Standard Model?

> Test for general SM extensions without results

- Independent of basis used: Zero hints for hidden new physics in **charged Multibosons** …

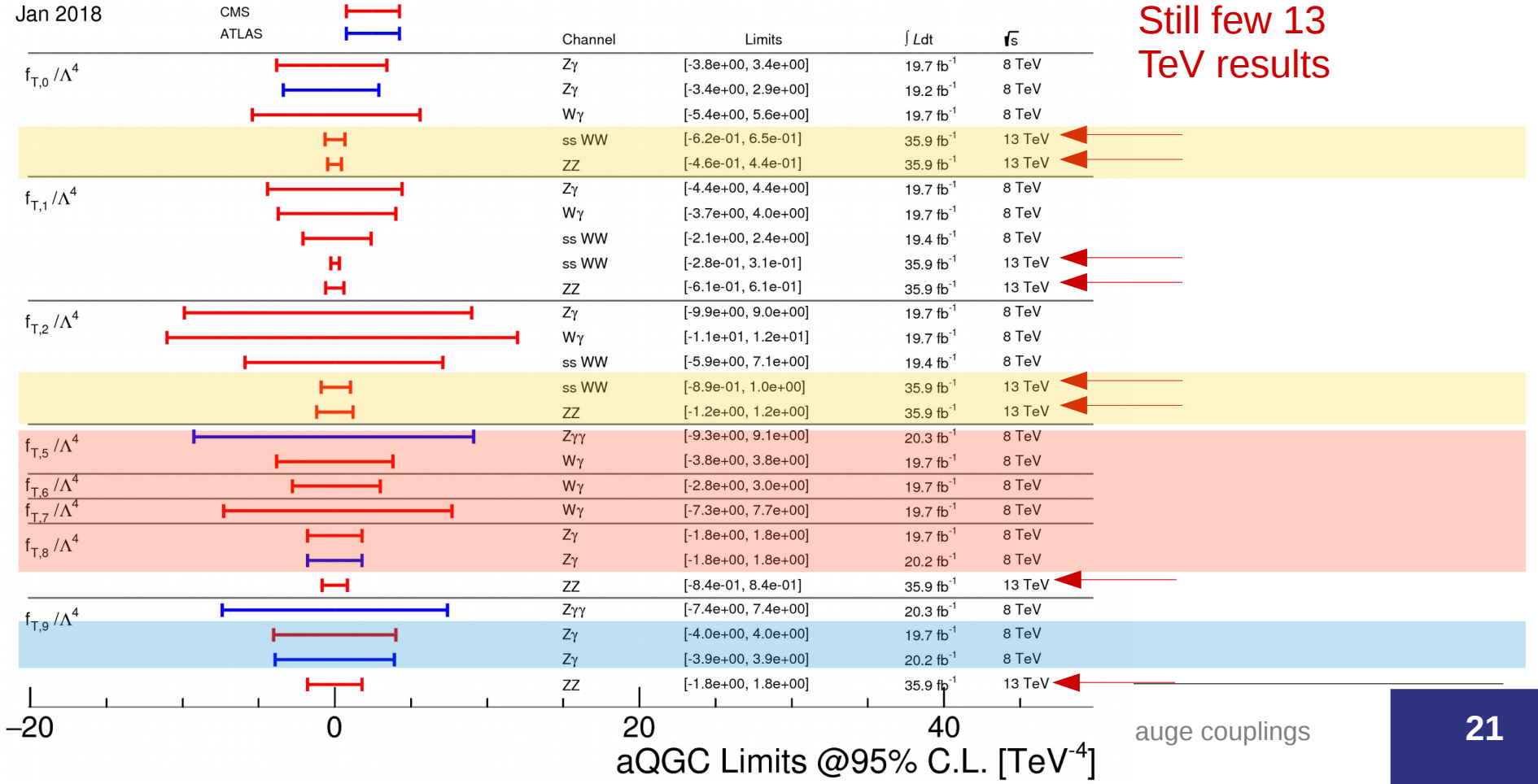
> LHC results superseeding all previous experiments



- Still few 13 TeV results

Shattering the Standard Model?

- > Same for pure aQGC transversal parameters
- > Future potential for improvements obvious
  - Combination (between channels)
  - Updates to $\sqrt{s}$ = 13 GeV
  - Combination (between experiments)



Still few 13 TeV results

auge couplings

Conclusions

> Vector Boson Fusion, Multiboson production and Vector boson scattering can finally be scrutinized at the LHC

- Single boson VBF process provide large data sample to understand the kinematics of the tagging jets
- Entering the realm of precision physics – even for ZZ production the systematics can no longer be neglected
- Multiboson VBS processes start being measured: 2.7σ (ZZ) and 5.7σ (WW)

> No signs of subtle new physics effects

- Stringent limits on general extensions of the SM Lagrangian set

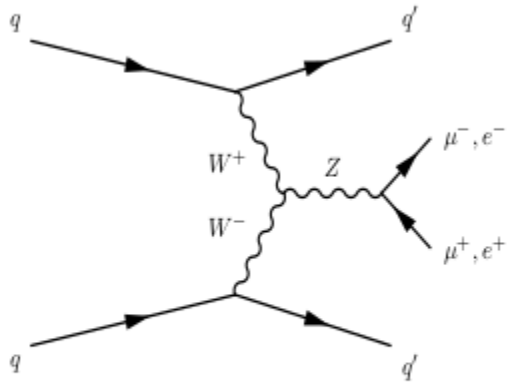
> More information in parallel session

- Tuesday and ***Friday*** →

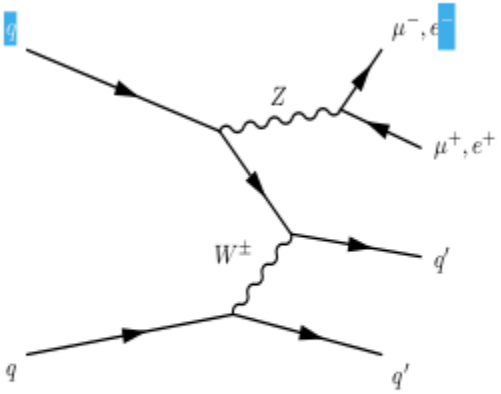
Latest results on VBF and VBS processes from the CMS experiment	*Nadezda Chernyavskaya*	
Sala della Traslazione	11:47 - 12:04	
Latest results on VBF and VBS processes from the ATLAS experiment	*Dimitrii Krasnopevtsev*	
Sala della Traslazione	12:14 - 12:31	
Latest results on single electroweak boson production from the ATLAS experiment	*Oleh Kivernyk*	
Sala della Traslazione	14:47 - 15:04	
Latest results on single electroweak boson production from the ALICE experiment	*Mohamad Tarhini*	
Sala della Traslazione	15:04 - 15:21	
Latest results on single electroweak boson production from the CMS experiment	*Marco Cipriani*	
Sala della Traslazione	15:47 - 16:04	
Latest results on single electroweak boson production from the LHCb experiment	*Lorenzo Sestini*	
Sala della Traslazione	16:04 - 16:21	

BACKUP

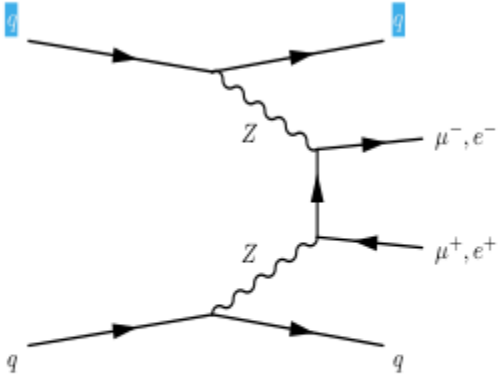
Backup



(a) vector boson fusion



(b) Z-boson bremsstrahlung



(c) non-resonant $\ell^+\ell^- jj$

Backup

	Fiducial region					
Object	Baseline	High-mass	High-p_{T}	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$\lvert\eta\rvert < 2.47$, $p_{\mathrm{T}} > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Dilepton pair	$81 < m_{\ell\ell} < 101$ GeV					
	—			$p_{\mathrm{T}}^{\ell\ell} > 20$ GeV		
Jets	$\lvert y\rvert < 4.4$					
	$p_{\mathrm{T}}^{j_1} > 55$ GeV		$p_{\mathrm{T}}^{j_1} > 85$ GeV	$p_{\mathrm{T}}^{j_1} > 55$ GeV		
	$p_{\mathrm{T}}^{j_2} > 45$ GeV		$p_{\mathrm{T}}^{j_2} > 75$ GeV	$p_{\mathrm{T}}^{j_2} > 45$ GeV		
Dijet system	—	$m_{jj} > 1$ TeV	—	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	—			$N_{\text{jet }(p_{\mathrm{T}}>25\text{ GeV})}^{\text{interval}} = 0$		$N_{\text{jet }(p_{\mathrm{T}}>25\text{ GeV})}^{\text{interval}} \geq 1$
Zjj system	—			$p_{\mathrm{T}}^{\text{balance}} < 0.15$		$p_{\mathrm{T}}^{\text{balance,3}} < 0.15$

Backup

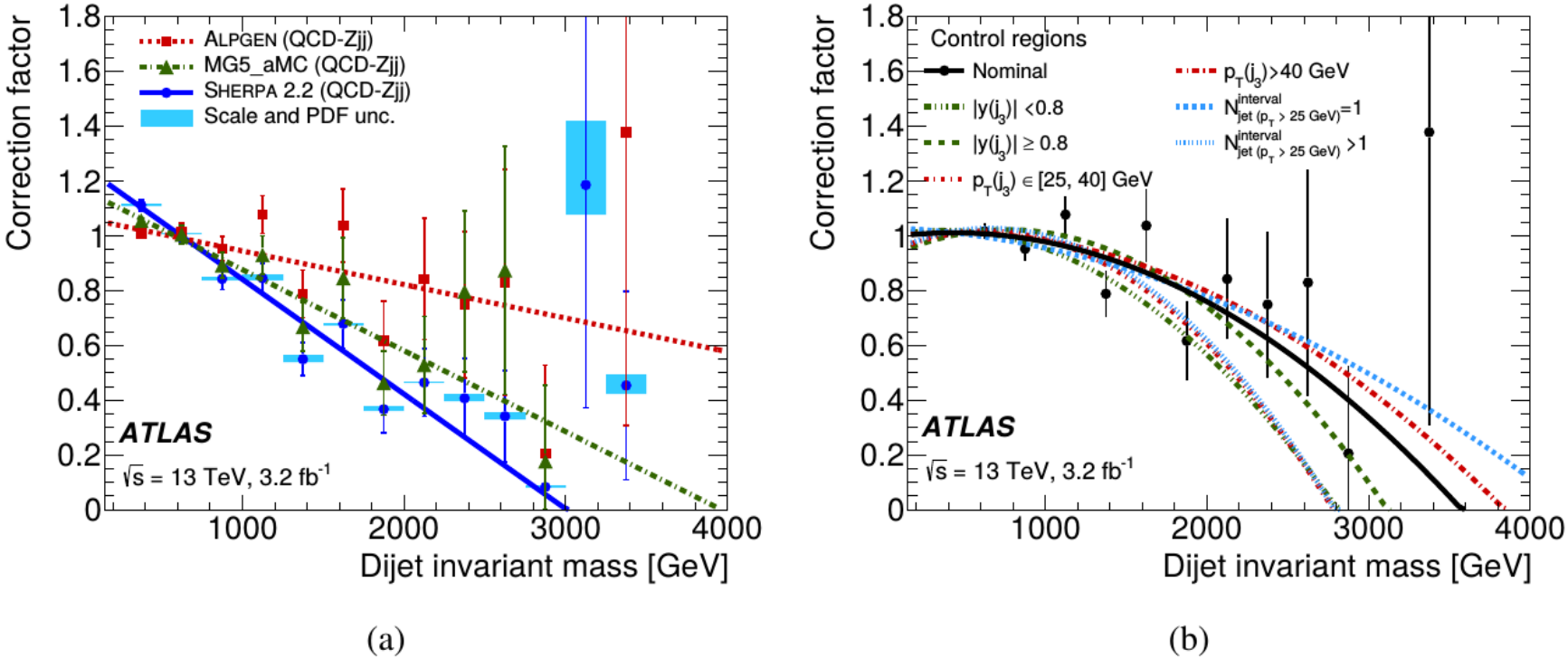


Figure 3: Binned data-to-simulation normalised ratio shape correction factors as a function of dijet invariant mass in the QCD-enriched region. (a) Ratio for three different QCD-*Zjj* MC samples with uncertainties corresponding to the combined statistical uncertainties in the data and QCD-Zjj MC samples added in quadrature. Scale and PDF uncertainties in SHERPA predictions are indicated by the shaded bands. Lines represent fits to the ratios using a linear fit. (b) Ratio for subregions of the QCD-enriched region for the ALPGEN MC sample. Curves represent the result of fits with a quadratic function for the various subregions.