VV + jets and vector boson scattering at the CMS experiment

Riccardo Bellan

Università di Torino and INFN

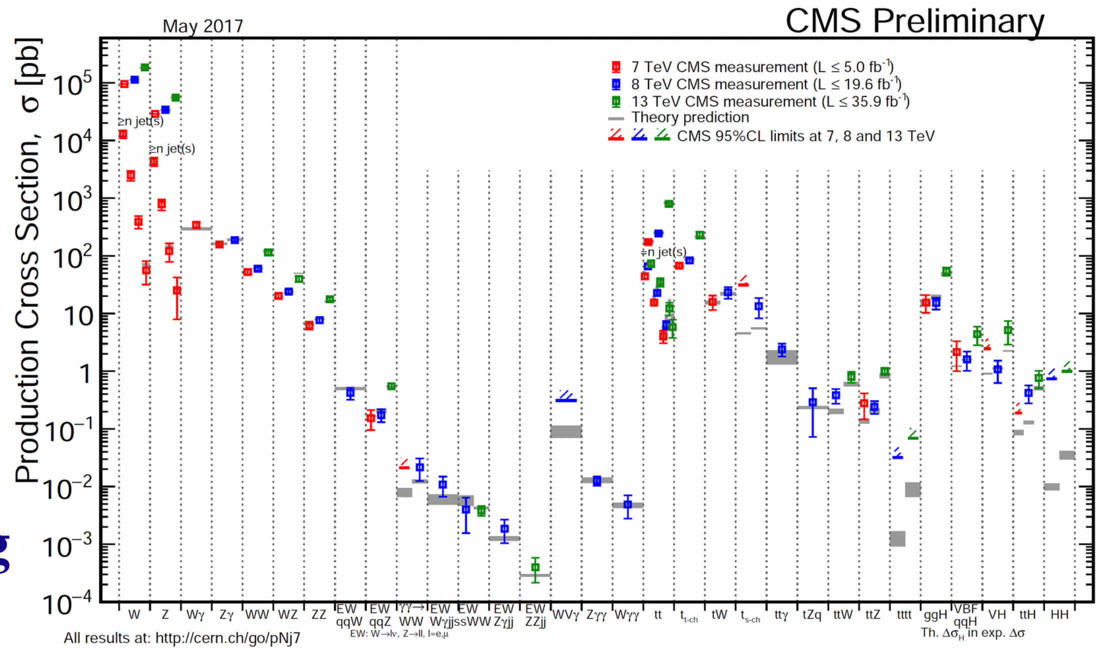
On behalf of the **CMS** Collaborations

EPS2017: ***The European Society Conference on High Energy Physics***

Venezia, Italy, 5 July – 12 July, 2017

Top and electroweak physics session

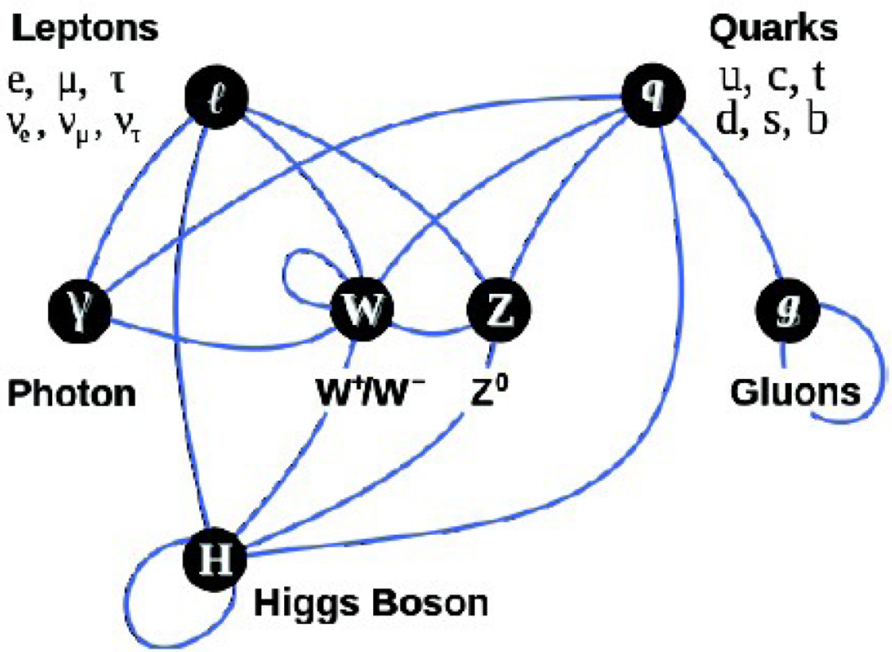
- Standard Model cross sections successfully tested over **9 orders of magnitude**
- We **discovered a Higgs boson**
- ***Still*** we have to understand **<u>in detail</u> the Electroweak Symmetry Breaking Mechanism** (*and if there is new physics beyond the SM*)



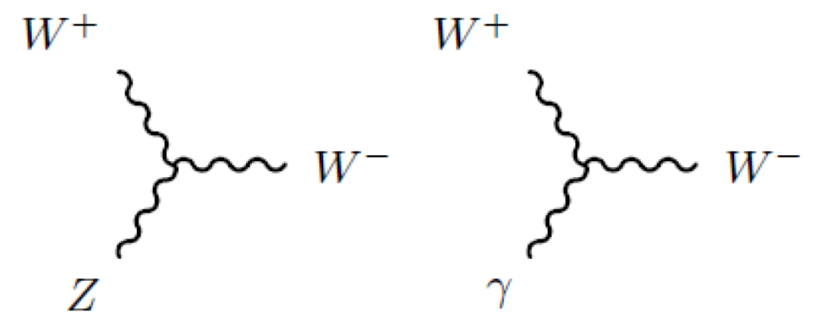
It is crucial to deeply understand the final states **mediated by heavy gauge boson pair production**: do we ***master*** them, using our N^nLO computations?

Measure with **high precision the <u>differential cross sections</u>**	Measure exclusive multi boson production mechanisms, such as **<u>VV scattering</u>** and **<u>QGC mediated</u>**	Investigate the **<u>high VV mass region</u>**

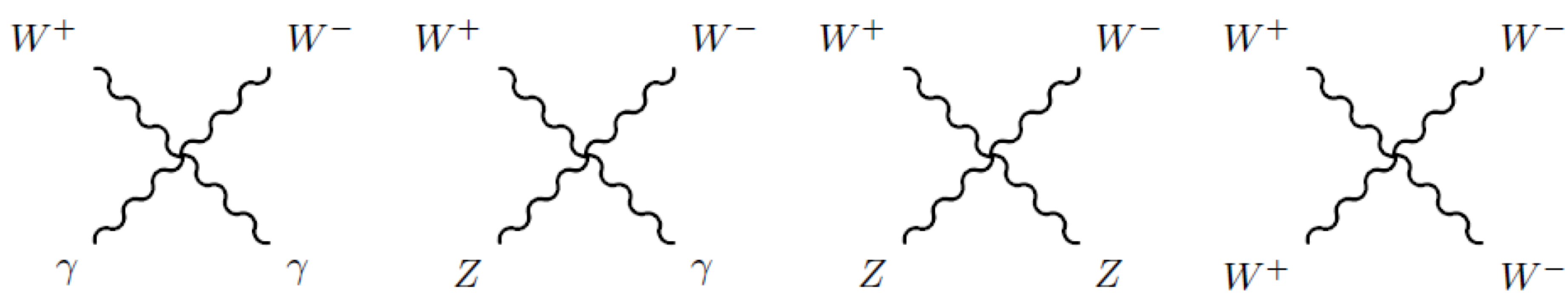
What interesting EW features can the VV production probe?



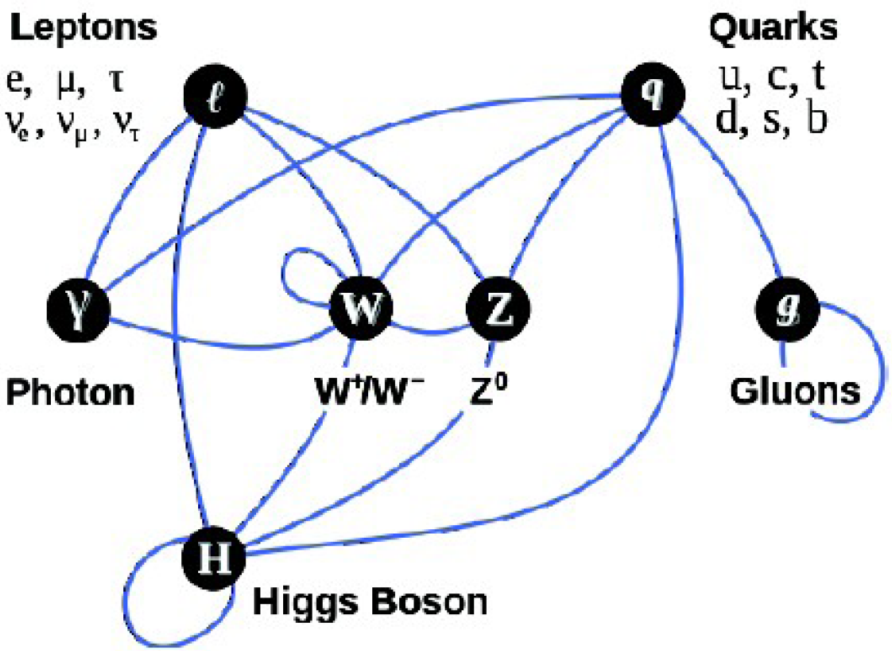
- **Triple gauge couplings (TGC)**



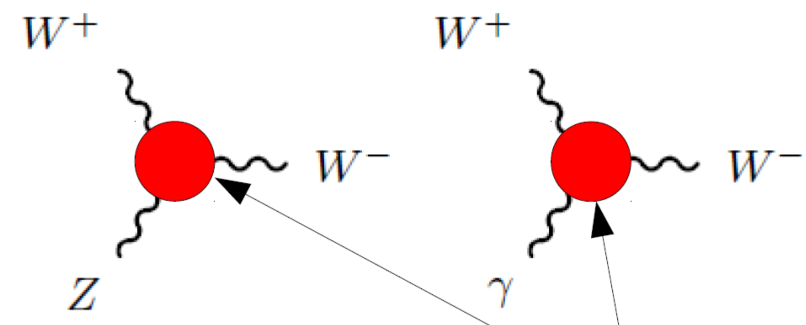
- **Quartic gauge couplings (QGC)**



What interesting EW features can the VV production probe?

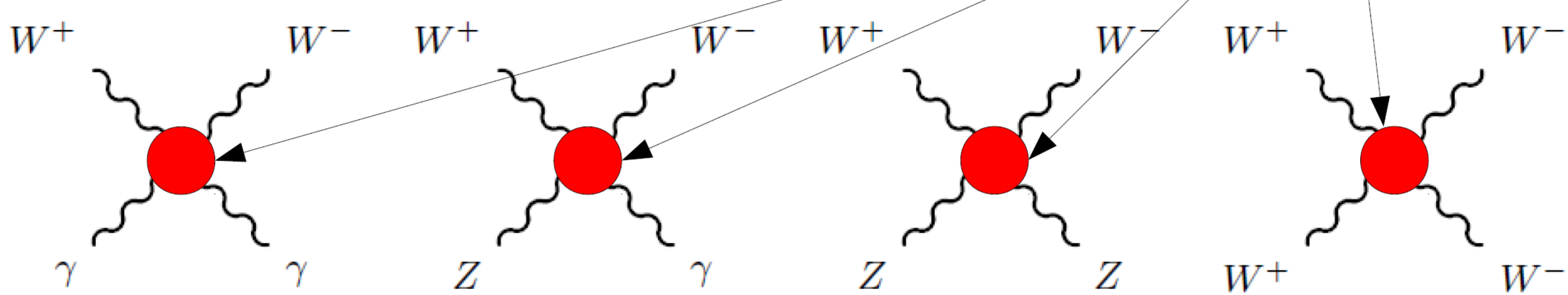


- **Triple gauge couplings (TGC)**

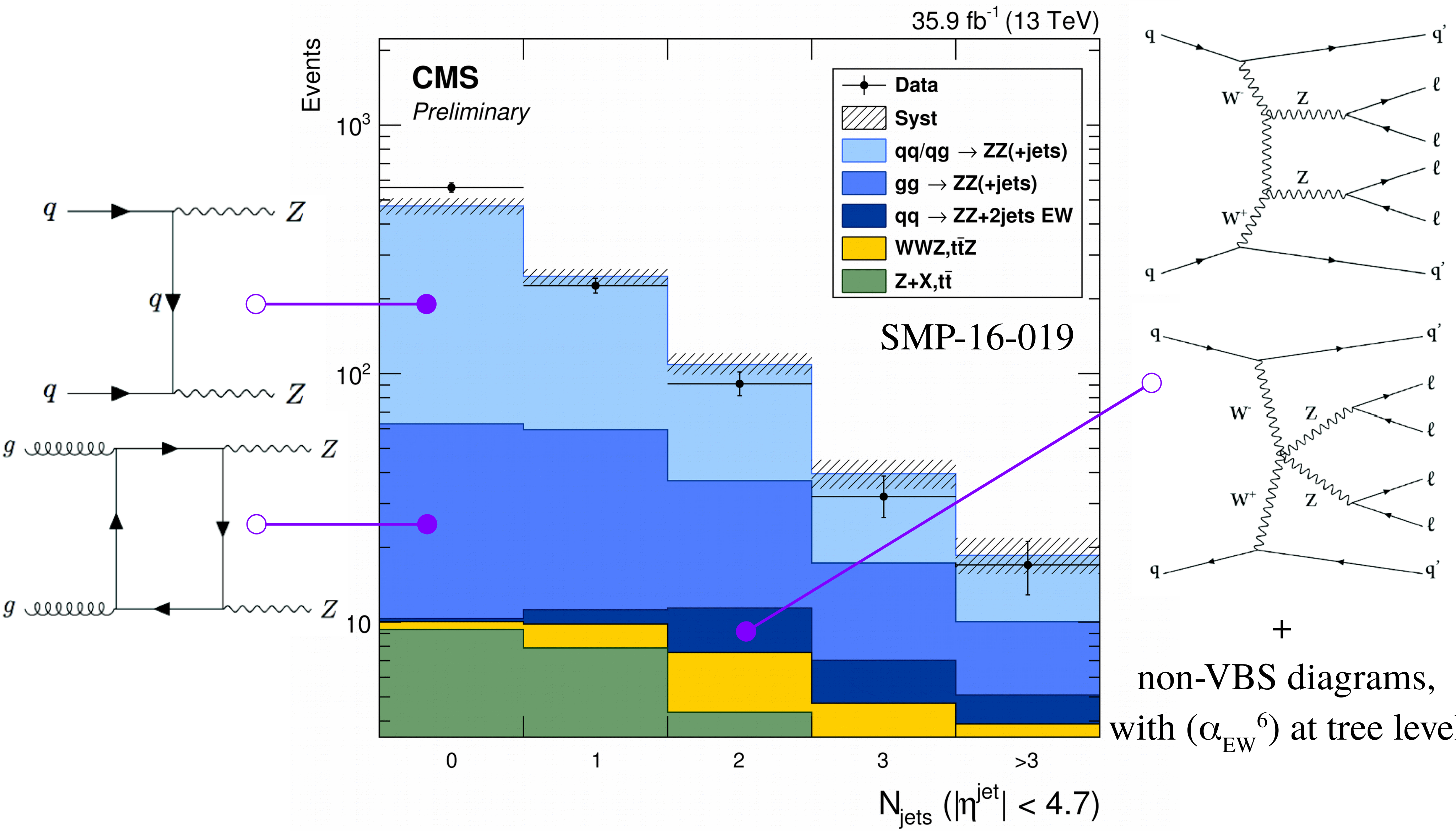


Anomalous couplings + what forbidden in SM

- **Quartic gauge couplings (QGC)**



Experimental and theoretical challenges



ZZ+jets analysis

SMP-16-019

Search for two **on-shell** (**60 < $m_{\ell\ell}$ < 120 GeV**) **Z** bosons decaying into **electrons** or **muons** pairs, consider jets if their p_T is > 30 GeV

Pros

- Final state can be **fully reconstructed**

  → **all kinematic variables are accessible**

- **Very clean** final state

  → **low reducible background**

Cons

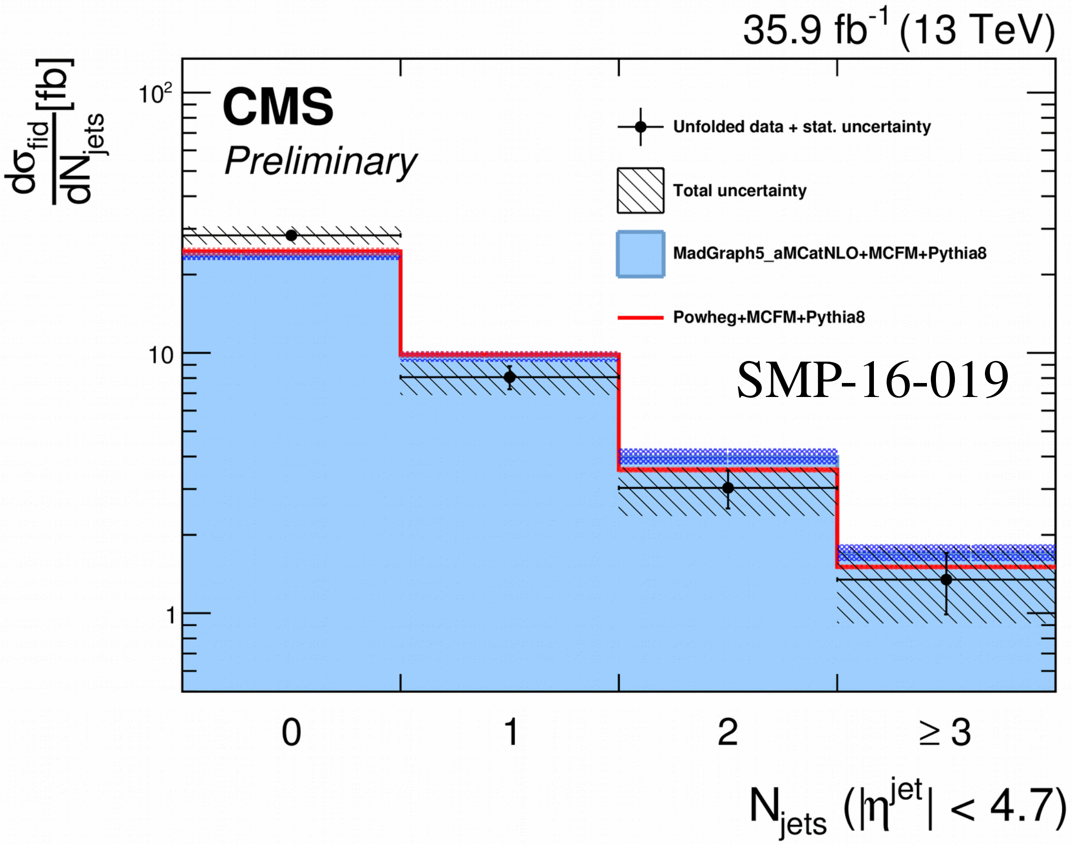
- **Low σxBR** compared to other channels

  → **maximize the selection efficiency** (minimal cuts on lepton mainly driven by trigger thresholds, detector acceptance)

- **ZZ + QCD-induced jets** (irreducible background) **highly dominant** compared to pure EW production

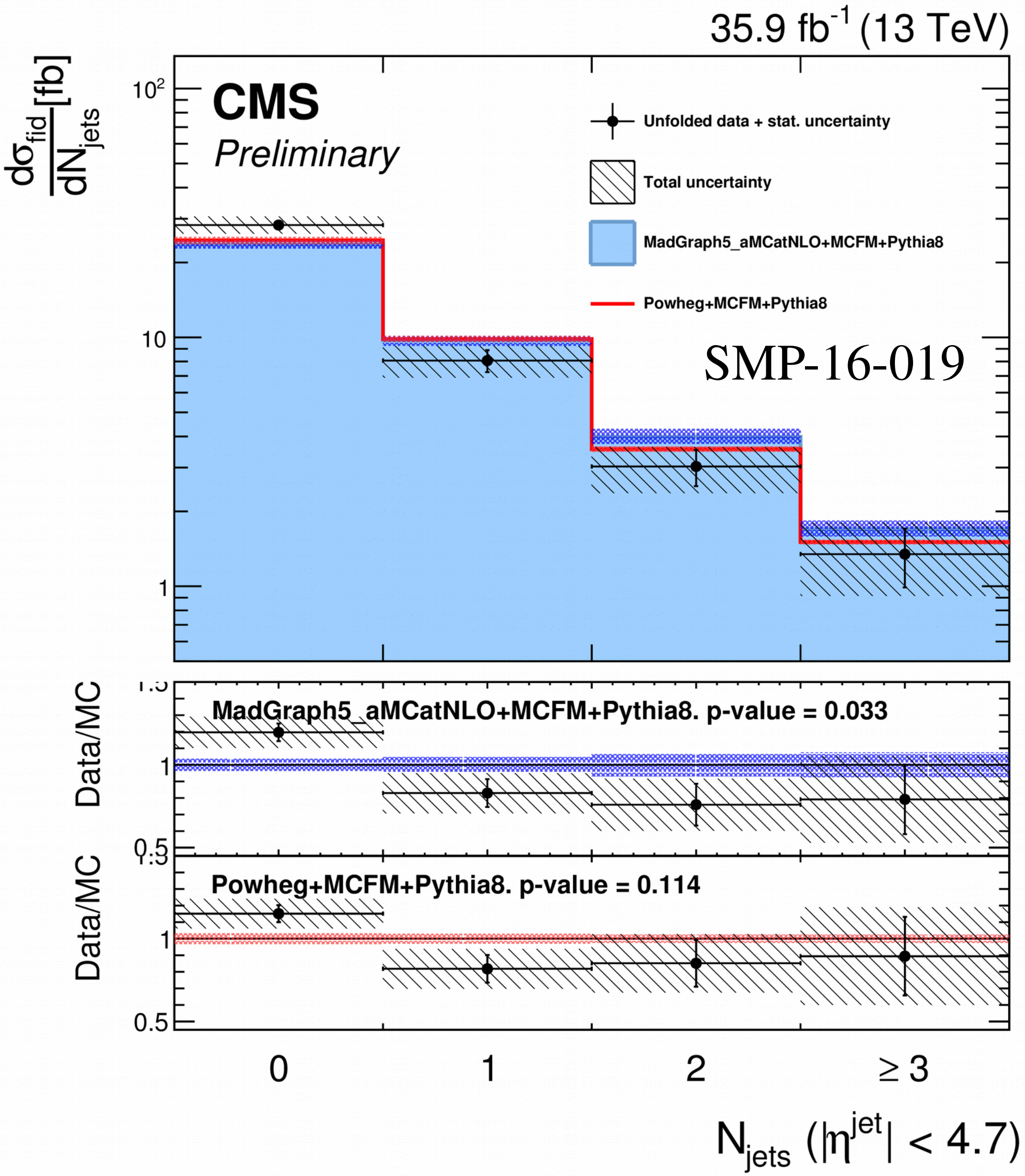
  → **understanding of the irreducible background is paramount**

Understanding the irreducible background: differential cross sections of ZZ+jets (I)

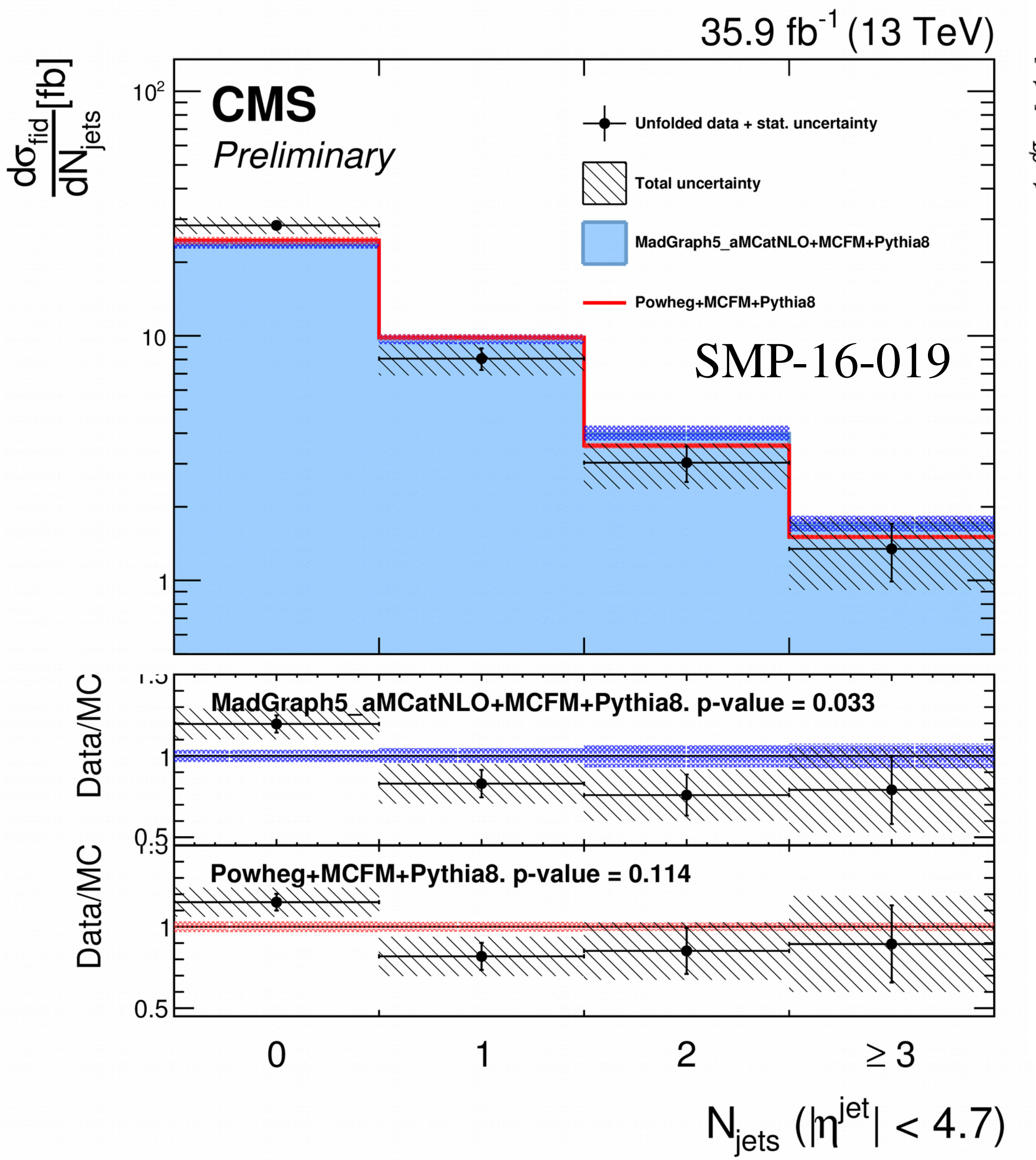


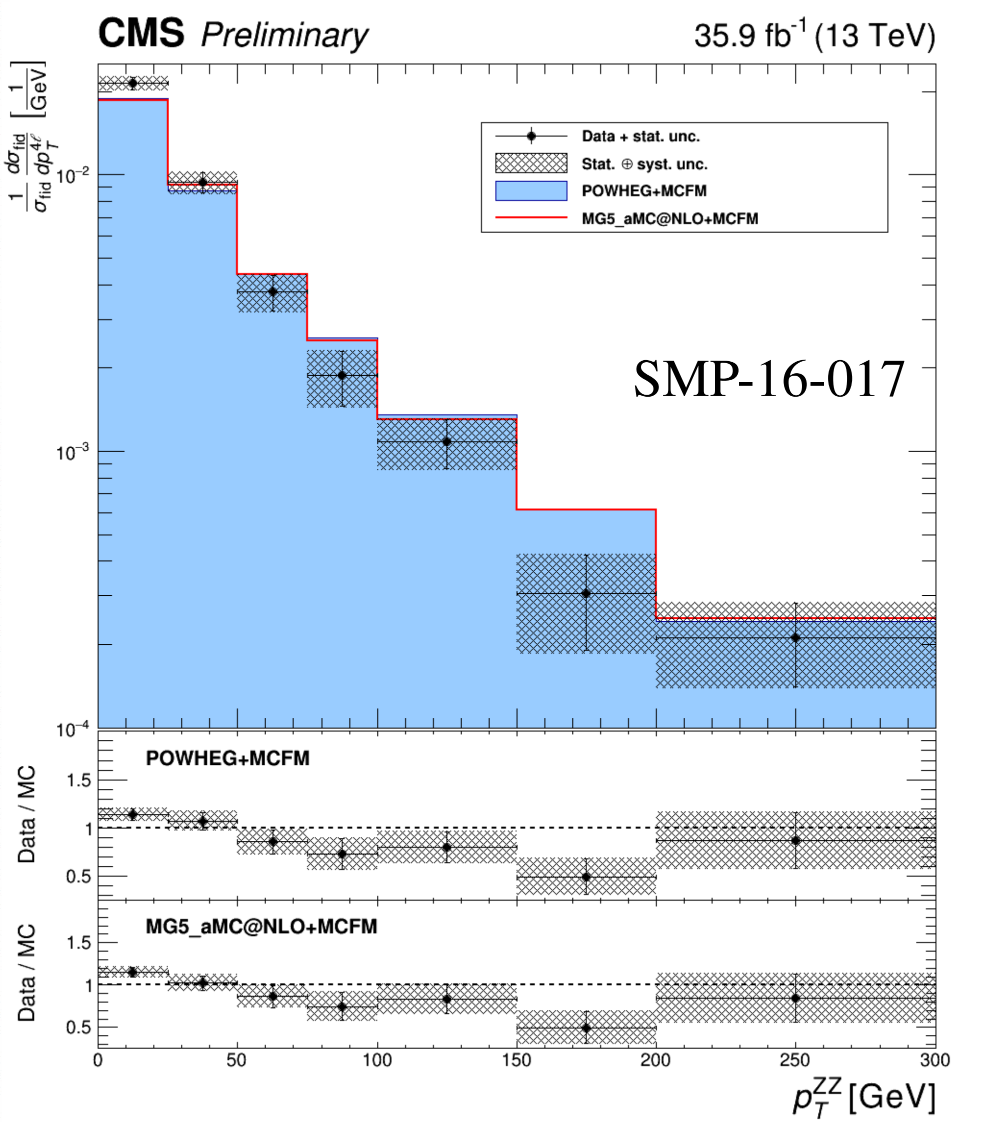
Number of jets ($\|\eta^{jet}\| < 4.7$)	Fiducial cross section [fb]	Theo. cross section [fb]
0	$28.3 \pm 1.3\ (\text{stat})^{+1.7}_{-1.6}\ (\text{syst}) \pm 0.7 (\text{lumi})$	$23.6^{+0.8}_{-0.9}$
1	$8.1 \pm 0.8\ (\text{stat})^{+0.8}_{-0.8}\ (\text{syst}) \pm 0.2 (\text{lumi})$	$9.7^{+0.4}_{-0.4}$
2	$3.0 \pm 0.5\ (\text{stat})^{+0.3}_{-0.4}\ (\text{syst}) \pm 0.1 (\text{lumi})$	$4.0^{+0.3}_{-0.2}$
≥ 3	$1.3 \pm 0.4\ (\text{stat})^{+0.3}_{-0.2}\ (\text{syst})$	$1.7^{+0.1}_{-0.1}$

Understanding the irreducible background: differential cross sections of ZZ+jets (I)

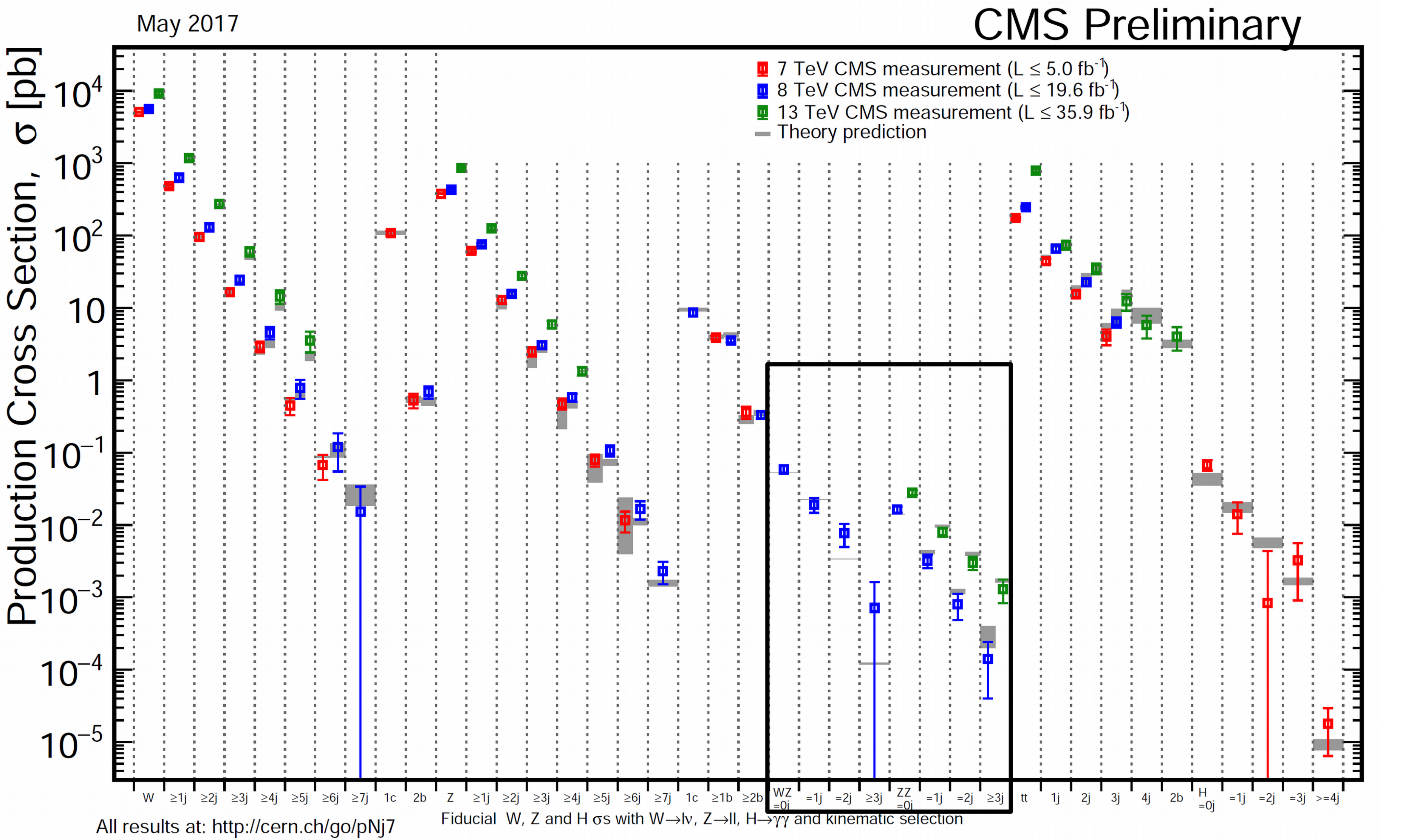


Understanding the irreducible background: differential cross sections of ZZ+jets (I)



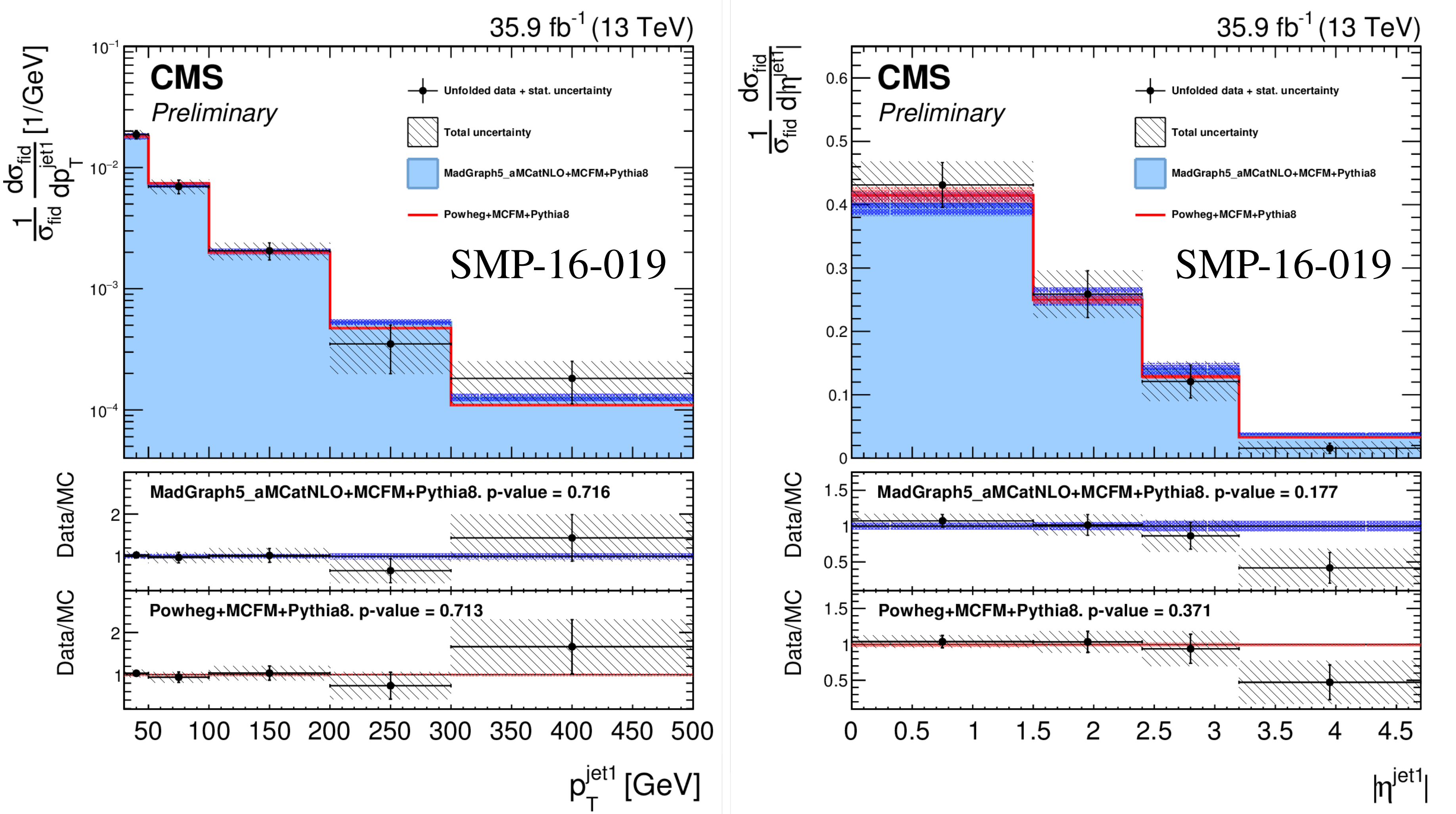


Summary of VV+jets measurements



Understanding the irreducible background: differential cross sections of ZZ+jets (II)

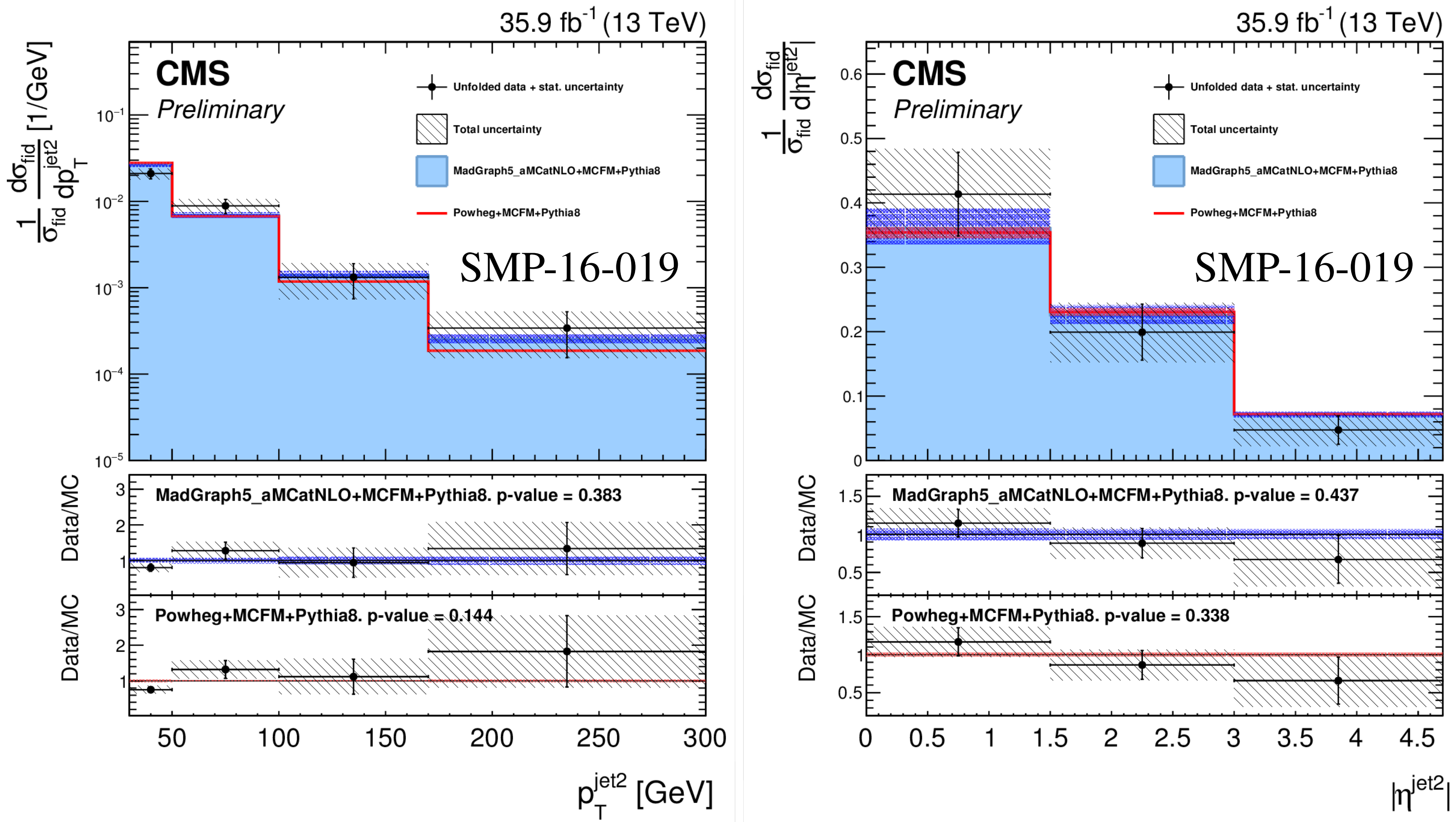
as a function of the leading-p_T jet variables



Overall **good** agreement with two type of MC sets

Understanding the irreducible background: differential cross sections of ZZ+jets (III)

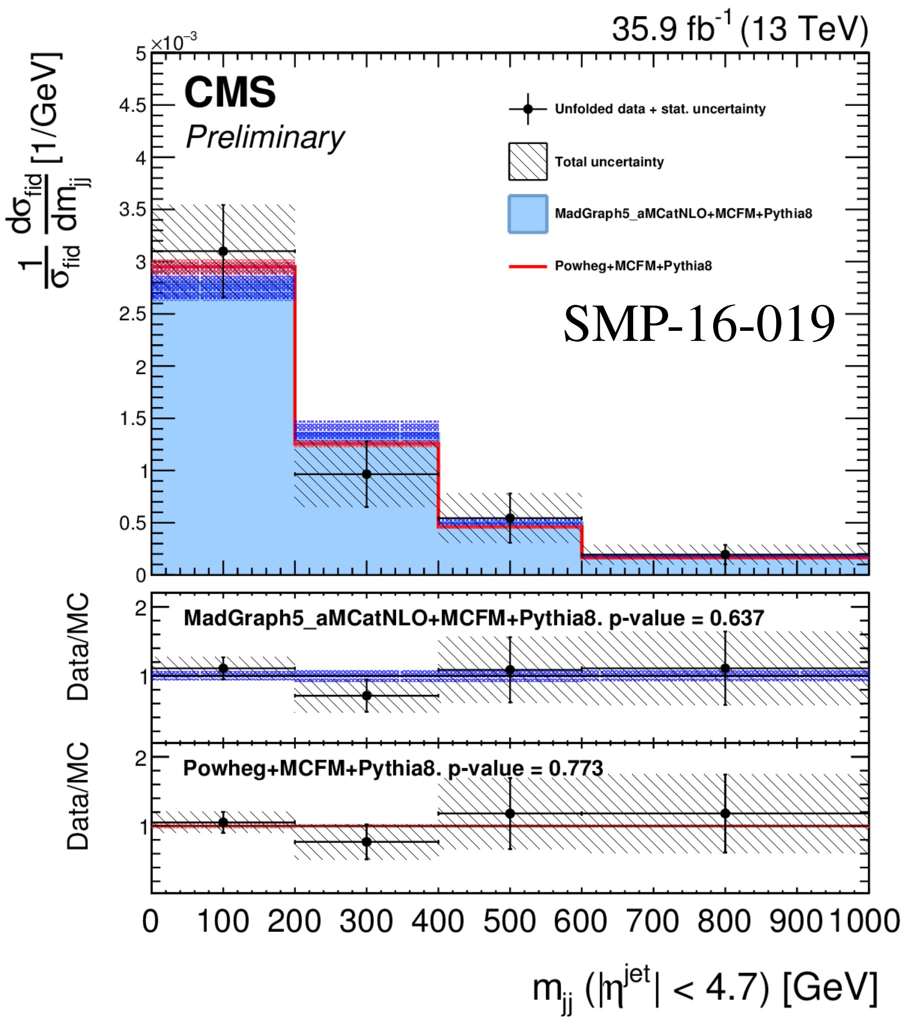
as a function of the subleading-p_T jet variables

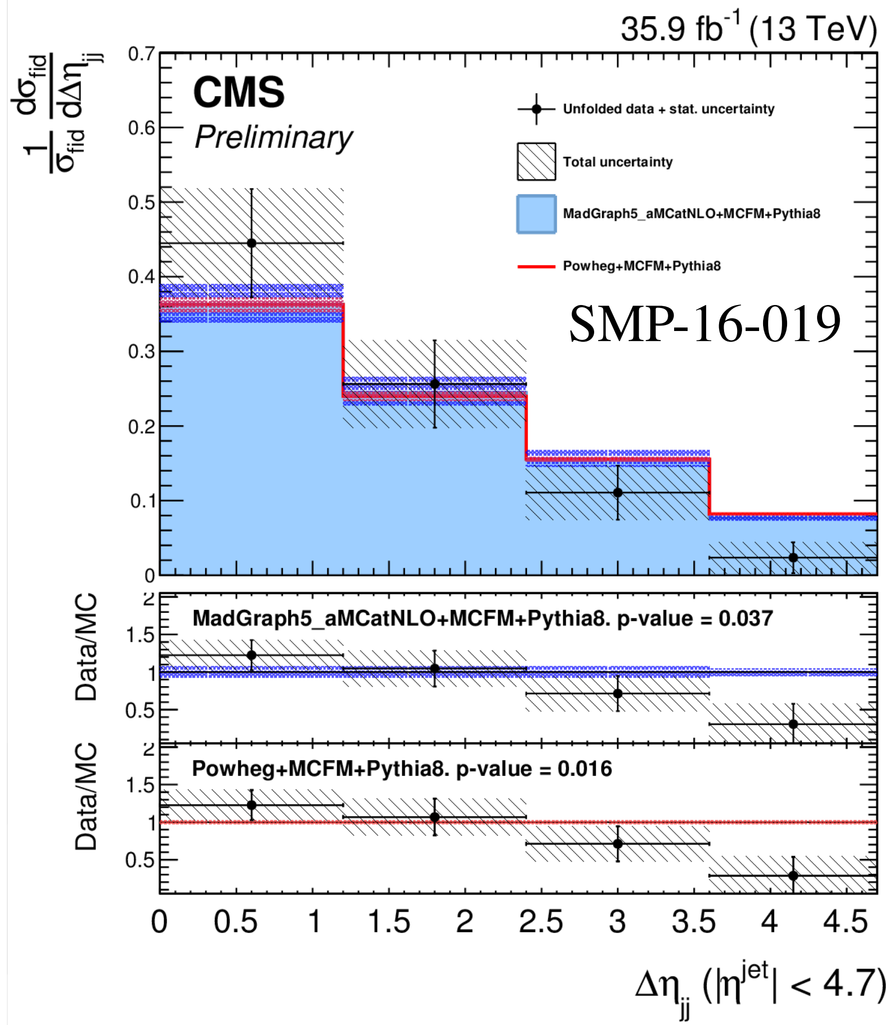


Overall **good** agreement with two type of MC sets

Understanding the irreducible background: differential cross sections of ZZ+jets (IV)

as a function of the dijet variables





m_{jj} in **good** agreement with MC while $|\Delta\eta_{jj}|$ seems **steeper** in data than in MC

Search for the ZZ+jets EW production

Overall **very good data-theory agreement**

Little discrimination on individual variables ⇒

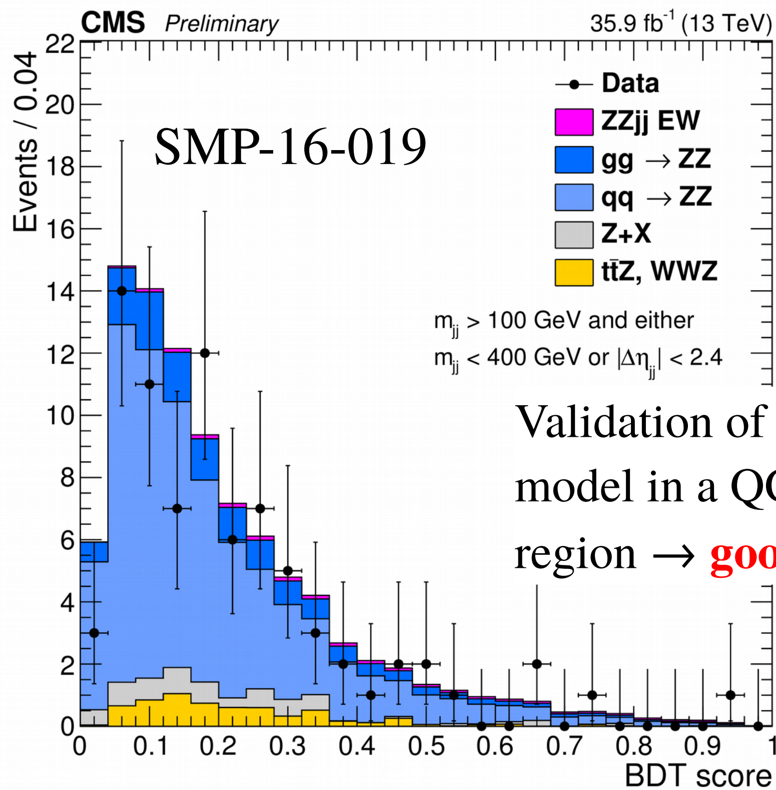
Few expected signal events

BDT optimized to separate **EW ZZ+jets** from **QCD-induced jet** production

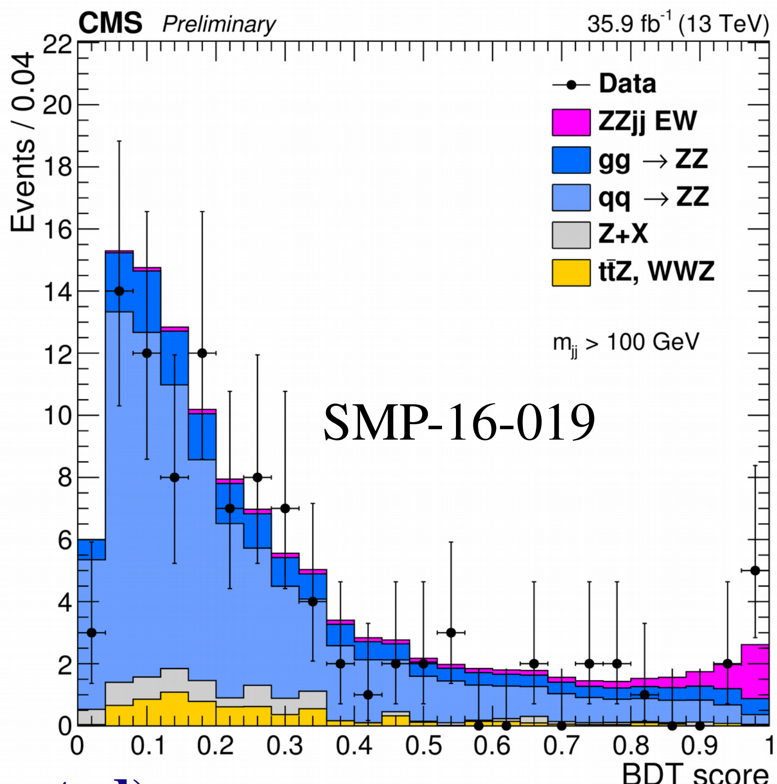
7 inputs: $\mathbf{m_{jj}}$, $\mathbf{\Delta\eta_{jj}}$, $\mathbf{z_1^*}$, $\mathbf{z_2^*}$, $\mathbf{R(p_T)}$, **dijet** $\mathbf{p_T}$ **balance**, $\mathbf{m_{4l}}$

Signal extracted via **template fit of full BDT spectrum**

Constrains **background normalization with data**



Validation of background model in a QCD-enriched region → **good** agreement



Measured signal strength: $\mu = 1.39^{+0.72}_{-0.57}(\text{stat})^{+0.46}_{-0.31}(\text{syst})$

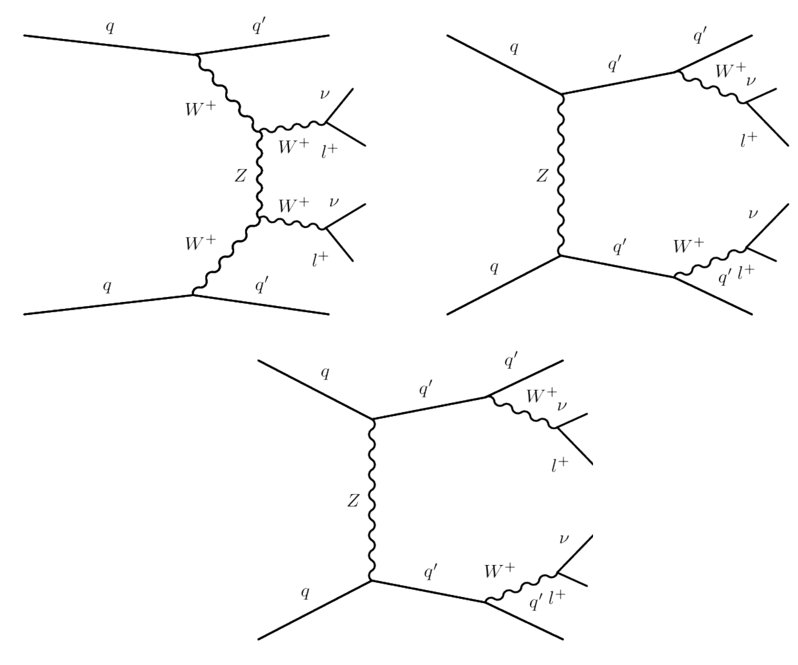
With an **observed significance of 2.7 σ (1.6 σ, expected)**

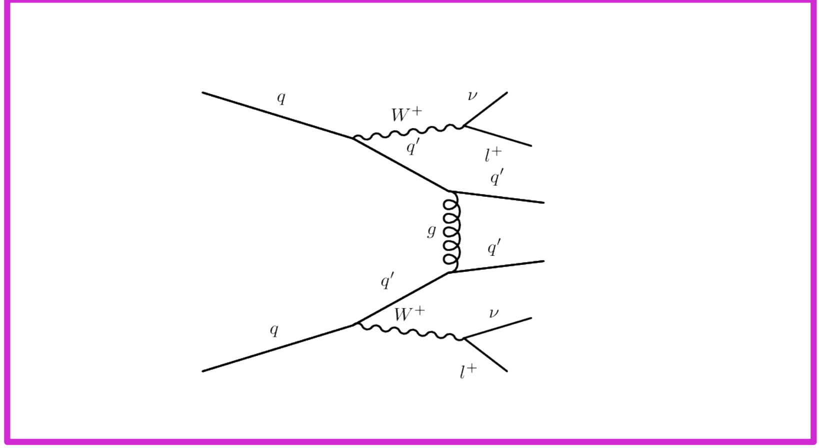
Measured fiducial cross section $\sigma(\text{EW } pp \rightarrow ZZ + jets \rightarrow lll'l' + jets) = 0.40^{+0.21}_{-0.16}(\text{stat})^{+0.13}_{-0.09}(\text{syst})\,\text{fb}$

EW $pp \rightarrow W^{\pm}W^{\pm}jj \rightarrow l^{\pm}l^{\pm}\nu\nu jj$ production

SMP-17-004

- Search for a **pair of same charge lepton** (μ, e) with $p_{T,1(2)}$ > 25 (20) GeV m_{ll} > 20 GeV, **vetoing additional leptons** (including τ's) in the event
- **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
- **Low background contamination** compared to other VBS search channels (thanks to its quite large σxBR) **→ # signal events ~ half of all background events**
- Background from **W±W±+jets induced by QCD** ***very small*** compared to the **signal**. **Main background** from **multi non-prompt leptons** in the event and **WZ → 3lυ** where a charged lepton is lost
  - To suppress DY → E_T^{miss} > 40 GeV and Z → e^+e^- veto
  - To reduce top background: anti b-tagging, m_{ll} > 20 GeV



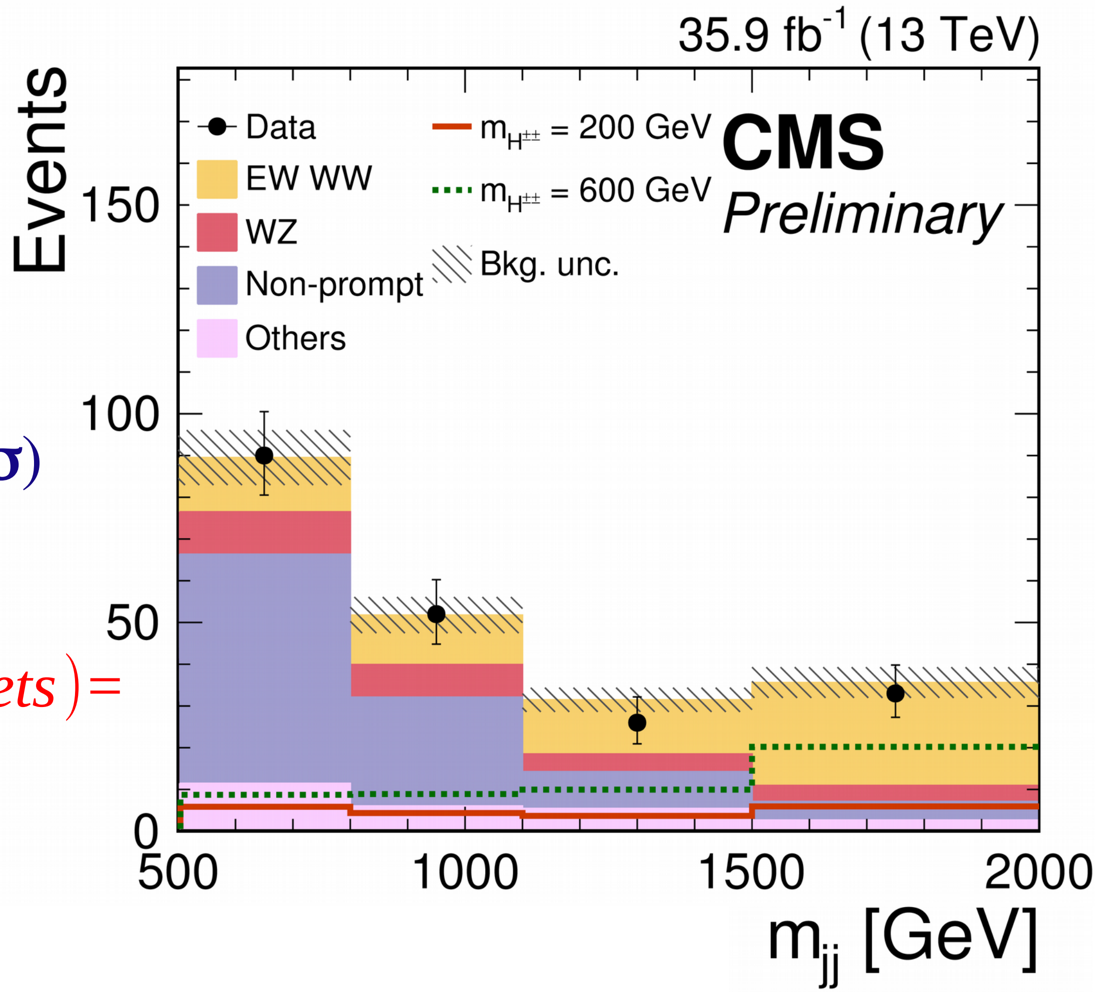


EW $pp \rightarrow W^{\pm}W^{\pm}jj \rightarrow l^{\pm}l^{\pm}\upsilon\upsilon jj$ production

SMP-17-004

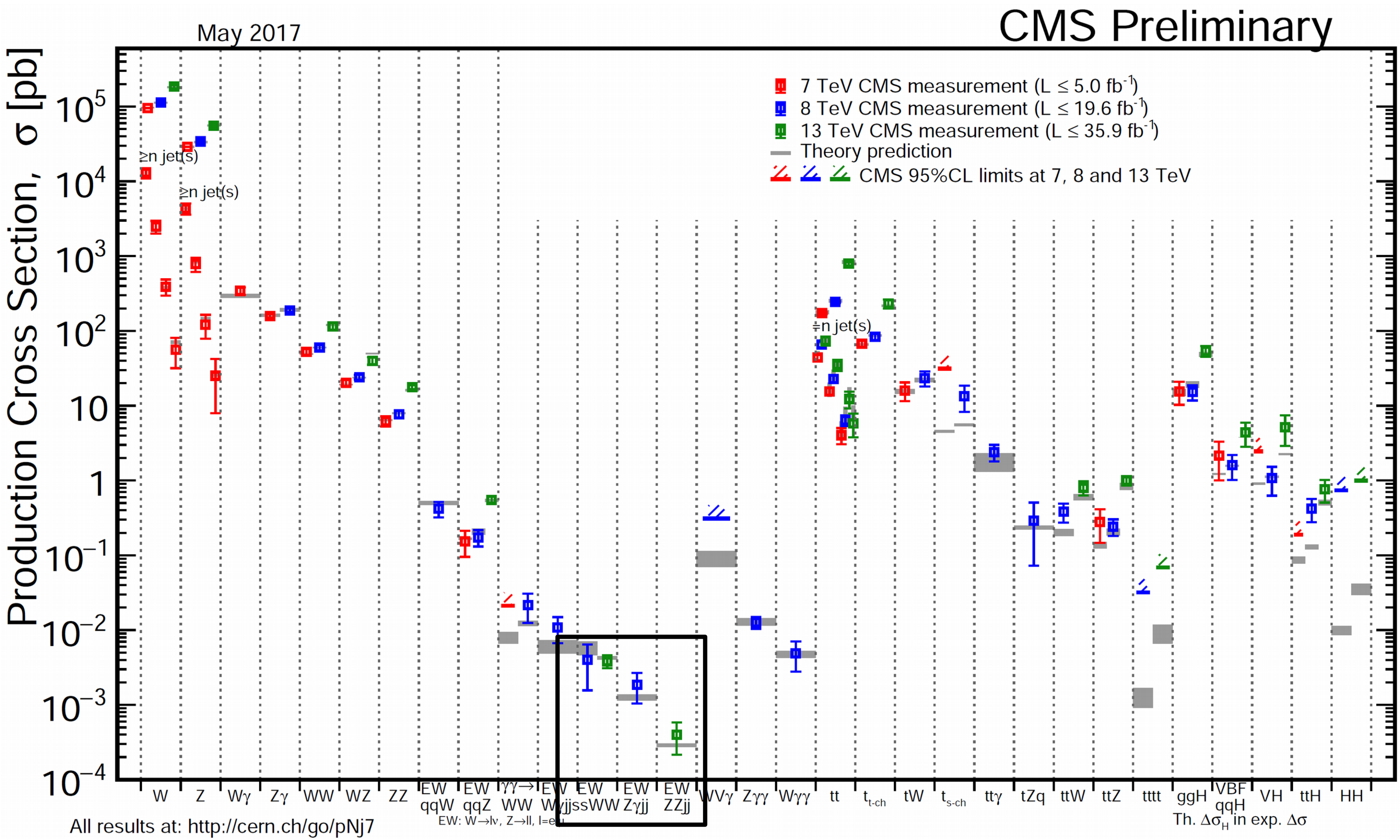
- Signal event yield extracted using a **2D fit of m_{jj} and m_{ll}**
- EW production observed with a significance of **5.5 σ** (expected **5.7 σ**)

$$\sigma(\text{EW } pp \rightarrow W^{\pm}W^{\pm} + jets \rightarrow l^{\pm}l'^{\pm}\nu\nu + jets) = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})\,\text{fb}$$



- Analysis also used to constrain the σxBR for the production of **doubly charged Higgs boson** decaying into two same sign W, resulting in a **limit at 95% CL** well **below 100 fb** for a large range of the $H^{\pm\pm}$ mass

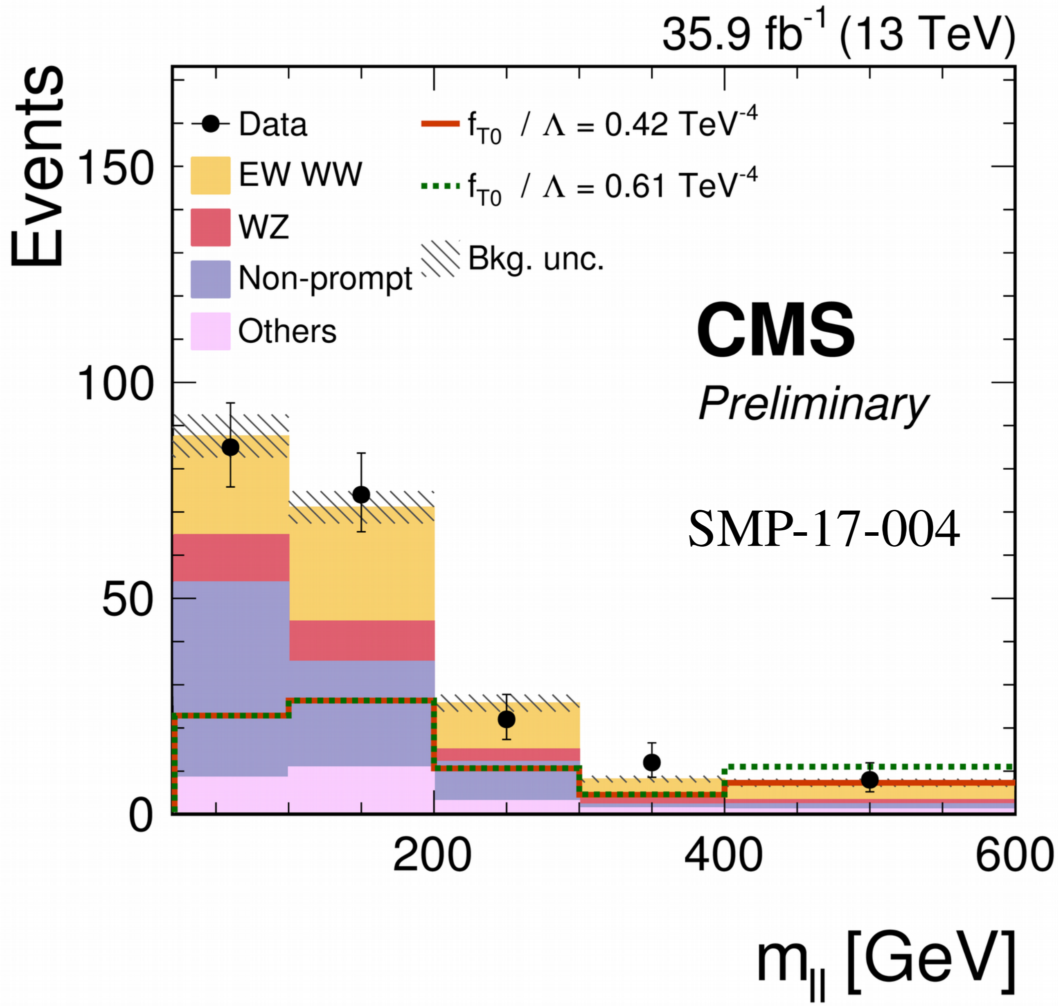
Cross sections summary

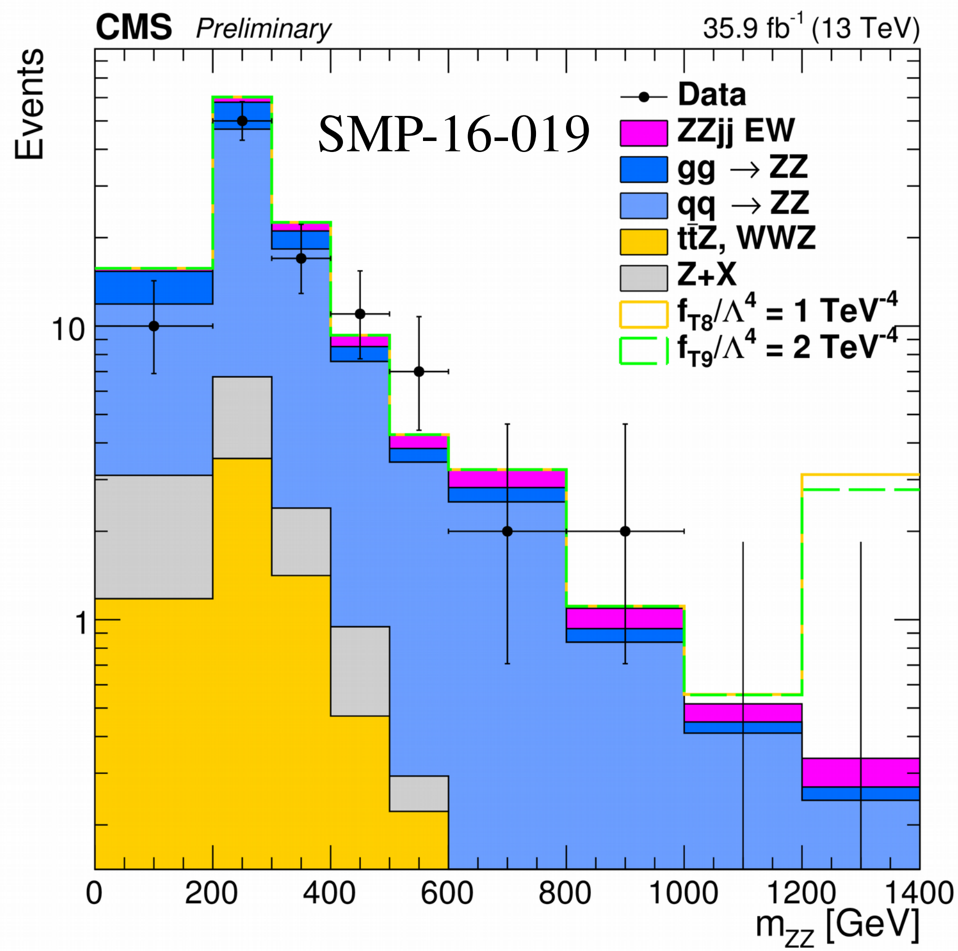


Anomalous vector boson couplings

- Search for **new physics** *while doing* **EW measurements**
- Look for deviations from SM in tail of distributions (**m_{VV}, m_{ll}, m_{jj}, $p_{T,V}$**, …)
- Parametrize the new physics **adding terms to the SM lagrangian**
- Several possibilities, for the analyses presented here we made use of the **Effective field theory approach** [Phys. Rev. D 48(1993) 2182, Phys. Rev. D 74 (2006) 073005] to extract limits on **anomalous quartic gauge couplings**
- Parameters are varied ***one-by-one***.

Anomalous quartic gauge couplings

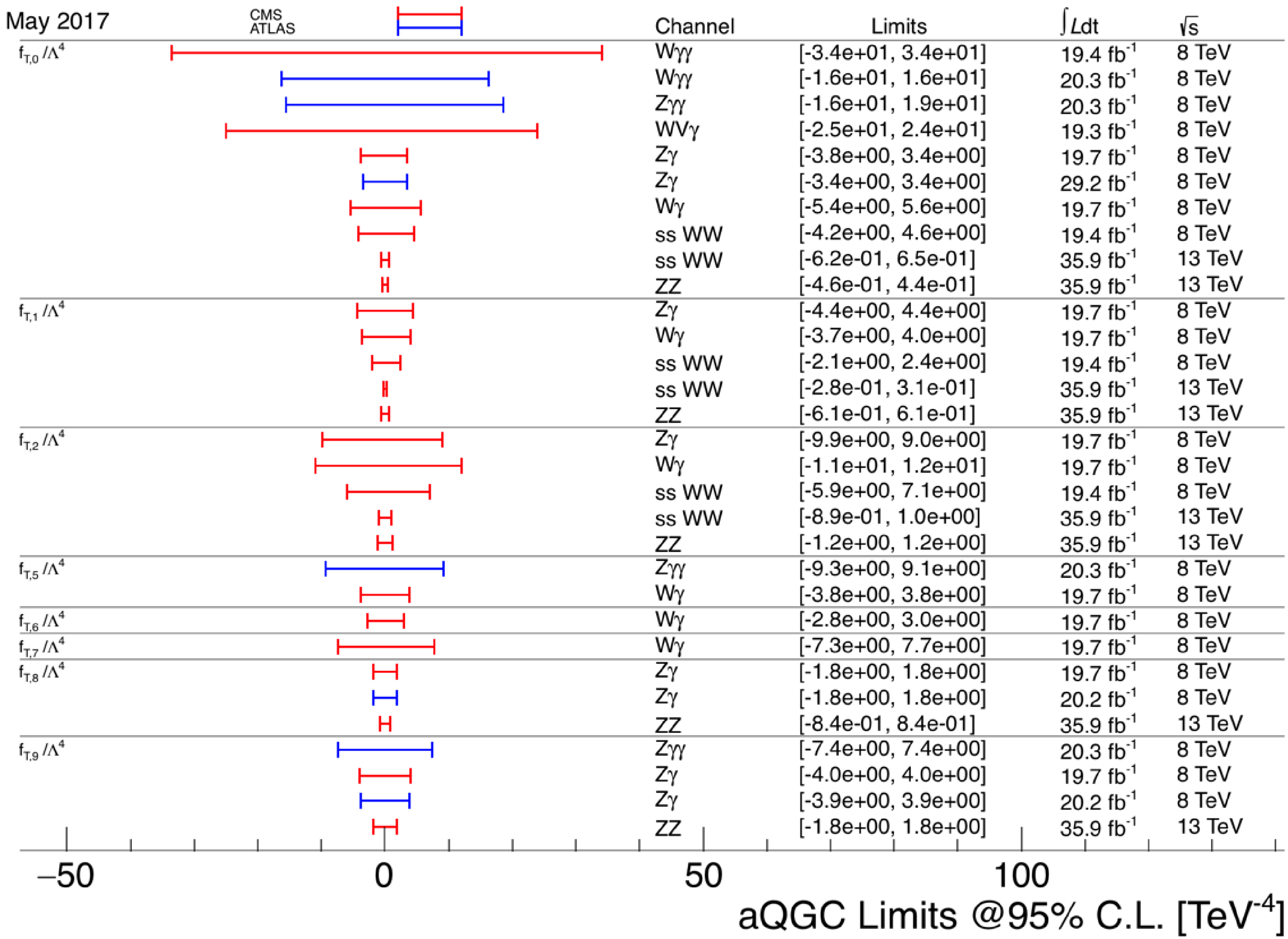




Main variables for the search of anomaluous quartic gauge couplings

→ no evidence found so far

aQGC summary table



Coupling	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

Conclusions

- We discovered a Higgs boson, yet **the comprehension of the Electroweak Symmetry Breaking is not completed**

  → Understanding the Multi-boson production in association with jets is the key point!

  - **Complementary** to Higgs boson properties studies and high mass searches

- **Observation of Electroweak production of two same sign W and two jets**
  - **Hint** of the production of ZZ+jets through EW process

Time of multi-boson production is now, the New Frontier will be:

VV + jets, Vector Boson Scattering and triboson production

→ they will be ones of the hot topic of LHC Run II!

Details on results can be found in the public pages of the CMS experiment:

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

More Material

ZZ+jets Complete Cut List

Fiducial region (baseline)

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

Fiducial region (VBS)

+ m_{jj} > 100 GeV

Search region (baseline)

- $|\eta_e|$< 2.5 $p_T^{\ e}$ > 7 GeV, $|\eta_\mu|$< 2.4 $p_T^{\ \mu}$ > 5 GeV, relative isolation < 0.35 in a cone of ΔR = 0.3, CMS tight ID and SIP= $|IP/\sigma_{IP}|$ < 4
- At least a lepton with p_T > 20 GeV and a μ(e) with p_T > 10(12) GeV
- 60 < m_Z < 120 GeV (On shell), $m_{ll\ \text{crossed(Opposite sign same flavour)}}$ > 4 GeV
- Loosely ID jets, reco with anti-k_T 0.4; $|\eta_{jet}|$ < 4.7 and p_T > 30 GeV

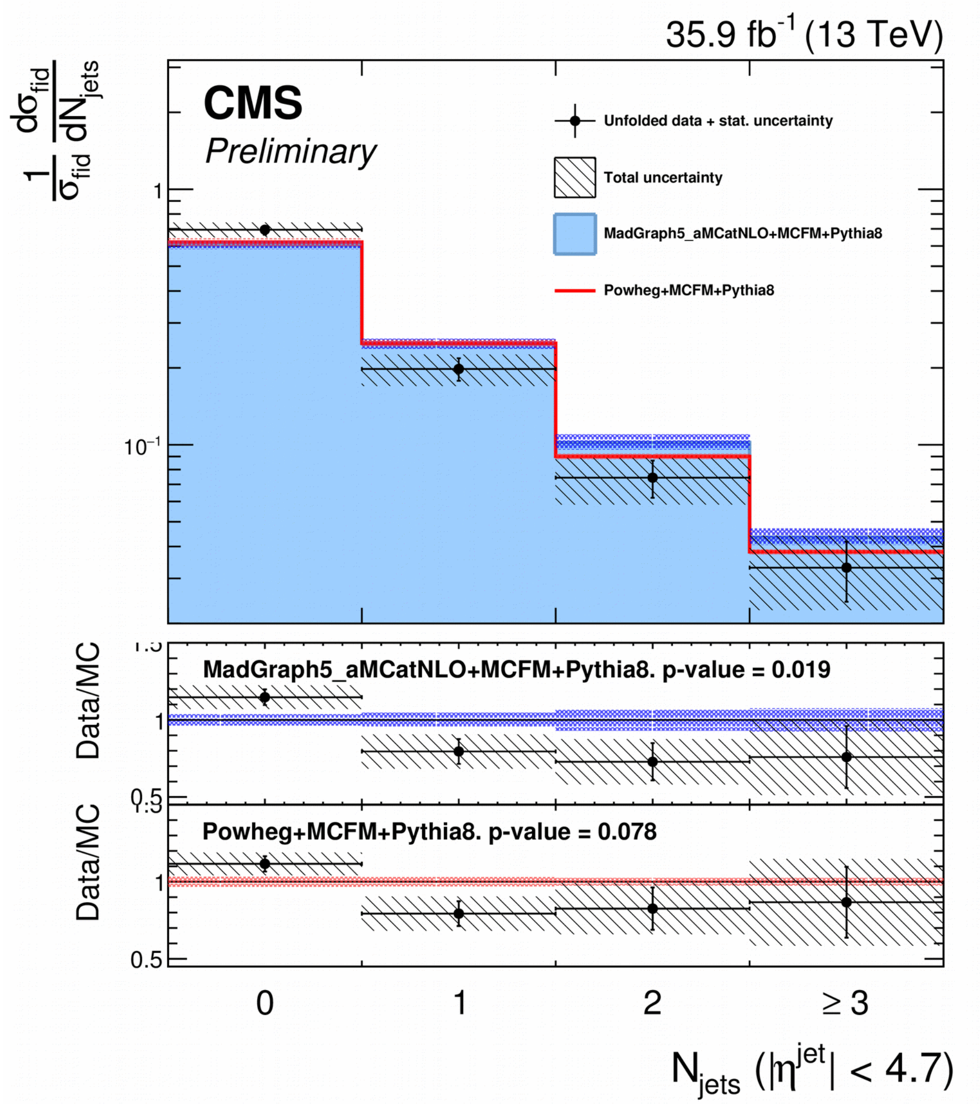
Search region (VBS)

+ m_{jj} > 100 GeV

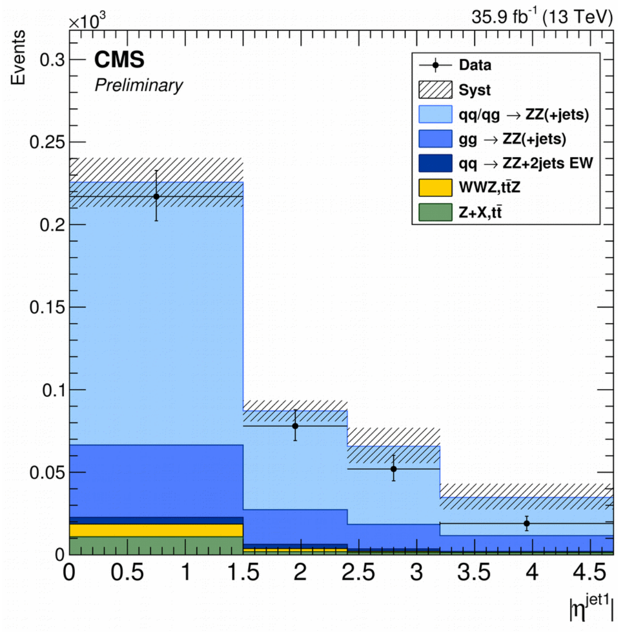
ZZ+jets systematic uncertainties

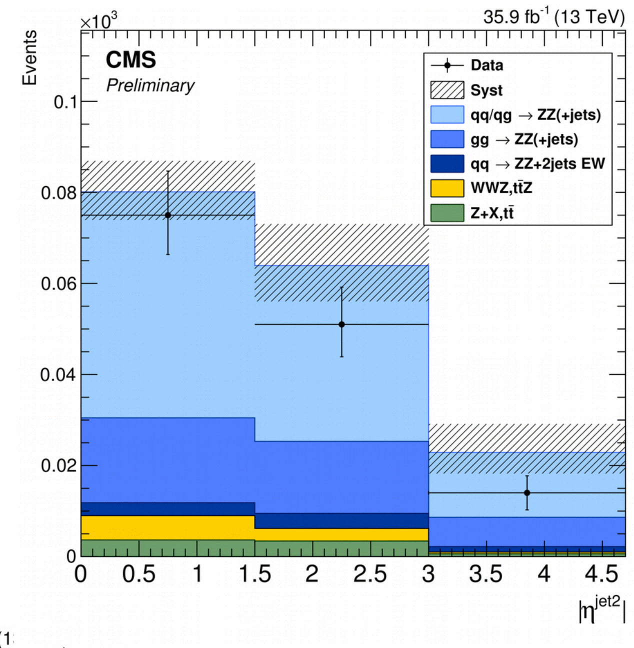
Systematic source	Absolute	Normalized
Trigger	2.0 %	-
Muon ID, ISO and Tracking	0.9 - 1.0 %	<0.1 - 0.1 %
Electron ID, ISO and Tracking	2.8 - 3.5 %	0.1 - 0.7 %
Jet energy resolution	2.1 - 8.4 %	2.1 - 8.4 %
JES correction	4.6 - 17.6 %	4.6 - 17.6 %
Reducible background	0.5 - 2.5 %	0.3 - 1.8 %
Irreducible background	<0.1 - 1.2 %	<0.1 - 1.1 %
Pileup	0.3 - 1.9 %	0.6 - 1.8 %
Luminosity	2.5 %	-
Monte Carlo choice	0.5 - 5.1 %	0.8 - 4.8 %
qq/gg cross section	<0.1 - 0.3 %	0.1 - 0.2 %
PDF	<0.1 - 0.2 %	<0.1 - 0.2 %
α_S	<0.1 - 0.1 %	<0.1 - 0.1 %

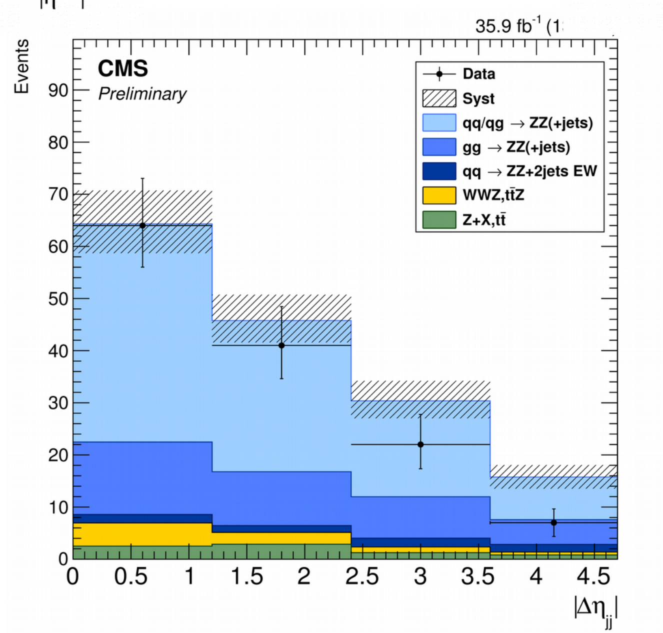
ZZ njets differential cross section



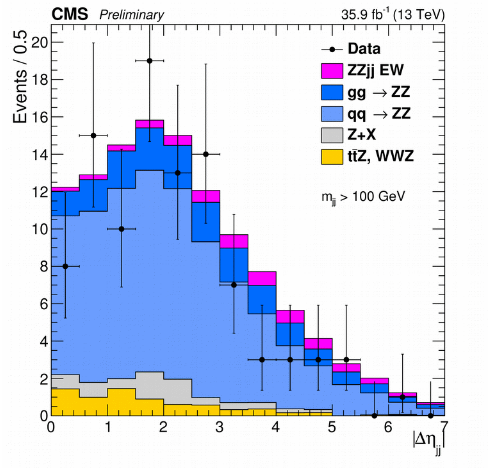
ZZ+jets, Pseudorapidity distributions

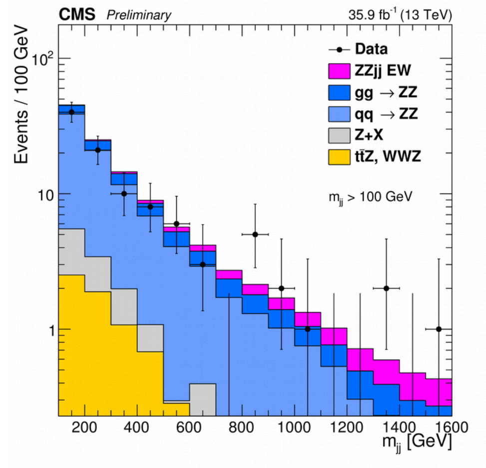


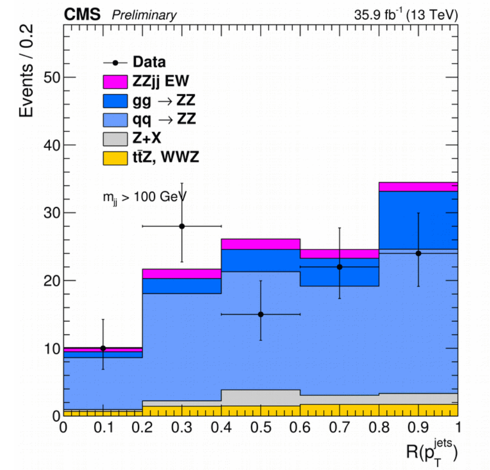




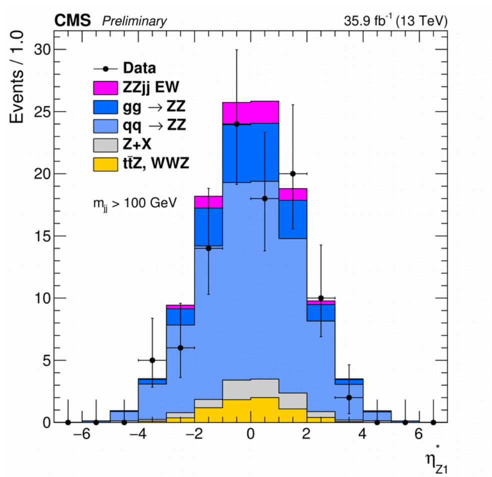
ZZ+jets MVA input variablses

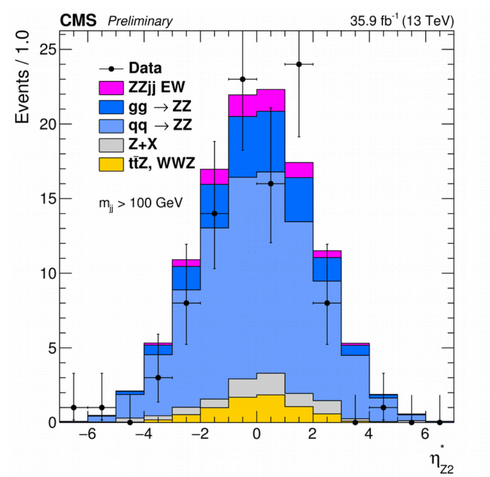


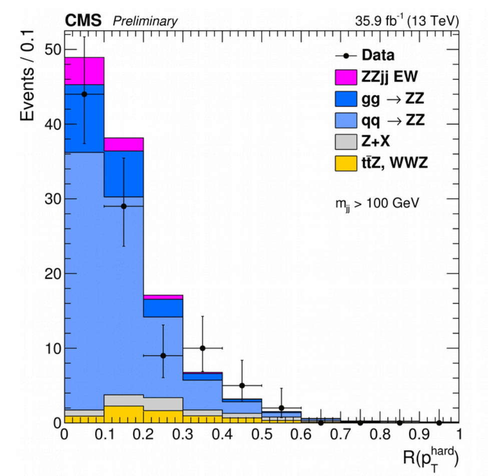




$$R(p_T^{hard})=\frac{\|\boldsymbol{p}_T^{jet\,1}+\boldsymbol{p}_T^{jet\,2}+\boldsymbol{p}_T^{Z_1}+\boldsymbol{p}_T^{Z_2}\|}{p_T^{jet\,1}+p_T^{jet\,2}+p_T^{Z_1}+p_T^{Z_2}}$$



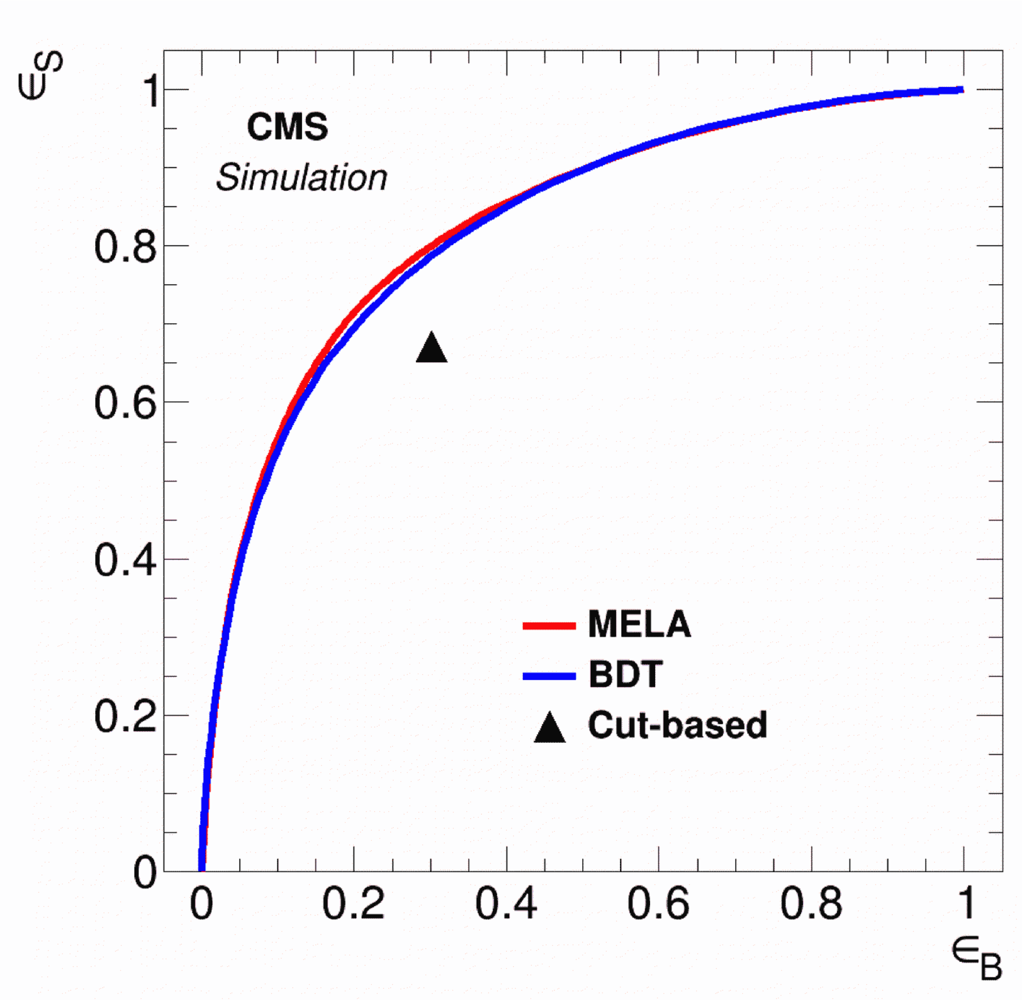




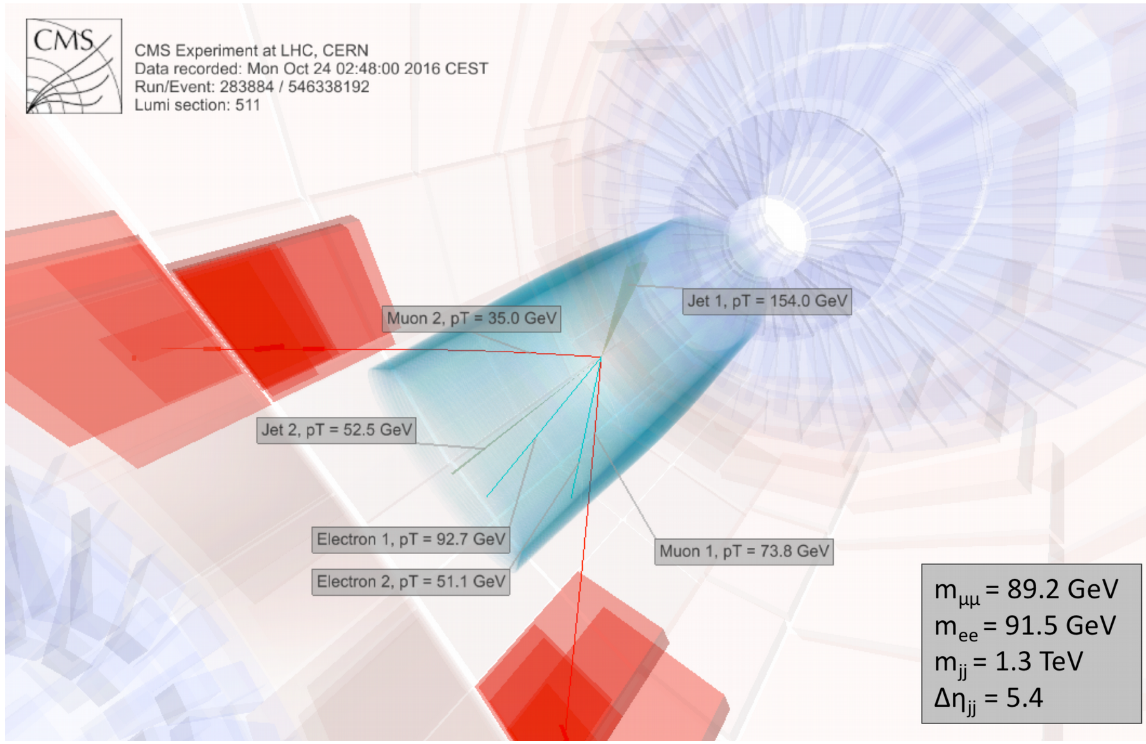
$$Z_i^*=\eta_{Z_i}-(\eta_{jet,1}+\eta_{jet,2})/2$$

$$R(p_T^{jets})=\frac{\|\boldsymbol{p}_T^{jet\,1}+\boldsymbol{p}_T^{jet\,2}\|}{p_T^{jet\,1}+p_T^{jet\,2}}$$

ZZ+jets: ROC Curve



ZZ+jets: Event Display



$m_{4\ell}$ [GeV]	m_{Z1} [GeV]	m_{Z2} [GeV]	m_{jj} [GeV]	$\|\Delta\eta_{jj}\|$	$\eta^{\star}_{Z_1}$	$\eta^{\star}_{Z_2}$	BDT score
365.8	91.4	101.1	844.1	3.4	-0.7	0.0	0.97
325.1	93.1	96.3	1332.9	5.2	0.0	-1.8	0.98
263.8	91.9	88.0	829.7	2.2	-0.5	1.1	0.94
562.8	93.7	88.0	947.3	2.8	0.6	0.6	0.93
248.8	91.5	89.2	1340.9	5.4	-0.5	0.2	0.98
375.2	89.4	98.5	1052.5	3.8	0.7	-0.2	0.96
482.1	95.0	95.6	1543.1	4.8	-1.6	2.5	0.99

ZZ+jets: aQGC Limits

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

ssWW+jets Complete Cut List

Search region

- **Two same charge lepton** (μ, e) with $p_{T,1(2)}$ > 25 (20) GeV, $|\eta|$ < 2.4 (2.5), m_{ll} > 20 GeV
- **Veto events with additional leptons** if p_T of a 3rd loosely ID lepton is > 10 GeV or the p_T of an identified τ (to hadrons) is > 18 GeV
- **Two jets** (anti-k_T 0.4) with p_T > 30 GeV, $|\eta|$ < 5 leading jets taken as tagging jets, m_{jj} > 500 GeV, $|\Delta\eta_{jj}|$>2.5, max (z_l*) < 0.75 $Z_i^* = |\eta_l - (\eta_{jet,1} + \eta_{jet,2})/2| / |\Delta\eta_{jj}|$
- E_T^{miss} > 40 GeV, $Z \rightarrow e^+e^-$ veto (requiring $|m_{ll} - m_Z|$ > 15 GeV), anti b-tag, m_{ll} > 20 GeV

Fiducial region

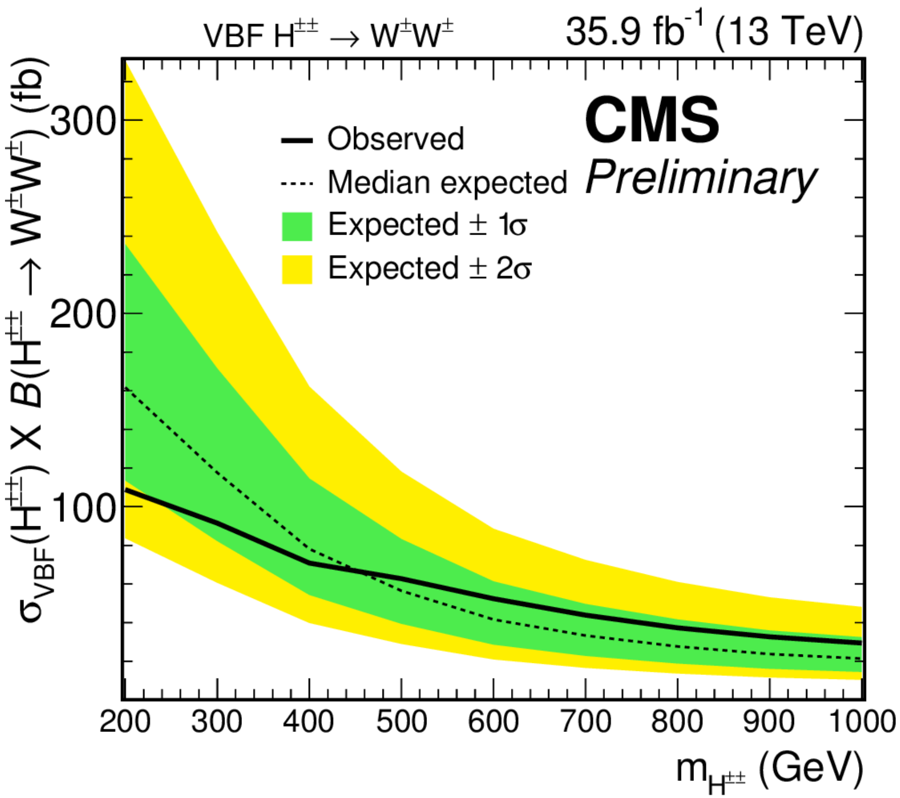
- p_T > 20 GeV, $|\eta|$ < 2.5, for both leptons
- p_T > 30 GeV, $|\eta|$ < 5 for the two leading jets and m_{jj} > 500 GeV, $|\Delta\eta_{jj}|$>2.5
- Taus decay into leptons are excluded from this definition

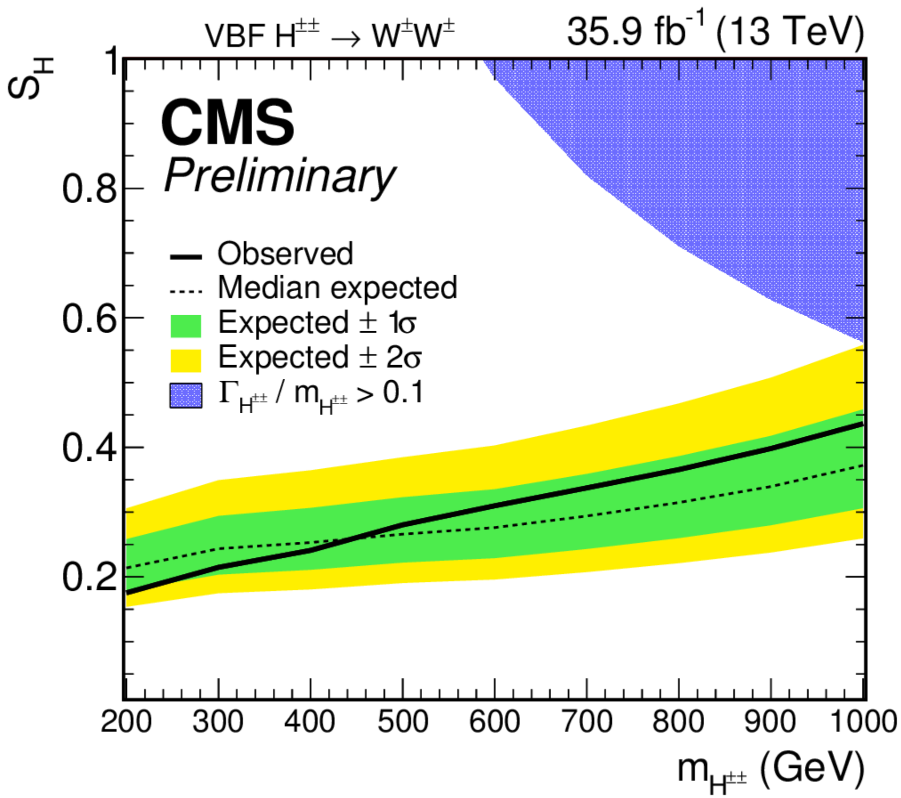
- Fiducial region
- p_T > 20 GeV, $|\eta| < 2.5$, for both leptons
- p_T > 30 GeV, $|\eta| < 5$ for the two leading jets and m_{jj} > 500 GeV, $|\Delta\eta_{jj}|>2.5$
- Taus decay into leptons are excluded from this definition

ssWW+jets: Yields

	$\mu^+\mu^+$	e^+e^+	$e^+\mu^+$	$\mu^-\mu^-$	e^-e^-	$e^-\mu^-$	Total
Data	40	14	63	26	10	48	201
Signal+Total bkg.	44.1 ± 3.4	19.0 ± 1.9	67.6 ± 3.8	23.9 ± 2.8	11.8 ± 1.8	38.9 ± 3.3	204.8 ± 7.2
Signal	18.3 ± 0.4	6.2 ± 0.2	24.7 ± 0.4	6.5 ± 0.2	2.5 ± 0.1	8.7 ± 0.2	66.9 ± 0.7
Total bkg.	25.7 ± 3.4	12.8 ± 1.9	42.9 ± 3.8	17.4 ± 2.8	9.4 ± 1.8	30.2 ± 3.3	137.9 ± 7.1
Non-prompt	18.4 ± 3.3	5.6 ± 1.7	24.9 ± 3.6	14.2 ± 2.8	5.0 ± 1.6	19.9 ± 3.2	87.9 ± 6.9
WZ	4.4 ± 0.2	3.0 ± 0.2	8.5 ± 0.3	2.2 ± 0.1	1.9 ± 0.2	5.2 ± 0.3	25.1 ± 0.6
QCD WW	1.3 ± 0.1	0.6 ± 0.1	1.7 ± 0.1	0.4 ± 0.1	0.2 ± 0.1	0.6 ± 0.1	4.8 ± 0.2
Wγ	0.2 ± 0.2	1.4 ± 0.5	3.6 ± 0.9	-	0.8 ± 0.4	2.3 ± 0.7	8.3 ± 1.3
Triboson	1.2 ± 0.3	0.8 ± 0.2	2.2 ± 0.4	0.5 ± 0.2	0.3 ± 0.1	0.9 ± 0.3	5.8 ± 0.7
Wrong sign	-	1.5 ± 0.6	1.4 ± 0.4	-	1.1 ± 0.5	1.2 ± 0.4	5.2 ± 1.0

ssWW+jets: charged Higgs limits





ssWW+jets: aQGC limits

	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] [?]
f_{S1}/Λ	[-21.6,21.8]	[-19.9,20.2]	[-118 , 120] [?]
f_{M0}/Λ	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6 , 4.6] [?]
f_{M1}/Λ	[-8.7 ,9.1]	[-7.9, 8.5]	[-17 , 17] [?]
f_{M6}/Λ	[-11.9,11.8]	[-11.1,11.0]	[-65 , 63] [?]
f_{M7}/Λ	[-13.3,12.9]	[-12.4,11.8]	[-70 , 66] [?]
f_{T0}/Λ	[-0.62,0.65]	[-0.58,0.61]	[-3.8 , 3.4] [?]
f_{T1}/Λ	[-0.28,0.31]	[-0.26,0.29]	[-1.9 , 2.2] [?]
f_{T2}/Λ	[-0.89,1.02]	[-0.80,0.95]	[-5.2 , 6.4] [?]

Other WW Production Analyses

- CMS made two beautiful analyses aiming to observe the **first evidence of $W^{\pm}W^{\pm}jj$** produced via **Electroweak** processes at 8 TeV
  - CMS: 114 (2015) 051801
- Production of **WW via photon-photon scattering** at 7 and 8 TeV
  - CMS: JHEP 07 (2013) 116, JHEP 08 (2016) 119

Why VV Scattering

In the symmetry breaking (EWSB) mechanism the **W** and **Z** bosons get their **masses** and acquire a **longitudinal degree of polarization**.

The mechanism responsible for the EWSB has to **regulate the $V_L V_L \rightarrow V_L V_L$ cross section** such that the unitarity is preserved above $m_{VV} \sim$ 1-2 TeV

VV scattering is the key process to probe EWSB and high energy vector boson scattering will play a central role:

- both as a **test of the Higgs boson nature**
  - If the discovered Higgs boson contributes **fully to the EWSB**, then most probably the interaction among longitudinal weak bosons would remain ***weak*** at high energy
- and as a **model independent research** of alternative theory to explain EWSB
  - if the 125.5 GeV Higgs boson is only **partially responsible for the EWSB**, then the VV interaction could get ***strong*** at high energy.
- Also **TGC** and **QGC** processes may carry **new physics phenomena**

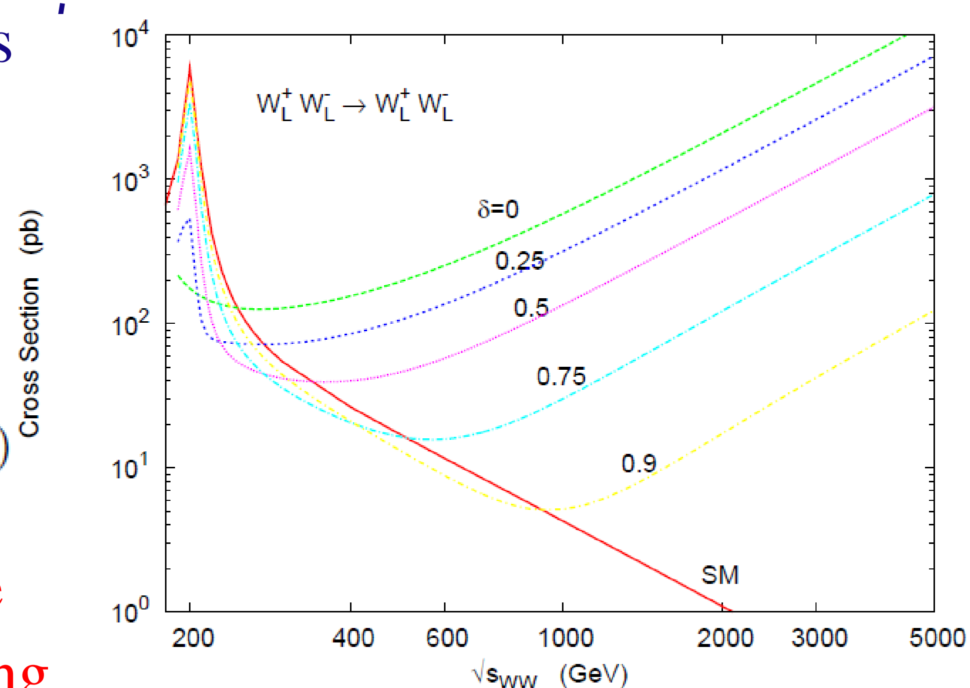
The Higgs Job

- If the cancellation of the **Higgs diagrams is not complete**, then we expect a **g_{HWW} coupling smaller than the SM**.
- The **$W_L W_L$ will keep growing with √s**, up to the the new resonance, or more generally to the **new physics scale Λ**.
- Suppose the Higgs-WW coupling is ' amplitudes become

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

$$i\mathcal{M}^{\text{higgs}} = i\frac{g^2}{4m_W^2}\, u\,\delta + \mathcal{O}((E/m_W)^0)$$

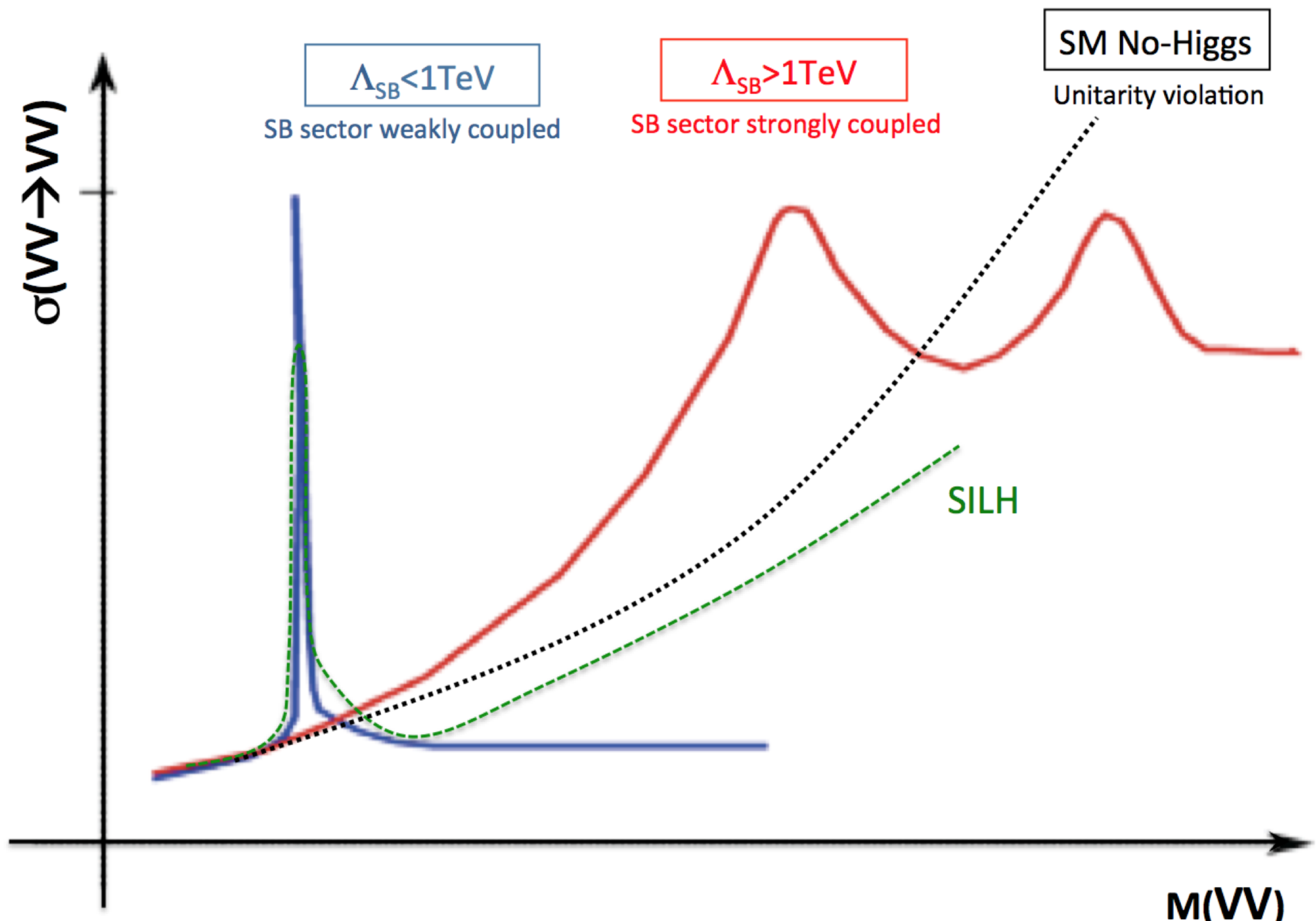
$$i\mathcal{M}^{\text{all}} = -i\frac{g^2}{4m_W^2}\, u(1-\delta) + \mathcal{O}((E/m_W)^0)$$



Cheung, Chiang, Yuan

Measure with high precision both the HVV coupling and the $V_L V_L$ scattering

VV Scattering to test the EWSB



$$g_h \rightarrow g_h / \sqrt{1+\xi c_H}, \xi = v^2 / f^2$$

SILH :

Higgs a pseudo Goldstone Boson of a new strong sector

Both a light Higgs and Bosons strongly coupled

Modified higgs coupling $h \longrightarrow h/\sqrt{1+\xi c_H},\ \xi = v^2/f^2$

SILH Giudice et al arXiv:hep-ph/0703164v2

Anomalous Quartic Gauge Couplings Modelling

- Extension of the SM Lagrangian by introducing additional **dimension-8 (or 6) operators**:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \ldots$$

desideratum: $\Lambda \sim$ 1-2 TeV

- **Effective field theory** is useful as a methodology for studying possible new physics effects from massive particles that are **not directly detectable**.
  - Underlying assumption: scale **Λ is large compared with the experimentally-accessible energy**
  - These operators have **coefficients of inverse powers of mass** (Λ), and hence are suppressed if this mass is large compared with the experimentally-accessible energy
  - **Limit**: Λ so large that the effect is comparable to missing higher order corrections from SM
  - An effective field theory is the **low-energy approximation of the new physics**
- coefficients in **dimension-6** (i.e. c_i/Λ^2) (e.g., hep-ph/9908254), **may affects 3 boson vertices too**:
  - **$C_{\varphi W}/\Lambda^2$ (VBFNLO), a_0^W/Λ^2, a_C^W/Λ^2 (CALCHEP)…**
- coefficients in **dimension-8** (i.e. c_i/Λ^4) (e.g., hep-ph/0606118), **modifies 4 boson vertices only**:
  - **$f_{S,0}/\Lambda^4$, $f_{T,0}/\Lambda^4$…**

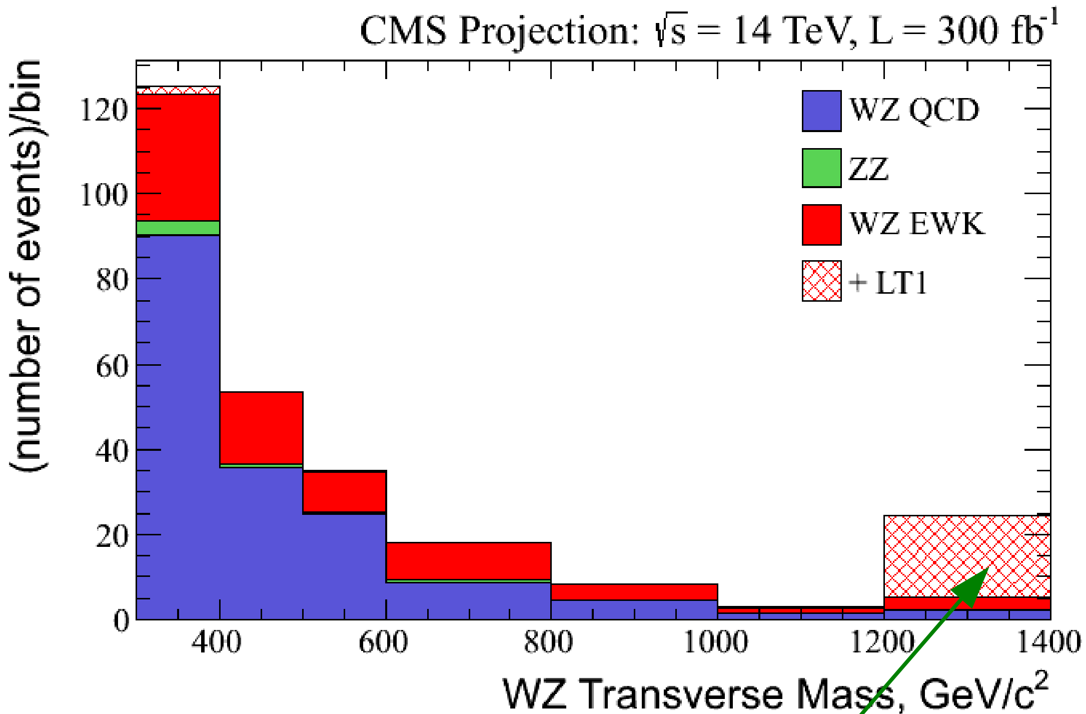
Future Projections

- Several final states investigated by both Collaborations (ATLAS-PHYS-PUB-2013-006 and CMS-PAS-FTR-13-006) for **$\sqrt{s}$ = 14 TeV** and two luminosity scenarios, **300 fb^{-1}** and **3000 fb^{-1}**:
  - $pp \rightarrow ZZqq \rightarrow 4ljj$ (VBS)
  - $pp \rightarrow WZqq \rightarrow 3l\nu jj$ (VBS)
  - $pp \rightarrow W^{\pm}W^{\pm}qq \rightarrow l^{\pm}\nu l^{\pm}\nu jj$ (VBS)
  - $pp \rightarrow Z\gamma\gamma \rightarrow ll\gamma\gamma$ (QGC)
- Results interpreted in terms of **Effective Lagrangian**, to estimate the sensitivity to new physics.

pp → WZqq → 3lνjj - VBS @ 14 TeV

CMS-PAS-FTR-13-006

- 300 fb^{-1} (*Phase 1*) with **50 pile-up** event and **current detector**
- 3000 fb^{-1} (*Phase 2*) with **140 pile-up** events and with the **detector upgrade** (new tracker and Ecal, mu-detection down to η < 4)
- **Typical VBF/VBS cuts**:
  - Lepton p_T > 20 GeV, jet p_T > 50 GeV, $\Delta\eta(j,j) > 4$, $M(jj) > 600$ GeV



Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1} f_{T1}/Λ^4 at 3000 fb^{-1}	0.8 TeV^{-4} 0.45 TeV^{-4}	1.0 TeV^{-4} 0.55 TeV^{-4}

Additional contribution from aQGC with $f_{T1}/\Lambda^4 = 1\ TeV^{-4}$.

Final States and their Cross-sections

- Needs to simulate all $2 \rightarrow 6$ processes at least at the order $\mathcal{O}(\alpha_{EW}{}^6)$
- **Large interference** among same order diagrams
- **Signal has to be defined a posteriori**, using kinematic cuts

arXiv:0801.3359

- Cross Sections for $\sqrt{s}$ = 14 TeV from Phantom Monte Carlo Generator:

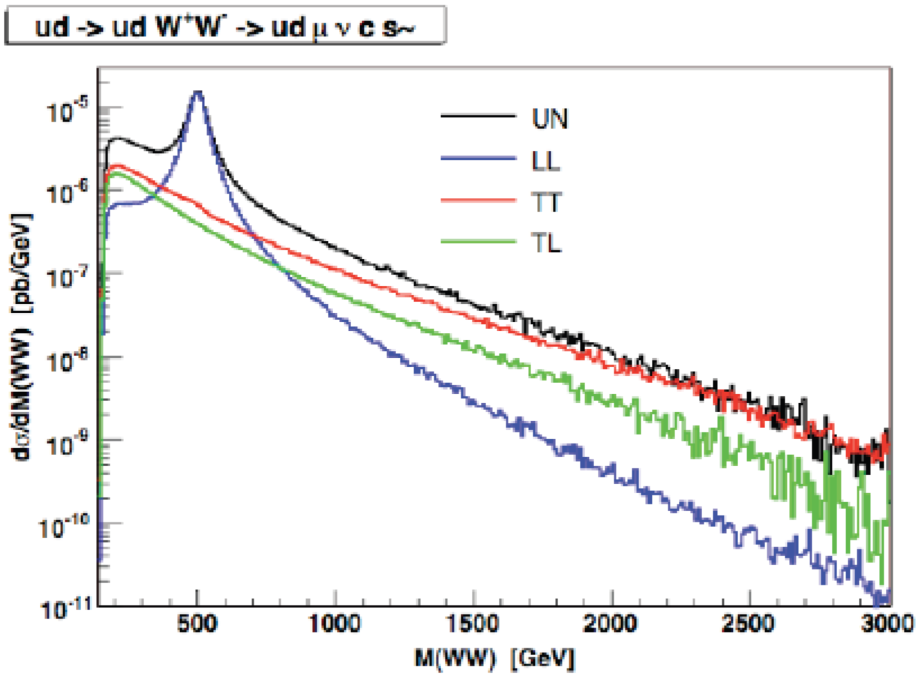
full simulation of $2 \rightarrow 6$ @ $\mathcal{O}(\alpha_{EW}{}^6) + \mathcal{O}(\alpha_{EW}{}^4\alpha_{QCD}{}^2)$

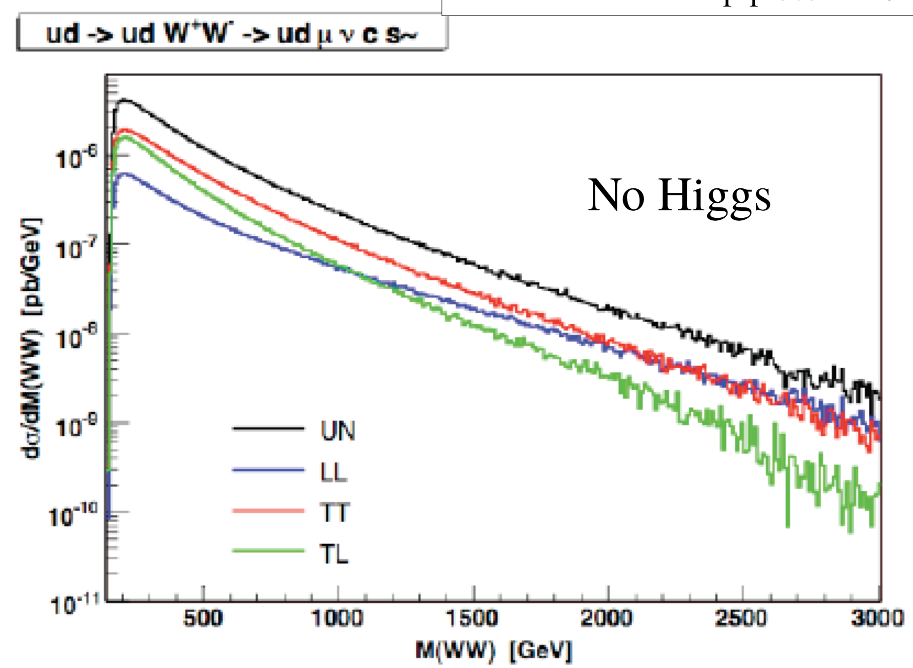
	$qqqq\mu\nu/e\nu$				$qqqq\mu\mu/ee$			
	no-Higgs		500 GeV		no-Higgs		500 GeV	
	σ (pb)	perc.	σ (pb)	perc.	σ (pb)	perc.	σ (pb)	perc.
total	0.689	100%	0.718	100%	0.0305	100%	0.0350	100%
signal	0.158	23%	0.184	26%	0.0125	41%	0.0165	47%
top	0.495	72%	0.494	69%	0.0137	45%	0.0137	39%
non resonant	0.020	3%	0.023	3%	0.0030	10%	0.0035	10%
three bosons	0.016	2%	0.017	2%	0.0012	4%	0.0014	4%

	$qq\mu\mu\mu\mu/eeee$				$qq\mu\mu\mu\nu$				$qq\mu^{\pm}\nu\mu^{\pm}\nu$			
	no-Higgs		500 GeV		no-Higgs		500 GeV		no-Higgs		500 GeV	
	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.
total	0.180	100%	0.310	100%	4.182	100%	4.152	100%	4.29	100%	4.16	100%
signal	0.120	66.4%	0.229	74.1%	1.317	31.5%	1.281	30.8%	3.26	76%	3.11	75%
top	0	0%	0	0%	1.817	43.5%	1.828	44.01%	0	0%	0	0%
non resonant	0.0364	20.2%	0.0533	17.2%	0.673	16.1%	0.651	15.7%	0.47	11%	0.46	11%
three bosons	0.0241	13.4%	0.0268	8.66%	0.375	8.9%	0.392	9.5%	0.56	13%	0.58	14%

Scattering of Polarized Vector Bosons

Accomando et al: hep-ph/0512219



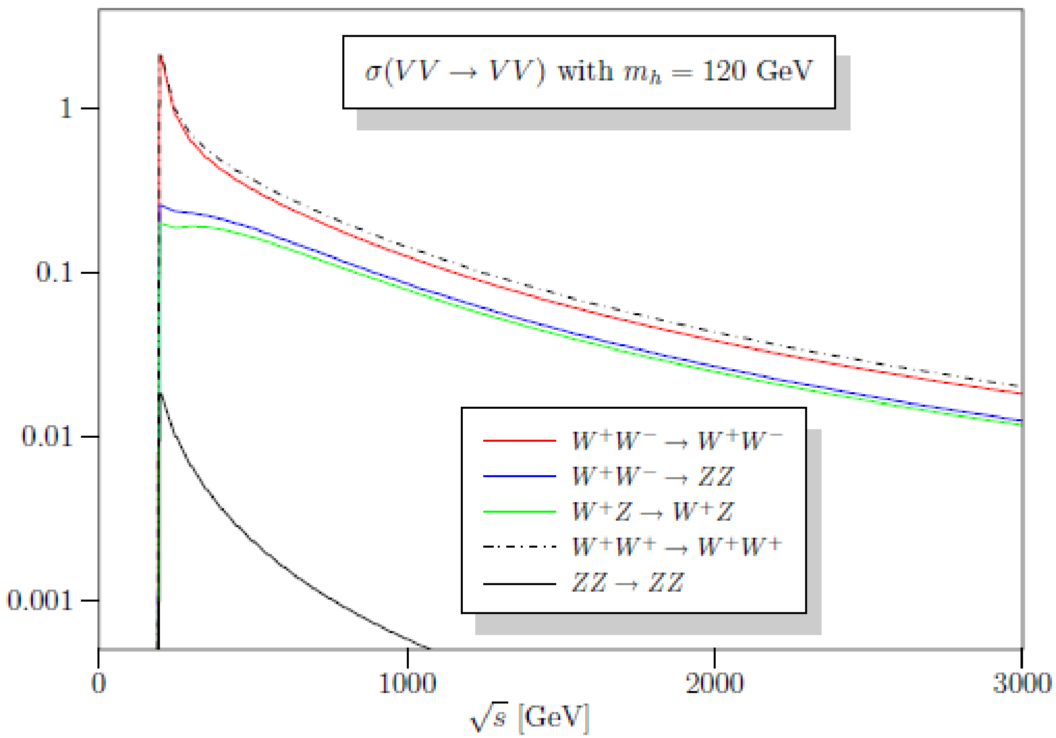


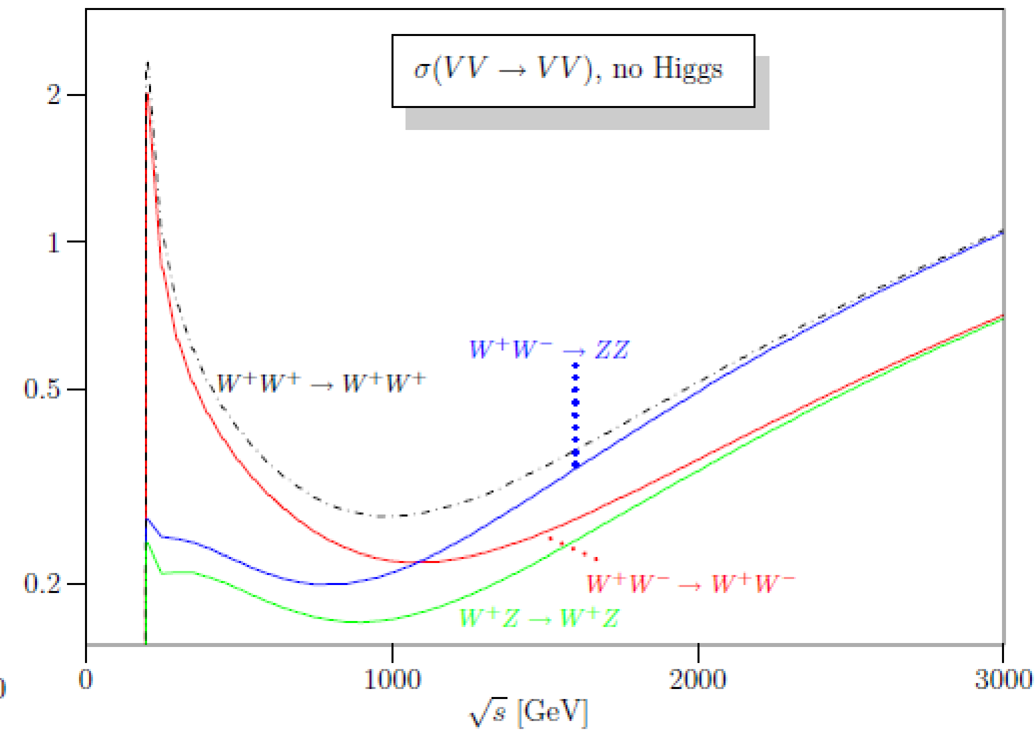
- The VL are coupled to the Higgs and they are the ones sensitive to the EWSB.
- The behavior of the LL cross section only can give information on the scale at which the symmetry breaks.
- At large M(VV) the TT cross section is of the same order as the LL (in the no-Higgs case)

If there is a new resonance at a scale L, the LL cross section will not decrease until L.

□ Experimentally we should enhance LL wrt TT and measure XS at the highest M(VV)

- The cross section decreases rapidly at high invariant masses due to PDF – Hard life for LHC @14 TeV !
- The invariant VV mass is the equivalent of the CM energy of the elastic VV scattering





arxiv:0806.4145