VBS/VBF results from CMS

Mariarosaria D'Alfonso
Massachusetts Institute of Technology

on behalf of the CMS collaborations

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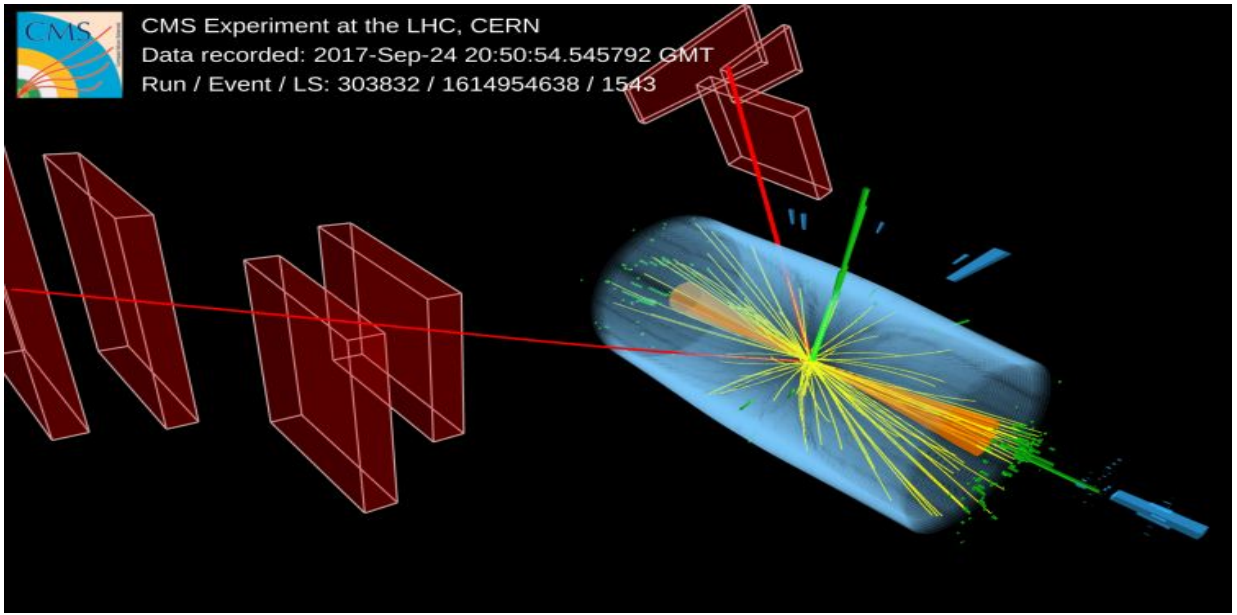
VBS Motivation

The unitarization of the longitudinal Vector Boson Scattering (VBS) cross section by the Higgs boson is a fundamental prediction of the SM which has not been experimentally verified yet.



Two high energetic forward-backward jets, with two central bosons

SMP-19-012

$W Z jj \rightarrow 3\ell jj$

VBS Signatures

Diboson pair production via VBS at 13TeV being observed:

Very rare processes, cross sections typically ~ few fb

137 /fb

$W^{+/-}W^{+/-}jj \rightarrow 2\ell\, jj$: SMP-19-012

best EWK vs QCD ratio

$W\,Z\,jj \rightarrow 3\ell\, jj$: SMP-19-012

$Z\,Z\,jj \rightarrow 4\ell\, jj$: SMP-20-001 *new*

clean final state, small BR, large contamination from $gg \rightarrow ZZjj4ljj$

36 /fb

$Z\gamma\, jj \rightarrow 2\ell\, \gamma\, jj$: SMP-18-007

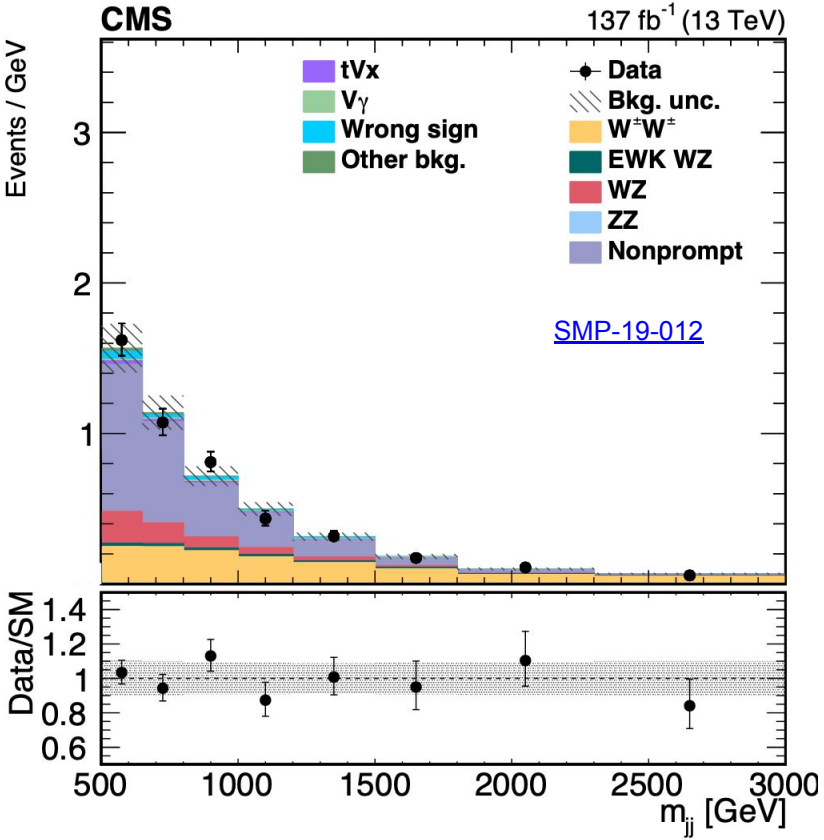
$W\gamma\, jj \rightarrow \ell\, \gamma\, jj$: SMP-19-008 *new*

$WV\, jj \rightarrow \ell\, jj\, jj + ZV\, jj \rightarrow \ell\ell\, jj\, jj$: SMP-18-006

Challenges:

- *Dominant experimental uncertainty: jet energy scale from forward jets*
- *Monte Carlo simulations critical to VBS measurements: rely on differential predictions for EW/QCD separation*

$W^{+/-}W^{+/-}$



Same sign lepton signature

EWK Signal generated at LO with MadGraph5

Background divided in two classes:

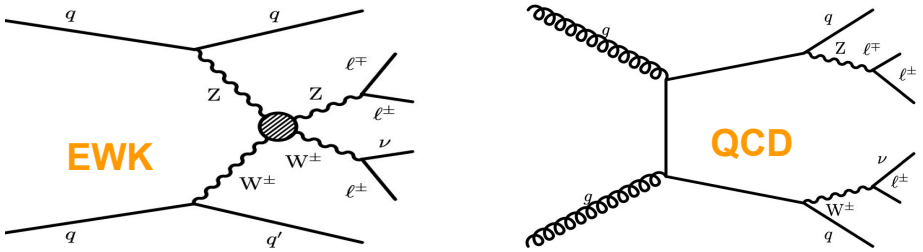
- ➢ Non prompt / Fakes from data CR
- ➢ Prompt irreducible from MC:
  - measured in the CR with ZZ and tZq

WZ signal vs Background

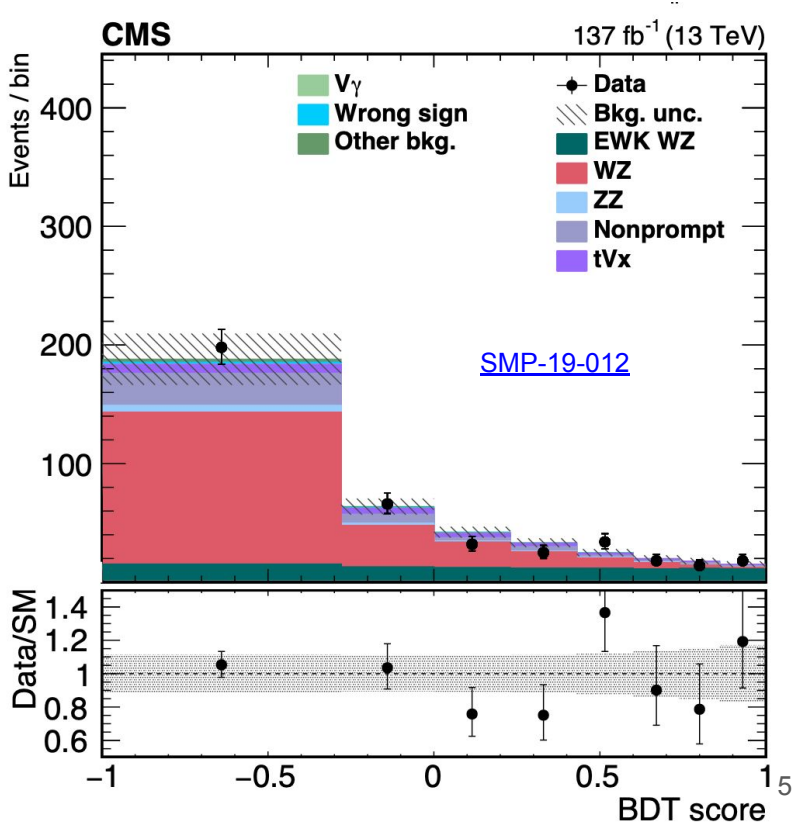
Three leptons final state

Larger QCD induced background:

→ BDT discriminant to isolate the EWK signal



Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\lvert\Delta\eta_{jj}\rvert$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{jj}$	Absolute difference in azimuthal angles of the leading and trailing jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the trailing jet
η^{j1}	Pseudorapidity of the leading jet
$\lvert\eta^W - \eta^Z\rvert$	Absolute difference between the rapidities of the Z boson and the charged lepton from the decay of the W boson
$z^*_{\ell_i}(i = 1-3)$	Zeppenfeld variable of the three selected leptons
$z^*_{3\ell}$	Zeppenfeld variable of the vector sum of the three leptons
$\Delta R_{j1,Z}$	ΔR between the leading jet and the Z boson
$\lvert\vec{p}_T^{\,tot}\rvert / \Sigma_i p_T^i$	Transverse component of the vector sum of the bosons and tagging jets momenta, normalized to their scalar p_T sum



Results $W^{+/-}W^{+/-}$ and WZ

Extract signal strength from binned maximum-likelihood fit:

- WW and WZ measurement made simultaneously
- Simultaneous fit of several regions so that signal and main background are measured at the same time.

Inclusive cross sections

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

Theoretical uncertainties include statistical, PDF, and scale uncertainties.

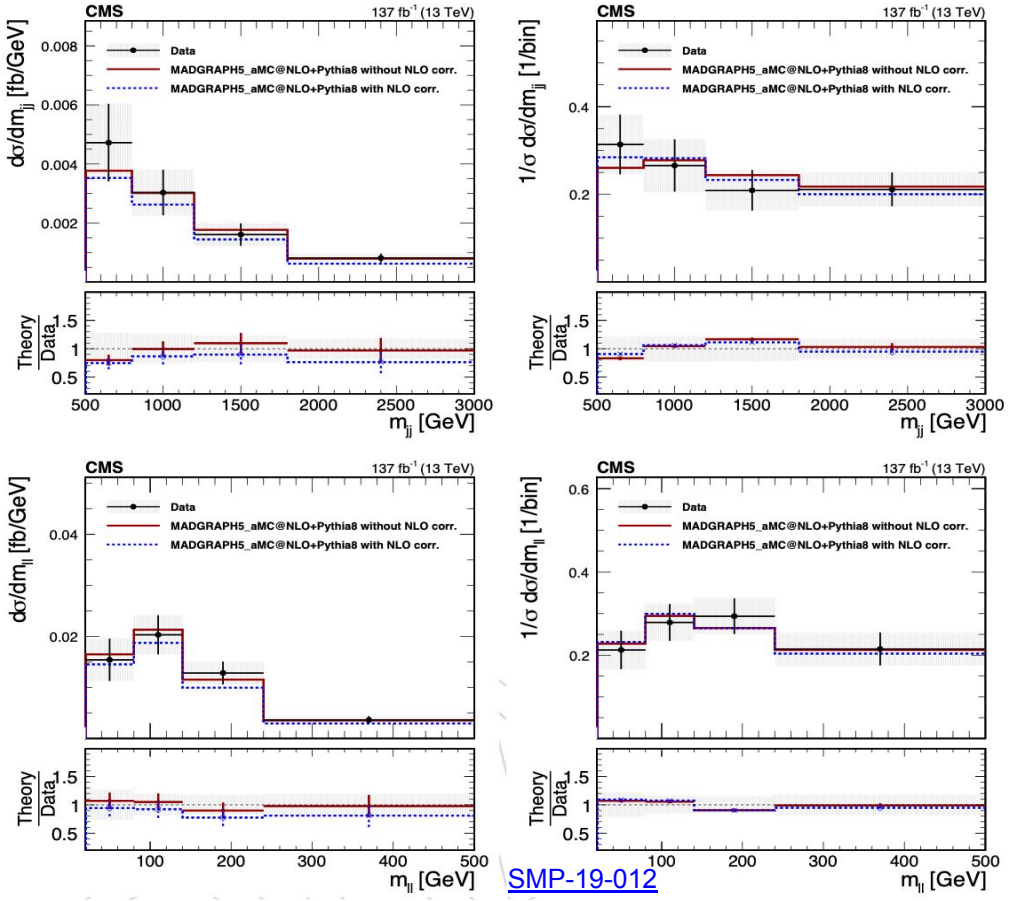
Electroweak production of WZ boson pairs:
observed (expected) significance of 6.8 (5.3) σ

Statistics limited,
expect continued progress in future.

From observation to Measurement.

absolute

normalized

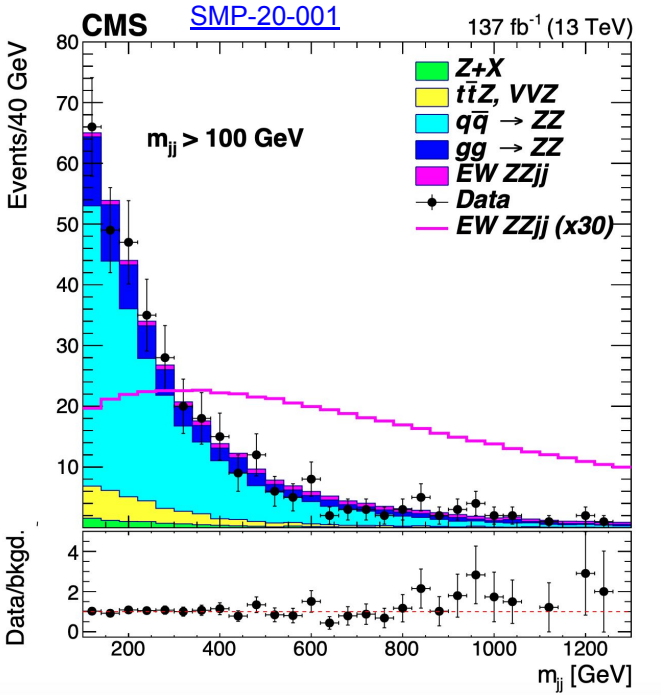


SMP-19-012

Test of NLO corrections

ZZ

4-leptons final state

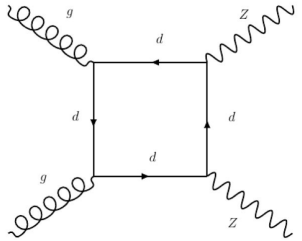


EWK signal:

VBS LO vs triboson (ZZW and ZZZ) NLO

ggZZ simulation:

QCD ggZZ + 0/1/2 jets at LO with MG5_aMC@NLO + MLM matching to include the box diagrams



Irreducible BKG From MC: qqbarZZ , ggZZ , ttbar Z, WWZ, WZZ, ZZZ

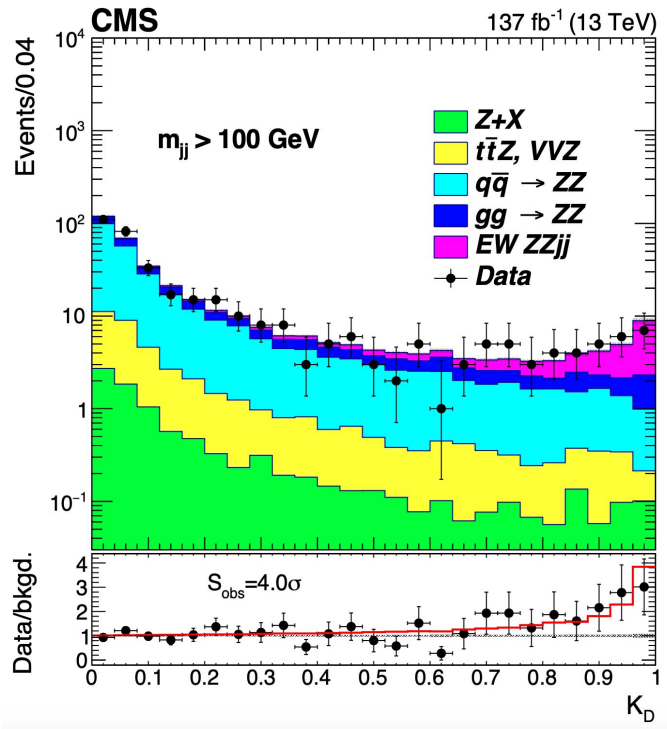
Irreducible Z+X : from fake rate method

Results ZZ

Using the matrix-element discriminant (MELA) to extract the signal

SMP-20-001

	μ_{exp}	SM σ (fb)	μ_{obs}	Measured σ (fb)
		ZZjj baseline		
EWK	$1.00\ ^{+0.43}_{-0.36}\ (^{+0.39}_{-0.34})$	$0.275 \pm 0.021_{\text{th.}}$	$1.22\ ^{+0.47}_{-0.40}$	$0.33\ ^{+0.11}_{-0.10\,\text{stat.}}\ ^{+0.04}_{-0.03\,\text{syst.}}$
EWK+QCD	$1.00\ ^{+0.13}_{-0.12}\ (\pm 0.06)$	$5.35 \pm 0.51_{\text{th.}}$	$0.99\ ^{+0.13}_{-0.12}$	$5.29\ ^{+0.31}_{-0.30\,\text{stat.}} \pm 0.46_{\text{syst.}}$
		VBS-enriched (loose)		
EWK	$1.00\ ^{+0.45}_{-0.38}\ (^{+0.40}_{-0.35})$	$0.186 \pm 0.015_{\text{th.}}$	$1.08\ ^{+0.47}_{-0.38}$	$0.200\ ^{+0.078}_{-0.067\,\text{stat.}}\ ^{+0.023}_{-0.013\,\text{syst.}}$
EWK+QCD	$1.00\ ^{+0.16}_{-0.15}\ (^{+0.13}_{-0.12})$	$1.21 \pm 0.09_{\text{th.}}$	$0.83\ ^{+0.15}_{-0.13}$	$1.00\ ^{+0.12}_{-0.11\,\text{stat.}}\ ^{+0.06}_{-0.05\,\text{syst.}}$
		VBS-enriched (tight)		
EWK	$1.00\ ^{+0.87}_{-0.65}\ (^{+0.82}_{-0.64})$	$0.050 \pm 0.005_{\text{th.}}$	$1.21\ ^{+0.91}_{-0.68}$	$0.06\ ^{+0.05}_{-0.04\,\text{stat.}} \pm 0.01_{\text{syst.}}$
EWK+QCD	$1.00\ ^{+0.29}_{-0.24}\ (^{+0.27}_{-0.23})$	$0.171 \pm 0.012_{\text{th.}}$	$0.98\ ^{+0.29}_{-0.24}$	$0.17 \pm 0.04_{\text{stat.}} \pm 0.01_{\text{syst.}}$



4.0 observed (3.5 expected)

→ evidence for EWK production!

Statistics limited, expect continued progress in future.

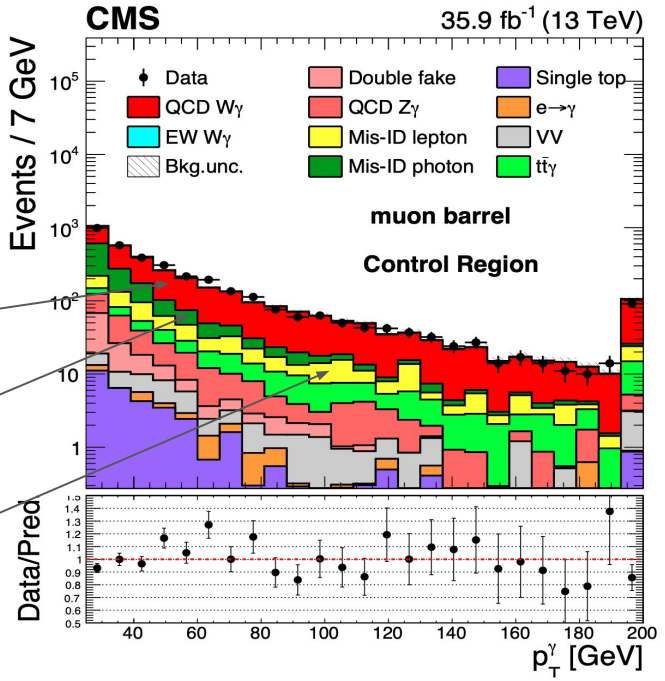
Wγ

p_T γ >25 GeV

W candidate:

- Exactly one central electron (muon) with pT > 30 GeV
- P_T^{miss} > 30 GeV
- Transverse mass of the W boson m_T (W) > 30 GeV

SMP-19-008



Major backgrounds in the SR

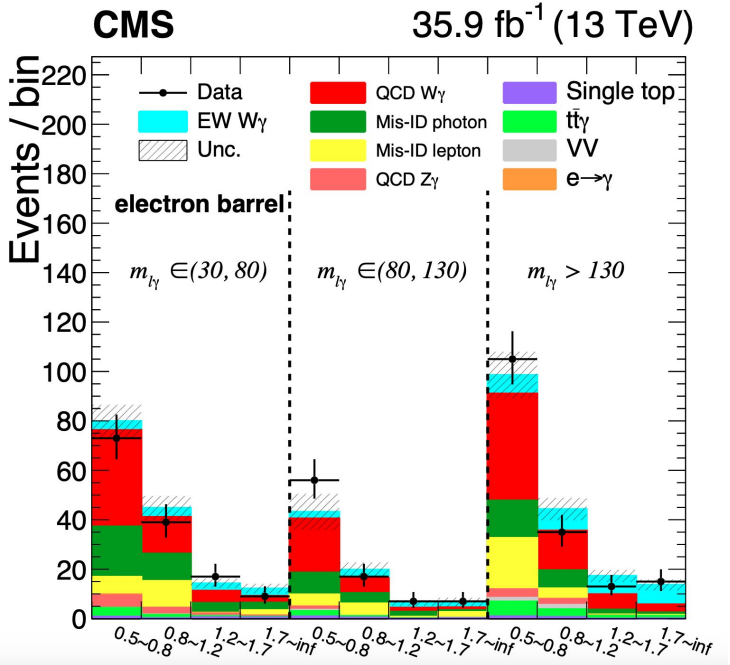
Simulation

Template fit method, data-driven

From fake rates and "Tight+Loose" "Loose+Loose" data events

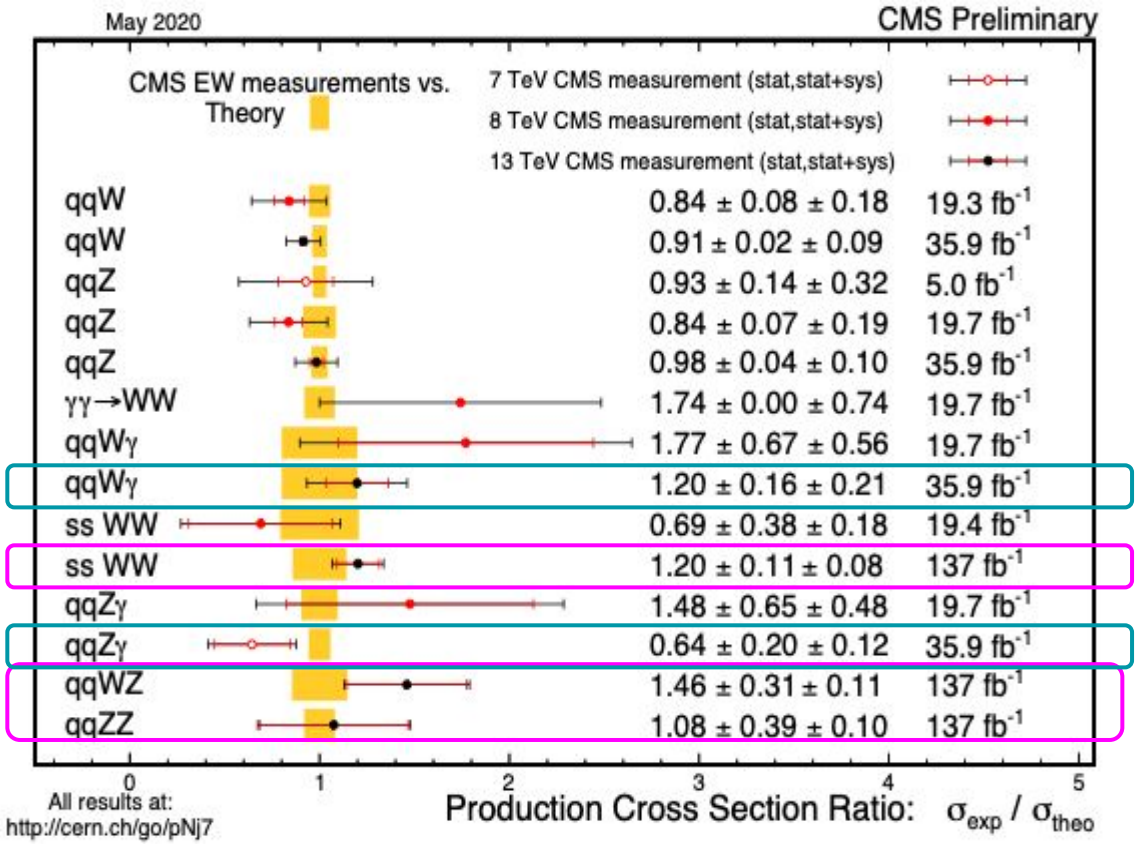
Results Wγ

Fiducial cross section is extracted using the *m* jj - *m* lγ



After combining with previously reported CMS results based on 8 TeV data, the observed (expected) signal significance is 5.3 (4.8) σ.

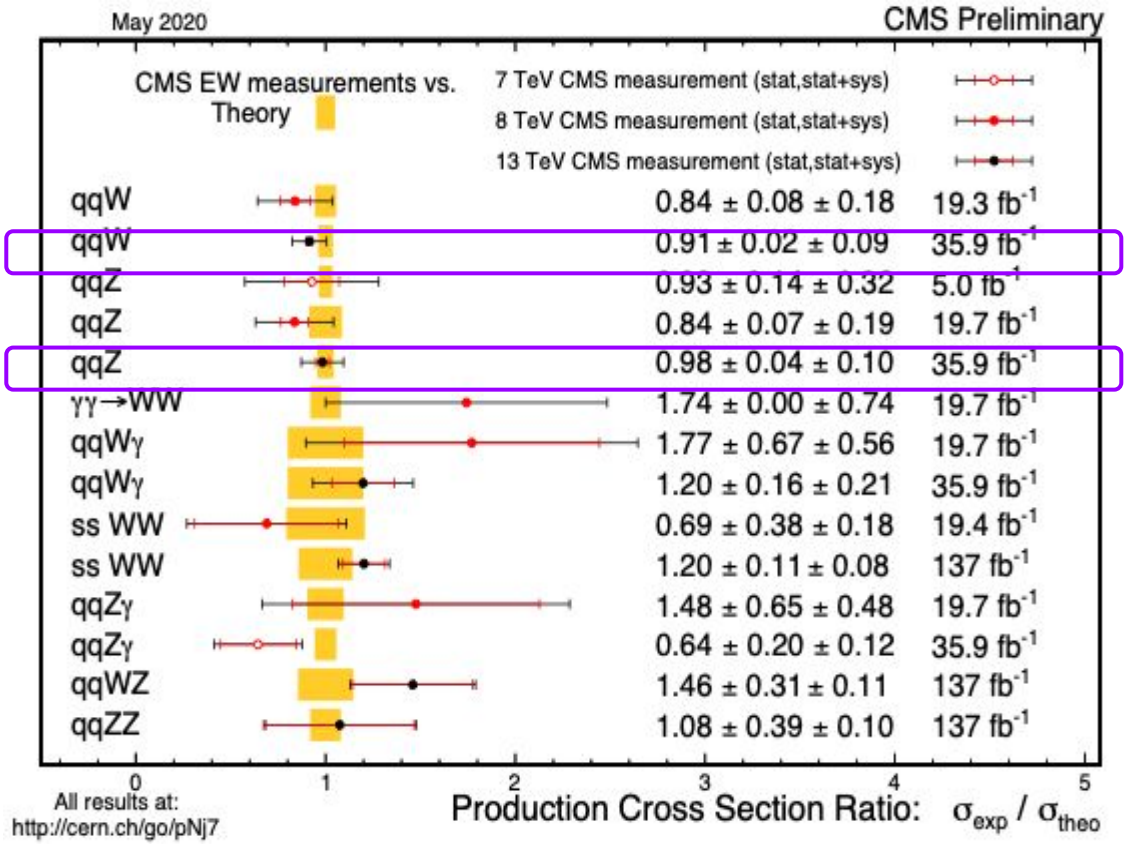
Test of the electroweak sector

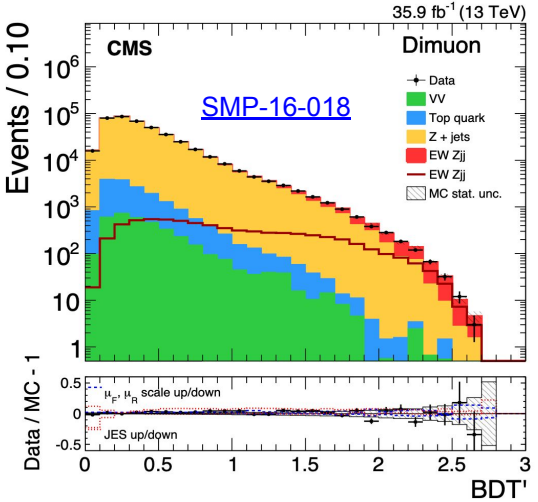


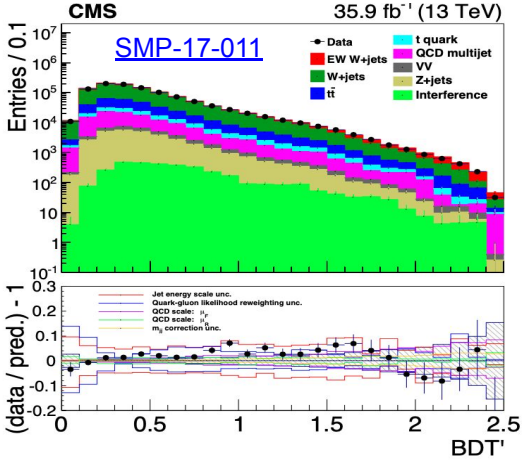
Summary of the cross sections of pure Electroweak (EWK) interactions among the gauge bosons presented as a ratio compared to theory.

Improvement on the EWK measurement, *no significant deviation from the SM*.

VBF production







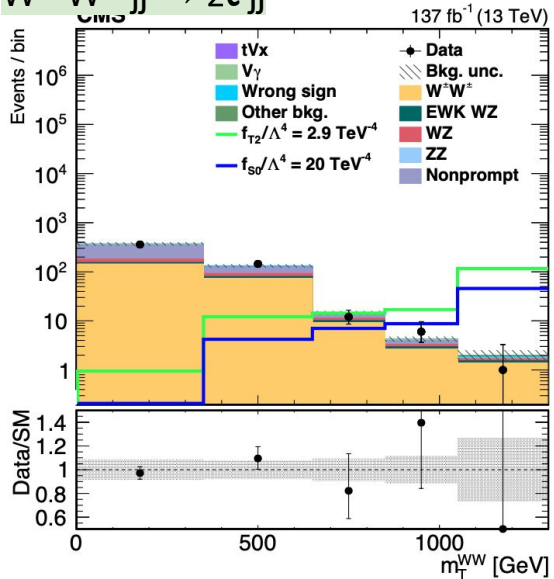
Important “standard candle” for VBF Higgs

Anomalous Quartic Gauge Coupling

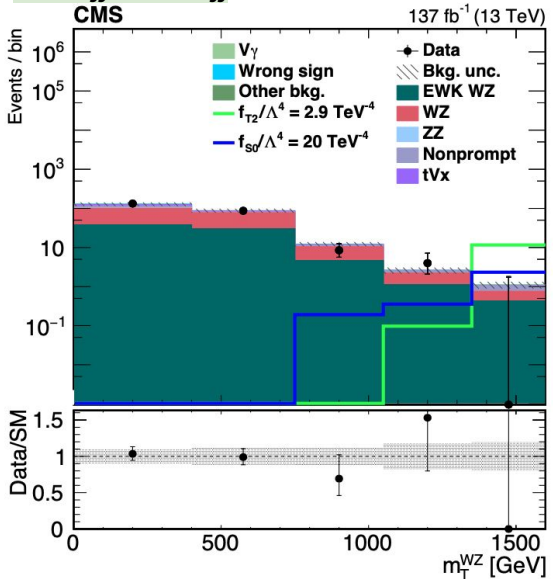
Modification of the SM lagrangian with additional dimension-8 operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^4} \mathcal{O}_i$$

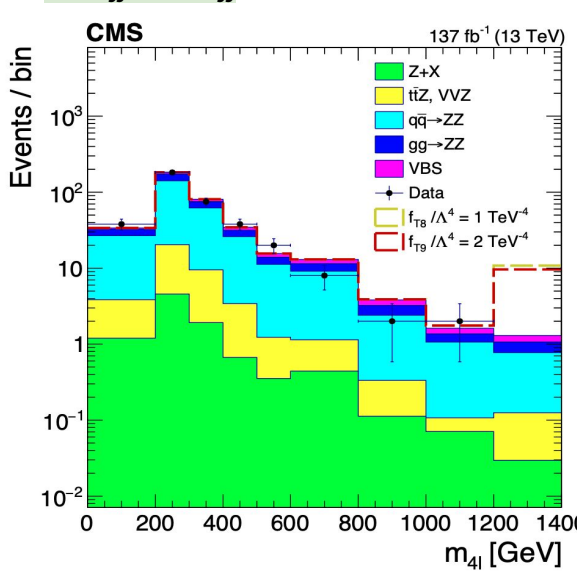
$W^{+/-}W^{+/-}jj \rightarrow 2\ell jj$ SMP-19-012



W Z jj → 3ℓ jj SMP-19-012



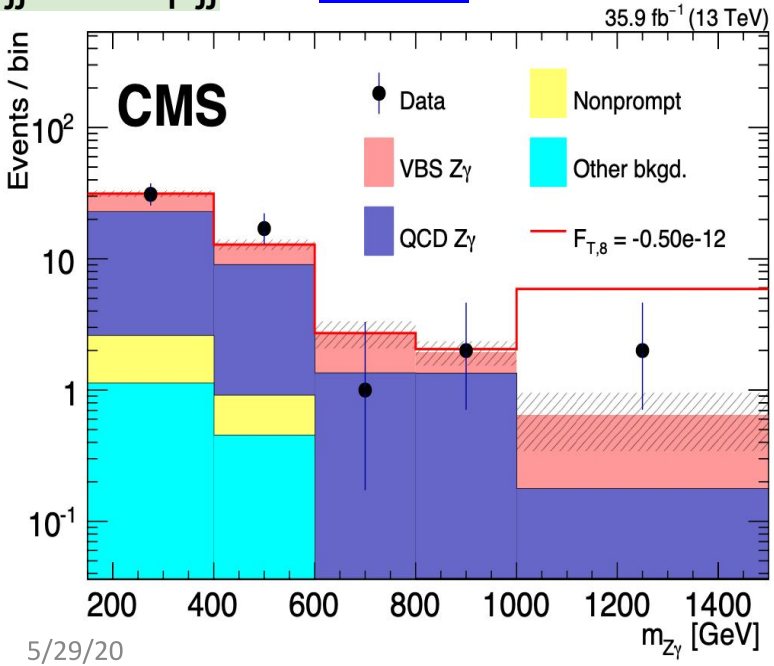
Z Z jj→ 4ℓ jj SMP-20-001



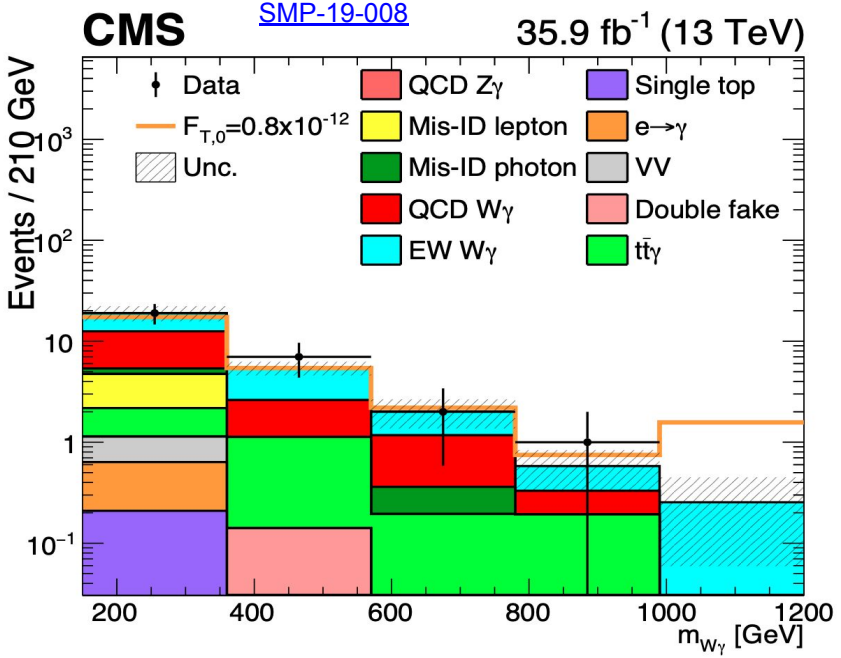
Anomalous Quartic Gauge Coupling

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^4} \mathcal{O}_i$$

$Z\gamma\ jj \rightarrow 2\ell\,\gamma\ jj$ SMP-18-007

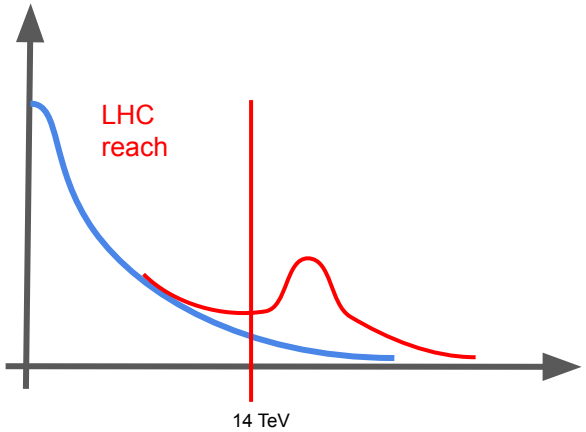


$W\gamma\ jj \rightarrow \ell\,\gamma\ jj$ SMP-19-008



Anomalous Quartic Gauge Coupling

Setting limits on quartic gauge couplings (aQGCs). No evidence for SM deviations.



Eboli-Gonzalez parametrization

channel	SMP-20-001 ZZ	SMP-19-012 ssWW+WZ	SMP-19-008 Wγ	SMP-18-007 Zγ	SMP-19-006 WV + ZV
T0	-0.24, 0.22	-0.69, 0.97	0.6, 0.64	0.74, 0.69	0.12, 0.11
T1	-0.31, 0.31	-0.81, 1.2	0.35, 0.39	0.98, 0.96	0.12, 0.13
T2	-0.63, 0.59	-1.6, 3.1	0.99, 1.18	1.97, 1.86	0.28, 0.28
T5			0.45, 0.46	0.70, 0.75	
T6			0.36, 0.38	1.64, 1.68	
T7			0.87, 0.93	2.59, 2.82	
T8	-0.43, 0.43			0.47, 0.47	
T9	-0.92, 0.92			1.27, 1.27	
M0		-11, 12	8.07, 7.99	19.5, 20.3	0.69, 0.70
M1		11.8, 12.1	40.5, 39.5	2.0, 2.1	0.28, 0.28
M2			2.81, 2.81	8.22, 8.10	
M3			4.41, 4.49	17.7, 17.9	
M4			4.99, 4.95	15.3, 15.8	
M5			8.27, 8.31	25.1, 24.5	
M6		-22, 25	16.2, 16.0	38.9, 40.6	1.3, 1.3
M7		-16, 18	20.8, 20.2	60.3, 62.5	3.4, 3.4
S0		-34, 35			2.7, 2.7
S1		-86, 99			3.4, 3.4

Summary and outlook

First measurements with Run2 data completed, more to come with full Run2.

Looking for new physics interactions: interpretation in terms of generic EFT settings or specific models.

Test of the EWK sector will continue in Run3 and at HL-LHC.

backup

WW and WZ signal extraction

- **EWK WW (Signal) Region:** 8 X 4 = 32 bins
  - mjj : [500, 650, 800, 1000, 1200, 1500, 1800, 2300, ∞] GeV
  - mll : [20, 80, 140, 240, ∞] GeV
- **EWK WZ (Signal) Region:** 8 bins
  - BDT: [-1,-0.28,0.00,0.23,0.43,0.60,0.74,0.86,1]
- **Nonprompt (Control) Region:** 4 bins
  - Inverted b-tagging requirements
  - mjj : [500, 800, 1200, 1800, ∞] GeV
- **ZZ (Control) Region:** 4 bins
  - Select ZZ → 4l candidates with the same VBS-like selection as in the SR
    - Exactly four selected leptons (p_T > 25/20/10/10 GeV) paired up with each other
  - mjj : [500, 800, 1200, 1800, ∞] GeV
- **WZb(tZq) (Control) Region:** 4 bins
  - Same as WZ SR with Inverted b-tagging requirements
  - mjj : [500, 800, 1200, 1800, ∞] GeV