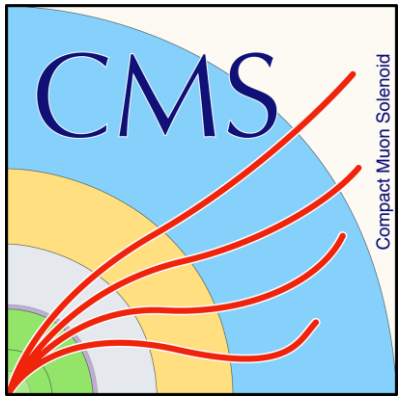

Northern Illinois University

Recent Vector Boson Scattering measurements from CMS

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(on behalf of CMS Collaboration)

The 28th International Workshop on Weak Interactions and Neutrinos (WIN 2021)

University of Minnesota, 7 – 12 Jun 2021

Vector Boson Scattering at LHC

- Vector Boson Scattering (VBS)

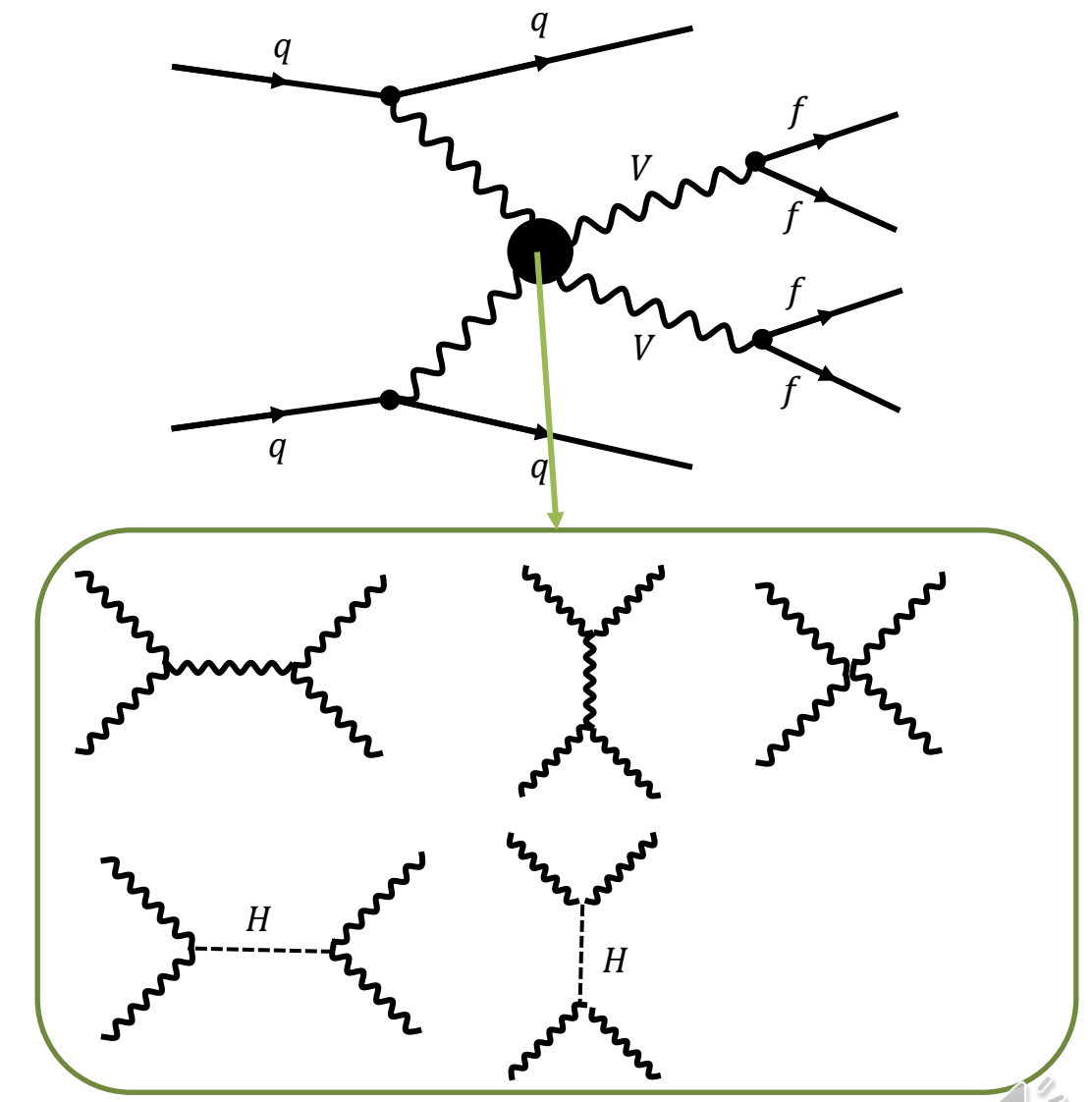
$$VV \rightarrow VV, (V = W/Z)$$

at LHC

  - Initial VV, radiated from incoming quarks
  - Final $VV + 2j$
  - Two final state jets with large $\Delta\eta$ and m_{jj}

  – Electroweak (EW) – $O(\alpha^6)$
  – QCD Induced - $O(\alpha^4 \alpha_S^2)$
  – Interference - $O(\alpha^5 \alpha_S)$

- Electroweak Symmetry Breaking (EWSB)
  – Probe the nature of EWSB in the framework of Standard Model (SM).
- Complimentary to direct Higgs boson measurement.
  – Perturbative cross section of longitudinal VBS diverges without Higgs mechanism



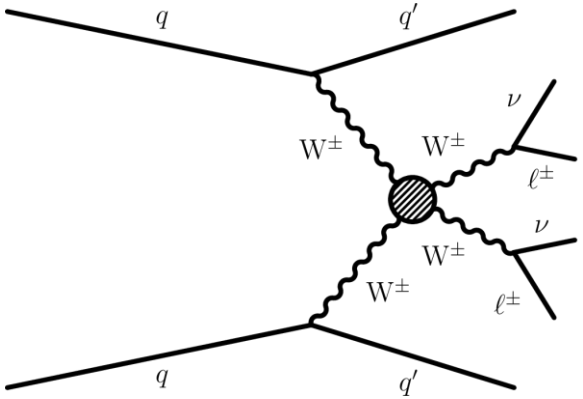
Recent VBS measurements from CMS

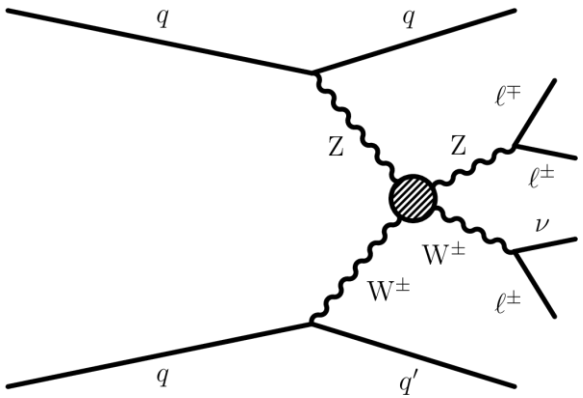
- $W^{\pm}W^{\pm}jj$ and $WZjj$
  - (SMP-19-012) PLB 809 (2020) 135710
- **Polarized $W^{\pm}W^{\pm}jj$**
  - (SMP-20-006) PLB 812 (2020) 136018
- $W\gamma jj$ (2016 data)
  - (SMP-19-008) PLB 811 (2020) 135988
- $ZZjj$
  - (SMP-20-001) PLB 812 (2020) 135992
- $Z\gamma jj$
  - (SMP-20-016) CDS preliminary result

Same sign EW $WWjj$ and $WZjj$

CMS-SMP-19-012 (Phys. Lett. B 809 (2020) 135710)

- Fully leptonic final states
- Best σ_{EW}/σ_{QCD} ratio for SS WW
- Simultaneous fit in several signal regions (SRs) and control regions(CRs)
  - $W^{\pm}W^{\pm}$ SR: $m_{jj} - m_{ll}$ 2D distributions
  - WZ SR: BDT discriminant variable
  - CRs to estimate the normalization of non-prompt leptons, tZq, and ZZ background processes
- Signal significance and cross section
  - $W^{\pm}W^{\pm} \gg 5\sigma$; inclusive and differential cross section as functions of m_{jj}, m_{ll} and p_T^{max} in fiducial region
  - WZ: 6.8σ obs. (5.3σ exp.); inclusive and differential cross section as function of m_{jj} in fiducial region

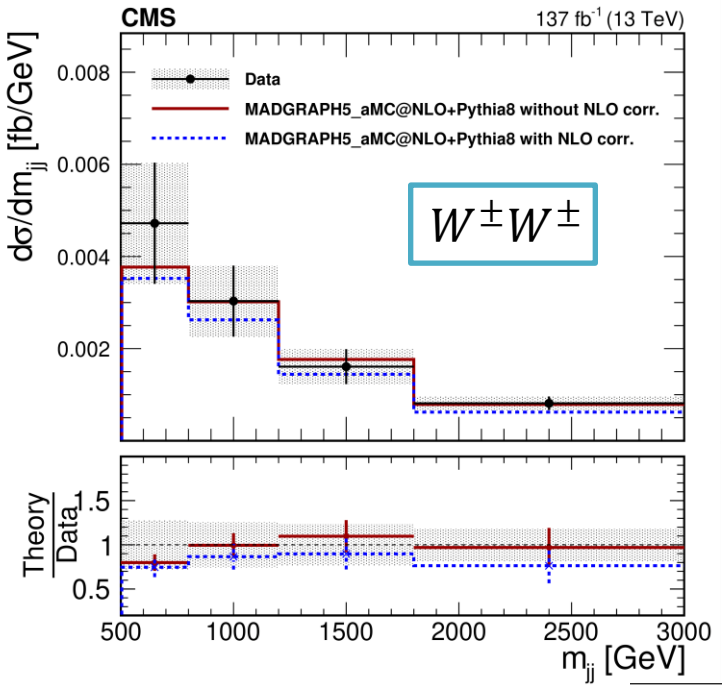




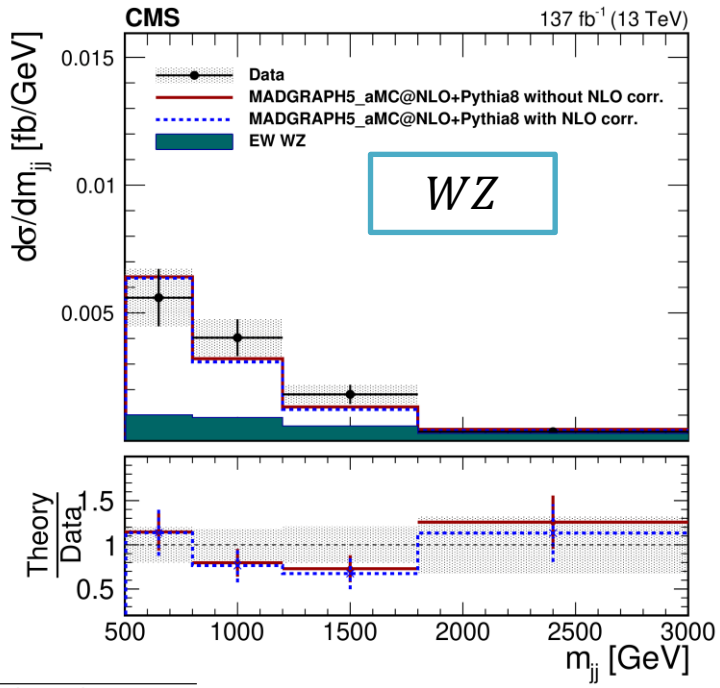
Summary of selection requirements defining SRs

Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	>50 GeV	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b quark veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5	>2.5

Same sign EW $WWjj$ and $WZjj$



- Measured absolute $W^{\pm}W^{\pm}$ (left) and WZ (right) cross section measurements in bins of m_{jj}
- Rivet analysis available
  - First time for the VBS analysis
  - Will be released in next release of rivet



Measured inclusive cross sections and the theoretical predictions with MadGraph5_aMC@NLO at LO

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 (stat) $\pm$ 0.25 (syst))	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 (0.39 (stat) $\pm$ 0.25 (syst))	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 (0.39 (stat) $\pm$ 0.14 (syst))	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 (0.40 (stat) $\pm$ 0.23 (syst))	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 (0.45 (stat) $\pm$ 0.18 (syst))	3.12 ± 0.70	3.12 ± 0.70

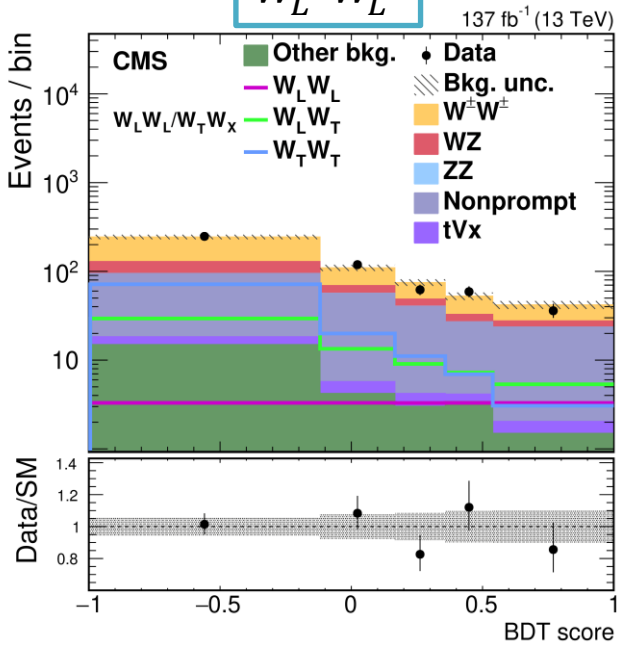
Polarized same sign EW $WWjj$

CMS-SMP-20-006 (Phys. Lett. B 812 (2020) 136018)

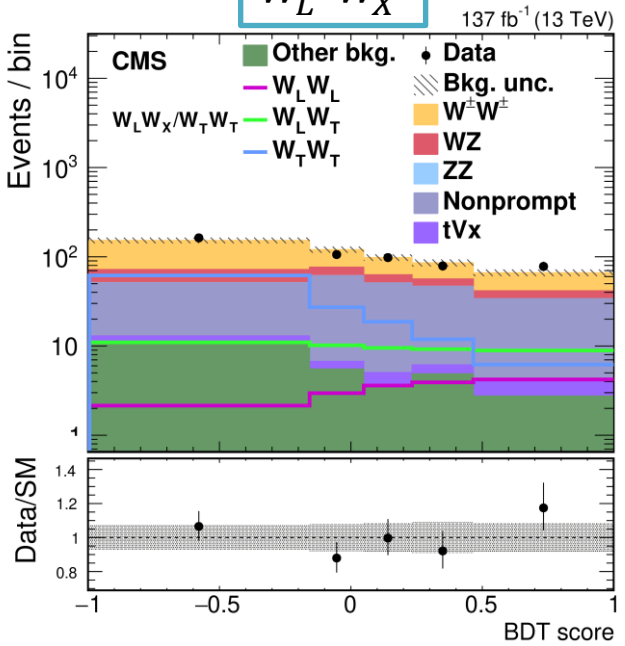
- First measurement of the EW production cross sections for polarized same-sign $W^{\pm}W^{\pm}$ pairs
- Signal sample $W_L^{\pm}W_L^{\pm}$ in center-of-mass frame of WW and pp
- Same selection and CRs as EW $W^{\pm}W^{\pm}$

- Simultaneous fit in bins of two BDT discriminant variables
  - $W_L^{\pm}W_L^{\pm}$
    - Signal BDT ($W_L^{\pm}W_L^{\pm}$ vs $W_T^{\pm}W_X^{\pm}$) and inclusive BDT (EW VBS vs Bkg.)
  - $W_L^{\pm}W_X^{\pm}$
    - Signal BDT ($W_L^{\pm}W_X^{\pm}$ vs $W_T^{\pm}W_T^{\pm}$) and inclusive BDT (EW VBS vs Bkg.)
- m_{jj} and $|\Delta\eta|$ are most powerful variables.

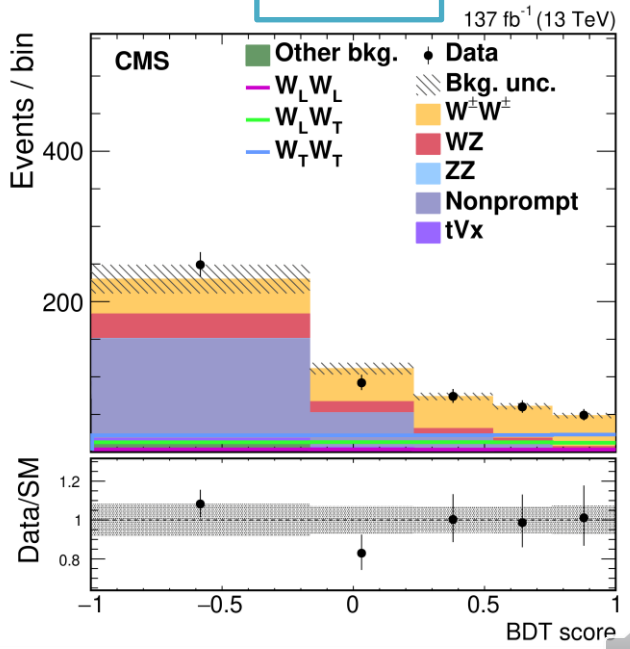
$W_L^{\pm}W_L^{\pm}$



$W_L^{\pm}W_X^{\pm}$



$W^{\pm}W^{\pm}$



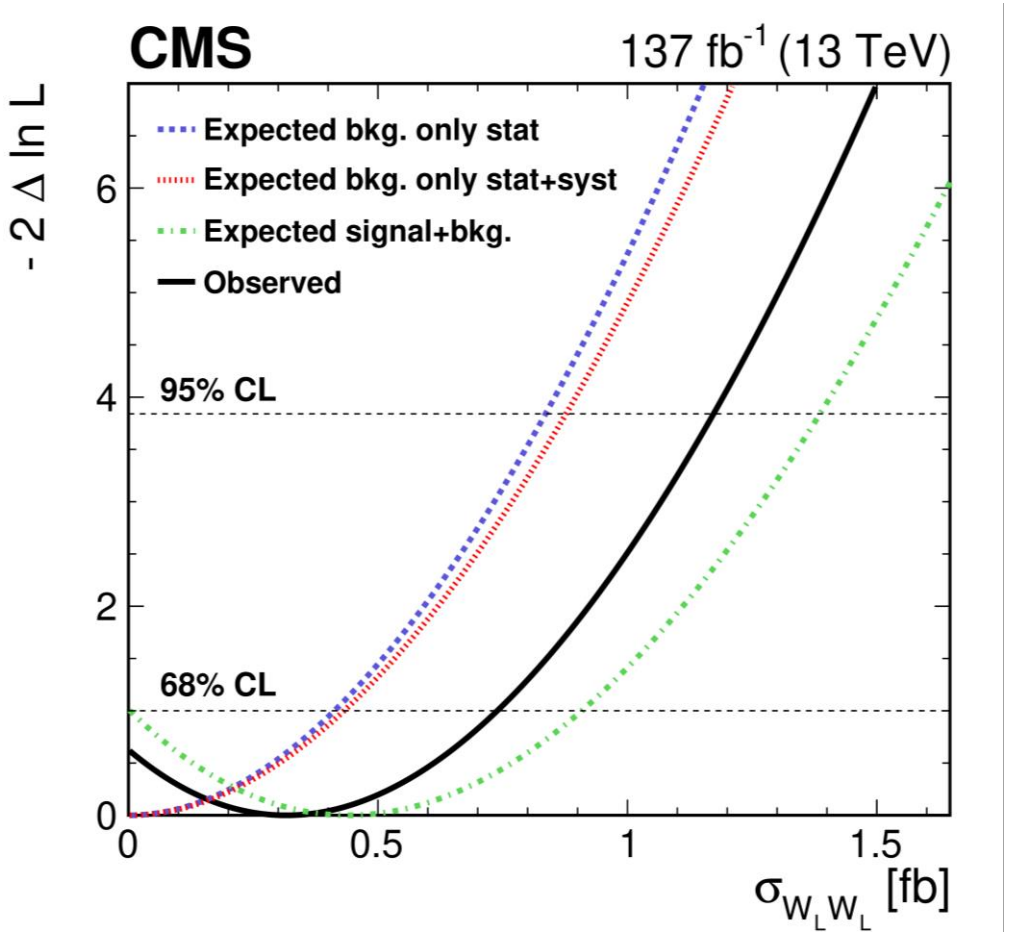
Polarized same sign EW $WWjj$

- WW frame: Observed (expected)
  - Production cross section limit of 1.17 (0.88) fb for $W_L^{\pm}W_L^{\pm}$
  - Significance 2.3σ (3.1σ) for $W_L^{\pm}W_X^{\pm}$

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

- pp frame: Observed (expected)
  - Production cross section limit of 1.06 (0.85) fb for $W_L^{\pm}W_L^{\pm}$
  - Significance 2.6σ (2.9σ) for $W_L^{\pm}W_X^{\pm}$

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W_X^{\pm}W_T^{\pm}$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W_L^{\pm}W_X^{\pm}$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W_T^{\pm}W_T^{\pm}$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

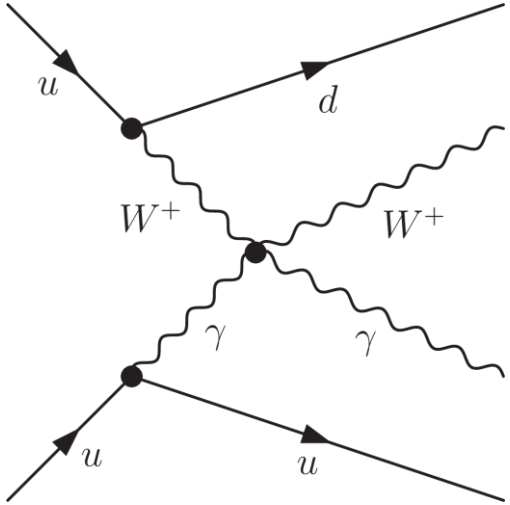


Profile likelihood scan as a function of the $W_L^{\pm}W_L^{\pm}$ cross section

EW $W\gamma jj$

CMS-SMP-19-008 (Phys. Lett. B 811 (2020) 135988)

- First observation of the VBS $W\gamma$ production with leptonic final states
- 2D distribution $m_{jj} - m_{l\gamma}$
- Simultaneous fit SR and CR



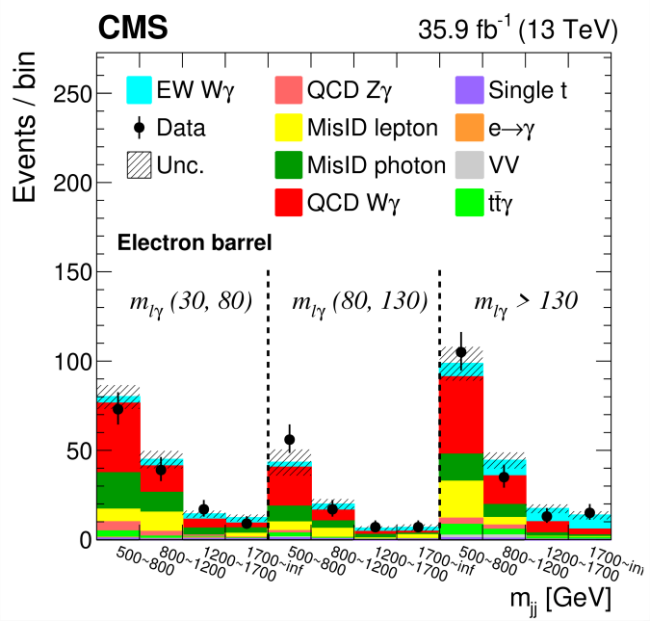
Signal significance and cross section

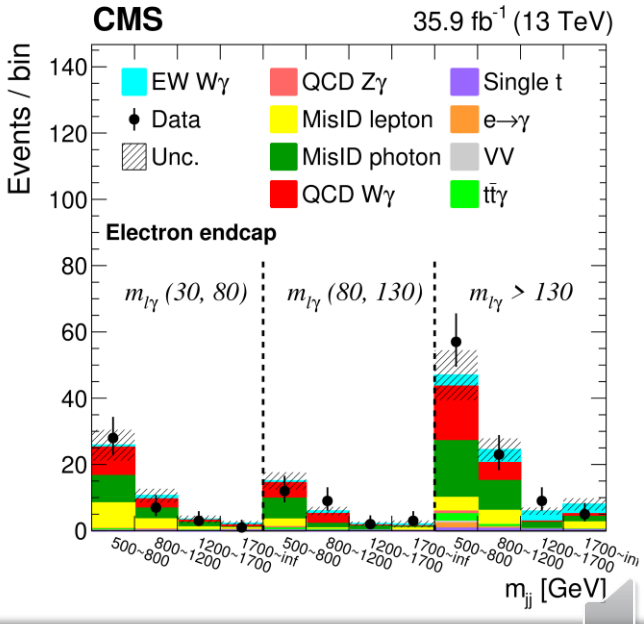
- Observed (expected) significance 5.3σ (4.8σ) (13 TeV + 8 TeV)

Fiducial cross section are measured as:

$\sigma_{EW} = 20.4 \pm 4.5$ fb $\quad \sigma_{EW}^{theory} = 17.0 \pm 4.1$ fb

$\sigma_{EW+QCD} = 108 \pm 16$ fb $\quad \sigma_{EW+QCD}^{theory} = 89.7 \pm 13.9$ fb



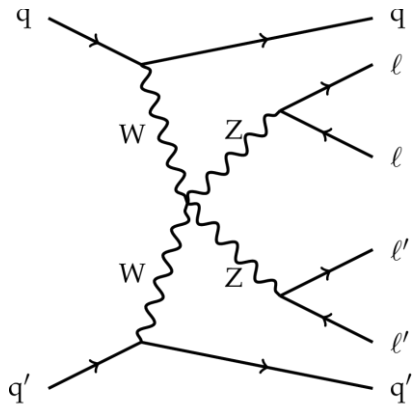


EW $ZZjj$

CMS-SMP-20-001 (Phys. Lett. B 812 (2020) 135992)

- Evidence of VBS ZZ production with fully leptonic final states
- Irreducible background $q\bar{q} \to ZZjj$ simulated in NLO, loop-induced production $gg \to ZZjj$ simulated at LO
  - First time results for simulation based on matrix element for loop-induced $ZZ + 0,1,2$ patron process at LO arxiv:2006.12860
- Signal events are extracted from the K_D discriminant distribution (Similar sensitivity with BDT)

$$\left[1 + c(m_{4l})\frac{P_{QCD}\left(\vec{\Omega}^{4l+jj}\middle|m_{4l}\right)}{P_{VBS}\left(\vec{\Omega}^{4l+jj}\middle|m_{4l}\right)}\right]^{-1}$$



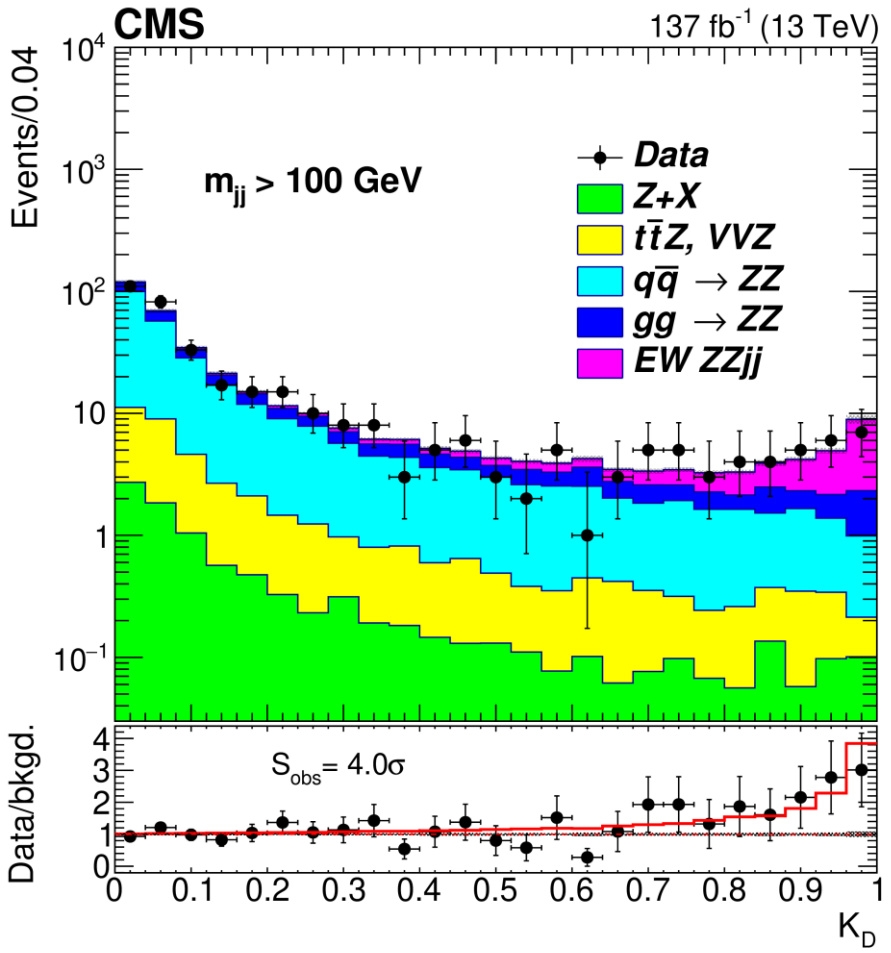
- Fiducial cross section is measured in the three phase-spaces
  - $ZZjj$ inclusive
  - Loose VBS-enriched
  - Tight VBS-enriched

Particle type	Selection
	ZZjj inclusive
Leptons	$p_T(\ell_1) > 20\,\text{GeV}$
	$p_T(\ell_2) > 10\,\text{GeV}$
	$p_T(\ell) > 5\,\text{GeV}$
	$\lvert\eta(\ell)\rvert < 2.5$
Z and ZZ	$60 < m(\ell\ell) < 120\,\text{GeV}$
	$m(4\ell) > 180\,\text{GeV}$
Jets	at least 2
	$p_T(\text{j}) > 30\,\text{GeV}$
	$\lvert\eta(\text{j})\rvert < 4.7$
	$m_{\text{jj}} > 100\,\text{GeV}$
	$\Delta R(\ell,\text{j}) > 0.4$ for each ℓ,j
	VBS-enriched (loose)
Jets	ZZjj inclusive +
	$\lvert\Delta\eta_{\text{jj}}\rvert > 2.4$
	$m_{\text{jj}} > 400\,\text{GeV}$
	VBS-enriched (tight)
Jets	ZZjj inclusive +
	$\lvert\Delta\eta_{\text{jj}}\rvert > 2.4$
	$m_{\text{jj}} > 1\,\text{TeV}$

EW ZZ*jj*

- Observed (expected) signal significance 4.0 (3.5) standard deviations.
- The fiducial cross section in three regions are measured

	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
EW	LO	0.275 ± 0.021	$0.33^{+0.11}_{-0.10}\,(\text{stat})^{+0.04}_{-0.03}\,(\text{syst})$
	NLO QCD	0.278 ± 0.017	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}\,(\text{stat}) \pm 0.46\,(\text{syst})$
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.200^{+0.078}_{-0.067}\,(\text{stat})^{+0.023}_{-0.013}\,(\text{syst})$
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}\,(\text{stat})^{+0.06}_{-0.05}\,(\text{syst})$
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}\,(\text{stat}) \pm 0.02\,(\text{syst})$
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}\,(\text{stat}) \pm 0.02\,(\text{syst})$

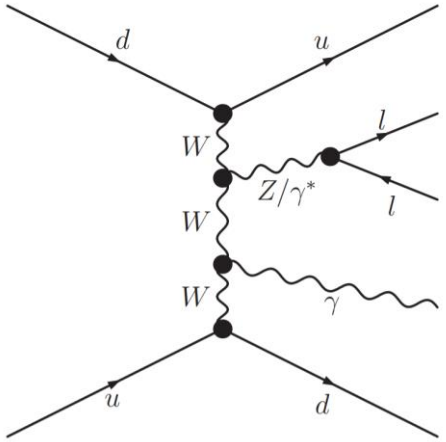


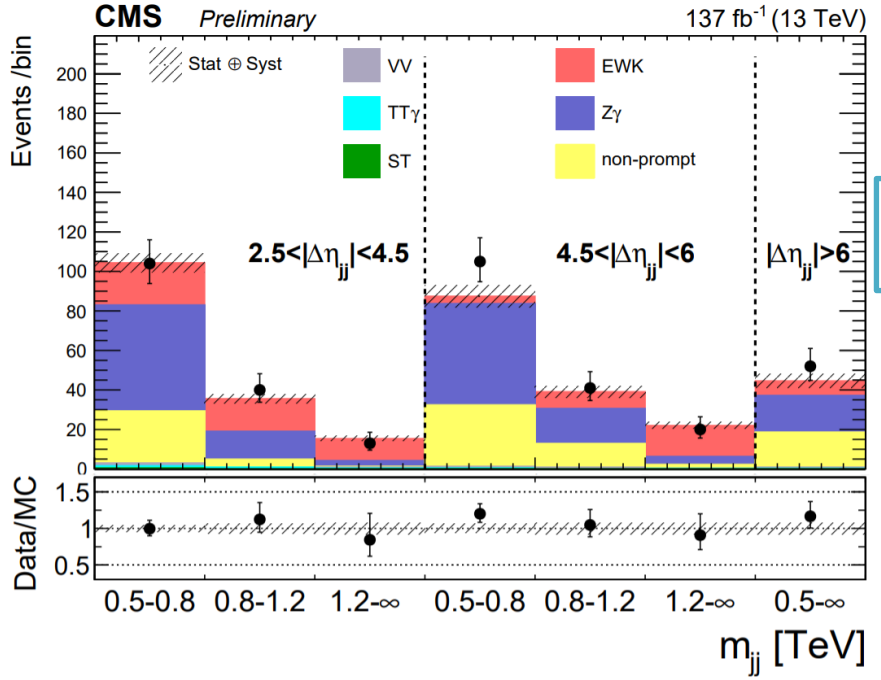
EW $Z\gamma jj$

- First observation of the VBS $Z\gamma$ production with leptonic final states.

- Simultaneous fit in CR and SR
  - SR: 2D distribution $m_{jj} - |\Delta\eta_{jj}|$
  - CR: 1D distribution m_{jj}

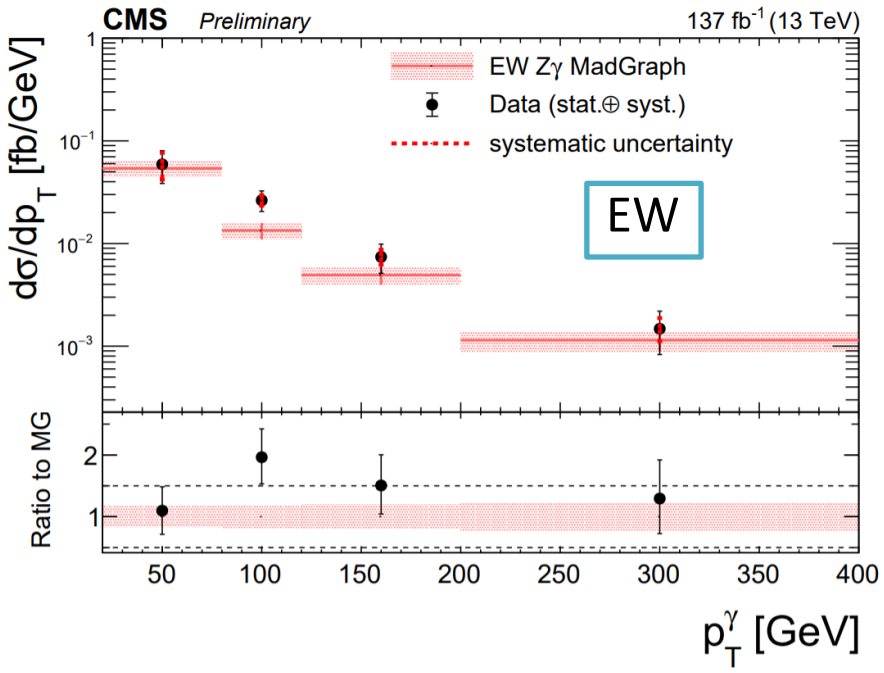
- Signal significance and cross section
  - Observed (expected) significance $\gg 5\ \sigma$
  - Fiducial cross section for EW and EW+QCD
  - Differential cross section for EW/EW+QCD as functions of 1D variables $p_T^{l_1}$, $p_T^{j_1}$, p_T^{γ} and 2D variable $m_{jj} - |\Delta\eta_{jj}|$



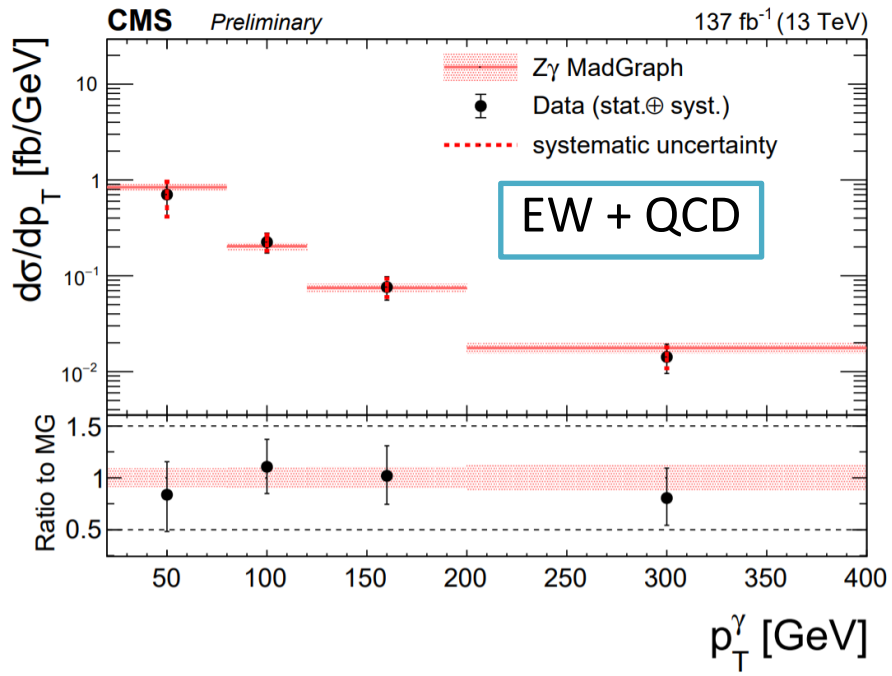


Dielectron + γ(barrel)

EW $Z\gamma jj$



Unfolded differential cross –section distribution as function of p_T^γ for EW $Z\gamma jj$ (left) and for EW+QCD (right)



$$\sigma_{EW}^{theory} = 4.34 \pm 0.26\,(scale) \pm 0.06\,(PDF) fb$$
$$\sigma_{EW}^{fid} = 5.21 \pm 0.52\,(stat) \pm 0.56\,(syst)\,fb = 5.21 \pm 0.76\,fb$$

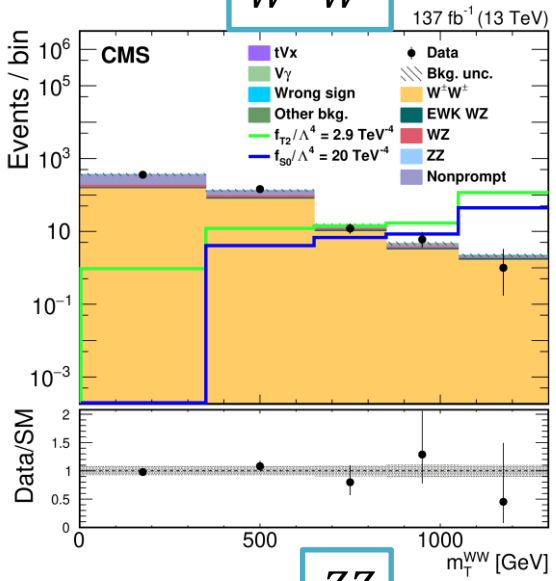
$$\sigma_{EW+QCD}^{theory} = 13.3 \pm 1.72\,(scale) \pm 0.10\,(PDF)\,fb$$
$$\sigma_{EW+QCD}^{fid} = 14.7 \pm 0.80\,(stat) \pm 1.26\,(syst)\,fb = 14.7 \pm 1.53\,fb$$

Anomalous coupling

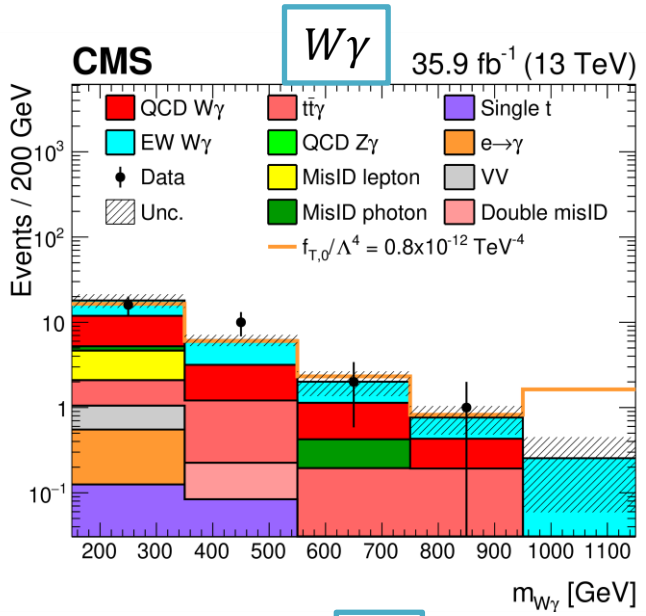
- Limits on dimension-8 aQGC in all states using variables sensitive to $\sqrt{\hat{s}}$
- The most stringent limits to date on the aQGC parameters.
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC#aQGC_Results

Parameters	Channel	Observed Limit (TeV^{-4})	$\int L\mathrm{d}t$
f_{M_2}/Λ^4	$W\gamma$	[−2.8, 2.8]	35.9 fb^{-1}
f_{M_3}/Λ^4	$W\gamma$	[−4.4, 4.4]	35.9 fb^{-1}
f_{M_4}/Λ^4	$W\gamma$	[−5.0, 5.0]	35.9 fb^{-1}
f_{M_5}/Λ^4	$W\gamma$	[−8.3, 8.3]	35.9 fb^{-1}
f_{T_2}/Λ^4	$W^\pm W^\pm$ $WV\ ZV$	[-0.38, 0.50] [−0.28, 0.28]	137 fb^{-1} 35 fb^{-1}
f_{T_5}/Λ^4	$W\gamma$	[−0.5, 0.5]	35.9 fb^{-1}
f_{T_6}/Λ^4	$W\gamma$	[−0.4, 0.4]	35.9 fb^{-1}
f_{T_7}/Λ^4	$W\gamma$	[−0.9, 0.9]	35.9 fb^{-1}
f_{T_8}/Λ^4	ZZ	[-0.43, 0.43]	137 fb^{-1}
f_{T_9}/Λ^4	$Z\gamma$	[-0.91 , 0.91]	137 fb^{-1}

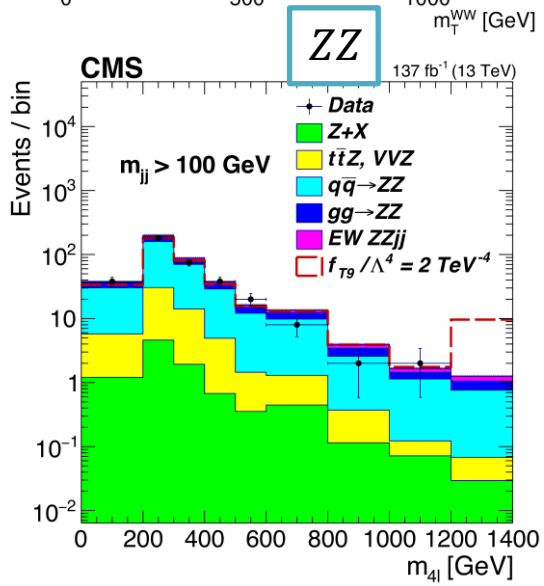
$W^\pm W^\pm$



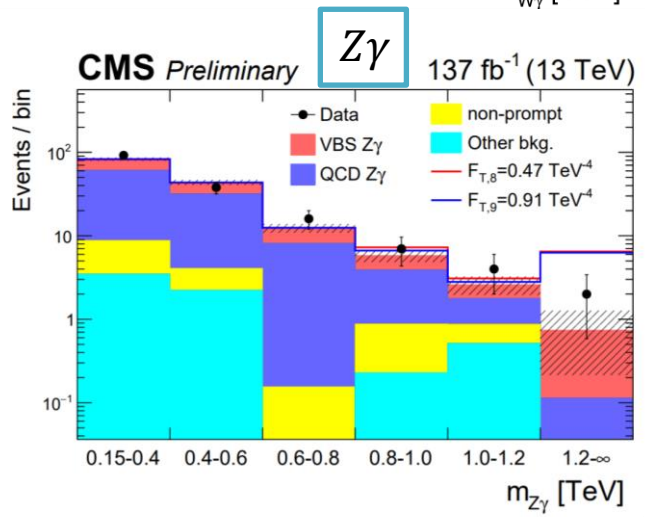
$W\gamma$



ZZ

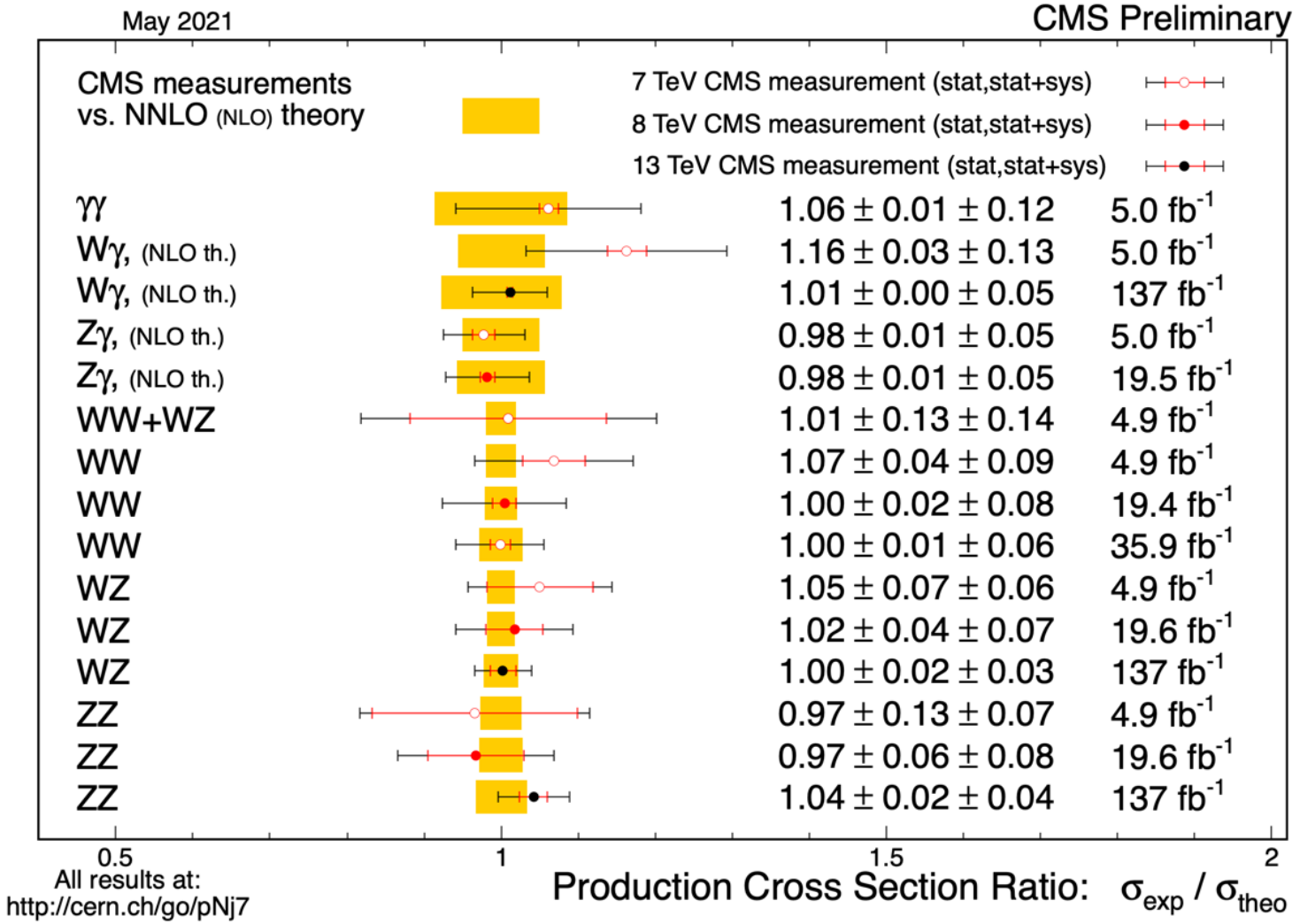


$Z\gamma$



Summary

- The first polarized same-sign $W^{\pm}W^{\pm}$ measurement.
- The first observation of EW production of WZ (CMS), $Z\gamma$ and $W\gamma$.
- Fiducial cross-sections are measured in all channels.
- Differential cross sections as functions of interesting variables are measured in EW production of $W^{\pm}W^{\pm}$, WZ, and $Z\gamma$
- AQGC limits on dimension 8 operators are set, most stringent limits are provided by VBS



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined