Recent Results on Vector Boson Scattering from CMS

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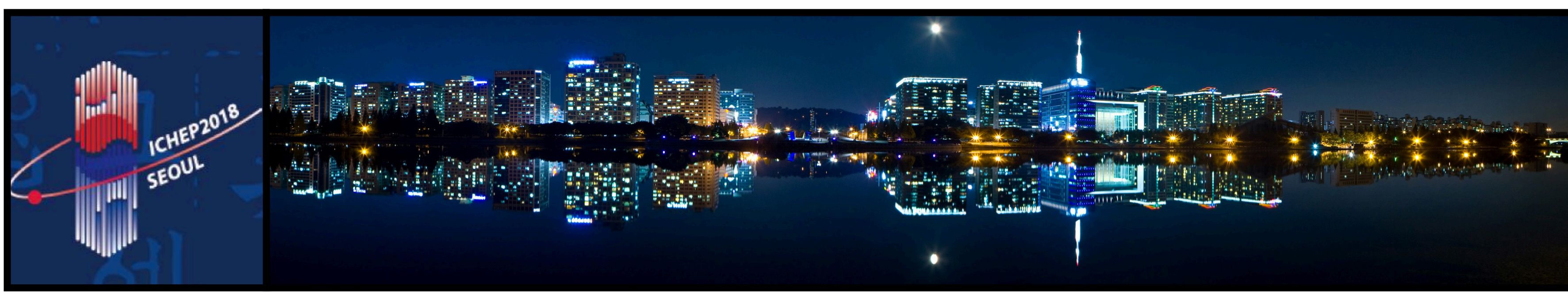
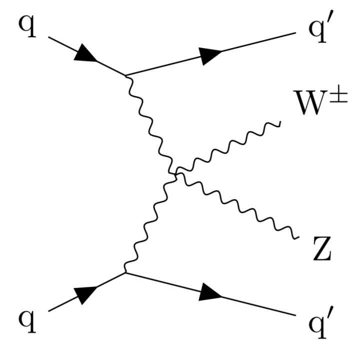
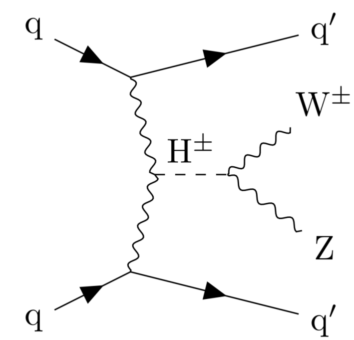


Introduction and Motivation

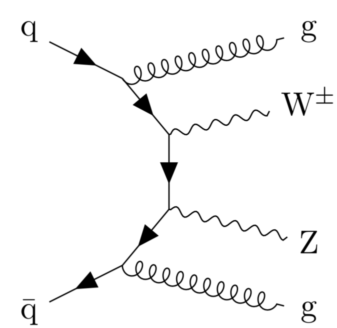
- Diboson production via vector boson scattering
  - Important component of VVjj production proceeding entirely via EW interactions at tree level
  - Given SM Higgs, vector boson self-interactions precisely predicted
    - Deviations from predictions signal new physics in EW sector



VBS WZ



H± Production

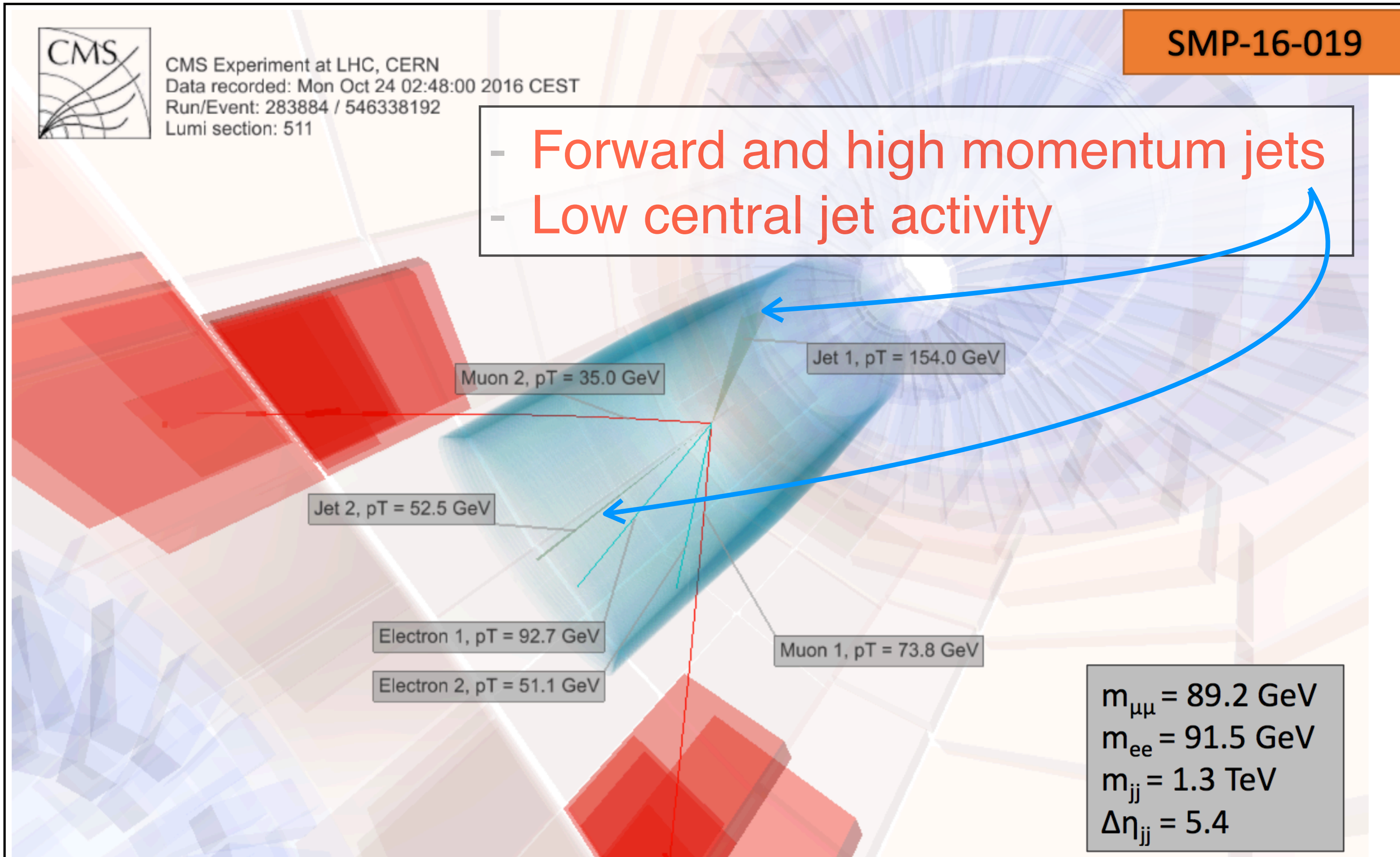


Non-VBF ($\alpha_s^2\alpha^2$) WZjj production

- Low cross sections for VBS just becoming accessible
  - Measurements in new channels at 13 TeV
  - Some channels moving from observation to measurement with the full Run 2 data set

Picture of a VBS Candidate Event

- Radiation of vector bosons, lack of color flow between jets
  - ➡ Distinct kinematic signature for VVjj EW component

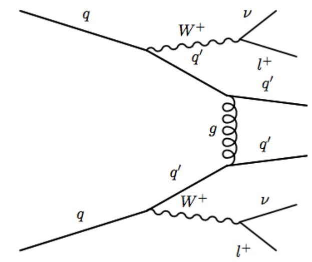


VBS ZZjj Candidate Event from PLB 774 (2017) 682

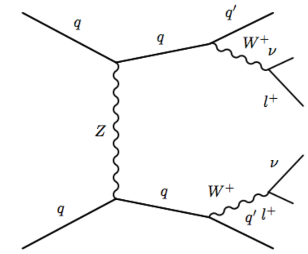
Overview of a VBS Measurement

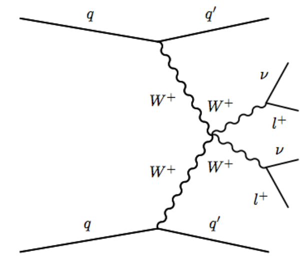
- Backgrounds divided into two classes
  - Nonprompt/fake (reducible)
    - Selected due to mis-ID from data
  - Prompt (irreducible)
    - Selected without mis-ID ⟹ from MC
- All EW-induced $O(\alpha^4)$ as signal
- QCD-induced $O(\alpha_s^2\alpha^2)$ as background
  - ★ Almost always dominant background
    - Notable exception: same-sign WW production
- Mixed QCD/EW interference terms, $O(\alpha_s\alpha^3)$
  - Uncertainty on signal or background
- Procedure: select VVjj events, estimate non-VVjj backgrounds, distinguish EW and QCD via kinematic selections
  - Low stats, S/B ⟹ MVA or shape-based fit ⟹ theory uncertainty
- Major uncertainties
  - Jet energy scale/resolution, background modeling
  - EW/QCD modeling dependence reduced for combined EW+QCD measurement

Non-VBS ($\alpha_s^2\alpha^2$)



Non-VBS (α^4)





VBS $W^\pm W^\pm$

WZ VBS at 13 TeV: Overview

CMS-SMP-18-001

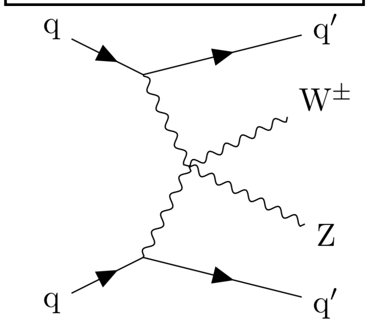
New Result

- Why WZjj $\longrightarrow \ell^{\pm}\ell^{\pm}$jj?
  - Sensitive to charged resonances or couplings
  - Less clean signature than ZZ, $W^{\pm}W^{\pm}$, but cross section accessible with large dataset
- Event selection
  - Exactly 3 leptons with moderate p_T + p_T^{miss}
  - Tight dijet kinematic cuts to reduce QCD WZjj and significant nonprompt contributions
  - Expected S/B ~ 1/4 for events in signal region

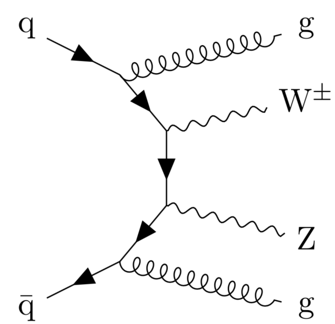
Event selection

	Electroweak Signal
$p_{\mathrm{T}}(\ell_{\mathrm{Z},1})$ [GeV]	> 25
$p_{\mathrm{T}}(\ell_{\mathrm{Z},2})$ [GeV]	> 15
$p_{\mathrm{T}}(\ell_{\mathrm{W}})$ [GeV]	> 20
$\lvert\eta(\mu)\rvert$	< 2.4
$\lvert\eta(e)\rvert$	< 2.5
$\lvert m_{\mathrm{Z}} - m_{\mathrm{Z}}^{\mathrm{PDG}}\rvert$ [GeV]	< 15
$m_{3\ell}$ [GeV]	> 100
$m_{\ell\ell}$ [GeV]	> 4
p_{T}^{miss} [GeV]	> 30
$\lvert\eta(\mathrm{j})\rvert$	< 4.7
$p_{\mathrm{T}}(\mathrm{j})$ [GeV]	> 50
$\lvert\Delta R(\mathrm{j}, \ell)\rvert$	> 0.4
n_{j}	≥ 2
$p_{\mathrm{T}}(\mathrm{b})$ [GeV]	> 30
$n_{\mathrm{b-jet}}$	$= 0$
m_{jj}	> 500
$\lvert\Delta\eta(\mathrm{j}_1, \mathrm{j}_2)\rvert$	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$	< 2.5

VBS production



QCD production



WZ VBS at 13 TeV: Backgrounds

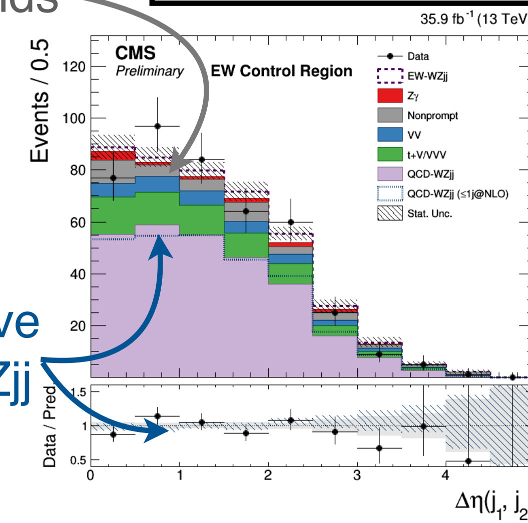
CMS-SMP-18-001

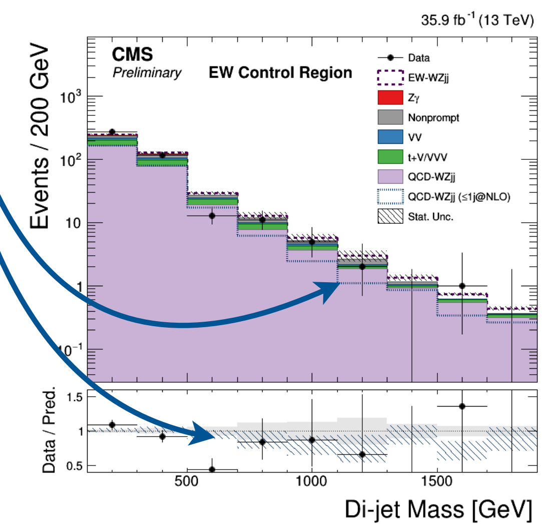
- Nonprompt background
  1. Define "loose" ID with ID+isolation relaxed from "tight"
  2. Measure tight/loose ratio in Z+jet (dijet) events
  3. Apply loose ⟶ tight factors to events passing full analysis selection but failing analysis ID (tight)

- QCD WZjj background
  - Simulated with MG5_aMC+Py8 ≤3j@LO
    - Compare to predictions from MG5_aMC+Py8 ≤1j@NLO, each normalized to data in control region
  - Normalization constrained in control region
    - m_{jj} > 100 GeV, but fail dijet signal cuts
  - Uncertainty: LO scale+PDF+10% normalization from MC comparisons

Nonprompt backgrounds

Alternative QCD-WZjj

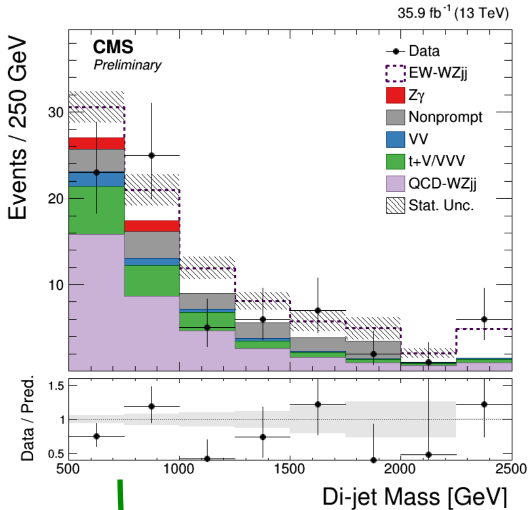




WZ VBS at 13 TeV: EW Extraction

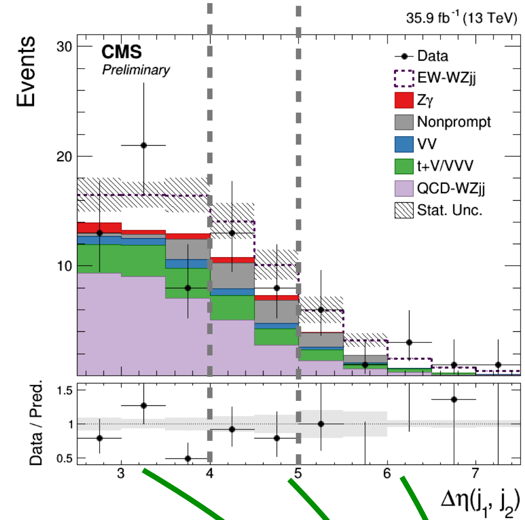
CMS-SMP-18-001

- Simultaneously fit yield from background control region and 2D distribution of m_{jj} and $\Delta\eta(j_1,j_2)$



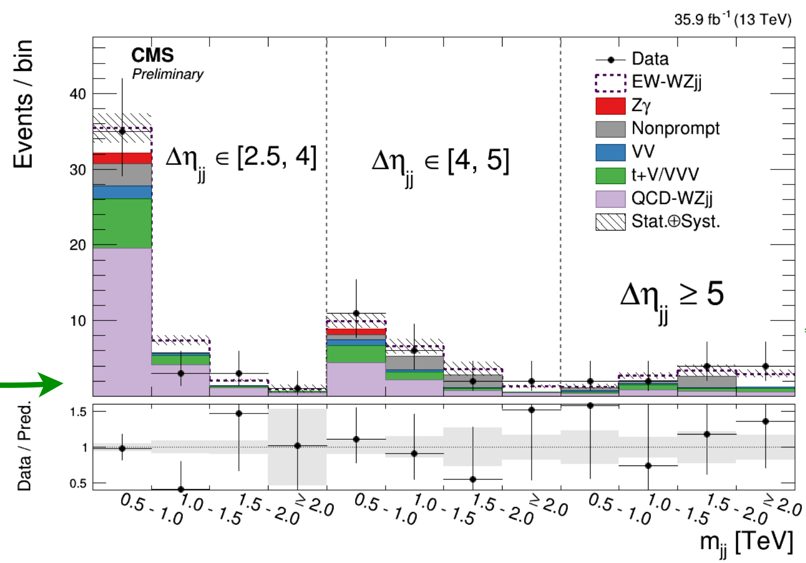
Prefit

  - Fit 4 leptonic decay channels independently
  - Uncertainties correlated across bins and with control region



Prefit

EW contribution (purple dashed, stacked) rises with increasing $m_{jj}/\Delta\eta_{jj}$



Postfit

WZ VBS at 13 TeV: Results

CMS-SMP-18-001

- Observed (expected) significance of EW WZ 1.9σ (2.7σ)

$$\mu_{EW} = \sigma_{EW,obs}/\sigma_{EW,\mathrm{theo}} = 0.64^{+0.45}_{-0.37}$$

- Measure WZjj EW+QCD cross section in VBS-enhanced phase space
  - Fit yields in signal region (NOT shape based) to reduce dependence on theory prediction
  - Extrapolate results to loose fiducial regions for easier comparison with theory, following Les Houches 2017 Report [1]

Tight $\sigma^{\mathrm{fid}}_{\mathrm{WZjj}} = 2.91^{+0.53}_{-0.49}\,(\mathrm{stat})\ ^{+0.41}_{-0.34}\,(\mathrm{syst})$

Loose $\sigma^{\mathrm{fid,loose}}_{\mathrm{WZjj}} = 4.01^{+0.72}_{-0.68}\,(\mathrm{stat})\ ^{+0.57}_{-0.47}\,(\mathrm{syst})$

Fiducial Regions

	Tight Fiducial	Loose Fiducial
$p_{\mathrm{T}}(\ell_{\mathrm{Z},1})$ [GeV]	> 25	> 20
$p_{\mathrm{T}}(\ell_{\mathrm{Z},2})$ [GeV]	> 15	> 20
$p_{\mathrm{T}}(\ell_{\mathrm{W}})$ [GeV]	> 20	> 20
$\lvert\eta(\mu)\rvert$	< 2.5	< 2.5
$\lvert\eta(e)\rvert$	< 2.5	< 2.5
$\lvert m_{\mathrm{Z}} - m_{\mathrm{Z}}^{\mathrm{PDG}}\rvert$ [GeV]	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4
p_{T}^{miss} [GeV]	-	-
$\lvert\eta(\mathrm{j})\rvert$	< 4.7	< 4.7
$p_{\mathrm{T}}(\mathrm{j})$ [GeV]	> 50	> 30
$\lvert\Delta R(\mathrm{j},\ell)\rvert$	> 0.4	> 0.4
n_{j}	≥ 2	≥ 2
$p_{\mathrm{T}}(\mathrm{b})$ [GeV]	-	-
$n_{\mathrm{b-jet}}$	-	-
m_{jj}	> 500	> 500
$\lvert\Delta\eta(\mathrm{j}_1,\mathrm{j}_2)\rvert$	> 2.5	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$	< 2.5	-

- Compare tight fiducial to $\sigma_{\mathrm{fid,MG}} = 3.27^{+0.39}_{-0.32}(\mathrm{scale}) \pm 0.15\,(\mathrm{PDF})$ computed using MG5_aMC@NLO+Py8 at LO with particle-level events from RIVET

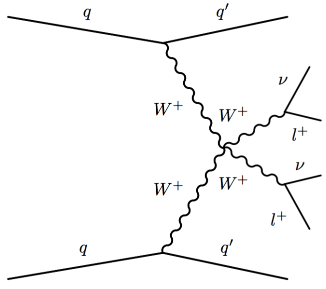
[1] https://arxiv.org/abs/1803.07977

W±W± VBS at 13 TeV: Overview

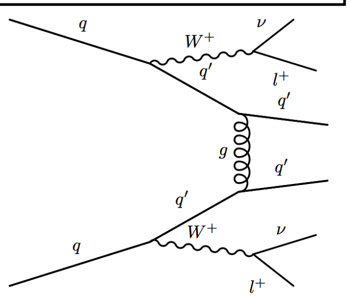
PRL 120, 081801 (2018)

- Why $W^{\pm}W^{\pm}jj \rightarrow \ell^{\pm}\ell^{\pm}jj$?
  - EW production dominant over QCD-induced
  - Distinct same-sign (SS) lepton state
    - ➡ Low background
- Selection
  - Exactly 2 SS leptons, $|m_{e^{\pm}e^{\pm}} - m_Z| > 15$ GeV
  - $p_T^{miss} > 40$ GeV
  - Two jets, $m_{jj} > 500$ GeV; $\Delta\eta_{jj} > 2.5$; $\max(|z^*(\ell)|) = \max(|(\eta_\ell - 1/2(\eta_{j1}+\eta_{j2}))/\Delta\eta_{jj}|) < 0.75$
  - Expected S/B ~ 1/2 in signal region
- Backgrounds
- ≥ 2 prompt SS leptons (WZ, QCD WW) ⟹ from Monte Carlo
  - Correct WZ using data in 3ℓ control regions
- Non-prompt backgrounds (dominant) ⟹ data driven
  - As for WZ (tight-to-loose ratios from dijet events)
- Charge mis-ID
  - Simulation corrected with data

VBS production



QCD production



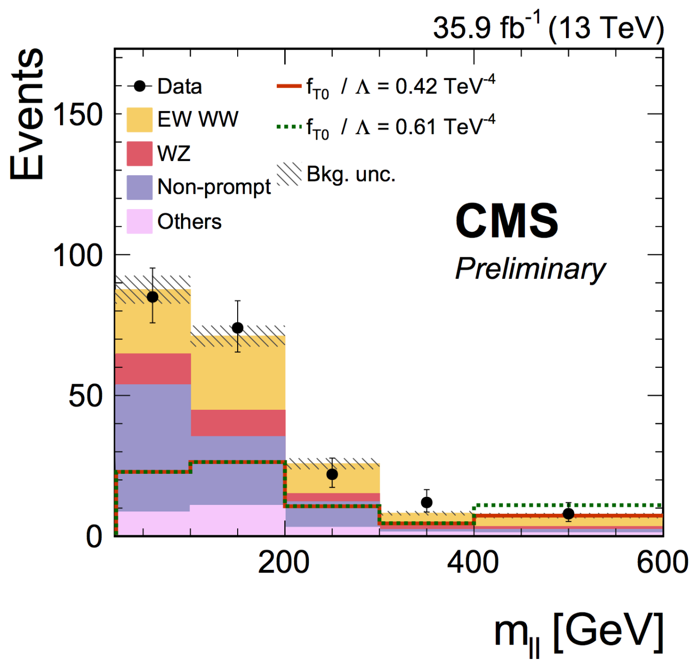
$W^{\pm}W^{\pm}$ VBS at 13 TeV: Results

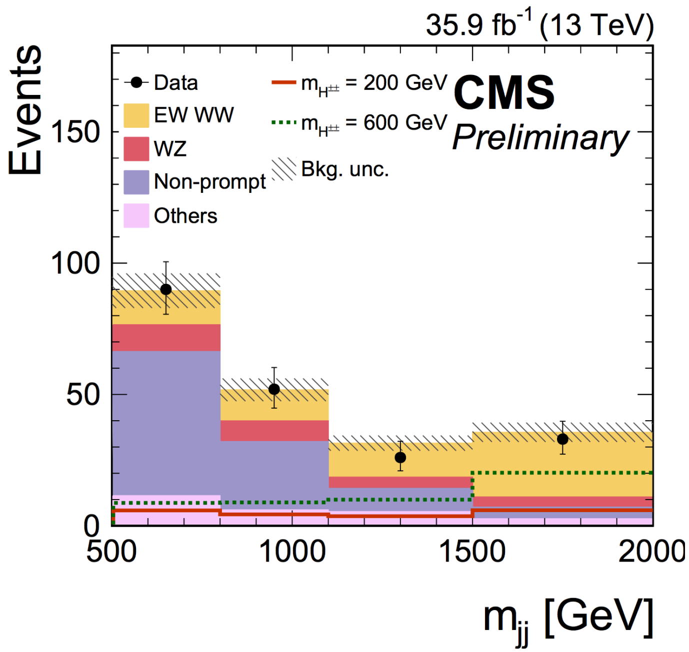
PRL 120, 081801 (2018)

- EW significance and cross section measurement via fit to 2D distribution of m_{jj} and m_{ll}
- Observed (expected) significance of 5.5σ (5.7σ)
  - ★ First > 5σ VBS measurement

$$\sigma_{fid} = 3.83 \pm 0.66\ (\text{stat}) \pm 0.35\ (\text{syst})\ \text{fb}$$

- Agrees with MG5_aMC prediction, $\sigma_{LO} = 4.25 \pm 0.27$





Precision result expected with full Run II dataset!

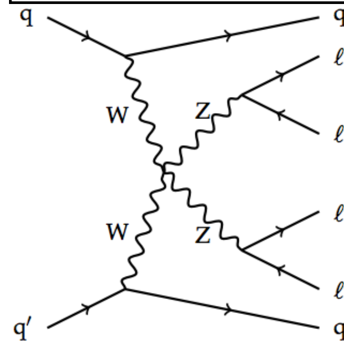
ZZ VBS at 13 TeV: Overview

PLB 774 (2017) 682

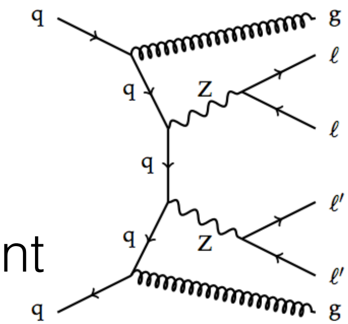
- Why ZZjj ⟶4ℓjj?
  - Extremely clean four lepton signal (ℓ = e, μ)
    - Very low nonprompt (fake) background
  - Fully reconstructed final state
    - Sensitive to resonances (including SM Higgs)
    - Access to boson polarizations via spin correlations

  … But very low production cross section
- Selection
  - 4 leptons, 2 Z candidates with $m_{\ell^+\ell^-} \in [60, 120]$ GeV
  - Two jets, $m_{jj} > 100$ GeV; Expected S/B ~ 1/20
- Backgrounds
  - ≥ 4 prompt leptons (ttV, VVV, QCD ZZ) ⟹ from MC
    - QCD ZZ production via MG5_aMC ≤2j@NLO
      - Low theory uncertainty, good data/MC agreement
      - Validate background modeling in background
      - dominated region with $m_{jj} < 400$ GeV or $\Delta\eta_{jj} < 2.5$
  - Non-prompt backgrounds ⟹ data driven
    - Same technique as for WZ

VBS production



QCD production



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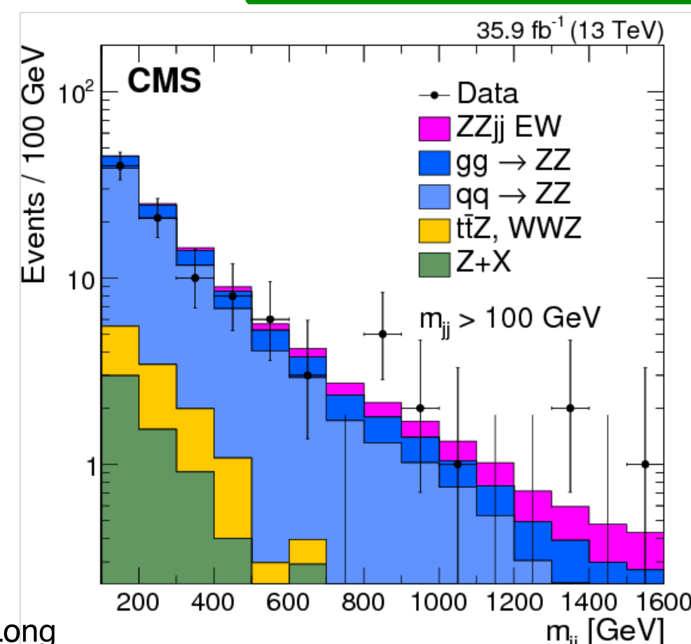
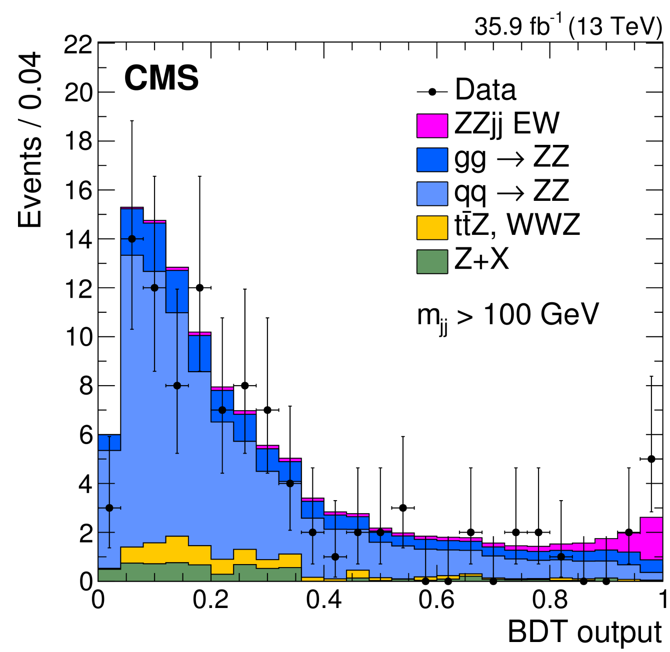
ZZ VBS at 13 TeV: Results

PLB 774 (2017) 682

- Limited statistics, but strong discrimination feasible
- ➡ Train BDT with 7 discriminating variables
  - m_{jj}, $\Delta\eta_{jj}$, $z^*(Z_1)$, $z^*(Z_2)$, $R(p_T)$, dijet p_T balance, $m_{4\ell}$
  - Use all events with $m_{jj} > 100$ GeV
- Significance extracted via fit to BDT output distribution
  - Observed (expected) of 2.7σ (1.6σ)

$$\mu = \sigma_{obs}/\sigma_{th.} = 1.39 \, {}^{+0.72}_{-0.57} \, \text{(stat)} \, {}^{+0.46}_{-0.31} \, \text{(syst.)}$$

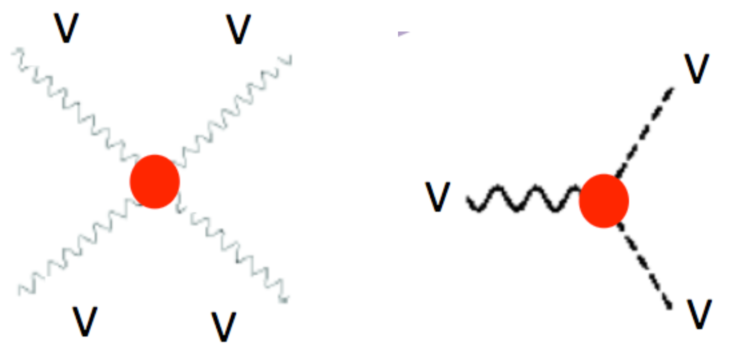




Searches for Anomalous Couplings

Overview of Anomalous Couplings / EFT

- Generalized language for new physics in vector boson interactions
- Anomalous couplings (triple and quartic)
  - Observed as deviations at high mass
  - Defined by modifying SM Lagrangian or effective vertices



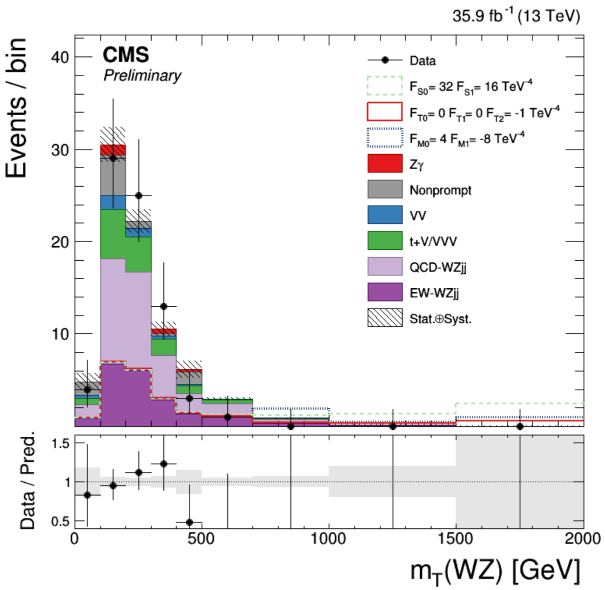
  - Alternatively… expand in effective field theory (EFT)
    - in terms of Wilson coefficients c_i and New Physics scale Λ

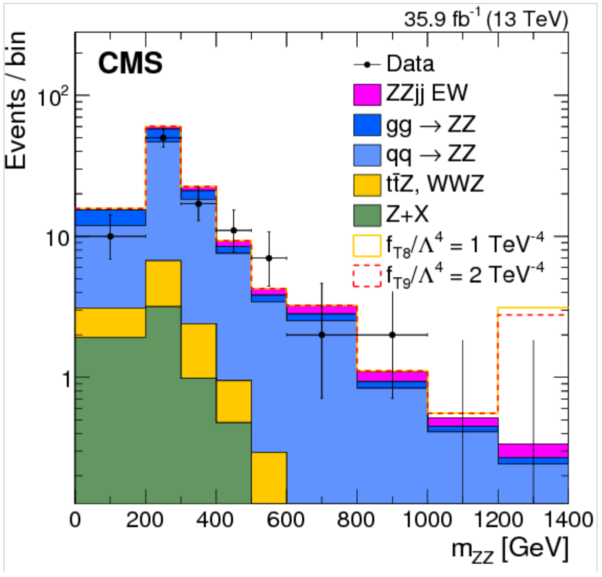
$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

  - Non-unitary as $\sqrt{\hat{s}} \longrightarrow \Lambda$ without form factor
    - Often presented without form factor for simplicity
    - Inclusion of form factor decreases limits

Limits on aQGCs: Procedure

- Fit to variable sensitive center of mass energy of the scattering system
  - WZ: $m_T(WZ)$
  - ZZ: $m_{4\ell}$
  - SS WW: $m_{\ell\ell}$
- Parameterization from Eboli, Gonzlez-Garcia, Mizukoshi [2] using MG5_aMC@NLO with reweighted events to grid of aQGC parameters
  - Interpolate between parameter points with quadratic fit to yields



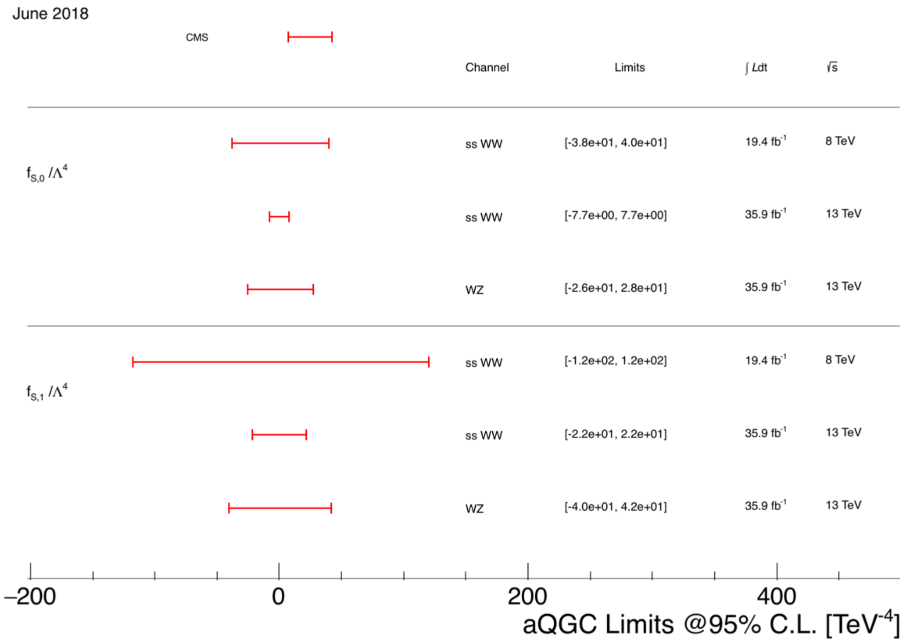


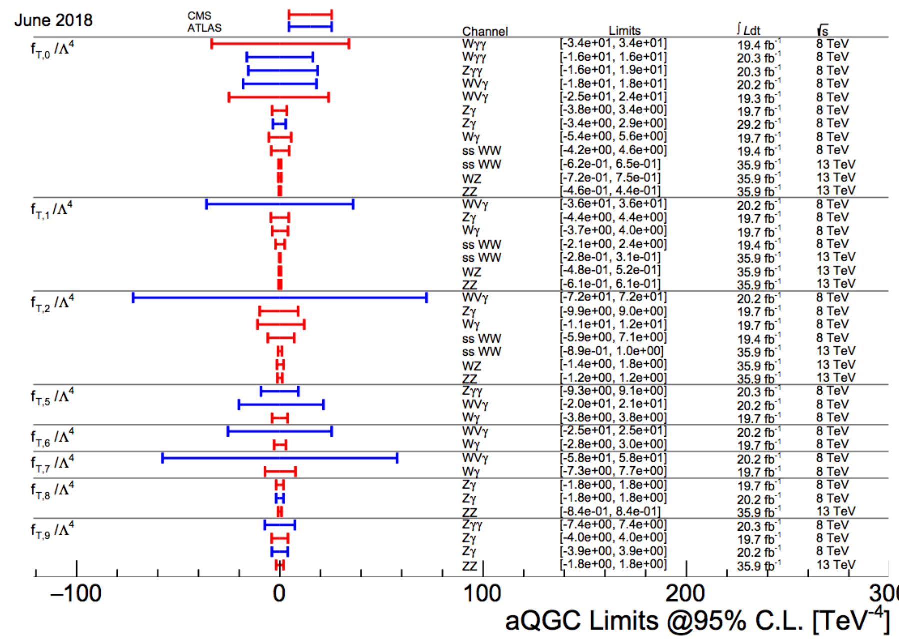
CMS-SMP-18-001; PLB 774 (2017) 682; PRL 120, 081801 (2018)

[2] https://arxiv.org/abs/hep-ph/0606118

Limits on aQGCs: Results

- Analyses improve constraints on wide range of operators
  - Limits presented without unitarization scheme (shown in plots)
  - Unitary bounds provided for ZZ

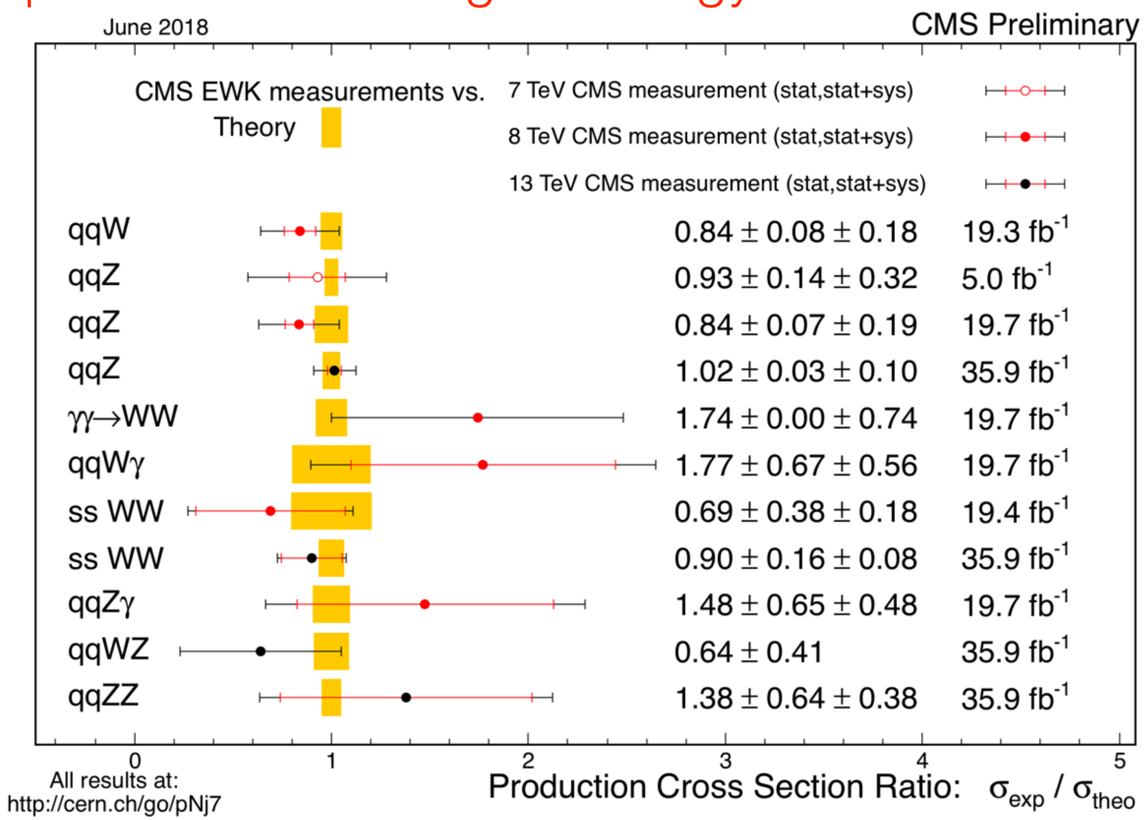




CMS-SMP-18-001; PLB 774 (2017) 682; PRL 120, 081801 (2018)

Conclusions

- VBS measurements provide an important probe of a previously untested sector of the standard model
- So far the standard model is withstanding these new tests
  - Deviations could be subtle
  - More data and improved techniques help look for cracks with increased precision and at higher energy scales



Backup

Overview of Experimental Status: 13 TeV

Energy	Measurement	CMS
13 TeV	$W^\pm W^\pm jj \longrightarrow \ell^\pm \nu \ell^\pm \nu jj$	**PRL 120, 081801** EW Sig. 5.5σ obs (5.7σ exp) Cross section (EW) aQGC Limits
	$ZZjj \longrightarrow 4\ell jj$	**PLB 774 (2017) 682** EW Sig. 2.7σ obs (1.6σ exp) Cross section (EW) aQGC Limits
	$WZjj \longrightarrow 3\ell \nu jj$	**CMS-SMP-18-001** EW Sig. 1.9σ obs (2.7σ exp) Cross section (EW, EW+QCD) aQGC Limits

Overview of Experimental Status: 8 TeV

Energy	Measurement	ATLAS	CMS
8 TeV	$W^\pm W^\pm jj \longrightarrow \ell^\pm \nu \ell^\pm \nu jj$	**PRL 113, 141803** EW Sig. 3.6σ obs (2.8σ exp) Cross sec (EW, EW+QCD) aQGC Limits **PRD 96, 012007** Updated aQGC Limits	**PRL 114, 051801** EW Sig. 1.9σ obs (2.9σ exp) Cross sec (EW+QCD) aQGC Limits
	$W\gamma jj \longrightarrow \ell^\pm \nu \gamma jj$		**JHEP 06 (2017) 106** EW Sig. 2.7σ obs (1.5σ exp) Cross sec (EW, EW+QCD) aQGC Limits
	$Z\gamma jj \longrightarrow \ell^\pm \nu \gamma jj$	**JHEP 07 (2017) 107** EW Sig. 2.0σ obs (1.8σ exp) Cross sec (EW, EW+QCD), aQGC Limits	**PLB 770 (2017) 380** EW Sig. 3.0σ obs (2.1σ exp) Cross sec (EW, EW+QCD) aQGC Limits
	$WZjj \longrightarrow 3\ell \nu jj$	**PRD 93, 092004 (2016)** Cross sec (EW, EW+QCD)	**PRL 114, 051801** Cross sec (EW+QCD)
	$WVjj \longrightarrow \ell^\pm \nu jjj(j)$	**PRD 95, 032001 (2017)** aQGC Limits	