Overview of CMS vector boson scattering measurements

Kenneth Long, CERN

for the CMS Collaboration

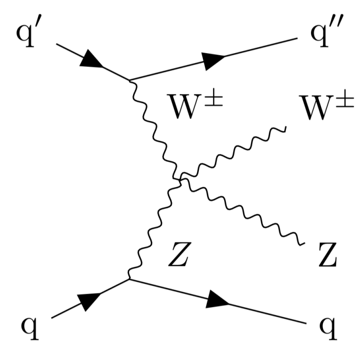
Overview of CMS vector boson scattering measurements

Kenneth Long, CERN

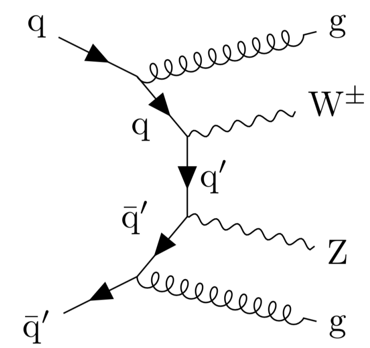
for the CMS Collaboration

Introduction and experimental motivation

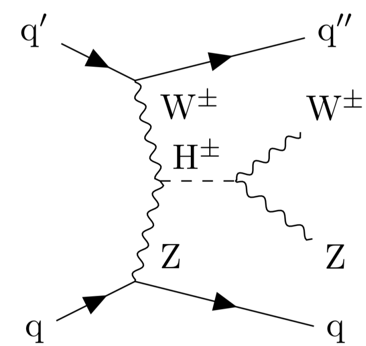
- VV production via vector boson scattering
  - Important component of VVjj production proceeding entirely via EW interactions at tree level
  - V self-interactions and interactions with H precisely predicted
    - Deviations from predictions signal new physics in EW sector



VBS WZjj



Non-VBS WZjj



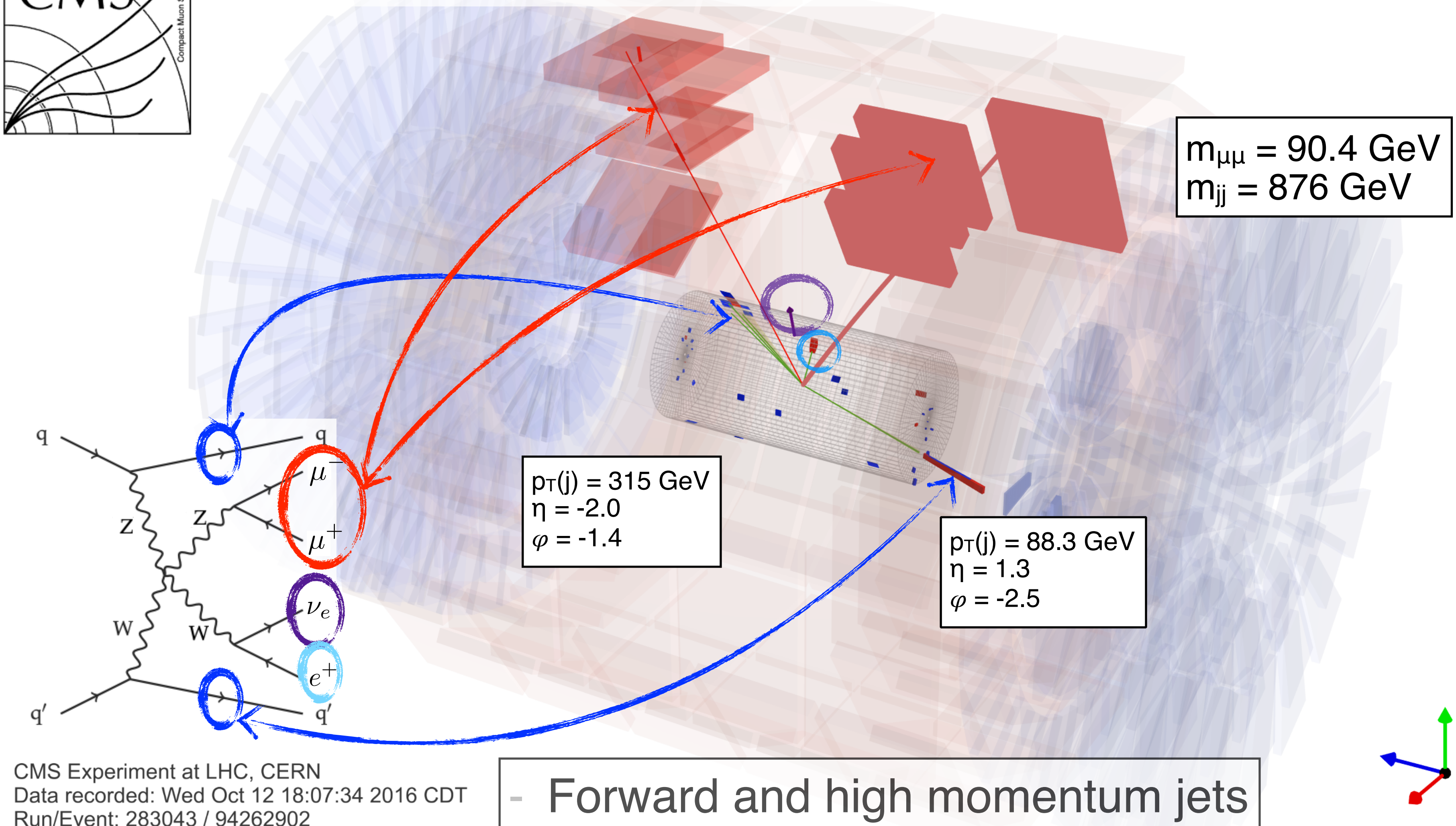
BSM H± Production

- New probe of the SM in the EW sector given high Run II (and Run III) lumi
  - Does VBS production occur with the rate predicted by the SM?
  - Do distributions show any signs of BSM physics?

- Excellent experimental challenge — can we achieve precision?
  - High multiplicity final state, complex and forward objects (jets)

Characteristics of VBS events

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

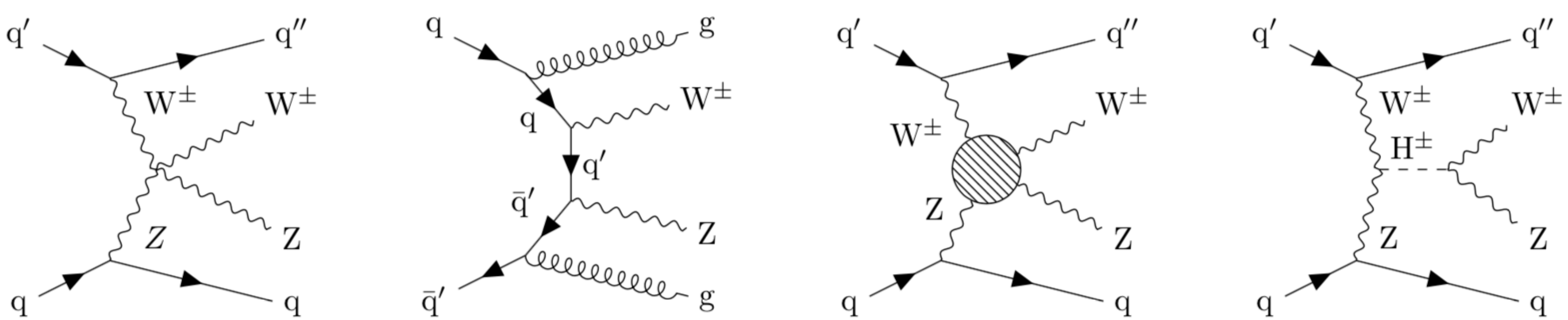


- Forward and high momentum jets
- Leptons central wrt jets

Anatomy of a VBS measurement

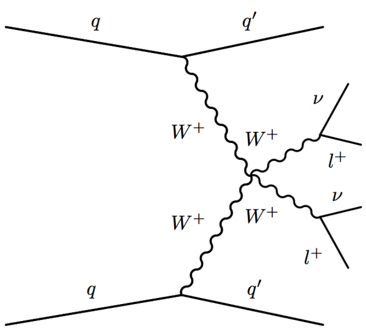
- Select VV events with VBS-like jets
  - Dominant experimental uncertainty: jet energy scale
- Estimate non-VV backgrounds — usually data driven

1. Measure VVjj cross section (treat (a) + (b) as signal)
   - Theoretical dependence minimal for cut-and-count analysis
2. Distinguish EW and QCD production mechanisms through kinematics variables (e.g., of two highest p_T jets)
   - Treat (a) as signal, (b) as background
   - Modeling uncertainties important for MC-driven backgrounds
   - Multi-variate — best sensitivity, less explicit theoretical assumptions
3. Look for new physics modifying VVV (VVVV) interaction
   - Interpret in terms of generic (EFT) (c) or explicit models (d)



(a) $O(\alpha^4)$ (b) $O(\alpha_s^2\alpha^2)$ (c) (d)

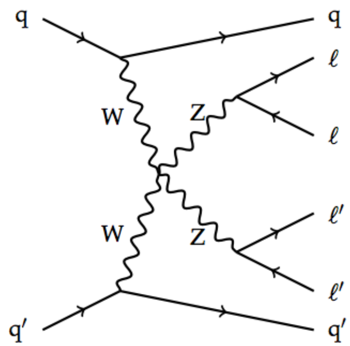
Landscape of VBS measurements ~1 year ago



PRL 120, 081801 (2018)
- EW obs (exp) 6.5 (4.4)
- Via it to m_{jj}+CR

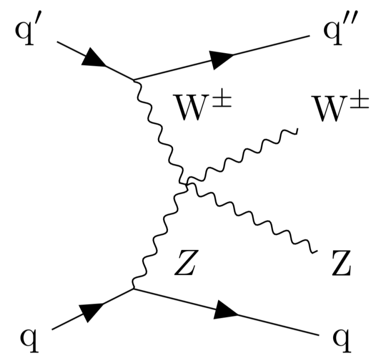
★PRL 123, 161801 (2019)
- EW obs (exp) 2.2 (2.5)
- via 2D fit to mjj/dEtajj

Also at 8 TeV



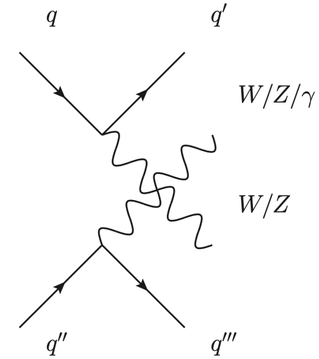
PLB 793 (2019) 469
- EW obs (exp) 5.6 (3.2)
- via fit to BDT+CR

★PLB 795 (2019) 281
- EW obs (exp) 2.7 (1.9)
- Via fit to BDT



★ ATLAS-CONF-2019-033
- EW obs (exp) 5.6 (3.2)
- fit to BDT+CRs

PLB 774 (2017) 682
- EW obs (exp) 2.7 (2.5)
- Via fit to BDT



CERN-EP-2019-206
- EW obs (exp) 4.1 (4.1)
- Via fit to BDT

CMS-SMP-18-007
- EW 3.9 (5.2)
- 2D fit to mjj/ηjj+CR
- combined w/ 8 TeV 4.7 (5.5)

Also at 8 TeV

Wγ at 8 TeV only

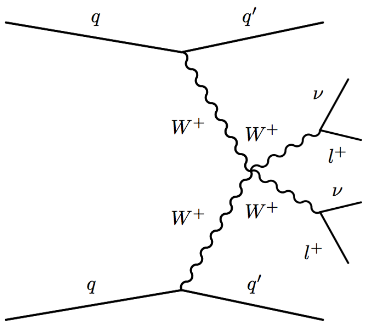
Semi-leptonic decays

PRD 100, 032007 (2019)
EW obs (exp) 2.7 (2.5)
via fit to BDTs in 9 SR+CR

Phys. Lett. B 798 (2019)134985
Only BSM search

Results from ATLAS and CMS at 13 TeV (36 fb^{-1} or ★140 fb^{-1})

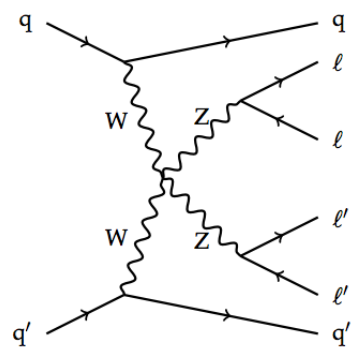
Landscape of VBS measurements today



PRL 120, 081801 (18)
- EW obs (exp) 6.5 (4.4)
- Via it to m_{jj}+CR

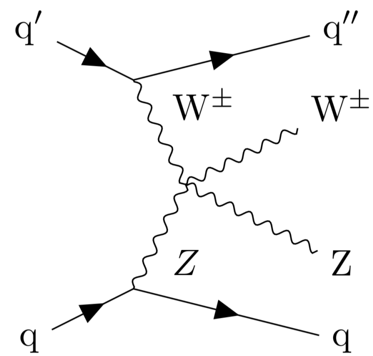
★PLB 809 (20) 135710
- EW obs ≫ 5.0σ
- via 2D fit to mjj/dEtajj
- unfolded xsecs

★PLB 812 (21) 135992
- Polarisation search



PLB 793 (2019) 469
- EW obs (exp) 5.6 (3.2)
- via fit to BDT+CR

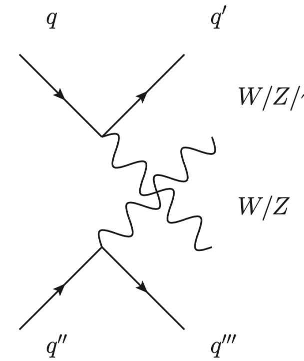
★PLB 812 (20) 135992
- EW obs (exp) 4.0 (3.5)
- Via fit to ME discriminant



★ ATLAS-CONF-2019-033
- EW obs (exp) 5.6 (3.2)
- fit to BDT+CRs

★PLB 809 (20) 135710
- EW obs (exp) 6.8 (5.3)
- via 2D fit to mjj/ηjj +CRs

\+ Via fit to BDT



PLB 803 (20) 135341
- EW obs (exp) 4.1 (4.1)
- Via fit to BDT

JHEP 2006 (20) 076
- EW 3.9 (5.2)
- 2D fit to mjj/ηjj+CR
- combined w/ 8 TeV 4.7 (5.5)

PLB 811 (2020) 13598
- EW 4.9 (4.6)
- combined w/ 8 TeV 5.3 (4.8)

Semi-leptonic decays

PRD 100, 032007 (2019)
EW obs (exp) 2.7 (2.5)
via fit to BDTs in 9 SR+CR

Phys. Lett. B 798 (2019)134985
Only BSM search

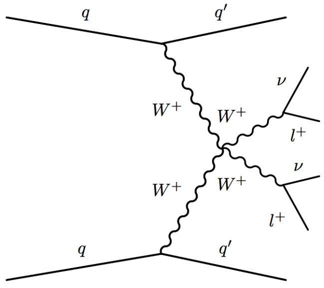
Results from ATLAS and CMS at 13 TeV (36 fb^{-1} or ★140 fb^{-1})

Electroweak W±W±: the golden channel

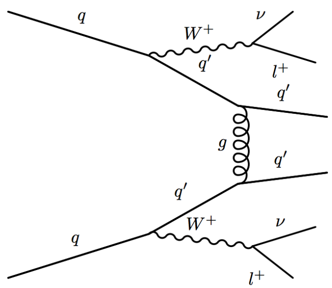
PLB 809 (2020) 135710

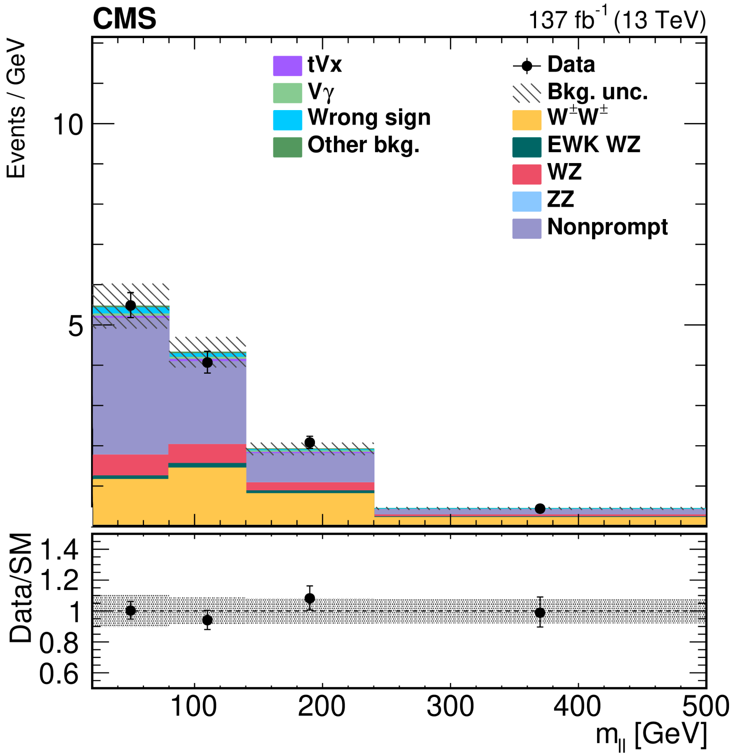
- ★ EW production dominant over QCD-induced
- ★ Distinct same-sign (SS) lepton state
- First studied at 8 TeV, observations with 2016 data
- Moving from search to precise measurement with full Run II data and beyond
- Backgrounds
  - Non-prompt backgrounds $\Longrightarrow$ data driven
  - Charge mis-ID
    - Simulation corrected with data
  - $\geq$ 2 prompt SS leptons from MC
    - WW QCD (small)
    - ★ WZ EW+QCD
      - Correct using 3ℓ data

VBS production



QCD production



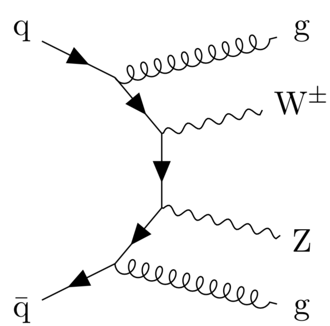


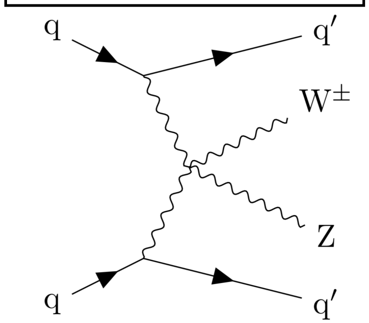
Electroweak WZ: massive charged probe

PLB 809 (2020) 135710

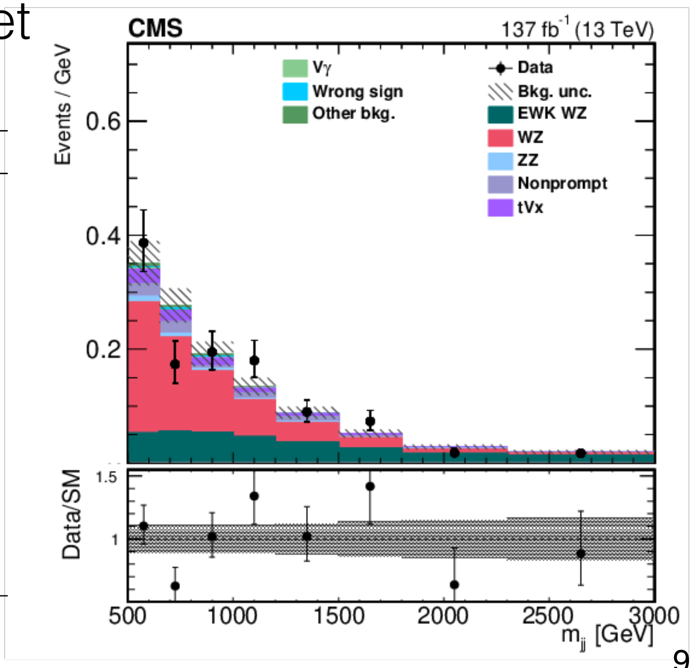
- Background estimation for $W^\pm W^\pm$ is a measurement
  - ➡ Measure simultaneously
- Use huge data set to constrain other MC estimates (ZZ), (top)
- Sensitive to charged resonances or couplings (including Higgs-like)
  - Less clean signature than ZZ, $W^\pm W^\pm$, but cross section accessible with large dataset

QCD production | VBS production





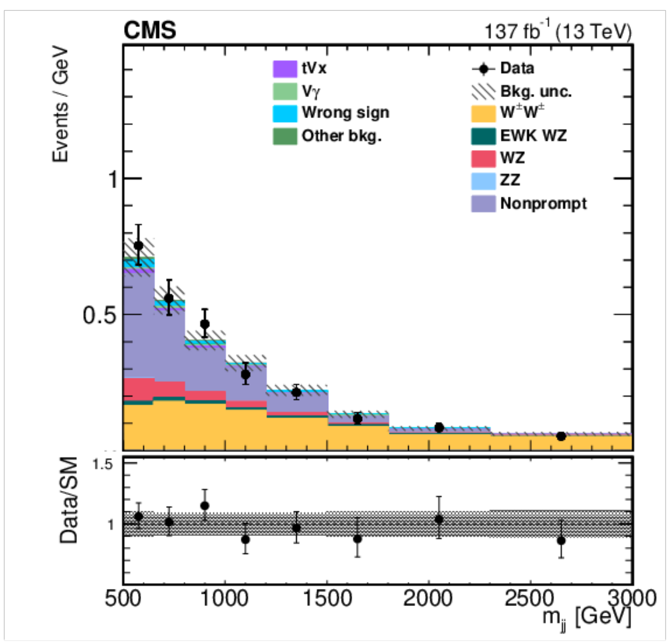
Variable	$W^\pm W^\pm$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	>50 GeV	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b quark veto	Required	Required
$\max(z_\ell^*)$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

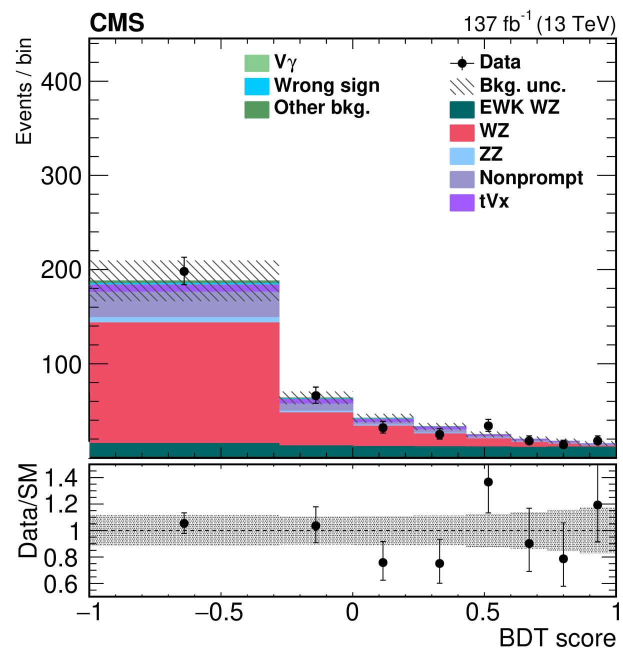


Electroweak W±W±+WZ: combined approach

PLB 809 (2020) 135710

- Simultaneous maximum likelihood fit with WZ and WW treated as signal
  - For WZ, train BDT with 13 variables to distinguish EW from QCD
    - Jet, V (lepton, MET), jet+V kinematics
    - ~20% improvement wrt 2D η_{jj}/m_{jj} approach used for WW
- Likelihood built from bins of WZ BDT in WZ SR, WW in 2D η_{jj}/m_{jj} in WW SR, and m_{jj} in b-tagged non prompt, tVq, and ZZ cRs
- Signals + tZq ,ZZ with unconstrained normalisations

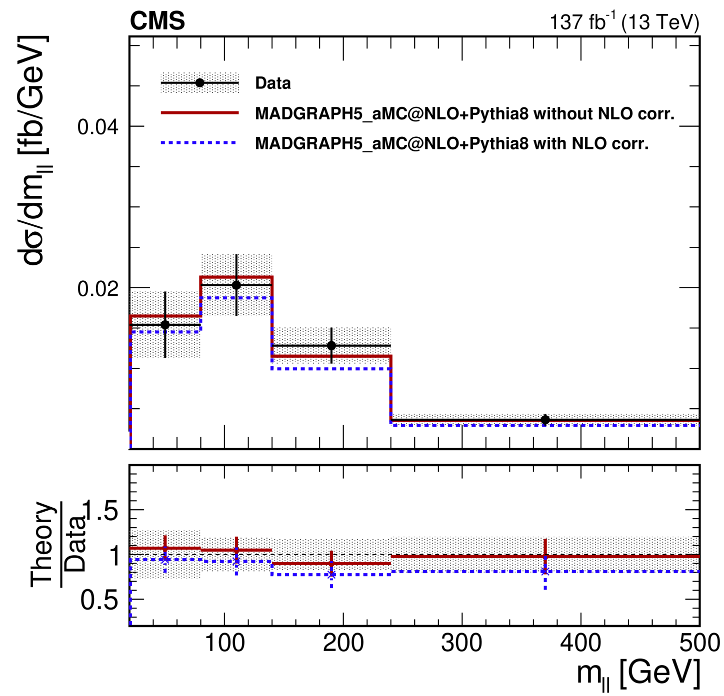


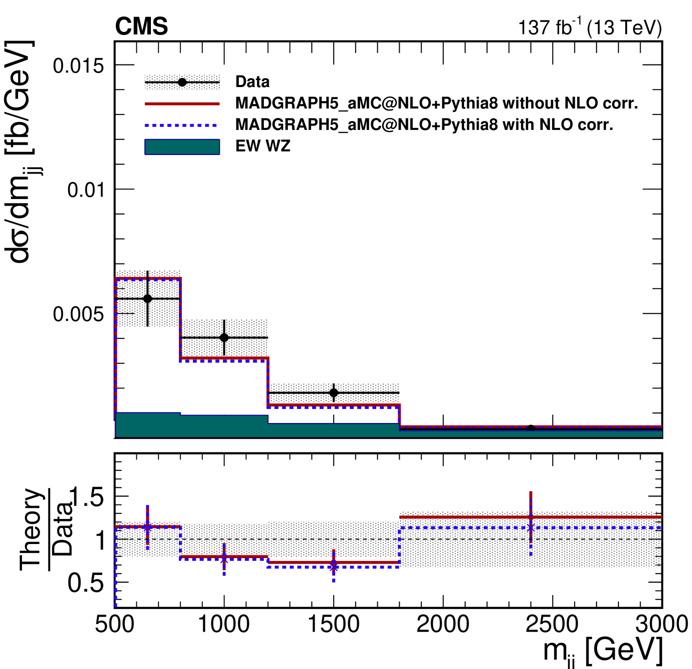


Electroweak $W^{\pm}W^{\pm}$ and WZ: results

PLB 809 (2020) 135710

- Sensitivity to WW far exceeds 5 sigma
- WZ significance obs. 6.8 (5.3 exp) s.d.
- Fiducial cross sections and unfolded distributions also reported
  - Unfolding via maximum likelihood fit without regularisation
  - WZ BDT replaced by mjj or observable





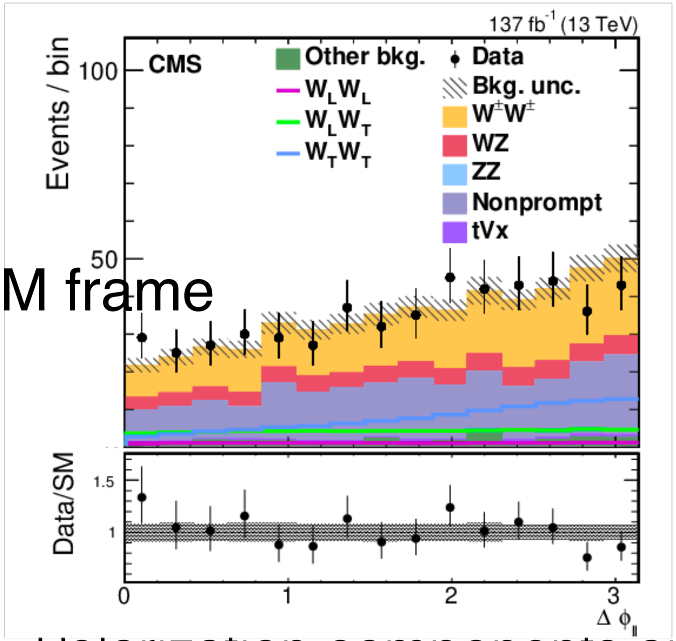
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	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

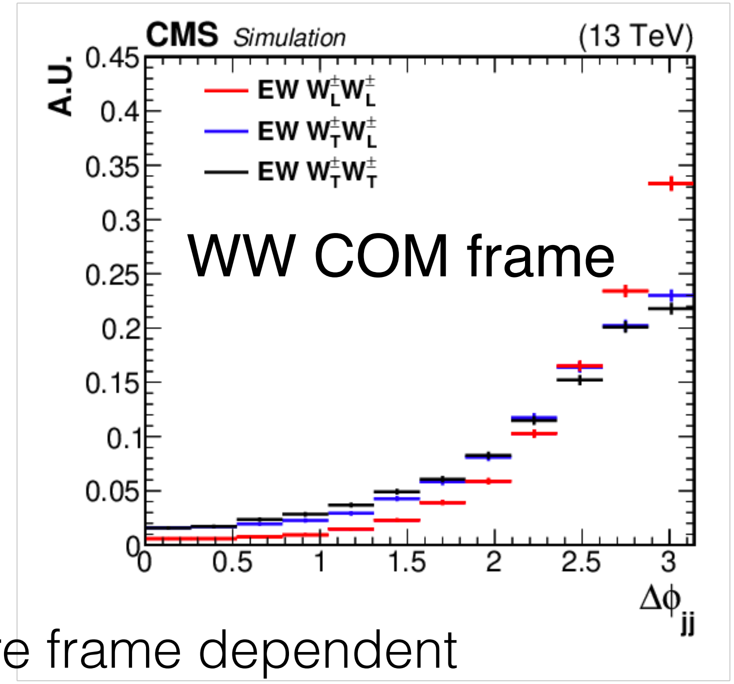
Electroweak W±W±: polarization study

PLB 809 (2020) 135710

- Longitudinal component of W±W± large is of large interest (coupling to H, regulating perturbative SM)
  - ➡ Measurement of EW W±W± at ~10% precision allows first study
    - LL component ~10% of total
- Same selection and CRs (WZjj as background) as previous work
  - + use BDT to separate W±W± from all backgrounds (esp. nonprompt)
  - + BDTs to distinguish polarised components

WW COM frame





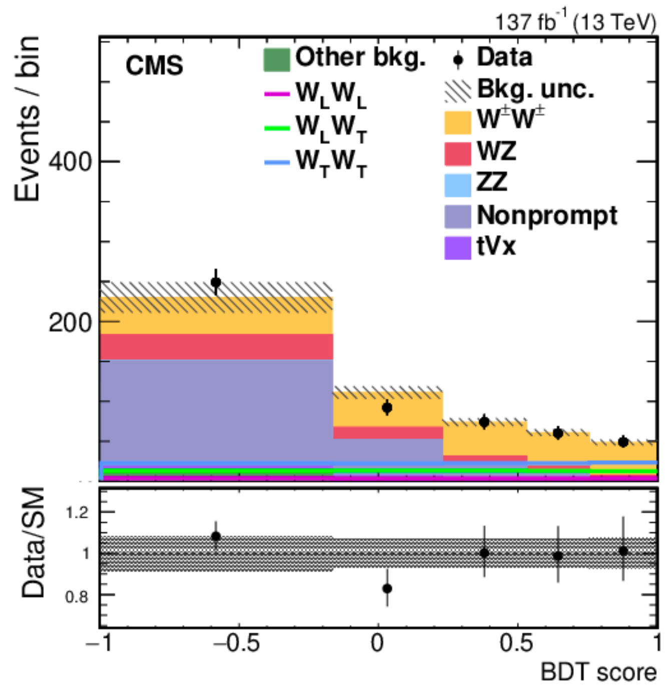
- Polarization components are frame dependent
  - Consider both WW and parton-parton COM frames

Electroweak W±W±: polarization results

PLB 809 (2020) 135710

- Size of data set is not sufficient to measure LL, LT, and TT all simultaneously
  - Consider LL vs. XT and TT vs LX $\Longrightarrow$ BDTs trained for each
    - Jet, lepton/MET kinematics, and jet+V kinematics
  - Retrained for WW or parton-parton com frame
- Results in WW com frame
- 95% CL limits on LL ~2-3x SM
  - LL 95% CL limit: 1.17 (0.88) fb
  - LX observed at 2.3 (3.1) s.d.

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



WW COM frame

Electroweak ZZ: strong at high lumi

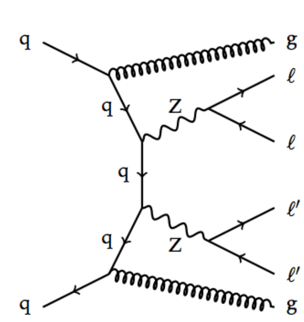
PLB 812 (2021) 135992

- Extremely clean four lepton signal (ℓ = e, μ)
  - Very low nonprompt (fake) background
  - Fully reconstructed final state
    - Access to boson polarizations

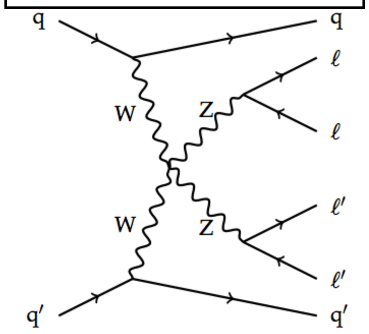
… But very low production cross section

- ZZ(4ℓ) Selection
  - 4 loose ID leptons, p_T(μ, e) > 5, 7 GeV
  - m_{jj} > 100 GeV (ptr > 30 GeV)
    - Expected S/B ~1/20

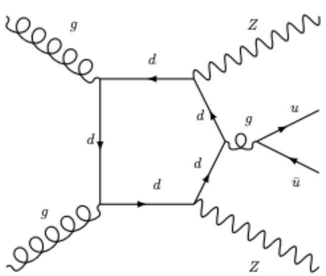
QCD production



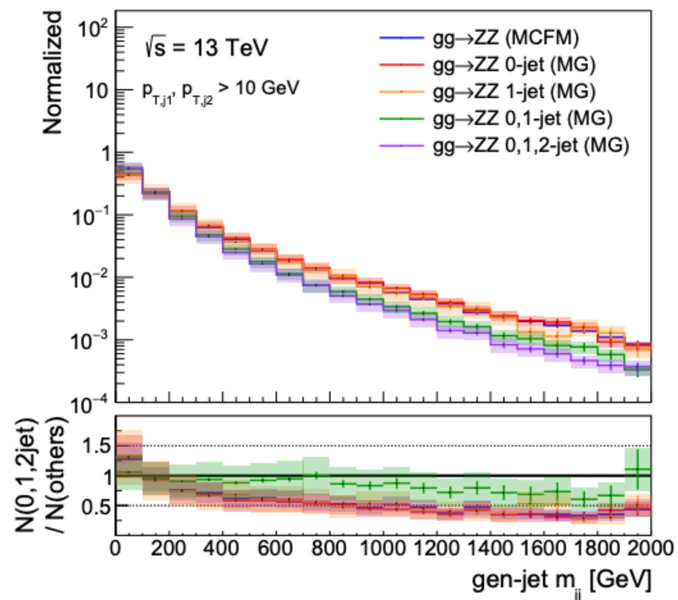
VBS production



- Estimating ZZjj QCD background is primary challenge
  - Predominately qq and qg induced, but gg-induced component significant in most signal-like region
  - Simulated with merged gg loop-induced +jets predictions with MG5_aMC



+



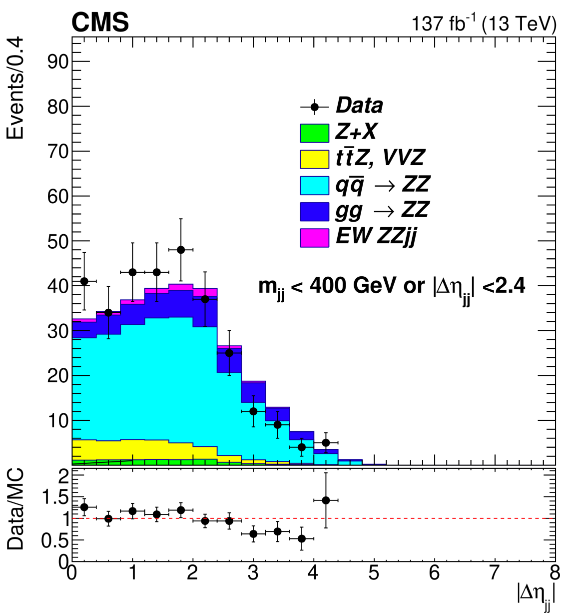
Kenneth Long

https://arxiv.org/abs/2006.12860

Electroweak ZZ results

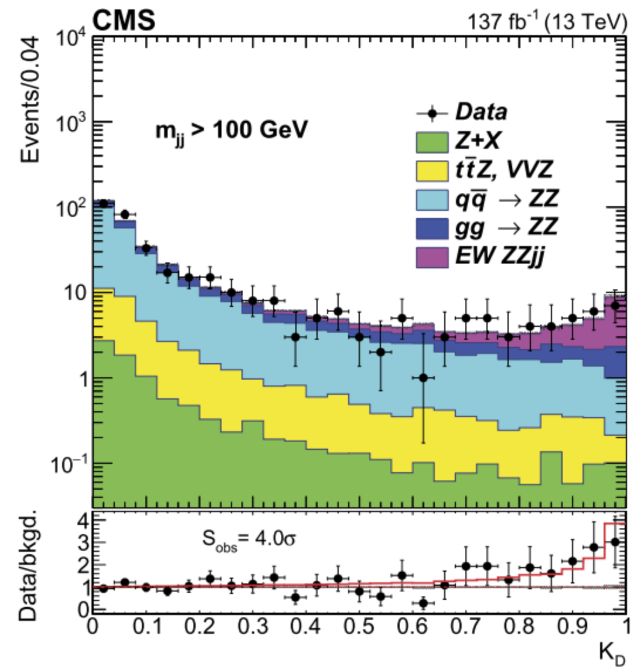
PLB 812 (2021) 135992

- Low S/B, but discrimination possible
  - Exploit matrix element discriminant (K_D)
  - Fit distribution in loose selection



Left: subset of distribution used in fit (right)

$$\mu = \sigma_{obs}/\sigma_{th.} = 1.22^{+0.47}_{-0.40}$$



  - Observed (expected) of 4.0σ (3.5σ)
- Several fiducial cross sections of EW, EW+QCD production

MG5_aMC at LO
POWHEG NLO

	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
	LO	0.275 ± 0.021	
EW	NLO QCD	0.278 ± 0.017	$0.33^{+0.11}_{-0.10}\,(\text{stat})^{+0.04}_{-0.03}\,(\text{syst})$
	NLO EW	$0.242^{+0.015}_{-0.013}$	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}\,(\text{stat}) \pm 0.47\,(\text{syst})$

$Z\gamma$: neutral interactions + photons

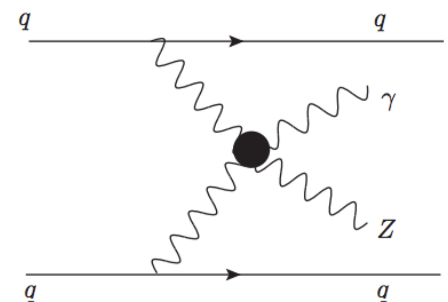
JHEP 2006 (2020) 076

- Probe neutral quartic couplings
  - Clean signal from leptonic Z decay
  - Fully reconstructed final state
  - Neutral probe with higher cross section than ZZ

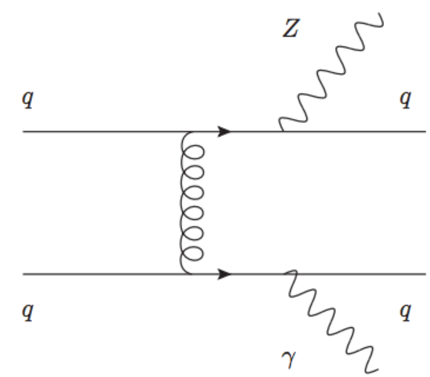
$$\eta^* = |\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2|$$

Common selection	$p_T^{\ell 1,\ell 2} > 25\,\text{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.5$ for electron channel $p_T^{\ell 1,\ell 2} > 20\,\text{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.4$ for muon channel $p_T^{\gamma} > 20\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.444$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_T^{j1,j2} > 30\,\text{GeV}$, $\lvert\eta^{j1,j2}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\,\text{GeV}$, $m_{Z\gamma} > 100\,\text{GeV}$ ΔR_{jj}, $\Delta R_{j\gamma}$, $\Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Control region	$150 < m_{jj} < 400\,\text{GeV}$, Common selection
EW signal region	$m_{jj} > 500\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$, $\eta^* < 2.4$, $\Delta\phi_{Z\gamma,jj} > 1.9$, Common selection

VBS production



QCD production



- Backgrounds with nonprompt photons and leptons estimated with data-driven approach
  - Other background from MC
  - Control region to validate and constrain QCD $Z\gamma$

Electroweak $Z\gamma$: CMS results

JHEP 2006 (2020) 076

- Fit to 2D distribution of m_{jj} and $\Delta\eta_{jj}$
  - EW cross section obtained from best-fit signal strength
    - Include yield in 100 < mjj < 400 GeV CR (constrain QCD VVjj)
  - Separate bins per photon barrel/endcap and lepton flavour

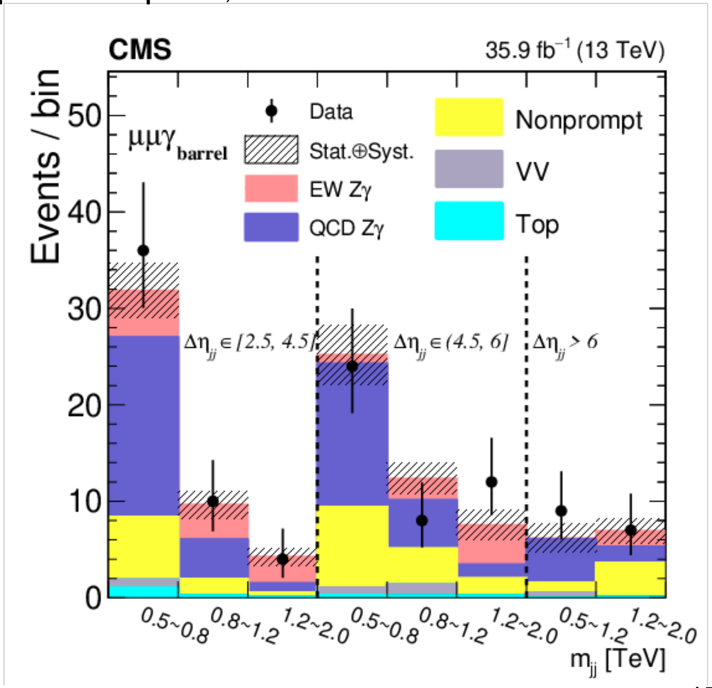
$$\mu_{EW} = \sigma_{obs}/\sigma_{th.} = 0.65 \pm 0.24$$

$\sigma_{th.}$ from MG_aMC LO

- Observed (expected) significance 3.9σ (5.2σ)
  - ➡4.7 (5.5) combined with 8 TeV assuming $\mu_{EW} = \mu_{EW,SM} = 1$
- Also perform fit with EW and QCD signal

$$\sigma_{fid} = 14.3 \pm 1.1\ (\text{stat}) \pm 2.7\ (\text{syst})\ \text{fb}$$

- Agrees with MG5_aMC prediction, $\sigma_{LO} = 15.7 \pm 1.7$ fb

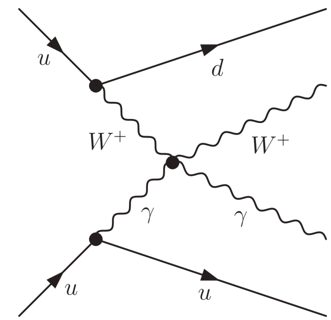


Wγ: charged interactions + photons

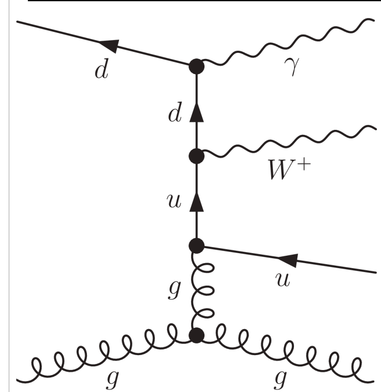
PLB 811 (2020) 135988

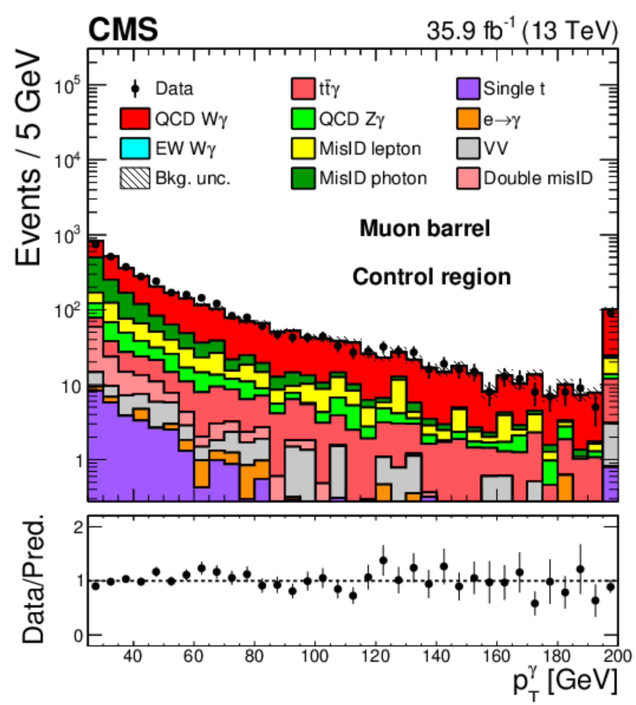
- Probe charged couplings with photons
  - Highest VBS cross section
  - Challenging experimental state
    - Significant contribution from mis-ID photons and leptons
- Select moderate pt lepton, MET, photon
  - Electron channel: $m_{\ell\gamma}$ not consistent with m_Z
  - $m_{jj} > 500$ GeV and $\Delta\eta > 2.5$
  - $|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 1.2$
- Very similar approach to $Z\gamma$ for background estimation
  - Backgrounds data driven or MC (prompt/nonprompt)

VBS production



QCD production





Electroweak Wγ: results

- Very similar approach to Gamma analysis
  - EW, EW+QCD via fit to 2D distribution of m_{jj} and $\Delta\eta_{jj}$
  - Control region of m_{jj} 200 - 400 to constrain QCD norm.

PLB 811 (2020) 135988

$$\mu = \sigma_{obs}/\sigma_{th.} = 1.20 \ {}^{+0.26}_{-0.24}$$

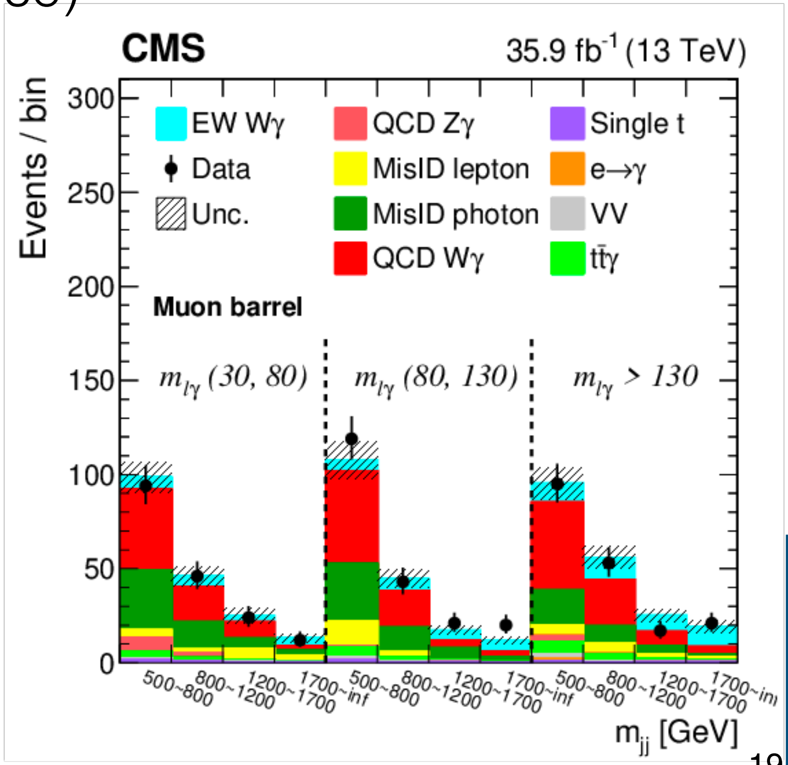
$\sigma_{th.}$ from MG_aMC LO

- Observed (expected) significance 4.9σ (4.6σ)
  ➡ 5.3 (4.8) combined with 8 TeV assuming $\mu_{EW} = \mu_{EW,SM} = 1$
- Also perform fit with EW and QCD signal

$$\sigma_{fid} = 108 \pm 5 \text{ (stat)} \pm 15 \text{ (syst) fb}$$

- Agrees with MG5_aMC prediction @LO

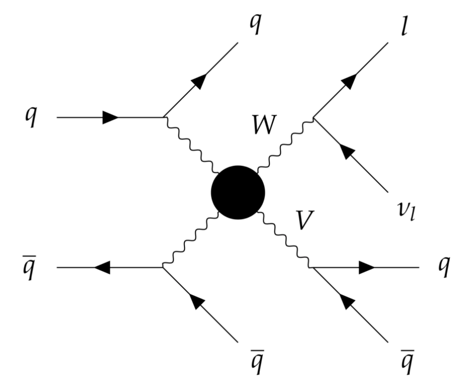
$$\mu = \sigma_{obs}/\sigma_{th.} = 1.21 \ {}^{+0.17}_{-0.16}$$

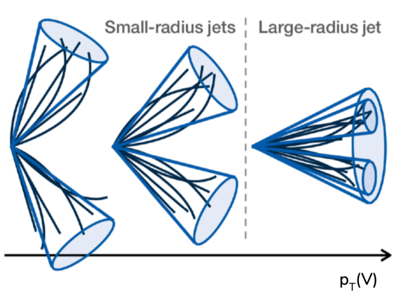


Semi-leptonic VBS: experimental challenge

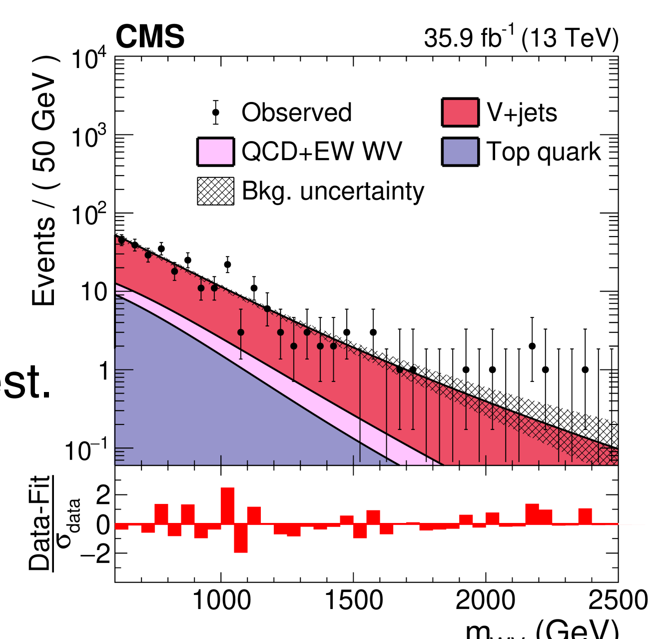
PLB 798 (2019)134985

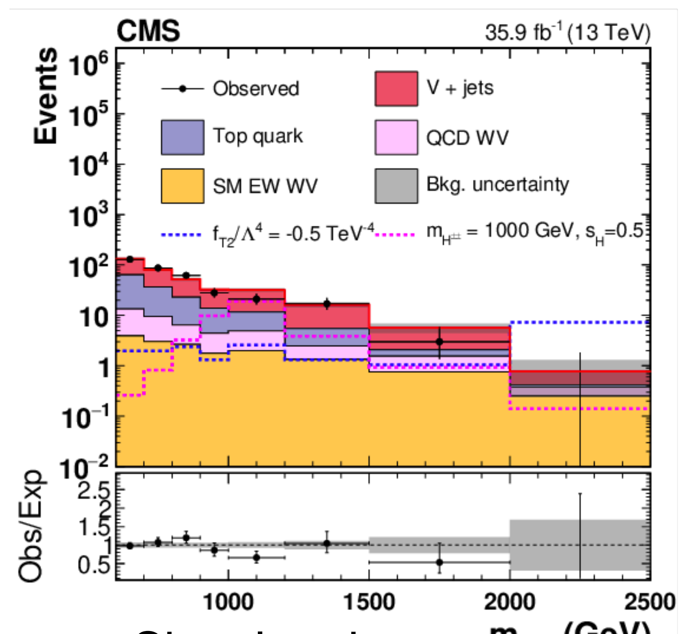
- High cross section $\Longrightarrow$ sensitive to BSM
  - But very experimentally complex!
  - Overwhelming backgrounds not just from VVjj, but also from V+jets and top production
    - Focus on BSM, boosted Vqq events ("fat" V jets)
- Require high-pt lepton + MET or two leptons
- V+jets background estimation primary challenge
  - Estimated from sideband region of fat jet mass (off m_V)





Background est.





Signal region

Anomalous couplings: overview

- Studied using basis of Eboli, Gonzlez-Garcia, Mizukoshi [2]
  - All parity and charge conserving operators with pure V,H couplings

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

  - Operators constructed from Higgs fields only, gauge field only, and Higgs and gauge fields

$$\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \mathrm{Tr} \left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right]$$

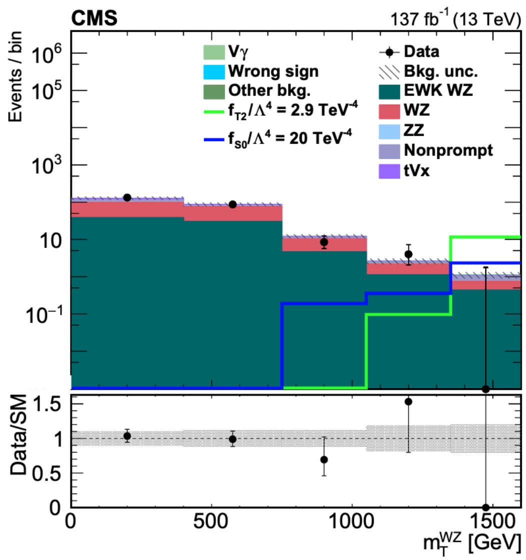
(Φ denotes H field)

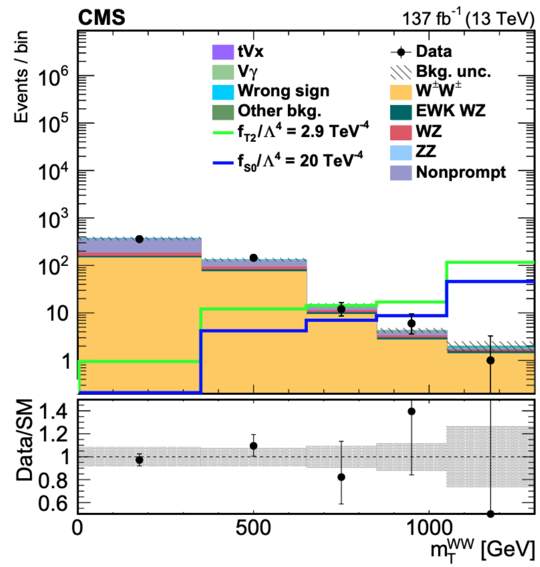
- All realized as excess at high m_{WZ}
- Generalizes V,H interactions
- With some caveats…
  - Assume dimension-6 operators (should dominate) are negligible
  - Applicability of EFT assumes $\hat{s} \ll \Lambda$
- We are aware of recent studies of dimension-6 affects in VBS channels
  - Expect to explore this at CMS in the future

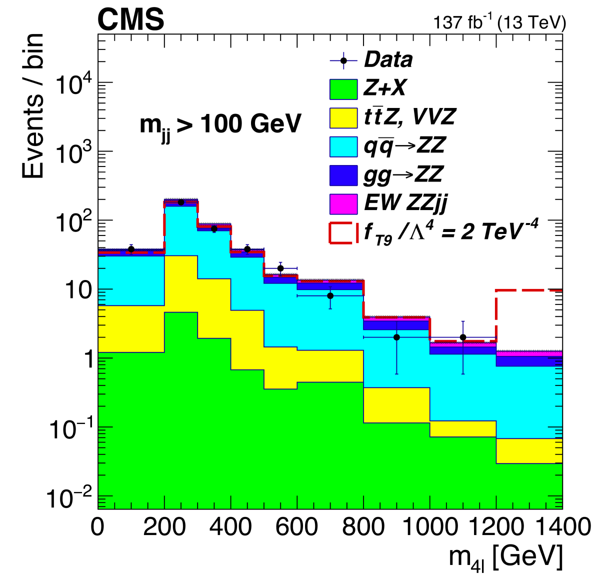
[2] https://arxiv.org/abs/hep-ph/0606118

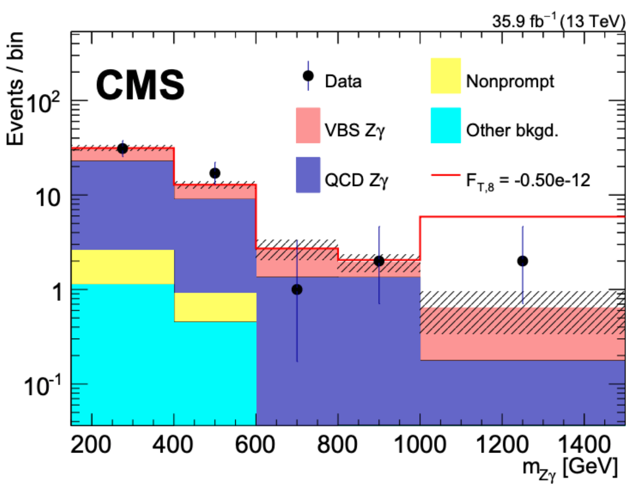
Anomalous couplings: approach

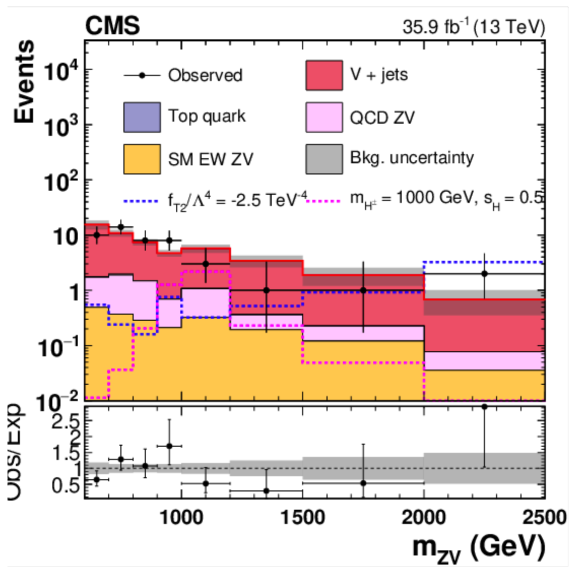
- Exploit variables sensitive to modification from high-mass interaction

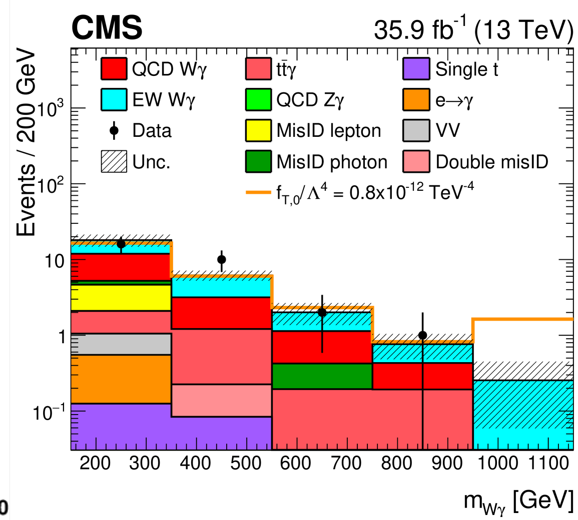






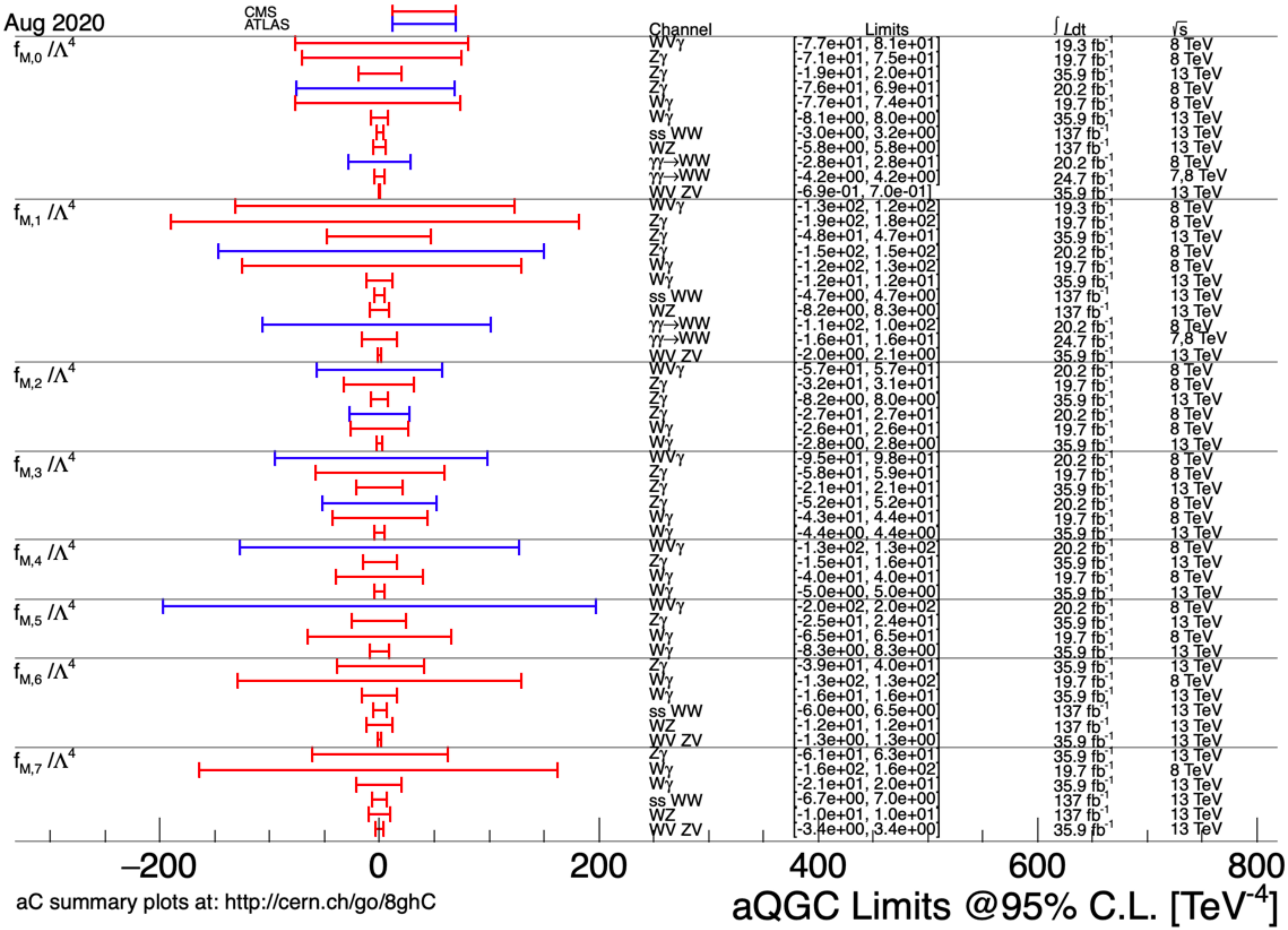






Kenneth Long

Anomalous couplings: illustrative results



Conclusions

- Vector boson scattering processes are quickly moving from search to measurement
  - Stringent probe of the SM as a search for BSM physics
  - Several channels explored with 140 fb^{-1}, others in progress
    - SM-like properties have been demonstrated
    - Subtle deviations will take more data, better ideas, and better interplay with theoretical predictions
- Sensitivity to longitudinal polarization is possible at HL-LHC
  - First studies have been made with real data, will help us understand our projections better
  - Can we do better?
    - Control modeling with improved calculations tuned from measurements
- Many opportunities to continue exploiting high luminosity