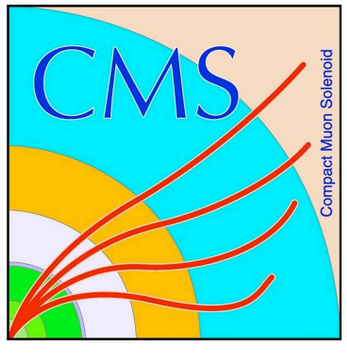
Electroweak Physics with Single and Diboson Final States in CMS

Phenomenology 2019 Symposium
University of Pittsburgh, USA

May 7th, 2019



Vieri Candelise

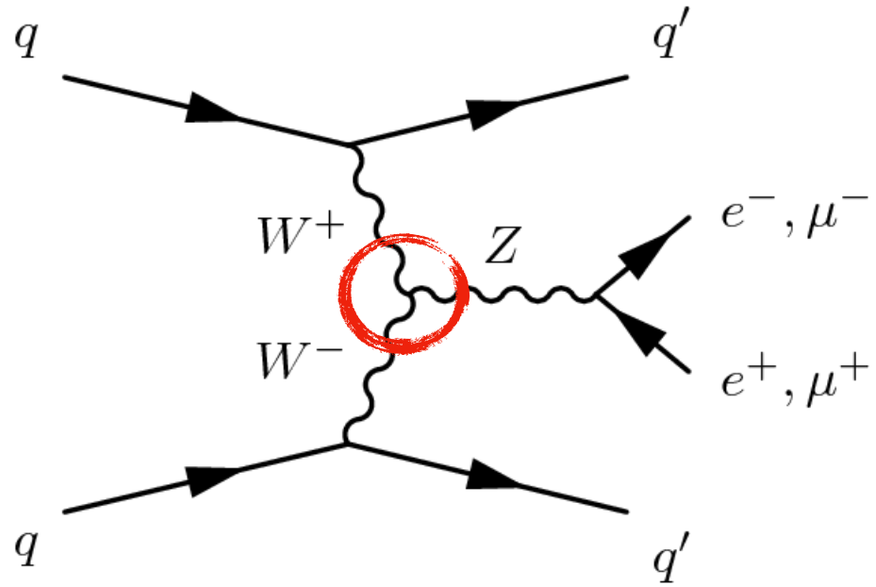
on behalf of the CMS Collaboration

Phenomenology of EW bosons at the LHC

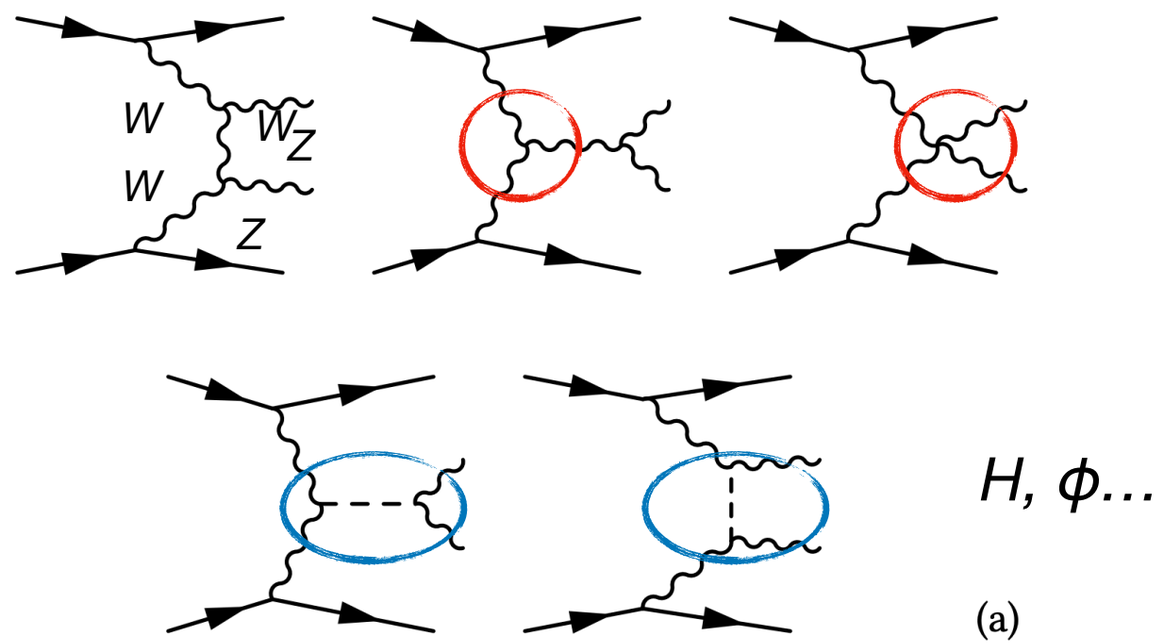
Exploiting the non-Abelian nature of the SU(2)XU(1) symmetry group: vector bosons interact!

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - igf^a_{bc}A^b_\mu A^c_\nu$$

single boson



diboson



very clean signature at colliders: 2 isolated leptons + 2 high energy jet highly separated in Δη

- pure EW production: order α^4_{EW} versus Drell-Yan order $\alpha^2_{QCD}\,\alpha^2_{EW}$
- includes diagrams with VBF processes: highly sensitive to EWSB and potential New Physics
- constrain SM-forbidden diagrams including higher order operators: anomalous triple/quartic gauge couplings

$$\mathscr{L}_{aQGC} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^{d-4}} O_i + \ldots$$

A model-independent way of searching for New Physics

Overview

COVERED IN THIS TALK

REFERENCE

- Electroweak production of Z+JJ

  Published in EPJC
  doi:10.1140/epjc/s10052-018-6049-9

- Electroweak production of W+JJ

  Submitted to EPJC
  arXiv:1903.04040

- Same-Sign $W^{\pm}W^{\pm}$ production

  Published in Physical Review Letters
  PhysRevLett.120.081801

- Electroweak $W^{\pm}Z$ production

  Submitted to Physics Letters B
  arXiv:1901.04060

NOT COVERED IN THIS TALK

REFERENCE

- Electroweak ZZ+JJ

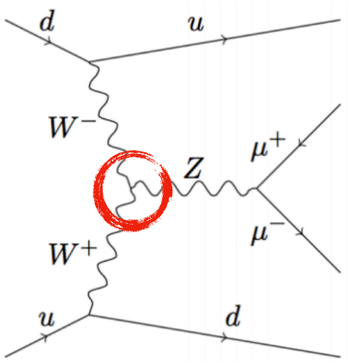
  Published in Physical Review Letters
  Phys. Lett. B 774 (2017) 682

- Electroweak γ+JJ

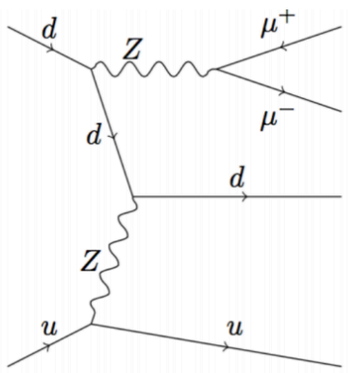
  ongoing

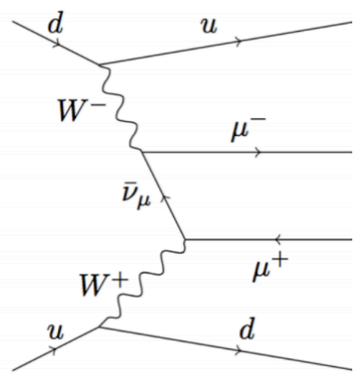
Electroweak production of Z+JJ

$\sqrt{s} = 13$ TeV
$\int L = 35.9$ fb^{-1}

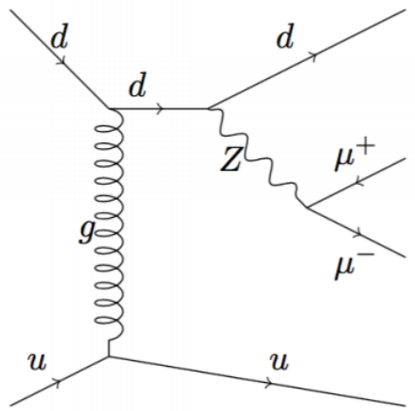


VBF Signal





Pure Electroweak



DY background

Signal definition

pT(j)>25 GeV, |η(j)|< 5, m(jj)>120 GeV, m(ll)>50 GeV and cross section

Vector Boson Fusion Z topology:

- Central Z decay +2 forward-backward jets
- Large dijet Δη separation
- Large invariant dijet mass

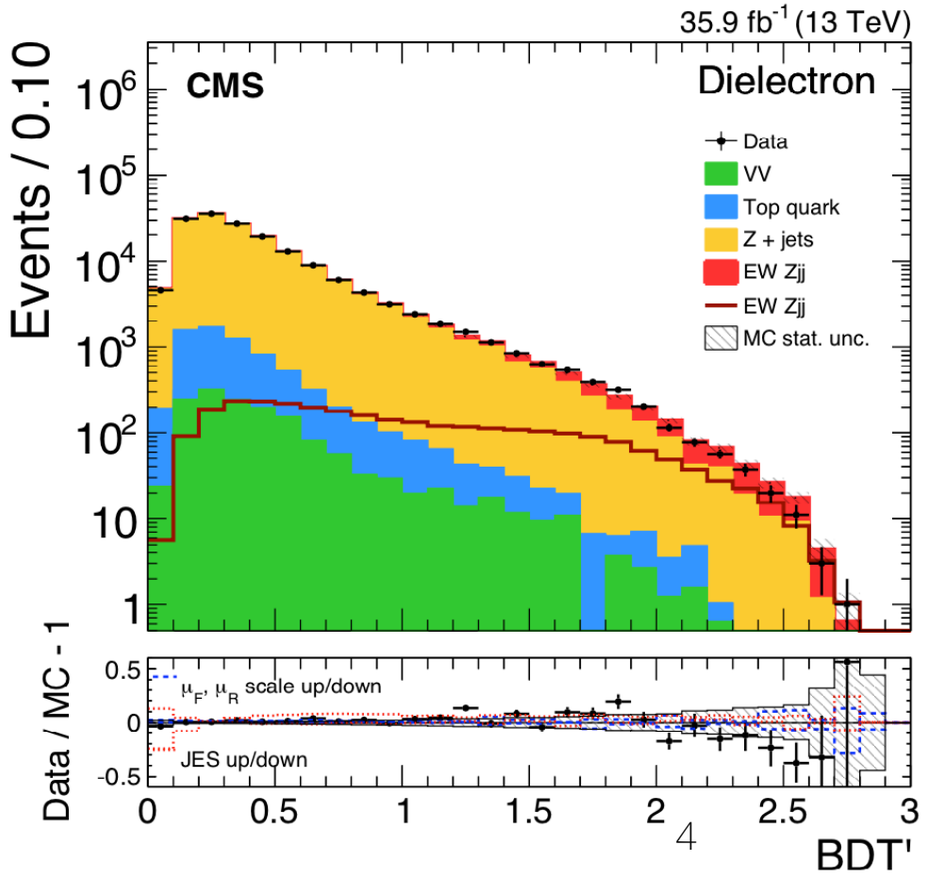
pure EW production: only q-jets initiated
DY production: ~50% jets produced are g-induced
Quark-Gluon Likelohood discrimination (**QGL**)

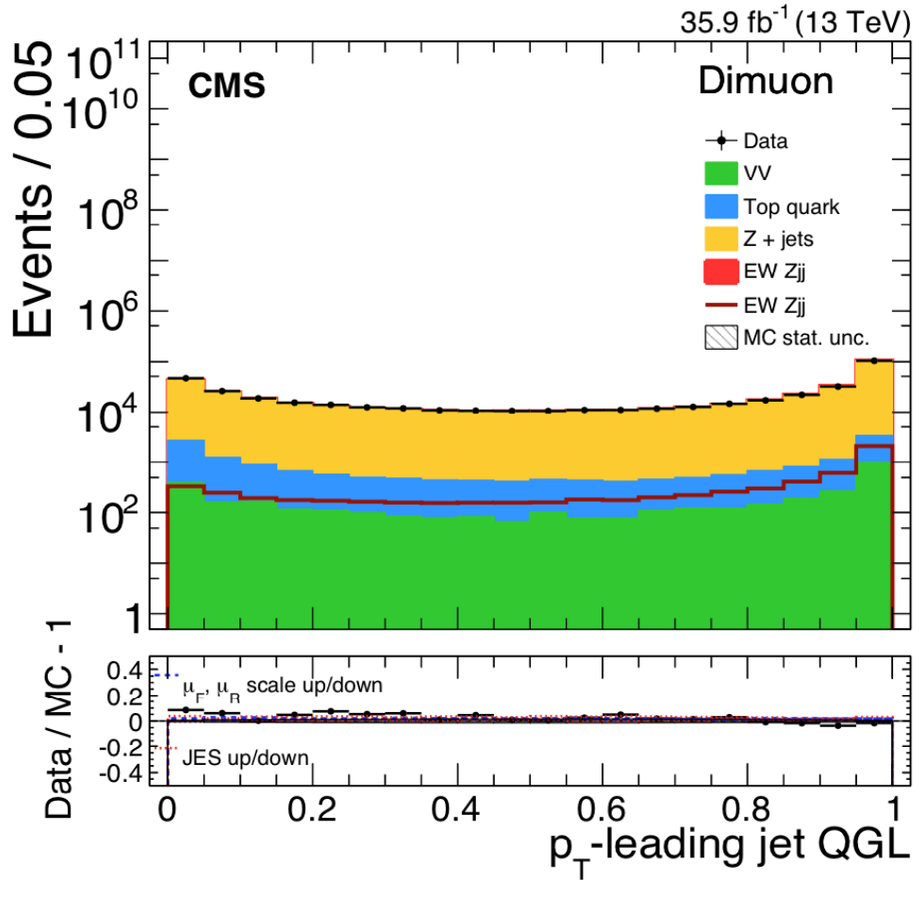
Signal is generally covered by the DY background

Signal Extraction:

Use multivariate analysis techniques to separate signal events from large DY background

- m(qq), Δη(qq),
- QGL,
- pT(qq),
- R(pThard),
- z*ll



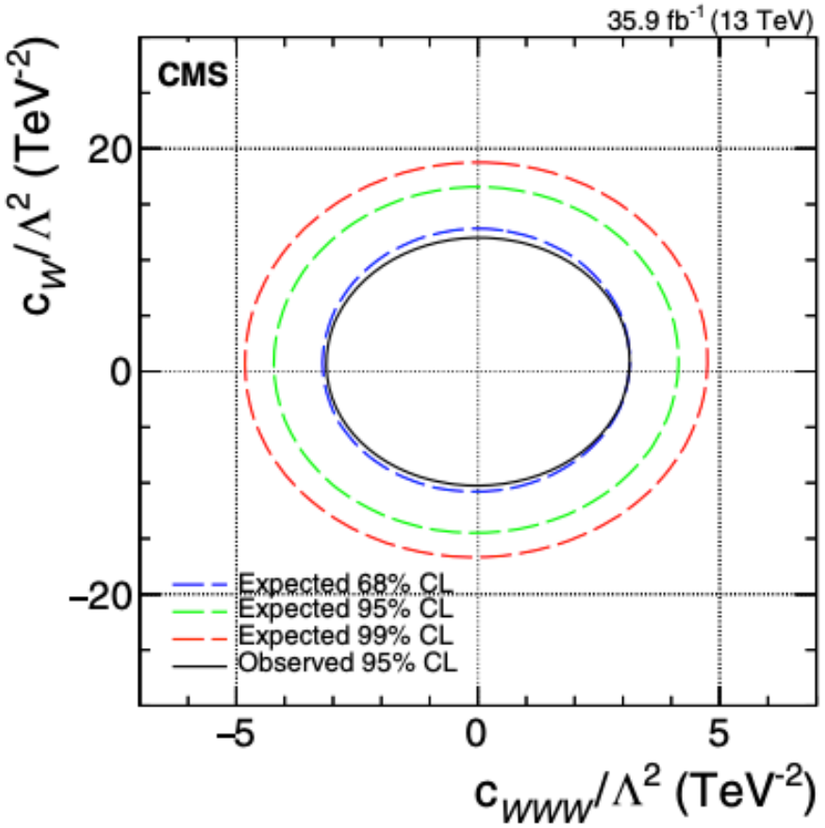


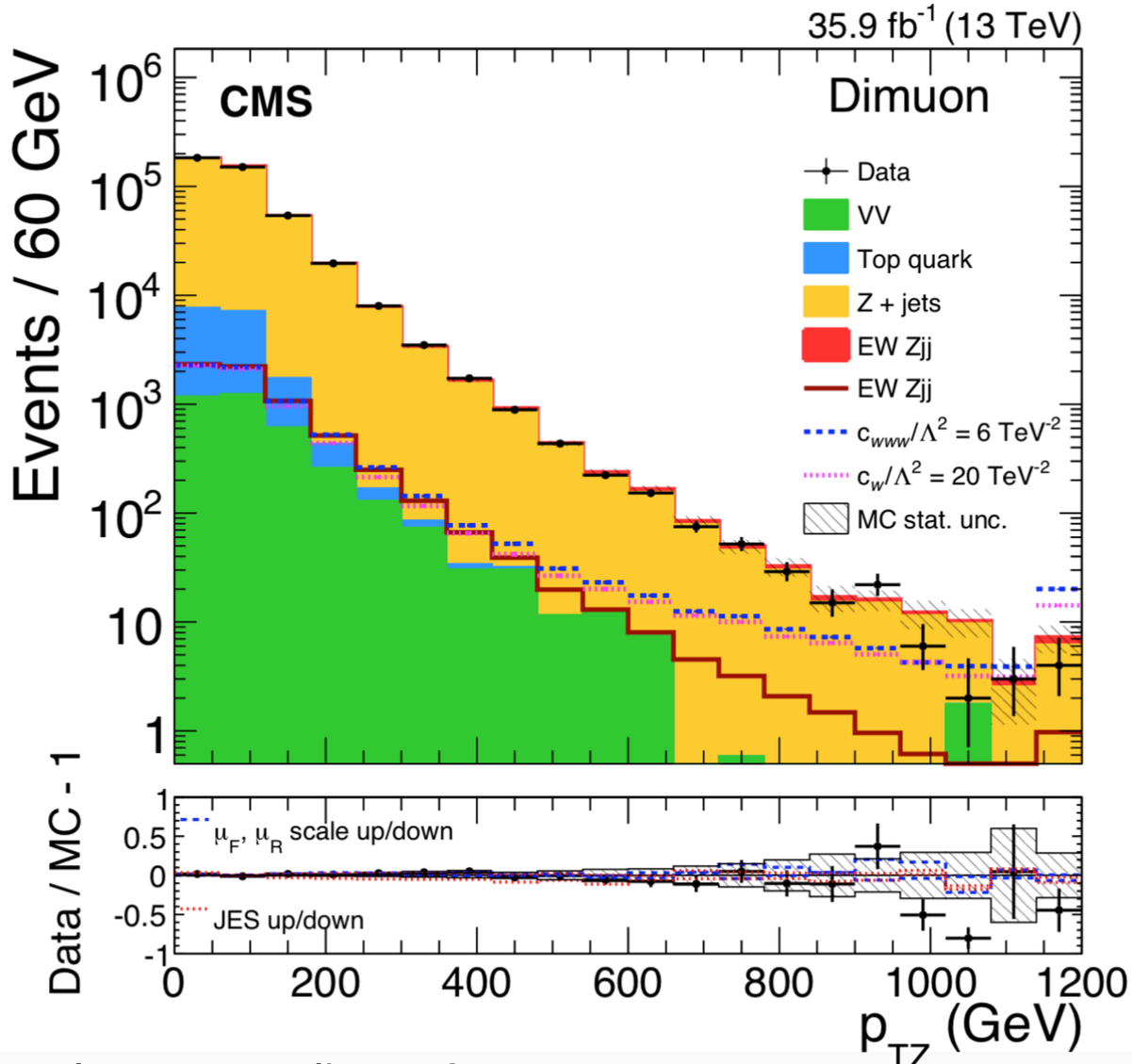
Electroweak production of Z+JJ

$\sqrt{s}$ = 13 TeV
$\int L$ = 35.9 fb^{-1}

→ **σ(EW lljj) = 534 ± 20 (stat) ± 57 (syst) fb = 534 ± 60 (total) fb**

σLO (EW lljj) = 543 ± 24 fb





$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho},$$
$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} W_{\mu\nu} (D^{\nu}\Phi),$$
$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} B_{\mu\nu} (D^{\nu}\Phi),$$
$$\tilde{\mathcal{O}}_{WWW} = \frac{\tilde{c}_{WWW}}{\Lambda^2} \tilde{W}_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho},$$
$$\tilde{\mathcal{O}}_{W} = \frac{\tilde{c}_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} \tilde{W}_{\mu\nu} (D^{\nu}\Phi),$$

- Limits on anomalous couplings from dilepton p_T spectrum after preselection
- 6-dimensional EFT approximation
  simulated with MADGRAPH5 aMC@NLO

95%CL

$-8.4 < c_W/\Lambda^2 < 10.1\,\text{TeV}^{-2}$

$-2.6 < c_{WWW}/\Lambda^2 < 2.6\,\text{TeV}^{-2}$

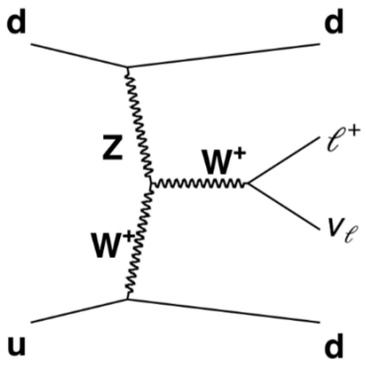
most stringent constraints on ***cWWW*** to date with the Z

Electroweak production of *W+JJ*

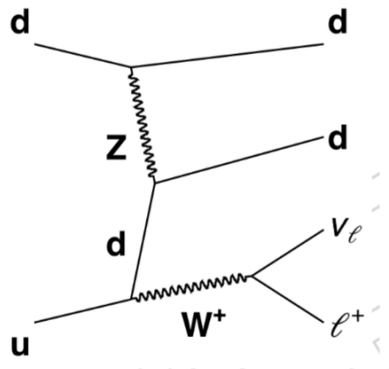
$\sqrt{s} = 13$ TeV

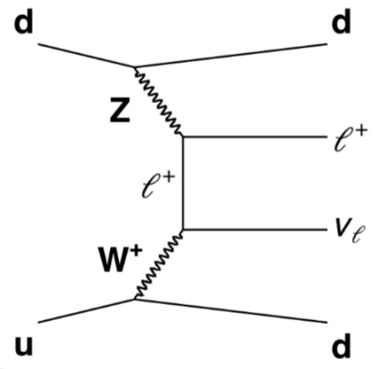
$\int L = 35.9\ \text{fb}^{-1}$

Signal



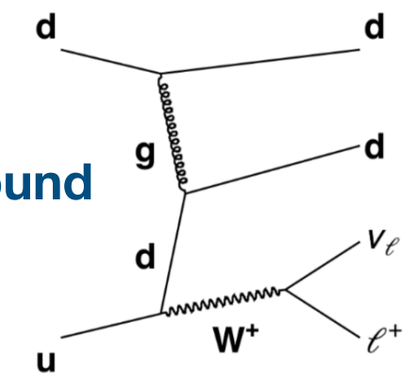
VBF

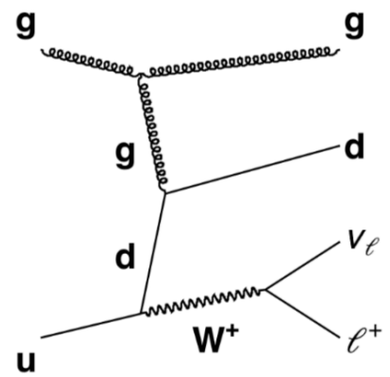




pure electroweak

Background





Drell-Yan

Vector Boson Fusion *Z* topology:

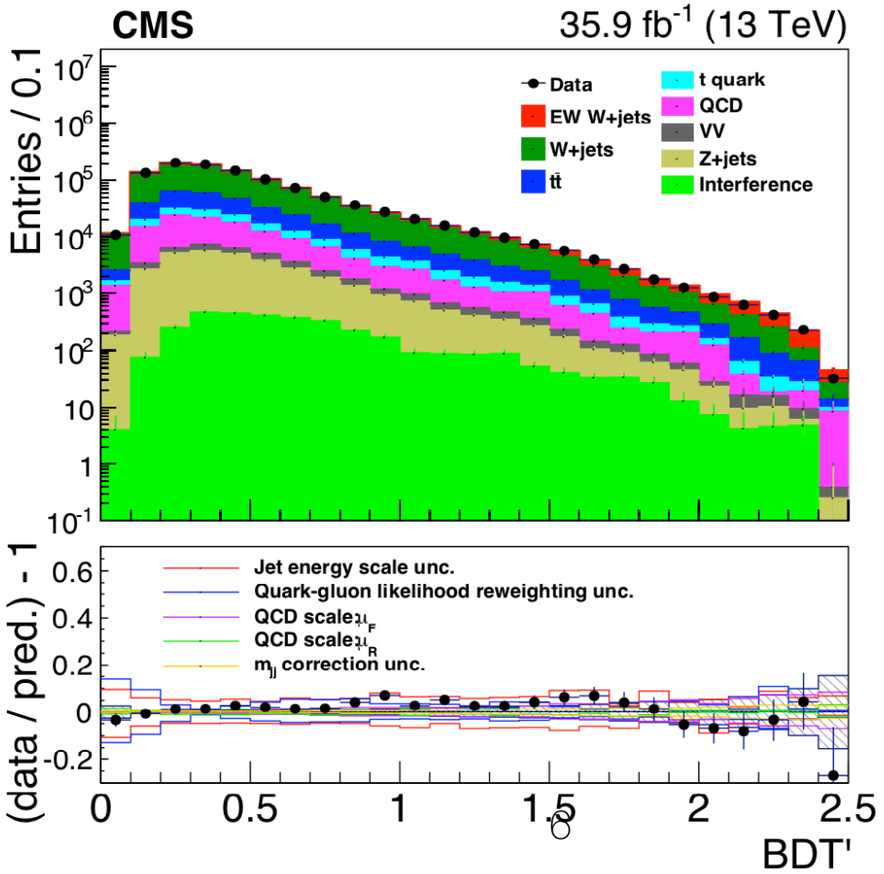
- Central *W* decay plus 2 forward-backward jets
- Large dijet Δη separation
- Invariant dijet mass > 200 GeV
- Jet p_T > 50,30 GeV

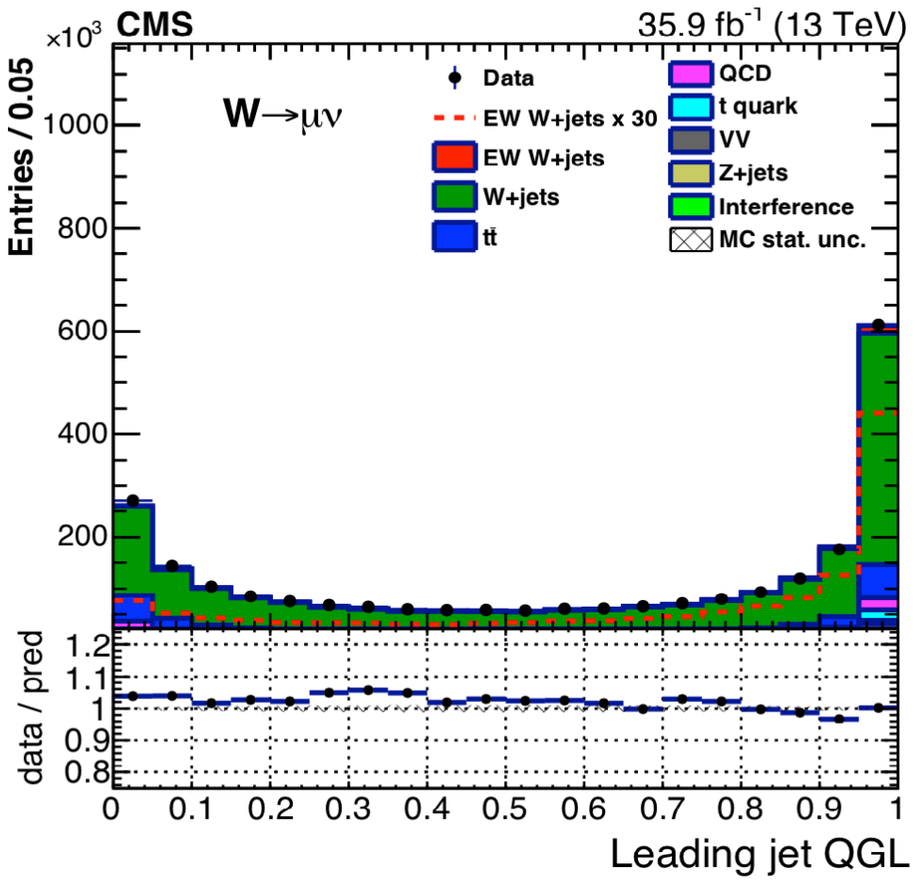
Signal Extraction:

BDT to separate signal events from large DY background

- m(qq), Δη(qq),
- QGL,
- pT(qq),
- z*(W)
- y*(W)

pure EW production: only q-jets initiated
DY production: ~50% jets produced are gluon-induced g-Gluon Likelihood discrimination (**QGL**)



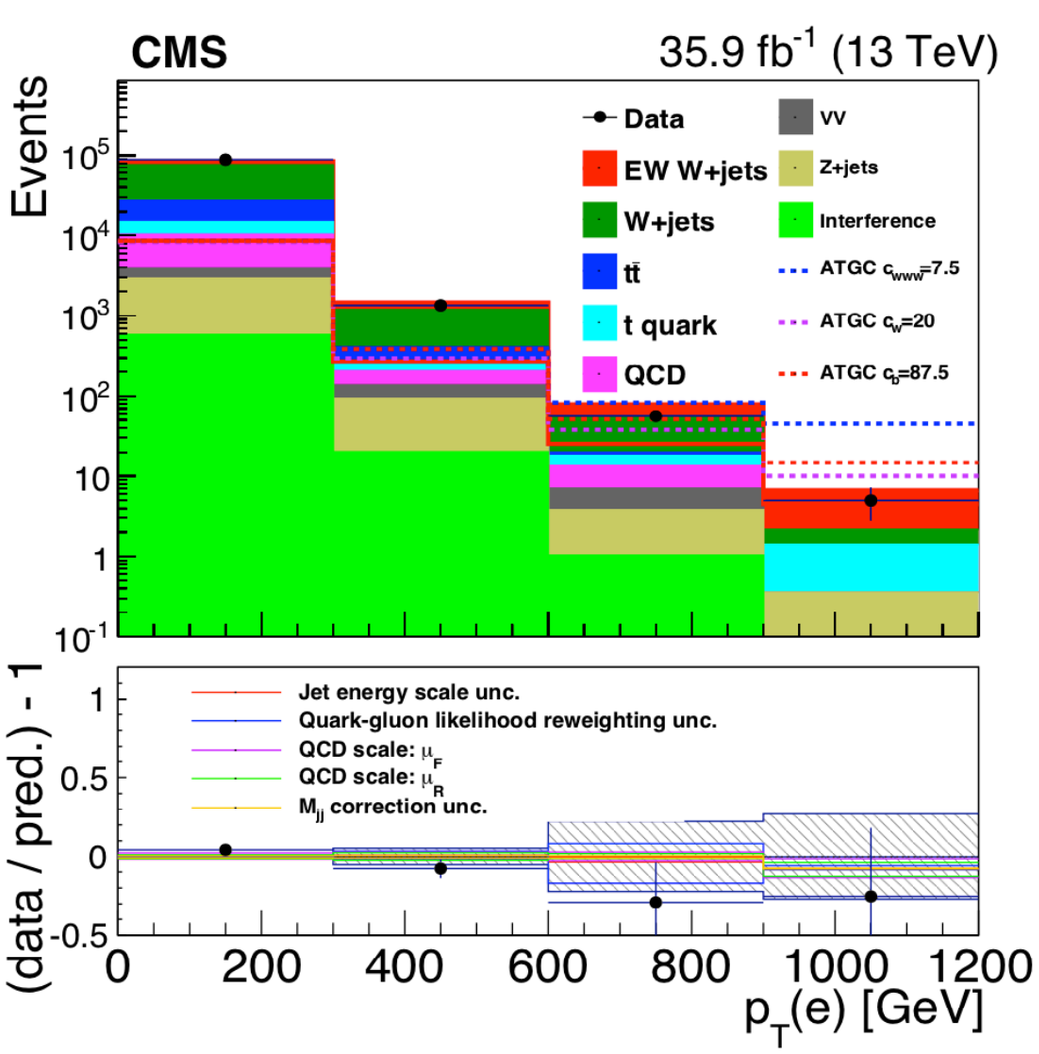


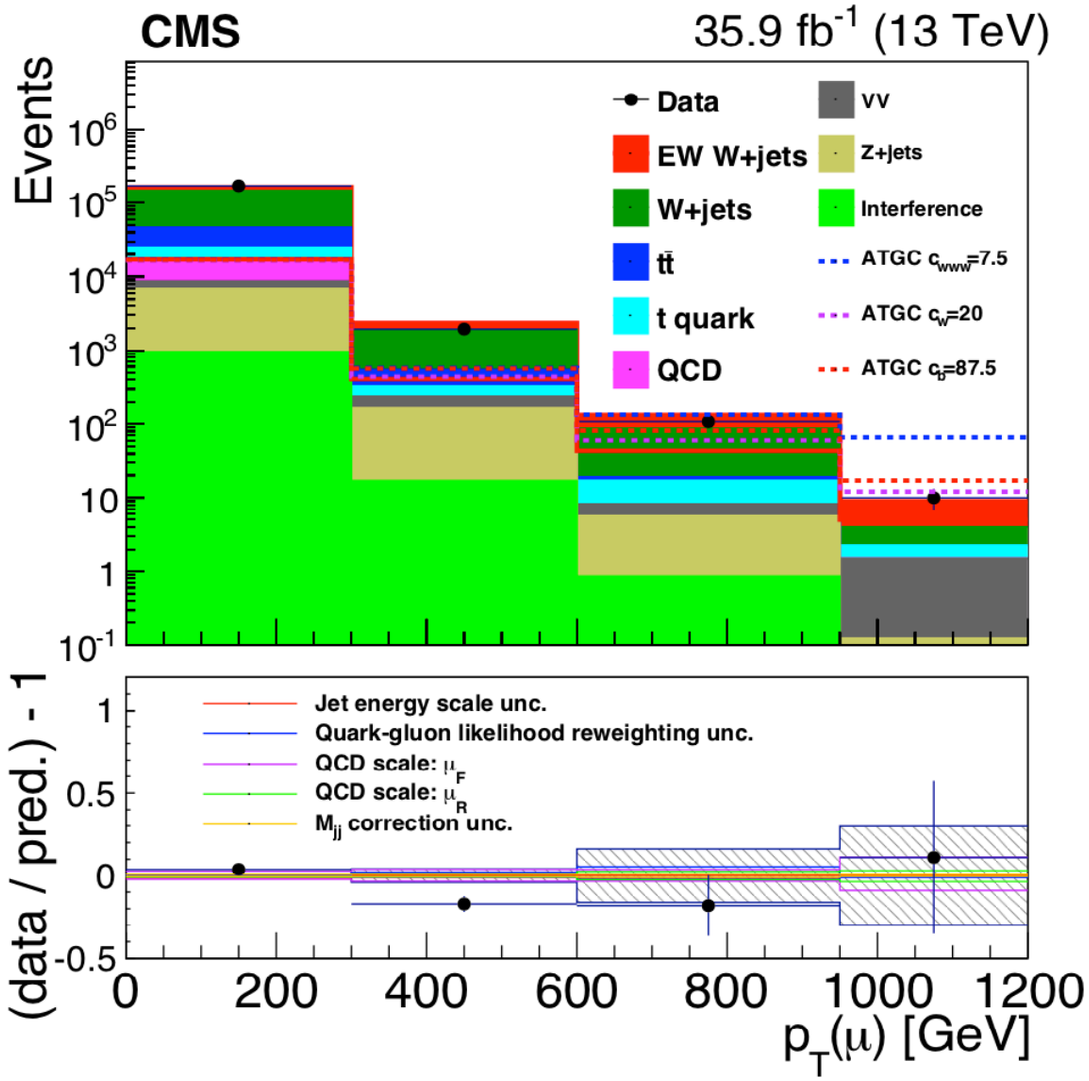
Electroweak production of *W+JJ*

$\sqrt{s}$ = 13 TeV
$\int L$ =35.9 fb^{-1}

σ(EW lνjj) = 6.23 ± 0.12 (stat) ± 0.61 (syst) pb = 0.91 ± 0.10 (total) pb

σLO (EW lνjj) = 6.81 ± 0.04 (scale) ± 0.04 (PDF) pb





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$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} W_{\mu\nu} (D^{\nu}\Phi),$$
$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} B_{\mu\nu} (D^{\nu}\Phi),$$
$$\widetilde{\mathcal{O}}_{WWW} = \frac{\widetilde{c}_{WWW}}{\Lambda^2} \widetilde{W}_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho},$$
$$\widetilde{\mathcal{O}}_{W} = \frac{\widetilde{c}_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} \widetilde{W}_{\mu\nu} (D^{\nu}\Phi),$$

- Limits on anomalous couplings from the sigle lepton p_T (with mild BDT>0.5 selection)
- 6-dimensional EFT approximation
  simulated with MADGRAPH5 aMC@NLO

95%CL

$-8.8 < c_W/\Lambda^2 < 16$ TeV^{-2}

$-2.3 < c_{WWW}/\Lambda^2 < -2.5$ TeV^{-2}

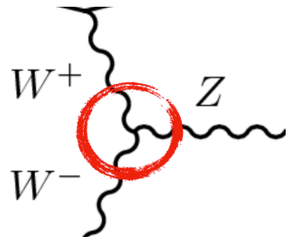
$-45 < c_B/\Lambda^2 < 46$ TeV^{-2}

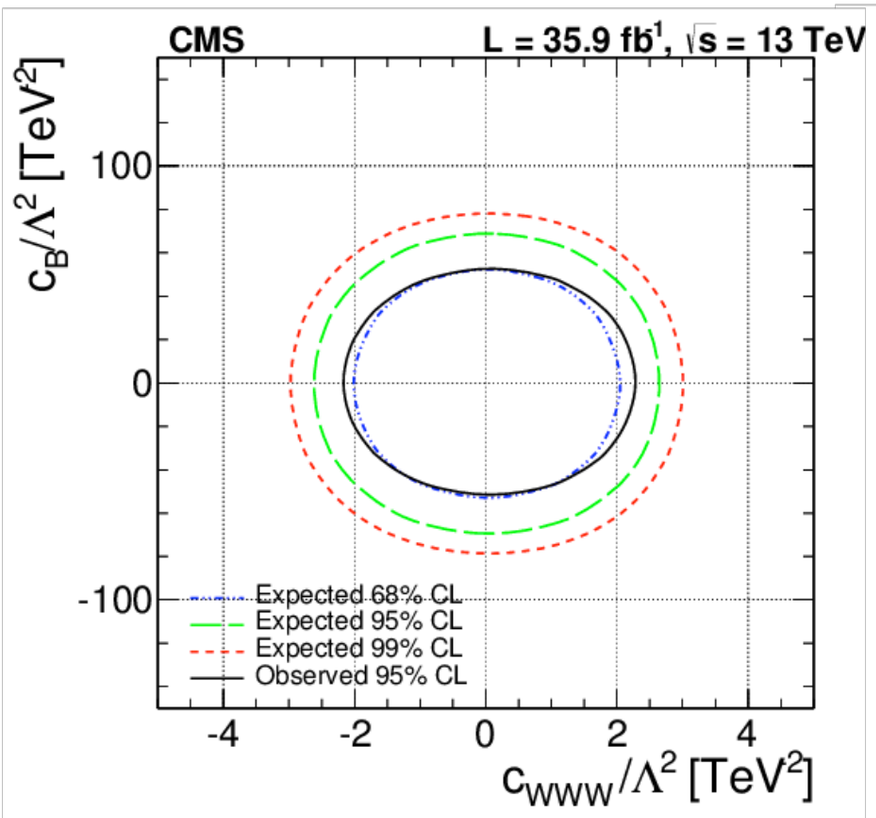
Electroweak production of *W+JJ*

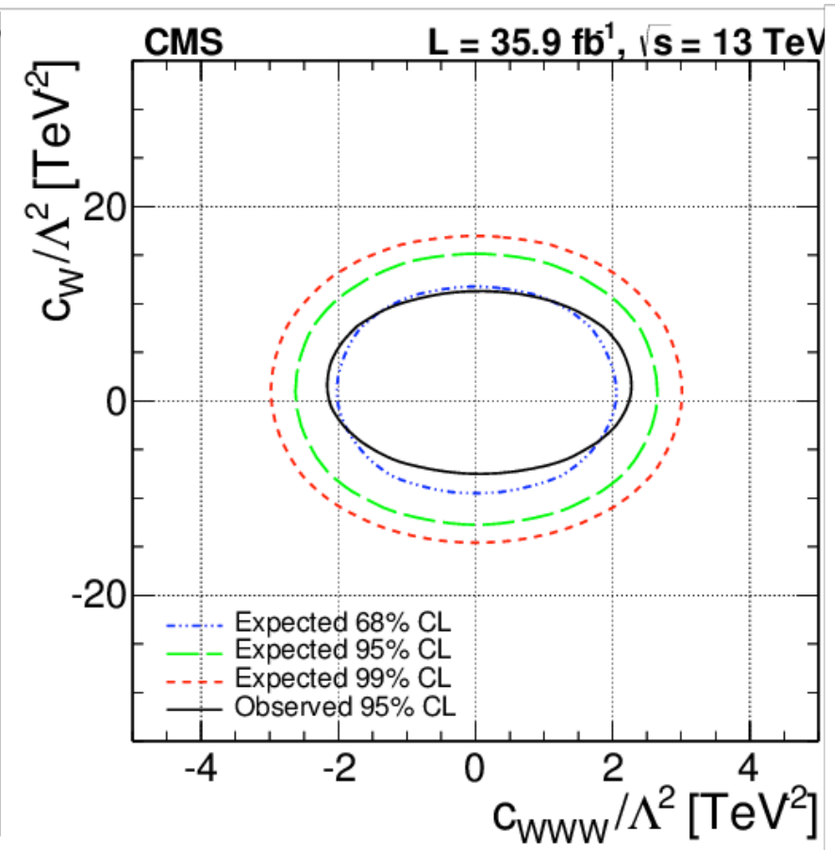
$\sqrt{s}$ = 13 TeV
$\int$ L =35.9 fb^{-1}

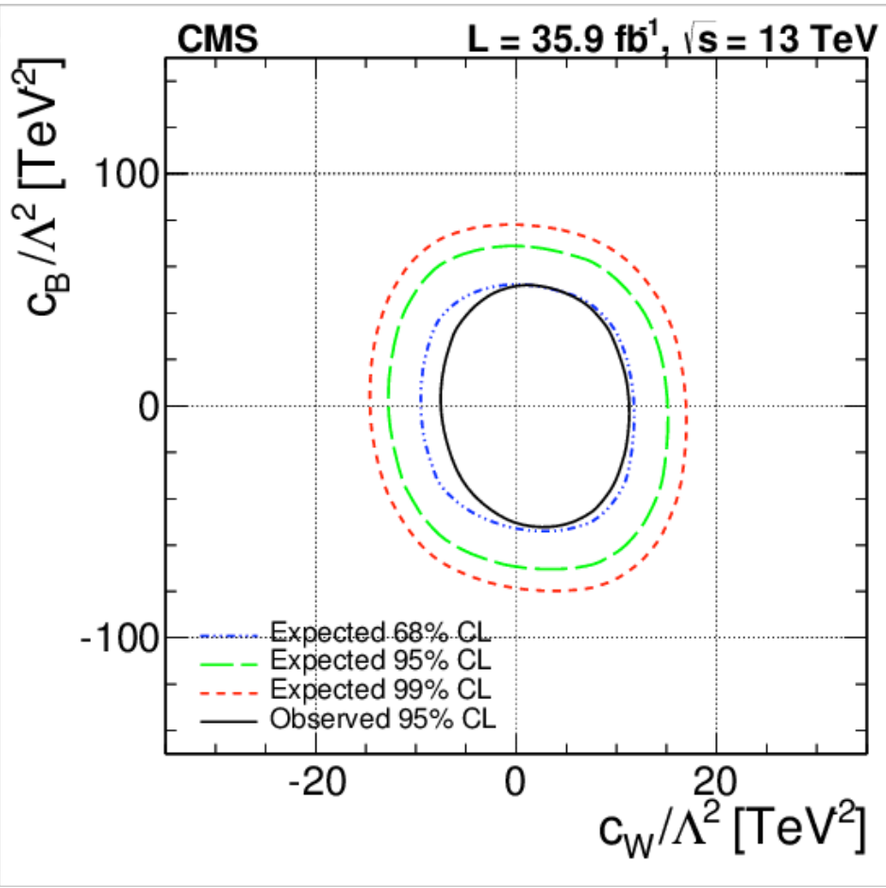
aTGC combination EW *ZJJ* + *WJJ*

enhancing sensitivity on the common *WWZ* vertex









simultaneous fit to p_T^Z (EW-*Z*) and p_T^{lep} (EW-*W*)

Most stringent experimental constrain on c_{WWW}/Λ^2 so far!

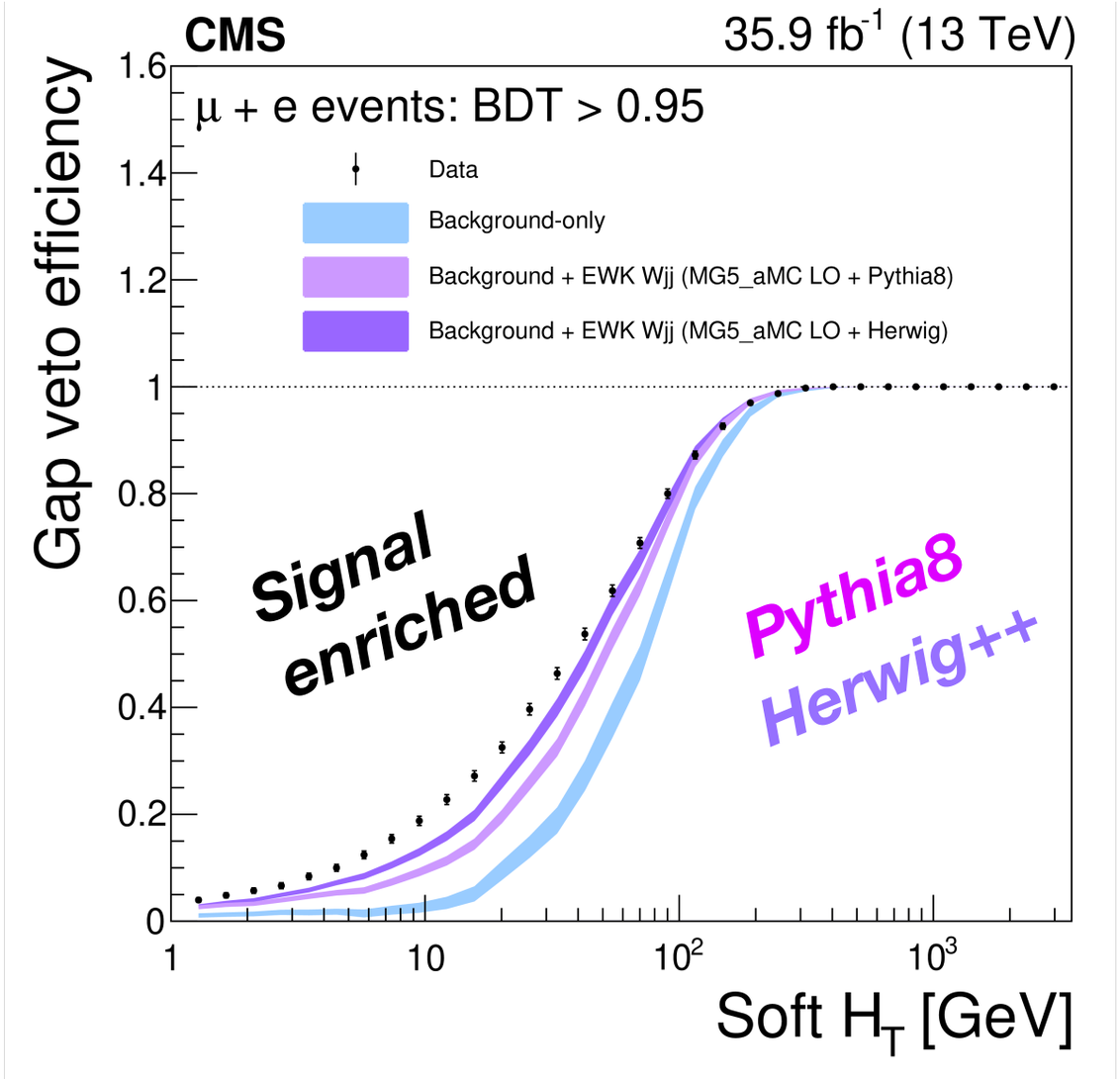
Rapidity Gap in VBF topologies

$\sqrt{s} = 13$ TeV
$\int L = 35.9$ fb^{-1}

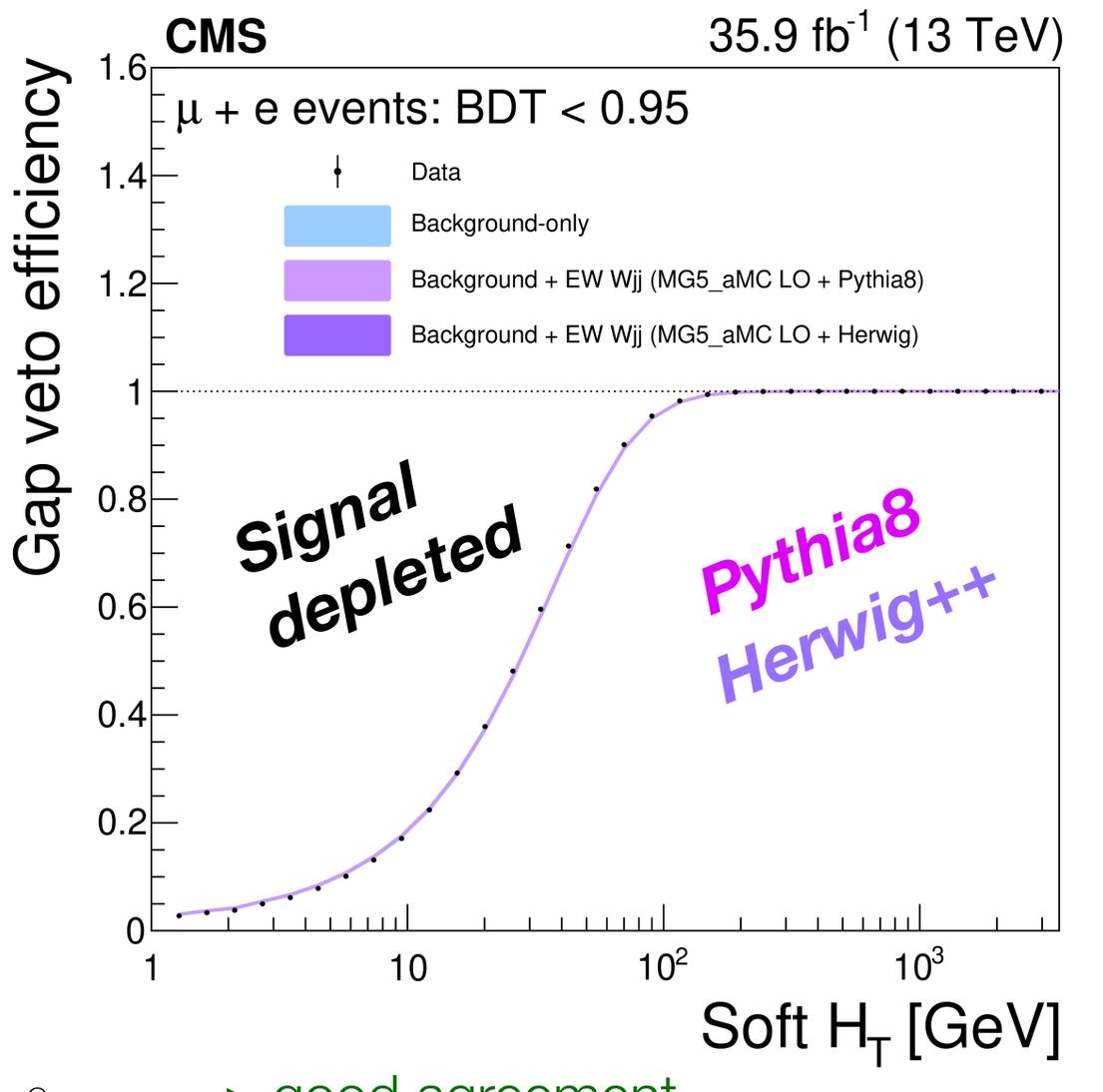
Rapidity Gap

- Low hadronic activity is expected in the ΔηJJ region due to the pure EW nature of the interaction
- No color flow between the two tagged highly separated jets

additional jets produced and generated by the Parton Shower (Pythia and Herwig++) → powerful test of the Parton Shower model in Generators



→ Pythia not describing the rapidity gap

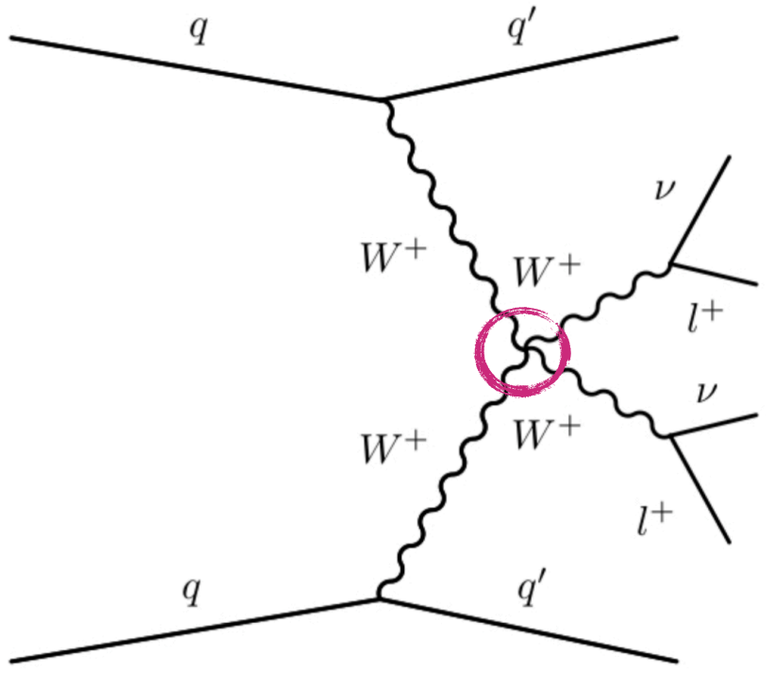


→ good agreement

Same-Sign $W^{\pm}W^{\pm}+JJ$ production

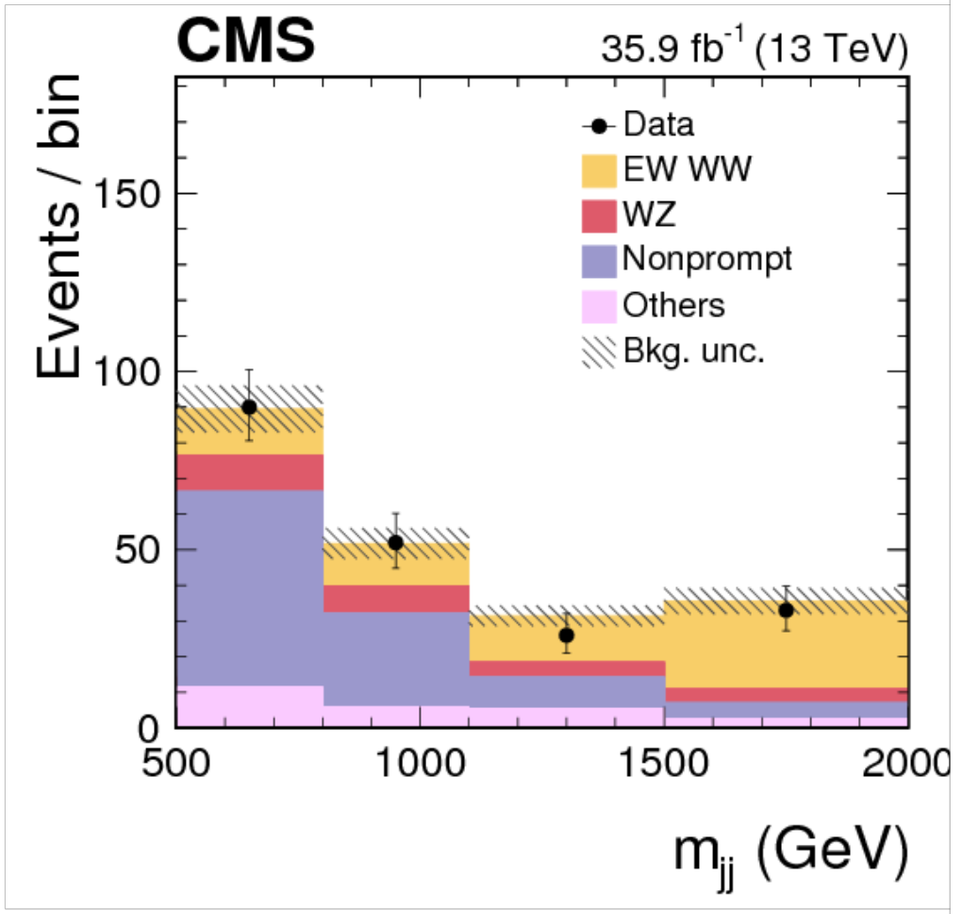
$\sqrt{s} = 13$ TeV
$\int L = 35.9$ fb^{-1}

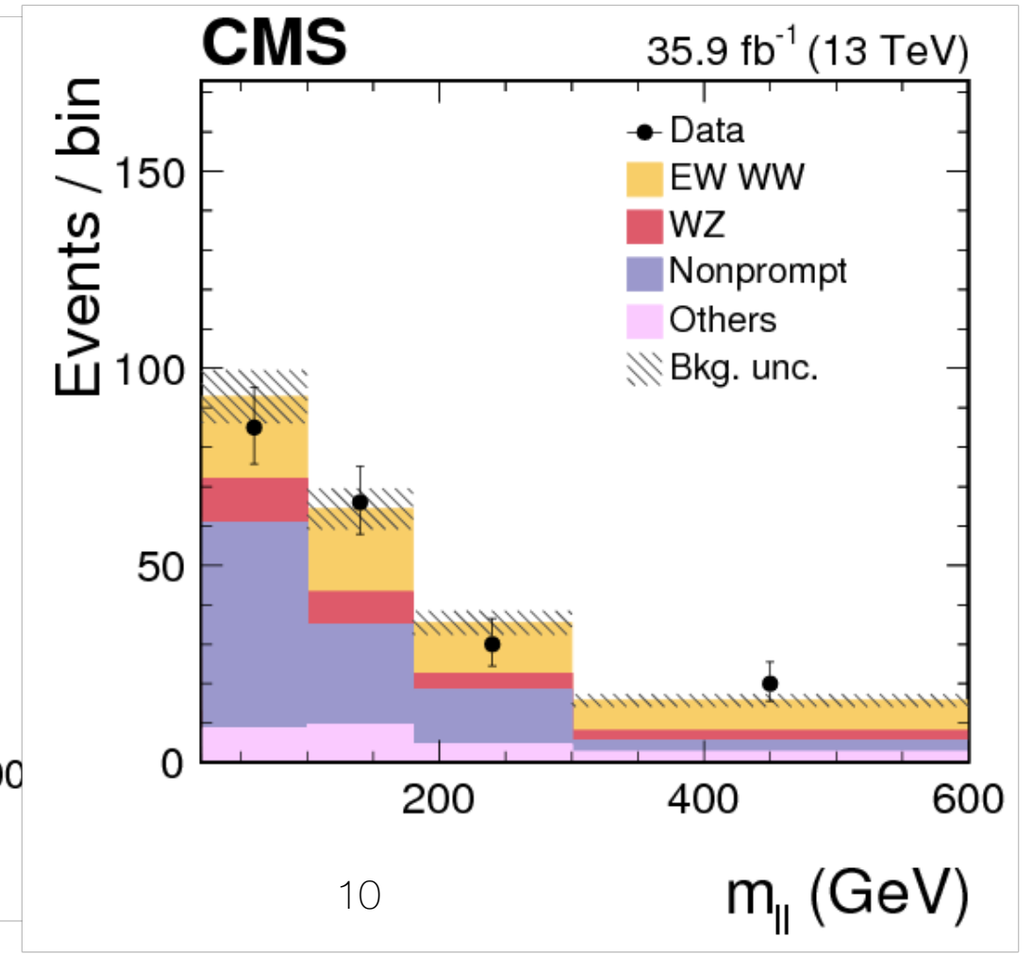
VBS EW production of same sign WW in ee,μe, μμ final states: probe of the quartic 4W coupling



selection criteria

- Exactly 2 S.S. isolated leptons p_T>25,20 GeV and |η|<2.5
- VBS selection: 2 jets with p_T > 30 GeV
- m_{JJ} > 500 GeV $|\Delta\eta_{JJ}|$> 2.5
- b-jet veto + 3rd lepton veto for ttbar/WZ





- signal strength μ = σ/σSM from 2D fit to the dilepton and dijet distributions
- data driven estimation of WZ background (from non-prompt leptons)

Same-Sign $W^{\pm}W^{\pm}+JJ$ production

$\sqrt{s} = 13$ TeV

$\int L = 35.9$ fb^{-1}

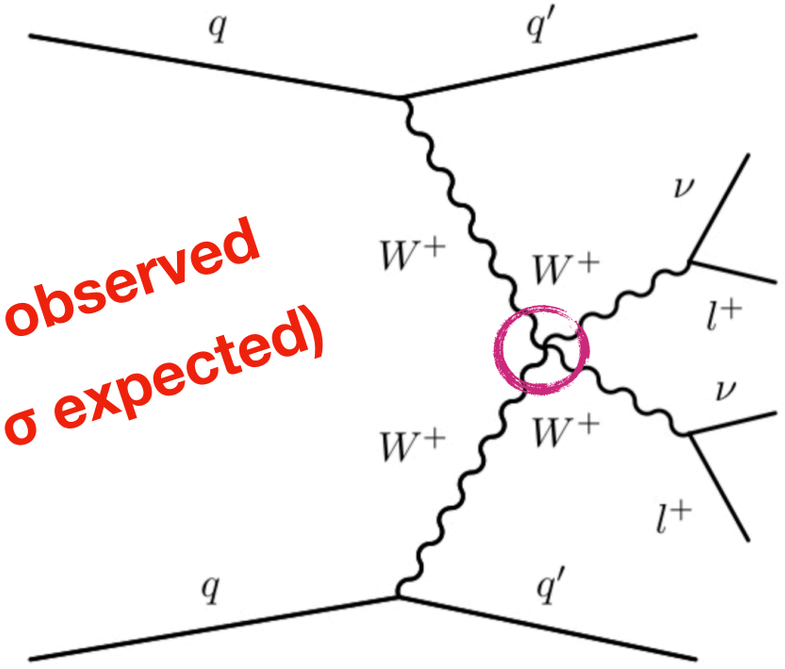
dominant systematics:

jet energy scale (~7%)

non-prompt background (*WZ,* lepton mis-id, 30-40%)

$\sigma(W^{\pm}W^{\pm})^{\text{meas.}} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})$ fb

$\sigma(W^{\pm}W^{\pm})^{\text{MadGraph LO}} = 4.25 \pm 0.27$ fb



5.5σ observed

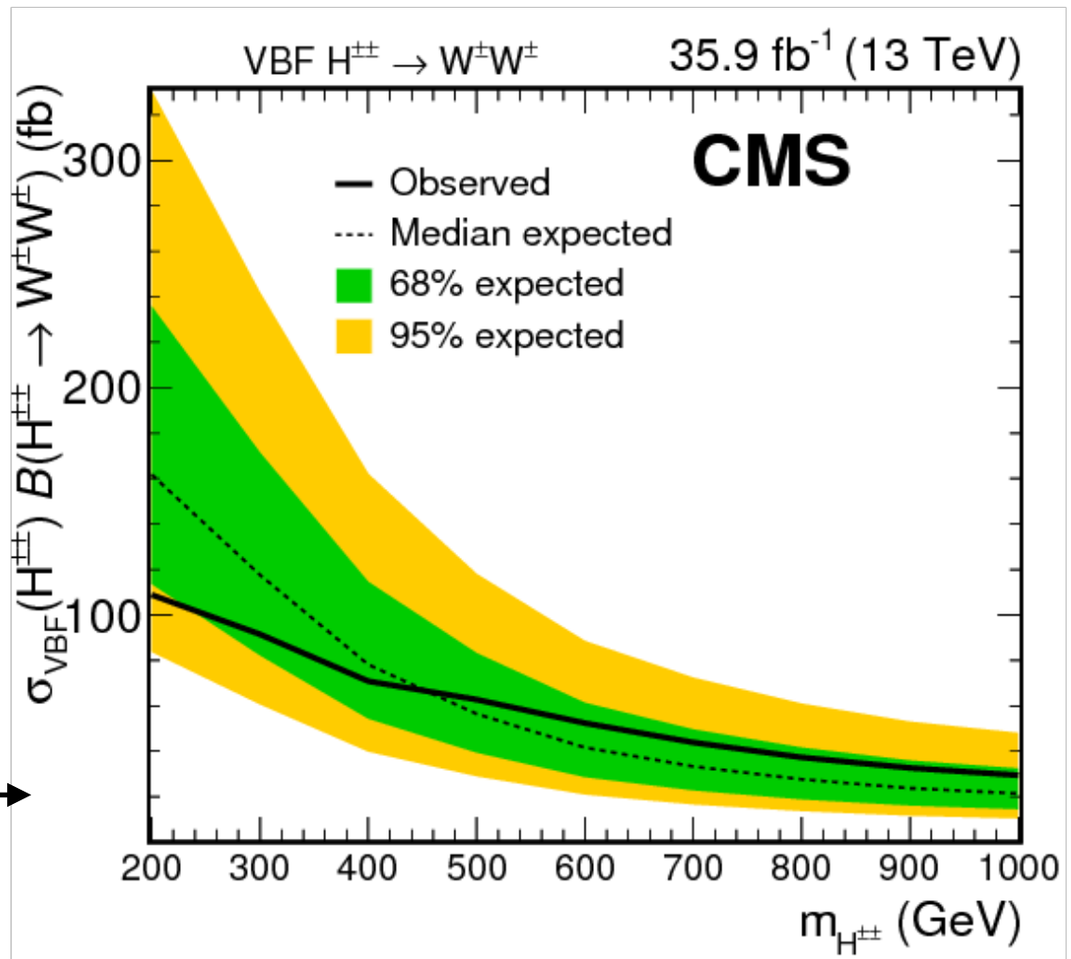
(5.7σ expected)

limits on dim-8 operators in aQGC EFT

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
f_{S0}/Λ^4	$[-7.7, 7.7]$	$[-7.0, 7.2]$
f_{S1}/Λ^4	$[-21.6, 21.8]$	$[-19.9, 20.2]$
f_{M0}/Λ^4	$[-6.0, 5.9]$	$[-5.6, 5.5]$
f_{M1}/Λ^4	$[-8.7, 9.1]$	$[-7.9, 8.5]$
f_{M6}/Λ^4	$[-11.9, 11.8]$	$[-11.1, 11.0]$
f_{M7}/Λ^4	$[-13.3, 12.9]$	$[-12.4, 11.8]$
f_{T0}/Λ^4	$[-0.62, 0.65]$	$[-0.58, 0.61]$
f_{T1}/Λ^4	$[-0.28, 0.31]$	$[-0.26, 0.29]$
f_{T2}/Λ^4	$[-0.89, 1.02]$	$[-0.80, 0.95]$

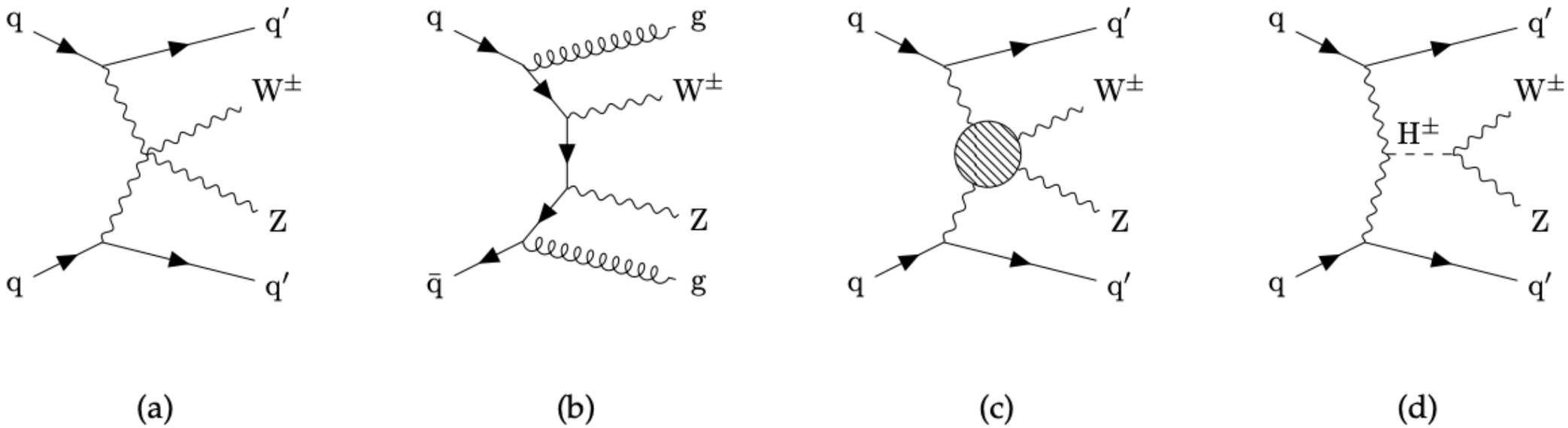
Georgi–Machacek Higgs Triplet Model →

95% CL limits on $H^{\pm} \longrightarrow W^{\pm} W^{\pm}$



Electroweak $W^{\pm}Z$+JJ production

$\sqrt{s}$ = 13 TeV
$\int L$ =35.9 fb^{-1}



probing the *WWZZ* coupling

3-lepton final state (*e*,*μ*)

main background: QCD-WZ+dijet, tri-bosons

strategy: from MC constrained in data sidebands

signal region	control region
m_{JJ} > 500 GeV, $\|\Delta\eta_{JJ}\|$>2.5, $\|\eta^*\|$<2.5	m_{JJ} > 100 GeV, fail $\|\Delta\eta_{JJ}\|$ or $\|\eta^*\|$<2.5

Signal extraction:

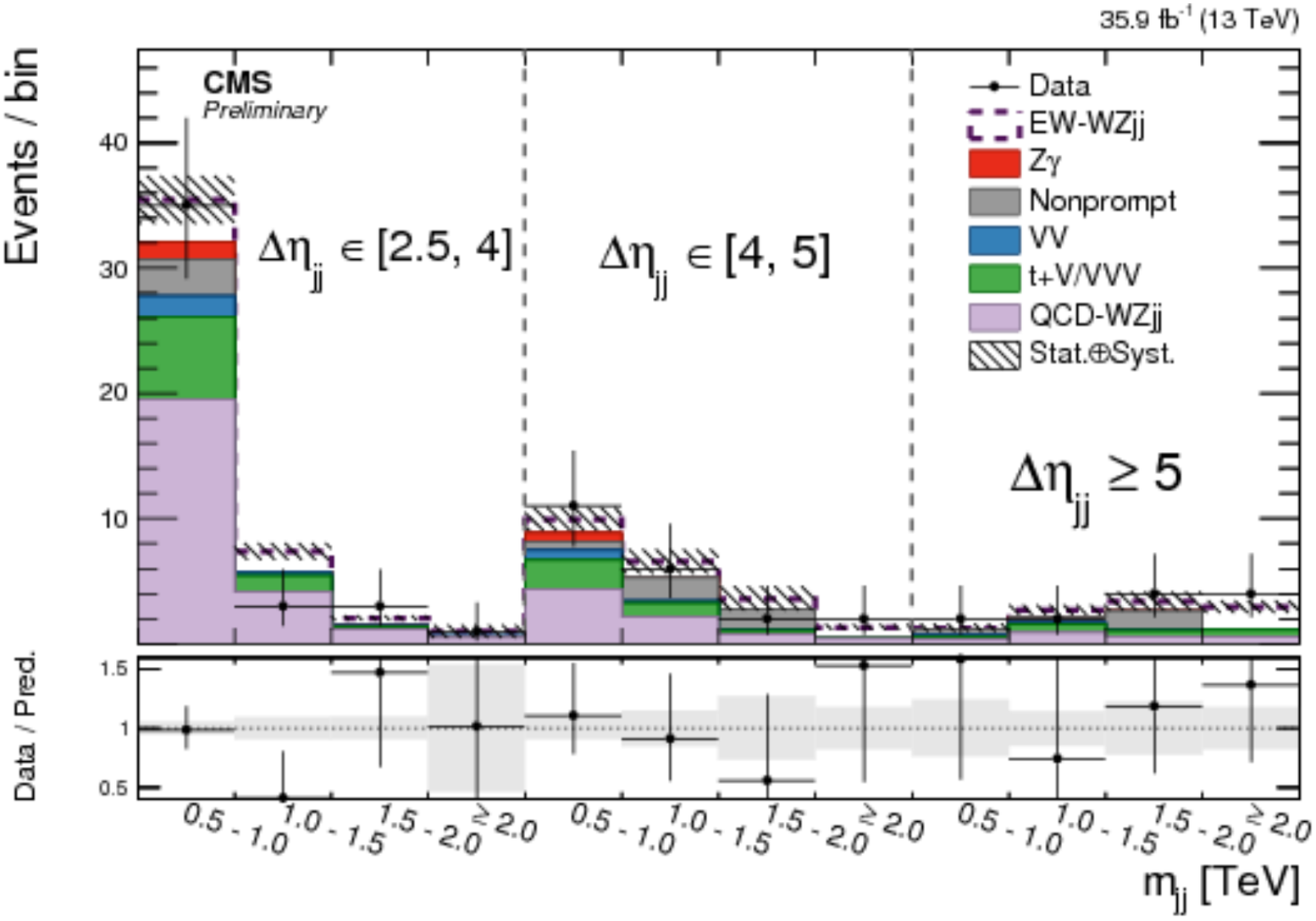
2-D m_{JJ} vs. $|\Delta\eta_{JJ}|$ combined fit w/ control region

selection criteria

	Electroweak Signal	Loose Fiducial
$p_T(\ell_{Z,1})$ [GeV]	> 25	> 20
$p_T(\ell_{Z,2})$ [GeV]	> 15	> 20
$p_T(\ell_W)$ [GeV]	> 20	> 20
$\|\eta(\mu)\|$	< 2.4	< 2.5
$\|\eta(e)\|$	< 2.5	< 2.5
$\|m_Z - m_Z^{PDG}\|$ [GeV]	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4
p_T^{miss} [GeV]	> 30	-
$\|\eta(j)\|$	< 4.7	< 4.7
$p_T(j)$ [GeV]	> 50	> 30
$\|\Delta R(j,\ell)\|$	> 0.4	> 0.4
n_j	≥ 2	≥ 2
$p_T(b)$ [GeV]	> 30	-
n_{b-jet}	= 0	-
m_{jj}	> 500	> 500
$\|\Delta\eta(j_1,j_2)\|$	> 2.5	> 2.5
$\|\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\|$	< 2.5	-

Electroweak $W^{\pm}Z$+JJ production

$\sqrt{s}$ = 13 TeV
$\int L$ =35.9 fb^{-1}



Signal extraction:

2-D m_{JJ} vs. $|\Delta\eta_{JJ}|$
combined fit w/ control region

Systematics

biggest contribution from
JES, non prompt statistics

$$\mu_{EW} = 0.64^{+0.45}_{-0.37}$$

$$\sigma_{WZjj} = 4.01^{0.72}_{-0.68}(stat)^{0.57}_{-0.47}(syst)$$ **Measured**

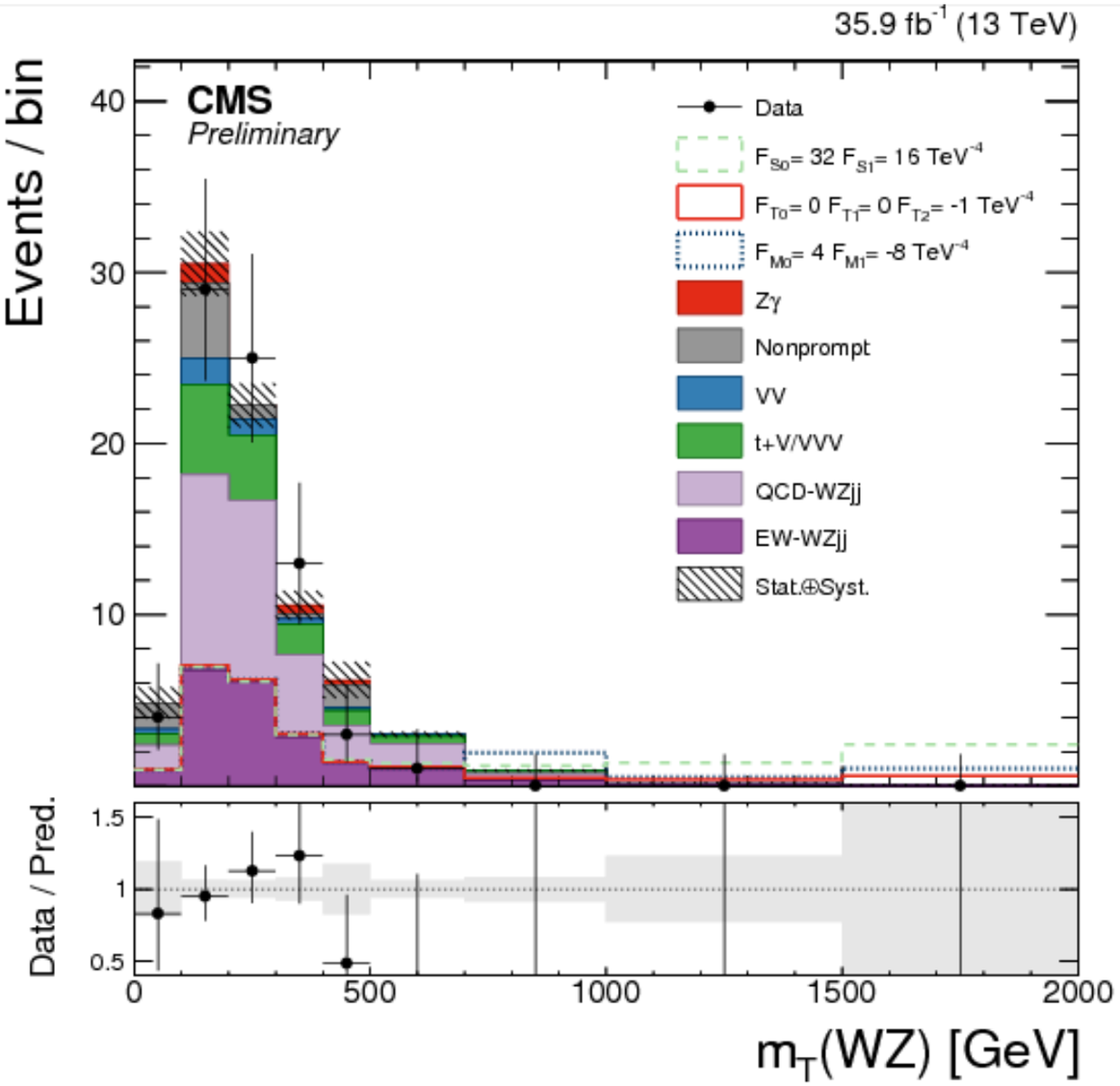
$$\sigma_{LO} = 4.51^{+0.59}_{-0.45}(scale) \pm 0.18(PDF)$$ **MadGraph5_aMC@NLO @LO**

expected significance: 2.7σ, observed: 1.9σ

EW+QCD NLO
corrections
not included

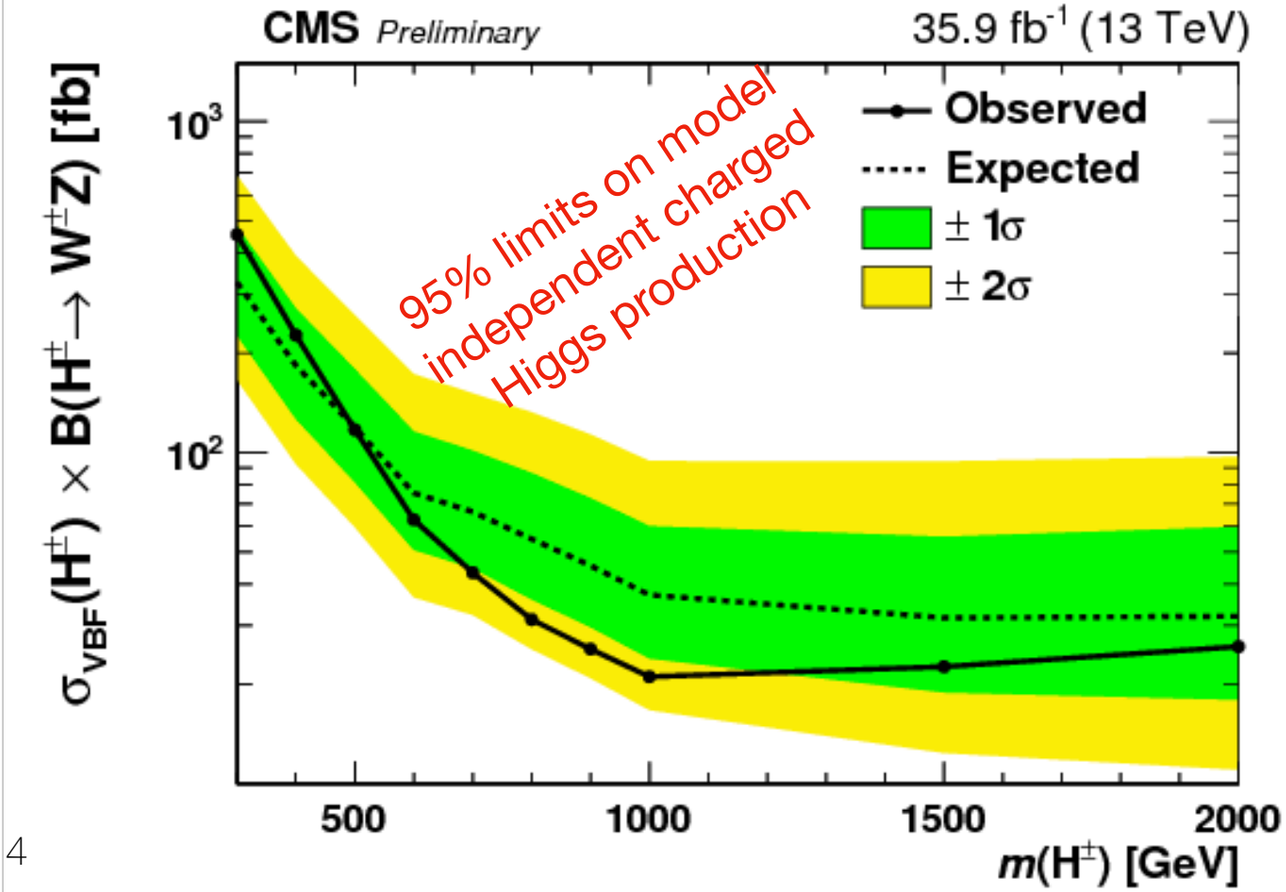
Electroweak $W^{\pm}Z$+JJ production

$\sqrt{s}$ = 13 TeV
$\int L$ =35.9 fb^{-1}



$$m_T(WZ) = \sqrt{(E_T(W) + E_T(Z))^2 - (p_T(W) + p_T(Z))^2}$$

Parameters	Expected limit (TeV^{-4})	Observed limit (TeV^{-4})
f_{M0}/Λ^4	[-10.7, 10.7]	[-8.80, 8.55]
f_{M1}/Λ^4	[-10.1, 10.6]	[-8.25, 8.85]
f_{S0}/Λ^4	[-31.5, 33.5]	[-25.7, 27.5]
f_{S1}/Λ^4	[-50.5, 51.5]	[-40.5, 41.5]
f_{T0}/Λ^4	[-0.85, 0.85]	[-0.72, 0.75]
f_{T1}/Λ^4	[-0.55, 0.55]	[-0.48, 0.52]
f_{T2}/Λ^4	[-2.98, 2.92]	[-1.42, 1.83]



constraining aQGC in EFT with dim-8 operators: sensitive to

T0,T1,T2 -> SU(2) structure
S0,S1 -> Higgs field
M0,M1 -> Higgs-gauge interaction

Summary and conclusions

Impressive set of single and multiboson results from CMS at 13 TeV!

- Measurement of cross sections for *Z,W,WW, WZ, ZZ* in VBF mode with 2016 Run2 data presented
- Overall very good agreement with the Standard Model predictions at LO and NLO
- Several EFT higher order operators describing anomalous couplings constrained with high precision using single and diboson channels
- Limits extracted on model-independent New Physics scenarios with additional Higgs boson in VBF topologies

much more to come… stay tuned for 140 fb^{-1} results coming!!