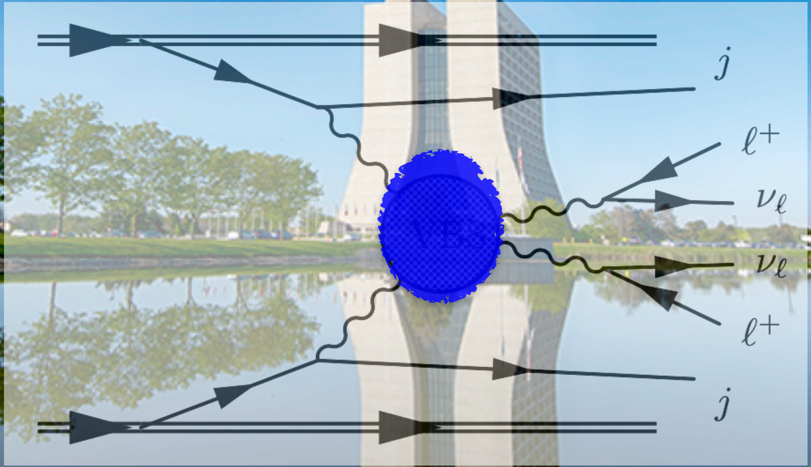
EFT in Multiboson physics at CMS

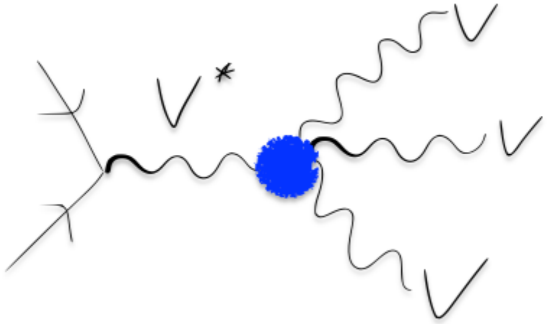


Irene Zoi

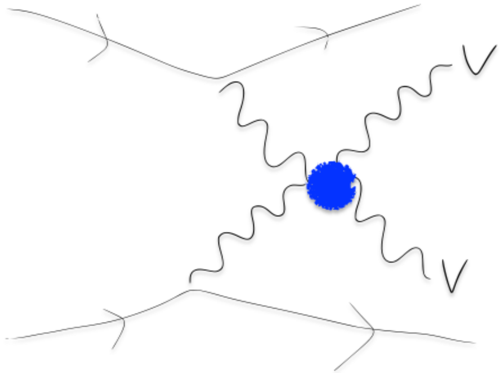
CMS EFT workshop at the LPC, September 2023

The SM (and beyond?) physics processes

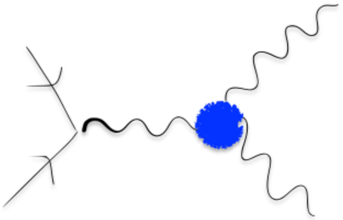
Triboson



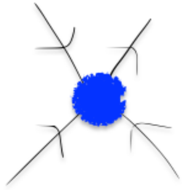
Vector Boson Scattering



Diboson

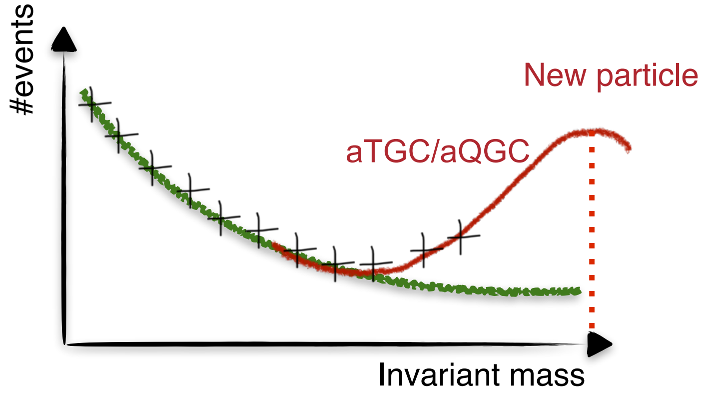


Contact interactions



The EFT framework

- Parametrize deviations from the SM in terms of an Effective Field Theory (EFT)
  - Beyond the LHC direct reach!



$$\mathscr{L}_{EFT} \sim \mathscr{L}_{SM} + \cancel{\mathscr{L}_5} + \mathscr{L}_6 + \cancel{\mathscr{L}_7} + \mathscr{L}_8 + \ldots$$

Dimension-6 operators

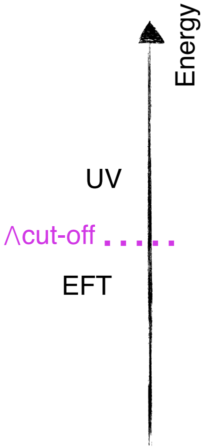
Dimension-8 operators

$$\sum_i c_i \frac{\mathcal{O}_i}{\Lambda^2} \qquad \sum_j f_j \frac{\mathcal{O}_j}{\Lambda^4}$$

New BSM couplings

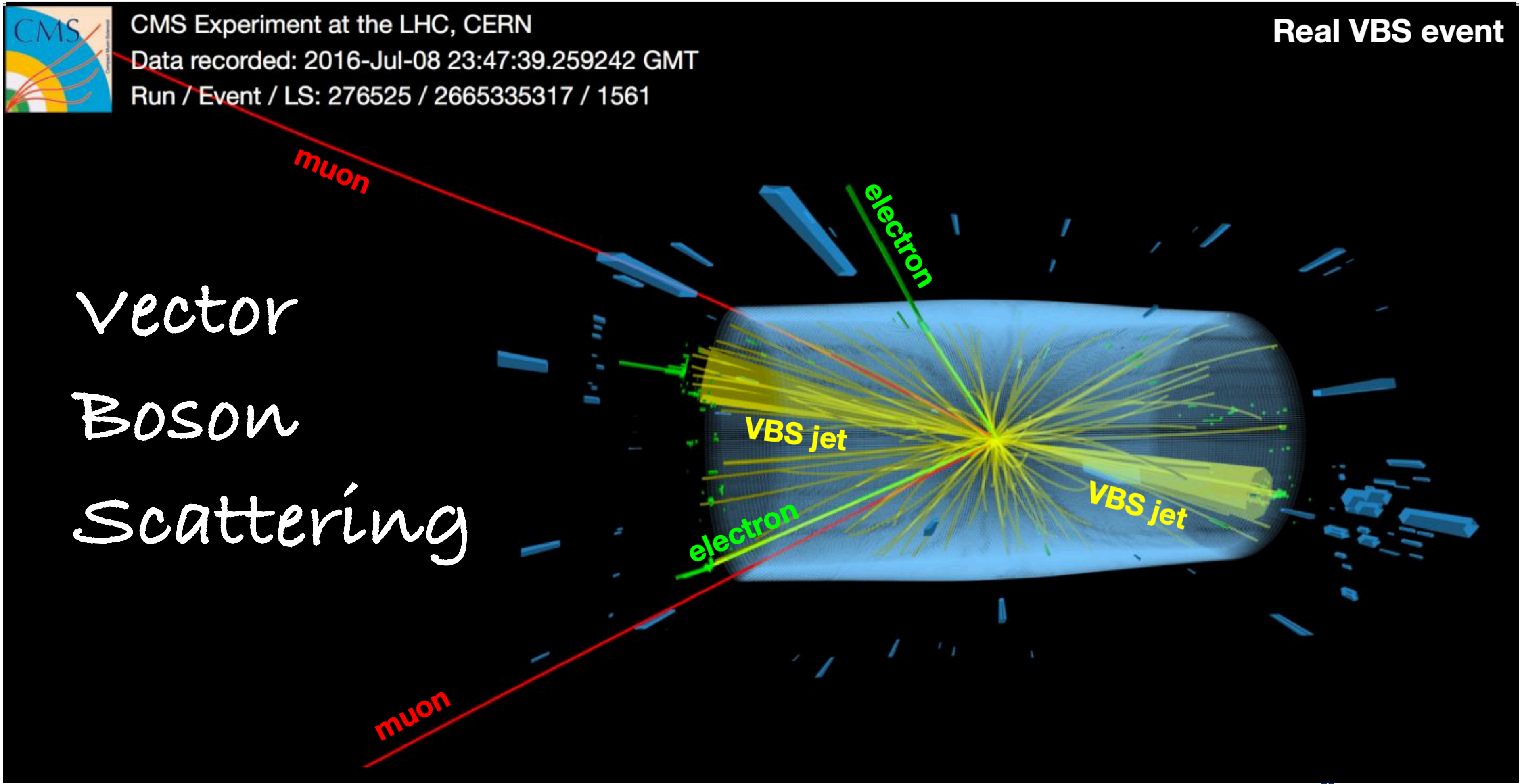
BSM scale

New BSM couplings



- In the past: Diboson for dim6 & VBS for dim8

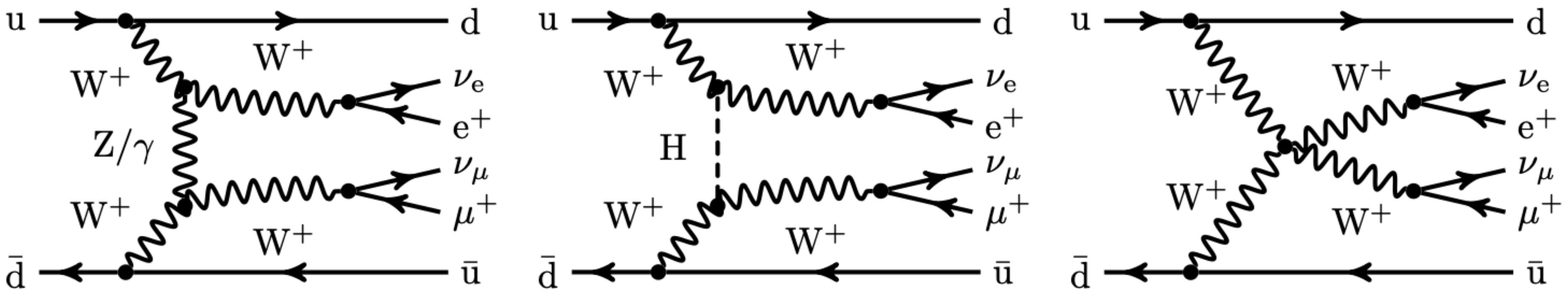
Vector Boson Scattering



Fermilab

Vector Boson Scattering

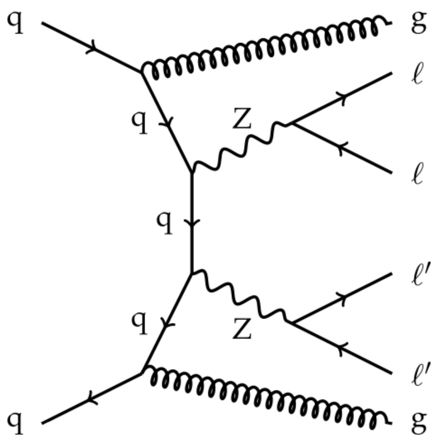
- Three contributions at LO:
  1. **Pure EWK $O(\alpha_{EW}^6)$ → signal**
  2. QCD-induced $O(\alpha_{EW}^4 \alpha_S^2)$ - irreducible contribution
  3. EWK-QCD interference $O(\alpha_{EW}^5 \alpha_S)$

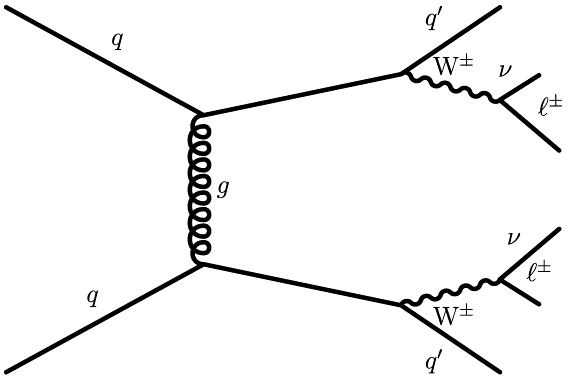


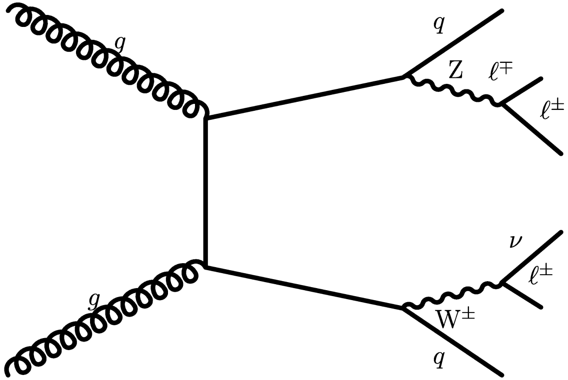
Fermilab

Vector Boson Scattering

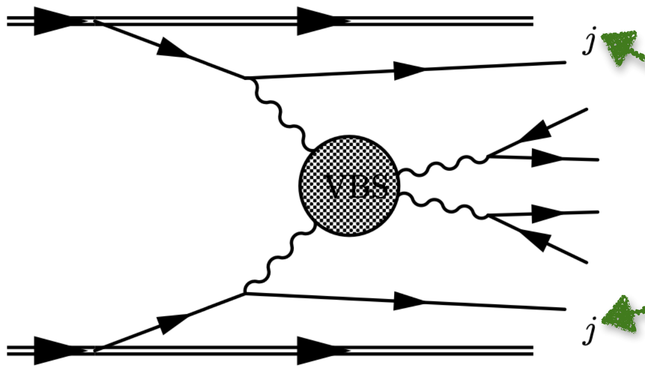
- Three contributions at LO:
  1. Pure EWK $O(\alpha_{EW}^6)$ → signal
  2. **QCD-induced** $\boldsymbol{O(\alpha_{EW}^4\,\alpha_S^2)}$ **- irreducible contribution**
  3. **EWK-QCD interference** $\boldsymbol{O(\alpha_{EW}^5\alpha_S)}$







VBS signal



- **VBS jets:** Two very energetic forward-backward QUARK-initiated jets
  - Large m_{jj} and $\Delta\eta_{jj}$

3 signatures depending on the decay of the vector bosons:

Fully leptonic:
Pure but low BR

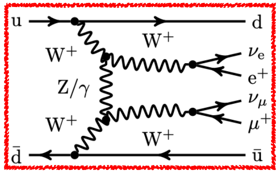
Semi-leptonic:
Balance purity & BR

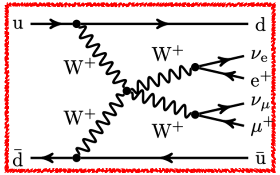
Fully hadronic: High BR & access to high energy tails but high bkg, Run2 results are yet to come!

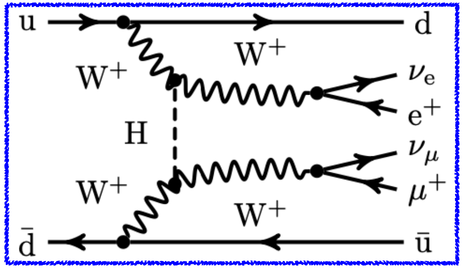
Main backgrounds: ttbar/top, DY, non-prompt leptons, diboson

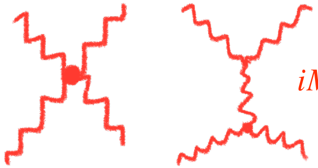
why VBS processes?

- Probes two key aspects of the SM together
  - Gauge interactions: triple and quartic gauge couplings
  - Couplings between the Higgs and the gauge bosons
    - complementary to direct measurements

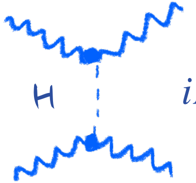




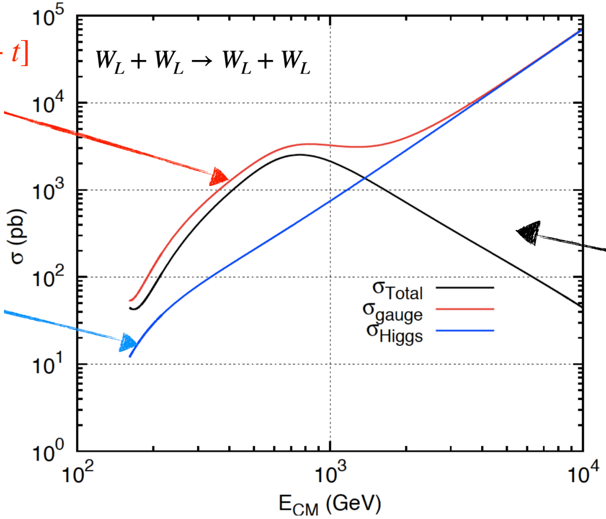




$$iM_{gauge} \simeq -i\frac{g^2}{4m_W^2}[s+t]$$



$$iM_{Higgs} \simeq i\frac{g^2}{4m_W^2}[s+t]$$



cancels exactly the E^2 dependence of the cross section at high energy

[“QFT and SM”, M. Schwartz]

Fermilab

VBS Run2 results:

First evidence and observations for rare processes

	PROCESS	LUMI [fb^{-1}]	RESULTS	REFERENCE
Fully leptonic	VBS in ssWW + WZ	Full Run 2 (137/fb)	Observation & XS + dim-8 EFT limits	PLB 809 (2020) 135710
	polarized VBS ssWW	Full Run 2 (137/fb)	$W_L W_L$ measurement	PLB 812 (2020) 136018
	VBS ZZ	Full Run 2 (137/fb)	Evidence + dim-8	PLB 812 (2021) 135992
	VBS osWW	Full Run 2 (137/fb)	Observation & XS	arXiv:2205.05711, sub. PLB
Semi-leptonic	VBS WV	Full Run 2 (137/fb)	Evidence	PLB 834 (2022) 137438
	VBS WV/ZV	2016 data (36/fb)	Dim-8 EFT limits	PLB 798 (2019)134985
NEW	VBS ssWW with taus	Full Run 2 (137/fb)	2.7 σ	CMS-SMP-22-008
	VBS Wγ	Full Run 2 (137/fb)	Observation, differential XS + dim-8 EFT limits	PLB 811 (2020) 135988 arXiv:2212.12592, acc. PRD
	VBS Zγ	Full Run 2 (137/fb)	Observation, differential XS + dim-8 EFT limits	PRD 104 (2021) 072001
Forward protons and hadronic V	VBS PPS γγVV	Full Run 2 PPS (100/fb)	Dim-6 and dim-8	arXiv:2211.16320, acc. JHEP

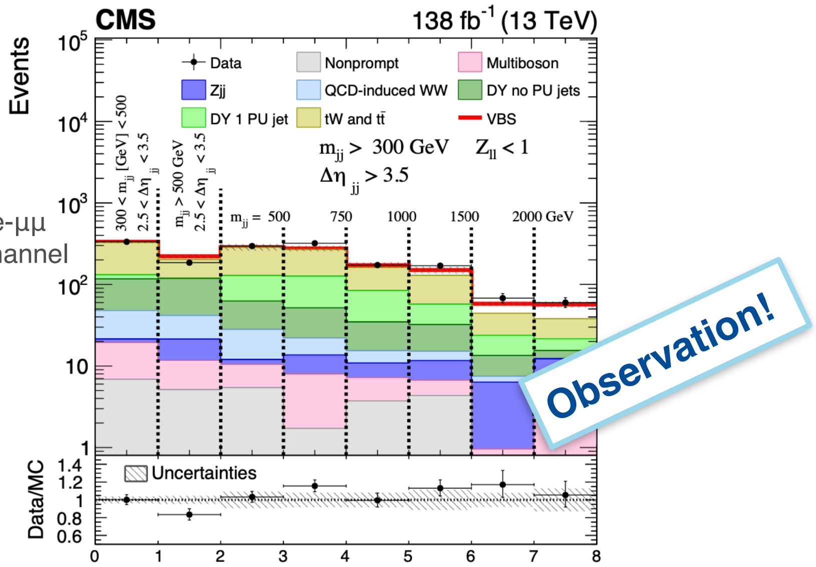
Stringent limits on EFT coefficients

Highlights on "Firsts":

- **VBS osWW [arXiv:2205.05711]**
  - Obs. (exp.) significance 5.6 (5.2)
  - Fiducial cross-sections:

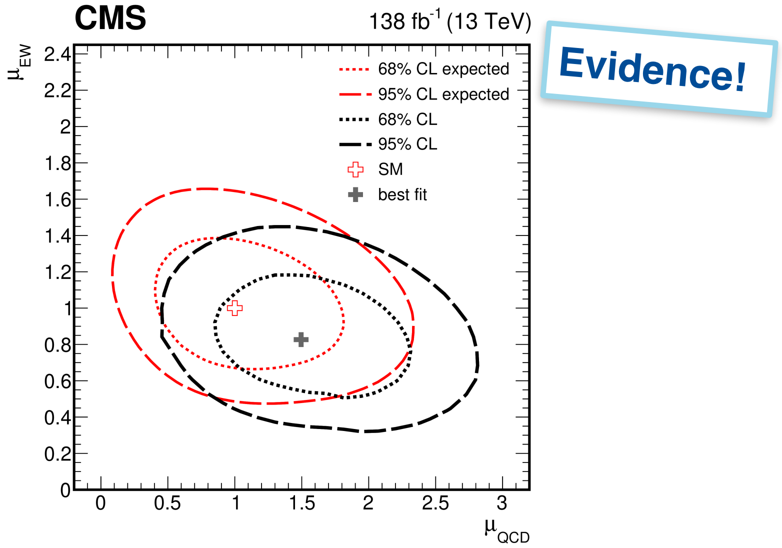
    10.2 ± 2.0 fb (theory: 9.1 ± 0.6 fb)

ee-μμ channel



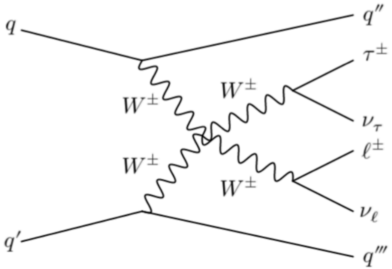
$$Z_{\ell\ell} = \frac{1}{2}|Z_{\ell_1} + Z_{\ell_2}|, \quad \text{where } Z_{\ell_i} = \eta_{\ell_i} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$$

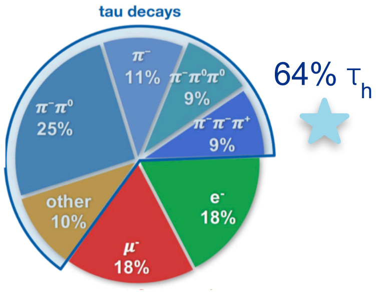
- **VBS WV semileptonic [PLB 834 (2022) 137438]**
  - Evidence obs. (exp.) significance 4.4 (5.1)
  - EW_{WV} xsec obs. (exp.) $1.90^{+0.53}_{-0.46}$ pb (2.23)
  - μ_{EW}=0.85±0.12(stat) $^{+0.19}_{-0.17}$(syst)



Fermilab

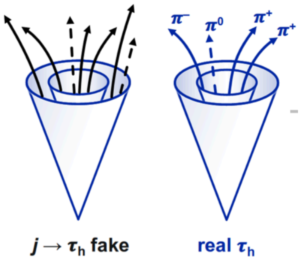
New:

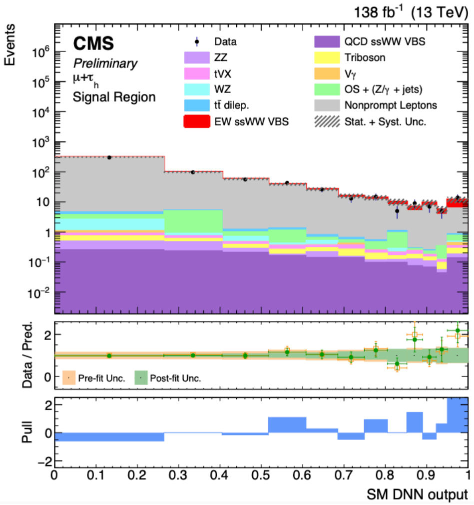




Tau decay for the first time in VBS ssWW!

- **VBS ssWW with τ_h** [[CMS-SMP-22-008](https://cms-results.web.cern.ch)]
  - Main background nonprompt leptons from jets misreconstructed as e,μ, or τ_h
    - estimated from data, and validated in a CR
  - Uncertainty is statistically dominated





- VBS jet pair invariant mass M_{jj};
- transverse mass $M_T(\ell, \vec{p}_T^{\,\text{miss}})$;
- transverse mass M_{1T};
- transverse mass M_{o1};
- p_T of leading VBS jet;
- p_T of subleading VBS jet;
- p_T of τ_h;
- p_T of ℓ;
- ratio of p_T of the leading track of the jet associated with τ_h to the τ_h p_T.

$$M_{1T}^2 = \left(\sqrt{M_{\tau l}^2 + p_T^{\tau l\,2}} + p_T^{\text{miss}}\right)^2 - \left|\vec{p}_T^{\,\tau l} + \vec{p}_T^{\,\text{miss}}\right|^2,$$

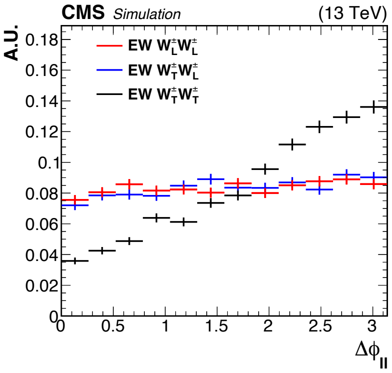
$$M_{o1}^2 = \left(p_T^\tau + p_T^l + p_T^{\text{miss}}\right)^2 - \left|\vec{p}_T^{\,\tau} + \vec{p}_T^{\,l} + \vec{p}_T^{\,\text{miss}}\right|^2.$$

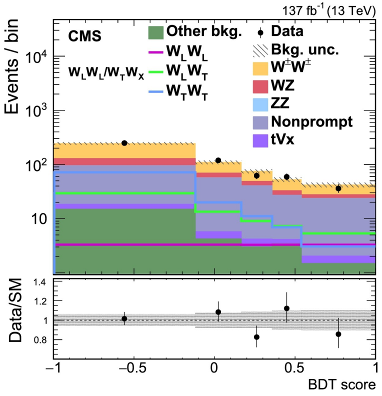
Signal	Significance $[\sigma]$ Expected	Significance $[\sigma]$ Observed
pure EW ssWW VBS	1.94	2.74
EW + QCD ssWW VBS	2.04	2.87

τ high mass → preferential coupling to the Higgs

Highlights on firsts:

- **VBS fully leptonic**
  - Differential ssWW xsec measurement + observation of VBS WZ Obs. (exp.) significance 6.8(5.3) [PLB 809 (2020) 135710]
  - Polarization in ssWW [PLB 812 (2020) 136018]
    - obs. (exp.) xsec for $W_L^\pm W_L^\pm$: 1.17 (0.88) fb (in WW RF)
    - obs. (exp.) significance for $W_L^\pm W_X^\pm$: 2.3 (3.1)





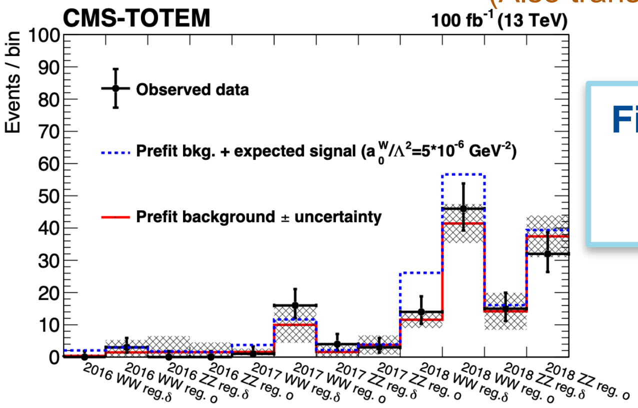
- **VBS PPS γγWW/ZZ [arXiv:2211.16320]** (CMS+TOTEM)
- Upper limits on pp → pWWp / pZZp cross sections
- aQGC limits w/o "clipping" for unitarity

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert a_0^W/\Lambda^2\rvert$	$4.3\ (3.9) \times 10^{-6}\,\mathrm{GeV}^{-2}$	$5.2\ (5.1) \times 10^{-6}\,\mathrm{GeV}^{-2}$
$\lvert a_C^W/\Lambda^2\rvert$	$1.6\ (1.4) \times 10^{-5}\,\mathrm{GeV}^{-2}$	$2.0\ (2.0) \times 10^{-5}\,\mathrm{GeV}^{-2}$
$\lvert a_0^Z/\Lambda^2\rvert$	$0.9\ (1.0) \times 10^{-5}\,\mathrm{GeV}^{-2}$	—
$\lvert a_C^Z/\Lambda^2\rvert$	$4.0\ (4.5) \times 10^{-5}\,\mathrm{GeV}^{-2}$	—

~ 15-20 times better than Run1

Dim6

(Also translated to dim8)

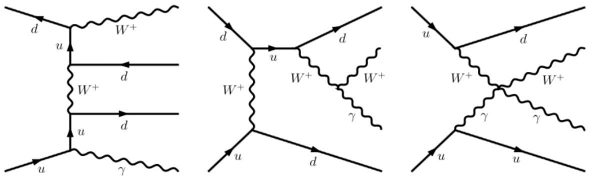


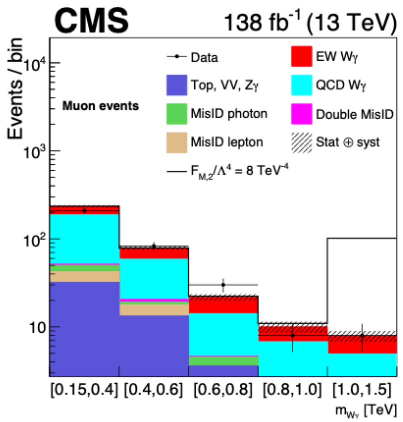
First limits on aQGC in γγ→ZZ

VBS Wγ

arXiv:2212.12592

- Final states: $e\nu\gamma$ + 2jets and $\mu\nu\gamma$ + 2jets
- Data-driven background estimate:
  - Template fit: non-prompt photon
  - Tight-loose method: non-prompt lepton
- Fiducial and differential cross section
- Probes quadratic and triple gauge couplings
- Limits setting on EFT dim-8 operators





- Limits obtained varying the coefficient of one operator at a time
  - all others set to zero (SM value).
- Unitary bound: scattering energy at which the aQGC coupling strength, when set equal to the observed limit, would result in a scattering amplitude that violates unitarity.

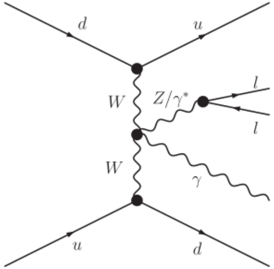
Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

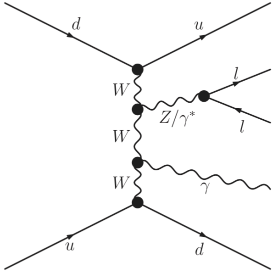
Most stringent

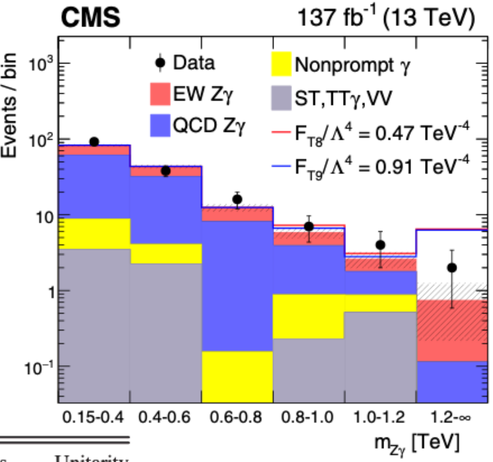
Fermilab

VBS Zγ

PRD 104 (2021) 072001







- Final states: $\ell^+\ell^-\gamma$ + 2jets with $\ell = e, \mu$
- Main background QCD-induced Zγjj, from simulation, constrained in data
- Z+jets with selected photon not prompt, data-driven

- Obs. (exp.) significance 9.4 (8.5)
- Fiducial EW cross-sections: 5.21 ± 0.52 (stat) ± 0.56 (syst) fb
- Provide several unfolded differential xsecs

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

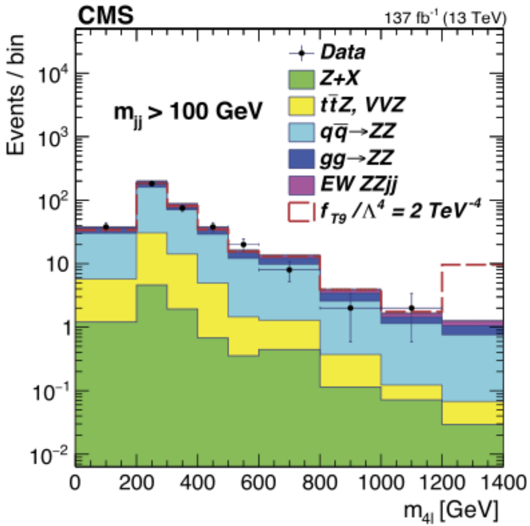
Most stringent

- Uncertainty is statistically dominated

VBS ZZ

Fully leptonic

- Main background: production of 2Z bosons + QCD-induced jets, from simulation, constrained in data
- Other irreducible backgrounds: processes with high-pT isolated leptons $t\bar{t}$Z+jets and VVZ+jets, from simulation
- Reducible backgrounds: heavy-flavor jets produce secondary leptons or jets misidentified as leptons as Z+jets, tt+jets and WZ+jets
- Main uncertainty on Xsec measurements: QCD renormalization and factorization scales (signal) and jet energy scale ~10%

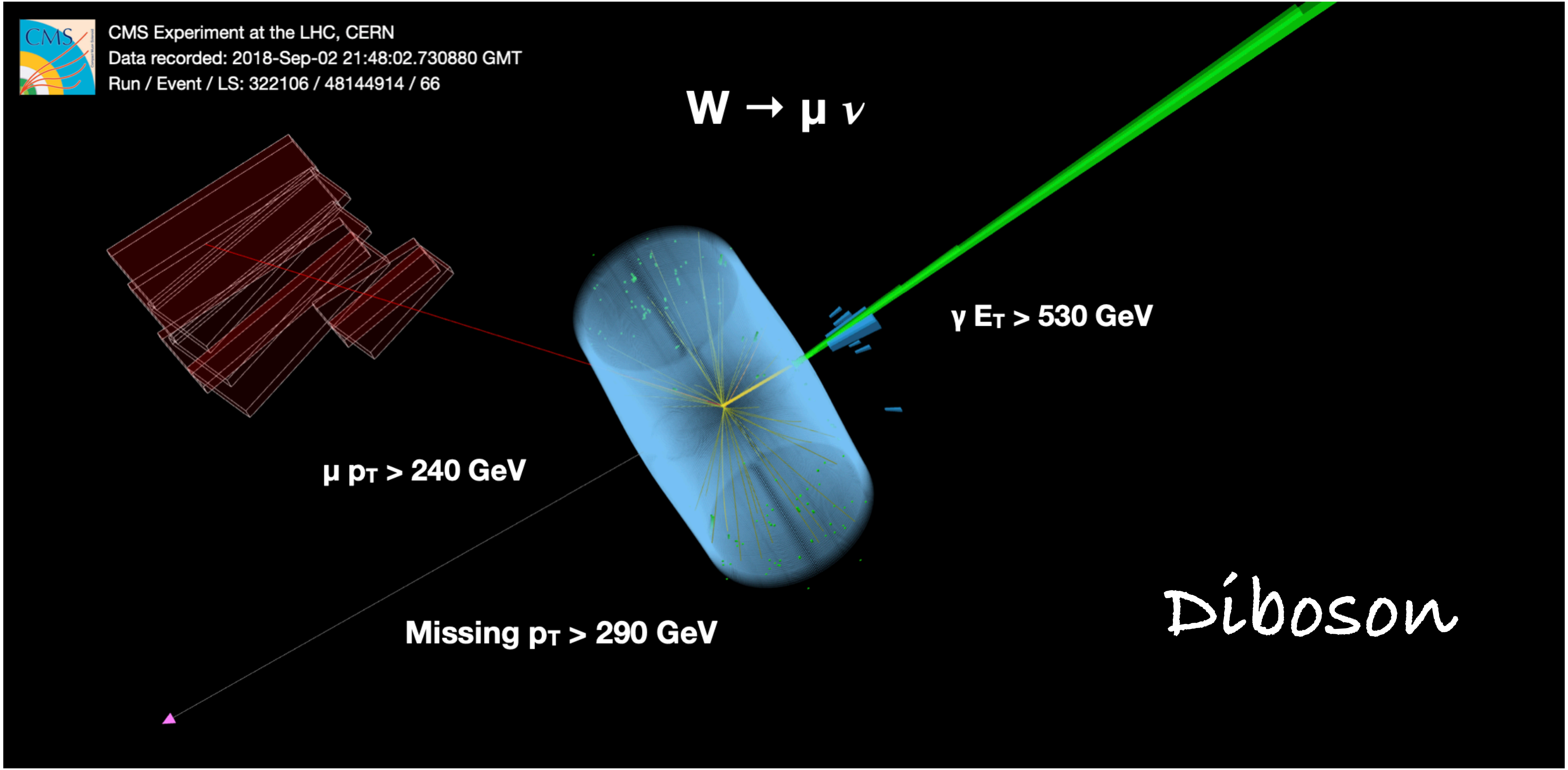


- Two approaches, the distributions of the SM processes, including the EW component, are normalized
  1) to their measured values in the EW signal extraction
  2) to their expected values.
- Uncertainty is statistically dominated

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24 (−0.26)	0.22 (0.24)	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31 (−0.34)	0.31 (0.34)	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63 (−0.69)	0.59 (0.65)	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43 (−0.47)	0.43 (0.48)	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92 (−1.02)	0.92 (1.02)	1.8

Most stringent

Fermilab


CMS Experiment at the LHC, CERN
Data recorded: 2018-Sep-02 21:48:02.730880 GMT
Run / Event / LS: 322106 / 48144914 / 66
W → μ ν
γ E$_T$ > 530 GeV
μ p$_T$ > 240 GeV
Missing p$_T$ > 290 GeV
Diboson

Diboson Run2 results:

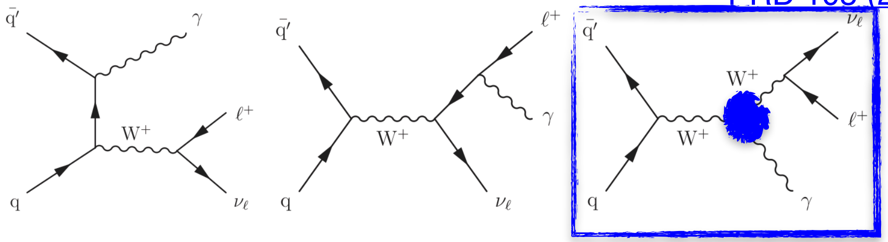
Interference resurrection

PROCESS	LUMI [fb^{-1}]	RESULTS	REFERENCE
WZ	Full Run 2 (137/fb)	Differential XS + aTGC limits	JHEP 07 (2022) 032
WW, WZ, ZZ	2017 (302/pb) 5.02 TeV	EWK XS	PRL 127 (2021) 191801
ZZ	Full Run 2 (137/fb)	XS + aTGC limits	EPJC 81 (2021) 200
osWW	2016 (35.9/fb)	XS + dim6 limits	PRD 102 (2020) 092001
Wγ	Full Run 2 (138/fb)	differential XS + dim-6 EFT limits	PRD 105 (2022) 052003 PRL 126 (2021) 252002

Stringent limits on EFT coefficients

Wγ: interference resurrection

[PRD 105 (2022) 052003](PRD 105 (2022) 052003)

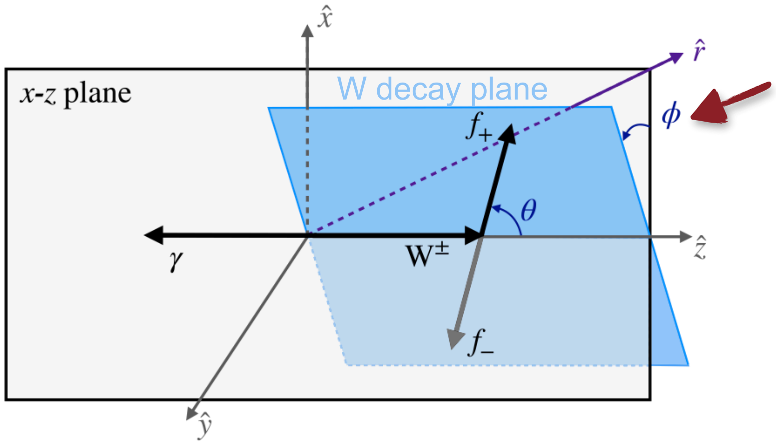


- Dim6 O_{3W} CP-even modification of the WWV TGC

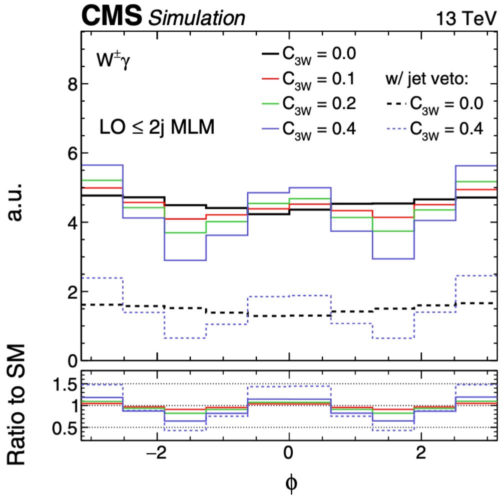
$$\sigma(C_{3W}) = \sigma^{SM} + C_{3W}\sigma^{int} + C_{3W}^{2}\sigma^{BSM}$$

Wilson Coefficient

Interference term (~ Λ^{-2}) → not accessible with variables inclusive over the decay angles



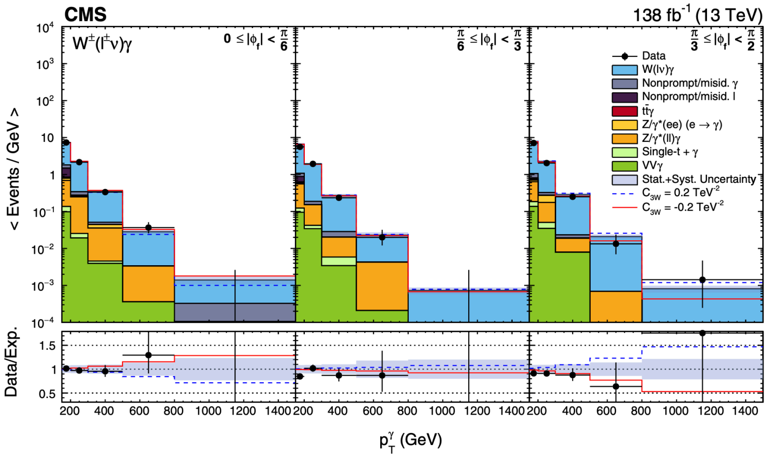
- coordinate system: Lorentz boost to the center-of-mass frame of the Wγ system

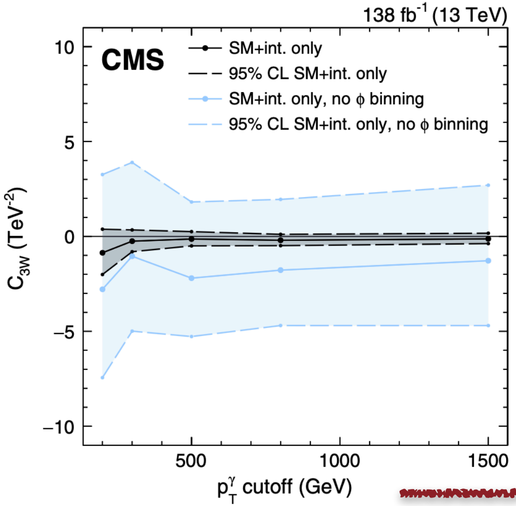


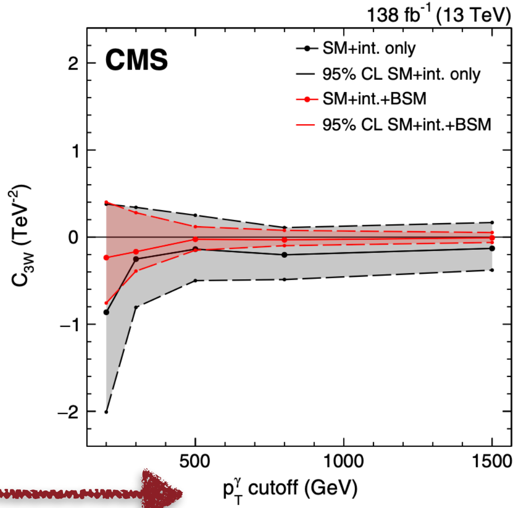
Fermilab

PRD 105 (2022) 052003

Wγ: interference resurrection







- Prefit: good background modeling

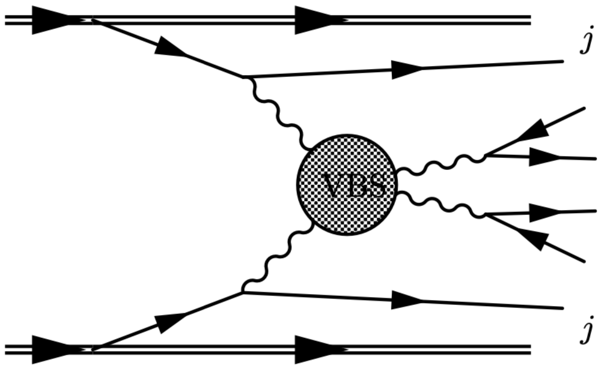
Factor 10 improvement using the ϕ binning

- For interpretations with highest bins beyond the validity of the EFT or specific BSM model

	Best fit C_{3W} (TeV^{-2})		Observed 95% CL (TeV^{-2})		Expected 95% CL (TeV^{-2})	
p_T^{γ} cutoff (GeV)	SM + int. only	SM + int. + BSM	SM + int. only	SM + int. + BSM	SM + int. only	SM + int. + BSM
200	−0.86	−0.24	[−2.01, 0.38]	[−0.76, 0.40]	[−1.16, 1.27]	[−0.81, 0.71]
300	−0.25	−0.17	[−0.81, 0.34]	[−0.39, 0.28]	[−0.56, 0.60]	[−0.33, 0.33]
500	−0.13	−0.025	[−0.50, 0.25]	[−0.15, 0.12]	[−0.35, 0.38]	[−0.17, 0.16]
800	−0.20	−0.033	[−0.49, 0.11]	[−0.10, 0.08]	[−0.29, 0.31]	[−0.097, 0.095]
1500	−0.13	−0.009	[−0.38, 0.17]	[−0.062, 0.052]	[−0.27, 0.29]	[−0.066, 0.065]

Multiboson results* in CMS

Run2 is wrapping up but is too early for Run3 results



*and some(!) ideas

Jet tagging

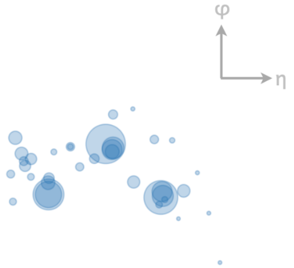
ML taggers are improving the identification performance

- B-tagging to reduce ttbar background
- (Boosted) W/Z tagging
- q/g discrimination

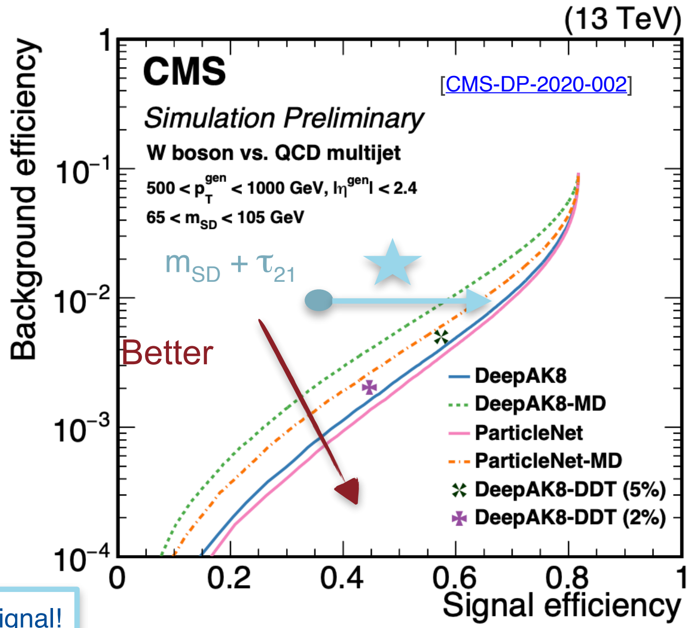
Could be applied to other tasks

One example: ParticleNet [PRD 101 (2020) 056019]

- Graph NN with jets as an unordered set of particles



- Particle cloud
  - particles are intrinsically *unordered*
  - primary information:
    - 2D coordinates in the η-φ space
    - Plus all other particle properties as momentum, charge, etc.



50% more signal!

Jet tagging

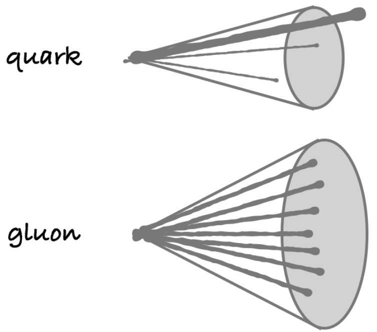
ML taggers are improving the identification performance

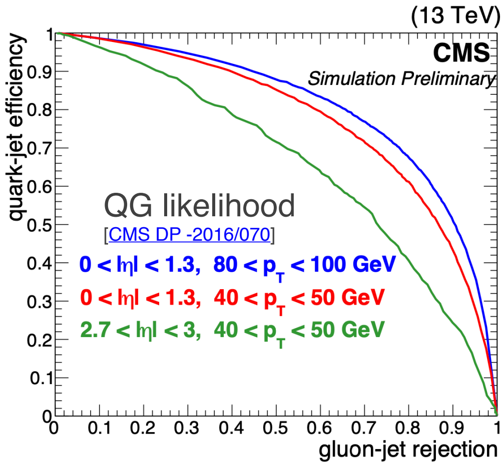
- B-tagging to reduce ttbar background
- (Boosted) W/Z tagging
- q/g discrimination

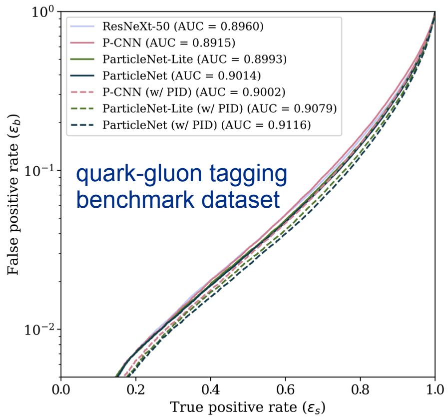
Could be applied to other tasks

One example: ParticleNet [PRD 101 (2020) 056019]

- Graph NN with jets as an unordered set of particles

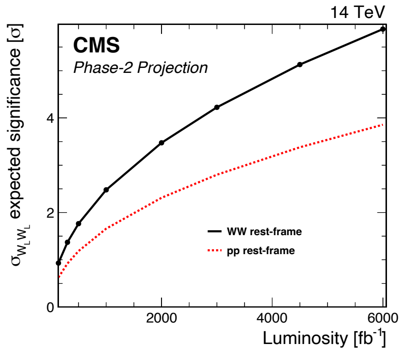






Polarization

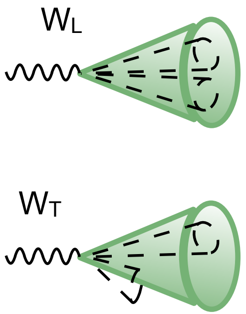
[CMS-PAS-FTR-21-001]

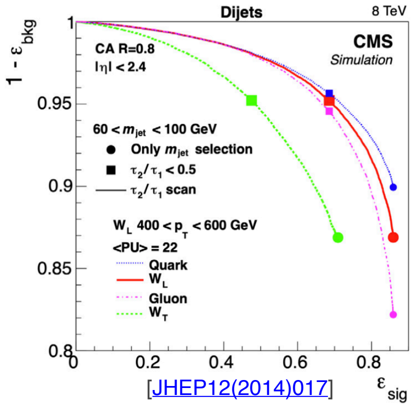


- Challenging measurement: $V_L V_L \to V_L V_L$ is ~10% of the total EW WW scattering cross section
  - Still! Significance of ~1 (3) standard deviations for WLWL (WLWX) in Run2 [PLB 812 (2020) 136018]
  - Extrapolating it the prediction at HL-LHC are improved wrt previous estimates
    - use of more sophisticated techniques to discriminate between signal and backgrounds

- Can we improve the sensitivity? Can we use other channels?

(Boosted) hadronic channel has info on all final state objects! → but improvements are needed





[JHEP12(2014)017]

Tune SD, τ_{21} & gradient BDT for W_L and W_T separately → improves subjet finding

[arXiv:2110.02773v2]

particle-based DNNs and permutation-invariant algorithms graph NN → same efficiency on hadronic W_L and W_T

JEDI-Net [arXiv:1908.05318]
ParticleNet [PRD 101 (2020) 056019]

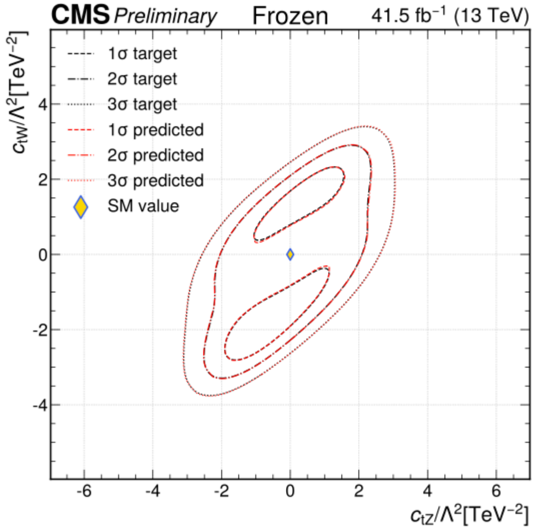
More details?

Do we see something?

- Run1 & Run2:
  - Observe SM rare processes
  - First EFT limits
    - Obtained varying the coefficient of one operator at a time (all others set to zero - SM value).

- **IF** we see something, we need to characterize it
- Can we better describe the correlations among operators?

- [CMS DP -2023/027] uses a DNN to approximate the profiled ΔNLL with high accuracy
  - Samples ~50 million points across the 16D Wilson coefficient spac with the nuisances profiled away in the process
    - Regions with high likelihood are more heavily sampled to enhance DNN performance in these regions of interest.
  - Validated reproducing published 1D & 2D scans
  - Can be used also for reparametrizations in WC space



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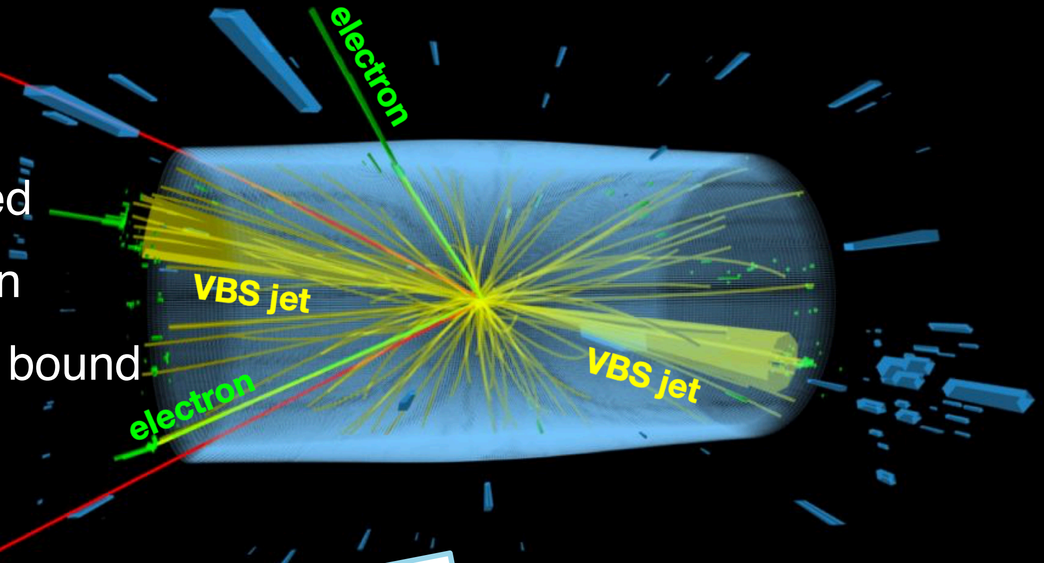
Summary



- Run2 is wrapping up:
  - First polarization
  - Some channels are still uncovered
  - Explored interference resurrection
  - Limit setting w/ clipping & unitary bound
    - And as a function of the cutoff
- New opportunities to get the most of Run3 & HL-LHC

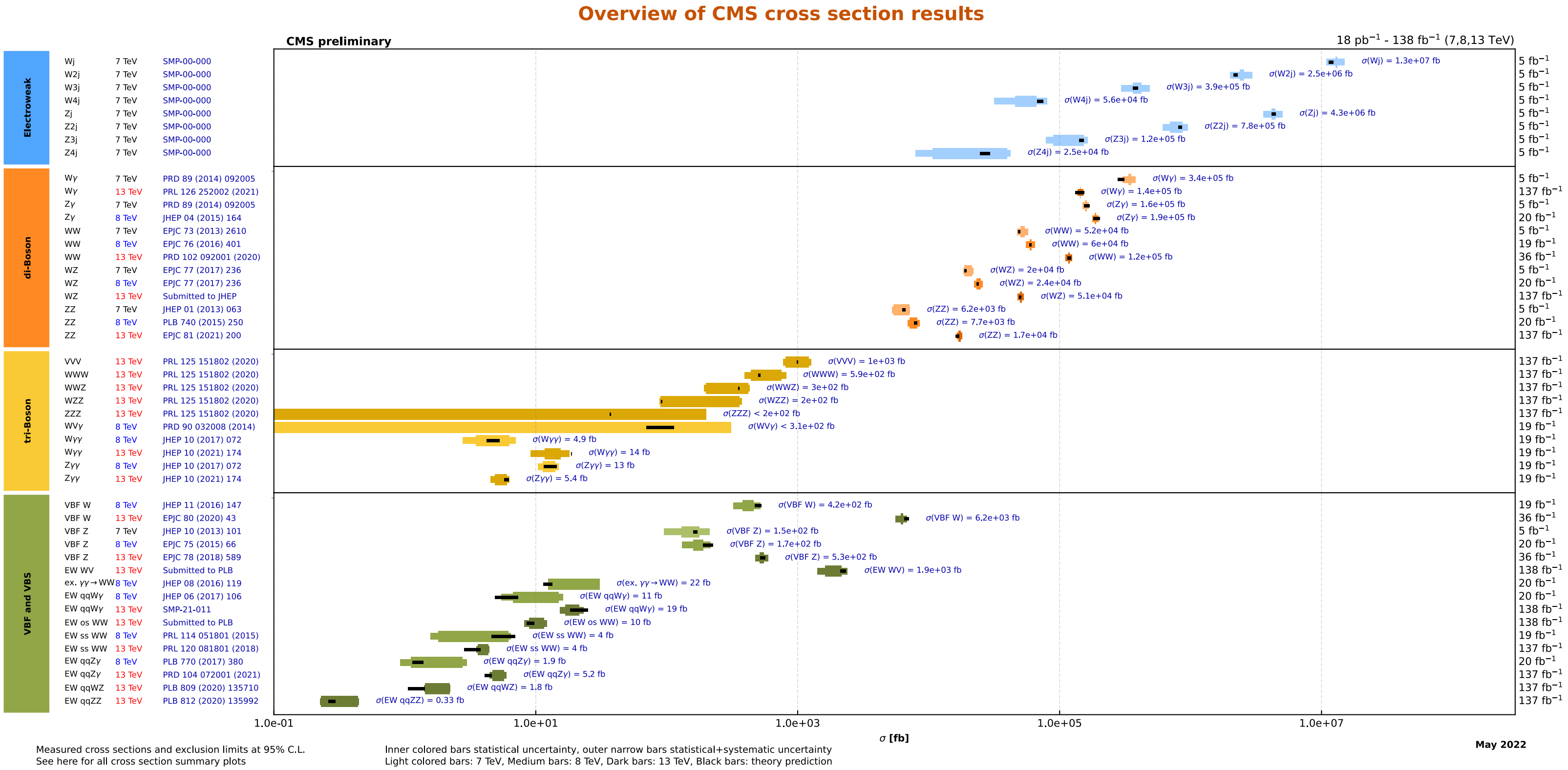
More to come!!

Fermilab

Thanks!

Many inputs from the Report from Standard Model Physics Analysis Group at Physics Days: Effective Field Theory
Saptaparna Bhattacharya, Giacomo Boldrini, Andrew Gilbert, Pietro Govoni

Additional material



Full slew of Effective Filed Theory operators at dimension-6

$\mathcal{L}_6^{(1)} - X^3$		$\mathcal{L}_6^{(6)} - \psi^2 XH$		$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\sigma^i H W^i_{\mu\nu}$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{\widetilde{G}}$	$f^{abc} \widetilde{G}_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_W	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^a u_r)\widetilde{H}\, G^a_{\mu\nu}$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\sigma^i \widetilde{H}\, W^i_{\mu\nu}$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{L}_6^{(2)} - H^6$		Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
Q_H	$(H^\dagger H)^3$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^a d_r) H\, G^a_{\mu\nu}$	$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{L}_6^{(3)} - H^4 D^2$		Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\sigma^i H\, W^i_{\mu\nu}$	$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^a u_r)(\bar{d}_s\gamma^\mu T^a d_t)$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$		
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$				
$\mathcal{L}_6^{(4)} - X^2 H^2$		$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$		$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^{a\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^{a\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_r)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^{I\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^{i\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p\sigma^i\gamma^\mu q_r)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{u}_s\gamma^\mu T^a u_t)$
Q_{HWB}	$H^\dagger\sigma^i H\, W^i_{\mu\nu} B^{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu} B^{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$	$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{d}_s\gamma^\mu T^a d_t)$
$\mathcal{L}_6^{(5)} - \psi^2 H^3$		$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$		$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$	$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^a u_r)\varepsilon_{jk}(\bar{q}_s^k T^a d_t)$
		$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\sigma^i l_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

- Use Warsaw basis
- Gauge boson self-interactions highlighted

Fermilab

Full slew of Effective Filed Theory operators at dimension-6

$\mathcal{L}_6^{(1)} - X^3$		$\mathcal{L}_6^{(6)} - \psi^2 XH$		$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\sigma^i H W_{\mu\nu}^i$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{\widetilde{G}}$	$f^{abc} \widetilde{G}_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_W	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^a u_r)\widetilde{H}\, G_{\mu\nu}^a$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\sigma^i \widetilde{H}\, W_{\mu\nu}^i$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{L}_6^{(2)} - H^6$		Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
Q_H	$(H^\dagger H)^3$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^a d_r) H\, G_{\mu\nu}^a$	$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{L}_6^{(3)} - H^4 D^2$		Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\sigma^i H\, W_{\mu\nu}^i$	$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^a u_r)(\bar{d}_s \gamma^\mu T^a d_t)$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$		
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$				
$\mathcal{L}_6^{(4)} - X^2 H^2$		$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$		$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^a G^{a\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^a G^{a\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^i H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^i W^{I\mu\nu}$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^i W^{i\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^i H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{u}_s \gamma^\mu T^a u_t)$
Q_{HWB}	$H^\dagger \sigma^i H\, W_{\mu\nu}^i B^{\mu\nu}$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}_{\mu\nu}^i B^{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{d}_s \gamma^\mu T^a d_t)$
$\mathcal{L}_6^{(5)} - \psi^2 H^3$		$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$		$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$	$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \sigma^i q_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^a u_r)\varepsilon_{jk}(\bar{q}_s^k T^a d_t)$
		$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

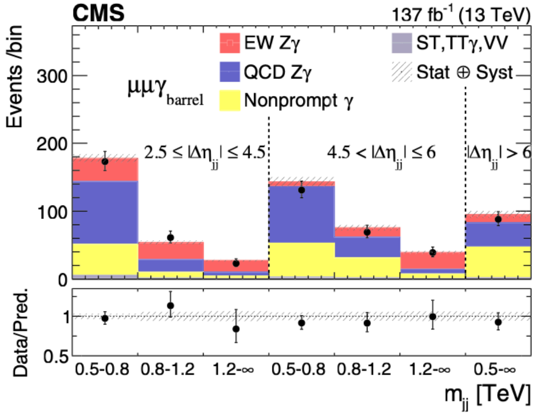
- Use Warsaw basis
- Gauge boson self-interactions highlighted

[PRD 104 (2021) 072001](PRD 104 (2021) 072001)

VBS Zγ

- $\ell+\ell$-γjj final states (ℓ = e or μ)
- Main background QCD-induced Zγjj, from simulation, constrained in data
- Z+jets with selected photon is not prompt, data-driven
- Cross section in the fiducial volume
  - EW Zγjj: 5.21±0.52(stat)±0.56(syst) fb
  - EW and QCD-induced Zγjj: 14.7±0.80(stat)±1.26(syst) fb

Common selection	$p_T^{\ell 1,\ell 2} > 25$ GeV, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.5$ for electron channel $p_T^{\ell 1,\ell 2} > 20$ GeV, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.4$ for muon channel $p_T^{\gamma} > 20$ GeV, $\lvert\eta^{\gamma}\rvert < 1.442$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_T^{j1,j2} > 30$ GeV, $\lvert\eta^{j1,j2}\rvert < 4.7$ $70 < m_{\ell\ell} < 110$ GeV, $m_{Z\gamma} > 100$ GeV ΔR_{jj}, $\Delta R_{j\gamma}$, $\Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Fiducial volume	Common selection, $m_{jj} > 500$ GeV, $\lvert\Delta\eta_{jj}\rvert > 2.5$
Control region	Common selection, $150 < m_{jj} < 500$ GeV
EW signal region	Common selection, $m_{jj} > 500$ GeV, $\lvert\Delta\eta_{jj}\rvert > 2.5$, $\eta^* < 2.4$, $\Delta\phi_{Z\gamma,jj} > 1.9$
aQGC search region	Common selection, $m_{jj} > 500$ GeV, $\lvert\Delta\eta_{jj}\rvert > 2.5$, $p_T^{\gamma} > 120$ GeV



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

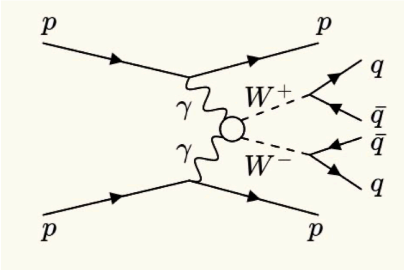
Best

VBS PPS γγWW/ZZ

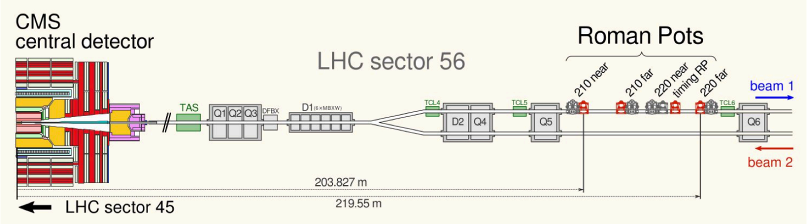
CMS + TOTEM

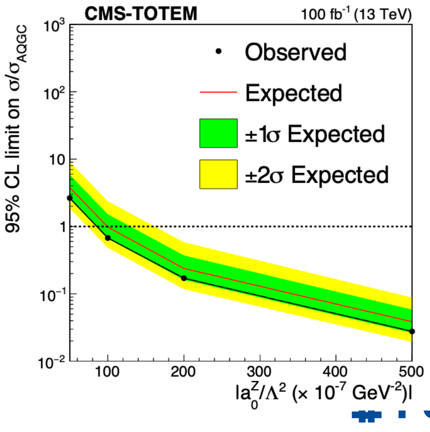
arXiv:2211.16320

- ξ: fractional momentum loss of forward proton > 0.05
- Standard VV selection and mj1+ mj2 to distinguish WW from ZZ
- Proton-jet matching requirements
- Data-driven bkg estimation in 3 SBs
  - 2 jets (QCD, V+jets, ttbar)
  - Protons from pileup/diffractive collisions or fake proton tracks from showers/beam bckg
- Main uncertainties: jet energy scale, proton ξ measurement, proton reconstruction efficiency, and integrated luminosity
- ML fit in 12 bins: 3 years, WW vs ZZ SR and 2 or 1 signal protons



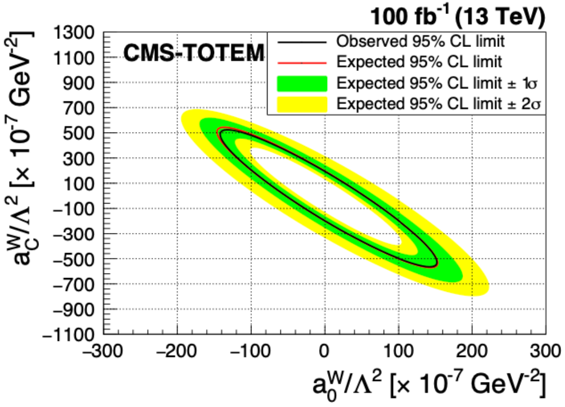
Precision Proton Spectrometer (PPS)

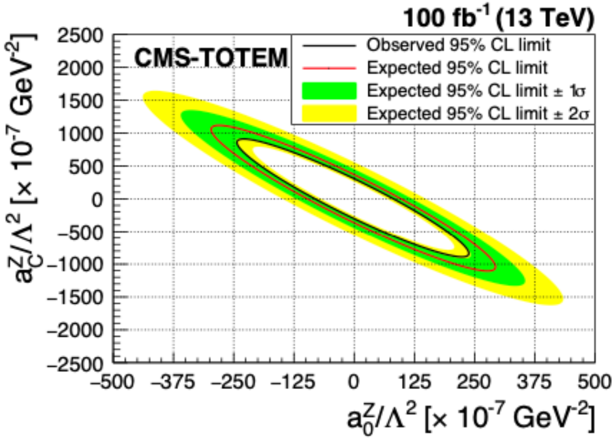




VBS PPS γγWW/ZZ

arXiv:2211.16320





Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert a_0^W/\Lambda^2\rvert$	$4.3\ (3.9) \times 10^{-6}$ GeV^{-2}	$5.2\ (5.1) \times 10^{-6}$ GeV^{-2}
$\lvert a_C^W/\Lambda^2\rvert$	$1.6\ (1.4) \times 10^{-5}$ GeV^{-2}	$2.0\ (2.0) \times 10^{-5}$ GeV^{-2}
$\lvert a_0^Z/\Lambda^2\rvert$	$0.9\ (1.0) \times 10^{-5}$ GeV^{-2}	—
$\lvert a_C^Z/\Lambda^2\rvert$	$4.0\ (4.5) \times 10^{-5}$ GeV^{-2}	—

Dim-6

$$a_0^W = -\frac{m_W}{\pi\alpha_{em}}\left[s_w^2\frac{f_{M,0}}{\Lambda^2} + 2c_w^2\frac{f_{M,2}}{\Lambda^2} + s_w c_w\frac{f_{M,4}}{\Lambda^2}\right]$$

Translated

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4\rvert$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4\rvert$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4\rvert$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4\rvert$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4\rvert$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4\rvert$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

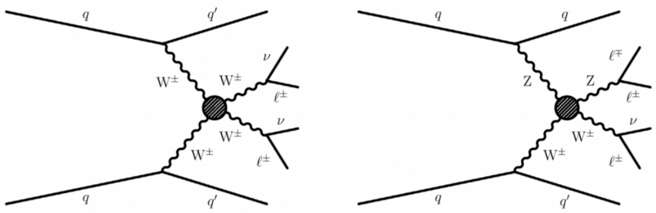
Dim-8

VBS ssWW & VBS WZ

Fully leptonic

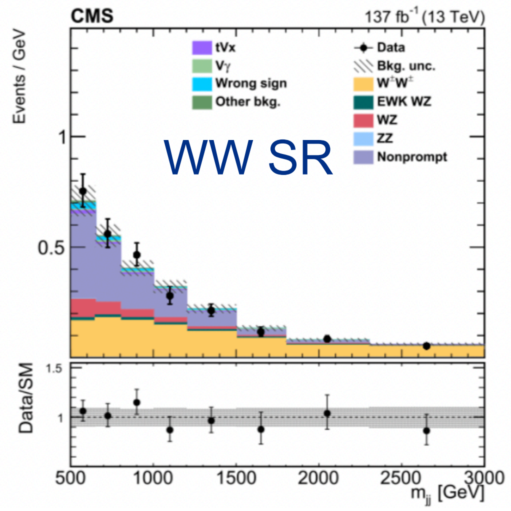
$$z^*_\ell = \left|\eta^\ell - \frac{\eta^{j_1}+\eta^{j_2}}{2}\right| / |\Delta\eta_{jj}|$$

[PLB 809 (2020) 135710]



- Background estimation with CR in data & simulation
  - Simultaneous fit of WZ and W±W± SR
  - data-to-simulation efficiency correction for charge-misidentified electron

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



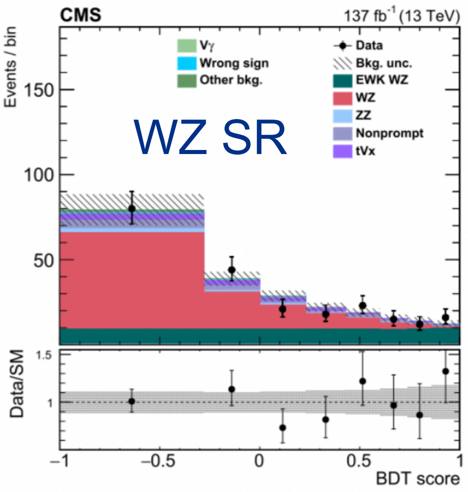


Table 3
List and description of all the input variables used in the BDT analysis for the WZ SR.

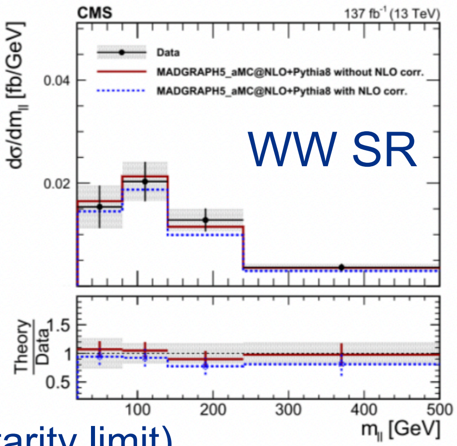
Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\lvert\Delta\eta_{jj}\rvert$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{jj}$	Absolute difference in azimuthal angles of the leading and trailing jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T 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
$\lvert\vec{p}_T^{\,tot}\rvert / \sum_i p_T^i$	Transverse component of the vector sum of the bosons and tagging jets momenta, normalized to their scalar p_T sum

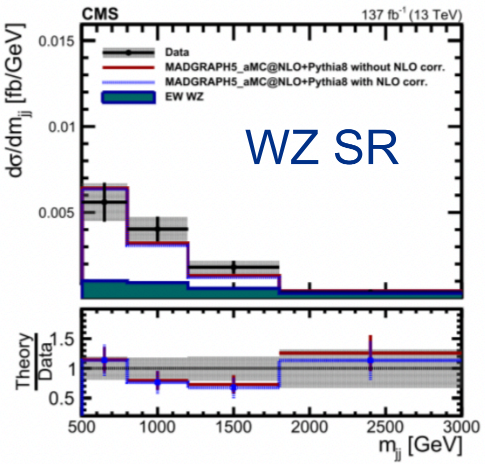
VBS ssWW & VBS WZ

Fully leptonic

[PLB 809 (2020) 135710]

- **EW WZ obs. (exp.) significance 6.8 (5.3)**
- **EW W±W± signal >> 5 standard deviations**





Dim-8 limits (cutting the EFT expansion at the unitarity limit)

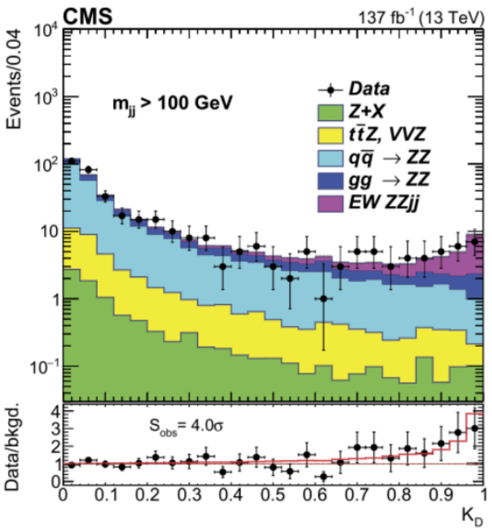
	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

[PLB 812 (2021) 135992]

VBS ZZ

Fully leptonic

- Main bckg: production of 2Z bosons + QCD-induced jets, estimated from simulation but further constrained in data
- Other irreducible bckgs: processes with high-pT isolated leptons $t\bar{t}$Z+jets and VVZ+jets, from simulation
- Reducible bckgs: heavy-flavor jets produce secondary leptons or jets misidentified as leptons as Z+jets, tt+jets and WZ+jets
- Main unc: QCD renormalization and factorization scales (signal) and jet energy scale ~10%
- signal strength for the EW production,
- $\mu = \sigma / \sigma SM$, extracted with matrix element discriminant (KD)



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24 (−0.26)	0.22 (0.24)	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31 (−0.34)	0.31 (0.34)	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63 (−0.69)	0.59 (0.65)	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43 (−0.47)	0.43 (0.48)	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92 (−1.02)	0.92 (1.02)	1.8

Best

Polarized VBS ssWW

Fully leptonic

PLB 812 (2020) 136018

- Electron charge misidentification in simulation is corrected to reproduce the rate measured in data, using Z→ee events: mis. rate is about 0.01% (0.3%) in the barrel (endcap) region. Contri [50]. Contribution in OS dilepton final states from t̄t, tW, W+W–, and Drell–Yan
- CRs to estimate the normalization of the main backgrounds from data: WZ, nonprompt lepton, tZq, and ZZ
- 2 fits are performed for the cross-sections on 2D variable (inclusive + signal BDTs)
  - WL± WL± and WX±WT±
  - WL± WX± and WT±WT±

Variables	Definitions
$\Delta\phi_{jj}$	Difference in azimuthal angle between the leading and subleading jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the subleading jet
$p_T^{\ell_1}$	Leading lepton p_T
$p_T^{\ell_2}$	Subleading lepton p_T
$\Delta\phi_{\ell\ell}$	Difference in azimuthal angle between the two leptons
$m_{\ell\ell}$	Dilepton mass
$p_T^{\ell\ell}$	Dilepton p_T
m_T^{WW}	Transverse WW diboson mass
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$\Delta R_{j1,\ell\ell}$	ΔR between the leading jet and the dilepton system
$\Delta R_{j2,\ell\ell}$	ΔR between the subleading jet and the dilepton system
$(p_T^{\ell_1} p_T^{\ell_2})/(p_T^{j1} p_T^{j2})$	Ratio of p_T products between leptons and jets
p_T^{miss}	Missing transverse momentum

Source of uncertainty	$W_L^\pm W_L^\pm$ (%)	$W_X^\pm W_T^\pm$ (%)	$W_L^\pm W_X^\pm$ (%)	$W_T^\pm W_T^\pm$ (%)
Integrated luminosity	3.2	1.8	1.9	1.8
Lepton measurement	3.6	1.9	2.5	1.8
Jet energy scale and resolution	11	2.9	2.5	1.1
Pileup	0.9	0.1	1.0	0.3
b tagging	1.1	1.2	1.4	1.1
Nonprompt lepton rate	17	2.7	9.3	1.6
Trigger	1.9	1.1	1.6	0.9
Limited sample size	38	3.9	14	5.7
Theory	6.8	2.3	4.0	2.3
Total systematic uncertainty	44	6.6	18	7.0
Statistical uncertainty	123	15	42	22
Total uncertainty	130	16	46	23

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)	
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05	WW RF
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	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	
$W_L^\pm W_L^\pm$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03	Partons RF
$W_X^\pm W_T^\pm$	$3.25^{+0.50}_{-0.48}$	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	

obs. (exp.) significance WL±WX± 2.3 (3.1)

obs. (exp.) significance WL±WX± 2.6 (2.9)

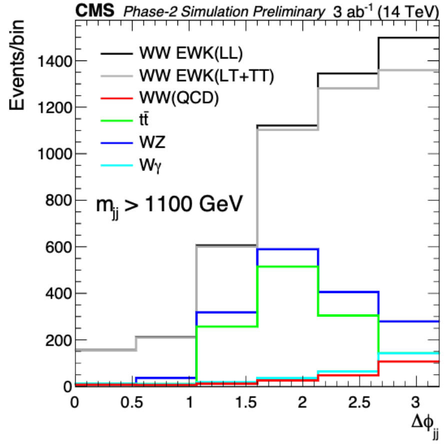
Polarization

Fully leptonic

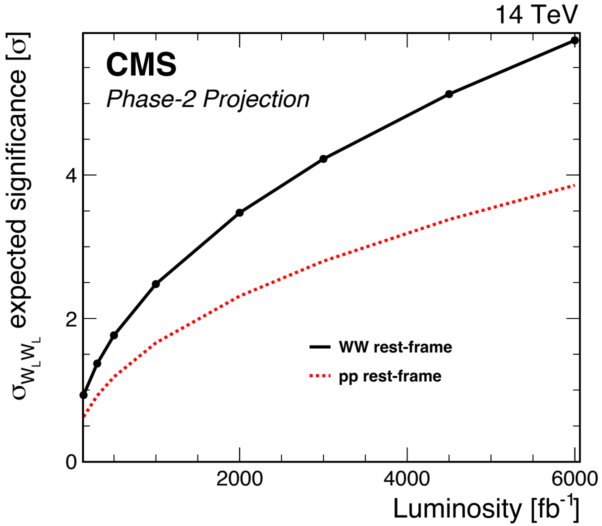
[CMS-PAS-FTR-21-001]

Simultaneous fit of Dphi jj variable in two mjj regions

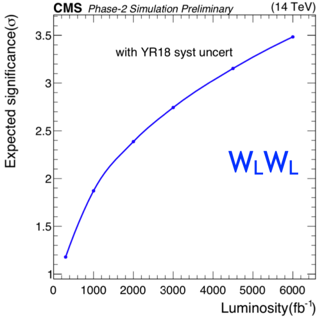
[CERN-LPCC-2018-03]

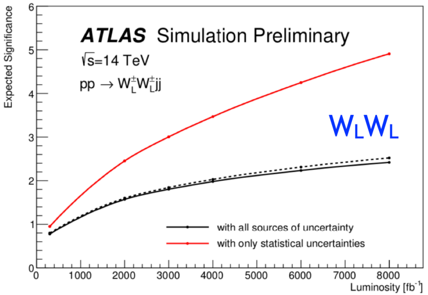


From 3 to 4 sigma at 3000/fb!



$Z_L Z_L$	significance	
	w/ syst. uncert.	w/o syst. uncert.
HL-LHC	1.4σ	1.4σ
HE-LHC	5.2σ	5.7σ

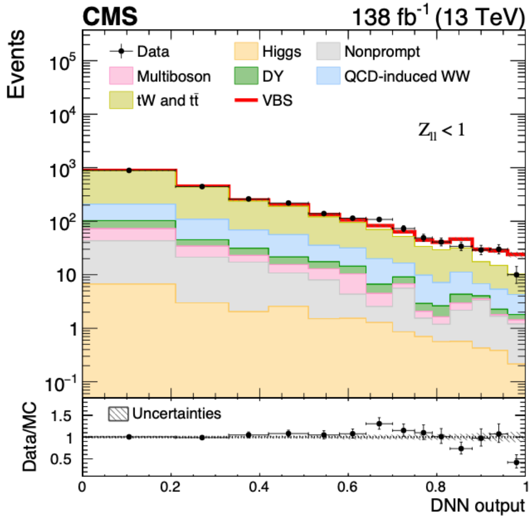


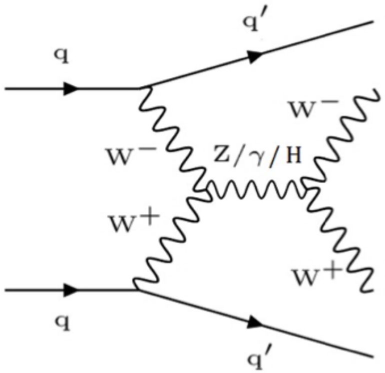


VBS osWW Fully leptonic

[arXiv:2205.05711]

- VBS SR in 3 channels ee, μμ, eμ
- DY & ttbar CR
- Dedicated DNN for the eμ channel
- Signal strength from fit in SR+CR





Inclusive cross section
99 ± 20 fb (89 ± 5 fb theory)

Fiducial cross section
10.2 ± 2.0 fb (9.1 ± 0.6 fb theory)

Objects	Requirements
Leptons	$e\mu, ee, \mu\mu$ (not from τ decay), opposite charge
	$p_T^{\text{dressed}\,\ell} = p_T^{\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell,\gamma_i) < 0.1$
	$p_T^{\ell_1} > 25\,\text{GeV}$, $p_T^{\ell_2} > 13\,\text{GeV}$, $p_T^{\ell_3} < 10\,\text{GeV}$
	$\lvert\eta\rvert < 2.5$
	$p_T^{\ell\ell} > 30\,\text{GeV}$, $m_{\ell\ell} > 50\,\text{GeV}$
Jets	$p_T^{j} > 30\,\text{GeV}$
	$\Delta R(j,\ell) > 0.4$
	At least 2 jets, no b jets
	$\lvert\eta\rvert < 4.7$
	$m_{jj} > 300\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$
p_T^{miss}	$p_T^{\text{miss}} > 20\,\text{GeV}$

Fiducial volume: Requirements at Gen level

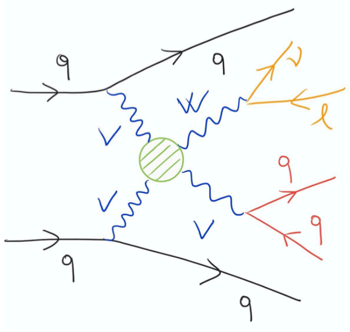
eμ DNN

Variable	Description
m_{jj}	Invariant mass of the two tagging jets pair
$\Delta\eta_{jj}$	Pseudorapidity separation between the two tagging jets
$p_T^{j_1}$	p_T of the highest p_T jet
$p_T^{j_2}$	p_T of the second-highest p_T jet
$p_T^{\ell\ell}$	p_T of the lepton pair
$\Delta\phi_{\ell\ell}$	Azimuthal angle between the two leptons
Z_{ℓ_1}	Zeppenfeld variable of the highest p_T lepton
Z_{ℓ_2}	Zeppenfeld variable of the second-highest p_T lepton
$m_T^{\ell_1}$	Transverse mass of the $(p_T^{\ell_1}, p_T^{\text{miss}})$ system

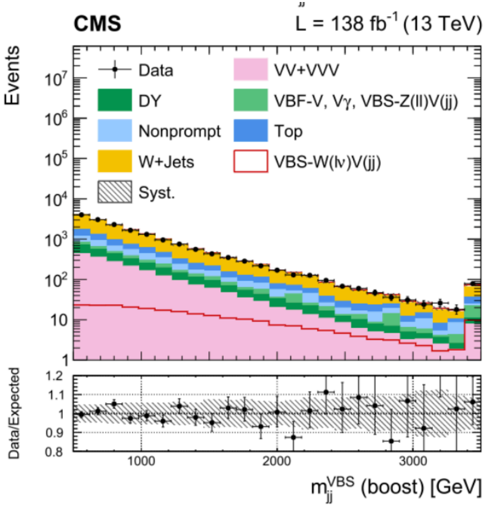
PLB 834 (2022) 137438

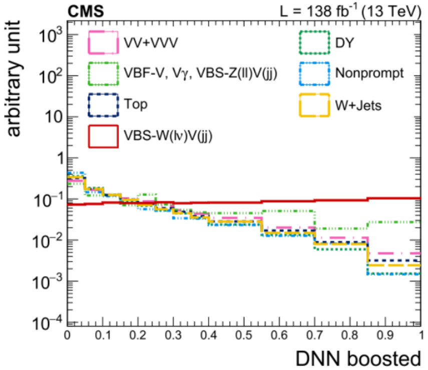
VBS WV (SM) semi-leptonic

- Large BR but large irreducible backgrounds
- No public predictions beyond LO accuracy for semileptonic signatures
- Advances in signal modeling of parton-shower effects (Dipole recoil scheme used for the first time) [arXiv:1710.00391]
- Data-driven bkg estimation for Top and W+jets backgrounds:
    - Top: one free floating parameter per category in the ML fit
    - Wjets: several free floating parameters per category in the ML fit, to perfect the modeling of VBS-jets momenta.
- Main uncertainties: statistical, theoretical and b-tagging



Boosted & resolved categories



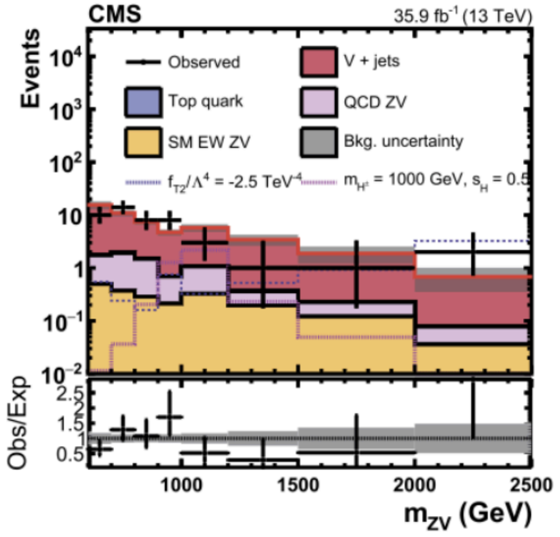


Variable	Resolved	Boosted	SHAP ranking	
			Resolved	Boosted
Lepton pseudorapidity	✓	✓	13	12
Lepton transverse momentum	✓	✓	16	10
Zeppenfeld variable for the lepton	✓	✓	2	2
Number of jets with $p_T > 30$ GeV	✓	✓	7	3
Leading VBS tag jet p_T	-	✓	-	11
Trailing VBS tag jet p_T	✓	✓	7	6
Pseudorapidity interval $\Delta\eta_{jj}^{VBS}$ between tag jets	✓	✓	4	4
Quark/gluon discriminator of leading VBS tag jet	✓	✓	9	7
Azimuthal angle distance between VBS tag jets	✓	-	10	-
Invariant mass of the VBS tag jets pair	✓	✓	1	1
p_T of the leading V_{had} jet	✓	-	14	-
p_T of the trailing V_{had} jet	✓	-	12	-
Pseudorapidity difference between V_{had} jets	✓	-	8	-
Quark/gluon discriminator of the leading V_{had} jet	✓	-	3	-
Quark/gluon discriminator of the trailing V_{had} jet	✓	-	5	-
p_T of the AK8 V_{had} jet candidate	-	✓	-	8
Invariant mass of V_{had}	✓	✓	11	5
Zeppenfeld variable for V_{had}	-	✓	-	9
Centrality	-	✓	15	13

VBS WV/ZV (dim-8) semi-leptonic

PLB 798 (2019)134985

- Includes also a search for charged Higgs bosons
- Main bckg V+jets from data is SB region
  - Fit of the mwv & mzv & obtain transfer factor
- Unitarity constraints not included
- First aQGC search in this channel



	Observed (WV) (TeV^{-4})	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{S0}/Λ^4	[−2.7, 2.7]	[−4.2, 4.2]	[−40, 40]	[−31, 31]	[−2.7, 2.7]	[−4.2, 4.2]
f_{S1}/Λ^4	[−3.3, 3.4]	[−5.2, 5.2]	[−32, 32]	[−24, 24]	[−3.4, 3.4]	[−5.2, 5.2]
f_{M0}/Λ^4	[−0.69, 0.69]	[−1.0, 1.0]	[−7.5, 7.5]	[−5.3, 5.3]	[−0.69, 0.70]	[−1.0, 1.0]
f_{M1}/Λ^4	[−2.0, 2.0]	[−3.0, 3.0]	[−22, 23]	[−16, 16]	[−2.0, 2.1]	[−3.0, 3.0]
f_{M6}/Λ^4	[−1.4, 1.4]	[−2.0, 2.0]	[−15, 15]	[−11, 11]	[−1.3, 1.3]	[−1.4, 1.4]
f_{M7}/Λ^4	[−3.4, 3.4]	[−5.1, 5.1]	[−35, 36]	[−25, 26]	[−3.4, 3.4]	[−5.1, 5.1]
f_{T0}/Λ^4	[−0.12, 0.11]	[−0.17, 0.16]	[−1.4, 1.4]	[−1.0, 1.0]	[−0.12, 0.11]	[−0.17, 0.16]
f_{T1}/Λ^4	[−0.12, 0.13]	[−0.18, 0.18]	[−1.5, 1.5]	[−1.0, 1.0]	[−0.12, 0.13]	[−0.18, 0.18]
f_{T2}/Λ^4	[−0.28, 0.28]	[−0.41, 0.41]	[−3.4, 3.4]	[−2.4, 2.4]	[−0.28, 0.28]	[−0.41, 0.41]

Softdrop

[JHEP 05 (2014)146]

- Soft drop: reduce the jet contamination from initial state radiation, underlying event and pileup

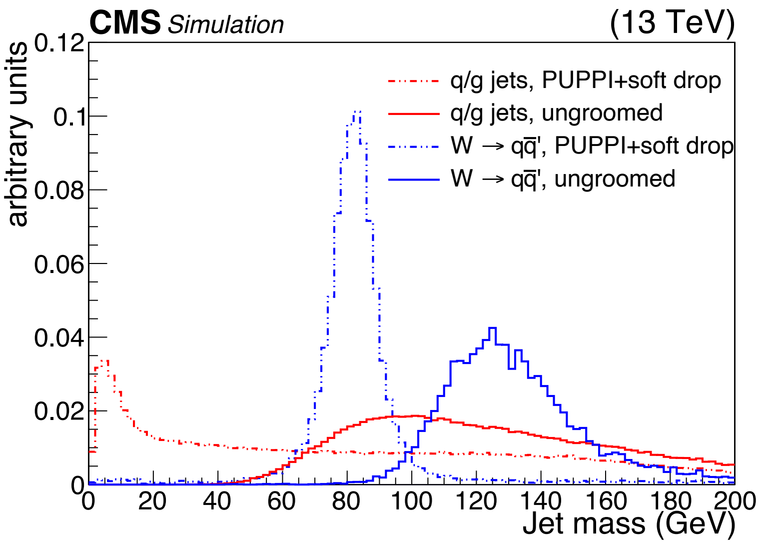
Soft drop condition: $$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

1. Jet j clustered with CA
2. Decluster last step and obtain j1 and j2
3. Check if soft drop condition is satisfied

Yes → j is the final SD jet

No → decluster jet with higher p_T, remove the other, Repeat

[B2G-17-001]



Nsubjettiness

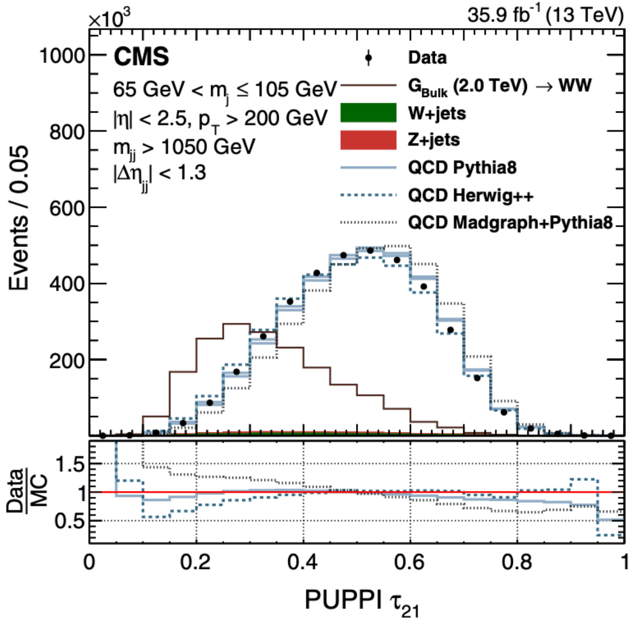
[arXiv:1011.2268]

- N-subjettiness τ_N tells how likely a jet has N subjets

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\} \qquad d_0 = \sum_k p_{T,k} R$$

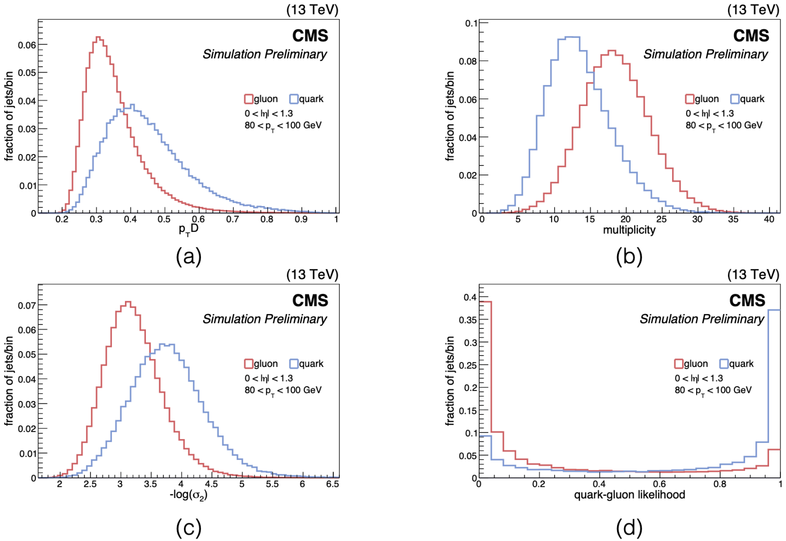
N = identified subjets
k = jet constituents

[B2G-17-001]



- $\tau_N \sim 0$: N subjets likely
- $\tau_N >> 0$: more than N subjets likely

QG likelihood [CMS DP -2016/070]

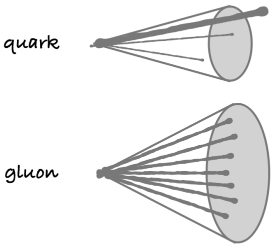


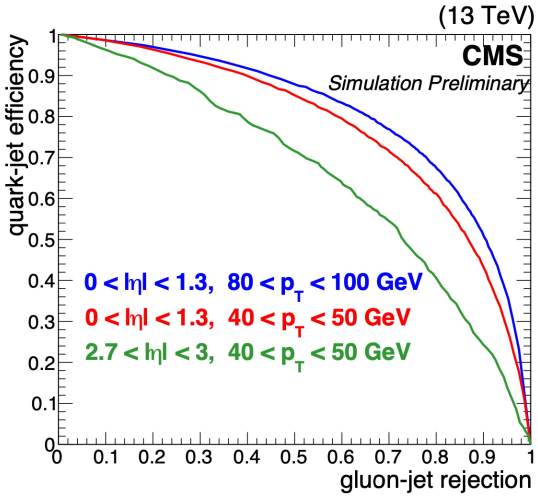
Quark-gluon discrimination variables from simulation: (a) $p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$ (b) multiplicity (c) $-log(\sigma_2)$, where σ_2 is the ellipse minor axis (d) the Quark-Gluon Likelihood.

3

Main differences are:

- the **particle multiplicity** is higher in gluon jets than in light-quark jets;
- the **fragmentation function** of gluon jets is considerably softer than that of a quark jet;
- gluon jets are less **collimated** than quark jets.





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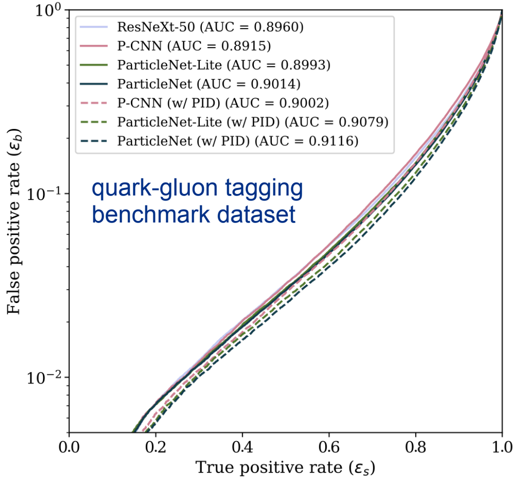
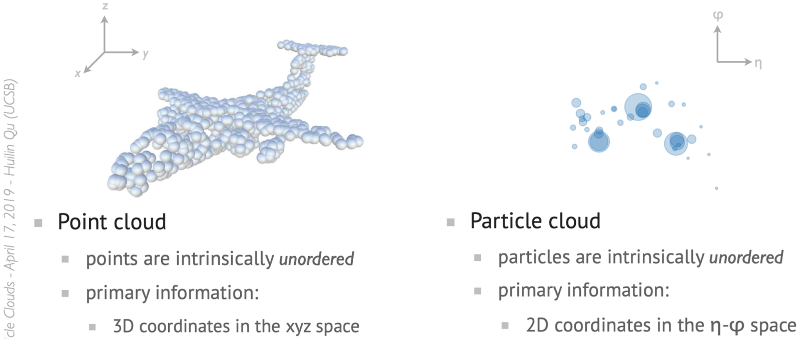
ParticleNet [Phys. Rev. D 101 (2020) 056019]

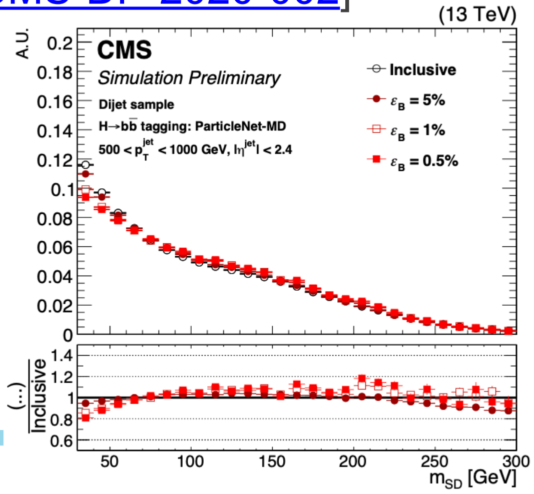
- Customized neural network architecture based on the particle cloud representation → jet as an unordered set of particles
  - Uses a permutation-invariant graph neural network architecture
- In CMS:
  - multi-class tagger for t/W/Z/H tagging
  - same inputs as DeepAK8 (PF candidates/secondary vertices)
  - significant performance improvement
  - Mass decorrelation obtained with training using a dedicated signal sample with flat mass spectrum: $m_X \in [15, 250]$ GeV





• Plus all other particle properties as momentum, charge, etc.

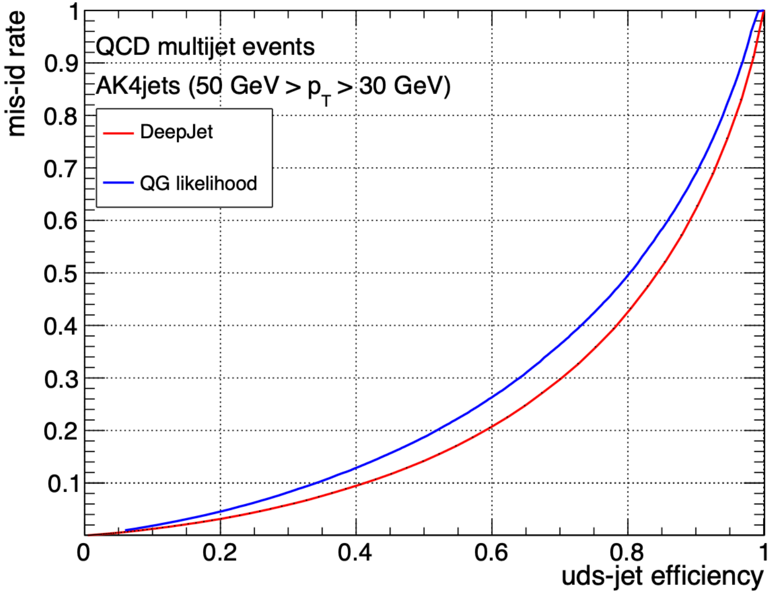
[CMS-DP-2020-002]

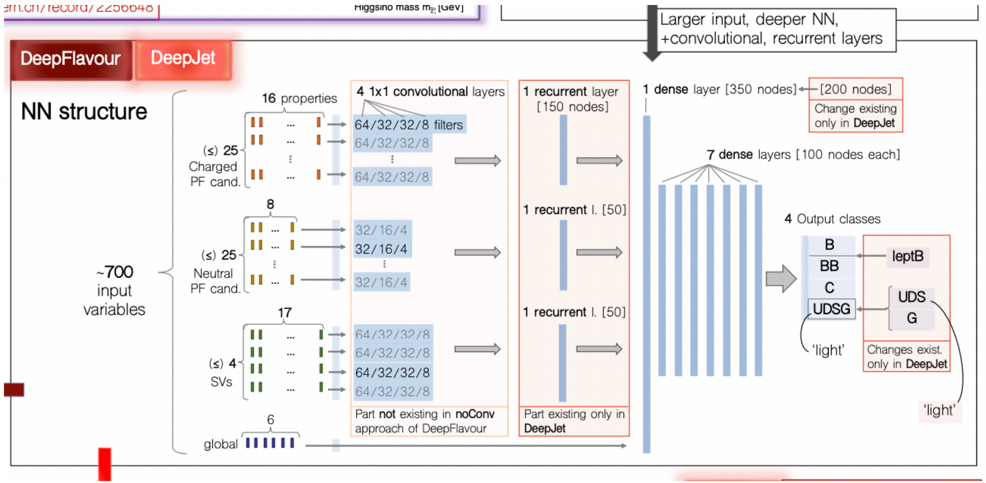


DeepJet

[JINST 15 (2020) P12012]

- DeepJet: Deep neural network algorithm
  - 16(8) properties of up to 25 charged (neutral) particle-flow jet constituents
  - 12 properties of up to 4 secondary vertices associated with the jet





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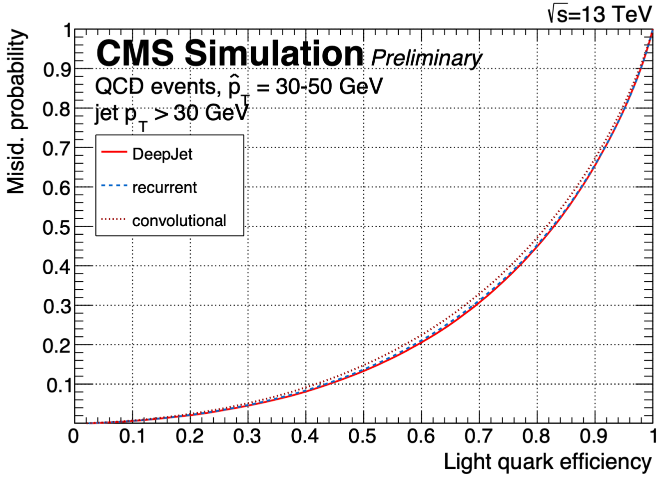
- 2 Comparable approches to DeepJet [CMS-DP-2017-027]

Long short-term memory (LSTM)

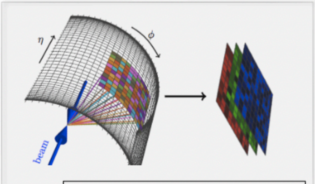


DeepJet | CMS DP 2017-027 cds.cern.ch/record/2275226

NN approaches compared to **DeepJet** in Quark/Gluon discrimination [Quark:'light']:

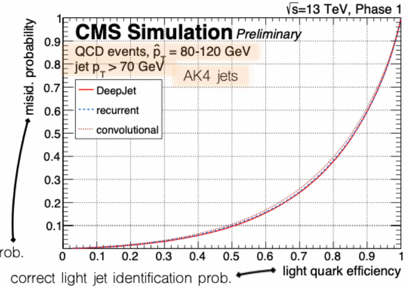
recurrent [inspired by arXiv:1702.00748]: Input: **relative** $\mathbf{p_T/\eta/\varphi}$, and **PUPPI** (Pileup Per Particle Identification) **weight** (arXiv:1407.6013) of **charged** (fed to one recurrent layer of 100 nodes – LSTM) and **neutral PF cand.** (fed to identical layer). LSTM output then merged with **global*** variables in a dense NN [1 layer of 200 nodes, 5 of 100].

convolutional: Jet treated as image on $\boldsymbol{\eta - \varphi}$ plane. 3rd dimension – **color**: (separate study for charged and neutral PF cand.) **relative** $\mathbf{p_T}$ and **particle multiplicity** within the pixel. This input info fed to a CNN (Convolutional NN) [as in arXiv:1612.01551], then merged with the **global*** variables in a dense layer of 128 nodes.



Part of figure from arXiv:1612.01551

*Jet variables:
jet p_T/η,
#(charged PF cand.),
#(neutral PF cand.),
#(SV within the jet)



gluon jet misid. (as a light jet) prob.

correct light jet identification prob.

[Jets originating from gluon splitting to bb or cc not considered as gluon jets]

➢ **Similar performance** among **DeepJet** and 2 alternative **approaches**

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- End-to-end jet classification [NIM A 977 (2020) 164304]