Vector boson scattering results in CMS

Andrea Piccinelli
On behalf of the CMS Collaboration

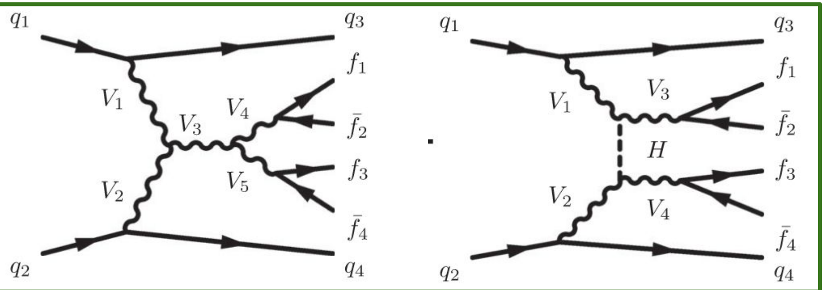
ICHEP 2024 - July 20th, 2024 @ Prague

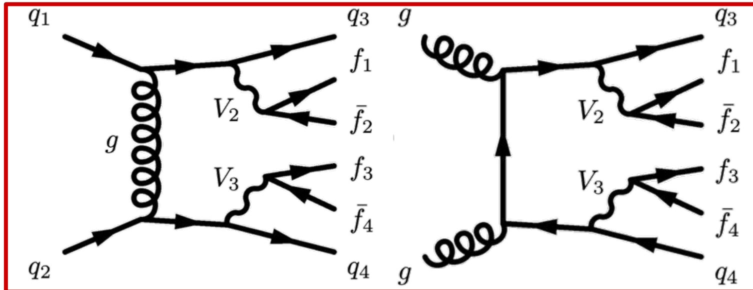
What is VBS?

What is VBS?

- **Scattering of two Vector Bosons (V = W, Z, γ)**
  - Triple and Quartic Gauge Couplings (TGC/QGC)
- Three possible contributions (at LO)
  - **pure EWK** $O(\alpha_{EW}^6)$ - **signal**
  - **QCD-induced** $O(\alpha_{EW}^4\,\alpha_S^2)$ - **background**

pure EWK



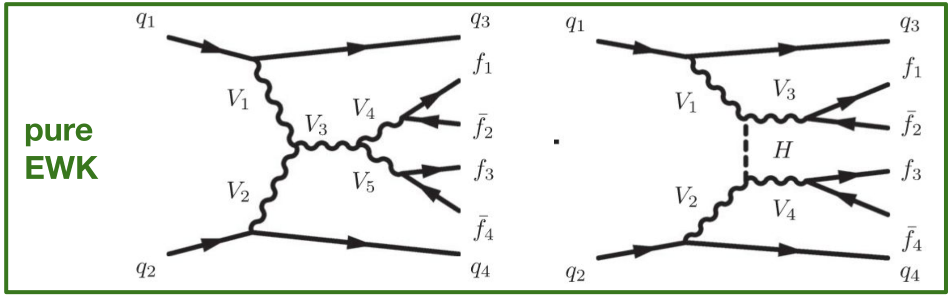


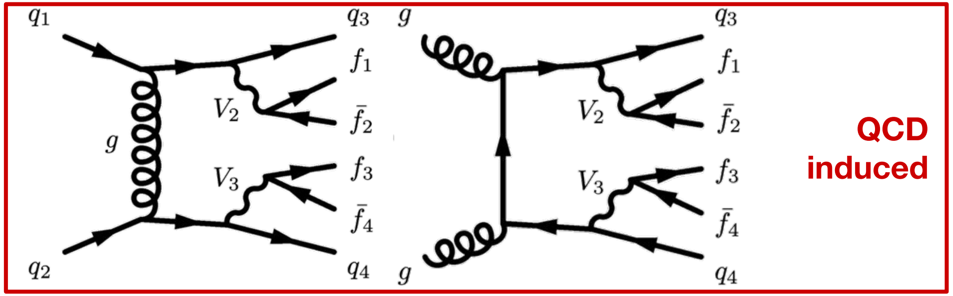
QCD induced

What is VBS?

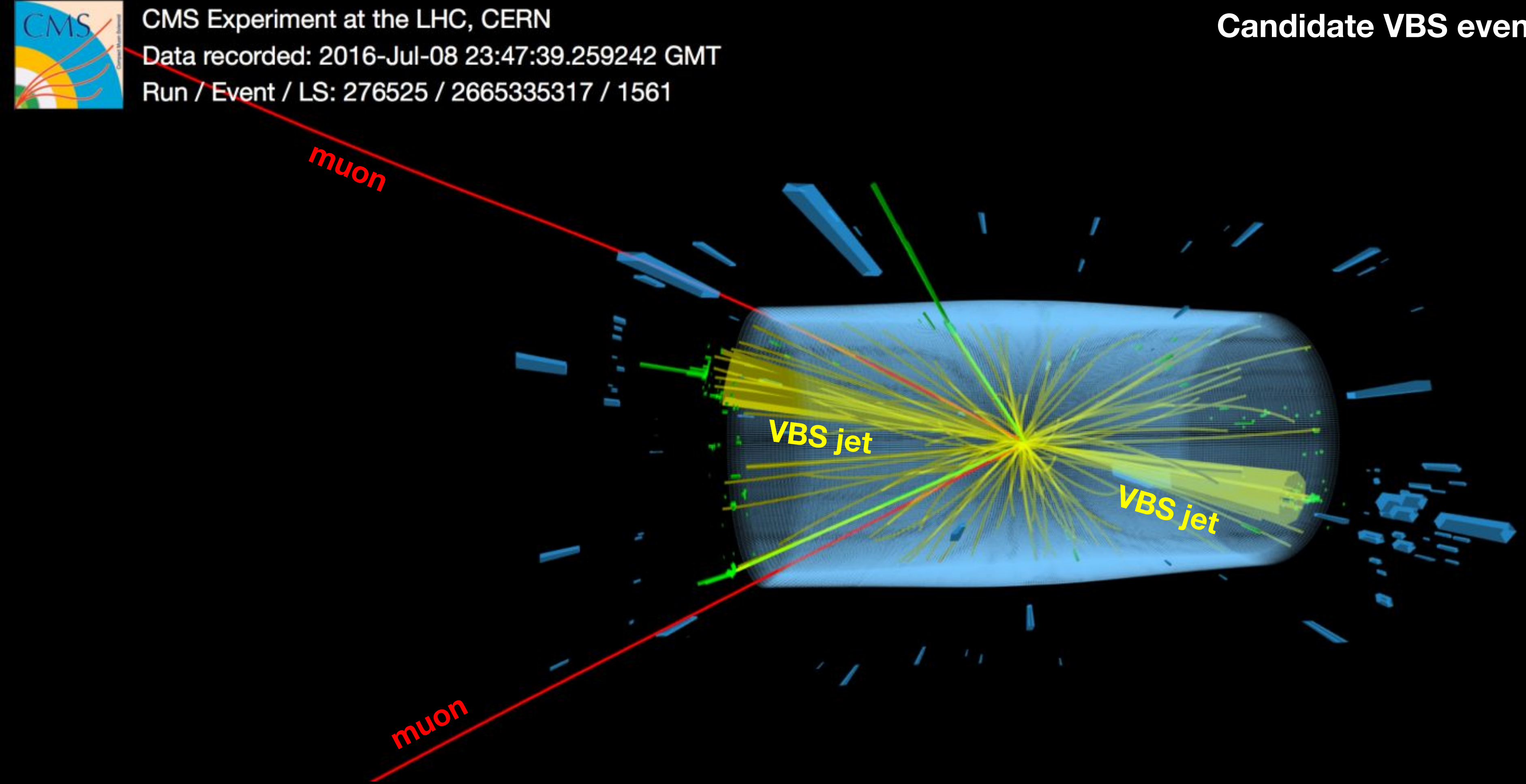
- **Scattering of two Vector Bosons (V = W, Z, γ)**
  - Triple and Quartic Gauge Couplings (TGC/QGC)
- Three possible contributions (at LO)
  - **pure EWK** $O(\alpha_{EW}^6)$ - **signal**
  - **QCD-induced** $O(\alpha_{EW}^4\,\alpha_S^2)$ - **background**

- Peculiar experimental signature
  - 2 very energetic forward-backward jets: **VBS jets**
  - 4 fermions coming from the scattered Vs
- Main background due to non prompt leptons
  - QCD-induced jets reconstructed as leptons





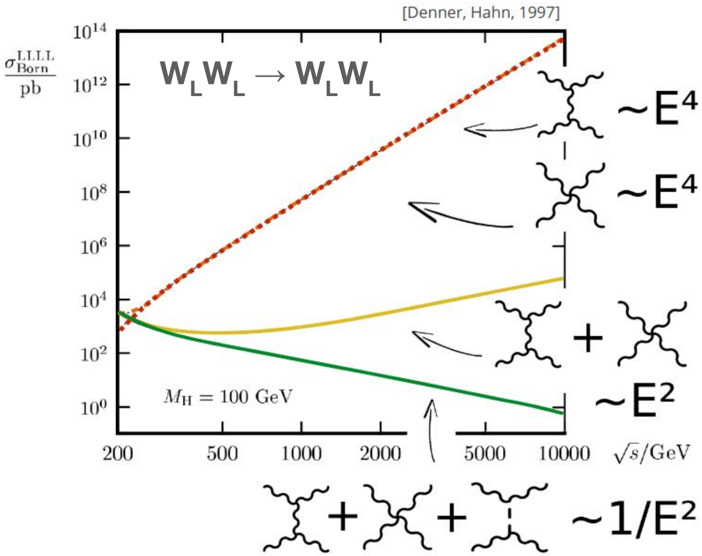
Candidate VBS event



Why study VBS?

Why study VBS?

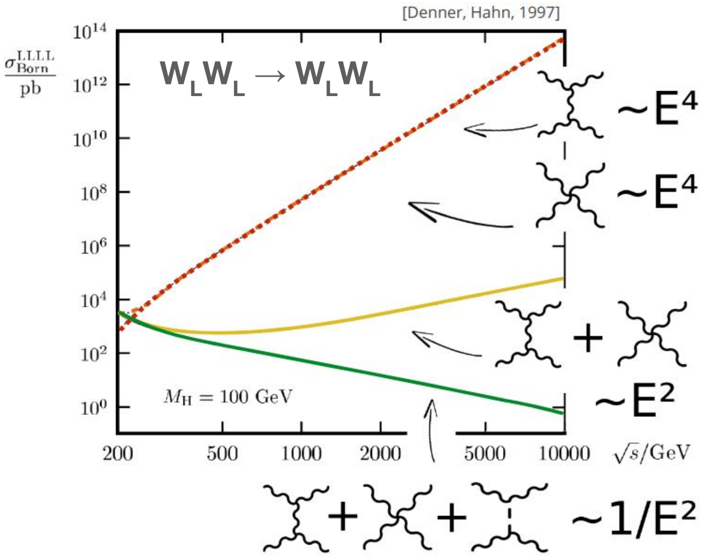
- **Key process to probe EW Symmetry Breaking**
  - Higgs-like field necessary to preserve unitarity
  - Only investigable in VV scattering
  - Complimentary to Higgs-sector studies
- General test of the EW sector in SM
- Background wrt other signals with similar final state

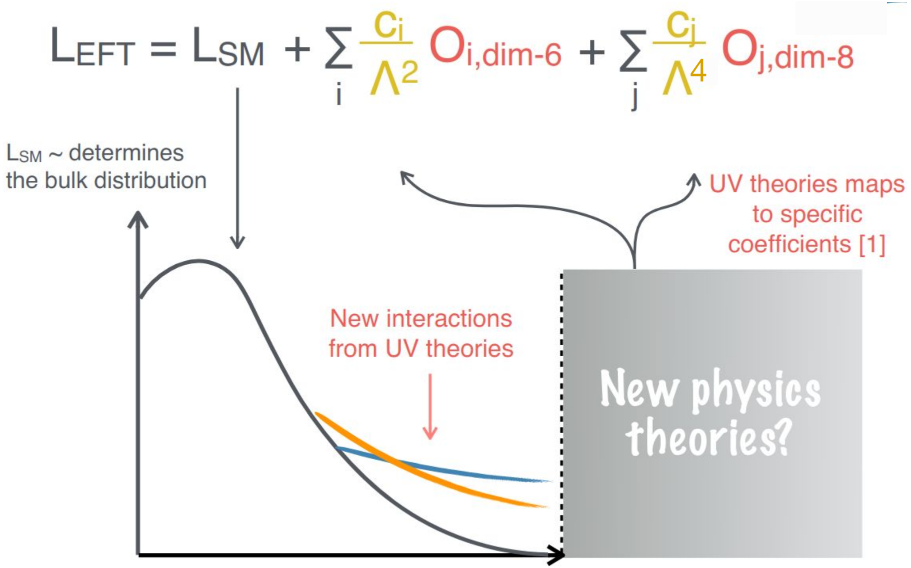


Why study VBS?

- **Key process to probe EW Symmetry Breaking**
  - Higgs-like field necessary to preserve unitarity
  - Only investigable in VV scattering
  - Complimentary to Higgs-sector studies
- General test of the EW sector in SM
- Background wrt other signals with similar final state

- Higgs affecting VBS processes → **New Physics!**
  - Suitable to investigate indirect NP effects
    - anomalous Triple/Quartic Gauge Coupling **(aTGC/aQGC)**
    - **Model-independent EFT** approach
  - Direct search for new resonances





VBS measurements in CMS

- **Big effort** to investigate VBS processes with full Run-II dataset
  - Fiducial and differential x-sections
  - Indirect search for New Physics
- Several final state analyzed
  - Fully-leptonic → very clean
  - Semileptonic/fully-hadronic → sensitive to aQGCs
  - Photonic → clean, but with larger background

VBS measurements in CMS

- **Big effort** to investigate VBS processes with full Run-II dataset
  - Fiducial and differential x-sections
  - Indirect search for New Physics
- Several final state analyzed
  - Fully-leptonic → very clean
  - Semileptonic/fully-hadronic → sensitive to aQGCs
  - Photonic → clean, but with larger background

- Outstanding results with the full Run-II dataset
  - Scattering $W^{\pm}W^{\pm}$ with one hadronic tau - SMP-22-008
  - Semileptonic WV scattering - SMP-20-013
  - High-mass γγ→WW/ZZ production - SMP-21-014
  - Leptonic Wγ scattering - SMP-21-011
  - Leptonic $W^{+}W^{-}$ scattering - SMP-21-001
  - Zγ scattering - SMP-20-016
  - Leptonic WZ scattering - SMP-20-014
  - Polarized scattering $W^{\pm}W^{\pm}$ - SMP-20-006

VBS measurements in CMS

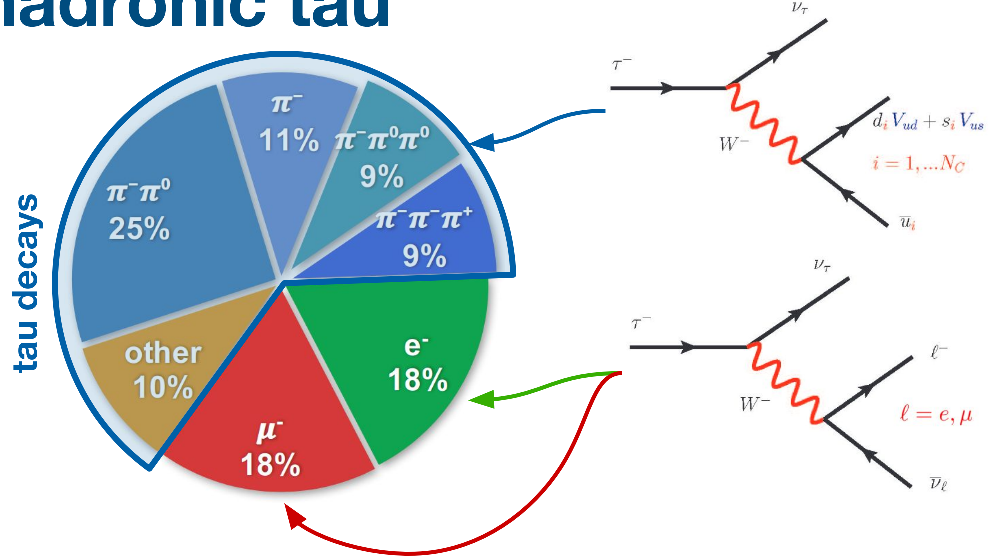
- **Big effort** to investigate VBS processes with full Run-II dataset
  - Fiducial and differential x-sections
  - Indirect search for New Physics
- Several final state analyzed
  - Fully-leptonic → very clean
  - Semileptonic/fully-hadronic → sensitive to aQGCs
  - Photonic → clean, but with larger background

- Outstanding results with the full Run-II dataset
  - **Scattering $W^{\pm}W^{\pm}$ with one hadronic tau - SMP-22-008**
  - **Semileptonic WV scattering - SMP-20-013**
  - **High-mass γγ→WW/ZZ production - SMP-21-014**
  - Leptonic Wγ scattering - SMP-21-011
  - Leptonic $W^{+}W^{-}$ scattering - SMP-21-001
  - Zγ scattering - SMP-20-016
  - Leptonic WZ scattering - SMP-20-014
  - Polarized scattering $W^{\pm}W^{\pm}$ - SMP-20-006

Scattering $W^\pm W^\pm$ with one hadronic tau

CMS-SMP-22-008 – Overview

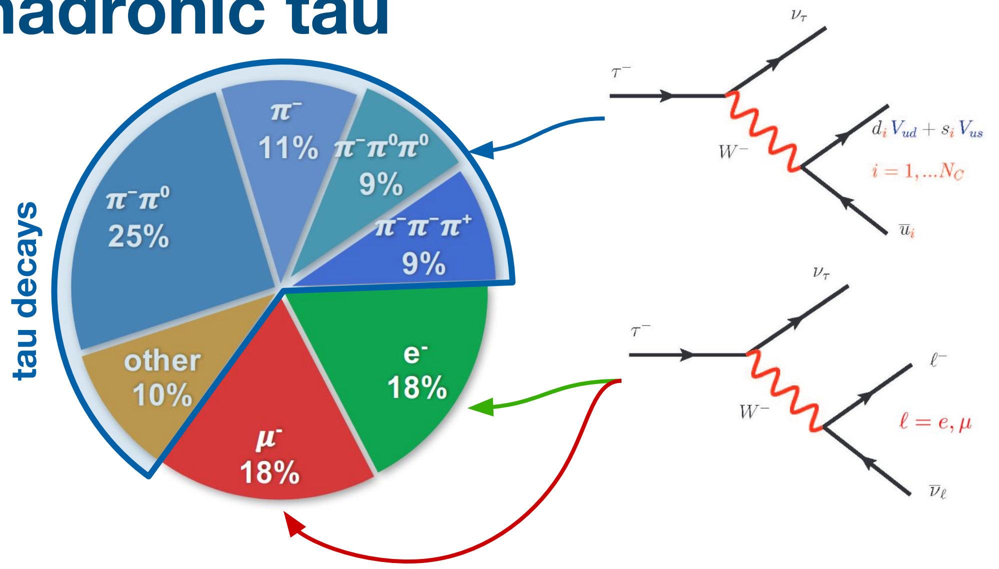
- Tau lepton decaying in hadrons (first time ever!)
- Main background: jets faking ℓ or τ_h ($\ell = e, \mu$)
- 137 fb^{-1} RunII dataset explored

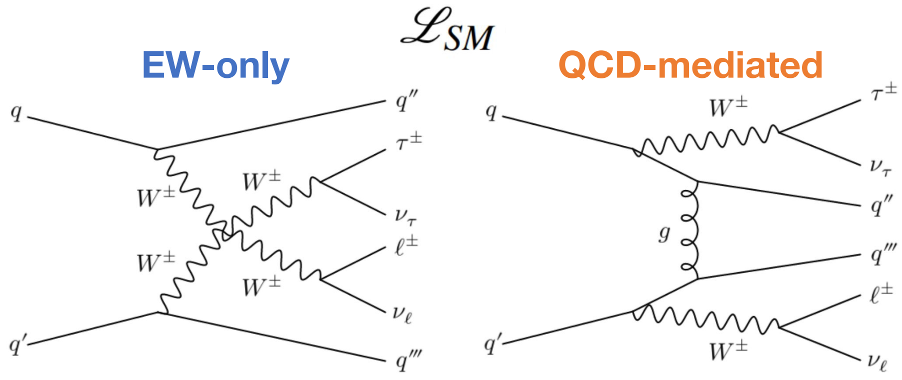


Scattering $W^{\pm}W^{\pm}$ with one hadronic tau

CMS-SMP-22-008 – Overview

- Tau lepton decaying in hadrons (first time ever!)
- Main background: jets faking ℓ or τ_h (ℓ = e, μ)
- 137 fb^{-1} RunII dataset explored
- Measurement of SM contributions

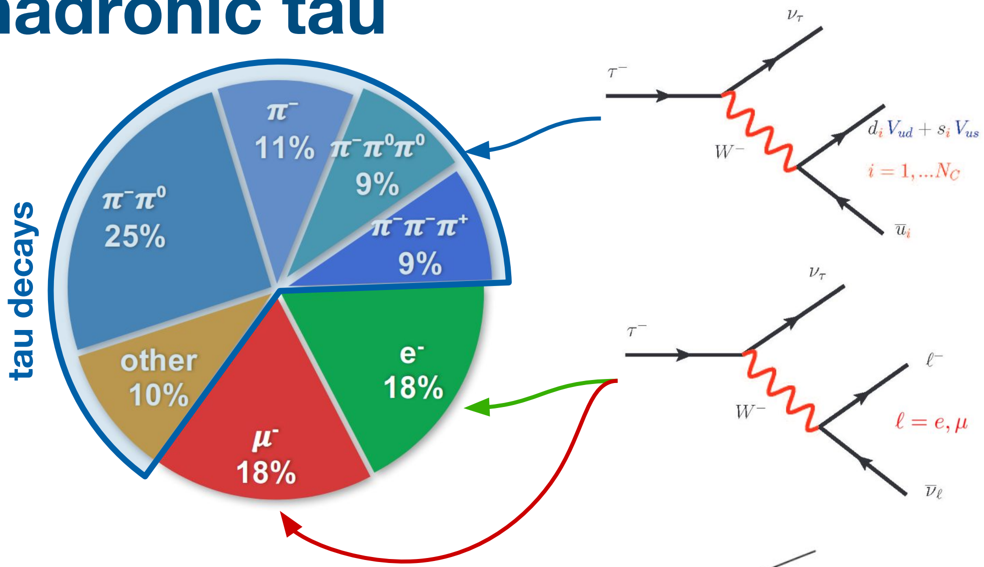




Scattering W±W± with one hadronic tau

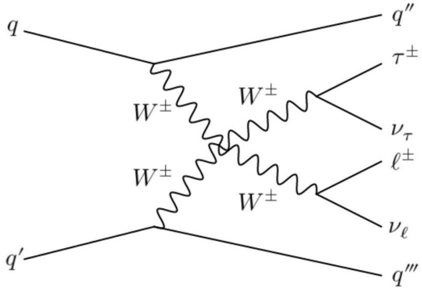
CMS-SMP-22-008 – Overview

- Tau lepton decaying in hadrons (first time ever!)
- Main background: jets faking ℓ or τ_h (ℓ = e, μ)
- 137 fb^{-1} RunII dataset explored
- Measurement of SM contributions
- Indirect new physics effects with EFT
  - Operators with different dimensions acting on vertices
- Ad-hoc DNN models for both investigations

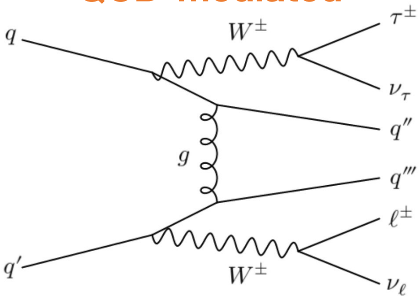


$\mathscr{L}_{SM}$

EW-only



QCD-mediated

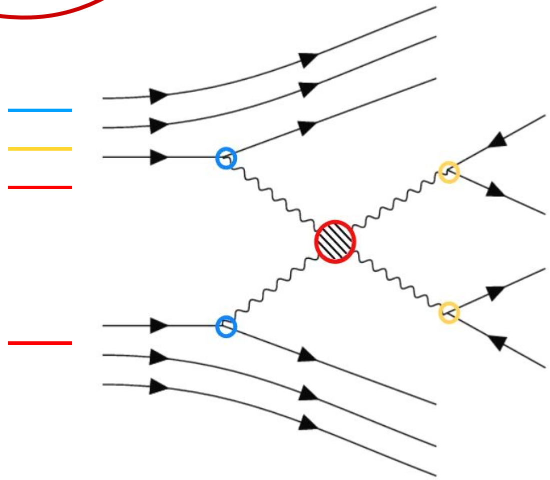


EFT dim-6

$$\sum_\alpha \frac{c_\alpha}{\Lambda^2} Q_\alpha$$

EFT dim-8

$$\sum_i \frac{f_i}{\Lambda^4} \mathscr{O}_i$$



Scattering $W^{\pm}W^{\pm}$ with one hadronic tau

SM measurements

- Simultaneous fit in SR + 2 CRs for both $e\tau_h$ and $\mu\tau_h$ channels
  - DNN output distributions as quantity to fit
- dileptonic ttbar and opposite-sign yield adjusted with dedicated CRs in the fit

Scattering W±W± with one hadronic tau

SM measurements

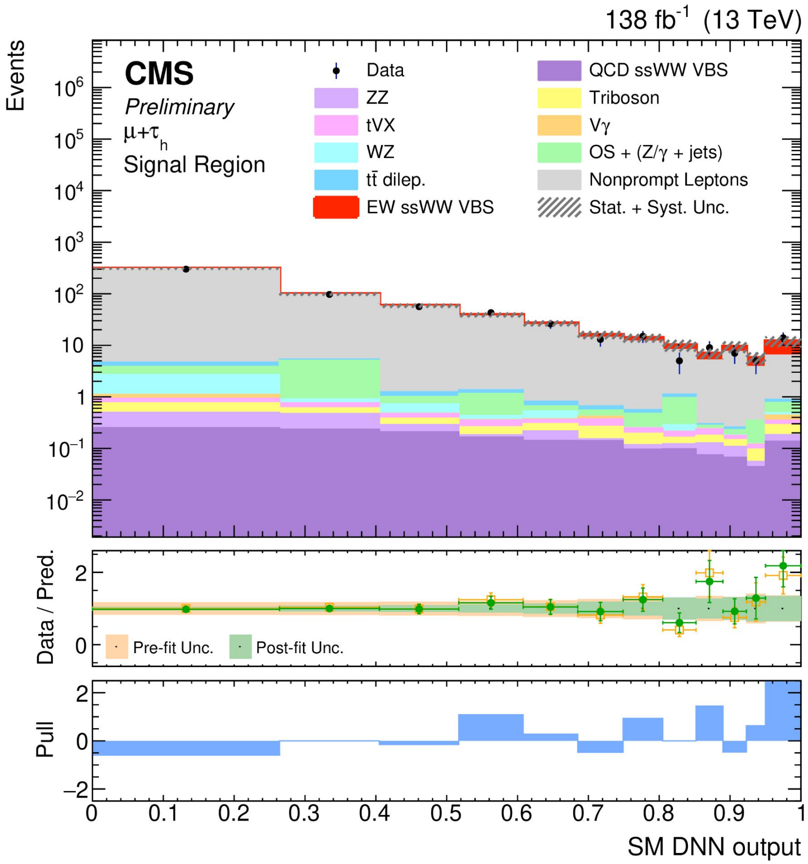
- Simultaneous fit in SR + 2 CRs for both $e\tau_h$ and $\mu\tau_h$ channels
  - DNN output distributions as quantity to fit
- dileptonic ttbar and opposite-sign yield adjusted with dedicated CRs in the fit

Two measurements performed:

1. signal strength for pure EW
   $1.44^{+0.63}_{-0.56}$ $(1.00^{+0.60}_{-0.53})$ (σ_{th} = 28.7 fb)
2. signal strength for EW + QCD
   $1.43^{+0.60}_{-0.54}$ $(1.00^{+0.57}_{-0.51})$ (σ_{th} = 22.3 fb)

Sensitivity affected by statistical uncertainty

First evidence of VBS with hadronic tau!



Scattering W±W± with one hadronic tau

EFT results

No deviation from SM expectations

- 11 dim-6 + 9 dim-8 EFT operators

1D limits on EFT coefficients

- First dim-6 investigation with a VBS process

Wilson coefficient		95% CL interval	
		Observed	Expected
dim-6	c_W	$[-0.842, 0.818]$	$[-0.987, 0.974]$
	c_{HW}	$[-8.68, 7.60]$	$[-9.99, 9.05]$
dim-8	f_{T0}	$[-1.32, 1.38]$	$[-1.52, 1.58]$
	f_{M0}	$[-13.1, 12.8]$	$[-14.6, 14.5]$
	f_{S0}	$[-15.9, 16.1]$	$[-17.4, 17.9]$

Scattering W±W± with one hadronic tau

EFT results

No deviation from SM expectations

- 11 dim-6 + 9 dim-8 EFT operators

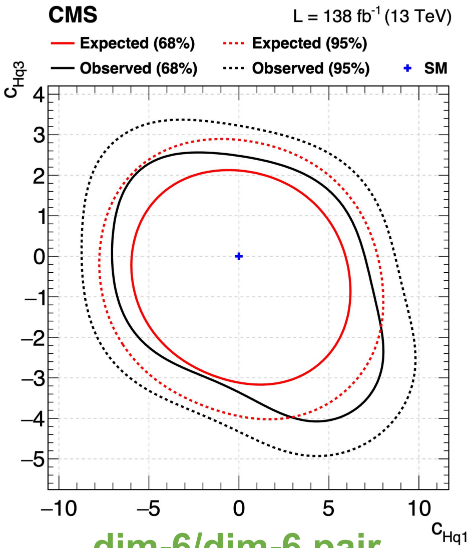
1D limits on EFT coefficients

- First dim-6 investigation with a VBS process

2D limits on EFT coefficients

- Correlation effects between dim-6 operators

Wilson coefficient		95% CL interval	
		Observed	Expected
dim-6	c_W	$[-0.842, 0.818]$	$[-0.987, 0.974]$
	c_{HW}	$[-8.68, 7.60]$	$[-9.99, 9.05]$
dim-8	f_{T0}	$[-1.32, 1.38]$	$[-1.52, 1.58]$
	f_{M0}	$[-13.1, 12.8]$	$[-14.6, 14.5]$
	f_{S0}	$[-15.9, 16.1]$	$[-17.4, 17.9]$



dim-6/dim-6 pair

Scattering $W^{\pm}W^{\pm}$ with one hadronic tau

EFT results

No deviation from SM expectations

- 11 dim-6 + 9 dim-8 EFT operators

1D limits on EFT coefficients

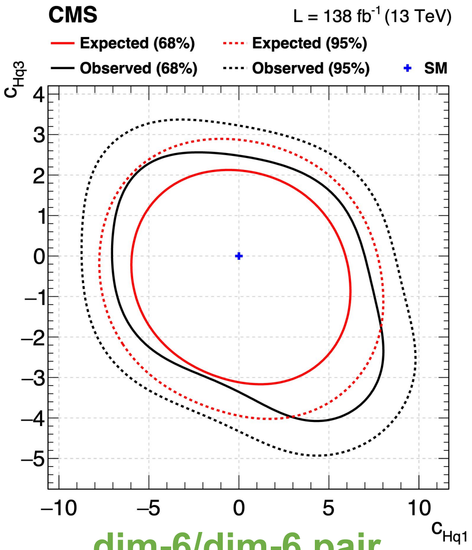
- First dim-6 investigation with a VBS process

2D limits on EFT coefficients

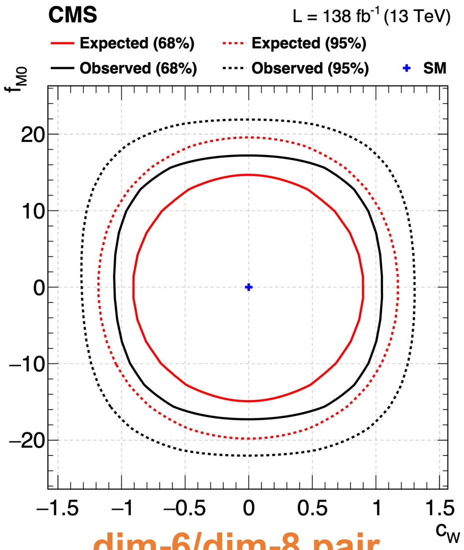
- Correlation effects between dim-6 operators
- First study of EFT operators with different dim.
- Addition of a competitive EFT operator reduces the sensitivity to individual operator
  - higher effect on the least relevant operators
  - dim-6 affected when dim-8 is competitive
  - dim-8 always affected by the presence of dim-6

Take-home message: don't forget the impact of operators with different dimensions!

Wilson coefficient		95% CL interval Observed	Expected
dim-6	c_W	$[-0.842, 0.818]$	$[-0.987, 0.974]$
	c_{HW}	$[-8.68, 7.60]$	$[-9.99, 9.05]$
dim-8	f_{T0}	$[-1.32, 1.38]$	$[-1.52, 1.58]$
	f_{M0}	$[-13.1, 12.8]$	$[-14.6, 14.5]$
	f_{S0}	$[-15.9, 16.1]$	$[-17.4, 17.9]$



dim-6/dim-6 pair



dim-6/dim-8 pair

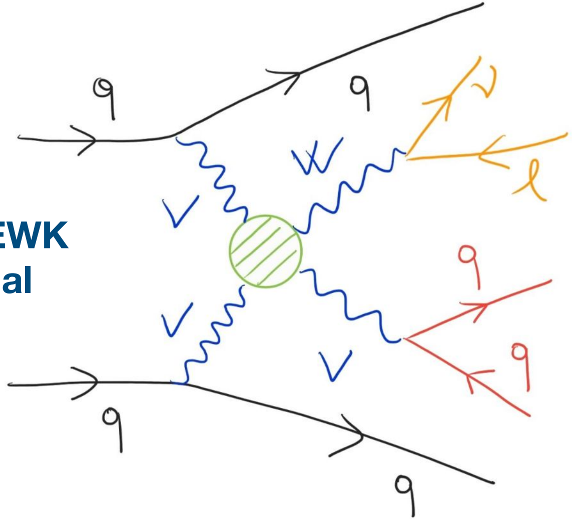
Full list of results in backup

Semileptonic WV scattering

Phys. Lett. B 834 (2022) 137438 - Overview

- **First evidence of the SM process at LHC!**
  - Performed with the full RunII dataset (137 fb^{-1})
- **WV scattering** in semileptonic channel
  - $V \rightarrow$ jets, $W \rightarrow e\nu$ or $\mu\nu$
  - irreducible contribution from QCD-induced process

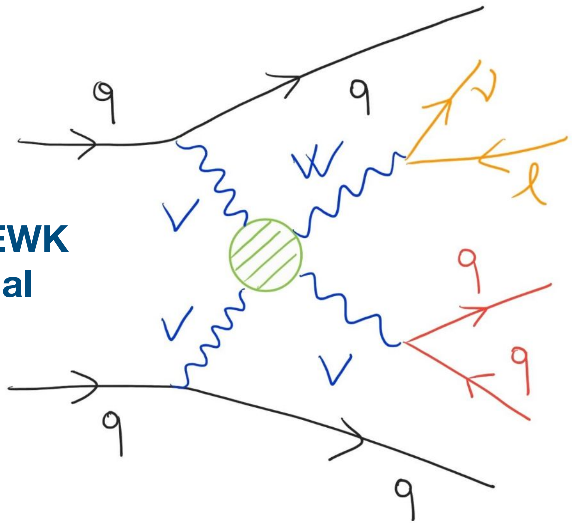
pure EWK signal



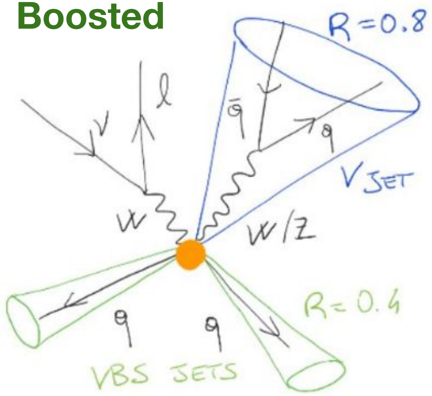
Semileptonic WV scattering
Phys. Lett. B 834 (2022) 137438 - Overview

- **First evidence of the SM process at LHC!**
  - Performed with the full RunII dataset (137 fb^{-1})
- **WV scattering** in semileptonic channel
  - $V \rightarrow$ jets, $W \rightarrow e\nu$ or $\mu\nu$
  - irreducible contribution from QCD-induced process
- **Resolved** and **boosted** hadronic decay regimes
  - Events separately categorized
- Big efforts to properly estimate backgrounds (more in backup)
  - DNN signal-vs-background discriminator in both categories
  - Dedicated Control Regions to constrain main sources

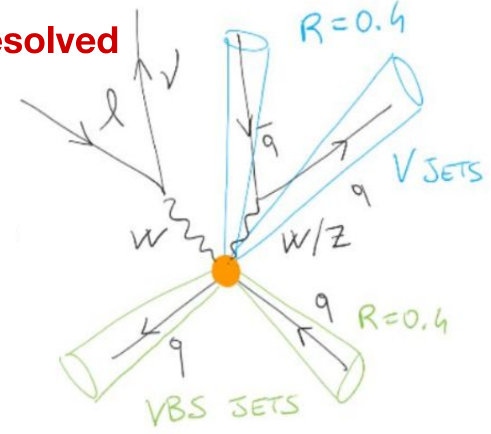
pure EWK signal



Boosted



Resolved



Semileptonic WV scattering
Statistical analysis

Simultaneous fits in all the regions

- Performed both for **pure EWK** and **EWK+QCD** signals
- **2D fit** of **EWK and QCD** signal strengths

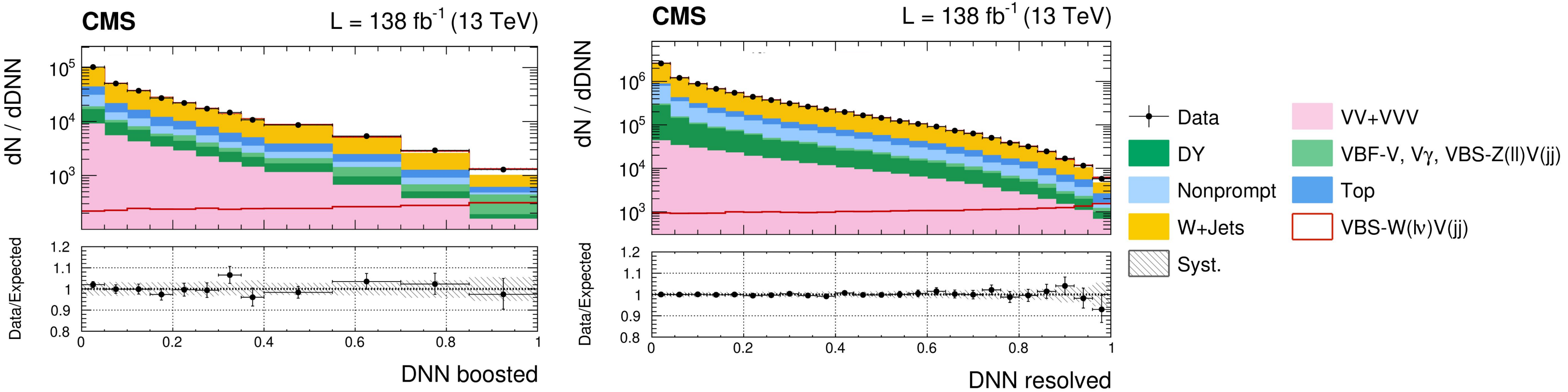
Semileptonic WV scattering
Statistical analysis

Simultaneous fits in all the regions
- Performed both for **pure EWK** and **EWK+QCD** signals
- **2D fit** of **EWK and QCD** signal strengths

Signal Regions
- Fit to DNN shape category-wise

Control Regions
- **W+jets**: fit to normalization in CR correction bins
- **ttbar**: fit to overall normalization in CRs

Post-fit SRs distributions



Semileptonic WV scattering

Results – observations!

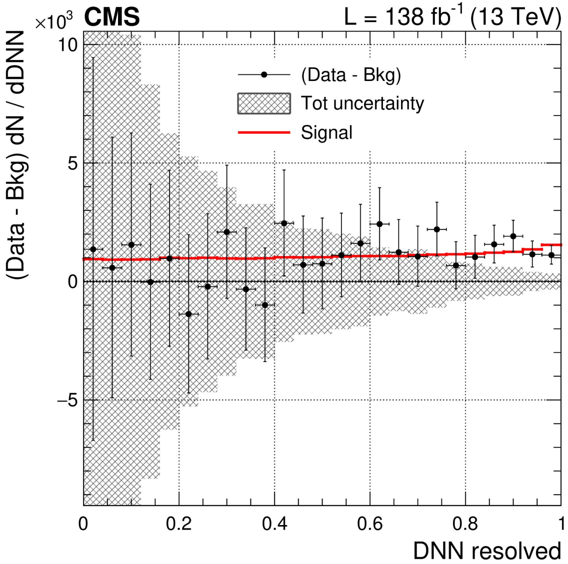
EWK

- Inclusive signal strength

$$\mu_{EWK} = 0.85 \pm 0.12(\text{stat})^{+0.19}_{-0.17}(\text{syst})$$

- Fiducial cross section measurement

$$\sigma_{EWK} = 1.90^{+0.53}_{-0.46} \text{ pb}$$



Semileptonic WV scattering

Results – observations!

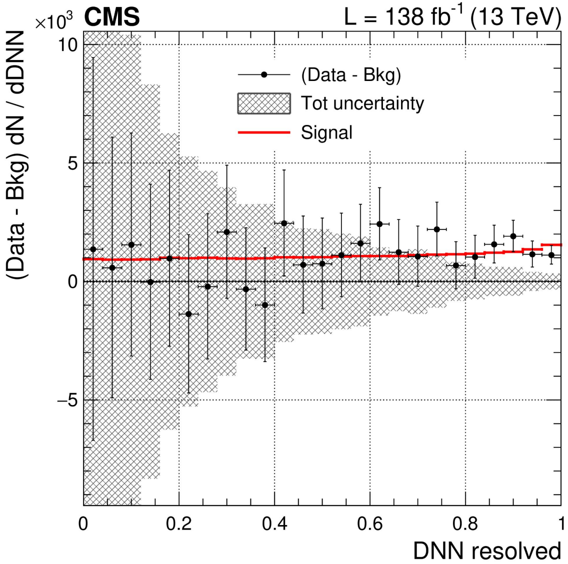
EWK

- Inclusive signal strength

$$\mu_{EWK} = 0.85 \pm 0.12(\text{stat})^{+0.19}_{-0.17}(\text{syst})$$

- Fiducial cross section measurement

$\sigma_{EWK} = 1.90^{+0.53}_{-0.46}$ **pb**



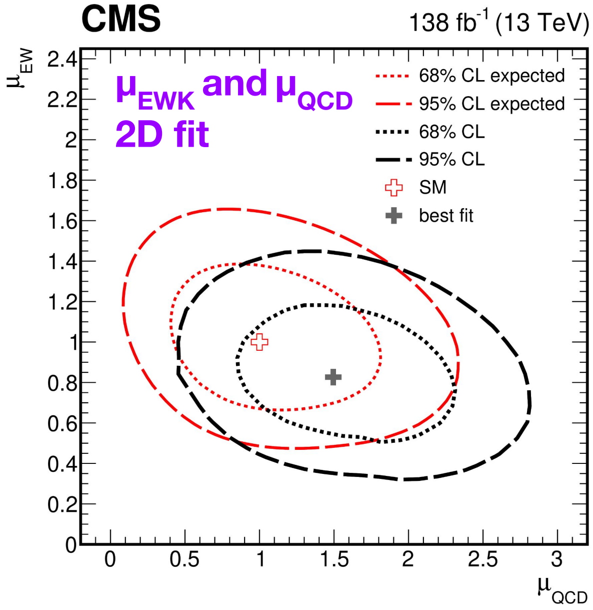
EWK + QCD

- Inclusive signal strength

$$\mu_{EWK+QCD} = 0.97 \pm 0.06(\text{stat})^{+0.19}_{-0.21}(\text{syst})$$

- Fiducial cross section measurement

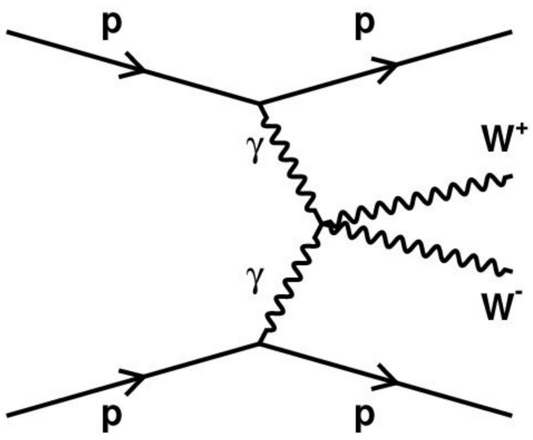
$\sigma_{EWK+QCD} = 16.4^{+3.5}_{-2.8}$ **pb**



High-mass γγ → WW/ZZ production

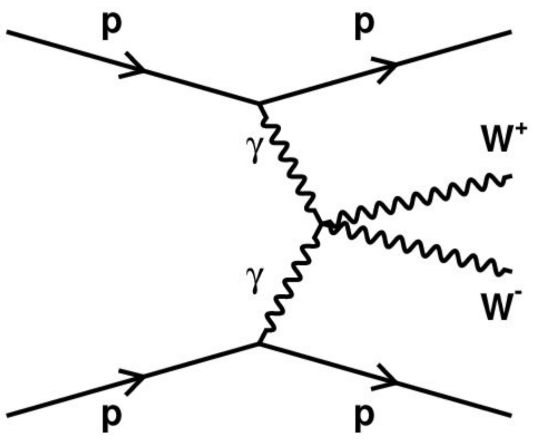
JHEP 2307 (2023) 229 – overview

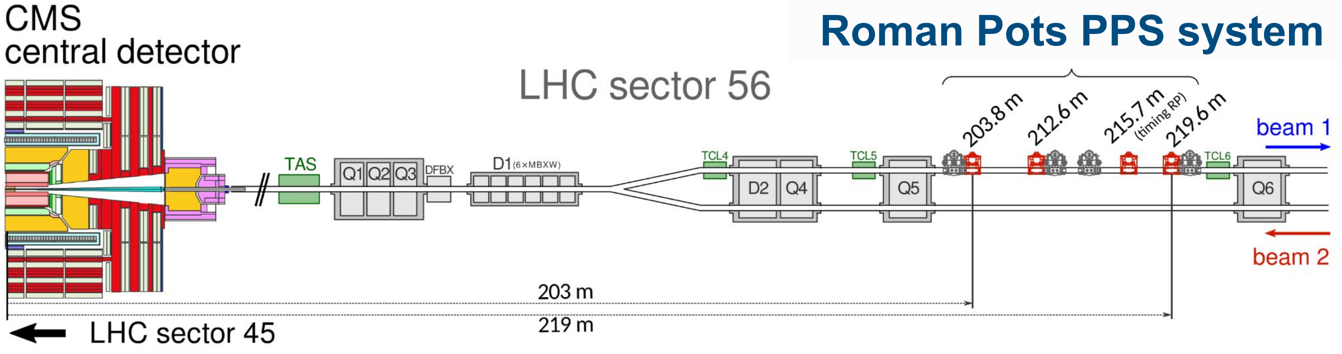
- γγ → WW/ZZ events at high mass smoking guns for new physics
  - Boosted W/Z hadronic decays (1 jet per boson)
  - New physics effects modeled with aQGC effects

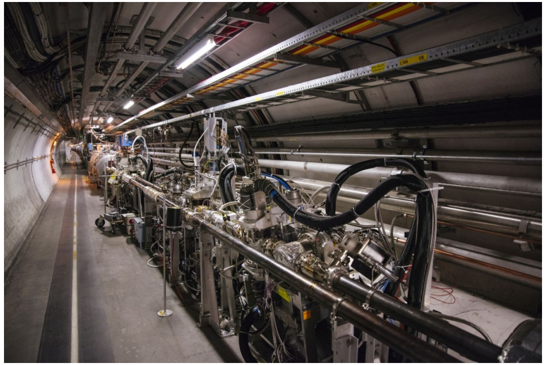


High-mass γγ → WW/ZZ production
JHEP 2307 (2023) 229 – overview

- γγ → WW/ZZ events at high mass smoking guns for new physics
  - Boosted W/Z hadronic decays (1 jet per boson)
  - New physics effects modeled with aQGC effects
- Protons are kept intact from γγ scattering
  - Four body ppWW/ppZZ system fully reconstructed at 13 TeV with the TOTEM Proton Precision Spectrometer (PPS)
  - Combined CMS + TOTEM 100 fb^{-1} RunII dataset







High-mass γγ→WW/ZZ production

Sensitivity to SM production and aQGCs

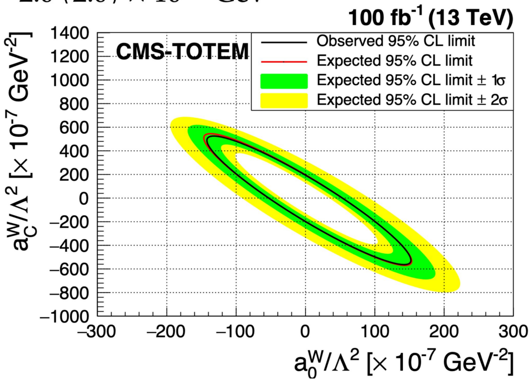
- Clipping applied to preserve unitarity bounds
  - Smaller impact wrt only-CMS similar analyses

LEP-like nonlinear aQGC operators

$$\mathcal{L}_6^0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}\vec{W}^{\alpha}\cdot\vec{W}_{\alpha}$$

$$\mathcal{L}_6^c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}\vec{W}^{\alpha}\cdot\vec{W}_{\beta}$$

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



High-mass γγ→WW/ZZ production

Sensitivity to SM production and aQGCs

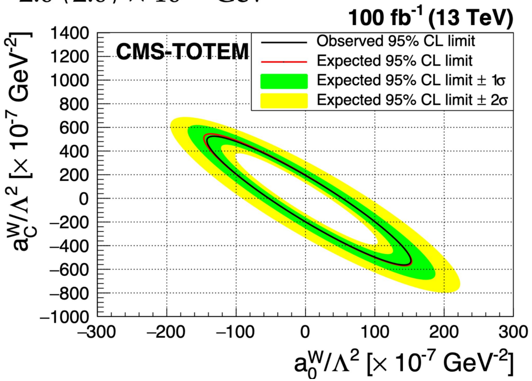
- Clipping applied to preserve unitarity bounds
  - Smaller impact wrt only-CMS similar analyses

LEP-like nonlinear aQGC operators

$$\mathcal{L}_6^0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}\vec{W}^{\alpha}\cdot\vec{W}_{\alpha}$$

$$\mathcal{L}_6^c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}\vec{W}^{\alpha}\cdot\vec{W}_{\beta}$$

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}	



translation

Linear EFT aQGC modeling (Éboli basis)

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}

High-mass γγ→WW/ZZ production

Sensitivity to SM production and aQGCs

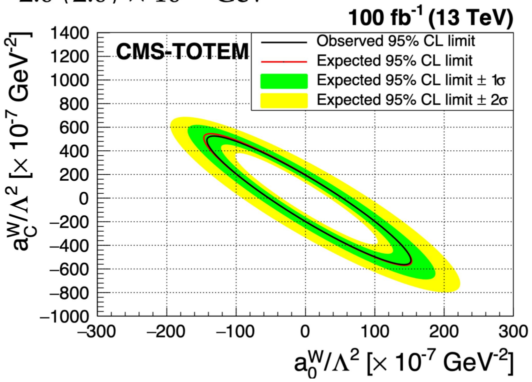
- Clipping applied to preserve unitarity bounds
  - Smaller impact wrt only-CMS similar analyses

LEP-like nonlinear aQGC operators

$$\mathcal{L}_6^0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}\vec{W}^\alpha \cdot \vec{W}_\alpha$$

$$\mathcal{L}_6^c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}\vec{W}^\alpha \cdot \vec{W}_\beta$$

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



translation

Linear EFT aQGC modeling (Éboli basis)

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

Upper bounds on SM fiducial x–sections

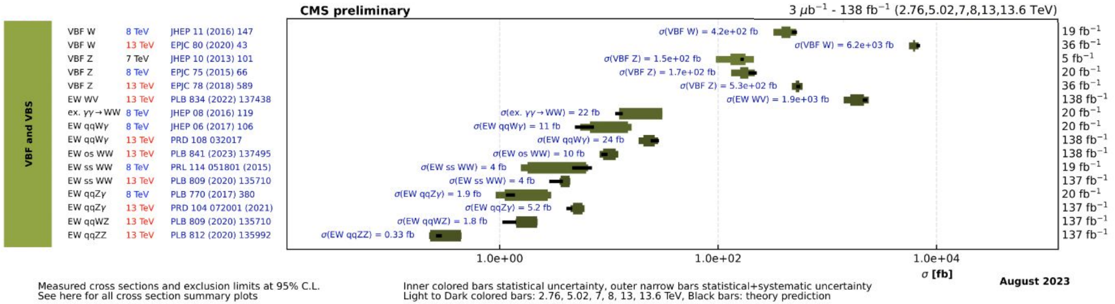
$$\sigma(pp \to pWWp)_{0.04<\xi<0.20, m>1000\ \text{GeV}} < 67(53^{+34}_{-19})\ \text{fb}$$

$$\sigma(pp \to pZZp)_{0.04<\xi<0.20, m>1000\ \text{GeV}} < 43(62^{+33}_{-20})\ \text{fb}$$

A bright future ahead of us!

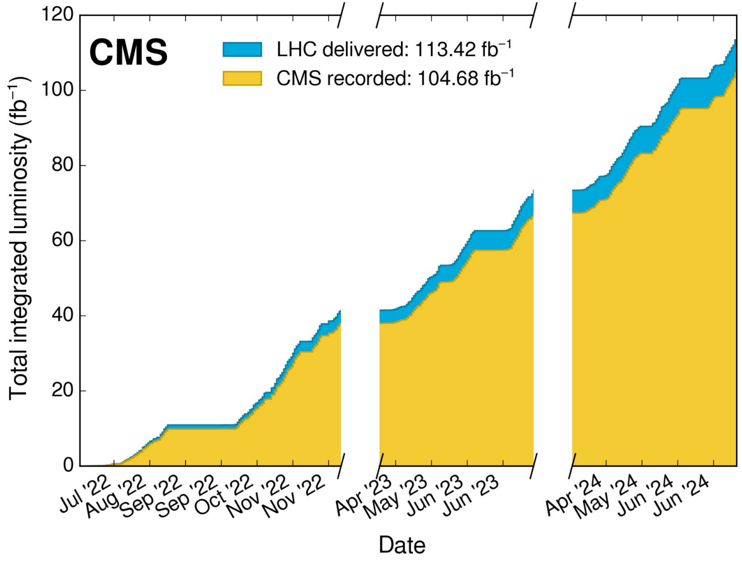
CMS perspective on future of the VBS

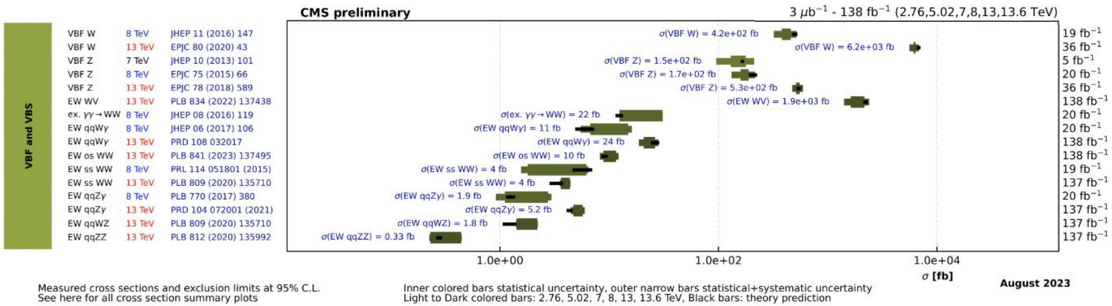
- Extensive VBS program with RunII dataset
  - Plenty of observations and evidences
  - Creative strategies to cover a wide phase space
  - Systematic searches for indirect new physics
  - Solid basis for a grand combination (SM and EFT)



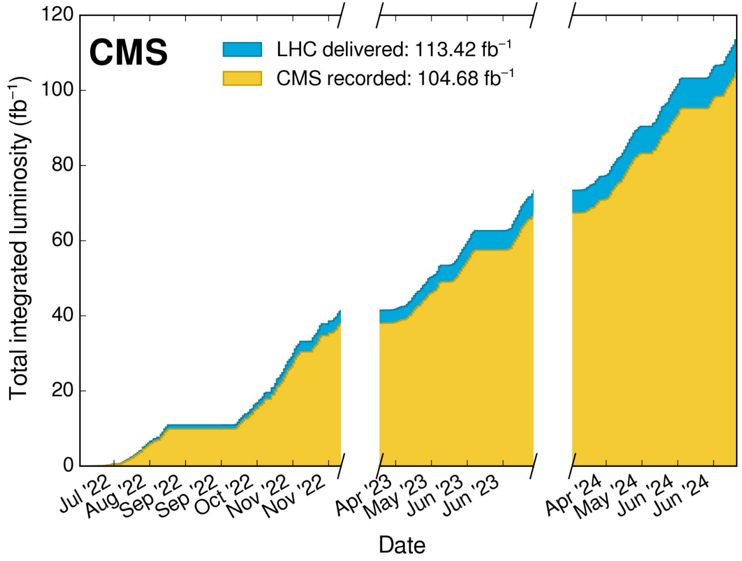
A bright future ahead of us!
CMS perspective on future of the VBS

- Extensive VBS program with RunII dataset
  - Plenty of observations and evidences
  - Creative strategies to cover a wide phase space
  - Systematic searches for indirect new physics
  - Solid basis for a grand combination (SM and EFT)
- Run3 data ready to be scrutinized!
  - VBS investigations will benefit from the increased recorded luminosity
  - Target specific boson polarization states
  - Thorough scrutiny of deviations from SM within the EFT framework

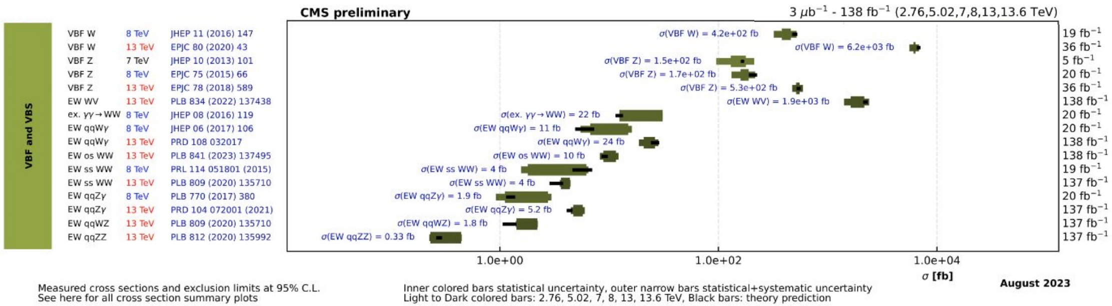




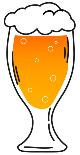
A bright future ahead of us!
CMS perspective on future of the VBS



- Extensive VBS program with RunII dataset
  - Plenty of observations and evidences
  - Creative strategies to cover a wide phase space
  - Systematic searches for indirect new physics
  - Solid basis for a grand combination (SM and EFT)
- Run3 data ready to be scrutinized!
  - VBS investigations will benefit from the increased recorded luminosity
  - Target specific boson polarization states
  - Thorough scrutiny of deviations from SM within the EFT framework



Thank you!



UNIVERSITY OF NOTRE DAME

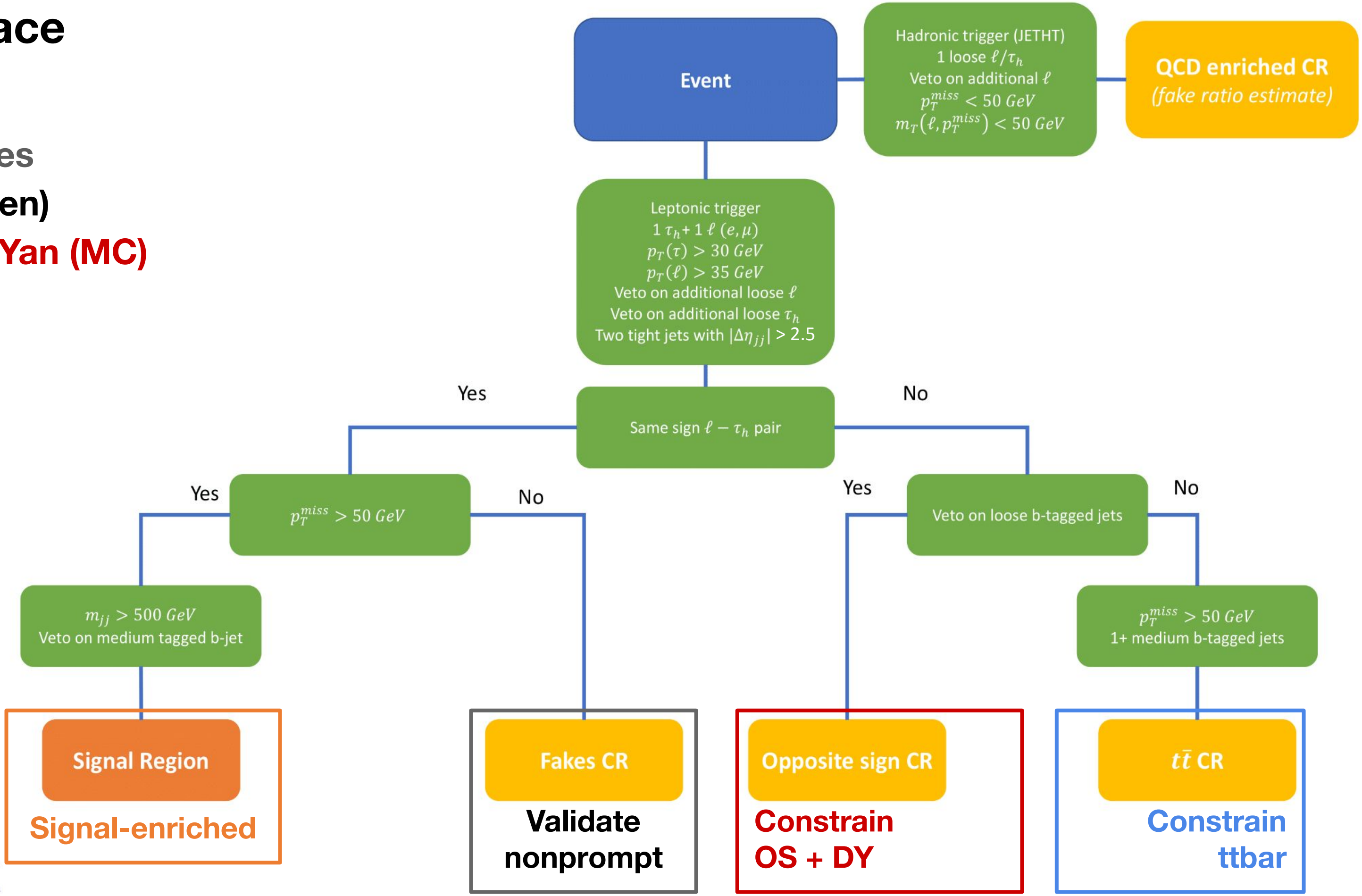
Additional slides

Scattering W±W± with one hadronic tau

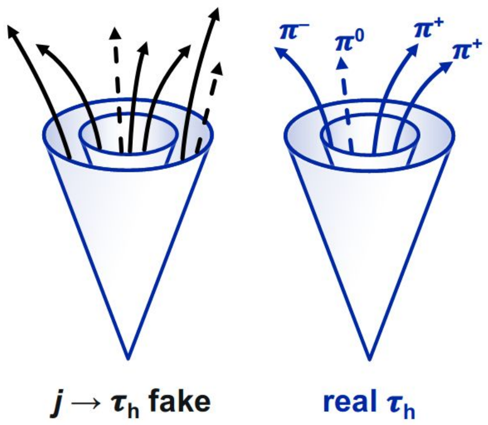
Analysis phase space

Main background sources

- non prompt (data-driven)
- Opposite Sign + Drell-Yan (MC)
- ttbar (MC)



Estimation of nonprompt ℓ/τ_h background



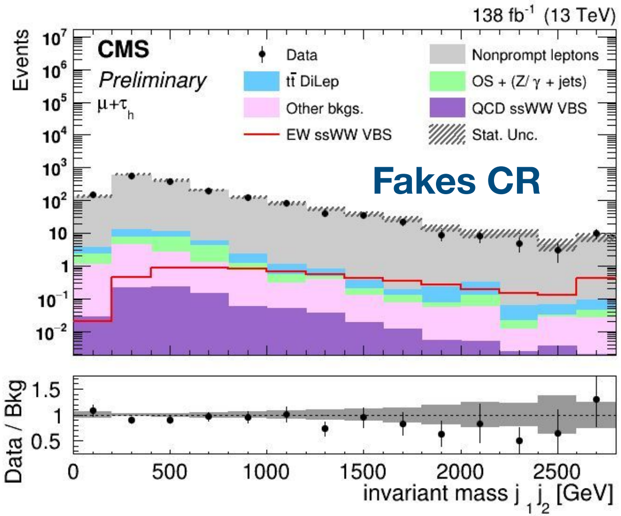
- Hadronic jets reconstructed as e, μ, or τ_h jets → fake τ_h outweighing contribution
- Due to QCD multijet, W+jets, Drell-Yan and ttbar pair productions with at least one jet in the final state

Data-driven "fakeable" method (for e, μ, τ_h)

- Fake Ratio as measure of the probability a (real) jet is reconstructed as lepton (jet faking lepton) → tight (loose) reconstructed lepton
- Estimated in the QCD-enriched region as lepton loose-to-tight ratio $\epsilon_{fake}(p_T, \eta) = N_{tight}/N_{loose}$
- Use Fake Ratio to extrapolate estimate in SR with event-wise

$$w_i = \frac{\epsilon_{fake}(p_{Ti}, \eta_i)}{1 - \epsilon_{fake}(p_{Ti}, \eta_i)}$$

- Estimate validated in the Fakes CR



Scattering W±W± with one hadronic tau

EFT investigations – 1D

first time in VBS

SMEFT basis

one dim-6 operator at time

$$|\mathcal{A}_{\mathrm{TOT}}|^2 = |\mathcal{A}_{SM}|^2 + \sum_{i}^{N_{dim6}} \left[\frac{c_i}{\Lambda^2} 2\Re\left(\mathcal{A}_{\mathcal{O}_i^{(6)}} \mathcal{A}_{SM}^*\right) + \frac{c_i^2}{\Lambda^4} |\mathcal{A}_{\mathcal{O}_i^{(6)}}|^2 \right] + \sum_{j \neq m}^{N_{dim6}} \left[\frac{c_j c_m}{\Lambda^4} 2\Re\left(\mathcal{A}_{\mathcal{O}_j^{(6)}} \mathcal{A}_{\mathcal{O}_m^{(6)}}^*\right) \right]$$

$$+ \sum_{k}^{N_{dim8}} \left[\frac{f_k}{\Lambda^4} 2\Re\left(\mathcal{A}_{\mathcal{O}_k^{(8)}} \mathcal{A}_{SM}^*\right) + \frac{f_k^2}{\Lambda^8} |\mathcal{A}_{\mathcal{O}_k^{(8)}}|^2 \right]$$

one dim-8 operator at time

Éboli basis

Any other coefficient fixed to 0

CMS UNIVERSITY OF NOTRE DAME

Scattering W±W± with one hadronic tau
EFT investigations – 2D

SMEFT basis

two dim-6 operator at time

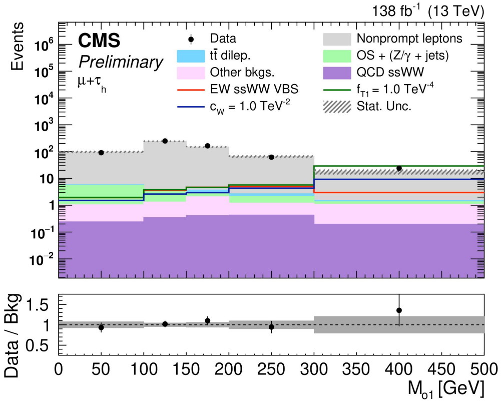
$$|\mathcal{A}_{\mathrm{TOT}}|^2 = |\mathcal{A}_{SM}|^2 + \sum_{i}^{N_{dim6}} \left[\frac{c_i}{\Lambda^2} 2\Re\left(\mathcal{A}_{\mathcal{O}_i^{(6)}} \mathcal{A}^*_{SM}\right) + \frac{c_i^2}{\Lambda^4} |\mathcal{A}_{\mathcal{O}_i^{(6)}}|^2 \right] + \sum_{j \neq m}^{N_{dim6}} \left[\frac{c_j c_m}{\Lambda^4} 2\Re\left(\mathcal{A}_{\mathcal{O}_j^{(6)}} \mathcal{A}^*_{\mathcal{O}_m^{(6)}}\right) \right]$$

$$+ \sum_{k}^{N_{dim8}} \left[\frac{f_k}{\Lambda^4} 2\Re\left(\mathcal{A}_{\mathcal{O}_k^{(8)}} \mathcal{A}^*_{SM}\right) + \frac{f_k^2}{\Lambda^8} |\mathcal{A}_{\mathcal{O}_k^{(8)}}|^2 \right]$$

one dim-8/dim-6 operator pair at time

Éboli basis

Used for these studies



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

Any other coefficient fixed to 0

Scattering $W^{\pm}W^{\pm}$ with one hadronic tau

1D EFT limits

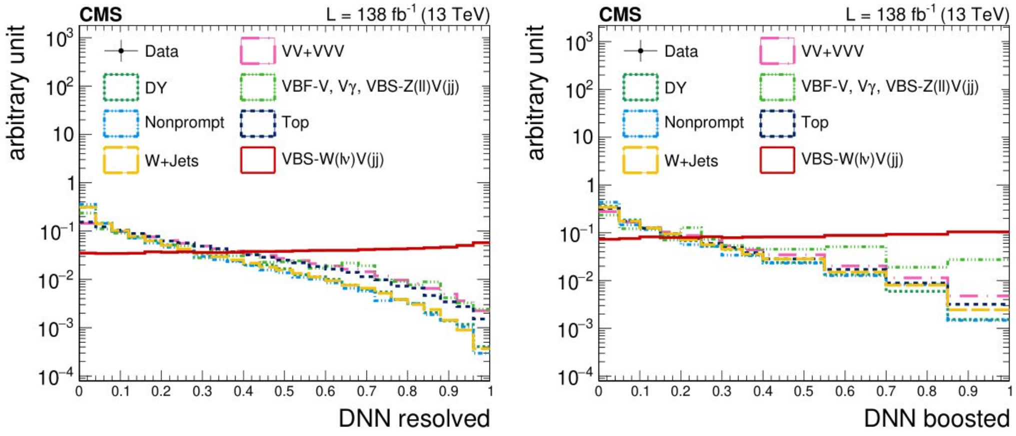
extracted with dim-6 DNN output distributions

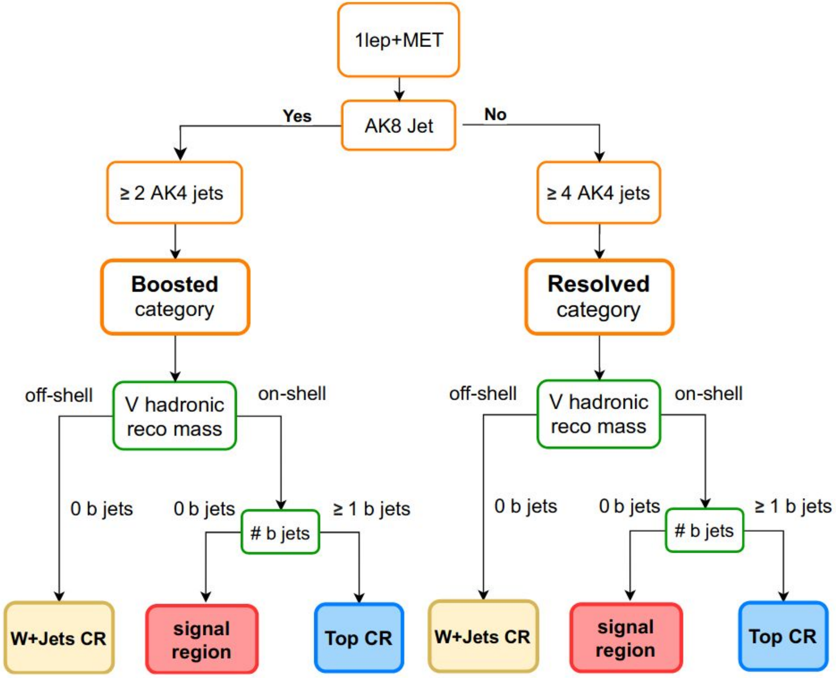
extracted with dim-8 DNN output distributions

	Wilson coefficient	1σ CL interval(s) Expected	1σ CL interval(s) Observed	2σ CL interval Expected	2σ CL interval Observed
dim-6	$c_{ll}^{(1)}$	$[-12.9, -8.03] \cup [-2.95, 1.91]$	$[-11.6, 0.045]$	$[-14.6, 3.53]$	$[-13.5, 2.11]$
	$c_{qq}^{(1)}$	$[-0.501, 0.576]$	$[-0.341, 0.416]$	$[-0.742, 0.818]$	$[-0.605, 0.681]$
	c_W	$[-0.681, 0.669]$	$[-0.513, 0.481]$	$[-0.987, 0.974]$	$[-0.842, 0.818]$
	c_{HW}	$[-7.00, 6.09]$	$[-5.48, 4.31]$	$[-9.99, 9.05]$	$[-8.68, 7.60]$
	c_{HWB}	$[-41.7, 69.6]$	$[30.7, 89.2]$	$[-66.6, 96.4]$	$[-49.7, 110]$
	$c_{H\square}$	$[-16.6, 18.1]$	$[-12.0, 14.0]$	$[-24.7, 26.3]$	$[-20.9, 22.7]$
	c_{HD}	$[-24.6, 34.7]$	$[-15.3, 31.5]$	$[-38.2, 48.8]$	$[-31.4, 45.5]$
	$c_{Hl}^{(1)}$	$[-28.8, 29.9]$	$[-38.2, 39.5]$	$[-49.4, 49.7]$	$[-69.3, 68.3]$
	$c_{Hl}^{(3)}$	$[-1.43, 2.23] \cup [5.88, 9.54]$	$[-0.045, 8.58]$	$[-2.64, 10.8]$	$[-1.59, 9.94]$
	$c_{Hq}^{(1)}$	$[-4.53, 4.42]$	$[-3.27, 3.44]$	$[-6.56, 6.44]$	$[-5.55, 5.60]$
	$c_{Hq}^{(3)}$	$[-2.39, 1.37]$	$[-1.88, 0.705]$	$[-3.24, 2.16]$	$[-2.82, 1.61]$
dim-8	f_{T0}	$[-1.02, 1.08]$	$[-0.774, 0.842]$	$[-1.52, 1.58]$	$[-1.32, 1.38]$
	f_{T1}	$[-0.426, 0.480]$	$[-0.319, 0.381]$	$[-0.640, 0.695]$	$[-0.552, 0.613]$
	f_{T2}	$[-1.15, 1.37]$	$[-0.851, 1.12]$	$[-1.75, 1.98]$	$[-1.51, 1.76]$
	f_{M0}	$[-9.89, 9.74]$	$[-8.07, 7.70]$	$[-14.6, 14.5]$	$[-13.1, 12.8]$
	f_{M1}	$[-12.5, 13.3]$	$[-9.54, 11.15]$	$[-18.7, 19.6]$	$[-16.4, 17.7]$
	f_{M7}	$[-20.3, 19.2]$	$[-17.6, 15.3]$	$[-29.9, 28.8]$	$[-27.6, 25.8]$
	f_{S0}	$[-11.6, 12.0]$	$[-9.60, 9.82]$	$[-17.4, 17.9]$	$[-15.9, 16.1]$
	f_{S1}	$[-37.4, 38.8]$	$[-40.9, 41.3]$	$[-57.2, 58.6]$	$[-60.9, 61.8]$
	f_{S2}	$[-37.4, 38.8]$	$[-40.9, 41.3]$	$[-57.2, 58.6]$	$[-60.9, 61.8]$

Semileptonic WV scattering – background estimation

- W + jets associated production
  - Differential data-driven corrections to predictions from simulation
    - Binned wrt to leptonic W p_T (**both** categories) and leading VBS jet p_T (only **resolved** category)
- ttbar pair production
  - Reduced with veto on b-tagged jets
- Nonprompt leptons
  - Estimated with the data-driven *fakeable* method
- **DNN** in both categories as **signal vs bkg discriminator**



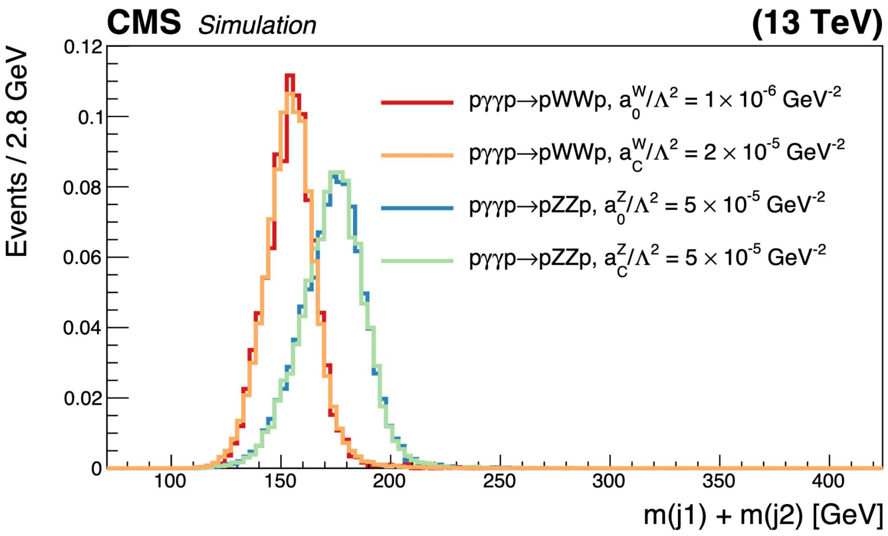


High-mass γγ→WW/ZZ production

Event categorization

WW vs ZZ separation

- CMS boosted jet pair with m_{jj} > 1126 GeV
- Combination of jet masses provides good separation between pWWp and pZZp
  - Cut independent from specific aQGC scenario



Signal regions

- Rapidity **y** and invariant mass **m** for pp and diboson systems correlated for the signals
- 2 jet-matched protons → region δ
- 1 jet-matched proton → region *o*