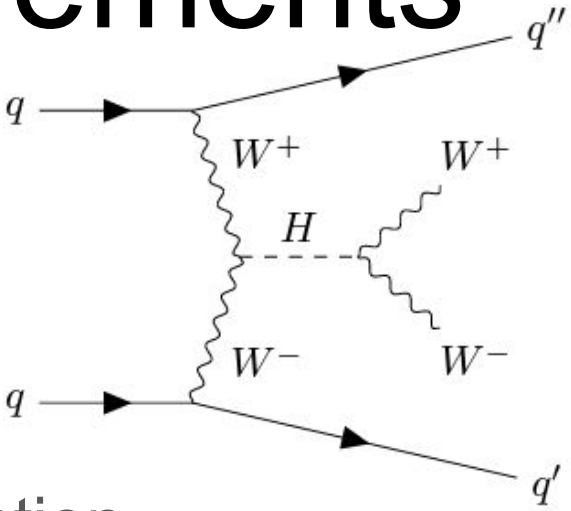
Multiboson measurements in CMS



Hakimi Alexandre

on behalf of CMS collaboration

30th international symposium on Lepton Photon interactions at High Energies

10/01/2022

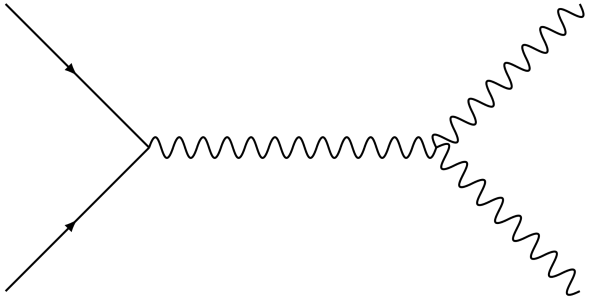
LLR, Ecole Polytechnique
Hakimi Alexandre

alexandre.hakimi@cern.ch

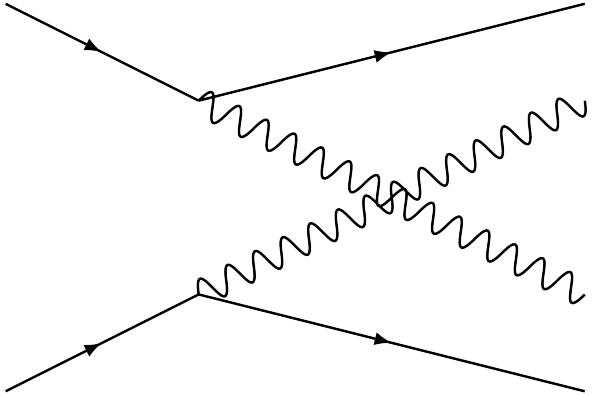
Introduction

Multiboson = production of multiple W, Z or γ

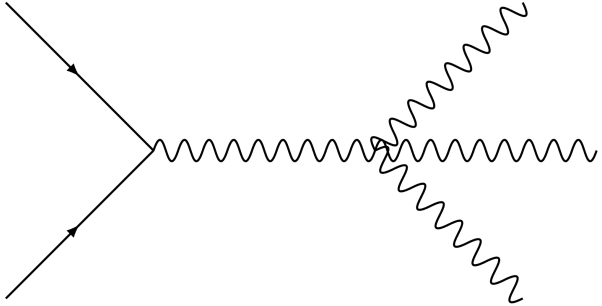
Diboson



Electroweak Diboson



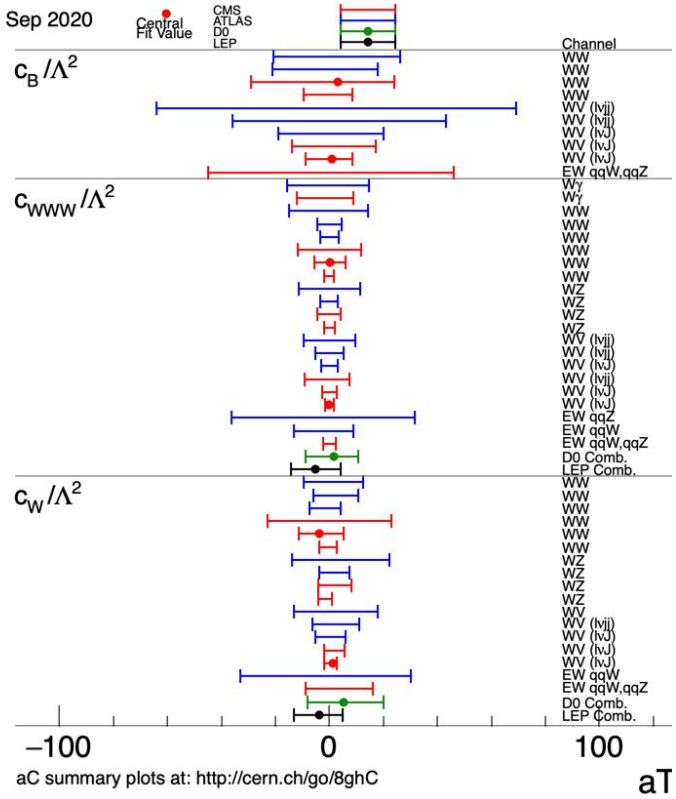
triboson



Motivations

Why study multiboson production?

- test the structure of electroweak (EW) theory
  - Boson couplings affect cross-sections and polarization
  - anomalous (triple/quartic) gauge couplings
    - higher dimension EFT operators
- Probe EW symmetry breaking in Vector Boson Scattering (VBS)
  - unitarity preserved in VBS with Higgs
    - w/o: x-sec ~E²
  - deviation would impact cross sections and aTGC/aQGC



EFT limits (twiki)

Recent CMS Results

Inclusive

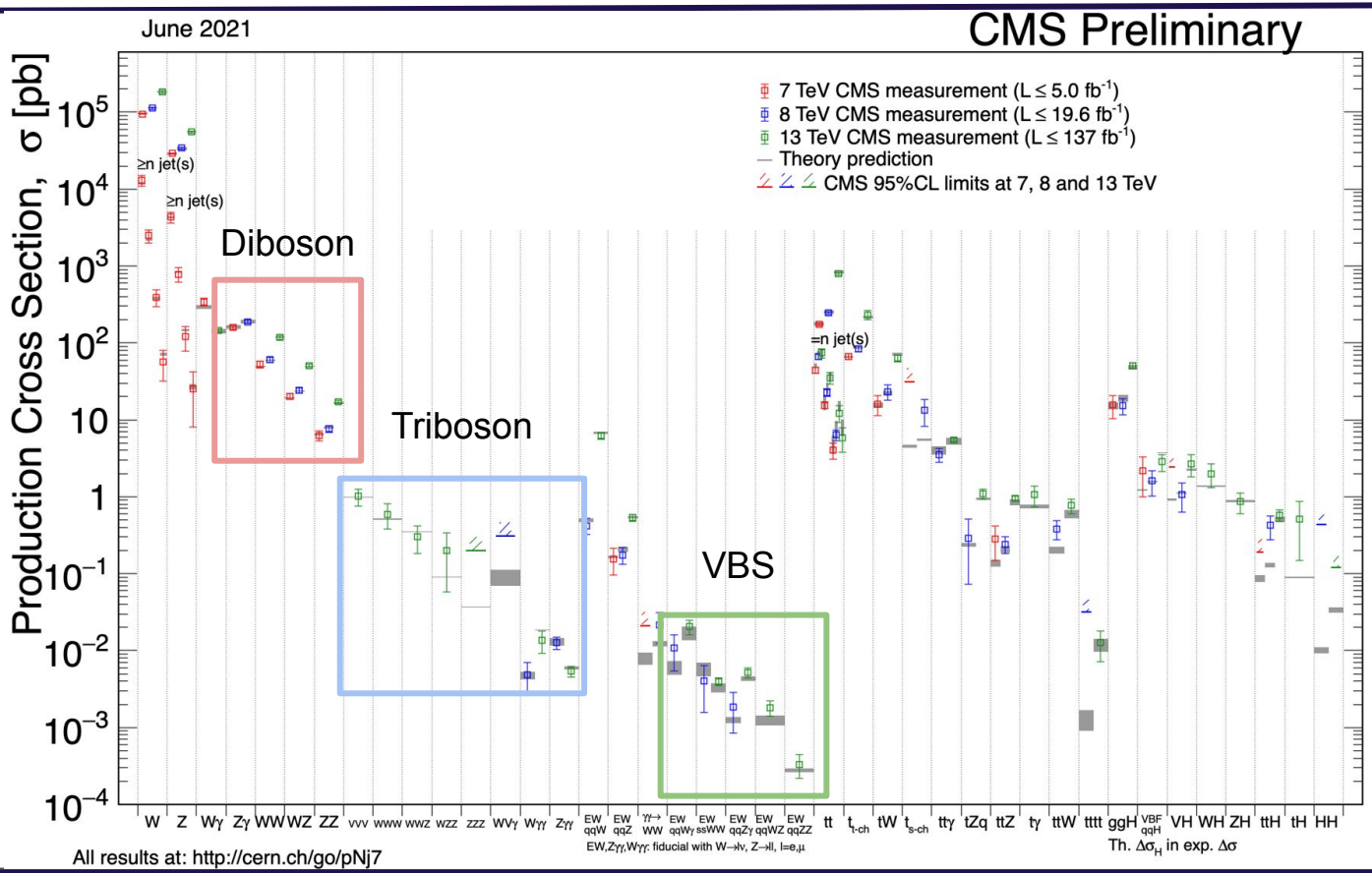
- **VV** (V=W/Z)
  - WW: PhysRevD.102.092001
  - ZZ: EurPhysJC 81:200 (2021)
  - **VV@ 5.02 TeV: PhysRevLett 127.191801**
- **Wγ**
  - inclusive ; PhysRevLett. 126.252002
  - **differential: arxiv 2111.13948**
- **VVV**: PhysRevLett.125.151802
- **V$\gamma\gamma$**: JHEP 2110.174
- Vector Boson Fusion:
  - VV: EurPhysJC 81:723 (2021)

VBS

- **Fully leptonic**
  - Polarized same-sign WW: PhysLetB.2020.136018
  - WZ & SS WW: PhysLetB.2020.135710
  - ZZ: PhysLetB.2020.135992
  - **OS WW: SMP-21-001**
- **Semi-leptonic**
  - **WV: arxiv 2112.05259**
- **Vγ**
  - **Zγ: PhysRevD.104.072001**
  - Wγ : PhysLetB.2020.135988

In red: results presented in this talk

Cross sections



low cross section (XS) for VBS in particular!

VV @ 5.02 TeV (302 pb^{-1})

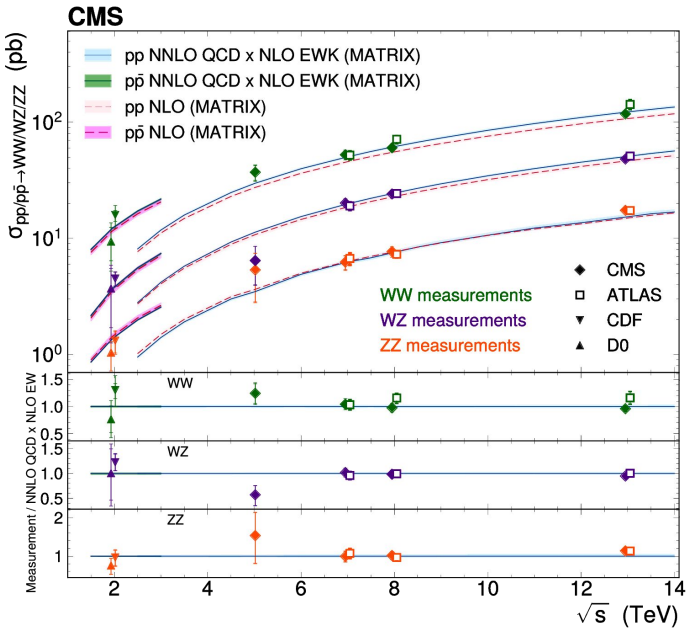
PhysRevLet.127.191801

- Low pile-up run: $\mu_{5TeV} = 2$ ($\mu_{13\ TeV}$ = 23,32)
- Categories:
  - WW -> $\ell\ell$
  - WZ -> (a) 3ℓ (b) 2 same-sign muons
  - ZZ (a) 4ℓ (b) $2\ell + 2\nu$

first measurement at 5.02 GeV

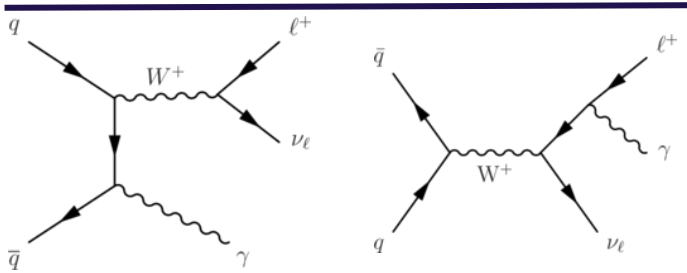
Consistent with NNLO QCD + NLO EWK predictions

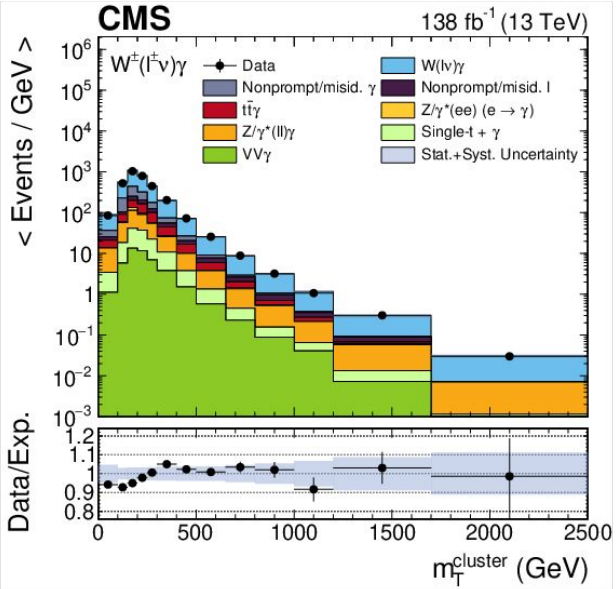
$$\sigma_{WW} = 37.0^{+5.5}_{-5.2}\,(\text{stat})^{+2.7}_{-2.6}\,(\text{syst}) = 37.0^{+6.2}_{-5.8}\,\text{pb},$$
$$\sigma_{WZ} = 6.4^{+2.5}_{-2.1}\,(\text{stat})^{+0.5}_{-0.3}\,(\text{syst}) = 6.4^{+2.5}_{-2.1}\,\text{pb},$$
$$\sigma_{ZZ} = 5.3^{+2.5}_{-2.1}\,(\text{stat})^{+0.5}_{-0.4}\,(\text{syst}) = 5.3^{+2.6}_{-2.1}\,\text{pb},$$



Wγ : Differential Cross sections

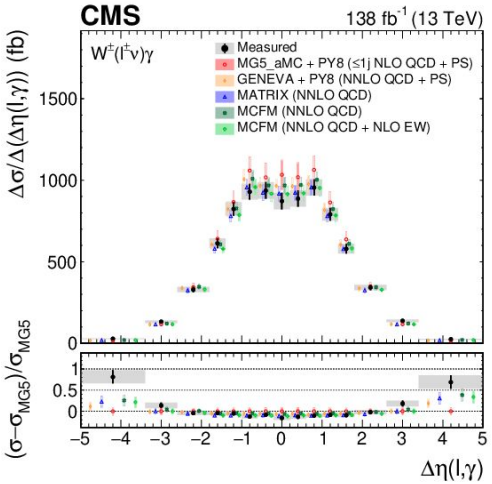
arxiv 2111.13948



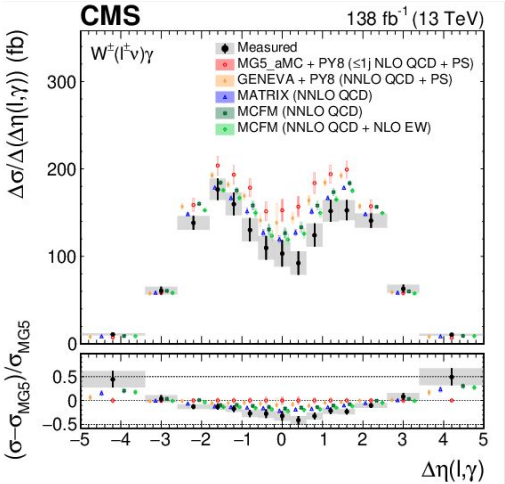


Differential cross section measurement to explore radiation amplitude zero effect RAZ

interference in LO diagrams make xs vanish in certain phase space region, could be affected by BSM



Good agreement with simulation, more signal in high Δη regions compared to predictions



Tighter selections to observe RAZ

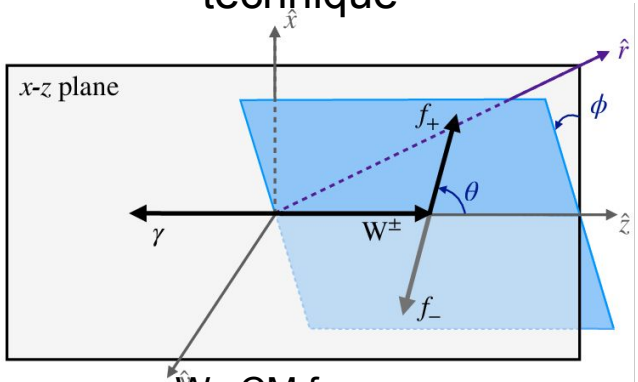
Bigger dip at $\Delta\eta(l,\gamma) = 0$ than in NNLO predictions

Wγ : aTGC constraints

arxiv 2111.13948

Laboratoire Leprince-Ringuet

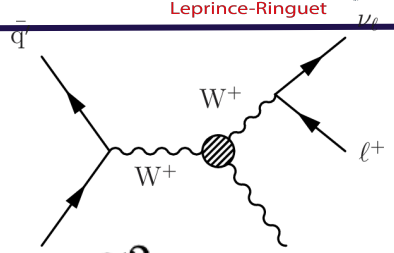
Interference resurrection technique



Wγ CM frame

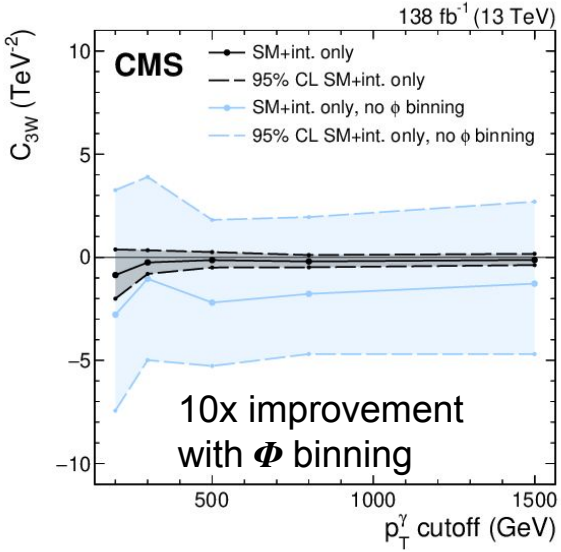
- At $E > m_W$, SM and BSM have different helicity configurations for $W_T V_T \rightarrow$ angle-inclusive variables insensitive to σ_{int}
- Solution: search in 2D space of $|\phi_f|$ and p_T^γ

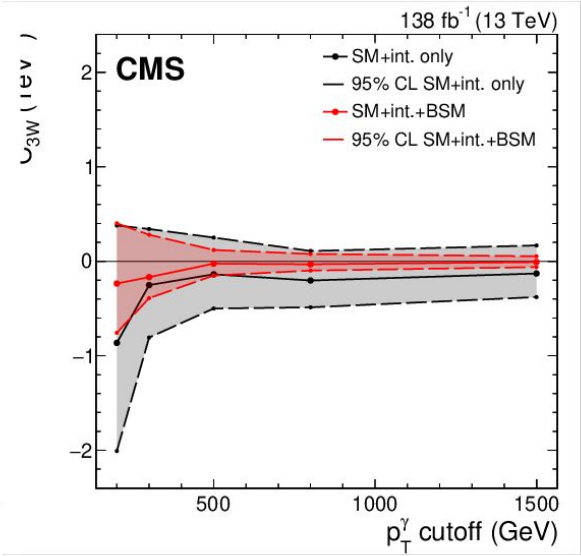
Sensitive to dim-6 aTGC



New constraints on C_{3W}

$$\sigma^{tot} = \sigma_{SM} + C_{3W}\sigma_{int} + C_{3W}^2\sigma_{BSM}$$





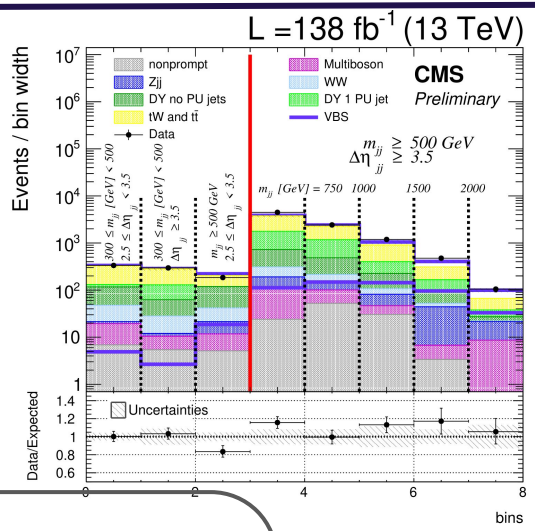
VBS multiboson production

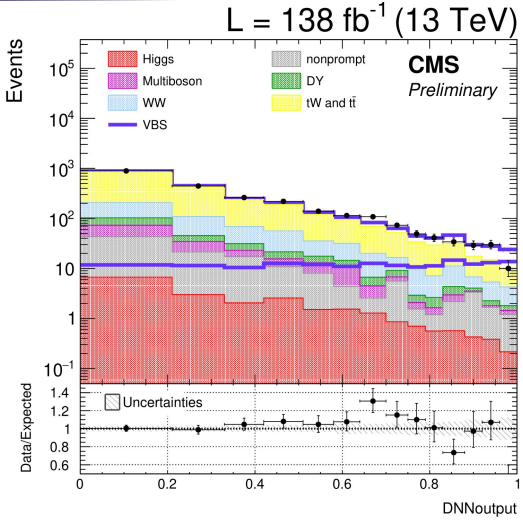
- Purely electroweak process with unique topology
  - two very forward jets, with large η separation and invariant mass
- very rare process (~fb^{-1}) with high irreducible background (from QCD)
  - only accessible with LHC run II
  - sophisticated signal extraction and data driven bkg estimation
- longitudinal polarized part of V connected to Higgs mechanism
- SM extension with dim-8 operators standing for anomalous couplings
- different channels depending on both V decay mode
  - fully leptonic
  - semi leptonic (one V decay leptonically, the other hadronicaly)
  - full hadronic

Fully leptonic VBS $W^{\mp}W^{\pm}$

PAS-SMP-21-001

- select ee, μμ, **eμ** final states, opposite charge
- p_T^{miss} > 20 GeV
- m_{jj} > 300 GeV, $\Delta\eta$ > 2.5
- b-jet veto to suppress top bkg





Signal discrimination

- ee/μμ category 1 variable depending on $m_{jj}/\Delta\eta$
  - m_{jj} at high $m_{jj}/\Delta\eta$
  - number of events the rest of phase space
- eμ : Deep Neural Network

Background data driven estimation

- normalization in bins of $m_{jj}/\Delta\eta$

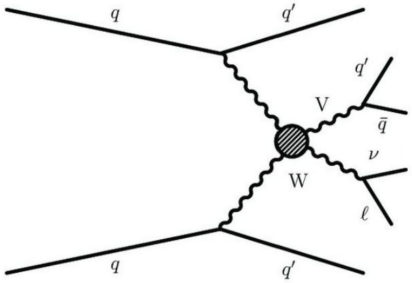
First observation

observed (expected) significance = 5.6 (5.2)σ

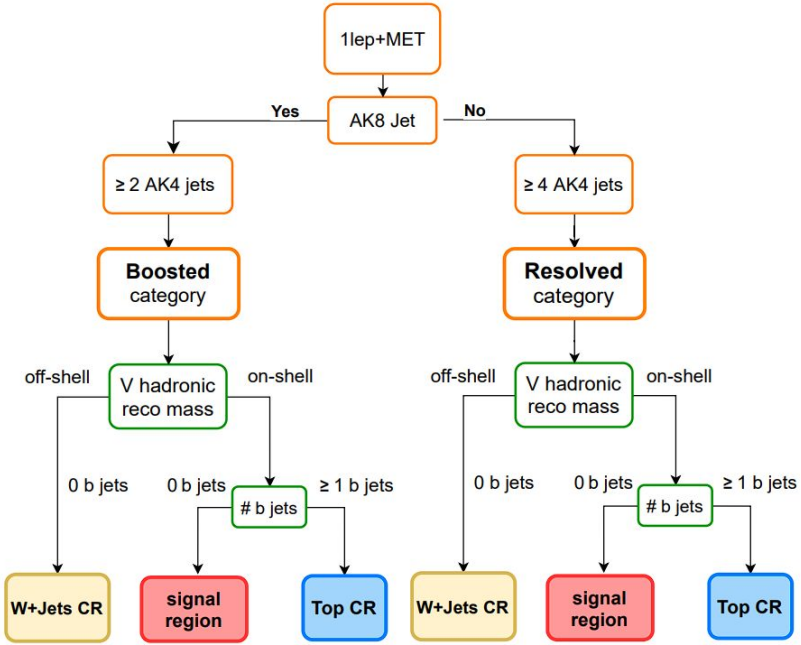
biggest nuisance: background data driven normalizations and QCD scale

VBS WV semi-leptonic

arxiv 2112.05259



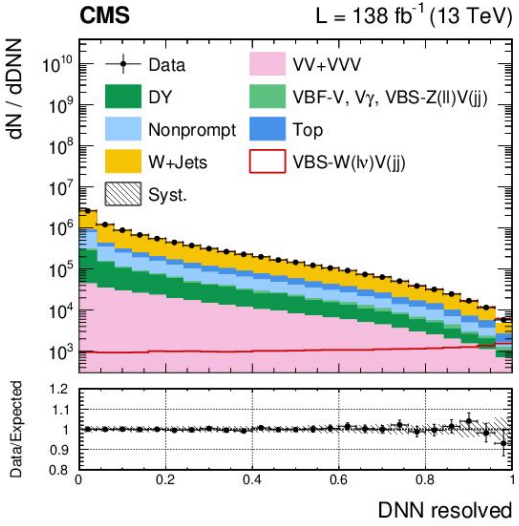
- larger XS than fully leptonic
- smaller bkg than fully hadronic
- two topologies: either two resolved jets or one boosted jet for the $V \to q\bar{q}$ candidate
- Data driven estimation in dedicated control regions for two main backgrounds: W + jets and tops

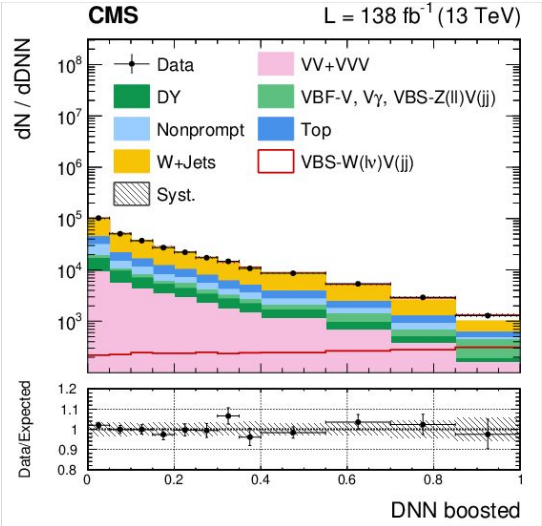


VBS WV semi-leptonic : results

arxiv 2112.05259

Signal discrimination with DNNs





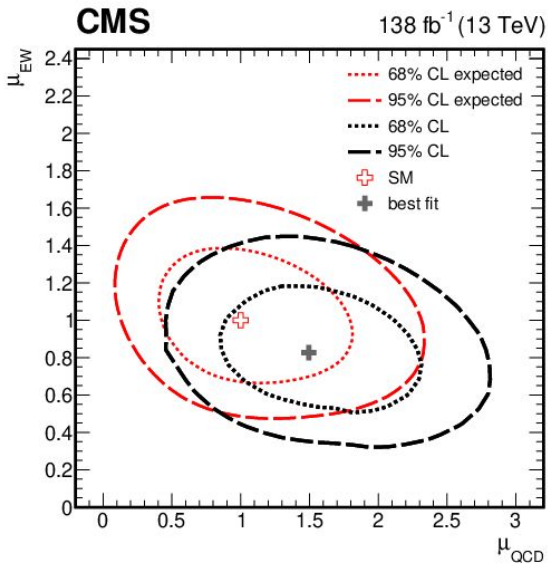
First evidence

observed (expected) significance = 4.4(5.1)σ

$$\mu_{\mathrm{EW}} = \frac{\sigma^{\mathrm{obs}}}{\sigma^{\mathrm{SM}}} = 0.85 \pm 0.12\,(\mathrm{stat})^{+0.19}_{-0.17}\,(\mathrm{syst}) = 0.85^{+0.23}_{-0.21}$$

$$\mu_{\mathrm{EW+QCD}} = 0.97 \pm 0.06\,(\mathrm{stat})^{+0.19}_{-0.21}\,(\mathrm{syst}) = 0.97^{+0.20}_{-0.22}$$

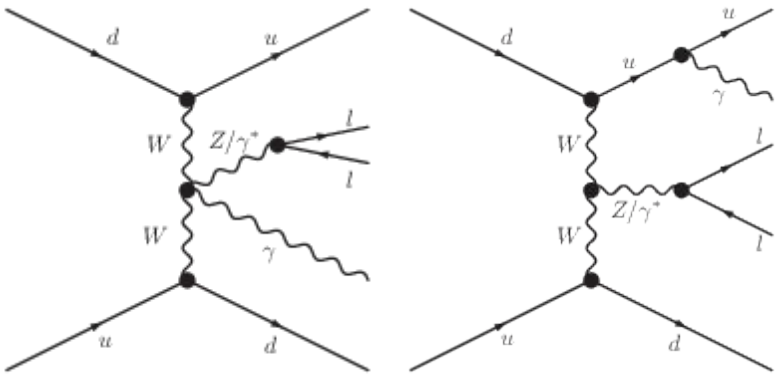
Simultaneous fit to QCD and EWK signal strengths



VBS $Z\gamma$

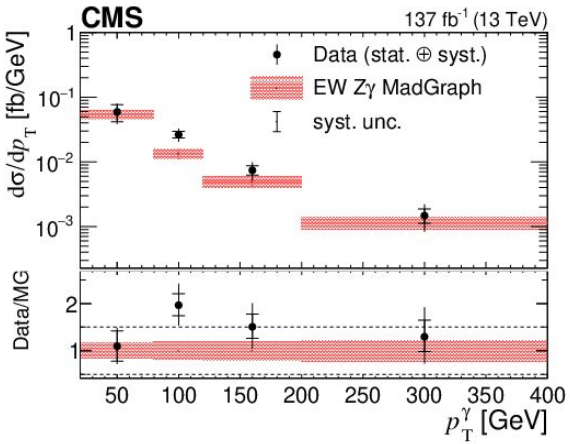
Phys. Rev. D 104.072001

- No photon coupling to Higgs
  - sensitivity to neutral **(a)QGC** and (a)TGC
- Main backgrounds:
  - QCD $Z\gamma$: estimated from MC, constrained in simultaneous fit
  - Non-prompt photon: data-driven estimate through photon shape fit
- Signal extracted with m_{jj} and $\Delta\eta_{jj}$



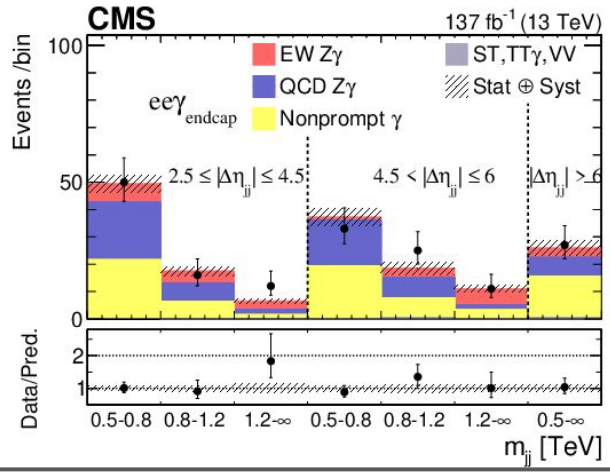
Differential XS in p_T of first lepton, first jet, photon & m_{jj}

Generally good agreement data/predictions



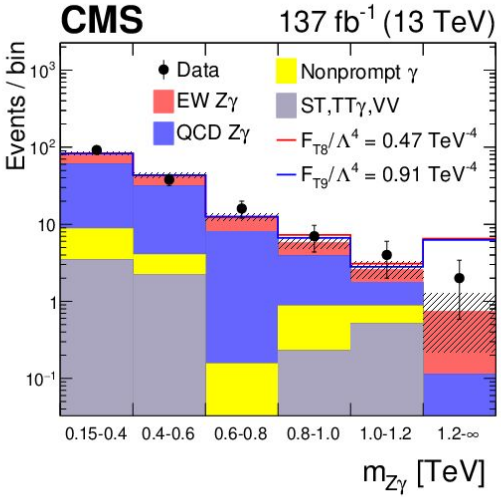
VBS Zγ : results

Phys. Rev. D 104.072001



Invariant mass of Z and photon used for aQGC study.

- Most stringent limit to date on dim-8 operator T9: $-0.91 < F_{T9}/\Lambda^4 < 0.91$
- competitive constraints on M0 to M2, T0 to T2 and T5 to T9



First observation at 9.4 (8.5) SD

$$\sigma_{EW}^{fid} = 5.21 \pm 0.52(stat) \pm 0.56(syst)fb = 5.21 \pm 0.76fb$$

$$\sigma_{EW}^{theo} = 4.34 \pm 0.26(scale) \pm 0.06(PDF)fb$$

$$\sigma_{EW+QCD}^{fid} = 14.7 \pm 0.80(stat) \pm 1.26(syst)fb = 14.7 \pm 1.53fb$$

$$\sigma_{EW+QCD}^{theo} = 13.3 \pm 1.72(scale) \pm 0.10(PDF)fb$$

Conclusion

- A lot of results in 2021 using run II data
  - measured XS generally agree well with predictions
  - limits on new physics with several EFT operators
- More results to come, several analysis are still underway
- Statistics is the limiting factor for most multiboson results
  - Run 3 is expected to improve them
  - large increase in HL-LHC