Vector Boson Fusion and Vector Boson Scattering: observations and limitations

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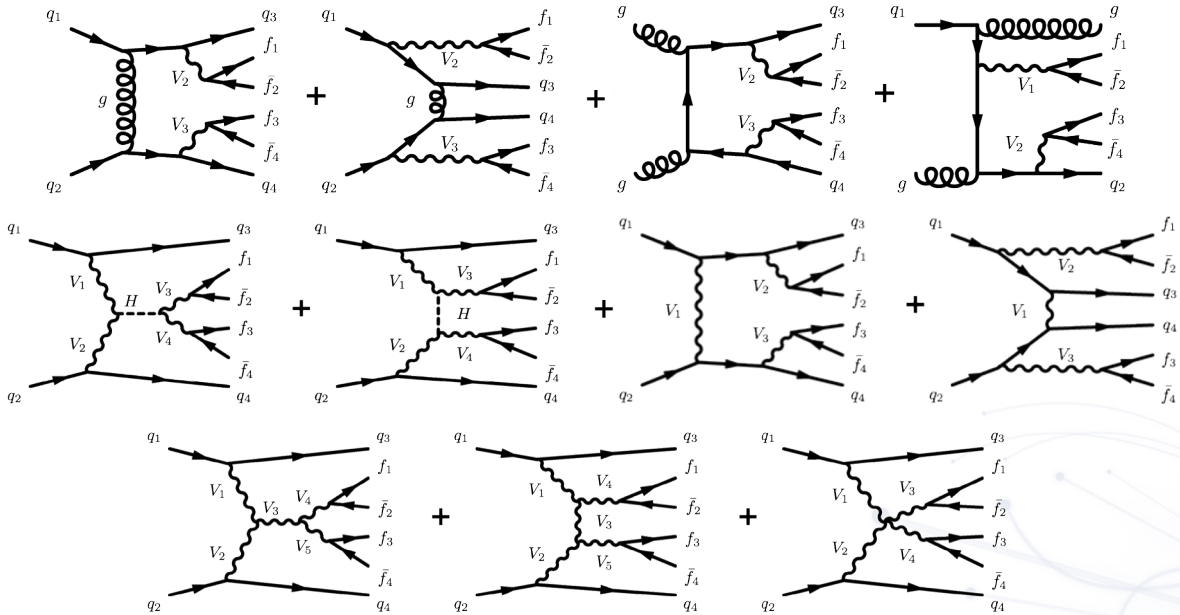
On behalf of CMS and ATLAS

Vector boson scattering @ LHC (LO)



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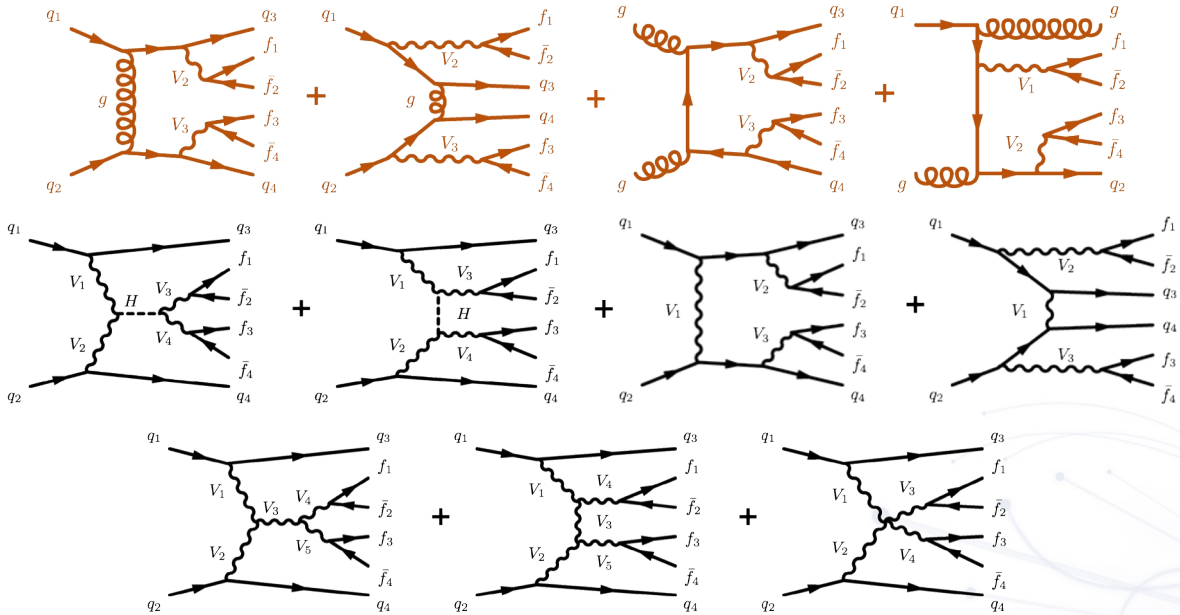

QCD $\vartheta(\alpha_{EWK}^2 \alpha_s^2)$

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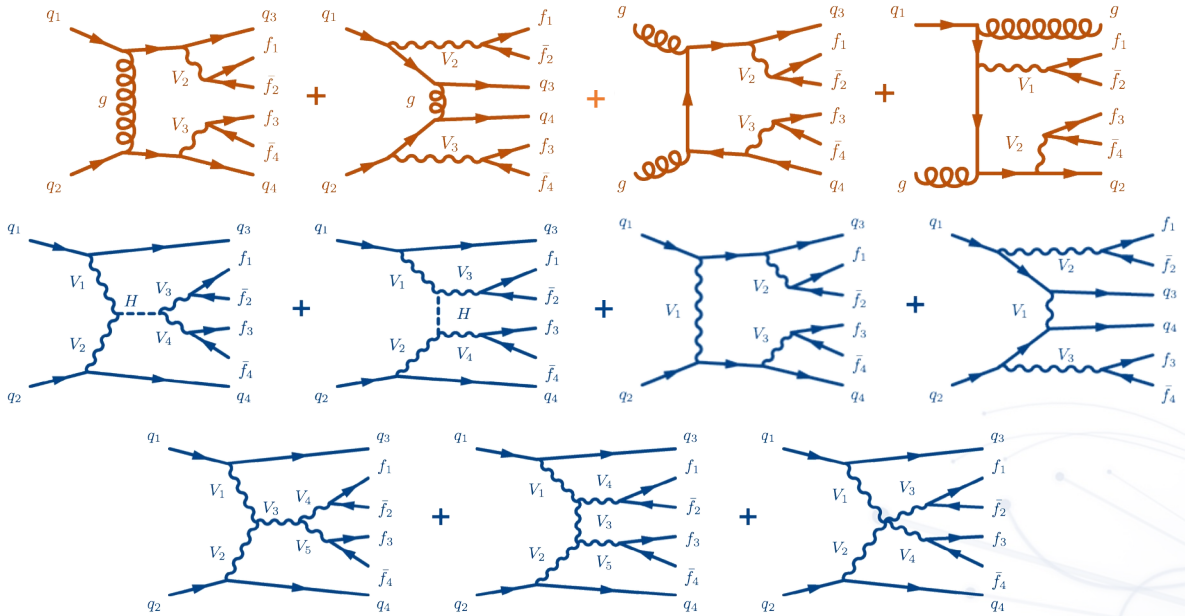

QCD $\vartheta(\alpha_{EWK}^2 \alpha_s^2)$

EWK $\vartheta(\alpha_{EWK}^4)$

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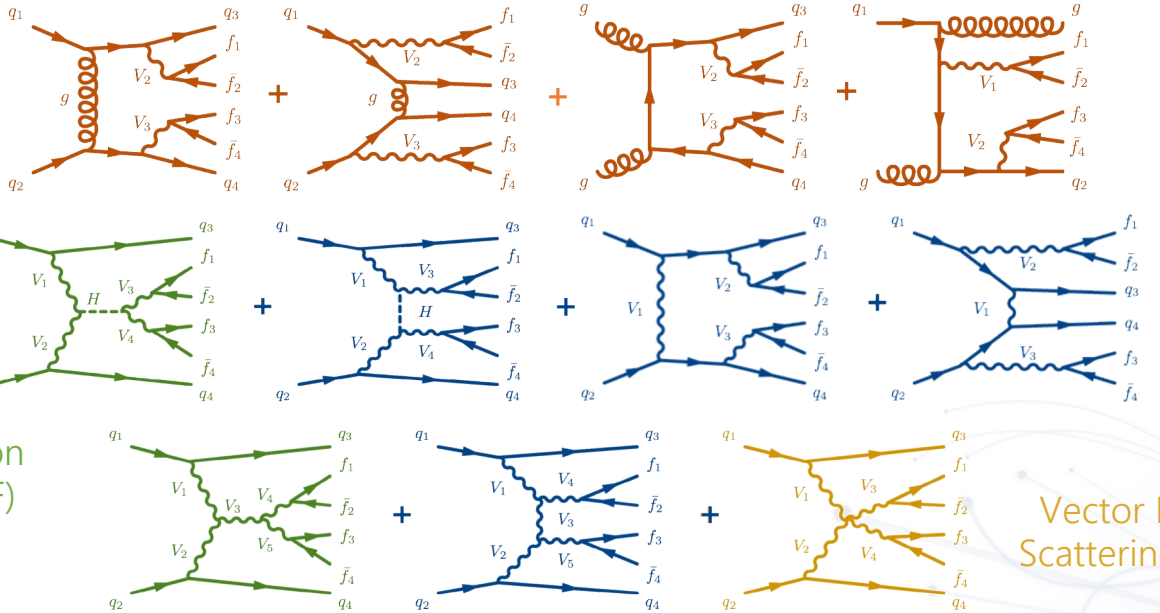
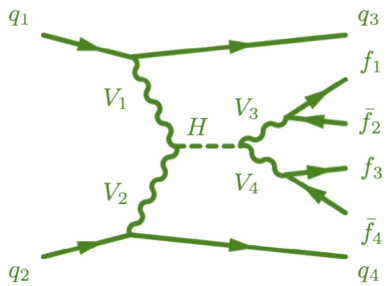
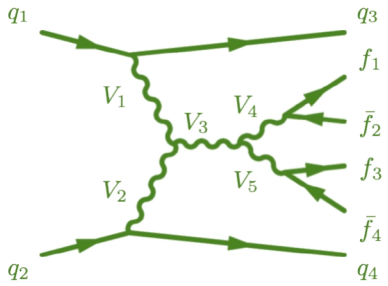


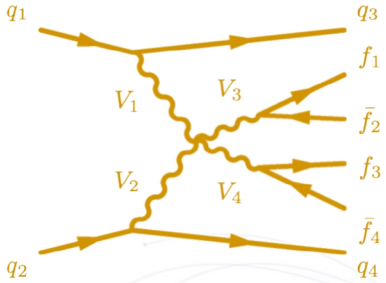
What are VBF and VBS? — Lowest Order

Vector Boson Fusion (VBF)

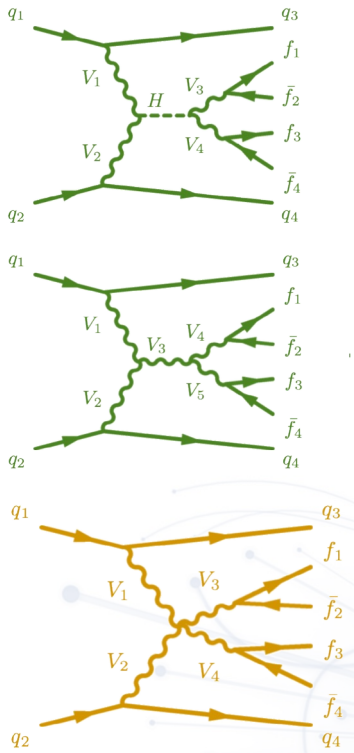




Vector Boson Scattering (VBS)

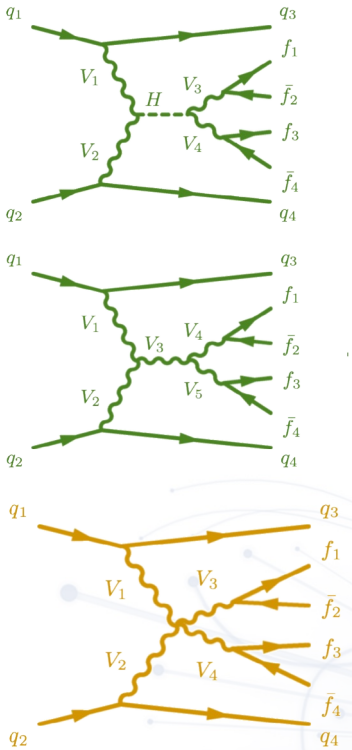


VBF and VBS importance



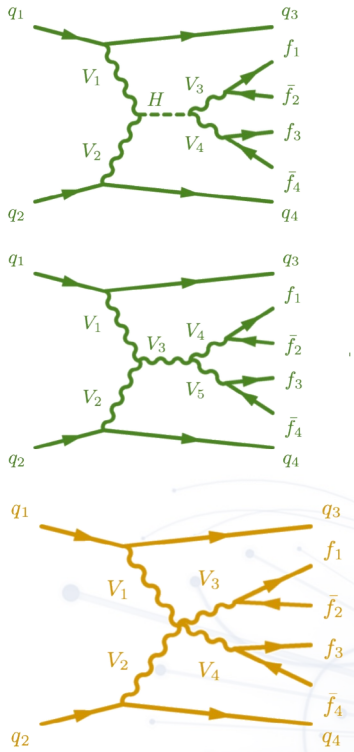
VBF and VBS importance

- **Self interactions** between vector bosons → anomalous triple/quartic gauge coupling



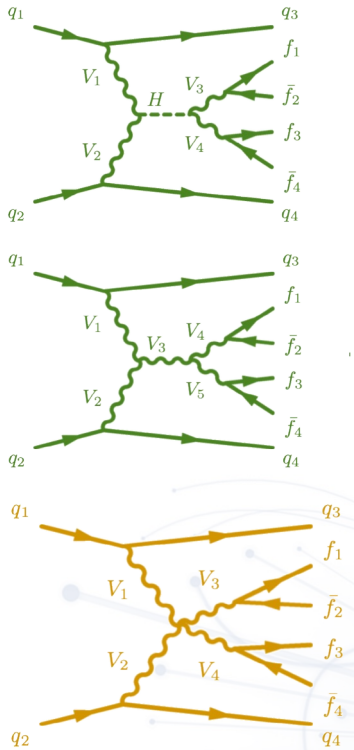
VBF and VBS importance

- **Self interactions** between vector bosons → anomalous triple/quartic gauge coupling
- Scattering of longitudinal polarizations really **sensible to variations in the Higgs sector**



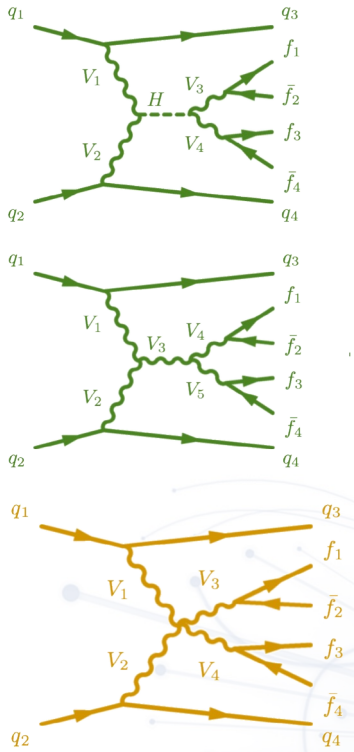
VBF and VBS importance

- **Self interactions** between vector bosons → anomalous triple/quartic gauge coupling
- Scattering of longitudinal polarizations really **sensible to variations in the Higgs sector**
- Allows EFT + model dependant approaches



VBF and VBS importance

- **Self interactions** between vector bosons → anomalous triple/quartic gauge coupling
- Scattering of longitudinal polarizations really **sensible to variations in the Higgs sector**
- Allows EFT + model dependant approaches
- **Peculiar topology** of the final state objects



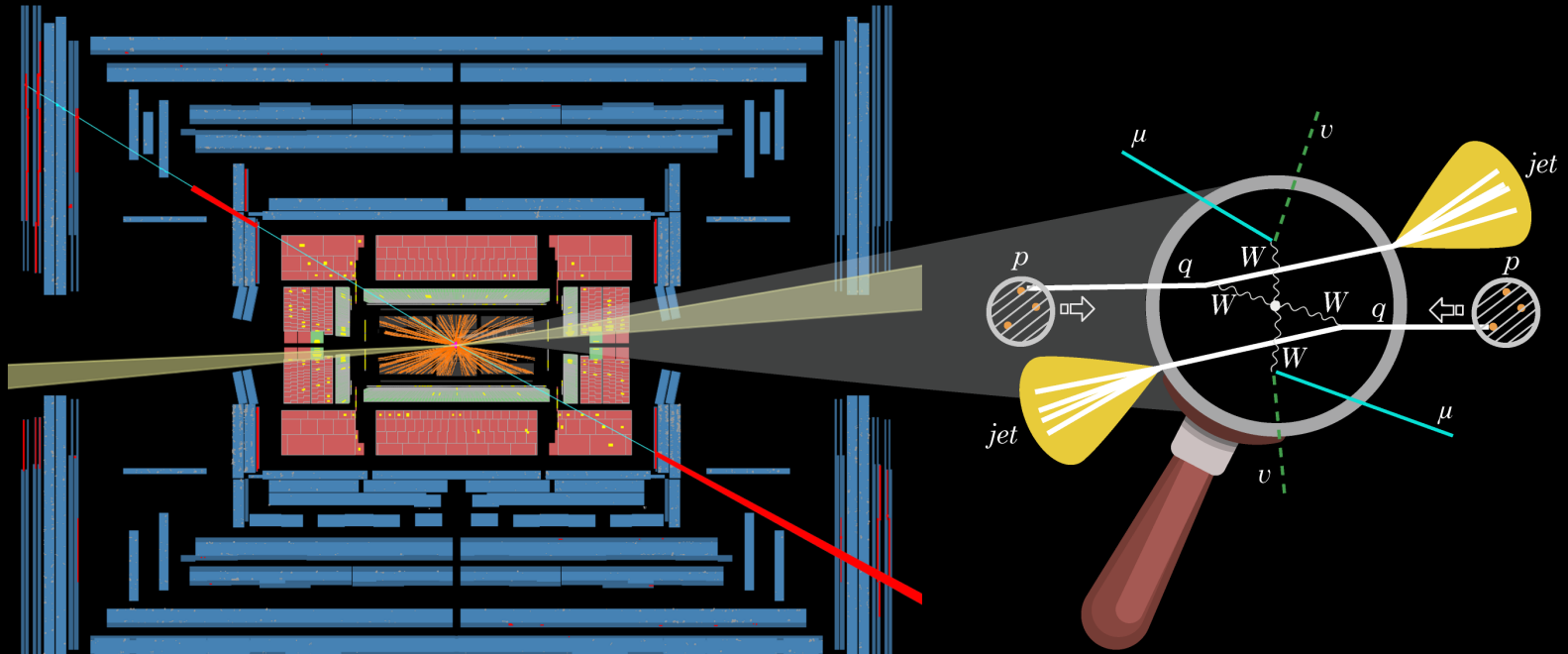


Fig. from ATLAS

VBF studies

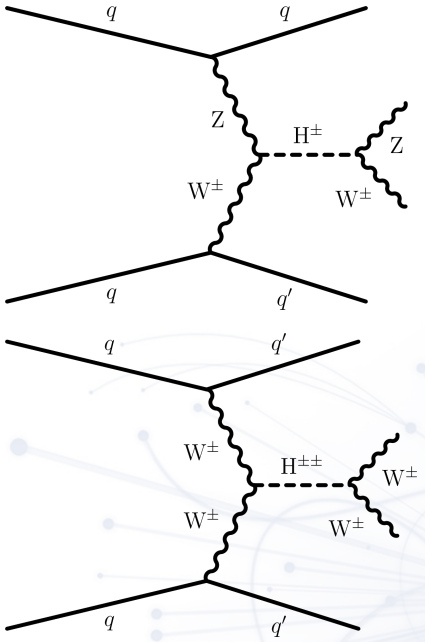
Search for charged Higgs boson

Search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector boson pairs in proton-proton collisions at $\sqrt{s} = 13\ TeV$ (Eur. Phys. J. C 81 (2021) 723)

- Search for $H^5 = \boldsymbol{H^{\pm}, H^{\pm\pm}}$ in Georgi-Machacek (GM) model

$$W^{\pm}W^{\pm} \to H^{\pm\pm} \to W^{\pm}W^{\pm} \to \ell^{\pm}\nu\ell'^{\pm}\nu'$$
$$W^{\pm}Z \to H^{\pm} \to W^{\pm}Z \to \ell^{\pm}\nu\ell^{+}\ell^{-}$$

- Only fermiophobic charged Higgs in the GM model considered



Search for charged Higgs boson

Search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector boson pairs in proton-proton collisions at $\sqrt{s} = 13\ TeV$ (*Eur. Phys. J. C 81 (2021) 723*)

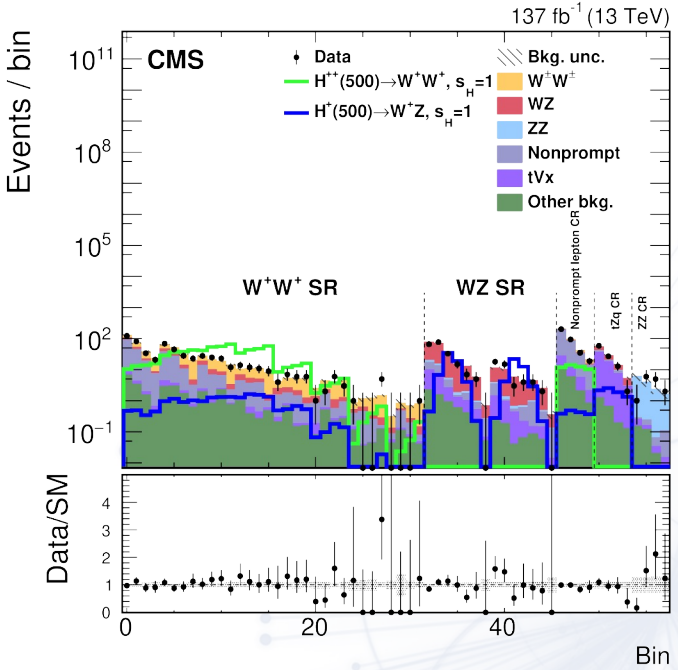
- Signal extraction → fit on 2-dim distribution in SR:

  m_{jj} — Discrimination VBS-non VBS

  VS

  m_T^{VV} — Discrimination resonant-non resonant

- Different binning for the 2 SR, just m_{jj} to fit the bkg
- No deviations from SM found



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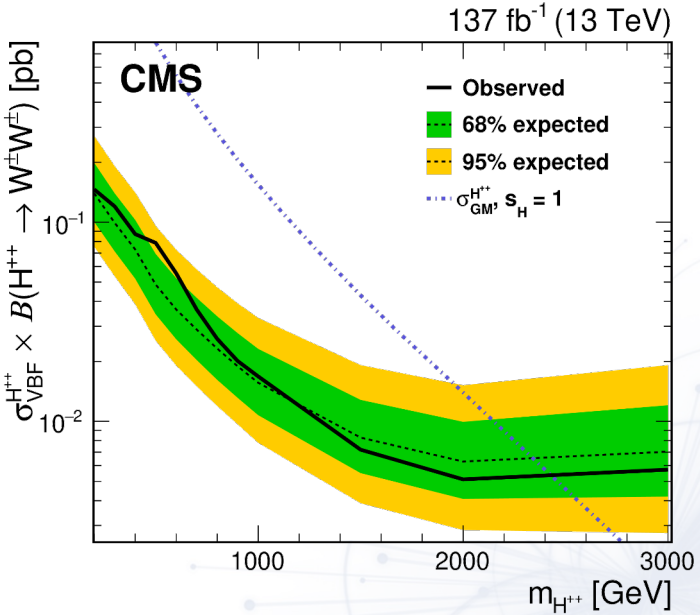
- Modified frequentist approach with the CLs criterion + asymptotic method for the test statistic
- $\sigma_{VBF}(H^{\pm\pm}) \times B(H^{\pm\pm} \to W^{\pm}W^{\pm})$ 95% limit extracted



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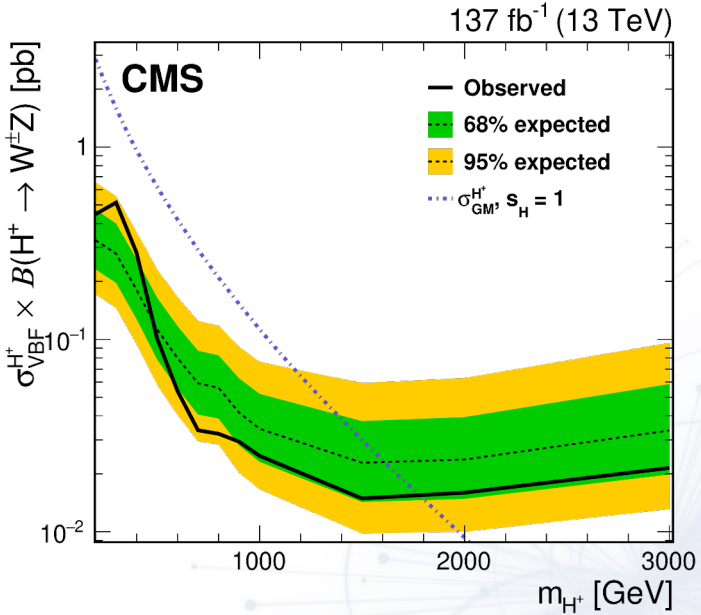
- $\sigma_{VBF}(H^{\pm}) \times B(H^{\pm} \to W^{\pm}Z)$ 95% limit extracted



Search for resonant WZ production

Search for Resonant $WZ \to \ell\nu\ell'\ell'$ Production in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector (ATLAS-CONF-2022-005)

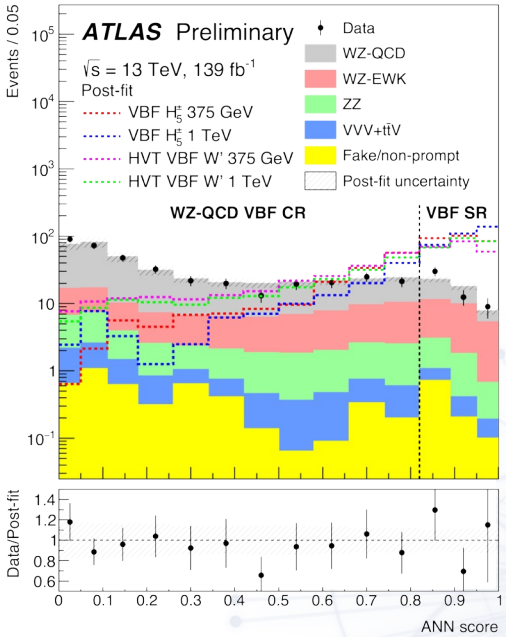
$$qq \to W'(H^{\pm}) \to W^{\pm}Z \to \ell'\nu\ell\ell$$

- Charged Higgs in GM models → only target single charged components of the fermiophobic fiveplet
- Parametrized lagrangians with **Heavy Vector Triplet (HVT)** → W′
  - VBF process only sensible to gauge coupling → benchmark model assumes no coupling between W′ and fermions

Search for resonant WZ production

Search for Resonant $WZ \to \ell\nu\ell'\ell'$ Production in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector (ATLAS-CONF-2022-005)

- Artificial Neural Network (**ANN**) trained to discriminate HVT and GM versus SM WZ production
- ANN output used to cut, maximizing significance at the lowest mass point
  - Proven not much difference in performance with one ANN for each mass point
  - Gain in computing time and simplicity
- **Good description of data in SR** by background with the ANN score



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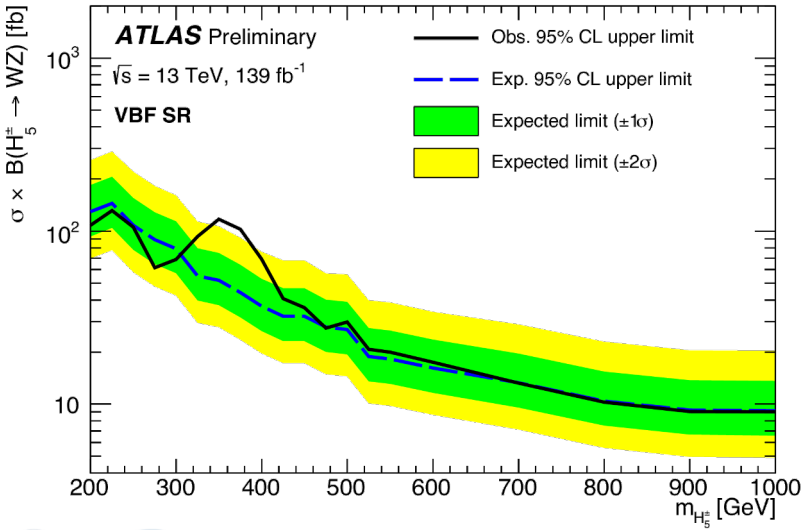
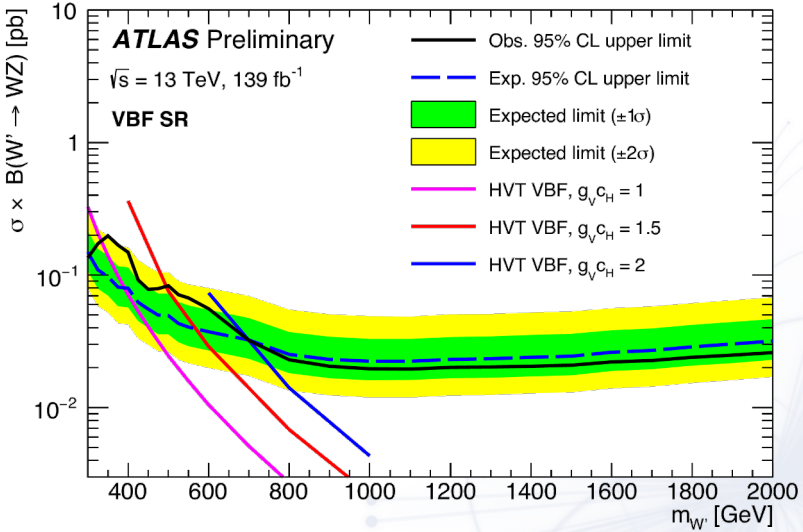
Limits on GM model



Limits on HVT model



VBF: temptative list of interesting searches

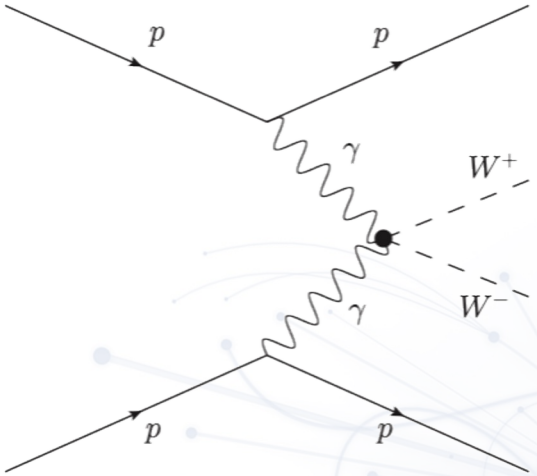
- Interested in VBF? Don't miss the talk by **Emmanuel Sauvan**! (14/04/2022, 12:48)
- A non-comprehensive list of suggested articles:
  - **CMS:**
    - Search for high mass resonances decaying into W+W− in the dileptonic final state with 138fb−1 of proton-proton collisions at https://cds.cern.ch/record/2803723
    - Search for Higgs boson pair production via vector boson fusion with highly Lorentz-boosted Higgs bosons in the four b quark final state at √s=13 TeV https://cds.cern.ch/record/2776802
    - Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.052004
  - **ATLAS:**
    - Electroweak production of dijets in association with a Z boson at 13 TeV (Physics Letters B 775 (2017) 206)
    - Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using 139 fb−1 of proton-proton data recorded by the ATLAS experiment https://inspirehep.net/literature/2033393
    - Observation of photon-induced W^+ W^- production in pp collisions at √s=13 TeV using the ATLAS detector Phys. Lett. B 816 (2021) 136190

VBS studies

VBS: $\gamma\gamma \rightarrow VV$

Search for exclusive $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production in final states with jets and forward protons (CMS-PAS-SMP-21-014)

- $\gamma\gamma \rightarrow WW$
- $\gamma\gamma \rightarrow ZZ$
- Precision Proton Spectrometer (PPS) → measure of scattered protons
- $W, Z \rightarrow jj$
- Exploits the full reconstruction of the energy of the event



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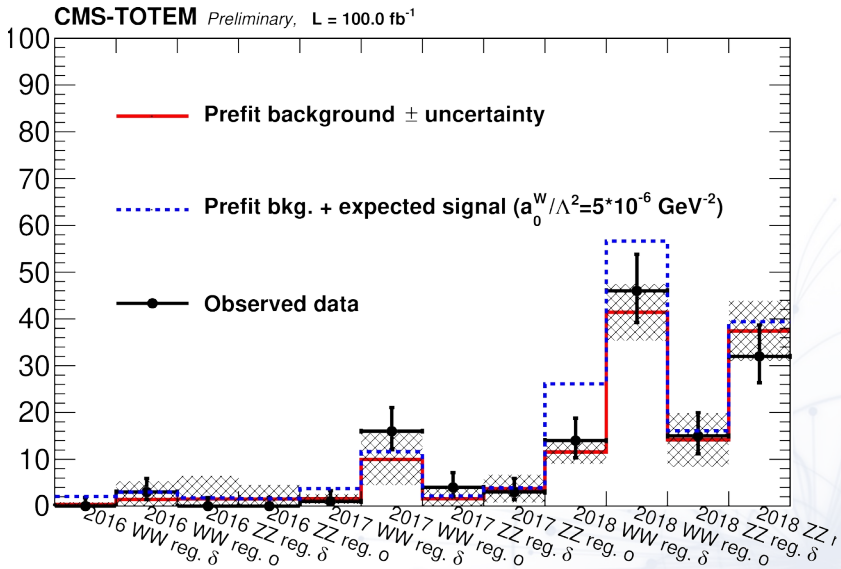
- Comparison data – bkg expectation
  - ''region δ''→ fully reconstructed events
  - ''region o'' →partially reconstructed events
- Non zero WW anomalous coupling → slightly above analysis sensitivity



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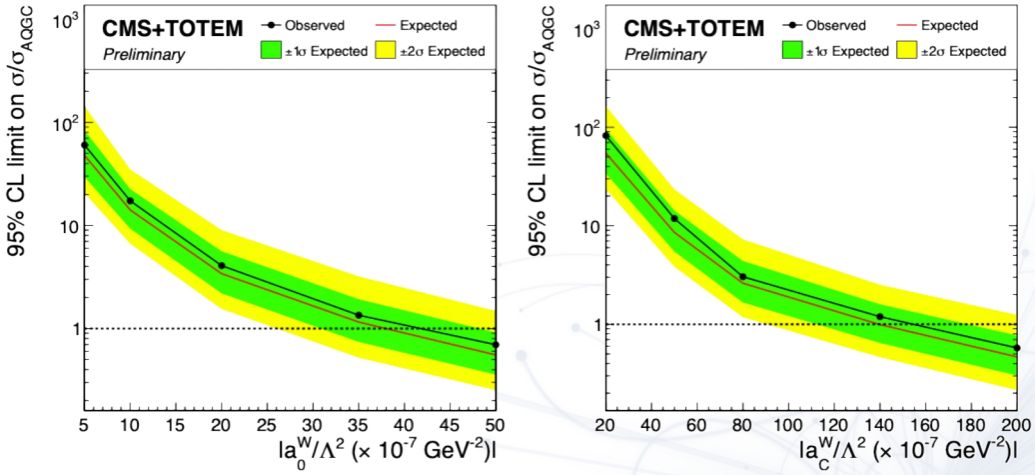
- aQGC interpretation of the results with dim6 operators:
  $a_0^W, a_C^W, a_0^Z, a_C^Z$
- Limits extrapolated for single operators



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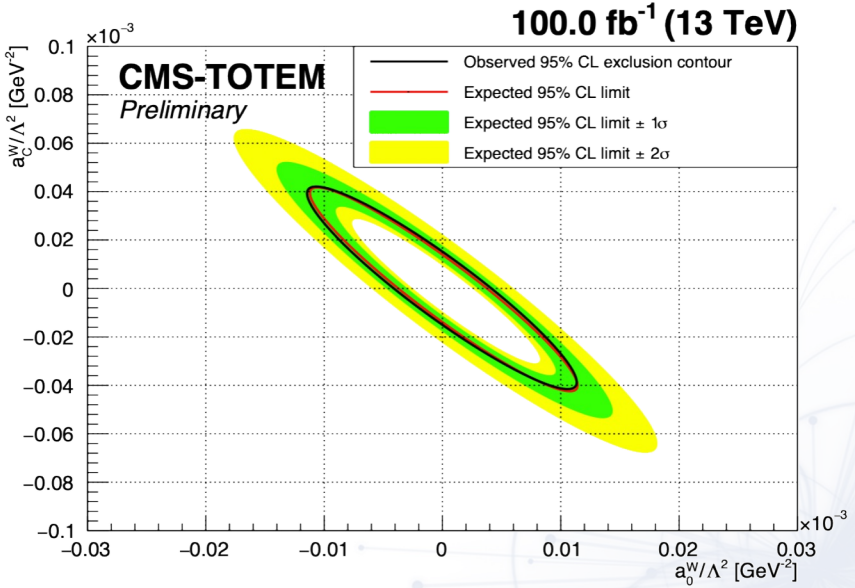

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- **aQGC interpretation** of the results with dim6 operators:
  $a_0^W, a_C^W, a_0^Z, a_C^Z$
- Limits extrapolated for single operators
- And simultaneous variation of two operators
- $a_{0,C}^{W,Z}$ for γ → **combination of dim8 couplings**

Coupling	Observed (expected) 95% CL upper limit	Clipping
$\lvert f_{M,0}/\Lambda^4\rvert$	66.0 (60.0) TeV^{-4}	-
$\lvert f_{M,1}/\Lambda^4\rvert$	245.5 (214.8) TeV^{-4}	-
$\lvert f_{M,2}/\Lambda^4\rvert$	9.8 (9.0) TeV^{-4}	-
$\lvert f_{M,3}/\Lambda^4\rvert$	73.0 (64.6) TeV^{-4}	-
$\lvert f_{M,4}/\Lambda^4\rvert$	36.0 (32.9) TeV^{-4}	-
$\lvert f_{M,5}/\Lambda^4\rvert$	67.0 (58.9) TeV^{-4}	-
$\lvert f_{M,7}/\Lambda^4\rvert$	490.9 (429.6) TeV^{-4}	-
$\lvert f_{M,0}/\Lambda^4\rvert$	79.8 (78.2) TeV^{-4}	1.4 TeV
$\lvert f_{M,1}/\Lambda^4\rvert$	306.8 (306.8) TeV^{-4}	1.4 TeV
$\lvert f_{M,2}/\Lambda^4\rvert$	11.9 (11.8) TeV^{-4}	1.4 TeV
$\lvert f_{M,3}/\Lambda^4\rvert$	91.3 (92.3) TeV^{-4}	1.4 TeV
$\lvert f_{M,4}/\Lambda^4\rvert$	43.5 (42.9) TeV^{-4}	1.4 TeV
$\lvert f_{M,5}/\Lambda^4\rvert$	83.7 (84.1) TeV^{-4}	1.4 TeV
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- aQGC interpretation of the results with dim6 operators:
  $a_0^W, a_C^W, a_0^Z, a_C^Z$
- Limits extrapolated for single operators
- And simultaneous variation of two operators
- $a_{0,C}^{W,Z}$ for γ → combination of dim8 couplings
- Limits 15-x20 times more stringent that ones from $\gamma\gamma \rightarrow WW$ in RunI and close to the ones obtained in WW VBS

Coupling	Observed (expected) 95% CL upper limit	Clipping
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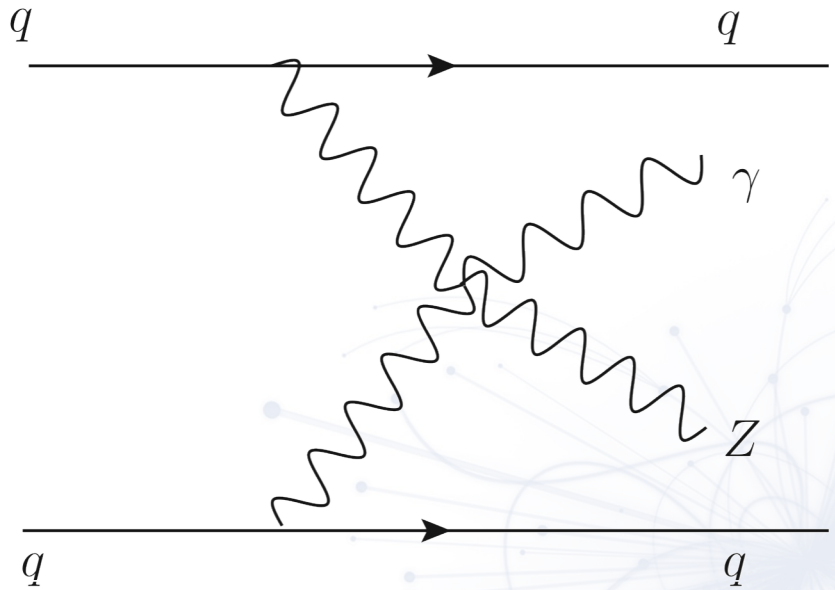
VBS: $Z\gamma \rightarrow \ell\ell\gamma$

Measurement of the cross-section of the electroweak production of a $Z\gamma$ pair in association with two jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (ATLAS-CONF-2021-038)

- Probes neutral quartic gauge coupling → forbidden in SM @ LO
- Full RunII statistics
- Final state: γe^+e^- + $\gamma\mu^+\mu^-$
- Measurement of the EWK cross section



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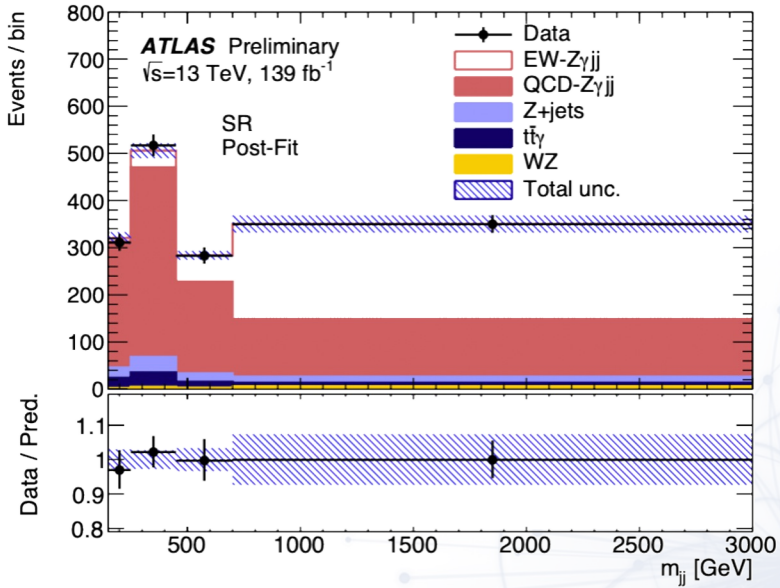
- Maximum likelihood fit on m_{jj}

$$\mu_{EW} = 0.95^{+0.14}_{-0.13}$$

$$\sigma_{EW} = 4.49 \pm 0.40\ (stat) \pm 0.42\ (syst) fb$$

$$\sigma_{EW+QCD} = 20.6 \pm 0.6^{+1.2}_{-1.0} (syst) fb$$

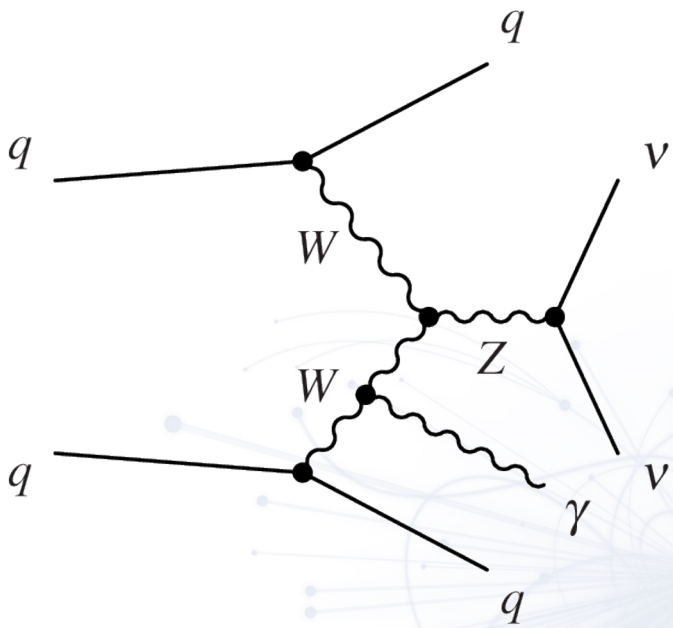
- No deviations from SM observed



VBS: invisibile + γ final state

Observation of electroweak production of two jets in association with an isolated photon and missing transverse momentum, and search for a Higgs boson decaying into invisible particles at 13 TeV with the ATLAS detector (Eur. Phys. J. C 82 (2022) 105)

- SM search:
  - $Z(\rightarrow \nu\nu)\gamma jj$
  - EWK SM $O(\alpha_{ewk}^5)$ process



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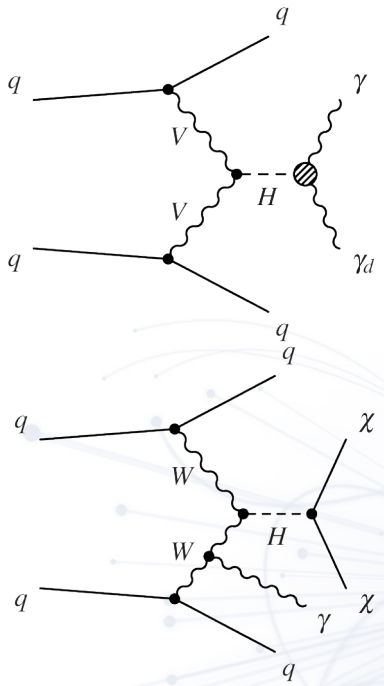
- SM search:
  - $Z(\rightarrow \nu\nu)\gamma jj$
  - EWK SM $O(\alpha_{ewk}^5)$ process
- BSM searches:
  - $H \rightarrow \gamma + \gamma_d$
  - $H \rightarrow invisibile + \gamma$
  - VBF → highest expected sensitivity in this channel



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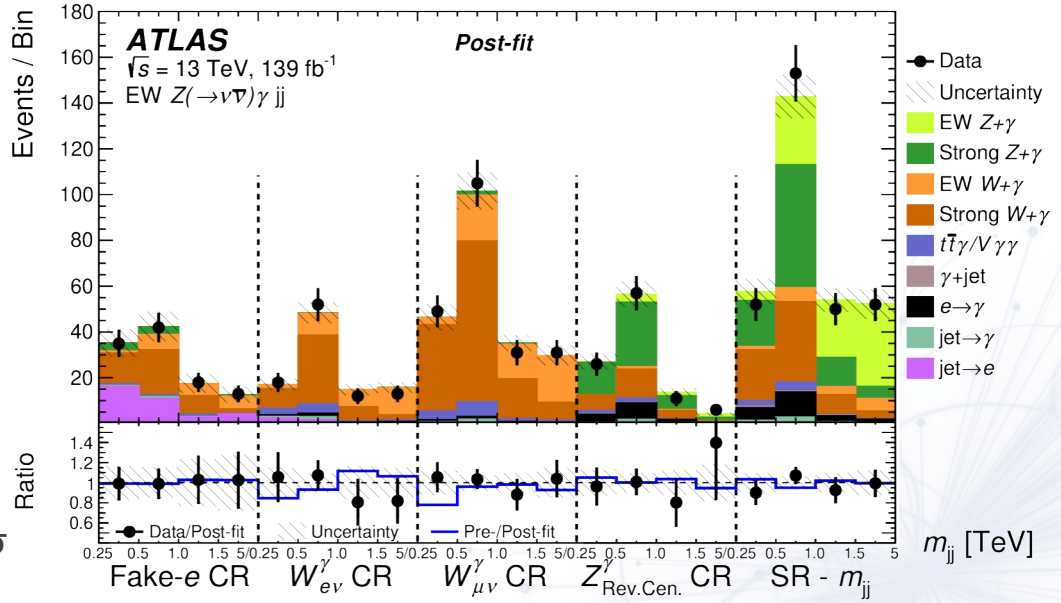
- SM search:
  - Events categorized in 4 $\mathbf{m_{jj}}$ bins
  - Expanded likelihood to $\mathbf{m_{jj}}$ bins for each signal and control region

$$\sigma^{\mathbf{fid}}_{\mathbf{Z(\to\nu\nu)\gamma EW}} = \mathbf{1.31 \pm 0.20(stat) \pm 0.20(syst) fb}$$

  - First observation with 5.2 σ significance



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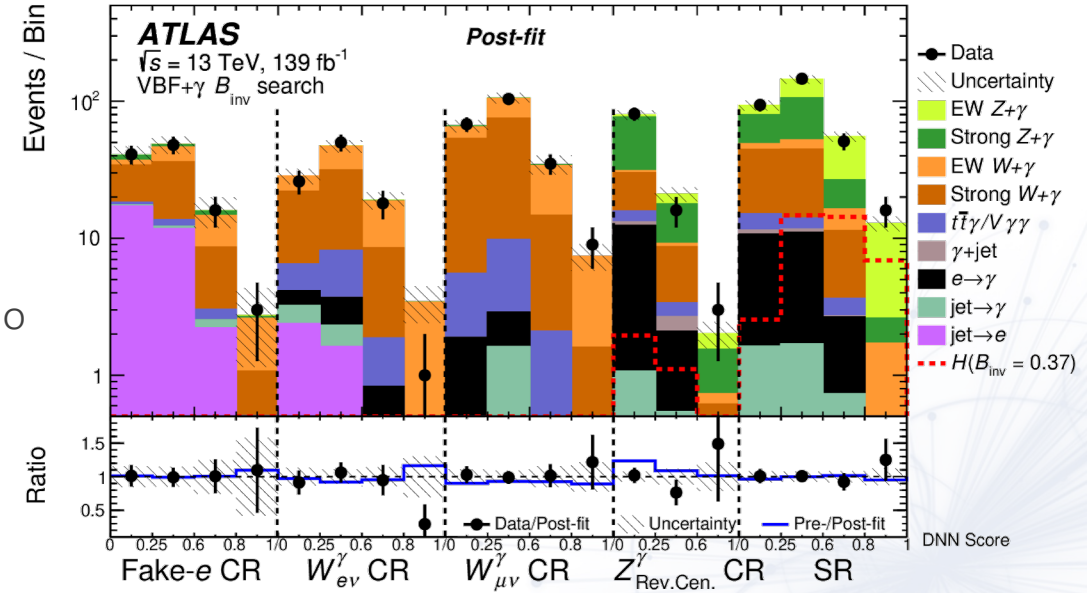
- H → invisible:
  - Dense neural network
  - Likelihood fit in each DNN output bin for each CR + signal region
  - Upper limit on branching ratio for $H \to inv$ @ 95% CL

$$\mathcal{B}_{\mathrm{inv}}^{\mathrm{obs(exp)}} = 0.37(0.34^{+0.15}_{-0.10})$$

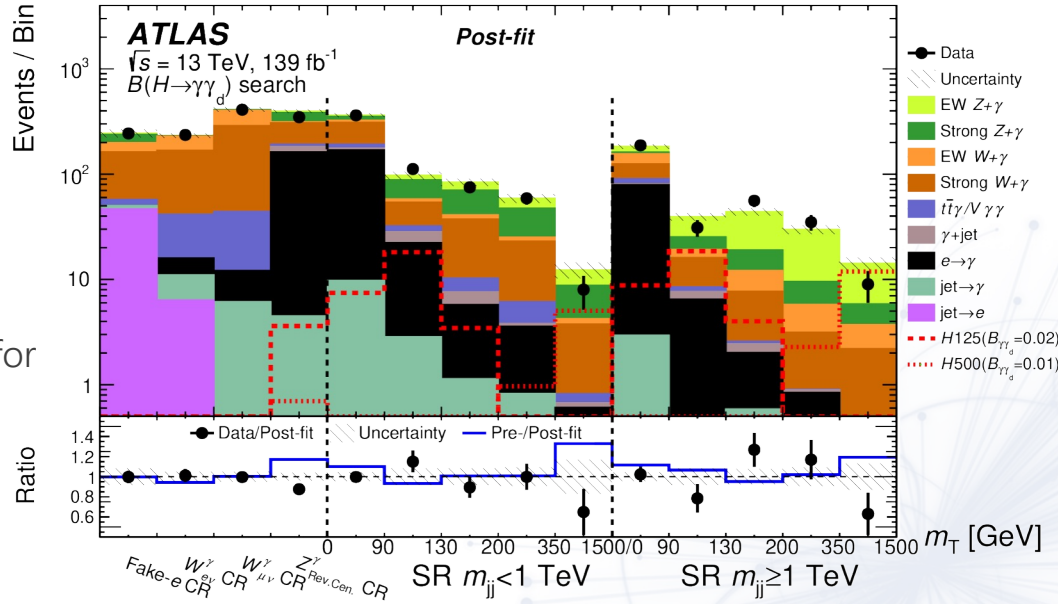


VBS: invisibile + γ final state

Observation of electroweak production of two jets in association with an isolated photon and missing transverse momentum, and search for a Higgs boson decaying into invisible particles at 13 TeV with the ATLAS detector (Eur. Phys. J. C 82 (2022) 105)

- $H \to \gamma\gamma_D$:
  - Most sensible variable: $m_T(\gamma, E_{miss})$ → five m_T bins
  - ggF and VBF contribution to $H \to \gamma\gamma_d$ vary with m_{jj} → two bins in m_{jj}
  - Upper limit on branching ratio for $H \to \gamma\gamma_d$ @ 95% CL

$$\mathcal{B}^{obs(exp)} = 0.018(0.017^{+0.007}_{-0.005})$$



VBS: a tentative list

- VBS is a quite in shape and nice field → if you're interested keep an eye on Roberto's talk!
- A non-comprehensive list of suggested articles:
  - **CMS**
    - Measurement of $W^{\pm}\gamma W^{\pm}\gamma$ differential cross sections in proton-proton collisions at $\sqrt{s}$= 13 TeV and effective field theory constraints https://cds.cern.ch/record/2791626
    - Search for vector boson scattering at the LHC Run 2 with CMS data in the semi-leptonic lvqq final state https://inspirehep.net/literature/1920670
    - Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at $\sqrt{s}$= 13 TeV https://cds.cern.ch/record/2786853
  - **ATLAS**
    - Observation of electroweak ZZjj production (Submitted to NPHYS)
    - Observation of electroweak production of two jets in association with an isolated photon and missing transverse momentum, and search for a Higgs boson decaying into invisible particles at 13 TeV with the ATLAS detector (https://cds.cern.ch/record/2779942)
    - Measurement of Vector Boson Scattering of VV final states in the Semileptonic decay channel (Phys. Rev. D 100 (2019) 032007)

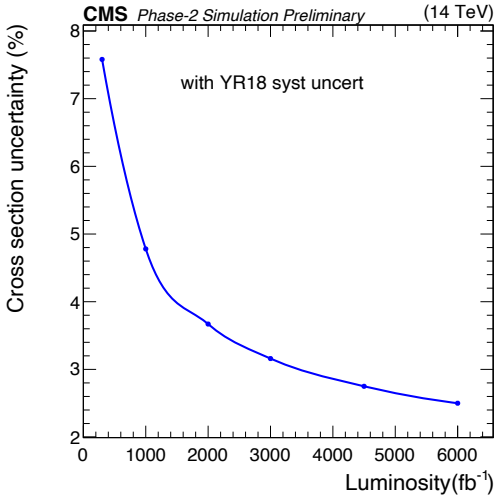
A glimpse into the future

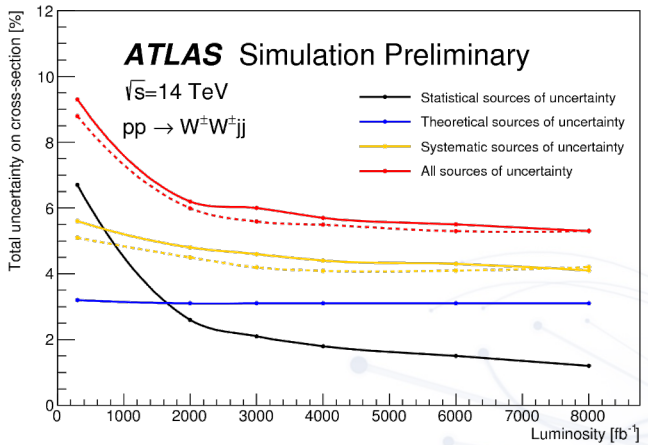
«Hey Doc, we bettere back up. We don’t have enough road to get to 88»

«Roads? Where we're going we don't need roads!»

Extrapolating to HiLumi

$W^{\pm}W^{\pm}jj$



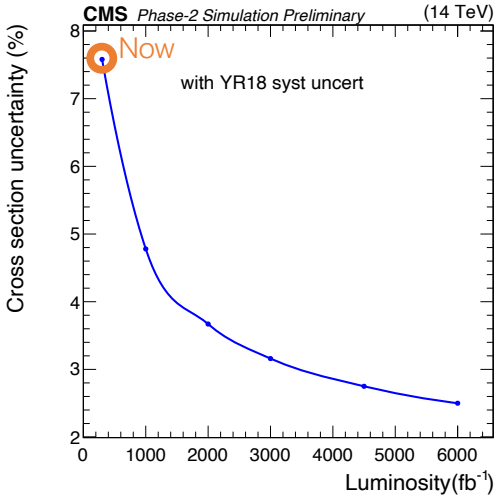


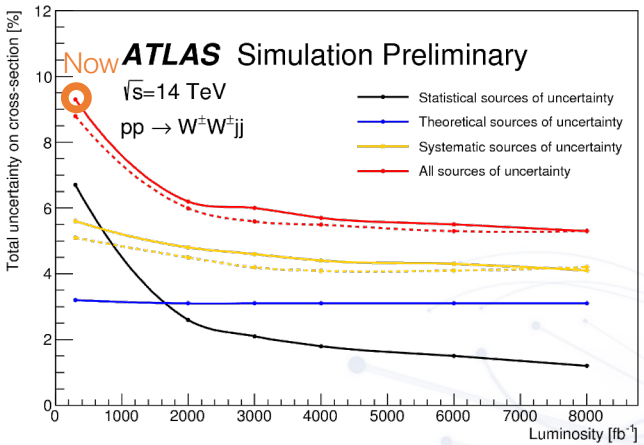
CMS-PAS-FTR-18-005

ATL-PHYS-PUB-2018-052

Extrapolating to HiLumi

$W^{\pm}W^{\pm}jj$



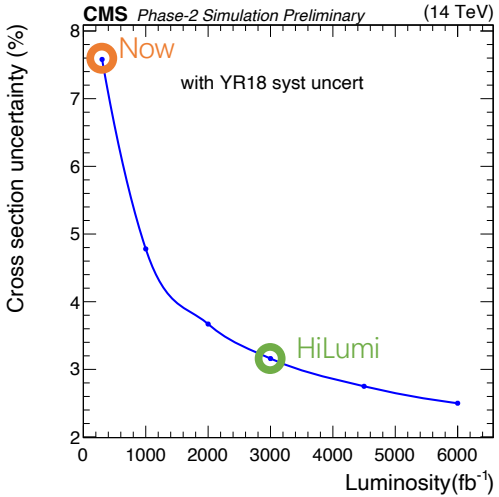


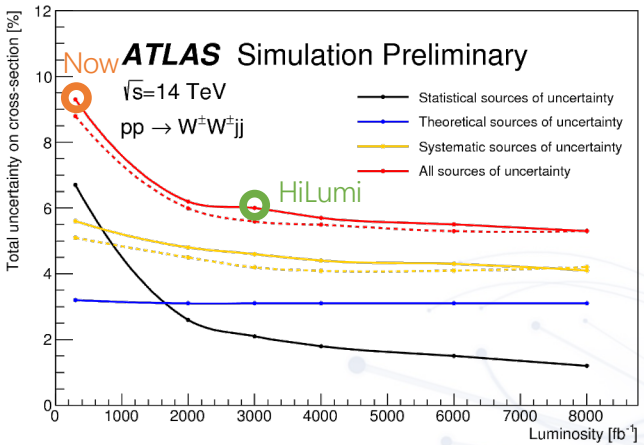
CMS-PAS-FTR-18-005

ATL-PHYS-PUB-2018-052

Extrapolating to HiLumi

$W^{\pm}W^{\pm}jj$





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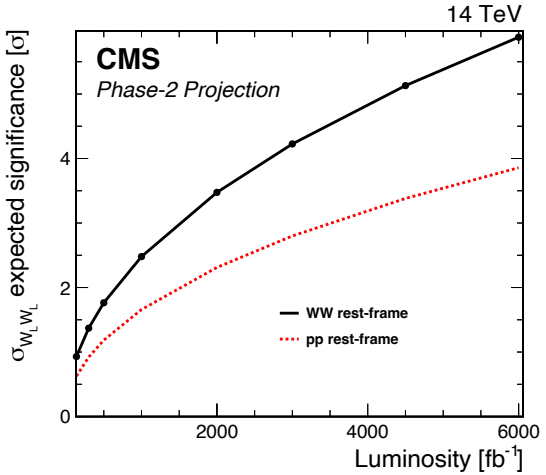
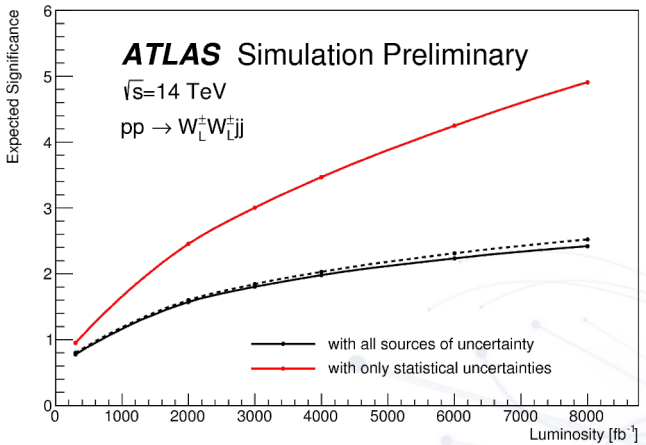
Extrapolating to HiLumi

$W_L^{\pm}W_L^{\pm}jj$



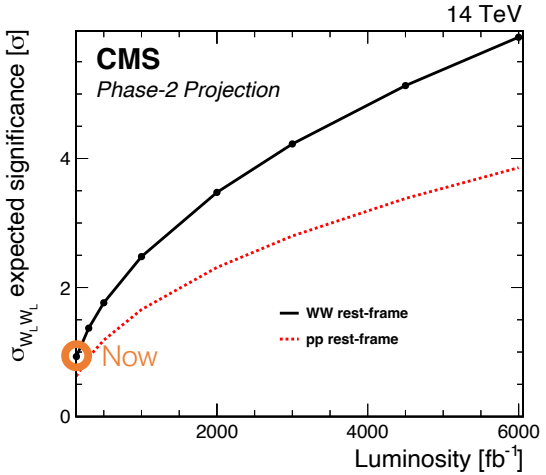


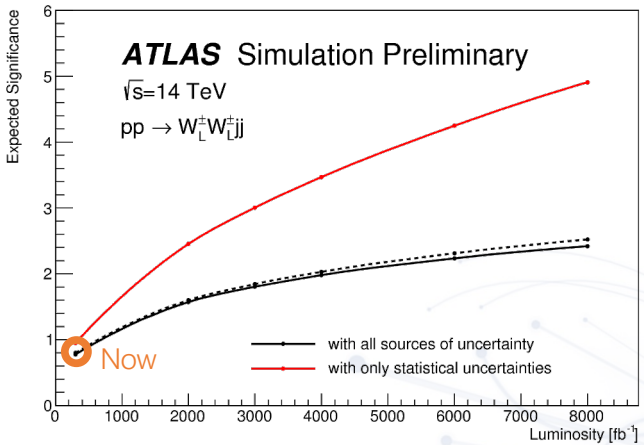
CMS-PAS-FTR-21-001

ATL-PHYS-PUB-2018-052

Extrapolating to HiLumi

$W_L^{\pm}W_L^{\pm}jj$



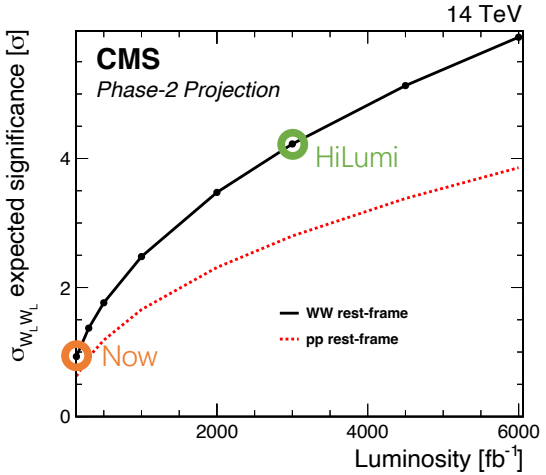


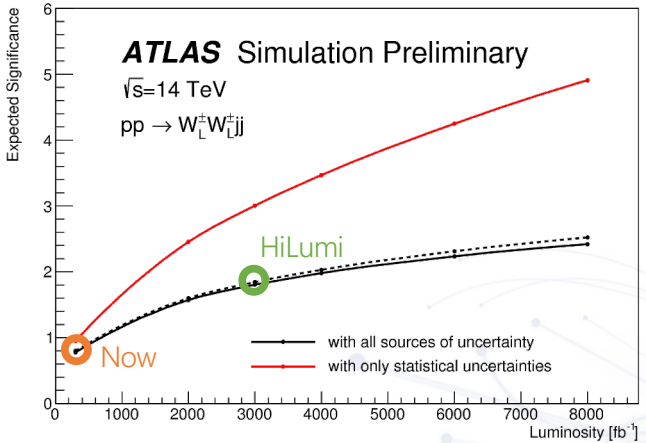
CMS-PAS-FTR-21-001

ATL-PHYS-PUB-2018-052

Extrapolating to HiLumi

$W_L^{\pm}W_L^{\pm}jj$





CMS-PAS-FTR-21-001

ATL-PHYS-PUB-2018-052

Conclusions

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Conclusions

- VBS and VBF are very active fields, which give us a **special probe to investigate both SM predictions and put limits on new physics** in a very versatile way
- Effort from the two collaborations to put limits in EFT framework and in model dependant theories
- Quite **impressive results** also in the rare processes and rarest decay
- **RunIII is coming!**

Backup

Search for resonant WZ production

Search for Resonant $WZ \to \ell\nu\ell'\ell'$ Production in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector (ATLAS-CONF-2022-005)

Baseline *WZ* selection		
Event cleaning and primary vertex Single-electron or single-muon trigger Exactly 3 *Loose* leptons (e or μ) with p_{T} >25 GeV(p_{T} >27 GeVfor trigger-matched lepton) *ZZ* veto: veto events with additional *Baseline* leptons *Z* candidate: A *Tight Z* Same-Flavour-Opposite-Sign lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert$ < 20 GeV *W* candidate: *Tight W* lepton requirements on non *Z* leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ > 25 GeV		
Selection	**Drell-Yan**	**VBF**
Signal region	$p_{\mathrm{T}}(V)/m(WZ)$ > 0.35	At least 2 *VBF jets* m_{jj} > 100 GeV Veto events with b-tagged jets ANN Output > 0.82
WZ-QCD control region	$p_{\mathrm{T}}(W)/m(WZ) \leq 0.35$ or $p_{\mathrm{T}}(Z)/m(WZ) \leq 0.35$ $p_{\mathrm{T}}(V)/m(WZ)$ > 0.1	At least 2 *VBF jets* m_{jj} > 500 GeV Veto events with b-tagged jets ANN Output < 0.82
ZZ control region	Additional *Baseline* lepton No $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement	Additional *Baseline* lepton No $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement At least 2 *VBF jets*

VBS: $Z\gamma \rightarrow \ell\ell\gamma$

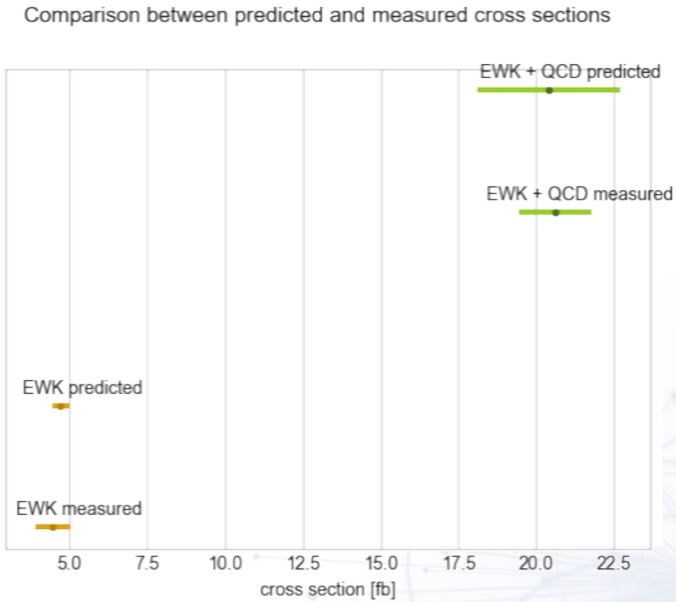
Measurement of the cross-section of the electroweak production of a $Z\gamma$ pair in association with two jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (ATLAS-CONF-2021-038)

- Maximum likelihood fit on m_{jj}

$$\mu_{EW} = 0.95^{+0.14}_{-0.13}$$

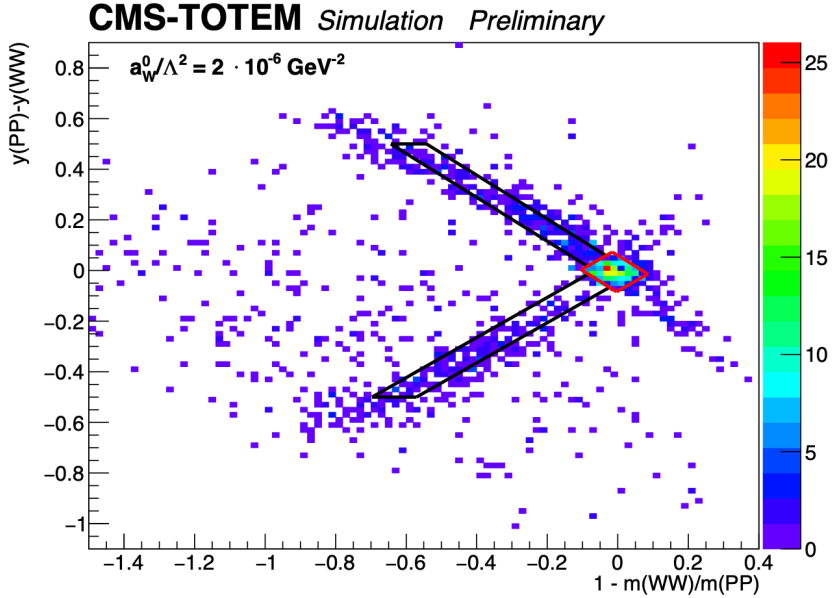
$$\sigma_{EW} = 4.49 \pm 0.40\ (stat) \pm 0.42\ (syst) fb$$

$$\sigma_{EW+QCD} = 20.6 \pm 0.6^{+1.2}_{-1.0} (syst) fb$$



VBS: $\gamma\gamma \rightarrow VV$

Search for exclusive $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production in final states with jets and forward protons (CMS-PAS-SMP-21-014)

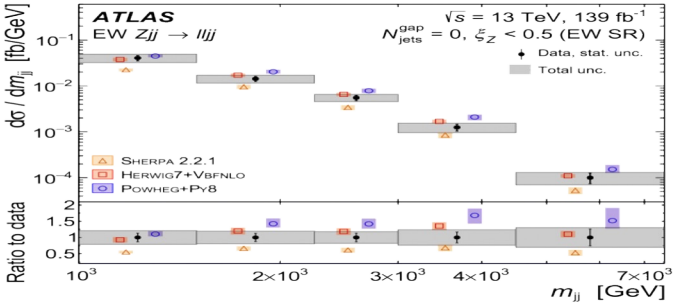


VBF Z production

Differential cross-section measurements for the electroweak production of dijets in association with a *Z* boson in proton–proton collisions at ATLAS (*Eur. Phys. J. C* **81,** 163 (2021))

$$\sigma_{EWK}^{meas} = 37.4 \pm 3.5(stat) \pm 5.5(syst) fb$$

- Comparison of the differential cross section between state-of-the-art theoretical predictions from:
  - Powheg+Pythia8
  - **Herwig7+Vbfnlo**
  - Sherpa



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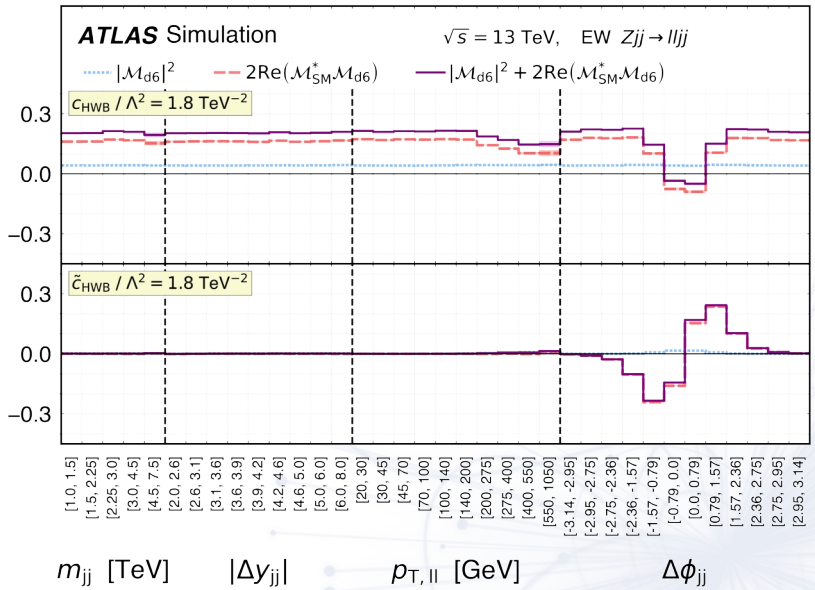
Differential cross-section measurements for the electroweak production of dijets in association with a Z boson in proton–proton collisions at ATLAS (*Eur. Phys. J. C* **81**, 163 (2021))

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2Re(\mathcal{M}^*_{SM}\mathcal{M}_{d6}) + |\mathcal{M}_{d6}|^2$$

- Interference and interference + pure dim6 terms considered
- 4 SMEFT dim-6 operators considered:
  $\mathcal{O}_W, \widetilde{\mathcal{O}}_W, \mathcal{O}_{HWB}, \widetilde{\mathcal{O}}_{HWB}$
- Differential cross section → limits extraction



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Differential cross-section measurements for the electroweak production of dijets in association with a Z boson in proton–proton collisions at ATLAS (*Eur. Phys. J. C* **81**, 163 (2021))

Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}]		p-value (SM)
		Expected	Observed	
c_W/Λ^2	No	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	Yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	No	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	Yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	No	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	Yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	No	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	Yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

VBS: invisible + γ final state

Observation of electroweak production of two jets in association with an isolated photon and missing transverse momentum, and search for a Higgs boson decaying into invisible particles at 13 TeV with the ATLAS detector (Eur. Phys. J. C 82 (2022) 105)

Variable	SR	$W^{\gamma}_{\mu\nu}$ CR	$W^{\gamma}_{e\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	Fake-e CR	Low-$E_{\text{T}}^{\text{miss}}$ VR
$p_{\text{T}}(j_1)$ [GeV]	> 60					
$p_{\text{T}}(j_2)$ [GeV]	> 50					
$p_{\text{T}}(j_{>2})$ [GeV]	> 25					
N_{jet}	2,3					
$N_{b\text{-jet}}$	< 2					
$\lvert\Delta\eta_{\text{jj}}\rvert$	> 3.0					
$\eta(j_1) \times \eta(j_2)$	< 0					
C_3	< 0.7					
$\Delta\phi(j_i, \vec{E}_{\text{T}}^{\text{miss,lep-rm}})$	> 1.0					
N_γ	1					
$\Delta\phi_{\text{jj}}$	< 2.5 [2.0]					
$\Delta\phi(\gamma, \vec{E}_{\text{T}}^{\text{miss,lep-rm}})$	> 1.8 [–]					
$p_{\text{T}}(\gamma)$ [GeV]	$> 15, < 110$ [$> 15, < \max(110, 0.733 \times m_{\text{T}})$]					
m_{jj} [TeV]	> 0.25					0.25–1.0
$E_{\text{T}}^{\text{jets,no-jvt}}$ [GeV]	> 130					> 100
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 150	–	> 80	> 150	< 80	110–150
$E_{\text{T}}^{\text{miss,lep-rm}}$ [GeV]	–	> 150	> 150	–	> 150	110–150
C_γ	> 0.4	> 0.4	> 0.4	< 0.4	> 0.4	> 0.4
N_ℓ	0	1 μ	1 e	0	1 e	0
$p_{\text{T}}(\ell)$ [GeV]	–	> 30	> 30	–	> 30	–

C3 equivalent centrality for 3rd jet