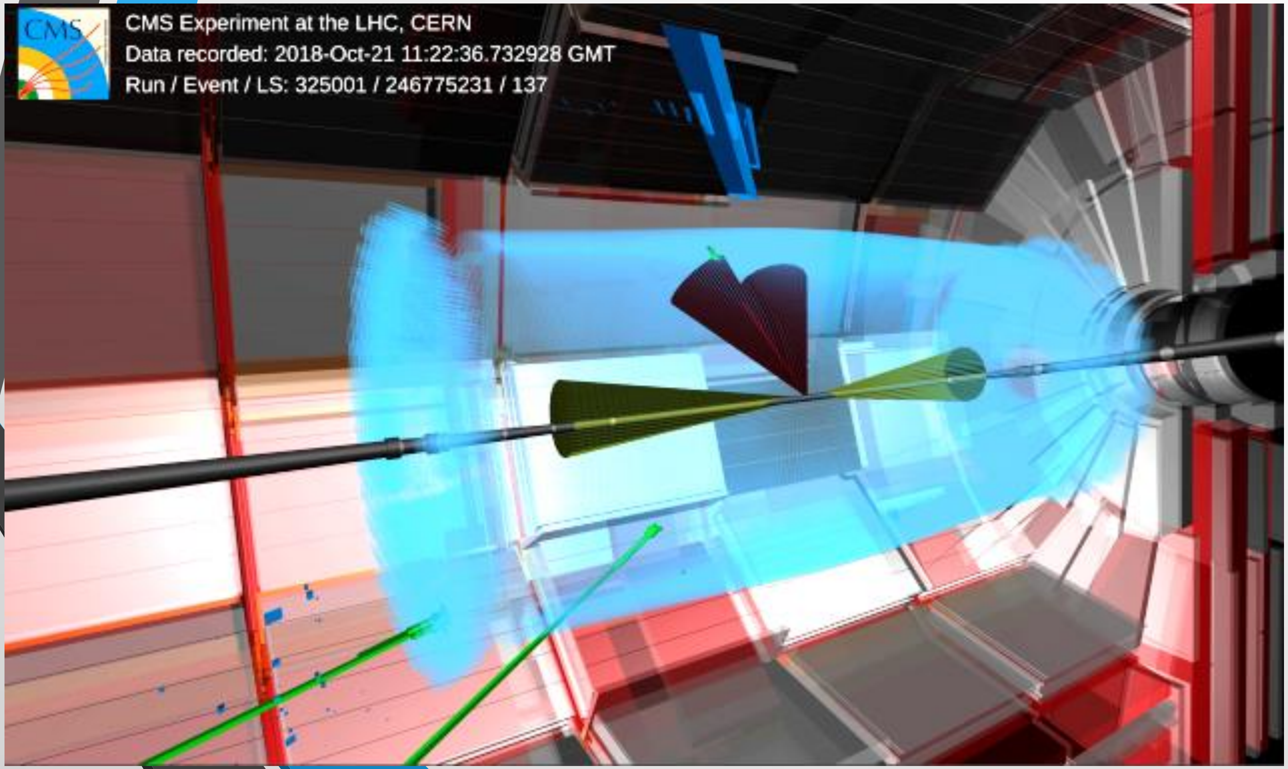
EFT interpretation in multiboson production: experimental overview



June 10, 2024

Roberto Covarelli – Università and INFN Torino (Italy)

EFT in multibosons COMETA workshop, Padova

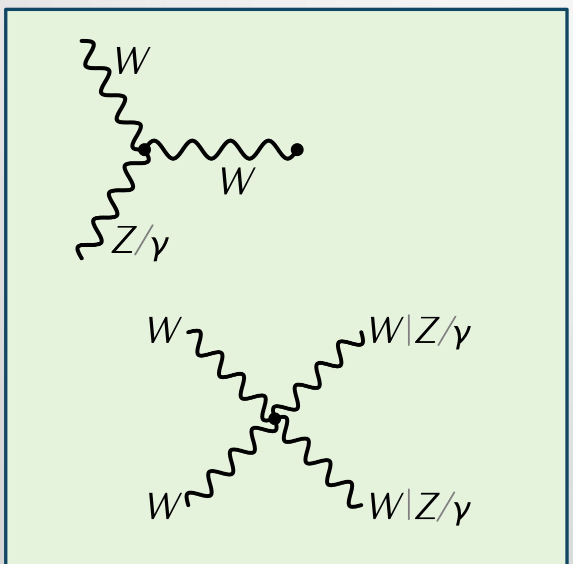
Experimental signatures

1. Only gauge

1A. Dibosons

1B. Vector-boson scattering

1c. ~~Tribosons~~ (Cristiano's talk)

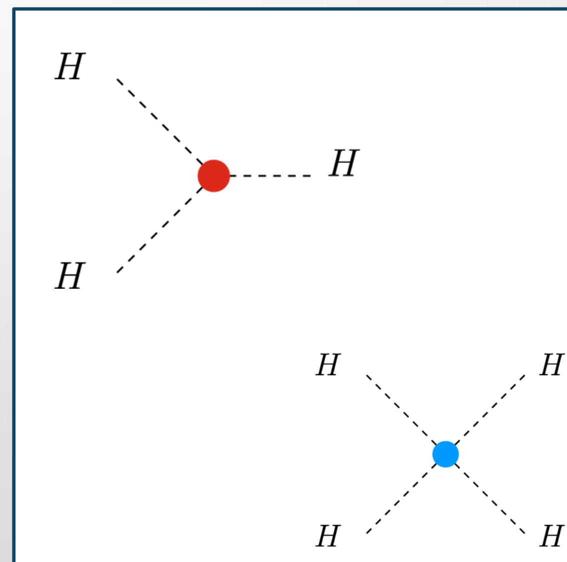


2. Also Higgs

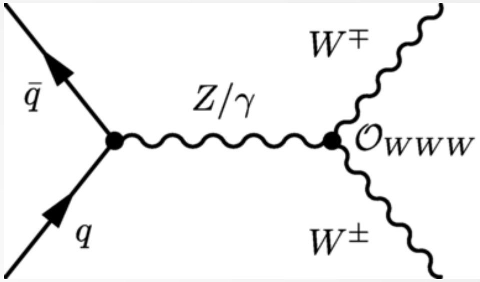
2A. gg ⟶ HH production

2B. Vector-boson fusion HH

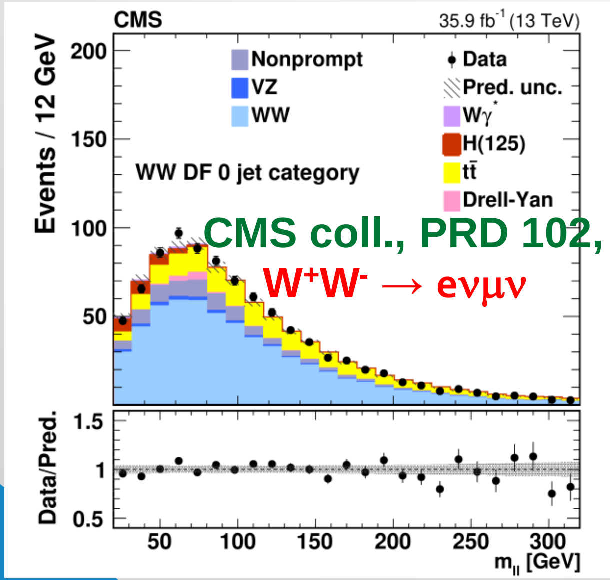
2c. VHH (and HHH?)



Inclusive dibosons

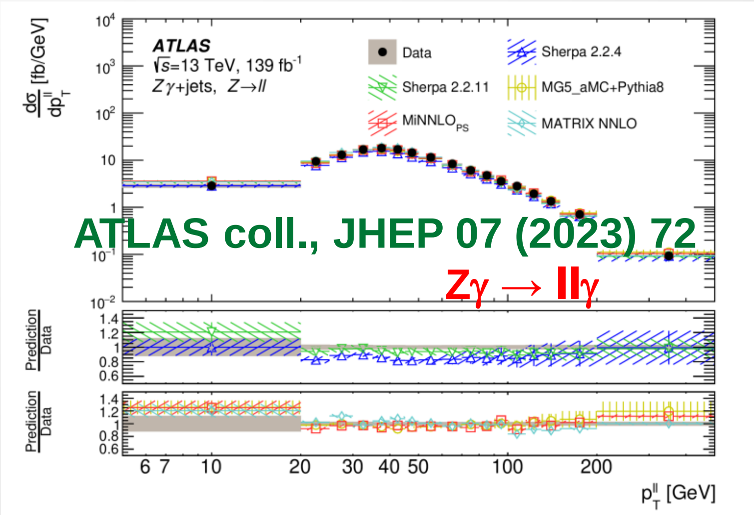


- Golden probe of SMEFT effects in triple gauge couplings at the LHC
  - Fairly large cross-sections (~ pb)
  - Relatively simple signal triggering/selection **in leptonic final states**
    - γ : stringent identification/isolation criteria against jets rich in π^0
    - $W \to l\nu$: lepton + $p_{T,miss}$, main background from $t\bar{t}$ events
    - $Z \to ll$: two leptons with $m_{ll} = m_Z$, very clean signature
- Differential cross-sections available for most channels
  - They require simulation-based unfolding
  - Accurate tests of high-order QCD tools



CMS coll., PRD 102, 092001

$W^+W^- \to e\nu\mu\nu$

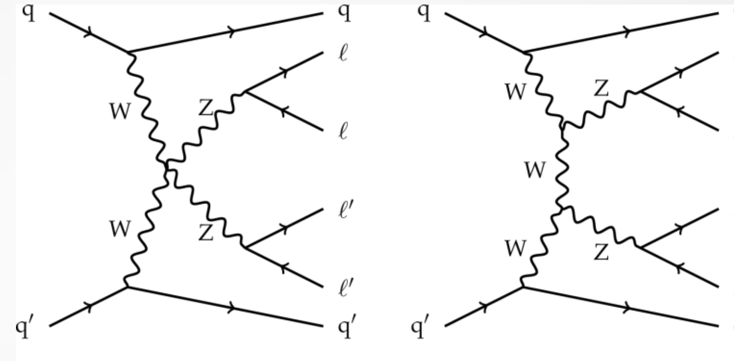


ATLAS coll., JHEP 07 (2023) 72

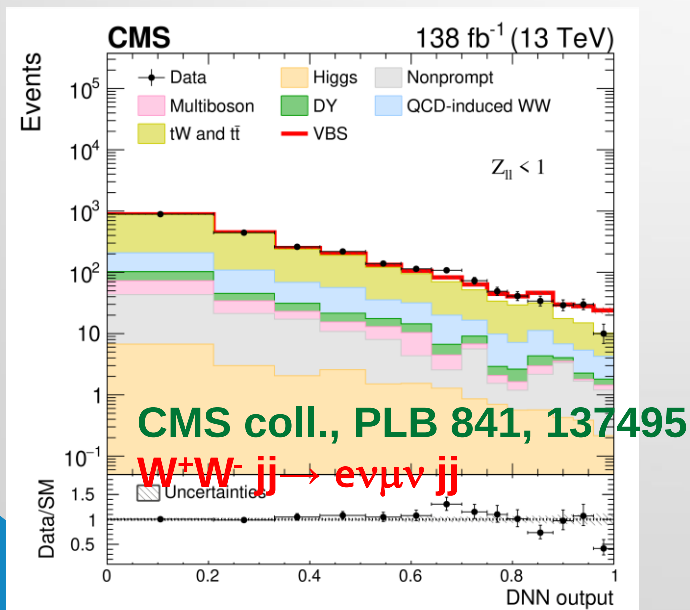
$Z\gamma \to ll\gamma$

Vector boson scattering (VBS)

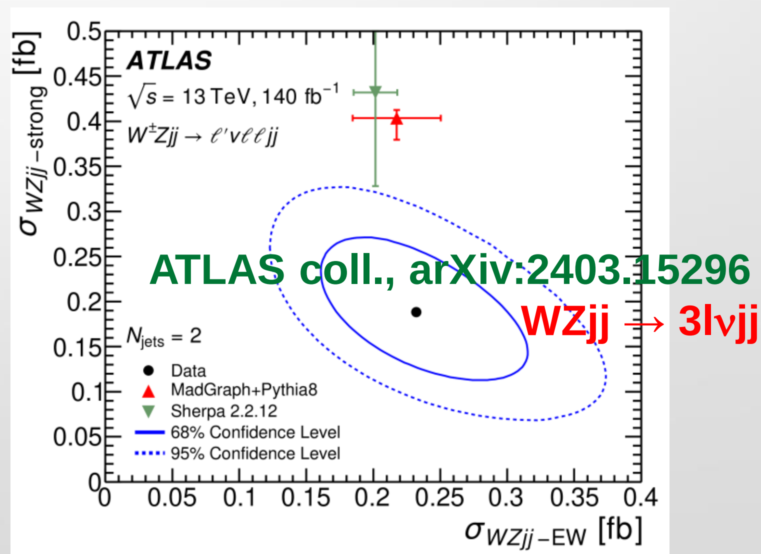
- With the exception of $W^{\pm}W^{\pm}jj$ mode, experimentally challenging
  - Very small cross-sections (~ fb)
  - Background from strong diboson production in association with 2 → large and not very well described by MC



- Selection based on machine-learning techniques (e.g. DNNs)

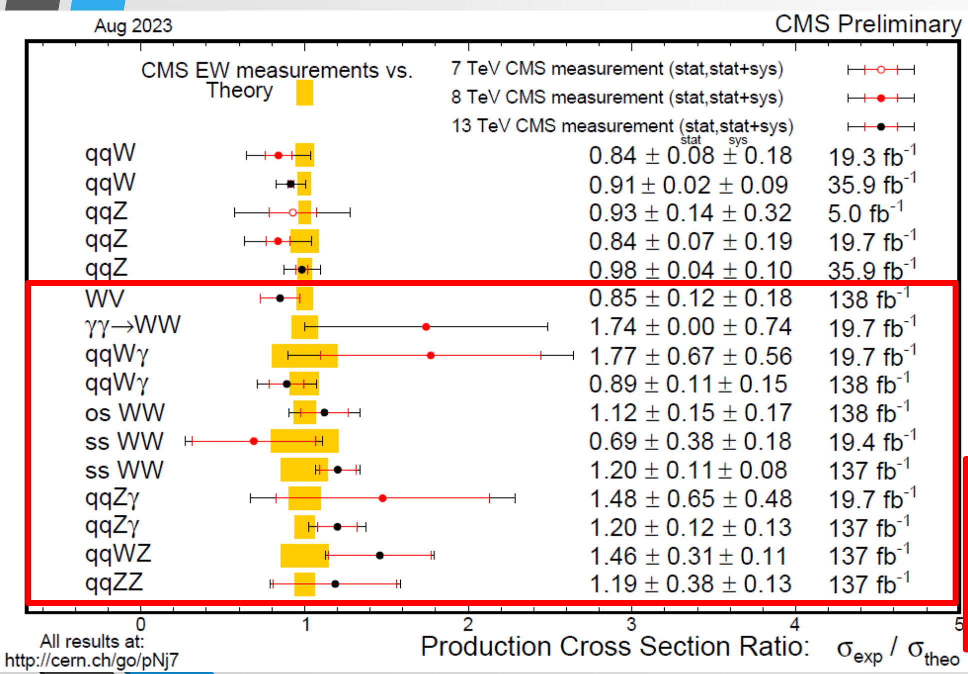


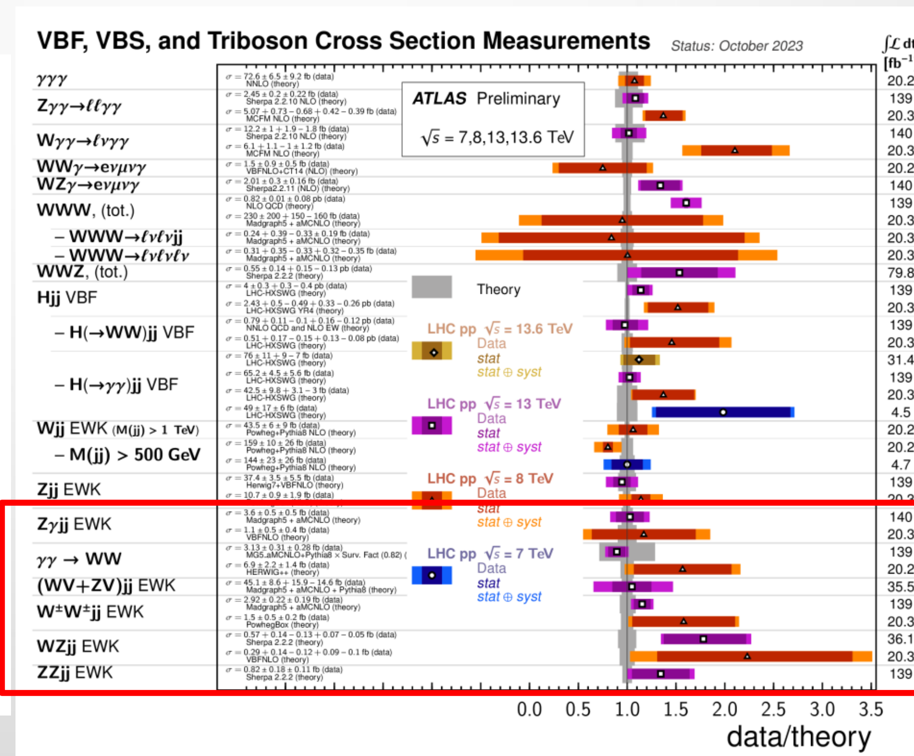
- Control regions left free in the fits to cure theory mismodeling



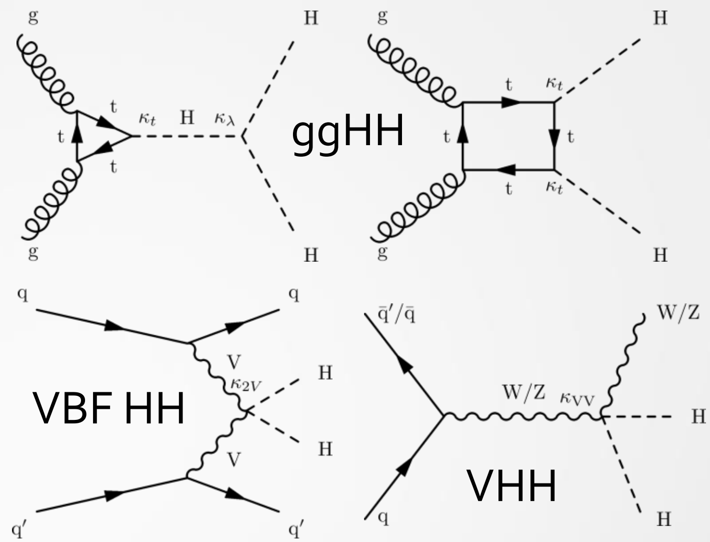
Vector boson scattering (VBS)

- Basically all final states observed (or at the edge of 5σ observation) using LHC Run2 data ← **major achievement** of 13 TeV runs
  - Clear trend to be «on the high side» of the SM appears to be cured since strong production is also fit from data





HH production



ggHH: experimentally need to combine many final states

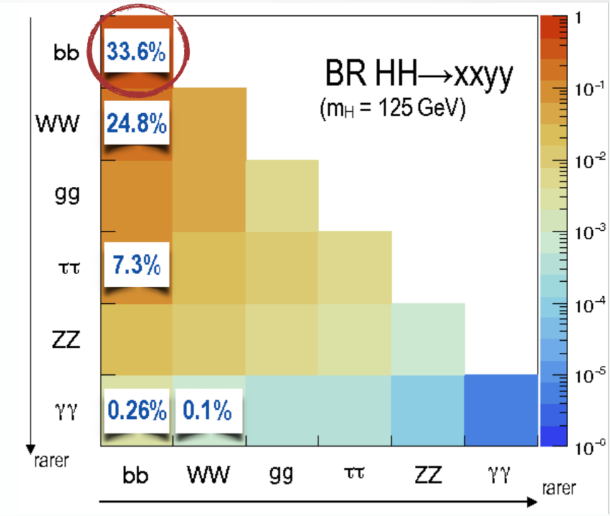
- «Higgs hunter's rule»: larger BRs correspond to lower purity and viceversa

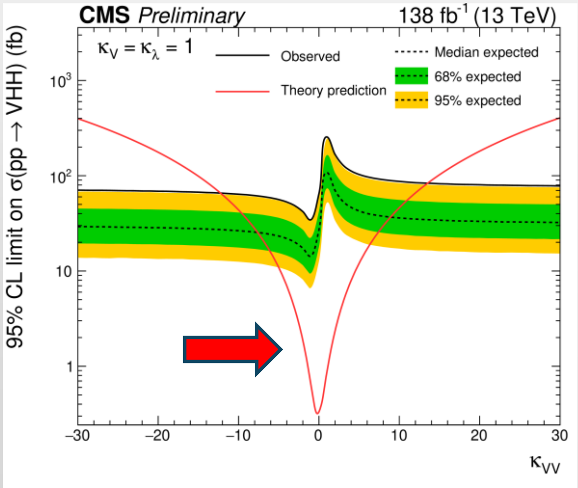
VBF HH and VHH: experimental observation hard even for HL-LHC

- basically only bb final states matter

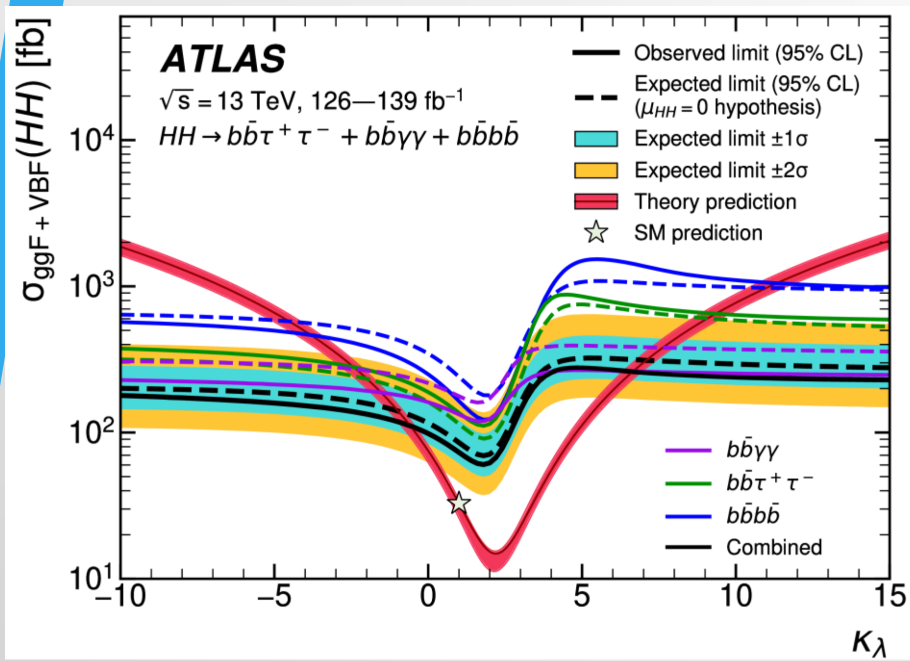
However, SM rates coming from extremely fine-tuned cancellations

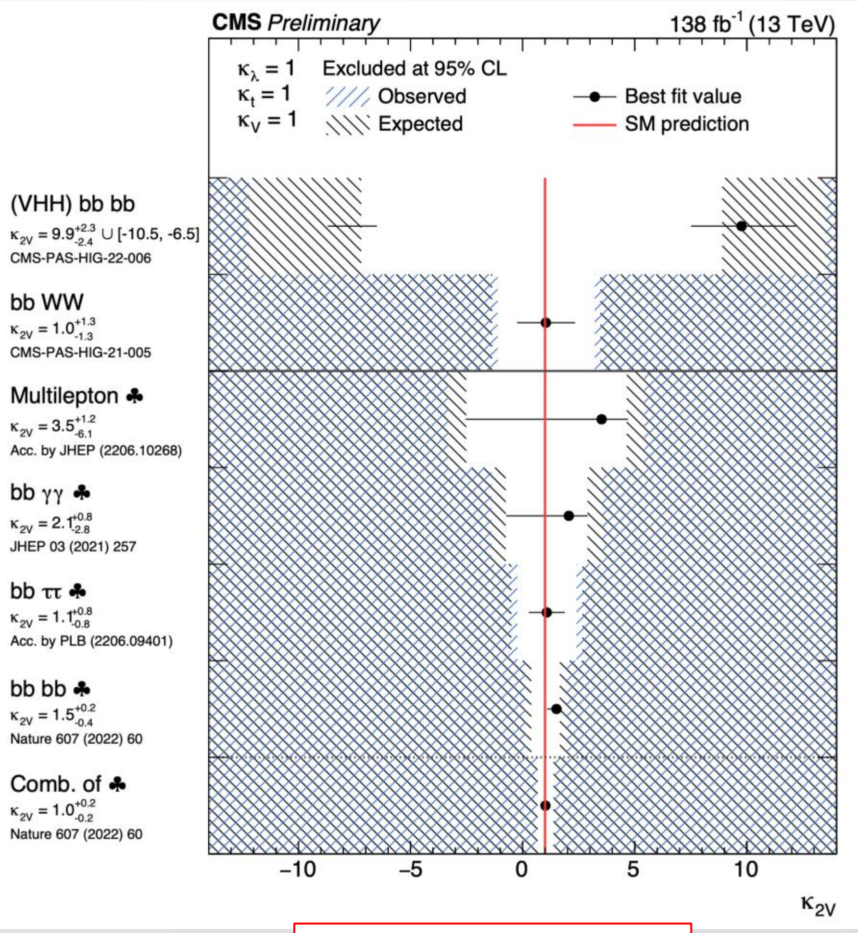
- Even a small modification of VVHH coupling leads to huge changes in σ





SM modifier limit summary





@ 95% CL
$-0.4 < \kappa_\lambda < 6.6$

κ_{2V} = 0 excluded

EFT experimental constraints

- **Standard Model Effective Field Theory (SMEFT):**

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\, O_i^{(6)} + \frac{1}{\Lambda^4}\sum_i c_i^{(8)}\, O_i^{(8)} + \dots$$

- Why experimentally appealing?
    - Model-independent
    - A variety of measurements can be combined leading to a more stringent / precise result
- Which main issues in publishing experimental results?
    - Invalid at energies too close to Λ or above (unitarity violation)
    - Lot of freedom to choose O's: power of the data is diluted
    - Not clear how to estimate uncertainties from missing higher orders (e.g. keep or discard Λ^{-4} terms from squared dim-6 amplitudes)

Dim-6 constraints in dibosons

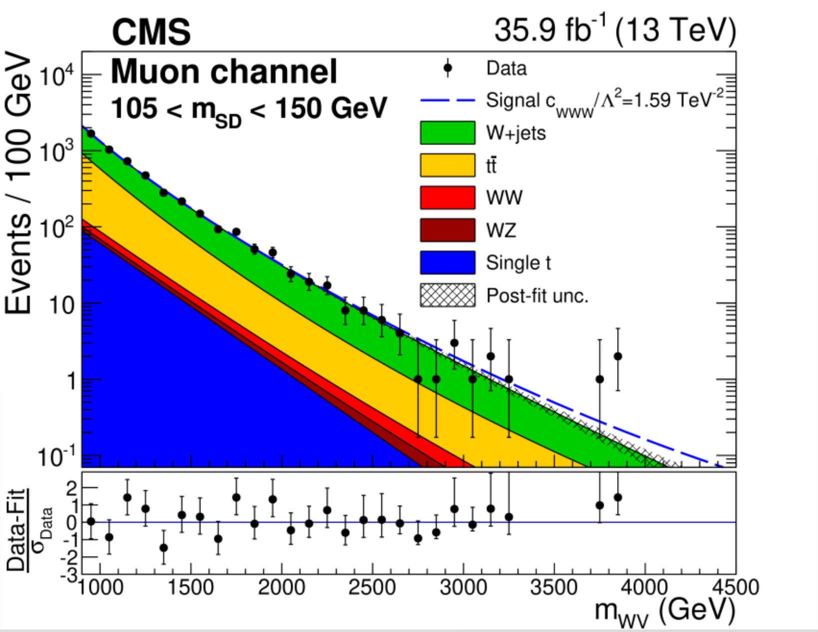
- How to look for SMEFT effects?
  - The simplest way is to search for event excesses at large scattering $\sqrt{\hat{s}}$ (or proxies thereof if this quantity is not an observable)
- **MC tools**: MadGraph5 + EWDim6 / SMEFTSim UFOs
- **Final states:** in spite of huge V+jets/$t\bar{t}$ backgrounds, semileptonic final states slightly better than fully leptonic

CMS coll., PRD 102, 092001
Run2-2016 $W^+W^- \rightarrow e\nu\mu\nu$

$|c_{WWW}|/\Lambda^2 < 1.8\ \mathrm{TeV}^{-2}$ @95% CL

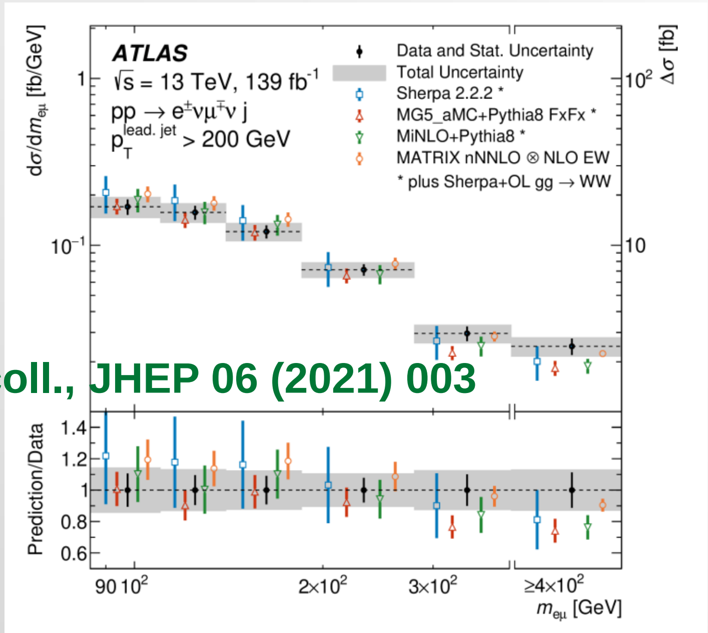
CMS coll., JHEP 12 (2019) 062
Run2-2016 $WV \rightarrow l\nu J$

$|c_{WWW}|/\Lambda^2 < 1.6\ \mathrm{TeV}^{-2}$ @95% CL



Improving on dibosons dim-6

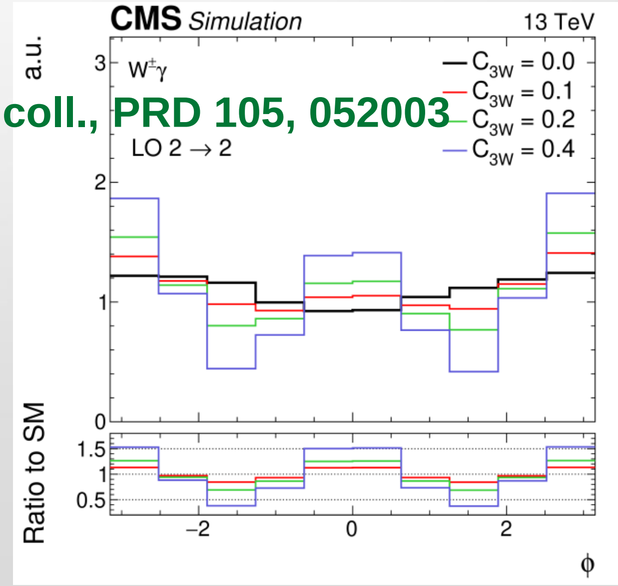
- Use dedicated regions of phase space and/or observables that enhance SM+EFT interference (or cancel destructive effects)



ATLAS coll., JHEP 06 (2021) 003

- ATLAS: WW → eμ +high-p_T jet: selection of highly-boosted WW pairs changes helicity composition (more sensitive to EFT)
  - $-0.60 < c_{WWW}/\Lambda^2 < 0.58$ TeV^{-2}

- CMS: Wγ. Choose specific frame to compute Δϕ between γ and lepton → enhances SM+EFT interference
  - $-0.062 < c_{WWW}/\Lambda^2 < 0.052$ TeV^{-2}



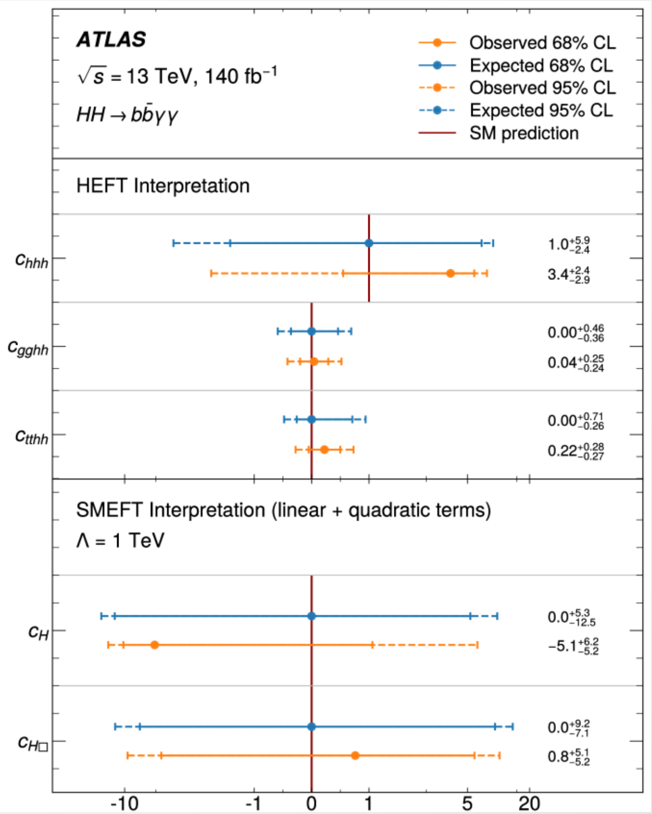
CMS coll., PRD 105, 052003

Dim-6 in multi-Higgs

- Rather simple formalism for ggHH
- Wilson coefficients and coupling modifiers linked by linear relationships:

LHCHSWG-2022-004

HEFT	SILH	Warsaw
c_{hhh}	$1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H + 3\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_t	$1 - \frac{\bar{c}_H}{2} - \bar{c}_u$	$1 + \frac{v^2}{\Lambda^2}C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}C_{uH}$
c_{tt}	$-\frac{\bar{c}_H + 3\bar{c}_u}{4}$	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}C_{uH} + \frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_{ggh}	$128\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}C_{HG}$
c_{gghh}	$64\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}C_{HG}$



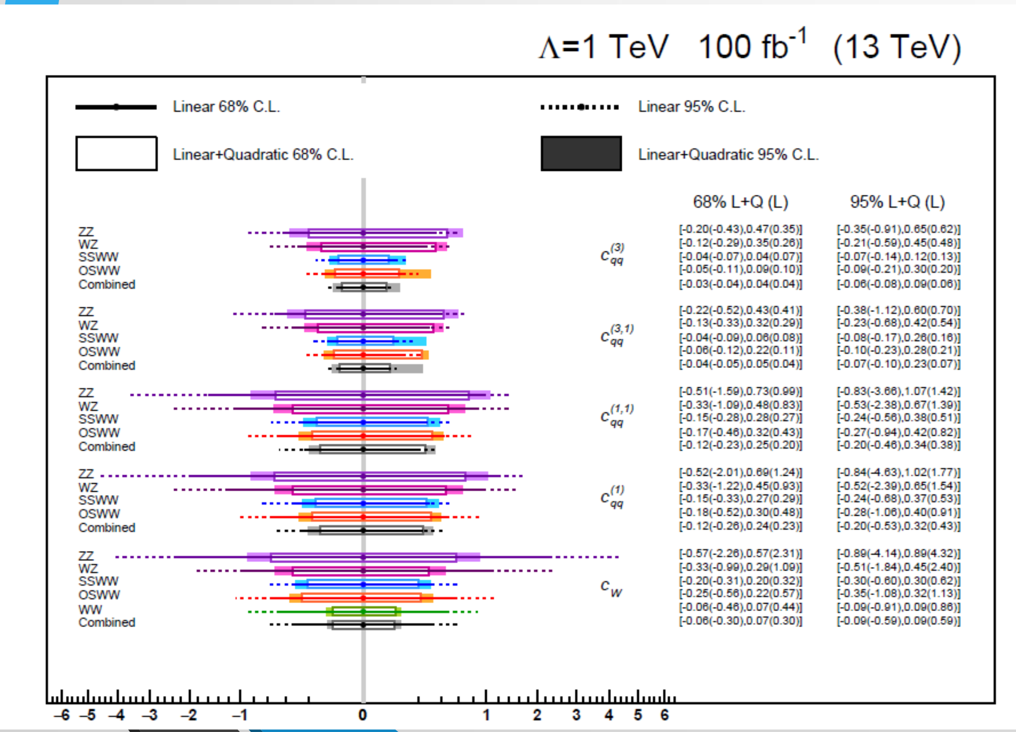
ATLAS coll., JHEP 01 (2024) 066

HH → bbγγ

- **MC tools**: MadGraph5 LO + dedicated UFO models → → → POWHEG ggHH_SMEFT (NLO)
- Compatibility with benchmark scenarios → → → actual EFT scans

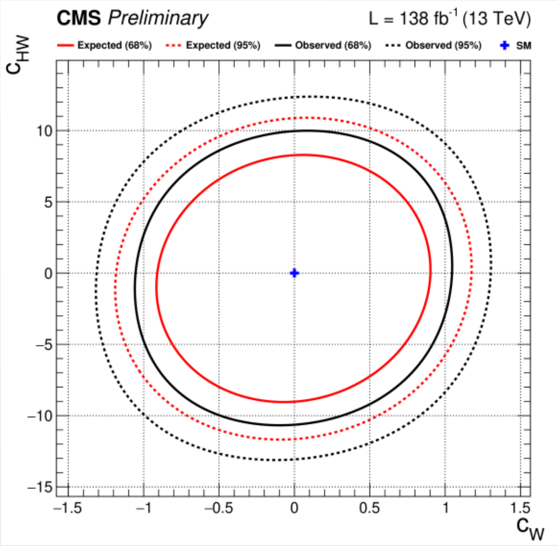
Dim-6 in VBS

- **VBS:** sensitive to HVV, triple and quartic gauge coupling anomalies simultaneously
- Important question: dim-6 constraints competitive with inclusive dibosons and Higgs production/decay? Few results from CMS/ATLAS
  - Additional operators can be constrained to which dibosons/HVV are not sensitive
  - Studies limited to leptonic final states, what about semileptonic? (both CMS and ATLAS have SM evidence!!!)

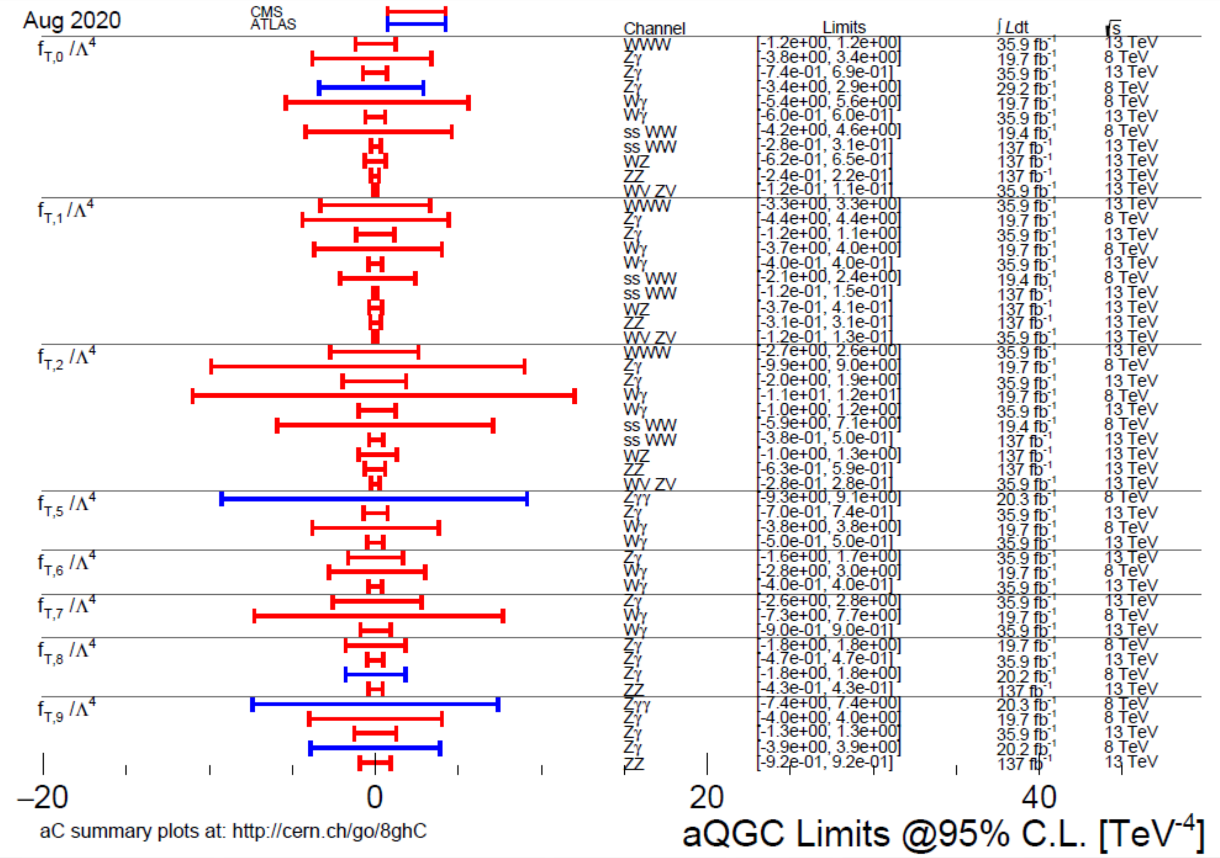


Bellan, Boldrini et al.
JHEP 05 (2022) 039

CMS coll.
CMS-PAS-SMP-22-008



Dim-8 in VBS

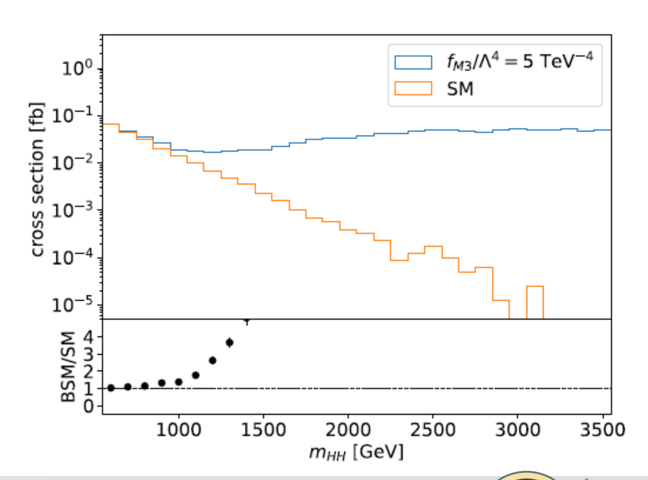


- VBS: Tree-level contribution of quartic gauge couplings → constraints on specific dim-8 SMEFT operators which only modify those
- **MC TOOLS:** MadGraph5 LO + «Eboli» model (revised a few times)
- Here showing «transverse» operators (containing 4 gauge field tensors)
  - Semileptonic final states dominating SMEFT dim-8 sensitivity (larger cross-sections and relatively clean signals at high invariant masses) → still no full-Run2 updates!

Other dim-8 probes?

1. Triple gauge bosons → see dedicated talk by Cristiano
2. VBF HH and VHH: only effective VVHH coupling modifiers studied by ATLAS and CMS, no EFT interpretation
   - Phenomenological studies show that VBF HH has in fact similar sensitivities (i.e. world-leading) as semileptonic VBS

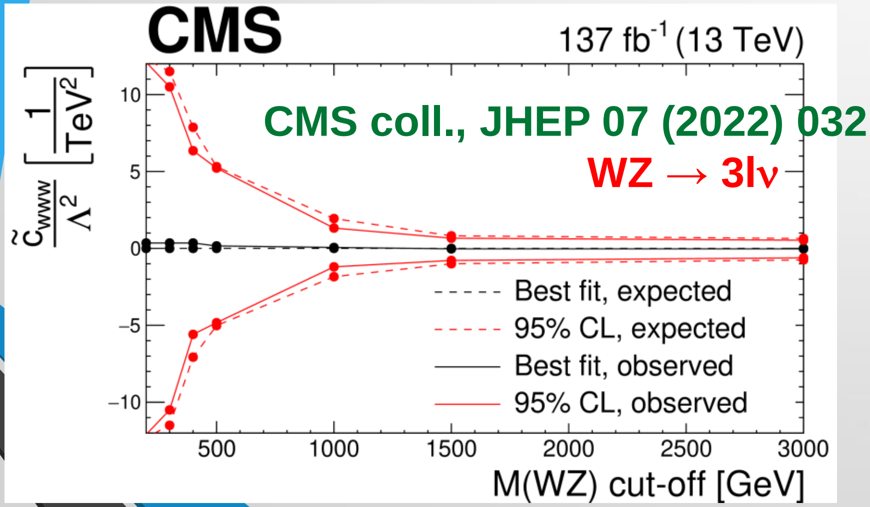
	VBS $W^{\pm}V$ semileptonic		VBF HH→ $b\bar{b}b\bar{b}$	
Coeff.	no unitarity	w/ unitarity	no unitarity	w/ unitarity
f_{M0}/Λ^4	[-1.0,1.0]	[-3.3,3.5]	[-0.95,0.95]	[-3.3,3.3]
f_{M1}/Λ^4	[-3.1,3.1]	[-7.4,7.6]	[-3.8,3.8]	[-13,14]
f_{M2}/Λ^4	[-1.5,1.5]	[-9.1,9.0]	[-1.3,1.3]	[-7.6,7.3]
f_{M3}/Λ^4	[-5.5,5.5]	[-32,30]	[-5.2,5.3]	[-29,30]
f_{M4}/Λ^4	[-3.1,3.1]	[-8.6,8.7]	[-4.0,4.0]	[-14,14]
f_{M5}/Λ^4	[-4.5,4.5]	[-10,10]	[-7.1,7.1]	[-26,26]
f_{M7}/Λ^4	[-5.1,5.1]	[-11,11]	[-7.6,7.6]	[-27,27]
f_{S0}/Λ^4	[-4.2,4.2]	[-8.5,9.5]	[-30,29]	/
f_{S1}/Λ^4	[-5.2,5.2]	/	[-11,10]	/
f_{S2}/Λ^4	-	[-21,25]	[-17,16]	/

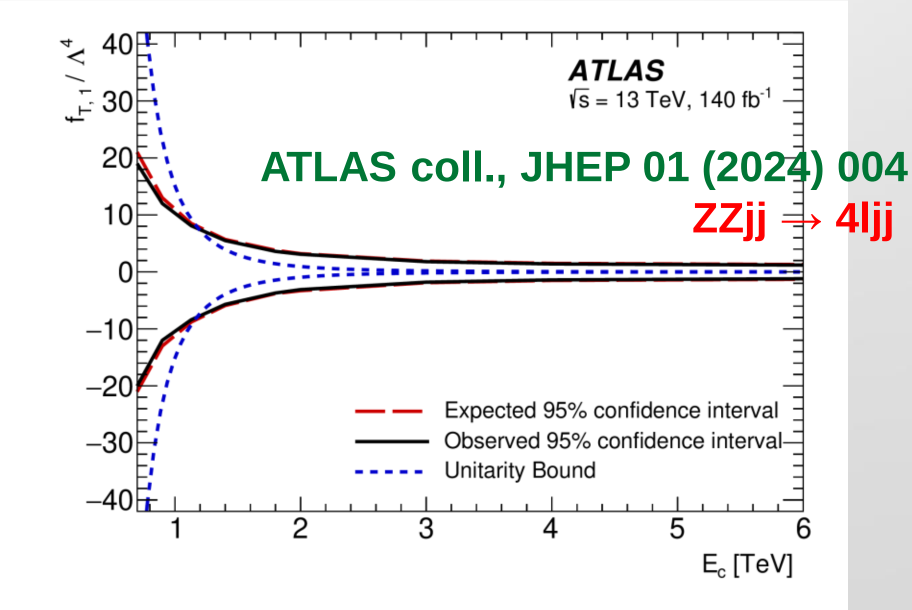


A. Cappati et al., JHEP 09 (2022) 038

Unitarity preservation

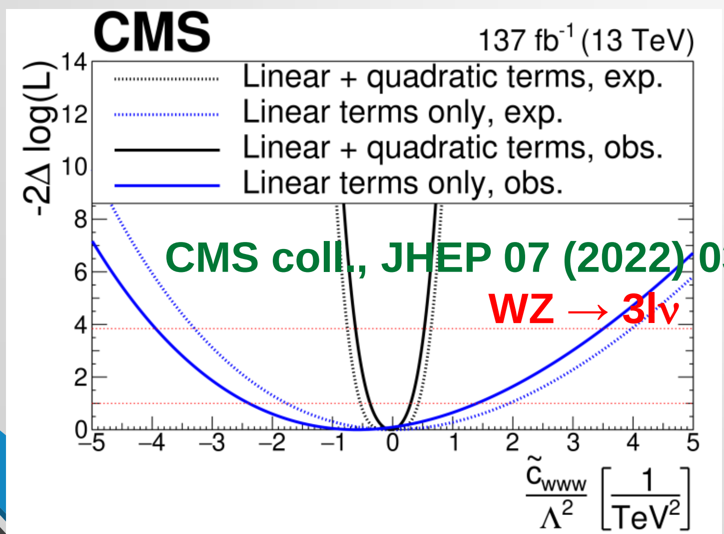
- Several methods adopted throughout Run2, not all of them really satisfactory
- Common in recent papers: **clipping method with variable cutoff**
  - Always consider all data
  - Fit model is SM+EFT below $E_{cut\text{-}off}$, just SM above $E_{cut\text{-}off}$
  - Constraints on c_x derived as a function of $E_{cut\text{-}off}$
  - If estimate of the unitarity bound exists, only consider experimental limits not superseded by it

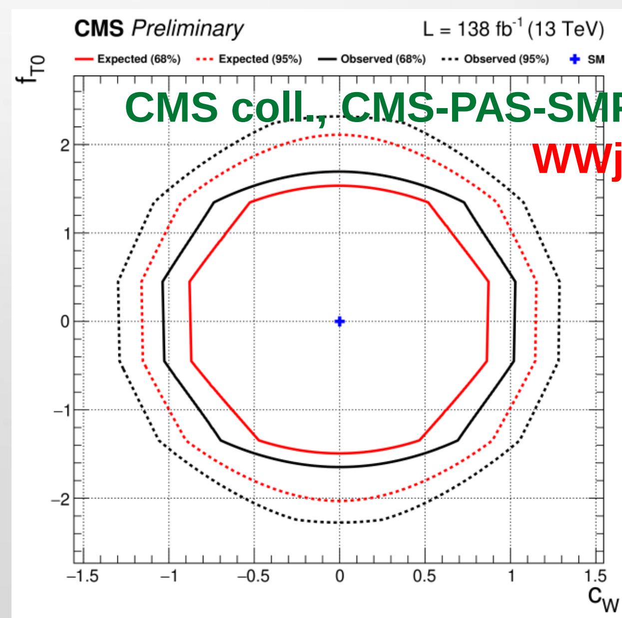




Linear vs. linear+quadratic

- Full dim-6 EFT (including quadratic terms) not completely general without assumptions on dim-8 terms → truncation at Λ^{-2} terms?
- Common experimental approach is to derive constraints in both scenarios (linear only and linear+quadratic)
    - With current precisions on c_x, the difference between the two approaches is huge
- In few analyses, correlation between dim-6 quadratic terms and «genuine aQGC» dim-8 operators is tested





Folded vs. unfolded

- EFT-to-data fits can be performed on reconstruction-level or unfolded distributions
- While the two approaches appear similar, at very high-mass the unfolded approach is limited by the number of events in the last bin of the distribution (e.g. cannot be zero)
  - Brings to visible discrepancies in constraints in some cases
  - Mostly a statistical question, not EFT

CMS coll., PLB 812 (2020) 135992
full-Run2 ZZjj → 4ljj

Coupling	Exp. lower	Exp. upper
f_{T0}/Λ^4	−0.37	0.35
f_{T1}/Λ^4	−0.49	0.49
f_{T2}/Λ^4	−0.98	0.95
f_{T8}/Λ^4	−0.68	0.68
f_{T9}/Λ^4	−1.5	1.5

ATLAS coll., JHEP 01 (2024) 004
full-Run2 ZZjj → 4ljj

Wilson coefficient	$\lvert\mathcal{M}_{d8}\rvert^2$ Included	95% confidence Expected
$f_{T,0}/\Lambda^4$	yes	[-0.98, 0.93]
	no	[-23, 17]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]
	no	[-160, 120]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]
	no	[-74, 56]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]
	no	$[-4.6, 3.1]\times10^4$
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]
	no	$[-7.5, 5.5]\times10^4$

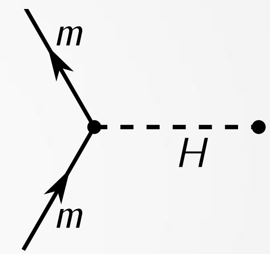
Conclusions

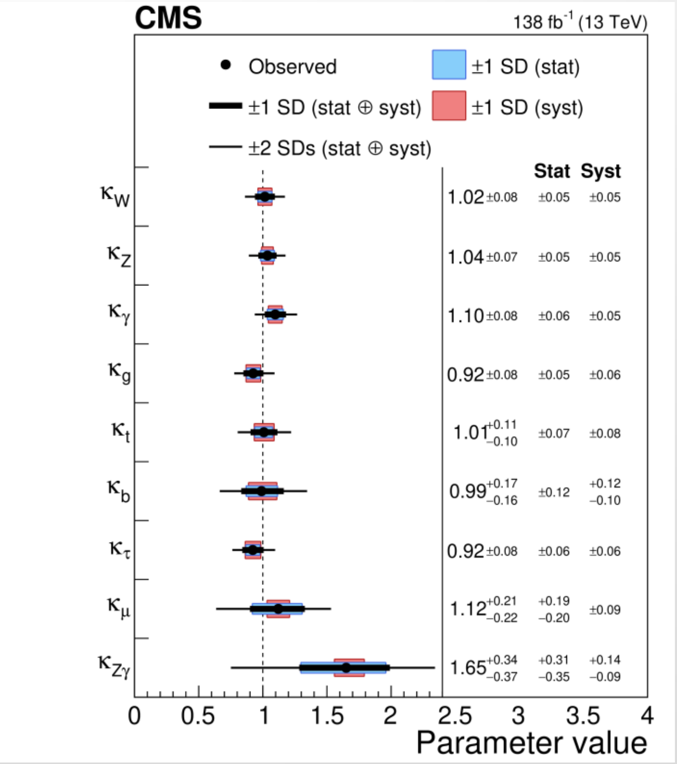
- Starting from Run2, LHC data dramatically changed our knowledge of multiboson final states
  - High-precision diboson cross-sections
  - Discovery of VBS in many channels
  - ggHH closing up on SM… etc.
- EFT «best practices» starting to be consolidated / uniform between LHC collaborations
  - Theory-experiment collaboration in various forms (LHC WGs, experiment EFT fora, COST actions…) need to be acknowledged for this
- Still work ahead towards a consensus for an EFT framework which is sufficiently general, while highlighting the constraining power of single analyses / observables

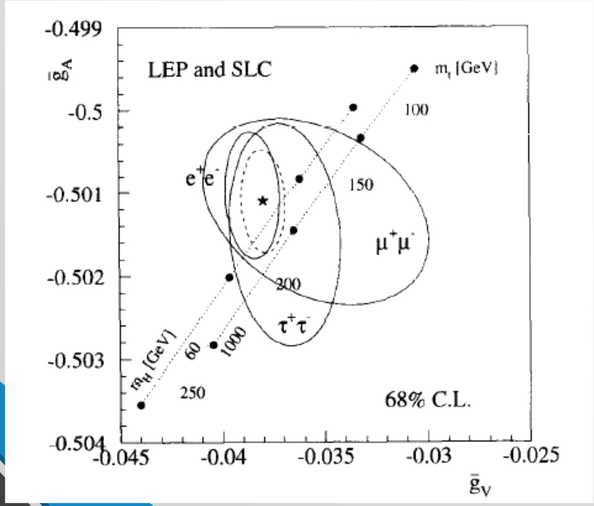
BACKUP

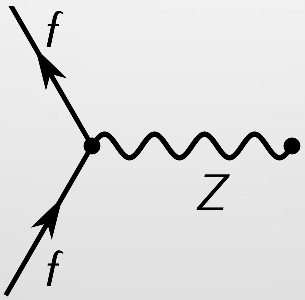
Electro-weak interactions

- The electro-weak sector of the Standard Model (SM): an extremely predictive and successful theory
  - Unified ($SU(2)_L \times U(1)_Y$ group)
  - Perturbative down to small energy scale
  - Only very few free parameters
- Tested to high precision by last and next-to-last generation of HEP experiments



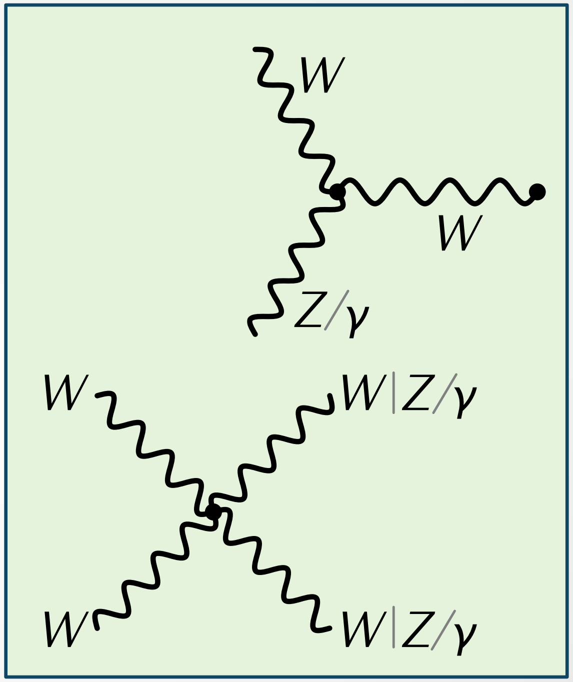


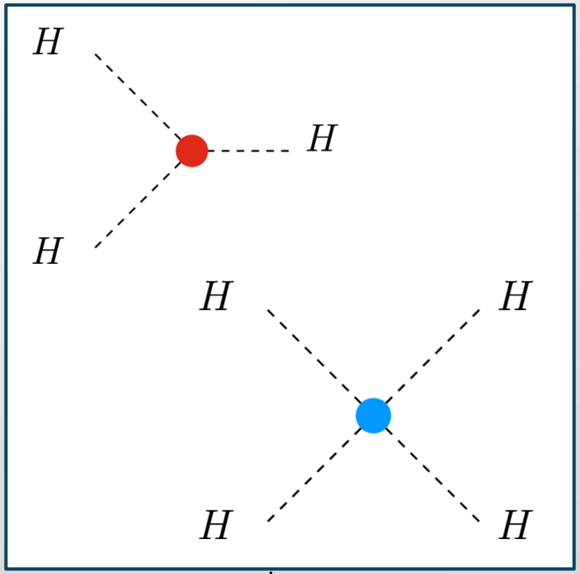




Multiboson couplings

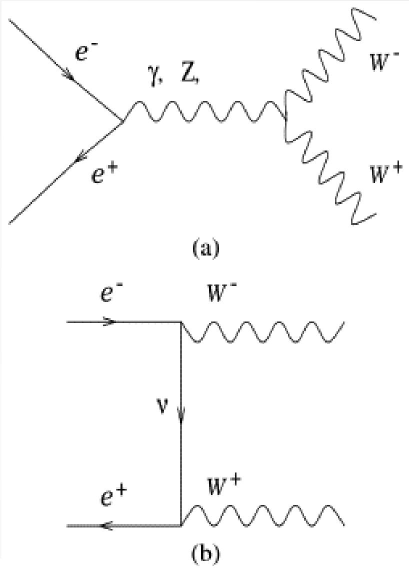
- For different reasons, the SM also predicts the existence of multi-boson couplings
- **Multi-gauge** from non-Abelian structure of SU(2)
  - Gauge invariance of vector-boson kinetic terms enforces triple and quartic vertices
  - No vertices with only Z/γ, since they both stem from the same field W_3 after GWS mixing
- **Multi-Higgs** from shape of Higgs potential (quartic) and field expansion around the VEV (triple), after symmetry breaking
- In common:
  - In EW theory, **all coupling strengths predicted exactly**
  - **Very hard** to measure experimentally, since relevant processes also occur through competing (dominant) diagrams

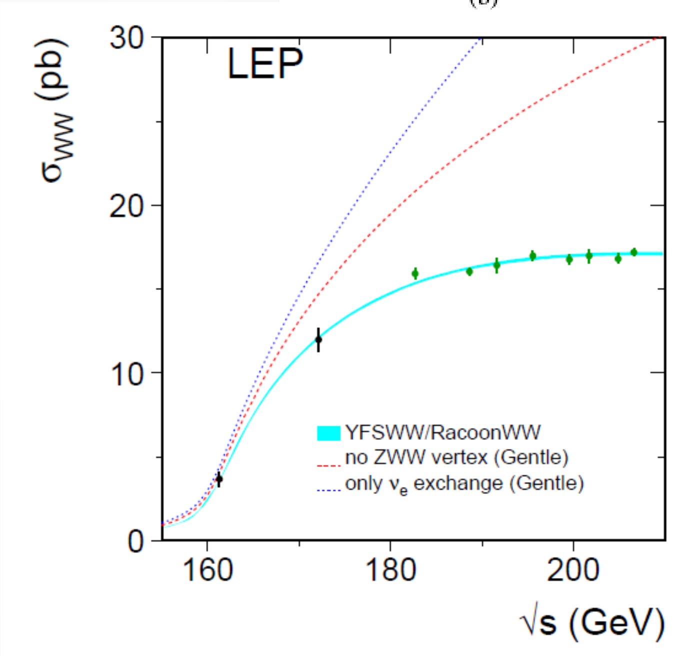




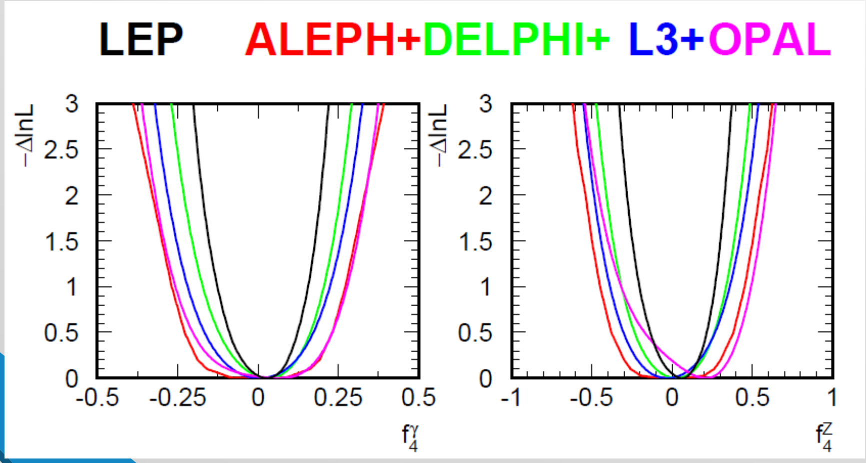
Before the LHC: LEP2

- Access only to WW and ZZ production
  - Already interesting constraints on triple-gauge couplings from observation of cancellations
  - Non-SM effects constrained using parameterization based on **effective vertices**



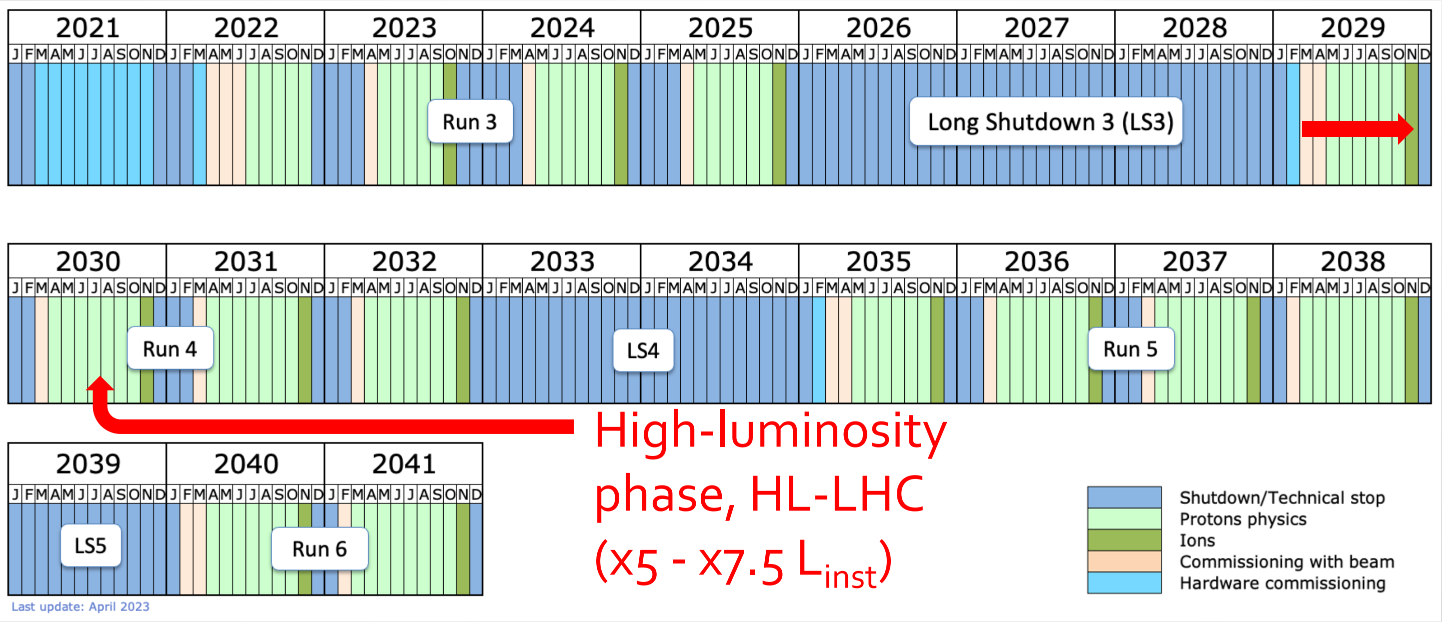


$$\mathcal{L}_{NP} = \frac{e}{m_Z^2}\Big[-[f_4^\gamma(\partial_\mu F^{\mu\beta}) + f_4^Z(\partial_\mu Z^{\mu\beta})]Z_\alpha(\partial^\alpha Z_\beta) +$$

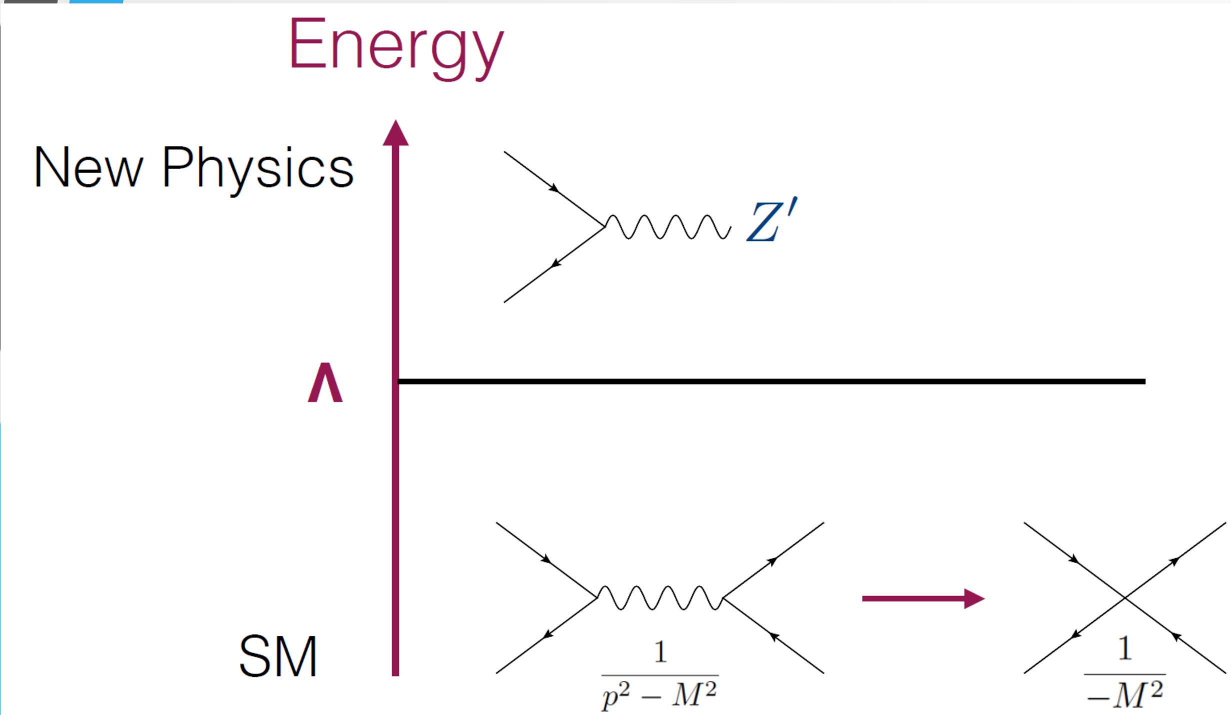


Now and future (experiment)

- No CM-energy increase expected in the next years (decades?)
  - Possibly no direct access to high-energy New Physics (NP) which could modify yet unexplored SM «corners»
- BUT LHC experiments have potential sensitivity to all processes involving multi-gauge and multi-Higgs mediated diagrams
  - **First need enough data…**



SMEFT in a nutshell



$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

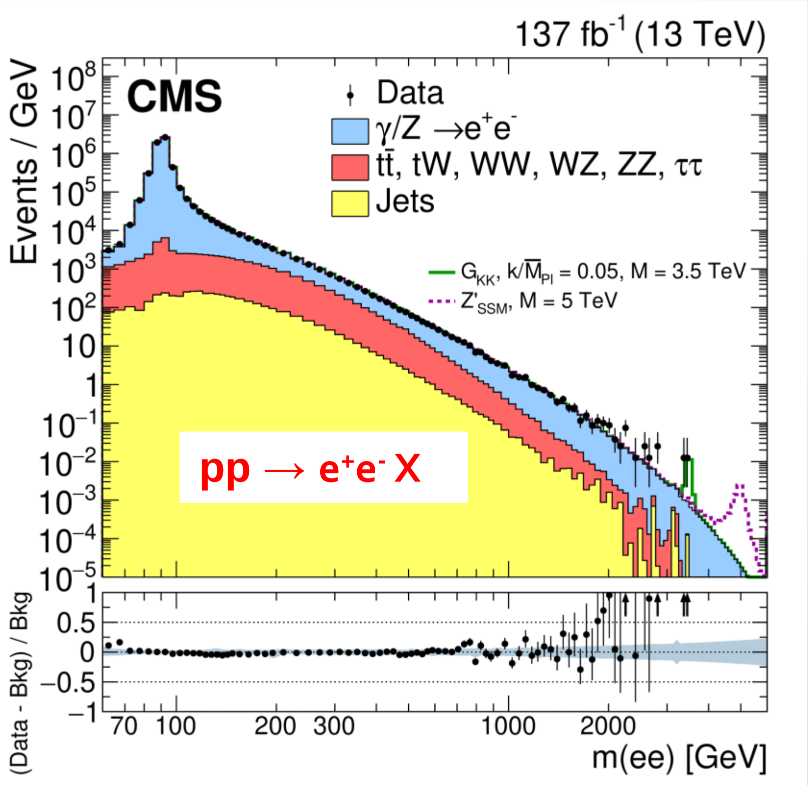
Wilson coefficient

$$\mathcal{L}_{SM}(\phi) + \mathcal{L}_{dim6}(\phi) + \ldots$$

$$\mathcal{L}_{dim6} = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

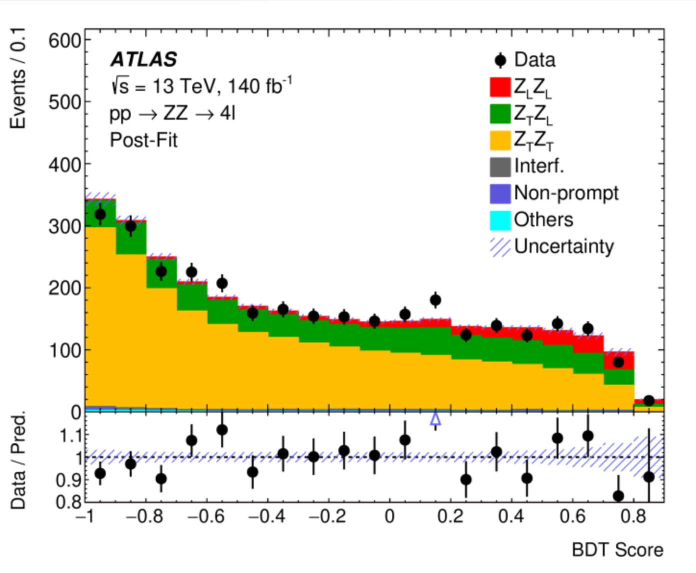
How is SMEFT challenging direct searches?

- Use best result on c_{WWW} from CMS Wγ
- In an illustrative way, assume that SMEFT becomes relevant when $c_{WWW} \sim g \sim 0.63$.
  - $c_{WWW}/\Lambda^2 < 0.052$ TeV^{-2} → **Λ > 3.5 TeV**
- **Competitive with direct Z′ searches**
- Key to best SMEFT limits: smart observables + larger statistics at high VV masses



Polarization (now and future)

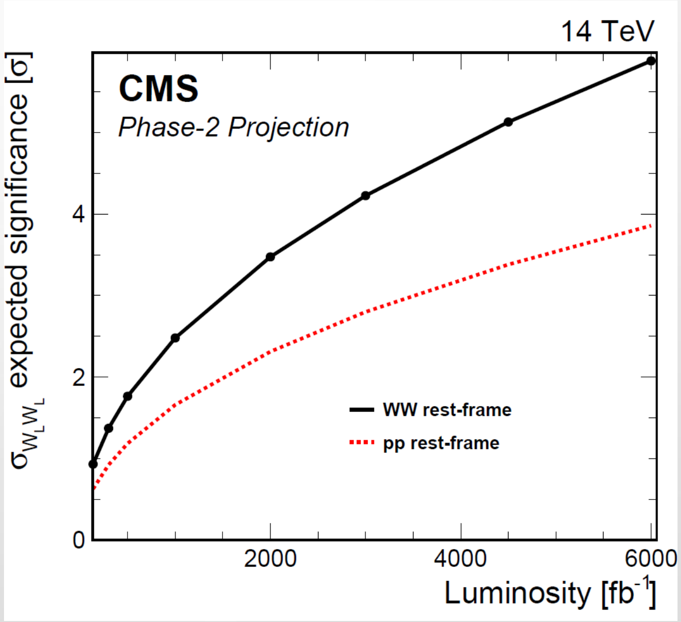
- Sensitivity to longitudinal polarization at the moment possible only on inclusive dibosons
  → Lay the ground for VBS measurements



ATLAS coll., PLB 843, 137895
ATLAS coll., arXiv:2310.04350

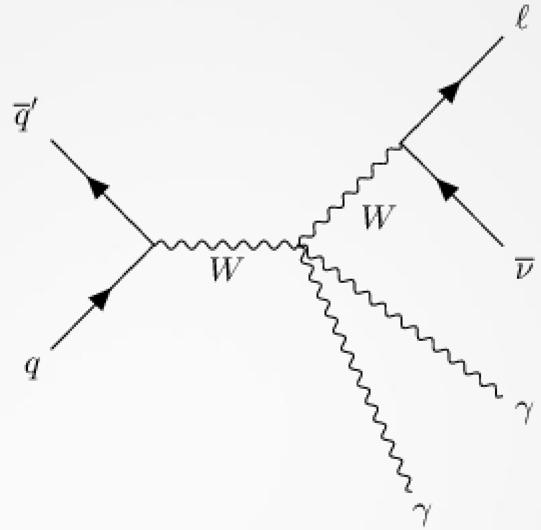
$W_L Z_L$ observed at 7σ,
Evidence for $Z_L Z_L$ at 4.3σ…

- **$W^{\pm}W^{\pm}jj$ VBS: perspectives at the HL-LHC**



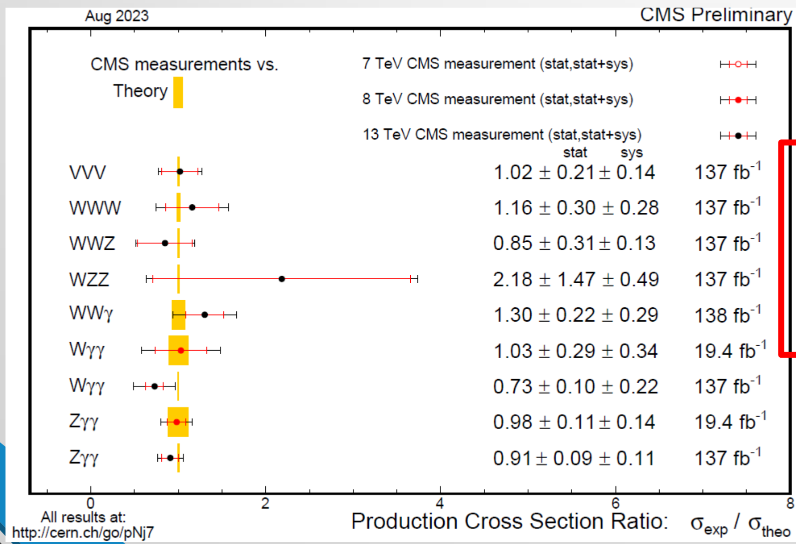
CMS coll., PAS-FTR-21-001

Tribosons

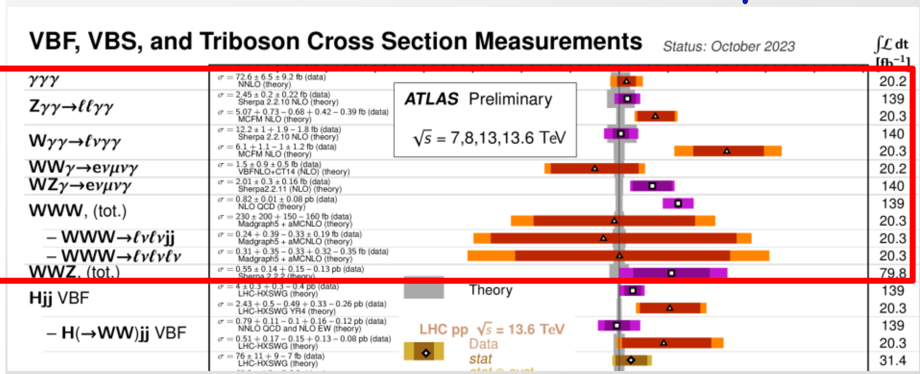


- The «natural» probe for anomalies in quartic gauge couplings

- Experimentally:
  - Clean final states → main backgrounds from non-prompt particles
  - 3γ or 2γ1V: generally well established, good agreement with SM
  - 2V1γ or 3V: tiny cross-sections, still mostly within LHC Run2 reach

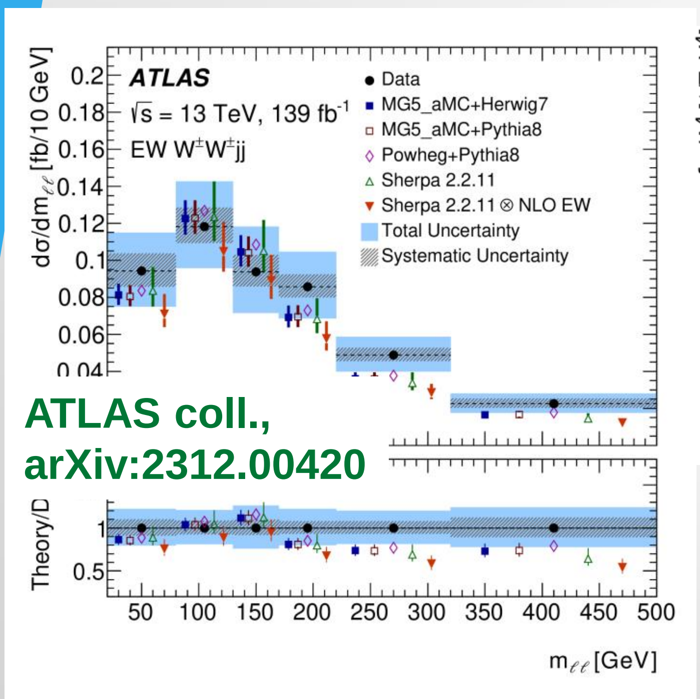


Recent 5σ observations: ATLAS: WZγ
CMS: WWγ

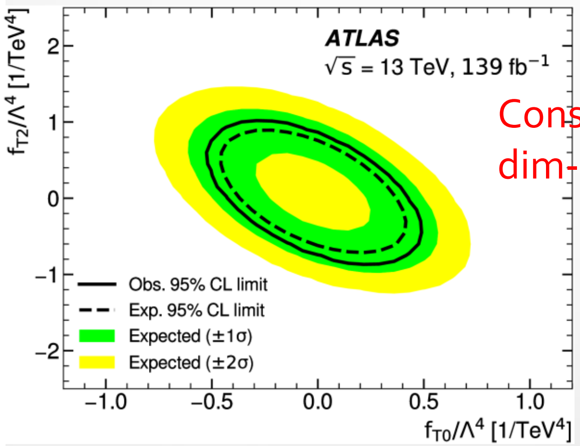


VBS golden channel ($W^{\pm}W^{\pm}jj$)

- Only case with very small non-VBS physical production
  - Background mainly from non-prompt leptons
  - Finely-binned differential cross-sections already possible



ATLAS coll., arXiv:2312.00420



Constraints on dim-8 SMEFT

CMS coll., PLB 812, 136018

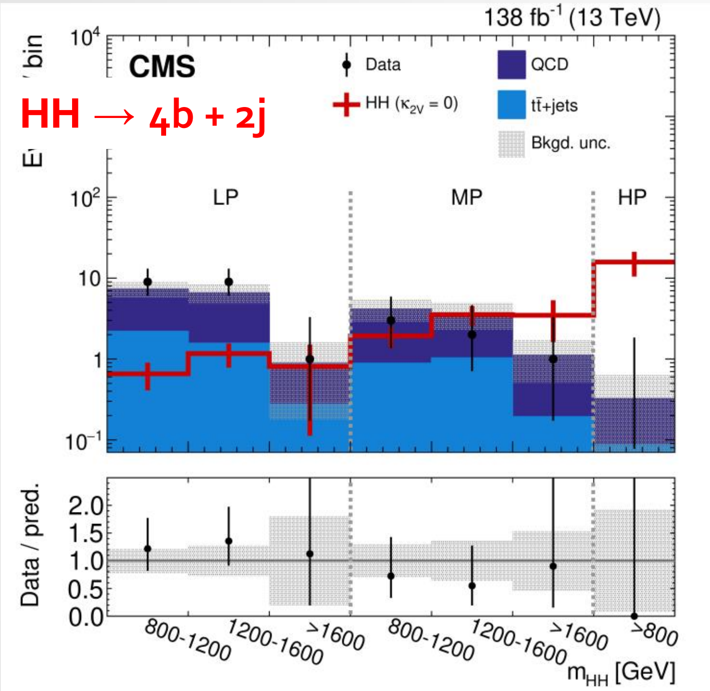
- First attempt to polarized final states in CMS
  - Still a long way to $W_L W_L$

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_{X}W^{\pm}_{T}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^{\pm}_{T}W^{\pm}_{T}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

A recent CMS analysis

CMS coll., PRL 131, 041803

- Use **4b, boosted final state ($p_{T,H}$ > 300 GeV)**
  - Each Higgs boson decay produces a large-radius jet whose constituents' 4-momenta add up to m_H
  - Large rejection factor of multijet events



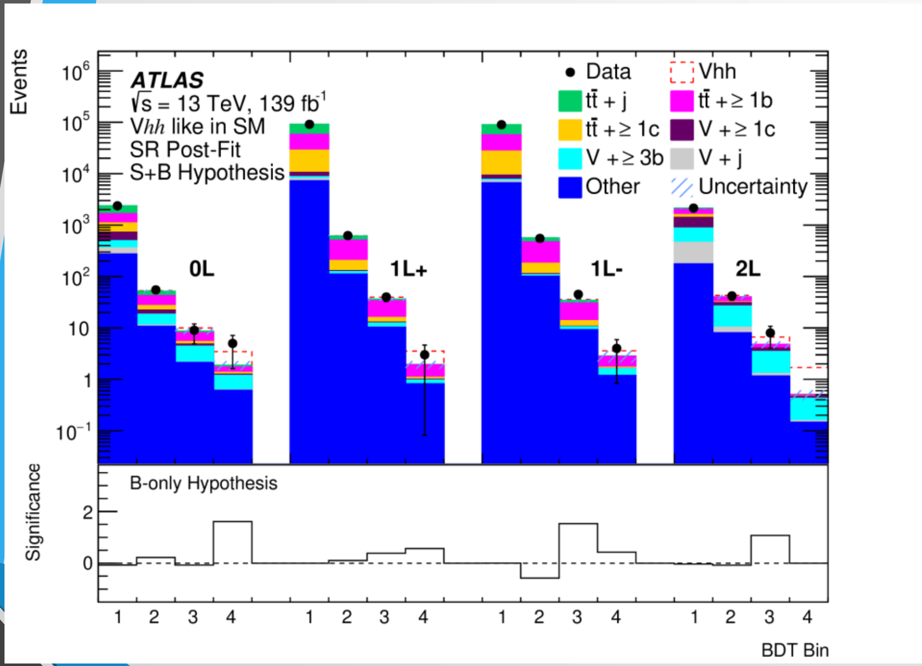
- Graph-neural network reconstruction algorithm (PNet)
  - Optimizes b-tagging performances and jet mass resolution
- Events analysed in categories
  - **VBF HH** (2 more jets with large m_{jj} and $\Delta\eta_{jj}$) or **ggHH**
  - b-tagging purity

Limits @ 95% CL
$-9.9 < \kappa_\lambda < 16.9$
$0.62 < \kappa_{2V} < 1.41$

A recent ATLAS analysis

ATLAS coll., EPJ C 83, 519

- **VHH:** Use **4b final state + W/Z selection**
  - «0L»: target $Z \rightarrow \nu\nu$, require very large $p_{T,miss}$
  - «1L»: target $W \rightarrow l\nu$, require tight e or μ
  - «2L»: target $Z \rightarrow ll$, require 2e or 2μ with mass close to m_Z



- Boosted decision trees trained based on:
  - FSR corrected masses of b-jet pairs
  - B-tagging scores of b-jets
  - Number and energy of all jets in the event

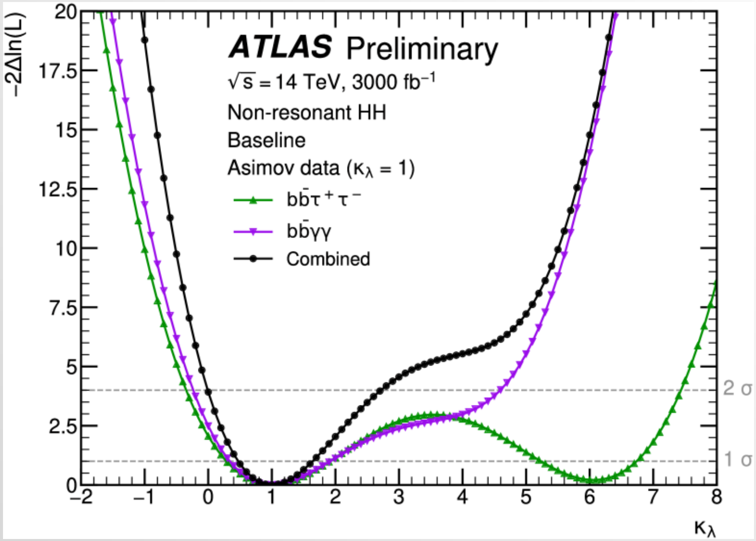
Limits @ 95% CL

$-34 < \kappa_\lambda < 33$

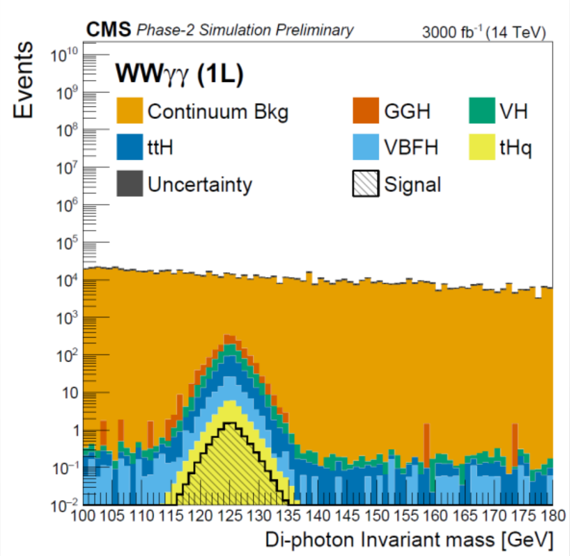
$-8.6 < \kappa_{2V} < 10.0$

HL-LHC perspectives for HH

- Combination of the two most sensitive search channels ($bb\tau\tau$, $bb\gamma\gamma$)
  - **Expected significance of $gg \rightarrow HH$ signal: 3.2-4.6σ**



- Assess contribution of less sensitive but more pile-up robust channels (**$WW\gamma\gamma$, $\tau\tau\gamma\gamma$**)
  - **0.22σ significance → room for improvement?**



- More physics channels can be explored:
  - New decay modes, e.g. bb4l (σ x BR = o(ab) but pileup-insensitive)
  - New production modes, e.g. ttHH

Cross-section limit summary