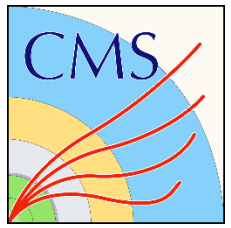


EFT interpretation of EW (including Higgs) measurements

Thomas CALVET for the ATLAS and CMS collaborations
CPPM, Aix-Marseille Université, CNRS/IN2P3

SM@LHC – Online
April 30th, 2021

Introduction

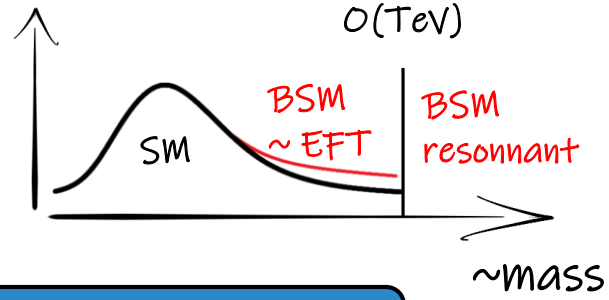
$\mathcal{L}_{\text{nature}} = \mathcal{L}_{\text{SM}} + ?$

- No direct BSM evidence : $M(BSM) > \mathcal{O}(1 - 40\ TeV)$ while $M(EW) \sim \mathcal{O}(100\ MeV)$
  - See summaries ATLAS : SUSY-link, Exotic-link; CMS : SUSY-link, Exotic-link

=> *Effective Field Theory*

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)}$$

basis (Warsaw, HISZ, SILH, Higgs, …) + **assumptions** (global sym, $U(3)^5$, …)



More concepts in Francesco's talk, EW sector importance in Ilaria's

- Implementation in ATLAS and CMS analyses :

1) EFT re-parametrization : $L(data \mid \mu) \xrightarrow{\mu(c_i^{(n)})} L(data \mid c_i^{(n)})$

Fully reproducible, can be done at any "combination stage"

Can handle many operators in t < ∞

2) Dedicated measurements :

Full sim SM and $c_i^{(n)}$ => direct fit to data

Expect best sensitivity, fully parametrize acceptances

This talk : EW + Higgs

Alessia's talk : Top + Higgs

Electro-Weak analyses part 1 : HVV, VVV, Vff vertices

$\Rightarrow$ dimension 6 EFT

Neglecting all contributions/uncertainties from higher-order

The dictionary

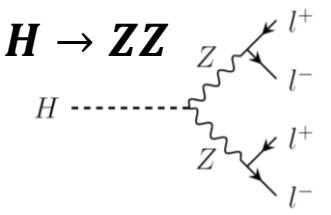
A hand full of results (several covered in this conference)

ATLAS - arXiv:2103.01918

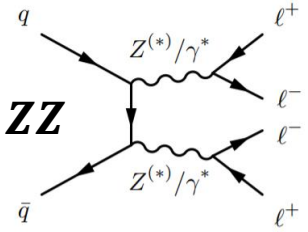
ATLAS - arXiv:2004.03447
CMS-PAS-HIG-19-009

CMS - EPJC 81 (2021) 200

$H \to ZZ$



ZZ

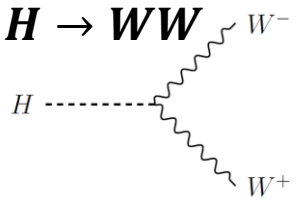


EW+H interface

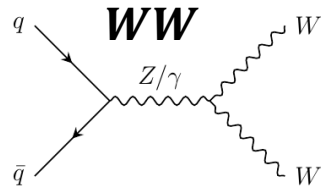
ATL-PHYS-PUB-2021-010

Phys. Rev. D 102 (2020) 092001

$H \to WW$

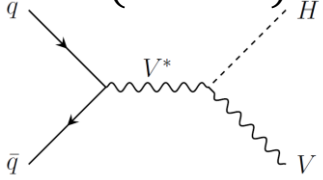


WW



Higgs analyses with impact on EW sector

$VH(H \to bb)$

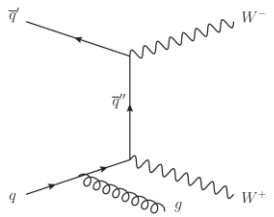


resolved Eur. Phys. J. C 81 (2021) 178
high pT Phys. Lett. B 816 (2021) 136204

Higgs combination :
ATLAS-CONF-2020-053 / CMS-PAS-HIG-19-005

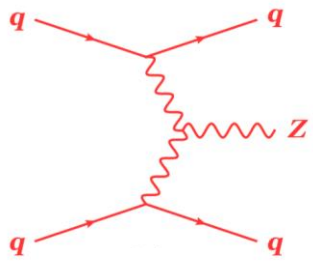
EW analyses

$WW + \geq 1\ jet$



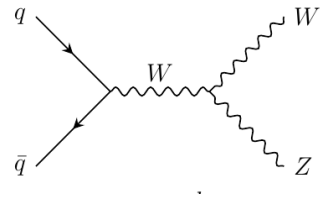
ATLAS - arXiv:2103.10319

EW Z + jj



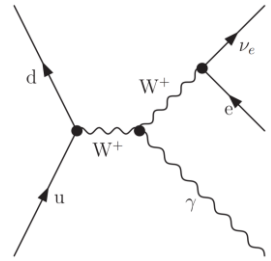
ATLAS - arXiv:2103.01918

WZ



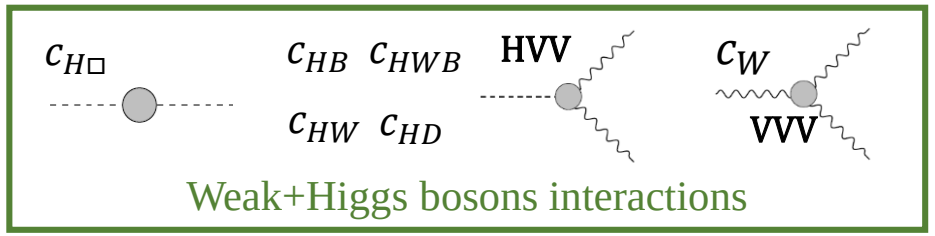
CMS-PAS-SMP-20-014

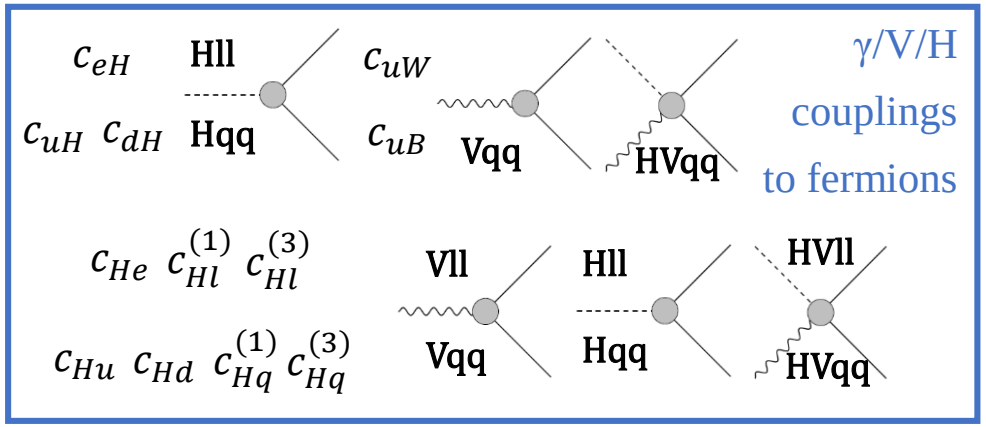
W + γ

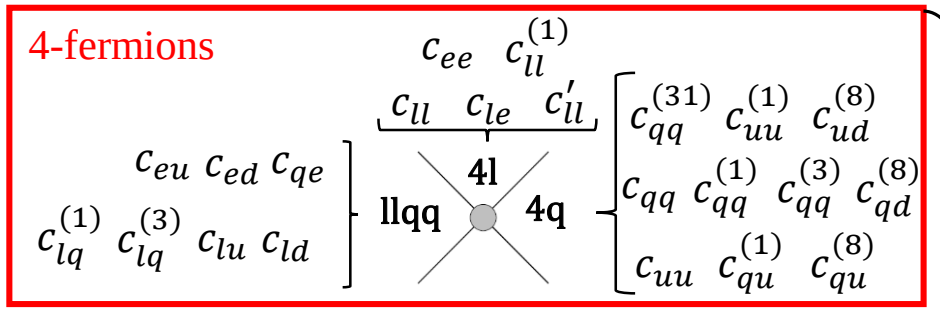


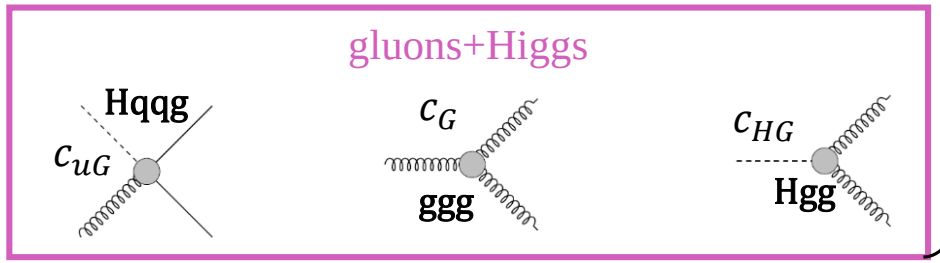
CMS - arXiv:2102.02283

The dictionary







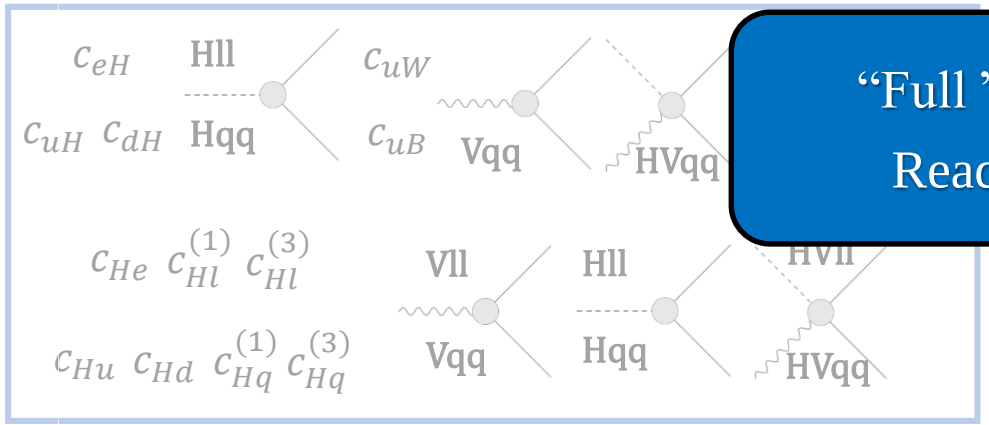


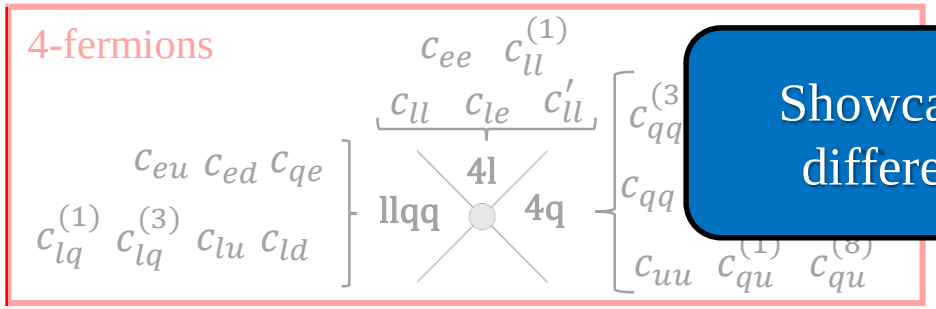
Including some not directly related to EW sector

Constrain large variety of operators

The dictionary

Wilson coefficients in the Higgs and/or EW analyses



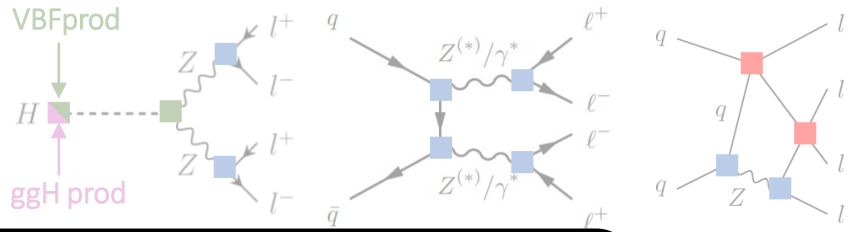


"Full " mapping in backup (link)

Read helpers in backup (link)

Showcase how results contribute to difference aspects of EFT studies

Recent analyses relevant in the electro-weak sector



pp→4l measurement

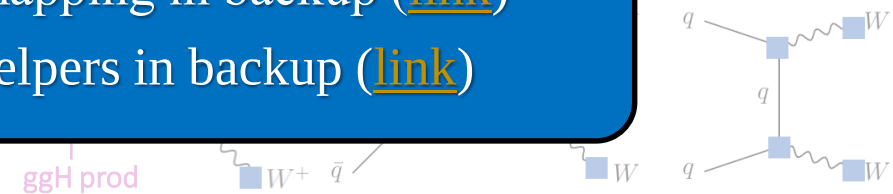
ATLAS (Higgs+SM) - arXiv:2103.01918

CMS (no Higgs) - EPJC 81 (2021) 200

H→4l (acc, opti, …)

ATLAS - arXiv:2004.03447

CMS-PAS-HIG-19-009



H→WW and WW EFT

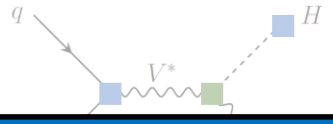
ATL-PHYS-PUB-2021-010

WW+≥1jet measurement

ATLAS - arXiv:2103.10319

CMS pp→WW

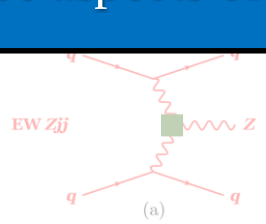
Phys. Rev. D 102 (2020) 092001



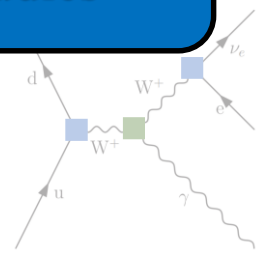
VH(bb) resolved Eur. Phys. J. C 81 (2021) 178

and high pT (boosted) Phys. Lett. B 816 (2021) 136204

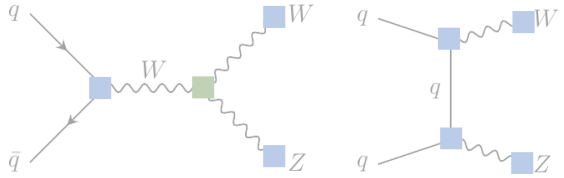
ATLAS-CONF-2020-053 / CMS-PAS-HIG-19-005



EW Z+jj ATLAS - arXiv:2103.01918



Wγ CMS - arXiv:2102.02283



WZ CMS-PAS-SMP-20-014

Electro-Weak analyses part 1 : HVV, VVV, Vff vertices

$\Rightarrow$ dimension 6 EFT

Higgs sector

ElectroWeak - H interface

ElectroWeak sector

Higgs Simplified Template Cross-Sections

- STXS : simplified fiducial volume definition for differential measurement :
  - split production phase spaces in truth-bins,
  - mostly : p_T^H (p_T^V in VH), $N(jet)$, m_{jj} (VBF and ggH)).

See Nicolas' talk yesterday

- STXS bin content dependence on EFT parameter from (truth-)MC :

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

XS partial/total widths

$$(\sigma \times B)^{i,H\to X} = (\sigma \times B)^{i,H\to X}_{\text{SM,(N(N))NLO}} \left(1 + \frac{\sigma^i_{\text{int,(N)LO}}}{\sigma^i_{\text{SM,(N)LO}}} + \frac{\sigma^i_{\text{BSM,(N)LO}}}{\sigma^i_{\text{SM,(N)LO}}}\right) \left(\frac{1 + \frac{\Gamma^{H\to X}_{\text{int}}}{\Gamma^{H\to X}_{\text{SM}}} + \frac{\Gamma^{H\to X}_{\text{BSM}}}{\Gamma^{H\to X}_{\text{SM}}}}{1 + \frac{\Gamma^{H}_{\text{int}}}{\Gamma^{H}_{\text{SM}}} + \frac{\Gamma^{H}_{\text{BSM}}}{\Gamma^{H}_{\text{SM}}}}\right) \quad (1)$$

- Linear (in $c_i^{(6)}$) assumption : Taylor expand at $\mathcal{O}(\Lambda^{-2})$
- Quadratic assumption : (1) with all $\mathcal{O}(\Lambda^{-2})$ and $\mathcal{O}(\Lambda^{-4})$ terms and ratios

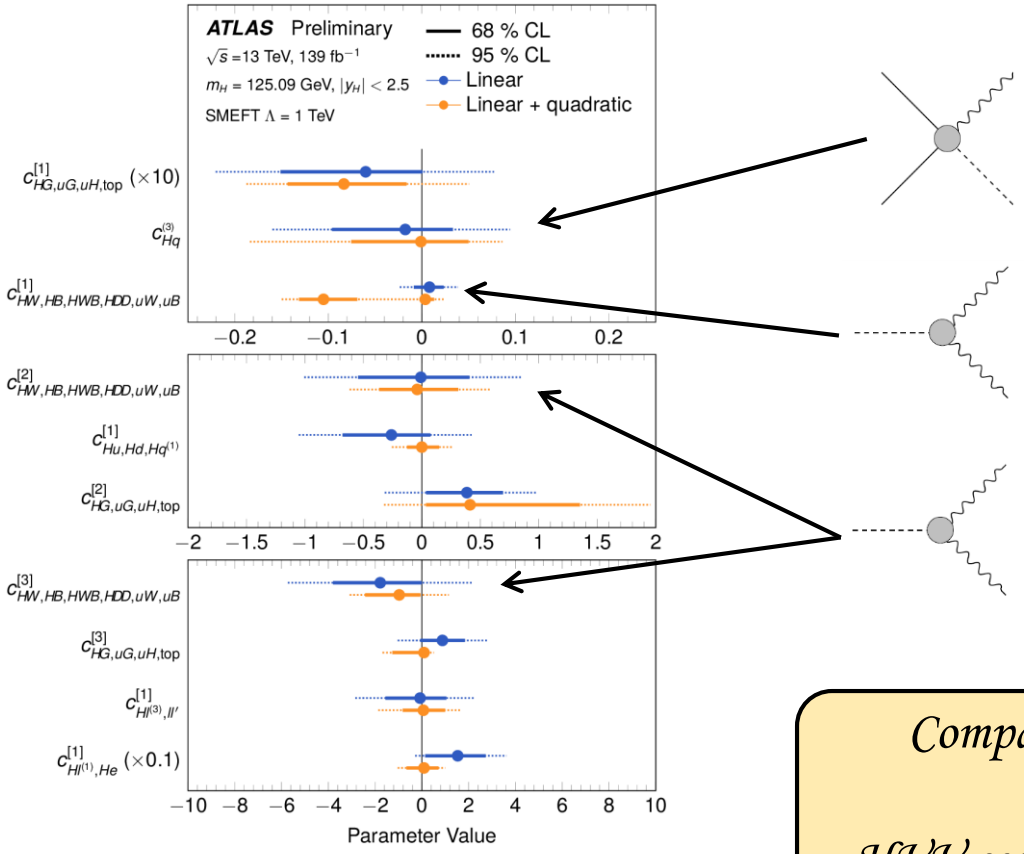
- Re-express full likelihood to extract constraints :

$$L(N_k|\mu^{i,X}, \boldsymbol{\theta}) = \text{Poisson}\left(N_k | s_k(\mu^{i,X}, \boldsymbol{\theta}) + b_k(\boldsymbol{\theta})\right)$$

$$s_k(c_i, \boldsymbol{\theta}) = \sum_{i,X} \left(\mu^{i,X} \equiv \frac{(\sigma \times B)^{i,H\to X}_{\text{SMEFT}}(c_i)}{(\sigma \times B)_{\text{SM,MC}}}\right) \times \mathcal{L} \times (\sigma \times B)^{i,X}_{\text{SM,MC}}(\boldsymbol{\theta}) \times \epsilon_k^{i,X}(\boldsymbol{\theta})$$

Constraints from combined Higgs measurements

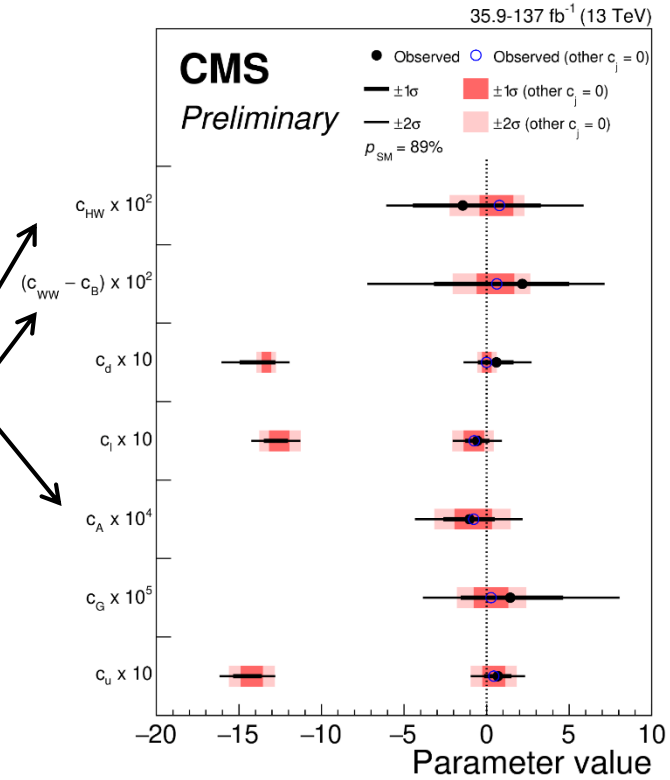
- July 2020 ATLAS Higgs combination : ATLAS-CONF-2020-053
  - $H \to \gamma\gamma, VH(H \to bb), H \to 4l$ @ 139 fb^{-1},
  - STXS merged stage 1.2 (backup-link),
  - Warsaw basis, c_i eigenvectors (backup-link), acceptance in H->4l (slide 12 - link).
- Jan 2020 CMS Higgs combination : CMS-PAS-HIG-19-005
  - $H \to 4l$ @ 137 fb^{-1}, other channels with partial data,
  - based on STXS stages 0, 1.0, and 1.1,
  - HEL basis, no acceptance corrections.



In VH production

In $H \to \gamma\gamma$ decay width

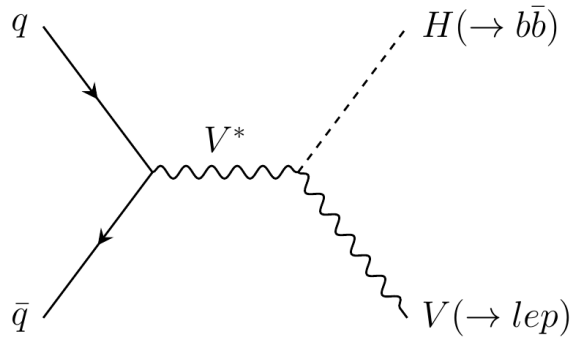
In HVV vertices (VBF/VH prods)



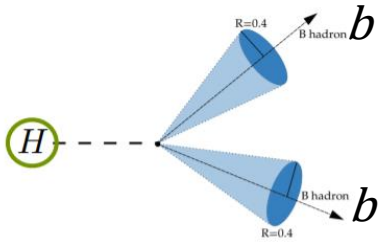
Compatible with SM, significant contribution from $\mathcal{O}(\Lambda^{-4})$.
Important correlations observed.
HVV constraints typically $\mathcal{O}(10)$ times worse than HVff and Hγγ.

Towards EFT optimized analyses : ATLAS VH(bb) inclusive and boosted

- 2 VH(bb) analyses :

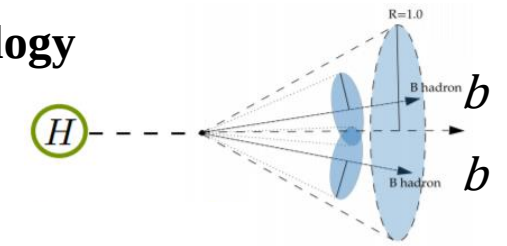


Resolved topology



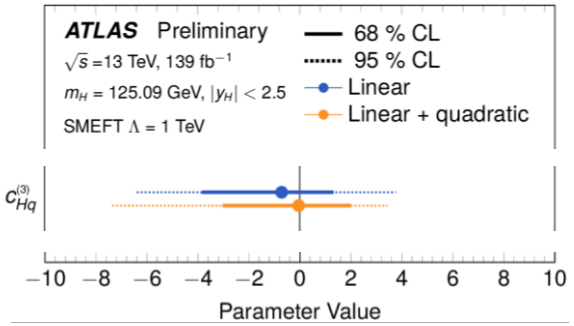
- Inclusive analysis $p_T(V) > 75$ GeV
- 30% uncertainty on $p_T(V) > 250$ GeV
- Can not isolate higher bins above 250 GeV

Boosted topology



- Dedicated high $p_T(V) > 250$ GeV
- Low statistics : 60% uncertainty
- Can isolate $p_T(V) > 400$ GeV

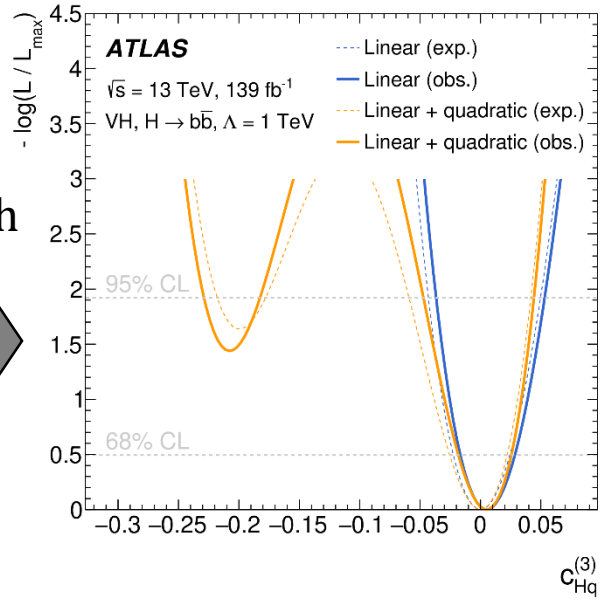
- VH(bb) resolved : constraints on $c_{Hq}^{(3)}$ in Higgs combination



Same approach
Only VH(bb)

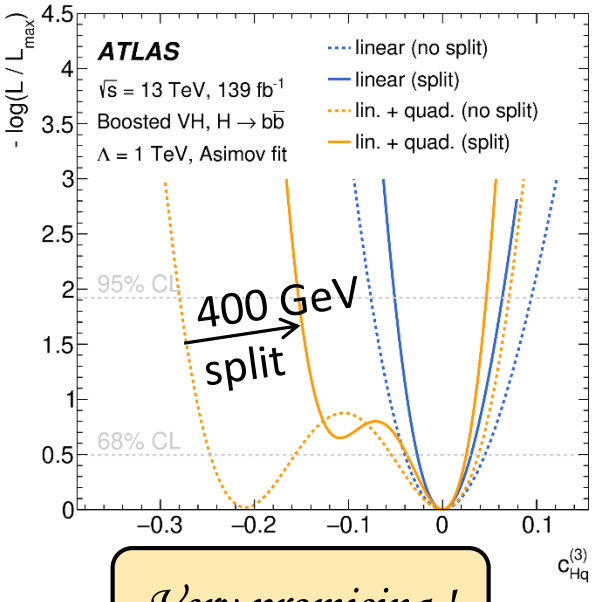
Only $c_{Hq}^{(3)}$

Eur. Phys. J. C 81 (2021) 178



boost

Phys. Lett. B 816 (2021) 136204

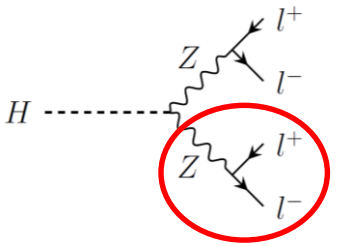


Very promising !

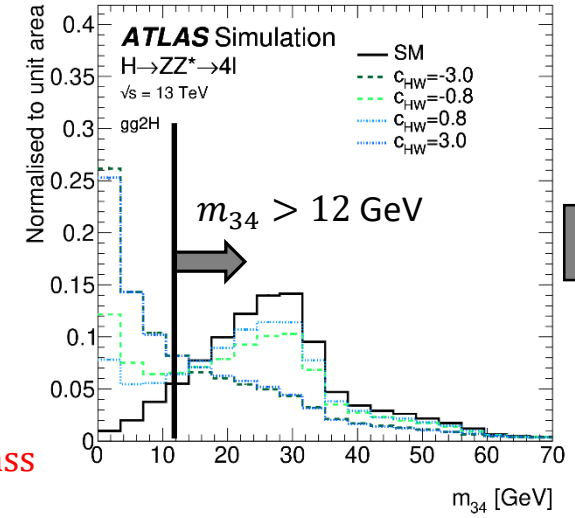
Acceptance effects : ATLAS H->4l (arXiv:2004.03447)

- STXS is not fully fiducial : does not include all analysis selection observables (no decay !)
  - acceptance parametrization difficult outside experiment.

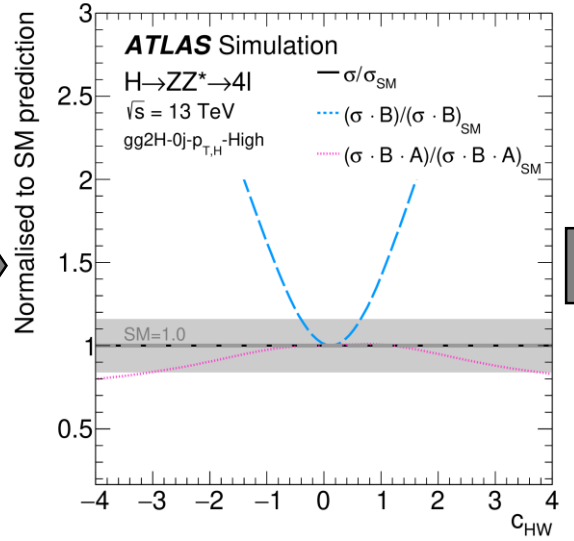
- In H→4l :



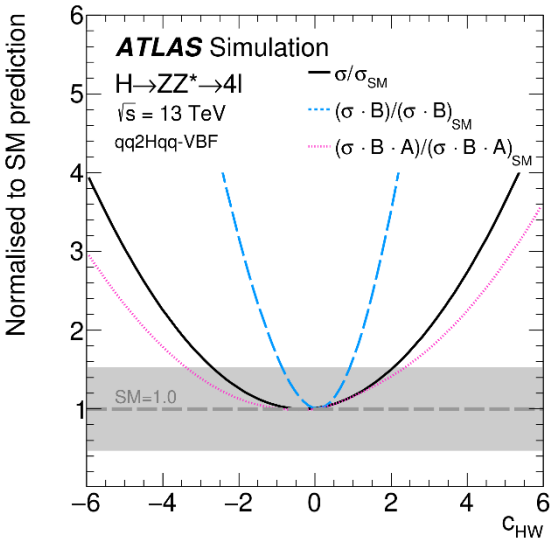
Sub-leading lepton pair mass



Lower efficiency in EFT hypothesis.



High $p_T(H)$:
… enhancement from change in σ · B
… reduction from efficiency loss.



Opposite effects => reduced sensitivity.

- Ways out :

1) Patch STXS re-interpretability :

Public access to acceptance EFT dependencies… ? Decay in STXS ?

2) Interpretable (unfolded) measurement :

ATLAS H→4l : Eur. Phys. J. C 80 (2020) 942

+ ATLAS pp→4l : in a few slides and general approach in SM analyses

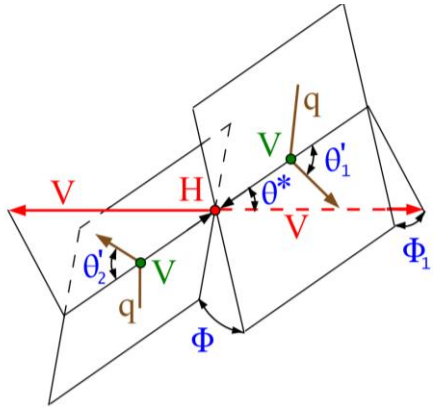
3) EFT dedicated measurements in data (hard to re-interpret, but opti constraints and fully accounting acceptances) :

CMS H→4l : next slide

CMS H->4l (CMS-PAS-HIG-19-009) : EFT dedicated measurement

H→4l signal model based with anomalous couplings (HVV, Htt, ggH) :

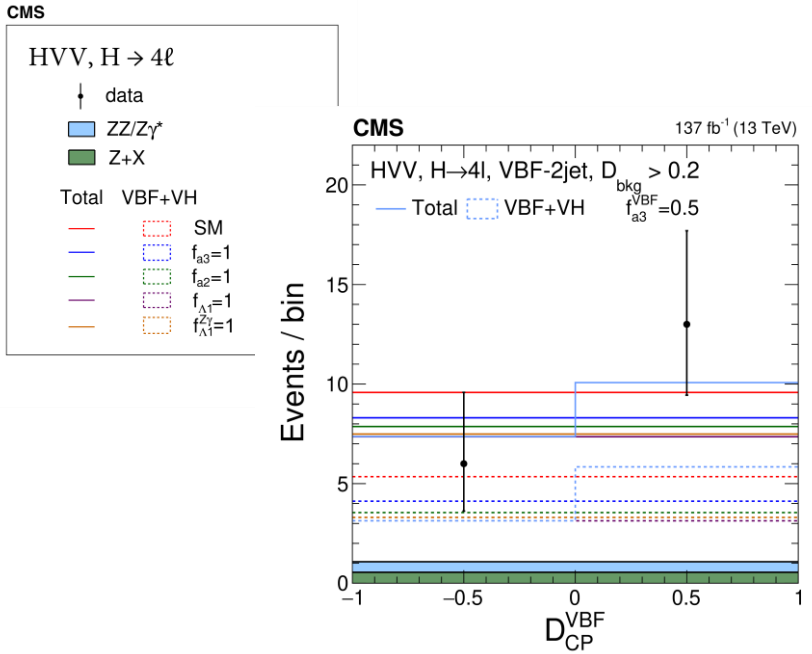
- Full simulation => fully integrated acceptance/efficiency effects.



$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}}(q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

Build optimal discriminants :

- sig/bkg and SM/BSM using Matrix-Elements.



$\mu = {}^{\sigma}/_{\sigma(pred)}$ and fractional coupling contribution* via extended maximum likelihood fit

* $$f_{ai}^{\mathrm{VV}} = \frac{|a_i^{\mathrm{VV}}|^2 \alpha_{ii}^{(\mathrm{dec})}}{\sum_j |a_j^{\mathrm{VV}}|^2 \alpha_{jj}^{(\mathrm{dec})}} \mathrm{sign}\left(\frac{a_i^{\mathrm{VV}}}{a_1}\right)$$

Convert to Warsaw basis

A priori most accurate strategy
… but difficult to combine and re-interpret.

In depth study of ggH loop VS ggH point like

Channels	Coupling	Observed	Expected	Observed correlation			
				c_{gg}	$\tilde{c}_{gg}$	κ_t	$\tilde{\kappa}_t$
tH & tt̄H & ggH	c_{gg}	$-0.0012^{+0.0022}_{-0.0174}$	$0.0000^{+0.0019}_{-0.0196}$	1	−0.050	−0.941	+0.029
	$\tilde{c}_{gg}$	$-0.0017^{+0.0160}_{-0.0130}$	$0.0000^{+0.0138}_{-0.0138}$		1	+0.046	−0.568
	κ_t	$1.05^{+0.25}_{-0.20}$	$1.00^{+0.34}_{-0.26}$			1	+0.168
	$\tilde{\kappa}_t$	$-0.01^{+0.69}_{-0.67}$	$0.00^{+0.71}_{-0.71}$				1
				δc_z	c_{zz}	$c_{z\Box}$	$\tilde{c}_{zz}$
VBF & VH & H → 4ℓ	δc_z	$-0.03^{+0.06}_{-0.25}$	$0.00^{+0.07}_{-0.27}$	1	+0.241	−0.060	−0.009
	c_{zz}	$0.01^{+0.11}_{-0.10}$	$0.00^{+0.22}_{-0.16}$		1	−0.884	+0.058
	$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$			1	+0.020
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$				1

Warsaw basis also studied

Electro-Weak analyses part 1 : HVV, VVV, Vff vertices

=> dimension 6 EFT

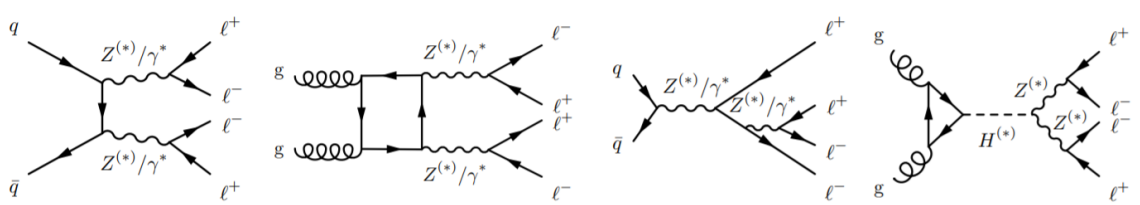
Higgs sector

ElectroWeak - H interface

ElectroWeak sector

Unfolded measurements : ATLAS pp->4l (arXiv:2103.01918)

- pp→4l inclusive (in m_{4l}) analysis of full Run 2 data ($139\ fb^{-1}$) :

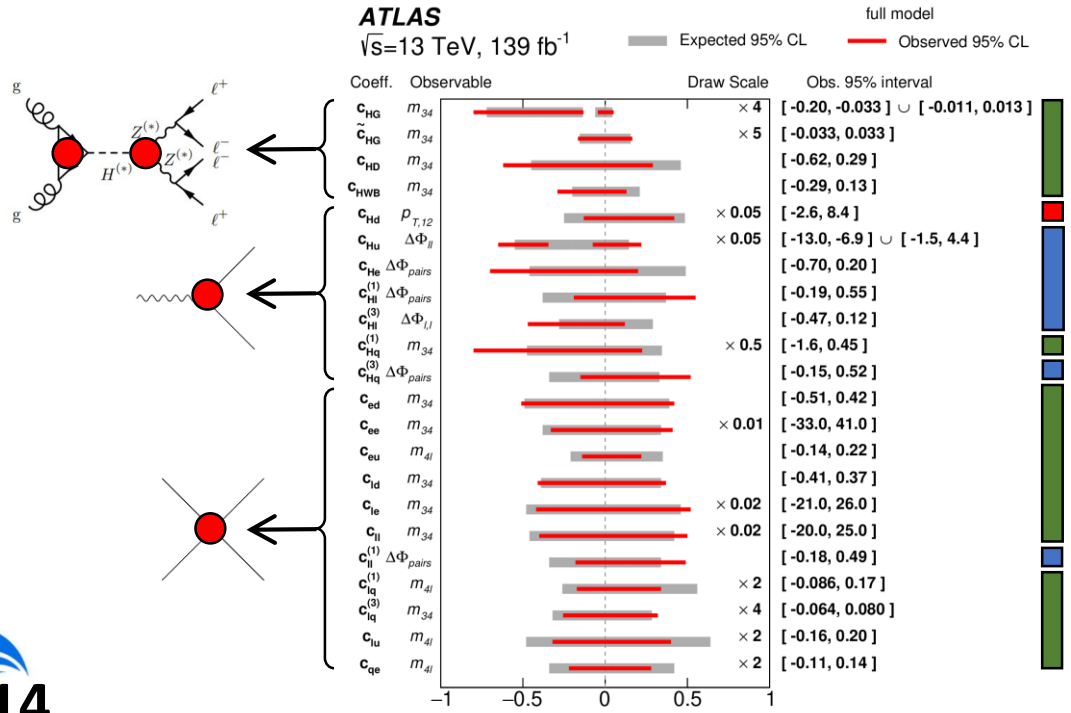


Double differential :
m_{4l} (separate channels)
× kinematic/angular observable (EFT/SM)

- Re-interpretation ($L(data \mid \mu) \xrightarrow{\mu(c_i^{(n)})} L(data \mid c_i^{(n)})$) :
  - demonstrate no bias from unfolding.

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k\,|C|}} \exp\left\{-\frac{1}{2}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}\left(\vec{\theta}\right)\right]^T C^{-1}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}\left(\vec{\theta}\right)\right]\right\} \times \prod_i \mathcal{G}\left(\theta_i, 0, 1\right)$$

$$\vec{\sigma}^{\text{pred}} = \vec{\sigma}^{\text{SM}} \times \left(1 + c_i \cdot \vec{\sigma}^{\text{INT}}/\vec{\sigma}^{\text{LO SM}} + c_i^2 \cdot \vec{\sigma}^{\text{BSM}}/\vec{\sigma}^{\text{LO SM}}\right)$$



$m_{4l} \times m_{34}$ or m_{4l} alone

$m_{4l} \times p_{T,12}$

$m_{4l} \times \Delta\Phi(Z,Z)$ or $\Delta\Phi(l1,l2)$

No deviations from SM

Significant impact of $\mathcal{O}(\Lambda^{-4})$ on several limits (linear VS linear+quadratic in backup)

WW and H->WW combination in ATLAS (ATL-PHYS-PUB-2021-010)

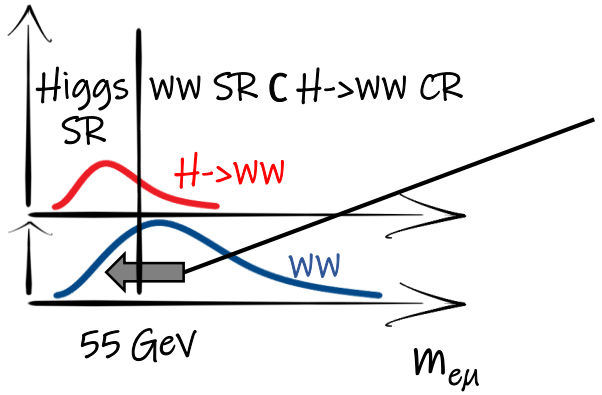
Towards combined EFT re-interpretation

$H \to WW \to e^{\pm}\nu_e\mu^{\mp}\nu_\mu$ 36.1 fb (Phys. Lett. B 789 (2019) 508)

ggH and VBF signatures => include 0 to 2 jets

$WW \to e^{\pm}\nu_e\mu^{\mp}\nu_\mu$ 36.1 fb (Eur. Phys. J. C 79 (2019) 884)

veto jets, differential in $p_T^{lead\ l}$.



Challenge 1 : "combined"

In Higgs : WW bkg constrained in CR

In comb : use WW-SR instead and ensure consistent systematic uncertainties

Challenge 2 : multiple final state => can simultaneously constraint multiple operators ?

- Linearized (interference terms) dim 6 EFT in Warsaw basis.
- Approximate the sub-space of the dim 6 EFT composed of measurable orthogonal directions :

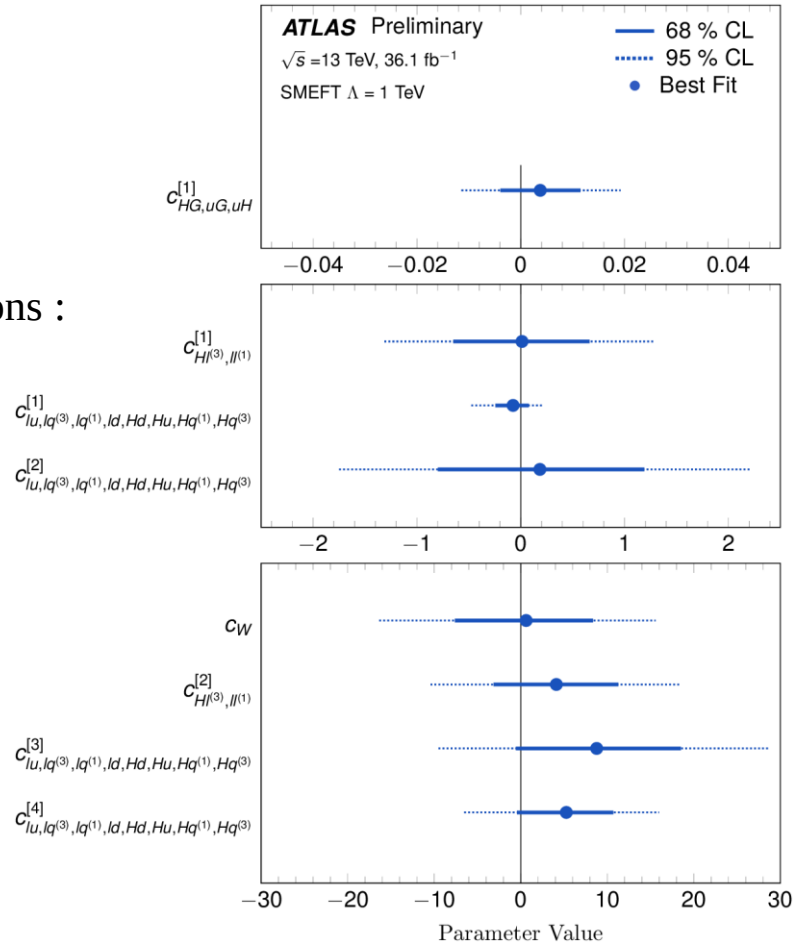
Step 1 : group operators

c_W	$c_{HG}\ c_{uG}\ c_{uH}$	$c_{Hl}^{(3)}\ c_{ll}^{(1)}$	$c_{lu}\ c_{lq}^{(3)}\ c_{lq}^{(1)}\ c_{ld}$
$c_{HB}\ c_{HW}\ c_{HWB}$	$c_{dH}\ c_{HDD}\ c_{H\Box}$	$c_{Hd}\ c_{Hu}\ c_{Hq}^{(1)}\ c_{Hq}^{(3)}$	

Step 2 : re-parametrize POI cov matrix for each group

Step 3 : get eigenvectors

Simultaneous fit in the 8 "eigen-directions"



Electro-Weak analyses part 1 : HVV, VVV, Vff vertices

=> dimension 6 EFT

Higgs sector
ElectroWeak - H interface
ElectroWeak sector

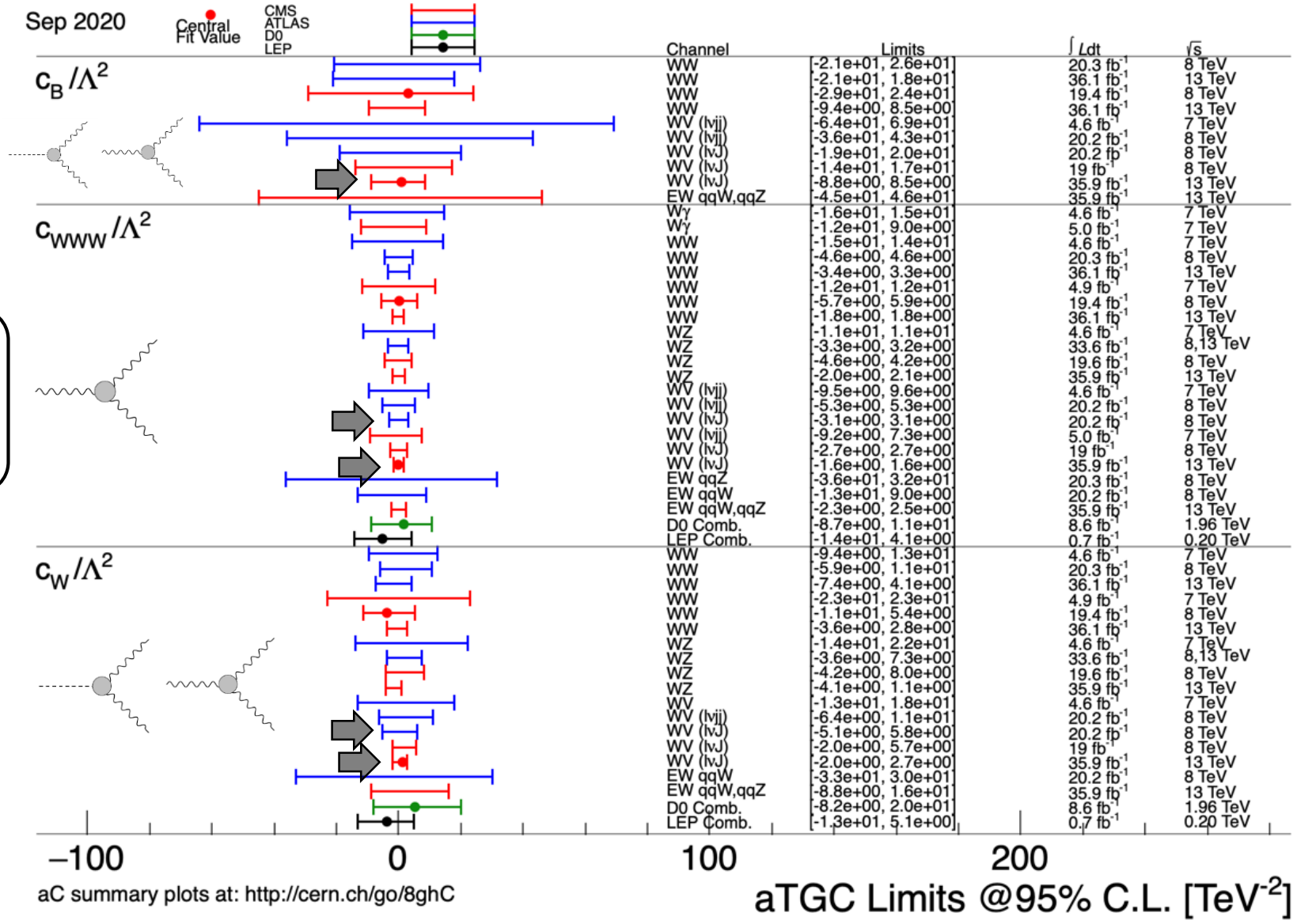
Overview

- Status of charged aTGC measurements in September 2020 : link

Most channels are competitive … all are complementary

W(→lep) V (boosted jet) analysis leading
- *ATLAS : fit m(WZ)*
- *CMS : fit m(WZ) × m(jet)*

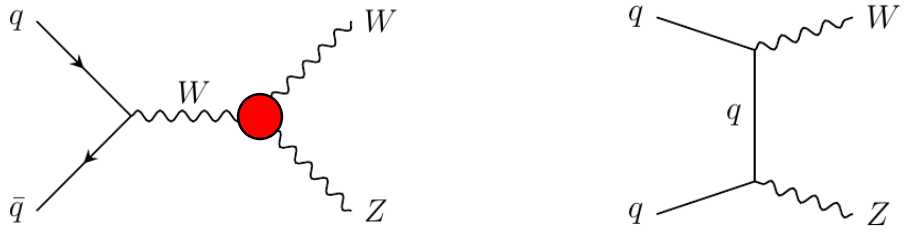
Next slides review what's new since then



Full Run 2 WZ in CMS (CMS-PAS-SMP-20-014) and EFT validity

CMS : pp→WZ→lllν full Run 2 ($137\ fb^{-1}$)

- Exploit M(WZ) differential information,
- Re-parametrized in HISZ basis.



Linear ($\mathcal{O}(\Lambda^{-2})$) and quadratic ($\mathcal{O}(\Lambda^{-4})$) terms

Parameter	95% CI, Exp. (TeV^{-2})	95% CI, Obs. (TeV^{-2})	Best fit, Obs. (TeV^{-2})
c_w/Λ^2	$[-2.05, 1.27]$	$[-2.52, 0.33]$	-1.34
c_{www}/Λ^2	$[-1.27, 1.33]$	$[-1.04, 1.19]$	0.15
c_b/Λ^2	$[-86.0, 125.0]$	$[-42.7, 113.0]$	43.6
$\tilde{c}_{www}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03
$\tilde{c}_w/\Lambda^2$	$[-46.1, 46.1]$	$[-45.9, 45.9]$	0.0

no sensitivity to c_b

2 times better than previous analysis

Linear ($\mathcal{O}(\Lambda^{-2})$) terms only

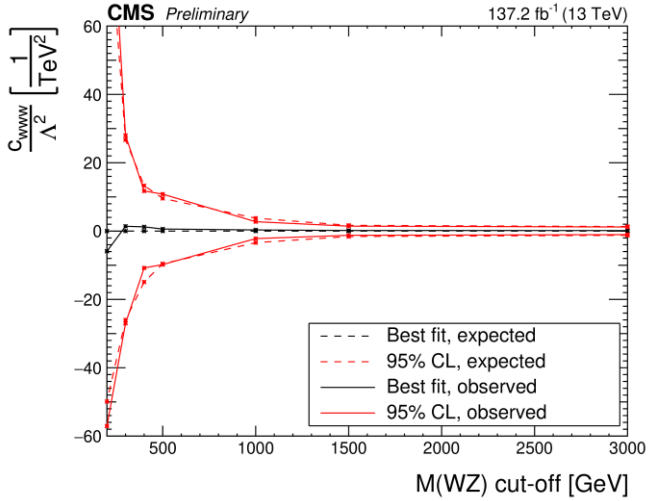
Parameter	95% CI, Exp. (TeV^{-2})	95% CI, Obs. (TeV^{-2})	Best fit, Obs. (TeV^{-2})
c_w/Λ^2	$[-1.82, 2.12]$	$[-3.11, 0.26]$	-1.59
c_{www}/Λ^2	$[-8.55, 8.46]$	$[-4.20, 14.25]$	5.48
c_b/Λ^2	$[-197.1, 183.3]$	$[9.3, 383.7]$	201.3
$\tilde{c}_{www}/\Lambda^2$	$[-3.35, 4.07]$	$[-4.01, 3.61]$	-0.59
$\tilde{c}_w/\Lambda^2$	$[-, -]$	$[-, -]$	-

Strong impact of $\mathcal{O}(\Lambda^{-4})$ => EFT validity ?

Further testing : validity at high scales

- fix yields to SM above given scale (in a given m(WZ) bin),
- re-evaluate limits.

=> address cases where high scales beyond EFT model validity.



Two ways to overcome interference suppression

SM-EFT interference suppression limiting factor in $\mathcal{O}(\Lambda^{-2})$ limits

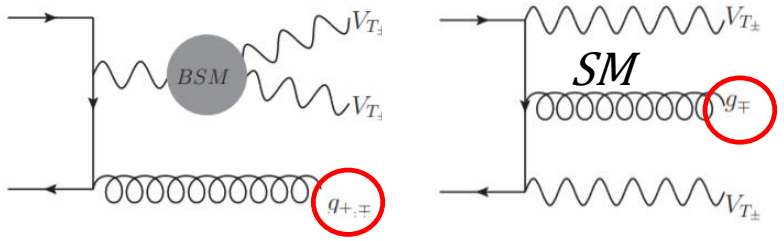
In 2→2 di-boson production

$$q\bar{q} \longrightarrow V_{T_\pm} V_{T_\mp} \quad \text{(in the SM)}\,,$$
$$q\bar{q} \longrightarrow V_{T_\pm} V_{T_\pm} \quad \text{(with } O_{3W} \text{ insertion)}\,.$$

=> interference suppression

2 ways to regain sensitivity to linear terms and improve EFT validity (see arxiv:1707.08060)

2→3 di-boson + jet production

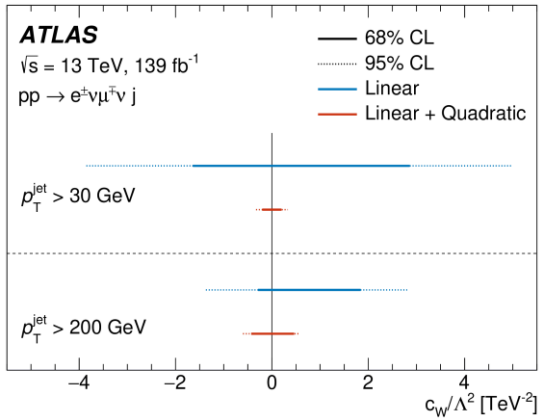


Helicity conflict in gluon

ATLAS : W(lν)W(lν)+≥1jets full Run 2 (137 fb^{-1})

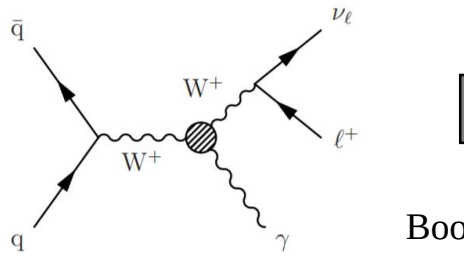
- New channel (complementary measurement),
- M(ll) fiducial measurement.

arXiv:2103.10319

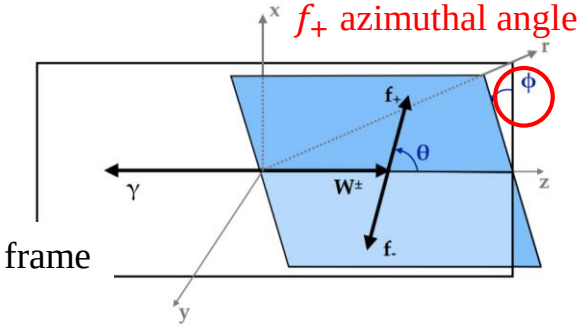


Even with enhanced interference $\mathcal{O}(\Lambda^{-4})$ are significant

Interference resurrection :

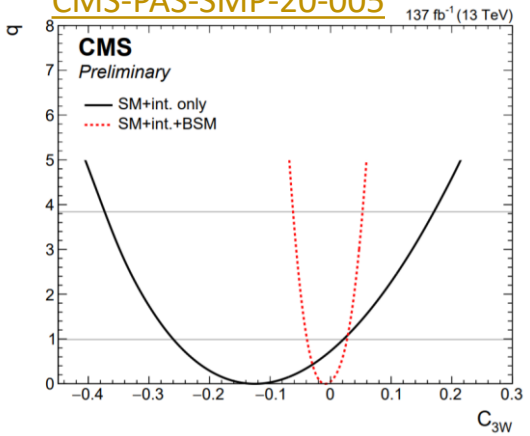


Boost in Wγ rest frame



CMS : EW W(lν)+γ full Run 2 (137 fb^{-1})

CMS-PAS-SMP-20-005



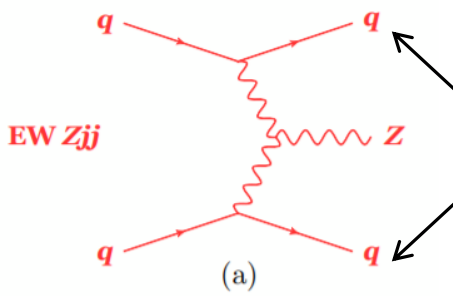
- 2D fiducial distributions : $p_T(\gamma)$ and ϕ
- Tighter selections than diff XS : $p_T(l) > 80$ GeV & $p_T(\gamma) > 150$ GeV

Linear limits improved by a factor 10 with ϕ differential information.

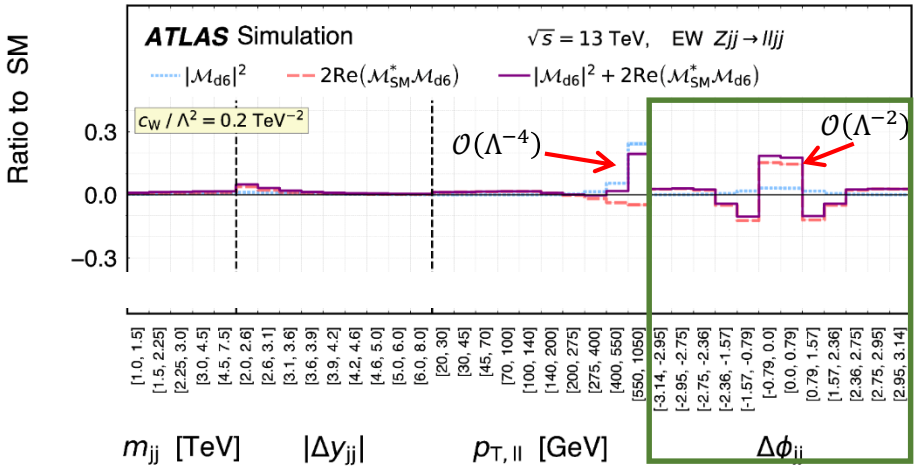
$\mathcal{O}(\Lambda^{-4})$ still dominant.

ATLAS Electro-Weak Z+jj analysis : Eur. Phys. J. C 81 (2021) 163

ATLAS EW Z(ll)+jj full Run 2 ($139\ fb^{-1}$) :



- Main sensitivity to linear EFT in $\Delta\phi_{jj}$ (signed azimuthal angle between the 2 jets)
- $p_T(ll)$ dominated by $\mathcal{O}(\Lambda^{-4})$



EFT configuration :

- Fiducial $\Delta\phi_{jj}$ distribution re-parametrisation,
- Warsaw basis (HISZ also available).

Best limits for interference terms alone
Small impact from $\mathcal{O}(\Lambda^{-4})$

Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
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%

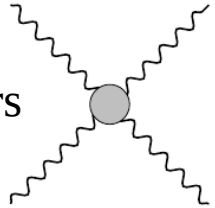
anomalous Quartic Gauge Couplings (aQGC)
neutral Triple Gauge Couplings (nTGC)

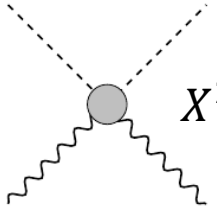
=> dimension 8 EFT

anomalous Quartic Gauge Coupling contraints

Quartic couplings in dimension 8 EFTs (def in backup link) :

X^4, tensor (index T) operators



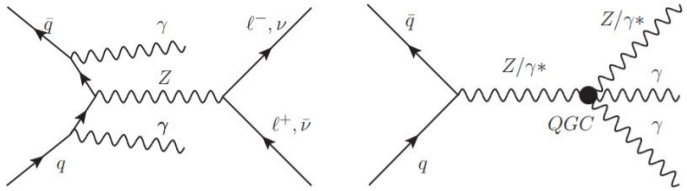


$X^2D^2H^2$, index M operators

Previous result summary (incl ATLAS) : link

CMS Vγγ full Run 2 analysis

CMS-PAS-SMP-19-013

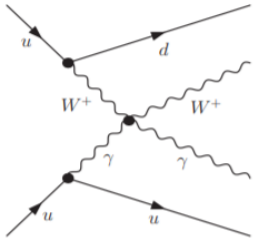


- Differential $p_T(\gamma\gamma)$ re-parametrization
- 95% CL

	$W\gamma\gamma$ (TeV^{-4})		$Z\gamma\gamma$ (TeV^{-4})	
Parameter	Expected	Observed	Expected	Observed
$f_{M,2}/\Lambda^4$	$[-57.3, 57.1]$	$[-39.9, 39.5]$	-	-
$f_{M,3}/\Lambda^4$	$[-91.8, 92.6]$	$[-63.8, 65.0]$	-	-
$f_{T,0}/\Lambda^4$	$[-1.86, 1.86]$	$[-1.30, 1.30]$	$[-4.86, 4.66]$	$[-5.70, 5.46]$
$f_{T,1}/\Lambda^4$	$[-2.38, 2.38]$	$[-1.70, 1.66]$	$[-4.86, 4.66]$	$[-5.70, 5.46]$
$f_{T,2}/\Lambda^4$	$[-5.16, 5.16]$	$[-3.64, 3.64]$	$[-9.72, 9.32]$	$[-11.4, 10.9]$
$f_{T,5}/\Lambda^4$	$[-0.76, 0.84]$	$[-0.52, 0.60]$	$[-2.44, 2.52]$	$[-2.92, 2.92]$
$f_{T,6}/\Lambda^4$	$[-0.92, 1.00]$	$[-0.60, 0.68]$	$[-3.24, 3.24]$	$[-3.80, 3.88]$
$f_{T,7}/\Lambda^4$	$[-1.64, 1.72]$	$[-1.16, 1.16]$	$[-6.68, 6.60]$	$[-7.88, 7.72]$
$f_{T,8}/\Lambda^4$	-	-	$[-0.90, 0.94]$	$[-1.06, 1.10]$
$f_{T,9}/\Lambda^4$	-	-	$[-1.54, 1.54]$	$[-1.82, 1.82]$

CMS Wγjj with 35.9 fb^{-1}

Phys. Lett. B 811 (2020) 135988



- First observation
- EFT additional selections

$m_{jj} > 800\ GeV, m_{W\gamma} > 120\ GeV,$
$p_T^{\gamma} > 150\ GeV, |\Delta\eta_{jj}| > 2.5$

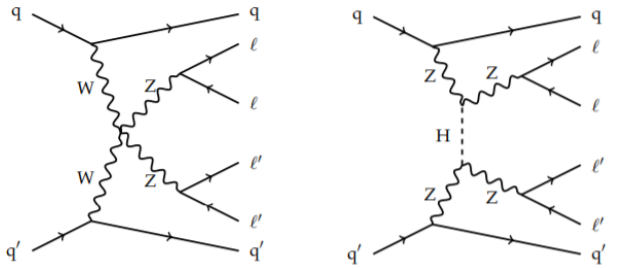
- Differential $m_{W\gamma}$ re-parametrization
- 95% CL

Current best constraints

Parameters	Obs. limit	Exp. limit	U_{bound}
$f_{M,0}/\Lambda^4$	$[-8.1, 8.0]$	$[-7.7, 7.6]$	1.0
$f_{M,1}/\Lambda^4$	$[-12, 12]$	$[-11, 11]$	1.2
$f_{M,2}/\Lambda^4$	$[-2.8, 2.8]$	$[-2.7, 2.7]$	1.3
$f_{M,3}/\Lambda^4$	$[-4.4, 4.4]$	$[-4.0, 4.1]$	1.5
$f_{M,4}/\Lambda^4$	$[-5.0, 5.0]$	$[-4.7, 4.7]$	1.5
$f_{M,5}/\Lambda^4$	$[-8.3, 8.3]$	$[-7.9, 7.7]$	1.8
$f_{M,6}/\Lambda^4$	$[-16, 16]$	$[-15, 15]$	1.0
$f_{M,7}/\Lambda^4$	$[-21, 20]$	$[-19, 19]$	1.3
$f_{T,0}/\Lambda^4$	$[-0.6, 0.6]$	$[-0.6, 0.6]$	1.4
$f_{T,1}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.5
$f_{T,2}/\Lambda^4$	$[-1.0, 1.2]$	$[-1.0, 1.2]$	1.5
$f_{T,5}/\Lambda^4$	$[-0.5, 0.5]$	$[-0.4, 0.4]$	1.8
$f_{T,6}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.7
$f_{T,7}/\Lambda^4$	$[-0.9, 0.9]$	$[-0.8, 0.9]$	1.8

CMS pp→4l2j full Run 2 analysis

Phys. Lett. B 812 (2020) 135992



- 95% CL from a fit to m_{ZZ}

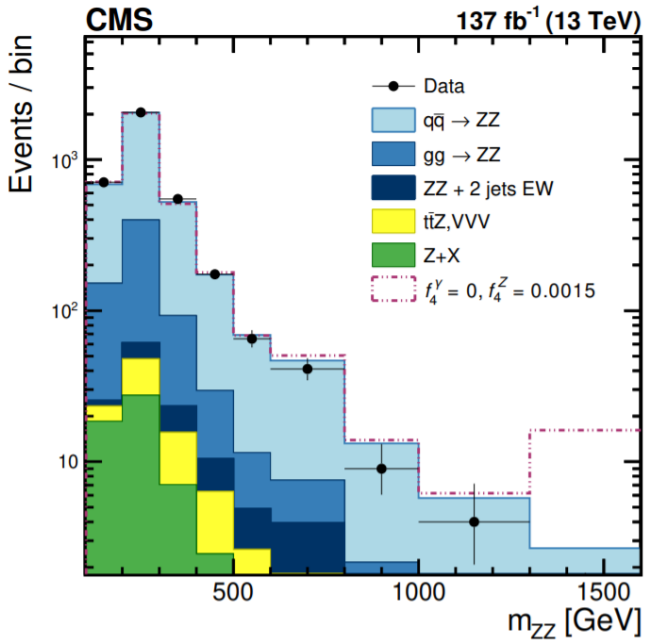
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24	0.22	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31	0.31	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63	0.59	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43	0.43	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92	0.92	1.8

Best constraint T8/9, statistically limited.

Restraining further EFTs with new and complementary results.

neutral Triple Gauge Coupling contraints

CMS pp→ZZ→4l full Run 2 analysis : EPJC 81 (2021) 200



- Require both Z on-shell (60 – 120 GeV)
- Constraints via fit to m_{ZZ}

ZZZ modifiers

ZZγ modifiers

$$\mathcal{O}_{BW} = i\,H^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\}\, H,$$
$$\mathcal{O}_{WW} = i\,H^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\}\, H,$$
$$\mathcal{O}_{BB} = i\,H^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\}\, H.$$

		Expected 95% CL	Observed 95% CL
aTGC parameter		$\times 10^{-4}$	$\times 10^{-4}$
ZZZ modifiers	f_4^Z	-8.8 ; 8.3	-6.6 ; 6.0
	f_5^Z	-8.0 ; 9.9	-5.5 ; 7.5
ZZγ modifiers	f_4^γ	-9.9 ; 9.5	-7.8 ; 7.1
	f_5^γ	-9.2 ; 9.8	-6.8 ; 7.5
EFT parameter		TeV^{-4}	TeV^{-4}
	$C_{\tilde{B}W}/\Lambda^4$	-3.1 ; 3.3	-2.3 ; 2.5
	C_{WW}/Λ^4	-1.7 ; 1.6	-1.4 ; 1.2
	C_{BW}/Λ^4	-1.8 ; 1.9	-1.4 ; 1.3
	C_{BB}/Λ^4	-1.6 ; 1.6	-1.2 ; 1.2

Most stringent constraints on ZZZ and ZZγ couplings to date.
One loop EW correction checked to have negligible impact (4-6% limit improvement)

Included in ATLAS/CMS summary : link

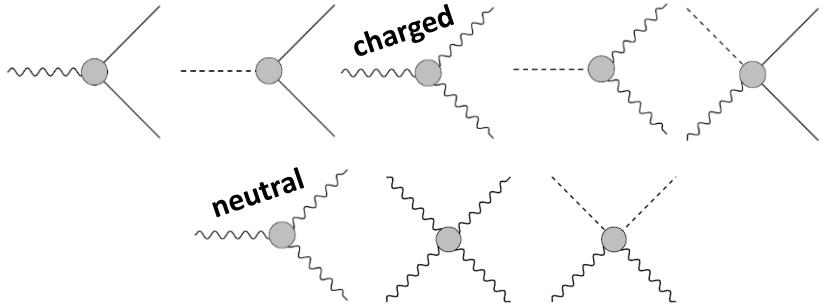
- Current best limits on ZZV parameters from ATLAS $pp \to Z(\nu\nu)\gamma$ analysis with 36 fb^{-1} of data

Conclusions

- Very rich phenomenology in the EW sector :
  - Multi-boson production (VV, VH),
  - VBF, VBS,
  - EW V+ jets or photons,
  - HVV decays,

=> many ATLAS/CMS analyses in various final states

- Affected by various EFT contributions



dim 6

dim 8

- Improving constraints but no deviations from the SM yet :
  - Various dimension 6 basis in use → convergence on Warsaw.
  - Assumes flavor universality $U(3)^5$ … sub-optimal when combining with top measurements.
  - Need to be careful with acceptance and efficiencies :
    - In SM analyses, unfolded measurement available in HEPdata form; more difficult in Higgs analyses
  - Explored dedicated analyses : EFT optimized, accurate/realistic constraints.

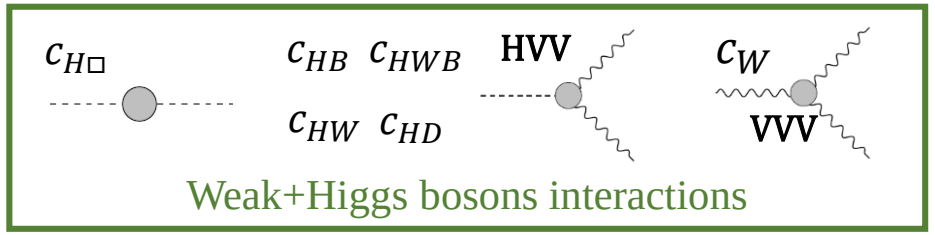
- Validity of EFT without dim 8 in Higgs and TGC analyses ?
  - Pure-BSM in dim 6 significant in most channels while higher order corrections/unc are neglected.
  - Improving interference sensitivity with new analysis and methods : VV+jets, decay angles.

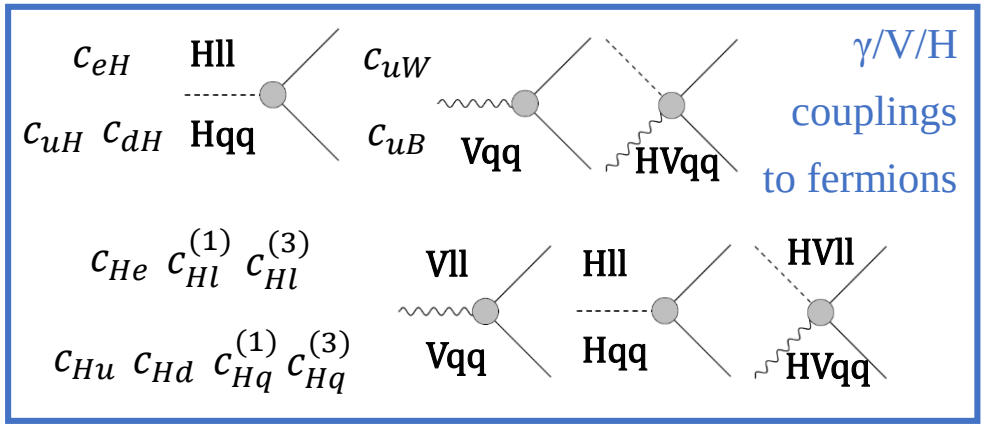
=> Towards more global (EFT parameters) and combined (experimental inputs) fits !

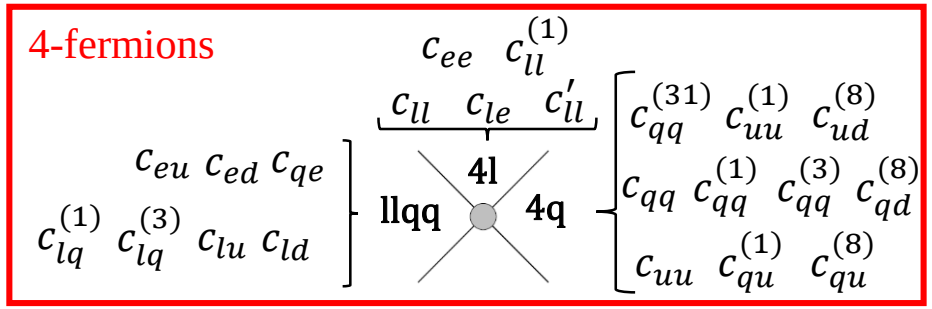
Thank you for your attention

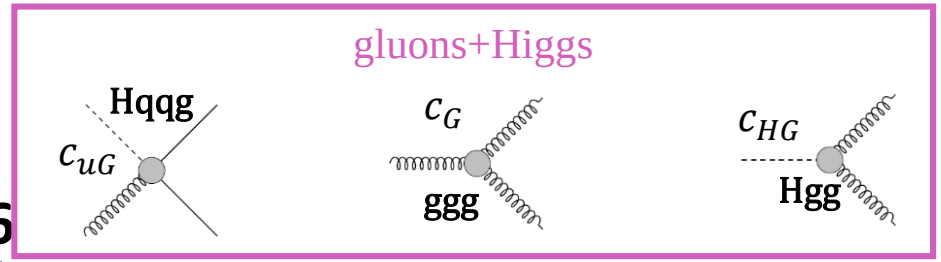
The dictionary

Wilson coefficients in the Higgs and/or EW analyses

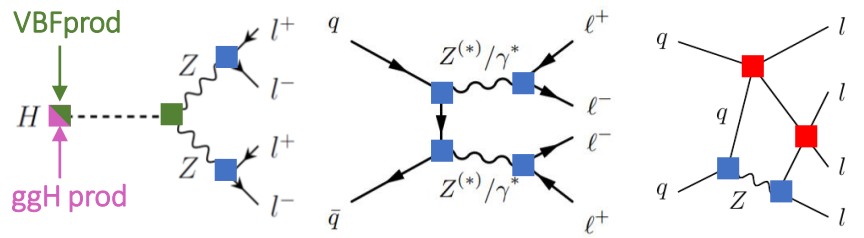






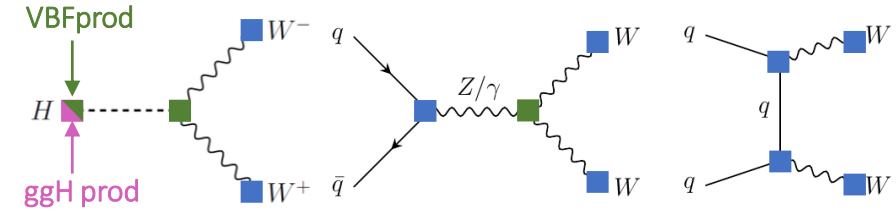


Recent analyses relevant in the electro-weak sector



pp→4l measurement
ATLAS (Higgs+SM) - arXiv:2103.01918
CMS (no Higgs) - EPJC 81 (2021) 200

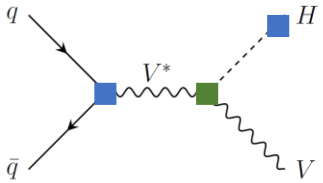
H→4l (acc, opti, …)
ATLAS - arXiv:2004.03447
CMS-PAS-HIG-19-009



H→WW and WW EFT
ATL-PHYS-PUB-2021-010

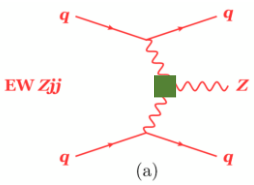
WW+≥1jet measurement
ATLAS - arXiv:2103.10319

CMS pp→WW
Phys. Rev. D 102 (2020) 092001

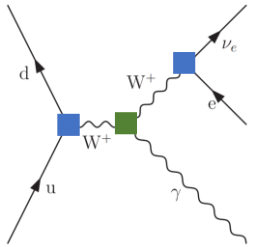


VH(bb) resolved Eur. Phys. J. C 81 (2021) 178
and high pT (boosted) Phys. Lett. B 816 (2021) 136204

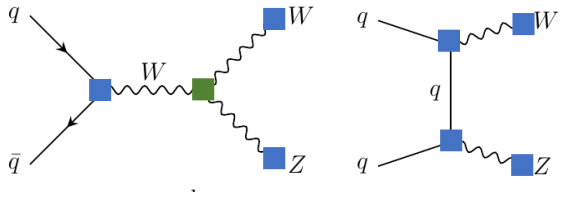
Higgs combination (all but llqq ops) ATLAS-CONF-2020-053 / CMS-PAS-HIG-19-005



EW Z+jj ATLAS - arXiv:2103.01918



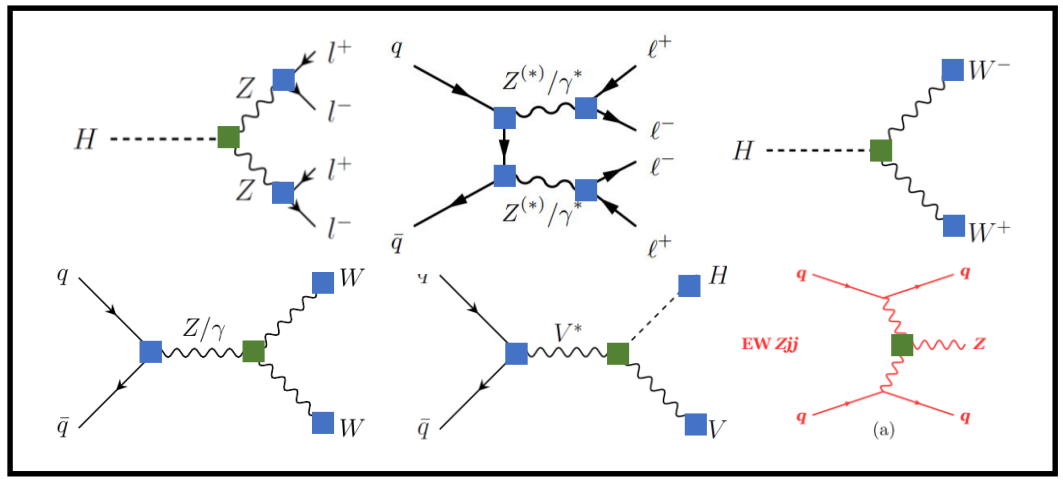
Wγ CMS - arXiv:2102.02283



WZ CMS-PAS-SMP-20-014

EFTs in the EW+Higgs sector : 4 Wilson coefficient groups

Typical EW+Higgs targets at LHC



Parameters of interest (POIs) from direct modification of SM (EW+H) vertices

Weak/Higgs boson interactions : classes H4D2, X2H2, X3

➢ intermediate vertices in LHC processes

$c_{H\Box}$

c_{HB} c_{HWB} c_{HW} c_{HD} HVV

c_W VVV

Couplings to fermions (but tops) psy2XH, psy2H2D

➢ production and decays of V/H at LHC

c_{He} $c_{Hl}^{(1)}$ $c_{Hl}^{(3)}$ c_{Hu} c_{Hd} $c_{Hq}^{(1)}$ $c_{Hq}^{(3)}$

Vll Vqq Hll Hqq HVll HVqq

c_{uB} c_{uW}

Vqq HVqq

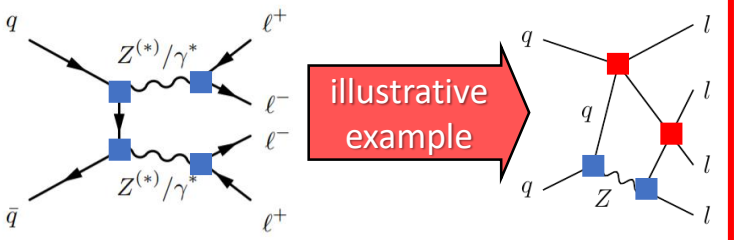
EFTs in the EW+Higgs sector : 4 Wilson coefficient groups

POIs from other sources

4 fermions operators :
- ➢ new diagrams with same final states as SM processes

c_{ee} $c_{ll}^{(1)}$ c_{ll} c_{le} c_{ll}' — 4l

llqq: c_{eu} c_{ed} c_{qe} $c_{lq}^{(1)}$ $c_{lq}^{(3)}$ c_{lu} c_{ld}

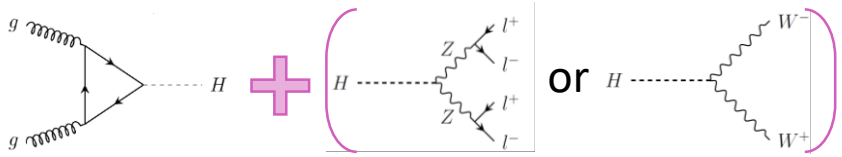


More couplings to fermions : psy2H3
- ➢ Higgs decay width, Hbb in VH

c_{eH} c_{uH} c_{dH} — Hll, Hqq

Strong+Higgs : leading Higgs production is ggF

Hqqg: c_{uG} — c_{HG}: Hgg



(add-ons) Higgs combination :
High relevance in both EW+H and strong+H

4q: $c_{qq}^{(31)}$ $c_{uu}^{(1)}$ $c_{ud}^{(8)}$ c_{qq} $c_{qq}^{(1)}$ $c_{qq}^{(3)}$ $c_{qd}^{(8)}$ c_{uu} $c_{qu}^{(1)}$ $c_{qu}^{(8)}$

c_G — ggg

anomalous Quartic Gauge Coupling operators

Eboli model for aQGC couplings : see [arXiv:hep-ph/0606118]

D^4H^4 operators

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$X^2D^2H^2$ operators

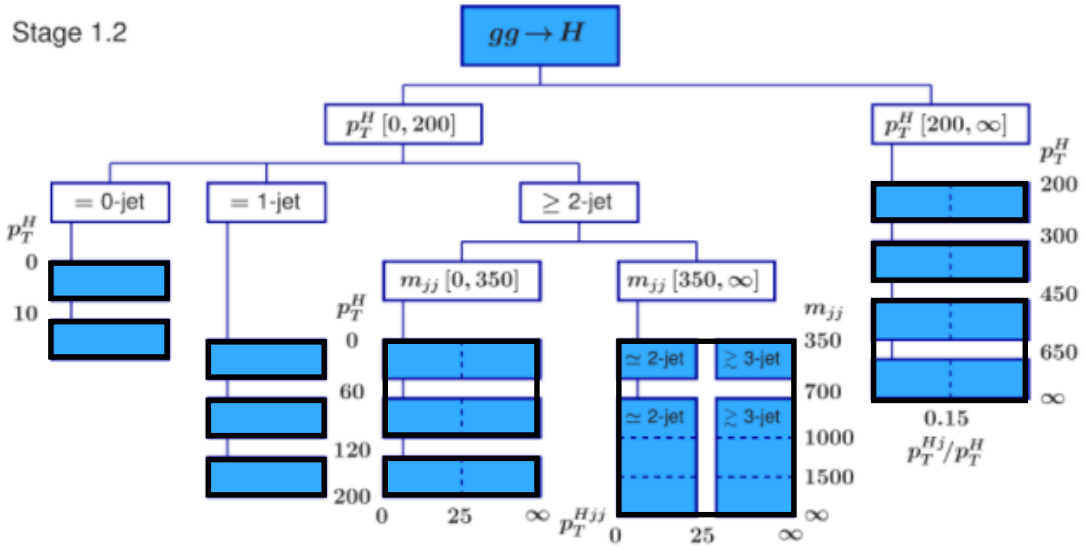
$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right]$$

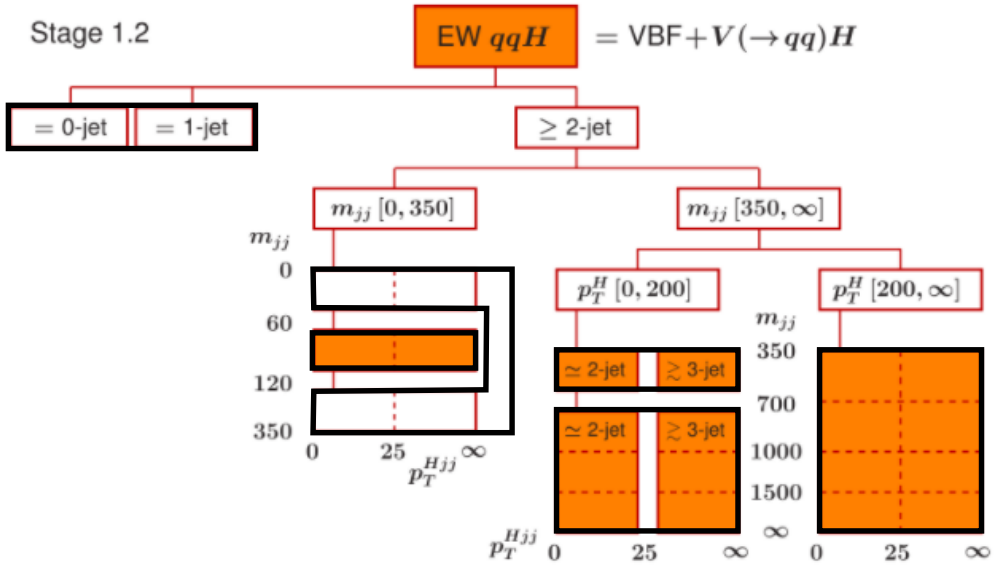
X^4 operators

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

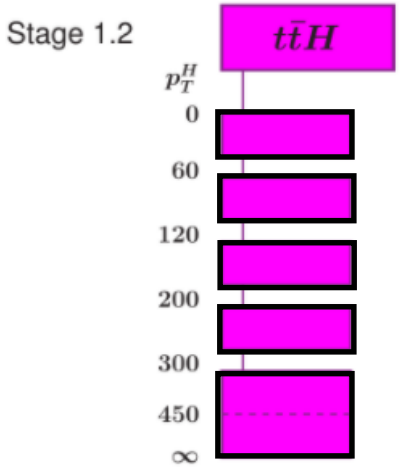
} neutral

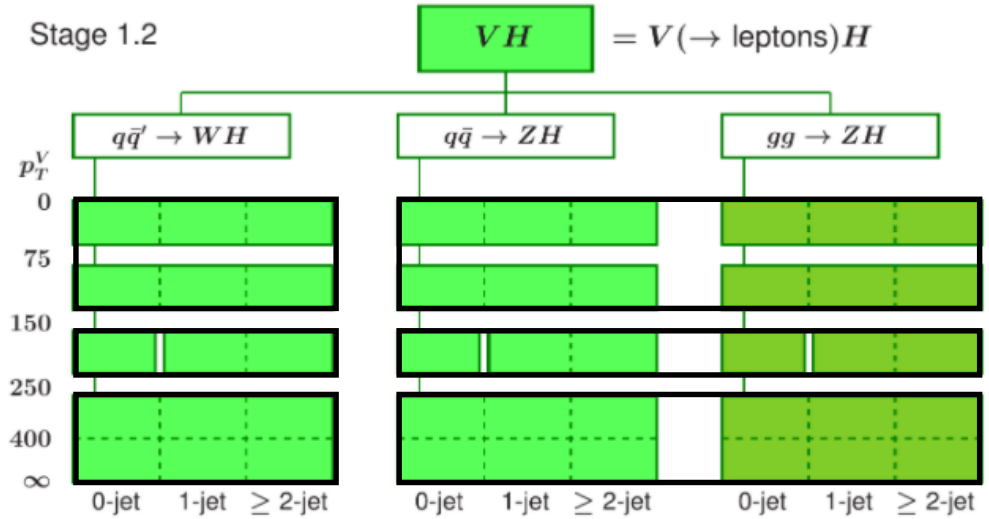
Higgs Simplified Template Cross-Sections





Merged STXS bins in ATLAS EFT interpretation



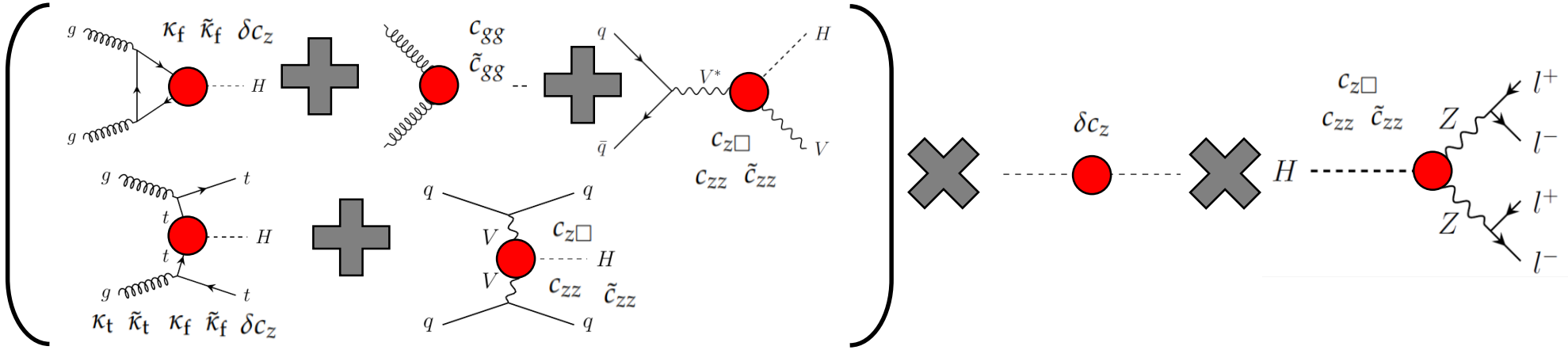


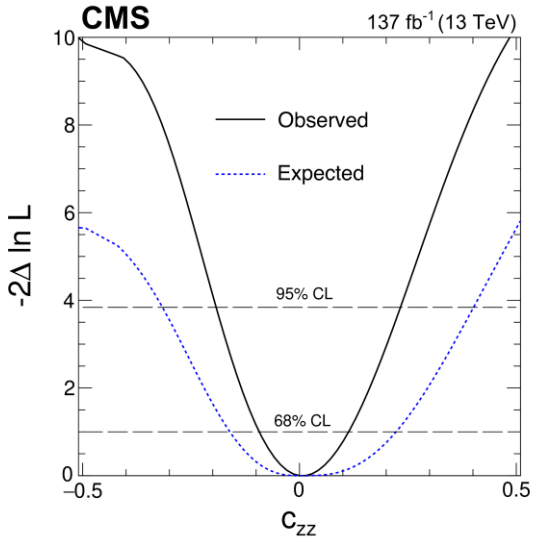
CMS H->4l (CMS-PAS-HIG-19-009) : direct EFT

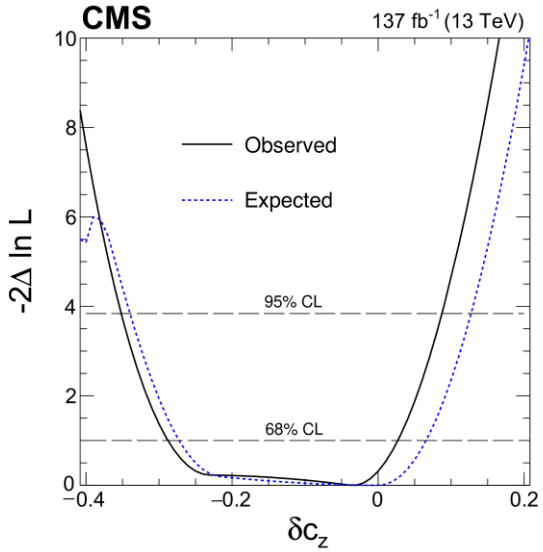
Re-interpretation

dim 6 EFT

Higgs basis







In depth ggH loop VS ggH point like

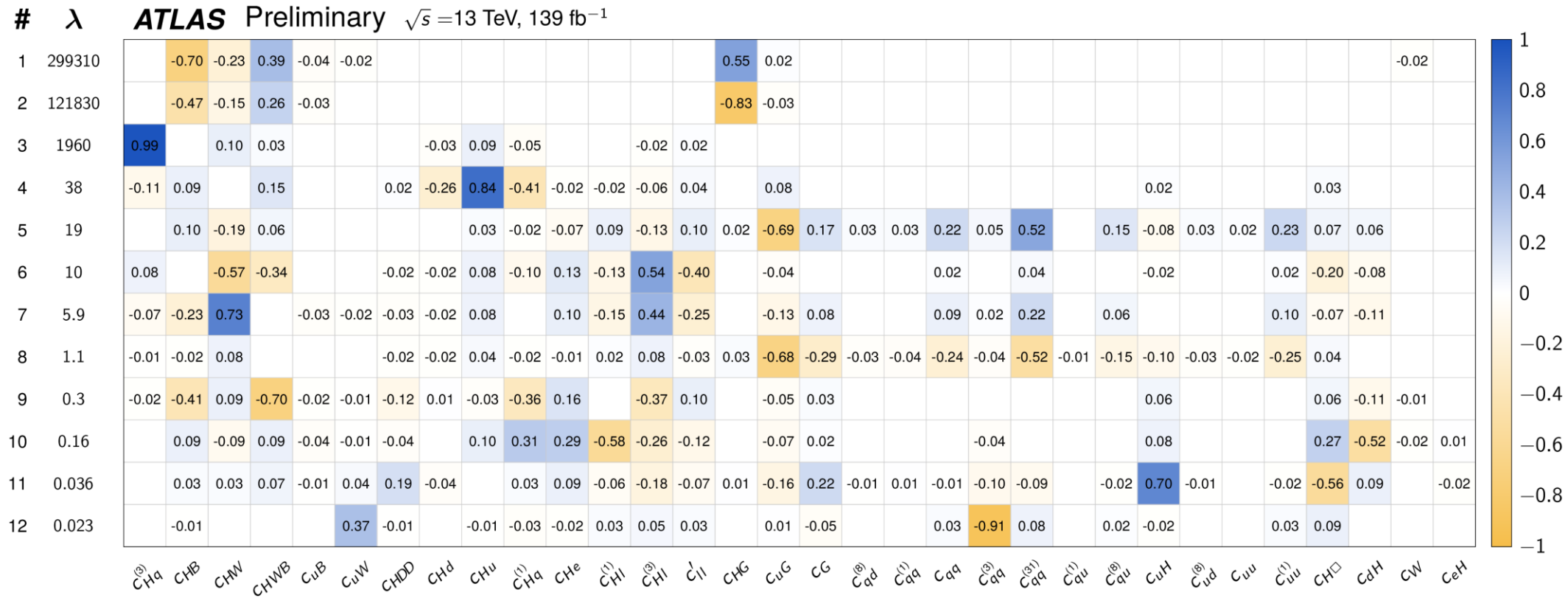
Channels	Coupling	Observed	Expected	Observed correlation			
				c_{gg}	$\tilde{c}_{gg}$	κ_t	$\tilde{\kappa}_t$
tH & $t\bar{t}$H & ggH	c_{gg}	$-0.0012^{+0.0022}_{-0.0174}$	$0.0000^{+0.0019}_{-0.0196}$	1	−0.050	−0.941	+0.029
	$\tilde{c}_{gg}$	$-0.0017^{+0.0160}_{-0.0130}$	$0.0000^{+0.0138}_{-0.0138}$		1	+0.046	−0.568
	κ_t	$1.05^{+0.25}_{-0.20}$	$1.00^{+0.34}_{-0.26}$			1	+0.168
	$\tilde{\kappa}_t$	$-0.01^{+0.69}_{-0.67}$	$0.00^{+0.71}_{-0.71}$				1
				δc_z	c_{zz}	$c_{z\Box}$	$\tilde{c}_{zz}$
VBF & VH & H → 4ℓ	δc_z	$-0.03^{+0.06}_{-0.25}$	$0.00^{+0.07}_{-0.27}$	1	+0.241	−0.060	−0.009
	c_{zz}	$0.01^{+0.11}_{-0.10}$	$0.00^{+0.22}_{-0.16}$		1	−0.884	+0.058
	$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$			1	+0.020
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$				1

Warsaw basis also studied

“Eigen-bases” : identifying flat (uncorrelated) directions

- In ATLAS Higgs combination : ATLAS-CONF-2020-053

- Linear combination of operators to define complete set of variations resolved by data
  - propagate EFT parametrization to $\sigma_i \times BR_X$ covariance matrix,
  - eigenvector decomposition => retain sensitive directions (low eigenvalues ⇔ poorly constrained).

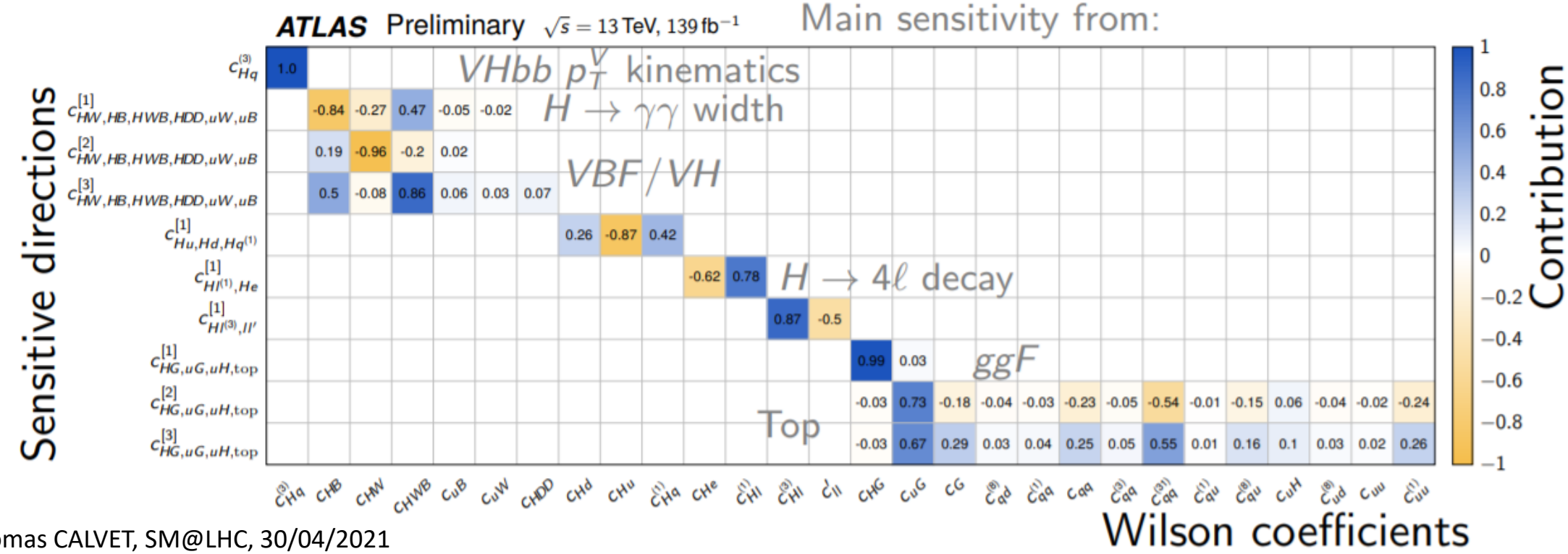


“Eigen-bases” : identifying flat (uncorrelated) directions

- In ATLAS Higgs combination : ATLAS-CONF-2020-053

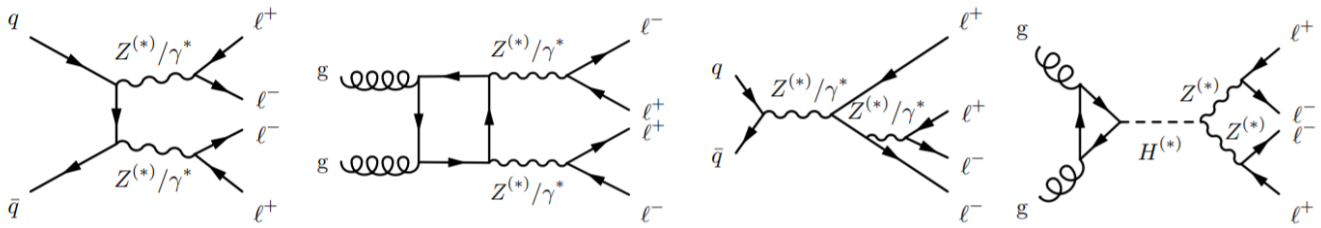
- Linear combination of operators to define complete set of variations resolved by data
  - propagate EFT parametrization to $\sigma_i \times BR_X$ covariance matrix,
  - eigenvector decomposition => retain sensitive directions (low eigenvalues ⇔ poorly constrained).

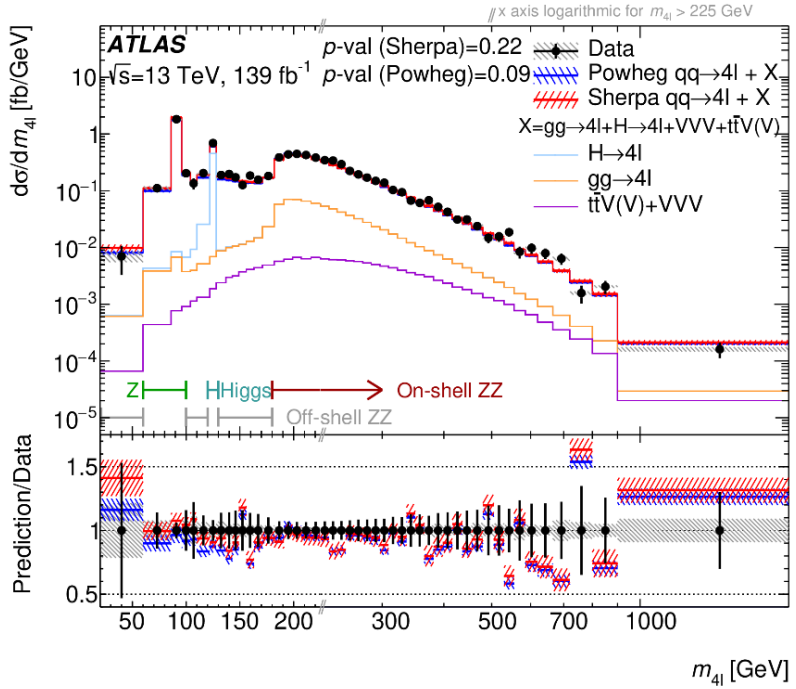
- Identify groups of operators with similar behavior in sensitive directions :
  - 10 final operators from eigenvector decompositions in each sub-spaces.



Using unfolded measurements : ATLAS pp->4l (arXiv:2103.01918)

- pp→4l inclusive (in m_{4l}) analysis of full Run 2 data ($139\ fb^{-1}$) :



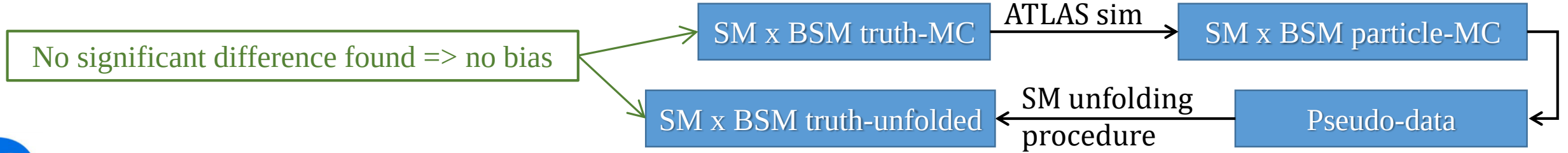


- Re-interpreting ($L(data\,|\,\mu) \xrightarrow{\mu(c_i^{(n)})} L(data\,|c_i^{(n)})$) unfolded double differential measurement :
  - m_{4l} (channel bins) × kinematic/angular observable,

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k\,|C|}} \exp\left\{-\frac{1}{2}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}\left(\vec{\theta}\right)\right]^T C^{-1}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}\left(\vec{\theta}\right)\right]\right\} \times \prod_i \mathcal{G}\left(\theta_i, 0, 1\right)$$

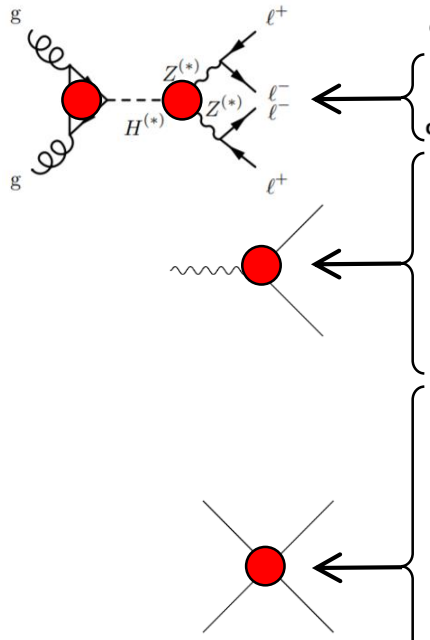
$$\vec{\sigma}^{\text{pred}} = \vec{\sigma}^{\text{SM}} \times \left(1 + c_i \cdot \vec{\sigma}^{\text{INT}}/\vec{\sigma}^{\text{LO SM}} + c_i^2 \cdot \vec{\sigma}^{\text{BSM}}/\vec{\sigma}^{\text{LO SM}}\right)$$

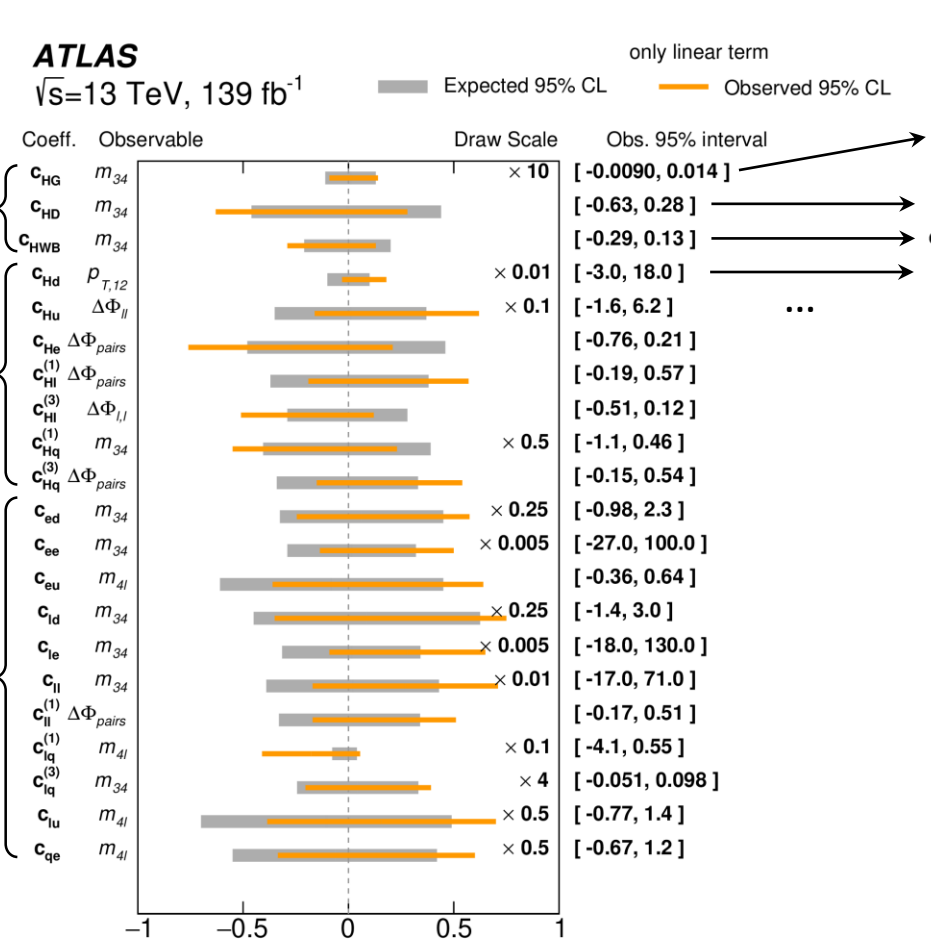
  - **demonstrate no bias in BSM measurements from unfolding.**

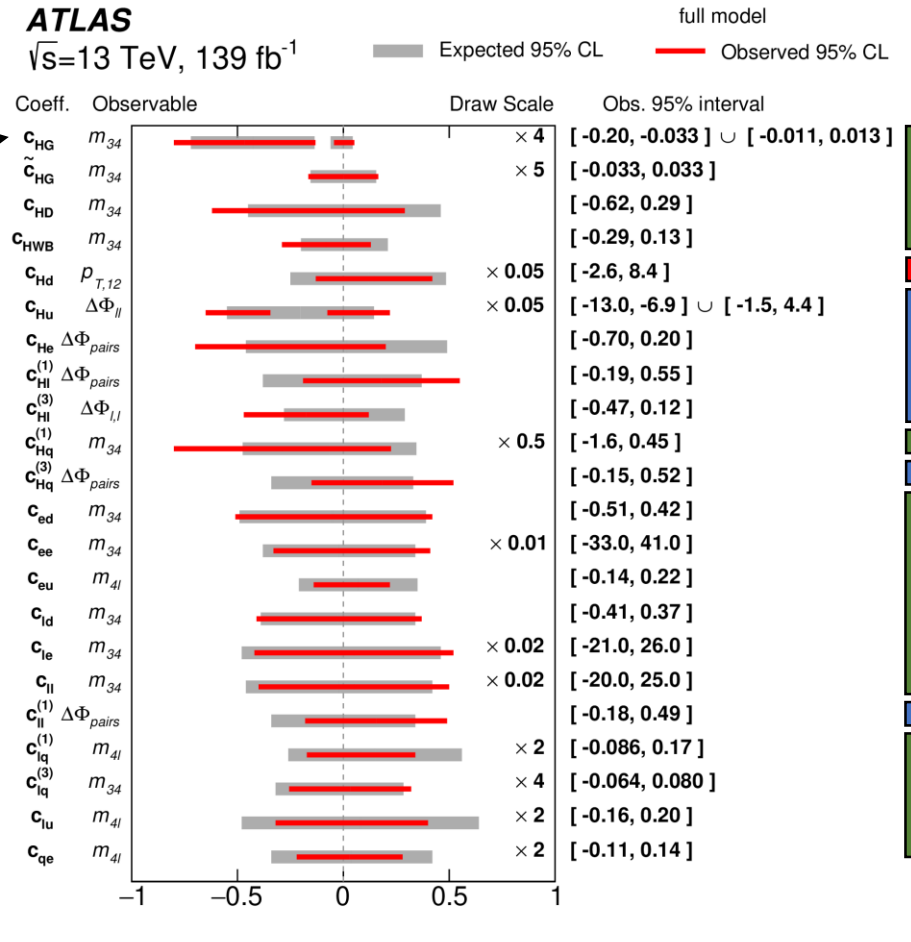


Using unfolded measurements : ATLAS pp->4l (arXiv:2103.01918)

Constrain Wilson coefficients one at a time using optimal pair of observable







$m_{4l} \times m_{34}$ or m_{4l} alone

$m_{4l} \times p_{T,12}$

$m_{4l} \times \Delta\Phi(Z,Z)$ or $\Delta\Phi(l1,l2)$

$$\vec{\sigma}^{\text{pred}} = \vec{\sigma}^{\text{SM}} \times \left(1 + c_i \cdot \vec{\sigma}^{\text{INT}} / \vec{\sigma}^{\text{LO SM}}\right)$$

$$\vec{\sigma}^{\text{pred}} = \vec{\sigma}^{\text{SM}} \times \left(1 + c_i \cdot \vec{\sigma}^{\text{INT}} / \vec{\sigma}^{\text{LO SM}} + \underbrace{c_i^2 \cdot \vec{\sigma}^{\text{BSM}} / \vec{\sigma}^{\text{LO SM}}}\right)$$

Significant impact of $\mathcal{O}(\Lambda^{-4})$ on several limits

WW and H->WW combination in ATLAS (ATL-PHYS-PUB-2021-010)

$H \to WW \to e^{\pm}\nu_e\mu^{\mp}\nu_\mu$ @ 36.1 fb (Phys. Lett. B 789 (2019) 508)

- "differential" in Higgs production : $\mu(ggF)$ and $\mu(VBF)$,
- anti-top cuts (b-tag veto), $m_{e\mu} < 55$ GeV.

$WW \to e^{\pm}\nu_e\mu^{\mp}\nu_\mu$ @ 36.1 fb (Eur. Phys. J. C 79 (2019) 884)

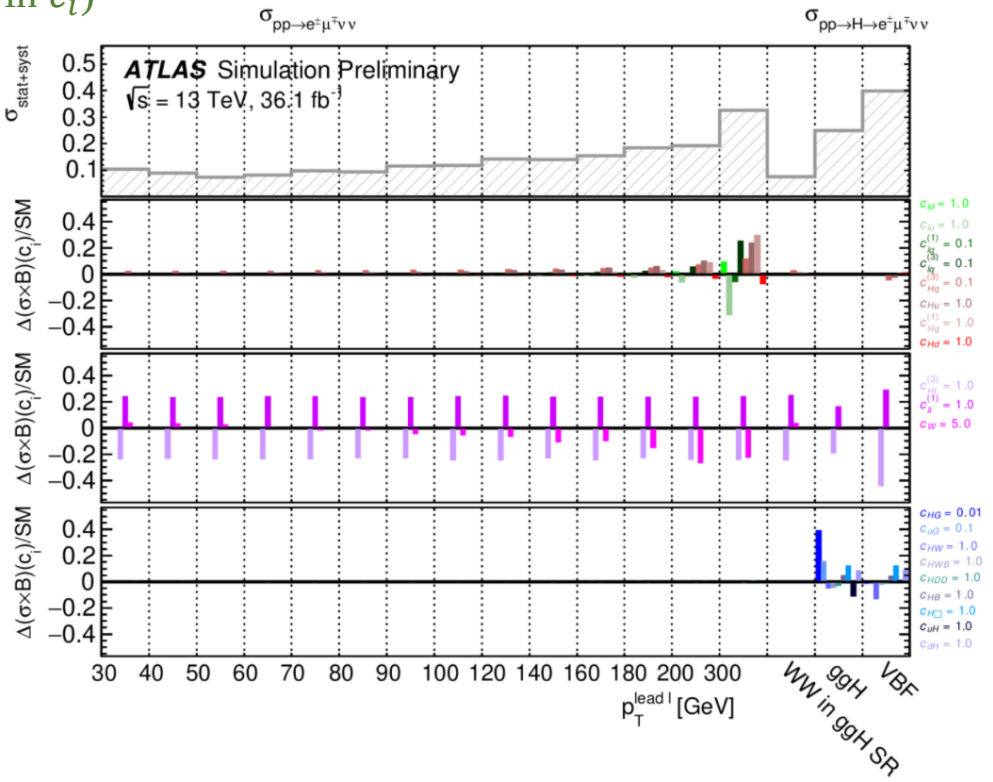
- differential in leading lepton $p_T^{lead\ l}$,
- anti-top cuts (jet vetos), $m_{e\mu} > 55$ GeV.

Combined EFT re-interpretation ($L(data \mid \mu) \xrightarrow{\mu(c_i^{(n)})} L(data \mid c_i^{(n)})$)

cross-sections — Higgs width and BR — Retain only interferences (linear terms in c_i)

$$\sigma^p \mathcal{B}^{H\to e\mu\nu\nu} = \sigma^p_{SM}\mathcal{B}^{H\to e\mu\nu\nu}_{SM}\left(1 + \sum_i A_i^p c_i + \sum_i c_i B_i^{H\to e\nu\mu\nu} - \sum_i c_i B_i^{tot}\right) + O\left(\Lambda^{-4}\right)$$

- Sensitive to 24 operators :
  - 4-fermions and $\psi^2 H^2 D$ operators affecting WW/VBF productions
  - 4-leptons, HWll, WWW, … vertices affecting decays
  - HWW, and ggF modiffiers
- Also consider groups of operators (8 eigen-directions)

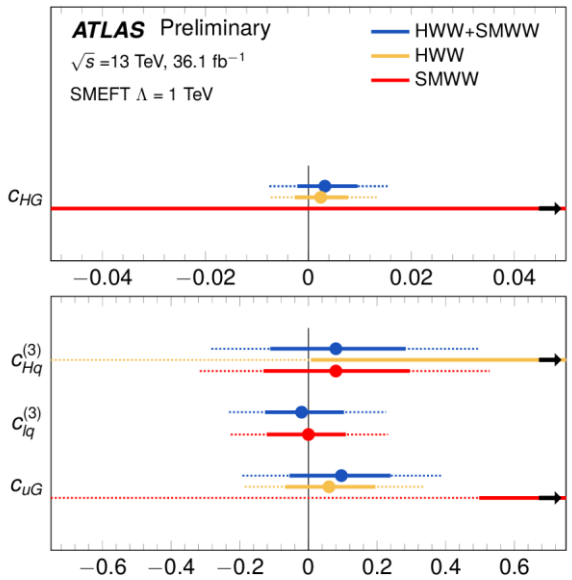


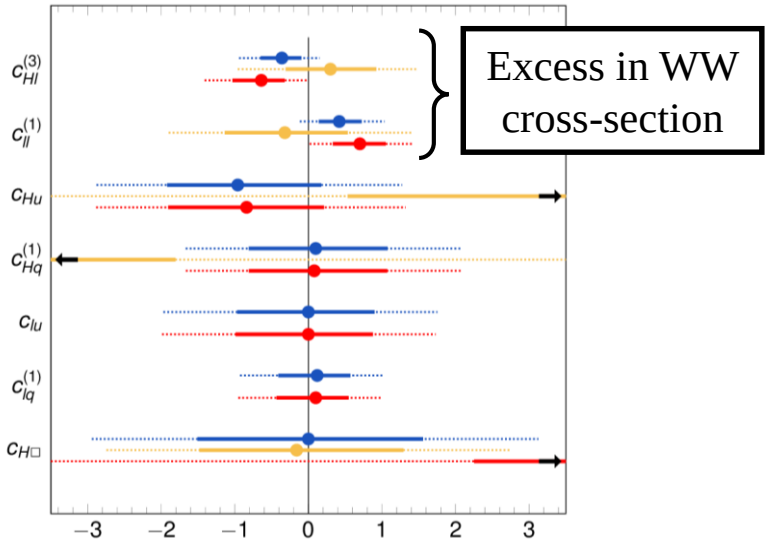
WW and H->WW combination in ATLAS (ATL-PHYS-PUB-2021-010)

- 1D (one parameter at a time) constraints on Wilson coefficients

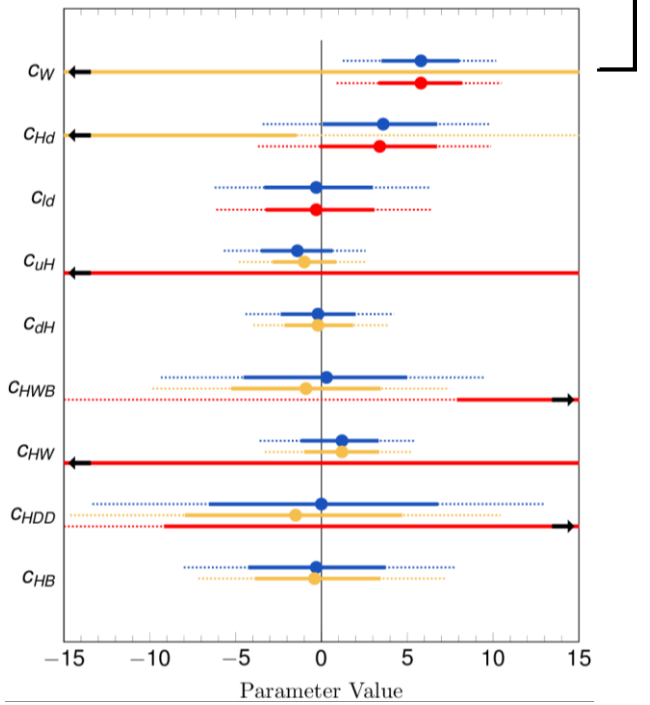
Generally good compatibility with SM (2σ or better)

Observe softer than expected leading lepton





Excess in WW cross-section



Constraining power

Introduction

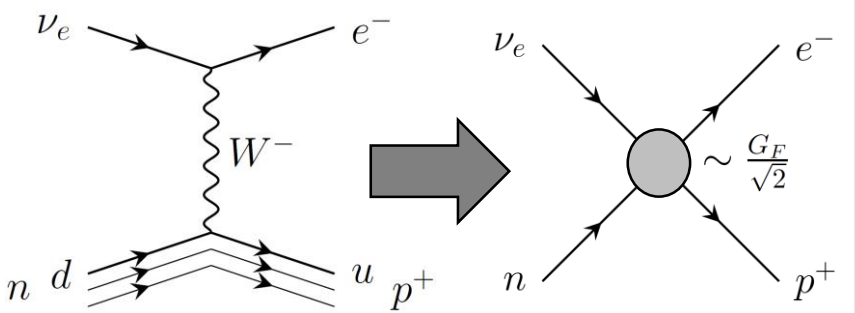
- 10 years pushing the energy frontier with data at the LHC
  - precisely described with the Standard Model

But SM does not describe all of nature's content and phenomena

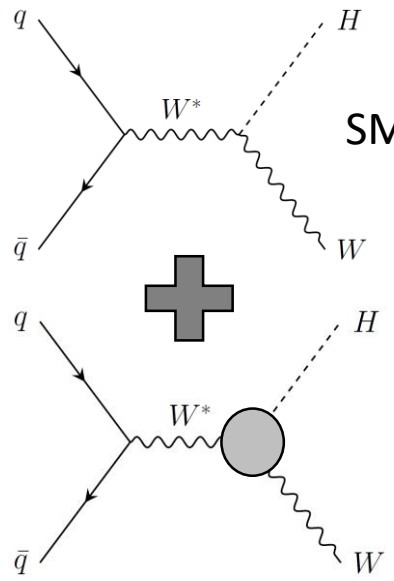
- No direct BSM evidence at "low" (i.e. EW) scales : $M(BSM) > \mathcal{O}(1-40\ TeV)$ while $M(EW) \sim \mathcal{O}(100\ MeV)$
  - See BSM summary plots (ATLAS : SUSY-link, Exotic-link; CMS : SUSY-link, Exotic-link

=> Effective Field Theory

In 1933 : Fermi's 4-point as EFT of the SM



Now : SM as an EFT of ???



EFT => generic correction of SM vertices (HWW in this example)