EFT interpretations in the Higgs and electroweak sectors

-- lecture 2 --

Ecole de Gif 2023 -- Annecy

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Content

1st lecture:

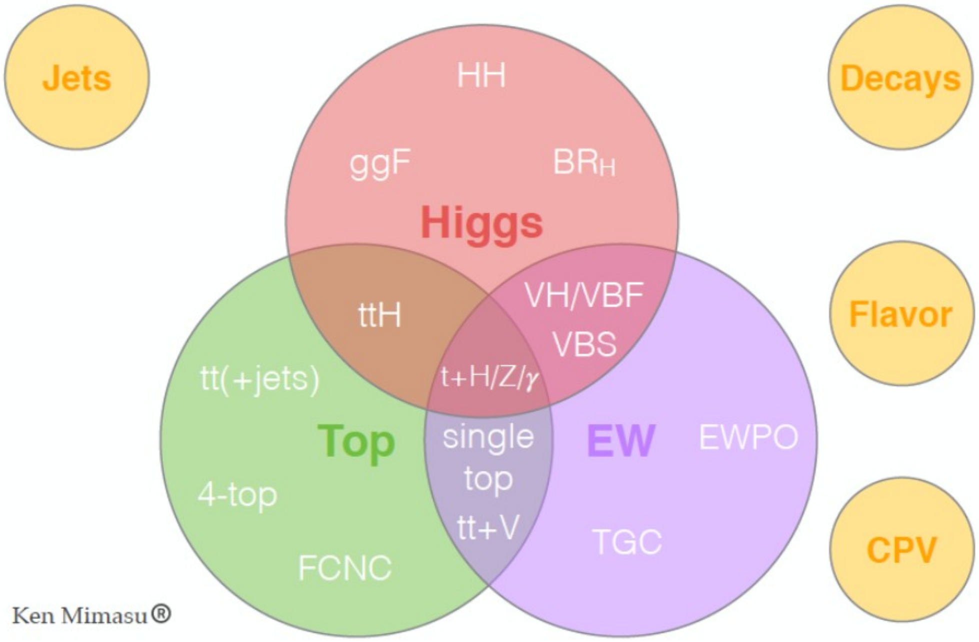
- Higgs physics
  - Higgs production and decay channels and their measurement
  - BSM and EFT sensitivity of each channel
- EW physics
  - Anomalous triple gauge couplings and dim-6 EFT interpretation
  - Beyond dim-6: neutral anomalous triple gauge couplings and quartic gauge couplings

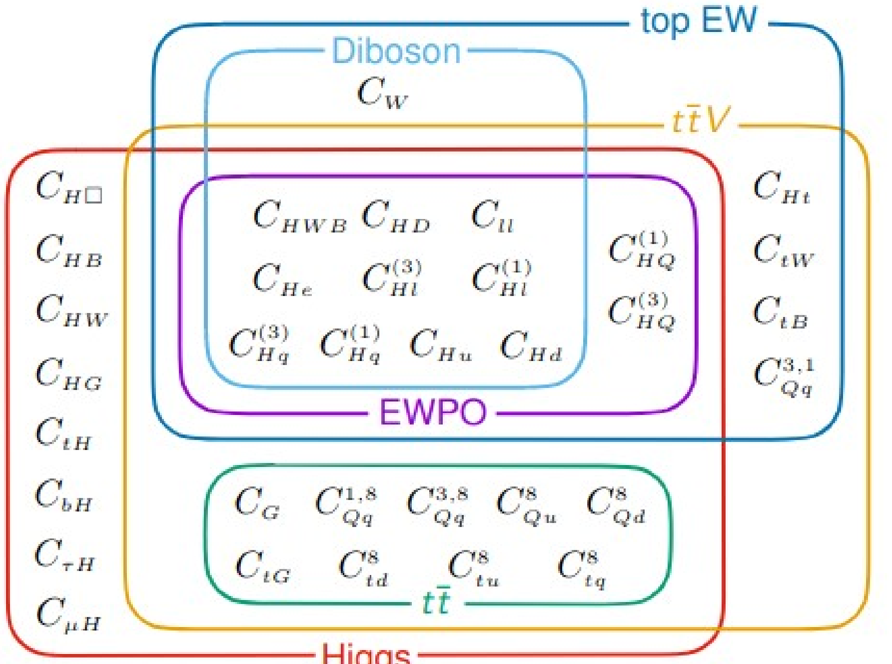
2nd lecture:

- Towards a global fit: combining the available information
  - Experimental challenges of combinations
  - Global fit in action: how to ensure generality / model independence of EFT fits
  - Limitations and perspectives for EFT fits – towards HL-LHC and beyond

Why doing a global fit?

- Complementary probes of SM interactions – sensitive to different BSM models
- Most channels sensitive to several EFT operators with overlap btw. channels → combination
    - Similar event kinematics, e.g. for VBS / VBF – common experimental techniques
    - EW might be dominant Higgs analyses backgrounds, e.g. ttW is main background of ttH in multilepton channel





Why doing a global fit?

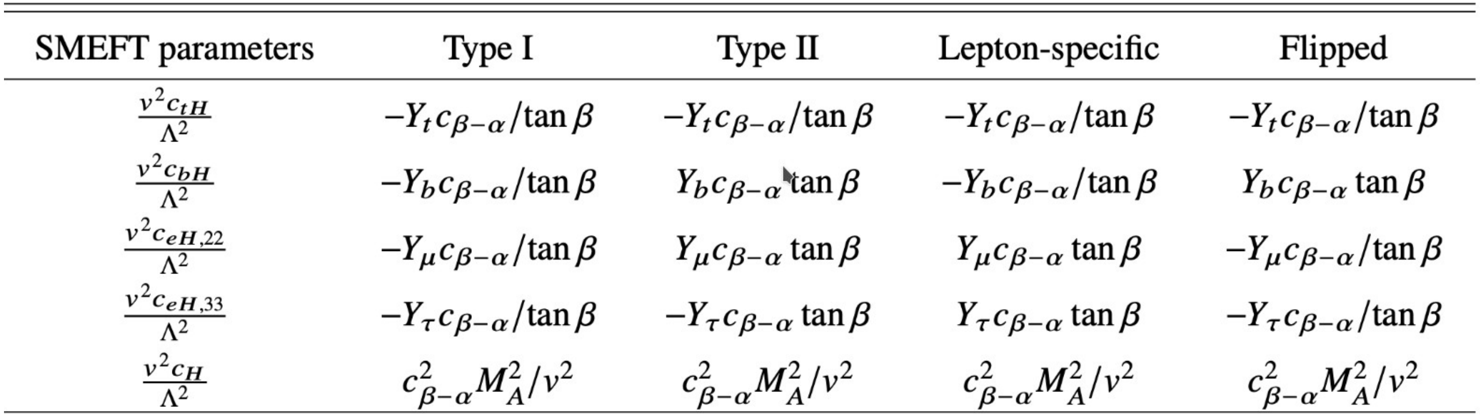
- Why combining at analysis level? -- Could do a simple statistical combination of EFT results
  - Often, no statistical power to constrain all operators simultanously in single analyses -- one EFT operator fit at the time, while others are fixed to 0
  - Why should BSM be so nice to introduce one single EFT operator at the time in each vertex?

    → inducing significant model dependence!

Example: 2 Higgs Doublet Model – excellent indirect limits from Higgs couplings

- Conversion to EFT: several operators impacted

  → no conclusion on 2HDM possible with constraint on one of these EFT operators!



SMEFT parameters	Type I	Type II	Lepton-specific	Flipped
$\frac{v^2 c_{tH}}{\Lambda^2}$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{bH}}{\Lambda^2}$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$
$\frac{v^2 c_{eH,22}}{\Lambda^2}$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{eH,33}}{\Lambda^2}$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$	$-Y_\tau c_{\beta-\alpha}\tan\beta$	$Y_\tau c_{\beta-\alpha}\tan\beta$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_H}{\Lambda^2}$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$

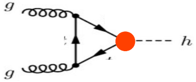
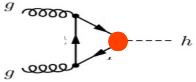
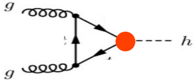
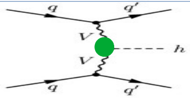
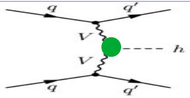
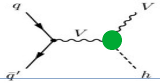
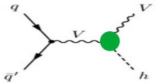
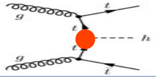
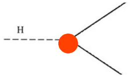
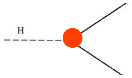
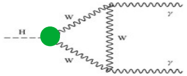
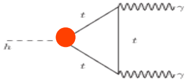
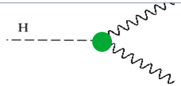
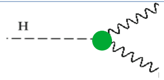
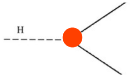
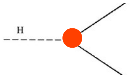
PHYSICAL REVIEW D 102, 055012 (2020)

Why doing a global fit?

- Ideal EFT interpretation: use all available information without making any assumption
  - Combine information from Higgs, EW, top quark physics, including LHC, LEP, etc.
  - Fit all operators with non-zero impact
- In practice, will always make some assumptions, but try to minimise them
- Limitations and needs discovered while practically working on it
- Field in active development, both from theory and experiments – let’s start small!

For those interested in current common LHC activities: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCEFT

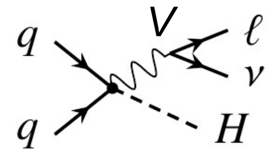
Overview of Higgs couplings to SM particles

Coupling Channel	H-W	H-Z	H-t	H-b	H-c	H-τ	H-μ
ggF							
VBF							
WH							
ZH							
ttH, tH							
H→bb							
H→cc							
H→yy							
H→WW							
H→ZZ							
H→ττ							
H →μμ							

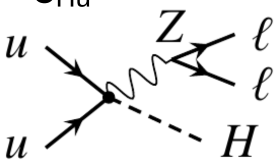
Decorrelating EFT operators through global picture

- Some operators have similar impact on certain distributions

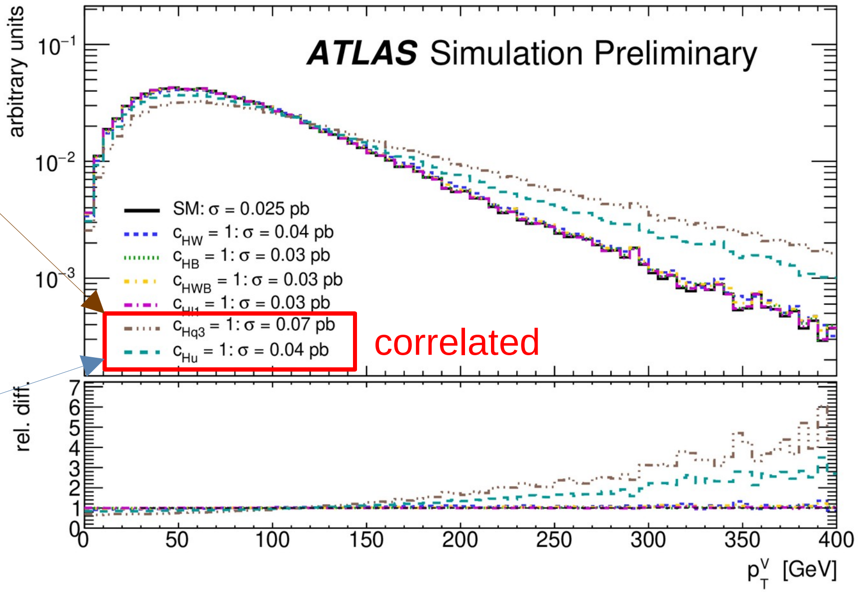
c_{Hq3}



c_{Hu}



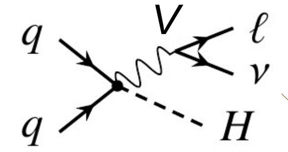
P_T^Z in ZH production:



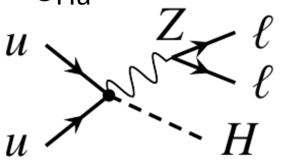
Decorrelating EFT operators through global picture

- Some operators have similar impact on certain distributions
- Adding more channels with different relative impact allows to differentiate

cHq3



cHu



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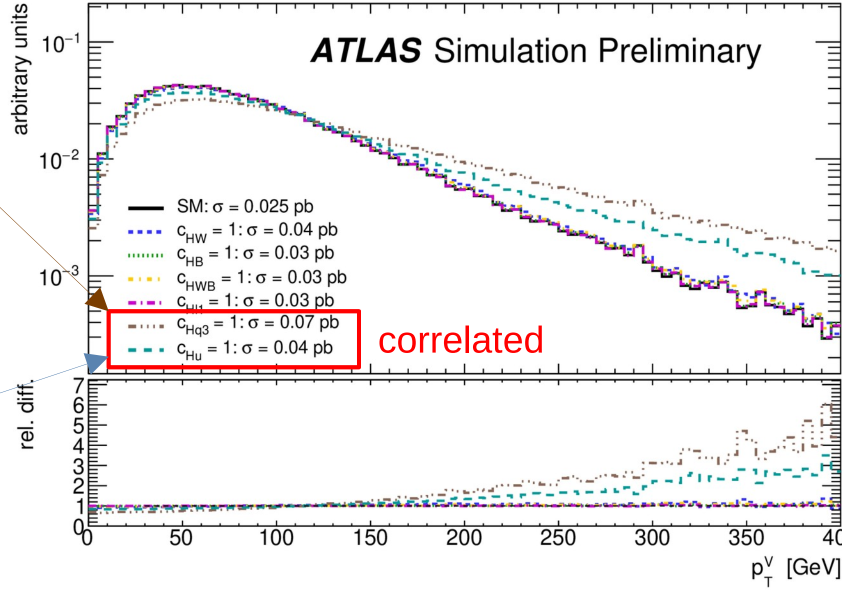
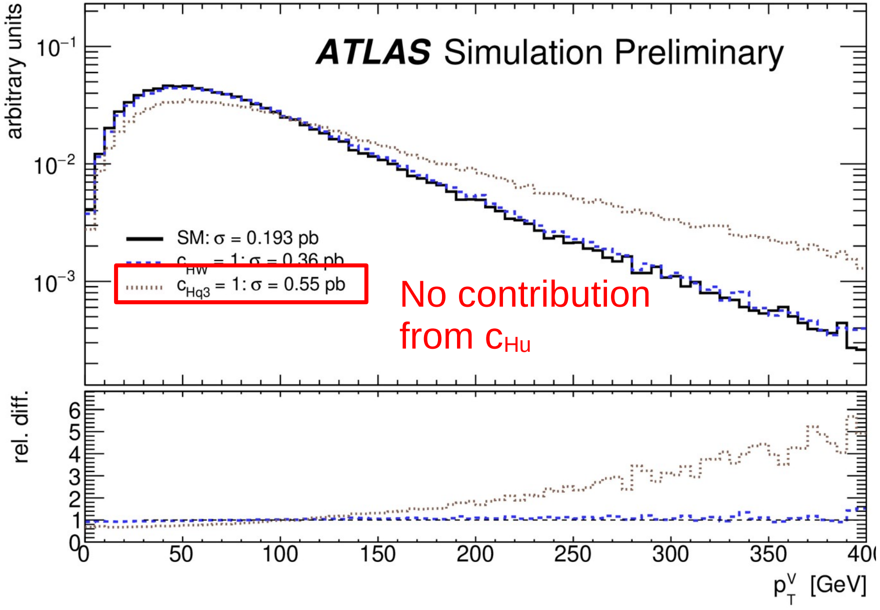


correlated

P_T^W in WH production:



No contribution from c_{Hu}

Decorrelating EFT operators through global picture

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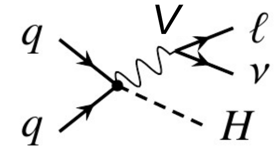
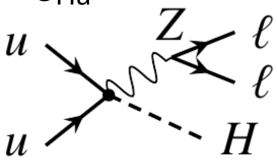


c_{Hu}



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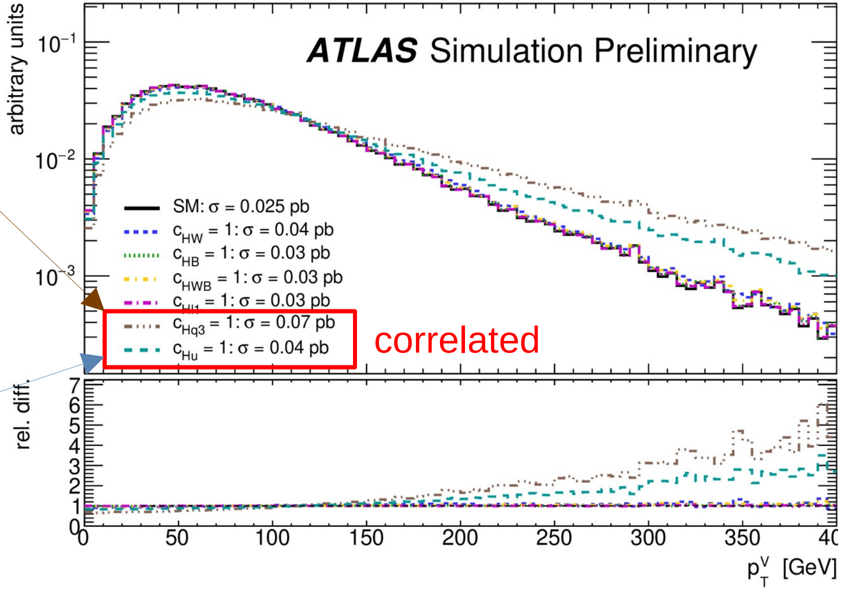
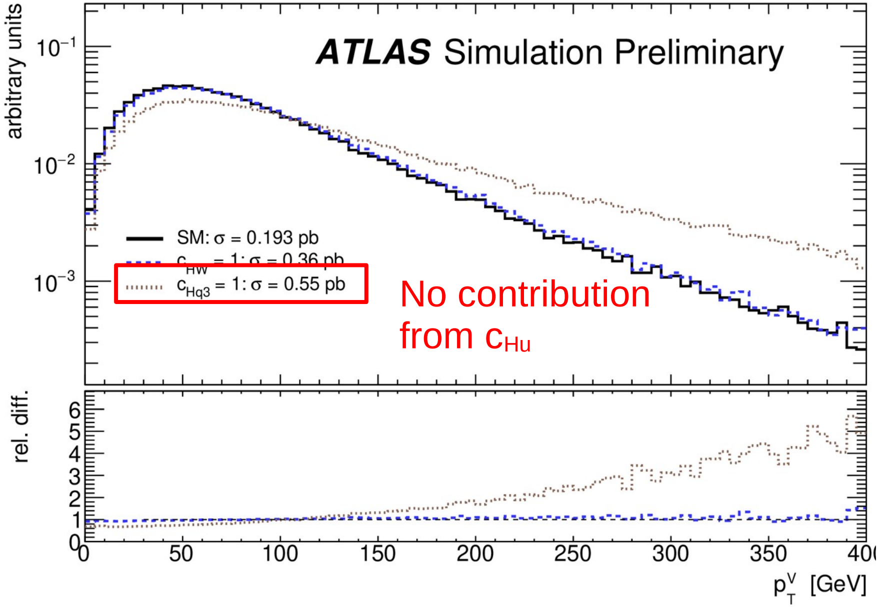


correlated

P_T^W in WH production:



No contribution from c_{Hu}

- In a similar way, measuring production x decay → correlation between relevant operators
- Decorrelation when measuring same production mode in different decay channels

Experimental challenges of a combination

- Choice of a common setup (need to work together between collaborations and with theorists:
  - Using SMEFT in Warsaw basis with defined input parameter set
  - BSM scale – staying in the validity regime, while still keeping sensitivity
- Analysis design:
  - As many as possible final states – general analyses, but with good BSM sensitivity
  - Ensure orthogonality between analyses (no common events)
  - Backgrounds of one analysis might be signal of another – orthogolality at the price of sensitivity?
  - Correlate common systematics to ensure consistent approach

Step-by-step towards a global combination

Detailed example:
Higgs combination...

Simplified Template Cross Sections (STXS)

Differential cross sections maximising sensitivity to BSM in combined measurement from all Higgs decays:

Simplified Template Cross Sections (STXS)

Differential cross sections maximising sensitivity to BSM in combined measurement from all Higgs decays:

- Categorisation in production modes: small model dependence, but allows to use all decay channels were they are best

Example: gluon fusion and VH

$gg \to H$
$[\ +\ gg \to Z(q\bar{q})H\ +\ pp \to b\bar{b}H\ ]$

Large statistics, but large background
→best in channels with full Higgs reconstruction and good mass resolution (e.g. H→γγ or H→4l)

VH
$[\ pp \to V(\ell\nu, \ell\ell, \nu\nu)H\ ]$

Rare, but good efficiency of leptonic V tagging
→ best in channels with large branching fraction (e.g. H→bb)

Simplified Template Cross Sections (STXS)

Differential cross sections maximising sensitivity to BSM in combined measurement from all Higgs decays:

- Categorisation in production modes: small model dependence, but allows to use all decay channels were they are best
- Kinematic binning defined in each production mode using well measured variables in dominant analysis channel

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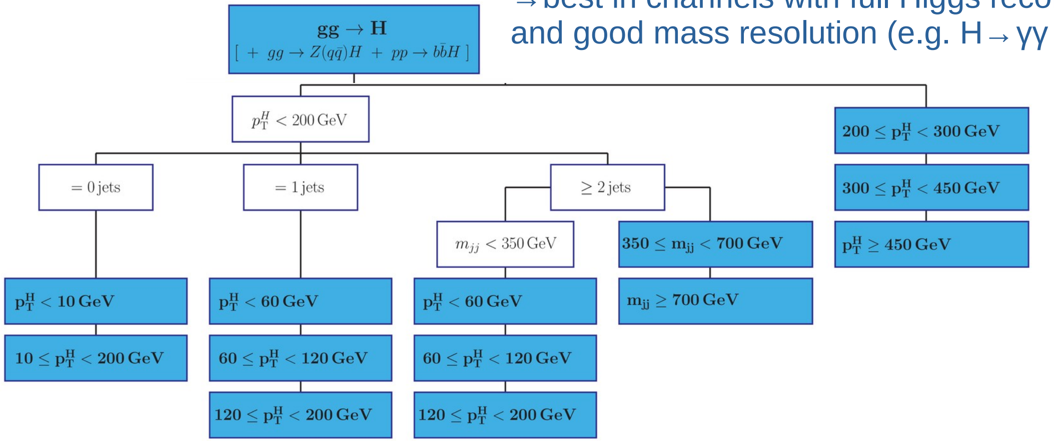

$gg \to H$
$[\ +\ gg \to Z(q\bar{q})H\ +\ pp \to b\bar{b}H\ ]$

$p_T^H < 200\,\mathrm{GeV}$

$= 0\,\mathrm{jets}$

$p_T^H < 10\,\mathrm{GeV}$

$10 \leq p_T^H < 200\,\mathrm{GeV}$

$= 1\,\mathrm{jets}$

$p_T^H < 60\,\mathrm{GeV}$

$60 \leq p_T^H < 120\,\mathrm{GeV}$

$120 \leq p_T^H < 200\,\mathrm{GeV}$

$\geq 2\,\mathrm{jets}$

$m_{jj} < 350\,\mathrm{GeV}$

$p_T^H < 60\,\mathrm{GeV}$

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$120 \leq p_T^H < 200\,\mathrm{GeV}$

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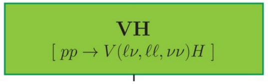

VH
$[\ pp \to V(\ell\nu, \ell\ell, \nu\nu)H\ ]$

Rare, but good efficiency of leptonic V tagging
→ best in channels with large branching fraction (e.g. H→bb)

Binning in:

- N-jets
- Dijet-mass (for ggF+≥2jets)
- Higgs p_T: well resolved in H→γγ or H→4l

Simplified Template Cross Sections (STXS)

Differential cross sections maximising sensitivity to BSM in combined measurement from all Higgs decays:

- Categorisation in production modes: small model dependence, but allows to use all decay channels were they are best
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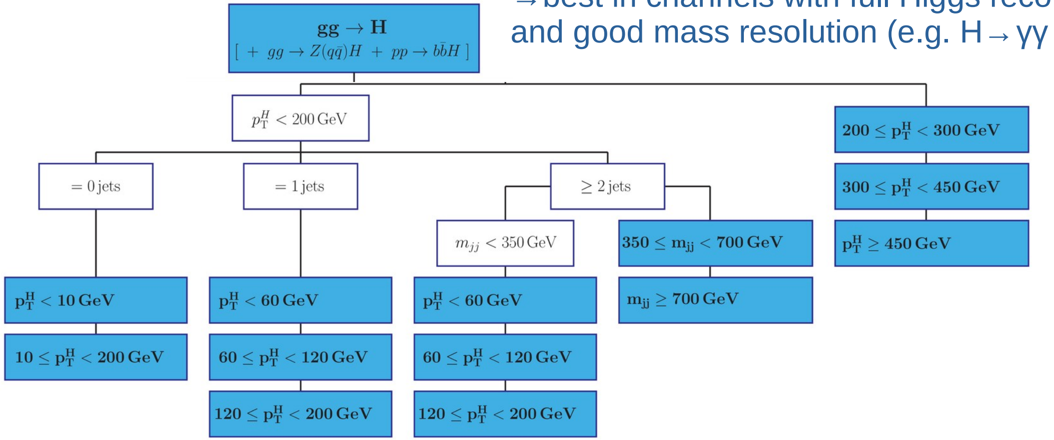

gg → H
$[\ +\ gg \to Z(q\bar{q})H\ +\ pp \to b\bar{b}H\ ]$

$p_T^H < 200\,\mathrm{GeV}$

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$\geq 2\,\mathrm{jets}$
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  - $p_T^H < 60$ GeV
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Rare, but good efficiency of leptonic V tagging
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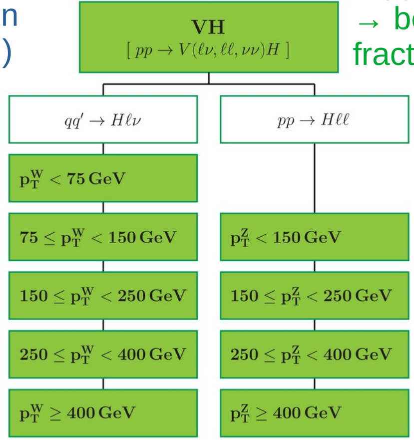


VH
$[\ pp \to V(\ell\nu, \ell\ell, \nu\nu)H\ ]$

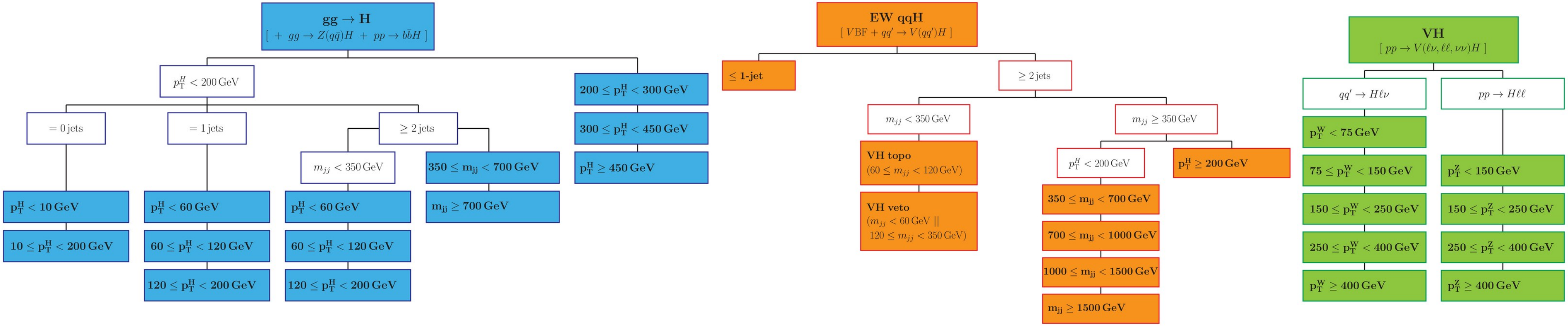
$qq' \to H\ell\nu$
- $p_T^W < 75$ GeV
- $75 \leq p_T^W < 150$ GeV
- $150 \leq p_T^W < 250$ GeV
- $250 \leq p_T^W < 400$ GeV
- $p_T^W \geq 400$ GeV

$pp \to H\ell\ell$
- $p_T^Z < 150$ GeV
- $150 \leq p_T^Z < 250$ GeV
- $250 \leq p_T^Z < 400$ GeV
- $p_T^Z \geq 400$ GeV

Binning in:
- N-jets
- Dijet-mass (for ggF+≥2jets)
- Higgs p_T: well resolved in H→γγ or H→4l

Binning in:
- Number of charged leptons (W→lν vs. Z→ll or Z→νν)
- Vector boson p_T: well measured (p_T^H hard in H→bb), good BSM sensitivity (correlated to p_T^H)

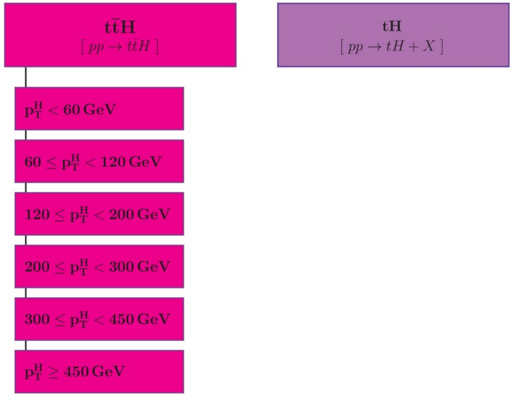
Simplified Template Cross Sections (STXS)



- **$gg \to H$** $[\, + \, gg \to Z(q\bar{q})H \, + \, pp \to b\bar{b}H \,]$
  - $p_T^H < 200\,\mathrm{GeV}$
    - $= 0\,\mathrm{jets}$
      - $p_T^H < 10\,\mathrm{GeV}$
      - $10 \le p_T^H < 200\,\mathrm{GeV}$
    - $= 1\,\mathrm{jets}$
      - $p_T^H < 60\,\mathrm{GeV}$
      - $60 \le p_T^H < 120\,\mathrm{GeV}$
      - $120 \le p_T^H < 200\,\mathrm{GeV}$
    - $\ge 2\,\mathrm{jets}$
      - $m_{jj} < 350\,\mathrm{GeV}$
        - $p_T^H < 60\,\mathrm{GeV}$
        - $60 \le p_T^H < 120\,\mathrm{GeV}$
        - $120 \le p_T^H < 200\,\mathrm{GeV}$
      - $350 \le m_{jj} < 700\,\mathrm{GeV}$
      - $m_{jj} \ge 700\,\mathrm{GeV}$
  - $200 \le p_T^H < 300\,\mathrm{GeV}$
  - $300 \le p_T^H < 450\,\mathrm{GeV}$
  - $p_T^H \ge 450\,\mathrm{GeV}$

- **EW qqH** $[\, \mathrm{VBF} + qq' \to V(qq')H \,]$
  - $\le$ 1-jet
  - $\ge 2\,\mathrm{jets}$
    - $m_{jj} < 350\,\mathrm{GeV}$
      - VH topo $(60 \le m_{jj} < 120\,\mathrm{GeV})$
      - VH veto $(m_{jj} < 60\,\mathrm{GeV} \;||\; 120 \le m_{jj} < 350\,\mathrm{GeV})$
    - $m_{jj} \ge 350\,\mathrm{GeV}$
      - $p_T^H < 200\,\mathrm{GeV}$
        - $350 \le m_{jj} < 700\,\mathrm{GeV}$
        - $700 \le m_{jj} < 1000\,\mathrm{GeV}$
        - $1000 \le m_{jj} < 1500\,\mathrm{GeV}$
        - $m_{jj} \ge 1500\,\mathrm{GeV}$
      - $p_T^H \ge 200\,\mathrm{GeV}$

- **VH** $[\, pp \to V(\ell\nu, \ell\ell, \nu\nu)H \,]$
  - $qq' \to H\ell\nu$
    - $p_T^W < 75\,\mathrm{GeV}$
    - $75 \le p_T^W < 150\,\mathrm{GeV}$
    - $150 \le p_T^W < 250\,\mathrm{GeV}$
    - $250 \le p_T^W < 400\,\mathrm{GeV}$
    - $p_T^W \ge 400\,\mathrm{GeV}$
  - $pp \to H\ell\ell$
    - $p_T^Z < 150\,\mathrm{GeV}$
    - $150 \le p_T^Z < 250\,\mathrm{GeV}$
    - $250 \le p_T^Z < 400\,\mathrm{GeV}$
    - $p_T^Z \ge 400\,\mathrm{GeV}$



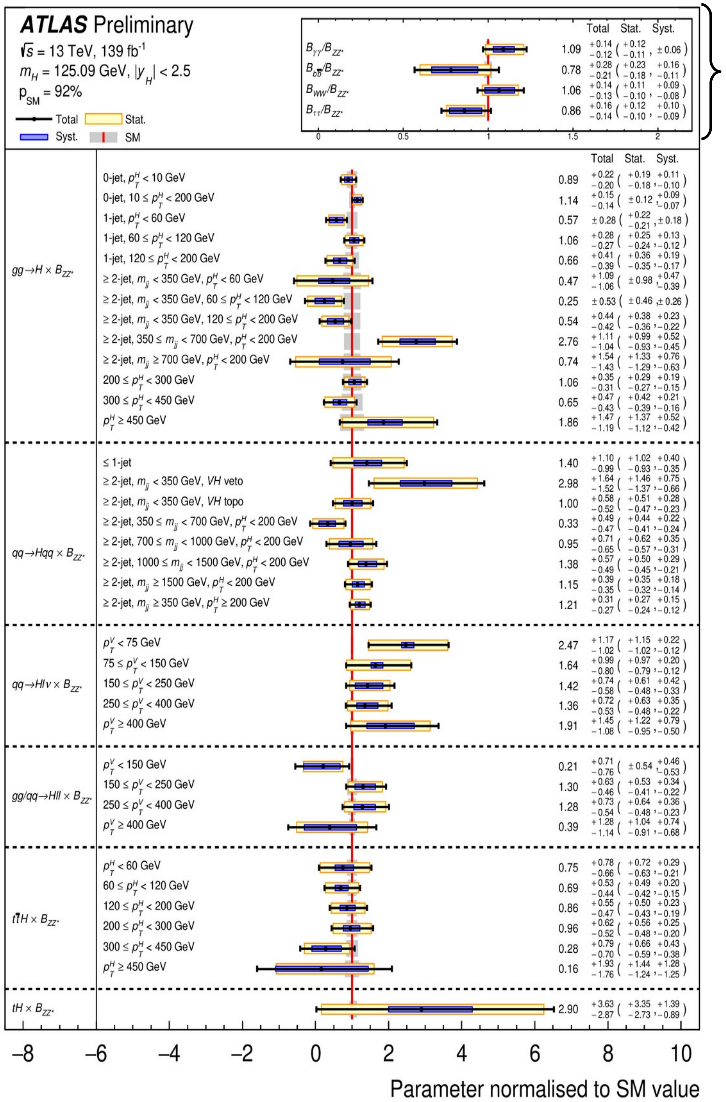
- **$t\bar{t}H$** $[\, pp \to t\bar{t}H \,]$
  - $p_T^H < 60\,\mathrm{GeV}$
  - $60 \le p_T^H < 120\,\mathrm{GeV}$
  - $120 \le p_T^H < 200\,\mathrm{GeV}$
  - $200 \le p_T^H < 300\,\mathrm{GeV}$
  - $300 \le p_T^H < 450\,\mathrm{GeV}$
  - $p_T^H \ge 450\,\mathrm{GeV}$

- **tH** $[\, pp \to tH + X \,]$

- Common binning across experiments defined for all (major) production modes
- Ensure flat acceptance within each bin (within stat. Uncertainties):
  - dedicated treatment of theory uncertainties to reduce impact
  - re-optimise binning with increasing amount of data
- Possibility to merge bins for single analyses depending on their sensitivity in specific regions
- Each analysis can be optimised for sensitivity to these bins using e.g. ML techniques

Input measurement

In combination, often measure cross section x reference decay (H→ZZ*) + ratios of other decays to reference → ensure good model independence



$$\frac{BR(H\to X)}{BR(H\to ZZ^*)}$$

ggF x BR(H→ZZ*)

VBF x BR(H→ZZ*)

WH x BR(H→ZZ*)

ZH x BR(H→ZZ*)

ttH x BR(H→ZZ*)

tH x BR(H→ZZ*)

Input measurement

- In combination, often measure cross section x reference decay ($H\rightarrow ZZ^*$) + ratios of other decays to reference → ensure good model independence
- Due to BR ratios, this is not anymore the fully Gaussian case and harder to re-interpret
- Working with experimental likelihood → access to full information for cross section in every channel

ggF x BR($H\rightarrow ZZ^*$)

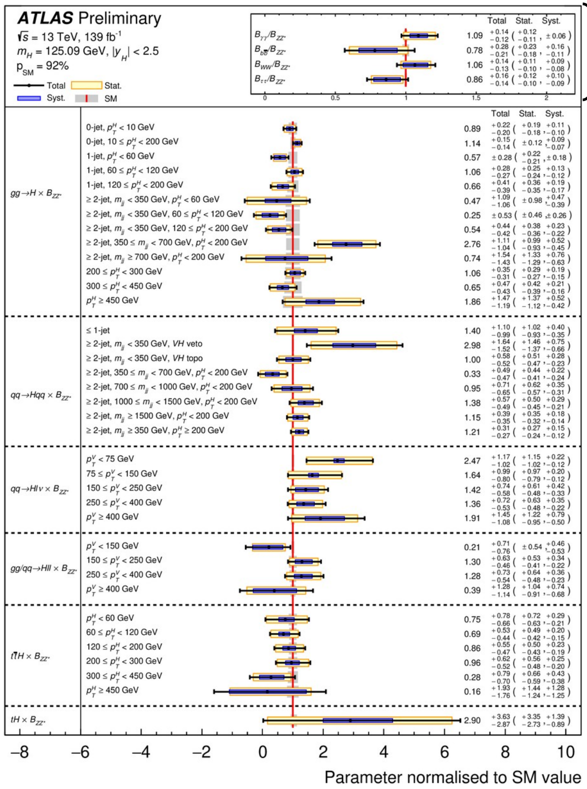
VBF x BR($H\rightarrow ZZ^*$)

WH x BR($H\rightarrow ZZ^*$)

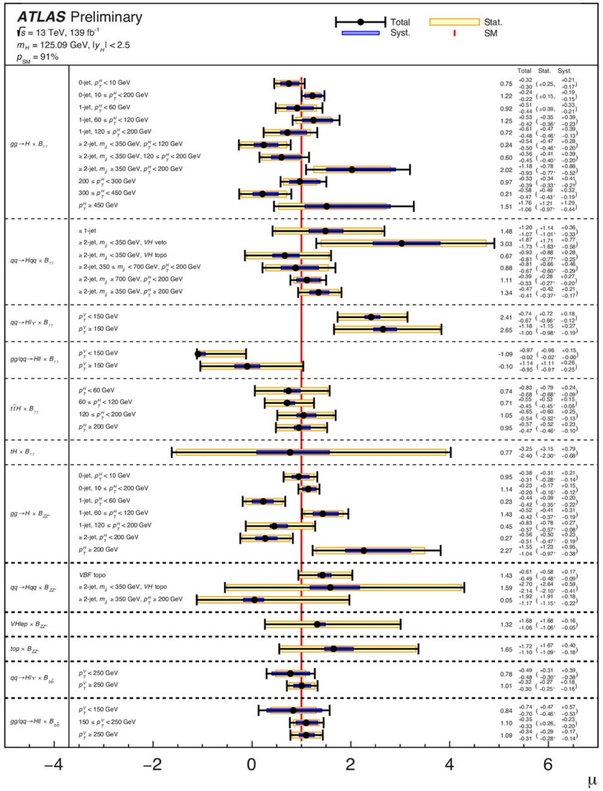
ZH x BR($H\rightarrow ZZ^*$)

ttH x BR($H\rightarrow ZZ^*$)

tH x BR($H\rightarrow ZZ^*$)



$$\frac{BR(H\rightarrow X)}{BR(H\rightarrow ZZ^*)}$$



ggF x BR($H\rightarrow \gamma\gamma$)

VBF x BR($H\rightarrow \gamma\gamma$)

WH x BR($H\rightarrow \gamma\gamma$)

ZH x BR($H\rightarrow \gamma\gamma$)

ttH x BR($H\rightarrow \gamma\gamma$)

tH x BR($H\rightarrow \gamma\gamma$)

ggF x BR($H\rightarrow ZZ^*$)

VBF x BR($H\rightarrow ZZ^*$)

VH x BR($H\rightarrow ZZ^*$)

ttH x BR($H\rightarrow ZZ^*$)

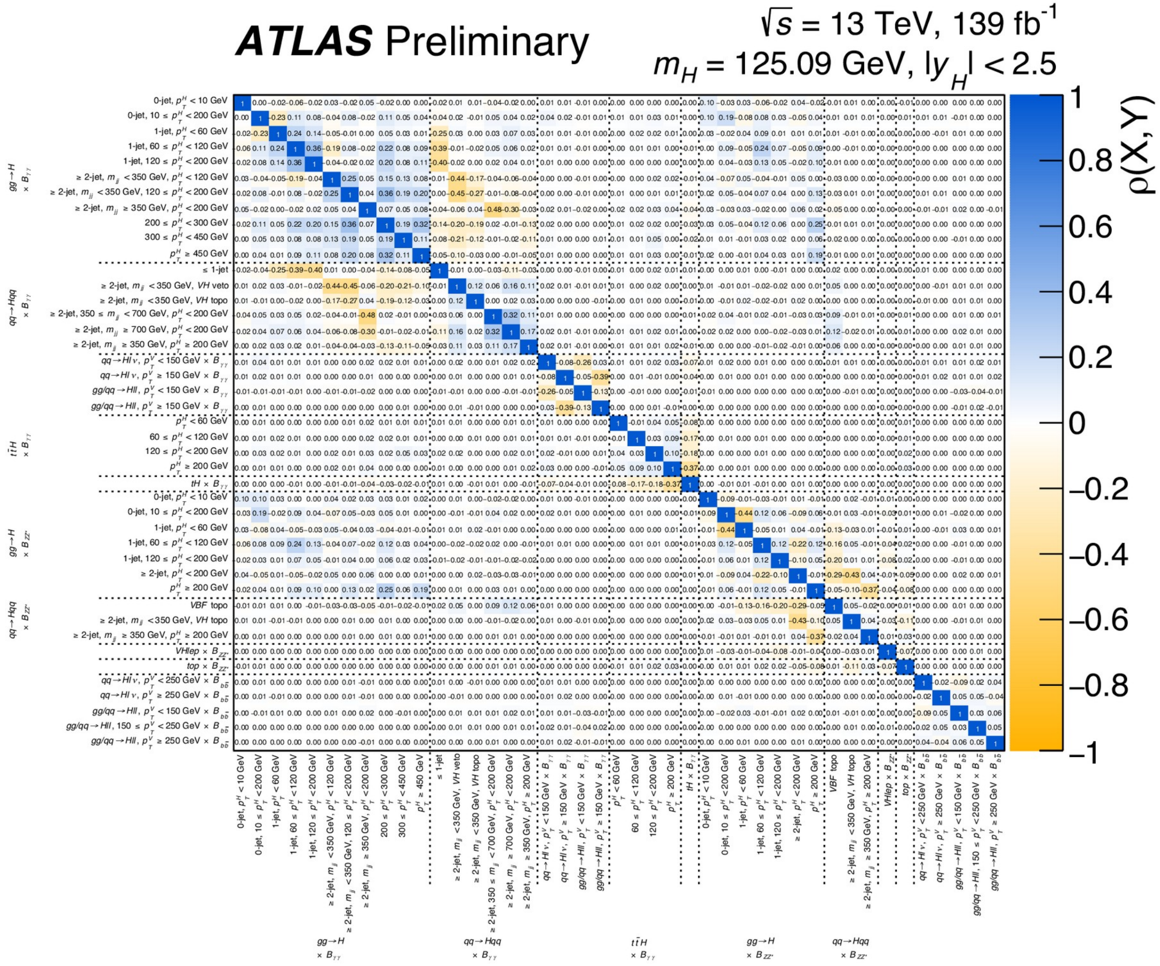
WH x BR($H\rightarrow bb$)

ZH x BR($H\rightarrow bb$)

Input measurement

Corresponding covariance matrix:

- can assume Gaussianity
- overall small correlations from common systematic uncertainties



EFT parametrisation

Reminder: $$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots$$

$$\sigma_{\text{STXS}} = \sigma_{\text{SM}} + \underbrace{\sigma_{\text{int}}}_{\sim 1/\Lambda^2} + \underbrace{\sigma_{\text{BSM}}}_{\sim 1/\Lambda^4} = \sigma_{\text{SM}}^{((\text{N})\text{N})\text{NLO}} \times \left(1 + \frac{\sigma_{\text{int}}^{(\text{N})\text{LO}}}{\sigma_{\text{SM}}^{(\text{N})\text{LO}}} + \frac{\sigma_{\text{BSM}}^{(\text{N})\text{LO}}}{\sigma_{\text{SM}}^{(\text{N})\text{LO}}}\right).$$

Parametrisation of production & decay product:

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

Production (σ) $\otimes$ Decay ($BR = \Gamma_{H\to X} / \Gamma_H$)

EFT parametrisation

Reminder:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

$$\sigma_{\rm STXS} = \sigma_{\rm SM} + \underbrace{\sigma_{\rm int}}_{\sim 1/\Lambda^2} + \underbrace{\sigma_{\rm BSM}}_{\sim 1/\Lambda^4} = \sigma_{\rm SM}^{\rm ((N)N)NLO} \times \left(1 + \frac{\sigma_{\rm int}^{\rm (N)LO}}{\sigma_{\rm SM}^{\rm (N)LO}} + \frac{\sigma_{\rm BSM}^{\rm (N)LO}}{\sigma_{\rm SM}^{\rm (N)LO}}\right).$$

Parametrisation of production & decay product:

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

Linear parametrisation
1st step: remove BSM terms

$$= (\sigma\times B)^{i,H\to X}_{\rm SM,((N)N)NLO} \times \left(1 + \sum_j A_j^{\sigma} \boxed{c_j}\right) \times \left(\frac{1 + \sum_j A_j^{\Gamma^{H\to X}} \boxed{c_j}}{1 + \sum_j A_j^{\Gamma^{H}} \boxed{c_j}}\right)$$

Parameters constrained from data

EFT parametrisation

Reminder:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots$$

$$\sigma_{\rm STXS} = \sigma_{\rm SM} + \underbrace{\sigma_{\rm int}}_{\sim 1/\Lambda^2} + \underbrace{\sigma_{\rm BSM}}_{\sim 1/\Lambda^4} = \sigma_{\rm SM}^{\rm ((N)N)NLO} \times \left(1 + \frac{\sigma_{\rm int}^{\rm (N)LO}}{\sigma_{\rm SM}^{\rm (N)LO}} + \frac{\sigma_{\rm BSM}^{\rm (N)LO}}{\sigma_{\rm SM}^{\rm (N)LO}}\right).$$

Parametrisation of production & decay product:

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

Linear parametrisation
1st step: remove BSM terms

$$= (\sigma\times B)^{i,H\to X}_{\rm SM,((N)N)LO} \times \left(1 + \sum_j A_j^{\sigma_i} c_j\right) \times \left(\frac{1 + \sum_j A_j^{\Gamma^{H\to X}} c_j}{1 + \sum_j A_j^{\Gamma^H} c_j}\right)$$

Cross terms of ~$1/\Lambda^4$

EFT parametrisation

$$(\sigma\times B)^{i,H\to X} = (\sigma\times B)^{i,H\to X}_{\mathrm{SM,((N)N)LO}} \times \left(1+\sum_j A_j^{\sigma_i} c_j\right) \times \left(\frac{1+\sum_j A_j^{\Gamma^{H\to X}} c_j}{1+\sum_j A_j^{\Gamma^{H}} c_j}\right)$$

Cross terms of ~$1/\Lambda^4$

Taylor expansion as a function of $1/\Lambda^2$

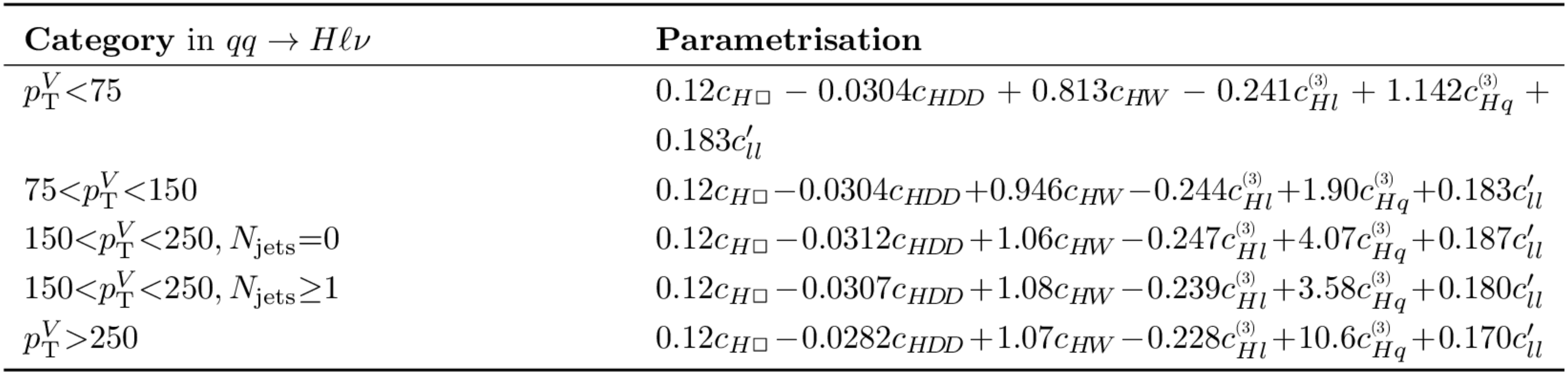
Fully linearised expression in $1/\Lambda^2$:

$$\begin{aligned}(\sigma\times B)^{i,H\to X}_{\mathrm{SM}+\Lambda^{-2}} &= (\sigma\times B)^{i,H\to X}_{\mathrm{SM,((N)N)LO}} \times \left(1+\sum_j A_j^{\sigma_i} c_j + \sum_j A_j^{\Gamma^{H\to X}} c_j - \sum_j A_j^{\Gamma^{H}} c_j\right) + O\left(\Lambda^{-4}\right) \\ &= (\sigma\times B)^{i,H\to X}_{\mathrm{SM,((N)N)LO}} \times \left(1+\sum_j \left(A_j^{\sigma_i} + A_j^{\Gamma^{H\to X}} - A_j^{\Gamma^{H}}\right) c_j\right) + O\left(\Lambda^{-4}\right),\end{aligned}$$

++ Acceptance parametrisation in H → 4l decay

Linear parametrisation of combined STXS

Example: WH production – STXS bins



Category in $qq \to H\ell\nu$	**Parametrisation**
$p_{\mathrm{T}}^{V}<75$	$0.12c_{H\Box} - 0.0304c_{HDD} + 0.813c_{HW} - 0.241c_{Hl}^{(3)} + 1.142c_{Hq}^{(3)} + 0.183c'_{ll}$
$75<p_{\mathrm{T}}^{V}<150$	$0.12c_{H\Box} - 0.0304c_{HDD} + 0.946c_{HW} - 0.244c_{Hl}^{(3)} + 1.90c_{Hq}^{(3)} + 0.183c'_{ll}$
$150<p_{\mathrm{T}}^{V}<250,\, N_{\mathrm{jets}}=0$	$0.12c_{H\Box} - 0.0312c_{HDD} + 1.06c_{HW} - 0.247c_{Hl}^{(3)} + 4.07c_{Hq}^{(3)} + 0.187c'_{ll}$
$150<p_{\mathrm{T}}^{V}<250,\, N_{\mathrm{jets}}\geq 1$	$0.12c_{H\Box} - 0.0307c_{HDD} + 1.08c_{HW} - 0.239c_{Hl}^{(3)} + 3.58c_{Hq}^{(3)} + 0.180c'_{ll}$
$p_{\mathrm{T}}^{V}>250$	$0.12c_{H\Box} - 0.0282c_{HDD} + 1.07c_{HW} - 0.228c_{Hl}^{(3)} + 10.6c_{Hq}^{(3)} + 0.170c'_{ll}$

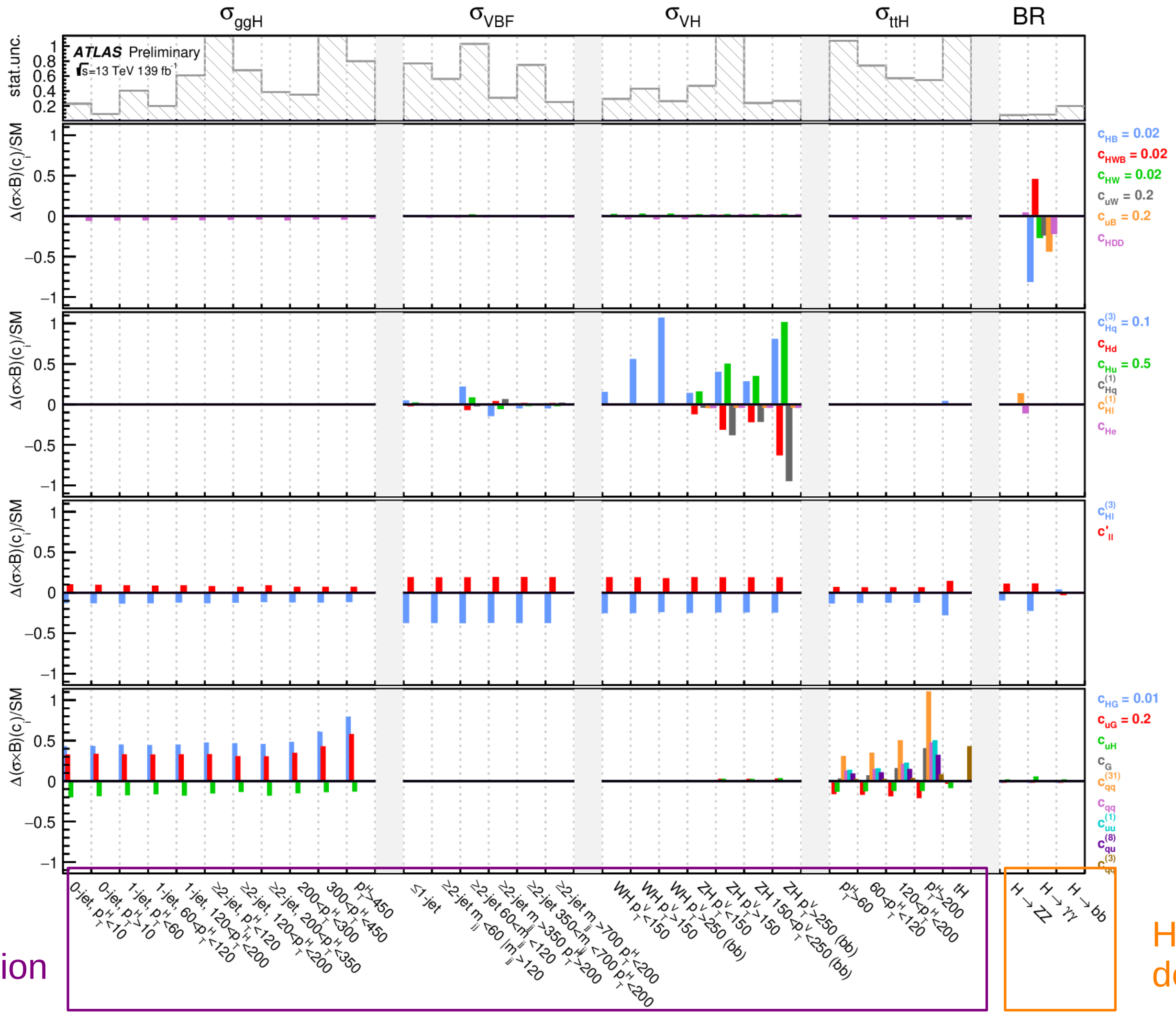
Let's look at a bit more intuitive representation!

Note:

Working under flavour symmetry assumption – possible because we are measuring explicitely only 3rd generation in Higgs physics (for now)

– only ~ 80 operators (yay!)

Linear parametrisation of combined STXS



Higgs production

Higgs decay

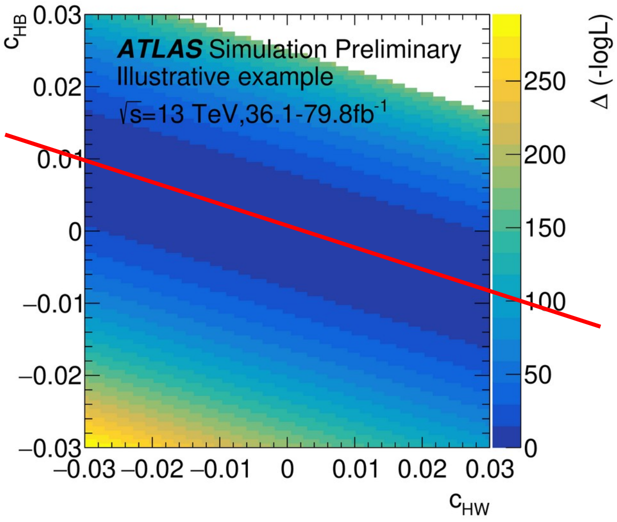
Most relevant operators shown here

- For model generality, perform simultaneous fit of all these operators
- Can already spot set of operators that will be strongly correlated

Flat directions

- Simultaneous fit of all operators in practice not possible → fit does not converge
- Reason: flat directions in likelihood due to operators with ± 100% correlation

Example: 2 operators constrained
mostly by H → γγ decay rate

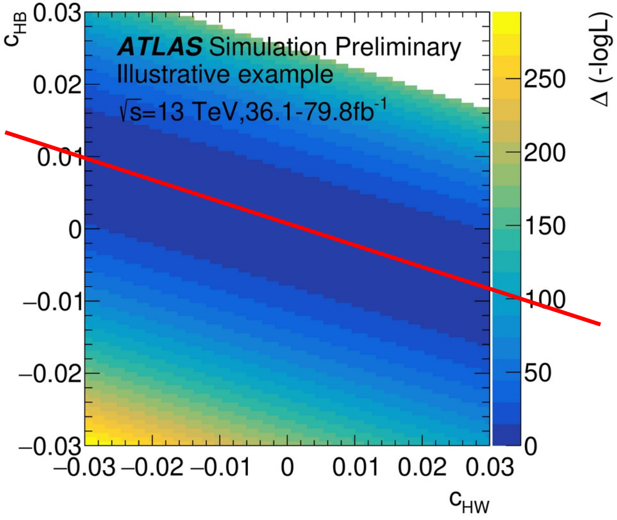


"valley" with equivalent
linear combinations of
operators

Flat directions

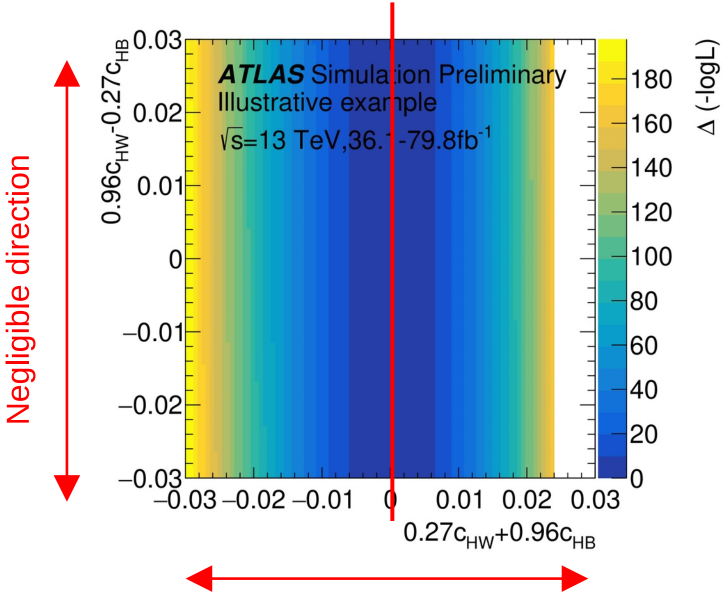
- Simultaneous fit of all operators in practice not possible → fit does not converge
- Reason: flat directions in likelihood due to operators with ± 100% correlation
- Solution: fit linear combinations that are sensitive

Example: 2 operators constrained
mostly by H→γγ decay rate



"valley" with equivalent linear combinations of operators

Basis rotation:
- 1 sensitive linear combination
- 1 without sensitivity, safe to neglect



Negligible direction

Sensitive direction

Principle component analysis

- Sensitive linear combinations = eigenvectors of covariance matrix with small eigenvalue
- Equivalent to eigenvectors of Fisher information matrix (inverse cov. matrix) with large eigenvalue
- Problem: how to get covariance matrix of a non-converging fit?

Principle component analysis

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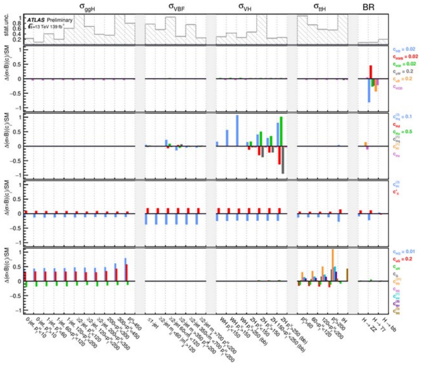
Solution: propagation of EFT parametrisation to combined STXS Fisher information matrix

$$V^{-1}_{\text{SMEFT}} = P^{T}_{(i,X)\to(j)} \, V^{-1}_{\text{STXS}} \, P_{(i,X)\to(j)}$$

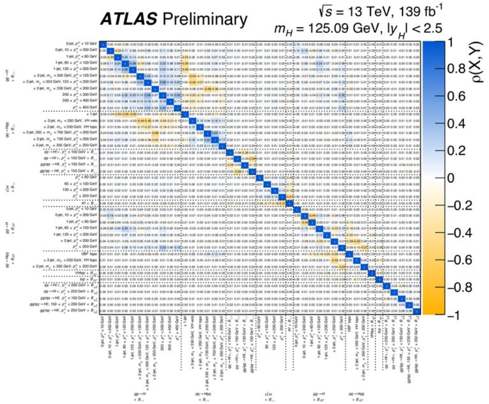
Caveats:
- Assuming Gaussian behaviour
- Only possible for linear parametrisation

Linear EFT parametrisation

$$P_{(i,X)\to(j)} = A^{\sigma_i}_{j} + A^{\Gamma^{H\to X}}_{j} - A^{\Gamma^{H}}_{j}$$



Inverse covariance matrix of STXS x decay measurement



Principle component analysis

- Sensitive linear combinations = eigenvectors of covariance matrix with small eigenvalue
- Equivalent to eigenvectors of Fisher information matrix (inverse cov. matrix) with large eigenvalue
- Problem: how to get covariance matrix of a non-converging fit?

Solution: propagation of EFT parametrisation to combined STXS Fisher information matrix

$$V_{\text{SMEFT}}^{-1} = P_{(i,X)\to(j)}^{T} \, V_{\text{STXS}}^{-1} \, P_{(i,X)\to(j)}$$

Caveats:

- Assuming Gaussian behaviour
- Only possible for linear parametrisation

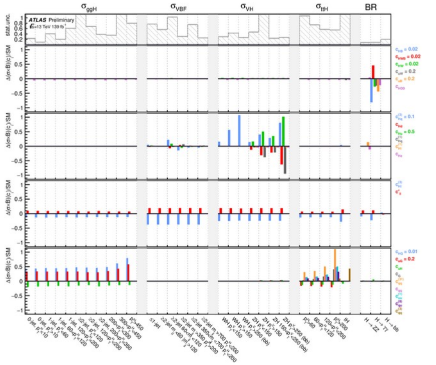
Note:

This is possible, because we have a fully linearised EFT parametrisation

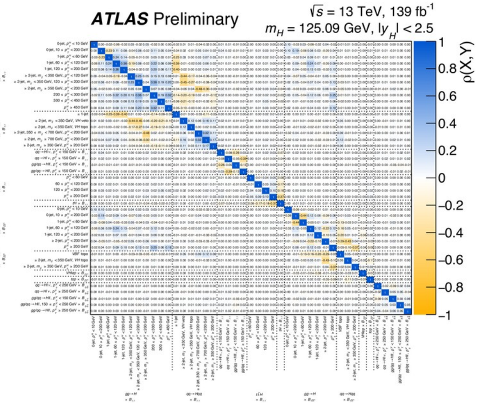
-- not possible when adding terms quadratic in Wilson coefficients

Linear EFT parametrisation

$$P_{(i,X)\to(j)} = A_j^{\sigma_i} + A_j^{\Gamma^{H\to X}} - A_j^{\Gamma^H}$$

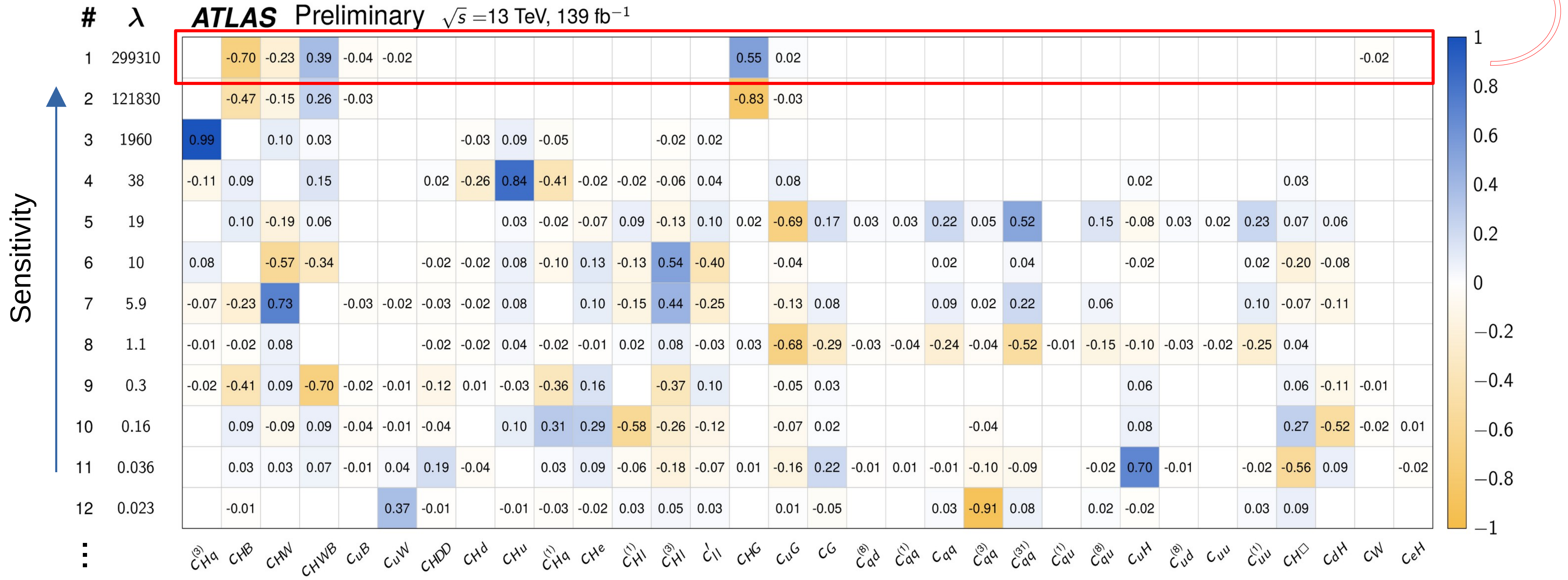


Inverse covariance matrix of STXS x decay measurement



Eigenvector decomposition

EV$_1$ = -0.70 $c_{Hq}^{(3)}$ + -0.23 c_{HB} + 0.39 c_{HW} + ...

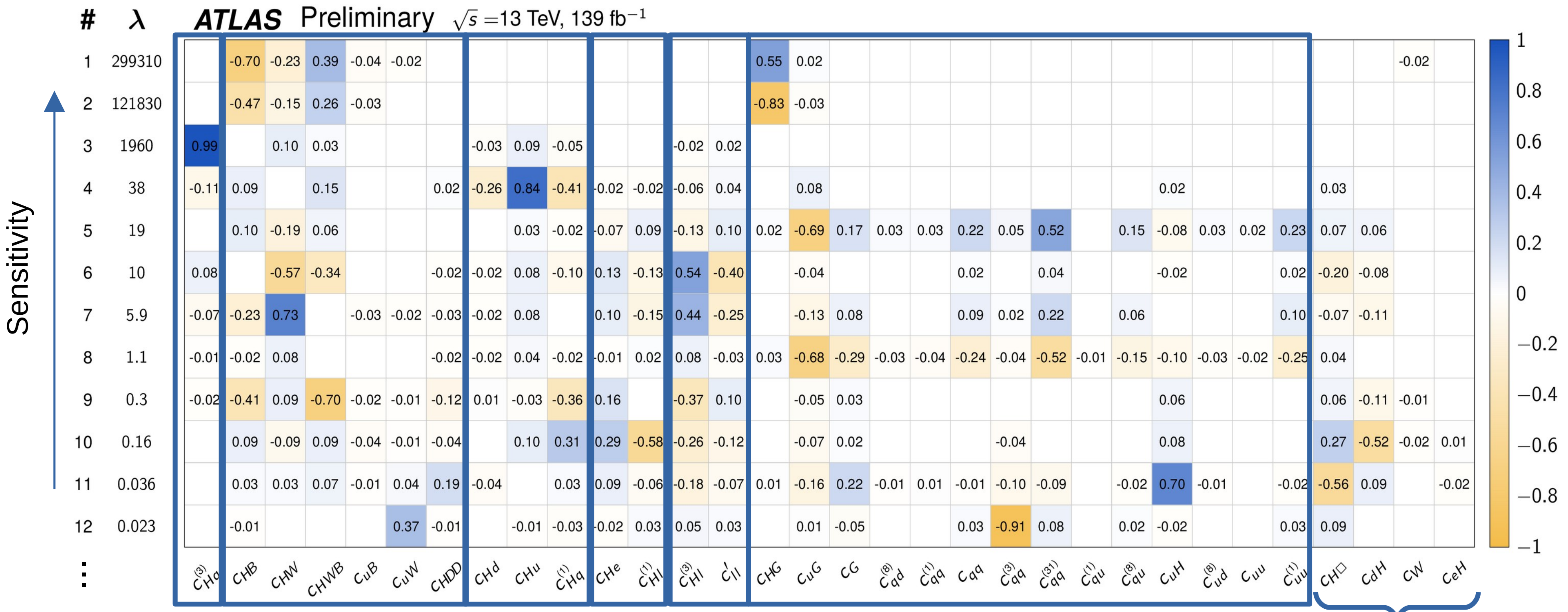


#	λ	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c_{ll}'	c_{HG}	c_{uG}	c_G	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$	$c_{H\Box}$	c_{dH}	c_W	c_{eH}
1	299310		-0.70	-0.23	0.39	-0.04	-0.02									0.55	0.02															-0.02	
2	121830		-0.47	-0.15	0.26	-0.03										-0.83	-0.03																
3	1960	0.99		0.10	0.03				-0.03	0.09	-0.05			-0.02	0.02																		
4	38	-0.11	0.09		0.15			0.02	-0.26	0.84	-0.41	-0.02	-0.02	-0.06	0.04		0.08									0.02				0.03			
5	19		0.10	-0.19	0.06					0.03	-0.02	-0.07	0.09	-0.13	0.10	0.02	-0.69	0.17	0.03	0.03	0.22	0.05	0.52		0.15	-0.08	0.03	0.02	0.23	0.07	0.06		
6	10	0.08		-0.57	-0.34			-0.02	-0.02	0.08	-0.10	0.13	-0.13	0.54	-0.40		-0.04				0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9	-0.07	-0.23	0.73		-0.03	-0.02	-0.03	-0.02	0.08		0.10	-0.15	0.44	-0.25		-0.13	0.08			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-0.01	-0.02	0.08				-0.02	-0.02	0.04	-0.02	-0.01	0.02	0.08	-0.03	0.03	-0.68	-0.29	-0.03	-0.04	-0.24	-0.04	-0.52	-0.01	-0.15	-0.10	-0.03	-0.02	-0.25	0.04			
9	0.3	-0.02	-0.41	0.09	-0.70	-0.02	-0.01	-0.12	0.01	-0.03	-0.36	0.16		-0.37	0.10		-0.05	0.03								0.06				0.06	-0.11	-0.01	
10	0.16		0.09	-0.09	0.09	-0.04	-0.01	-0.04		0.10	0.31	0.29	-0.58	-0.26	-0.12		-0.07	0.02				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036		0.03	0.03	0.07	-0.01	0.04	0.19	-0.04		0.03	0.09	-0.06	-0.18	-0.07	0.01	-0.16	0.22	-0.01	0.01	-0.01	-0.10	-0.09		-0.02	0.70	-0.01		-0.02	-0.56	0.09		-0.02
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01	-0.05			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			
⋮																																	

- Could fit most sensitive of these eigenvectors – cutoff at some min. eigenvalue
- **Problem:** difficult to validate – no straight forward physics meaning

Eigenvector decomposition

Define operator subspaces with similar physics impact – fit eigenvectors of sub-matrices



#	λ	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c'_{ll}	c_{HG}	c_{uG}	c_{G}	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$	$c_{H\Box}$	c_{dH}	c_{W}	c_{eH}
1	299310		-0.70	-0.23	0.39	-0.04	-0.02									0.55	0.02															-0.02	
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5	19		0.10	-0.19	0.06					0.03	-0.02	-0.07	0.09	-0.13	0.10	0.02	-0.69	0.17	0.03	0.03	0.22	0.05	0.52		0.15	-0.08	0.03	0.02	0.23	0.07	0.06		
6	10	0.08		-0.57	-0.34			-0.02	-0.02	0.08	-0.10	0.13	-0.13	0.54	-0.40		-0.04				0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9	-0.07	-0.23	0.73		-0.03	-0.02	-0.03	-0.02	0.08		0.10	-0.15	0.44	-0.25		-0.13	0.08			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-0.01	-0.02	0.08				-0.02	-0.02	0.04	-0.02	-0.01	0.02	0.08	-0.03	0.03	-0.68	-0.29	-0.03	-0.04	-0.24	-0.04	-0.52	-0.01	-0.15	-0.10	-0.03	-0.02	-0.25	0.04			
9	0.3	-0.02	-0.41	0.09	-0.70	-0.02	-0.01	-0.12	0.01	-0.03	-0.36	0.16		-0.37	0.10		-0.05	0.03								0.06				0.06	-0.11	-0.01	
10	0.16		0.09	-0.09	0.09	-0.04	-0.01	-0.04		0.10	0.31	0.29	-0.58	-0.26	-0.12		-0.07	0.02				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036		0.03	0.03	0.07	-0.01	0.04	0.19	-0.04		0.03	0.09	-0.06	-0.18	-0.07	0.01	-0.16	0.22	-0.01	0.01	-0.01	-0.10	-0.09		-0.02	0.70	-0.01		-0.02	-0.56	0.09		-0.02
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01	-0.05			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			
⋮																																	

P_T^V kinematics in ZH & WH production

H→yy + VBF/VH

ZH

H→4l

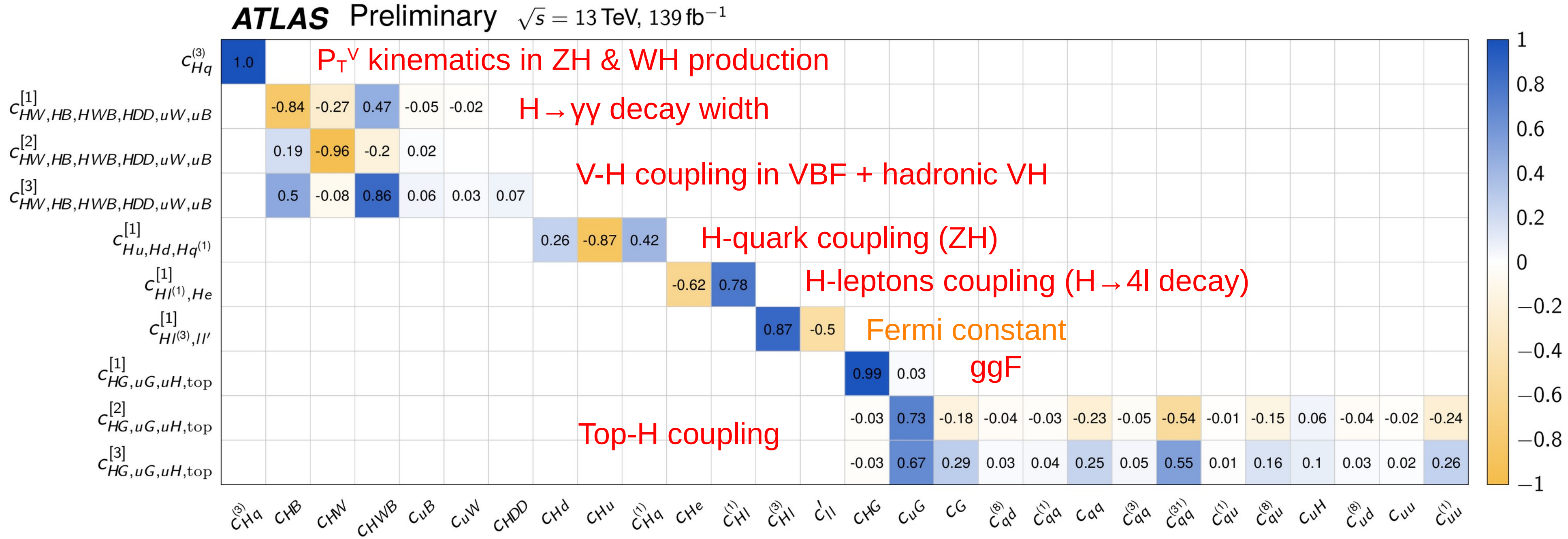
Fermi const.

ggF + ttH / tH

Not included here; included in later fit results (e.g. c_{dH}: b-Yukawa, c_{eH}: τ-Yukawa)

Eigenvector decomposition

Sensitive eigenvectors of sub-matrices – can mostly be associated to specific channel



	$C_{Hq}^{(3)}$	C_{HB}	C_{HW}	C_{HWB}	C_{uB}	C_{uW}	C_{HDD}	C_{Hd}	C_{Hu}	$C_{Hq}^{(1)}$	C_{He}	$C_{Hl}^{(1)}$	$C_{Hl}^{(3)}$	C'_{ll}	C_{HG}	C_{uG}	C_{G}	$C_{qd}^{(8)}$	$C_{qq}^{(1)}$	C_{qq}	$C_{qq}^{(3)}$	$C_{qq}^{(31)}$	$C_{qu}^{(1)}$	$C_{qu}^{(8)}$	C_{uH}	$C_{ud}^{(8)}$	C_{uu}	$C_{uu}^{(1)}$
$c_{Hq}^{(3)}$	1.0																											
$c^{[1]}_{HW,HB,HWB,HDD,uW,uB}$		-0.84	-0.27	0.47	-0.05	-0.02																						
$c^{[2]}_{HW,HB,HWB,HDD,uW,uB}$		0.19	-0.96	-0.2	0.02																							
$c^{[3]}_{HW,HB,HWB,HDD,uW,uB}$		0.5	-0.08	0.86	0.06	0.03	0.07																					
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$								0.26	-0.87	0.42																		
$c^{[1]}_{Hl^{(1)},He}$											-0.62	0.78																
$c^{[1]}_{Hl^{(3)},ll'}$													0.87	-0.5														
$c^{[1]}_{HG,uG,uH,\mathrm{top}}$															0.99	0.03												
$c^{[2]}_{HG,uG,uH,\mathrm{top}}$															-0.03	0.73	-0.18	-0.04	-0.03	-0.23	-0.05	-0.54	-0.01	-0.15	0.06	-0.04	-0.02	-0.24
$c^{[3]}_{HG,uG,uH,\mathrm{top}}$															-0.03	0.67	0.29	0.03	0.04	0.25	0.05	0.55	0.01	0.16	0.1	0.03	0.02	0.26

P_T^V kinematics in ZH & WH production

H → γγ decay width

V-H coupling in VBF + hadronic VH

H-quark coupling (ZH)

H-leptons coupling (H → 4l decay)

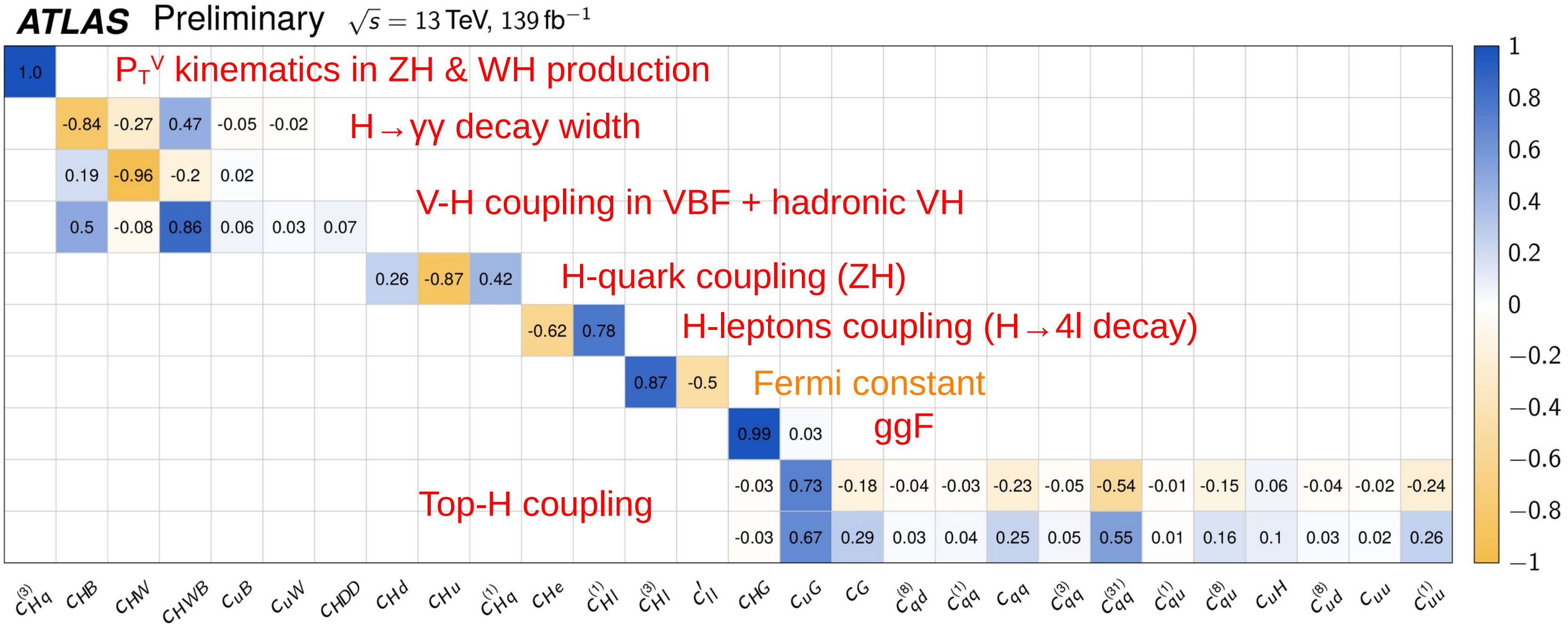
Fermi constant

ggF

Top-H coupling

Eigenvector decomposition

Sensitive eigenvectors of sub-matrices – can mostly be associated to specific channel



P_T^V kinematics in ZH & WH production

H→yy decay width

V-H coupling in VBF + hadronic VH

H-quark coupling (ZH)

H-leptons coupling (H→4l decay)

Fermi constant

ggF

Top-H coupling

	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c_{ll}'	c_{HG}	c_{uG}	c_{G}	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$
$c_{Hq}^{(3)}$	1.0																											
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$c^{[1]}_{HG,uG,uH,\mathrm{top}}$															0.99	0.03												
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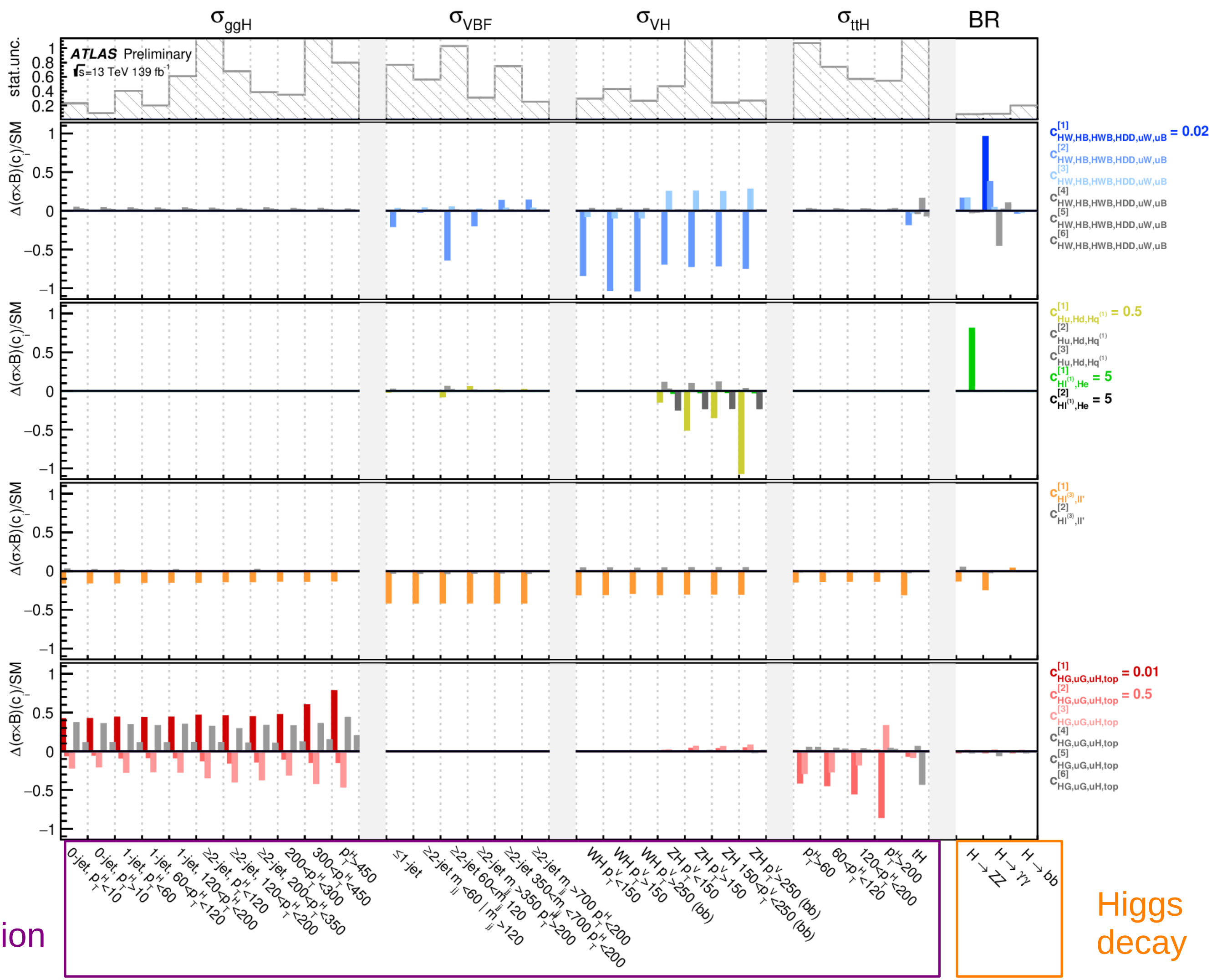
$c^{[3]}_{HG,uG,uH,\mathrm{top}}$															-0.03	0.67	0.29	0.03	0.04	0.25	0.05	0.55	0.01	0.16	0.1	0.03	0.02	0.26

Note: $c^{[1]}_{HW,HB.HWB,HDD,uW,uB}$ can be related to c_{yy} in Higgs basis

$$\tilde{c}_{\gamma\gamma} = \frac{v^2}{\Lambda^2}4\left(\frac{1}{g^2}w_{\phi\tilde{W}} + \frac{1}{g'^2}w_{\phi\tilde{B}} - \frac{1}{gg'}w_{\phi\tilde{W}B}\right)$$

Eigenvector impact

- Good association of directions with physics processes
- Remaining correlations from experimental sources

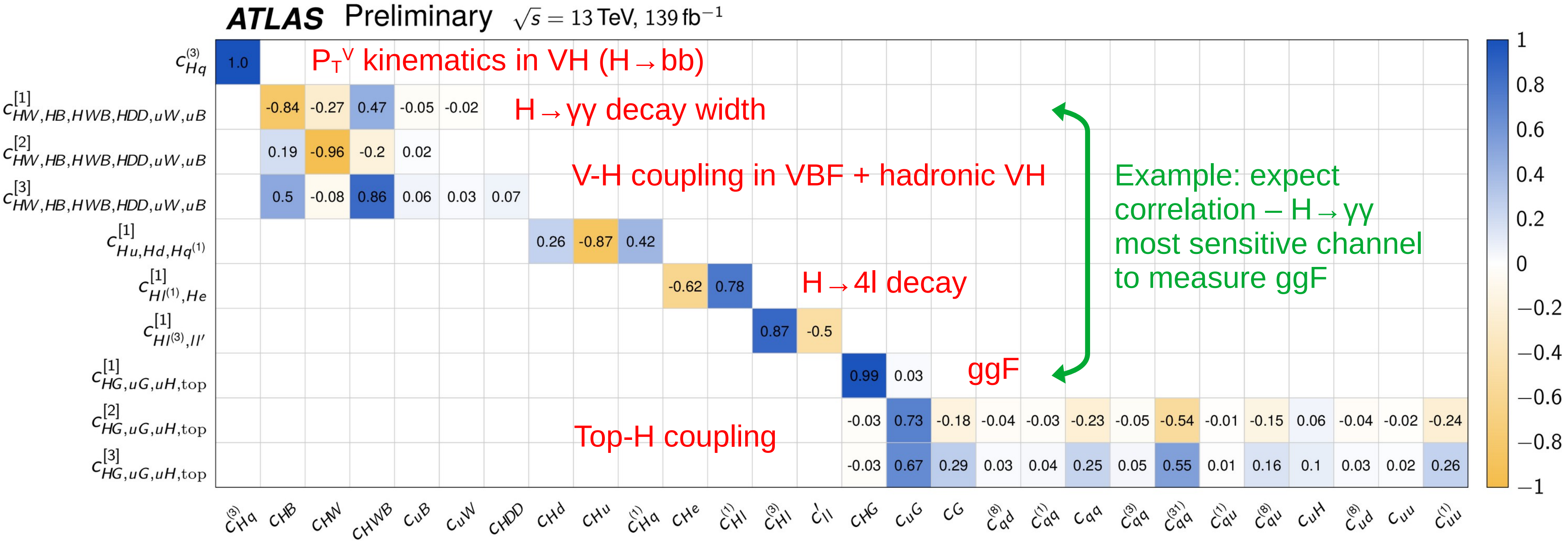


Higgs production

Higgs decay

Eigenvector correlations

Sensitive eigenvectors of sub-matrices – can mostly be associated to specific channel



	$c^{(3)}_{Hq}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c^{(1)}_{Hq}$	c_{He}	$c^{(1)}_{Hl}$	$c^{(3)}_{Hl}$	c'_{ll}	c_{HG}	c_{uG}	c_G	$c^{(8)}_{qd}$	$c^{(1)}_{qq}$	c_{qq}	$c^{(3)}_{qq}$	$c^{(31)}_{qq}$	$c^{(1)}_{qu}$	$c^{(8)}_{qu}$	c_{uH}	$c^{(8)}_{ud}$	c_{uu}	$c^{(1)}_{uu}$
$c^{(3)}_{Hq}$	1.0																											
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$c^{[3]}_{HG,uG,uH,\mathrm{top}}$															-0.03	0.67	0.29	0.03	0.04	0.25	0.05	0.55	0.01	0.16	0.1	0.03	0.02	0.26

P_T^V kinematics in VH (H → bb)

H → γγ decay width

V-H coupling in VBF + hadronic VH

H → 4l decay

ggF

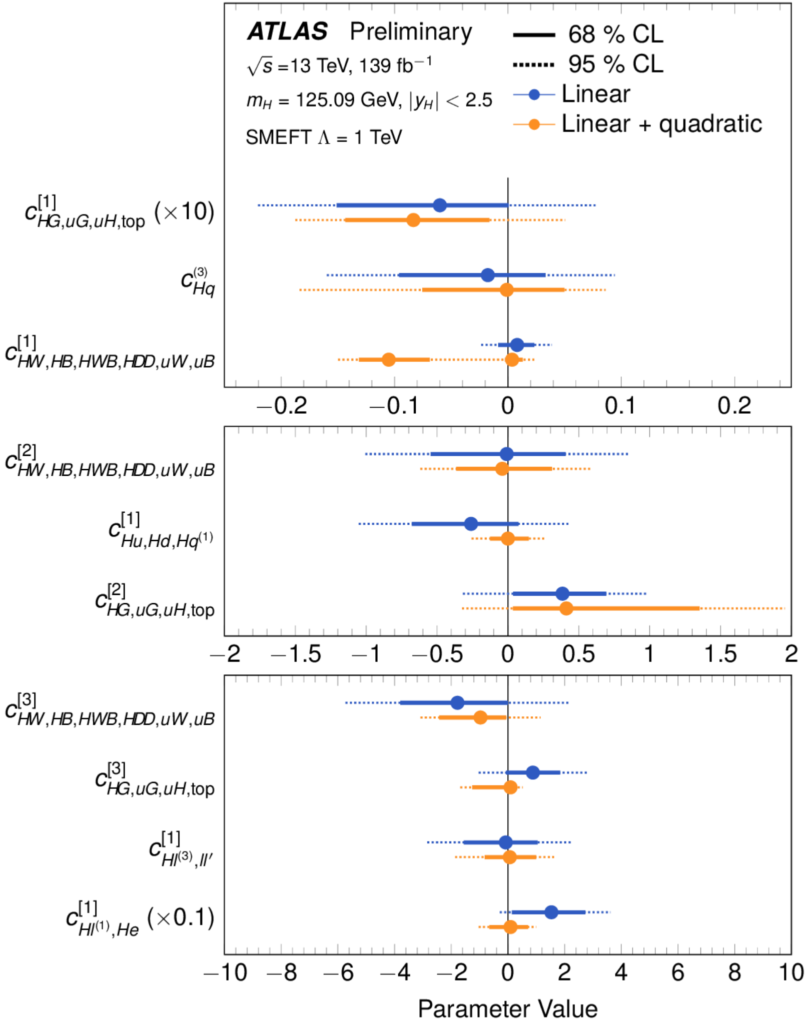
Top-H coupling

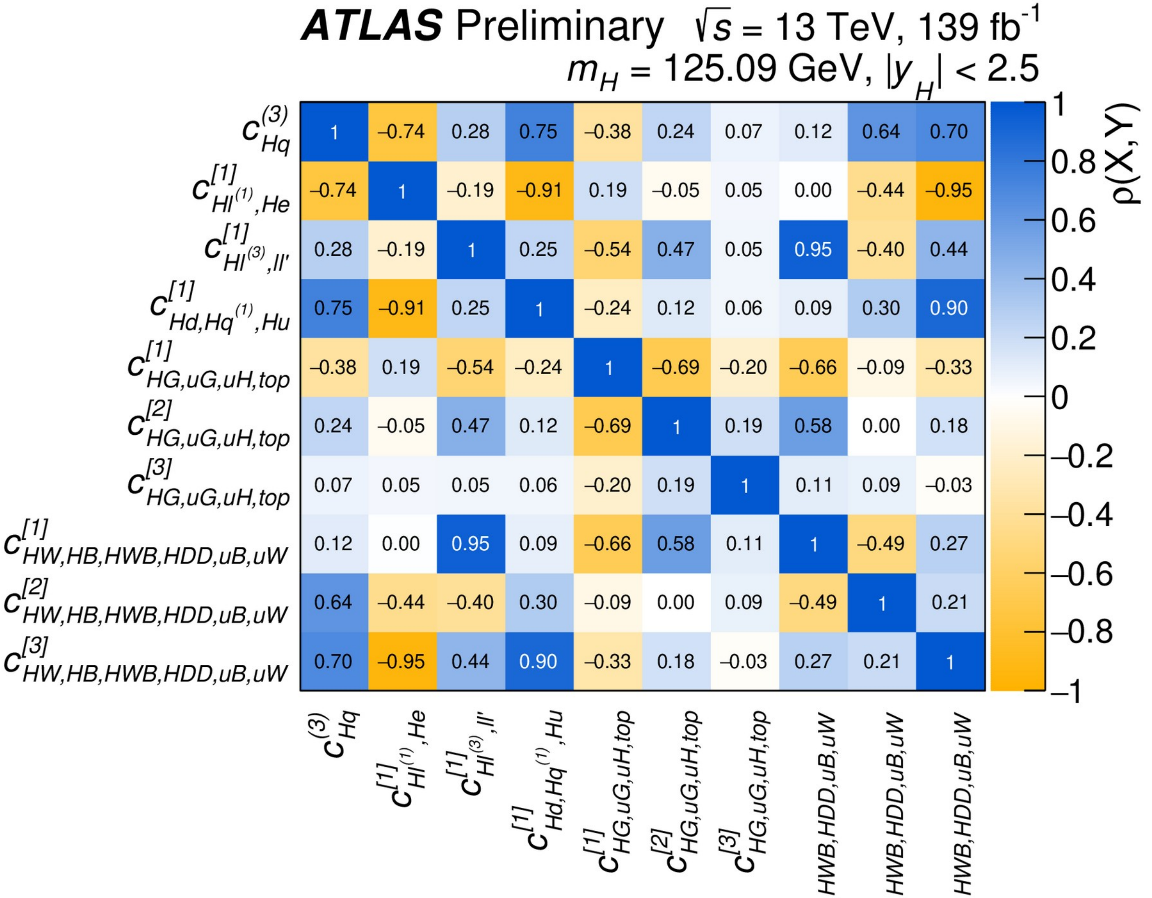
Example: expect correlation – H → γγ most sensitive channel to measure ggF

Note:

- Not eigenvectors to full covariance matrix – expect correlations between them due to experimental correlations among processes
- This is a choice and the price to pay for physics intuition – need to be careful neglecting directions (more later)

Fit results





	$c^{(3)}_{Hq}$	$c^{[1]}_{Hl^{(1)},He}$	$c^{[1]}_{Hl^{(3)},ll'}$	$c^{[1]}_{Hd,Hq^{(1)},Hu}$	$c^{[1]}_{HG,uG,uH,top}$	$c^{[2]}_{HG,uG,uH,top}$	$c^{[3]}_{HG,uG,uH,top}$	$c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$	$c^{[2]}_{HW,HB,HWB,HDD,uB,uW}$	$c^{[3]}_{HW,HB,HWB,HDD,uB,uW}$
$c^{(3)}_{Hq}$	1	−0.74	0.28	0.75	−0.38	0.24	0.07	0.12	0.64	0.70
$c^{[1]}_{Hl^{(1)},He}$	−0.74	1	−0.19	−0.91	0.19	−0.05	0.05	0.00	−0.44	−0.95
$c^{[1]}_{Hl^{(3)},ll'}$	0.28	−0.19	1	0.25	−0.54	0.47	0.05	0.95	−0.40	0.44
$c^{[1]}_{Hd,Hq^{(1)},Hu}$	0.75	−0.91	0.25	1	−0.24	0.12	0.06	0.09	0.30	0.90
$c^{[1]}_{HG,uG,uH,top}$	−0.38	0.19	−0.54	−0.24	1	−0.69	−0.20	−0.66	−0.09	−0.33
$c^{[2]}_{HG,uG,uH,top}$	0.24	−0.05	0.47	0.12	−0.69	1	0.19	0.58	0.00	0.18
$c^{[3]}_{HG,uG,uH,top}$	0.07	0.05	0.05	0.06	−0.20	0.19	1	0.11	0.09	−0.03
$c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$	0.12	0.00	0.95	0.09	−0.66	0.58	0.11	1	−0.49	0.27
$c^{[2]}_{HW,HB,HWB,HDD,uB,uW}$	0.64	−0.44	−0.40	0.30	−0.09	0.00	0.09	−0.49	1	0.21
$c^{[3]}_{HW,HB,HWB,HDD,uB,uW}$	0.70	−0.95	0.44	0.90	−0.33	0.18	−0.03	0.27	0.21	1

All linear combinations
fit simultaneously

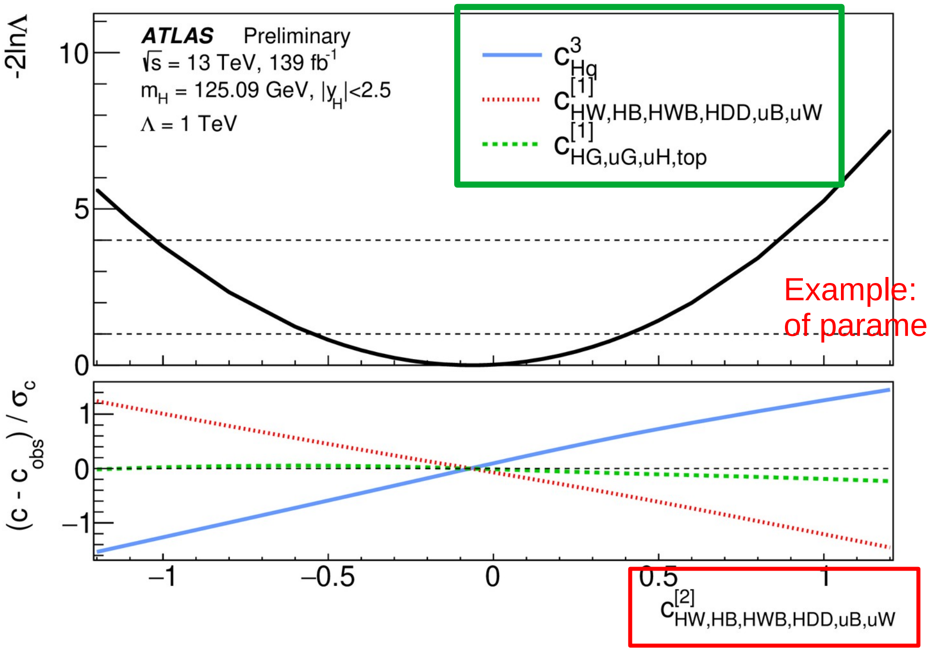
Generality check

- Linear operator combinations with significant eigenvalues included in the fit – all others fixed to 0
- Without correlations, e.g. in full eigenvector decomposition, this is fine
- In case of sub-matrix rotations and significant correlations, need to check that neglecting directions has no impact on generality of the fit

Generality check

- Linear operator combinations with significant eigenvalues included in the fit – all others fixed to 0
- Without correlations, e.g. in full eigenvector decomposition, this is fine
- In case of sub-matrix rotations and significant correlations, need to check that neglecting directions has no impact on generality of the fit

1st check: correlations among fitted directions are linear



Example: profile likelihood scan of parameter affecting VBF & VH

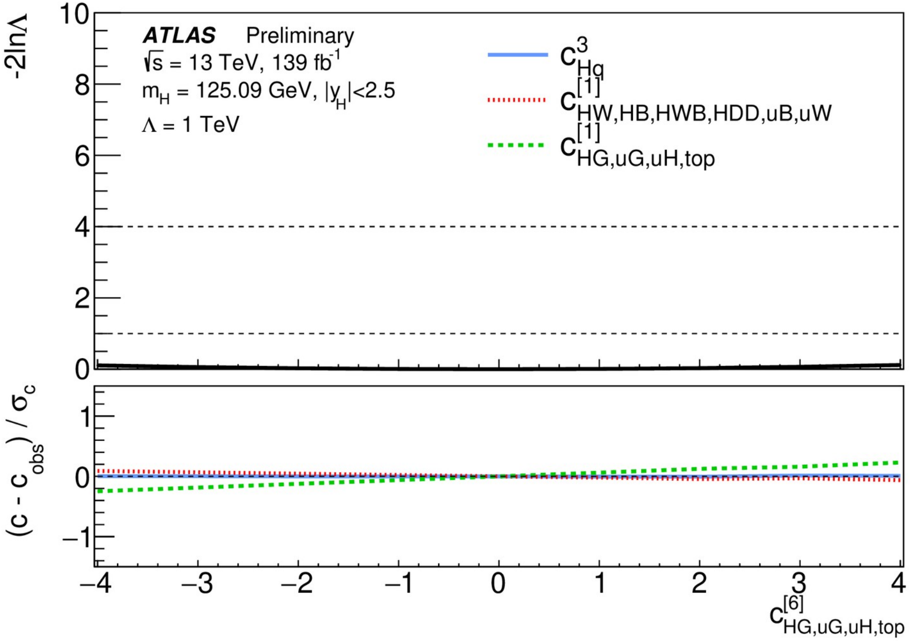
Linear evolution of parameter impacting pTV, H→γγ and ggF

- Profile likelihood scan of one direction
- Check evolution of profiled directions – expected to be linear if Gaussian approximation valid

Generality check

- Linear operator combinations with significant eigenvalues included in the fit – all others fixed to 0
- Without correlations, e.g. in full eigenvector decomposition, this is fine
- In case of sub-matrix rotations and significant correlations, need to check that neglecting directions has no impact on generality of the fit

2nd check: correlation between neglected directions and fitted directions is negligible

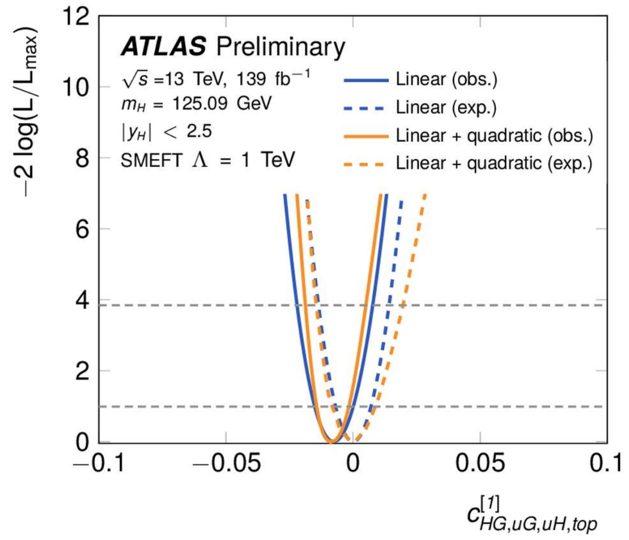


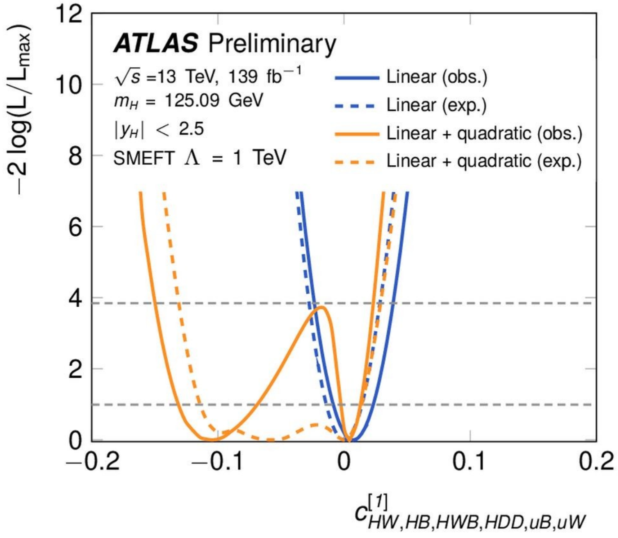
- Likelihood scan of neglected direction one-by-one; profiling all fitted directions
- Likelihood should be mostly flat in scanning range >> EFT validity range
- Evolution of profiled directions should be negligible within this range

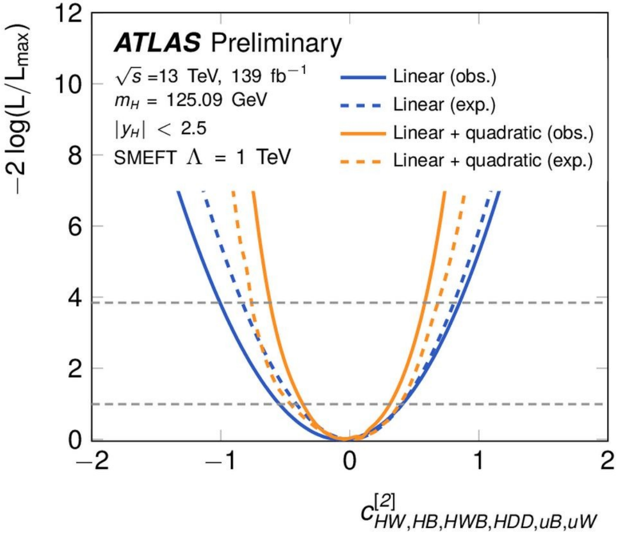
Example: 0.2σ variation max. within [-4,4] for scanned direction → can be neglected

Impact of quadratic (full BSM) terms

- General assumption: linear terms dominant, higher order terms can be neglected
  - Explicit check including quadratic terms shows non-negligible impact for some operator
- Should systematically include higher order terms?
  - Principle component analysis and rejection of non-sensitive direction relying on linearity of correlations
  - Need to compute dim-8 contributions (same order as quadratic dim-6) – theory calculations ongoing
  - Is EFT validity questioned by non-negligible impact of higher order terms?

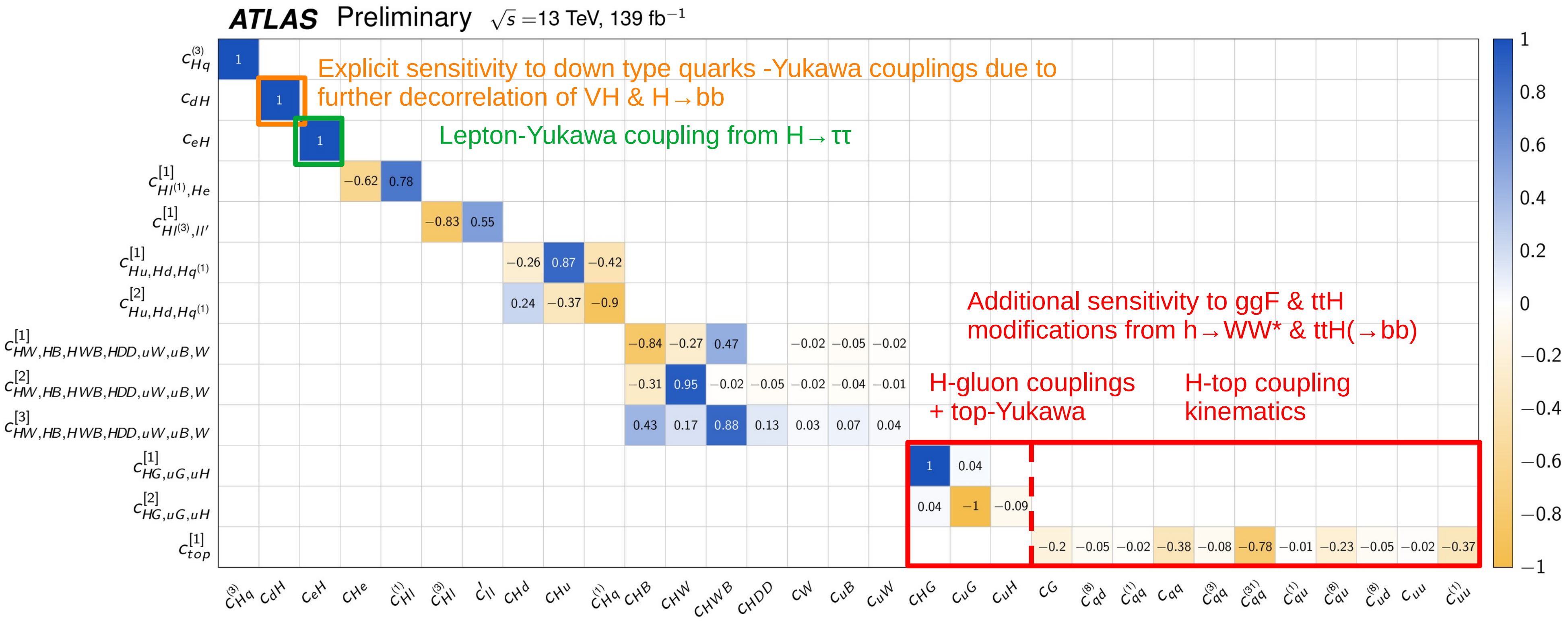






Adding more decay channels

- Previous example is STXS combination of H → yy, H → 4l & VH(H → bb)
- Newer results with more channels – additional sensitivity to operators & decorrelation of operators
  - adding H → WW* → 2l2v (ggF & VBF), H → ττ, H → bb (VBF & ttH)



Explicit sensitivity to down type quarks -Yukawa couplings due to further decorrelation of VH & H → bb

Lepton-Yukawa coupling from H → ττ

Additional sensitivity to ggF & ttH modifications from h → WW* & ttH(→ bb)

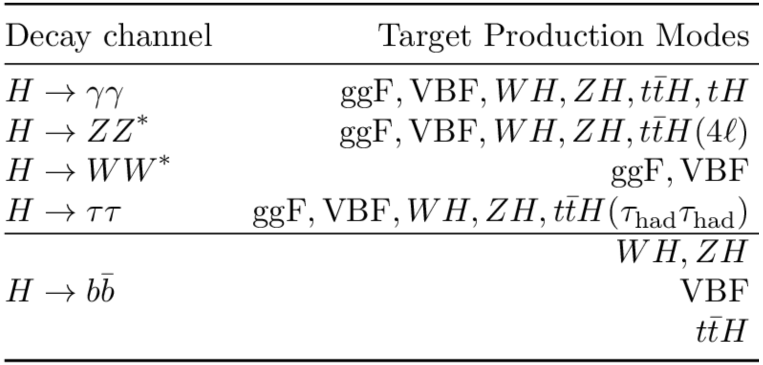
H-gluon couplings + top-Yukawa

H-top coupling kinematics

Note: still assuming U^5(3) flavour symmetry, i.e. no sensitivity to quark or lepton generation – further sensitivity expected from H → cc or H → μμ

Combining Higgs and EW measurements

Higgs measurements



Decay channel	Target Production Modes
$H \to \gamma\gamma$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H, tH$
$H \to ZZ^*$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H(4\ell)$
$H \to WW^*$	$\mathrm{ggF}, \mathrm{VBF}$
$H \to \tau\tau$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H(\tau_{\mathrm{had}}\tau_{\mathrm{had}})$
$H \to b\bar{b}$	WH, ZH VBF $t\bar{t}H$

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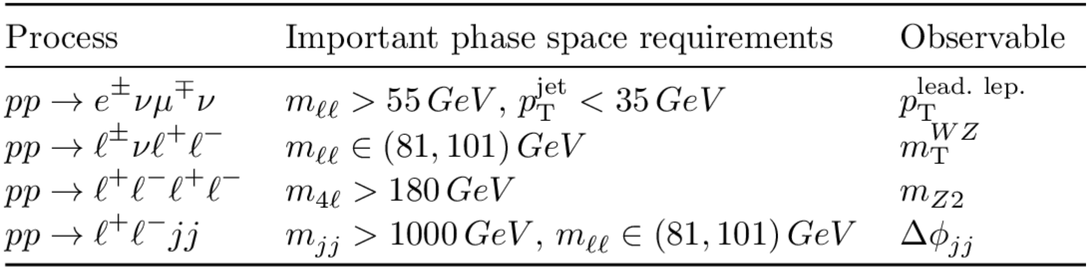
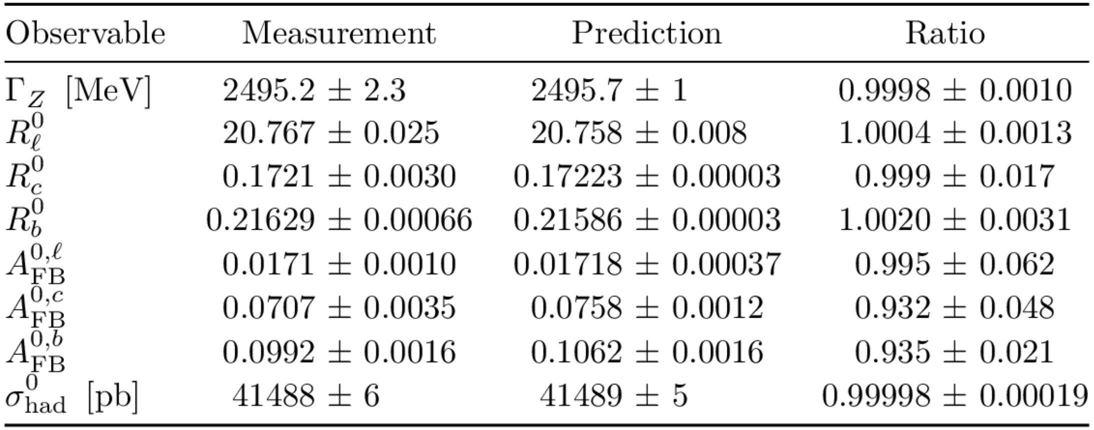
EW measurements



Process	Important phase space requirements	Observable
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55\,GeV$, $p_{\mathrm{T}}^{\mathrm{jet}} < 35\,GeV$	$p_{\mathrm{T}}^{\mathrm{lead.\ lep.}}$
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)\,GeV$	m_{T}^{WZ}
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180\,GeV$	m_{Z2}
$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000\,GeV$, $m_{\ell\ell} \in (81, 101)\,GeV$	$\Delta\phi_{jj}$

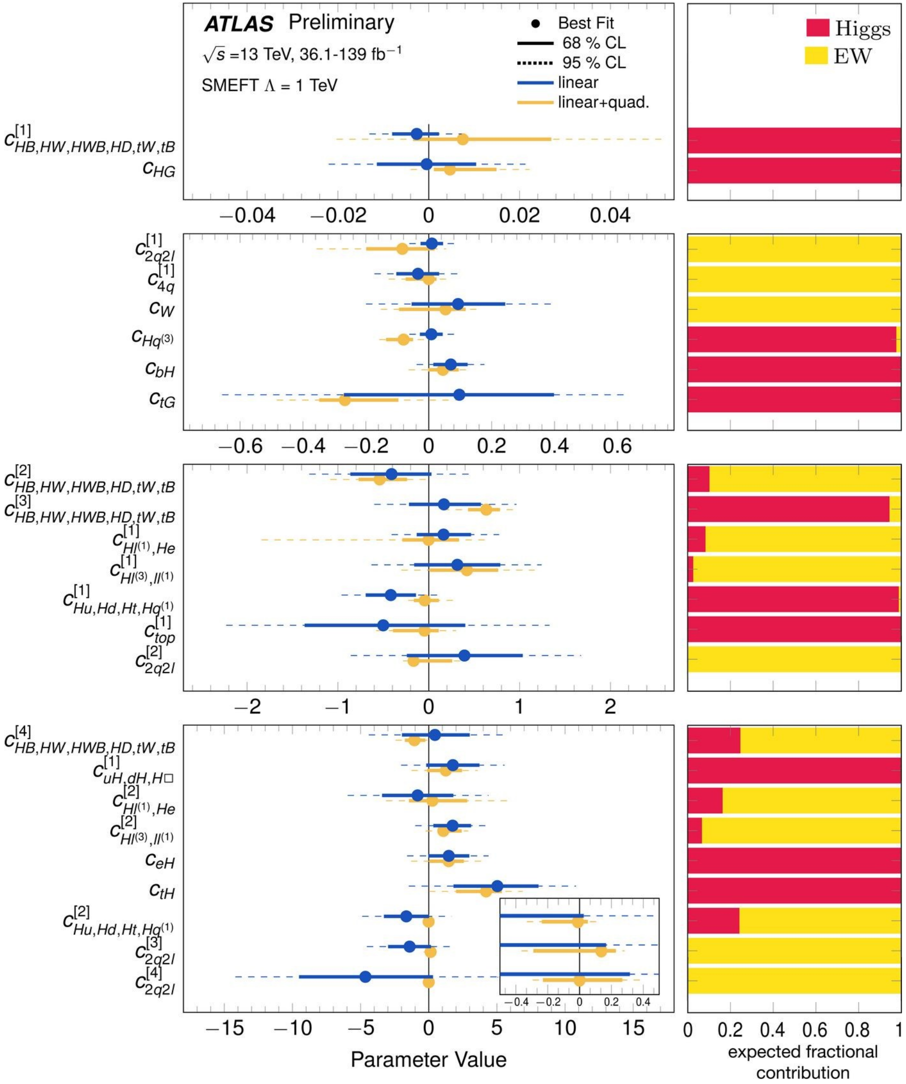
EW precision observables (measured at LEP)



Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R_ℓ^0	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R_c^0	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R_b^0	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A_{\mathrm{FB}}^{0,\ell}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A_{\mathrm{FB}}^{0,c}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A_{\mathrm{FB}}^{0,b}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ_{had}^0 [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

Combining Higgs and EW measurements

- Good complementarity between analyses
- Sensitivity to large number of operator (combinations)
- Ongoing effort to add more channels from several experiments
- Adding measurements with top quarks in final state will add sensitivity to flavour



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Some limitations to keep in mind

- EFT validity
  - Choice of energy scale: need to know q2 of processes / selected events – particular sensitive in high-p_T tails
  - Measurement of c/Λ – only depends on “observed impact”, energy scale interpretation can be made later on
  - Would it make sense to reject data events to probe lower energy scale?
  - How to interpret results on Wilson coefficients with uncertainties >~1
  - How to handle unitarity violation at hight energies – apply clipping procedure in global fits?

- Higher order terms in 1/Λ
  - Impact of quadratic terms often not negligible – what are the conclusion?
  - Neglecting quadratic terms can lead to negative cross sections – how to handle this?
  - What about dim-8 operators? Might become dominant in some processes and models – not yet fully calculated

- Higher order calculations
  - EFT is fully perturbative theory, but many interpretations currently only consider LO (or NLO) calculation – need to estimate uncertainty

Conclusion

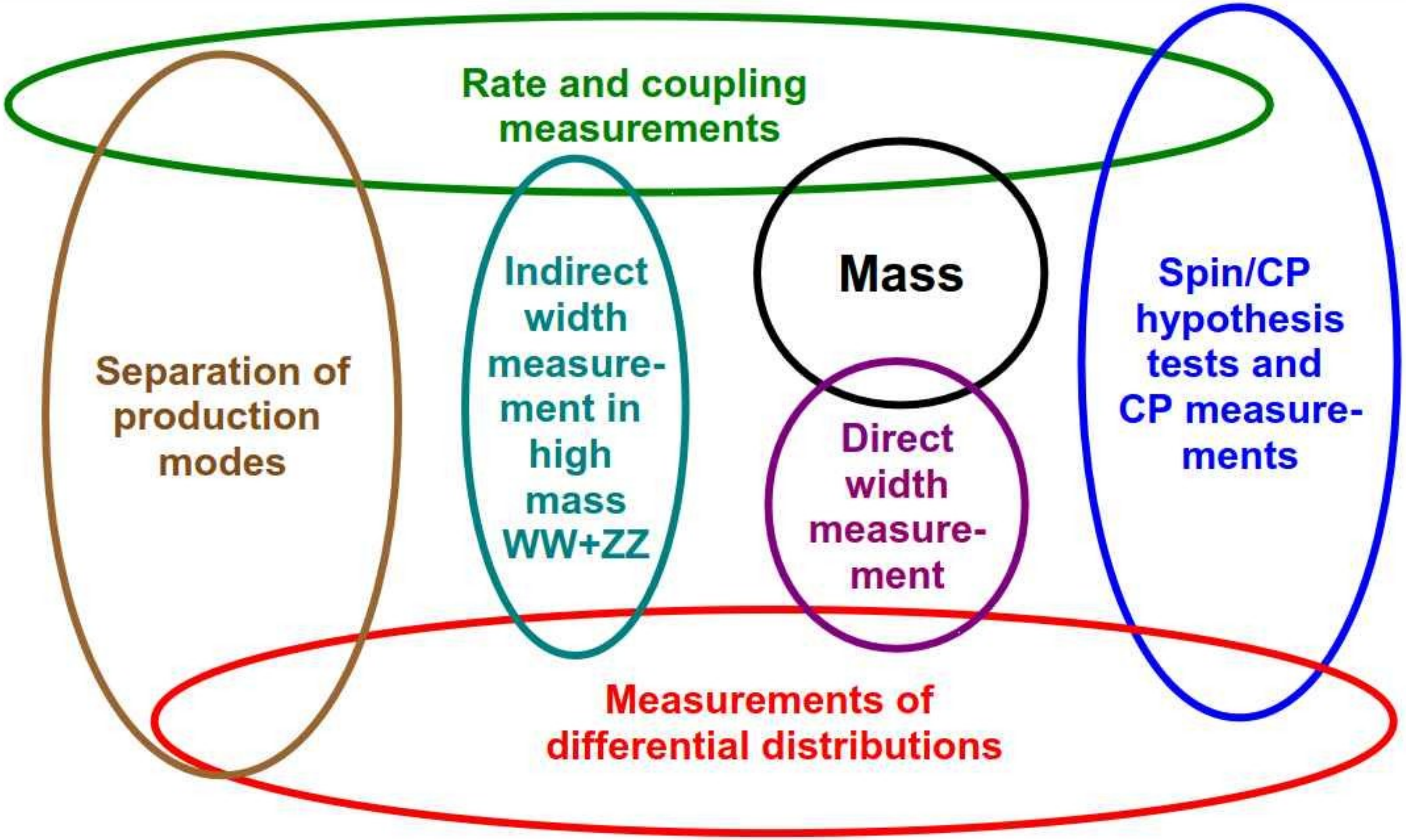
- A lot of things to do – toward a global EFT fit for HL-LHC including all main Higgs, SM and top analyses + potential constraints from flavour physics
- Keep in mind: we are doing physics!
  - EFTs can be matched to concrete BSM models – can set limits on their parameters from global EFT fit results
  - In case we find a deviation, the game really starts – what is it?
- Both, developments on experimental and theory side needed

A lot of things to do – have fun? ;-)

More information on current activities @ LHC: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCEFT

BACKUP

Higgs measurements from the experimental point of view



Rate and coupling measurements

Separation of production modes

Indirect width measurement in high mass WW+ZZ

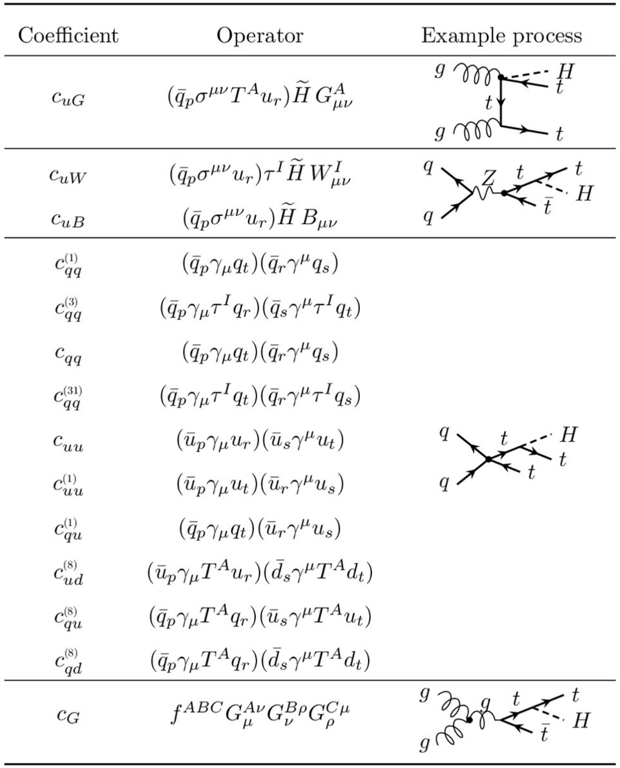
Mass

Direct width measurement

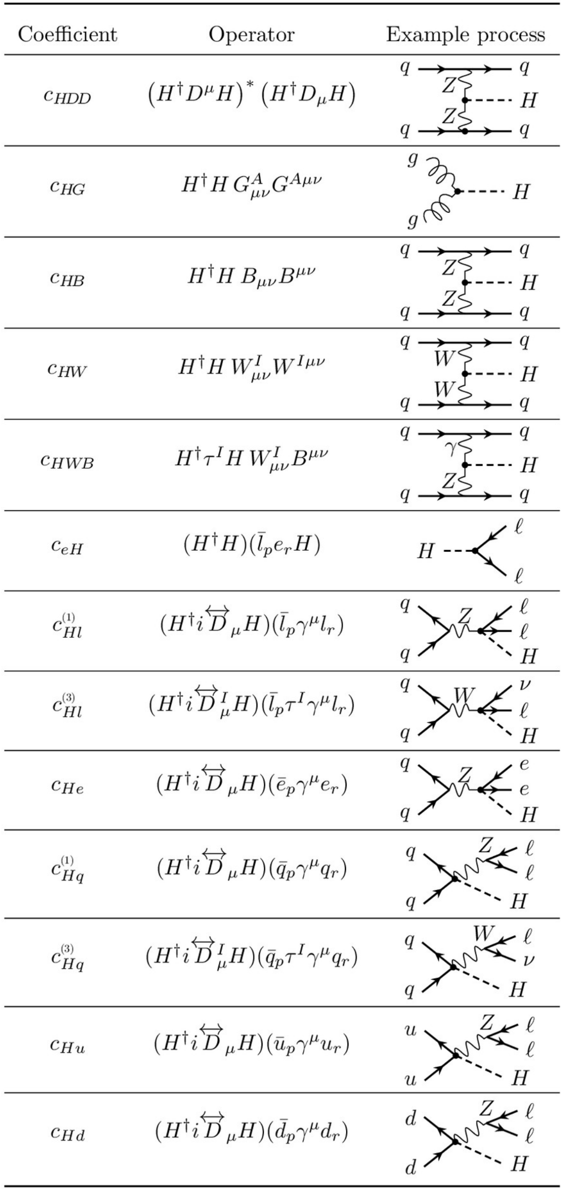
Spin/CP hypothesis tests and CP measurements

Measurements of differential distributions

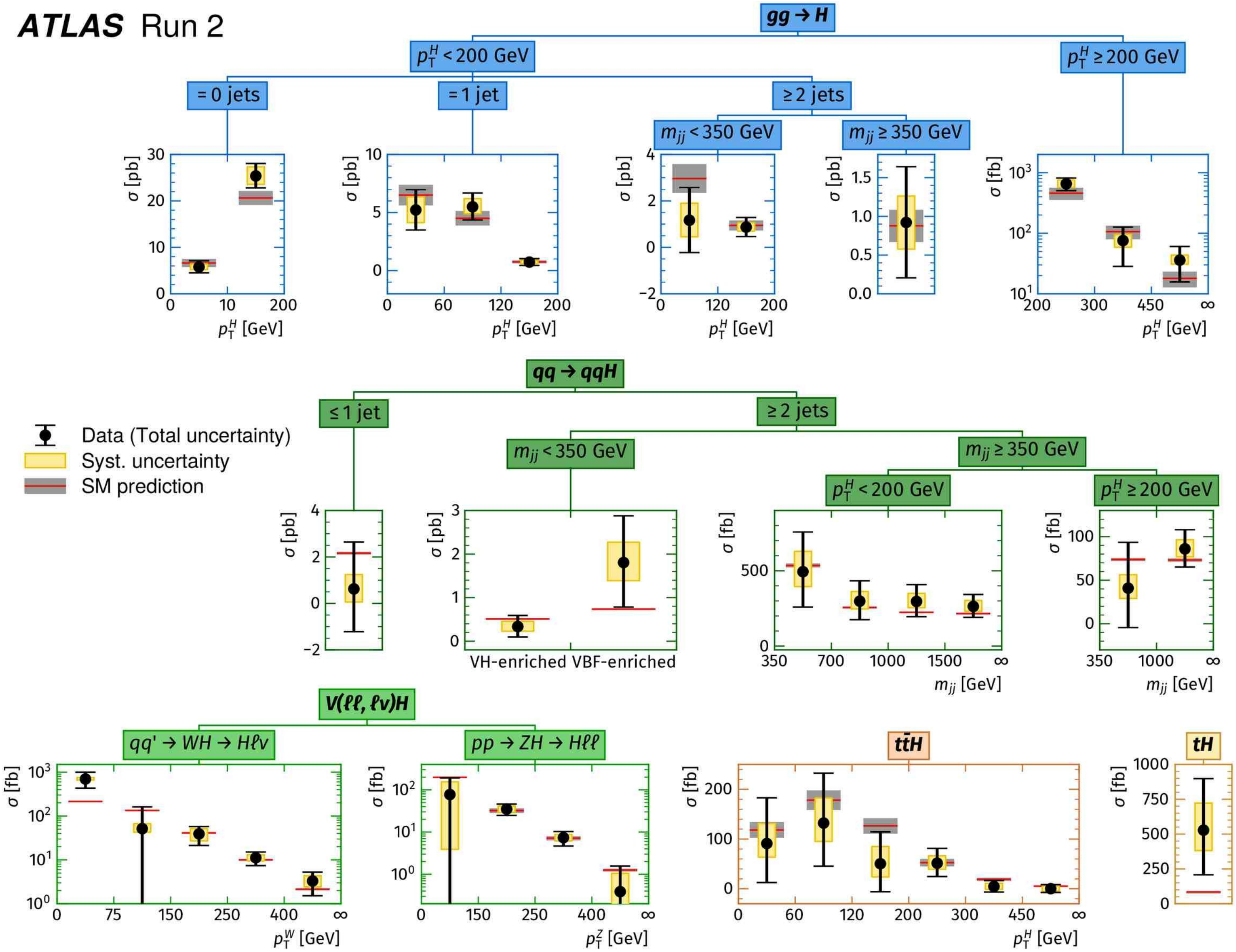
Impact of Warsaw basis SMEFT operators in Higgs physics

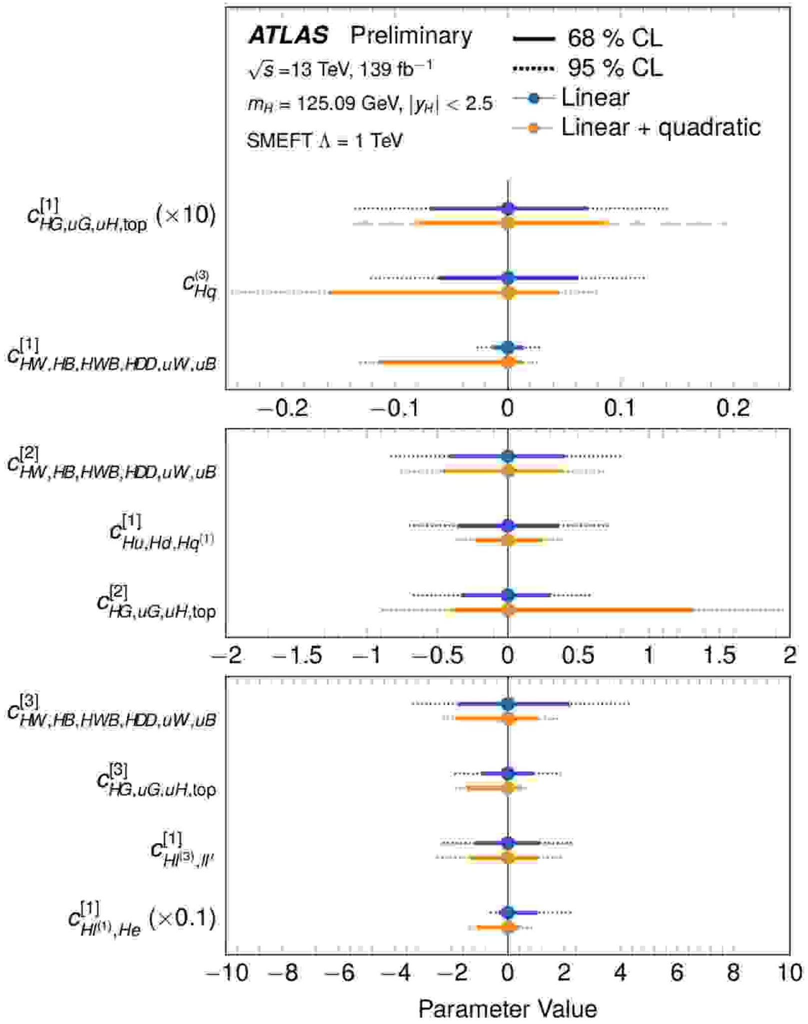


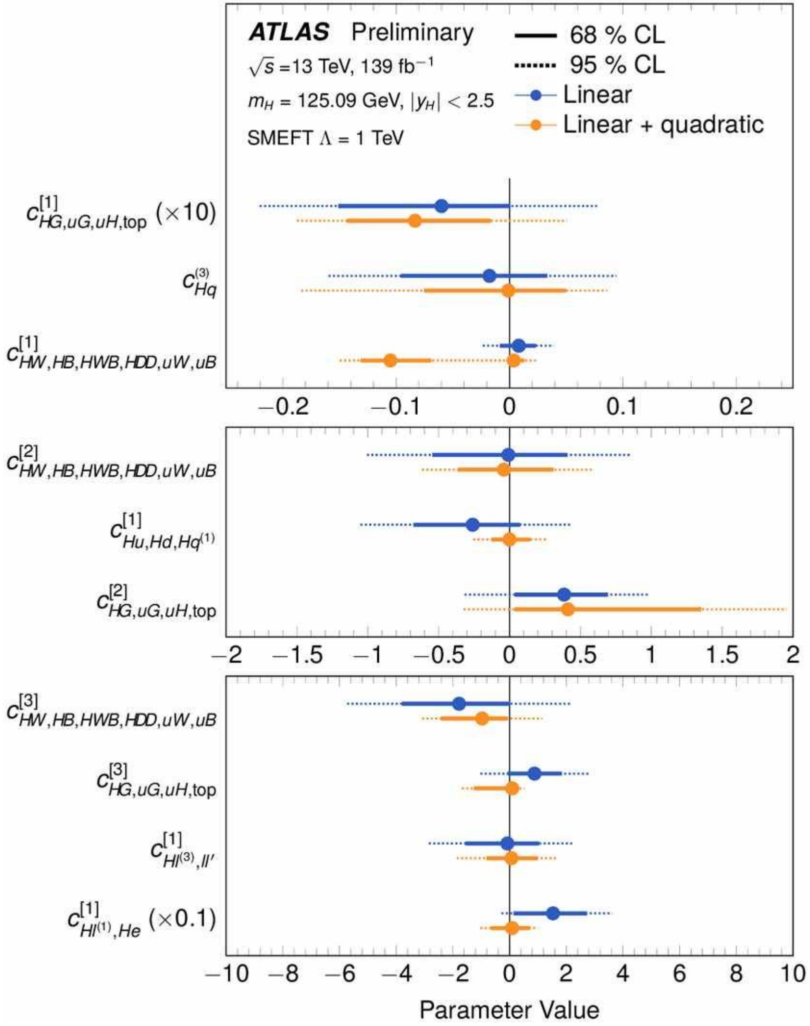
Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$	
c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$	
c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$	
$c^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$	
$c^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	
c_{qq}	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$	
$c^{(31)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$	
c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	
$c^{(1)}_{uu}$	$(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$	
$c^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$	
$c^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	
$c^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$	
$c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$	
c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	



Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	
c_{HW}	$H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$	
c_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	


ATLAS Run 2
gg → H
p_T^H < 200 GeV
p_T^H ≥ 200 GeV
= 0 jets
= 1 jet
≥ 2 jets
m_{jj} < 350 GeV
m_{jj} ≥ 350 GeV
σ [pb]
σ [fb]
p_T^H [GeV]
0 10 200
0 60 120 200
0 120 200
200 300 450 ∞
qq → qqH
≤ 1 jet
≥ 2 jets
m_{jj} < 350 GeV
m_{jj} ≥ 350 GeV
p_T^H < 200 GeV
p_T^H ≥ 200 GeV
VH-enriched VBF-enriched
350 700 1000 1500 ∞
350 1000 ∞
m_{jj} [GeV]
Data (Total uncertainty)
Syst. uncertainty
SM prediction
V(ℓℓ, ℓν)H
qq' → WH → Hℓν
pp → ZH → Hℓℓ
$t\bar{t}H$
tH
0 75 150 250 400 ∞
p_T^W [GeV]
0 150 250 400 ∞
p_T^Z [GeV]
0 60 120 200 300 450 ∞
p_T^H [GeV]


ATLAS Preliminary
$\sqrt{s}$ =13 TeV, 139 fb^{-1}
m_H = 125.09 GeV, $|y_H|$ < 2.5
SMEFT Λ = 1 TeV
68 % CL
95 % CL
Linear
Linear + quadratic
$c^{[1]}_{HG,uG,uH,\text{top}}$ (×10)
$c^{(3)}_{Hq}$
$c^{[1]}_{HW,HB,HWB,HDD,uW,uB}$
−0.2 −0.1 0 0.1 0.2
$c^{[2]}_{HW,HB,HWB,HDD,uW,uB}$
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$
$c^{[2]}_{HG,uG,uH,\text{top}}$
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
$c^{[3]}_{HW,HB,HWB,HDD,uW,uB}$
$c^{[3]}_{HG,uG,uH,\text{top}}$
$c^{[1]}_{Hl^{(3)},ll'}$
$c^{[1]}_{Hl^{(1)},He}$ (×0.1)
−10 −8 −6 −4 −2 0 2 4 6 8 10
Parameter Value


ATLAS Preliminary
$\sqrt{s}$ =13 TeV, 139 fb^{-1}
m_H = 125.09 GeV, $|y_H|$ < 2.5
SMEFT Λ = 1 TeV
68 % CL
95 % CL
Linear
Linear + quadratic
$c^{[1]}_{HG,uG,uH,\text{top}}$ (×10)
$c^{(3)}_{Hq}$
$c^{[1]}_{HW,HB,HWB,HDD,uW,uB}$
−0.2 −0.1 0 0.1 0.2
$c^{[2]}_{HW,HB,HWB,HDD,uW,uB}$
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$
$c^{[2]}_{HG,uG,uH,\text{top}}$
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
$c^{[3]}_{HW,HB,HWB,HDD,uW,uB}$
$c^{[3]}_{HG,uG,uH,\text{top}}$
$c^{[1]}_{Hl^{(3)},ll'}$
$c^{[1]}_{Hl^{(1)},He}$ (×0.1)
−10 −8 −6 −4 −2 0 2 4 6 8 10
Parameter Value

Impact of quadratic terms