Towards an EFT interpretation of STXS measurements at CMS

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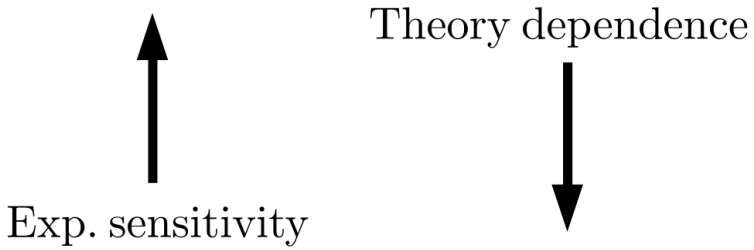
STXS: introduction

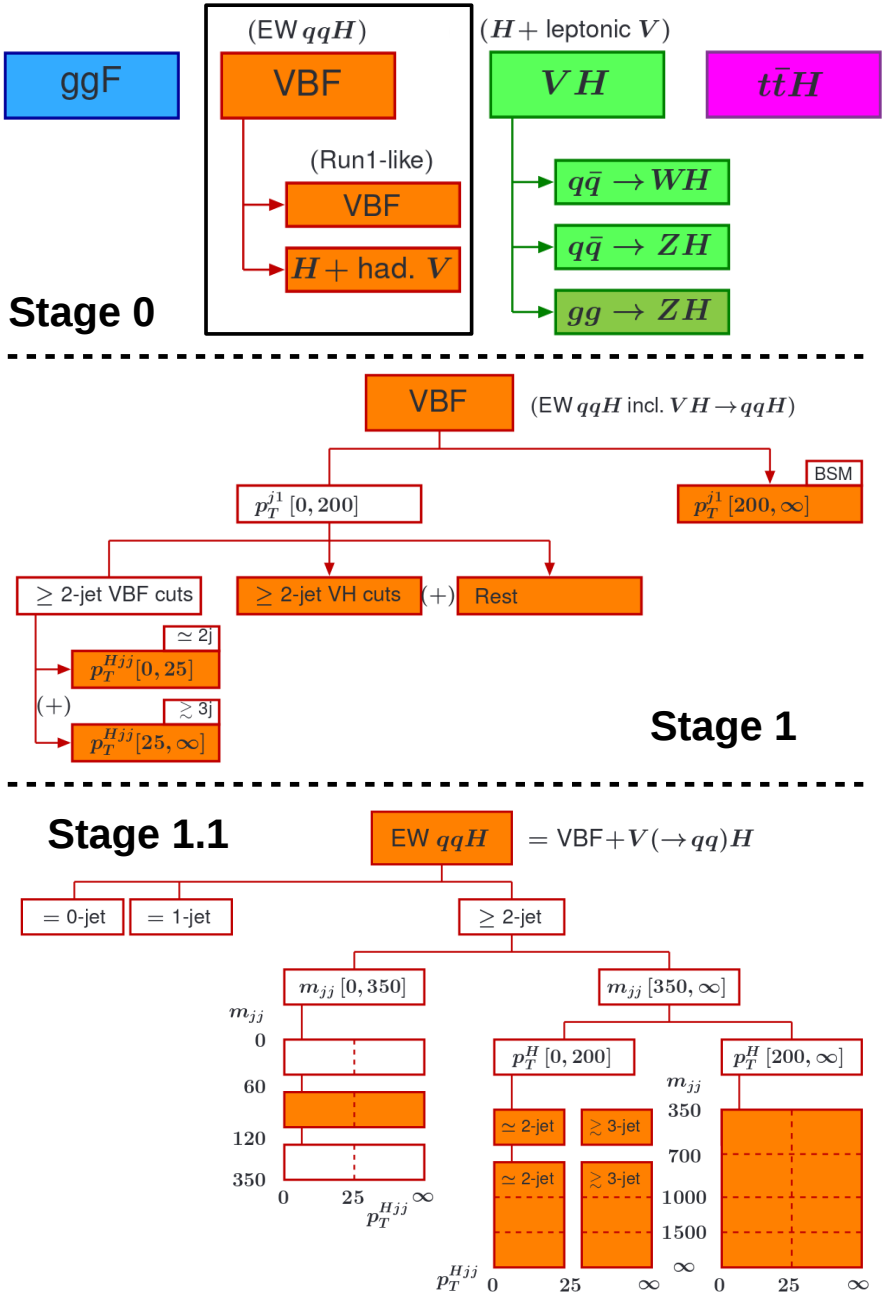
- Coherent framework:
  $\Rightarrow$ increasingly granular H meas.
  - split H phase space (bins)
  - production mode + kinematics



  - design bins ~constant theory unc.
  - + isolate possible BSM physics

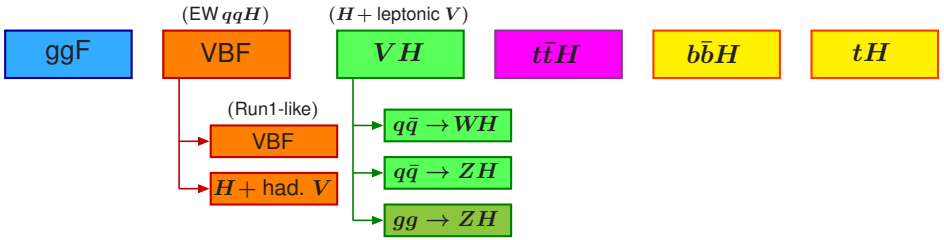
- Coherence permits combinations

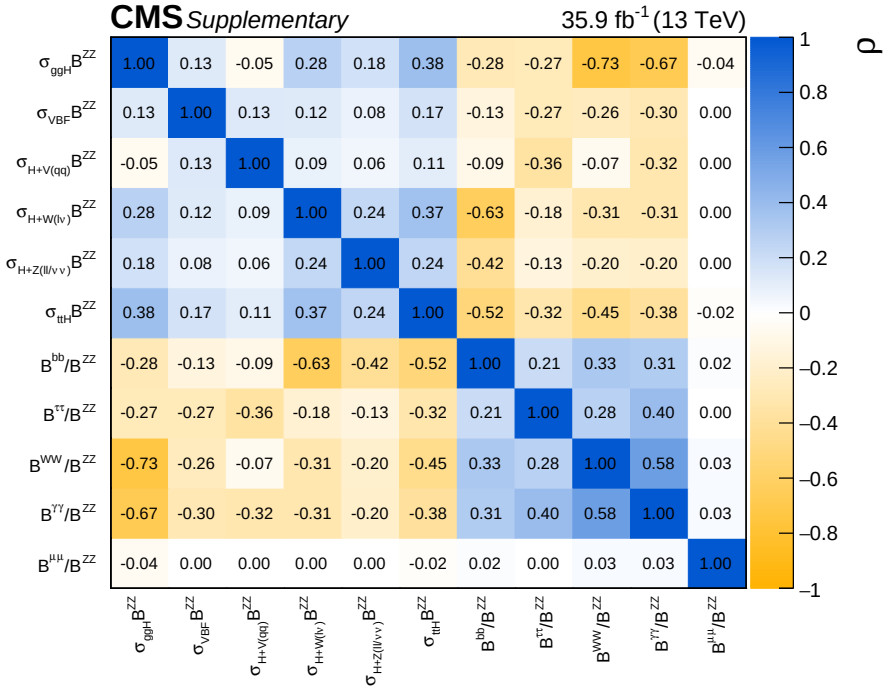
- Evolves with increasing stats: **Stages**
  - 0: SM production modes
  - 1: split by kinematics (e.g. p_T^H, N_{jets})
  - 1.1: expected sensitivity for full Run II



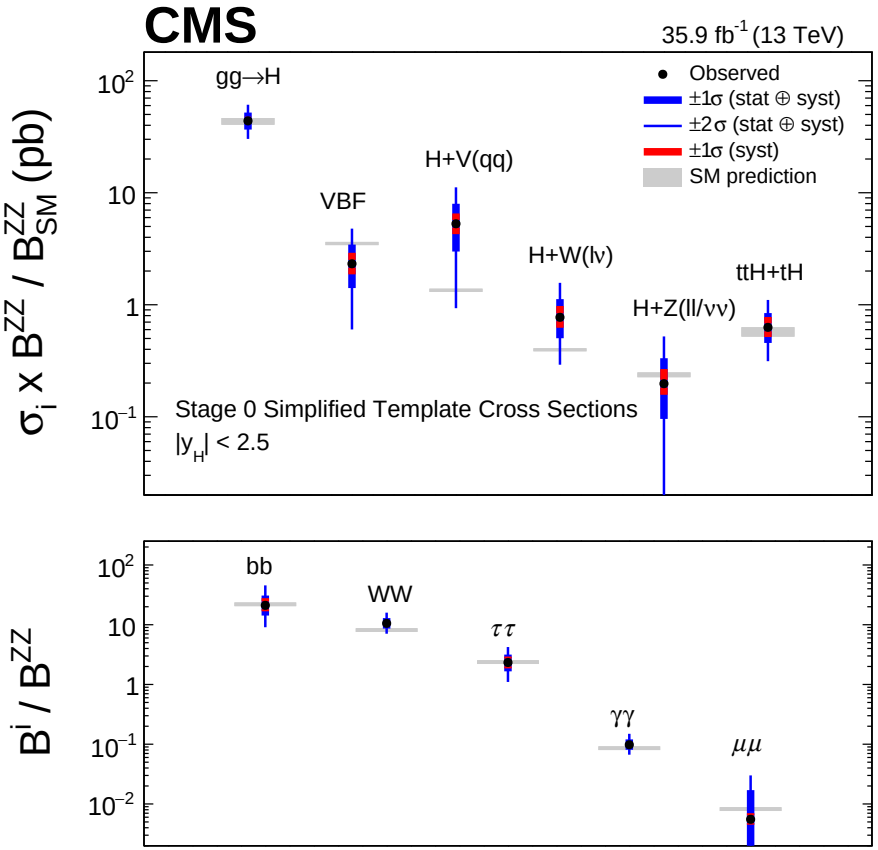
Status of STXS measurements @ CMS

- **Stage 0**: 2016 combination ($\gamma\gamma$,ZZ,WW,bb,$\tau\tau$,$\mu\mu$): [Eur. Phys. J. C (2019) 79: 421]



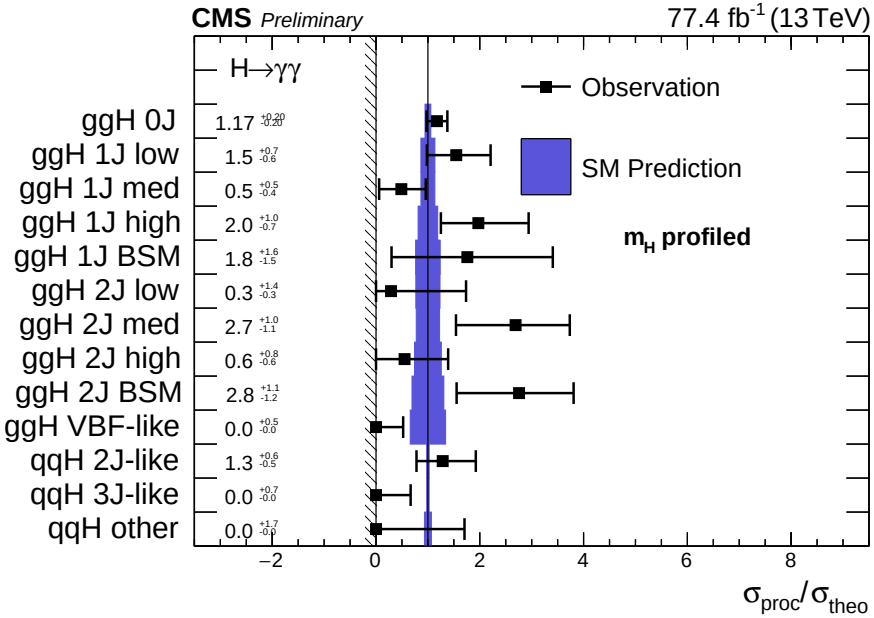


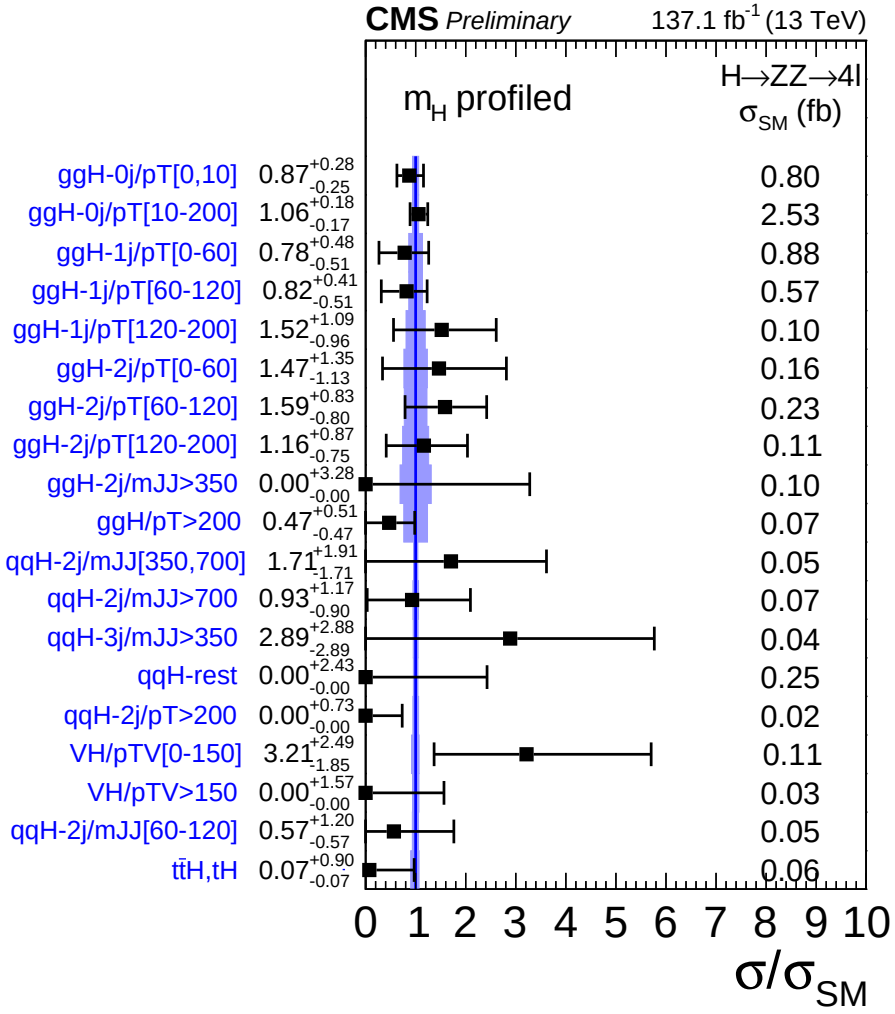
	$\sigma_{ggH}B^{ZZ}$	$\sigma_{VBF}B^{ZZ}$	$\sigma_{H+V(qq)}B^{ZZ}$	$\sigma_{H+W(l\nu)}B^{ZZ}$	$\sigma_{H+Z(ll/\nu\nu)}B^{ZZ}$	$\sigma_{ttH}B^{ZZ}$	B^{bb}/B^{ZZ}	$B^{\tau\tau}/B^{ZZ}$	B^{WW}/B^{ZZ}	$B^{\gamma\gamma}/B^{ZZ}$	$B^{\mu\mu}/B^{ZZ}$
$\sigma_{ggH}B^{ZZ}$	1.00	0.13	-0.05	0.28	0.18	0.38	-0.28	-0.27	-0.73	-0.67	-0.04
$\sigma_{VBF}B^{ZZ}$	0.13	1.00	0.13	0.12	0.08	0.17	-0.13	-0.27	-0.26	-0.30	0.00
$\sigma_{H+V(qq)}B^{ZZ}$	-0.05	0.13	1.00	0.09	0.06	0.11	-0.09	-0.36	-0.07	-0.32	0.00
$\sigma_{H+W(l\nu)}B^{ZZ}$	0.28	0.12	0.09	1.00	0.24	0.37	-0.63	-0.18	-0.31	-0.31	0.00
$\sigma_{H+Z(ll/\nu\nu)}B^{ZZ}$	0.18	0.08	0.06	0.24	1.00	0.24	-0.42	-0.13	-0.20	-0.20	0.00
$\sigma_{ttH}B^{ZZ}$	0.38	0.17	0.11	0.37	0.24	1.00	-0.52	-0.32	-0.45	-0.38	-0.02
B^{bb}/B^{ZZ}	-0.28	-0.13	-0.09	-0.63	-0.42	-0.52	1.00	0.21	0.33	0.31	0.02
$B^{\tau\tau}/B^{ZZ}$	-0.27	-0.27	-0.36	-0.18	-0.13	-0.32	0.21	1.00	0.28	0.40	0.00
B^{WW}/B^{ZZ}	-0.73	-0.26	-0.07	-0.31	-0.20	-0.45	0.33	0.28	1.00	0.58	0.03
$B^{\gamma\gamma}/B^{ZZ}$	-0.67	-0.30	-0.32	-0.31	-0.20	-0.38	0.31	0.40	0.58	1.00	0.03
$B^{\mu\mu}/B^{ZZ}$	-0.04	0.00	0.00	0.00	0.00	-0.02	0.02	0.00	0.03	0.03	1.00



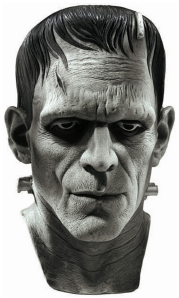
Status of STXS measurements @ CMS

- **Stage 1**: measurements in most decay channels: $\gamma\gamma$, VH(bb), $\tau\tau$
- **Stage 1.1**: Run II Legacy ⇒ public 1.1 measurements in 4ℓ (full dataset)



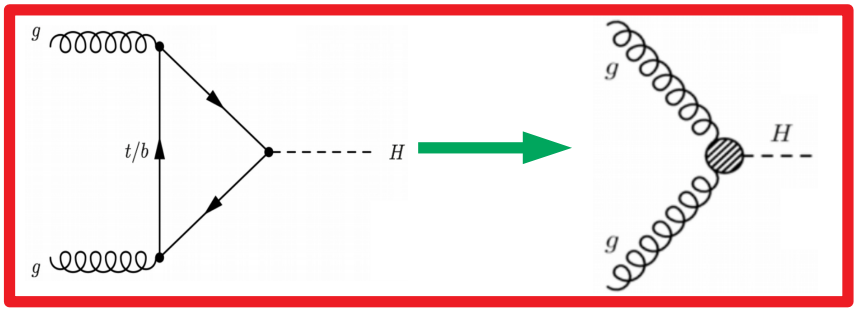


- Intermediate combination:
  - frankenstein of stages
  - direct XS meas. not possible
  - motivates interpretations...

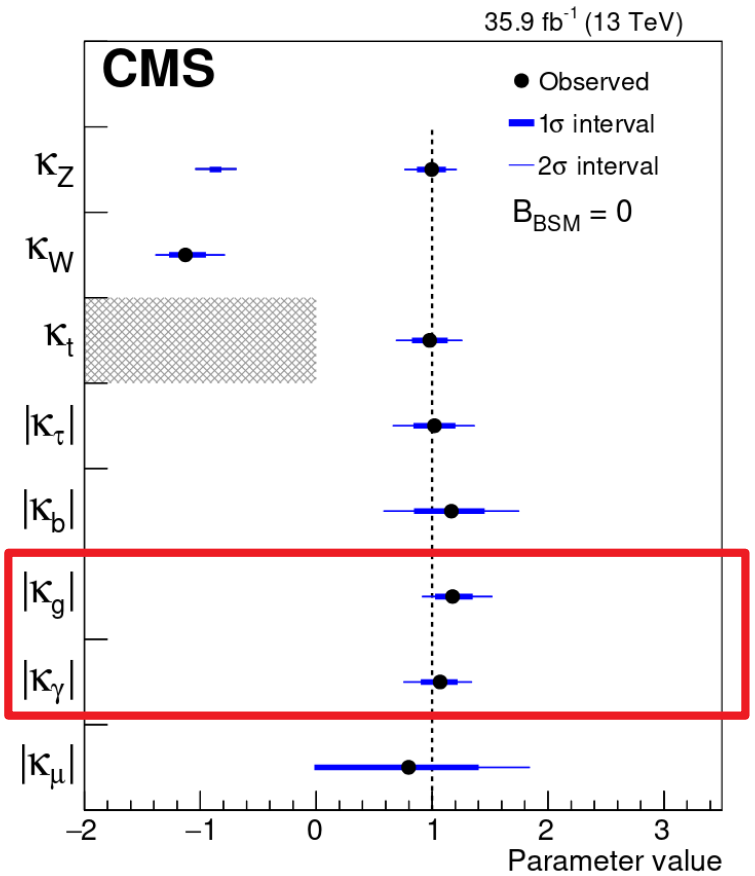


Higgs interpretations: pathway to EFT

- Previously used κ-framework: $\kappa_j^2 = \sigma_j/\sigma_j^{\rm SM}$ or $\kappa_j^2 = \Gamma^j/\Gamma^j_{\rm SM}$
  - introduced **effective** coupling modifiers: κ_g, κ_γ



  - NP @ $\Lambda \gg m_H$: accessible only in loops
- Issue: only considers shifts in total rates
  - desire more rigorous approach: shape effects



2016 combination: HIG-17-031

- **EFT**: increasingly popular tool investigate BSM

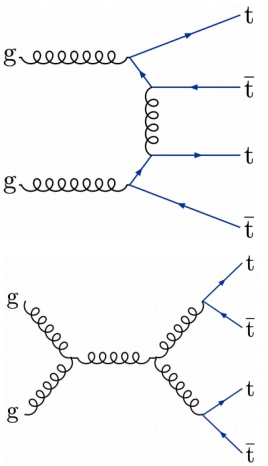
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_j \mathcal{O}_j^{(6)} f_j^{(6)} + \frac{1}{\Lambda^4}\sum_i \mathcal{O}_j^{(8)} f_j^{(8)} + \ldots$$

  - integrate out short-distance NP
  - dynamics described by higher dim operators
    $\Rightarrow$ feat. SM fields, obey SM symmetry group

EFT @ CMS

- Not a new concept in CMS...

- **Top**: e.g. $t\bar{t}t\bar{t}$
  - TOP-17-019
  - deviations in (tot) XS from 4 $\mathcal{O}_j^{(6)}$:

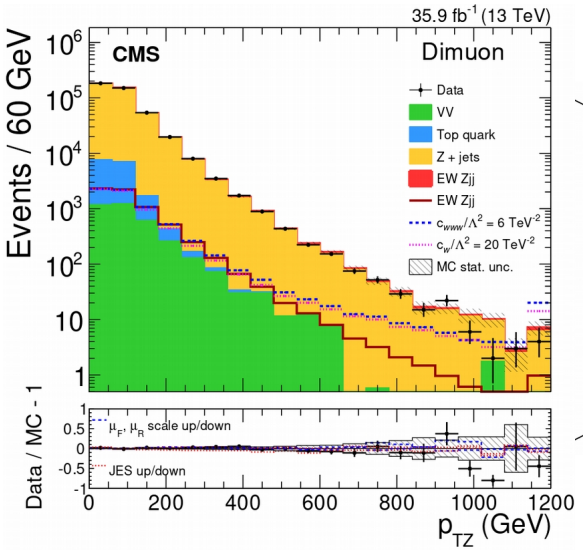


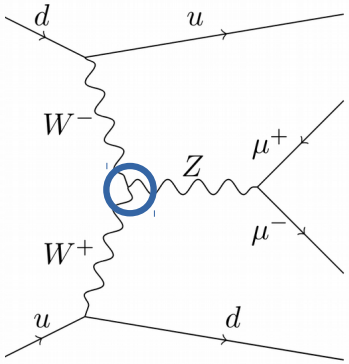
$$\mathcal{O}^1_{tt} = (\bar{t}_R\gamma^\mu t_R)\left(\bar{t}_R\gamma_\mu t_R\right),$$
$$\mathcal{O}^1_{QQ} = (\overline{Q}_L\gamma^\mu Q_L)\left(\overline{Q}_L\gamma_\mu Q_L\right),$$
$$\mathcal{O}^1_{Qt} = (\overline{Q}_L\gamma^\mu Q_L)\left(\bar{t}_R\gamma_\mu t_R\right),$$
$$\mathcal{O}^8_{Qt} = \left(\overline{Q}_L\gamma^\mu T^A Q_L\right)\left(\bar{t}_R\gamma_\mu T^A t_R\right)$$

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	$[-2.0, 1.8]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{QQ}$	$[-2.0, 1.8]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{Qt}$	$[-3.3, 3.2]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{Qt}$	$[-7.3, 6.1]$	$[-7.9, 6.6]$

- **SM**: Z($\ell\ell$)jj
  - SMP-16-018
  - aTGC: limits from tail of p_T^Z

$$\mathcal{O}_W = (D_\mu H)^\dagger W^{\mu\nu} D_\nu H$$
$$\mathcal{O}_{WWW} = \mathrm{Tr}[\mathrm{W}_{\mu\nu}\,\mathrm{W}^\nu_\rho\,\tilde{\mathrm{W}}^{\rho\mu}]$$





Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	$[-3.7, 3.6]$	$[-2.6, 2.6]$
c_W/Λ^2	$[-12.6, 14.7]$	$[-8.4, 10.1]$

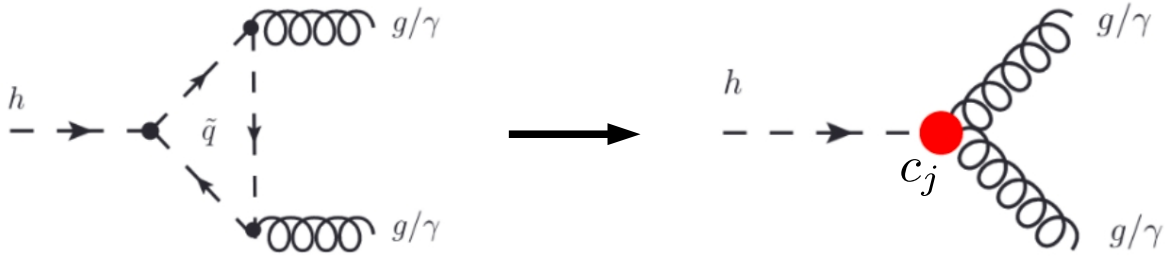
- Time for **Higgs sector** to follow suit...
  - Keep in mind: common approach permits global constraints

Re-interpretation of STXS in an EFT framework

- Goal: parametrize each STXS bin in terms of EFT parameters
- Higgs Effective Lagrangian (HEL): 39 flavour independent dim-6 operators

$$\mathcal{L}_{\rm HEL} = \mathcal{L}_{\rm SM} + \sum_j \mathcal{O}_j^{(6)} f_j/\Lambda^2$$

  - NP: deviations from zero in HEL parameters, $c_j \propto f_j/\Lambda^2$



- Require **scaling functions**: $\mu_i(c_j) = \sigma_i^{\rm EFT}/\sigma_i^{\rm SM}$
  - for each STXS bin, i

$$\sigma_i^{\rm EFT} = \sigma_i^{\rm SM} + \sigma_i^{\rm int} + \sigma_i^{\rm BSM}$$

$$\implies \quad \mu_i(c_j) = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- **Task**: derive A_j and B_{jk} coefficients for STXS bins

$$\mathcal{O}_g = |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\tilde{\mathcal{O}}_g = |H|^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$$
$$\mathcal{O}_\gamma = |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\tilde{\mathcal{O}}_\gamma = |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$$

$$\mathcal{O}_u = y_u |H|^2 \bar{Q}_L H^\dagger u_R + \text{h.c.}$$
$$\mathcal{O}_d = y_d |H|^2 \bar{Q}_L H d_R + \text{h.c.}$$
$$\mathcal{O}_\ell = y_\ell |H|^2 \bar{L}_L H \ell_R + \text{h.c.}$$

$$\mathcal{O}_H = \left(\partial^\mu |H|^2\right)^2$$
$$\mathcal{O}_6 = \left(H^\dagger H\right)^3$$

$$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger\, \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\tilde{\mathcal{O}}_{HW} = i\,(D^\mu H)^\dagger\, \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger\, (D^\nu H) B_{\mu\nu}$$
$$\tilde{\mathcal{O}}_{HB} = i\,(D^\mu H)^\dagger\, (D^\nu H) \tilde{B}_{\mu\nu}$$

$$\mathcal{O}_W = i\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = i\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

EFT parametrization: derivation

C. Hays, V. Sanz,
G. Zemaityte

$$\mu_i(c_j) = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- Scaling functions for **stage 1** bins calc. previously: [LHCHXSWG-INT-2017-001]
  - used directly in ATL-PHYS-PUB-2017-018: stage 1 $\gamma\gamma + 4\ell$ combination (2016)
  - same approach: derive A_j/B_{jk} for stage 0, 1 & 1.1 bins
  - also provide decay channel parametrization: $\Gamma^f(c_j)$

1. Generate events per Higgs prod. mode (LO): MADGRAPH w/ PYTHIA showering
2. Import HEL (UFO): reweight events for different points in HEL param space
   $\Rightarrow$ SM: all $c_j = 0$
   $\Rightarrow$ vary c_j individually + pairwise to calc. B_{jk} cross terms
3. Propagate events through RIVET tool: STXS classification (0, 1 and 1.1)
4. Extract dependence of STXS bin, i, on c_j (or $c_j c_k$): A_j & B_{jk}
   $\Rightarrow$ comparing reweighted cross section to SM

WH Leptonic

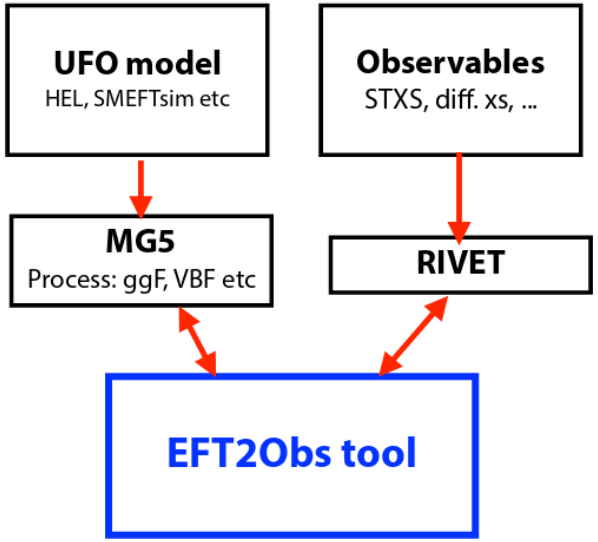
$$\boxed{p_T^V\,[0, 150]} = 1 + 33\, c_{WW} + 12\, c_{HW} + 320\, c_{WW}^2 + \ldots$$

EFT2Obs: common tool for EFT interpretation

- Clear advantage for combining measurements/experiments
  - **not STXS specific**:
    $\Rightarrow$ calc. coeff. for scaling of any binned observable as f^{nct} of EFT params

- Established @ Les Houches 2019: ajgilbert/EFT2Obs-Demo
  - useable inside & outside CMS: based on public tools (ROOT not required!)
  - agnostic to EFT implementation:
    $\Rightarrow$ extensively tested with HEL, ongoing validations with SMEFTsim
  - early stages, major developments over coming months: **feedback very useful**

- Steer reweighting with simple configs

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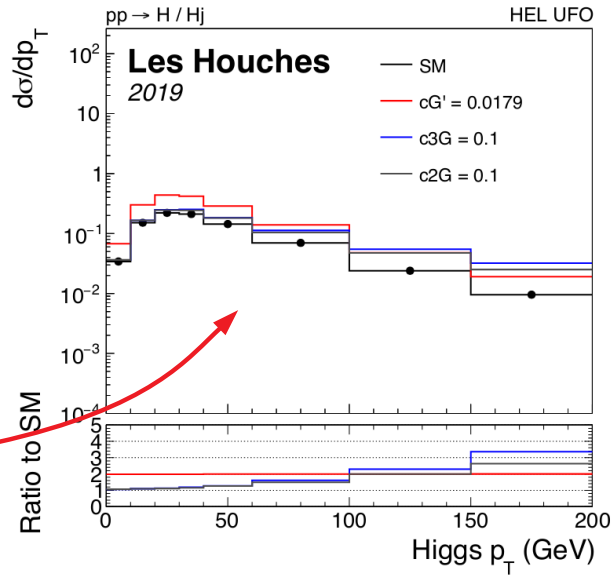
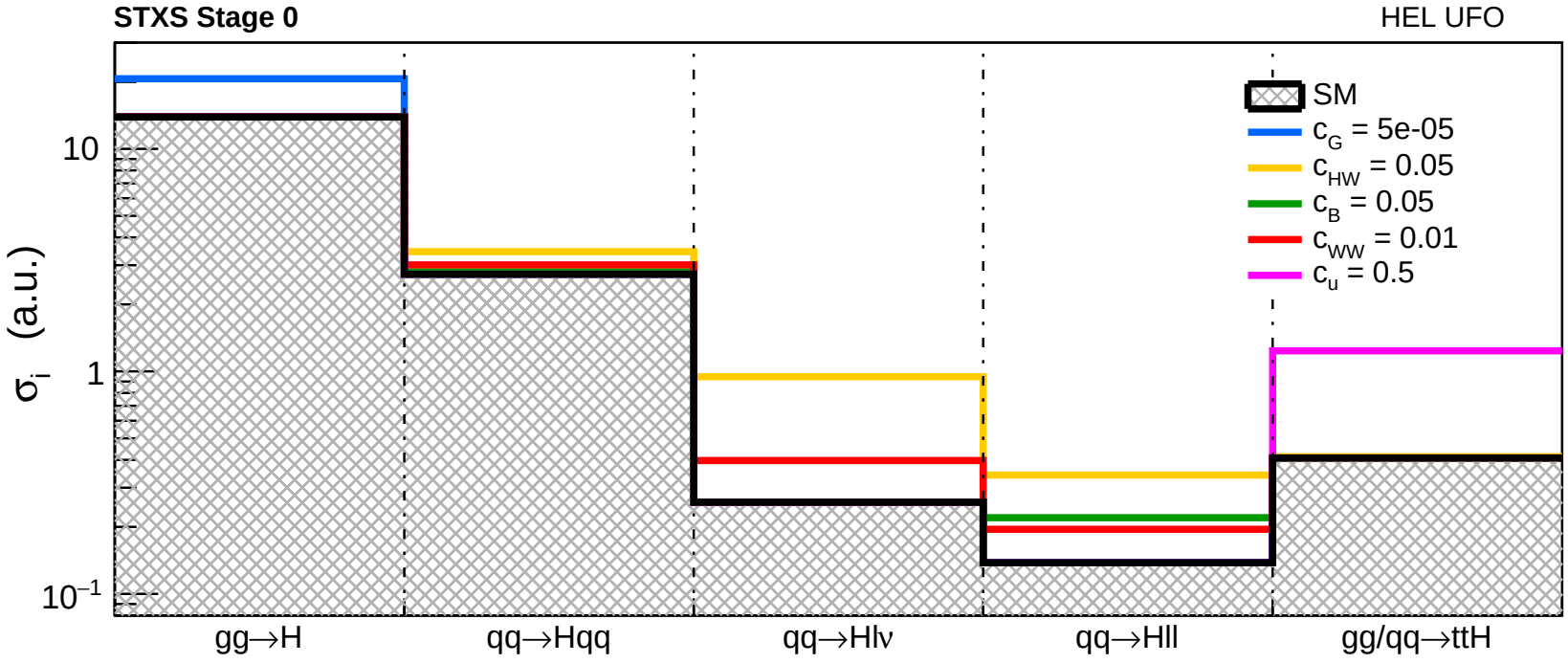
        "index": 30,
        "name": "c3g",
        "step": 0.0001
    },
...
]
```

$$\mu_i(c_j) = \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$



EFT parametrization: stage 0

- Varying c_j individually...



$$\mathcal{O}_G = |H|^2 G^A_{\mu\nu} G^{A,\mu\nu}$$

$$\mathcal{O}_{HW} = i(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

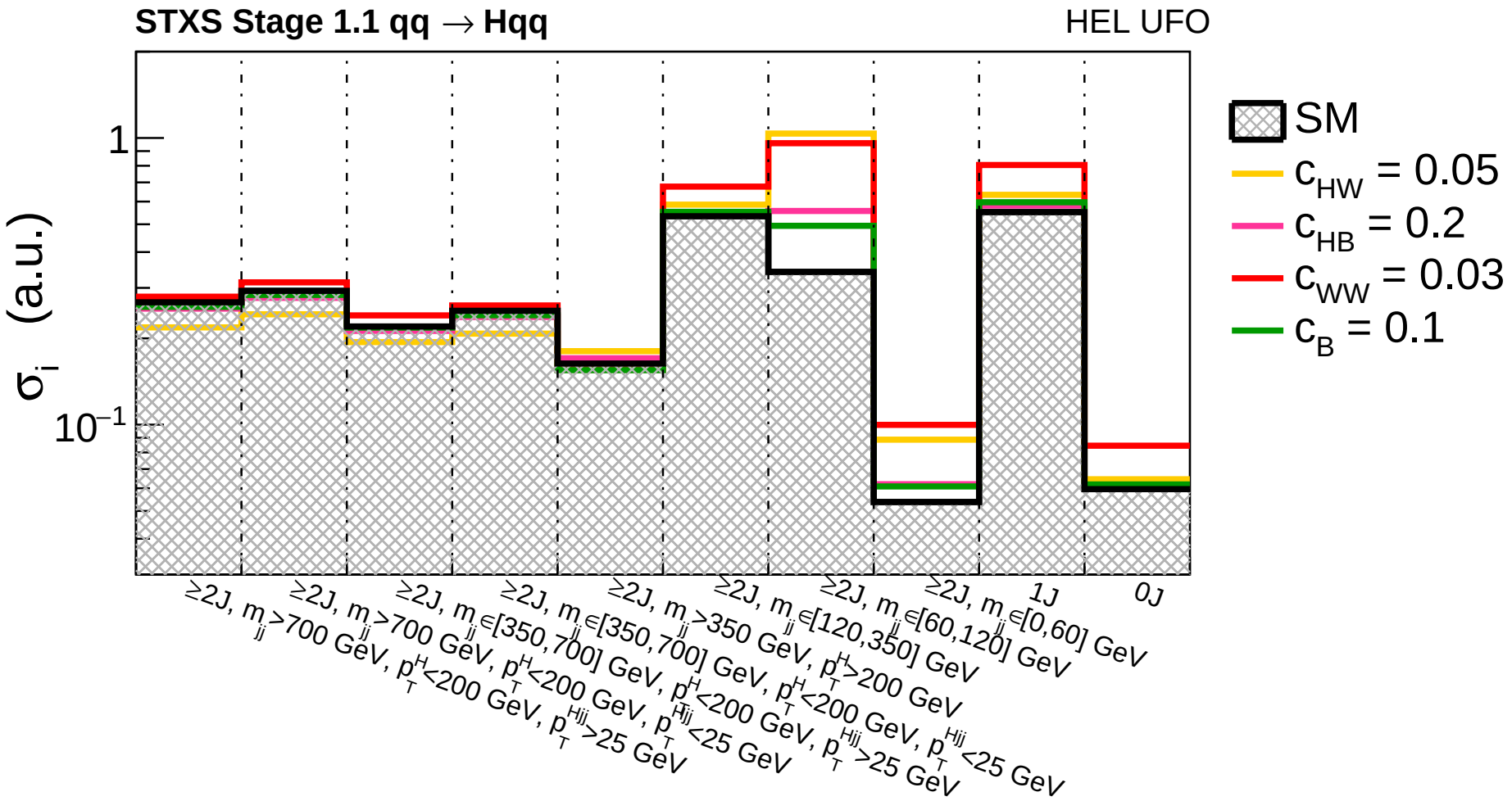
$$\mathcal{O}_B = i(H^\dagger \overleftrightarrow{D} H)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{WW} = i(H^\dagger \sigma^a \overleftrightarrow{D} H) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_u = y_u |H^2| \bar{Q}_L H^\dagger u_R + \text{h.c.}$$

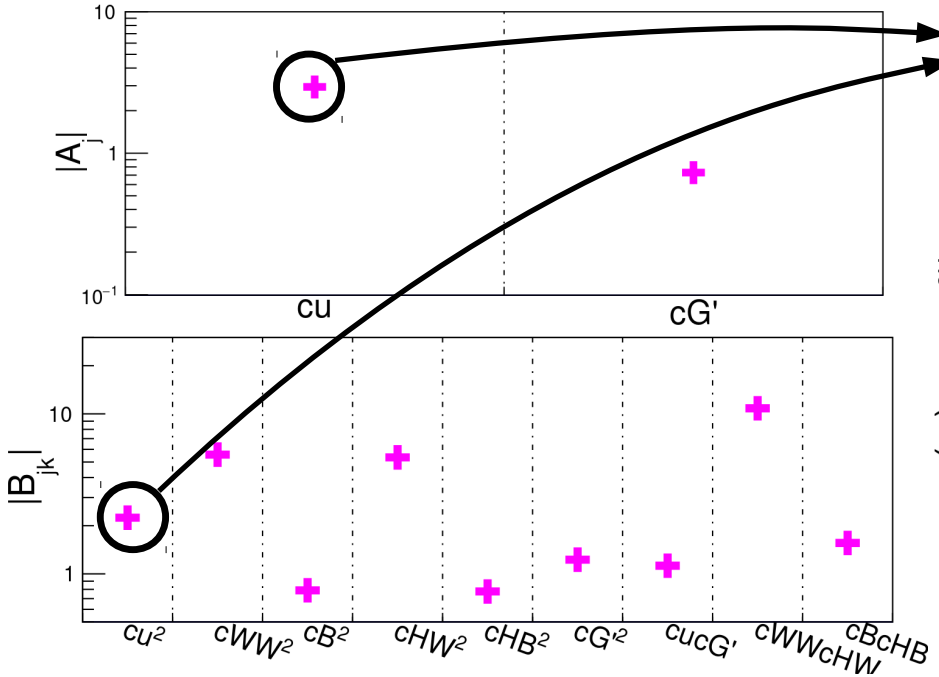
EFT parametrization: stage 1.1 qqH

- Beyond stage 0: account for shape effects as well as total rates

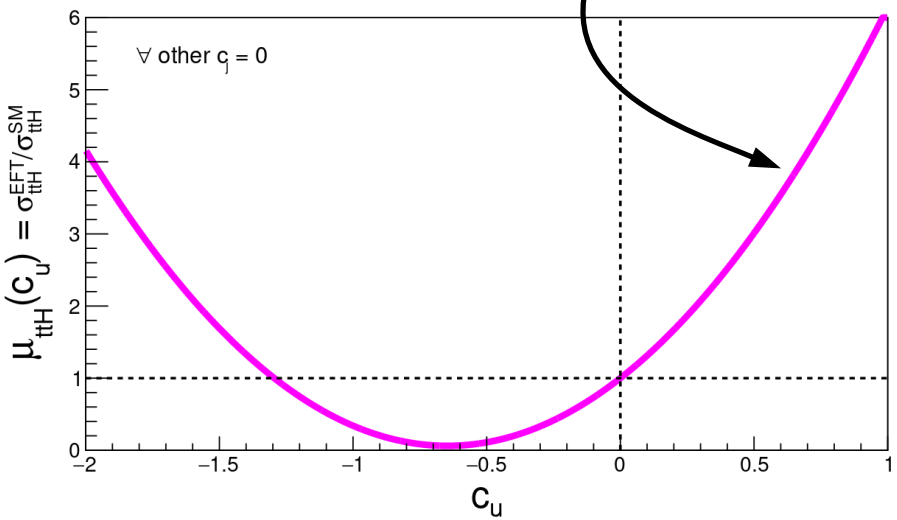


EFT parametrization: A_j/B_{jk} coefficients

- Impossible to fit for all 39 params given current scope...
  - variations in subset of HEL params: c_G, c_A, c_{HW}, c_{HB}, c_{WW}, c_B, c_u, c_d, c_l
  - leading CP-even terms + not strongly constrained by EWK precision data
- Extract relevant coefficients for Stage 0, 1 + 1.1 STXS bins: e.g. ttH...



$t\bar{t}H$ $= 1 + 2.9\,c_u + 2.24\,c_u^2$



- Successfully validated majority of Stage 1 A_j/B_{jk} against LHCHXSWG values
  - others are still in progress, finalise before integration into CMS analyses
- Max-likelihood fit: signal scale according to $\mu_i(c_j)$ × decay parametrization

Summary and outlook

- Status of STXS measurements @ CMS:
  - run II legacy adhere to stage 1.1 binning scheme: coherent with ATLAS
  - currently mix of stages: motivates interpretations

- Re-interpretation of STXS measurements in EFT framework
  - HEL: parametrize variations in STXS bins (0, 1 and 1.1)
  - extends upon κ-framework, using shape information
  - before integration into CMS analyses: $\mu_i(c_j)$ must be validated!
    $\Rightarrow$ in progress: comparing stage 1 A_j/B_{jk} coeff. to LHCHXSWG values

- Maximum-likelihood fit: extract constraints on HEL params, c_j
  - scale signal according to product of STXS & decay parametrizations
  - **machinery in place**
  - full scope in H combinations: explore more $\mathcal{O}_j$

- Ultimate constraints: global fit
  - combination with other areas of collider physics e.g. SM, VBS, top...
  - extremely challenging... but exciting
  - requires common EFT description: HEL (SILH) $\Rightarrow$ SMEFT (Warsaw)

Back-Up Slides

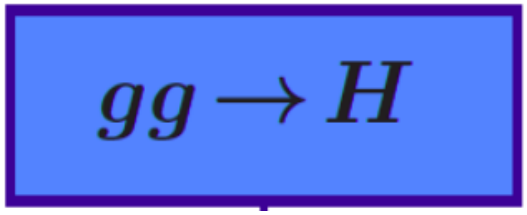
Total scaling functions

- Total scaling: product of STXS and decay parametrization
- For signal (i,f):

$$\mu_i^f(c_j) = \sigma_i^{\mathrm{EFT}}/\sigma_i^{\mathrm{SM}} \times \mathrm{BR}^{\mathrm{EFT}}(\mathrm{H} \to \mathrm{f})/\mathrm{BR}^{\mathrm{SM}}(\mathrm{H} \to \mathrm{f})$$

  - production: calculated A_j/B_{jk} ourselves
  - decay: taken directly from [LHCHXSWG-INT-2017-001]

- e.g. Stage 0



$\times H \to \gamma\gamma$