Towards an EFT interpretation of STXS measurements at CMS

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

Theory dependence

Exp. sensitivity
- design bins $\sim$ 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. $p_T^H$, $N_{\text{jets}}$)
- 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]

![Diagram showing STXS measurements](image)

### CMS Supplementary

<table>
<thead>
<tr>
<th>Observable</th>
<th>$\sigma_{\text{ggF}}$</th>
<th>$\sigma_{\text{VBF}}$</th>
<th>$\sigma_{\text{ttH}}$</th>
<th>$\sigma_{\text{bbH}}$</th>
<th>$\sigma_{\text{tH}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H+\text{V}(qq)$</td>
<td>$0.00 \pm 0.13$</td>
<td>$0.10 \pm 0.01$</td>
<td>$0.09 \pm 0.01$</td>
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### Observed vs. SM Prediction

- **Observed**: $35.9 \text{ fb}^{-1} (13 \text{ TeV})$
- **SM Prediction**: $35.9 \text{ fb}^{-1} (13 \text{ TeV})$

### Results

- **Stage 0 Simplified Template Cross Sections**
- **$|y_H| < 2.5$**
Status of STXS measurements @ CMS

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

### Histograms

- **CMS Preliminary**

  - $H\rightarrow\gamma\gamma$
  - ggH 0J
  - ggH 1J low
  - ggH 1J med
  - ggH 1J high
  - ggH 1J BSM
  - ggH 2J low
  - ggH 2J med
  - ggH 2J high
  - ggH 2J BSM
  - ggH VBF-like
  - qqH 2J-like
  - qqH 3J-like
  - qqH other

- **Observation**
- **SM Prediction**

  - $m_h$ profiled

### Table

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<thead>
<tr>
<th>Process</th>
<th>Observation</th>
<th>SM Prediction</th>
</tr>
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<tbody>
<tr>
<td>ggH-0j/pT[0,10]</td>
<td>0.87 $^{+0.28}_{-0.25}$</td>
<td>0.80</td>
</tr>
<tr>
<td>ggH-0j/pT[10-200]</td>
<td>1.06 $^{+0.19}_{-0.17}$</td>
<td>2.53</td>
</tr>
<tr>
<td>ggH-1j/pT[0-60]</td>
<td>0.78 $^{+0.48}_{-0.51}$</td>
<td>0.88</td>
</tr>
<tr>
<td>ggH-1j/pT[60-120]</td>
<td>0.82 $^{+0.41}_{-0.51}$</td>
<td>0.57</td>
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<tr>
<td>ggH-1j/pT[120-200]</td>
<td>1.52 $^{+1.09}_{-0.96}$</td>
<td>0.10</td>
</tr>
<tr>
<td>ggH-2j/pT[0-60]</td>
<td>1.47 $^{+1.35}_{-1.13}$</td>
<td>0.16</td>
</tr>
<tr>
<td>ggH-2j/pT[60-120]</td>
<td>1.59 $^{+0.80}_{-0.83}$</td>
<td>0.23</td>
</tr>
<tr>
<td>ggH-2j/pT[120-200]</td>
<td>1.16 $^{+0.87}_{-0.75}$</td>
<td>0.11</td>
</tr>
<tr>
<td>ggH-2j/mJJ&gt;350</td>
<td>0.00 $^{+0.32}_{-0.00}$</td>
<td>0.10</td>
</tr>
<tr>
<td>ggH/pT&gt;200</td>
<td>0.47 $^{+0.51}_{-0.47}$</td>
<td>0.07</td>
</tr>
<tr>
<td>qqH-2j/mJJ[350,700]</td>
<td>1.71 $^{+1.91}_{-1.71}$</td>
<td>0.05</td>
</tr>
<tr>
<td>qqH-2j/mJJ&gt;700</td>
<td>0.93 $^{+1.17}_{-0.90}$</td>
<td>0.07</td>
</tr>
<tr>
<td>qqH-3j/mJJ&gt;350</td>
<td>2.89 $^{+2.88}_{-2.89}$</td>
<td>0.04</td>
</tr>
<tr>
<td>qqH-rest</td>
<td>0.00 $^{+0.23}_{-0.00}$</td>
<td>0.25</td>
</tr>
<tr>
<td>qqH-2j/pT&gt;200</td>
<td>0.00 $^{+0.79}_{-0.00}$</td>
<td>0.02</td>
</tr>
<tr>
<td>VH/pTV[0-150]</td>
<td>3.21 $^{+2.49}_{-1.85}$</td>
<td>0.11</td>
</tr>
<tr>
<td>VH/pTV&gt;150</td>
<td>0.00 $^{+1.57}_{-1.00}$</td>
<td>0.03</td>
</tr>
<tr>
<td>qqH-2j/mJJ[60-120]</td>
<td>0.57 $^{+1.20}_{-0.57}$</td>
<td>0.05</td>
</tr>
<tr>
<td>tH, tH</td>
<td>0.07 $^{+0.90}_{-0.07}$</td>
<td>0.06</td>
</tr>
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### Intermediate combination:

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

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STXS to EFT

Higgs Couplings 2.10.19 3 / 12
Higgs interpretations: pathway to EFT

- Previously used $\kappa$-framework: $\kappa_j^2 = \sigma_j/\sigma_j^{SM}$ or $\kappa_j^2 = \Gamma_j/\Gamma_j^{SM}$
  
  - introduced **effective** coupling modifiers: $\kappa_g$, $\kappa_\gamma$

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

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

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_j O_j^{(6)} f_j^{(6)} + \frac{1}{\Lambda^4} \sum_i O_j^{(8)} f_j^{(8)} + ...$$

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

2016 combination: HIG-17-031
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 $4 \mathcal{O}_j^{(6)}$:
    
    
    $\mathcal{O}_{\text{tt}}^1 = (t_R \gamma^\mu t_R) (\bar{t}_R \gamma^\mu t_R)$,
    
    $\mathcal{O}_{\text{QQ}}^1 = (Q_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L)$,
    
    $\mathcal{O}_{\text{Qt}}^1 = (Q_L \gamma^\mu Q_L)(\bar{t}_R \gamma^\mu t_R)$,
    
    $\mathcal{O}_{\text{Qt}}^8 = (Q_L \gamma^\mu T^A Q_L)(\bar{t}_R \gamma^\mu T^A t_R)$

- **SM**: $Z(\ell\ell)jj$
  - **SMP-16-018**
  - aTGC: limits from tail of $p_T^Z$
    
    $\mathcal{O}_W = (D_\mu H)^\dagger W^{\mu\nu} D_\nu H$
    
    $\mathcal{O}_{WW} = \text{Tr}[W_{\mu\nu} W^{\nu\rho} W^{\rho\mu}]$

- 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

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

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

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

\[
\sigma_i^{\text{EFT}} = \sigma_i^{\text{SM}} + \sigma_i^{\text{int}} + \sigma_i^{\text{BSM}}
\]

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

- **Task:** derive \( A_j \) and \( B_{jk} \) coefficients for STXS bins
EFT parametrization: derivation

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

- 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
   \[ \Rightarrow \text{SM: all } c_j = 0 \]
   \[ \Rightarrow \text{vary } c_j \text{ individually + pairwise to calc. } B_{jk} \text{ cross terms} \]
3. Propagate events through Rivet tool: STXS classification (0, 1 and 1.1)
4. Extract dependence of STXS bin, $i$, on $c_j$ (or $c_j c_k$): $A_j$ & $B_{jk}$
   \[ \Rightarrow \text{comparing reweighted cross section to SM} \]

**WH Leptonic**

\[ p_T^V [0, 150] = 1 + 33 c_{WW} + 12 c_{HW} + 320 c_{WW}^2 + \ldots \]
EFT2Obs: common tool for EFT interpretation

- Clear advantage for combining measurements/experiments
  - not STXS specific:
    \[ \Rightarrow \text{calc. coeff. for scaling of any binned observable as } f_{\text{ntc}} \text{ of EFT params} \]

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

- Steer reweighting with simple configs

\[
\mu_i(c_j) = \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k
\]
EFT parametrization: stage 0

- Varying $c_j$ individually...

\[
\sigma_i \rightarrow \begin{cases} 
10 & \text{gg} \rightarrow \text{H} \\
1 & \text{qq} \rightarrow \text{Hqq} \\
1 & \text{qq} \rightarrow \text{Hlv} \\
1 & \text{qq} \rightarrow \text{Hll} \\
1 & \text{H} \rightarrow \text{gg/qq} 
\end{cases}
\]

\[
O_G = |H|^2 G_{\mu\nu}^A G^{A,\mu\nu} \\
O_{HW} = i(D^\mu H)^\dagger \sigma^a (D^{\nu} H) W^a_{\mu\nu} \\
O_B = i(H^\dagger \not{D} H) \partial^{\nu} B_{\mu\nu}
\]

\[
O_{WW} = i(H^\dagger \sigma^a \not{D} H) D^{\nu} W^a_{\mu\nu} \\
O_u = y_u |H|^2 |\tilde{Q}_L H^\dagger u_R + \text{h.c.}
\]
EFT parametrization: stage 1.1 qqH

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

![Graph showing STXS Stage 1.1 qq → Hqq]
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. $ttH$...

- 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 $\mu_i(c_j) \times$ decay parametrization

\[
ttH = 1 + 2.9 c_u + 2.24 c_u^2
\]
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 $\kappa$-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 $(i,f)$:
  \[ \mu_i^f(c_j) = \frac{\sigma_i^{\text{EFT}}}{\sigma_i^{\text{SM}}} \times \frac{\text{BR}_{\text{EFT}}(H \rightarrow f)}{\text{BR}_{\text{SM}}(H \rightarrow f)} \]
  
  ▶ **production**: calculated $A_j/B_{jk}$ ourselves
  ▶ **decay**: taken directly from [LHCHXSWG-INT-2017-001]

- e.g. Stage 0

\[ gg \rightarrow H \]
\[ \times H \rightarrow \gamma\gamma \]