SMEFT and searches for new physics

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CP3, UCLouvain
28th May 2020
Where are we?

10 years since the start of LHC run 1

- No clear sign of TeV scale new physics
- Direct searches have saturated the energy frontier
What do we know?

BSM states are either too...

**Weakly coupled**
- room limited

**Exotic**
- we aren’t looking in the right place

**Heavy**
- kinematically out of reach

Room for improvement with increasing luminosity
- Still 20x more data to come

Limited by our creativity
- Work for theorists & experimentalists to motivate & enable searches for new signatures

Worst-case scenario from direct search point of view
- Forced into the business of indirect searches
The indirect way

Not only direct searches…

LHC’s #1 objective (Higgs discovery) has been achieved.

We are in the midst of a huge programme of precision measurements of SM interactions up to the TeV scale.

Thanks to the efforts of th. and exp. colleagues, the LHC can equally be used as a precision machine.

**Big question:** Origin of the Electroweak scale.

**Where to look:** Interactions among the key players.
   
Higgs, EW gauge bosons, top quark,…. 
Pinning down EWSB

Independent of the outcome of direct NP searches

\textit{LHC legacy} = \textit{precise set of measurements of the interactions that govern EWSB}

\textbf{Gauge/Higgs:} all components of Higgs field

- Connects gauge and Goldstone boson interactions
- Equivalence of longitudinal modes at high energy

\[
\varphi = \frac{1}{\sqrt{2}} \left( \begin{array}{c} -iG^+ \\ v + h + iG^0 \end{array} \right) \quad \partial_\mu G^+ \leftrightarrow W_\mu^+ \\
\partial_\mu G^0 \leftrightarrow Z_\mu
\]

The top is special\ yet relatively poorly measured

- Being most strongly coupled to the Higgs has strong BSM implications
- The LHC is a top factory
Marrying energy & precision

Paradigm shift at the energy frontier for BSM searches

Direct (bump hunts)
Indirect (measuring tails)
⇒ New physics is heavy

Heavy new physics
Precision measurements
High energy

Standard Model Effective Field Theory (SMEFT)

A parameter space for BSM interactions between SM particles
Marrying energy & precision

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Standard Model

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Standard Model Effective Field Theory (SMEFT)

A parameter space for BSM interactions between SM particles
SMEFT: SM v2.0

We have access to a low energy effective description

- SM: all relevant & marginal (D ≤ 4) operators
- + EFT: tower of irrelevant (D > 4) operators

SM gauge symmetry & linear EWSB

More than ‘just’ a parametrisation of ignorance

- Unlike ‘Anomalous Couplings’
- Finite energy range < Λ (NP)

\[
\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i O_i^D}{\Lambda^{D-4}}
\]

\[
\varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : 2^\frac{1}{2}
\]

SU(3)_c \times SU(2)_L \times U(1)_Y

aTGC \quad y_f \quad \lambda_h \quad ffV

ggh(h) \quad \delta M_Z

' dipole' \quad 4F
Energy growth

Higher dimensional operators mean energy growth

\[ \mathcal{A} \sim \mathcal{A}_{SM} \left( 1 + c_i \frac{v^2}{\Lambda^2} \right) + \left( c_j \frac{vE}{\Lambda^2} + c_k \frac{E^2}{\Lambda^2} \right) \]

‘Energy helps accuracy’
[Farina et al.; PLB 772 (2017) 210-215]

Rate measurements will become systematics dominated
Increasingly high-energy measurements scale with lumi.

Outlines a systematically improvable process for improving
our understanding of the D>4 parameters of the SM

Slightly complicated by interference structure w/ \( \mathcal{A}_{SM} \)

- Cross sections contain terms up to order \( 1/\Lambda^4 \)
- Different energy growth/symmetries can mix the hierarchy in EFT expansion
- Dim-8 operators generally not studied
Global Fits

SMEFT seeks model independence
• **Only requirement:** BSM physics lives sufficiently above experimental energy
• Don’t know *a priori* which operators NP will generate

Ultimate goal: complete likelihood for general SMEFT
• Start small.. realistic subsets of measurements/operators (exploit symmetries)

**EWPO, Higgs, Diboson, top, DY, flavor,**…

LS2 is an opportune time to take stock
• Legacy papers coming out with full Run II dataset
• SMEFT fit is a fantastic *benchmarking* & *data preservation* exercise
• Progress in many complementary directions
• Good to have several groups working in parallel
• Expect many fit papers in 2020/21!

*Where do we stand and where to look next?* hints, blind/weak directions,…
EWPO at NLO in SMEFT

[Dawson & Giardino; PRD 101 (2020) 1, 013001]

QCD & EW corrections to Z & W pole observables

- First ‘complete NLO’ SMEFT fit result
- LO blind directions closed by adding in Diboson/Higgs data
- NLO fit nowhere near self-contained

LO: 10 operators* 8 constraints
NLO: 32 operators 10 constraints

O(20-30%) corrections in marginalised fit

See also [Hartmann, Shepherd & Trott; JHEP 03 (2017) 060] & Will Shepherd’s talk from Monday

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Combined Higgs/EW

[Ellis, Murphy, Sanz & You; JHEP 06 (2018)146]

Recent global analysis of LEP + LHC Run I & II data

• LO & linear; flavour universal assumption \(U(3)^5\) + Yukawa operators

Includes differential information for Higgs

• Stage 1 simplified template cross sections (STXS) for Higgs production

• High-\(p_T\) WW measurement

Improvement after adding Run II data
Map to UV models

Tree-level: scalar EW triplet & vector-like quark doublet

- Loop-level: MSSM w/ degenerate stops
  - mass = 1 TeV

Fit results are interesting & useful in and of themselves
- Real interpretation starts here

UV matching quasi-automated
- Complete tree-level dictionary
  - [de Blas et al.; JHEP 03 (2018) 109]
- Universal 1-loop effective action
  - [Henning, Lu & Murayama; JHEP 01 (2016) 023]
  - [Drozd et al.; JHEP 03 (2016) 180]

UV interpretations will usually involve subsets of full basis
- Better constrained than full SMEFT
- Need to retain likelihoods to re-fit
- Important to have an ‘agile’ framework
Flavorful Higgs/EW fit

[Falkowski & Straub.; JHEP 04 (2020) 066]

Relaxation to non-universal flavour assumption

- An important evolution direction for global analyses
- Separate 3 fermion gens.
- $19 \rightarrow 31$ parameters
- Custodial vector triplet interpretation

$$\mathcal{L} \supset \frac{1}{2} V_{\mu}^I \left( i g_H H^\dagger \tau^I D_\mu H - i g_H D_\mu H^\dagger \tau^I H \right) + \sum_i g_{li} \bar{t}_i \tau^I \gamma^\mu t_i + \sum_i g_{qi} \bar{q}_i \tau^I \gamma^\mu q_i$$

$$\frac{g_H}{M} = 0.231^{+0.067}_{-0.107} \text{ TeV}^{-1}, \quad \frac{g_{l_1}}{g_H} = 0.054 \pm 0.040, \quad \frac{g_{l_2}}{g_H} = 0.100 \pm 0.060, \quad \frac{g_{l_3}}{g_H} = 0.009 \pm 0.068,$$

multi-TeV

Results & likelihood available through smelli

- Global SMEFT likelihood tool

[Aebischer et al.; EPJ C79 (2019) no.6, 509]

https://smelli.github.io
Top sector

[Hartland et al.; JHEP 1904 (2019)100]

- (N)NLO QCD predictions for SM
- Mostly NLO QCD for SMEFT
- 34 Wilson coefficients (many 4F)

See also [Brivio et al.; JHEP 02 (2020) 131]
Higher orders

\[ \mathcal{O} = \mathcal{O}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_{\text{int}}^i + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} \mathcal{O}_{\text{sq}}^{ij} \]

Impact of NLO and 1/\(\Lambda^4\)  
LO vs NLO  
1/\(\Lambda^2\) vs 1/\(\Lambda^4\)
Experimental fits


Enthusiasm for SMEFT percolated to the exp. community
  • Too many results to cover here
  • One Higgs example here (honorable mention to the many top results)

SMEFT interpretations of STXS measurements
  • Experiments typically consider smaller parameter spaces
  • Better handle on uncertainties/correlations

CMS-PAS-HIG-19-001]

see talks by:
  Efe Yazgan (Tues)
  Elizaveta Shabalina (Tues)
  Andrea Gabrielli (Tues)
  Giacomo Zecchinelli (Tues)
  Luca Fiorini (Weds)

dedicated session (Fri)
Going forward

Fits are not ‘fun’… a slog of data creation/curation
- Beware of statistical overlap between datasets, correlated uncertainties

Legacy stage 1.1 STXS papers are out → next gen. fits
- Represent a controlled evolution towards combined, fully differential data
- Best compromise for ease of interpretation and global sensitivity
- Caveat: SM kinematics/acceptance assumed

Important to study their information content w.r.t SMEFT

[Compare WH STXS to ‘perfect’ info]

Proposal for improved STXS
SMEFT & BSM today

SMEFT-UV connection is model dependent by construction

- Implications on heavy new physics & validity of EFT is *a posteriori*
- Depends on sensitivity & energy scale probed by data
- Bottom-up philosophy: new physics scale unknown

\[
\frac{c_s}{\Lambda^2} = \frac{\lambda^2}{M^2}
\]

**constraint:** \( \frac{c_s}{\Lambda^2} < X \)

Difficult to address in a general way

- Today we are probing TeV scale new physics
- Hierarchies in sensitivity EWPO > Higgs > top (EW)
- Moderate-to-strong coupling scenarios most safe
- Generic NP in loops looks challenging for the LHC
- Concrete models should be better constrained
- We should widen enough to test **realistic models**
Next up: Top/Higgs/EW fit

Conspicuous split between top & Higgs/EW sector fits

- Several such results will appear soon
- Dedicated ‘top+Higgs’ parallel session at this workshop

If we are thinking about the origin of the weak scale, we should fit to SMEFT for full EWSB sector

Especially timely given recent measurement of relevant processes connecting the three sectors

$t\bar{t}H + \text{‘rare’}/EW$ top production ($tZj, 4\text{top},…$)

Unclear to what extent the two sectors will talk beyond $t\bar{t}H$

- Top measurements are important for $H$, $Hj$, $HH$
- LHC should observe $tHj$ process toward the end of its lifetime
SMEFT in the proton

Q: Can the PDF extraction procedure absorb NP effects?

- Slew of LHC data being used to determine them, some at high energy
- In principle, one should fit them together with the Wilson coefficients
- Proof of concept using DIS data & qqll contact operators

**Related issue:** impact of SMEFT on $\alpha_S$ determination

- Not yet studied: Lattice, $e^+e^-$, PDFs, ….

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**Figure:**
- **Left:** NNPDF3.1 NNLO DIS-only
  - Total (pre-fit) vs Total (post-fit)
- **Right:** Table of Wilson coefficients
  - Individual vs Marginalized
  - Fixed PDFs vs simultaneous extraction

**Graphical Notes:**
- Better fit
- Simultaneous extraction
Adding flavor constraints


Imposing flavor symmetry in SMEFT avoids tree-FCNC

- Flavor violation induced by SM interactions at loop level
- Down type FCNC processes at low energy: B-decay/mixing and some Kaon

SMEFT ($\Lambda$) $\rightarrow$ WET ($\nu$) $\rightarrow$ Flavour experiments

- Translate existing constraints on WET coefficients to SMEFT
- Combined with fit to EWPO/diboson/Higgs
- 5 new constrained directions

Minimal Flavor Violation


see also Will Shepherd’s backup slides from Monday
SMEFT in loops

Recent progress: top operators in EW loops

- Relatively poorly-known EW top quark interactions contributing to precisely measured observables
- Loop suppression overcome by ‘large’ allowed values for Wilson coefficients

Z-pole observables

EW Higgs production & decay

1) competitive sensitivity
2) marginalisation headache

Top pair production

[Zhang, Greiner & Willenbrock; PRD 86 (2012) 014024]

[Zhang & Vryonidou; JHEP 08 (2018) 036]

[Martini & Schulze; JHEP 04 (2020) 017]

See talk by Till Martini on Friday
Tools for SMEFT in loops

One-loop predictions in the SMEFT

- NLO QCD corrections / loop induced predictions
- Precision & scale uncertainties / new sensitivity
- Non-flat K-factors in EFT space

Recent results on NLO QCD corrections

- DY & VH  
  [Alioli et al.; JHEP 08 (2018) 205]  

Automated framework for Madgraph5_aMC@NLO

- SMEFTatNLO  
  [Degrande et al.; in preparation]  
  [http://powhegbox.mib.infn.it]

- Process independent, complete SMEFT, in top-specific flavor limit
- 4 fermion operators not yet public
SMEFTatNLO

[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; in preparation]

Preliminary results for di/triboson production @ NLO QCD

• Recent evidence for tri-boson by ATLAS & CMS
• Like VBS, sensitive to quartic gauge couplings (dimension-8)
• Potential additional probe of gauge fermion and TGC at dimension-6

W+W+W-

\[
\begin{array}{ccc}
\sigma_\text{SM} & \text{LO} & \text{NLO} \\
79.38(5) & 142.8(9) & 1.80 \\
\sigma_\text{3W} & 0.192(2) & 0.04959(6) \\
\sigma_\text{4W} & 2.93(2) & 4.07(3) \\
\sigma_\text{5W} & 251.7(3) & 252.2(5) \\
\end{array}
\]

\[
\begin{array}{ccc}
\sigma_\text{6W} & \text{LO} & \text{NLO} \\
0.2(8) & 10.8(2) & 21.5(7) \\
\sigma_\text{7W} & 0.00528(8) & 0.00696(1) \\
\sigma_\text{8W} & 0.43(1) & 0.606(2) \\
\sigma_\text{9W} & 0.1616(2) & 0.02057(3) \\
\end{array}
\]

\[
\begin{array}{ccc}
\sigma_\text{10W} & \text{LO} & \text{NLO} \\
1.55(5) & 1.99(6) & 2.94(5) \\
\sigma_\text{11W} & 36.03(3) & 34.04(5) \\
\sigma_\text{12W} & 44.11(9) & 66.3(1) \\
\sigma_\text{13W} & 121.2(1) & 111.7(2) \\
\end{array}
\]

\[
\begin{array}{ccc}
\sigma_\text{14W} & \text{LO} & \text{NLO} \\
1.00 & 1.39 & 0.85 \\
\sigma_\text{15W} & 2.176(2) & 0.1859(3) \\
\sigma_\text{16W} & 0.687(4) & 1.029(2) \\
\sigma_\text{17W} & -0.017(1) & 0.000475(7) \\
\sigma_\text{18W} & 0.005(56)(2) & 0.000555(1) \\
\sigma_\text{19W} & 0.65(4) & 120.0(2) \\
\sigma_\text{20W} & 0.0215(5) & 0.00789(3) \\
\sigma_\text{21W} & 0.005092(8) & 0.005092(8) \\
\sigma_\text{22W} & 1.801(4) & 0.4757(8) \\
\sigma_\text{23W} & 15.94(5) & 42.53(9) \\
\sigma_\text{24W} & 0.94 & 0.94 \\
\sigma_\text{25W} & 0.94 & 0.94 \\
\sigma_\text{26W} & 0.94 & 0.94 \\
\end{array}
\]

\[
\begin{array}{ccc}
\sigma_\text{27W} & \text{LO} & \text{NLO} \\
19.15(2) & 37.43(2) & 1.80 \\
\sigma_\text{28W} & 2.176(2) & 0.1859(3) \\
\sigma_\text{29W} & 0.687(4) & 1.029(2) \\
\sigma_\text{30W} & -0.017(1) & 0.000475(7) \\
\sigma_\text{31W} & 0.005(56)(2) & 0.000555(1) \\
\sigma_\text{32W} & 0.65(4) & 120.0(2) \\
\sigma_\text{33W} & 0.0215(5) & 0.00789(3) \\
\sigma_\text{34W} & 0.005092(8) & 0.005092(8) \\
\sigma_\text{35W} & 1.801(4) & 0.4757(8) \\
\sigma_\text{36W} & 15.94(5) & 42.53(9) \\
\sigma_\text{37W} & 0.94 & 0.94 \\
\sigma_\text{38W} & 0.94 & 0.94 \\
\sigma_\text{39W} & 0.94 & 0.94 \\
\end{array}
\]

\[\text{ZZW+}\]
Improving fits

[Ellis, Madigan, KM, Sanz, You; in preparation]

STXS for ggF: one-loop is LO for the SM

- Tree-EFT × loop-SM and loop-EFT × loop-SM interference terms
- Heavy top limit OK for 0-jet, breaks down for high-p_T
Higher orders in $\Lambda$

EFTs are systematically improvable in $1/\Lambda$

• Dimension-6 is the LO for baryon/lepton number conserving operators

Important to think about possible dim-8 effects

• Theoretical uncertainties / validity of the EFT expansion
• Some measurements are dominated by quadratic dim-6 effects ($1/\Lambda^4$)
• Small/no interference due to symmetry, helicity selection, color structure,…

Operator counting known to arbitrary dimensions

2, 84, 30, 993, 560, 15456, 11962, 261485, . . . : [Henning et al.; JHEP 08 (2017) 016]
higher dimension operators in the SM EFT

[Lehman & Martin; JHEP 02 (2016) 081]

New result: complete dimension 8 basis written down

• 44807 operators encoded in 1029 Lagrangian terms
• Paves the way for more exploratory studies of importance & unique pheno

First-principles positivity constraints applicable (e.g. VBS)
High energy & multiplicity

How can we improve with increasing statistics?

- Target energy growth (energy helps accuracy)
  - more differential
  - higher multiplicity

Dim-6 operators don’t guarantee energy growth

Operator contribution to a given process:

(a) May not grow maximally with energy $(E^2)$
(b) Have suppressed interference w/ SM

[Azatov et al.; PRD 95 (2017) no. 6, 065014]

There will always be some scattering amplitude that displays maximal $(E^2)$ growth w.r.t the SM

\[
\left(\varphi^\dagger \overleftrightarrow{D_\mu} \varphi\right) (\bar{f}_i \gamma^\mu f_j)
\]

- on-shell
- VH
- Longitudinal WW

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High energy & multiplicity

[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

Top-EW couplings: rare top production

- Processes that embed high-energy EW top scattering

\[
\begin{align*}
\bar{b}/b & \rightarrow W^\pm \ b/b \\
g & \rightarrow t/\bar{t} \\
\end{align*}
\]
High energy & multiplicity

Top-EW couplings: rare top production

Expected growth from 2→2 absent!

\[ C_i = 1 \]

Inclusive

\[ p_T(Z) > 500 \text{ GeV} \]
High energy & multiplicity

[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

Top-EW couplings: rare top production

Expected growth is there!

Very interesting process that should be measured at the LHC

$C_i = 1$

Inclusive

$p_T (W, Z) > 500$ GeV
High energy & multiplicity

[Henning et al.; PRL 123 (2019), no.18 181801]

Higgs couplings… without the Higgs

- Operators that affect Higgs signal strengths contain

\[ |H|^2 = \frac{1}{2} \left( v^2 + 2h \nu + h^2 + 2\phi^+ \phi^- + (\phi^0)^2 \right) \]

\[ \mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \quad \mathcal{O}_{yy} = y_{\psi} |H|^2 \psi_L H \psi_R \]
\[ \mathcal{O}_{BB} = g' |H|^2 B_{\mu\nu} B^{\mu\nu} \quad \mathcal{O}_{WW} = g^2 |H|^2 W^\alpha_{\mu\nu} W^\alpha_{\mu\nu} \]
\[ \mathcal{O}_{GG} = g_5^2 |H|^2 G^a_{\mu\nu} G^a_{\mu\nu} \quad \mathcal{O}_6 = |H|^6 \]

Modified EWSB sector interactions

Energy growth in high-multiplicity final states of Higgs, top & longitudinal gauge bosons

Promising avenue for the future
Conclusions

SMEFT is truly well established in the HEP community

- On the path to measuring the SM parameters up to dimension-6
- Extend the reach of the LHC beyond nominal energy
- Multi-TeV scale within reach, next step: more realistic models

Much work to do towards the global SMEFT likelihood

- Precision tools available
- Progress in many directions
- High energy & multiplicity as a roadmap for the future

Other important topics

- B-anomalies & SMEFT/BSM talk by Admir Greljo on Tuesday
- Overlap of signal & background in global analyses
- Interplay between Di-Higgs & other measurements in global fits
- CPV violation in SMEFT see Elina Fuchs’ talk just now
- Applying on-shell techniques (basis construction, RGEs, non-renormalisation)
LHC EFT working group
LHC EFT working group

Clear interest in EFT interpretation across multiple existing LHC working groups (HXSWG, Top, EW, …)

New, dedicated working group in the pipeline
• Centralised forum for exchange & discussion
• General aspects & common methodologies across WGs
• Tools, benchmarking, theoretical aspects,…
• Leading to recommendations on coherent & consistent EFT interpretations

A natural & welcome development
• Reinforces the global nature of the EFT approach
• Coordinated effort among all groups will lead to better scientific outcomes
• Facilitate combinations measurements for experimentalists and/or theorists
Thank you
Thank you

Zoom room:
https://universityofsussex.zoom.us/j/8579312707?pwd=VHZWaHdLTUNrYlY5L3JhWUM4NkIldz09
CMS exotic summary

Overview of CMS EXO results

36.140 fb^{-1} (8.13 TeV)

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

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SMEFT and searches for new physics
### D=6 operators

#### ‘Warsaw’ basis

Grzadkowski et al., JHEP 1010 (2010) 085

<table>
<thead>
<tr>
<th>X⁵</th>
<th>φ⁶ and φ⁴D²</th>
<th>ψ²φ³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q₁G</td>
<td>(φ¹φ)³</td>
<td>Qᵥφ</td>
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<td>(φ¹φ)³</td>
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#### ψ²Xφ

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<th>X²φ²</th>
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<td>Q₁E</td>
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#### ψ²φ²D

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<th>X²φ²</th>
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</tr>
<tr>
<td>Q₂E</td>
<td>(Tµνε)ε ν</td>
</tr>
</tbody>
</table>

#### (LL)(LR) and (RL)(LR)

| Q₁L  | (Tµνε)ε ν| (Tµnu)ν |
| Q₁L  | (Tµνε)ε ν| (Tµnu)ν |
| Q₁L  | (Tµνε)ε ν| (Tµnu)ν |
| Q₁L  | (Tµνε)ε ν| (Tµnu)ν |

#### B-violating

| Q₁L  | (Tµνε)ε ν| (Tµnu)ν |
| Q₁L  | (Tµνε)ε ν| (Tµnu)ν |
| Q₁L  | (Tµνε)ε ν| (Tµnu)ν |
| Q₁L  | (Tµνε)ε ν| (Tµnu)ν |
SMEFT

Direct $ttH$ measurement breaks **degeneracy** among $y_t$, $ggH$ and dipole in gg-fusion

Pin down heavy coloured particles in the loop

[SMEFT and searches for new physics](Maltoni, Vryonidou & Zhang; JHEP 10 (2016) 123)

[Azatov, Grojean, Paul & Salvioni; JHEP 09 (2016) 123]
tZj total & high energy xs

Expected growth from 2→2 absent!

Cancellations

Energy growth

Total rate impact

C_i = 1
Inclusive
p_T (Z) > 500 GeV
tZtW total & high energy xs

interference/SM

$p p \rightarrow tZtW$

square/SM

Cancellations gone!

Very interesting process that should be measured at the LHC/FCC

Expected growth is there!

$\sigma_{QCD} = -$  
$\sigma_{EW} = 114.6 \text{ fb}$
$\sigma_{HE} = 85.3 \text{ ab}$

$C_i = 1$
Inclusive
$p_T (W,Z) > 500 \text{ GeV}$
Charged current operator

\[ \mathcal{O}^{(3)}_{Q} \]

\[ \sigma_{\text{int}} / \sigma_{\text{SM}} \]

\[ \sigma_{\text{sq.}} / \sigma_{\text{SM}} \]

<table>
<thead>
<tr>
<th>LHC 13 TeV</th>
<th>CLIC VBF $\sqrt{s}$ (GeV)</th>
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<td>[ tV ]</td>
<td>380</td>
</tr>
<tr>
<td>[ th ]</td>
<td>1500</td>
</tr>
<tr>
<td>[ \bar{t} \bar{V} ]</td>
<td>3000</td>
</tr>
</tbody>
</table>

Inclusive \[ p_T > 0.5 \text{ TeV} \]
\[ p_T > 1 \text{ TeV} \]
\[ m_{\text{Higgs}} \text{ cut} \]
\[ \text{Negative} \]
Yukawa operator

\[ \mathcal{O}_{t\phi} \]

\[ \frac{\sigma_{int}}{\sigma_{SM}} \]

\[ \frac{\sigma_{sq}}{\sigma_{SM}} \]

\begin{tabular}{c|c|c|c|c}
 & LHC 13 TeV & CLIC VBF & \( \sqrt{s} \) (GeV) & VBF & 380 & 1500 & 3000 \\
\hline
\( t\bar{t}V \) & & & & & & & \\
\( th \) & & & & & & & \\
\( t\bar{t}V \) & & & & & & & \\
\( t\bar{t}h \) & & & & & & & \\
\hline
VBF & 380 & 1500 & 3000 & & & & \\
\end{tabular}

- Inclusive
- \( p_T > 0.5 \text{ TeV} \)
- \( p_T > 1 \text{ TeV} \)
- \( m_{t\bar{t}} \) cut
- Negative
ttZh: LHC vs FCC-hh

\[ \sigma_{13} = 1.2 \text{ fb} \]

Interference: phase space cancellations

\[ \sigma_{100} = 130 \text{ fb} \]

Interference: energy growth & O(1) effects

High energy: \( p_T (Z,h) > 500 \text{ GeV} \)

\( \sigma^{(1)}_{qQ} \log(r_i) \)

Quadratic: energy growth & O(10-100)

\( p p \to t \bar{t} Z h \)

\( \sigma^{(1)}_{qQ} \log(r_{1i}) \)

\( p p \to t \bar{t} Z h \) (100 TeV)

\( \sigma^{(3)}_{qQ} \log(r_i) \)

Quadratic: energy growth & O(1-10)