LHC HXS WG workshop

WG2 summary

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October 18th, 2019

WG2: Higgs properties

- **Topics**:
  - ✓ STXS and Differential observables
  - ✓ Pseudo Observables
  - ✓ EFT and BSM interpretations
  - ✓ Tools

- **Changes in the convenorship:**
  - ✓ Marco Delmastro
  - ✓ Mingshui Chen → Predrag Milenovic
  - ✓ David Marzocca → Jorge de Blas
  - ✓ Francesco Riva

Twiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG2

Roadmap

Topic	ShortDescription
STXS & differential XS	**STXS stage 1.1 TH uncertainties treatment** recommendation
STXS & differential XS	**STXS stage 1.1** binning recommendation
PO	**PO Summary for experiments**. Scenarios for h>4l decays. Mapping to other frameworks.
EFT	**BSM Benchmarks** and mapping to EFT. Determine benchmarks sensitive to differential and coupling measurements, define relevant EFT parameters
EFT	**Interpretation Workflow Summary:** Processes, Operators and BSM Interpretations
EFT	**Fit to STXS** using a standardized mapping of STXS stage 1.0
EFT	**Global Fit** in EFT Framework; inclusion of top and Electroweak measurements
EFT	**High-Energy Higgs Probes:** Longitudinal multiboson processes as tests of Higgs physics

WG2: what have we been discussing?

EFT parametrizations and tools

Higgs EFT parameterisation efforts
Speaker: Chris Hays (University of Oxford (GB))
LHCHXSWG_1610...

EFT parameterisation and Higgs total width in SMEFT
Speakers: Ilaria Brivio (Universidad Autonoma de Madrid (ES)), Ilaria Brivio (University of Heidelberg)
slides_HXSWGmee...

EFT parameterisation of STXS (CMS)
Speaker: Jonathon Mark Langford (Imperial College (GB))
lhchxswg_eft_para...

EFT parameterisation of STXS (ATLAS)
Speaker: Ana Rosario Cueto Gomez (Centre National de la Recherche Scientifique (FR))
MethodologyEF_ST...

EFT parameterisation tools within ATLAS/CMS
Speaker: Andrew Gilbert (Northwestern University (US))
LHCHXSWG-EFTTo...

EFT theory developments

Higgs + top EFT interpretations
Speakers: Ken Mimasu (Particle Physics-Rutherford Appleton Laboratory-STFC - Science &),
Mimasu_HXSWG.pdf

Higgs + multi-boson EFT interpretations
Speaker: Marc Riembau (Universite de Geneve (CH))
CERNhxswg_oct19...

Automated matching at 1-loop for EFTs
Speakers: Adrian Carmona (CERN), Adrian Carmona Bermudez (Universidad de Granada (ES))
MM.pdf

Differential observables

Motivation for differential observables
Speakers: Frank Tackmann, Frank Tackmann (Deutsches Elektronen-Synchrotron (DE))
2019-10-16_Higgs_...

Motivation for differential observables - follow-up
Speakers: Frank Tackmann (Deutsches Elektronen-Synchrotron (DE)), Frank Tackmann
2019-10-17_Higgs_...

Experimental summary of properties measurements

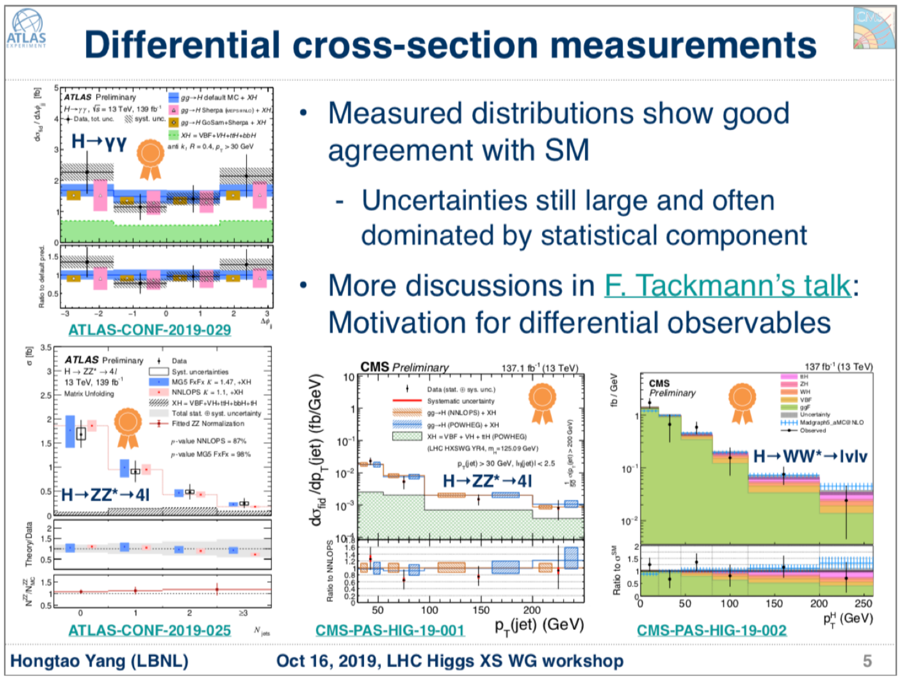
Experimental summary
Speaker: Hongtao Yang (Lawrence Berkeley National Lab. (US))
20191016_lhc_higg...

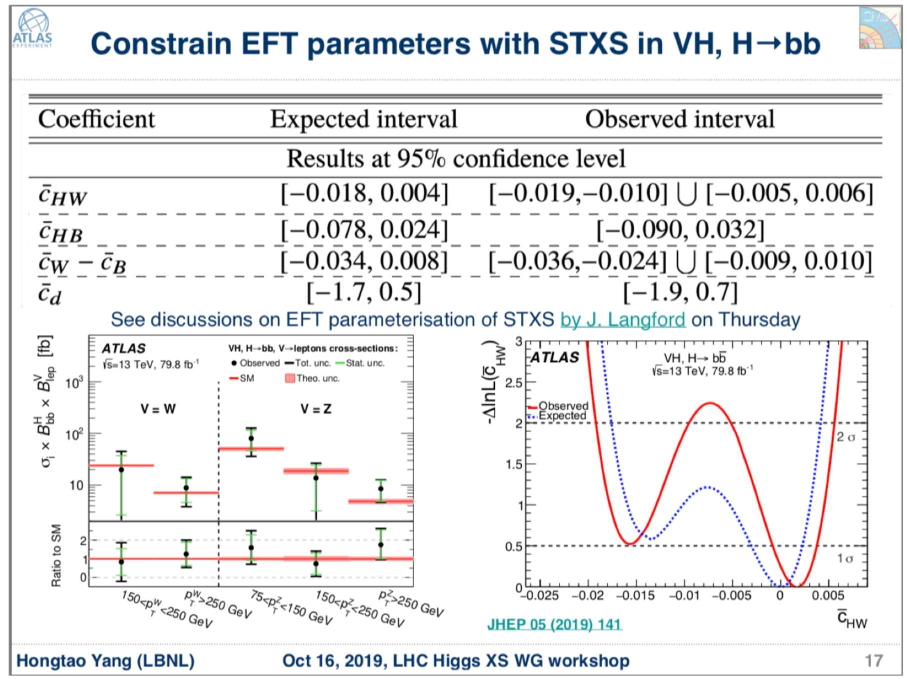
Measurements with final state information

Extending STXS with final state information
Speakers: Michael Duehrssen-Debling (CERN), Nicolas Berger (Centre National de la Recherche Scientifique (FR))
STXS_and_decay_i...

Experimental summary : Higgs properties

- **Higgs boson properties measurements:** Reach unprecedented precision
  - ✓ 10% uncertainty on inclusive production XS and coupling modifiers
  - ✓ Differential XS measurements extended to additional final states (added HWW)
  - ✓ STXS implemented in major channels (stage 0, stage 1.1), now used in EFT interpretations





Coefficient	Expected interval	Observed interval
Results at 95% confidence level		
$\bar{c}_{HW}$	[−0.018, 0.004]	[−0.019,−0.010] ⋃ [−0.005, 0.006]
$\bar{c}_{HB}$	[−0.078, 0.024]	[−0.090, 0.032]
$\bar{c}_W - \bar{c}_B$	[−0.034, 0.008]	[−0.036,−0.024] ⋃ [−0.009, 0.010]
$\bar{c}_d$	[−1.7, 0.5]	[−1.9, 0.7]

- **Suggestion:**
  - ✓ Compare the EFT sensitivity from STXS vs. differential XS (or dedicated) analyses

Experimental summary : Higgs properties

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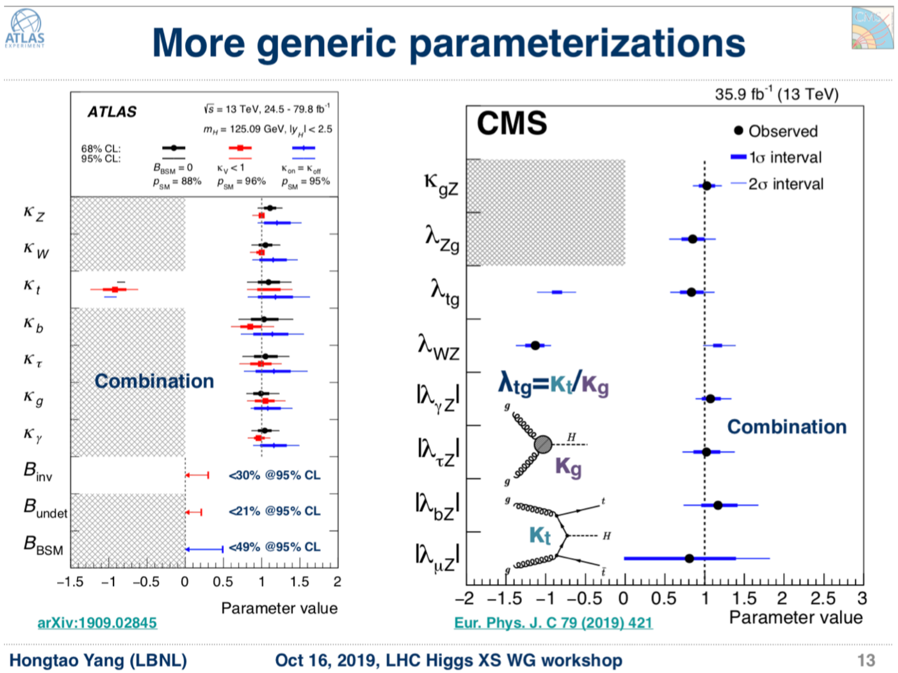
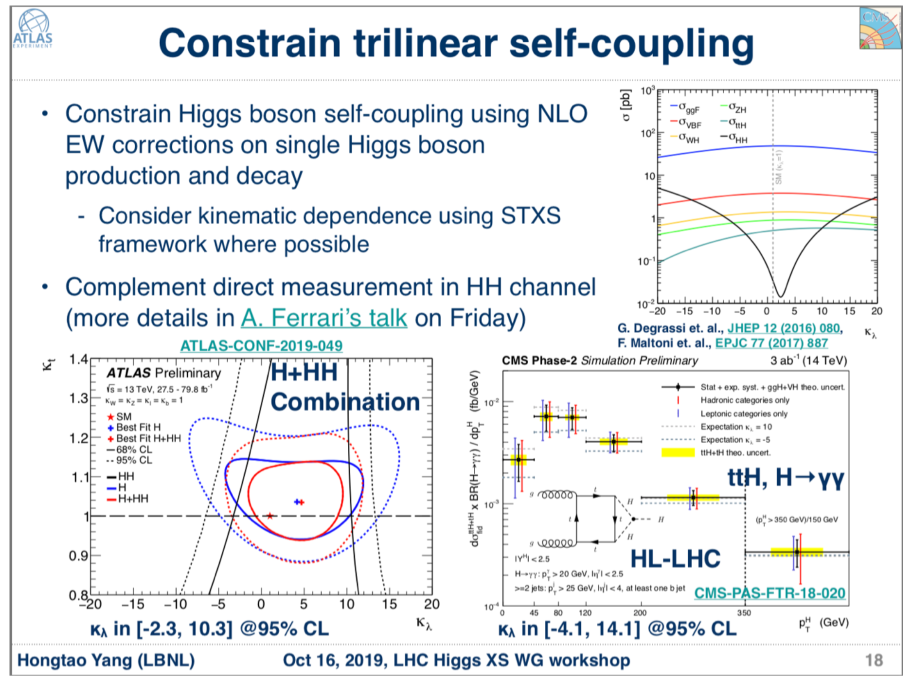




- **Constraints on trilinear self-couplings:**
  - ✓ From NLO EW corrections in single Higgs, complement direct measurement in HH channel
  - ✓ EFT interpretation discussions: joint parallel sessions WG2 - HH

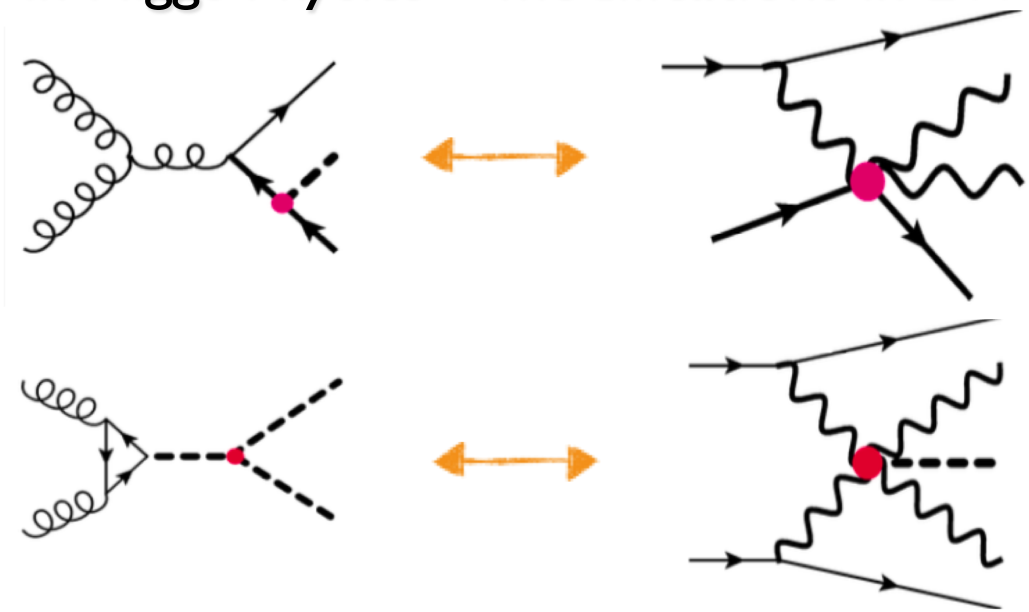
EFT theory development: high-energy probes

- In the SM, all scalars belong to the Higgs doublet:

$$\begin{pmatrix} h^+ \\ h + ih^0 \end{pmatrix} \quad h^+ \leftarrow W_L, \quad ih^0 \leftarrow Z_L$$

Modifications in Higgs Physics = modifications in EW physics

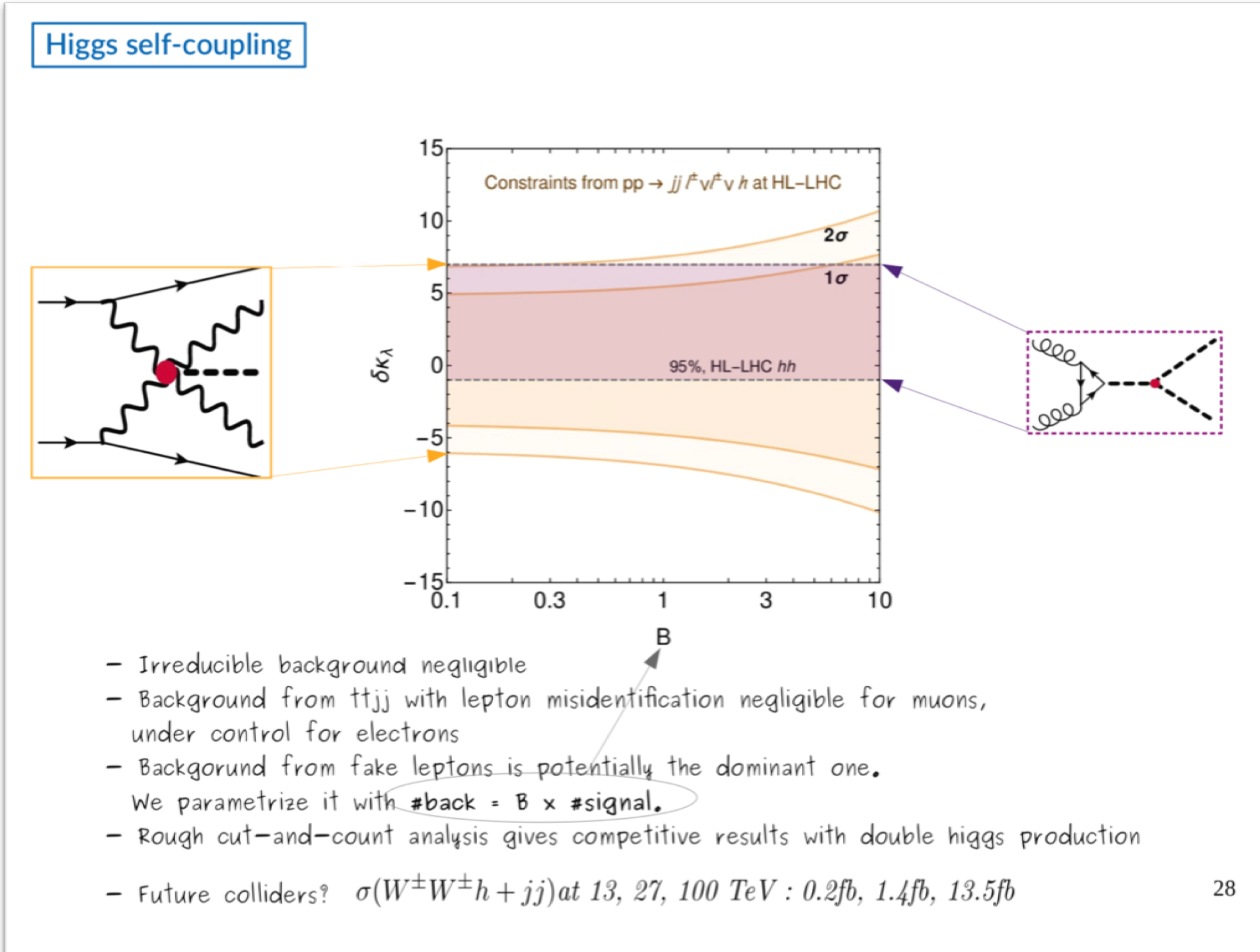
e.g.



EFT theory development: high-energy probes

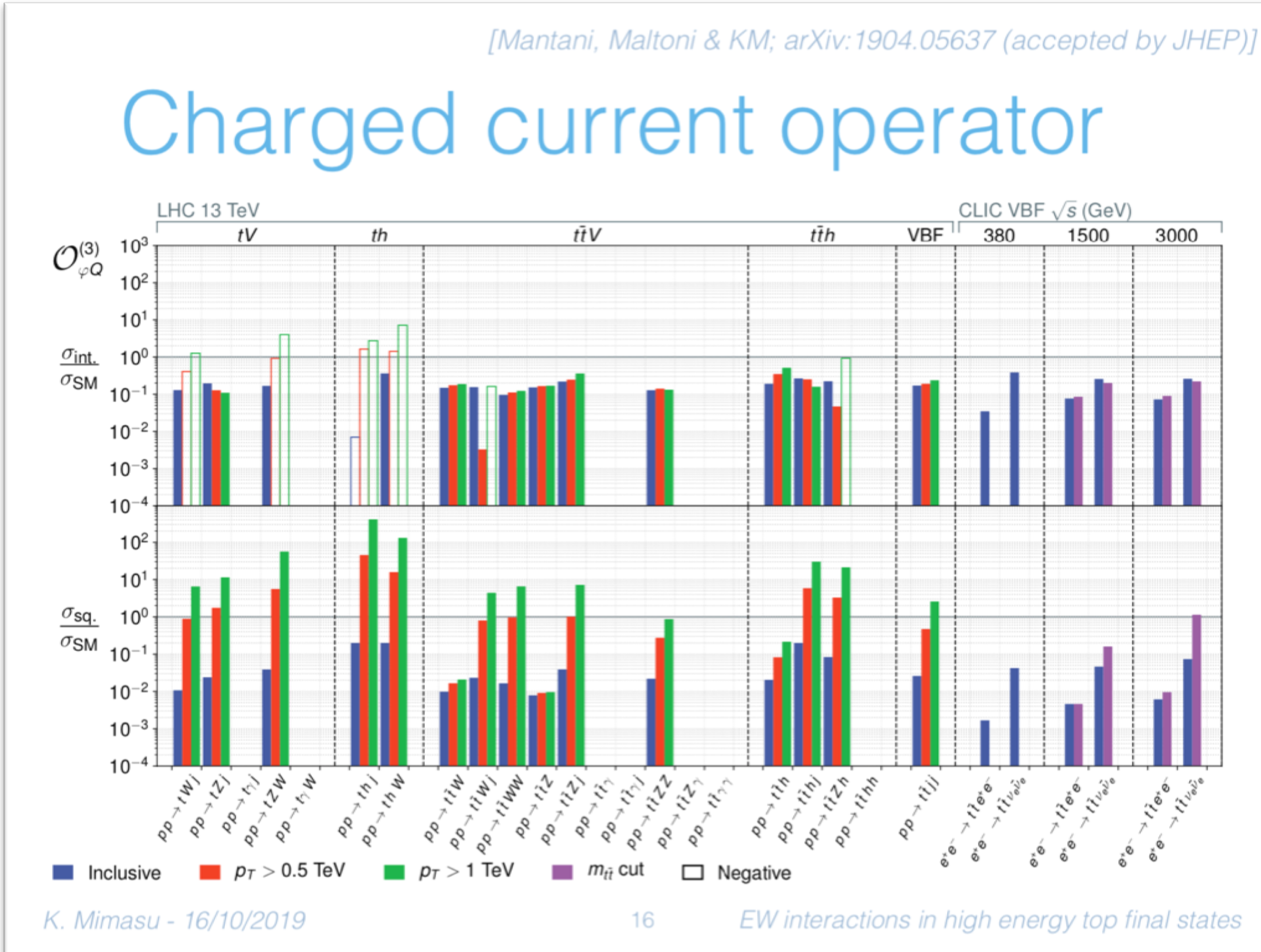
- The same EFT interactions modifying the Higgs properties can be probed in other processes involving EW bosons and benefit from growing with E effects…

Complementary probes of the same EFT interactions



EFT theory development: high-energy probes

- This type of effects and the relevant 2 → 2 processes (where they can be tested) have been already systematically classified for the case of interactions involving the top…

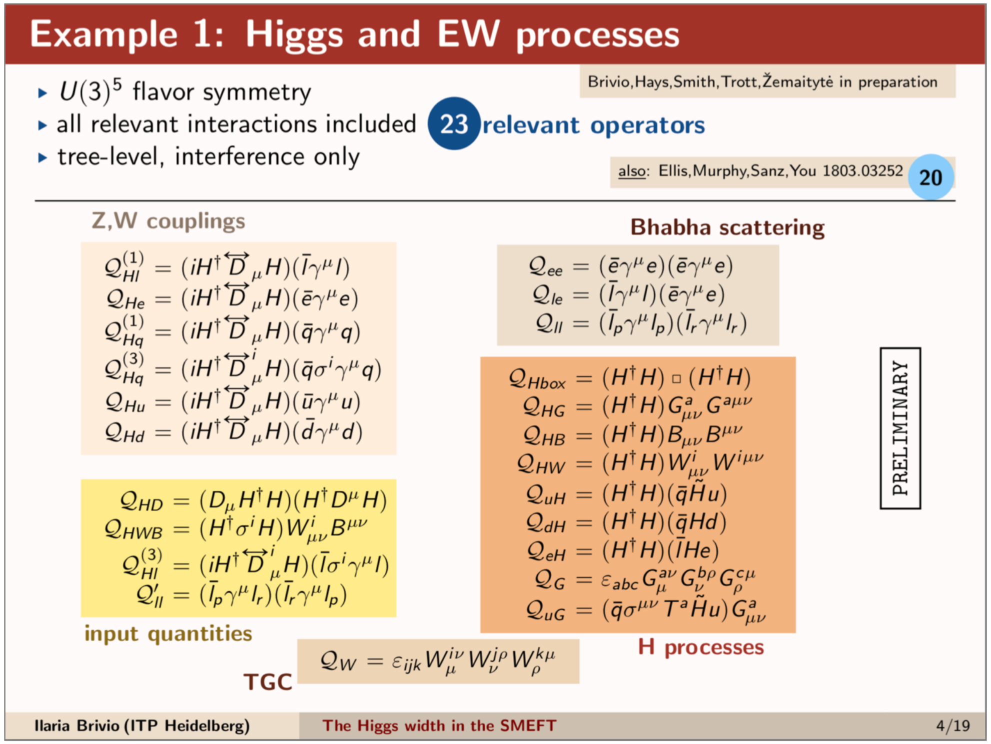


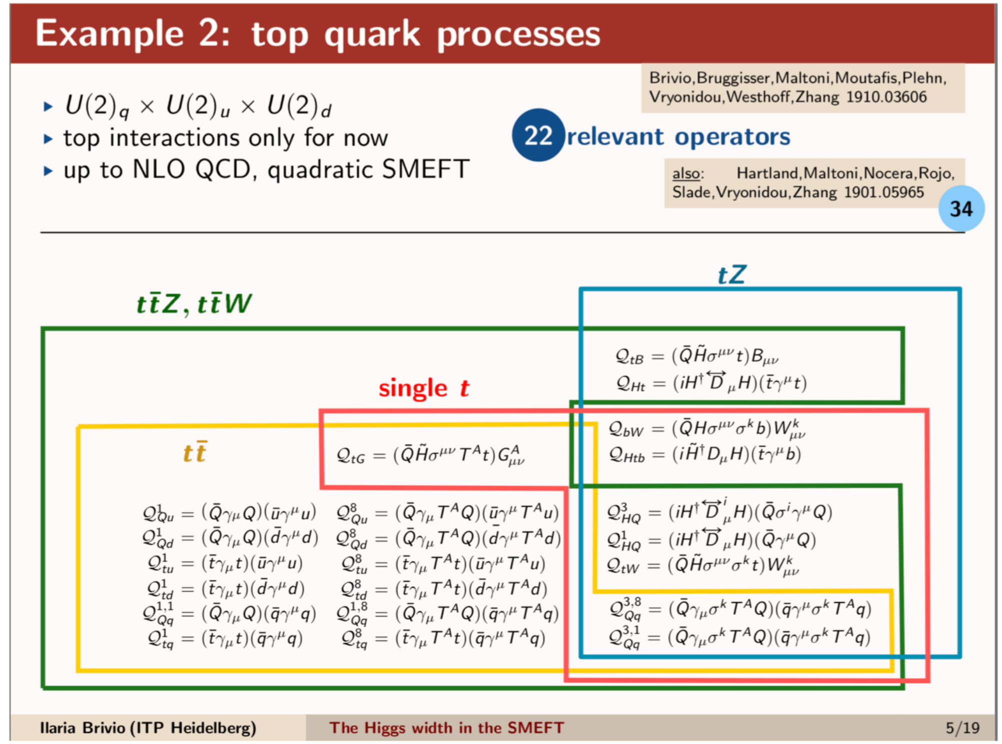
EFT theory development: high-energy probes

- Next steps
  - ✓ General study of high-energy probes of H EFT interactions using longitudinal multi-boson processes
  - ✓ Map process/operators
    - ✓ Only a small number of operators enters a given process
    - ✓ EFT Theory @ high-E
      - ✓ Preparation of note on "High-Energy Benchmarks"
  - ✓ Extend "proof-of-concept" studies presented at WS to more realistic studies
    - More realistic treatment of backgrounds
    - Better understanding signal/background kinematics
    - Explore vector boson polarisation information
    - Include more channels
    - Realistic detector simulations
    - …

EFT parameterisation and tools

- **SMEFT parameterization:** Include all EFT operators that contribute significantly





✓ individual processes necessarily have blind directions

✓ combination of different processes / sectors required

	total $N_f = 3$	WZH pole obs.
general	2499	~ 46
MFV	~ 108	~ 30
$U(3)^5$	~ 70	~ 24

Brivio,Jiang,Trott 1709.06492

EFT parameterisation and tools

- **SMEFT parameterization:** Include all EFT operators that contribute significantly

The Higgs width in the SMEFT

leading channels:

$H \to \bar{f}f$

$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f}f\gamma$

$H \to 4f$

available as $H \to ZZ^*$, $H \to WW^*$ $\times Br(Z, W)$ relying on narrow width approx. for Z, W.

good in SM but **not sufficient** in the SMEFT!

main reason: tree $\gamma\gamma, Z\gamma$ mediated diagrams

also missing:

- CC - NC interference
- crossed-current interference in ZZ diagrams
- $\delta\Gamma_V$, δm_V^2 corrections for off-shell boson

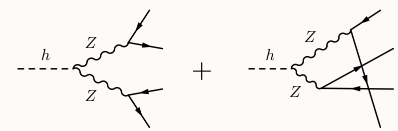
- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{tot} \to Br$

Ilaria Brivio (ITP Heidelberg) The Higgs width in the SMEFT 8/19

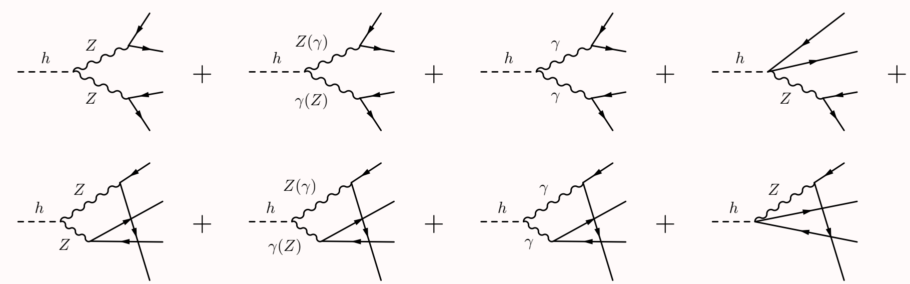
H → 4f in the SMEFT - complexity

$h \to e^+e^-e^+e^-$

SM



interfering with

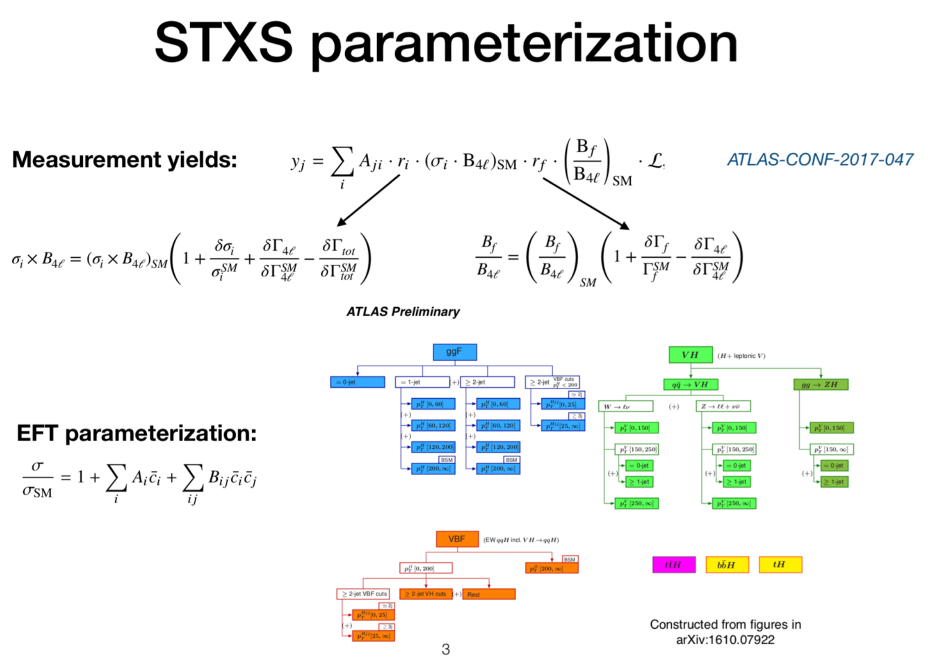


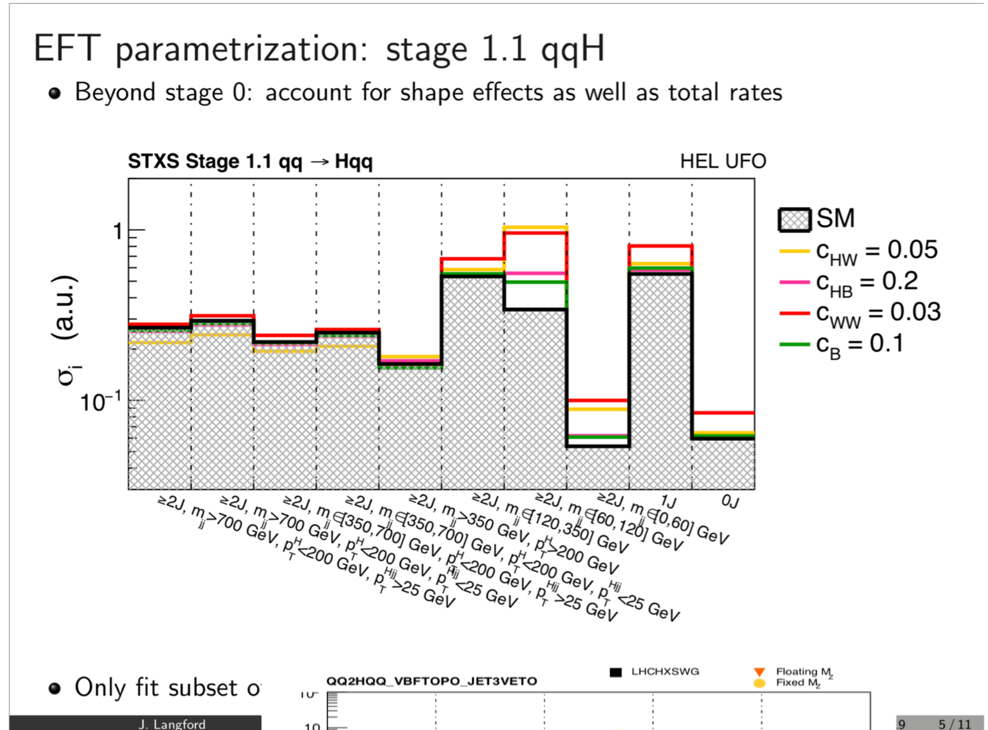
Ilaria Brivio (ITP Heidelberg) The Higgs width in the SMEFT 10/19

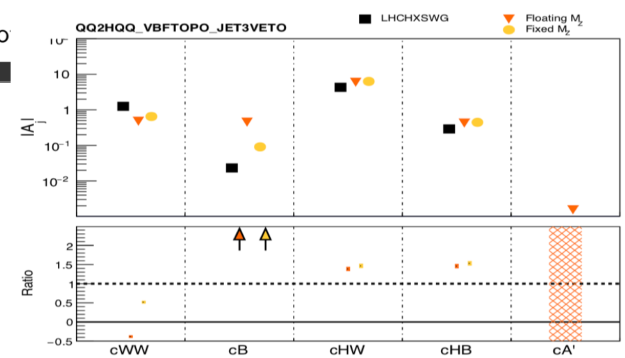
- **SMEFT tools**
  - ✓ Parameterization of Higgs total width (implemented, important effects)
  - ✓ Event-by-event reweighting tool (planned to be LHE-based)
    - Ready in ~ 6 months?
    - Modular implementation needed (e.g. should be able to compute weight from LHC input files)

EFT parameterisation and tools

- **ATLAS/CMS EFT parameterization efforts**
  - ✓ Move from SILH to Warsaw basis, from HEL to SMEFTsim model (towards global EFT fit)
  - ✓ Multiple tools/approaches (and public codes) in ATLAS/CMS







- ✓ Extensive validations for STXS EFT parameterization

EFT parameterisation and tools

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Acceptance corrections

SM extrapolation to total decay width biases EFT interpretation

Particularly for $H \to 4\ell$ and $H \to \ell\nu\ell\nu$ where new classes of diagrams appear at dimension-6

Ideally STXS would be split into $m_{\ell_3\ell_4}$ bins for $H \to 4\ell$ and $m_{\ell\ell}$ bins for $H \to \ell\nu\ell\nu$

For now we can estimate a correction based on published event selection in these channels
The correction for requirements on invariant masses is approximately universal for the production modes
Apply to decay ratio equations

$$y_j = \sum_i A_{ji} \cdot r_i \cdot (\sigma_i \cdot \mathrm{B}_{4\ell})_{\mathrm{SM}} \cdot r_f \cdot \left(\frac{\mathrm{B}_f}{\mathrm{B}_{4\ell}}\right)_{\mathrm{SM}} \cdot \mathcal{L},$$

$$\downarrow$$

$$\left(\frac{\mathcal{B}_S}{\mathcal{B}_{4\ell}}\right)_{SM}\left(\frac{\mathcal{A}_S}{\mathcal{A}_{4\ell}}\right)_{SM}\left[1+\sum_\alpha\left(\frac{\delta\Gamma_S}{\Gamma_S^{SM}}\right)^\alpha\left(\frac{\mathcal{A}_S^{SMEFT}}{\mathcal{A}_S^{SM}}\right)^\alpha-\sum_\beta\left(\frac{\delta\Gamma_{4\ell}}{\Gamma_{4\ell}^{SM}}\right)^\beta\left(\frac{\mathcal{A}_{4\ell}^{SMEFT}}{\mathcal{A}_{4\ell}^{SM}}\right)^\beta(\right]$$

Can be calculated with Madgraph or analytically, e.g.

$$\left[\frac{2\delta g_{L,ei}^{W,\ell}}{\mathrm{Re}[(g_{L,ej}^{W,\ell})^{SM}]}+\frac{2\delta g_{L,\mu k}^{W,\ell}}{\mathrm{Re}[(g_{L,\mu l}^{W,\ell})^{SM}]}+2\left[\frac{\delta M_W^2}{\hat{M}_W^2}-\frac{\delta G_F}{\sqrt{2}}+C_{H,\mathrm{kin}}\right]\right]\int dps^4\frac{\mathcal{A}_{WW}^{N_1}}{\mathcal{A}_{WW}^{SM}}+\ldots$$

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Outstanding issue is the EFT modifications to the (four-body) decays

Possible to estimate corrections ad hoc
Preferable for STXS decays to be split into the dominantly measured regions

$$\frac{B_{\ell\nu\ell\nu}}{B_{4\ell}} \to \frac{B_{\ell\nu\ell\nu}^{m_{\ell\ell}<55}}{B_{4\ell}^{m_{\ell_3\ell_4}>10}},\quad \frac{B_{\ell\nu\ell\nu}^{m_{\ell\ell}>55}}{B_{4\ell}^{m_{\ell_3\ell_4}>10}} \qquad + \frac{B_{4\ell}^{m_{\ell_3\ell_4}<10}}{B_{4\ell}^{m_{\ell_3\ell_4}>10}}$$

(or use $H \to \gamma\gamma$ as denominator)

- ✓ Extensive validations for STXS EFT parameterization
- ✓ Acceptance effects important for unfolded results – need corrections & STXS modifications
  - Full simulation of EFT effects at detector/reconstruction level mitigates problem

EFT parameterisation and tools

- **ATLAS/CMS EFT parameterization efforts**
  - ✓ Move from SILH to Warsaw basis, from HEL to SMEFTsim model (towards global EFT fit)
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Eigenvector decomposition

Production modes only (BRs set to SM values): Complete tables in backup

Eigenvalue	Eigenvector	
95892.10	$-1.00 \cdot c_{HG}$	From ggF
620	$-0.24 \cdot c_{HW} + 0.13 \cdot c_{Hl3} - 0.95 \cdot c_{Hq3}$	Mix of VBF+V(had)H and V(lep)H
34	$-0.14 \cdot c_G - 0.13 \cdot c_{Hbox} + 0.16 \cdot c_{Hl3} + 0.12 \cdot \lvert c_{uH}\rvert + 0.82 \cdot \lvert c_{uG}\rvert - 0.17 \cdot cqq_{11} - 0.40 \cdot cqq_{31} - 0.18 \cdot c_{uu1} - 0.11 \cdot c_{qu8}$	From top
10	$-0.64 \cdot c_{HW} + 0.18 \cdot c_{HWB} + 0.23 \cdot c_{Hl3} - 0.18 \cdot c_{Hq1} + 0.14 \cdot c_{Hq3} + 0.60 \cdot c_{Hu} - 0.21 \cdot c_{Hd} - 0.14 \cdot c_{ll1}$	

- Sensitivity to cHG, cHq3, |cuG|, cHW, cHu, cHl3 (potentially cHq1)
- Including the decay brings additional sensitivity to cHW, cHB and cHWB but also stronger correlations

H->$\gamma\gamma$ (good experimental sensitivity, no affected by acceptance) :

Eigenvalue	Eigenvector	
504594	$0.16 \cdot c_{HG} - 0.24 \cdot c_{HW} - 0.84 \cdot c_{HB} + 0.45 \cdot c_{HWB}$	From gg->H->$\gamma\gamma$
14290	$-0.99 \cdot c_{HG} - 0.14 \cdot c_{HB}$	
63	$0.14 \cdot c_{HW} + 0.96 \cdot c_{Hq3} + 0.11 \cdot c_{Hu} + 0.15 \cdot \lvert c_{uG}\rvert$	
7	$-0.11 \cdot c_G + 0.50 \cdot c_{HW} - 0.13 \cdot c_{HB} - 0.11 \cdot c_{Hl3} + 0.11 \cdot c_{Hq1} - 0.18 \cdot c_{Hq3} - 0.26 \cdot c_{Hu} + 0.65 \cdot \lvert c_{uG}\rvert - 0.13 c_{qq11} - 0.32 c_{qq31} - 0.14 \cdot c_{uu1}$	

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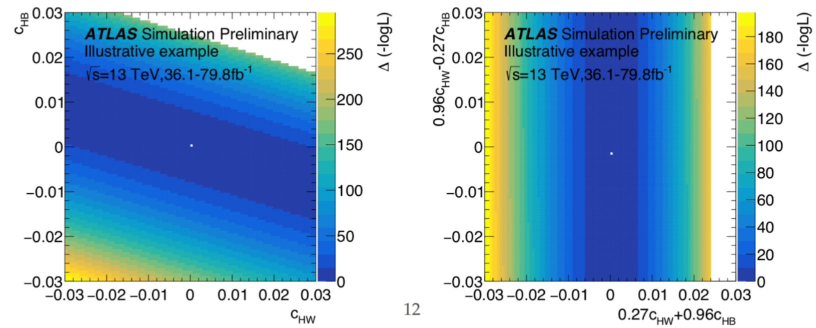
cHW, cHB and cHWB

- cHW, cHB and cHWB strongly correlated:
  - Sensitivity coming from H->$\gamma\gamma$. Little sensitivity from VBF and VH.
  - Analytic expression for H->$\gamma\gamma$ decay (CP-even case) width:

$$\frac{\Gamma(H \to \gamma\gamma)}{\Gamma_{SM}(H \to \gamma\gamma)} \approx \left|1 + \frac{8\pi^2 \bar{v}_T^2}{I^\gamma} C_{\gamma\gamma}\right|^2, \quad \text{with} \quad C_{\gamma\gamma} = \frac{1}{\bar{g}_2^2} c_{HW} + \frac{1}{\bar{g}_1^2} c_{HB} - \frac{1}{\bar{g}_1 \bar{g}_2} c_{HWB},$$

- Sensitive direction is calculated to be 0.27cHW+0.96 cHB



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- ✓ Possibilities to identify flat directions in the EFT fit (helps with the fit convergence)
- ✓ Next step is to move to SMEFT@NLO (important for loop effects in H→γγ and gg→H)

EFT parameterisation and tools

- **ATLAS/CMS EFT parameterization efforts**
  - ✓ Move from SILH to Warsaw basis, from HEL to SMEFTsim model (towards global EFT fit)
  - ✓ Multiple tools/approaches (and public codes) in ATLAS/CMS

Strategies

- Two approaches for constructing the signal model $\mathbf{P_s}$ as a function of observables $\mathbf{x}$ given coefficients $\mathbf{c_j}$

Sum of full-sim. signal PDFs

[1]

$$P_s(\mathbf{x}\,|\,c_j) = \sum_i a_i(c_j)\cdot p_i(\mathbf{x})$$

where:

- **i** runs over a set of fixed points in the EFT space
- $\mathbf{a_i}$ are normalisation coefficients
- $\mathbf{p_i(x)}$ are the pdfs for the fixed points - possibly from separate MC samples or matrix element reweighting of a smaller set of samples

Parameterise gen-level fiducial bins

[2]

$$P_s(\mathbf{x}\,|\,c_j) = \sum_k \left(p^k_{\mathrm{SM}}(\mathbf{x})\cdot \sum_j c_j\mu_j^k \right)$$

where:

- **k** runs over fiducial bins at generator level
- $\mathbf{p^k_{SM}(x)}$ is the SM reco.-level signal pdf for events in gen.-level bin **k**
- $\mathbf{\mu_j^k}$ is a scaling constant for the effect of $\mathbf{c_j}$ on bin **k**

- In the following slides show concrete examples of both (but not intended to be complete!)

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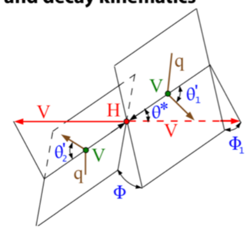
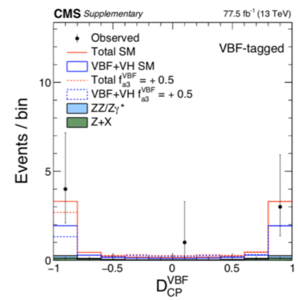
HVV anomalous couplings in CMS

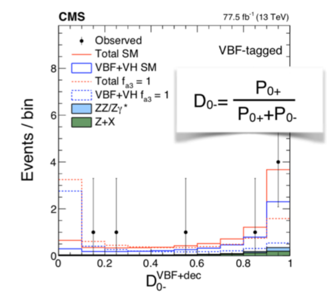
Phys. Rev. D 99, 112003 (2019)

- Construct optimal observables using the MELA technique (public code)

Contains both production and decay kinematics







- Simulation using the JHU generator and POWHEG, reweighting to different AC points using MELA
- Signal model construction follows a flexible and extensible approach:

PDFs for each component **Normalisation**

$$\mathcal{P}^{\mathrm{sig/int}}_{jk}\left(\vec{x};\vec{\xi}_{jk}, f_{ai}, \phi_{ai}\right) = \sum_{m=0}^{M} \mathcal{P}^{\mathrm{sig/int}}_{jk,m}\left(\vec{x};\vec{\xi}_{jk}\right) f_{ai}^{\frac{m}{2}} (1-f_{ai})^{\frac{M-m}{2}} \cos^m(\phi_{ai}),$$

M up to 4

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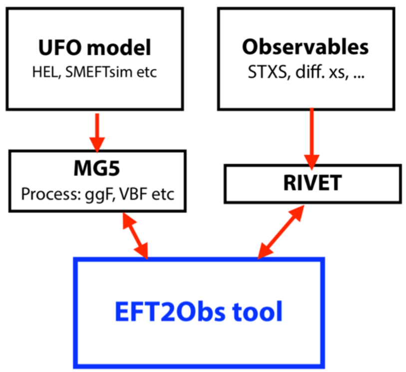
- ✓ Two strategies for constructing signal model as function of observables and EFT coefficients
  - Pros and cons, both can exist and be combined, as long as certain conventions are followed

EFT parameterisation and tools

- **ATLAS/CMS EFT parameterization efforts**
  - ✓ Move from SILH to Warsaw basis, from HEL to SMEFTsim model (towards global EFT fit)
  - ✓ Multiple tools/approaches (and public codes) in ATLAS/CMS

EFT2Obs

- Approach [2] implies finding scaling of each bin **i** as:
  - $\sigma_i = \sigma_i^{SM} + \sum_j c_j \sigma_{i,j}^{int} + \sum_{jk} c_j c_k \sigma_{i,jk}^{BSM}$, where j and k run over all relevant operators
  - $\mu_i = 1 + \sum_j c_j A_{i,j} + \sum_{jk} c_j c_k B_{i,jk}$, relative to the SM prediction ⇒ need to find A_j, B_{jk}
- EFT2Obs - Small project started in Les Houches, aims to be usable both inside and outside of the experiments
- Agnostic to specific EFT implementation, easy to implement new models
- **Developing solution based on Madgraph5_aMC@NLO + RIVET**



Demo code here
Full functionality in development

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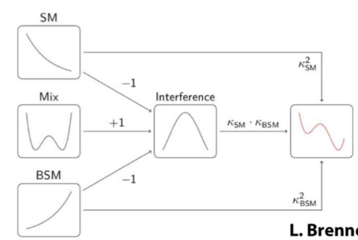
Effective Lagrangian morphing (ATLAS)

- Public code: RooLangrangianMorphing (based on RooFit)
- Given a set of input templates/PDFs and the corresponding EFT parameter points generates a morphing function to model any point in parameter space
- Supports approaches [1] and [2]. Inputs can be independent samples or ME reweighted
  - **Morphing function** for an observable T_{out} at any coupling point $\vec{g}_{target}$ constructed from weighted sum of input samples T_{in} at fixed coupling points $\vec{g}_i$

$$T_{out}(\vec{g}_{target}) = \sum_{i=1}^{N_{input}} w_i(\vec{g}_{target};\vec{g}_i)\cdot T_{in}(\vec{g}_i) \qquad \text{e.g. } T = \Delta\phi_{jj}$$

This method allows for more complicated distributions
- Continuous
- Analytic
- Fast

Combines rate and shape information simultaneously



L. Brenner

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- ✓ Two strategies for constructing signal model as function of observables and EFT coefficients
  - Pros and cons, both can exist and be combined, as long as certain conventions are followed
- ✓ Important to have multiple (public) implementations, for complementary and cross-check

BSM interpretation and tools

- **EFT interpretation is an intermediate step to easily translate experimental results in terms of (well motivated) new physics scenarios**
  - ✓ WG2 activities during 2018 focused on preparing a set of BSM benchmarks sensitive to H differential and coupling measurements and their mapping to the EFT.
  - ✓ Document has been just finalised
    - LHCHXSWG-2019-006
    - https://cds.cern.ch/record/2694087

BSM Benchmarks for Effective Field Theories in Higgs and Electroweak Physics

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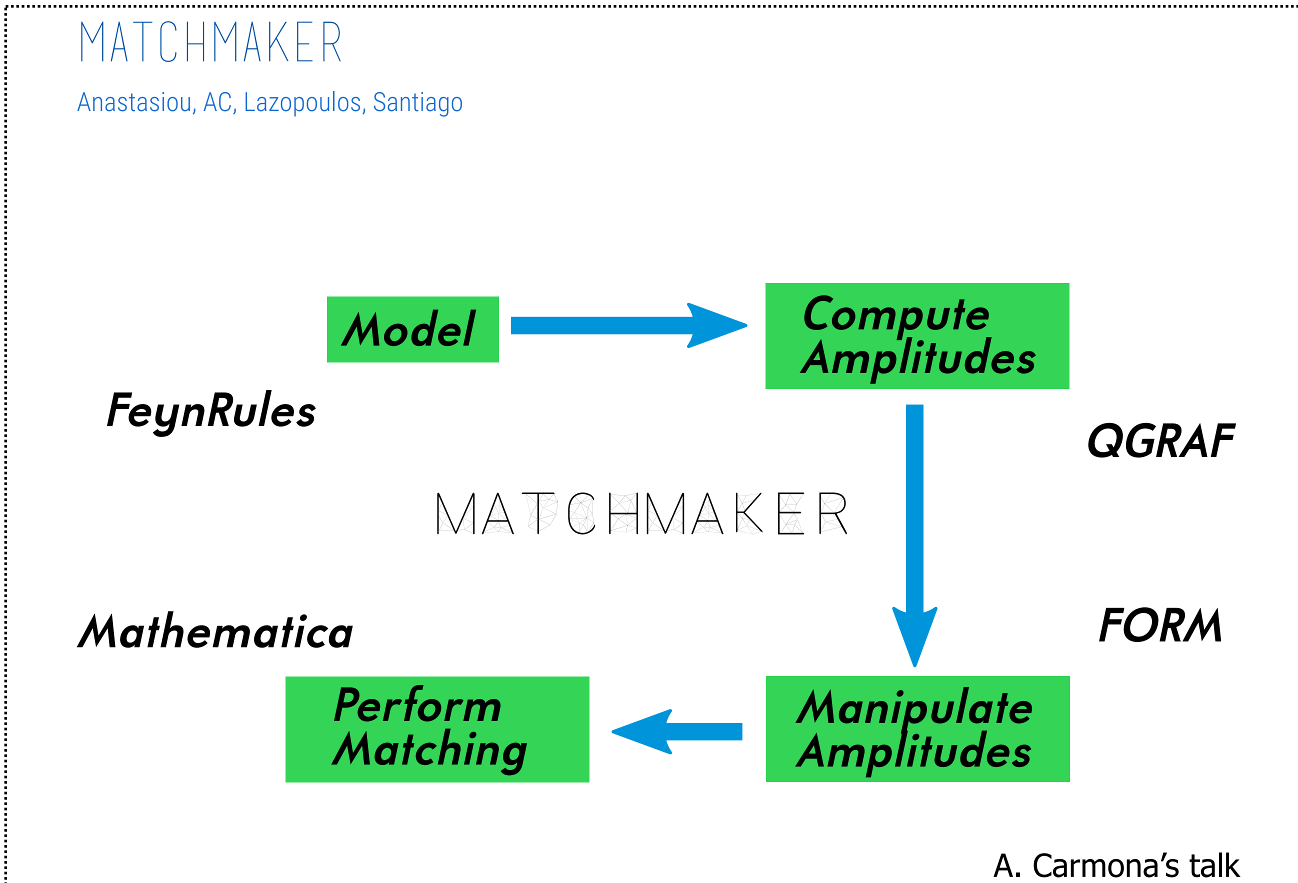
Abstract

Effective Field Theories (EFTs) capture effects from heavy dynamics at low energy and represent an essential ingredient in the context of Standard Model (SM) precision tests. This document gathers a number of relevant scenarios for heavy physics beyond the SM and presents explicit expressions for the Wilson coefficients in their low-energy EFT. It includes *i)* weakly coupled scenarios in which one or a few particles of different spins and quantum numbers interact linearly with the SM and generate EFT effects at tree-level, *ii)* scenarios where heavy particles interact quadratically whereupon the resulting EFT arises only at loop-level and *iii)* strongly coupled scenarios where the size of Wilson coefficients is controlled by symmetry arguments. This review aims at motivating experimental EFT studies in which only a subset of all possible EFT interactions is used, as well as facilitating the theoretical interpretation of EFT fits.

BSM interpretation and tools

- **BSM/EFT matching tools:**
  - ✓ Apart from tools dedicated to implement the EFT parameterization, matching the EFT results with non-minimal BSM scenarios can be greatly simplified using automated tools, e.g. MATCHMAKER (Automated matching at 1-loop)



Extending STXS with final state information

- *Motivations*
  - ✓ Agree on general decay-oriented measurements, as independent as possible on interpretation assumption (as STXS for production)
  - ✓ POs most general proposal so far, but a few cons
    - Interference terms difficult to treat
    - Meaning not necessarily intuitively or directly connected to observable quantities
    - Covariance matrix of a joined measurement with STXS bins could be insufficient

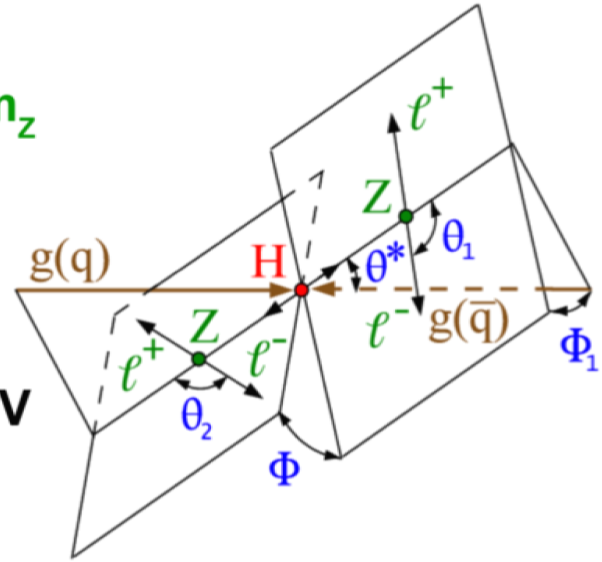
- **Still missing: something we can all agree upon to use for general Higgs decay measurements**
  - **Needs to be sufficiently general**
  - **Suitable to do measurements, e.g. should be closely related to observable quantities**
  - **If possible, assumptions needed for interpretations should be avoided for the measurements**

Extending STXS with final state information

A compromise ?

$H \rightarrow 4l$:

- 1^{st} Z usually ~ on-shell, mass m_{12} ~ m_Z
- 2^{nd} Z off-shell, mass $q^2 = m_{34}$
- STXS for q^2 dependence:
  make bins in m_{34}.
  Experiments usually cut m_{34}>~10 GeV
- Within each bin, q^2 is ~ constant
  - Can chose bins or continuous parameters without worry about q^2 expansion
  - Continuous parameters could be stage 2



$H \rightarrow l\nu l\nu$:

- Want to be as independent from production bins as possible
- Only one Lorentz invariant observable: m_{ll} → Let's make bins

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Extending STXS with final state information

Even more minimal starting point

We have seen in the EFT discussions that acceptance effects in decays play a role. Treat it like $|Y_H|>2.5$ in production

- $H\to ZZ^*$
  - Add 3 $H\to ZZ^*$ sub-bins
    - $H\to 4l$, $m_{34} < X$ (X ~ 10 GeV, not measured region)
    - $H\to 4l$, $X < m_{34} < 62.5$ GeV
    - $H\to ZZ^*\to !4l$ (populated in ttH multilepton)
- $H\to WW^*$
  - Add 4 $H\to WW^*$ sub-bins
    - $H\to l\nu l\nu$, $m_{ll} < X1$ (X1 ~ 10 GeV, not measured region)
    - $H\to l\nu l\nu$, $X1 < m_{ll} < X2$ (X2 ~ 50-60 GeV)
    - $H\to l\nu l\nu$, $X2 < m_{ll}$
    - $H\to WW^*\to !l\nu l\nu$ (populated in ttH multilepton, VHWW)

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Agreed to start from this "Stage 0"

Experiment to discuss details (e.g. m_{34} binning depending on p_T^{lep} selections)

More binning (e.g. angular variable to to define asymmetries) could be added at a later stage

Theory motivations for differential observables

The distinction between hard vs. resolution variables is also natural for BSM sensitivity

- Born/hard variables by definition probe the kinematics of the respective hard H+N-jet interaction
  - They are naturally sensitive to (indirect) BSM effects that change the hard interaction structure
  - Requires one to be in the appropriate genuine H+N-jet Born region
- Resolution variables probe the QCD emission pattern
  - They are naturally insensitive to BSM effects

Important to both cover and separate different phase-space regions

- 2D measurement is much more useful than several different but strongly correlated 1D projections
- Measuring as many observables as precisely as possible should have higher priority than combining differential spectra between channels or experiments

- The same for "colour singlet + jets" processes (e.g. Z/W+jets, H+jets, etc.)
- H+jets specific due to ggH loop - useful to measure

Differential observables proposal: H + 0 jets

Legend: hard/Born variables, resolution variables

Higgs observables

- Higgs: Y_H, p_T^H, eventually 2D $\{Y_H, p_T^H\}$
- $H \to \gamma\gamma$ decay:
  - 2D $\{p_{T1}, p_{T2}\}$ (exposes recoil, asymmetric cuts)
  - equivalent/redundant: η_1, η_2, $\cos\theta^*$, $\Delta\eta_{1,2}$
  - p_{Tt}, ϕ^* (alternatives to p_T^H)
- $H \to ZZ$ decay: 2D $\{m_{12}, m_{34}\}$, ...
- $H \to WW$ decay: 2D $\{p_{T1}, p_{T2}\}$, ...

Direct resolution observables

- p_T^{jet}, $\tilde{E}_T$
- $\mathcal{T}_f^{\text{jet}}$, $\tilde{\mathcal{T}}_f$ (some preference for $\mathcal{T}_C$ over $\mathcal{T}_B$, $\mathcal{T}_f$ vs. $\mathcal{T}_f^{\text{cm}}$?)
- dedicated track-based measurement: E_T, $\mathcal{T}_f$
- 2D $\{p_T^{\text{jet}}, \mathcal{T}_f^{\text{jet}}\}$ or $\{p_T^H, \mathcal{T}_f^{\text{jet}}\}$
  - equivalent/redundant: y^{jet} for $p_T^{\text{jet}} \geq p_T^{\text{cut}}$ or 2D $\{p_T^{\text{jet}}, y^{\text{jet}}\}$

"proposal" = suggestion of possible (multi-dimensional) observables
Exact set of variables and binning to be discussed by experiments depending on sensitivity and experimental challenges

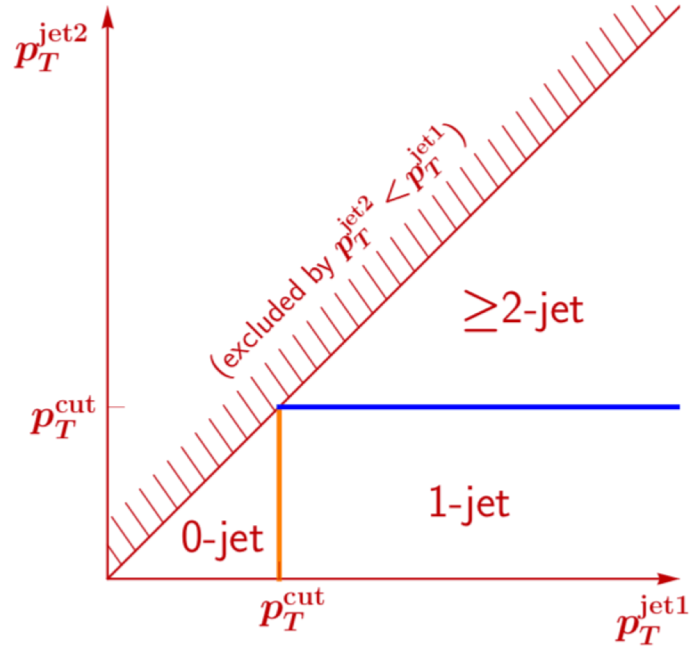
Differential observables proposal: H + 1 jets

Possible hard observables

- $pp \to Hj$ is $2 \to 2$ (ignoring decay now) $\to$ 3 independent variables
- $p_T^H, Y_H, p_T^{\text{jet}}, y^{\text{jet}}, \mathcal{T}_f^{\text{jet}}, \ldots$: already covered, see above
- More options: m_{Hj}, ...

Resolution observables

- Options: $p_T^{Hj}, p_T^{\text{jet2}}, \mathcal{T}_f^{\text{jet2}}, \mathcal{T}_1$, ...
- Genuine 2D needed
  - $\{p_T^H, p_T^{Hj}\}$, $\{p_T^{\text{jet1}}, p_T^{\text{jet2}}\}$,
    $\{p_T^H, p_T^{\text{jet}}\} \equiv \{p_T^H, p_T^H - p_T^{\text{jet}}\}$ (redundant)
  - $\{p_T^H, \mathcal{T}_1\}$
  - $\{m_{Hj}, p_T^{Hj}\}$, $\{m_{Hj}, \mathcal{T}_1\}$



Differential observables proposal: H + 2 jets

Here we are running into statistics limitations ...

Hard observables

- Previous variables: $p_T^H, p_T^{\text{jet1}}, m_{Hj}, p_T^{Hj}$, ...: already effectively covered
- $\Delta\phi_{jj}, m_{jj}, \Delta\eta_{jj}$, ...

Resolution observables

- $p_T^{Hjj}, \Delta\phi_{H,jj}, p_T^{\text{jet3}}$, ...

In all cases

- Separate genuine $H + 2$ region from $H + 0, 1$ regions
- e.g. measure in bins of $p_T^{\text{jet1,2}} \leq m_H/2$ and $p_T^{\text{jet1,2}} \geq m_H/2$

Next steps

- EFT interpretations
  - ✓ Great progress in theory tools and experimental implementations of parametrizations
  - ✓ Planning to have follow-up meeting to clarify pending issues
  - ✓ Plan to prepare note on high-energy probes of EFT

- STXS
  - ✓ Stage 1.2 STXS being finalized
  - ✓ STXS uncertainty paper to appear soon
  - ✓ "STXS-in-decay" Stage 0 proposal agreed on
    - Experiments to decide bin boundaries (e.g. m_{34})

- Differential observables
  - ✓ Plan to prepare "recommendation" writeup
    - Experiments to decide minimal set of observables of binning