Higgs & STXS

LPC EFT Workshop

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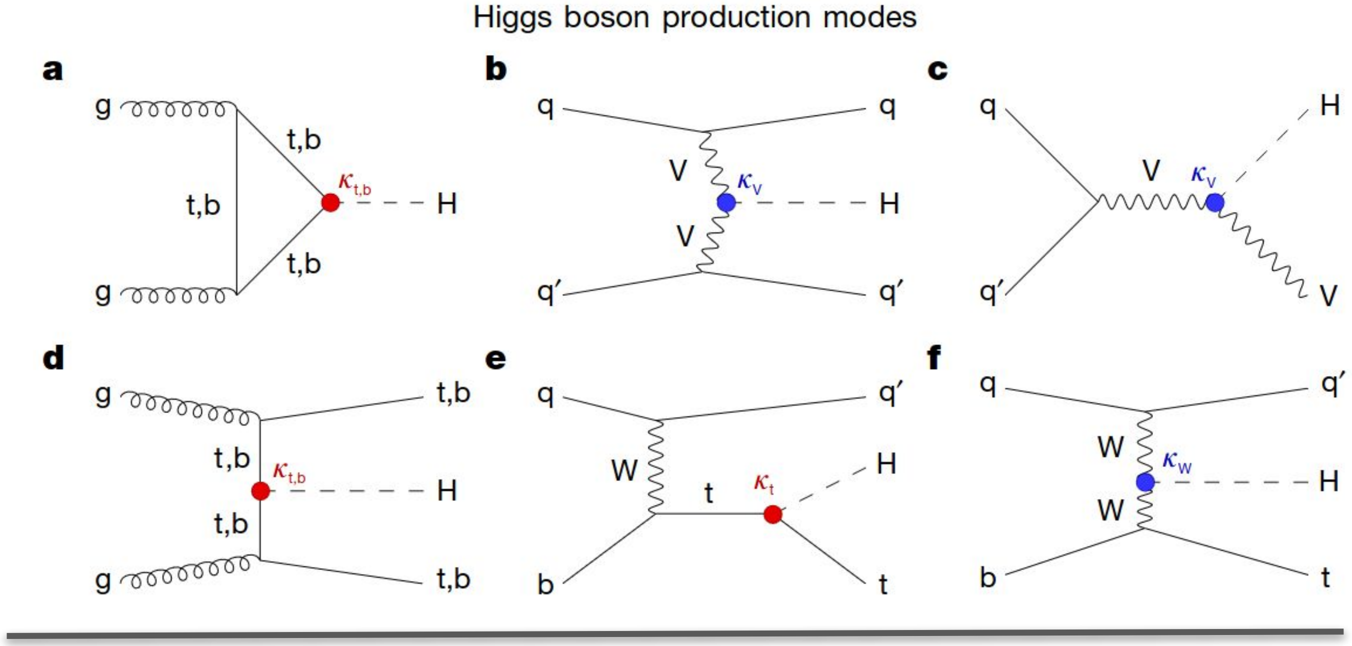
IMPERIAL

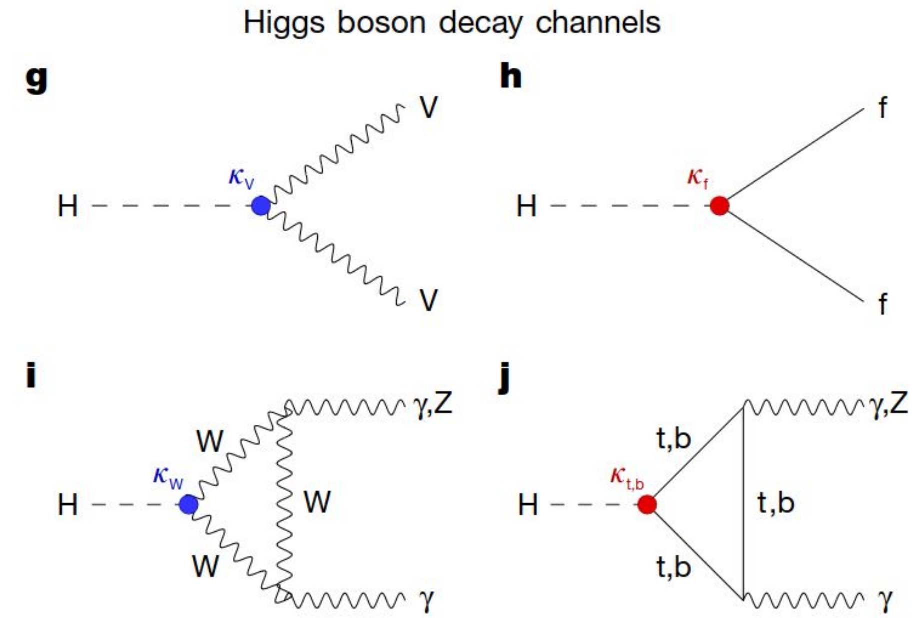
Imperial-X

CMS

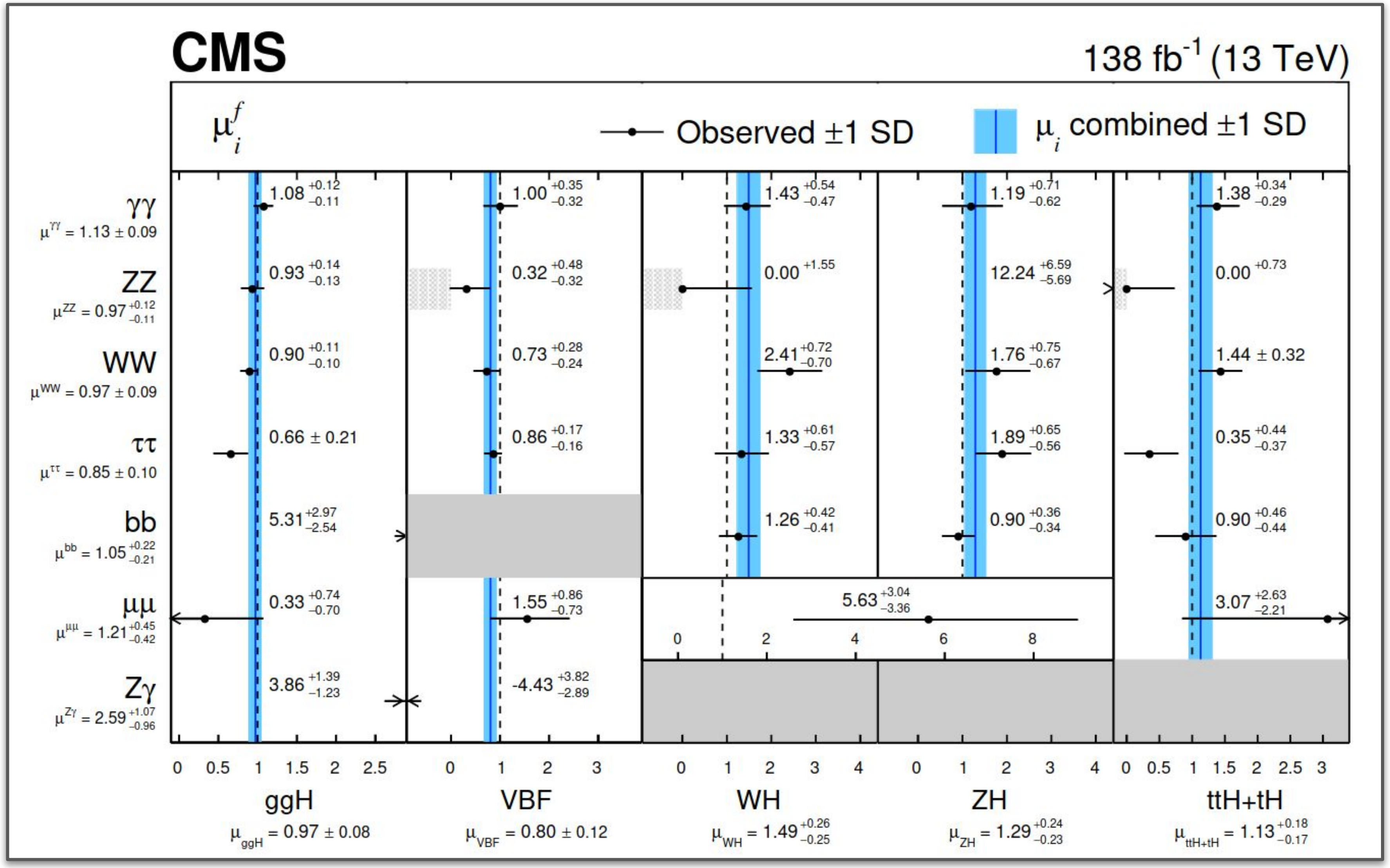
Introduction

- Since 2012 we have entered precision era of Higgs boson measurements





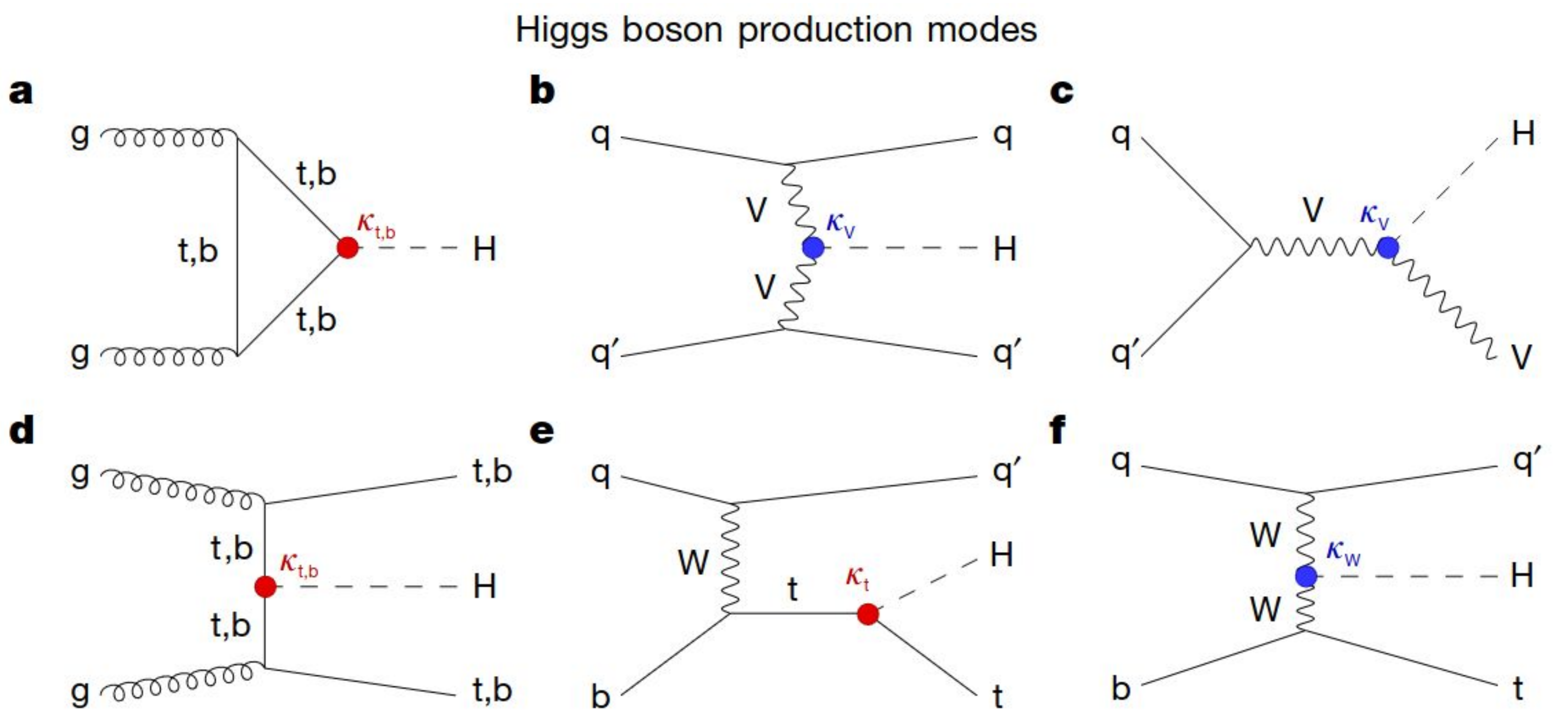
[Nature 607, 60-68 (2022)]

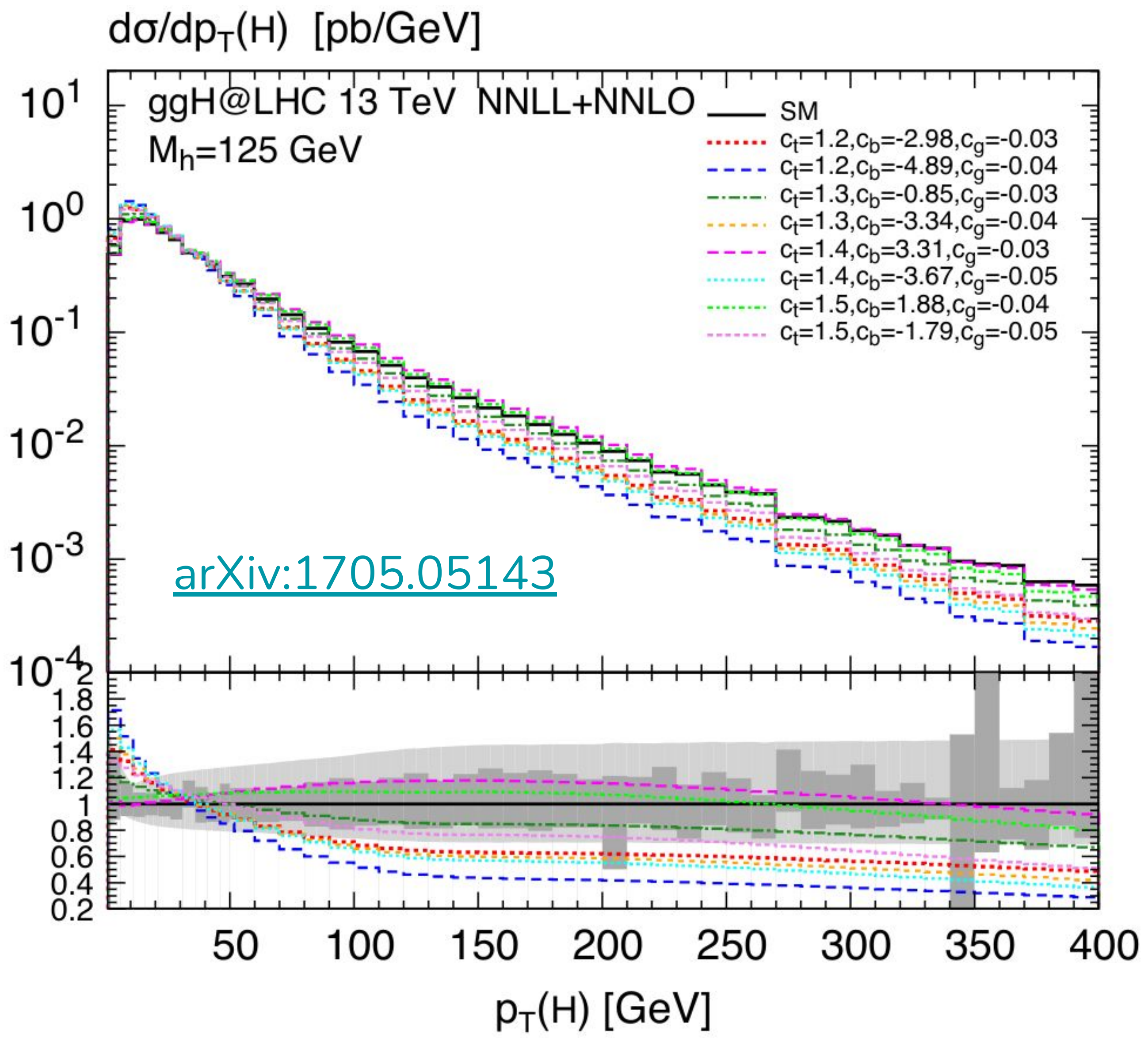


- Going beyond inclusive...

Simplified Template Cross Sections (STXS)

- Split events first by production mode, then by kinematics





- Measure cross section in each region (bin) → Develop granular description of Higgs boson production

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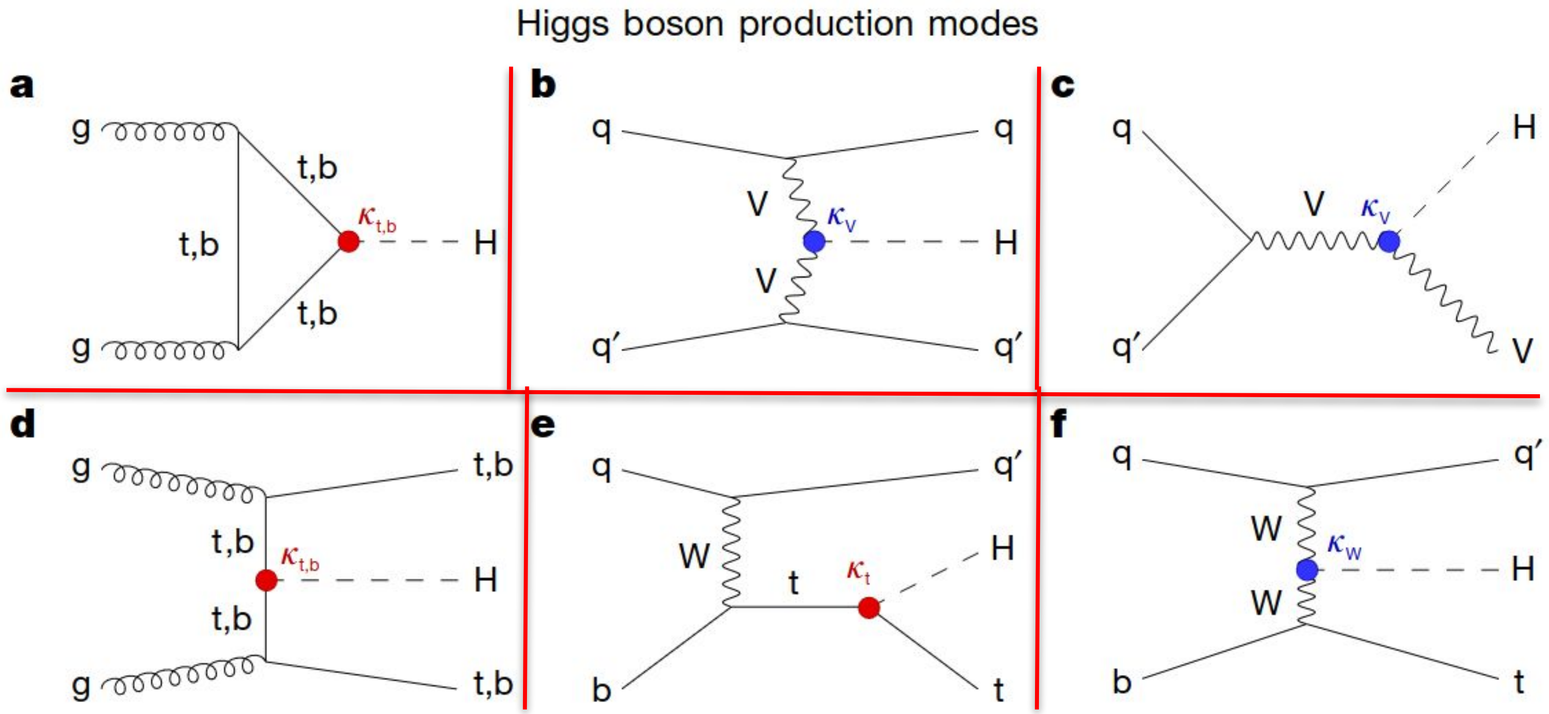

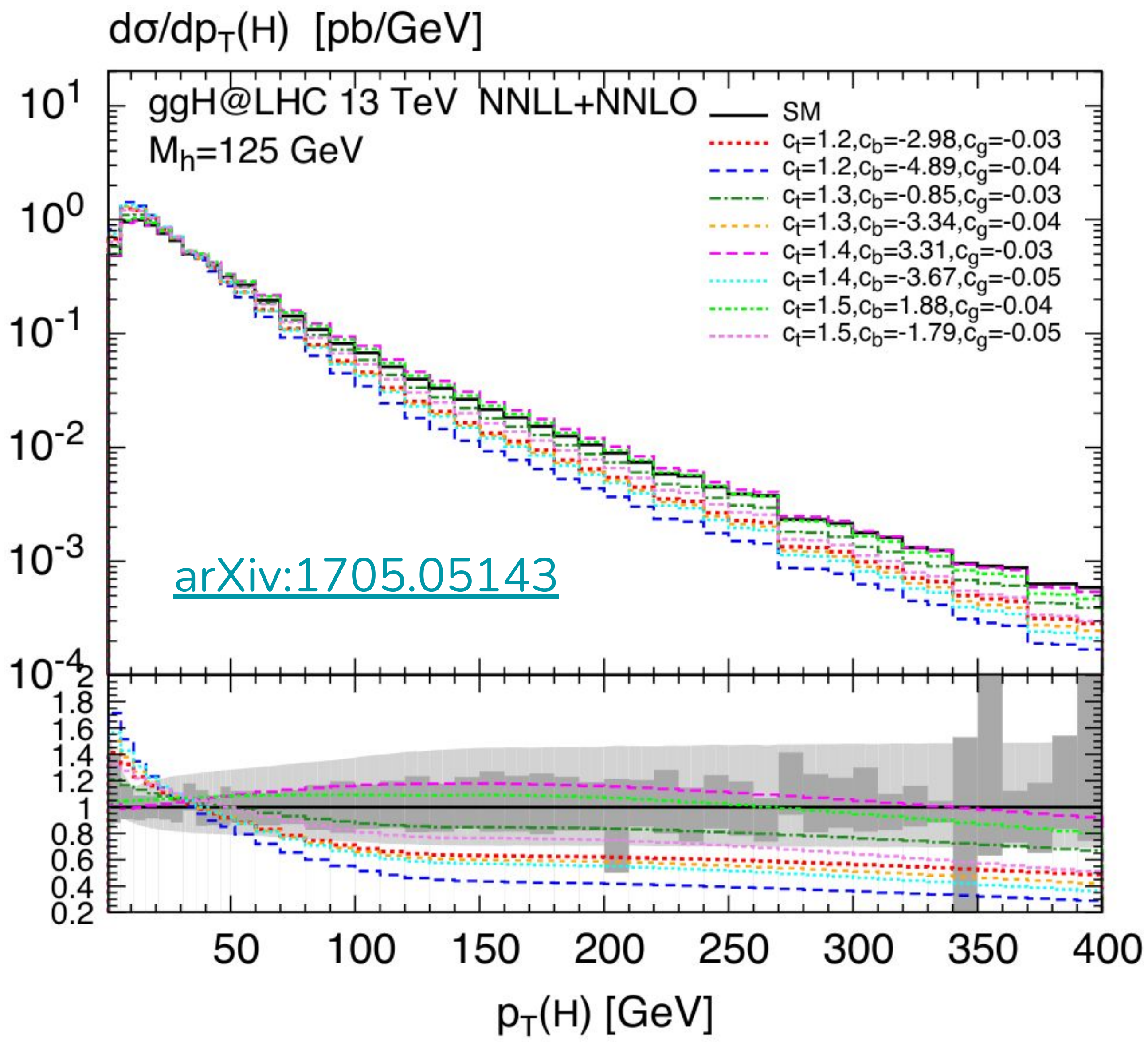

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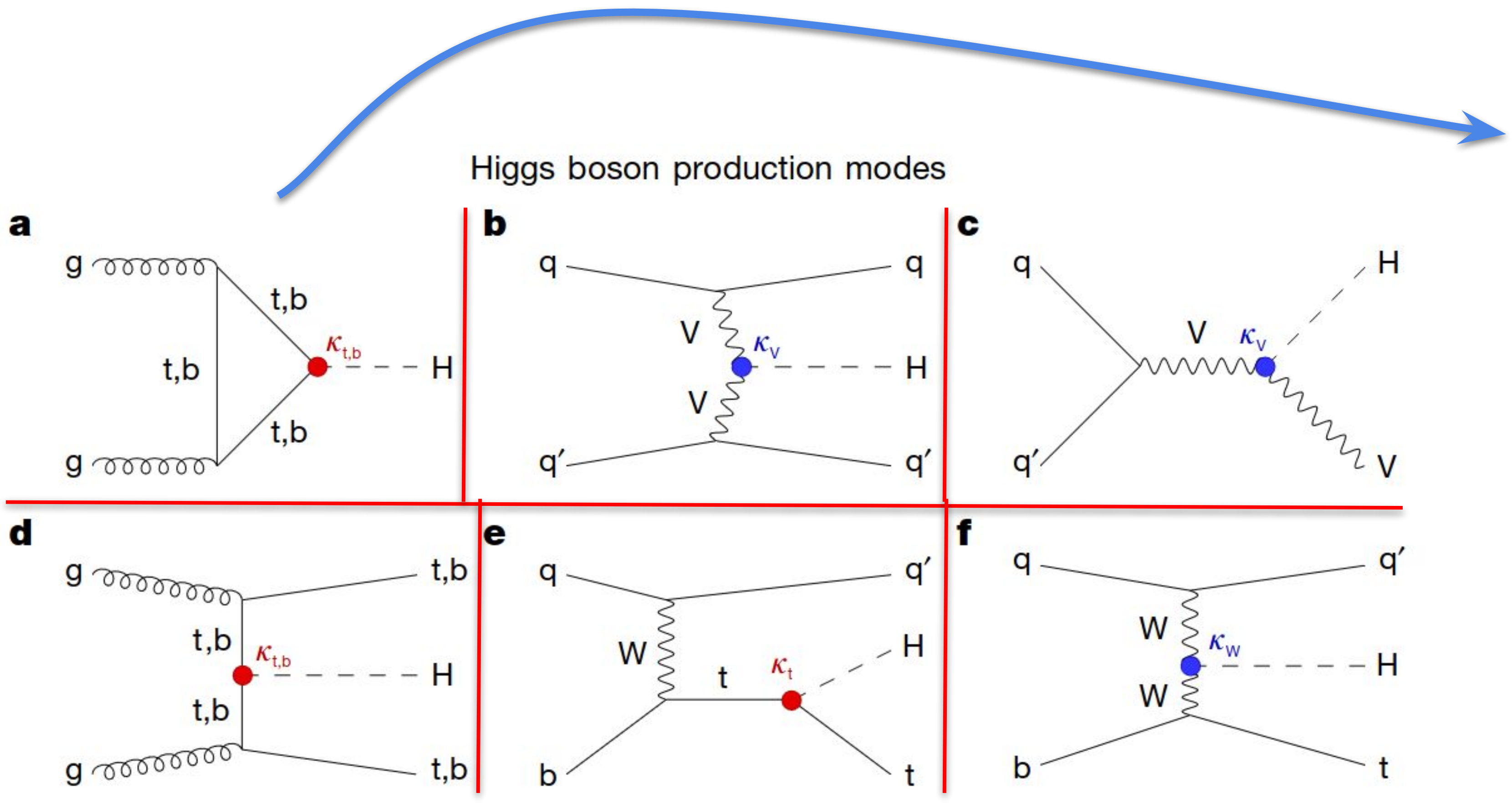

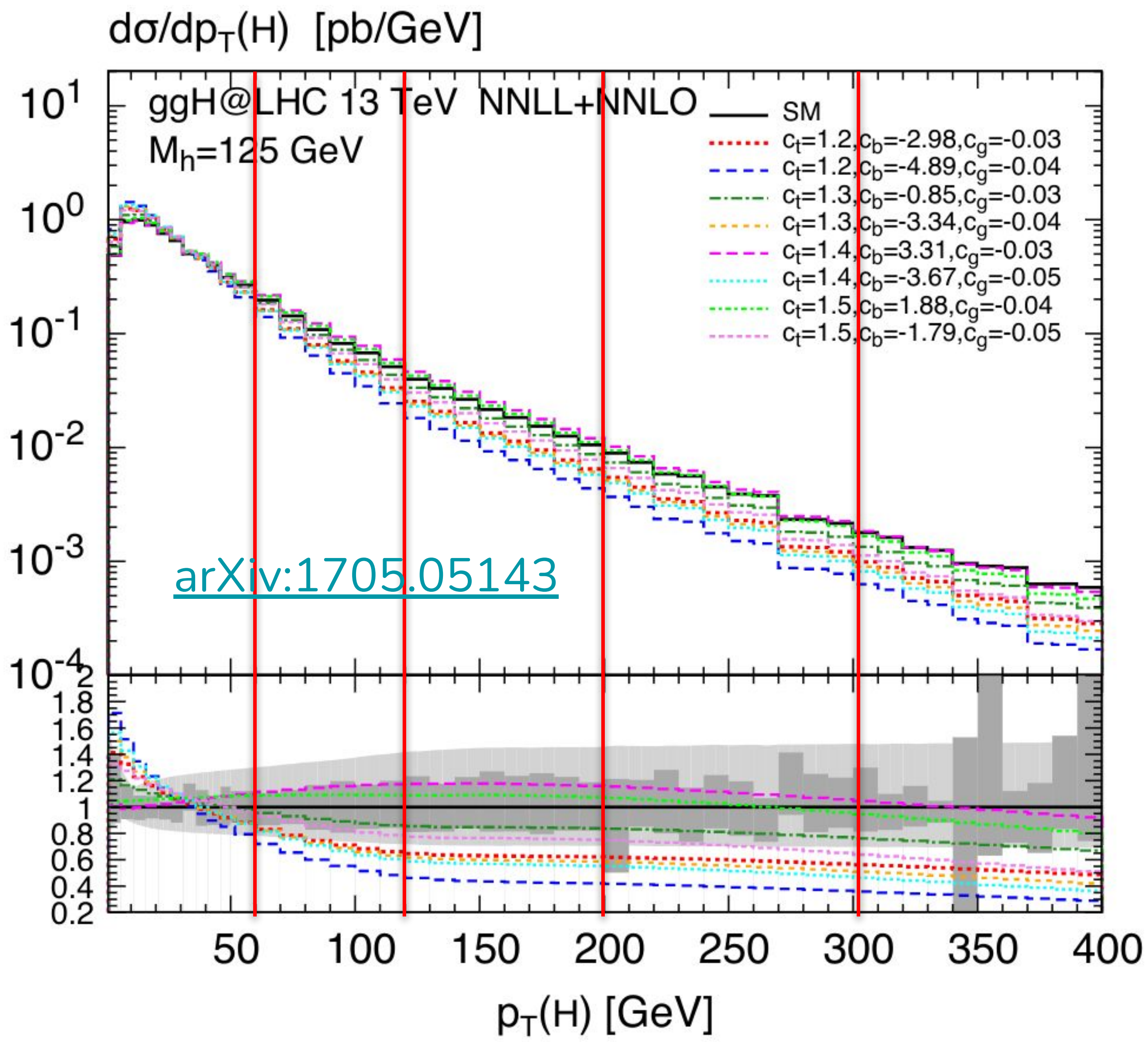

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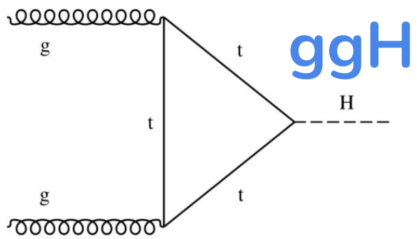
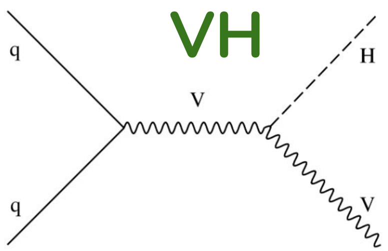
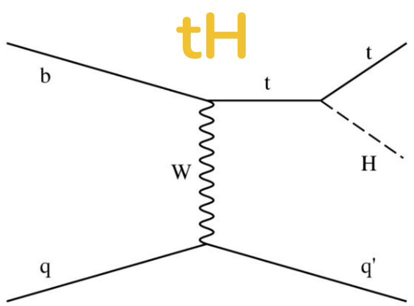
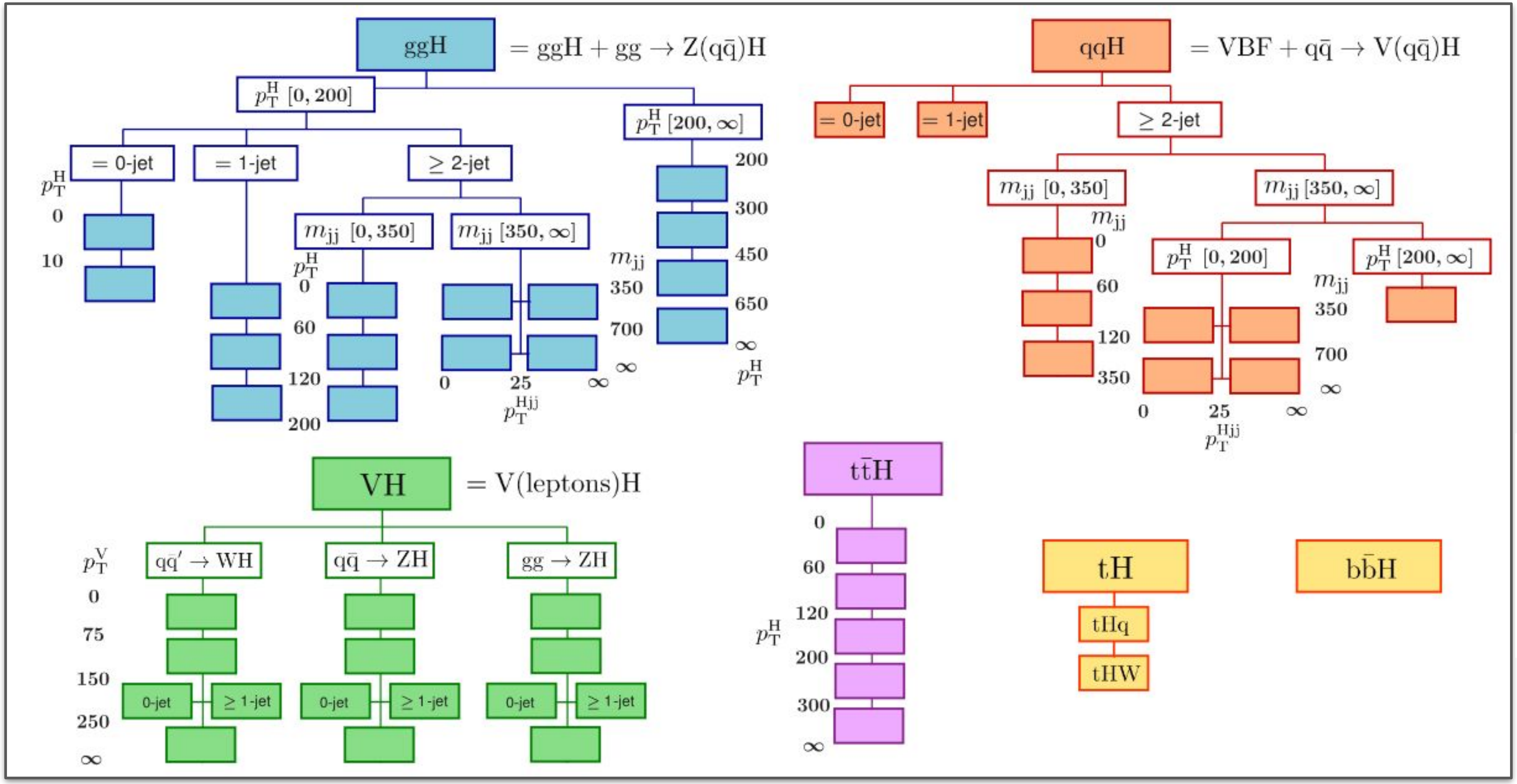
STXS (stage 1.2)

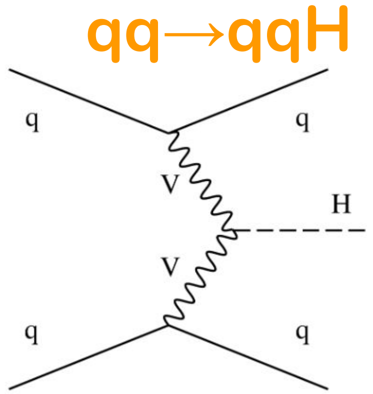
Split by p_T^H, n_{jets}, m_{jj}, p_T^{Hjj}, p_T^V

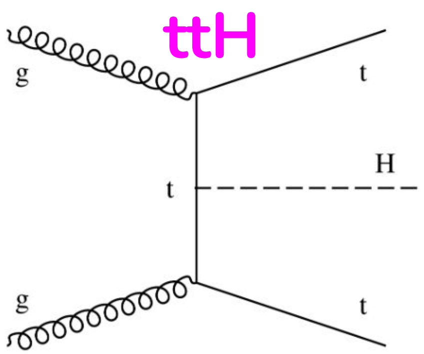










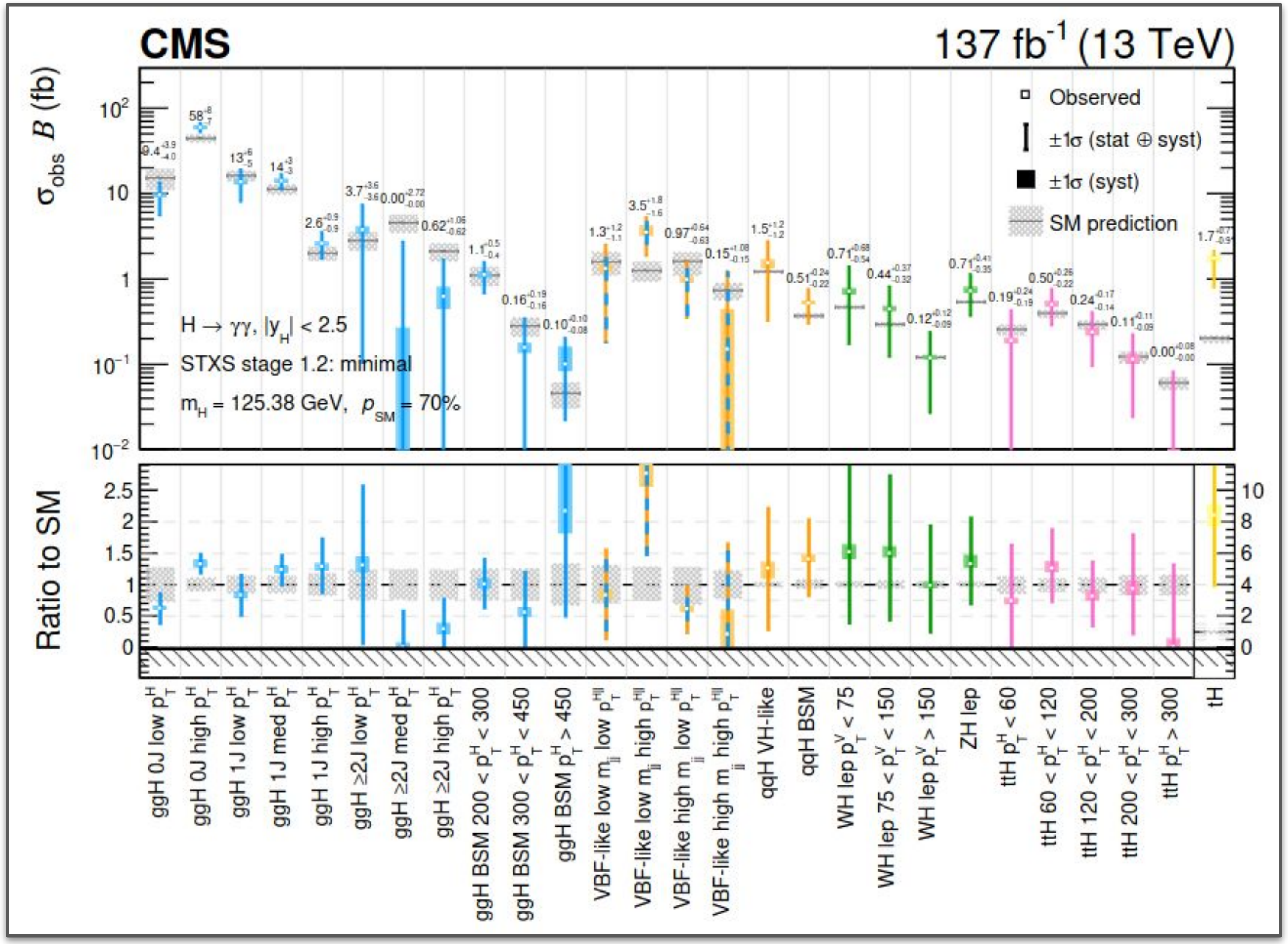


Advantages

- Common scheme across decay channels (eases combination)
- Systematically reduce theory dependence in measurements
- Isolate regions with enhanced BSM sensitivity
- Framework for BSM interpretations (e.g. SMEFT)

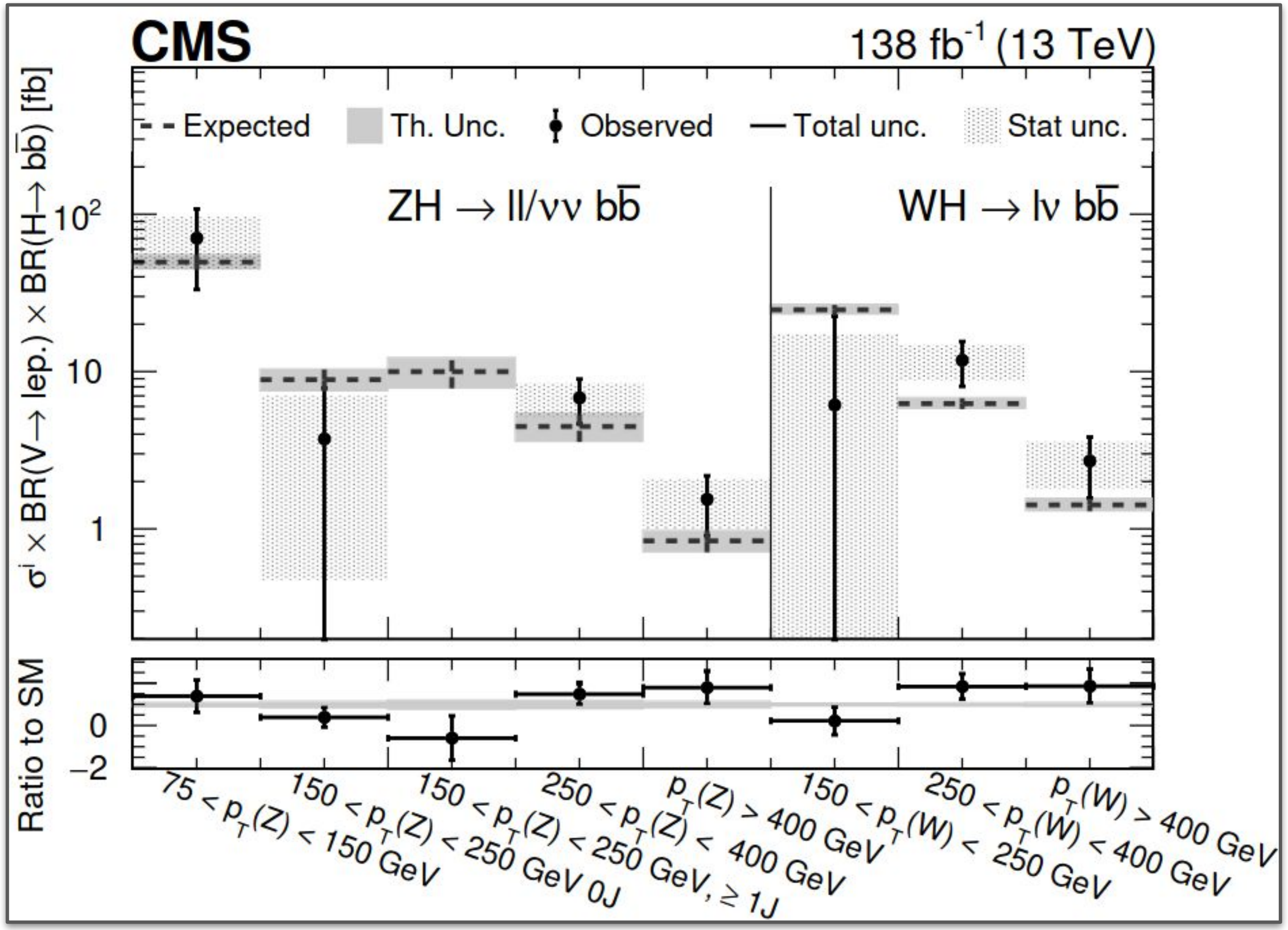
STXS measurements

- Both **CMS** & ATLAS have performed STXS measurements in major Higgs boson decay channels e.g.



[JHEP 07 (2021) 027]

$H \to \gamma\gamma$



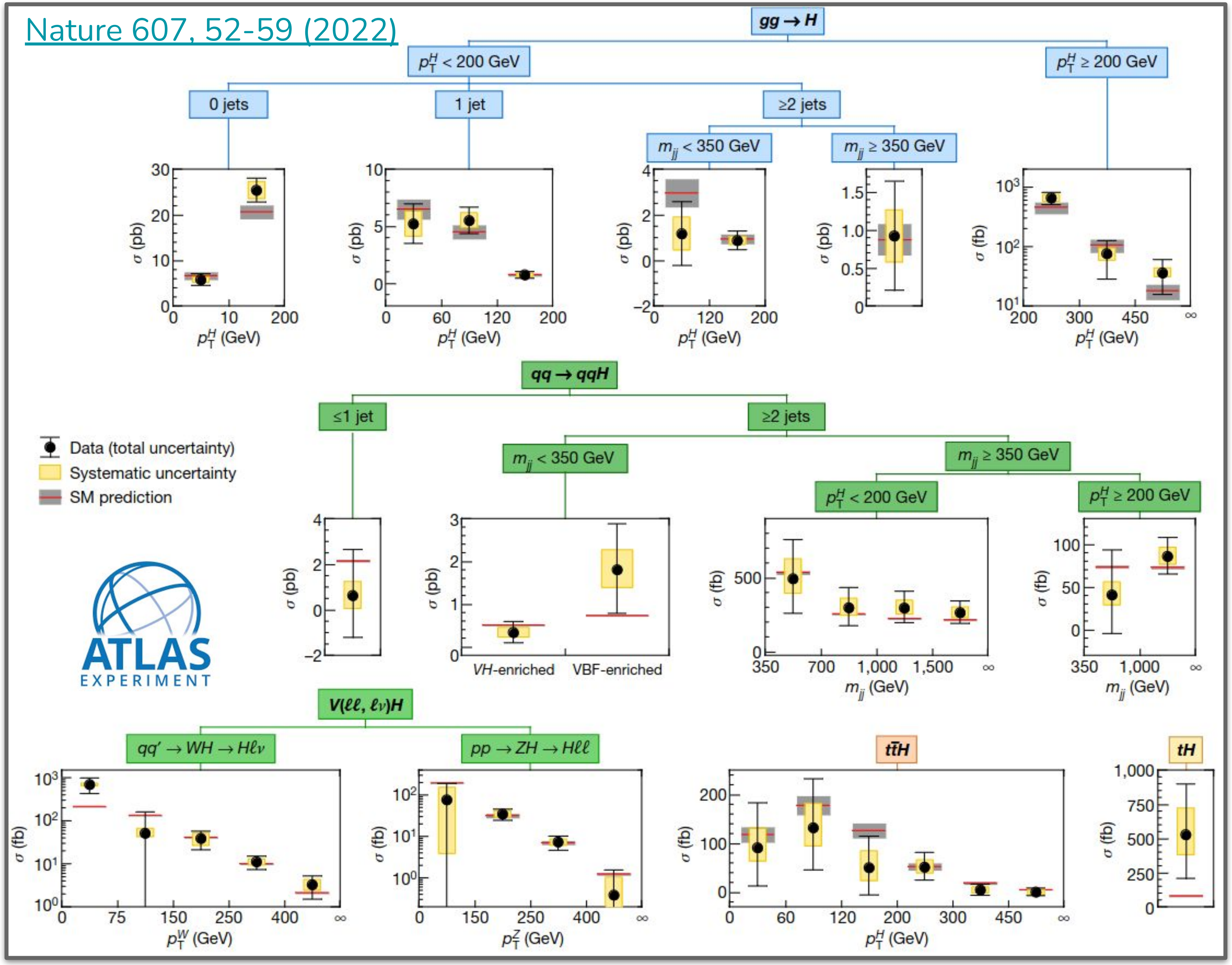
[Accepted by Phys.Rev.D]

$VH,\ H \to bb$

STXS combinations

- Common scheme enables combinations where we achieve ultimate sensitivity

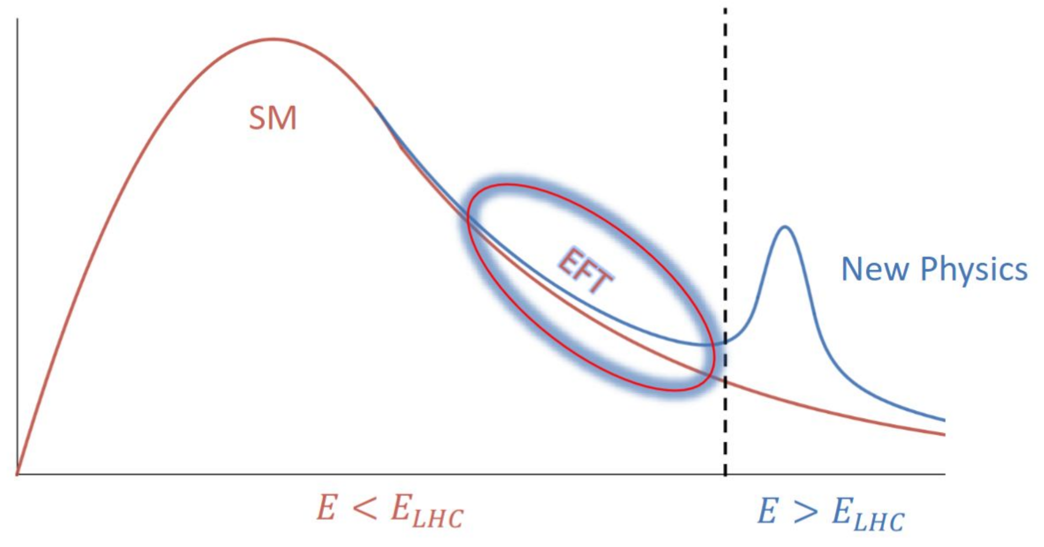
Nature 607, 52-59 (2022)



Stay tuned for CMS Legacy Run 2 combination

SMEFT interpretation

- STXS provides a useful framework for BSM interpretations e.g. SMEFT
  - Use kinematic information for stronger constraints
- Three types of SMEFT fits:



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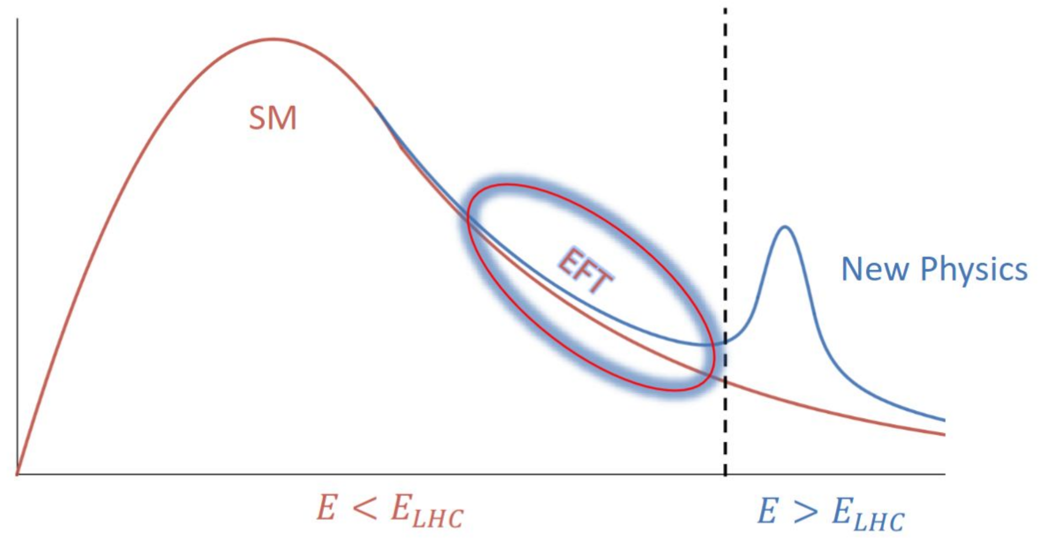

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1 **SMEFT <u>reinterpretation</u> of unfolded diff XS measurements**

$$\mathcal{L}(\text{data}\,|\,\vec{c}) = \frac{\exp\left(-\frac{1}{2}\Delta\vec{\mu}(\vec{c})^{\mathrm{T}}V^{-1}\Delta\vec{\mu}(\vec{c})\right)}{\sqrt{(2\pi)^m\det(V)}}$$

- "Theorists" approach
- Build simplified likelihood using measured cross sections relative to SM predictions (signal strengths, μ)
- As well as 68% confidence intervals + correlations

2 **SMEFT <u>interpretation</u> using full (reco-level) likelihood**

$$\mathcal{L}(\text{data}\,|\,\vec{c},\vec{\theta}) = \prod_i \text{Poisson}\Big(n_i\,\Big|\,\sum_j \mu^j(\vec{c})s_i^j(\vec{\theta}) + b_i(\vec{\theta})\Big)\,p(\tilde{\vec{\theta}}\,|\,\vec{\theta})$$

- Performed in-house by experiments
- Parameterise signal strengths in likelihood in terms of SMEFT Wilson coefficients
- Analysis not fixed/optimised to EFT model→ Reinterpretable
- Fair sensitivity to wide set of operators

3 **SMEFT <u>direct analysis</u>**

$$\mathcal{L}(\text{data}\,|\,\vec{c},\vec{\theta}) = \prod_i \text{Poisson}\Big(n_i\,\Big|\,\sum_j s_i^j(\vec{c},\vec{\theta}) + b_i(\vec{\theta})\Big)\,p(\tilde{\vec{\theta}}\,|\,\vec{\theta})$$

- Directly parameterise signal yields and shapes in terms of SMEFT Wilson coefficients
- Propagate SMEFT effects through detector
- Analysis optimised to EFT model
- Great sensitivity to handful of operators

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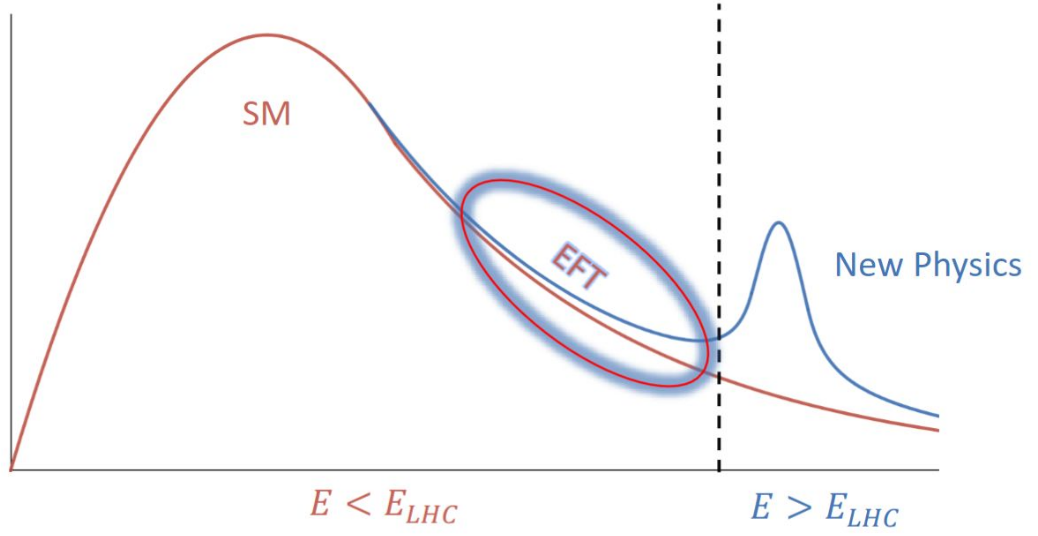

STXS approaches

1

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STXS-SMEFT parametrisation

- Key quantity to derive:

$$\mu^{i,f}(\vec{c}) = \frac{[\sigma^i \cdot \mathcal{B}^f](\vec{c})}{[\sigma^i \cdot \mathcal{B}^f]_{\mathrm{SM}}}$$

i = STXS bin, f = Higgs boson decay channel

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$$\mathcal{L}(\text{data} \,|\, \vec{c}, \vec{\theta}) = \prod_i \text{Poisson}\left(n_i \,\middle|\, \sum_j \mu^j(\vec{c}) s_i^j(\vec{\theta}) + b_i(\vec{\theta})\right) p(\tilde{\vec{\theta}} \,|\, \vec{\theta})$$

- Parameterise Higgs boson cross sections (STXS) and decay widths as functions of SMEFT Wilson coefficients

- Full details in talk by Charlotte later. Key assumptions:

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1. **Single insertions of (CP-even) dim-6 operators**
   - Cross sections, partial widths and total width have quadratic dependence
   - Use combination of Monte-Carlo tools and analytic solutions to obtain Aj, Bjk

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_j \frac{c_j}{\Lambda^2} \cdot \mathcal{O}_j^{(6)}$$

$$\mu = O^{\mathrm{EFT}}/O^{\mathrm{SM}} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

2. **Higgs boson narrow-width assumption**
   - Total scaling is product of production and decay-side scaling functions

$$\mu_i^f = \frac{\left(1+\sum_j A_j^i c_j + \sum_{jk} B_{jk}^i c_j c_k\right) \cdot \left(1+\sum_j A_j^f c_j + \sum_{jk} B_{jk}^f c_j c_k\right)}{1+\sum_j A_j^{\mathrm{tot}} c_j + \sum_{jk} B_{jk}^{\mathrm{tot}} c_j c_k}$$

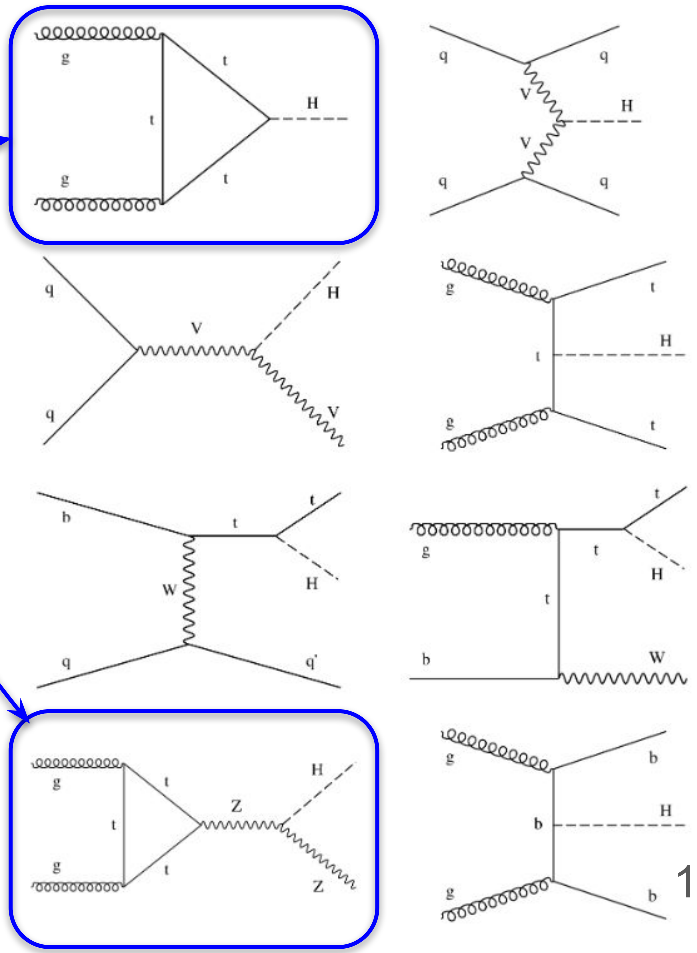
3. **EFT effects factorise from higher-order QCD/QED contributions**

$$\sigma^i_{\mathrm{SMEFT}} = \sigma_{\mathrm{SM}}^{i,((\mathrm{N})\mathrm{N})\mathrm{NLO}} \times \left(1 + \frac{\sigma_{\mathrm{int}}^{i,(\mathrm{N})\mathrm{LO}}}{\sigma_{\mathrm{SM}}^{i,(\mathrm{N})\mathrm{LO}}} + \frac{\sigma_{\mathrm{BSM}}^{i,(\mathrm{N})\mathrm{LO}}}{\sigma_{\mathrm{SM}}^{i,(\mathrm{N})\mathrm{LO}}}\right)$$

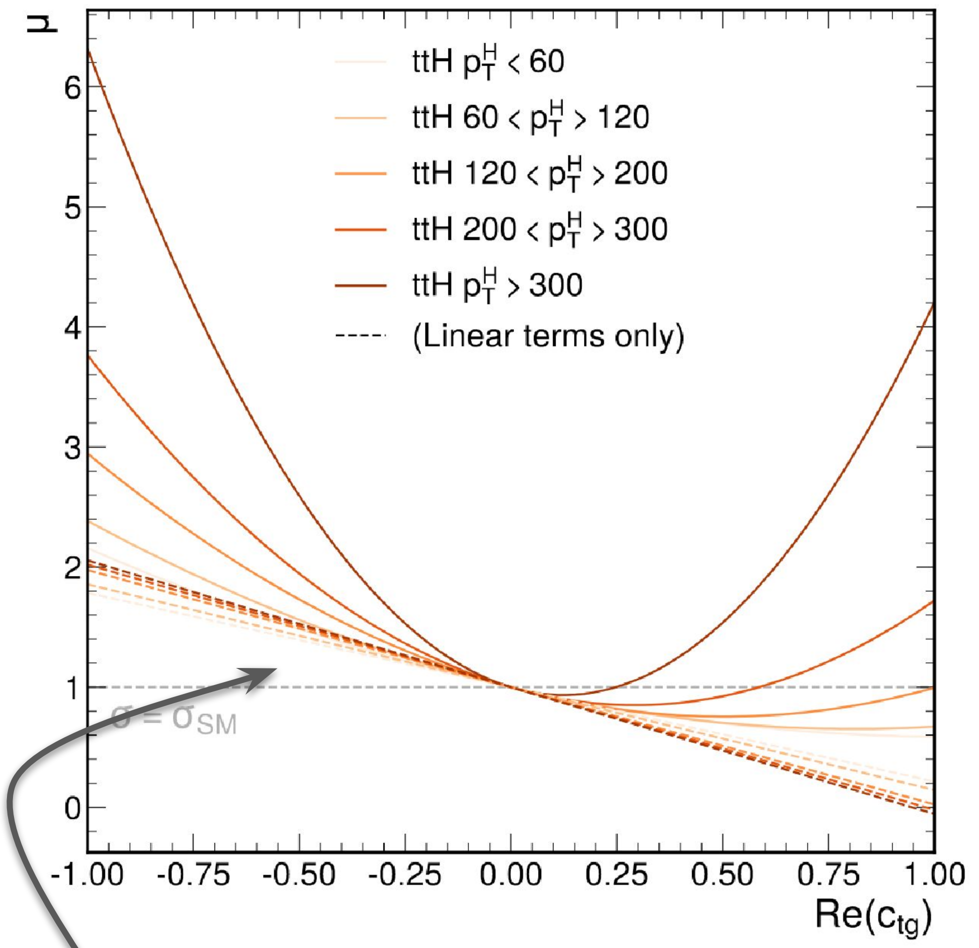
STXS-SMEFT derivation

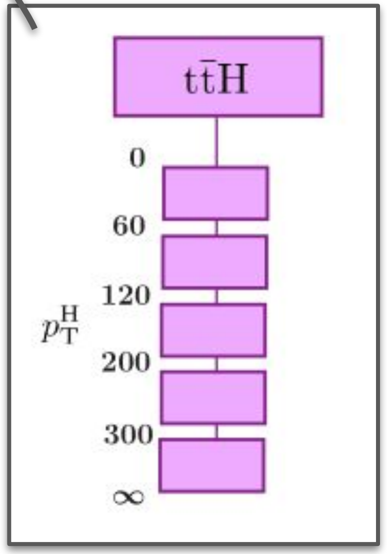
$$\mu = O^{\mathrm{EFT}}/O^{\mathrm{SM}} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- **Task:** determine Aj, Bjk coefficients for each STXS bin + decay widths
- EFT2Obs tool: used to derive quadratic parametrisation at STXS stage 1.2 granularity in Warsaw basis
  - All CP-even dim-6 operators under topU3l flavour symmetry
  - {GF, MZ, MW} input parameter scheme
  - Events generated with Madgraph (v2.6.7) → showered with Pythia → Categorised into STXS bins using Rivet routine
  - Reweight events to different points in SMEFT parameter space to extract cross section dependence
- ggH + ggZH derived using SMEFT@NLO (loop processes)
  - Translated to topU3l Warsaw basis using SMEFTsim manual
- EW Higgs production modes at LO with SMEFTsim v3: VBF, VH, ttH, tH, bbH
  - Propagator corrections included
- Higgs decay using mixture of SMEFTsim and analytic results
  - Total width = weighted sum of partial widths (validated using analytic linear result)



STXS-SMEFT parametrisation

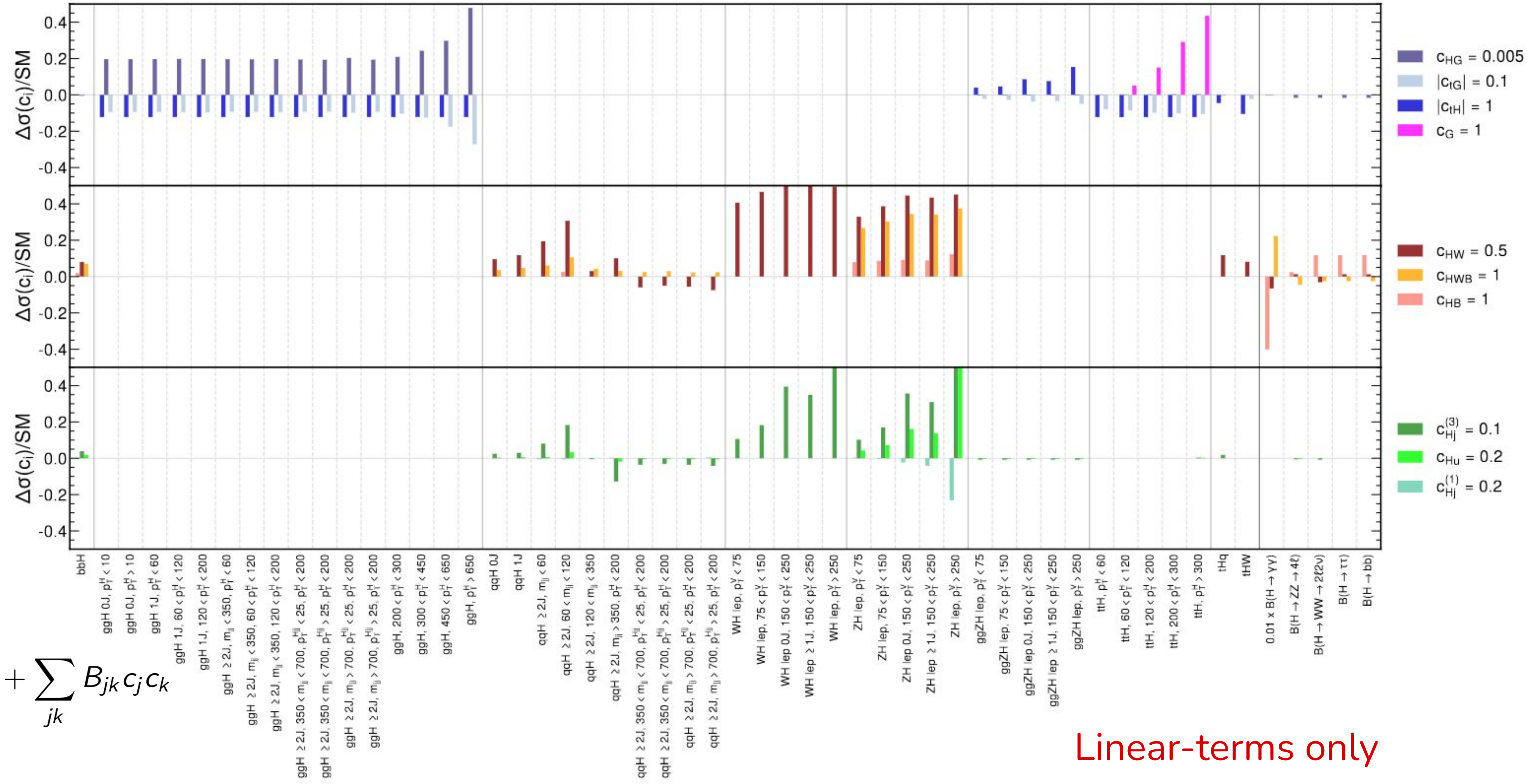




Perform two fits where we perform SMEFT expansion to only include:

1. **Linear terms:** $\mu_i^f = 1 + \sum_j (A_j^i + A_j^f - A_j^{tot}) c_j$

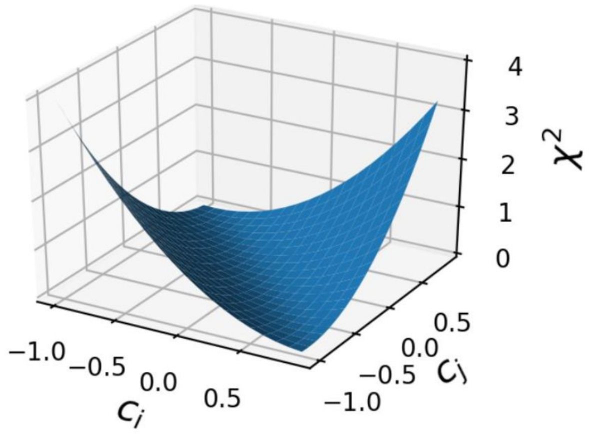
2. **Linear + quadratic terms:** $\mu_i^f \approx 1 + \sum_j (A_j^i + A_j^f - A_j^{tot}) c_j + \sum_{jk} (B_{jk}^i + B_{jk}^f - B_{jk}^{tot}) c_j c_k +$
$(\sum_j A_j^i c_j)(\sum_j A_j^f c_j) - (\sum_j A_j^i c_j)(\sum_j A_j^{tot} c_j) - (\sum_j A_j^f c_j)(\sum_j A_j^{tot} c_j) + (\sum_j A_j^{tot} c_j)^2 + \ldots$



Linear-terms only

$$\mu = O^{EFT}/O^{SM} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

PCA rotation



- STXS cannot simultaneously constrain O(40) CP-even operators relevant to Higgs physics
  - Large degeneracies/correlations between Wilson coefficients
- **Principal component analysis** on Fisher Information matrix → find constrained (+ unconstrained) directions in parameter sp

$$C^{-1}_{\mathrm{SMEFT}} = P^T C^{-1}_{\mathrm{STXS}} P$$

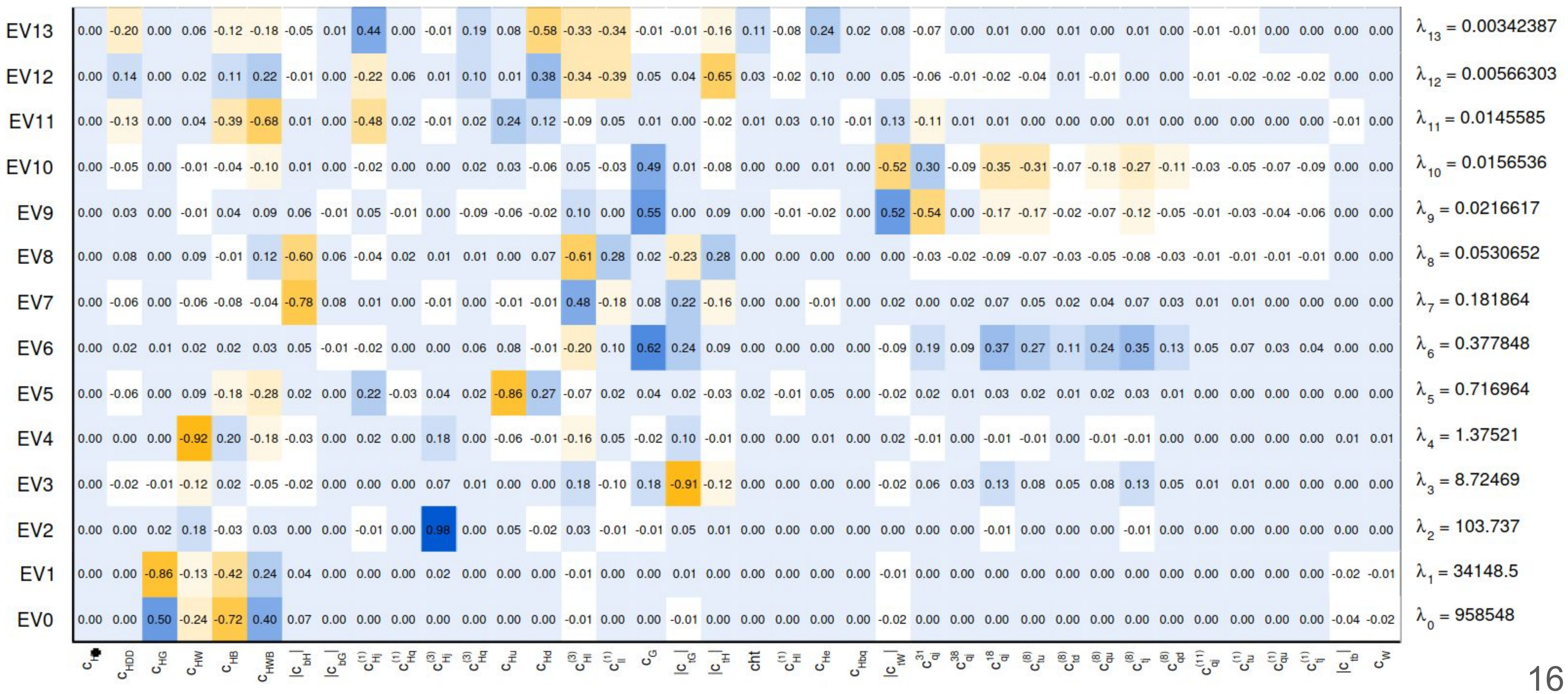
Fisher-information (Hessian) of STXS measurements

$$P^f_{ij} = A^{i\to H}_j + A^{H\to f}_j - A^{\mathrm{tot}}_j$$

Rotation using **linearised** SMEFT model

$$C^{-1}_{\mathrm{SMEFT}}:\ (C^{-1}_{\mathrm{SMEFT}} - \lambda_m I)\mathrm{EV}_m = 0$$

Eigenvector decomposition



Derived using CMS Run 2 H→$\gamma\gamma$ STXS workspace

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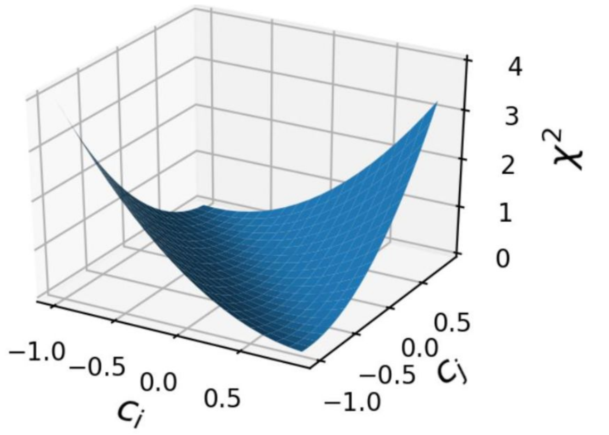

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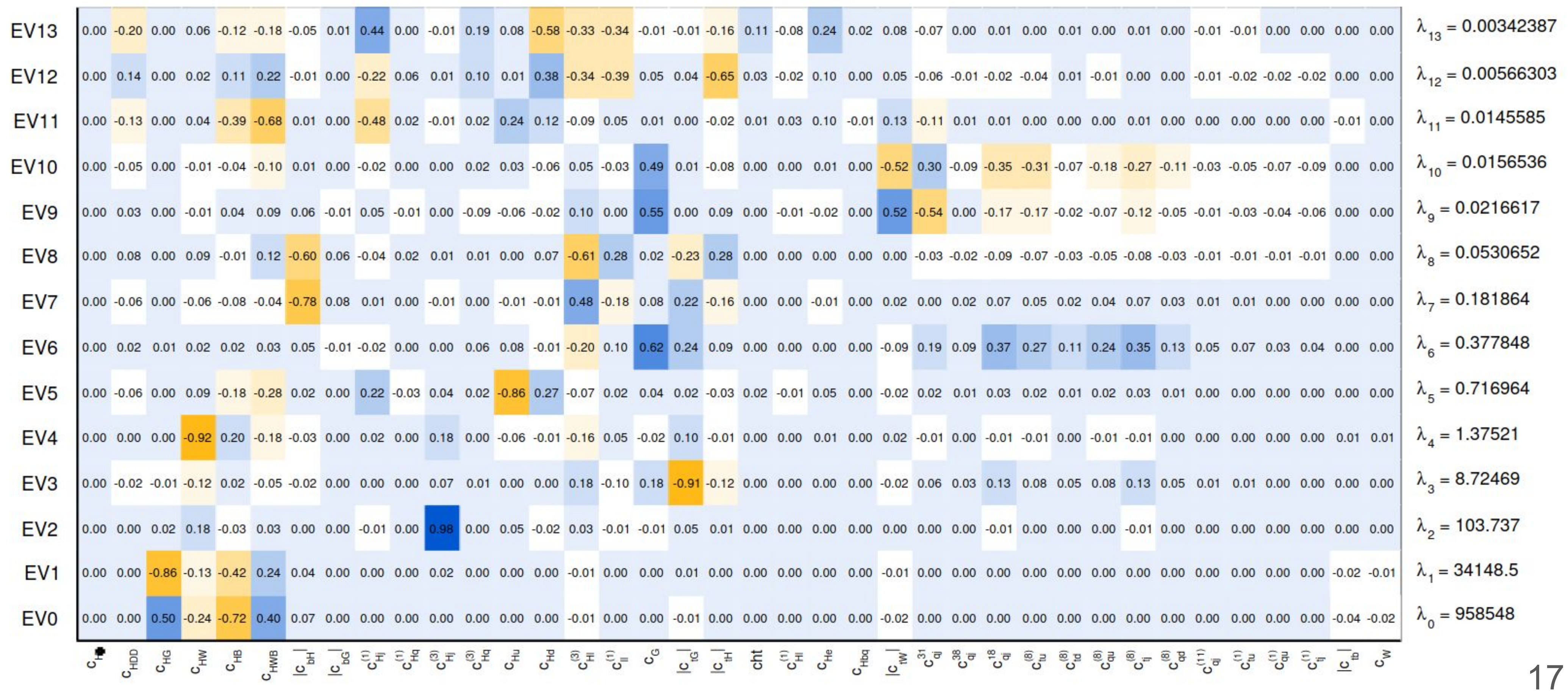
Eigenvector decomposition

EV = linear combinations of Wilson Coefficients

$$\mathrm{EV} = \sum_j \alpha_j c_j$$



Derived using CMS Run 2 H→$\gamma\gamma$ STXS workspace

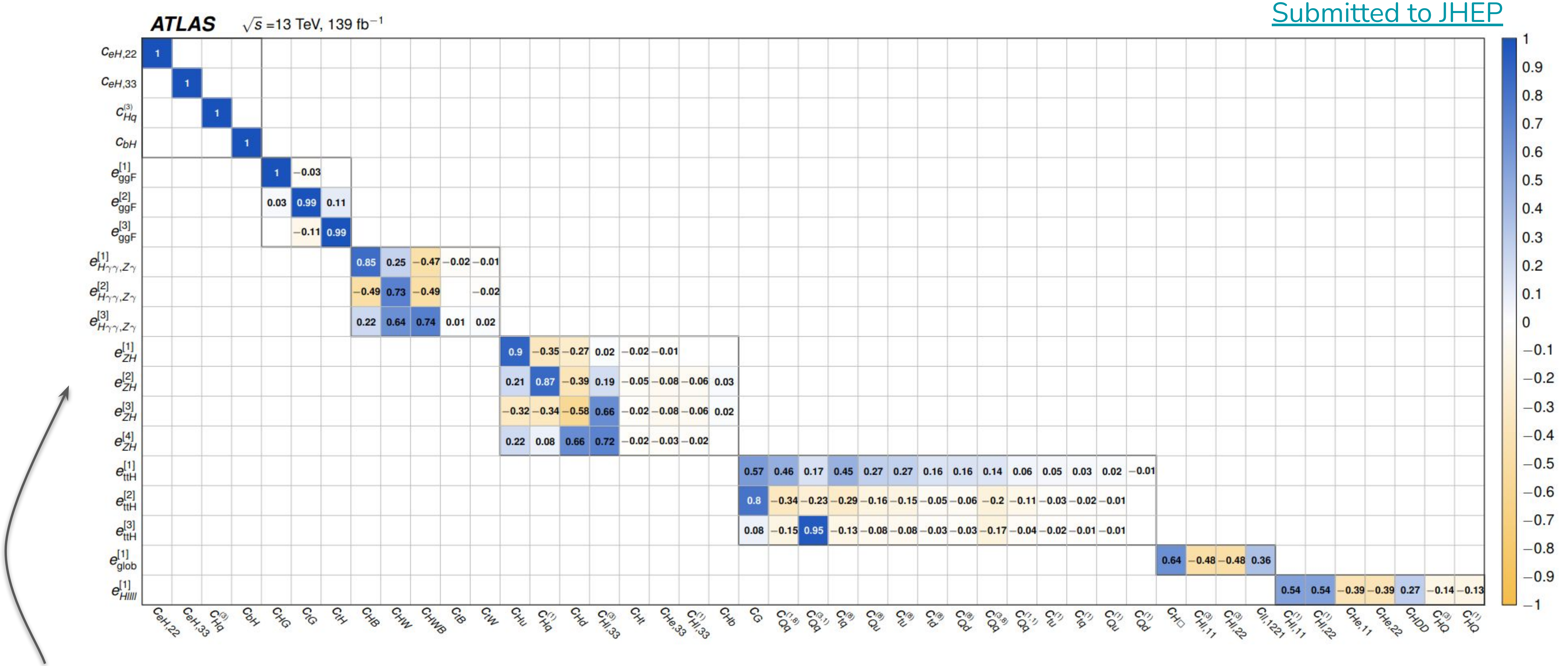
Uncertainty in direction EV is ~1/sqrt(λ)

Introduce cut-off, below which EVs are fixed to zero in fit (no loss in generality)

PCA rotation

- ATLAS prefer block diagonal approach to “maintain level of interpretability”

[Submitted to JHEP]



- How truly interpretable are these parameters? How can we compare results (e.g. CMS vs ATLAS) using different rotated bases?
  - Put more emphasis on UV matching: compare constraints on true physical parameters using benchmark models?
  - Define common (fixed) basis to be used across experiments: suboptimal choice with different inputs?

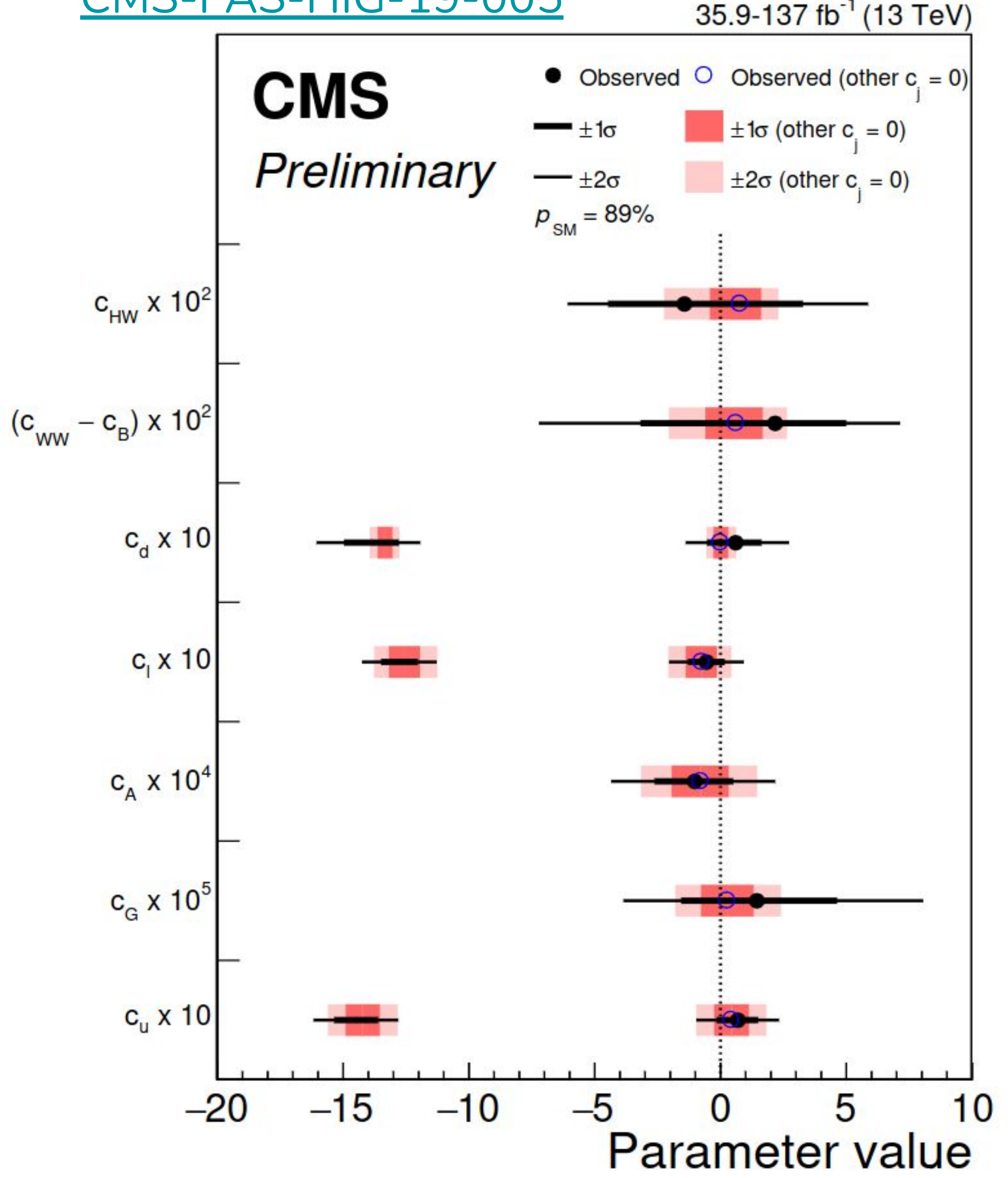
Extraction of results

$$\mathcal{L}(\text{data}\,|\,\vec{c},\vec{\theta}) = \prod_i \text{Poisson}\Big(n_i\,\Big|\,\sum_j \mu^j(\vec{c})s_i^j(\vec{\theta}) + b_i(\vec{\theta})\Big)\, p(\tilde{\vec{\theta}}\,|\,\vec{\theta})$$

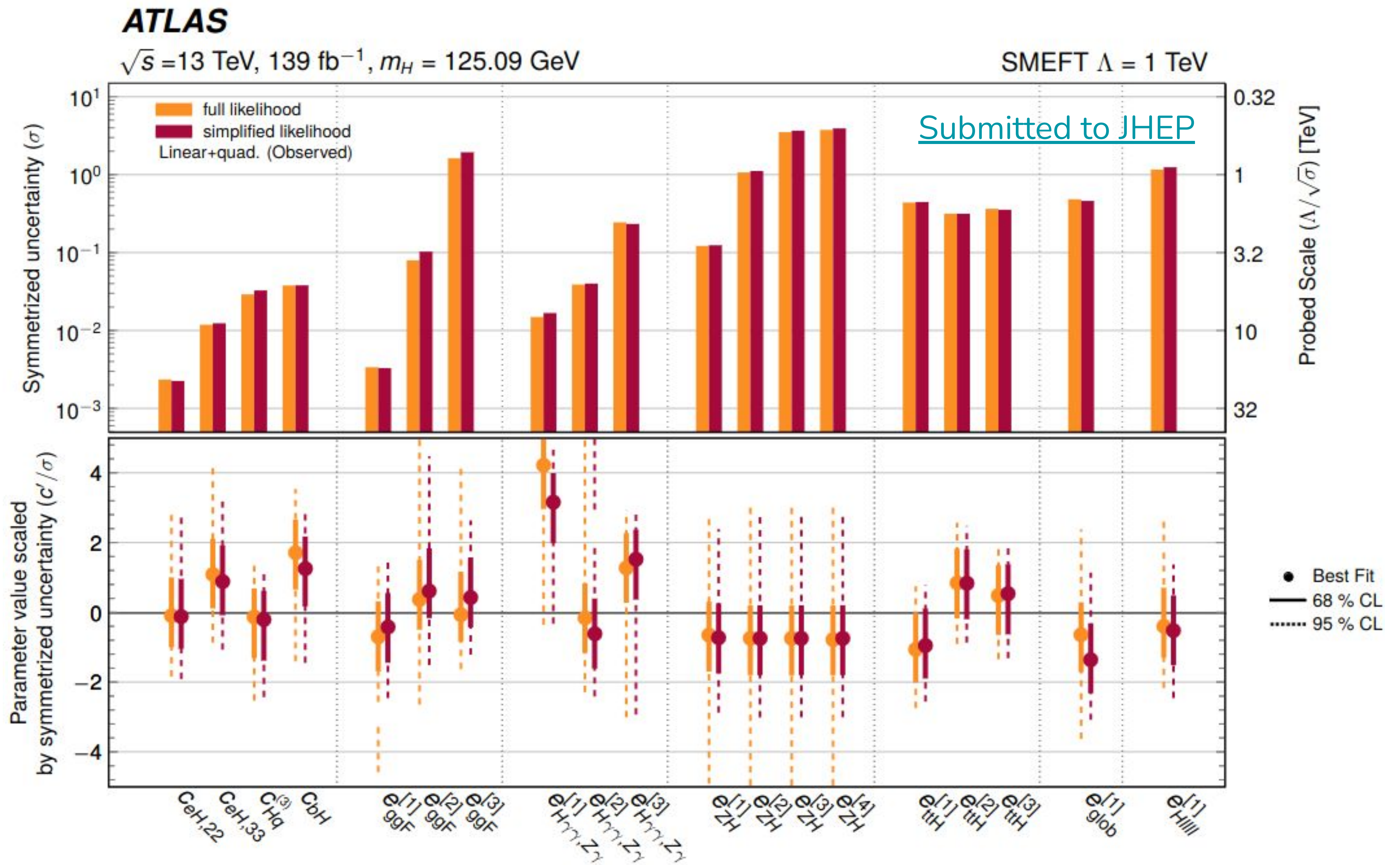
2

- STXS-SMEFT Higgs combination fits with full likelihood are a technical challenge

CMS-PAS-HIG-19-005



Old CMS result, no PCA



Compared to "theorist" approach

$$\mathcal{L}(\text{data}\,|\,\vec{c}) = \frac{\exp\left(-\frac{1}{2}\Delta\vec{\mu}(\vec{c})^{\mathrm{T}}V^{-1}\Delta\vec{\mu}(\vec{c})\right)}{\sqrt{(2\pi)^m \det(V)}}$$

1

Pitfalls of STXS

- So STXS is a great framework for SMEFT?

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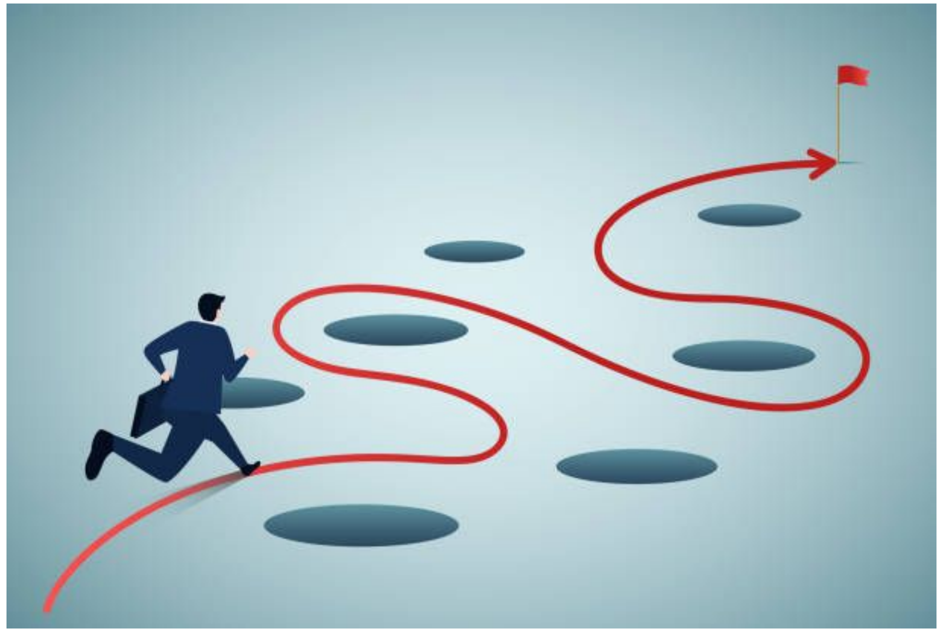
- There are a number of caveats…

1. Acceptance effects (no fiducial selection on Higgs decay products)
2. Suboptimal STXS binning
3. Selection effects (within-bin SMEFT variations)
4. Shape effects



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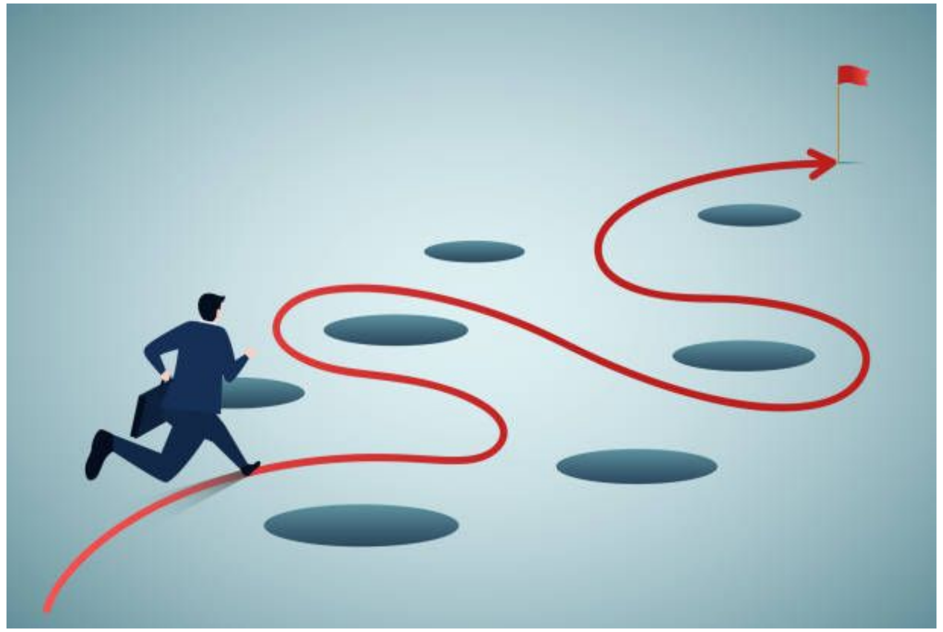

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- All artifacts of fact: **EFT affects kinematics as well as rates**
- Cannot encapsulate all effects in simple rate scaling functions

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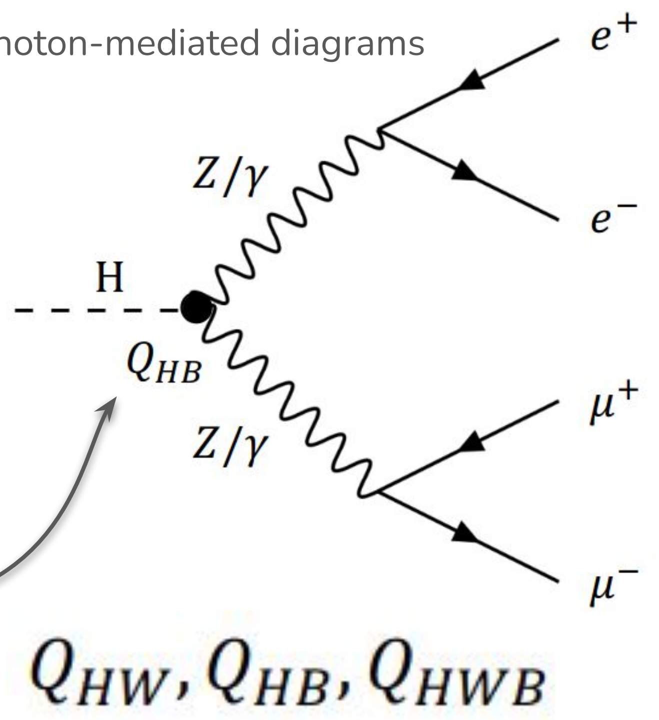
Acceptance corrections

- EFT dependence in experimental phase space $\neq$ EFT dependence in inclusive phase space
    - EFT effects can depend on analysis acceptance/selection
    - Exacerbated by fact that STXS has **no fiducial selection on Higgs boson decay products**

Acceptance corrections

Pesky photon-mediated diagrams



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  - EFT effects can depend on analysis acceptance/selection
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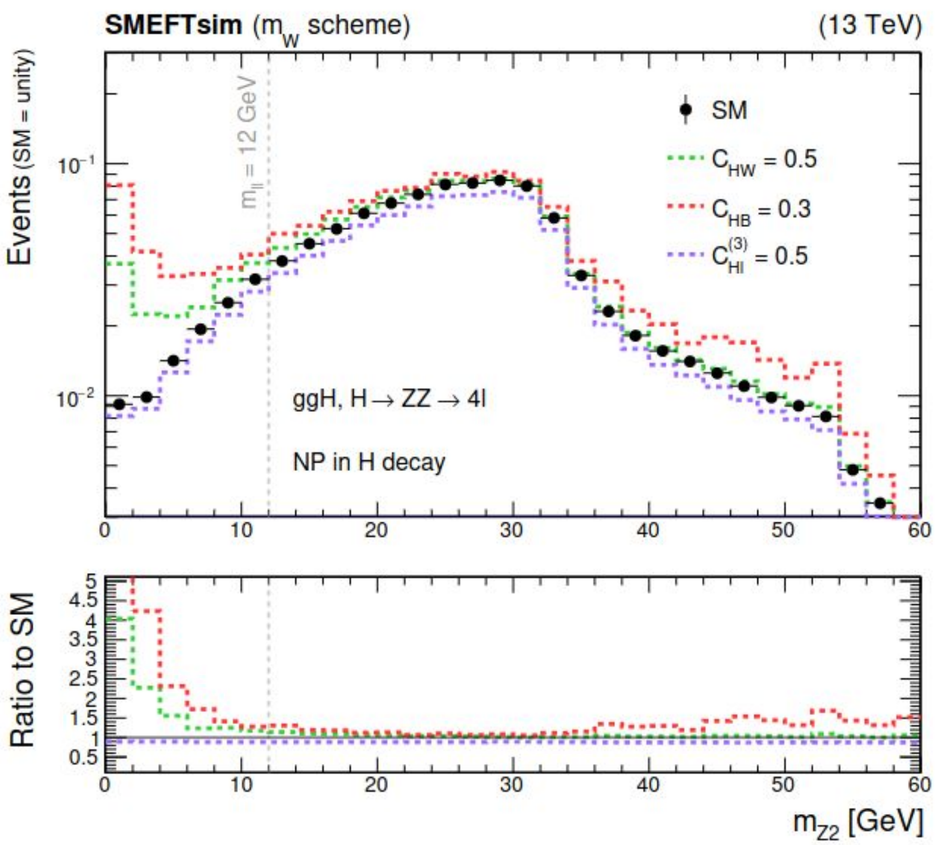
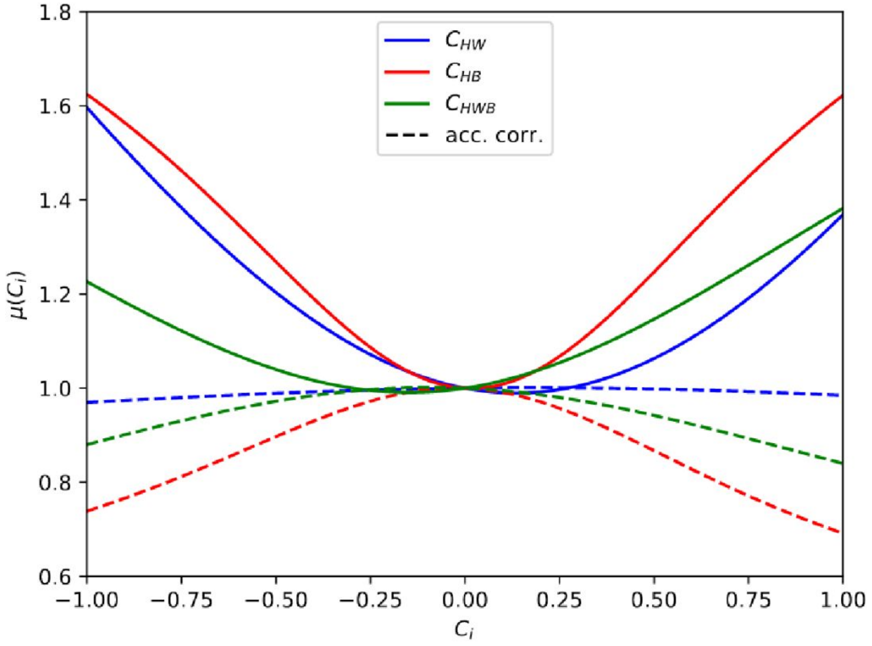
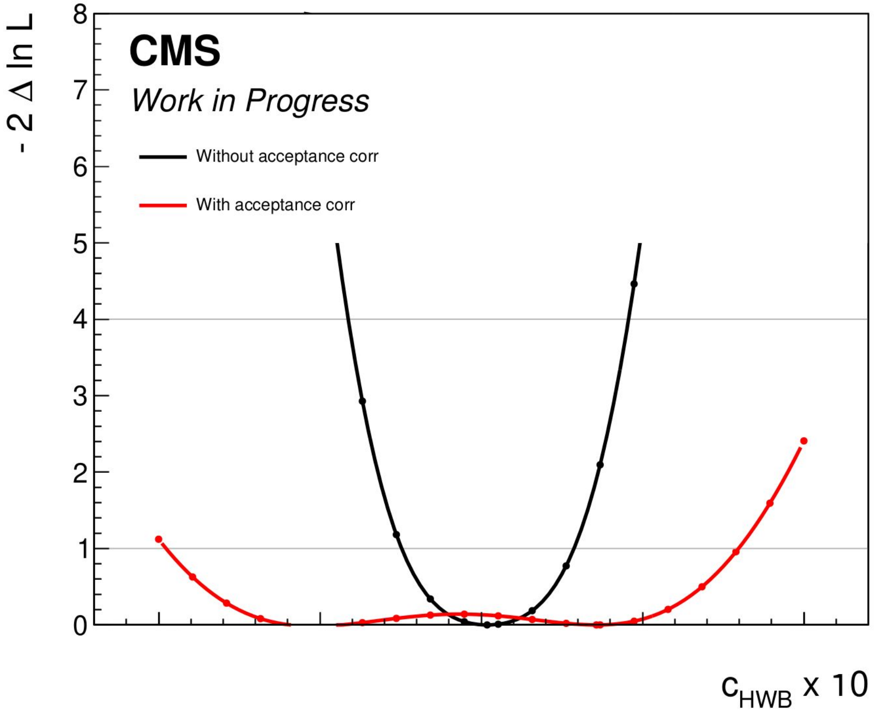
- Problem for Higgs four-body decays e.g. H → ZZ* → 4l
  - Analysis places cut on invariant mass of subleading lepton pair: m_{Z2} > 12 GeV
  - Removes phase space with largest EFT effects → washes out the dependence in this channel





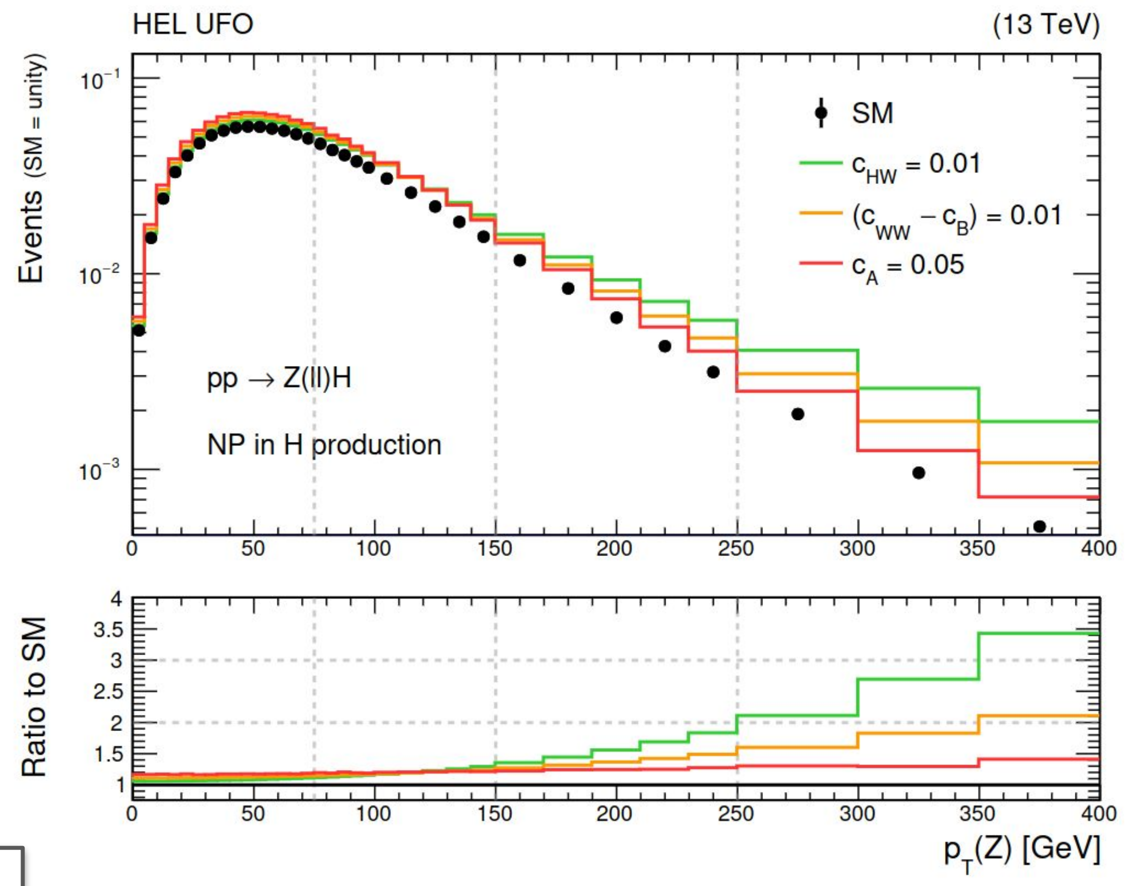


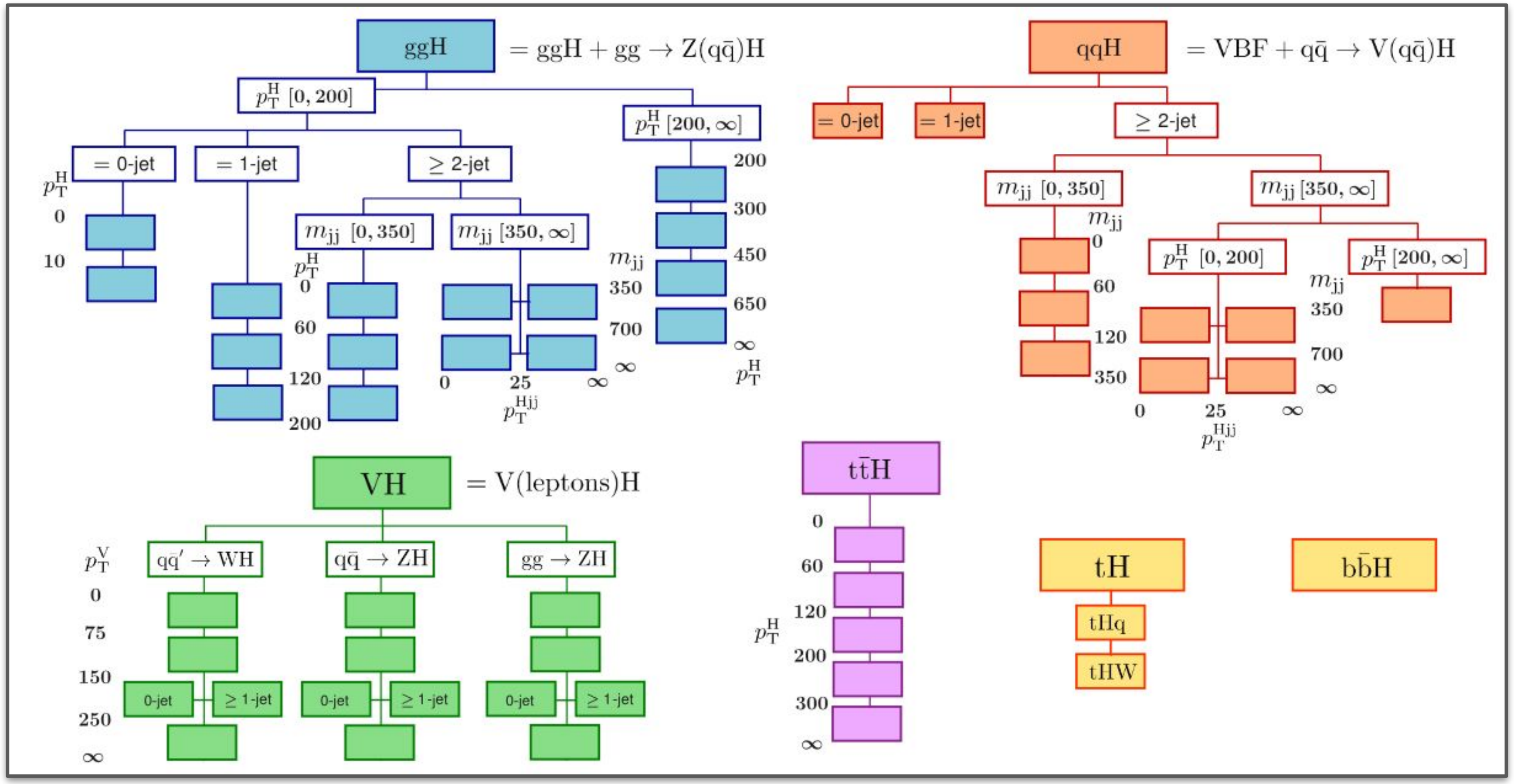
We add corrections to model EFT dependence in experimental phase space

Useful to introduce some fiducial-like selection in STXS definition?

Suboptimal binning

- Analyses are designed/optimised to measure STXS cross sections and **<u>not SMEFT parameters</u>**
- Binning design reflects our “SM sensitivity”
- Gain SMEFT sensitivity by additional splittings (particularly at high pT) or redesign with different variables (STXS 1.3?)





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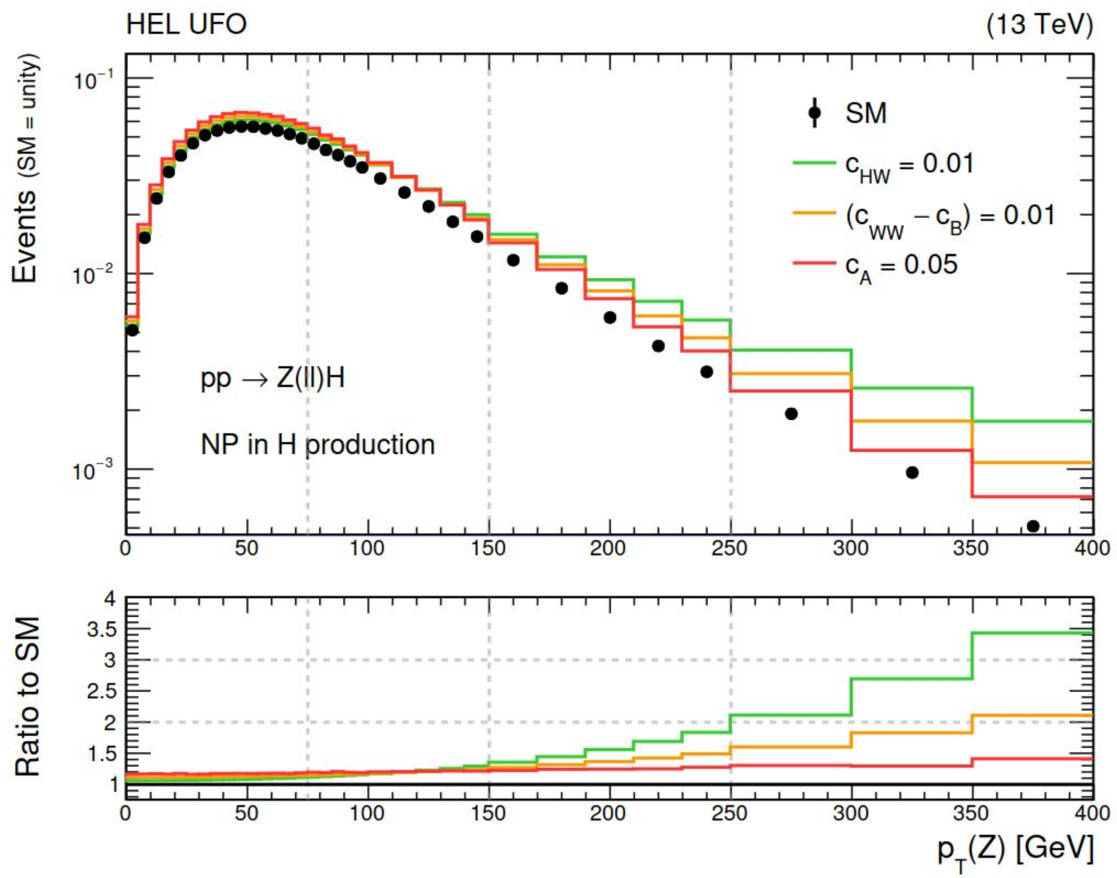
- Approach optimal sensitivity of “direct analysis” ?



3

Direct (MELA)

vs

interpretation (STXS)

2

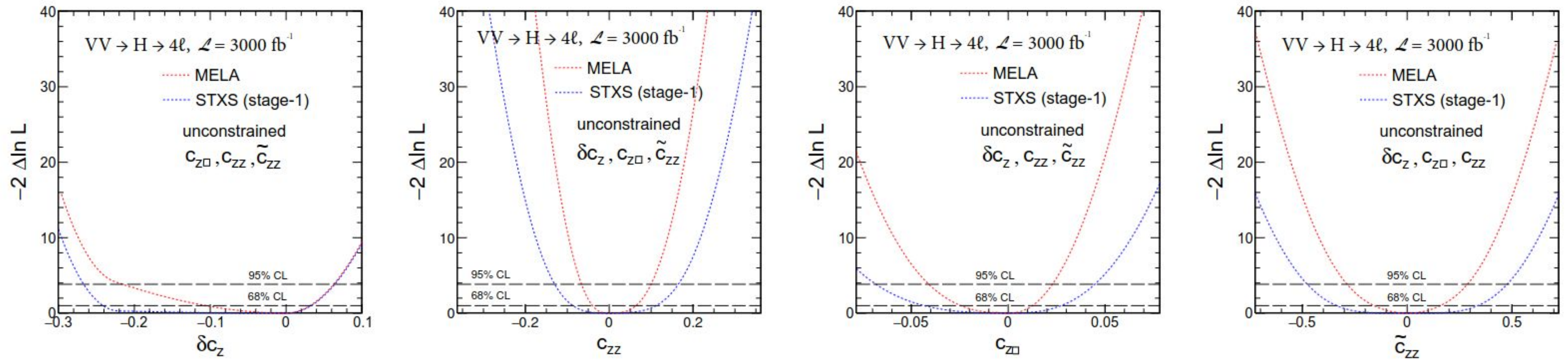
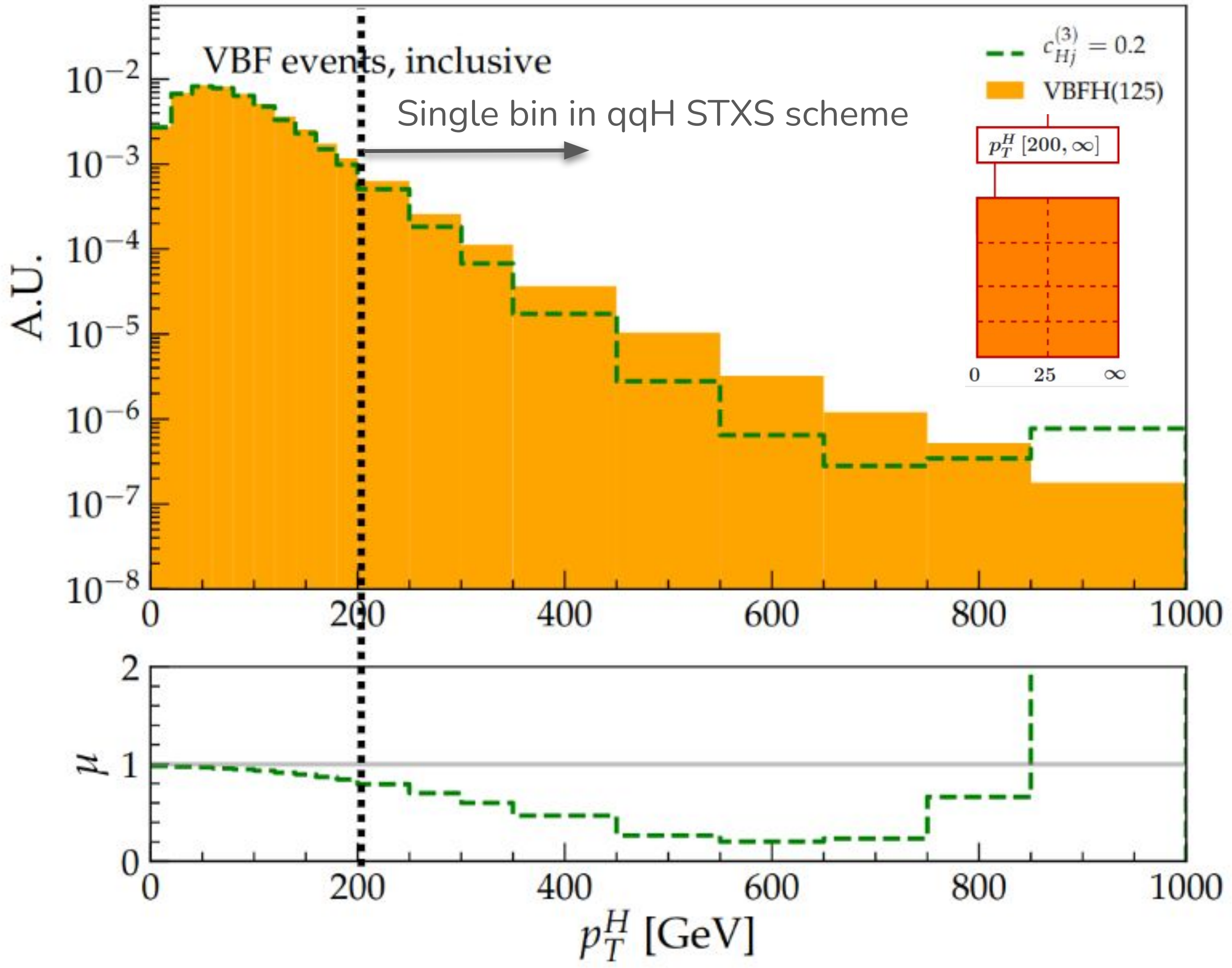


FIG. 11: Expected constraints from a simultaneous fit of (from left to right) δc_z, c_{zz}, $c_{z\Box}$, and $\tilde{c}_{zz}$ using associated production and $H \to 4\ell$ decay with 3000 fb^{-1} data. The EFT coupling constraints are the result of re-interpretation from the signal strength and f_{gi} measurements discussed in text. The constraints on each parameter are shown with the other parameters describing the HVV and Hgg couplings profiled. Two analysis scenarios are shown: using MELA observables and using STXS binning. The dashed horizontal lines show the 68 and 95% CL regions.

Selection effects

- EFT effects can vary considerably within same STXS bin
- Problematic if analysis selection efficiency varies across bin
- For the most part, STXS is sufficiently fine-grained to ensure these effects are small → Not always case for high pT bins!



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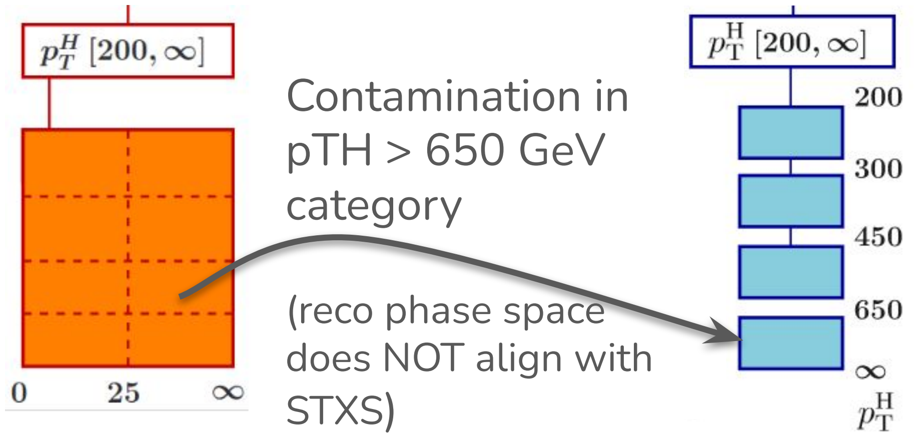

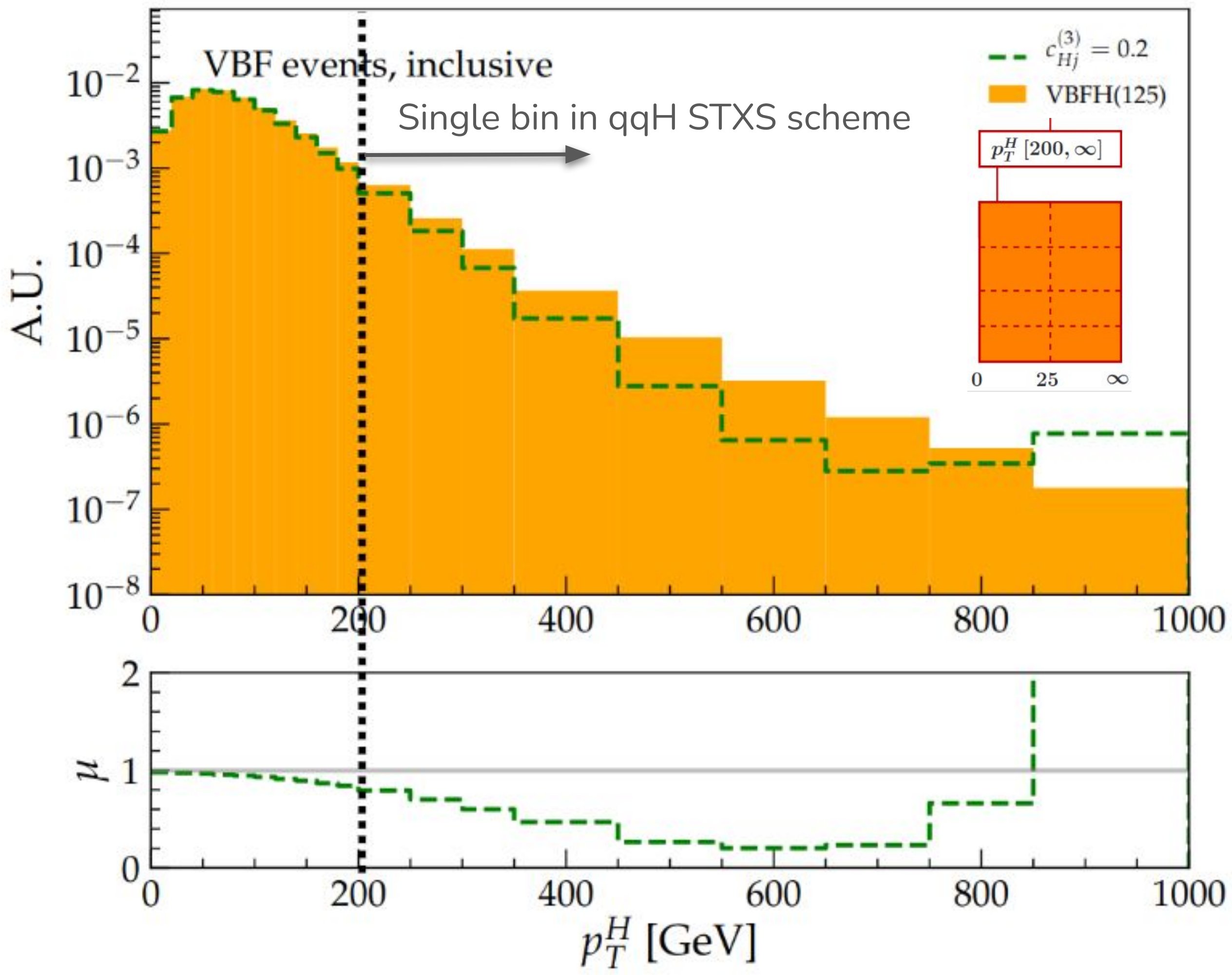

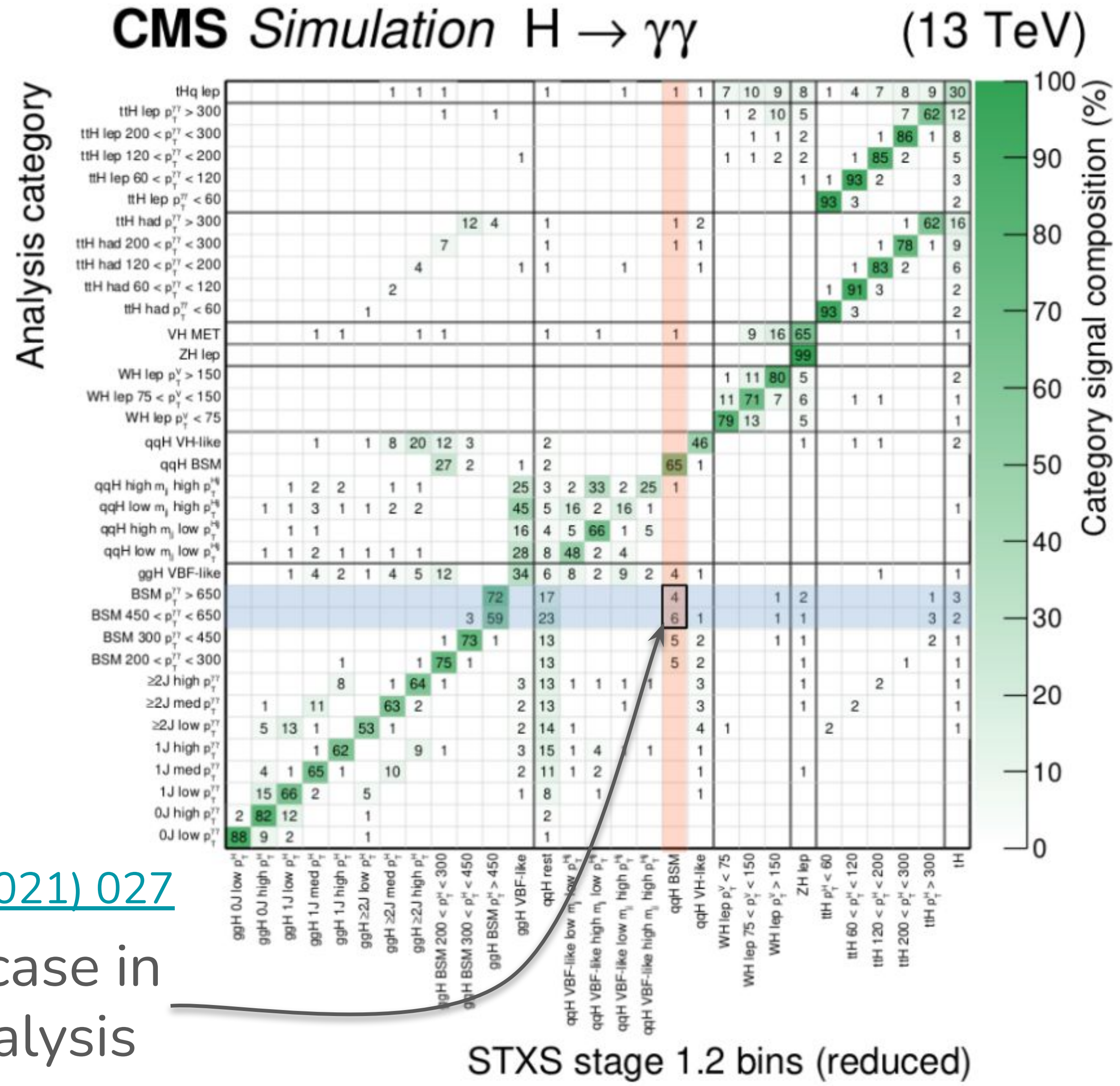

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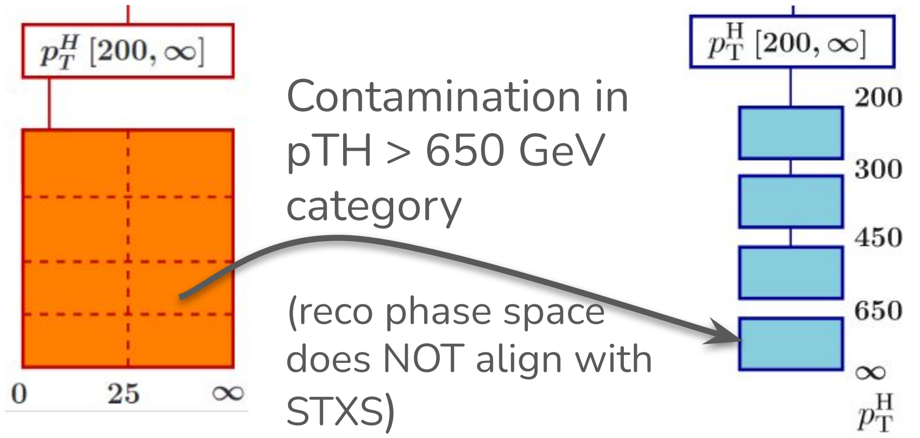
Extreme case in H→γγ analysis

Selection effects



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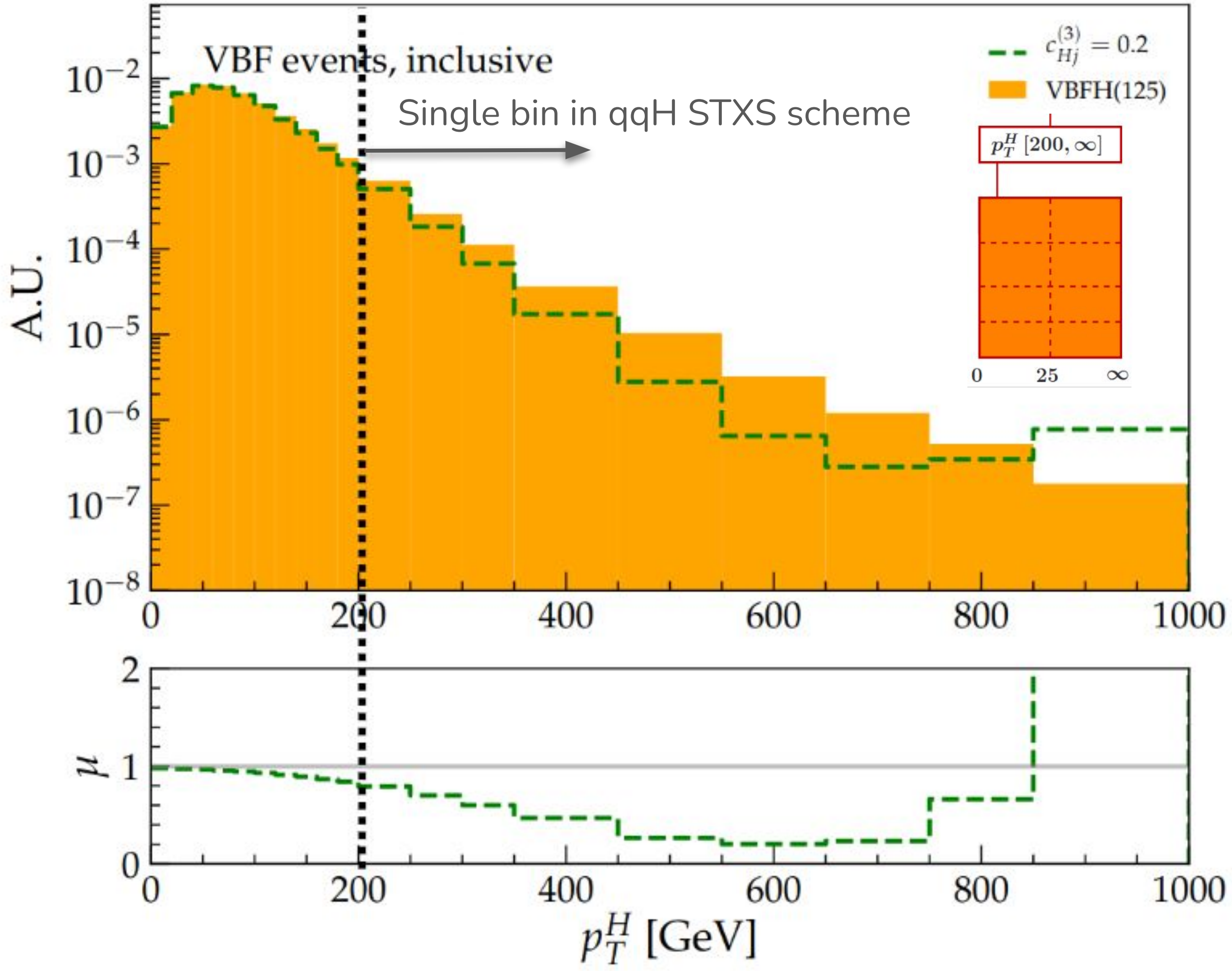

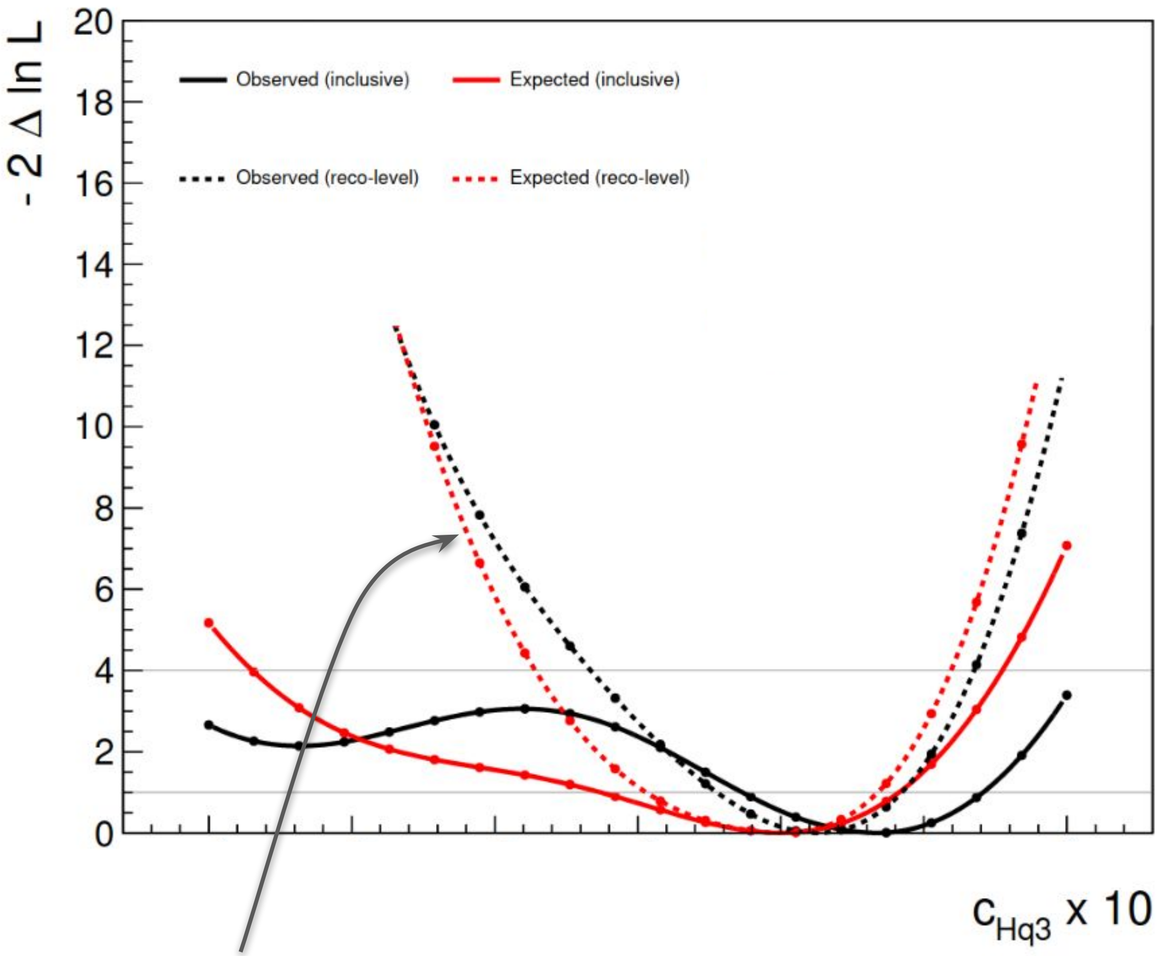

Apply full reco-level scaling functions i.e. separate scaling for each STXS bin in each (reco) analysis category → Requires propagating EFT effects through detector!

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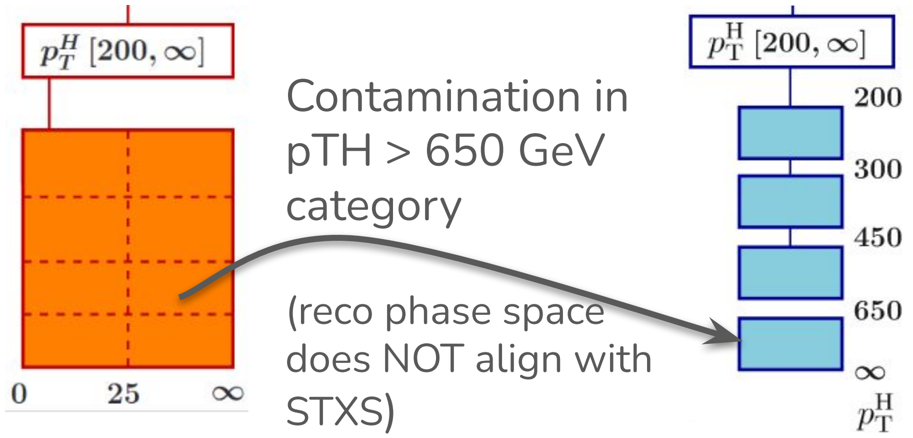

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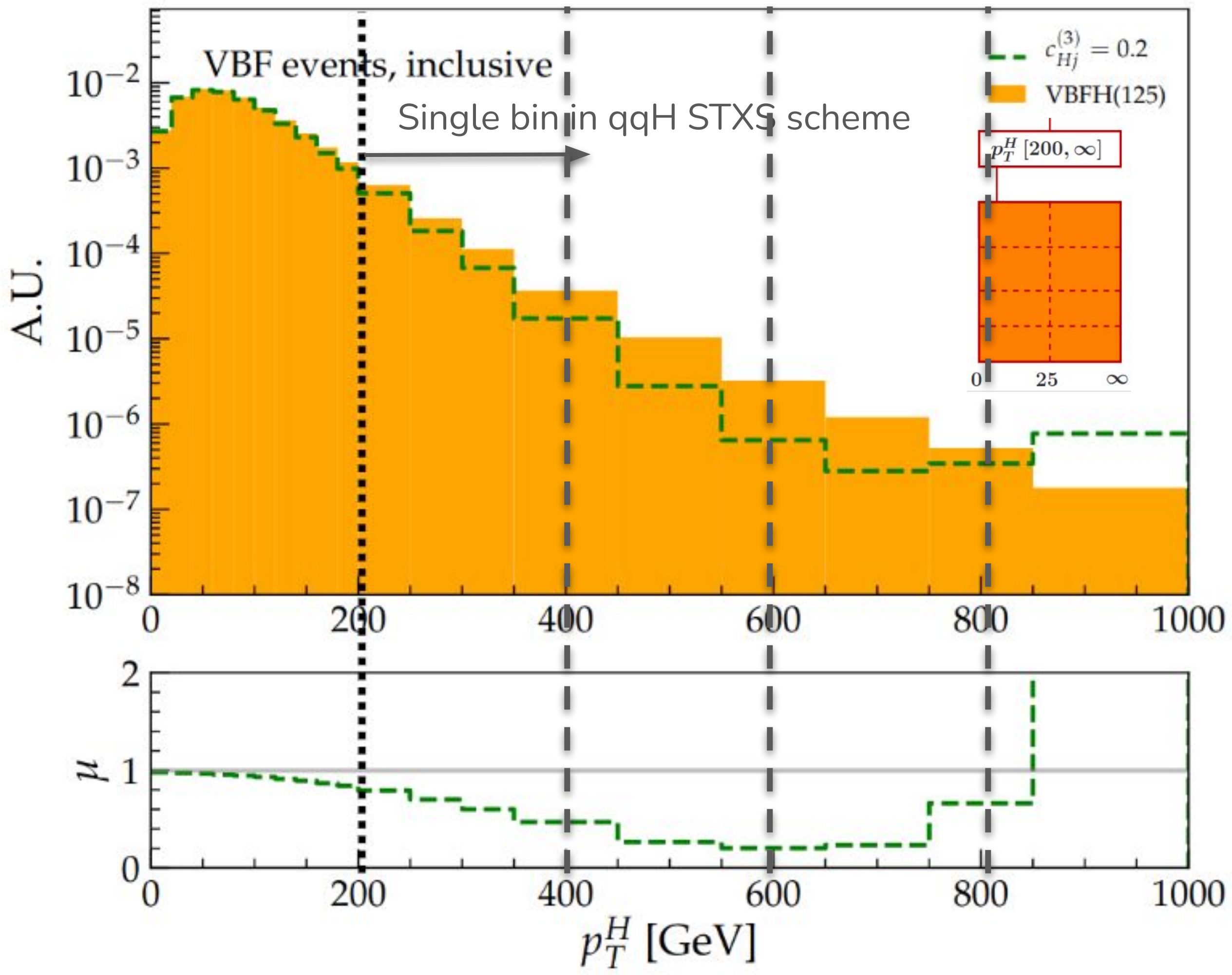

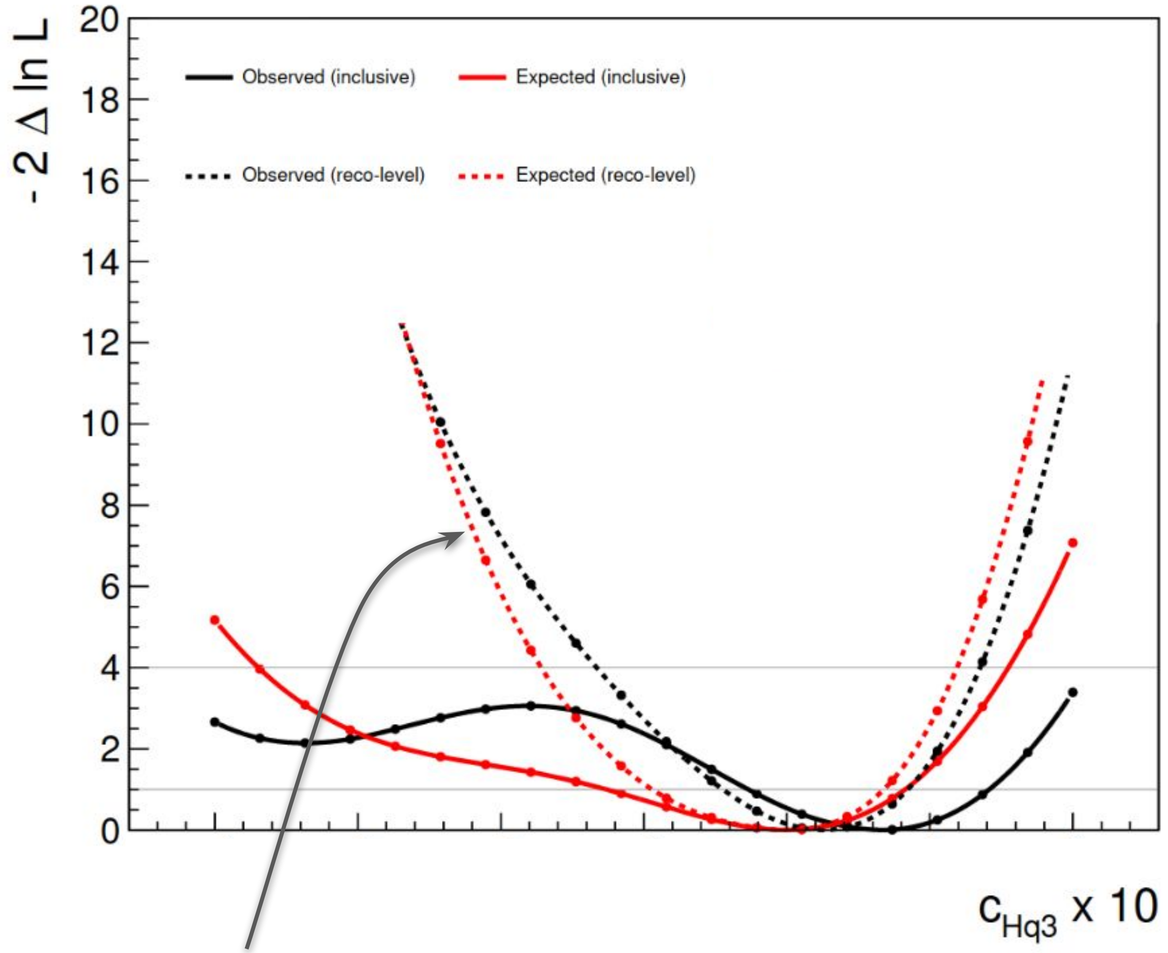

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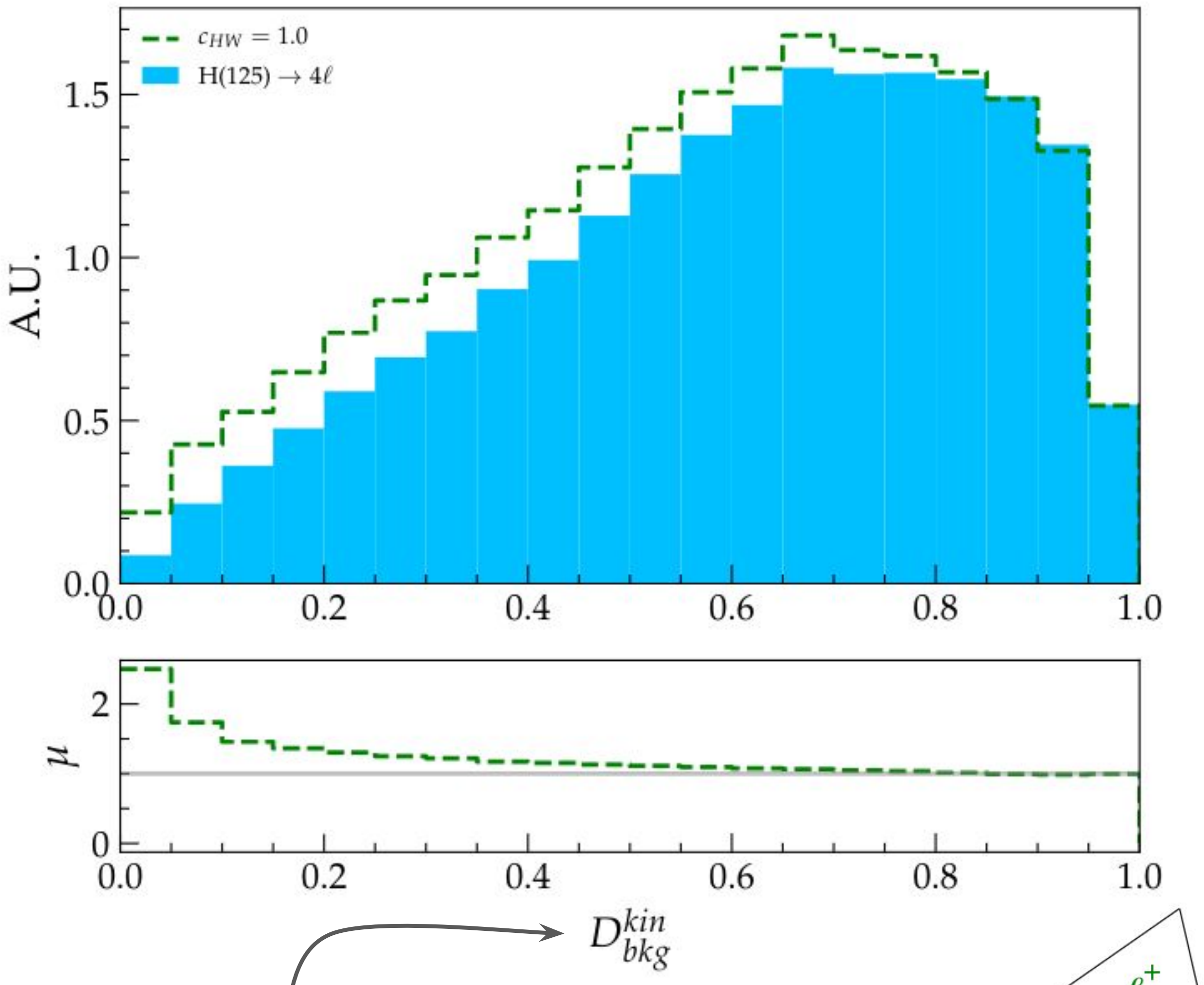
Or use a finer STXS binning?

Shape effects

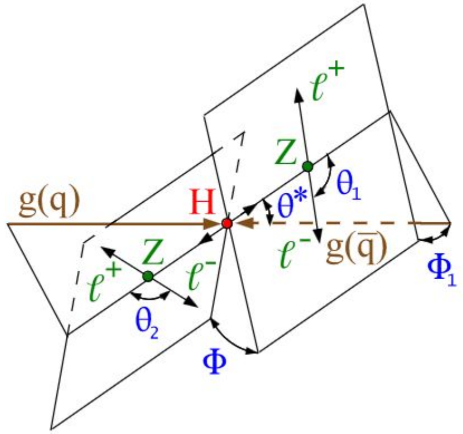
- EFT can also modify the shape of fitted observable e.g. for multivariate output

Background like ← → Signal like



Kinematic discriminant in H→ZZ*→4l

Exploits final-state lepton kinematics and angles



Shape effects

Compare inclusive vs per-bin scaling functions

$$\mathcal{L}_j = \prod_{k}^{\mathcal{D}\text{ bins}} \frac{(\mu S_k + B_k)^{n_k}}{n_k!} \cdot e^{-(\mu S_k + B_k)}$$

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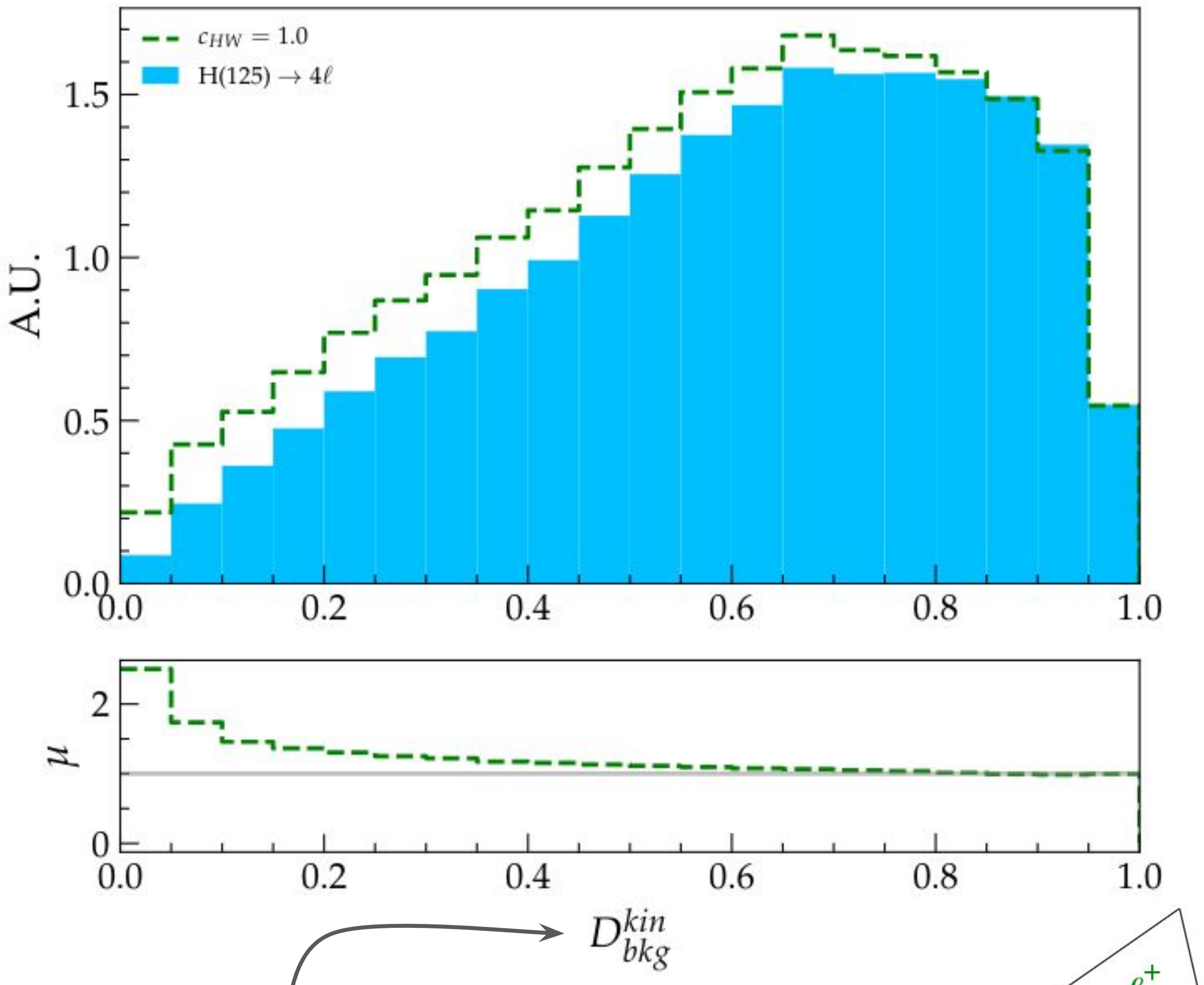
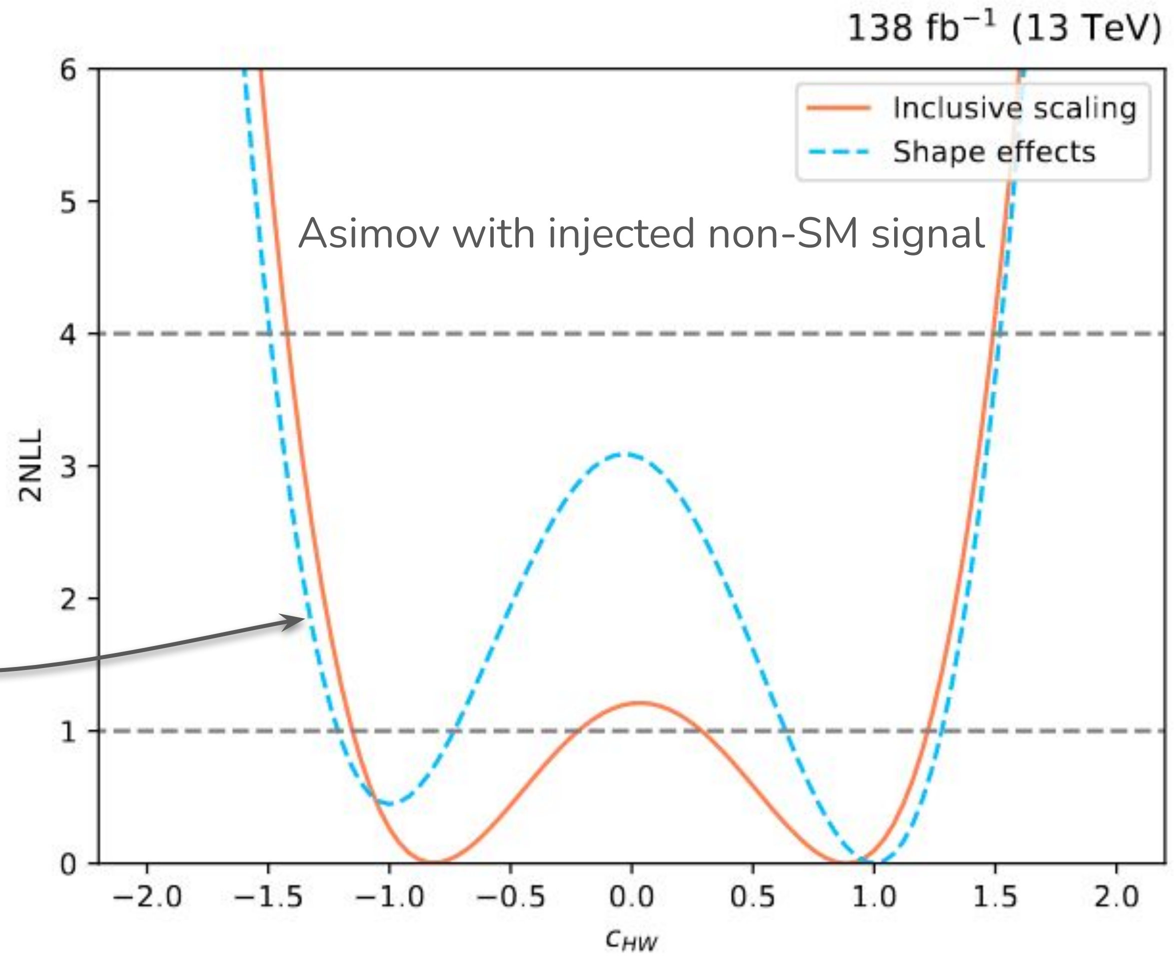


- EFT effects shape → concentrated towards background-like region
- Assessed impact with (simplified) binned-likelihood fit



Shape effects can become important in the presence of new physics!

Kinematic discriminant in H→ZZ*→4l

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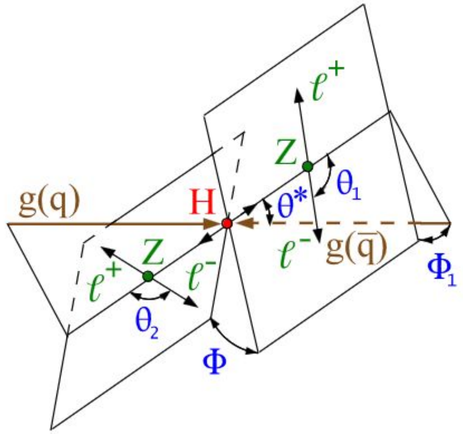

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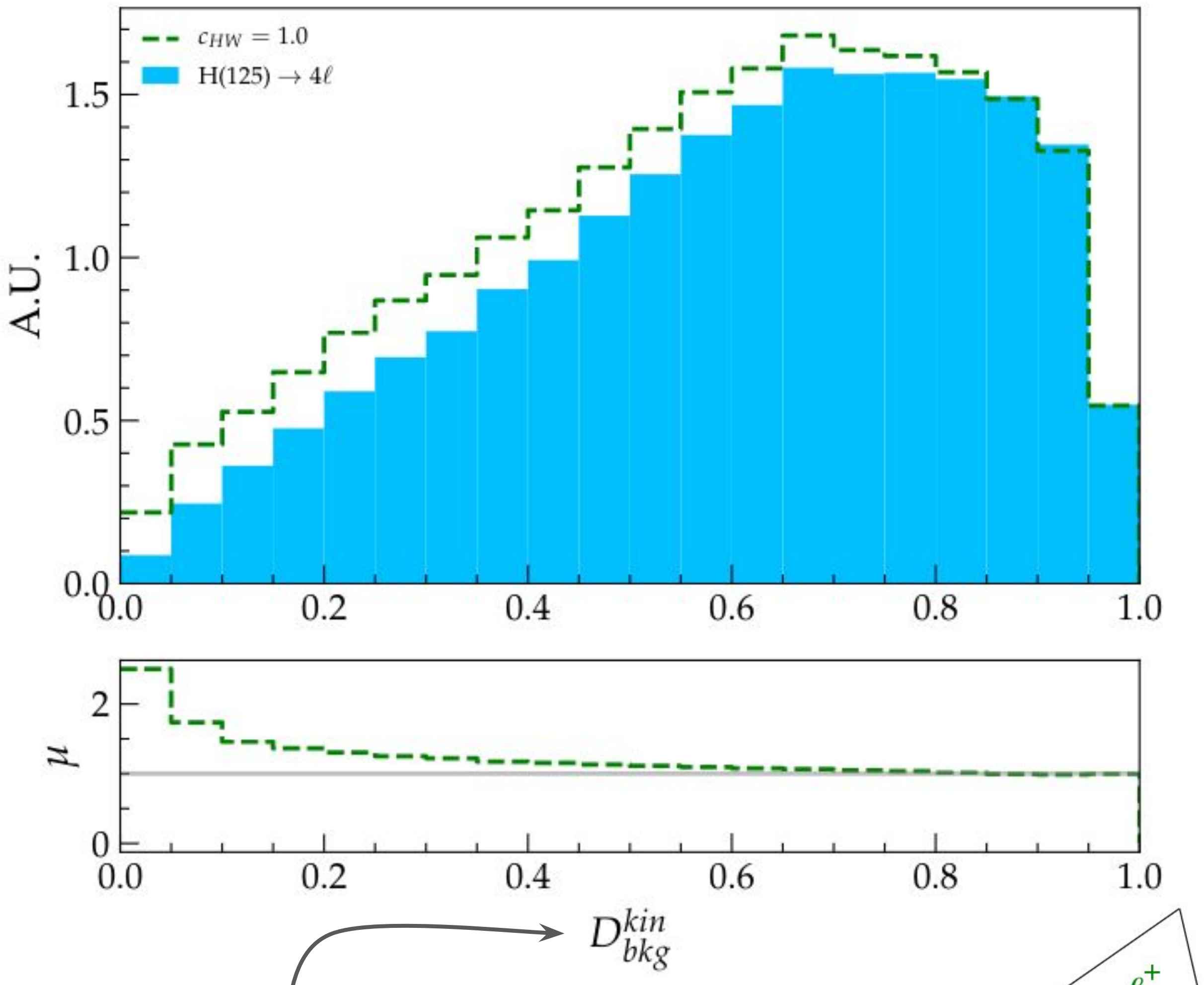

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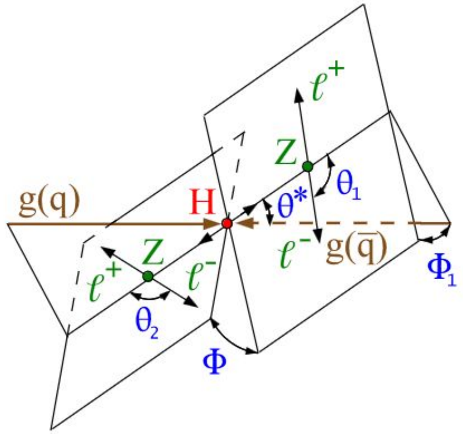

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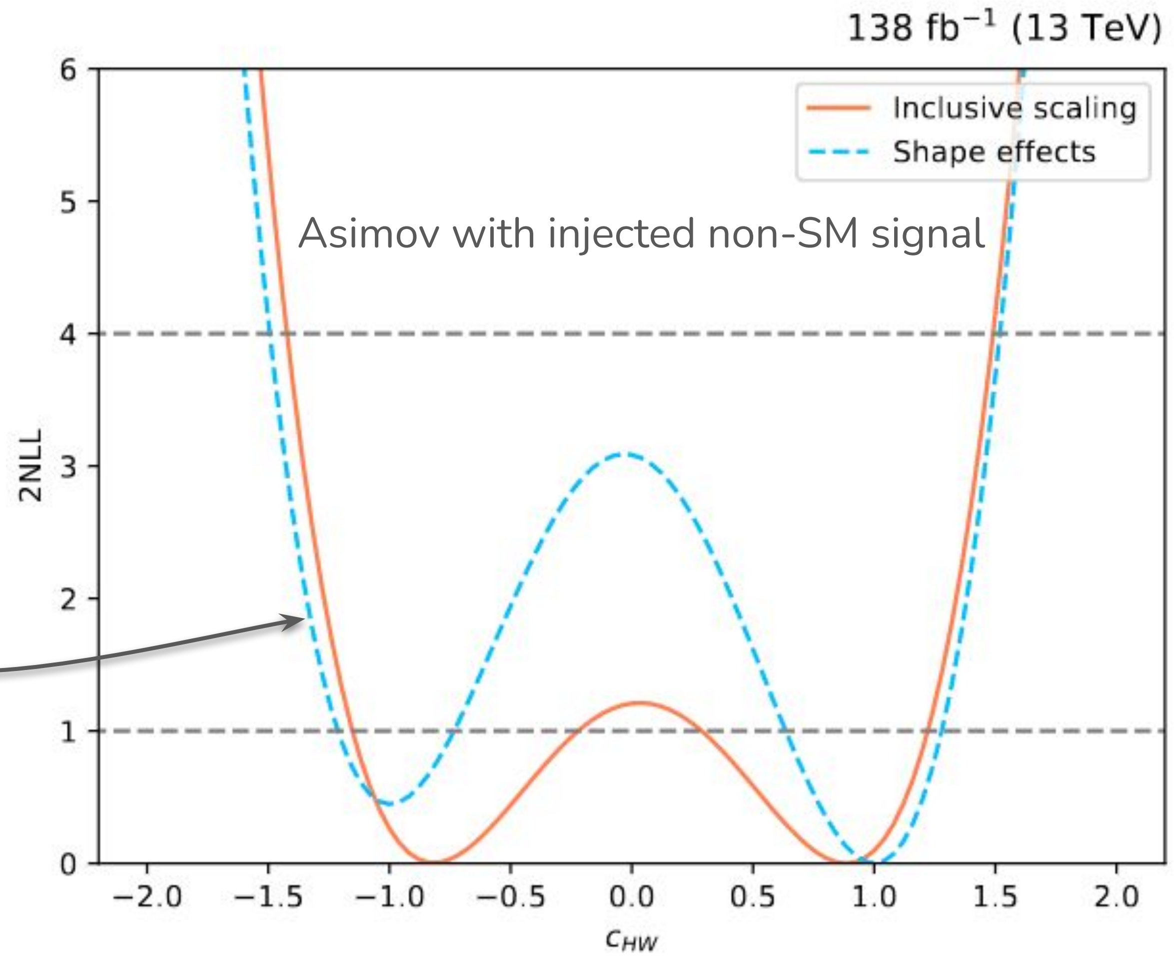

- Developing tools to include shape effects in fit
- Or reduce effect by introducing finer STXS binning

Future prospects

- What can we do to improve our STXS-SMEFT interpretations?

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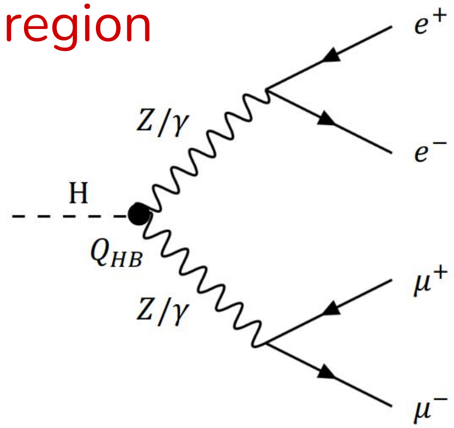
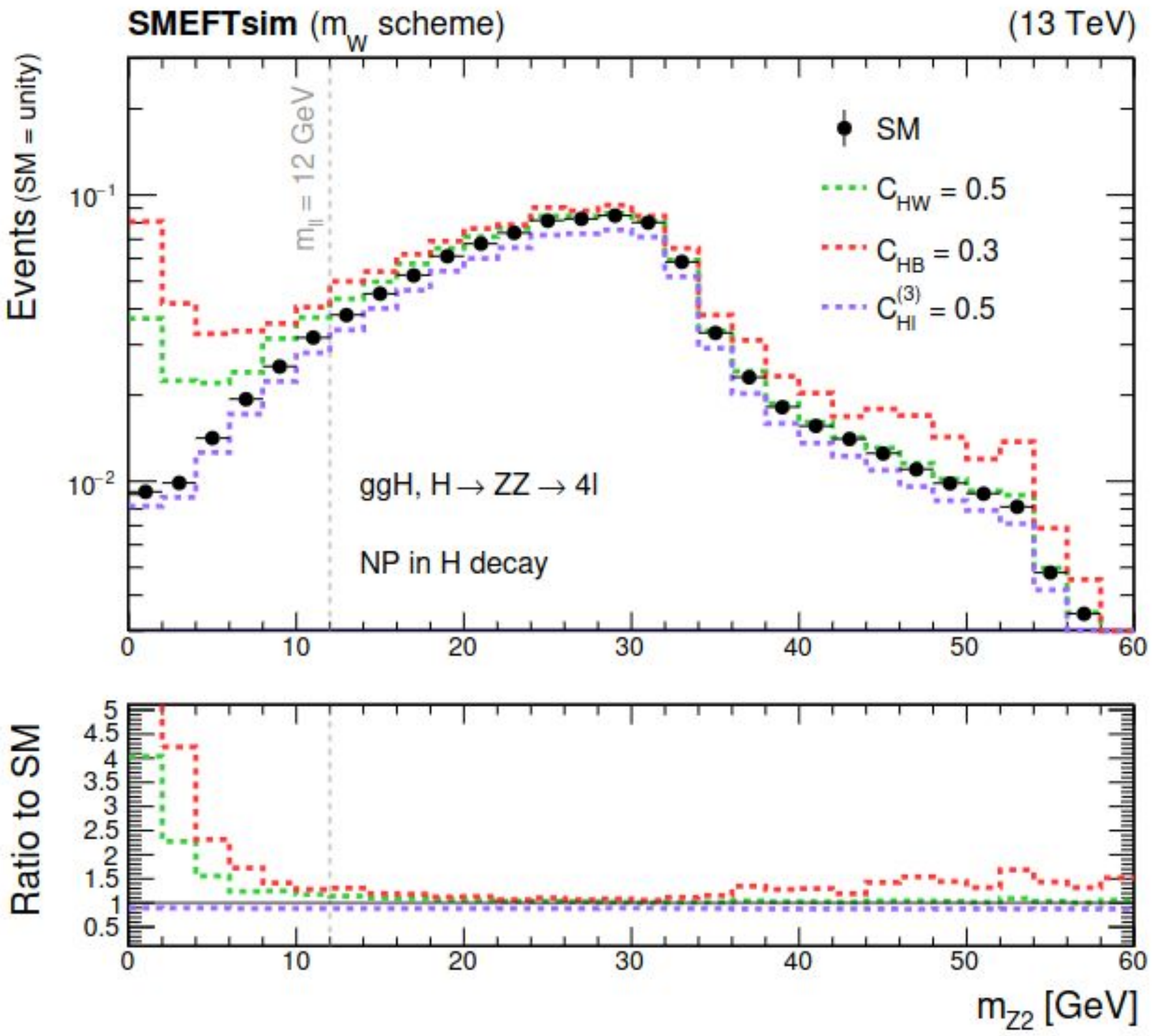
- What can we do to improve our STXS-SMEFT interpretations?

1. STXS @ decay: include fiducial selection on Higgs decay products
2. Updated binning scheme: STXS stage 1.3
3. Better tools/machinery
4. Ease comparisons/combinations
    - Common STXS-SMEFT parametrisation (see talk from Charlotte)
    - Align PCA rotation for common basis → can observe improvements over time
    - UV-matching benchmarks

STXS @ decay

- Acceptance corrections arise due to lack of fiducial selection on Higgs decay products
- Imposed fiducial region that approximates experimental acceptance → derive parametrisation within that region
- Discussions for binning @ decay in LHCHWG have been ongoing for some time





H → ZZ* → 4l

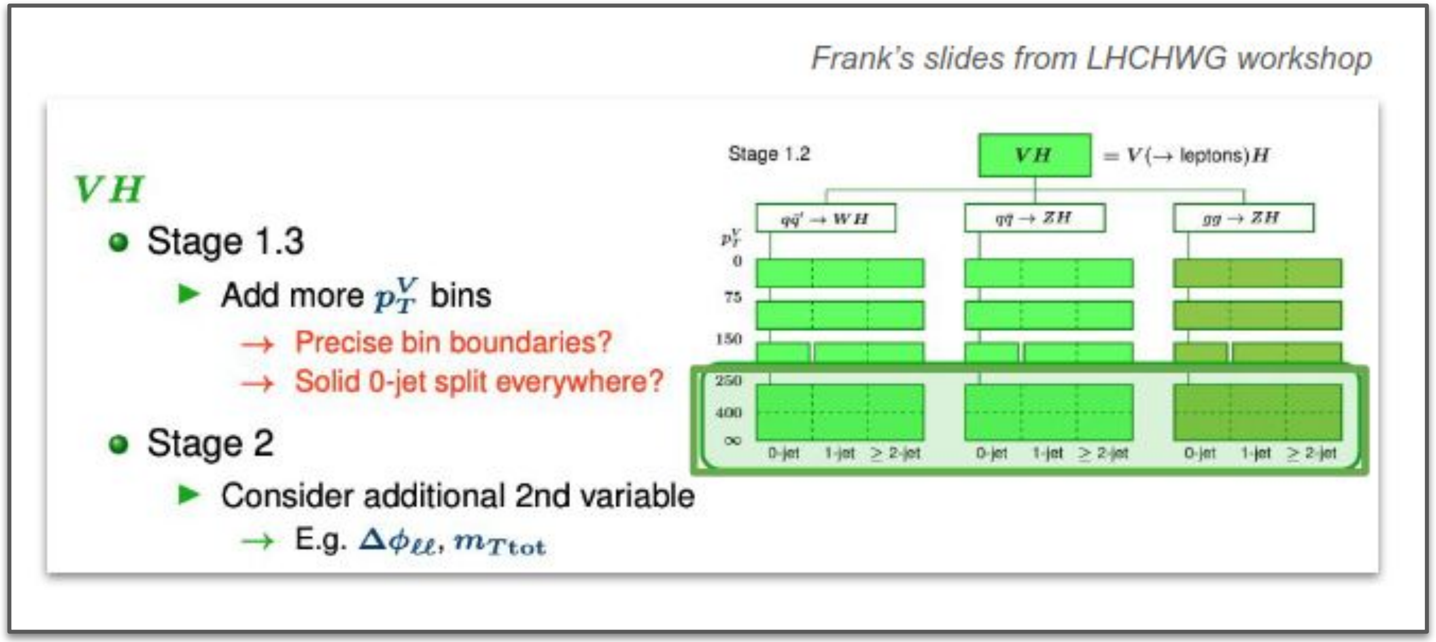
Selection	HIG-21-009	simplified*
Leading lepton	$p_T > 20$ GeV	$\boldsymbol{p > 4}$ **GeV**
Sub-leading lepton	$p_T > 10$ GeV	$\boldsymbol{p > 4}$ **GeV**
Additional electrons (muons)	$p_T > 7(5)$ GeV	$\boldsymbol{p > 4(4)}$ **GeV**
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5(2.4)$	no restrictions
Cone for dressing bare leptons with photons	$\Delta R = 0.3$	$\boldsymbol{\Delta R = 0.1}$
Inv. mass of the Z_1 candidate	$40 < m_{12} < 120$ GeV	$50 < m_{12} < 106$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{34} < 120$ GeV	$12 < m_{34} < 115$ GeV
Distance between selected four leptons	$\Delta R_{ll} > 0.02$	$\boldsymbol{\Delta R_{ll} > 0.1}$
Inv. mass of any opposite sign lepton pair	$m_{ll} > 4$ GeV	$m_{ll} > 5$ GeV
Inv. mass of the selected four leptons	$105 < m_{4l} < 160$ GeV	not (yet) implemented

* Almost identical to ATLAS fiducial selection, exception: angle in ΔR place

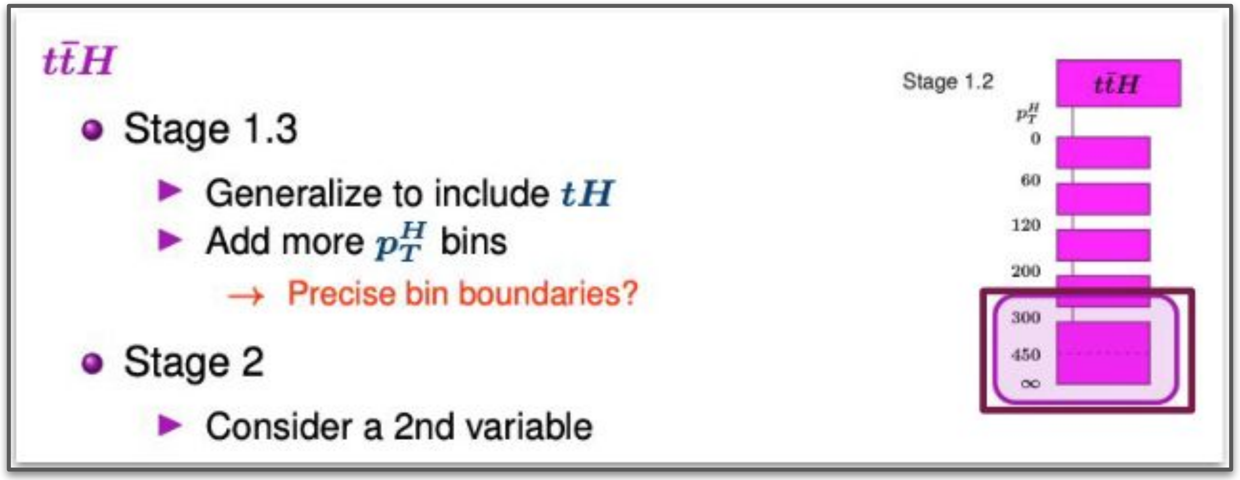
Suggested fiducial selection for STXS in decay

Evolution of STXS

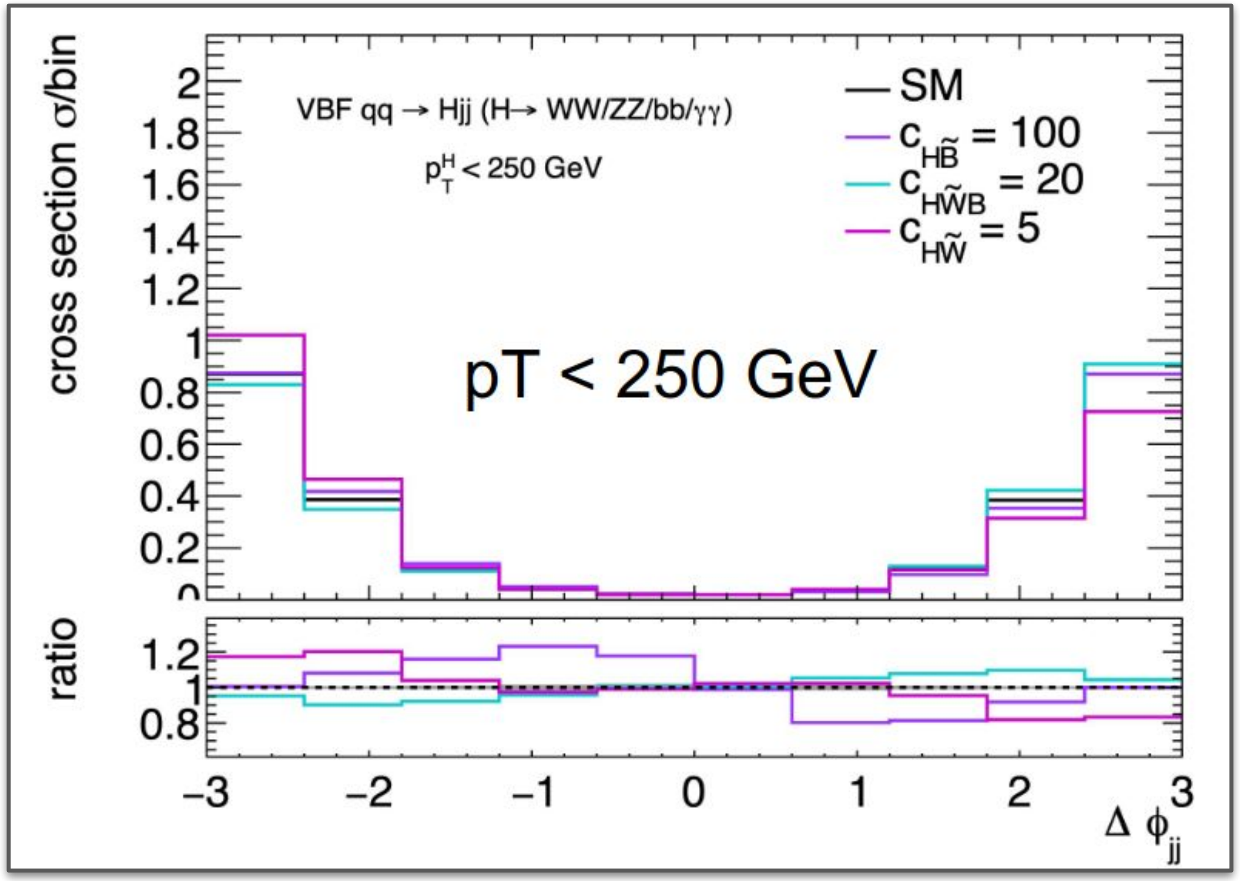
- Finer splittings could help alleviate some of the aforementioned pitfalls
- Also additional splittings will enhance SMEFT sensitivity → STXS 1.3 being finalized. Some highlights...



VH: Make additional solid splits at 400 and 600 GeV

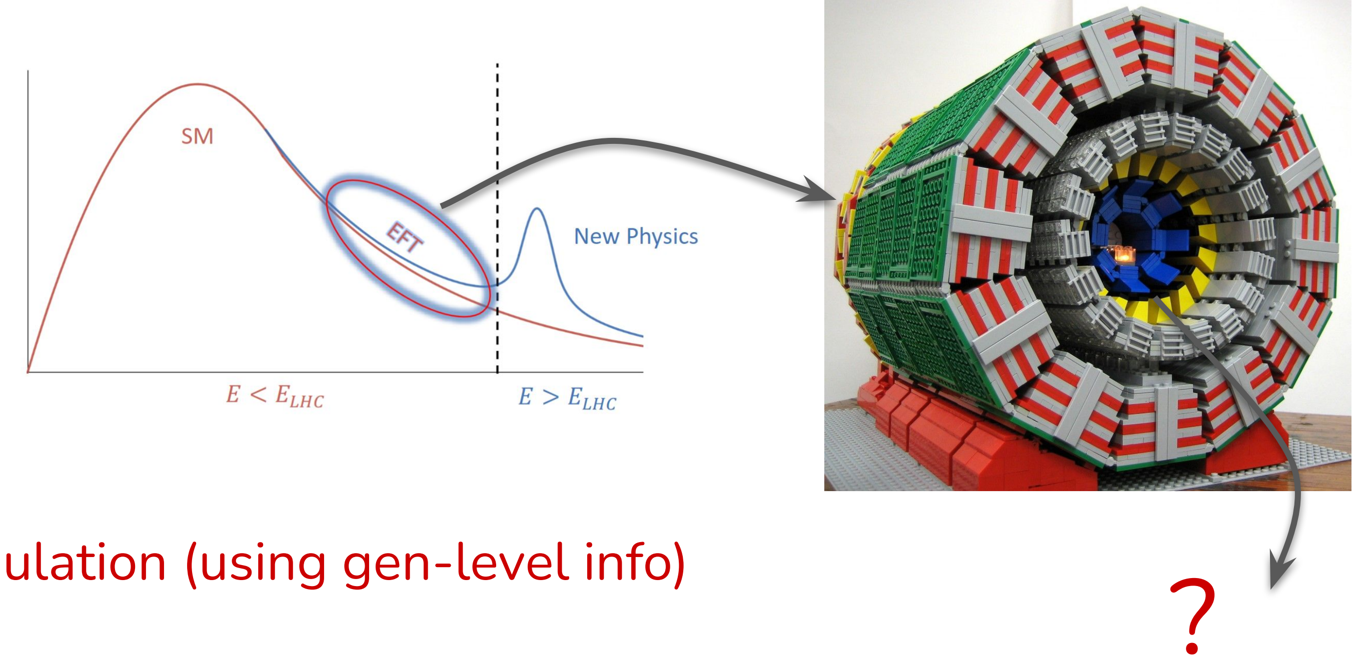


ttH: Add high pTH bins at 650 GeV



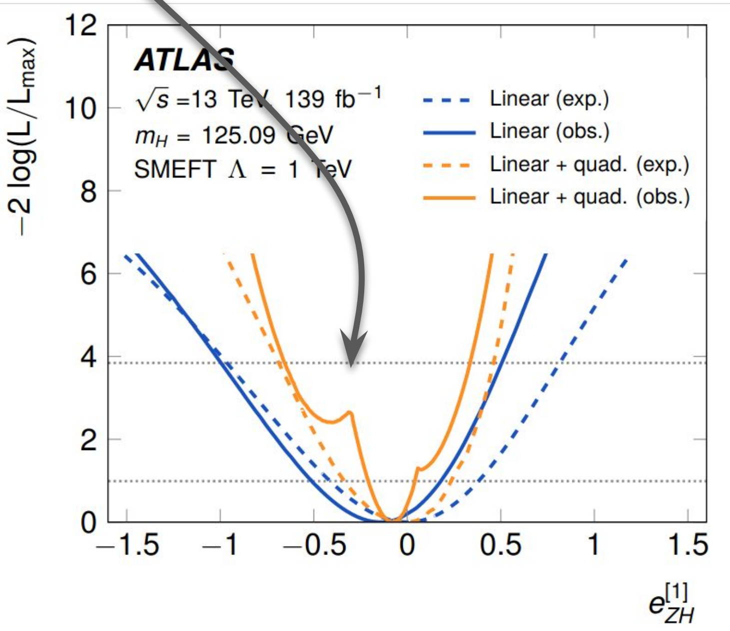
qqH: add dPhijj bins to gain CP sensitivity

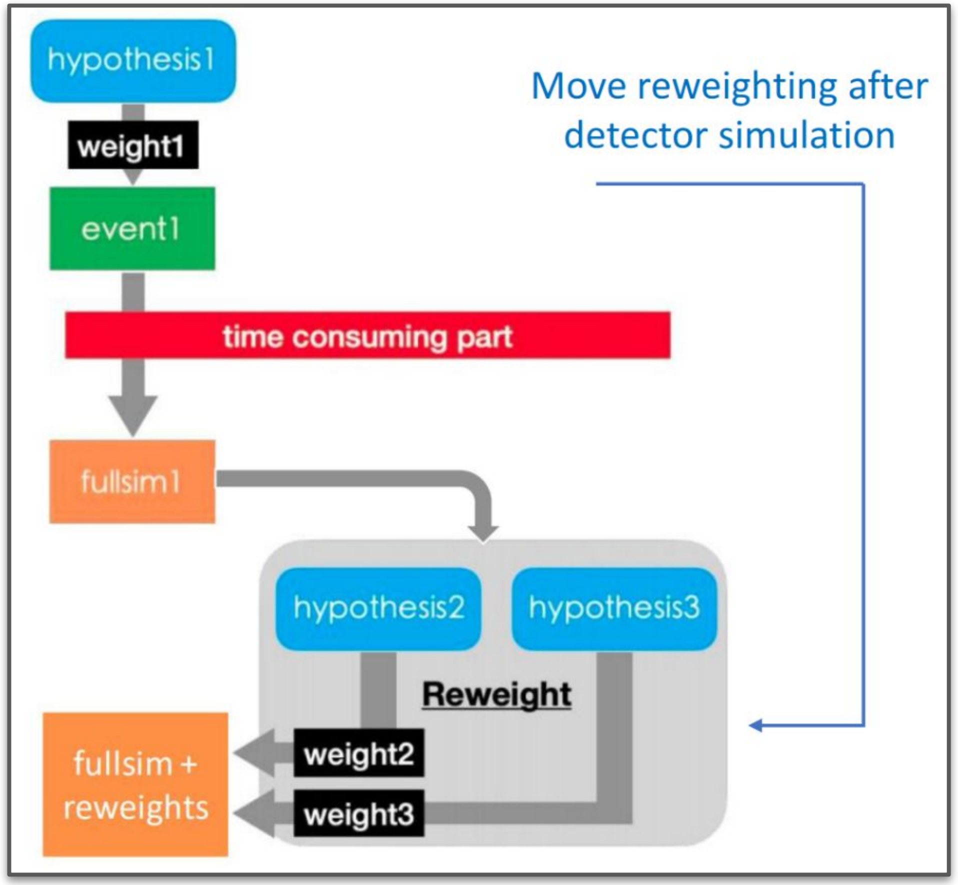
Improved tools



- Some caveats require knowledge of EFT effects “after detector”
  - Selection effects, shape variations in fitted observable, …
  - Developed tools for “post-mortem” reweighting after detector simulation (using gen-level info)

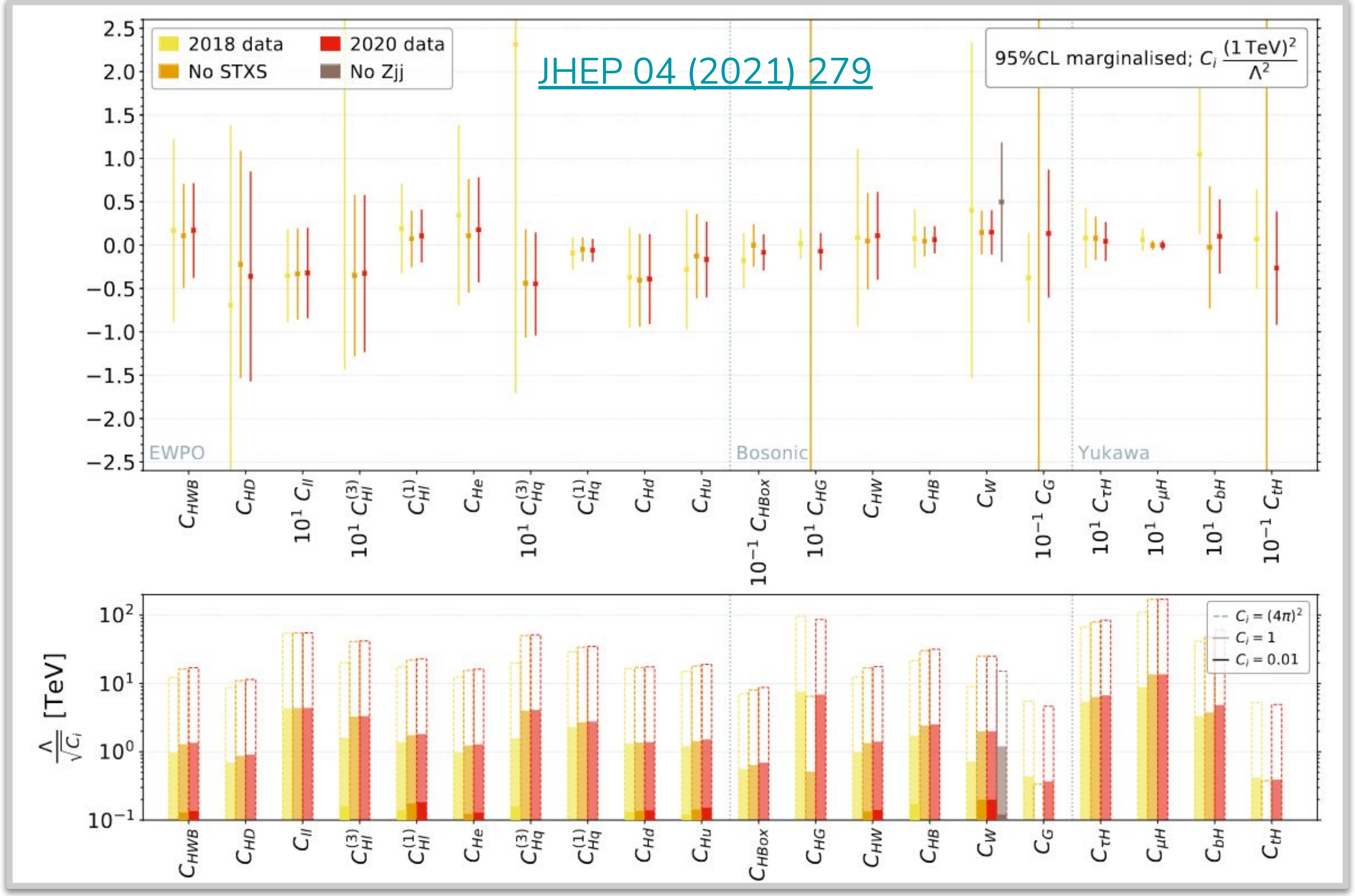
- Ultimately, STXS-SMEFT fits are a huge technical challenge
  - Especially quadratic parametrisation → Complicated likelihood surface
  - Performed with [CMS Combine tool]
  - Would benefit from recent RooFit advancements
    - Vectorised evaluations with GPUs
    - Auto-grad
    - …

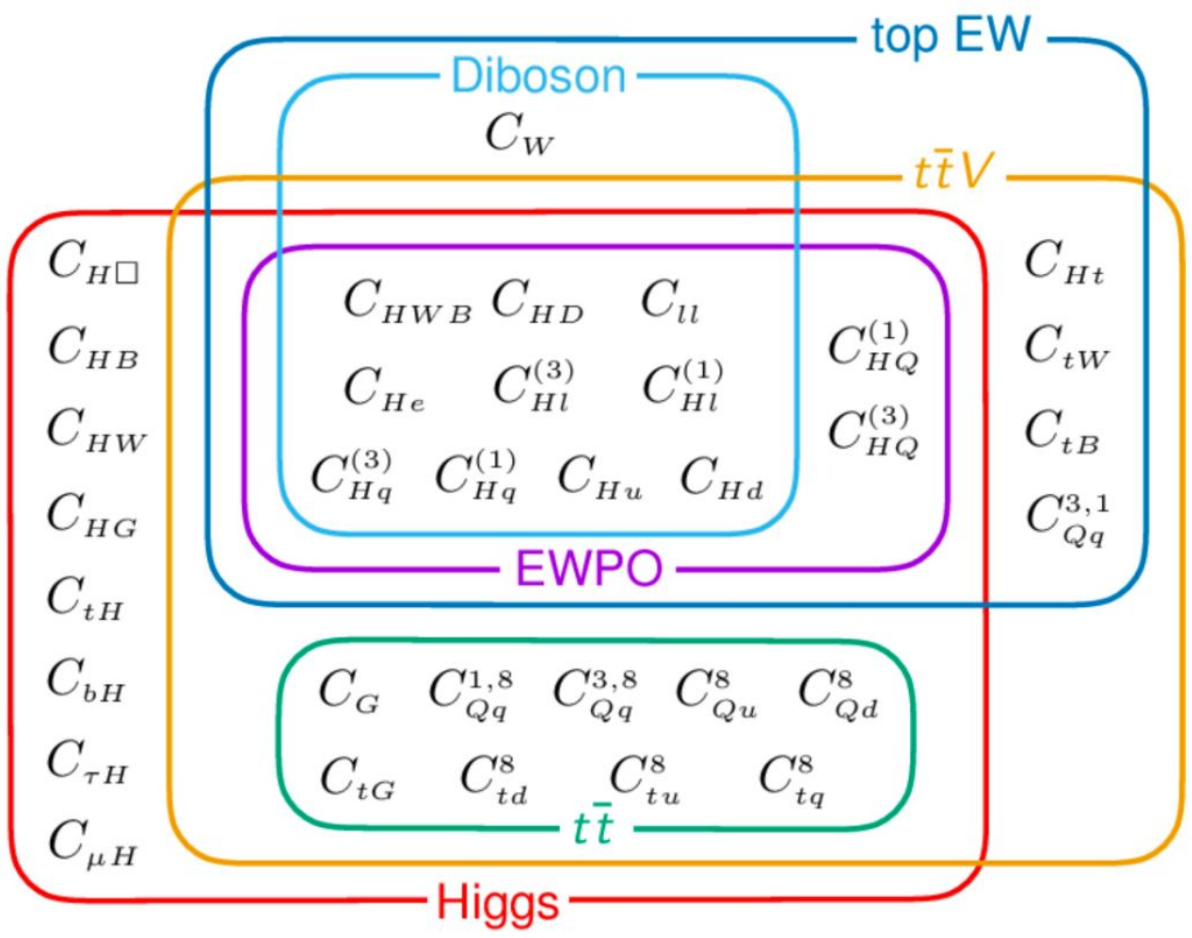




Global fit input

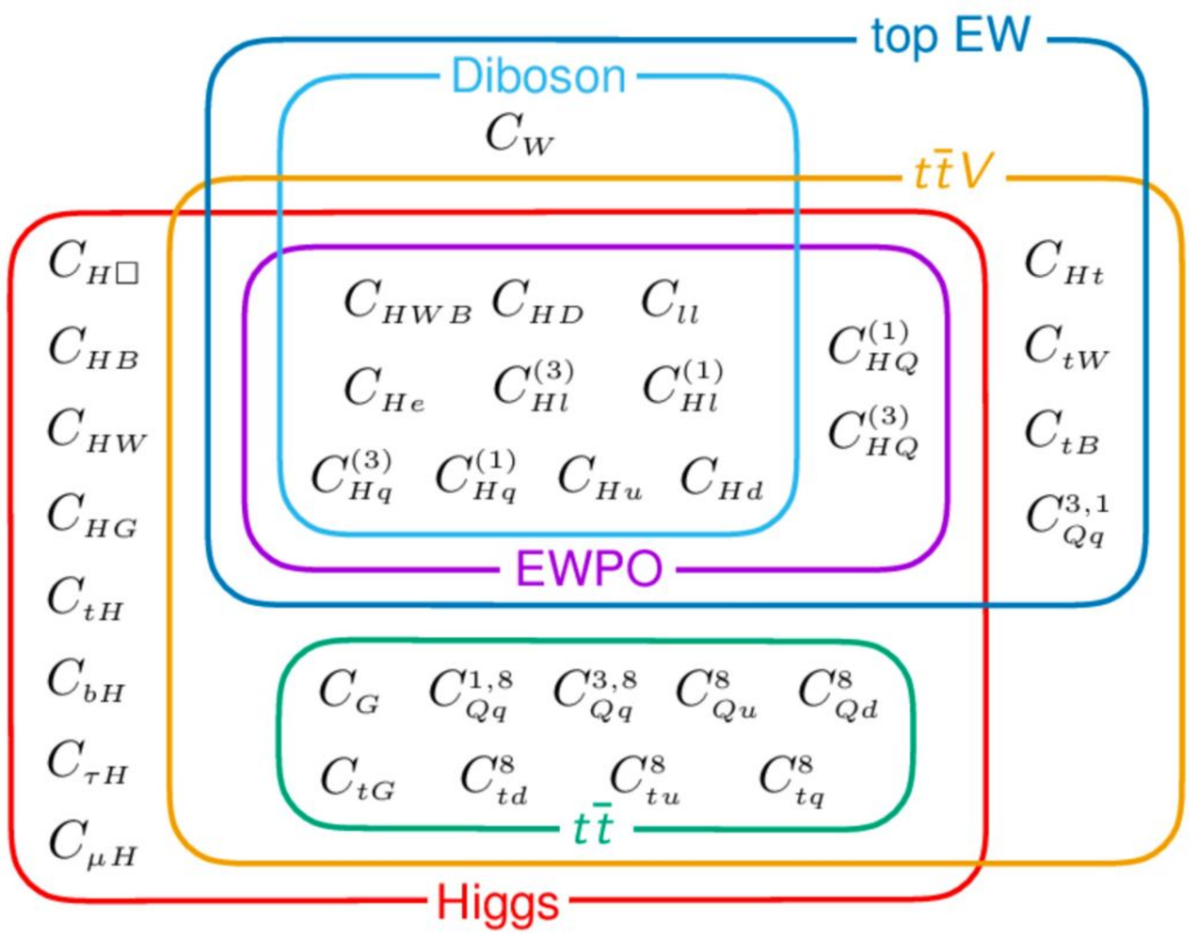
- STXS measurements are excellent input for SMEFT global fits

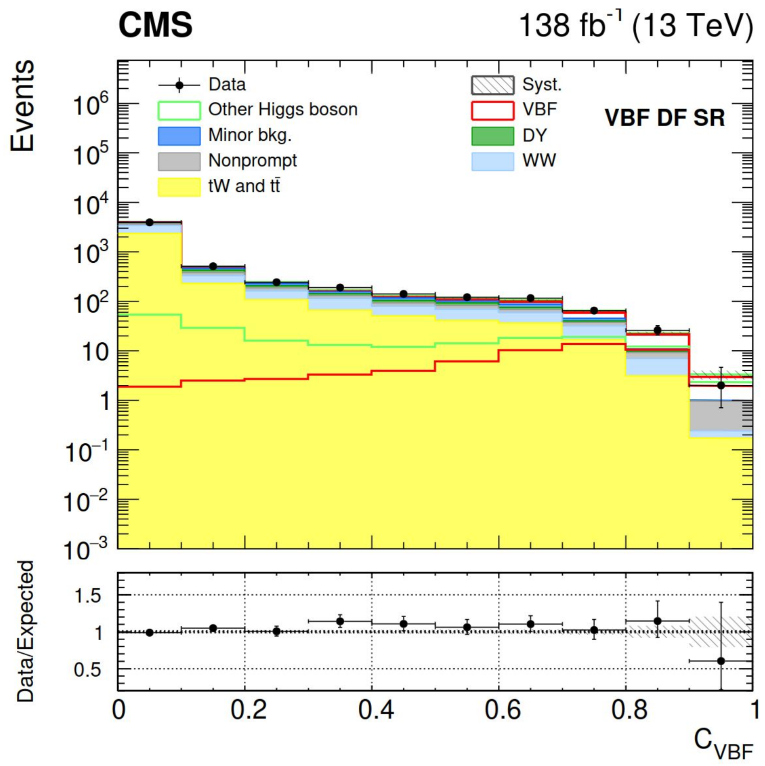




Global fit input

- STXS measurements are excellent input for SMEFT global fits
- A few things to consider:
  1. Choice of flavour scheme
  2. Current STXS interpretations only consider EFT in Higgs signal
     - Simultaneously parametrise signal and background?
  3. Statistical independence (orthogonality)
     - Control regions in STXS could overlap with signal regions elsewhere?
  4. Computationally challenging fits





Summary

- STXS provides a natural framework on which to base SMEFT interpretations
- Use kinematic information in measurements to further constrain BSM physics
- Caveats of STXS can somewhat limit the validity of interpretation
    - Particularly troublesome for “theorists approach” which only sees unfolded measurements
    - We (the experiments) have the knowledge (and inputs) to fully account for STXS pitfalls
    - Alleviate by improving STXS framework + developing tools
- Important ingredient for global EFT fits

1

$$\mathcal{L}(\text{data}\,|\,\vec{c}) = \frac{\exp\left(-\frac{1}{2}\Delta\vec{\mu}(\vec{c})^{\mathrm{T}}V^{-1}\Delta\vec{\mu}(\vec{c})\right)}{\sqrt{(2\pi)^m \det(V)}}$$

2

$$\mathcal{L}(\text{data}\,|\,\vec{c},\vec{\theta}) = \prod_i \text{Poisson}\Big(n_i\,\Big|\,\sum_j \mu^j(\vec{c})s_i^j(\vec{\theta}) + b_i(\vec{\theta})\Big)\,p(\tilde{\vec{\theta}}\,|\,\vec{\theta})$$