SMEFT Treatment for the Higgs Boson with the ATLAS Experiment

Les Rencontres de Physique de la Vallée d'Aoste

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Precision Program for the Higgs

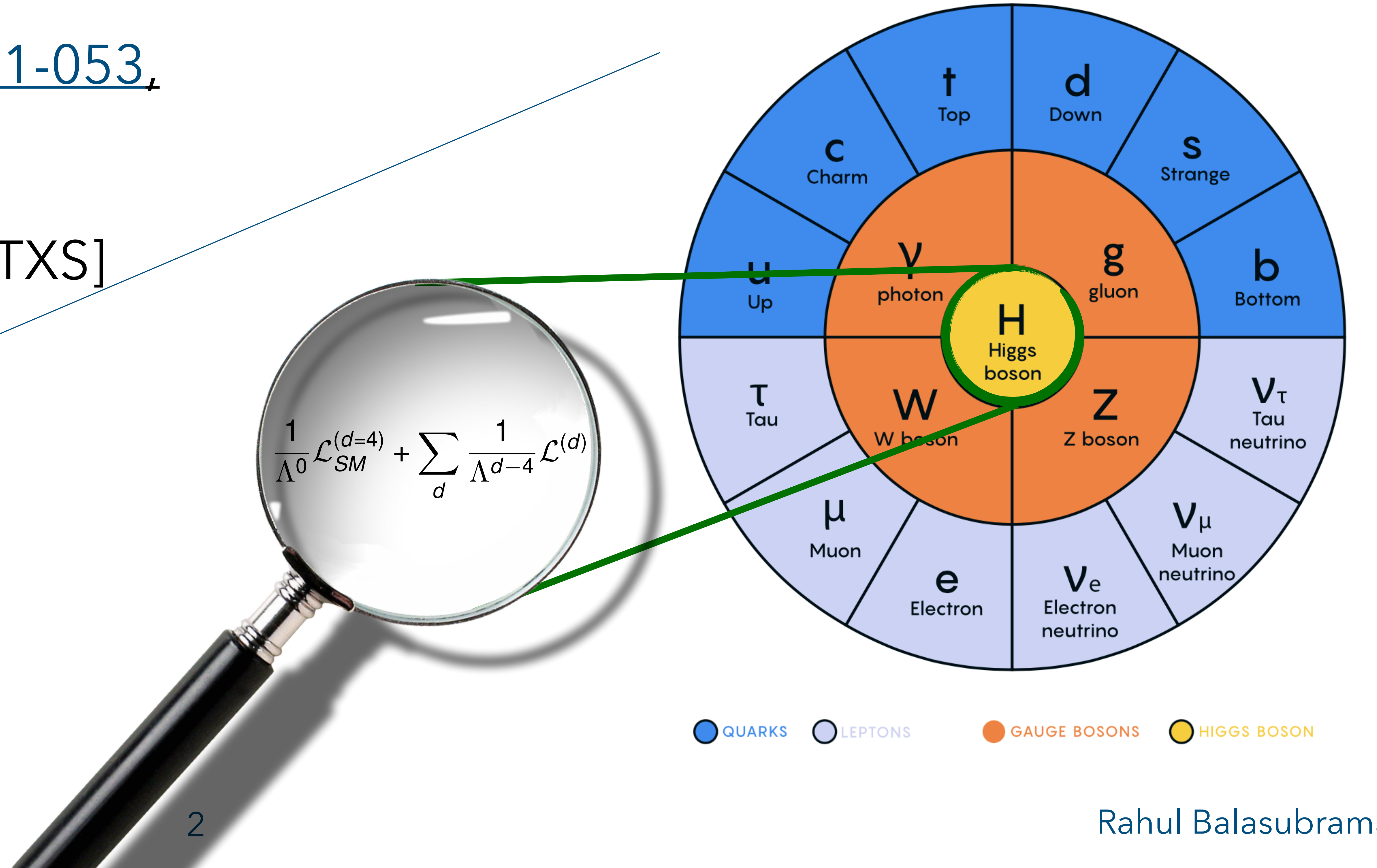
LHC Run-2 commences **precision program** of Higgs boson with ATLAS experiment

Differential Higgs cross-sections measurements provide valuable kinematic information

The **Standard Model Effective Field Theory** (SMEFT) provides a theoretically consistent framework to interpret these measurement in terms of new physical parameters

Today's talk based on ATLAS-CONF-2021-053,

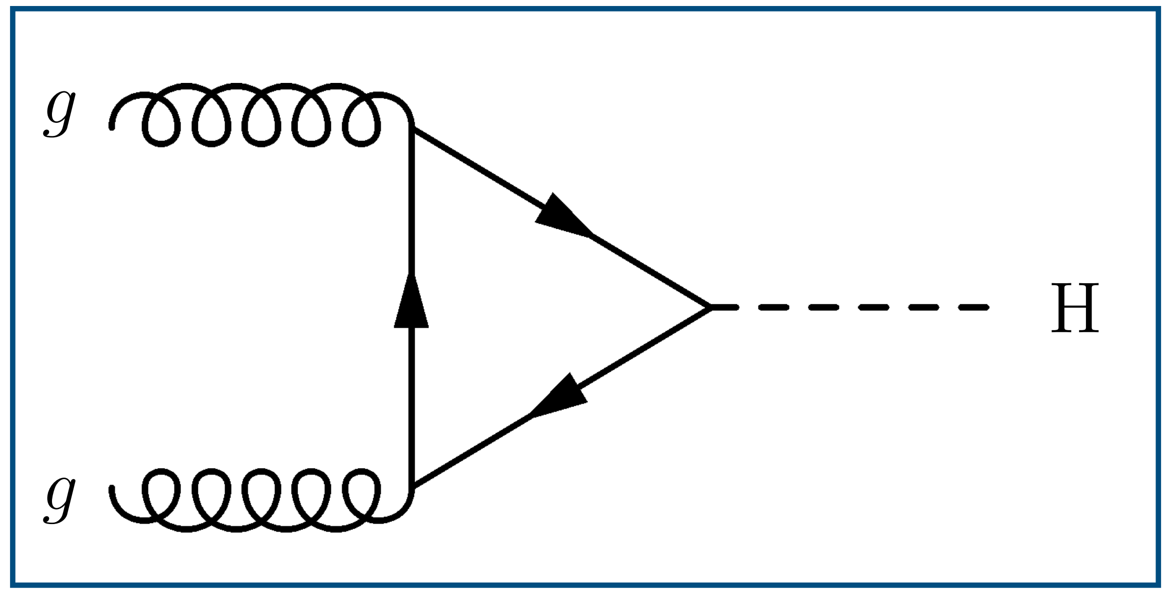
- Higgs kinematic properties with Simplified Template Cross Sections [STXS]
- Introduction to SMEFT framework
- Interpreting Higgs measurements in SMEFT framework



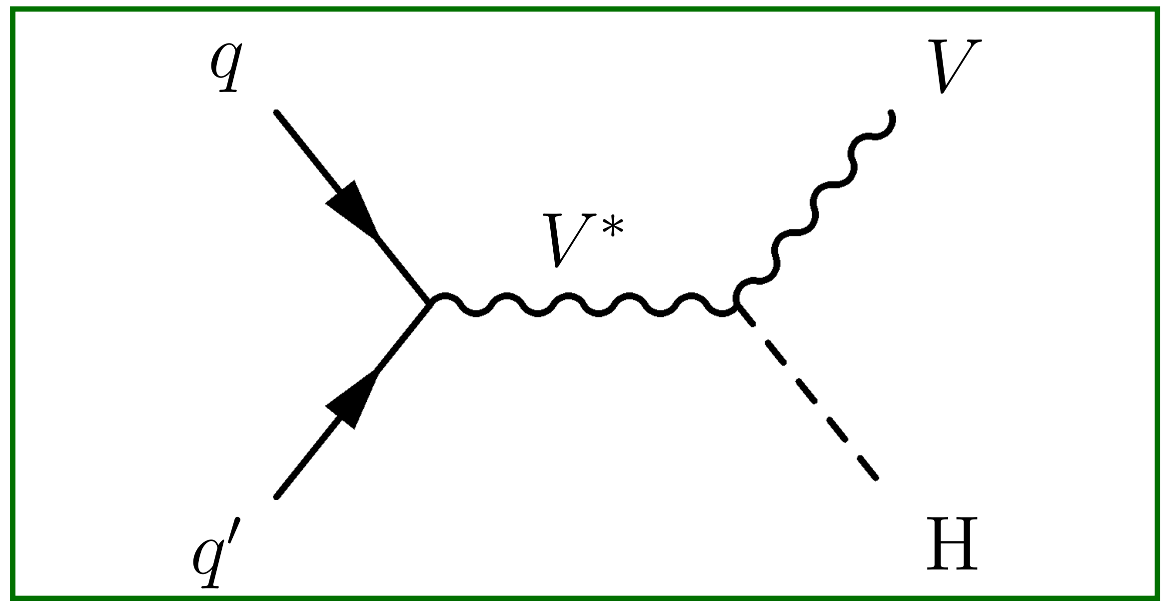
Inclusive Picture of Higgs Production

The **five major SM Higgs production modes** have been measured with **O(10-20)% precision**

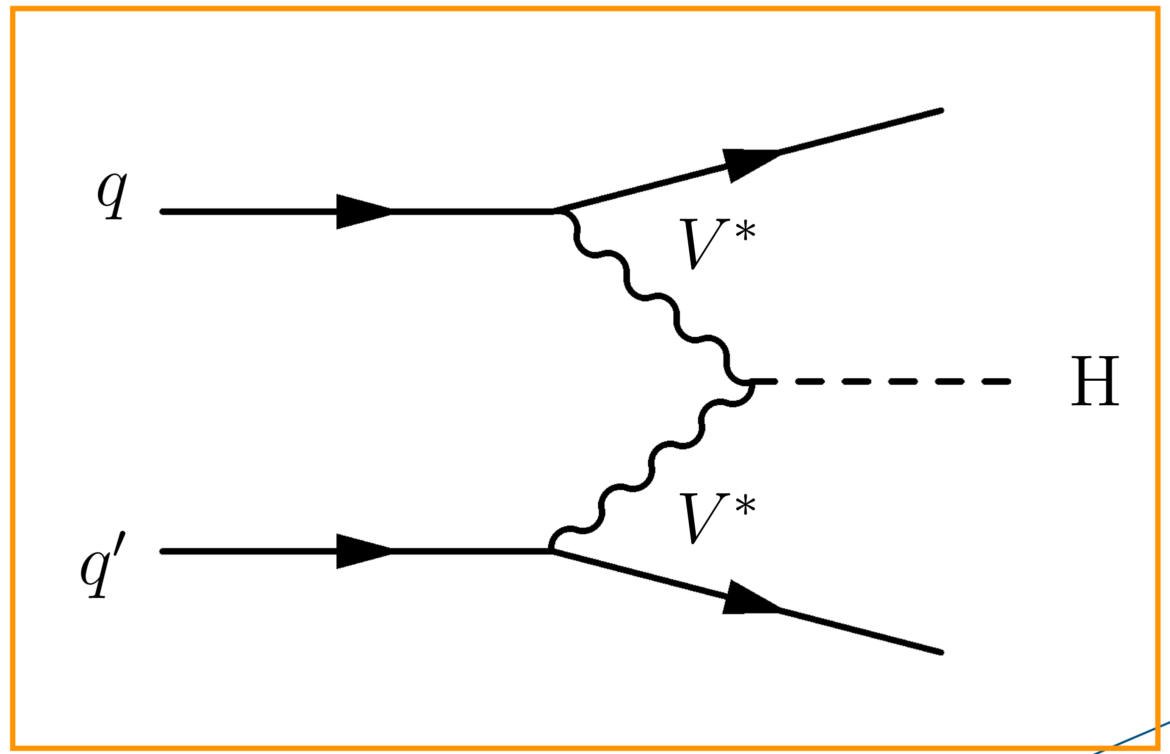
Gluon-gluon Fusion (ggF)



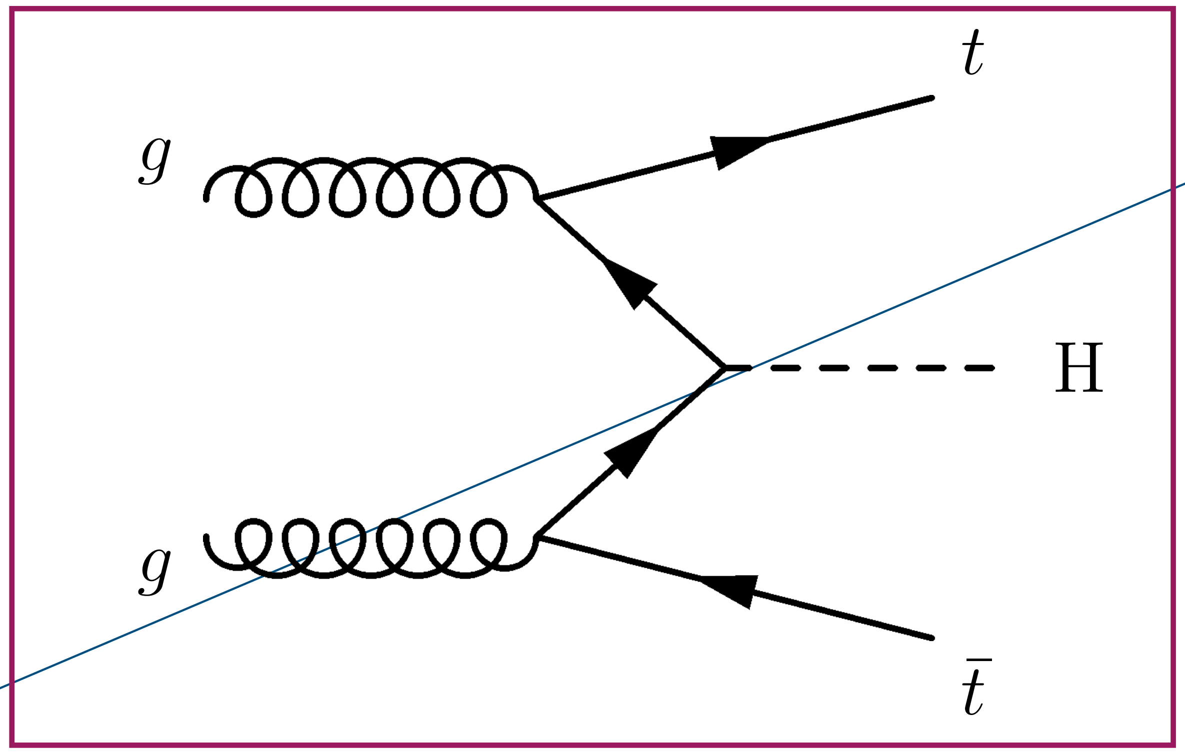
Higgstrahlung (VH)



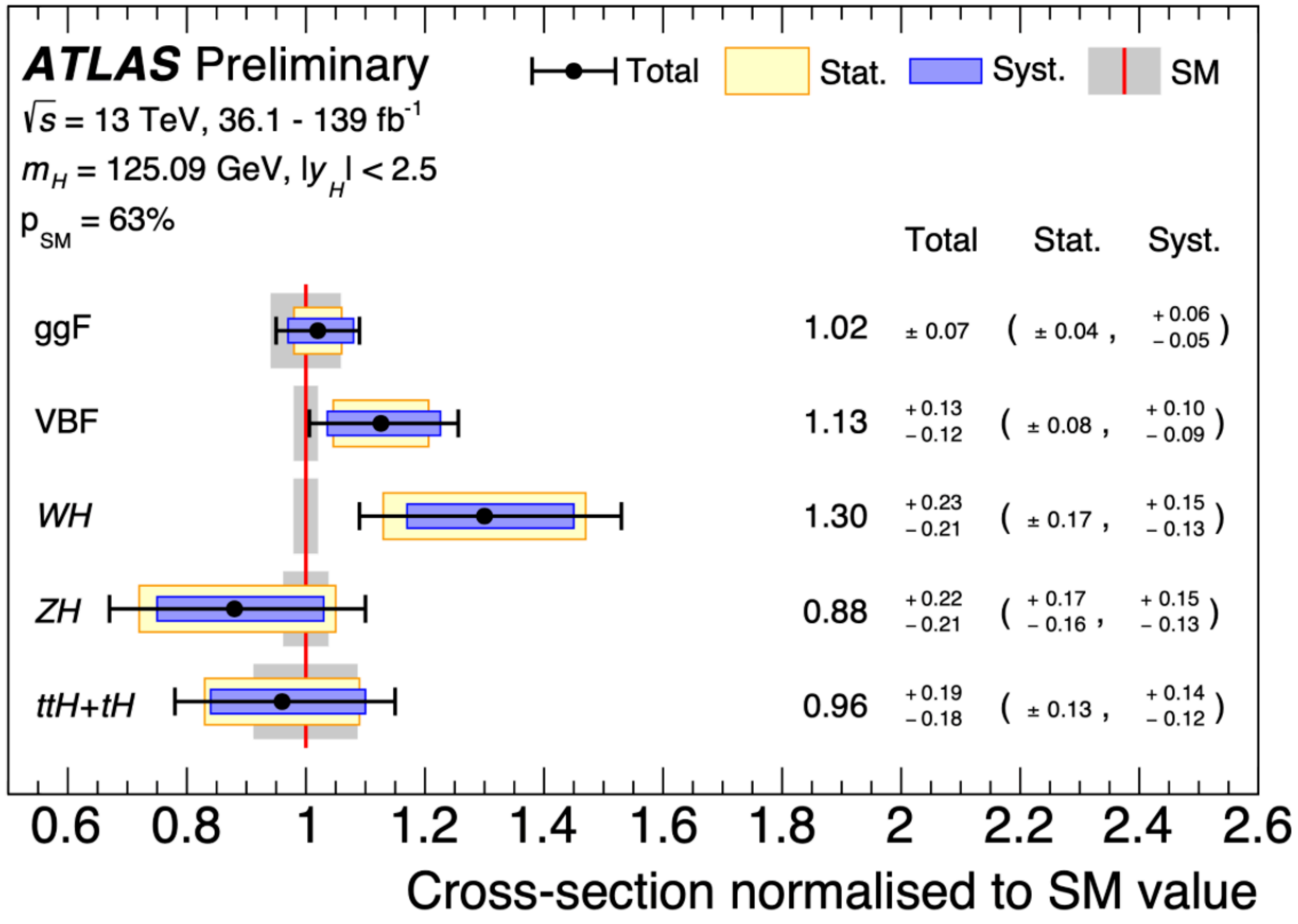
Vector Boson Fusion (VBF)



ttH



Measured cross-section for each production mode



Inclusive cross-section probe only changes to overall rate, no info. of underlying distributions

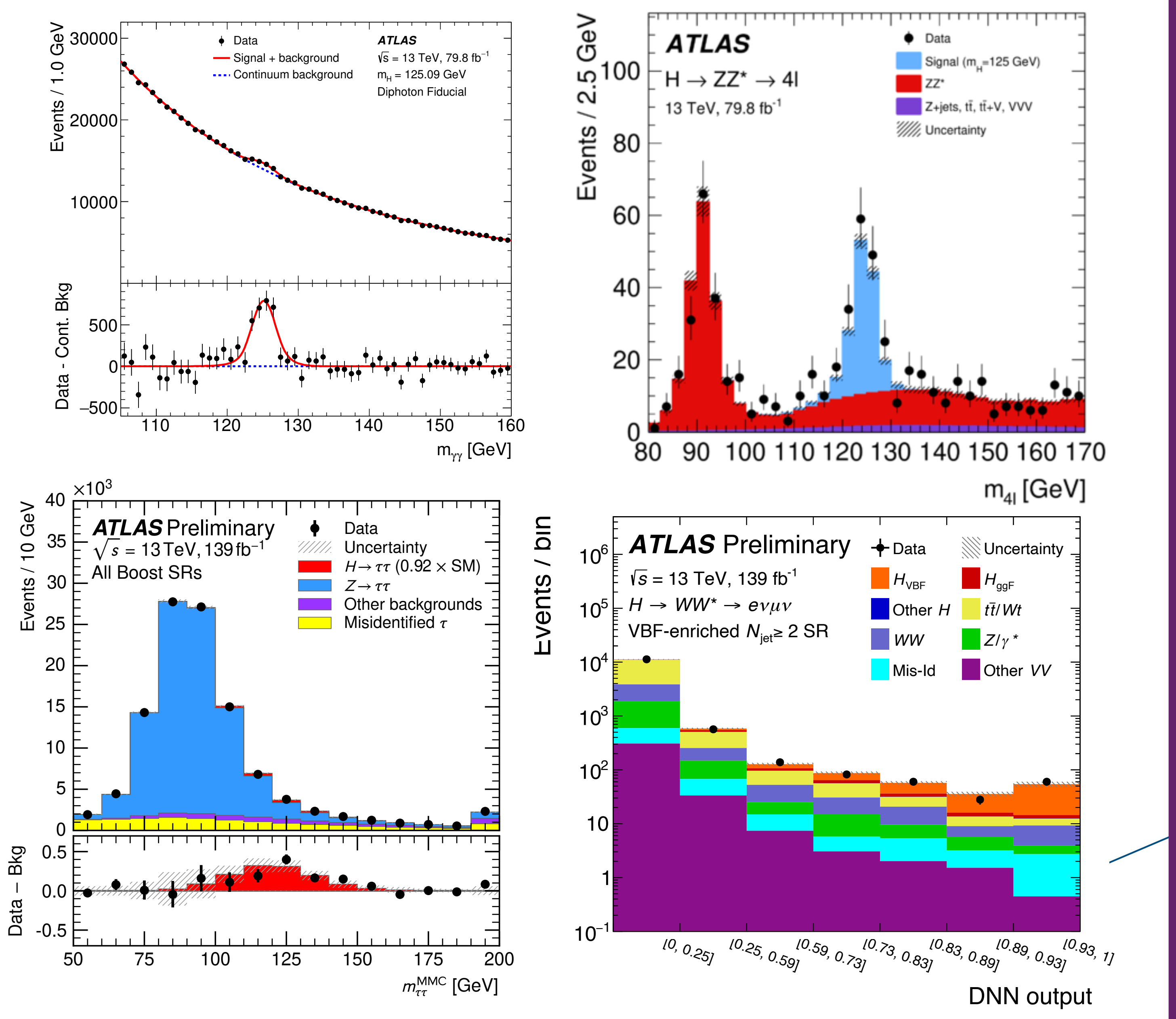
With Run-2 dataset, for the first time, we can measure **differential information** across all major Higgs production modes

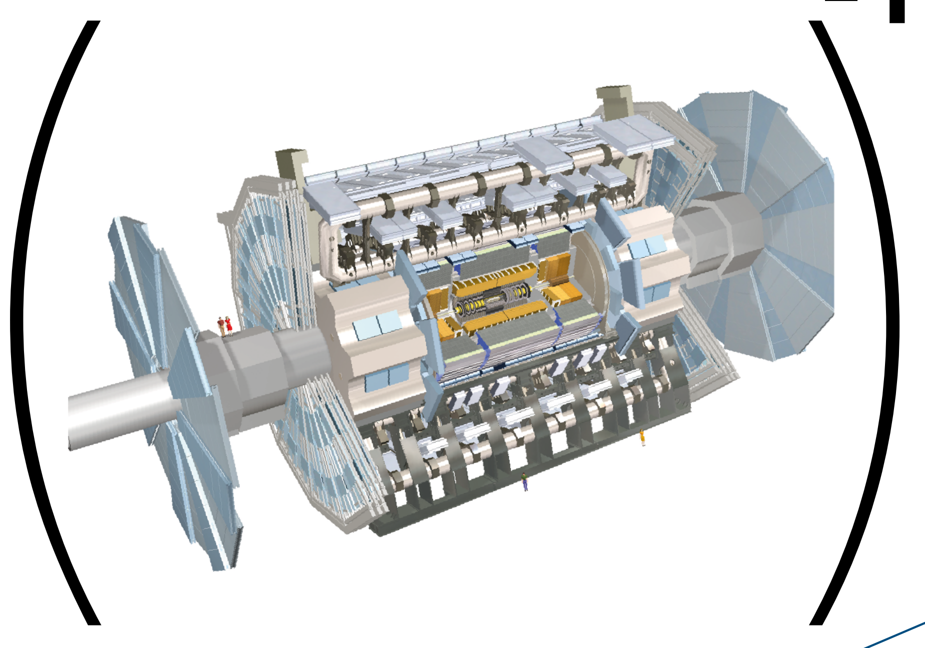
Kinematics with simplified template cross-sections

STXS framework - fiducial bins to measure kinematic properties across decay channels

Kinematic regions help isolate BSM effects (typically tails of distributions)

O(300) reconstructed categories across 5 Higgs decay channels

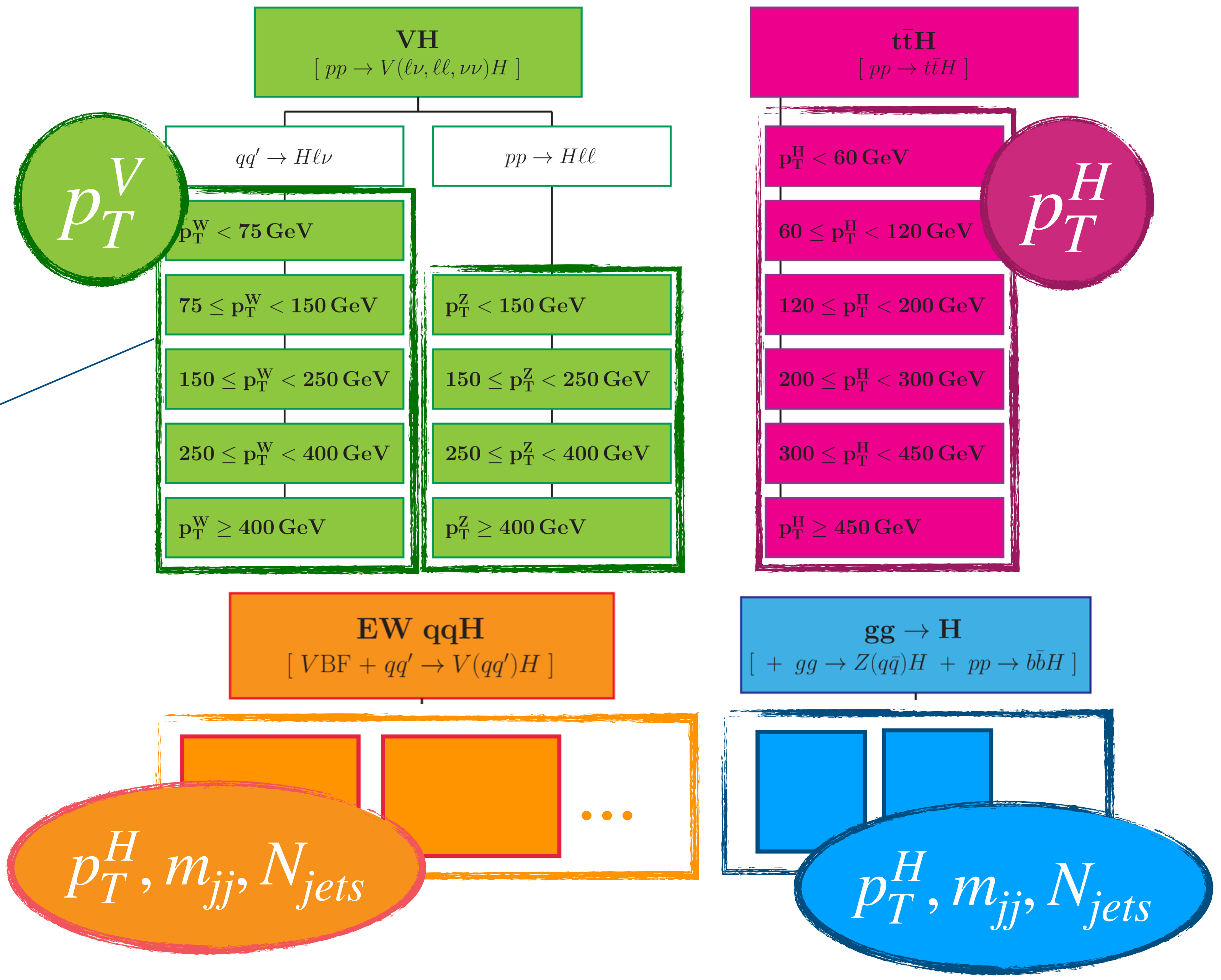




$\left(\quad \right)^{-1}$

Unfold experimental effects of detector in fit

Higgs production cross-sections in fiducial volume



SMEFT interpretation done at the level STXS, **no detector-level SMEFT simulation** required

Full systematic modelling from **experimental and theoretical sources** used

Measurements of Higgs kinematics

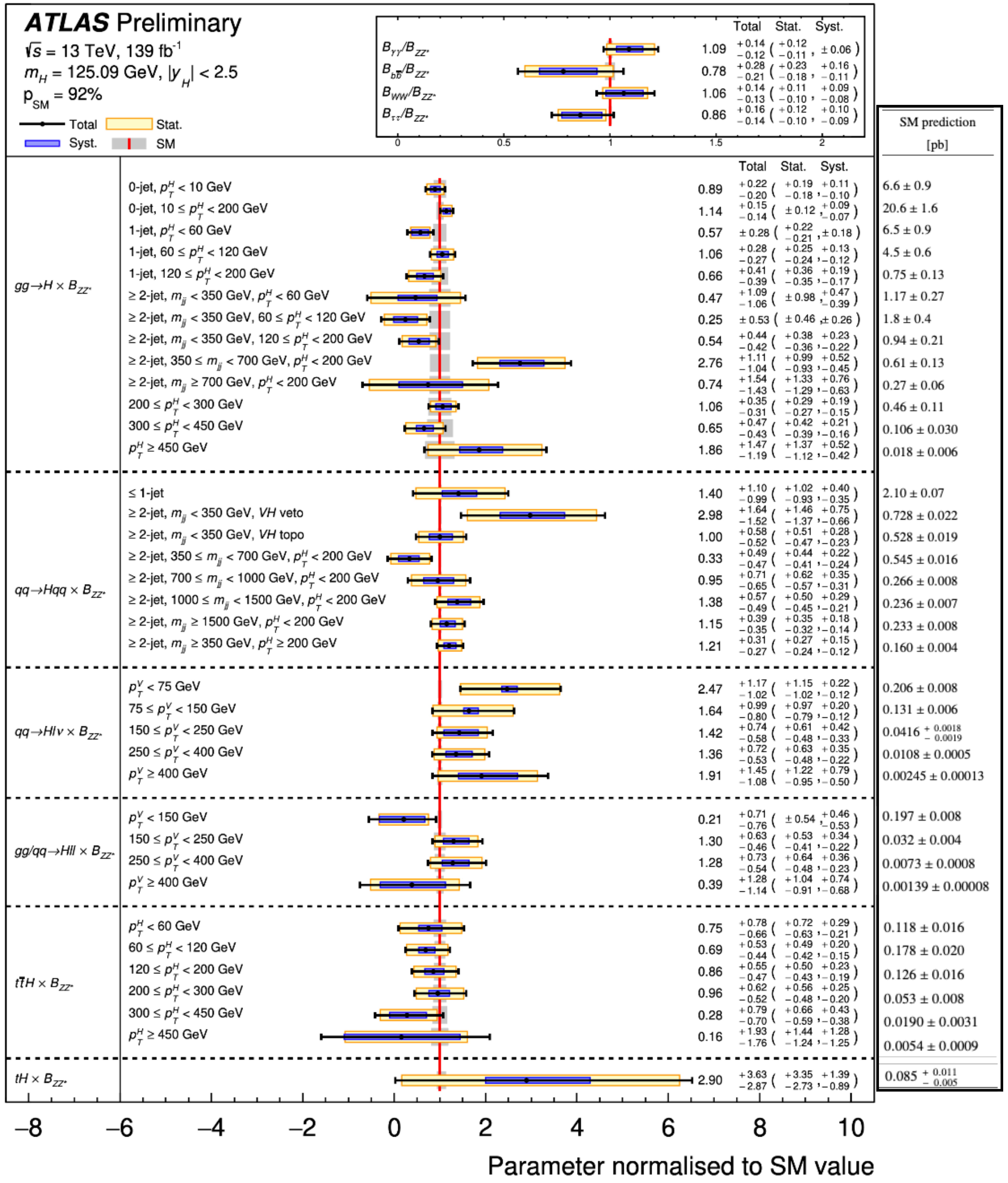
Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139
$H \to WW^*$	ggF, VBF	139
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\rm had}\tau_{\rm had})$	139
	$t\bar{t}H$	36.1
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139

→ *New w.r.t to 2020 Higgs combination*

Measure **37 kinematic bins** across 5 production modes using analyses of 5 major decay channels

Probe Higgs cross-sections ranging across 4 orders of magnitude !

Measurements are **statistically limited**



Standard Model Effective Field Theory

Taylor expansion of Lagrangian in terms of $\frac{E}{\Lambda}$ and $\frac{vev}{\Lambda}$,

$\Lambda \rightarrow$ scale of new physics

Effective Lagrangian

$$\mathcal{L} = \frac{1}{\Lambda^0}\mathcal{L}_{SM}^{(d=4)} + \frac{1}{\Lambda}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(d=6)} + \ldots = \mathcal{L}_{\mathrm{NP}}$$

SM Lagrangian, no information about Λ

Weinberg operator corresponding to majorana-ν mass

Leading contribution for Higgs physics

Lagrangian with new particles at Λ

$\mathcal{L}^{(d)} = \sum_i c_i \mathcal{O}_i^{(d)}$ all possible local interactions allowed by symmetries

c_i → Wilson coefficients - free parameters of model, using Warsaw basis here

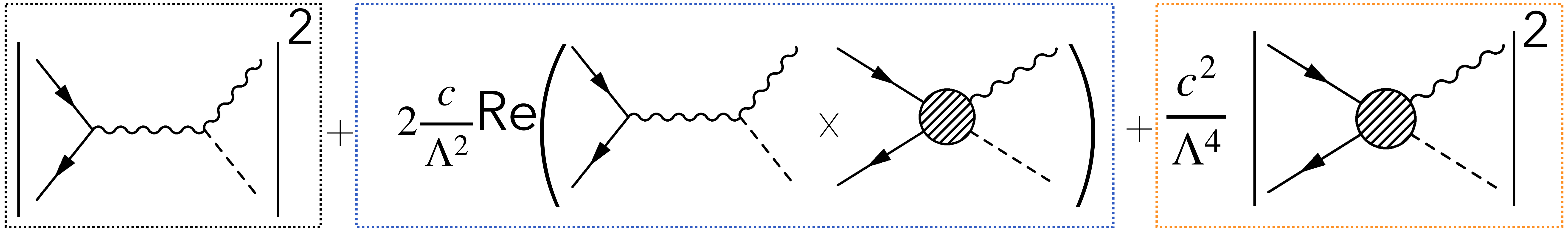
2499 operators at d=6 with ΔL=ΔB=0, **60 CP-even operators** with $U(3)^5$ flavour symmetry

Operators act as a basis to systematically classify heavy new physics signatures

SMEFT dependence of observables

SMEFT dependence parameterised as **polynomials in wilson coefficients**,

$\sigma_{\text{SMEFT}} \sim |A_{SMEFT}|^2 =$



SM

Linear : SM x d=6 interference

Quadratic : (d=6)^2, *missing SM x d=8 interference*

Only linear is considered for current results

Madgraph MC Predictions

- **SMEFTsim** to tree-level EFT contributions
- **SMEFTatNLO** for loop-induced QCD processes

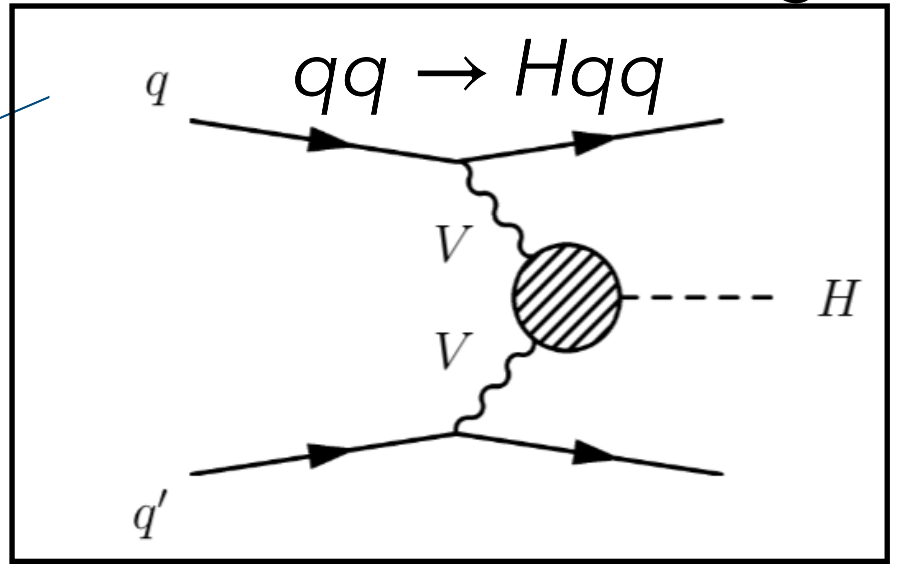
Analytic Prediction

- NLO EW calculation for $H \to \gamma\gamma$ to resolve important loop contribution (1807.11504)

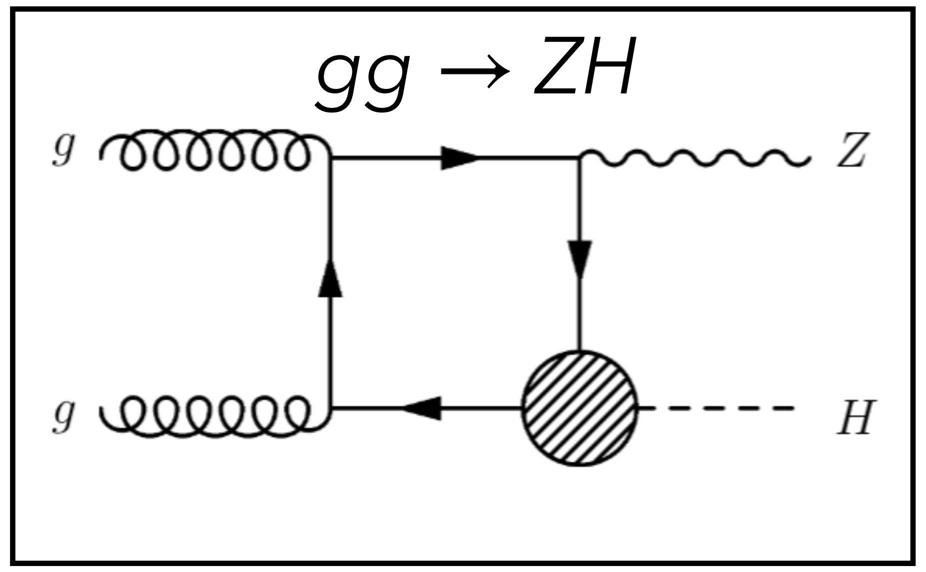
Analysis Acceptance

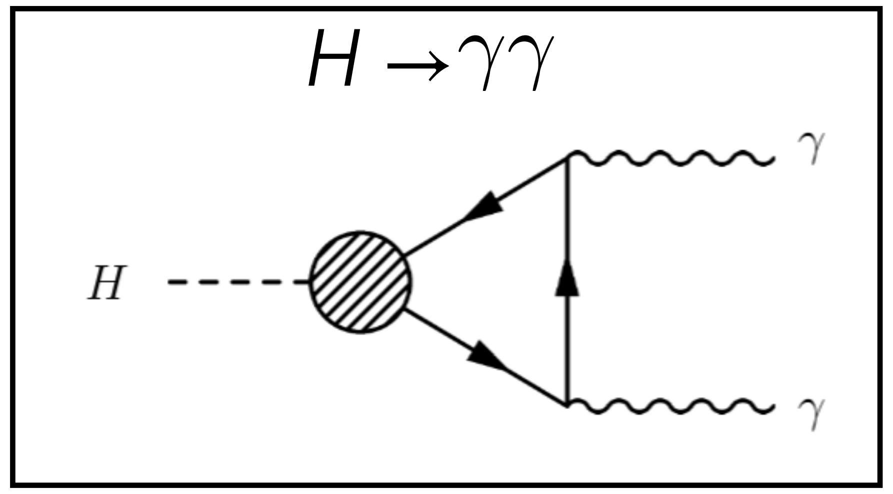
- Effect of analysis selections for 4-body Higgs decay

Tree-level insertion, eg,



NLO-QCD

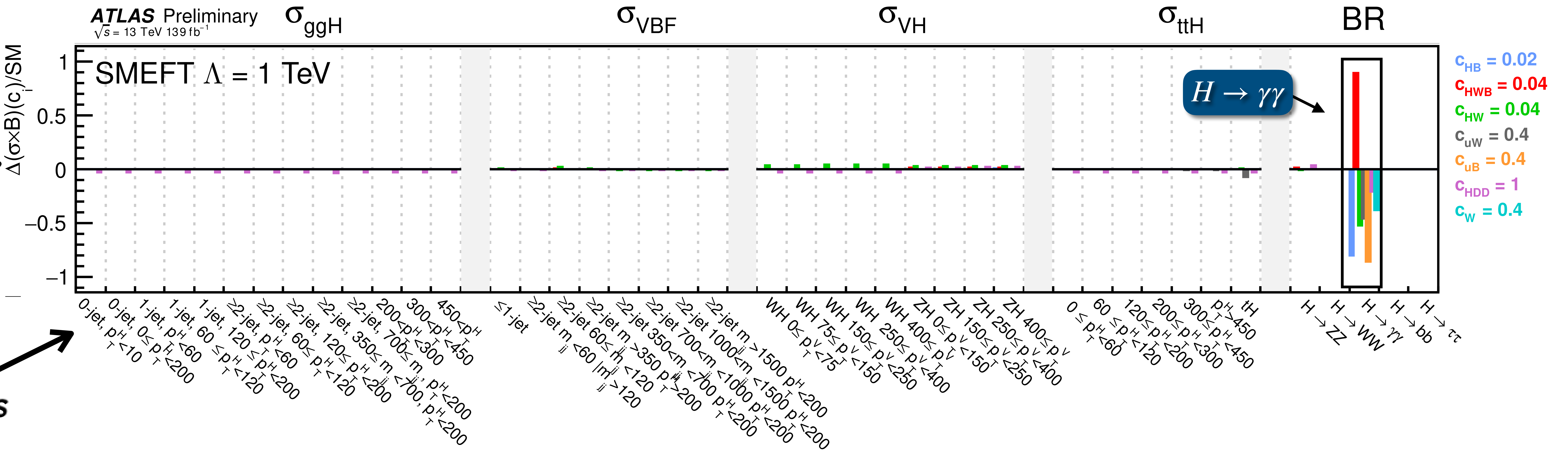




NLO-EW

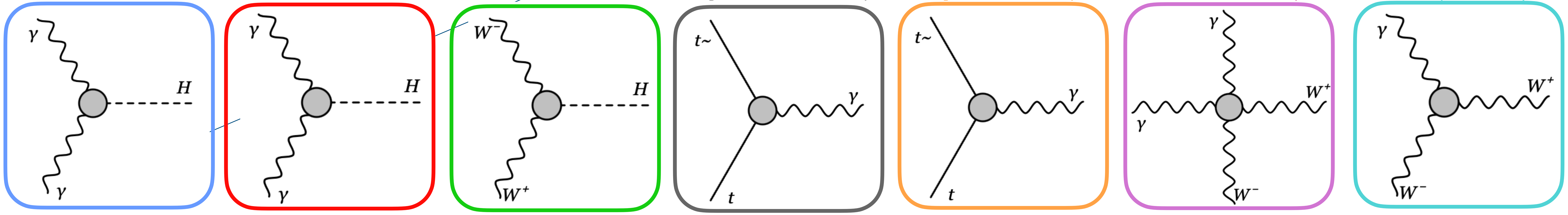
SMEFT Impact on kinematics

Relative Impact w.r.t SM



STXS bins

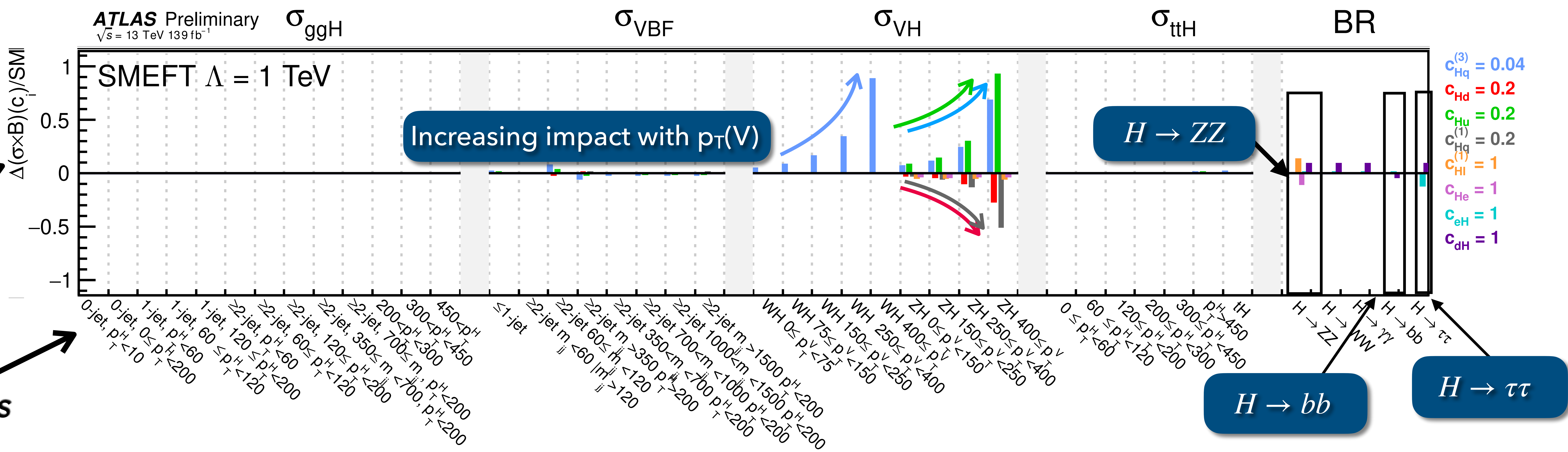
$H^\dagger\sigma^i H\, W^i_{\mu\nu}B^{\mu\nu}$ $H^\dagger H\, W^i_{\mu\nu}W^{I\mu\nu}$ $H^\dagger H\, W^i_{\mu\nu}W^{I\mu\nu}$ $(\bar{q}_p\sigma^{\mu\nu}u_r)\sigma^i\widetilde{H}\, W^i_{\mu\nu}$ $(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$ $(D^\mu H^\dagger H)(H^\dagger D_\mu H)$ $\varepsilon^{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$



Example vertices using **SMEFTsim**

SMEFT Impact on kinematics

Relative Impact w.r.t SM



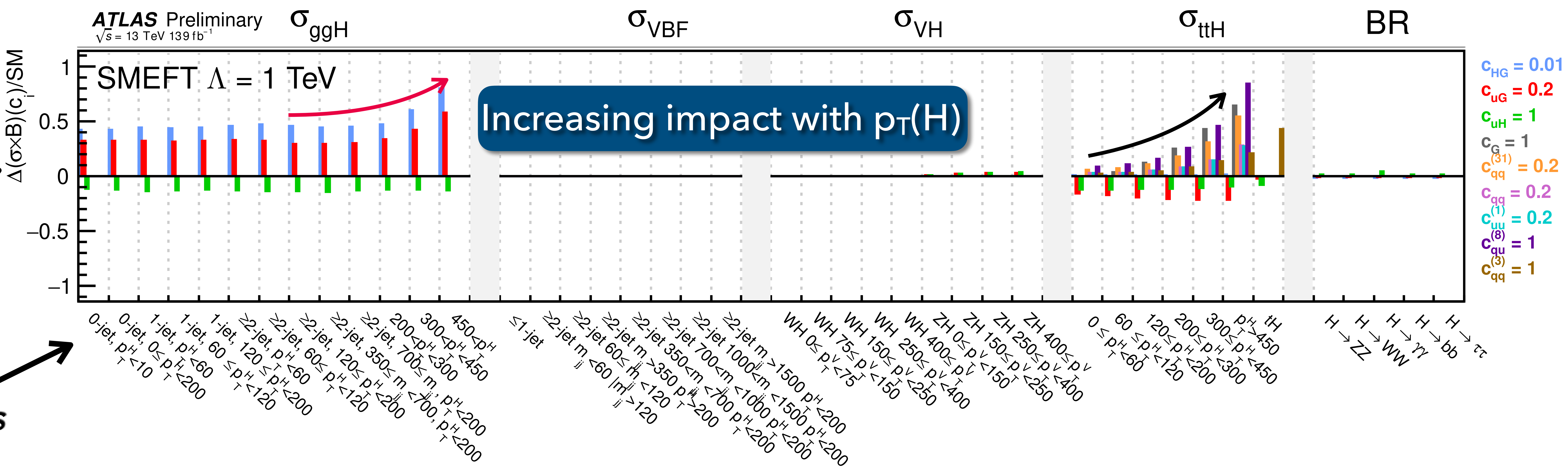
STXS bins

$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p\sigma^i\gamma^\mu q_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$ $(H^\dagger H)(\bar{l}_p e_r H)$ $(H^\dagger H)(\bar{q}_p d_r H)$

Example vertices using **SMEFTsim**

SMEFT Impact on kinematics

Relative Impact w.r.t SM

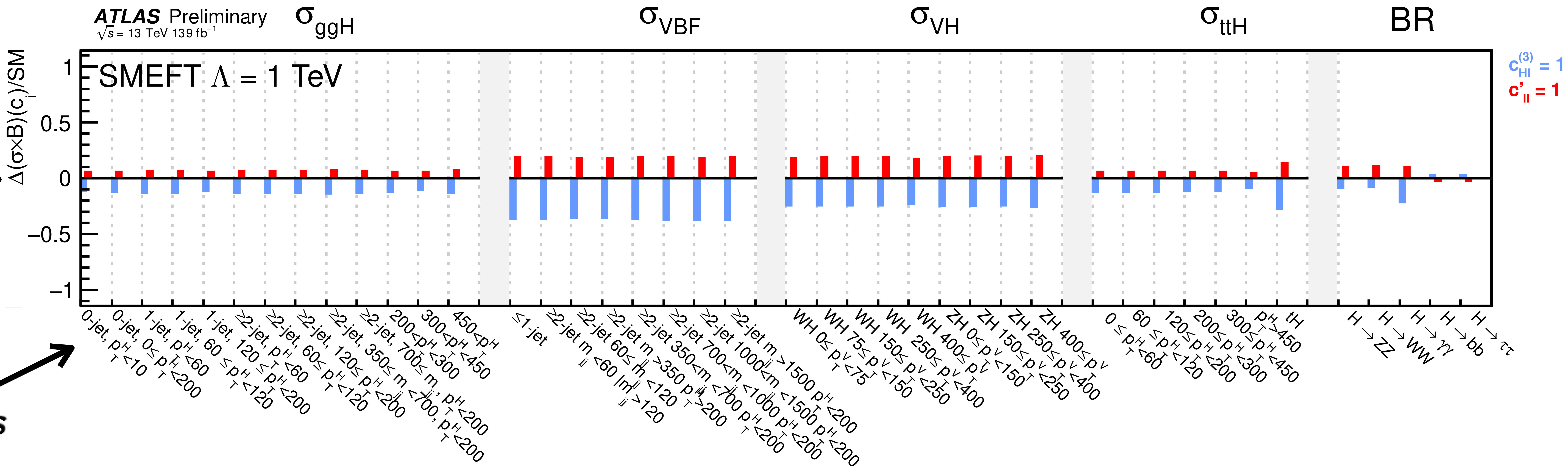


STXS bins

Example vertices using **SMEFTsim**

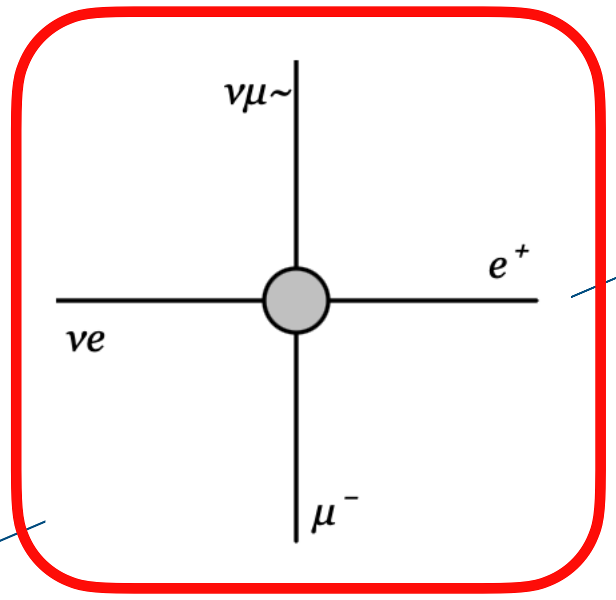
SMEFT Impact on kinematics

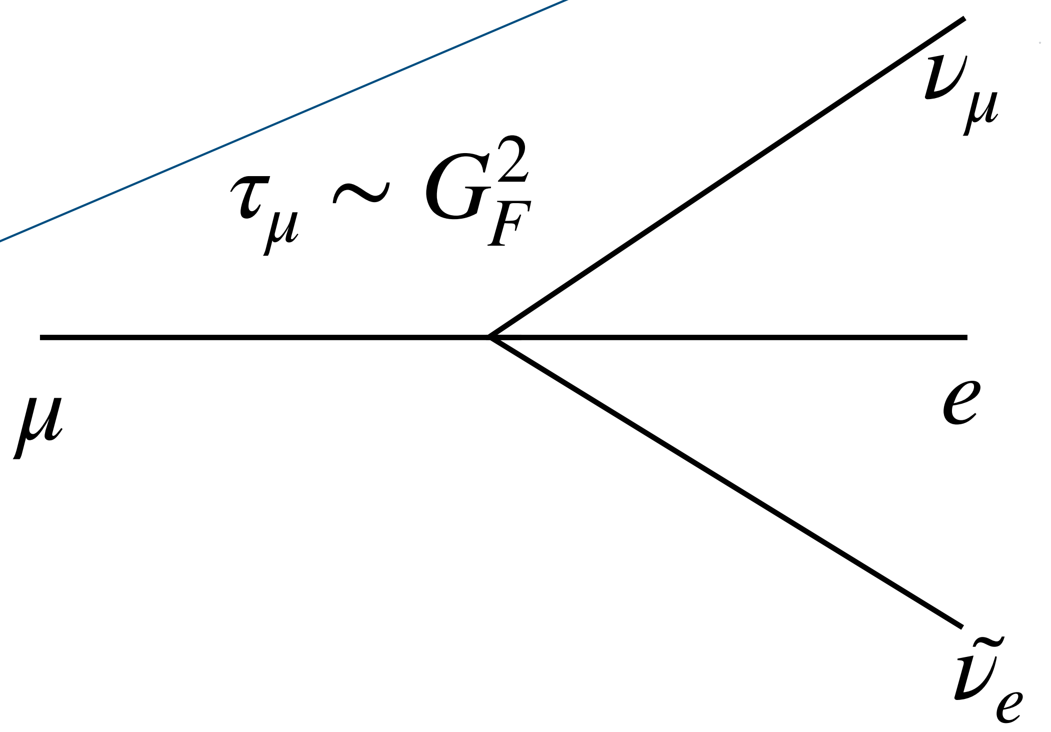
Relative Impact w.r.t SM



STXS bins

$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$





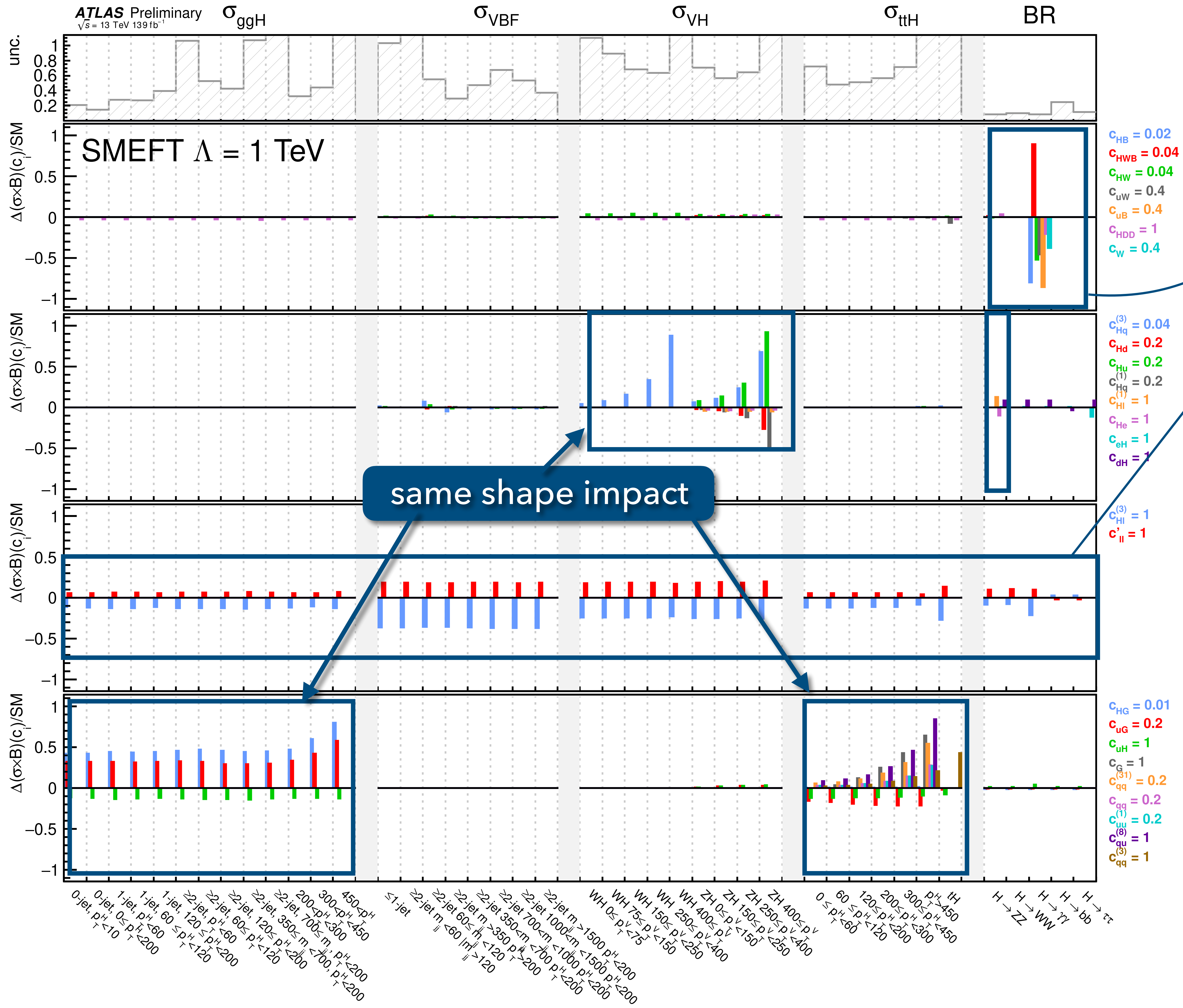
[2012.11343]

*Modification to Fermi Constant affecting **g_{EW}**, shift estimated from muon decay width in SMEFT*

$$G_F = G_F^{SM} + \sqrt{2} c_{Hl^{(3)}} - \frac{c_{ll}}{\sqrt{2}}$$

Example vertices using ***SMEFTsim***

All operators at a glance,



Many operators have similar impact

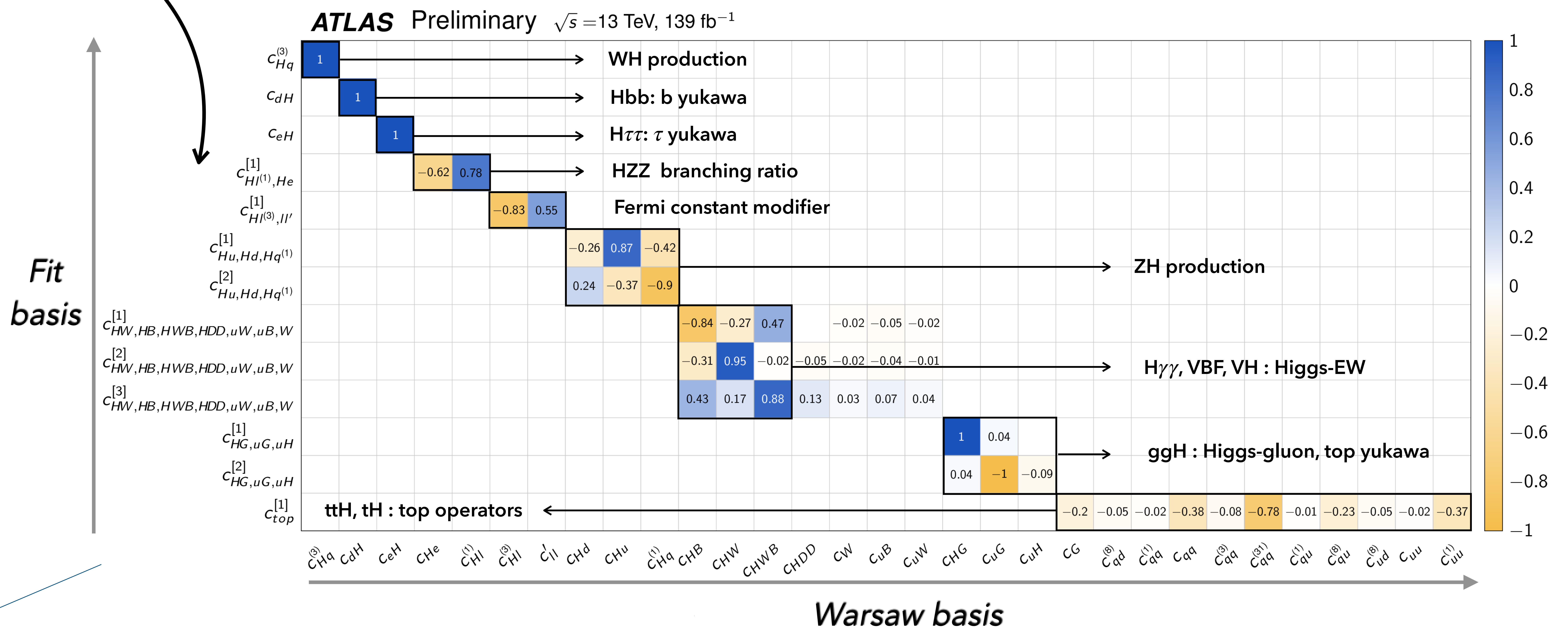
- affect inclusive observables
- appear as overall normalisation
- same shape across bins

Not enough information in measurements to **constrain all EFT parameters** !

Principal Component Analysis of Fisher information to identify sensitive directions

Fit basis definition

- Fit basis defined with **PCA in operator groups** - fit only sensitive components, rest fixed to SM
- Operator grouping dictated by experimental sensitivity to physics



SMEFT results

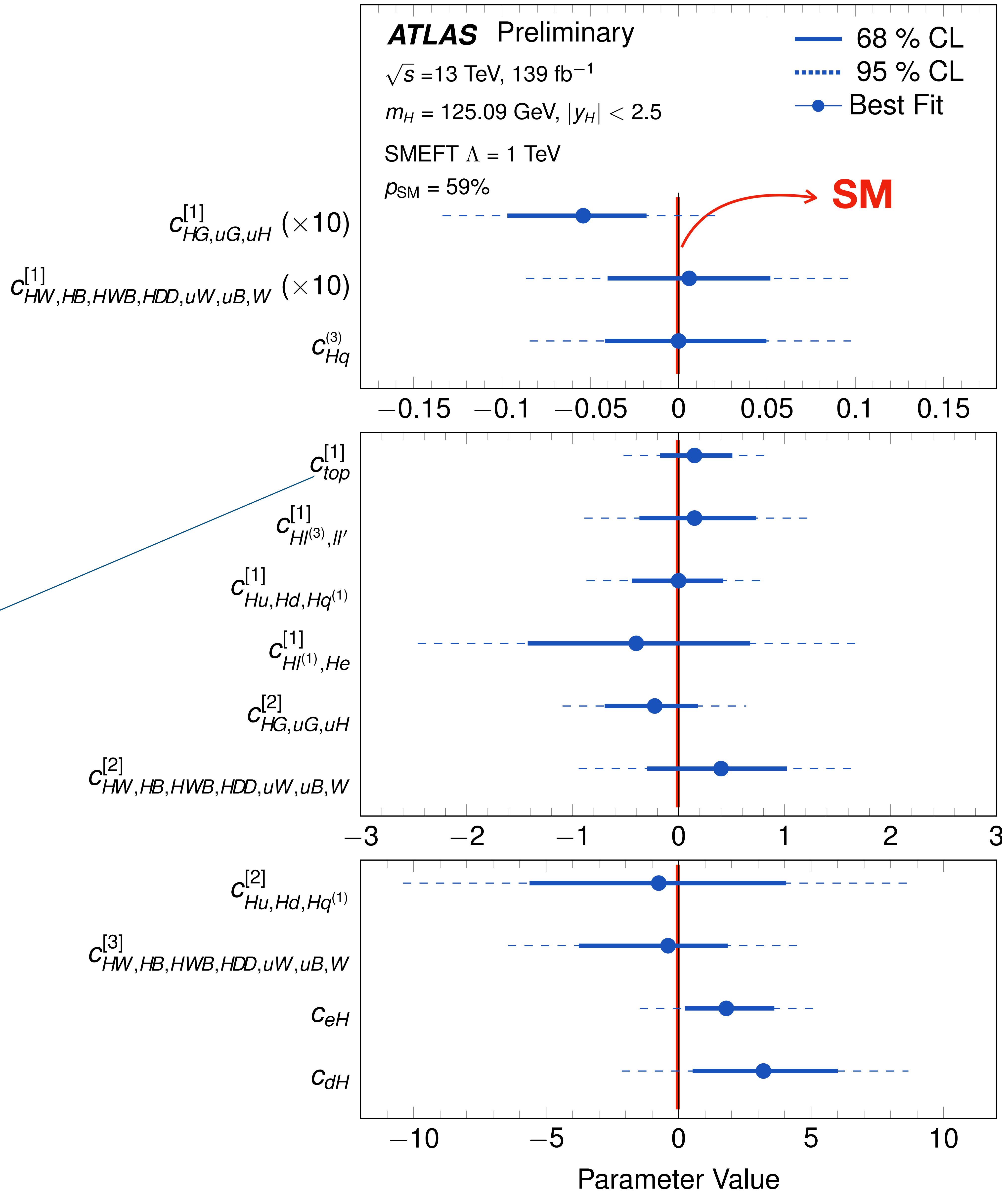
Limits obtained from **simultaneously measuring** 3 linear combination of wilson coefficients

No strong tensions with the SM, 59% compatibility w.r.t SM

Different models of BSM physics lead to different patterns of deviations

Limits provide a proxy to the **allowed scale of New Physics** in the relevant processes

$$c_{Hq}^{(3)} < 0.1 \rightarrow \frac{\Lambda}{\sqrt{c_{Hq}^{(3)}}} > 3 \text{ TeV}$$



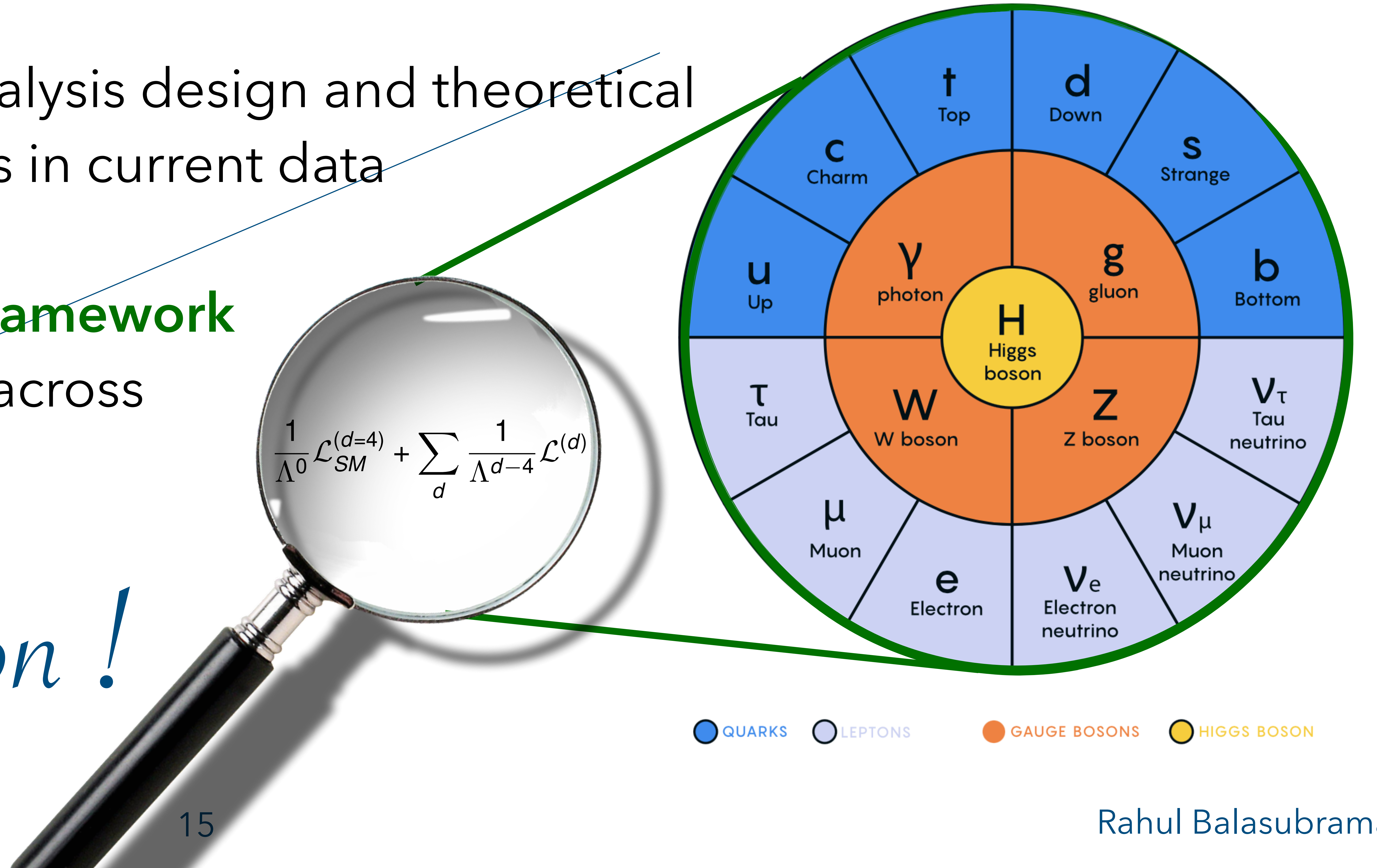
Outlook

Differential measurements of Higgs production gives **access to new kinematical information**, **improvement in statistics** and **kinematic splits with Run-3** and **beyond**

SMEFT becoming the standard interpretation method for Higgs STXS measurements, evolution of the κ framework

Lot of work ongoing both in terms of analysis design and theoretical considerations to uncover SMEFT effects in current data

SMEFT is global, provides an **unifying framework** to interpret measurements consistently across **different sectors** and **experiments**



Thanks for your attention !