Simplified Template Cross-sections of Higgs boson with the ATLAS experiment

France Berkeley Phystat Unfolding Workshop, 11th June 2024

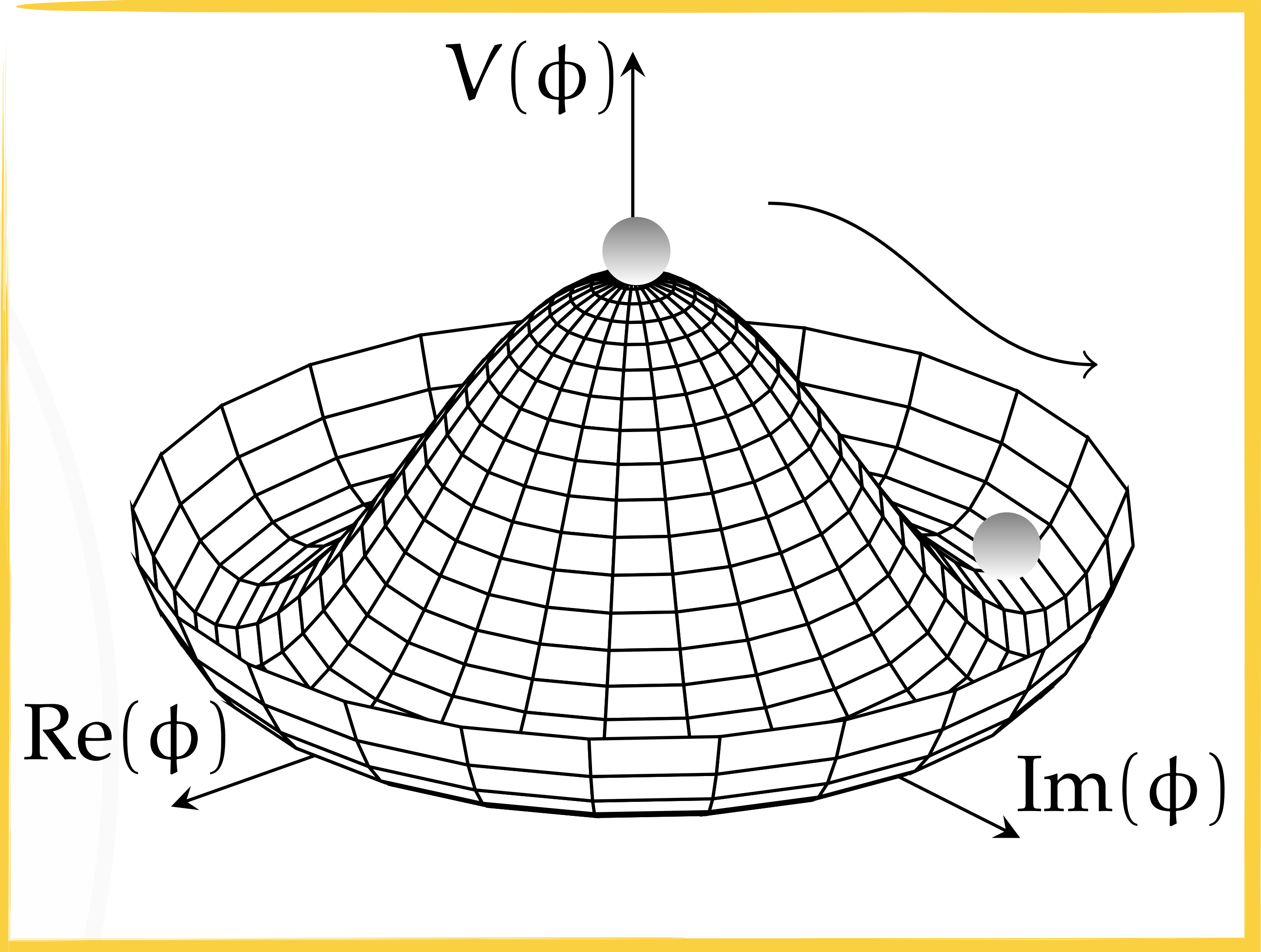
Rahul Balasubramanian

Funded by the European Union
European Research Council
Established by the European Commission
DITTO - GA 101089007

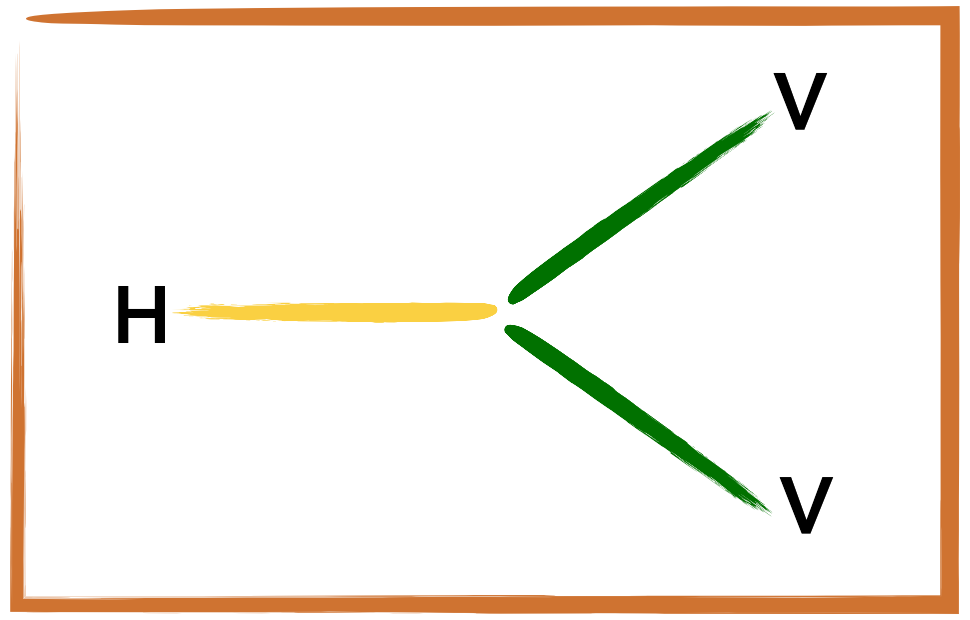
The heart of the Standard Model uncovered

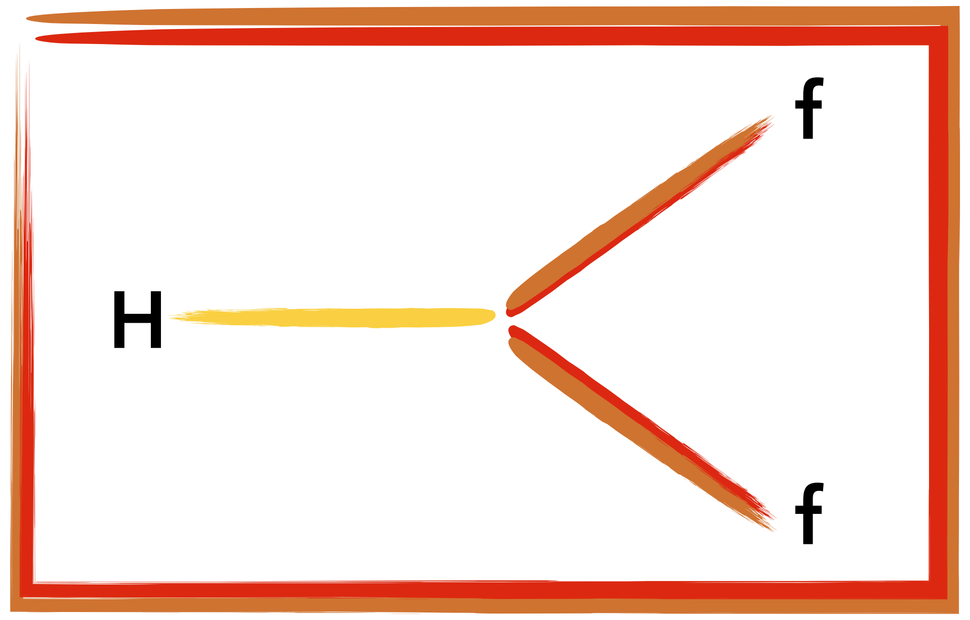
Higgs boson - the heart of the Standard Model (SM)

Particle with unique quantum numbers ($J^{CP} = 0^{+}$), ***needs to be studied in detailed***



15 out of 19 parameters in the SM connected to the Higgs Boson





$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

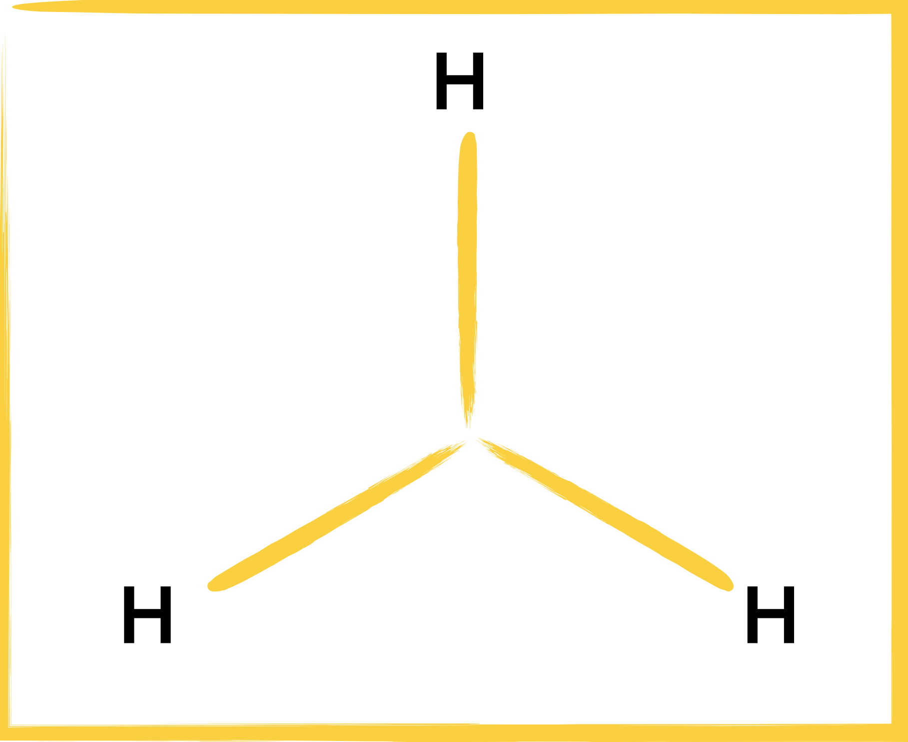
$$+ i\overline{\psi}^{\dagger}D\psi$$

Yukawa Interaction

$$+ y_{ij}\psi_i\phi\psi_j + h.c.$$

BEH Mechanism

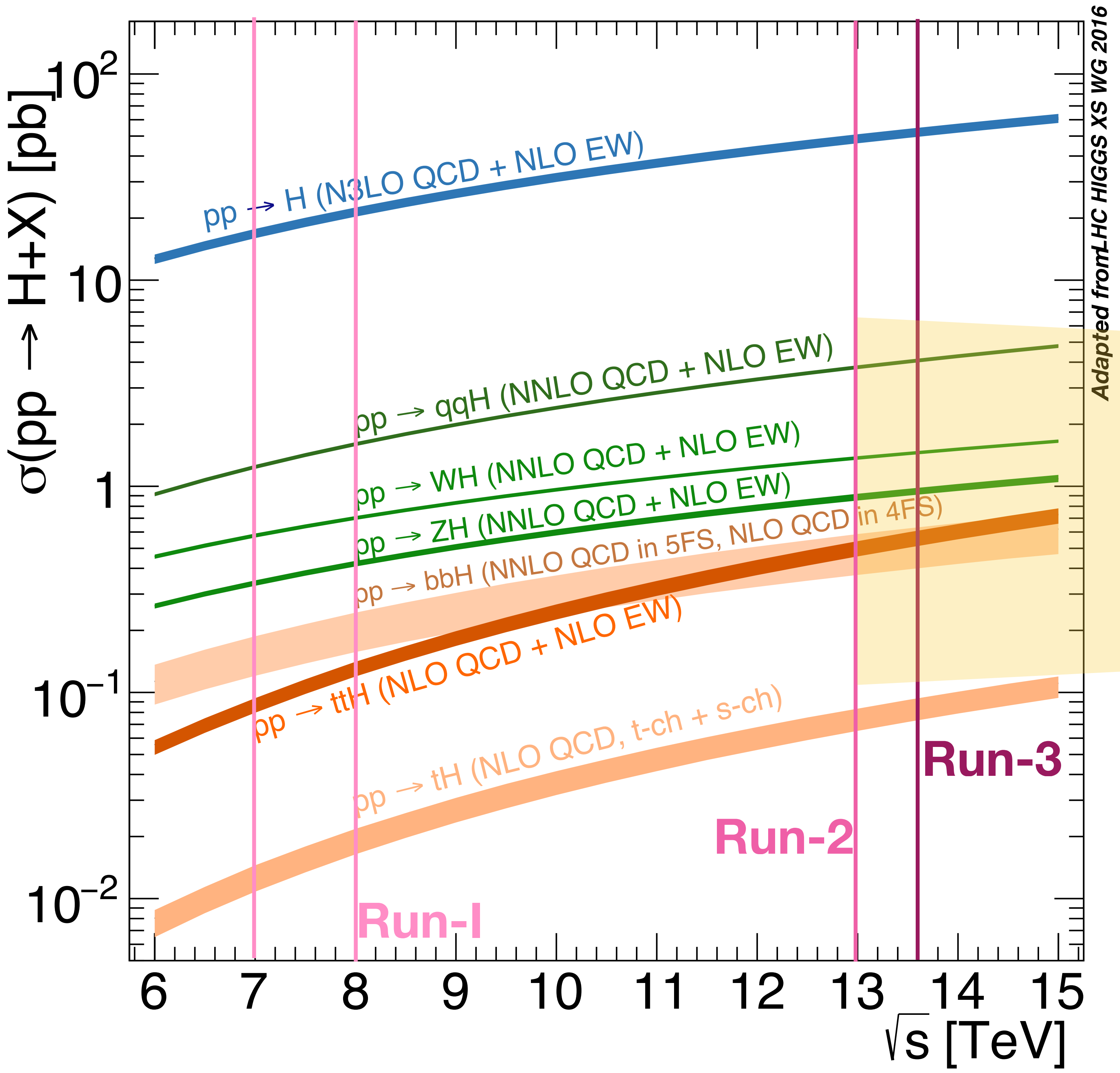
$$+ |D_\mu\phi|^2 - \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2$$

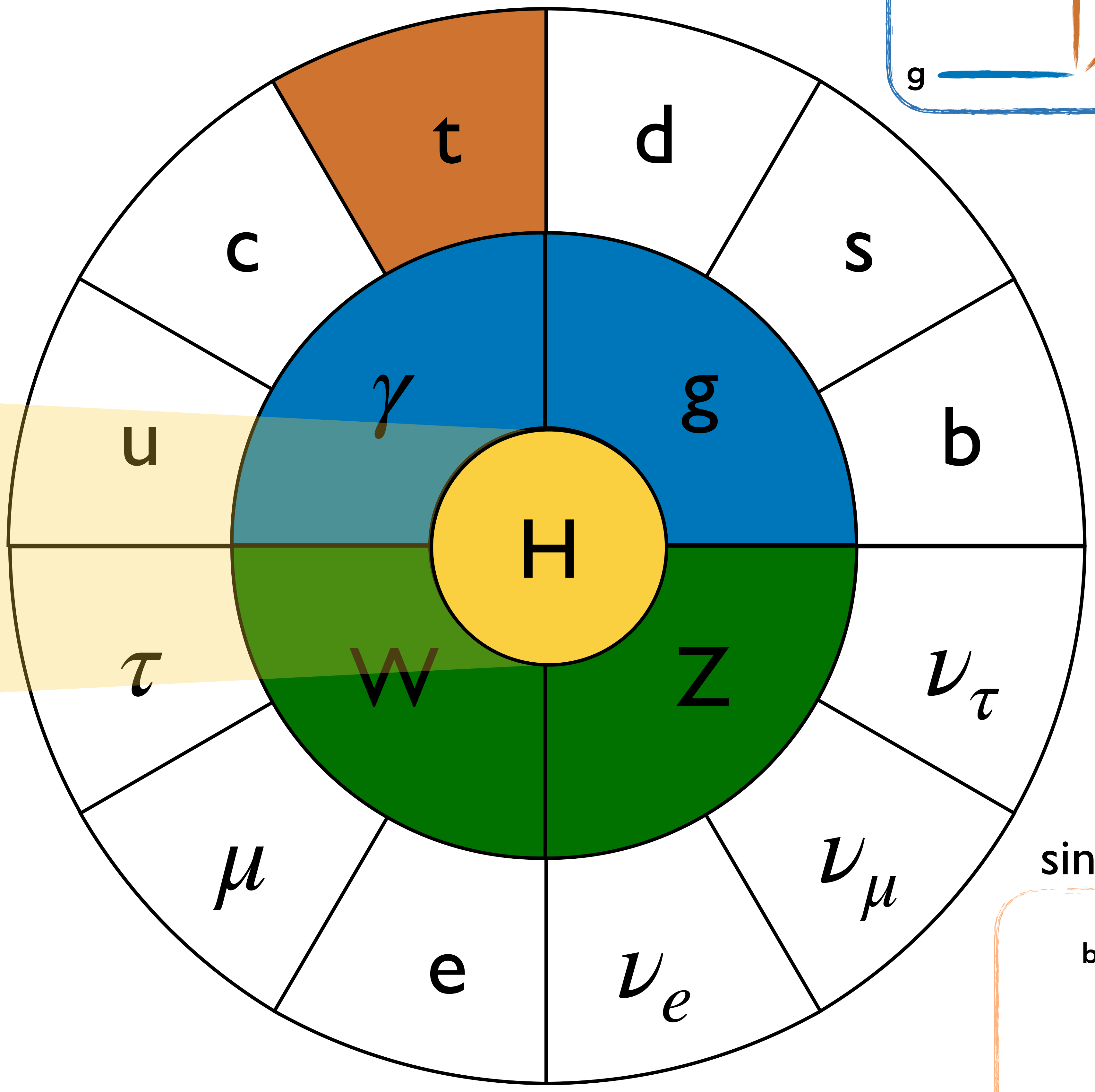


Interacts directly with all massive particles of the SM
(and indirectly with γ, g) → ***incredibly rich phenomenology !***

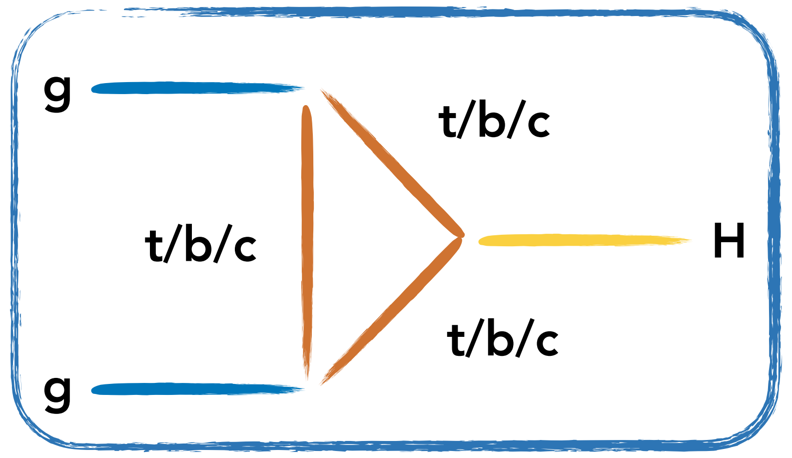
Producing Higgs bosons

Higgs boson production cross-section



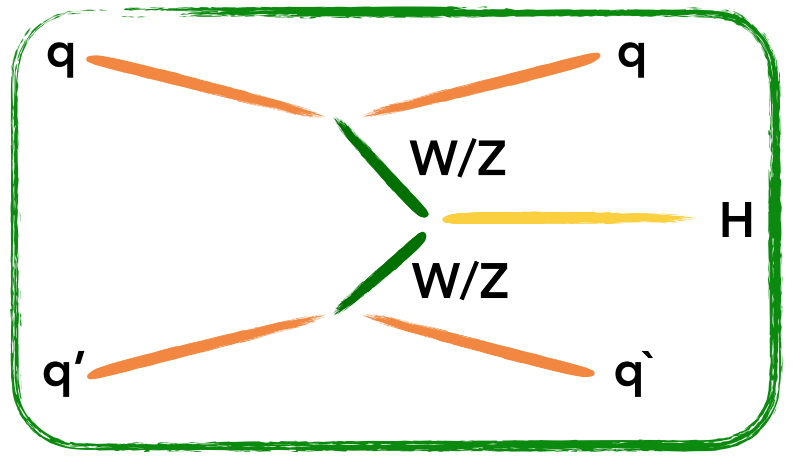


gluon-gluon fusion



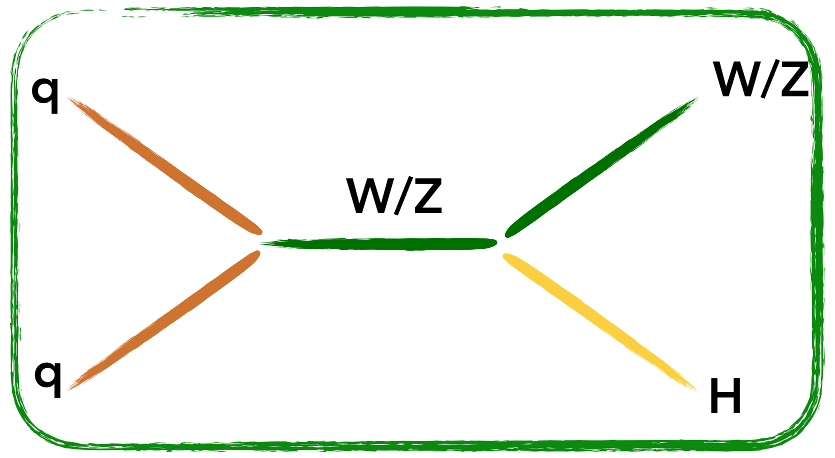
(ggF)

vector boson fusion



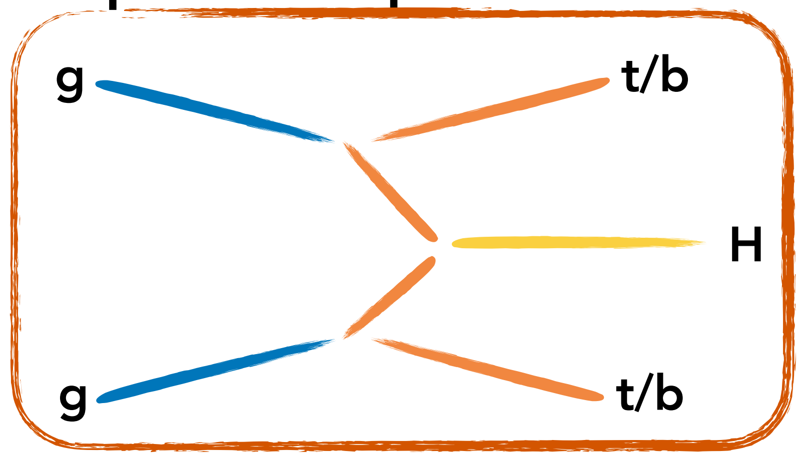
(VBF)

Higgstrahlung



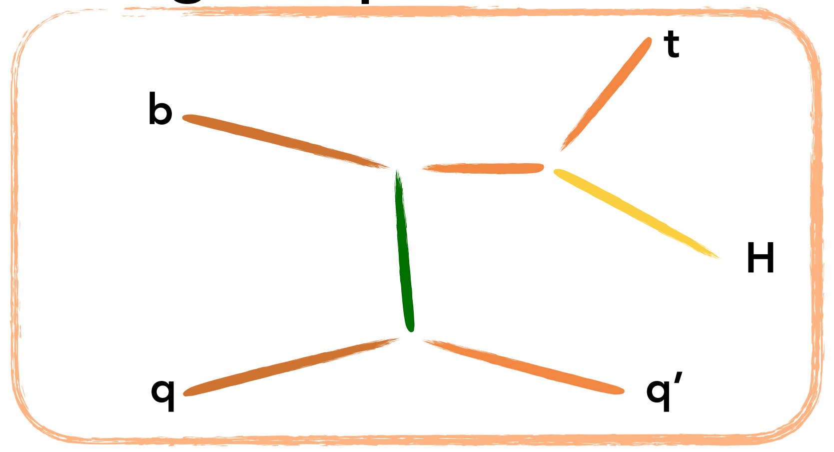
(VH,V=W,Z)

top-anti-top associated



(ttH)

single-top associated

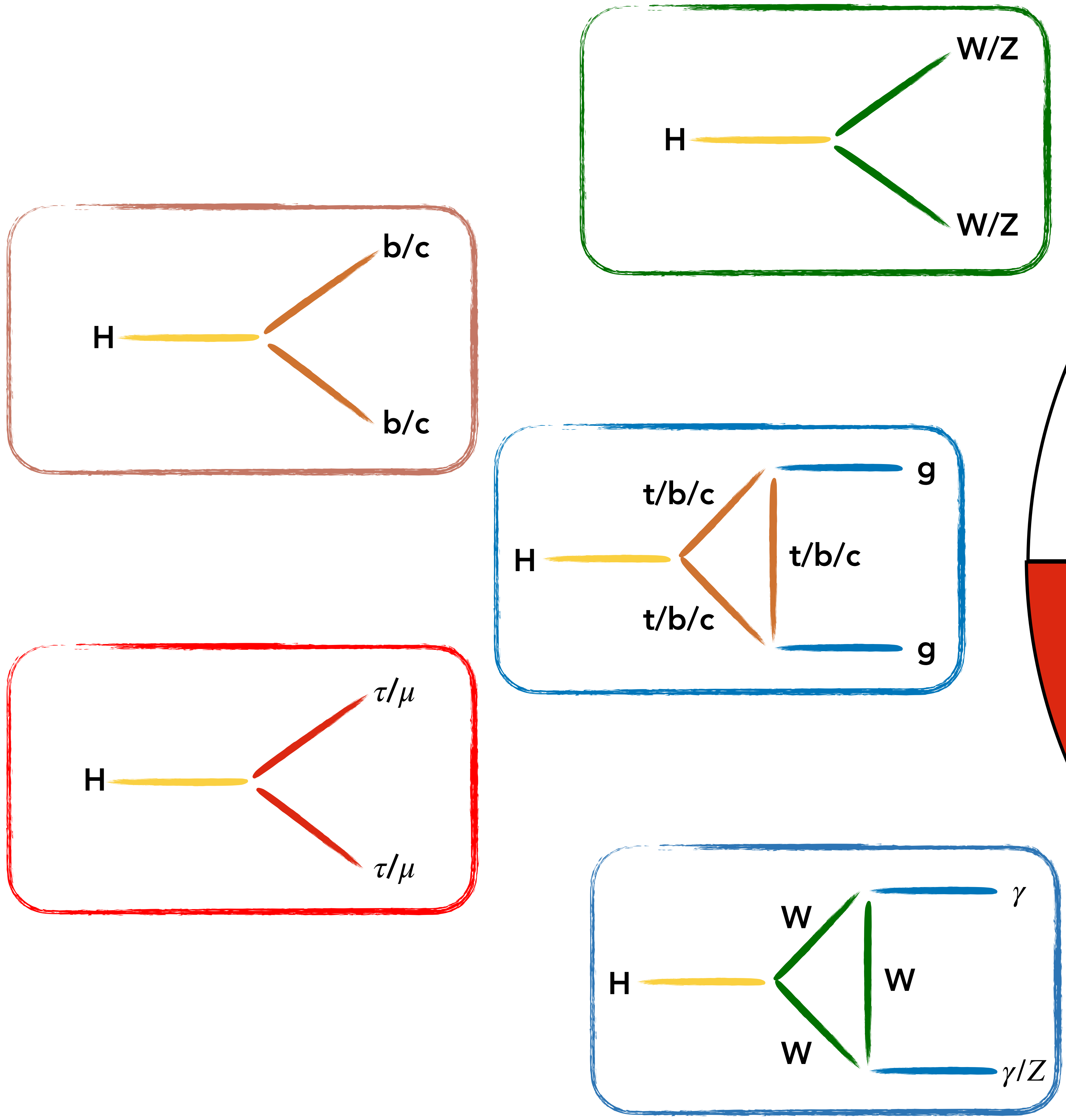


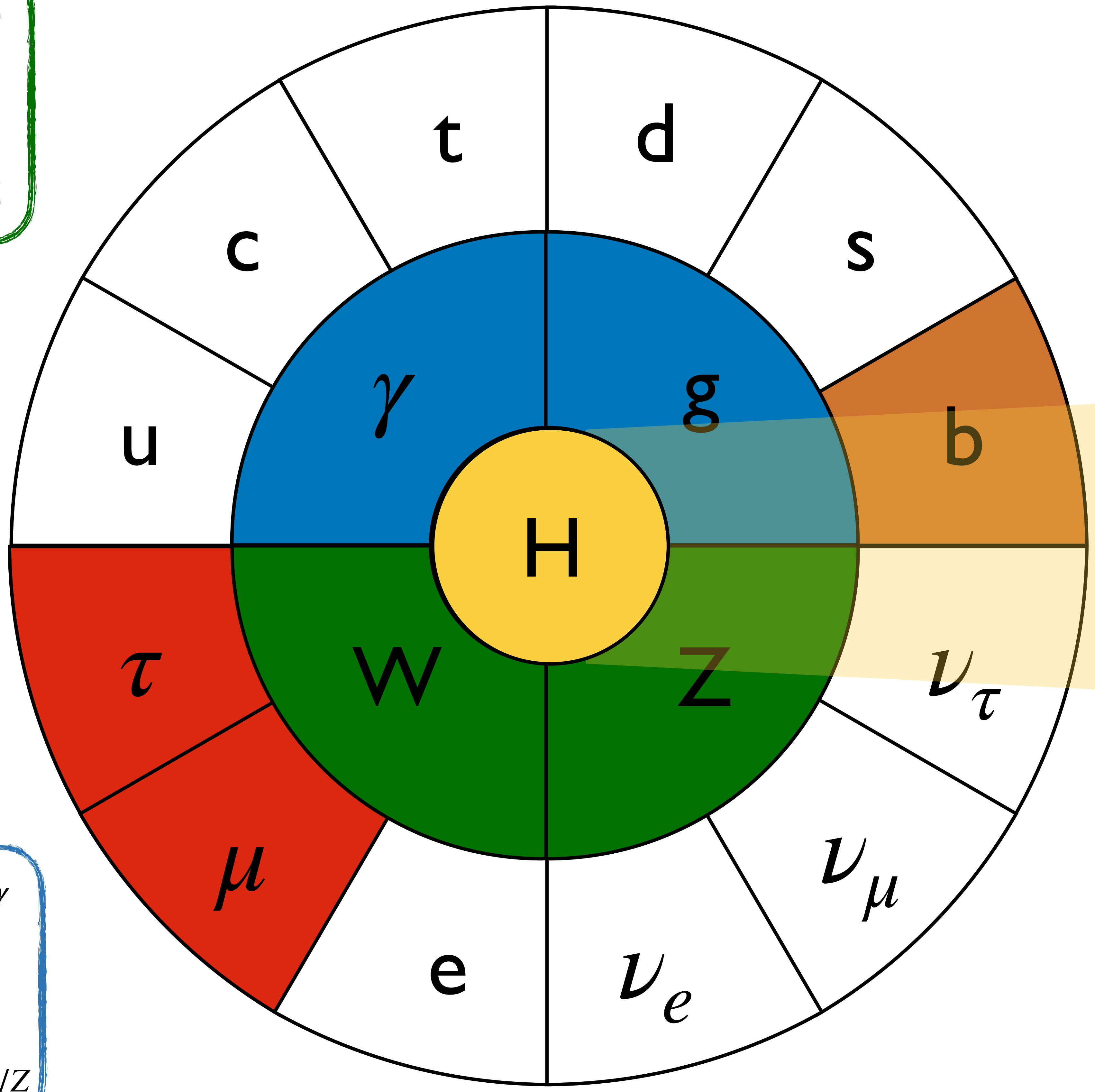
(tH)

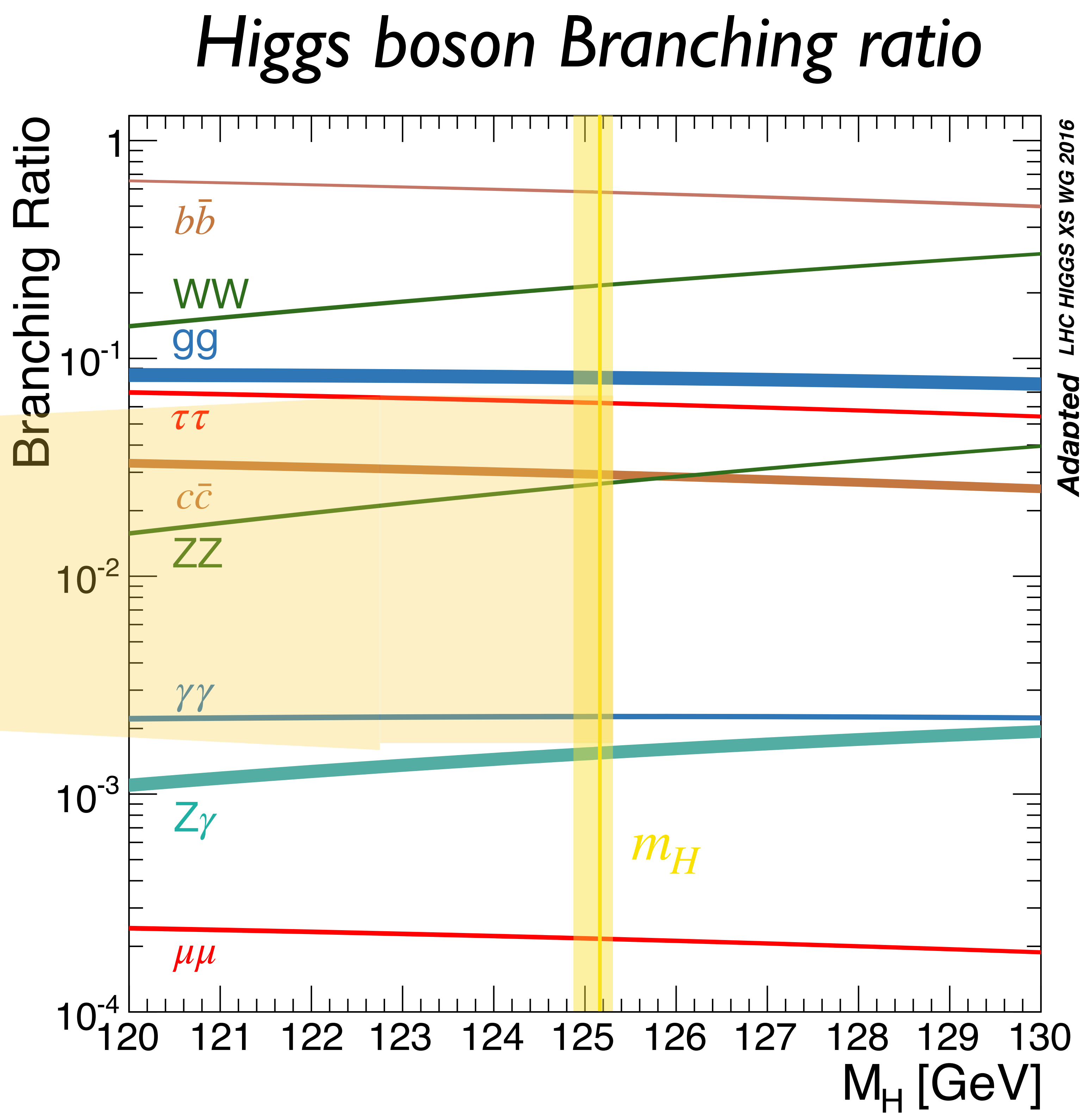
Cross-section of different modes, varies across 3-orders of magnitude !

Kinematic features of the processes allows to pin-down the production

Observing Higgs bosons



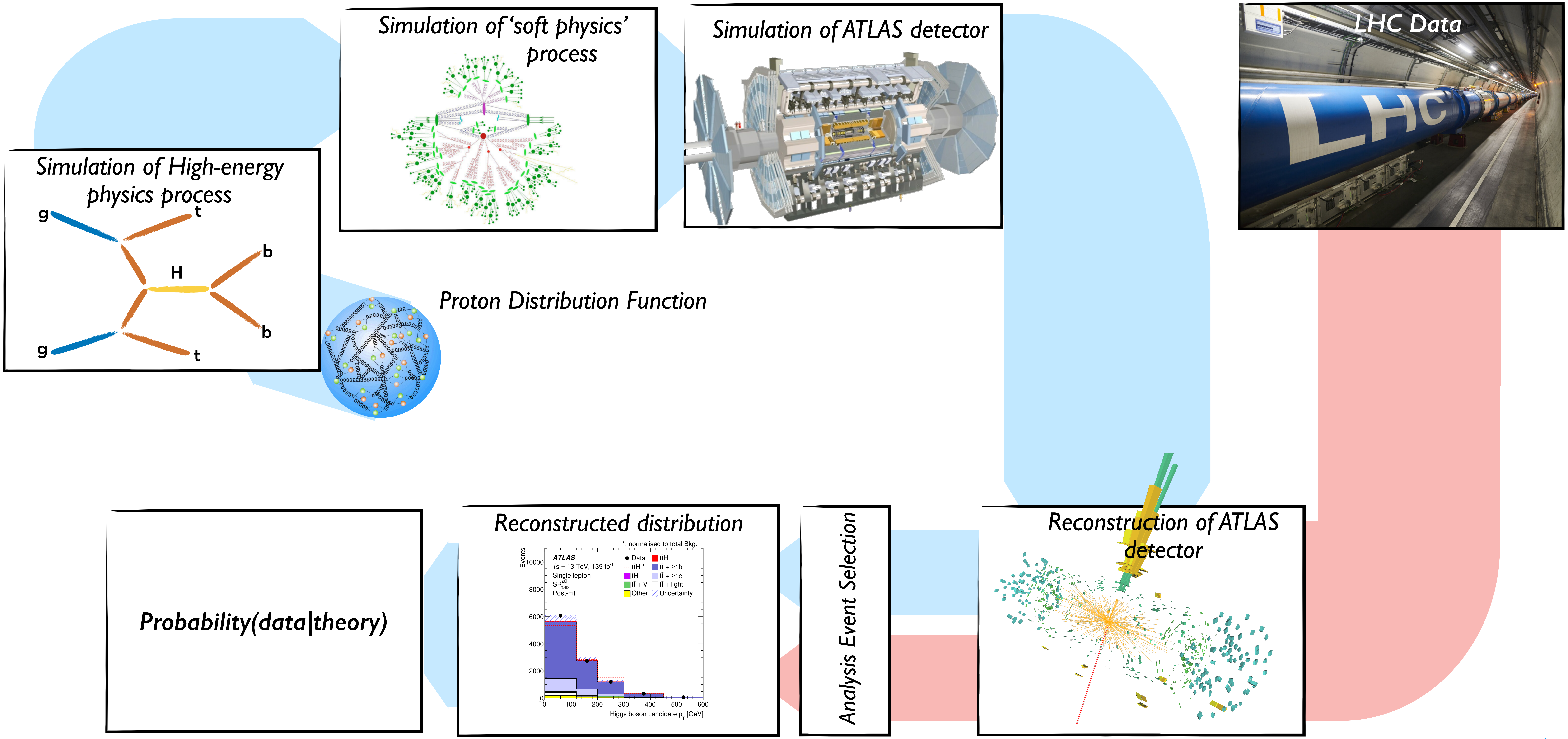




Higgs boson has a narrow width (4.07 MeV) and **decays instantaneously** ! (~10^{-22} sec)

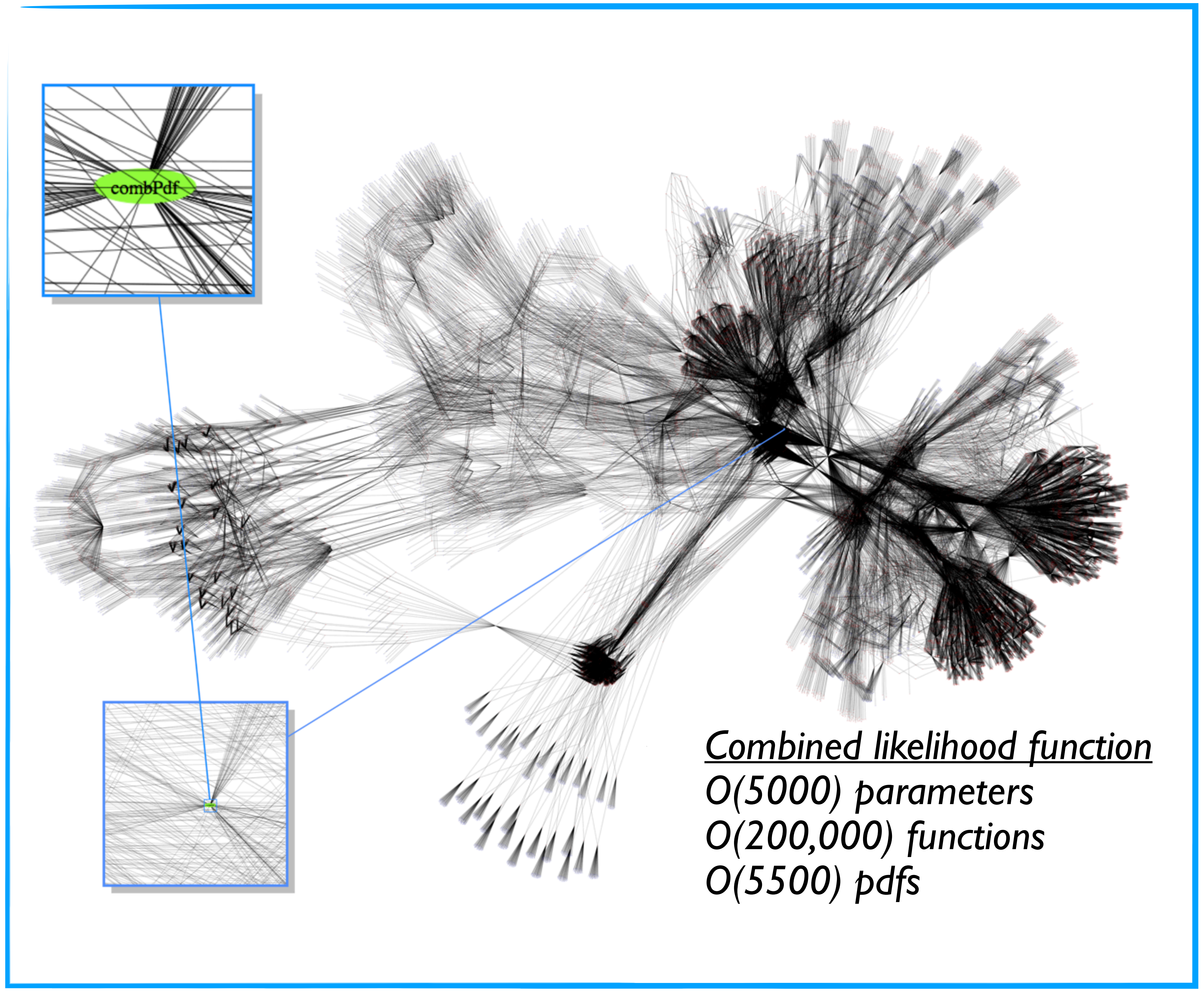
Decays to all particles except the top quark → multiple channels to study Higgs boson

ATLAS workflow : testing physics theories with data



testing physics theories with data : Likelihood function

Likelihood function, L(data|theory), is used to perform statistical inference on physics parameters



likelihood function captures,

i. Behaviour of theory model parameters on observables *For ex. :* ***Higgs boson signal strength*** — *Parameters of interest*

ii. Systematic uncertainties from experimental sources
For ex. : ***Calibration of Jet energy scale***

iii. Theoretical uncertainties on model
For ex. : ***PDF scale and factorisation uncertainty***

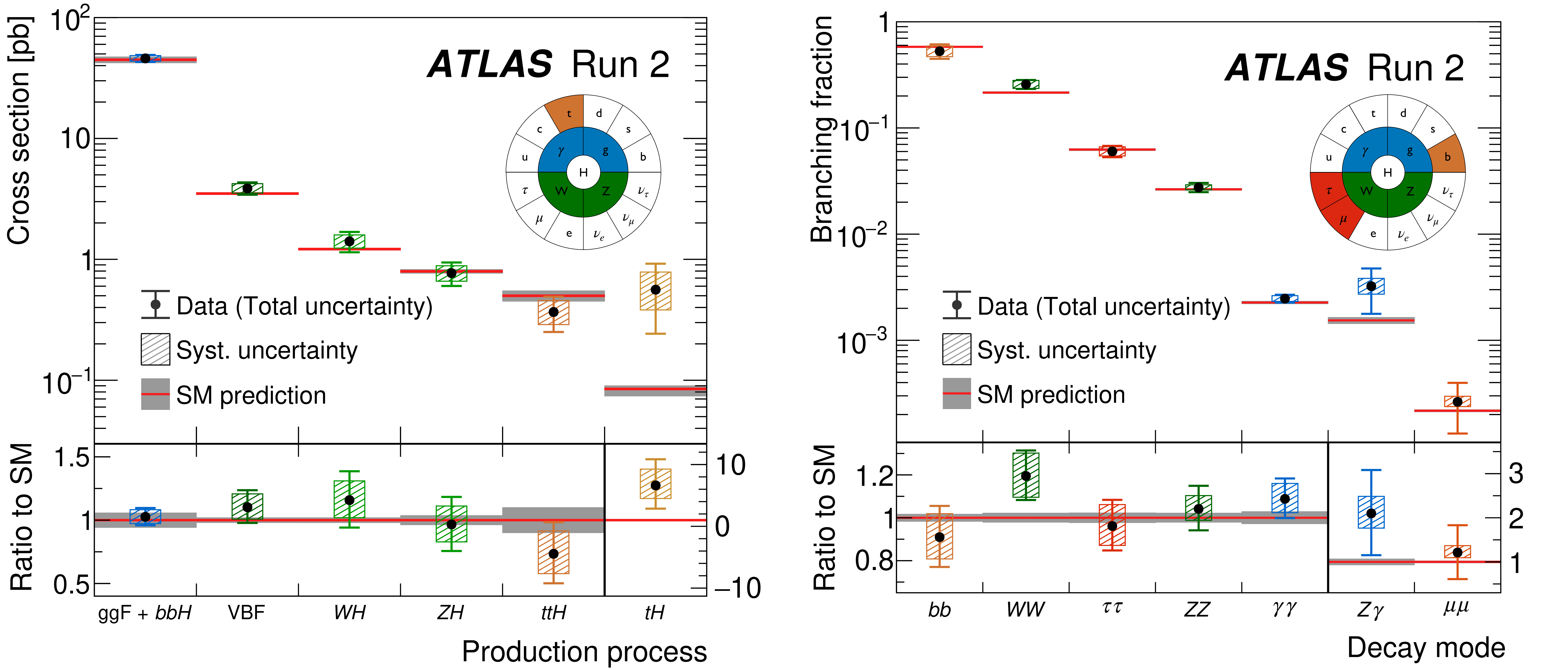
(ii and iii: *Nuisance Parameters*)

iv. Consistent signal & background modelling across different analyses
Avoid overlapping kinematic regions to extract information

Higgs inclusive measurements at ATLAS

Nature 607, 52 (2022)

Run-2 **30x as many Higgs** wrt Run-1, allows for precise measurements of cross-sections & couplings



All major production modes have 5σ observation and **for tH** 95% obs. (exp) upper limit of **15 (7) x SM**

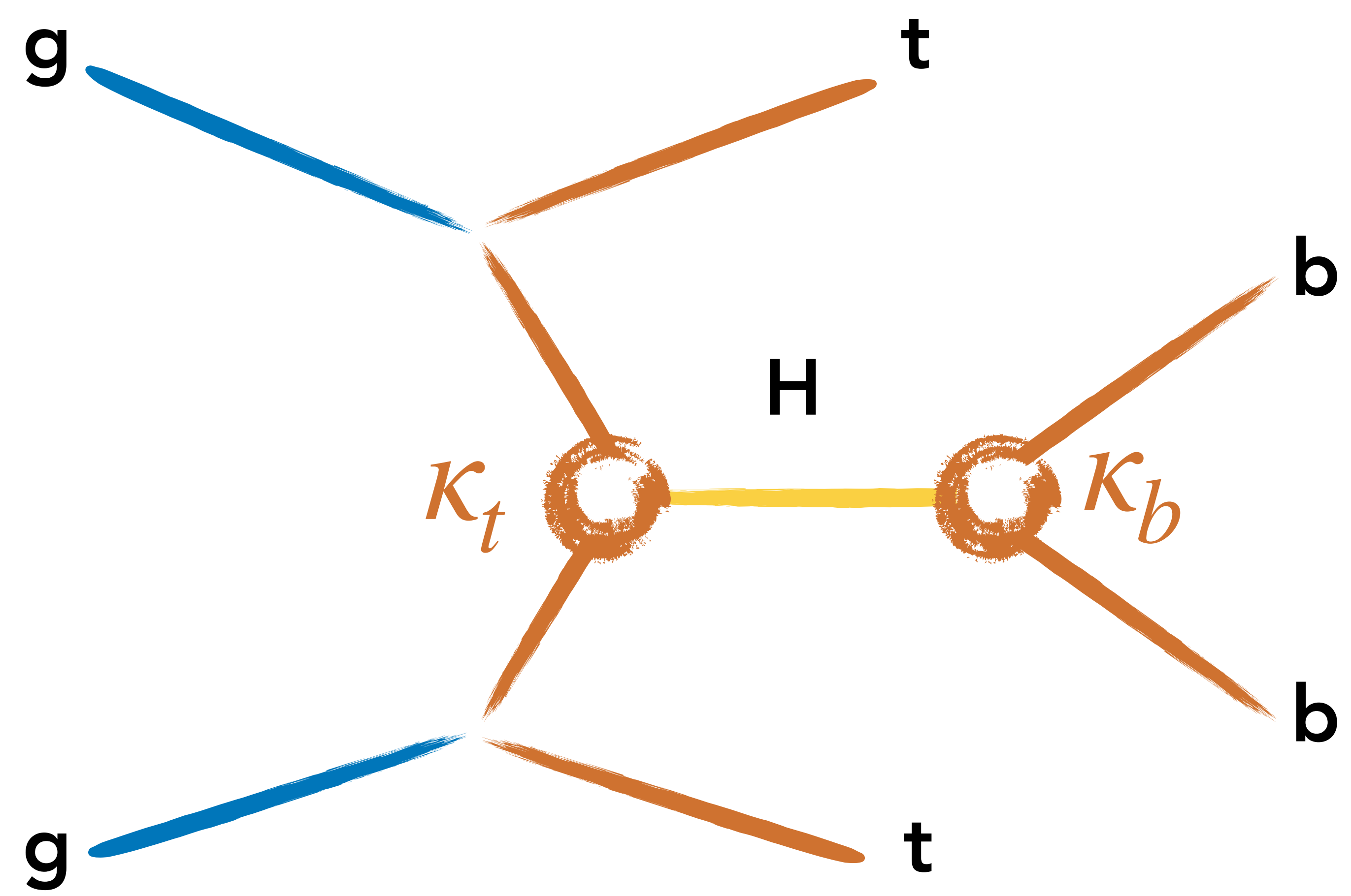
Strong indications for **rare Higgs decays** : obs. (exp) significance of 2.0σ (1.7σ) for $H \to \mu^+\mu^-$

and 2.3σ (1.1σ) for $H \to Z\gamma$

Higgs couplings to particles

Experimentally motivated couplings (κ) framework designed in Run-1 to check compatibility of inclusive measurements w.r.t SM

For instance, ttH, H→b$\bar{b}$,



$$\sigma(ttH, H \to b\bar{b}) = \sigma(ttH) \times \frac{\Gamma(H \to b\bar{b})}{\Gamma(H)}$$

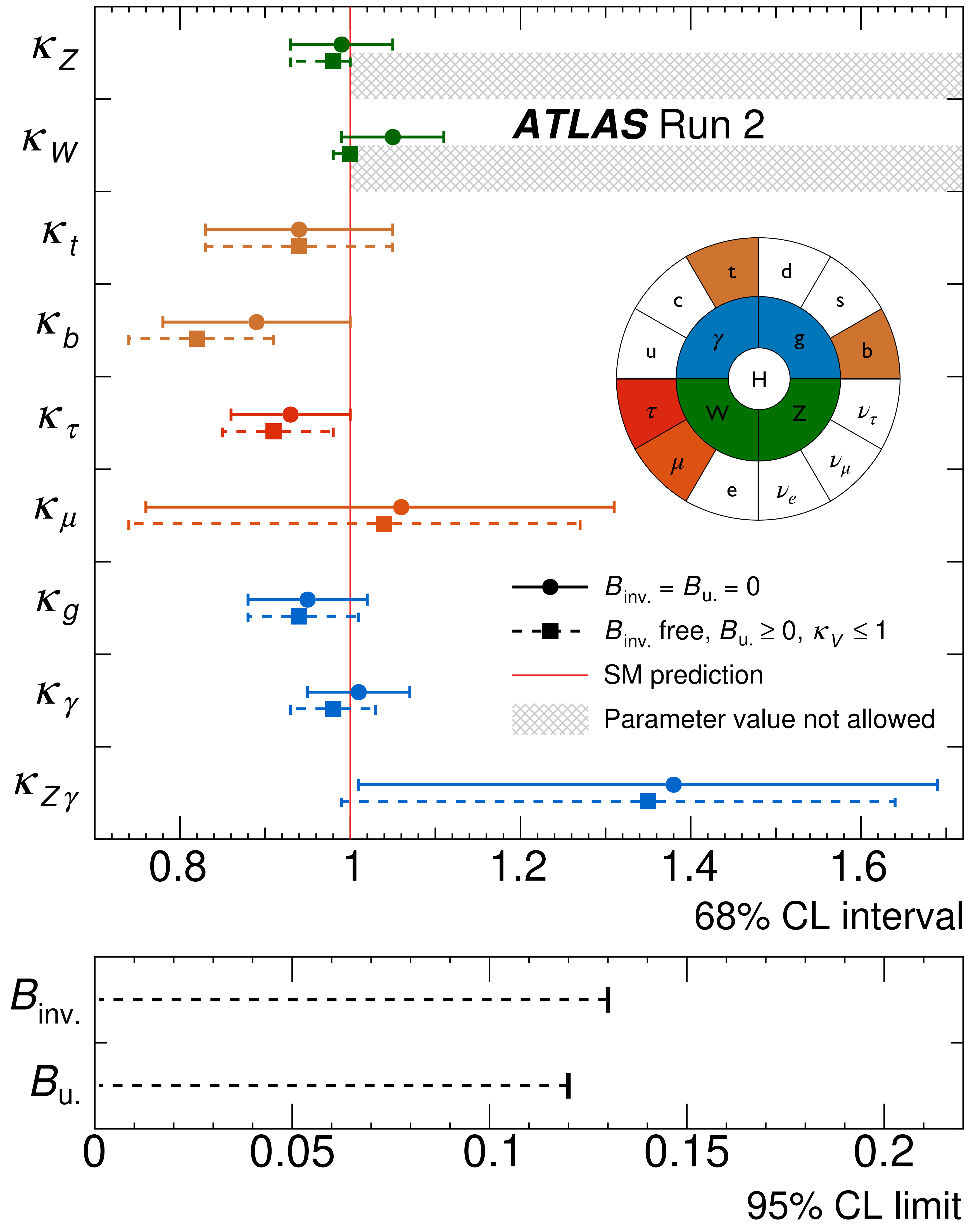
$$= \frac{k_t^2 k_b^2}{k_H^2} \sigma_{SM}(ttH) \times \frac{\Gamma_{SM}(H \to b\bar{b})}{\Gamma_{SM}(H)}$$

Framework is designed for rates, **not sensitive to kinematic distributions**

Is a LO - order framework and **not a QFT** that extends the SM

With a more sophisticated couplings framework like an Effective Field theory, information of kinematic distributions is crucial !

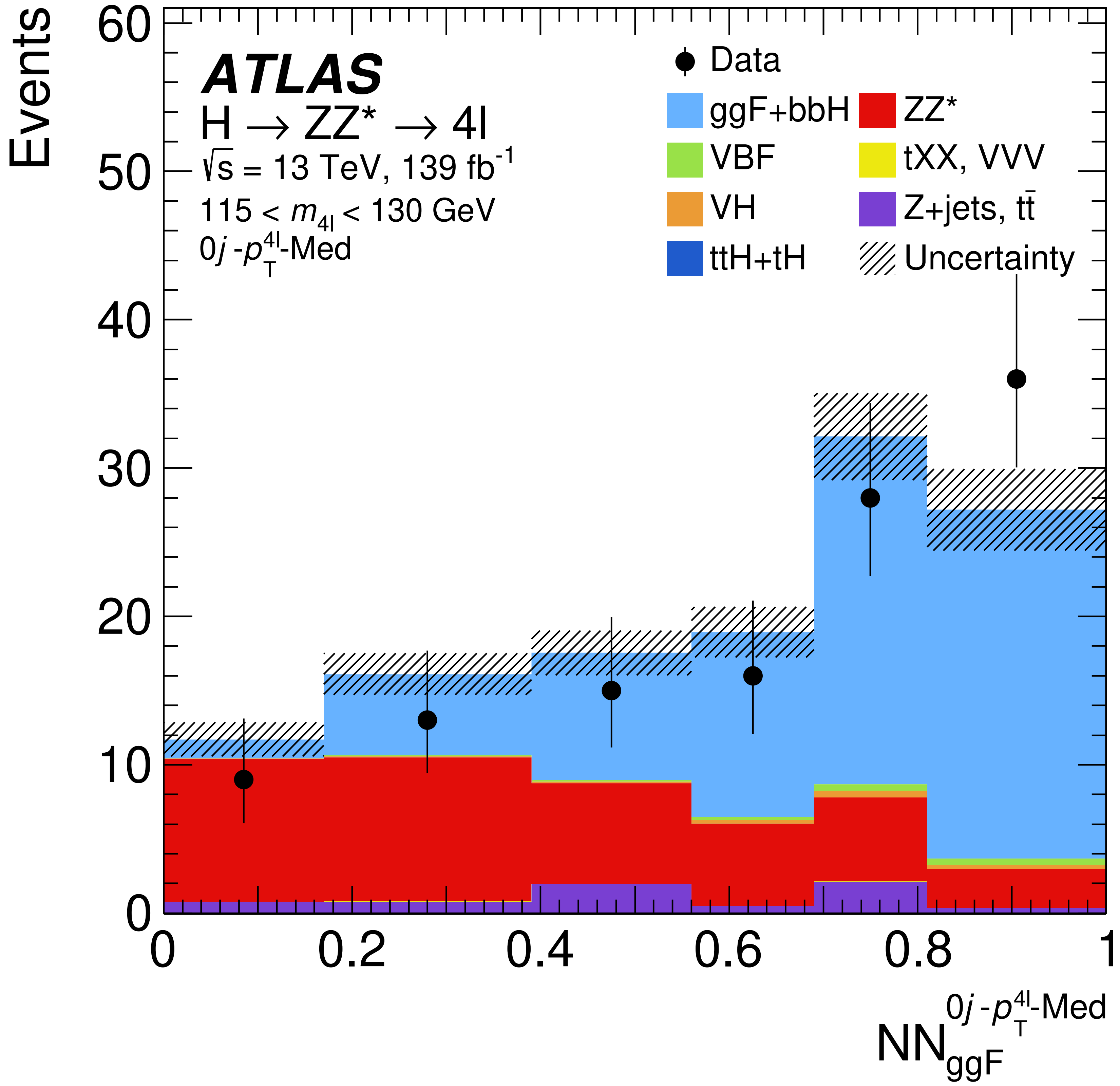
Higgs boson generic couplings to SM particles



Analysing Higgs boson - a concerted effort

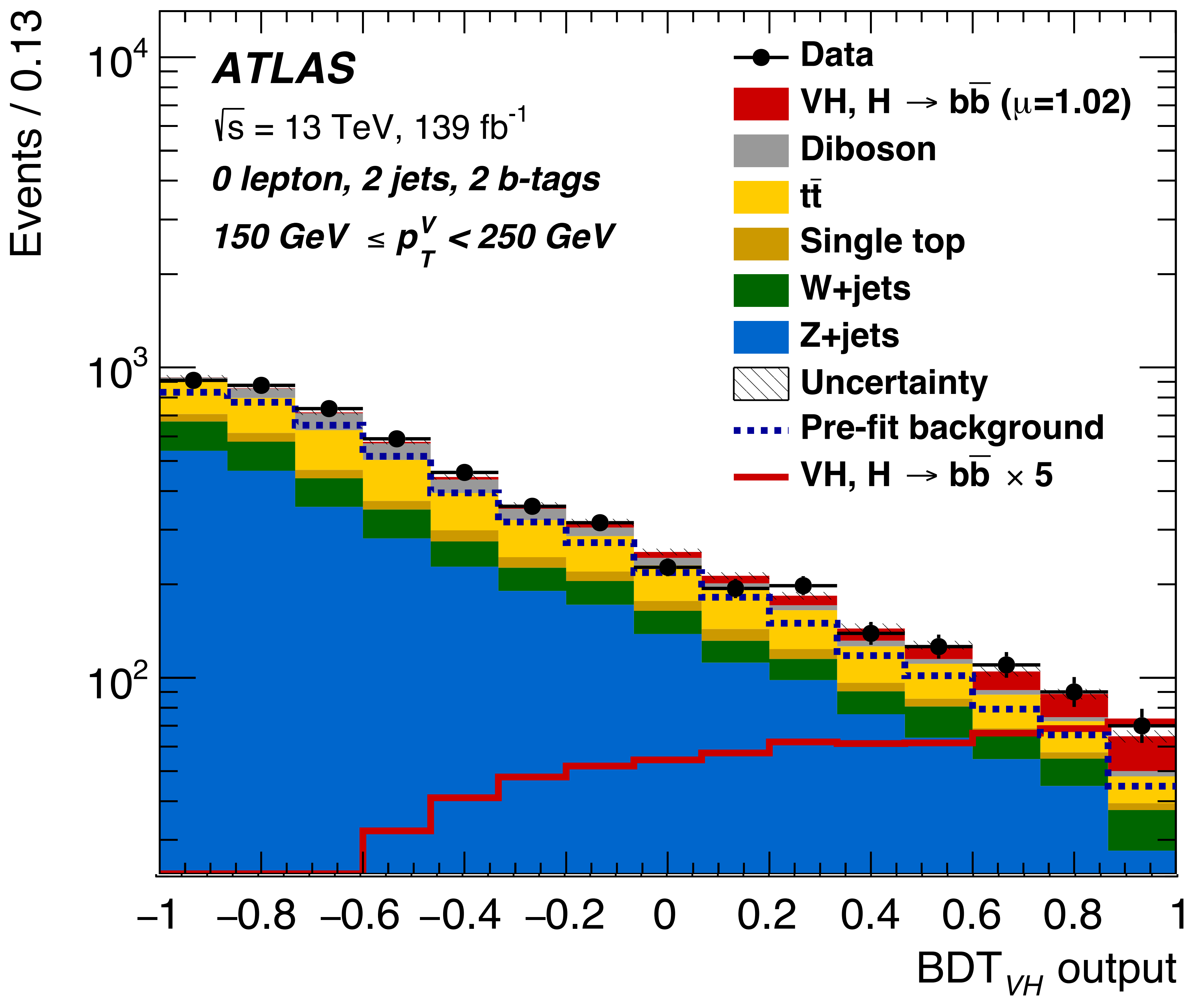
- Each measurement consists of multiple signal regions, designed to selected target Higgs production
- Distribution of a (multivariate) discriminant is interpreted in terms of sum of signal and background

$H \rightarrow ZZ^* \rightarrow 4l$



(low bkg, high res. : $\delta m \sim 2$ GeV)

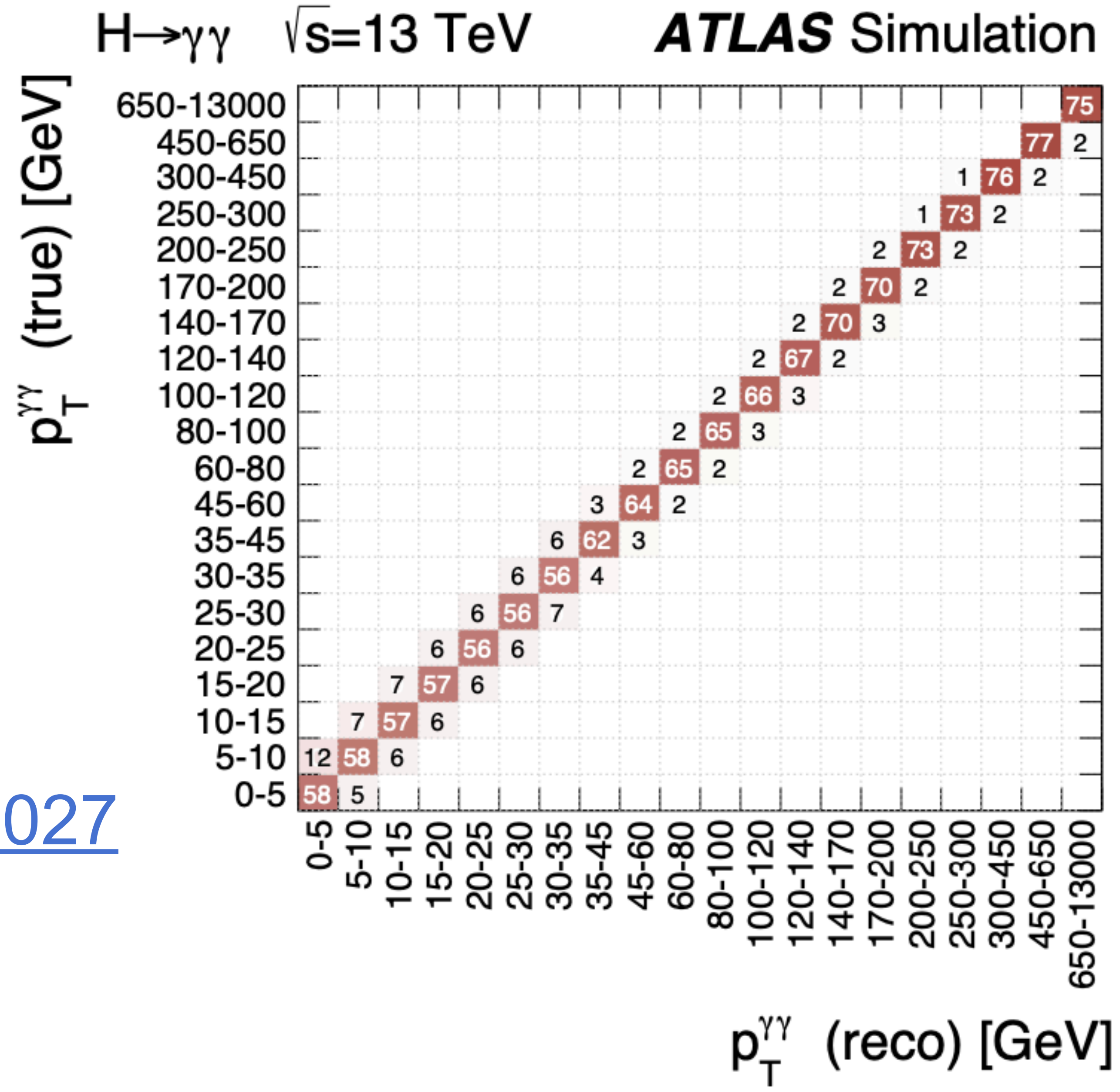
$H \rightarrow b\bar{b}$



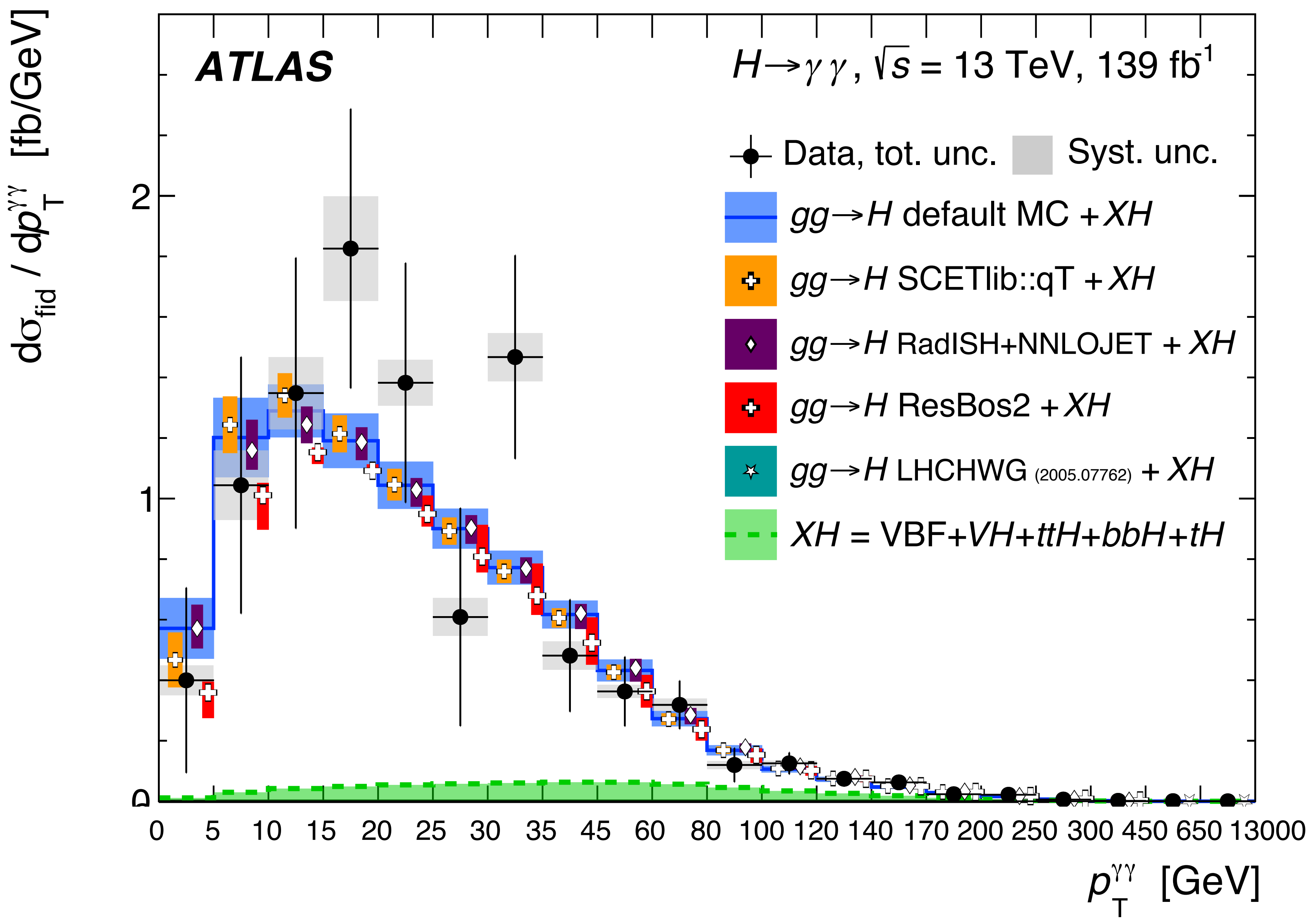
(large bkg, low res., : $\delta m \sim 10$ GeV)

Unfolding Higgs boson kinematics

A well conditioned response matrix



Fiducial differential cross-section of p_T^H with $H \rightarrow \gamma\gamma$



Ex. based on

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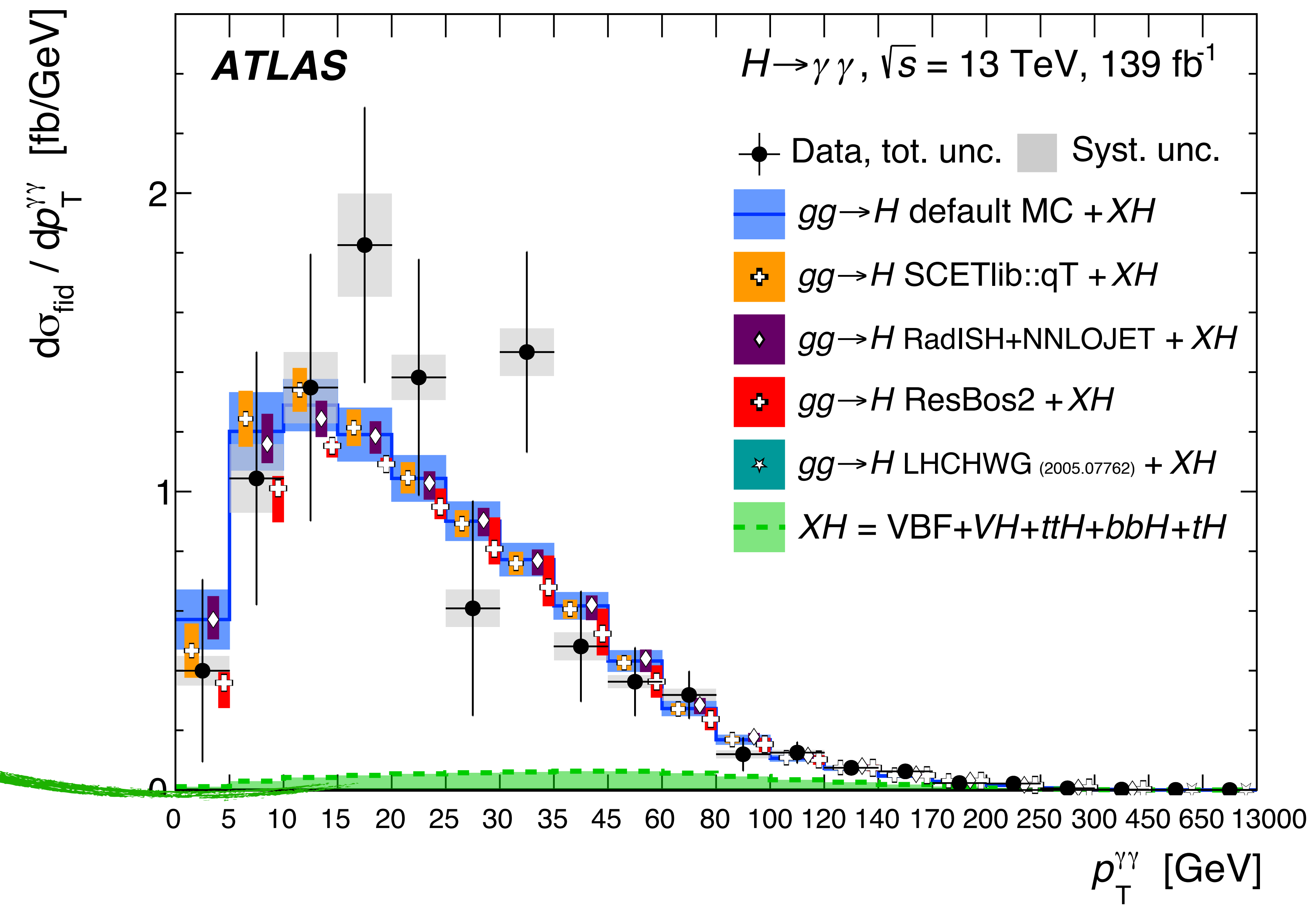
- One way to study kinematic properties of Higgs boson is to unfolding, typically with maximum likelihood method, to obtain differential measurements, *usually limited to one or two-dimensional distributions*
- Well suited for high precision, low background channels which can rely on simple cut-based analysis without needing multivariate discriminants, *non-trivial to map multivariate discriminants in fiducial phase space*
- Can be easily compared to theory predictions, *harder to combine different channels without involving extrapolation to full phase space*

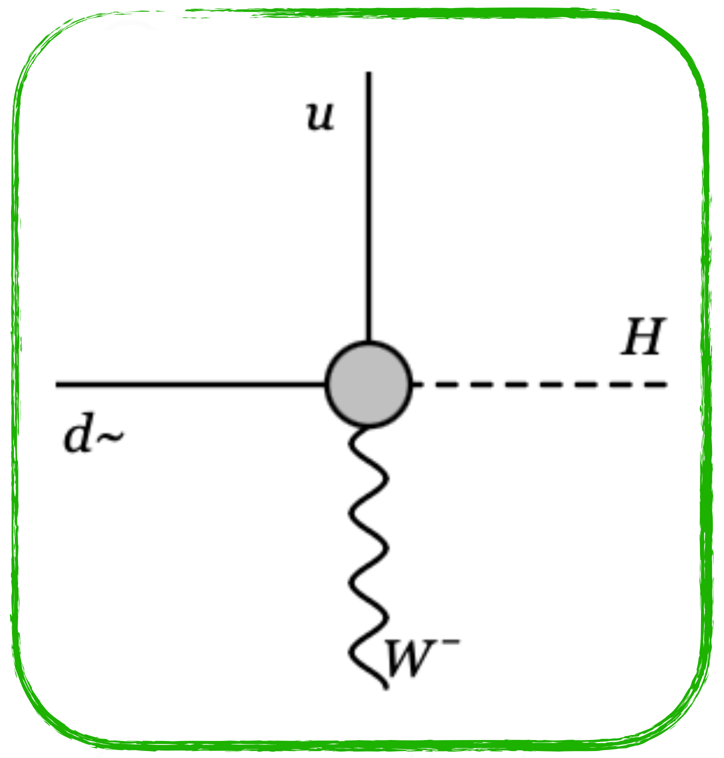
Sensitivity to new physics

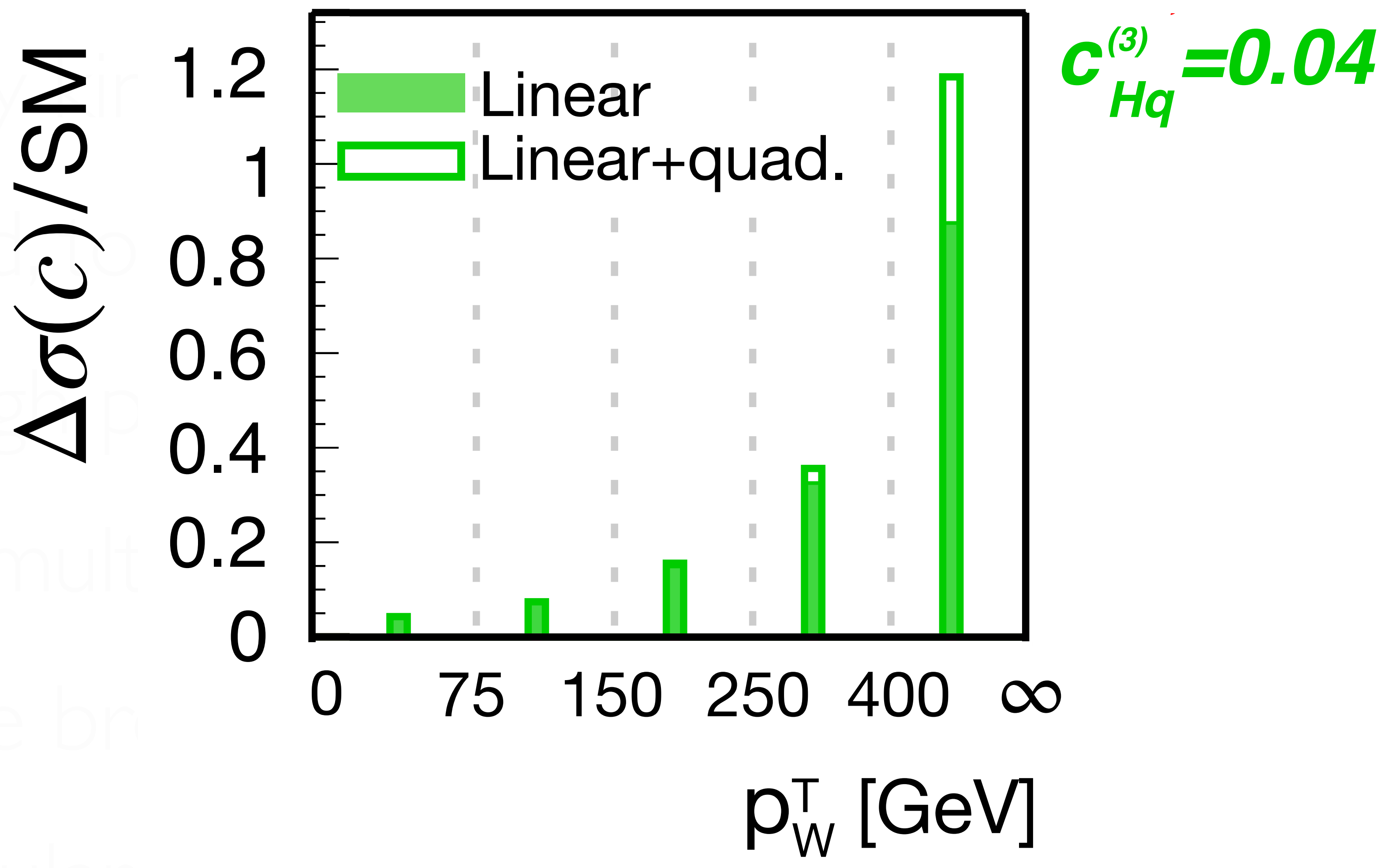
Fiducial differential cross-section of p_T^H with $H \to \gamma\gamma$



The p_T^H spectrum is dominated by gg→H, new physics affecting any other production mode will be diluted in this observable

For instance $O_{Hq}^{(3)}$,



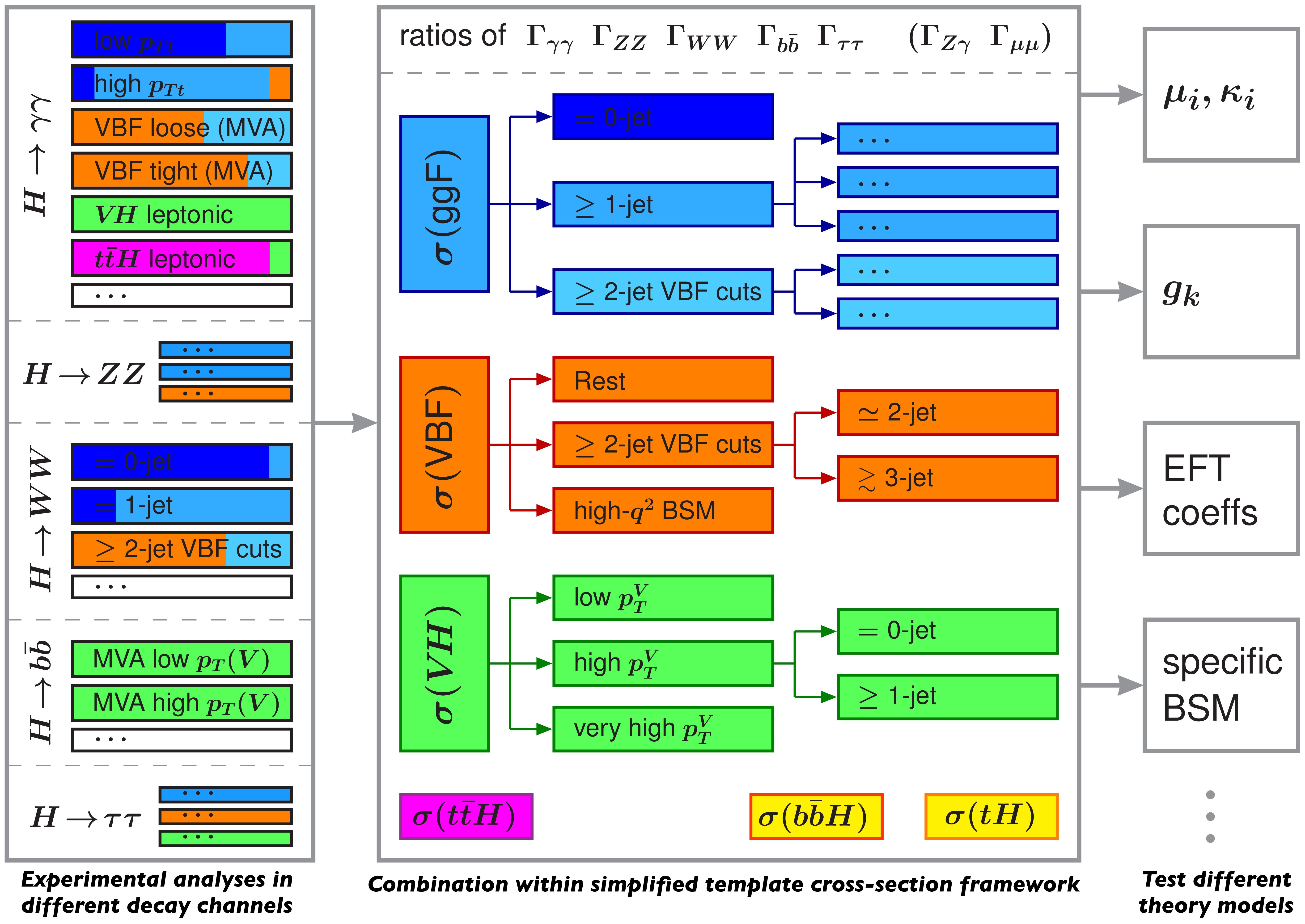


Need to measure different production modes separately to gain sensitivity

Measurement must isolate bins which are additionally sensitive to new physics effects (tails of operators)

Simplified template cross-sections (STXS)

✦ Measure production mode cross-section in fiducial volumes, designed to separate out different production modes



Design guided by,

- Minimise model dependence and maximise experimental sensitivity
- Allow isolation of possible BSM effects
- Staged binning : evolves in granularity with more data

There is some residual model dependence as some regions cannot be fully distinguished at reco. level ex. ggF+2jet vs VBF

Fiducial bins measured based on the maximum likelihood method

STXS analysis : the Higgs → $\gamma\gamma$ case

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- Analysis measures kinematic properties of key production modes with full Run-2 dataset

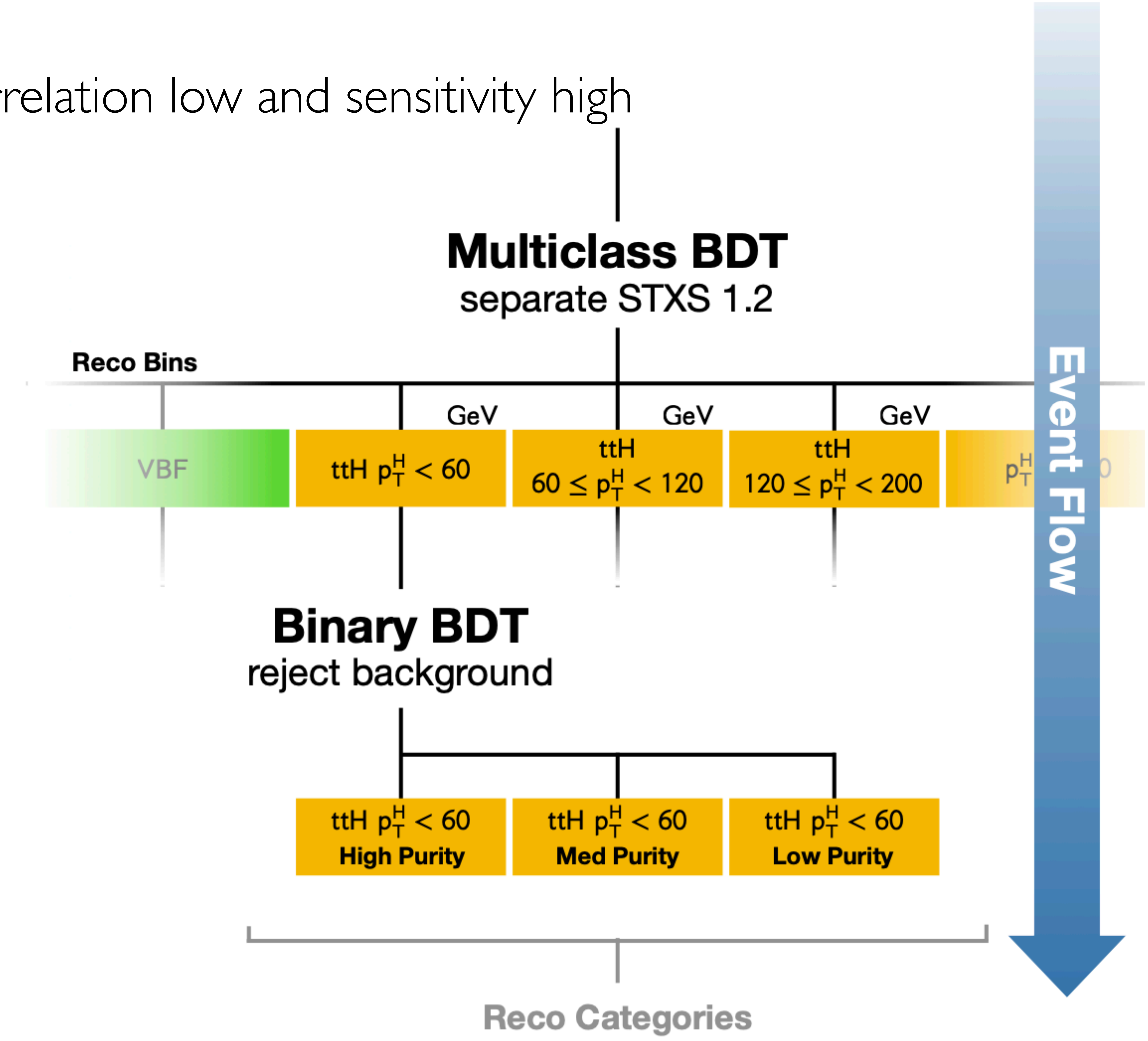
- Split events into different STXS bins while keeping correlation low and sensitivity high

- Two step categorisation approach,
  i. signal-vs-signal: First, a multiclass BDT to separate all signal classes

  ii. signal-vs-background: Second, a binary BDT to reject non-resonant background (γj, jj)

- Multiclass BDT boundaries decided based on D-optimality , perform iterative categorisation and minimise the determinant of the covariance matrix

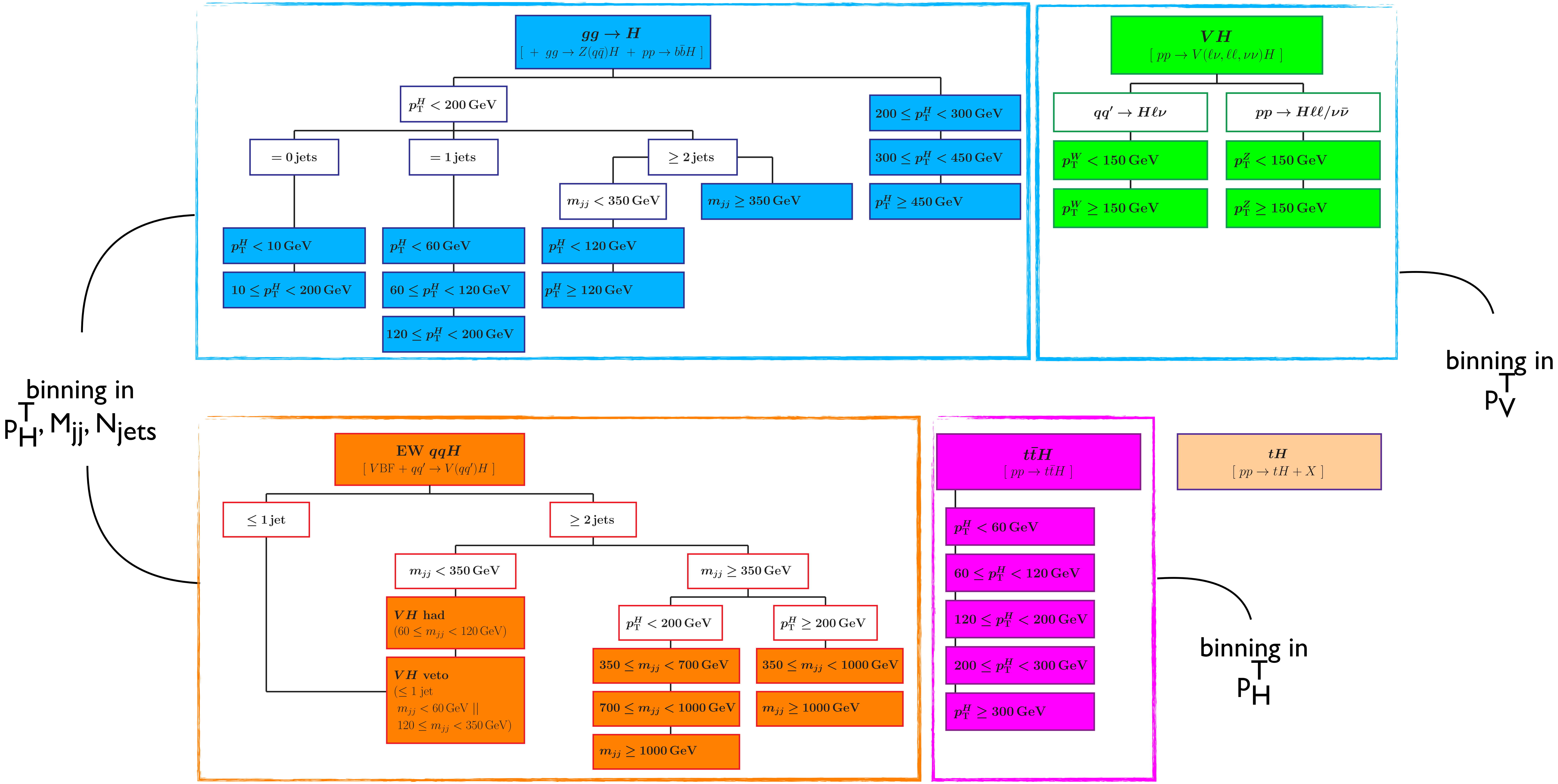
- Allows to minimise overall uncertainty and correlation across cross-section measurements



http://dx.doi.org/10.7488/era/3404

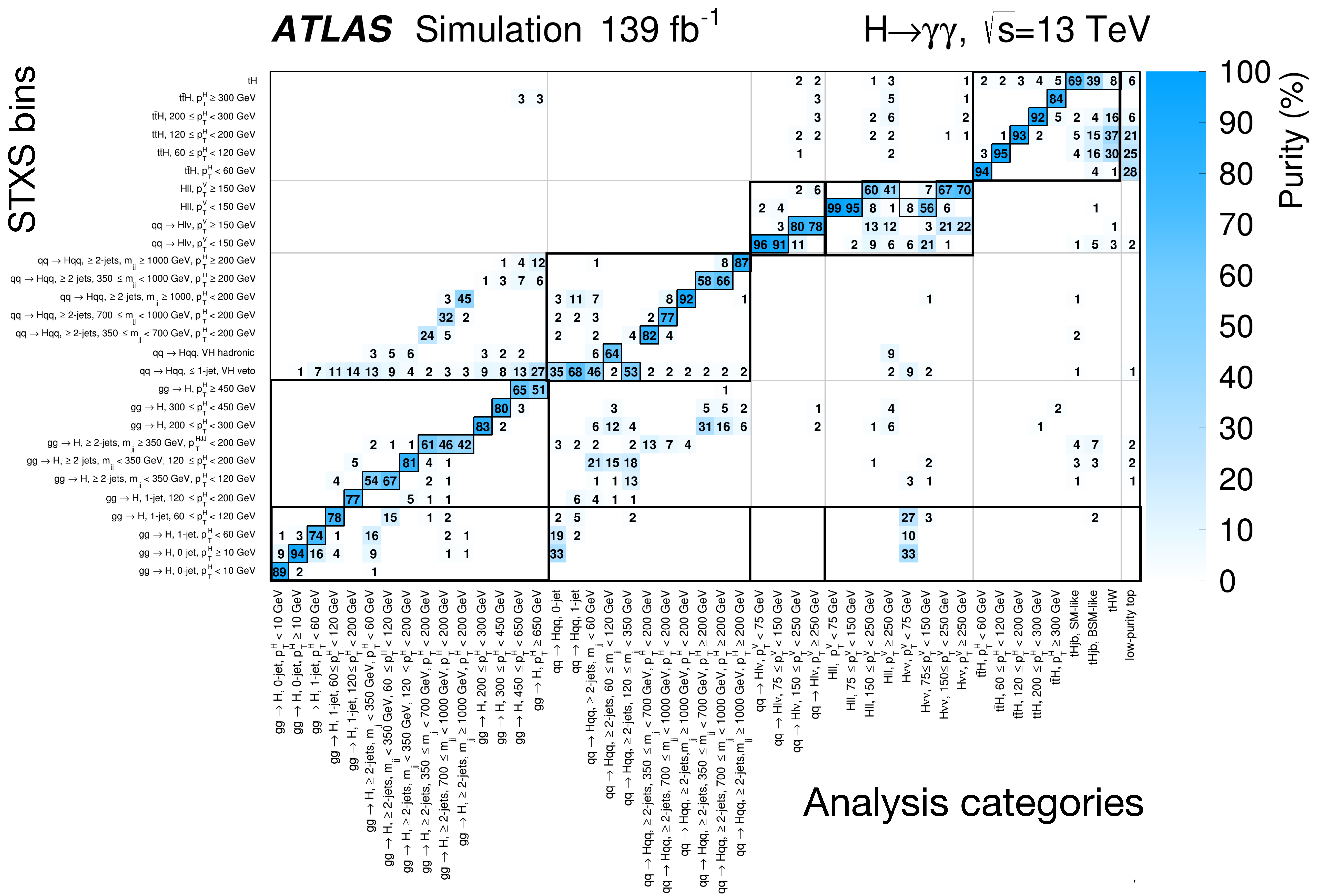
STXS bins measured

STXS bins reported by H → $\gamma\gamma$ corresponds to merged bins of the STXS fine bin definitions



Note that final STXS binning is much more finer when combining with

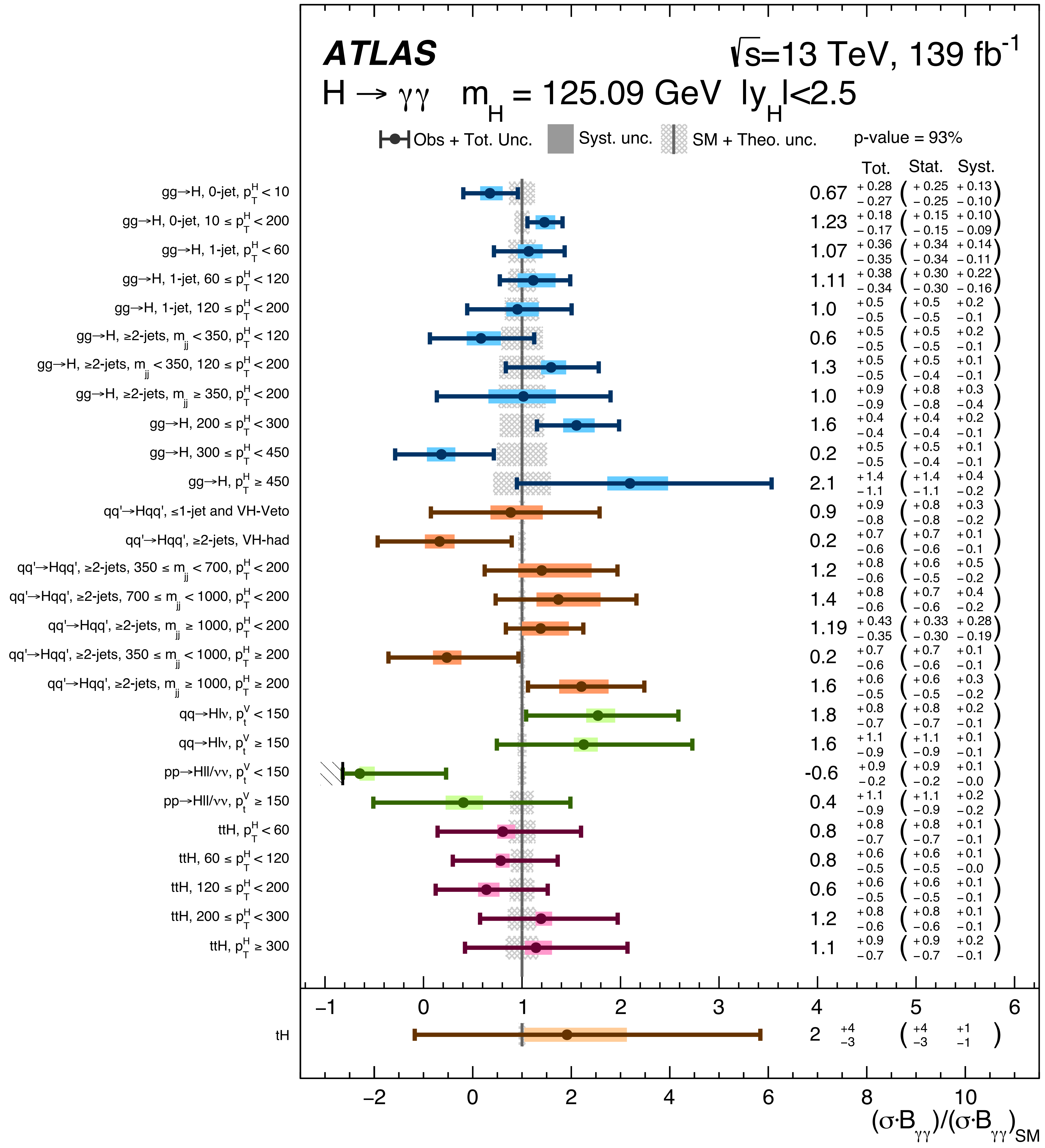
Signal purity for categories



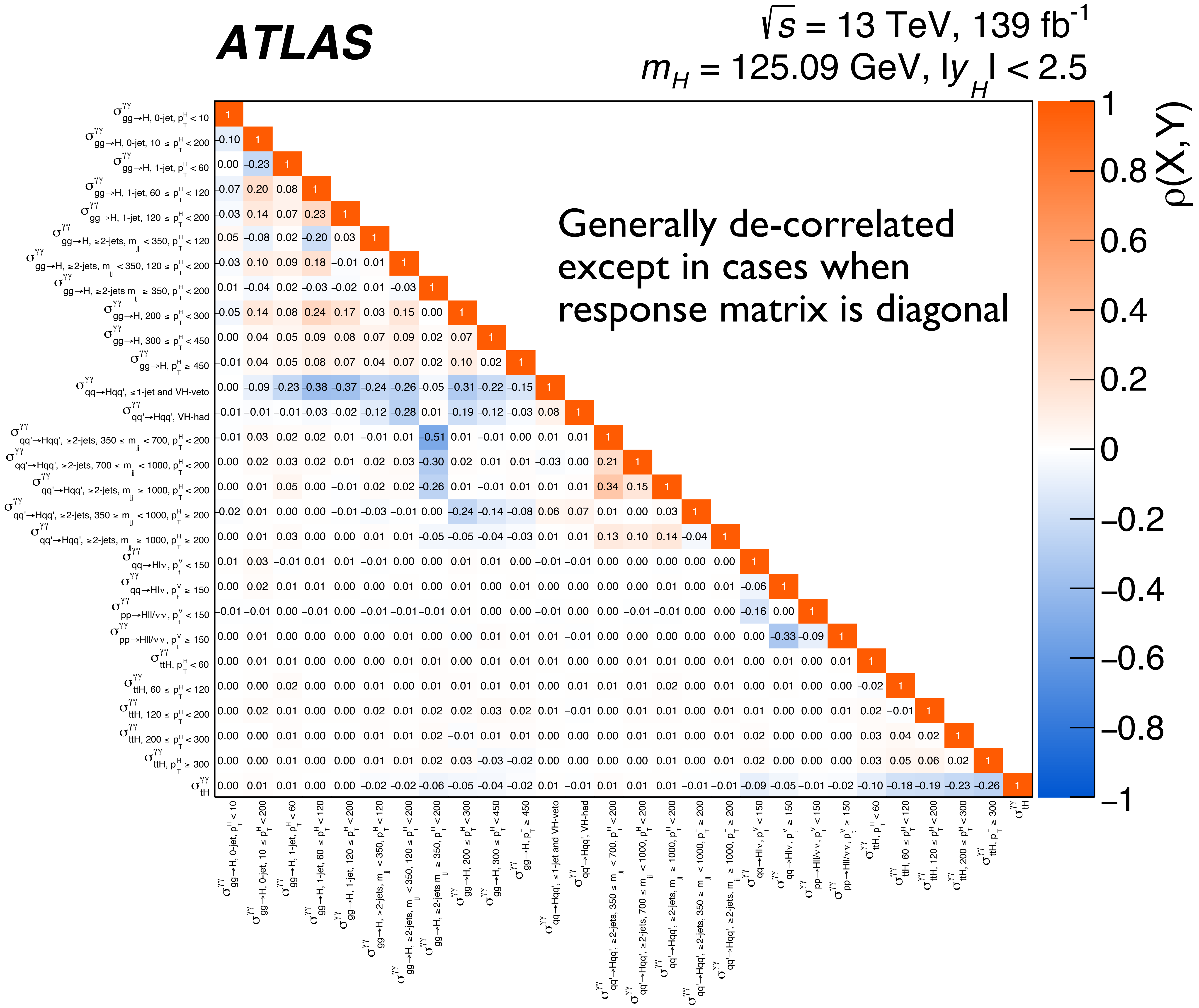
Typically, analysis categories finer than final STXS bins

What is published

Signal strength for each STXS bins



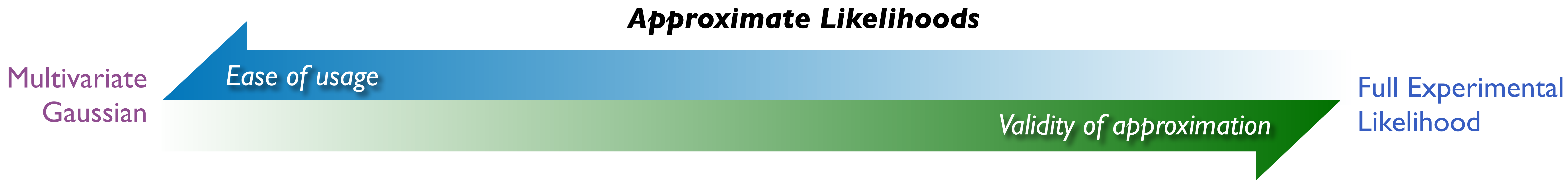
Correlation matrix of bins



Generally de-correlated except in cases when response matrix is diagonal

Interface between theory & experiment

Experimental likelihood function captures all relevant statistical information of measurement *(calibration, theory uncertainties, etc)*



Simplified likelihood

Multivariate Gaussian approximation of the signal-strength measurements → **best-fit + covariance matrix**

$$L(\boldsymbol{\mu}) = \frac{1}{\sqrt{(2\pi)^{n_\mu} \det(V_\mu)}} \exp\left(-\frac{1}{2}\Delta\boldsymbol{\mu}^\intercal V_\mu^{-1} \Delta\boldsymbol{\mu}\right)$$

$$\prod_b^{n_{\text{bins}}} \text{Poisson}\left(N_b \middle| N_b^{\text{pred}}(\boldsymbol{c}, \boldsymbol{\theta})\right)$$

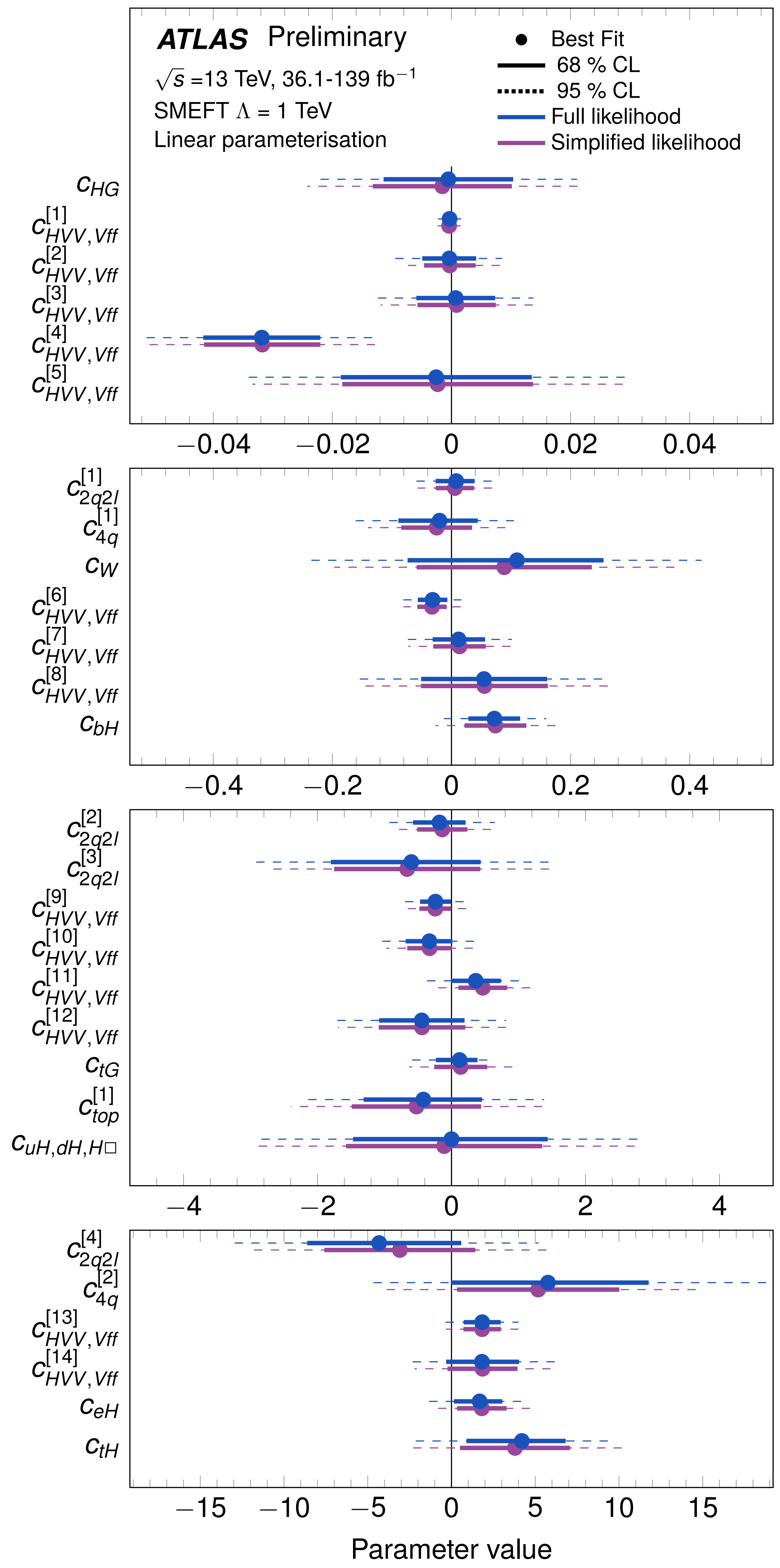
Higgs analyses categories

$$\times \prod_i^{n_{\text{theo syst}}} f_i\left(\theta_{\text{theo syst},i}\right) \times \prod_i^{n_{\text{exp syst}}} f_i\left(\theta_{\text{exp syst},i}\right)$$

Constraint term of systematic effects

Interface between theory & experiment

multivariate Gaussian provides a reliable approximation !



Simplified likelihood provides a good approximation of overall constraint,

but no additional information on systematic uncertainties!

Available on public page of ATLAS publication note ATL-PHYS-PUB-2022-037

i. **best-fit + covariance matrix** of 128 signal-strength measurements

ii. Corresponding EFT parameterisation

Generally good agreement between **simplified** and **full likelihood**, not expected to match exactly as the measurements are not exactly Gaussian

Outlook

- Good progress on Higgs boson kinematic measurements, evolved from inclusive cross-section measurements to measuring kinematic observables

- For Run-2, the STXS measurements are an important highlight to study Higgs boson properties. Well complemented by unfolded fiducial differential cross-section measurements across some channels.

- Results have also been used widely by the theory community for reinterpretation

- STXS is not by any means meant to be a static framework - serves as a guidance for analysis design and allow for combination across different Higgs decay channels

- active discussion within WG2: Higgs properties to extend and improve STXS, many ideas in the pipeline,
  - Including STXS-style binning on the Higgs decay side
  - Introducing kinematic splitting that are sensitive to CP-odd effects ($\Delta\phi_{jj}$)
  - Extending energy reach of STXS bin due to accommodate analyses with novel developments to probe boosted regime

Backup

Detailed kinematic picture of the Higgs boson

Increased dataset and new analysis techniques gives detailed kinematic information

Combining measurements from different analysis allows to study Higgs production across **4 orders of magnitude in cross-section**