HIGGS PAIR PRODUCTION
PROSPECTS FOR

Higgs Flavour and self-coupling

AT FUTURE COLLIDERS

SNOWMASS EF01 WORKING GROUP MEETING

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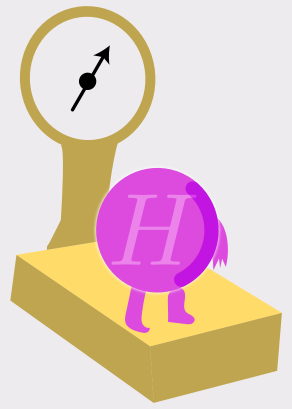
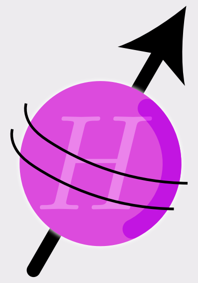
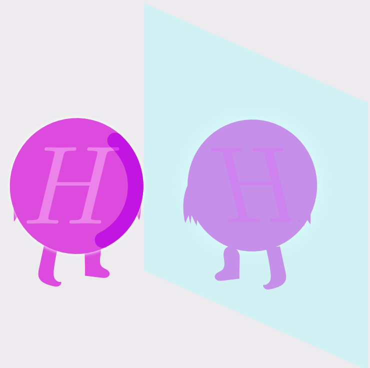
Knowns and unknowns about the Higgs



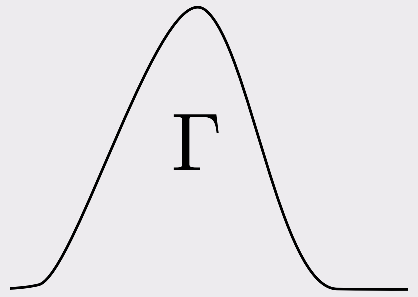
mass 124.94 GeV ATLAS, 1806.00242



spin 0 ATLAS 1506.05669

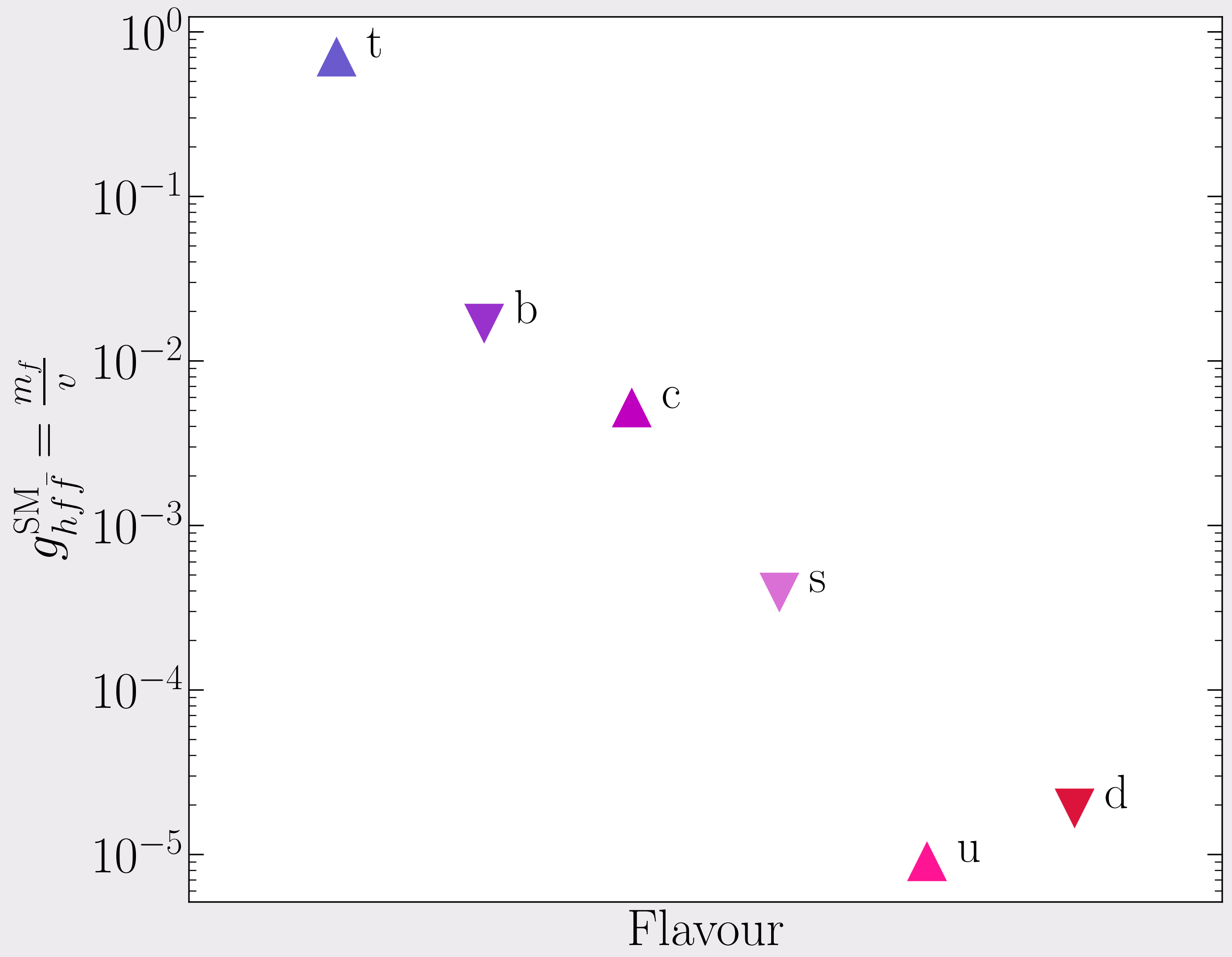


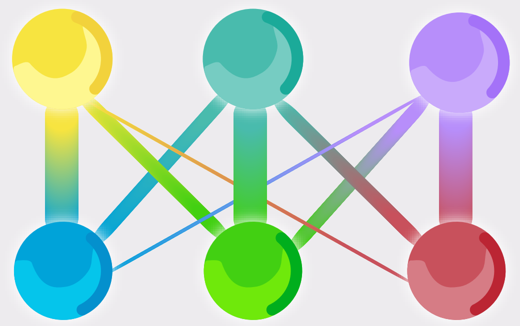
CP even mixture of CP even and odd is not fully excluded ATLAS 1506.05669



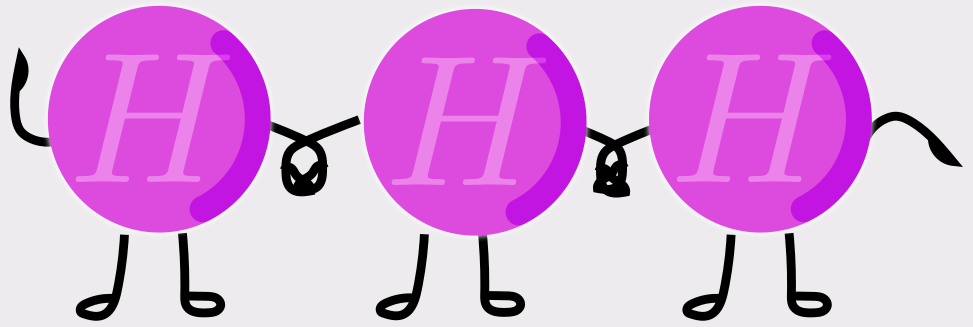
width $\Gamma < 3\Gamma_{SM}$

The LHC will not be able to measure the width better than this ATLAS 1808.001191





Coupling to lighter quarks and quark mixing remains a puzzle !



Not much is known about the trilinear coupling :(

Second gen. and electron Yukawa

- The future colliders' prospects of the second generation's Yukawa couplings, as well as the electron's have been studied in the literature extensively, the most recent studies are :

  - T. Han et al (2021), for muon Yukawa

  -J. Hernández-Sánchez et al. (2021) , for charm Yukawa.

  -D. d'Entrina et al (2021) , for electron Yukawa

  - Many others exist (only mentioned the most recent here).

- We shall focus here only on the prospects for first generation quarks' Yukawa couplings along with Higgs trilinear self coupling.

SMEFT VS κ-formalism

- Although most searches express their bounds in terms of a coupling modifier $\kappa := \frac{g}{g^{SM}}$, it is sometimes better to work within certain EFT, for example SMEFT, specially when considering multiple Higgs production.

- The SMEFT operators modifying the (quark) Yukawa couplings take the form

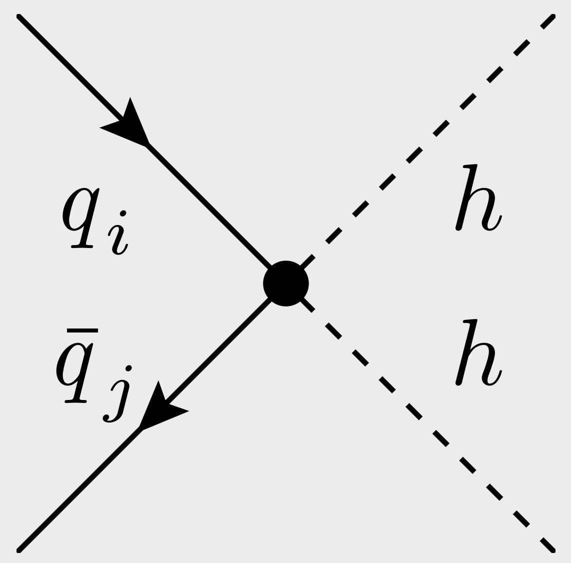
$$\Delta\mathcal{L}_y = \frac{H^\dagger H}{\Lambda^2}\left(c^u_{ij}\bar{Q}^i_L\tilde{H}u^j_R + c^d_{ij}\bar{Q}^i_L H d^j_R + h.c.\right),$$

the relation between SMEFT and κ-formalism is then given by (assuming only diagonal elements in the mass Eigenbasis).

$$\frac{C_{qH}}{\Lambda^2} = \frac{\sqrt{2}\,m_q}{v^3}(1-\kappa_q)$$
$$c^q_{ii} := C^{ii}_{qH}$$

Also notice that we also get the coupling

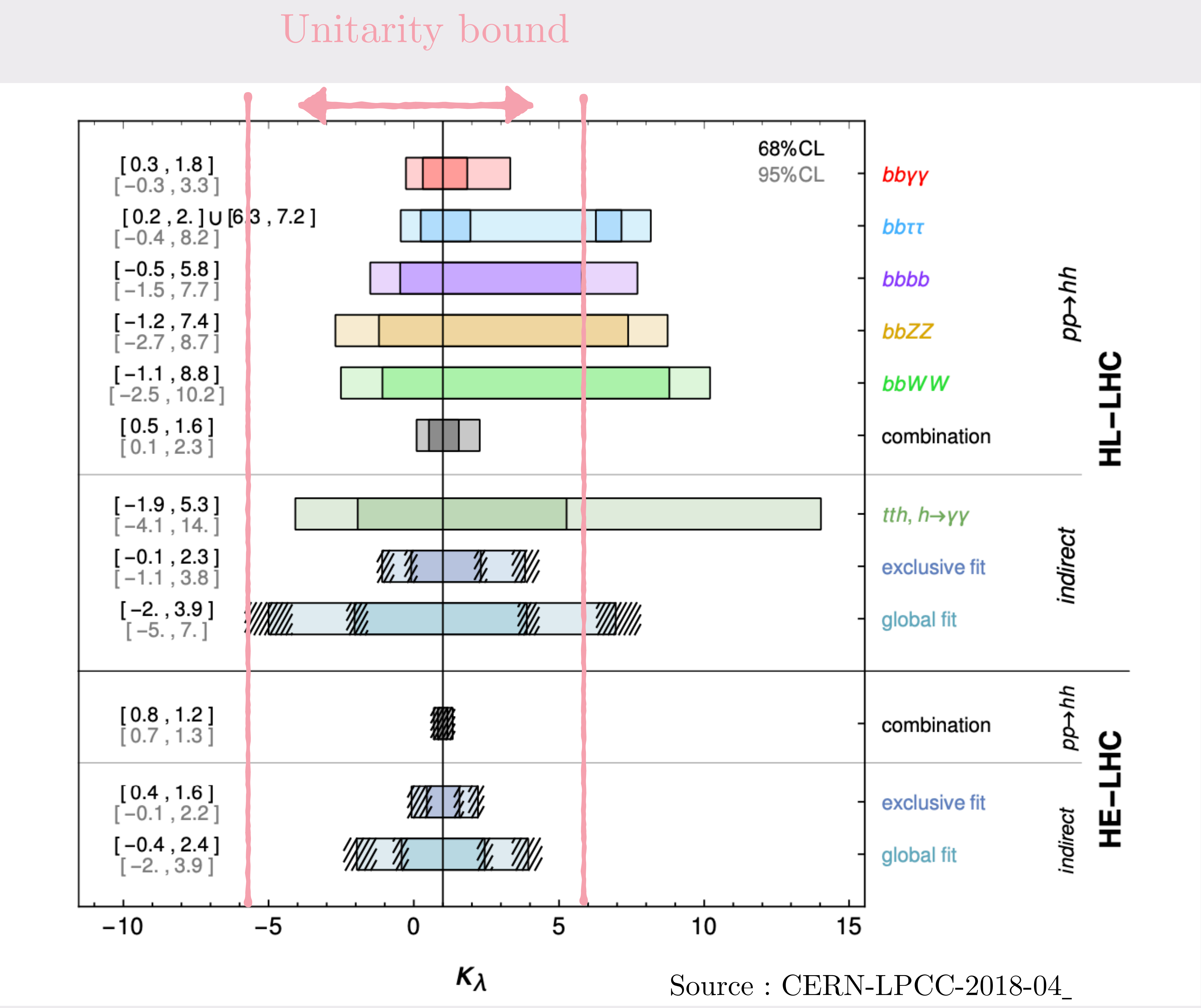
$$g_{hhq_i\bar{q}_i} = -\frac{3}{2}\frac{1-\kappa_q}{v}g^{\mathrm{SM}}_{hq_i\bar{q}_i},$$

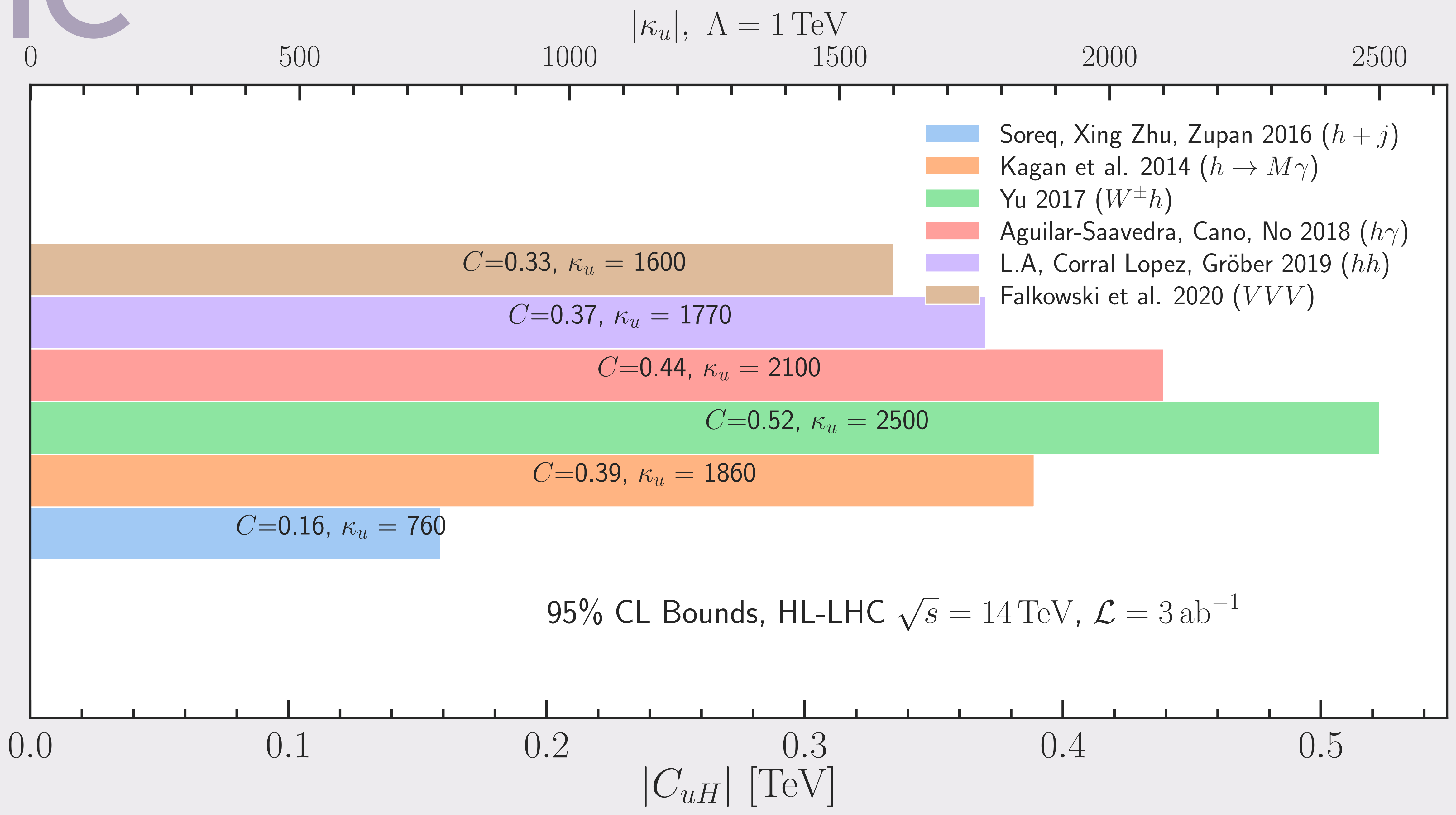


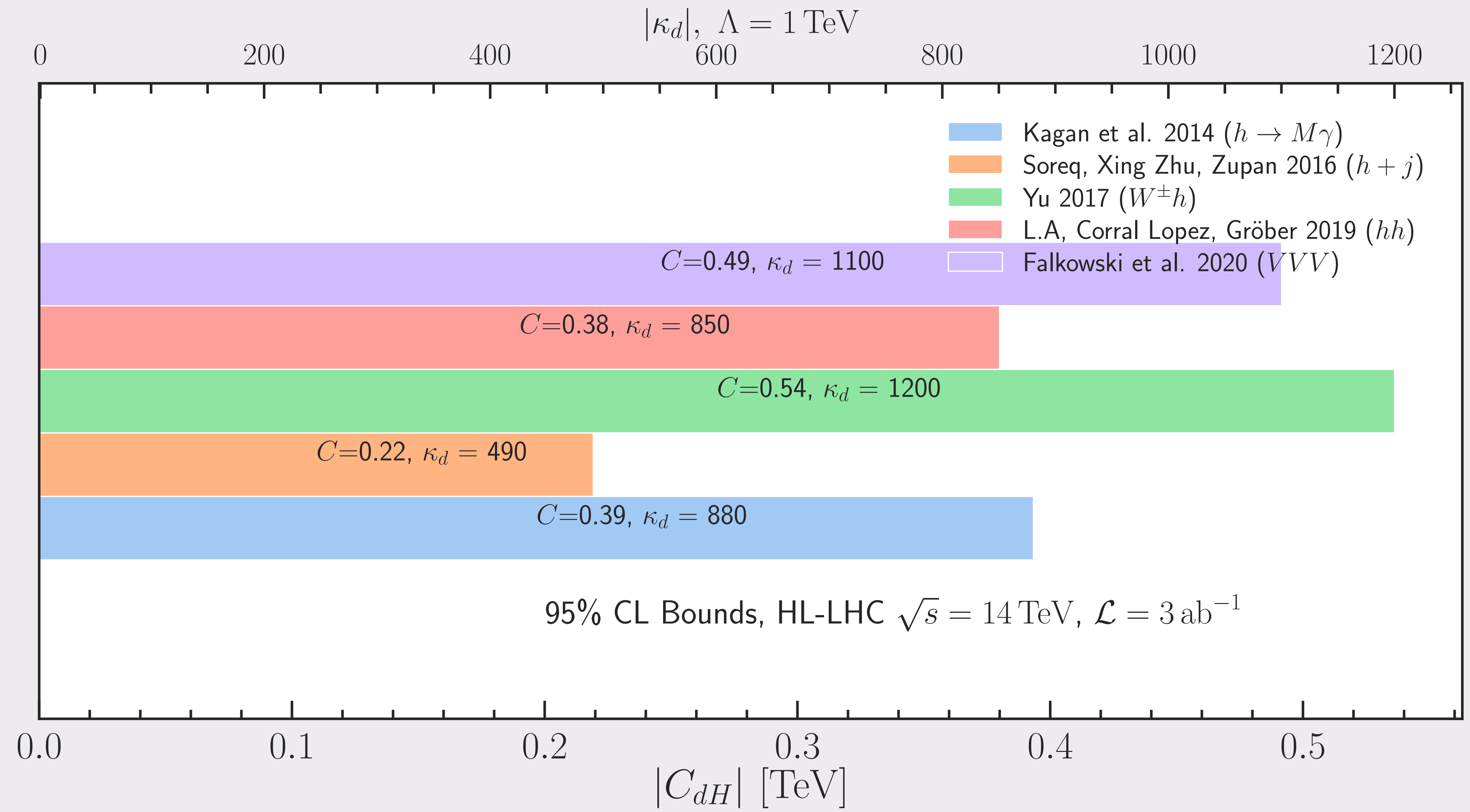
- We have also the Higgs self-coupling modifiers

$$\mathcal{L}_{\mathrm{SMEFT}} = C_{H,\Box}(H^\dagger H)\Box(H^\dagger H) + C_{H\,D}|(H^\dagger D_\mu H)|^2 + C_H(H^\dagger H)^3$$

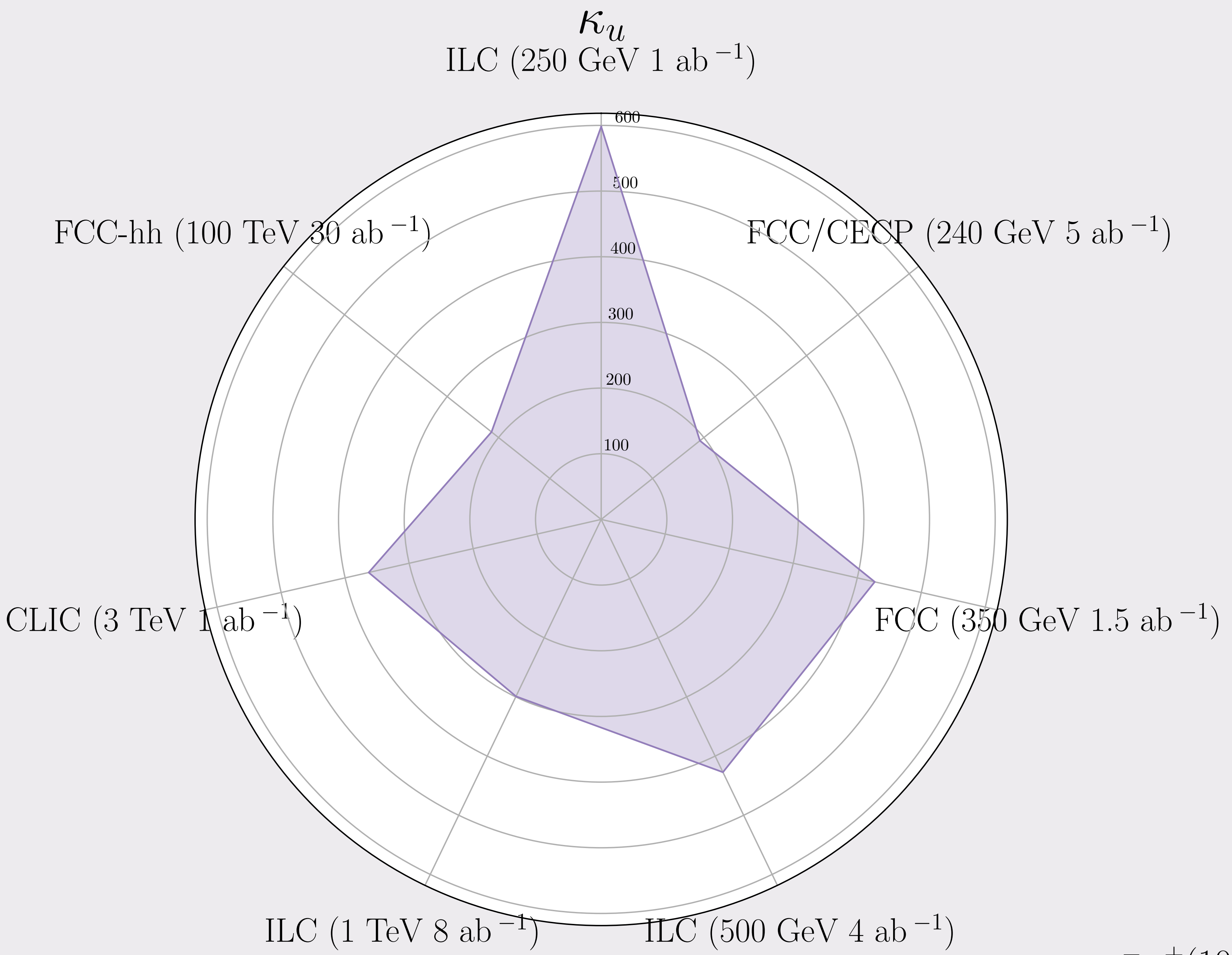
Sensitivity of the HL-LHC

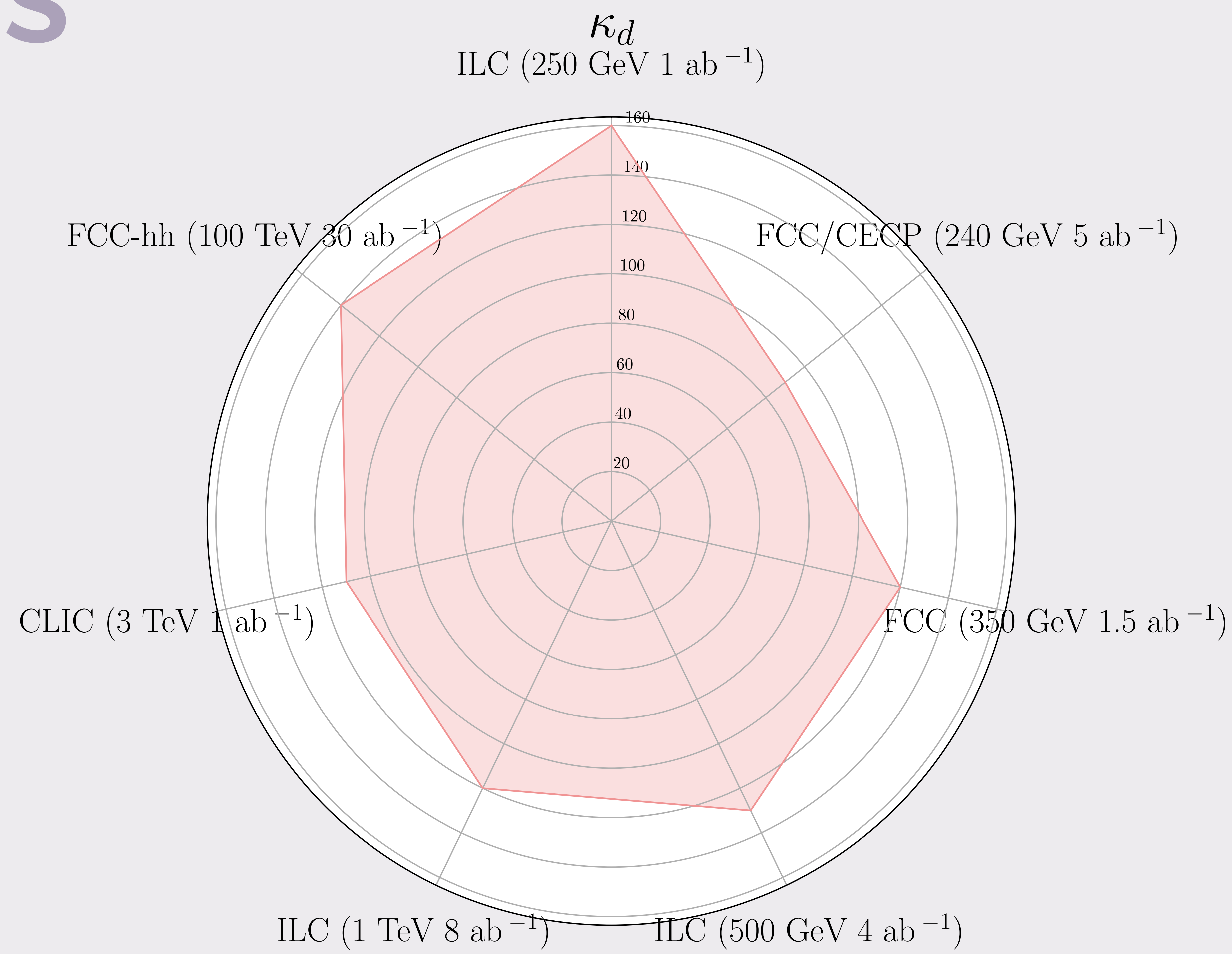


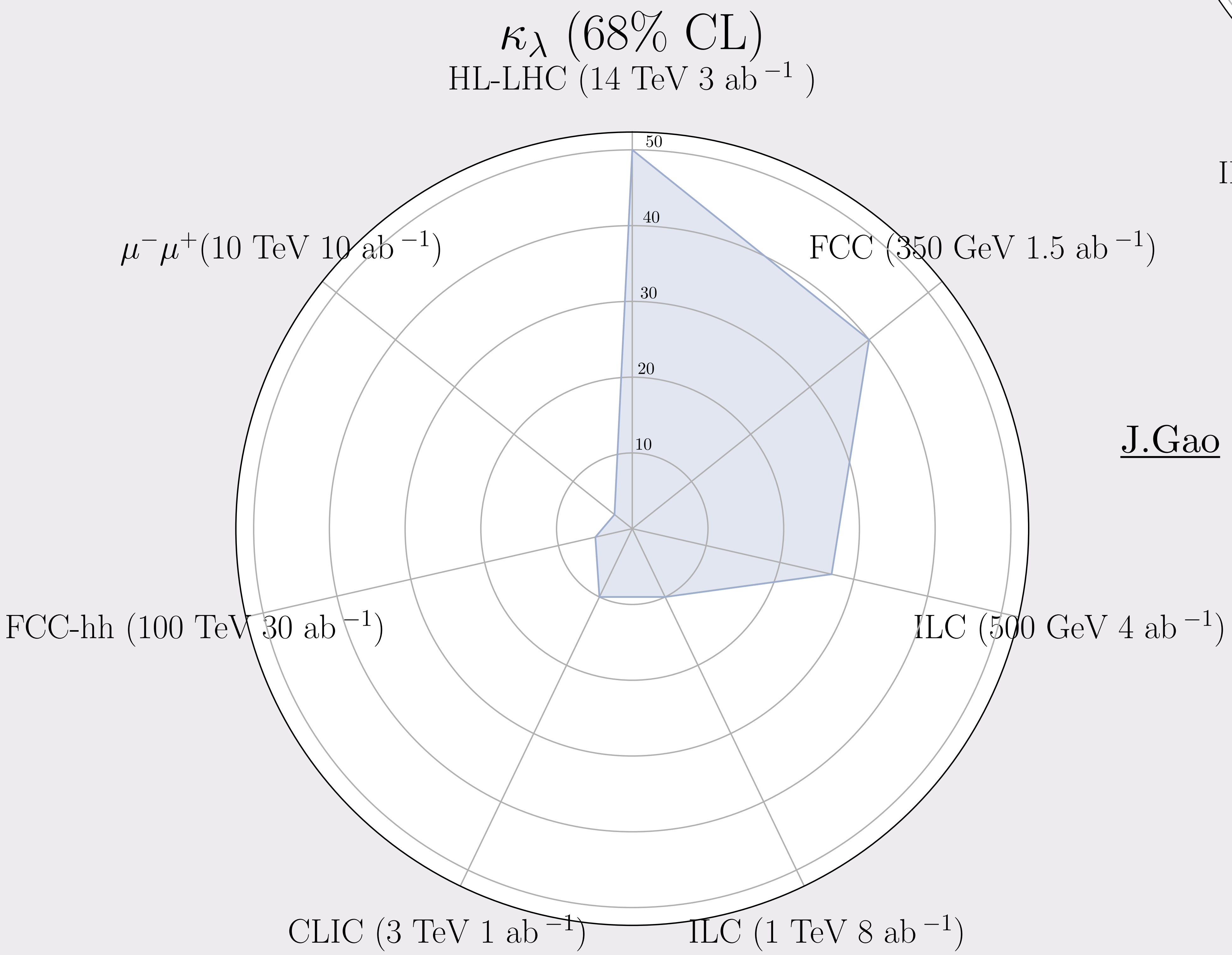




Prospects for future colliders







J.Gao (2018), S. Di Vita et al (2018) J.de Blas et al. (2020)

Why HH?

- Higgs Pair production provides a direct probe to measuring Higgs self-interaction, namely $\kappa_\lambda = \frac{g_{hhh}}{g_{hhh}^{\text{SM}}}$.

- Current bounds on this interactions are dominated by unitarity L. Di Luzio et al (2017).

- It is one of the most sensitive probes for light Yukawa coupling, particularly in models with resonant new scalar production D. Egana-Ugrinovic et al. (2021).

- The theoretical calculations for HH has been carried out up to 3 loops (QCD) M.Grazzini et al (2018), here is a complete list

- There is a large experimental effort to optimise the search for HH.

Experimentalists, need to optimise the selection of HH events for as many channels as possible

$BR \sim 0.34 - 0.016 \quad \epsilon \sim 4\% - 10\,\%$

$$\mathcal{N} = \mathcal{L} \times \sigma(pp \to hh) \times BR \times \epsilon_{exp}$$

$3 - 30\ \text{ab}^{-1}$

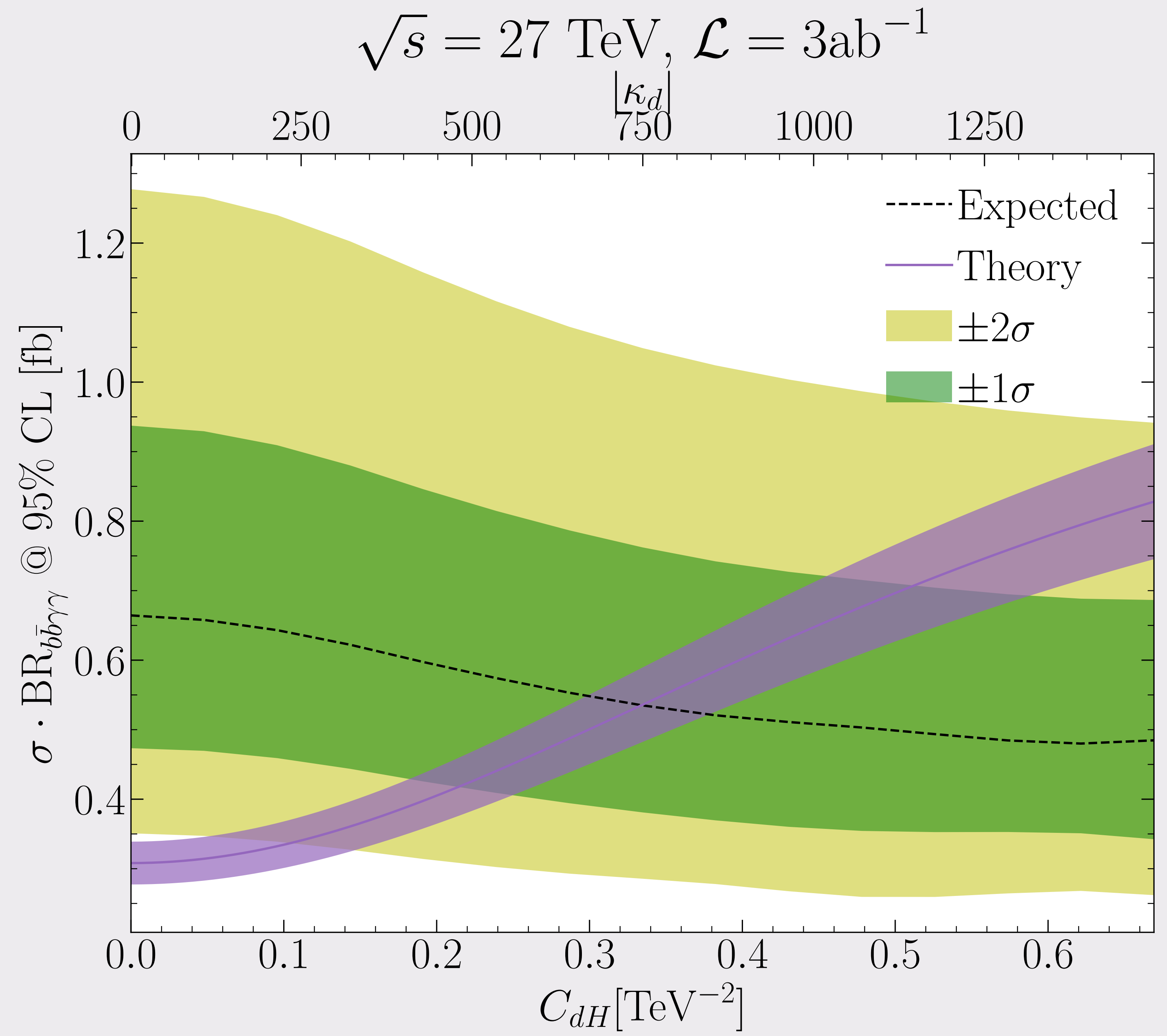
Higher energies, better detectors and longer run times for future colliders

$\sim 36 - 1000\ \text{fb}$

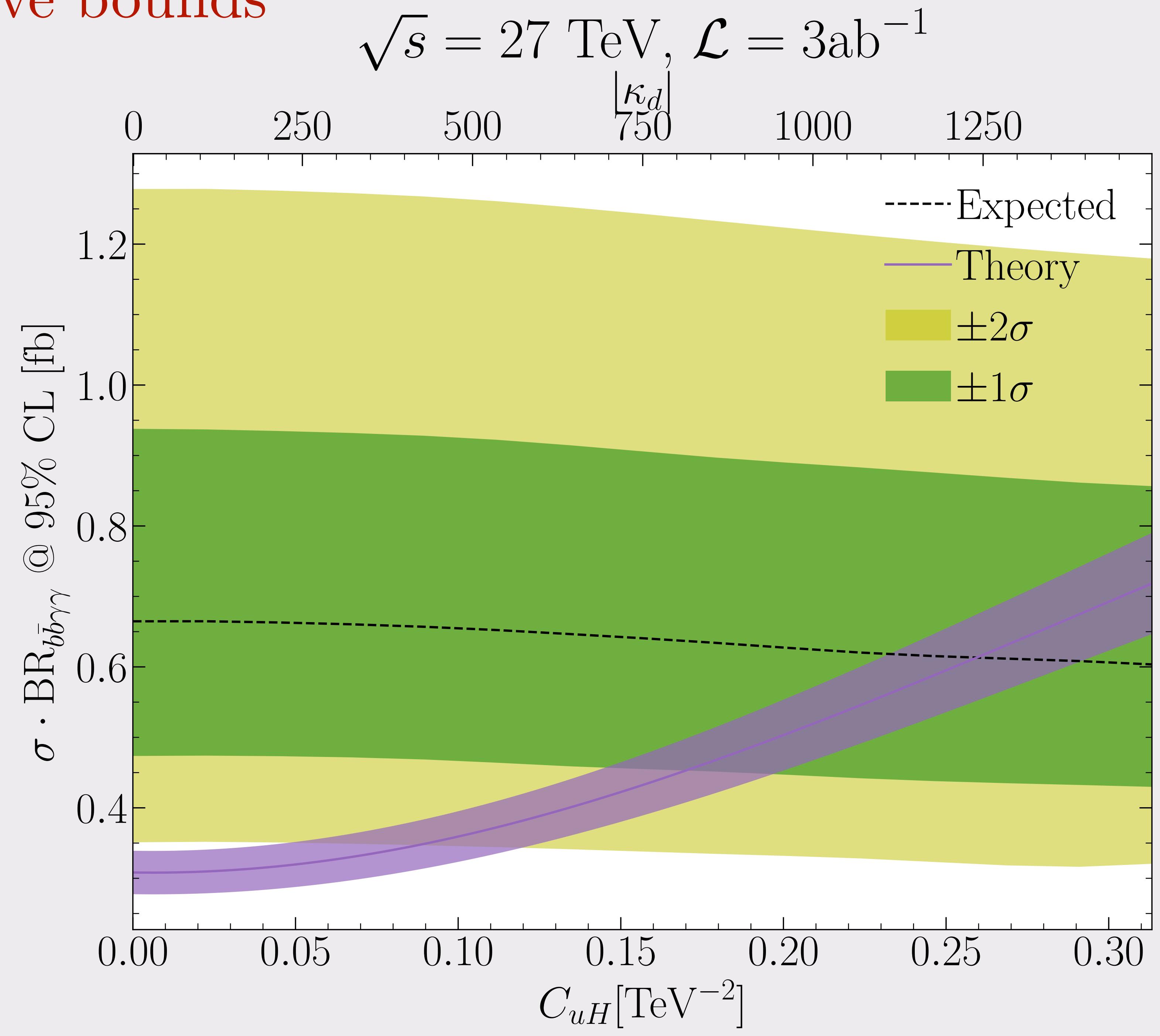
Theoreticians need to understand the systematic uncertainties as well as work on simulations

Cut-based analysis

- We started by investigating the potential sensitivity of a 27 TeV collider (HE-LHC) for HH. Then extracted the expected bounds on 1st gen Yukawa.
- This was done using the same analysis done for the HL-LHC in our paper (*JHEP* 11 (2019) 088)
- The bounds did not improve significantly over HL-LHC.
  Prospects for FCC-hh would be $\kappa_d \sim 70$, $\kappa_u \sim 100$
- But there is a lot of potential for improvement using differential distributions, but even better results can be achieved using Machine Learning !

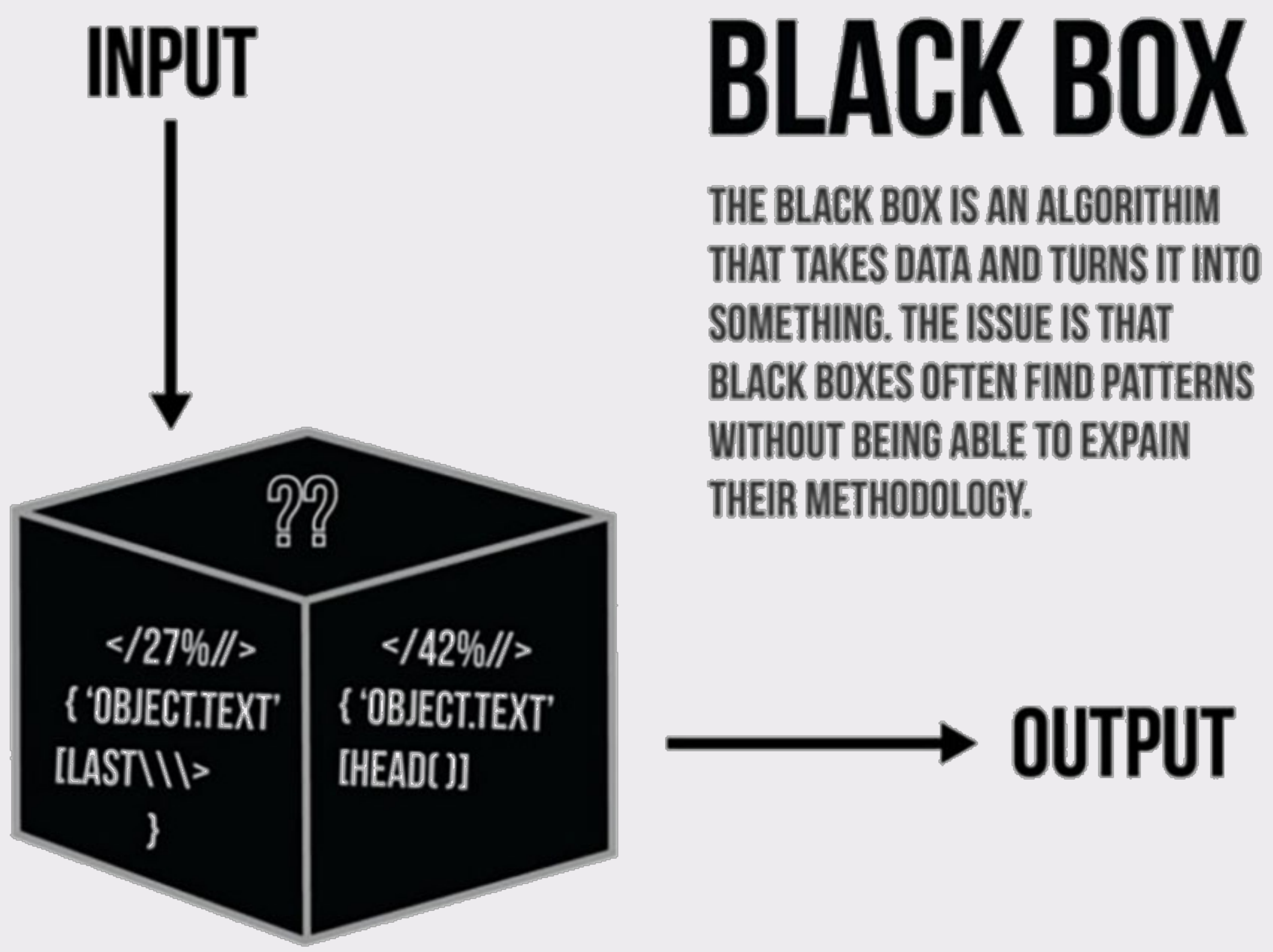


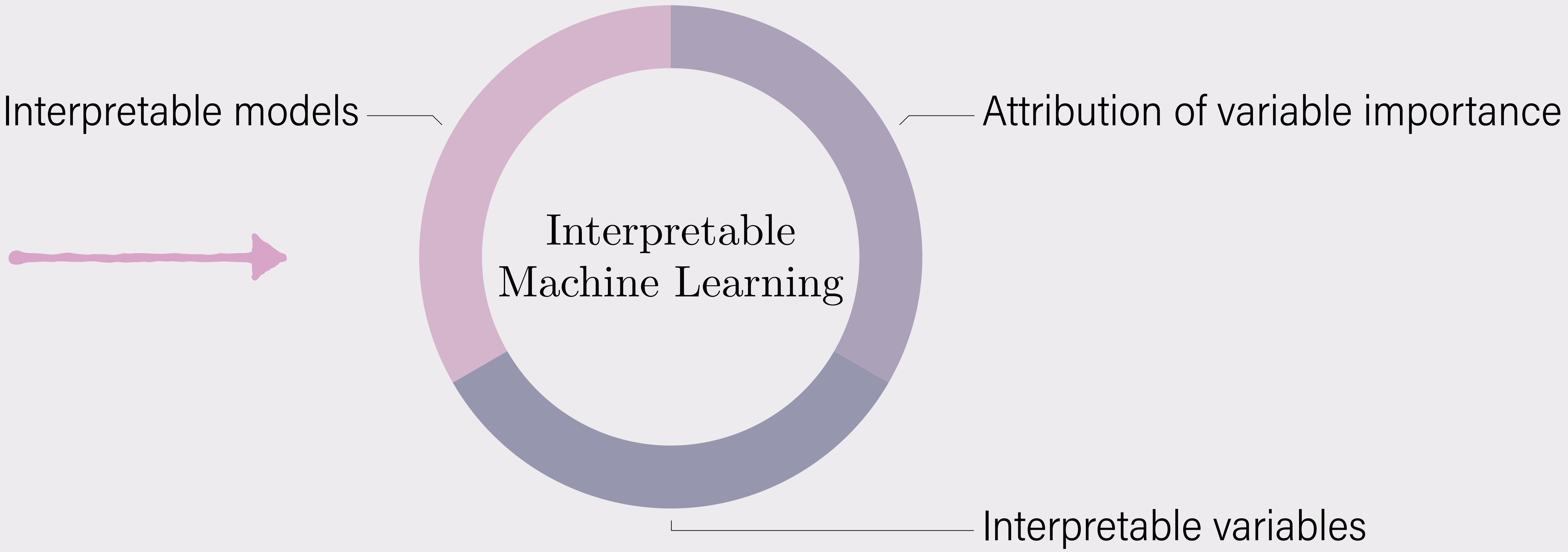
Inclusive bounds



Interpretable machine learning

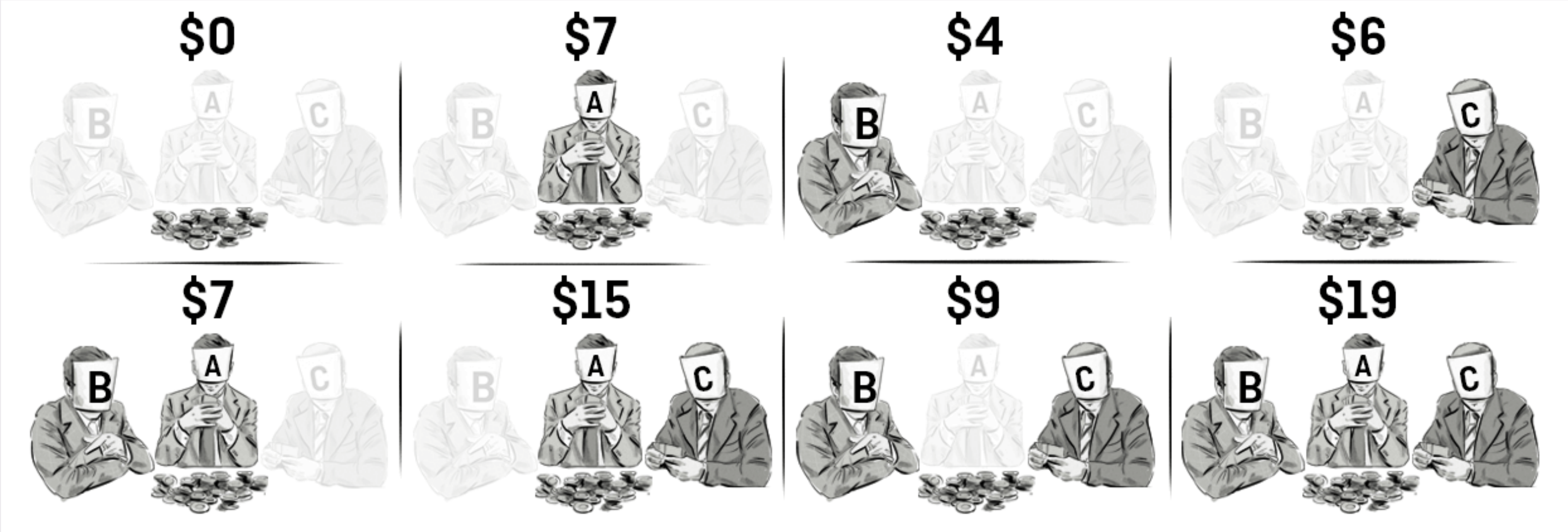
What is „Interpretable“ ML ? (Provided by Ayan Paul)



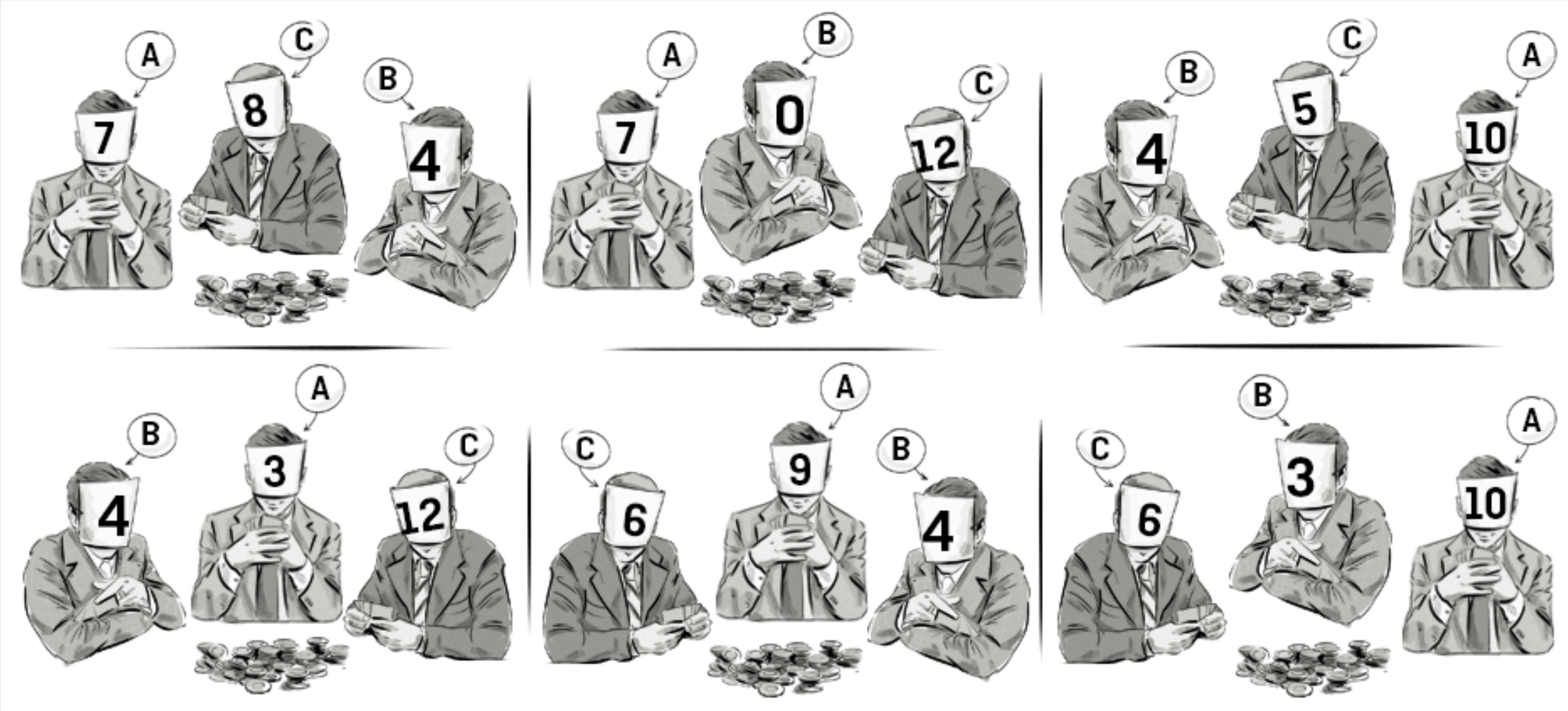


Cooperative games and Shapley values (Provided by Ayan Paul)

The value of each player and each combination of players

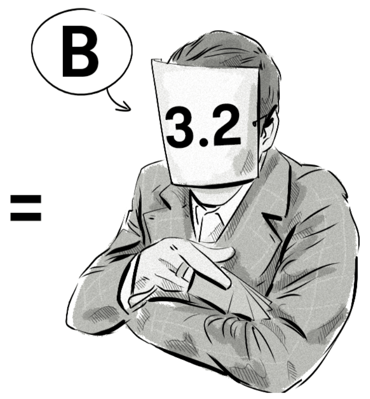


The value of the player in each game



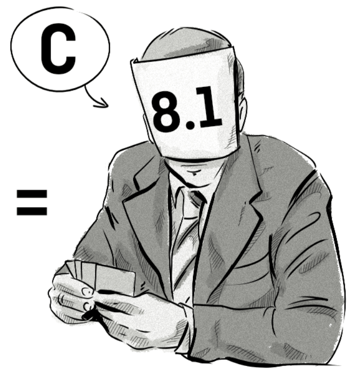
(7+7+10+3+9+10) / 6 =

(4+0+4+4+4+3) / 6 =



Marginalise the values

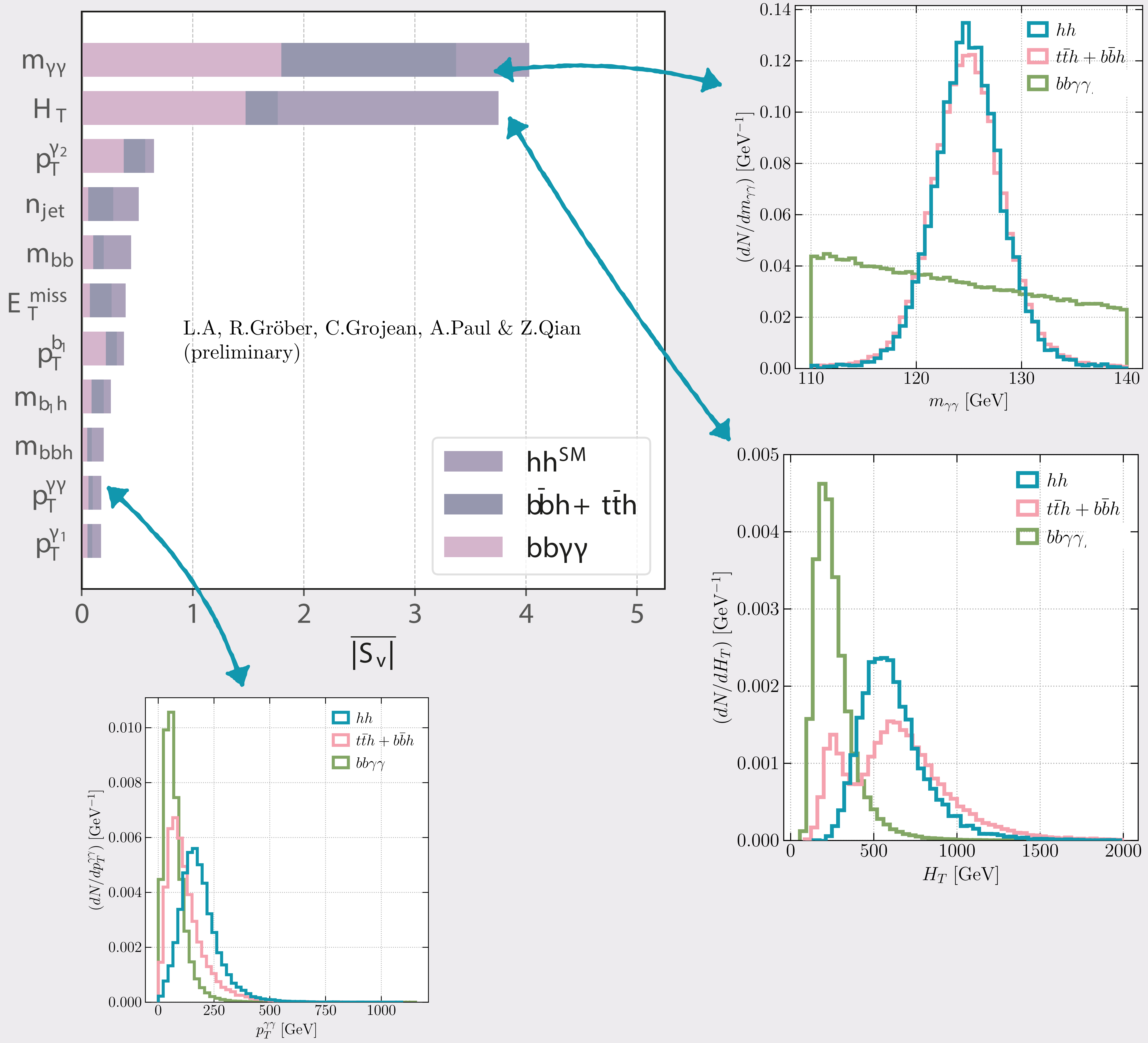
(8+12+5+12+6+6) / 6 =



The most important player

L. S. Shapley, Notes on the n-Person Game-II: The Value of an n-Person Game (1951).

The analysis I



- For Higgs pair production, we have chosen the final state (for HL-LHC) $pp \to hh \to b\bar{b}\gamma\gamma$ ($\sigma \cdot BR = 0.975$ fb) Then we have the following (main) backgrounds:

✴ $pp \to b\bar{b}\gamma\gamma$, $\sigma \cdot BR = 18.9$ fb

✴ $pp \to t\bar{t}h \to b\bar{b}W^+W^-\gamma\gamma$ $\sigma \cdot BR = 1.39$ fb

✴ $pp \to b\bar{b}h \to b\bar{b}\gamma\gamma$ $\sigma \cdot BR = 1.37$ fb

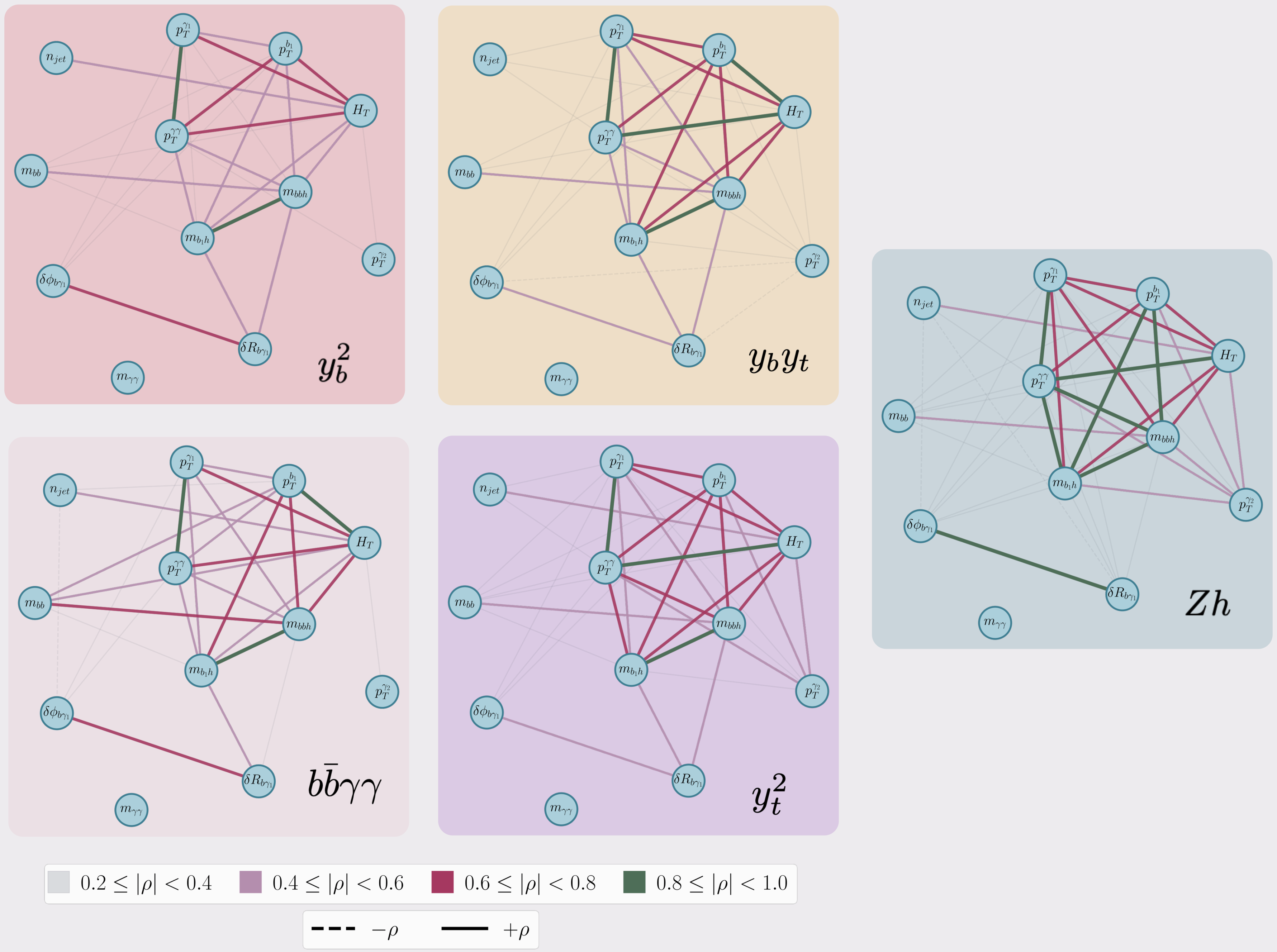
- We have selected the following list of observables similar to C. Grojean et al (2020):

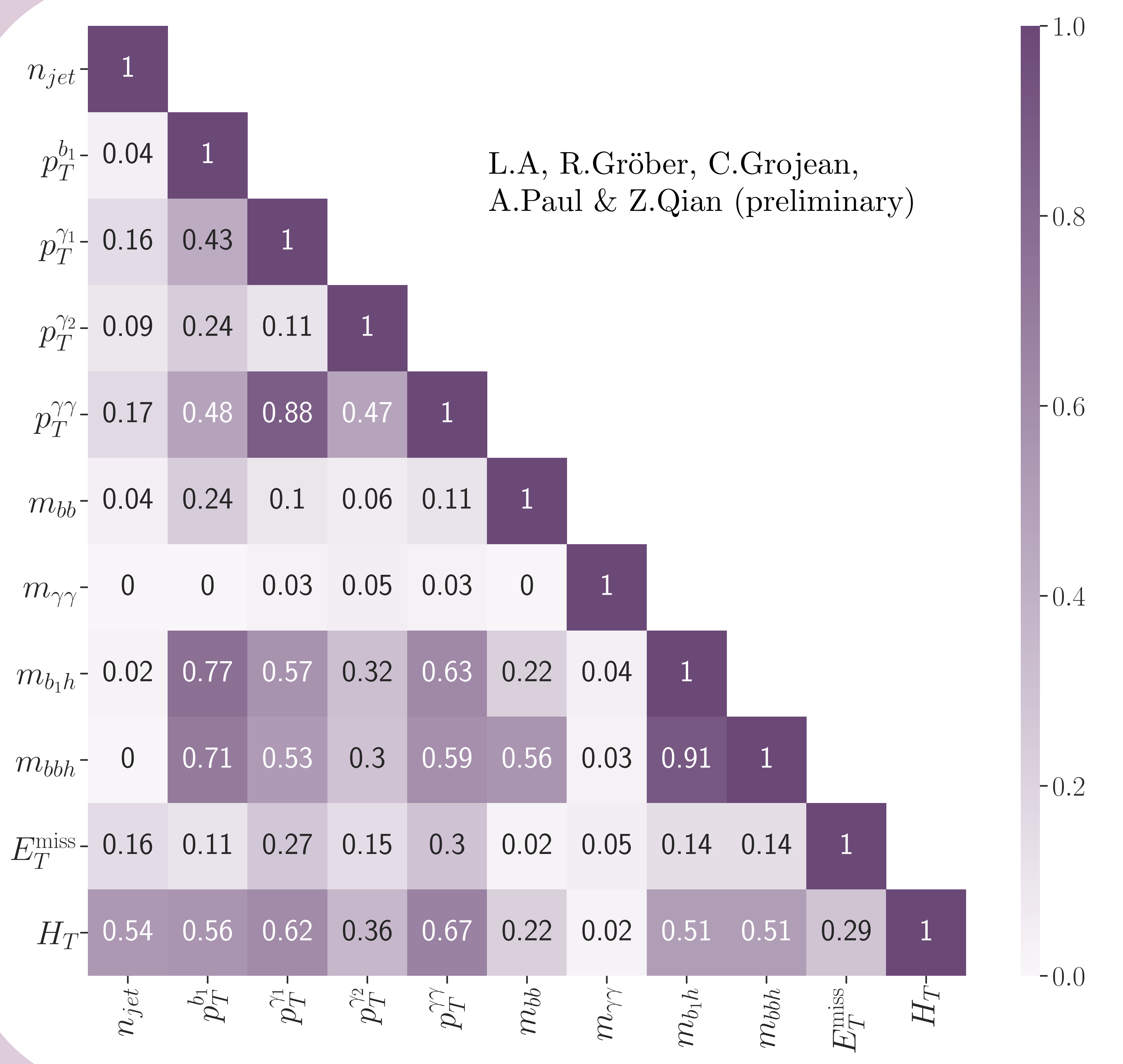
$$p_T^{b_1} p_T^{b_2}, p_T^{\gamma_1}, p_T^{\gamma\gamma}, \eta_{b_{j1}}, \eta_{b_{j2}}, \eta_{\gamma_1}, \eta_{\gamma\gamma}$$

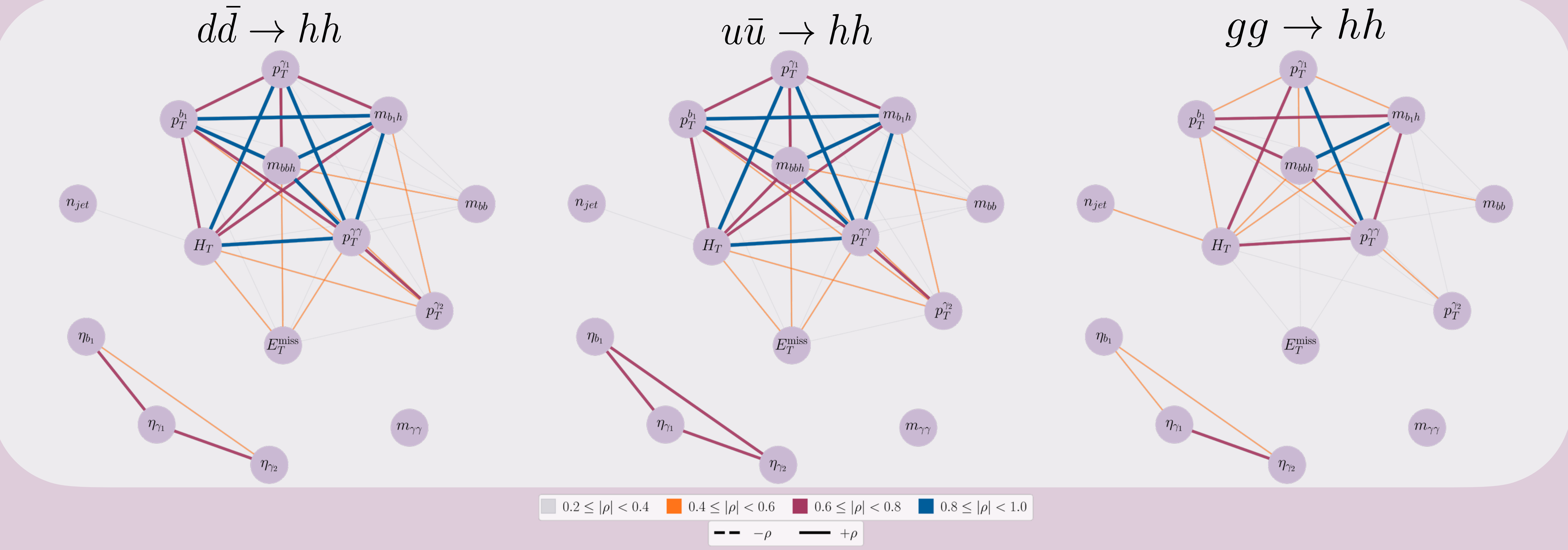
$$n_{bjet}, n_{jet}, \Delta R^{b\gamma}_{\min}, \Delta\phi^{bb}_{\min}, m_{\gamma\gamma}, m_{bb}, m_{b_1 h}, m_{b\bar{b}h}, H_T .$$

Cooperation in Physics

- Variables “cooperate” to bring the outcome
- Outcome can be a measurable quantity or a probability of being of a certain kind
- This covers both regression and classification



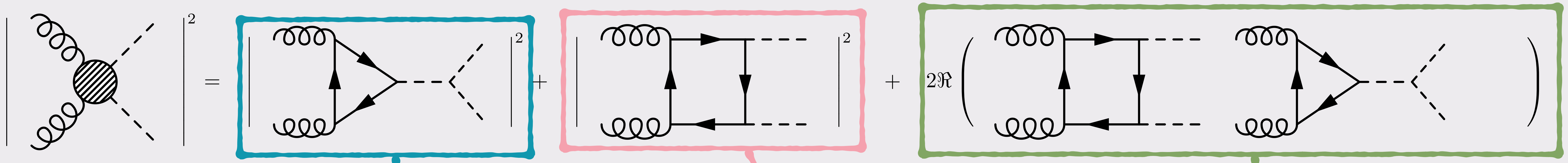




multivariate inherits correlations!

The analysis II

- We have generated separate MC for the Higgs pair signal components:



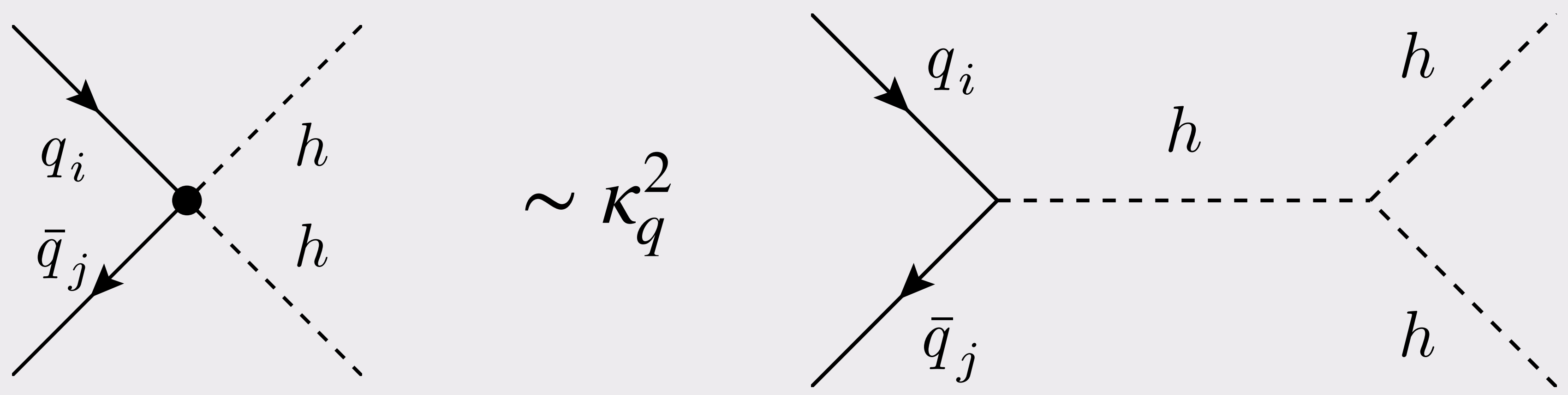
- Moreover, with enhanced Yukawa the quark-antiquark annihilation becomes dominant, while the gluon-fusion is pretty much unaffected

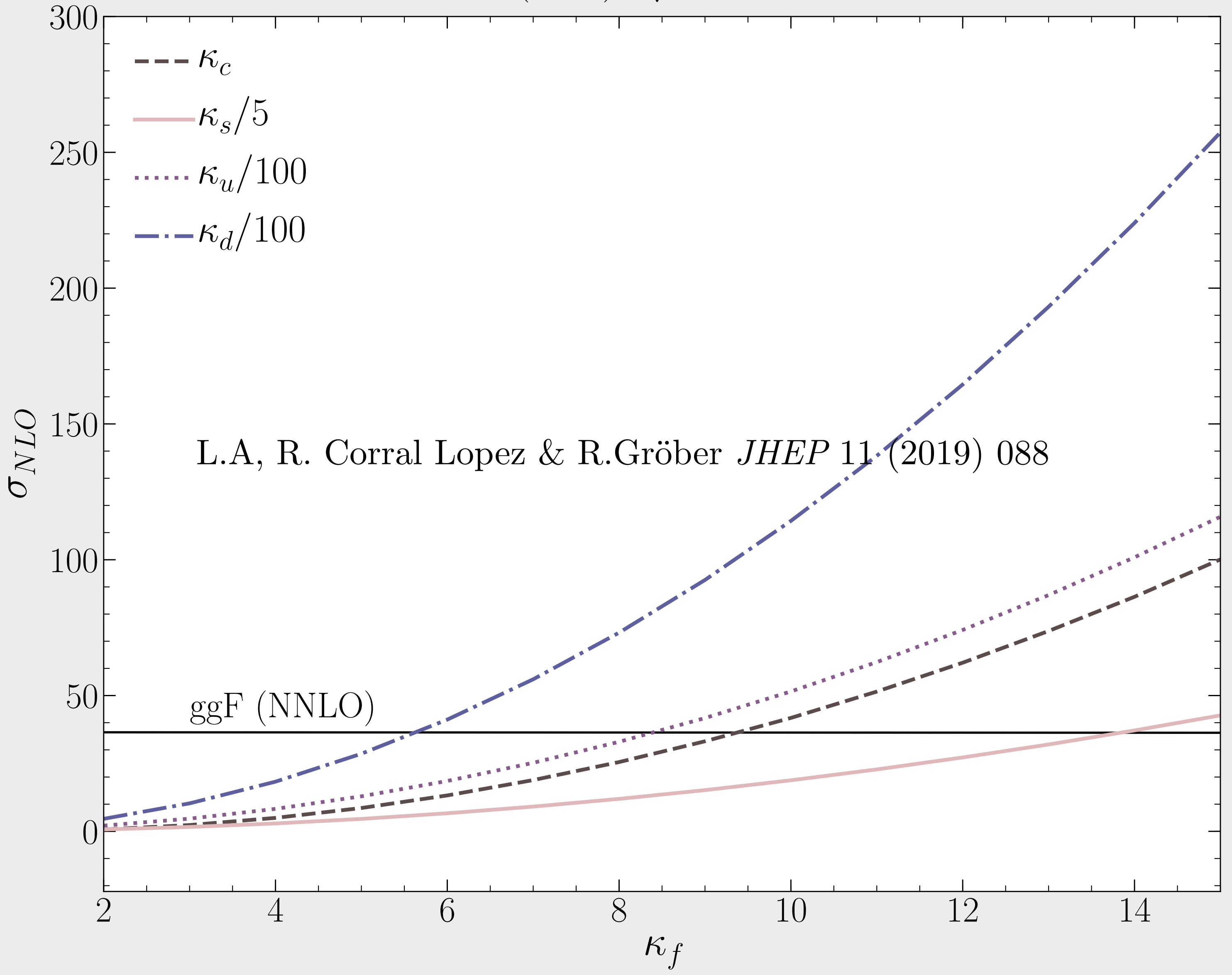
❖Recall that

$$\kappa_q := \frac{g_{hq\bar{q}}}{g^{\mathrm{SM}}_{hq\bar{q}}}$$

Though, we work in SMEFT, so we also have

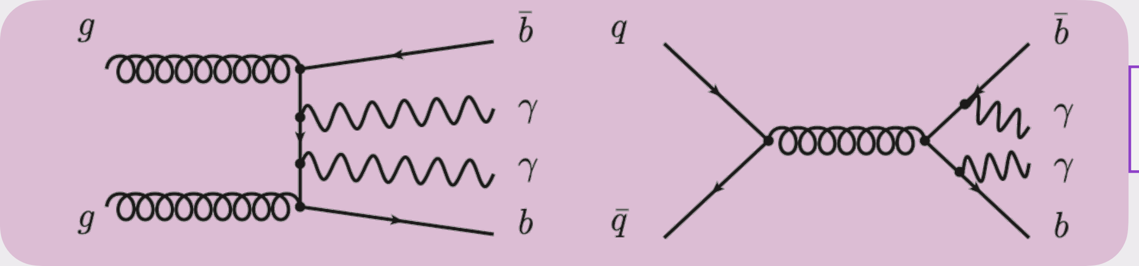
$$g_{hhq_i\bar{q}_i} = -\frac{3}{2}\frac{1-\kappa_q}{v}g^{\mathrm{SM}}_{hq_i\bar{q}_i},$$

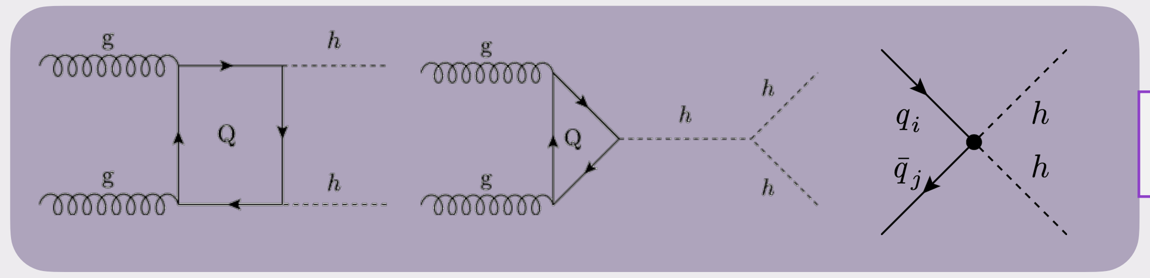


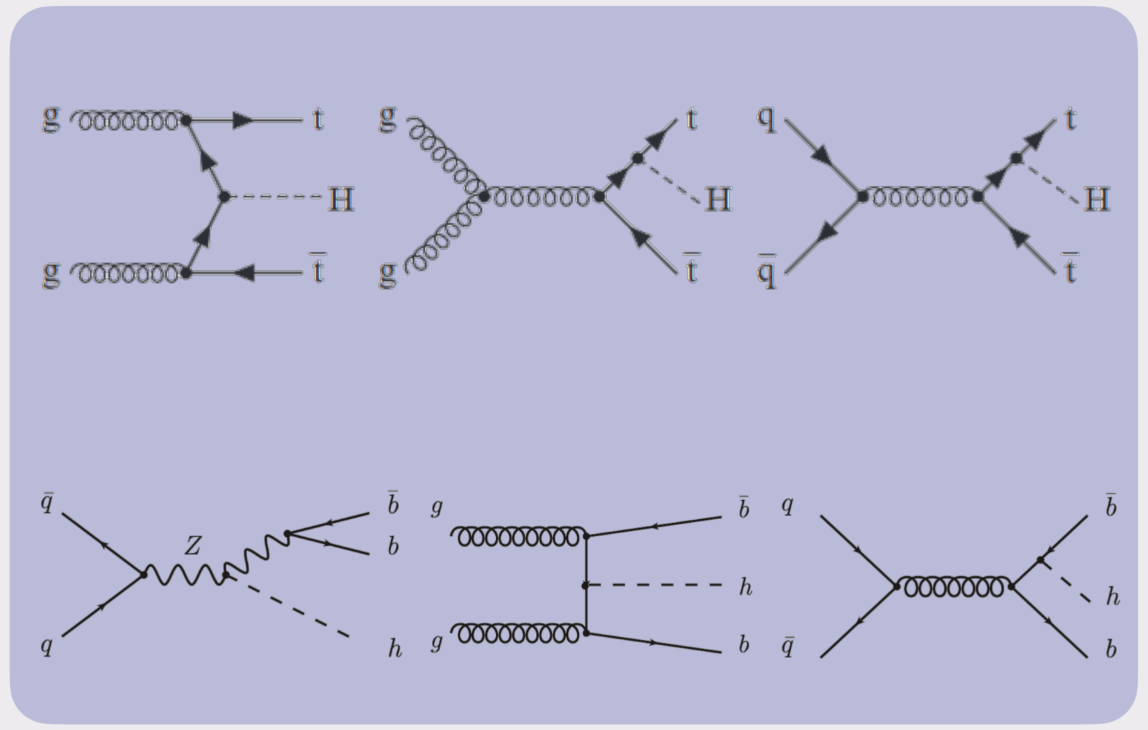


Analysis summery (Provided by Ayan Paul)

Interpretable Variables







Generate Monte Carlo events, with Parton shower and fast detector effects

QCD-QED Backgrounds

hh signal

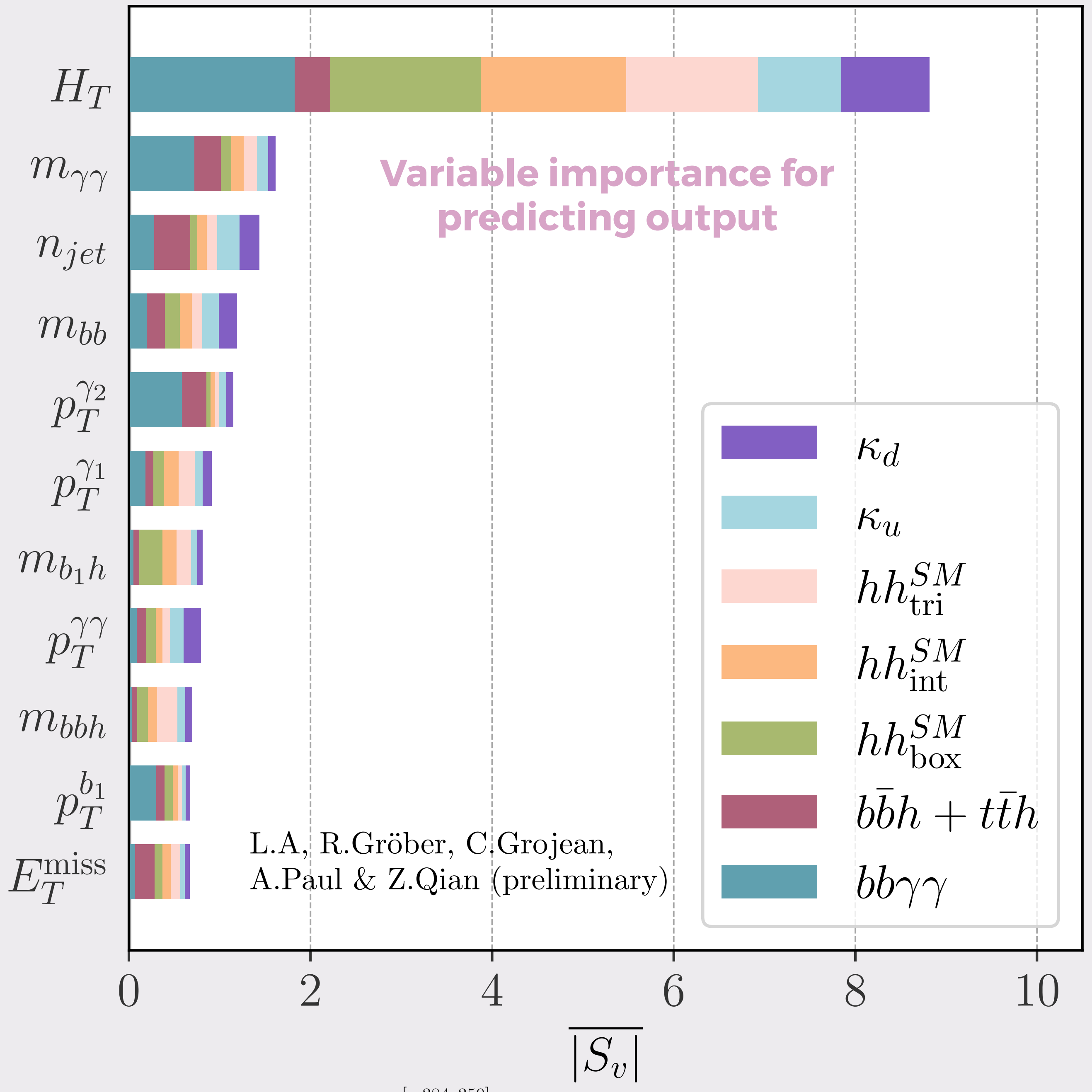
$b\bar{b}h + t\bar{t}h$ backgrounds

Construct high-level kinematic observables (features), with basic cuts

Shapley values + Physics Insights

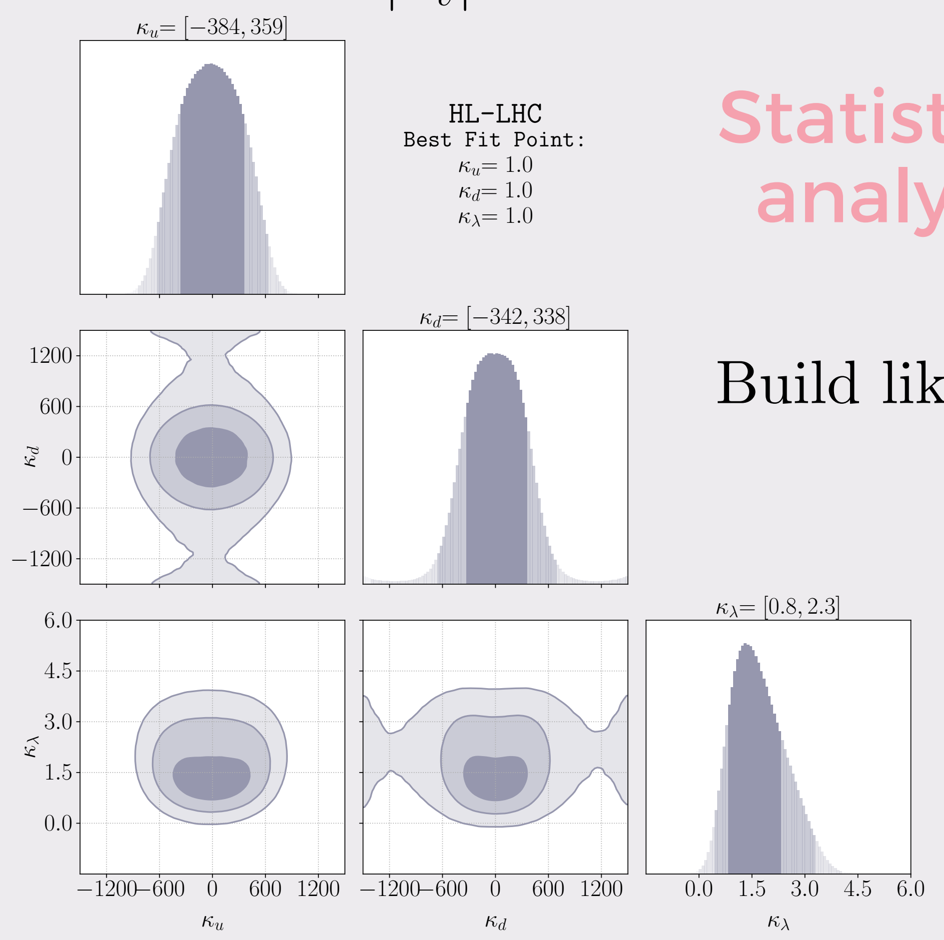
Boosted Decision Trees + Signal Classification

Interpretable models



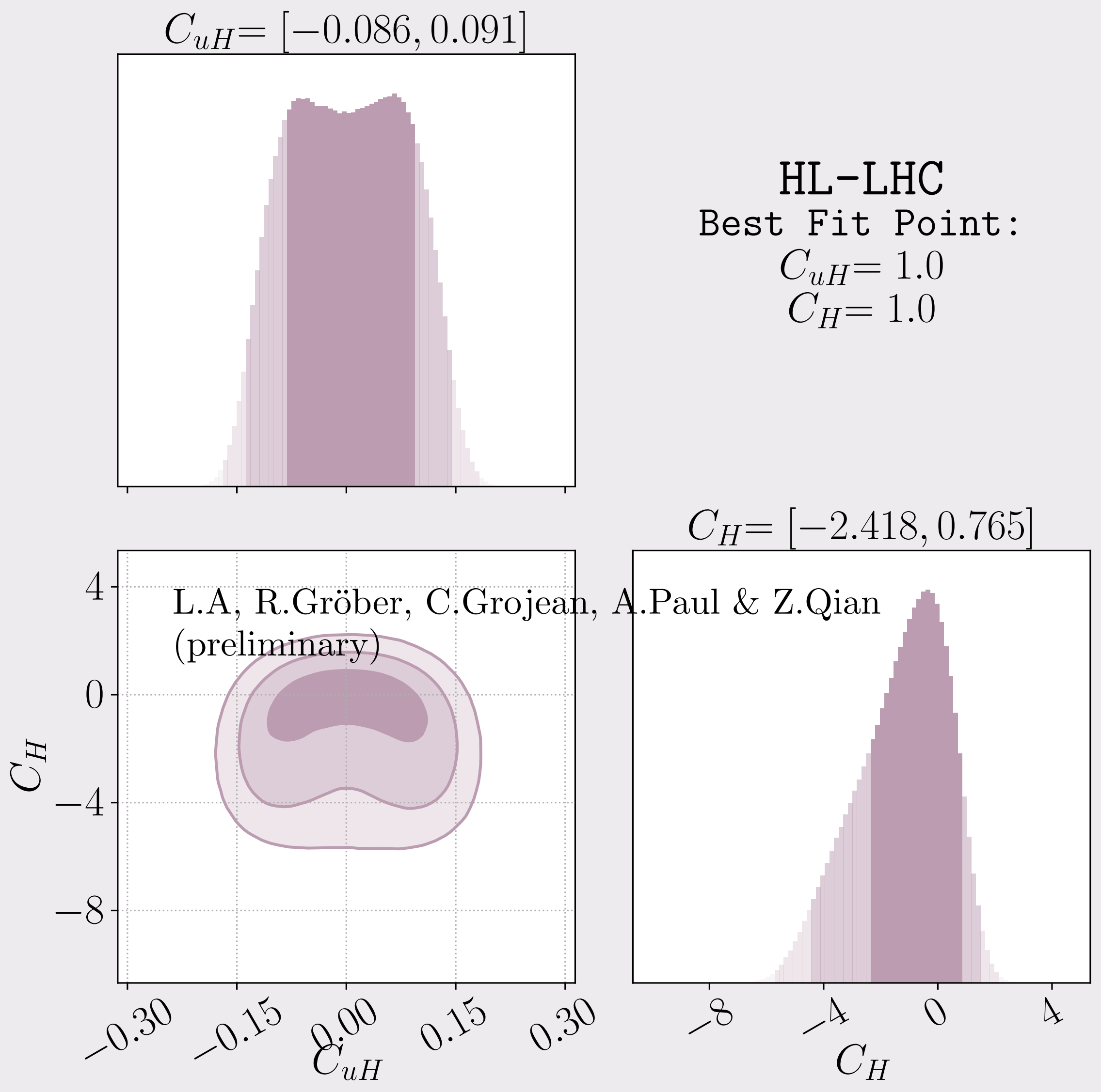
Statistical analysis

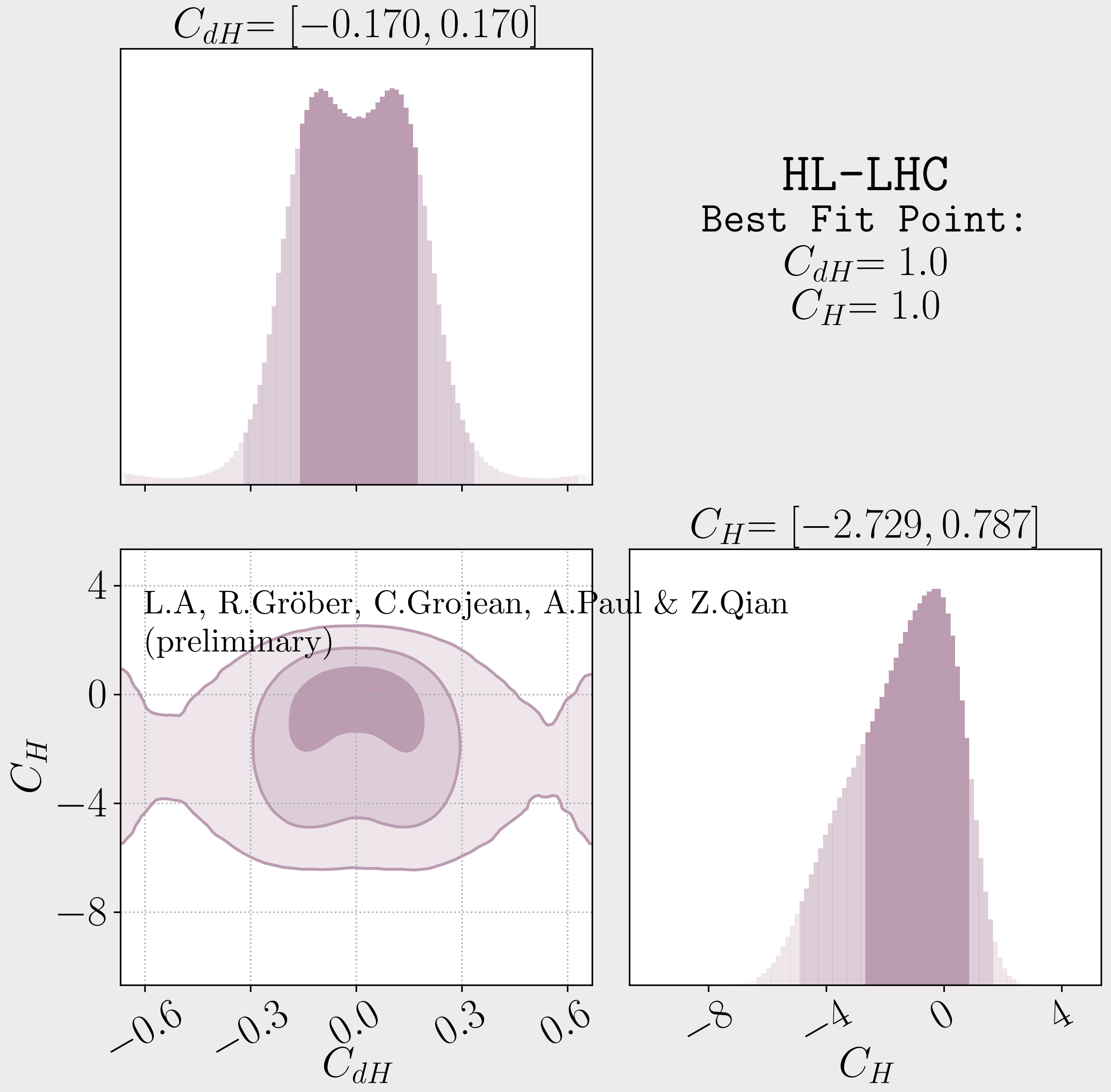
Build likelihoods

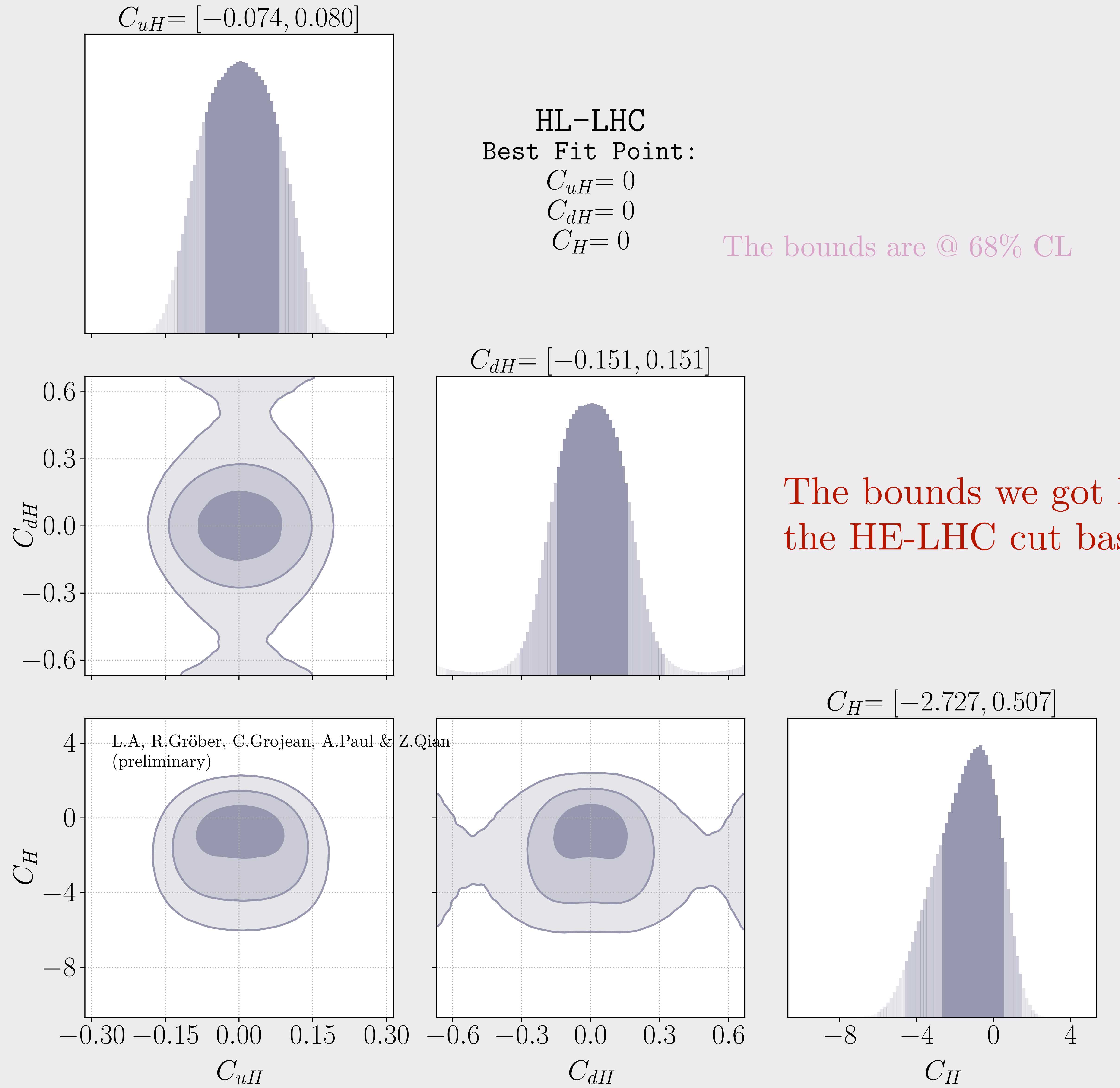


Results

Bounds Extraction (HL-LHC)





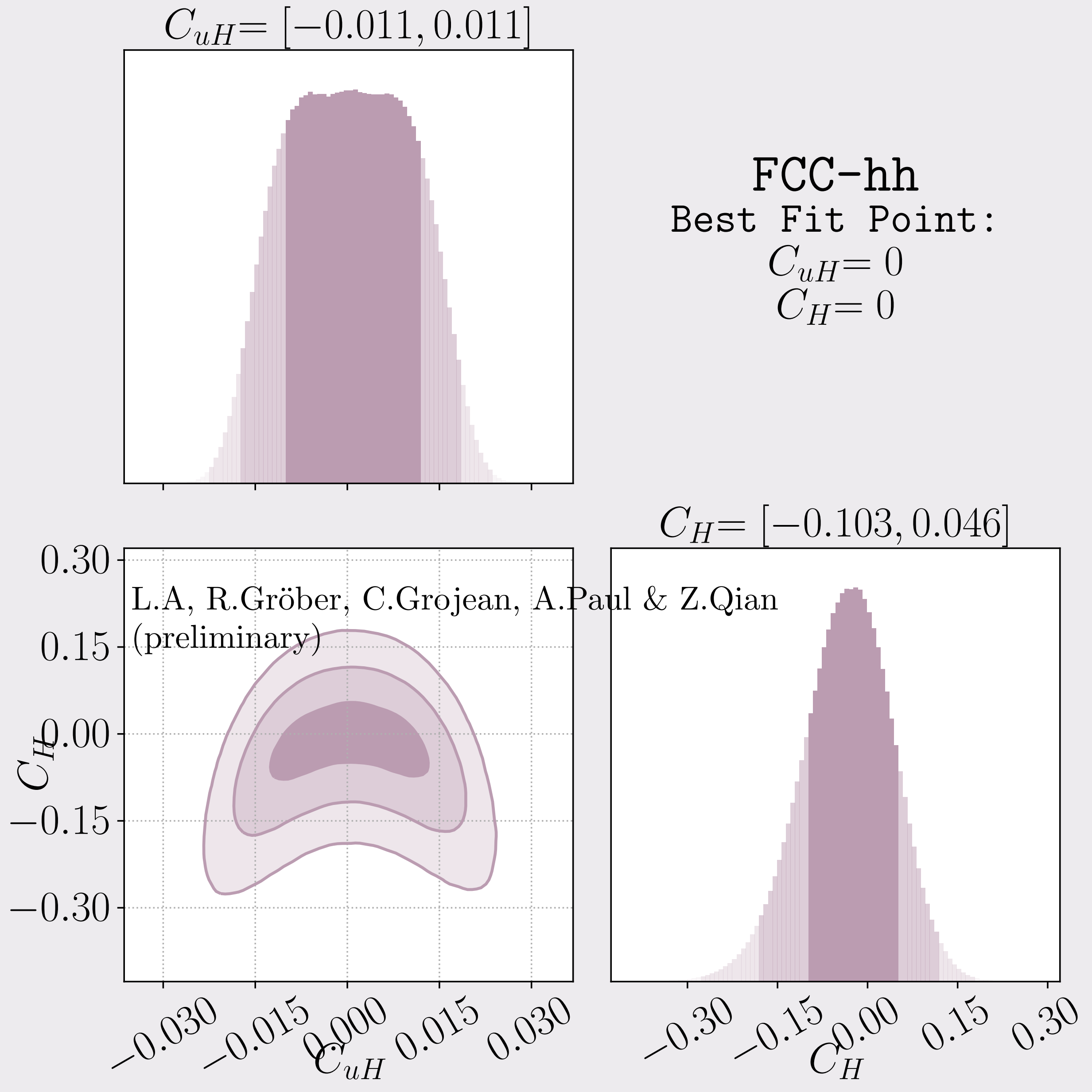


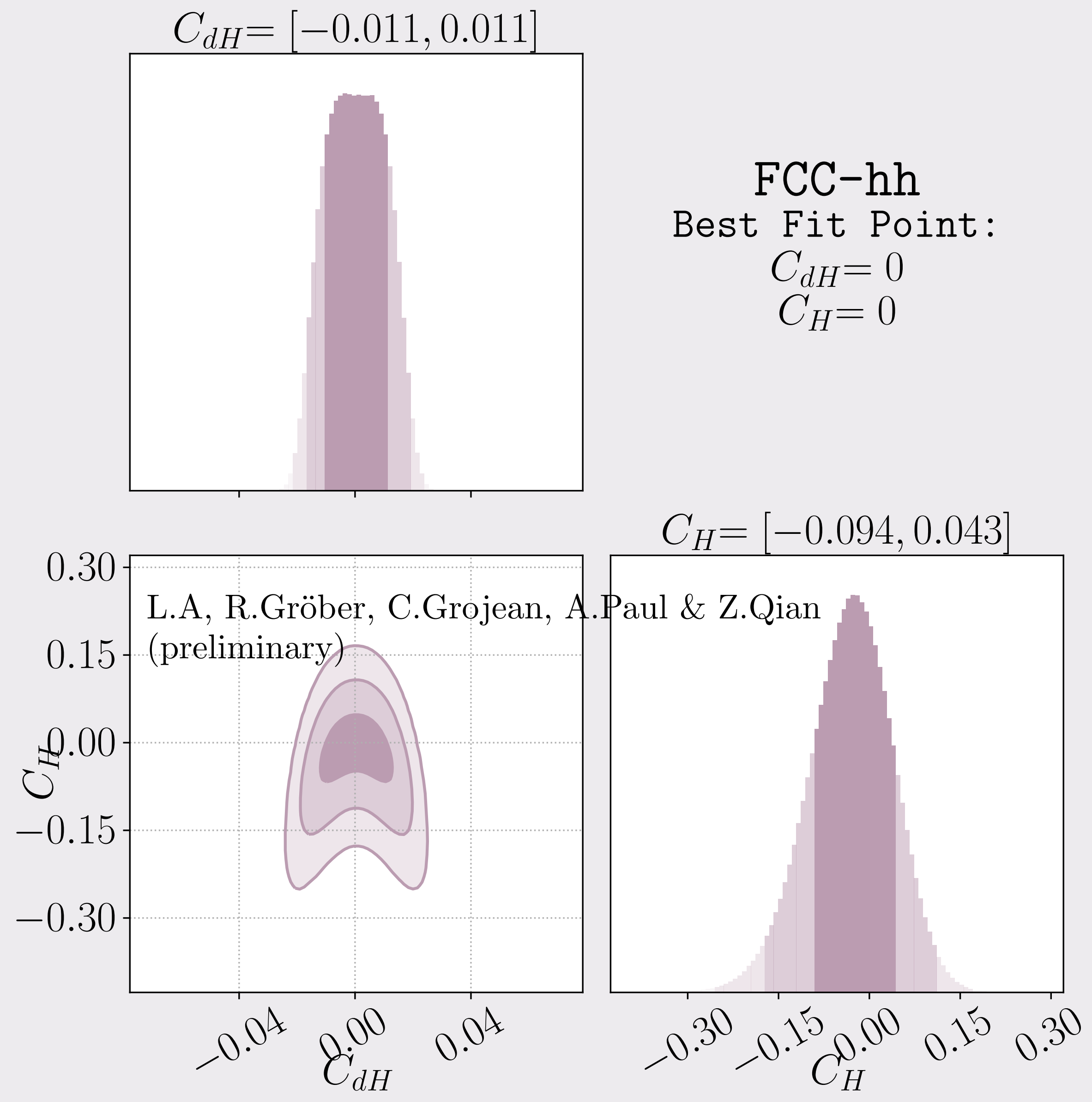
The bounds are @ 68% CL

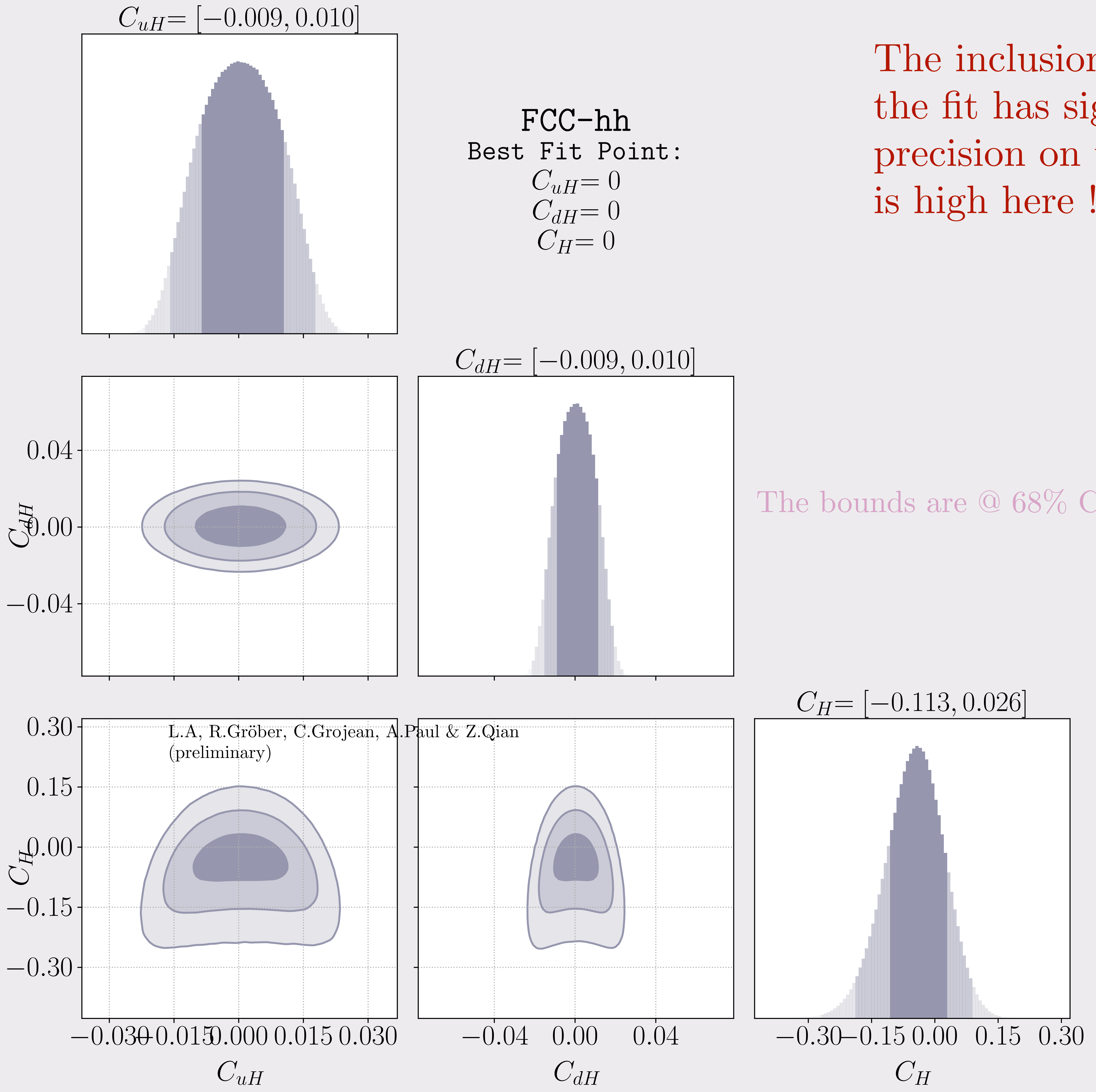
The bounds we got here are better than the HE-LHC cut based analysis !

Bounds Extraction for FCC-hh

$\sqrt{s} = 100\,\mathrm{TeV}, \mathscr{L} = 30\,\mathrm{ab}^{-1}$







The inclusion of Yukawa coupling modifiers the fit has significant effect, as the precision on the trilinear coupling modifier is high here !

The bounds are @ 68% CL

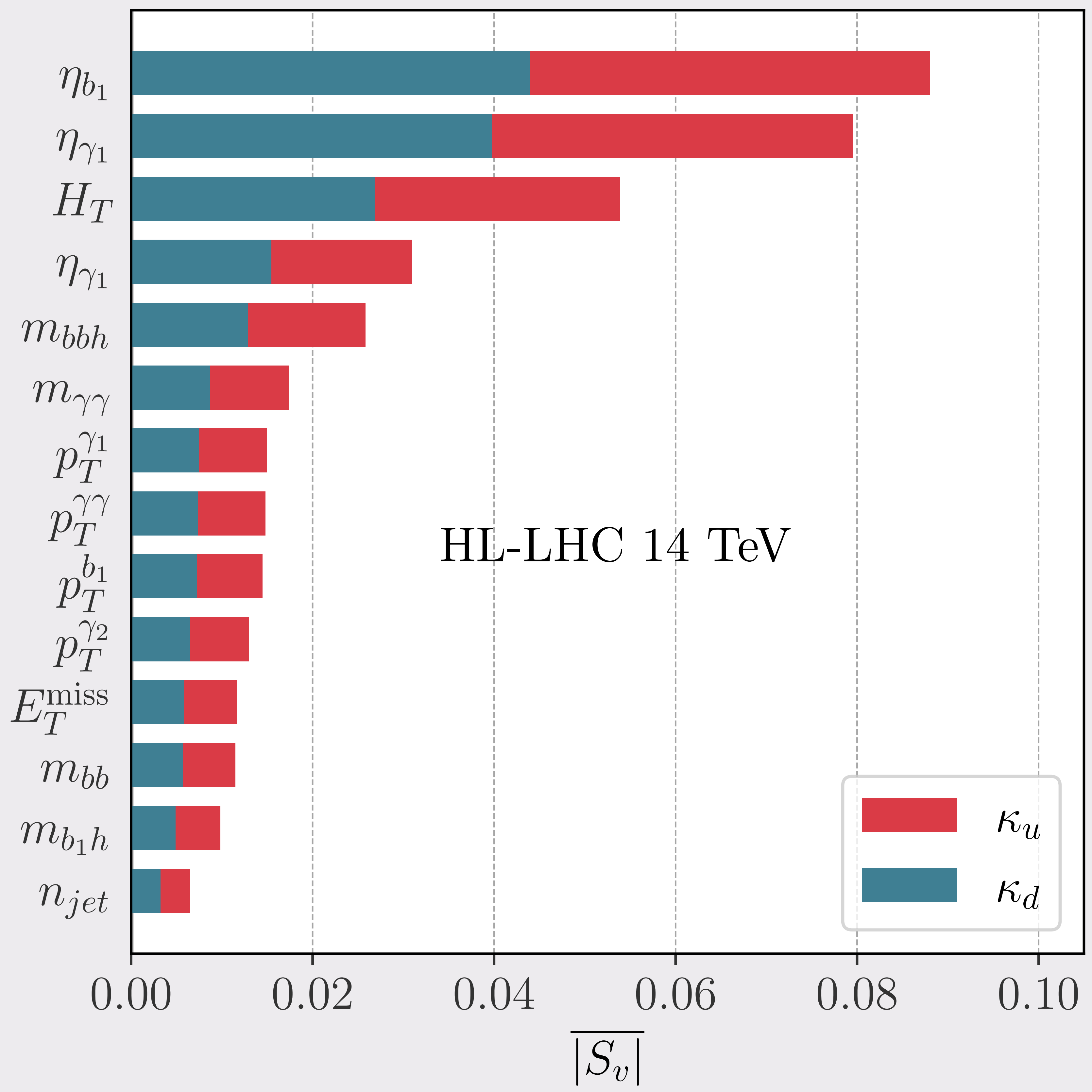
Conclusion

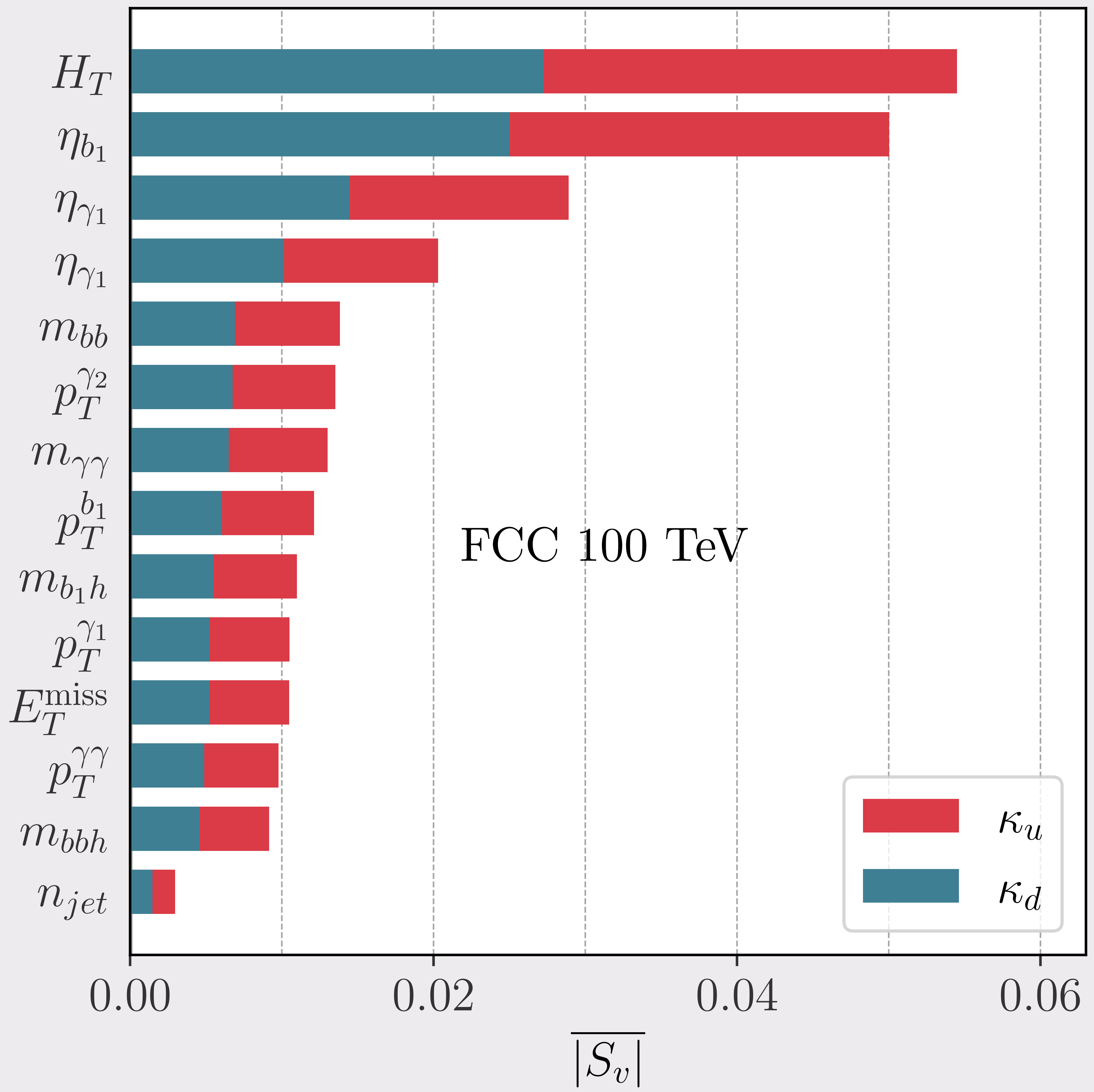
- Interpretable ML provides a strong tool for studying HEP processes, particularly HH production.
- We were able to improve the expected sensitivity for FCC-hh for HH using Interpretable ML.
- It was possible to distinguish the signal for κ_λ, κ_u & κ_d in our ML-based analysis.
  This allows to construct a sensitivity bound for all three parameters at the same time.
- When considering HH process, it is important not to ignore the correlation between κ_λ and light Yukawa coupling modification. Moreover, both are weakly constrained.
  This is particularly important for future colliders's sensitivity estimates.
- Models with aligned flavour violation (AFV) allow for large modifications to light Yukawa without having large FCNC, c.f. Bar-Shalom & Soni 18' .


Thank you !

Backup

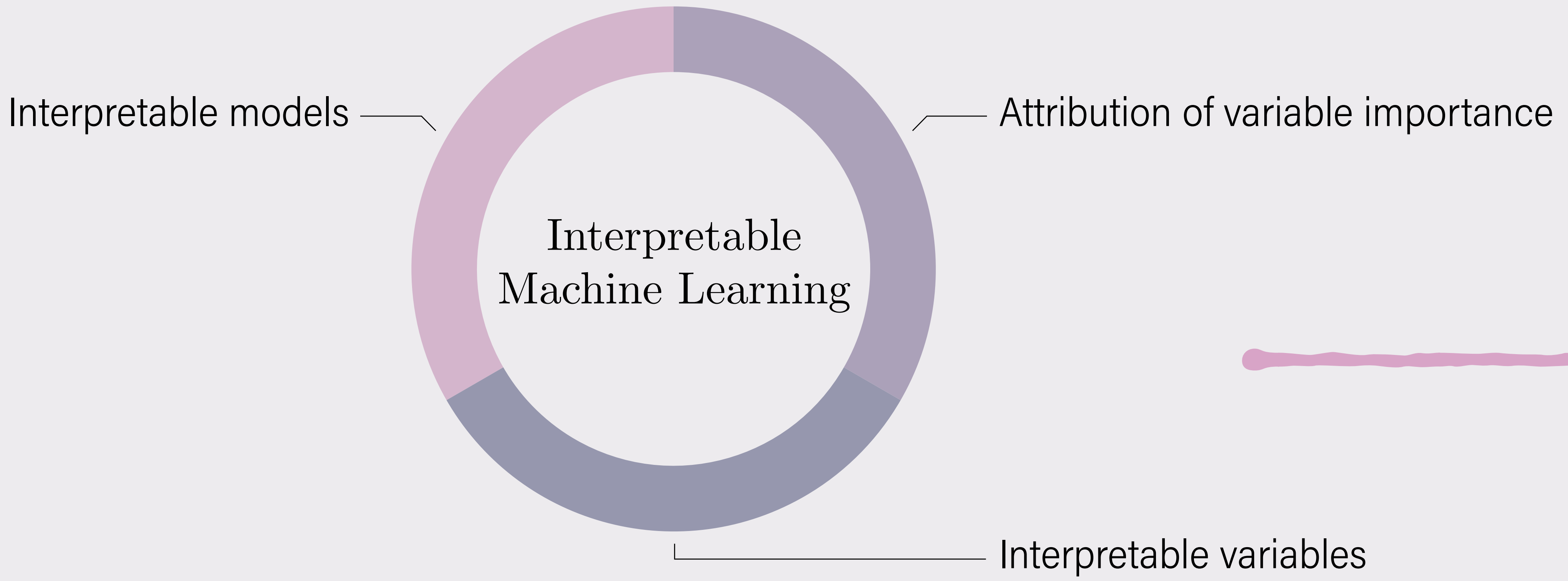
Disentangeling κ_u & κ_d

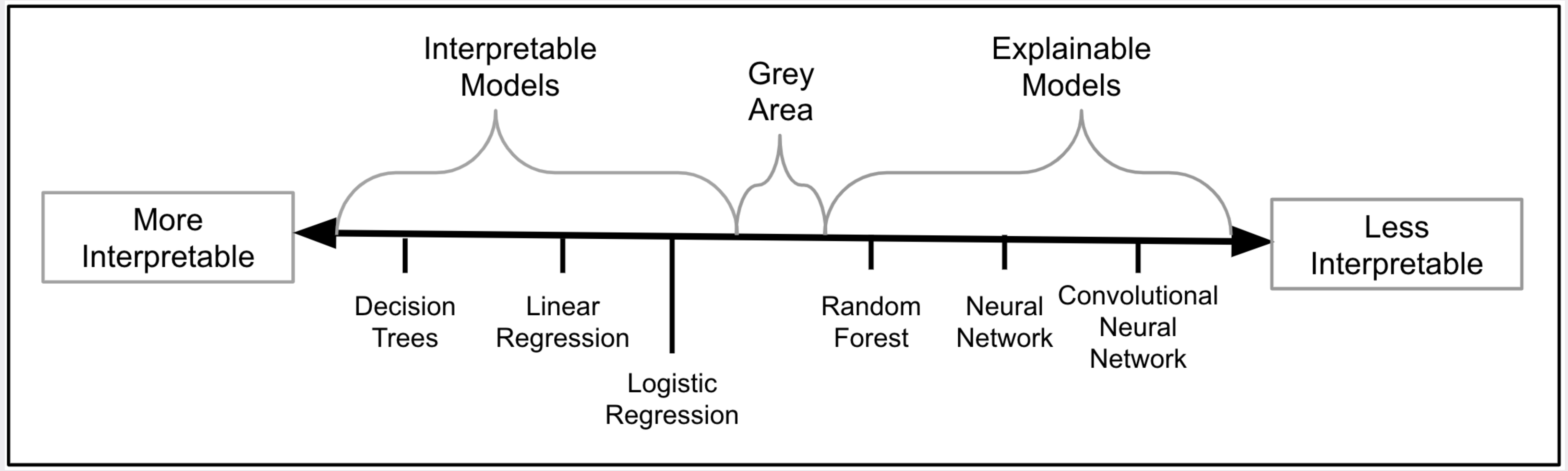




interpretable vs explainable ML

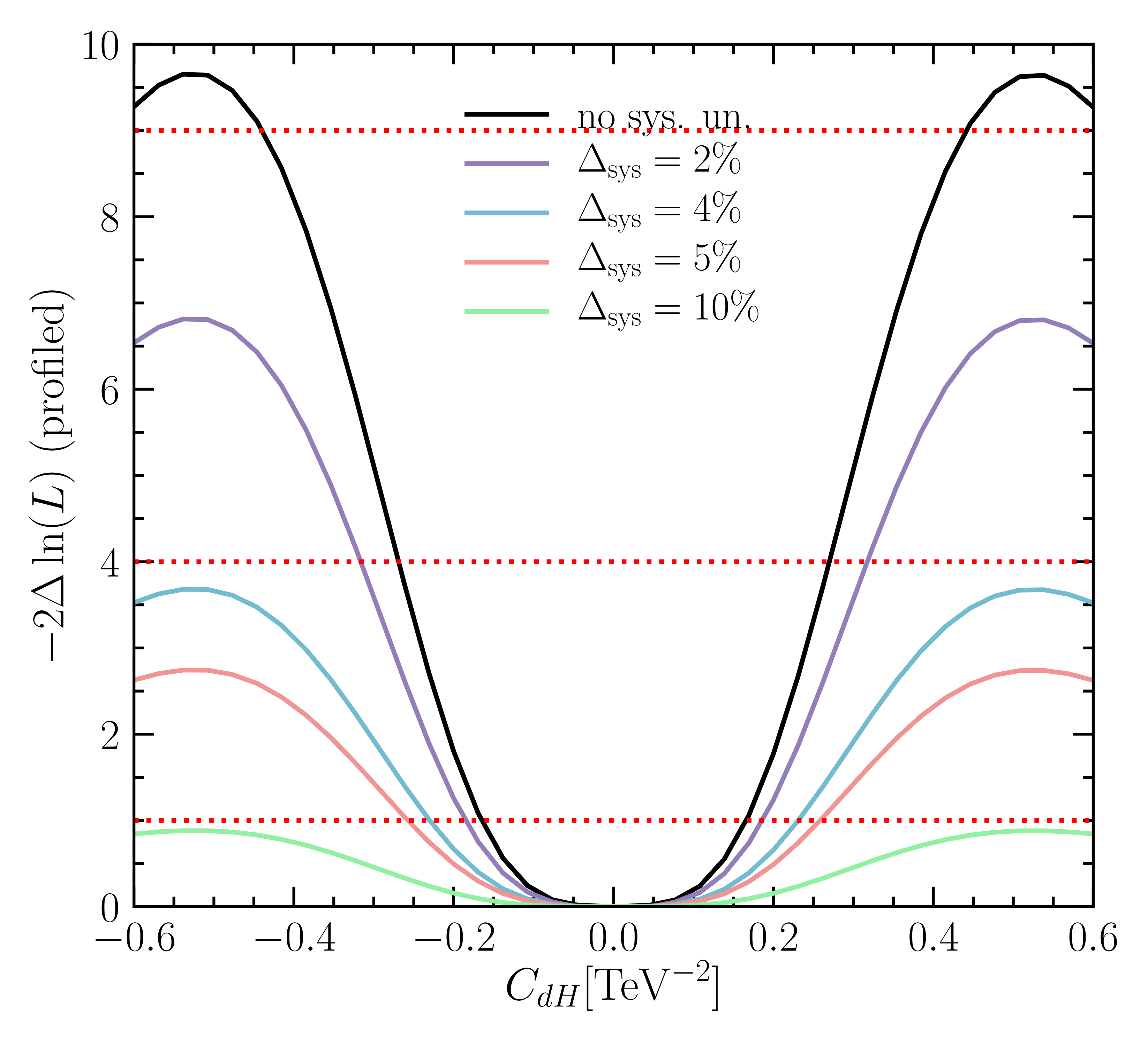
- Explainable models are not fully interpretable – proliferation of parameters can be a problem
- An interpretable model should be able to understandably map the input to the output
- Interpretability is important since an ML model should make the right decision for the right reasons.

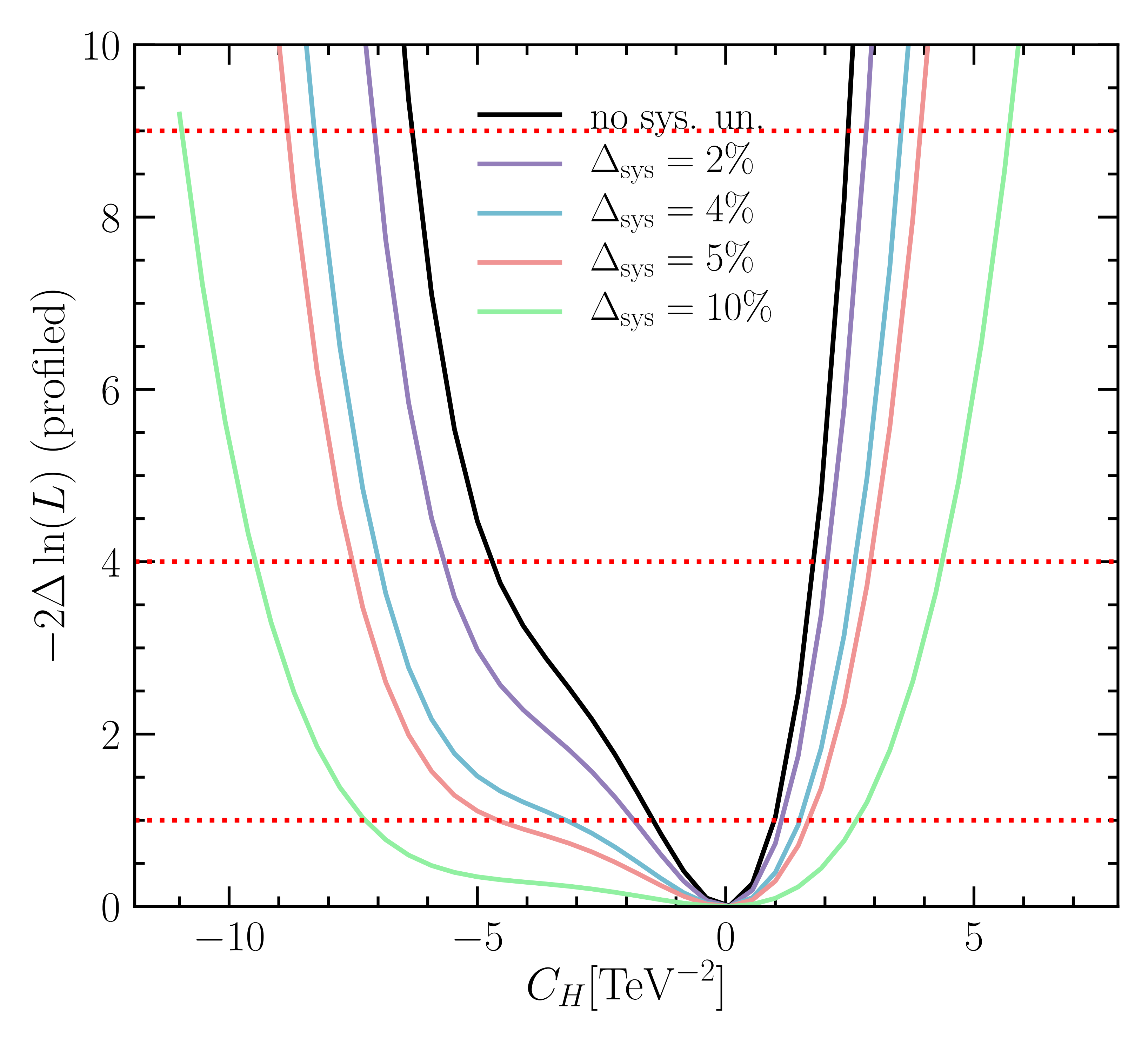


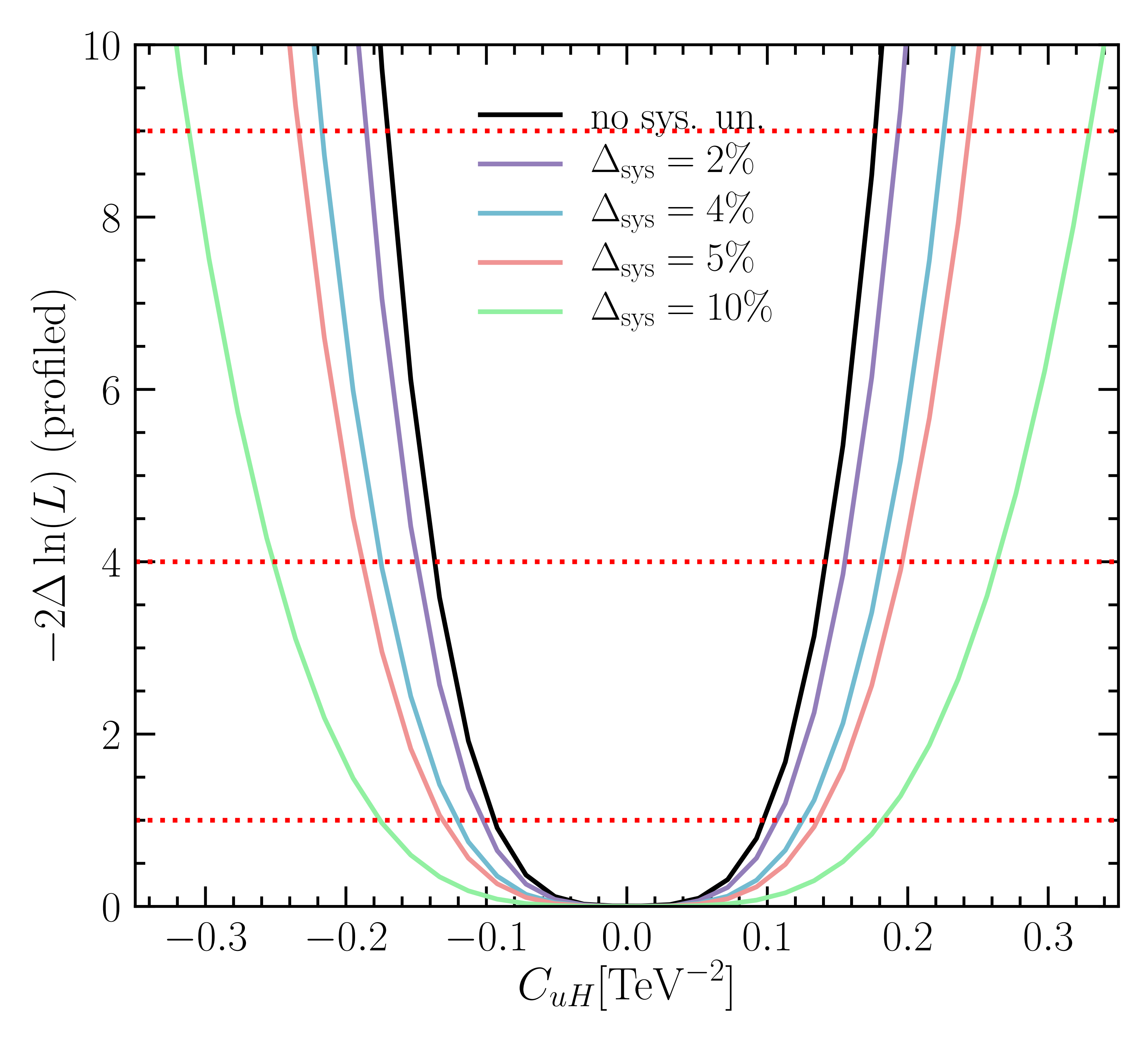


C. Rudin, *Stop explaining black box machine learning models for high stakes decisions and use interpretable models instead.* [Nature Machine Intelligence 1, 206–215] (2019)

Effects of systematic uncertainties







Aligned Flavour Violation (AFV)

- Recall that the CKM matrix $V = \mathcal{U}_u^T \mathcal{U}_d^*$ is the only matrix in the SM that transformed non-trivially under $U(1)_R^5$, leaving only one phase that correspond to CPV.

- We add new flavour spurions k_u, k_d that transform like the SM Yukawa matrices y^u, y^d.

- Aligned flavour violation *only* requires that the new spurions to transform trivially under $U(1)_R^6$, thus aligning FCNC with the CKM matrix (V is the only flavour spurion that breaks $U(1)_R^6$).

- Now we can write k_u, k_d -in the mass basis- as

Diagonal 3×3 complex matrices, invariant under flavour

$$k_u = \mathcal{U}_U \left(K_0^u + K_1^u V^* K_2^u V^T K_3^u + \mathcal{O}(V^4) \right) \mathcal{U}_{\bar{U}}^\dagger$$
$$(k_d)^\dagger = \mathcal{U}_D \left(K_0^d + K_1^d V^T K_2^d V^* K_3^d + \mathcal{O}(V^4) \right) \mathcal{U}_{\bar{D}}^\dagger$$

K_i^q are called Alignment expansion coefficients.

The construction of k_u, k_d is by construction „invariant“ under the bi-unitary transformations by $U(1)_R^6$, just like y_u, y_d

The bar notation correspond to a different matrix

UV models with AFV

❖Multi-Higgs Doublets

Peñuelas & Pich 17'

- Consider ϕ_a scalar doublets, were only ϕ_1 acquires a vev. The most general Yukawa takes the form

$$-\mathscr{L} = \sum_a \bar{Q}_L \left[\Gamma_a \phi_a d_R + \Delta_a \tilde{\phi}_a u_R\right] + h.c.$$

- Flavour alignment manifests in the conditions

$$\Gamma_a = e^{-i\theta_a}\xi_a^d \Gamma_1 \qquad \Delta_a = e^{i\theta_a}\xi_a^u \Delta_1$$

$$\xi_1 = 1 \quad \xi_{a\neq 1} \in \mathbb{C}$$

- Consistent with flavour bounds, but it is hard to get large Yukawa enhancement.

❖Vector-like quarks

Bar-Shalom & Soni 18'

$$\hat{Y}_d, \hat{Y}_u, \hat{\lambda}_{QD} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\hat{\lambda}_{QU}, \hat{\lambda}_{Uq} \in \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\hat{\lambda}_{Qd}, \hat{\lambda}_{Qu}, \hat{\lambda}_{Dq} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

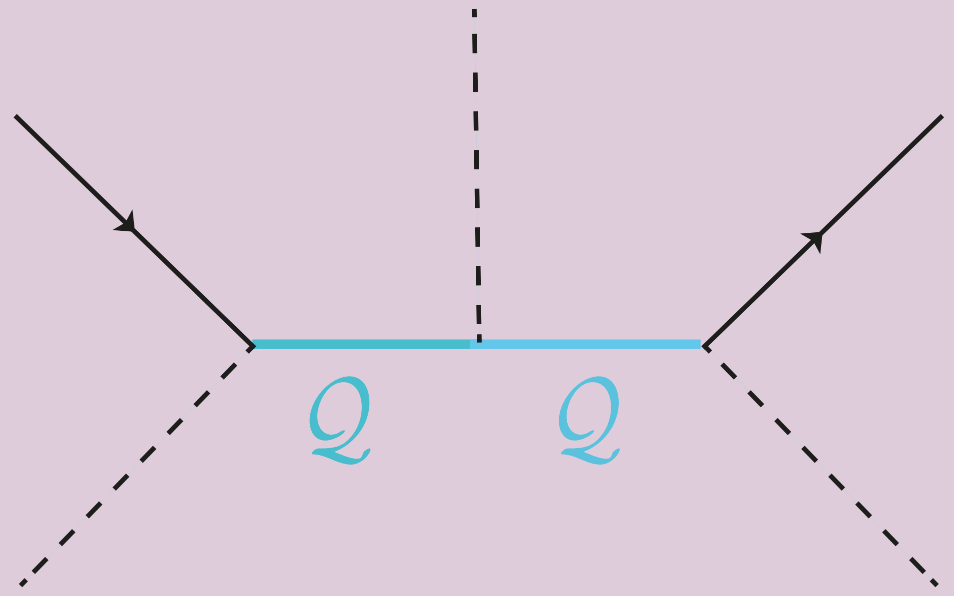
$$\hat{f}_{dH}, \hat{f}_{uH} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- The Yukawa-like interaction and mixing between the SM quarks and the VLQ (Doublet $\mathcal{Q}$ and singlets $\mathcal{U}, \mathcal{D}$) are given by

$$-\mathscr{L} = \lambda_{QU}\mathcal{Q}_L\tilde{\phi}U_R + \lambda_{QD}\mathcal{Q}_L\phi D_R + h.c.$$

$$-\mathscr{L} = \lambda_{Uq}\bar{Q}_L\tilde{\phi}\mathcal{U}_R + \lambda_{Dq}\bar{Q}_L\phi\mathcal{D}_R + \lambda_{Qu}\bar{\mathcal{Q}}_L\tilde{\phi}u_R + \lambda_{Qd}\bar{\mathcal{Q}}_L\phi d_R + h.c.$$

- Flavour alignment is achieved by constructing the mixing and VLQ Yukawa interaction matrices to satisfy certain discrete symmetries. $\mathbb{Z}_3$



- Requires fine-tuning, but not worse than the flavour one already existing in the SM.

- few TeV VLQ (1-3 TeV), generates significant enhancement to light Yukawa.

Summery of flavourful models

- This table contains a summery for the schema that flavourful models might have. Mainly theories with one or more extra Higgs doublets.

Schema \ Yukawa structure	Up-type	Down-type
MFV	Polynomial of SM Yukawa	Polynomial of SM Yukawa
General flavour conserving (AFV)	Non-universally aligned	Non-universally aligned
Natural flavour conserving	Real proportional	Real proportional
Aligned 2HDM	Complex proportional	Complex promotional
Up-type SFV	Real proportional	Non-universally aligned
Down-type SFV	Non-universally aligned	Real proportional

Table is taken from Egana-Ugrinovic, Homiller & Meade 19'