Machine learning augmented probes

OF LIGHT YUKAWA AND TRILINEAR COUPLINGS FROM HIGGS PAIR PRODUCTION

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Introduction

- Flavour physics is getting a lot of attention lately, e.g. $b \to s\ell\ell$ anomalies.

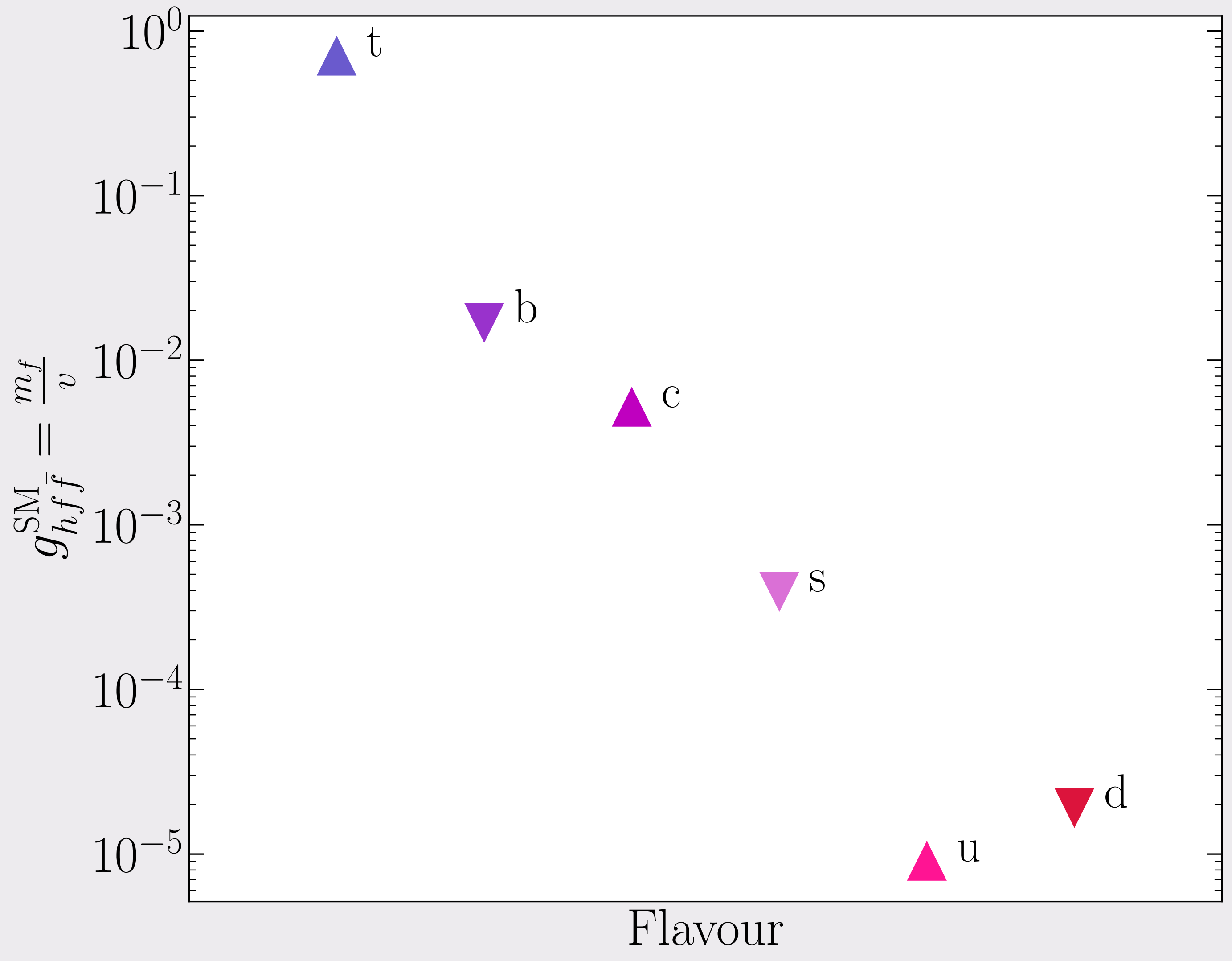
- Fermions interact with the Higgs, in the SM via Yukawa interaction, with the Lagrangian:

$$-\mathscr{L} = y^u Q\tilde{\phi}u + y^d Q\phi d + y^e L\phi e + \mathrm{h.c.},$$

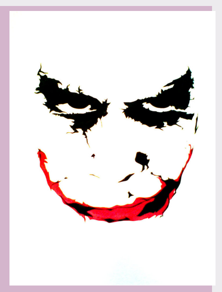
- The Yukawa matrices, e.g. for the quark sector (y^u, y^d) are the *spurions* breaking flavour symmetry $U(3)_Q \otimes U(3)_d \otimes U(3)_u \longrightarrow U(1)_B$. Making them the source of flavour.

- There is no current explanation for the hierarchy amongst quark-generations predicted by the SM.

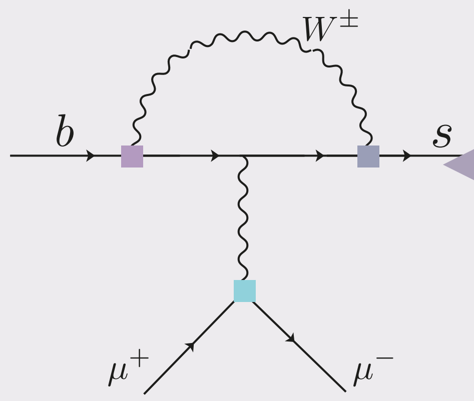
- Also, there are no direct measurements of 1st and 2nd generation quarks coupling with the Higgs. (Though it is a bit better for leptons CMS-HIG-19-006)



Why so hierarchical ?



In the SM, the Yukawa couplings are essentially free parameters, only fixed by observations.
We observe a huge hierarchy between the generations' Yukawa couplings, this is known as the old flavour puzzle.



We are famous now !

Things are getting better, particularly for charm , with ATLAS announcing 1st direct constraint

Why looking for HH ?

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

- 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).

- One of the main objectives of the High-Luminosity (HL)-LHC.

- There are over **10400** publications on the topic of Higgs !
  Over 60% of them came up since the LHC first launched !

- 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 in the next LHC runs CERN-LPCC-2018-04

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

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

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

$3000 - 6000\ \mathrm{fb}^{-1}$

Tax payers should keep paying for the LHC to keep running :) And scientists and engineers „ on the ground“ need to keep it working :)

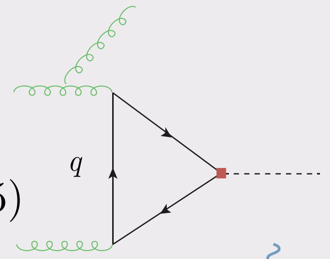
~ 36 fb

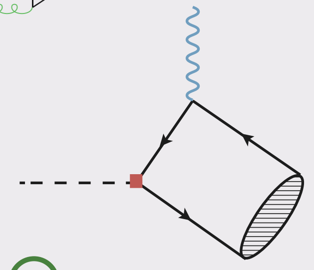
Theoreticians need to understand the systematic uncertainties as well as work on simulations

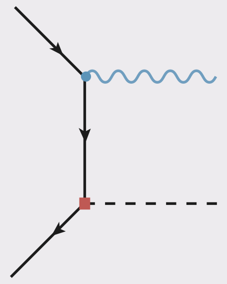
State of the art

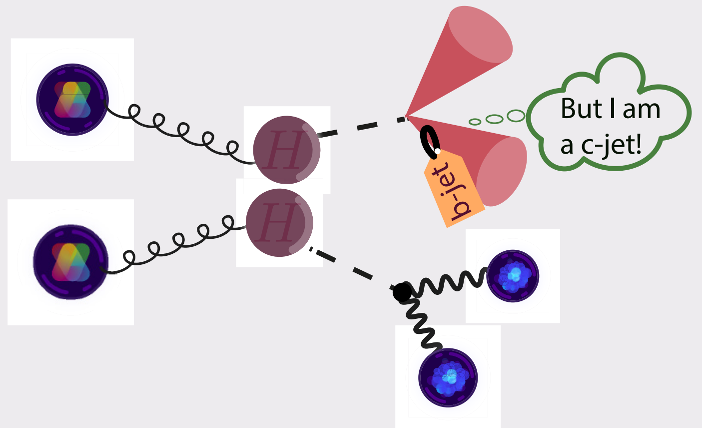
- There are many proposed processes for probing light quark Yukawa coupling

  - Higgs + jet, and kinematics Brivio, Isidori, Goertz (2015),Soreq, Xing Zhu, Zupan (2016) ,Bishara et al (2018)
  - Rare Higgs decays (decay to mesons) Bodwin et al (2013), Kagan et al (2014) and Konig, Neubert. (2015)
  - HW production charge asymmetry Yu (2017)
  - Higgs + photon Aguilar-Saavedra, Cano, No. (2020).
  - Tri-boson production Falkowski et al. (2020)
  - b-mistagging from (VH, VBF) Perez, et al. (2015 and 2016) Kim & Park (2015)
  - Higgs pair - or more- production M Bauer, M Carena, A Carmona(2018) LA, Corral Lopez, Gröber. (2019) Egana-Ugrinovic, Hollimer, Meade.(2021)

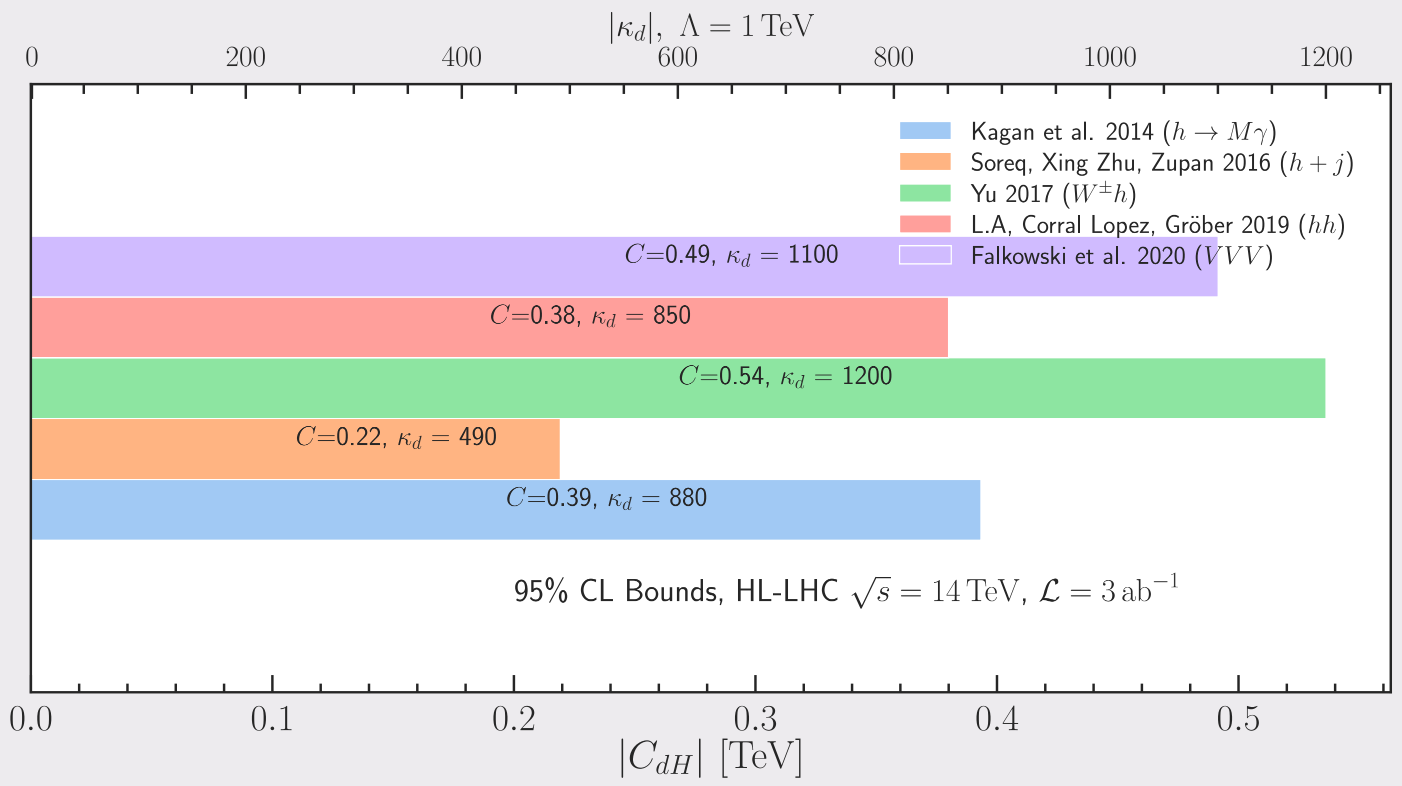


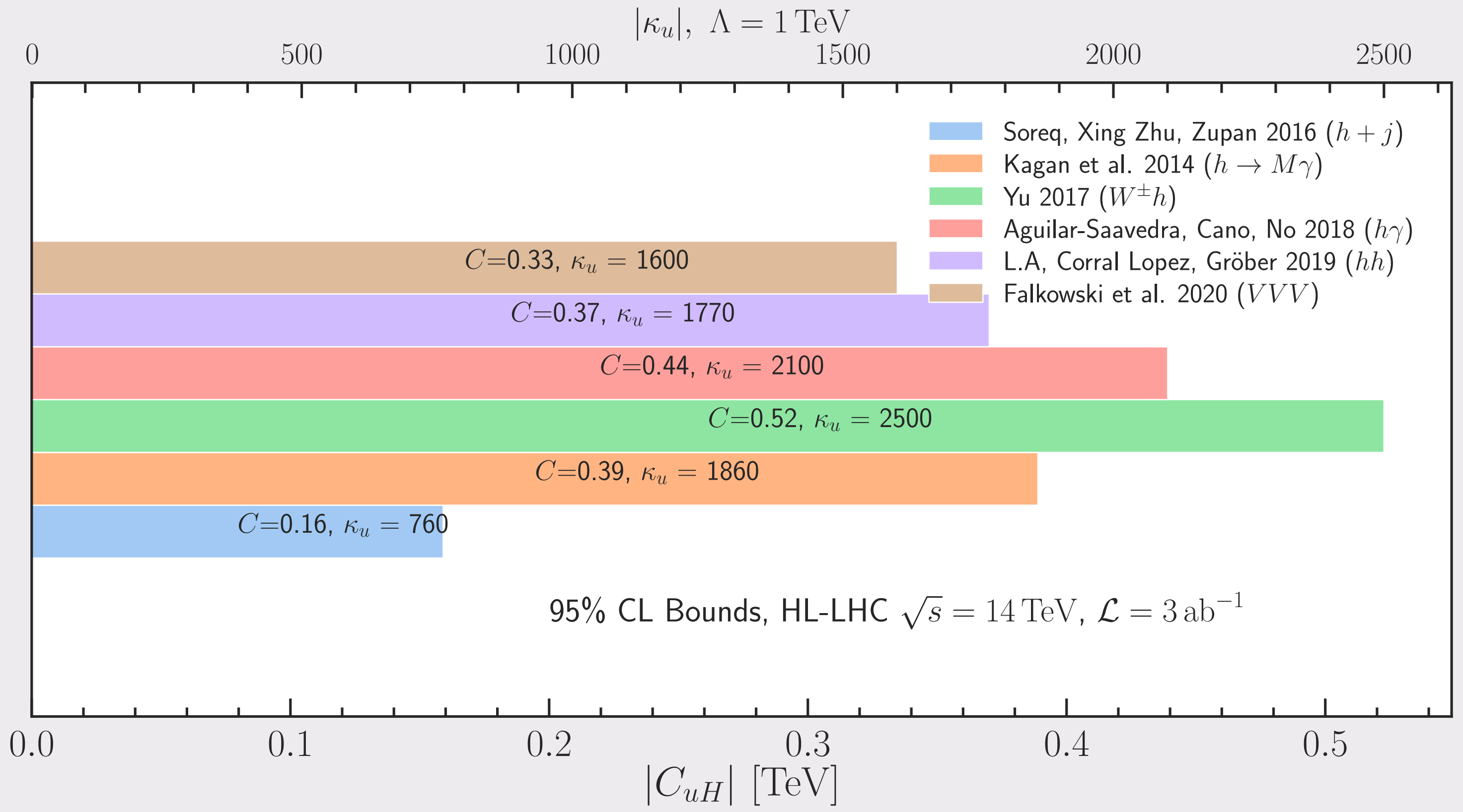


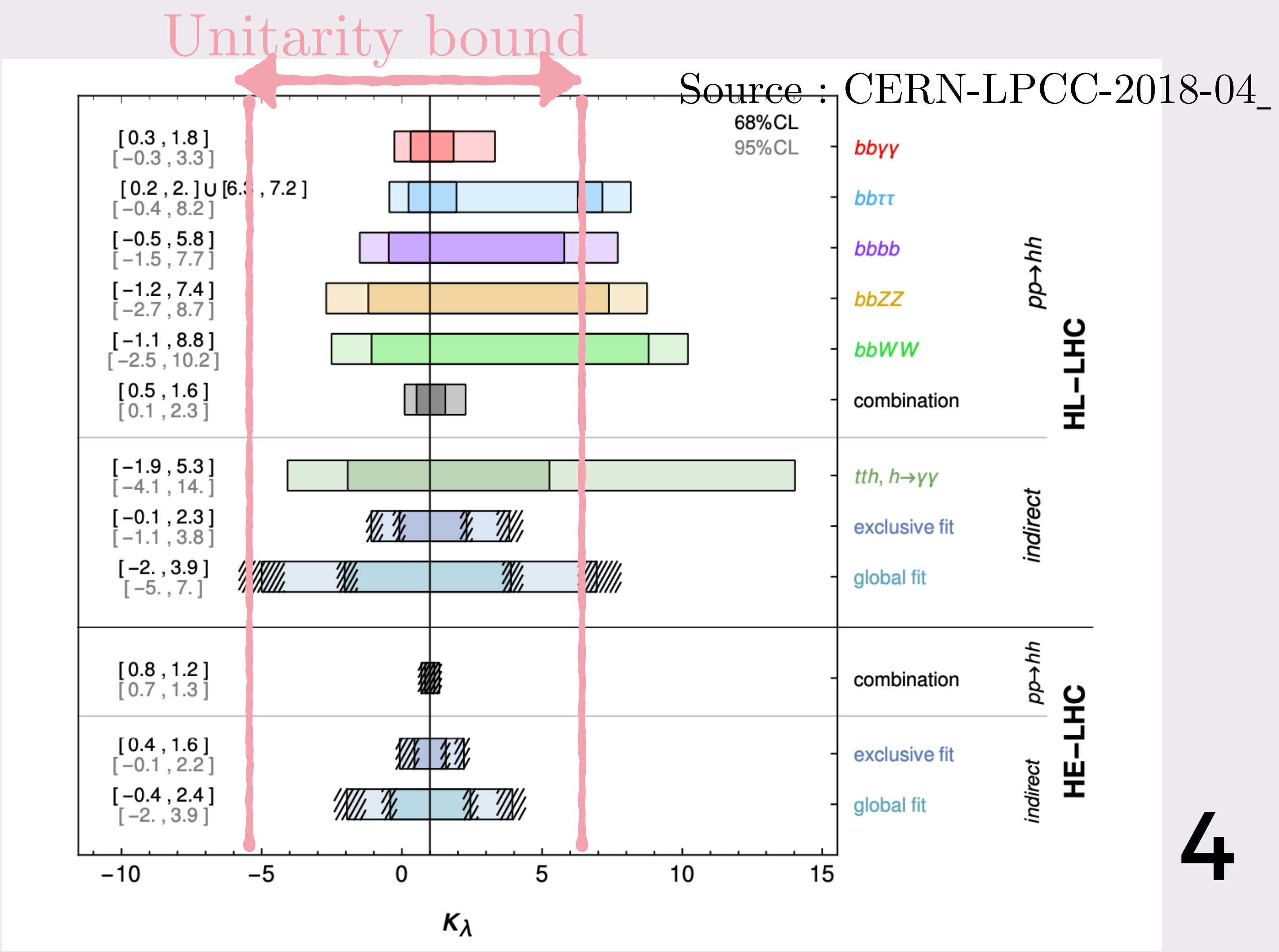




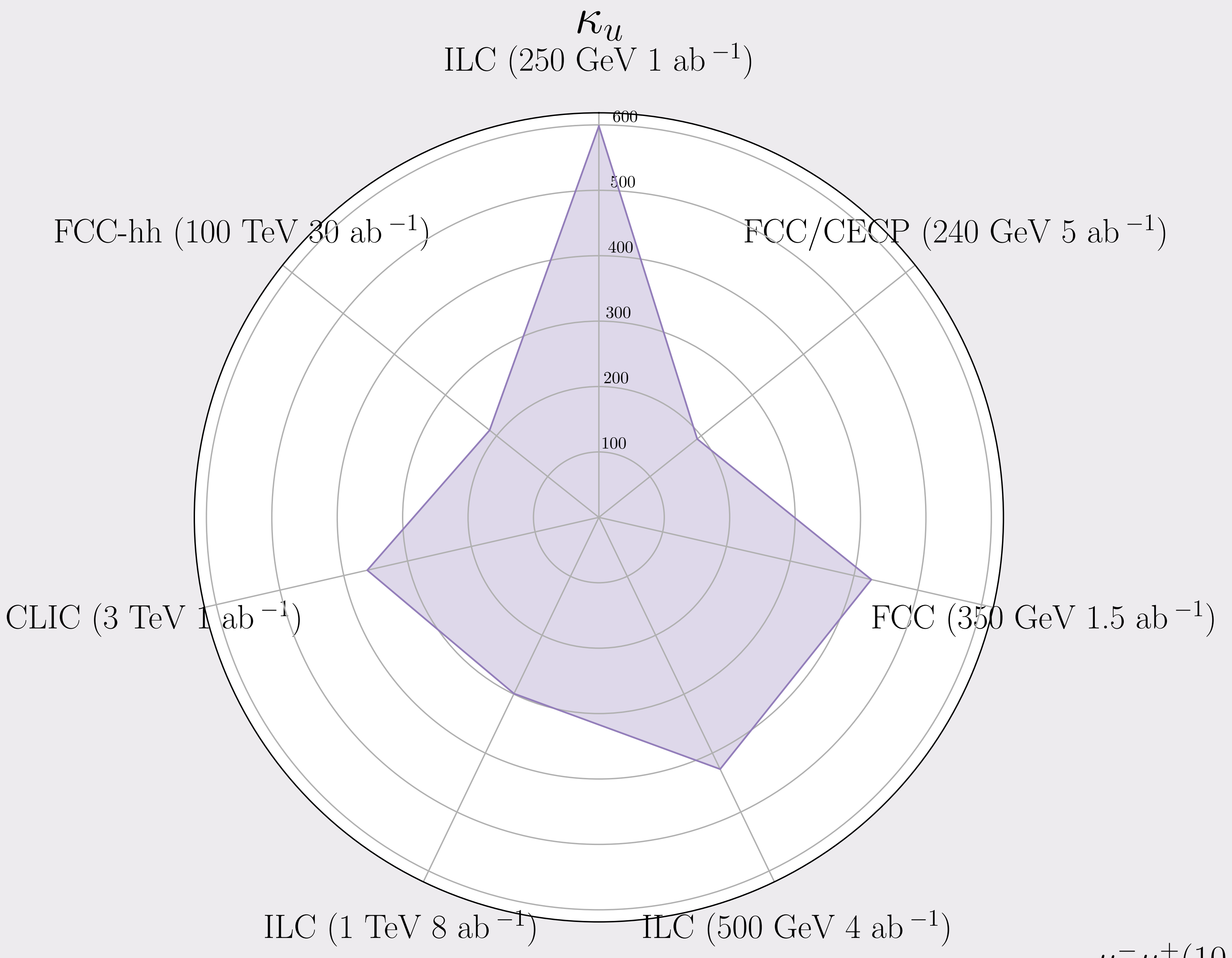
- The use of machine-learning for the analysis of HH has been proposed.
  It involved the use of (D)NN and BDT cf. ATL-PHYS-PUB-2018-053 , Han Kim et al. (2019), Tannenwald et al (2020) and others..

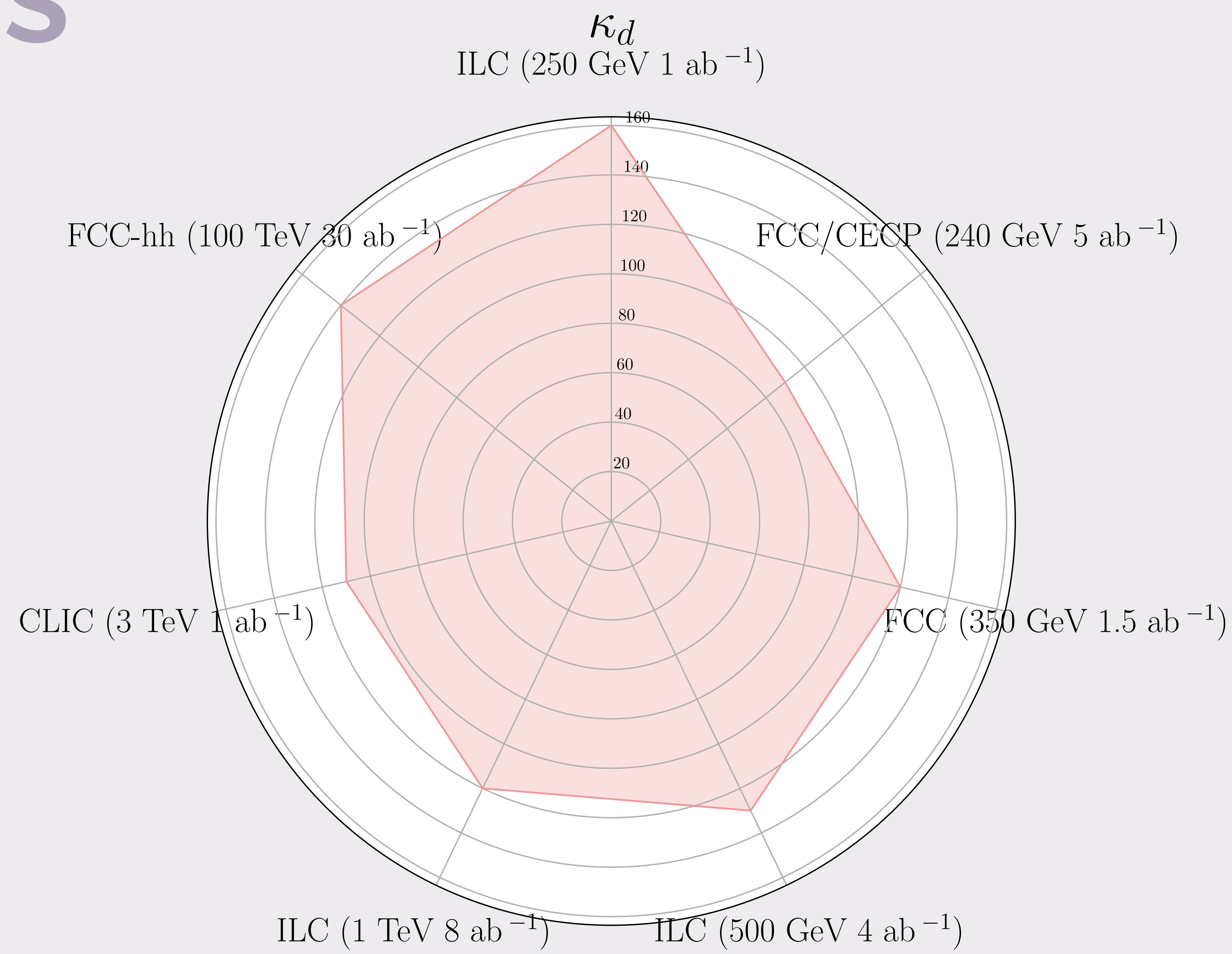


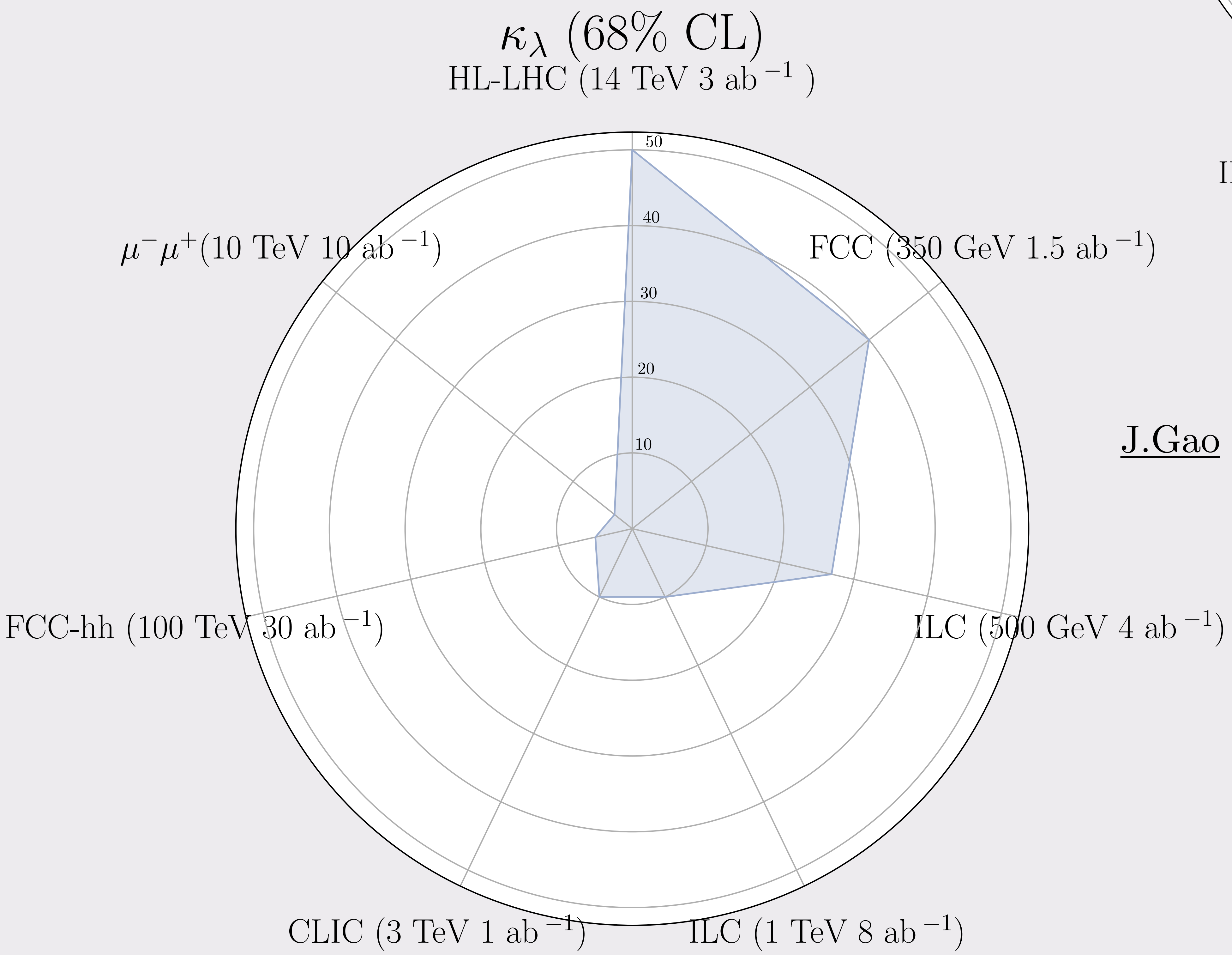




Prospects for future colliders



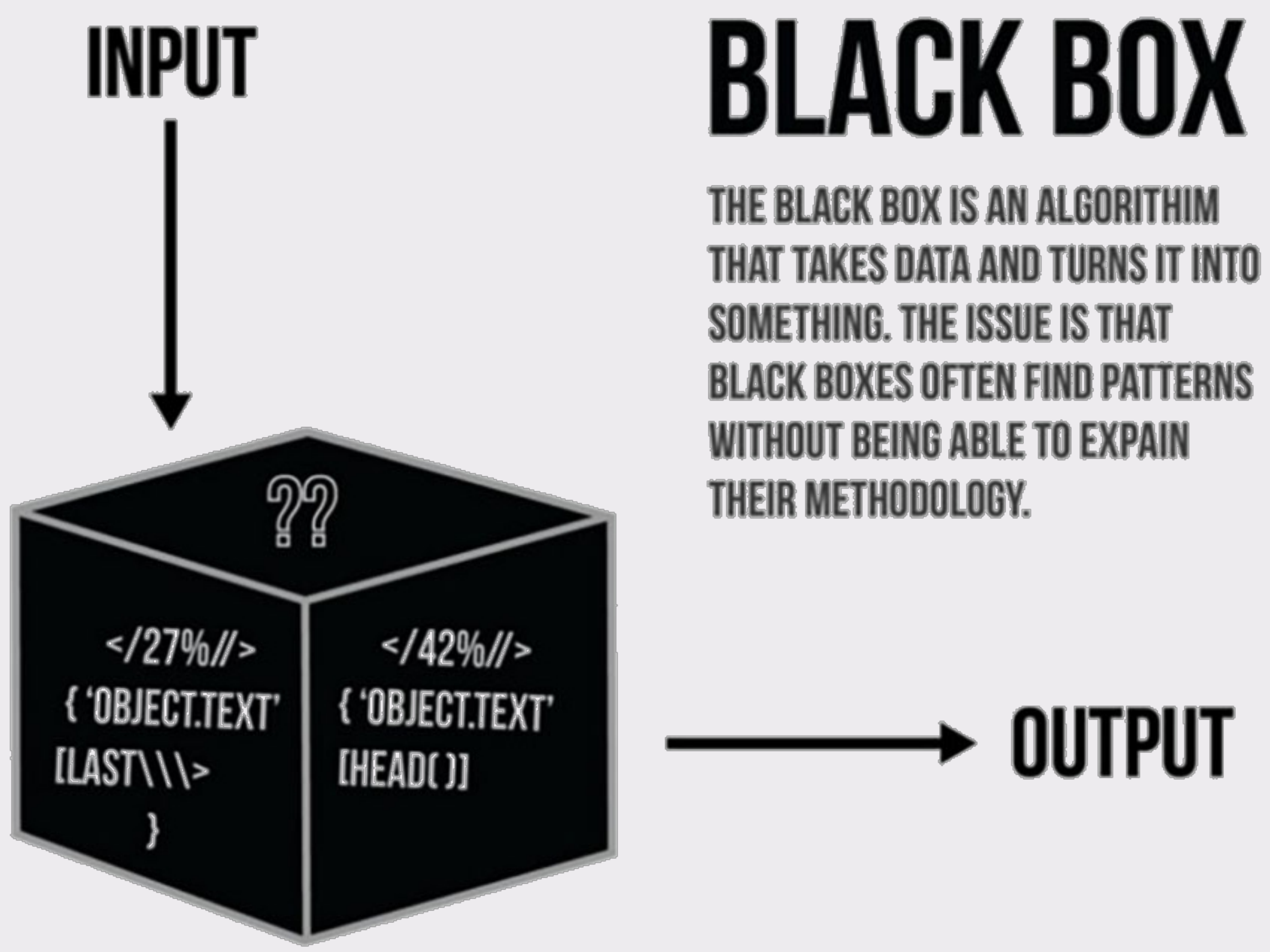


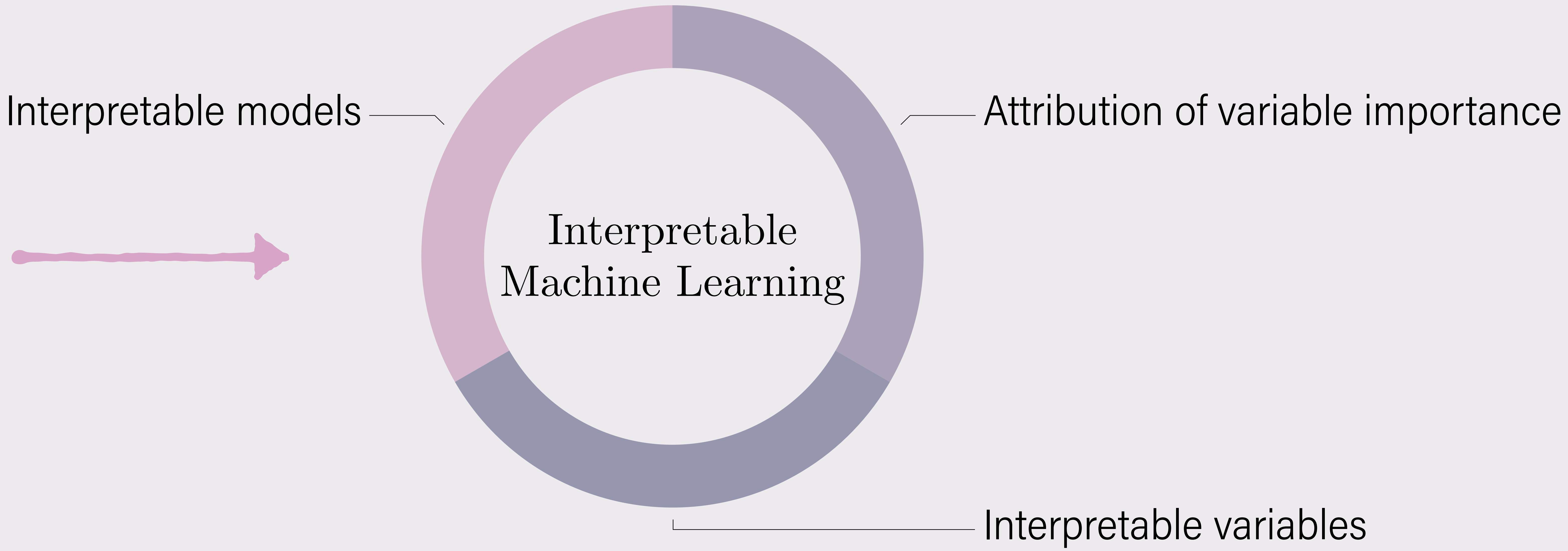


J.Gao (2018), S. Di Vita et al (2018) J.de Blas et al. (2020)

Interpretable machine learning

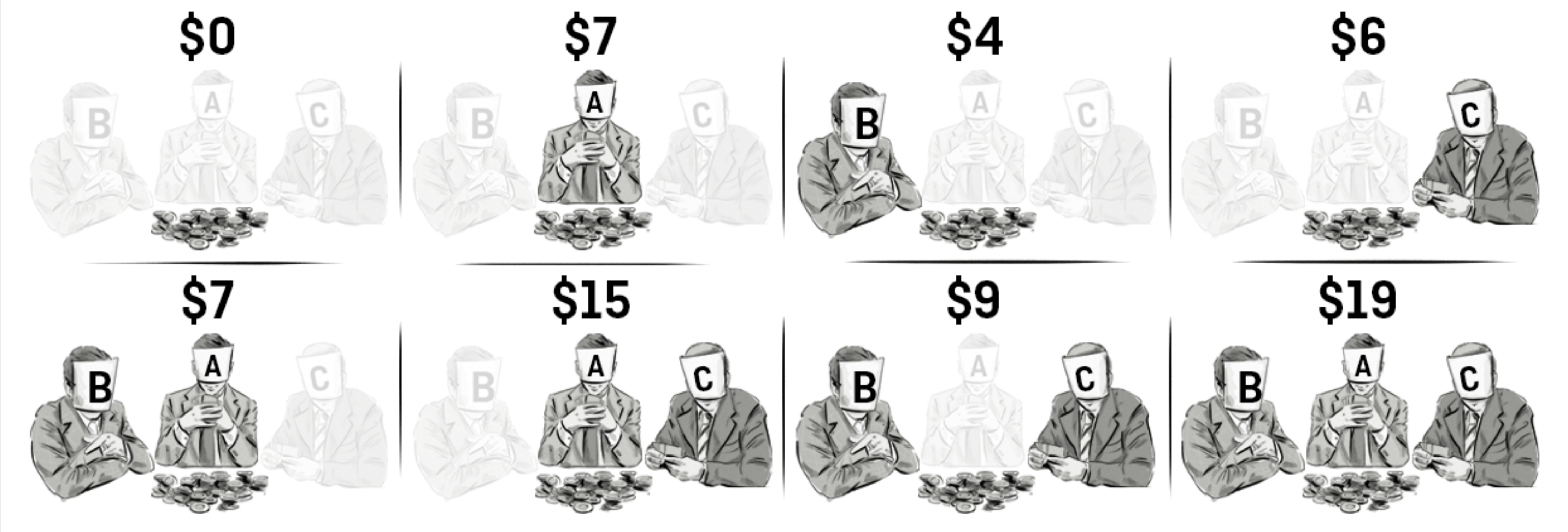
What is „Interpretable“ ML ? (Provided by Ayan Paul)



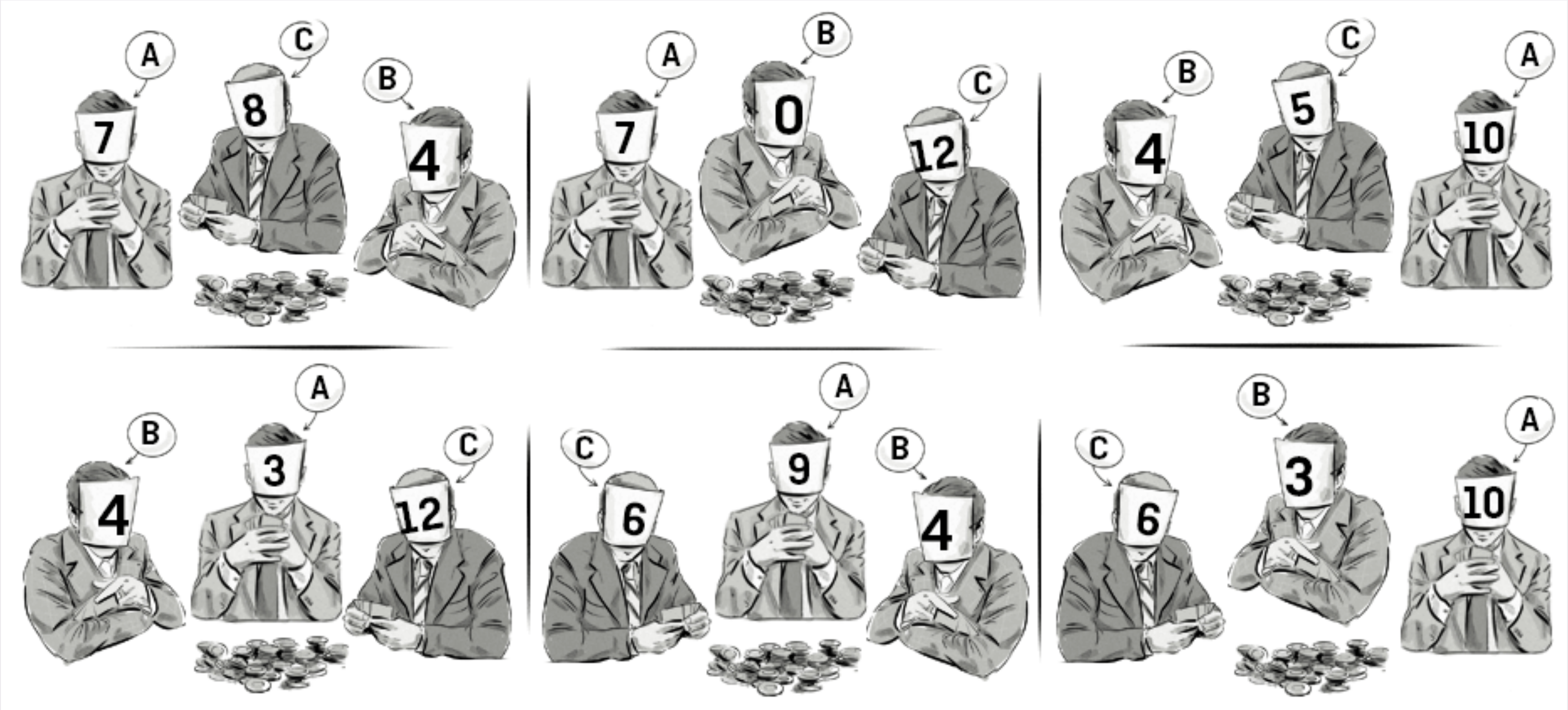


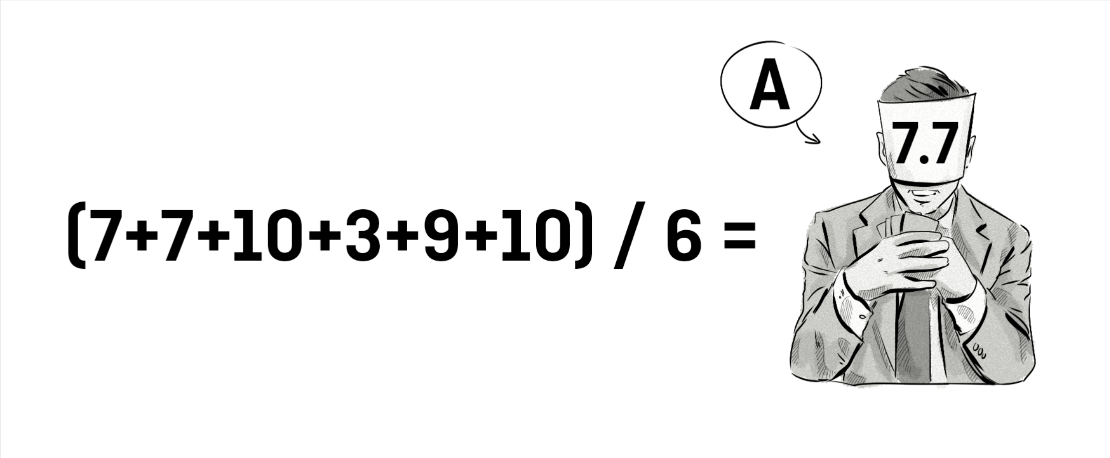
Cooperative games and Shapley values (Provided by Ayan Paul)

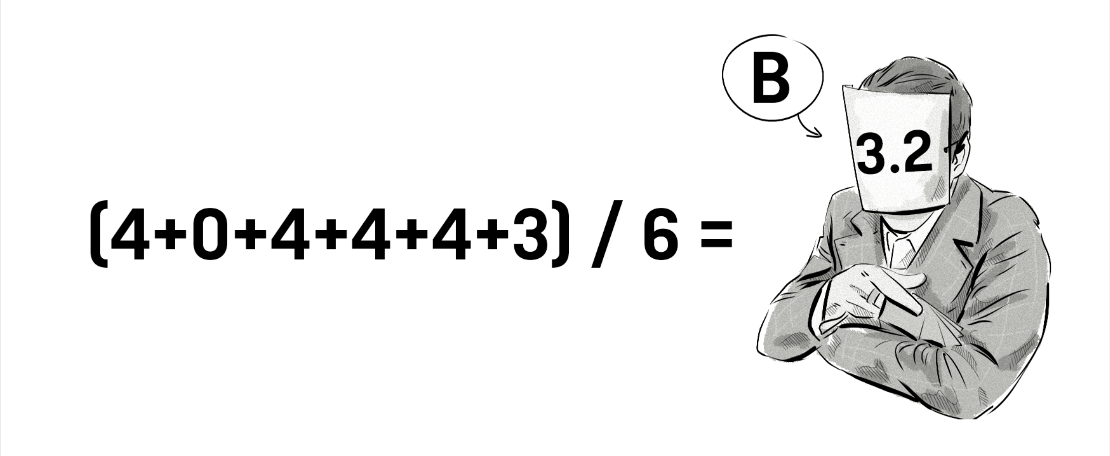
The value of each player and each combination of players



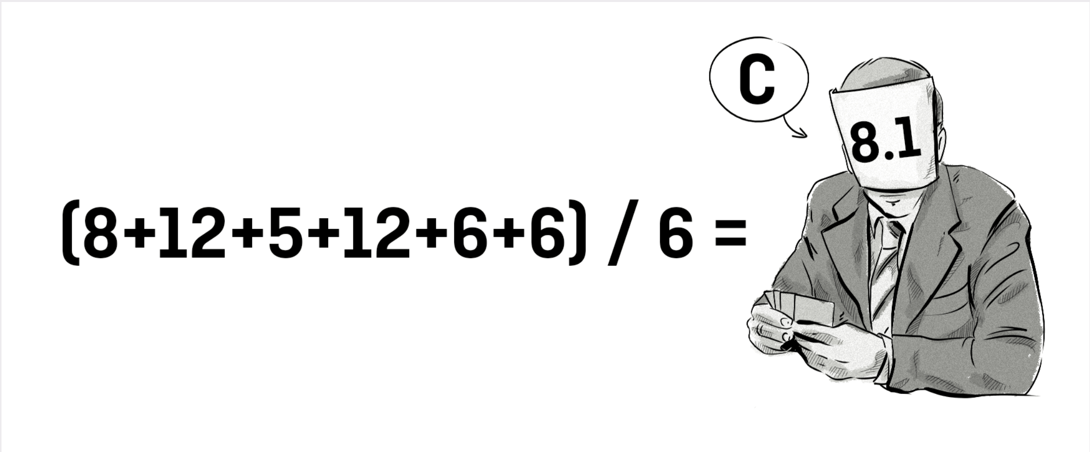
The value of the player in each game







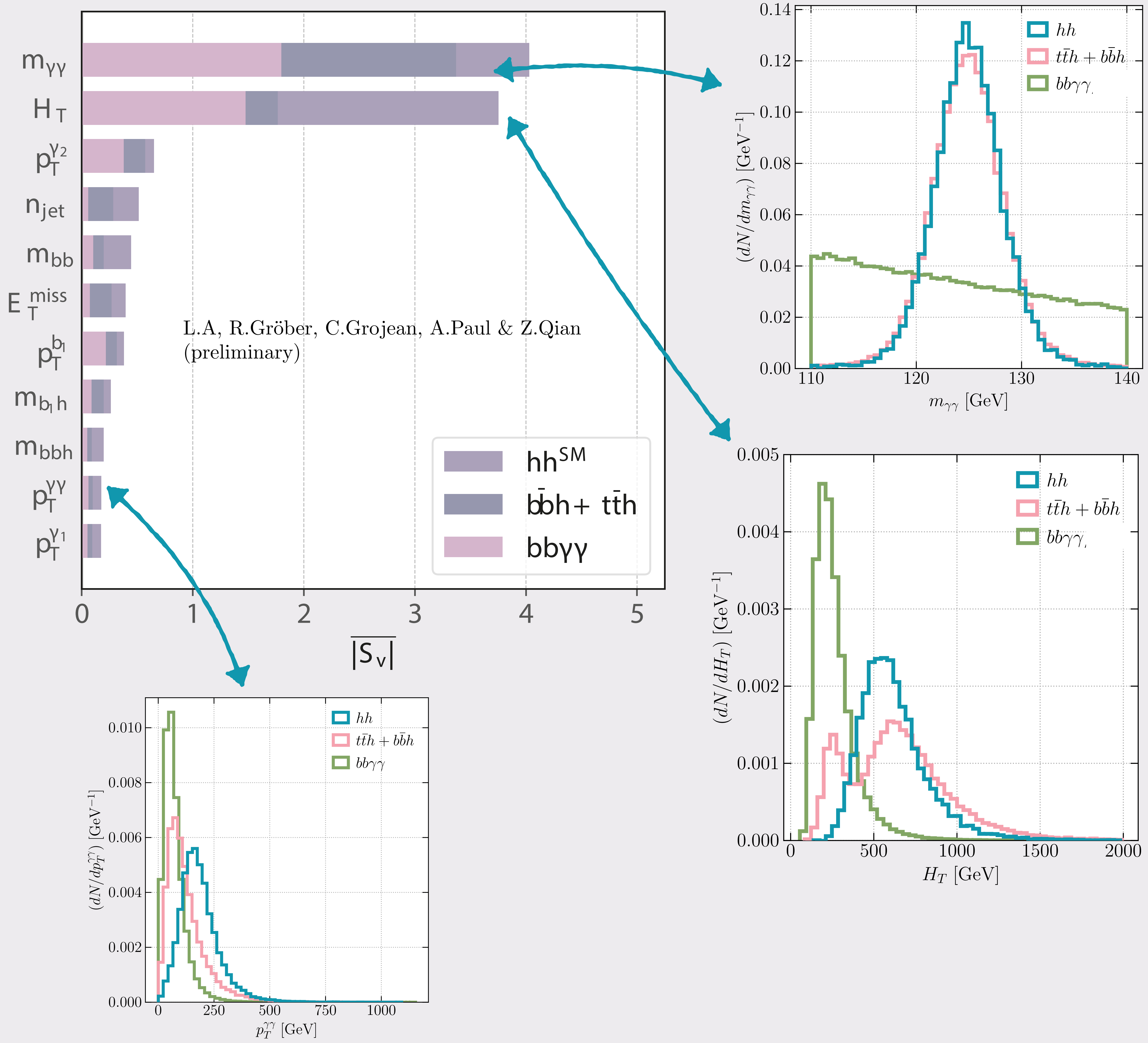
Marginalise the values



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 $pp \to hh \to b\bar{b}\gamma\gamma$ ($\sigma \cdot BR = 0.975$ 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

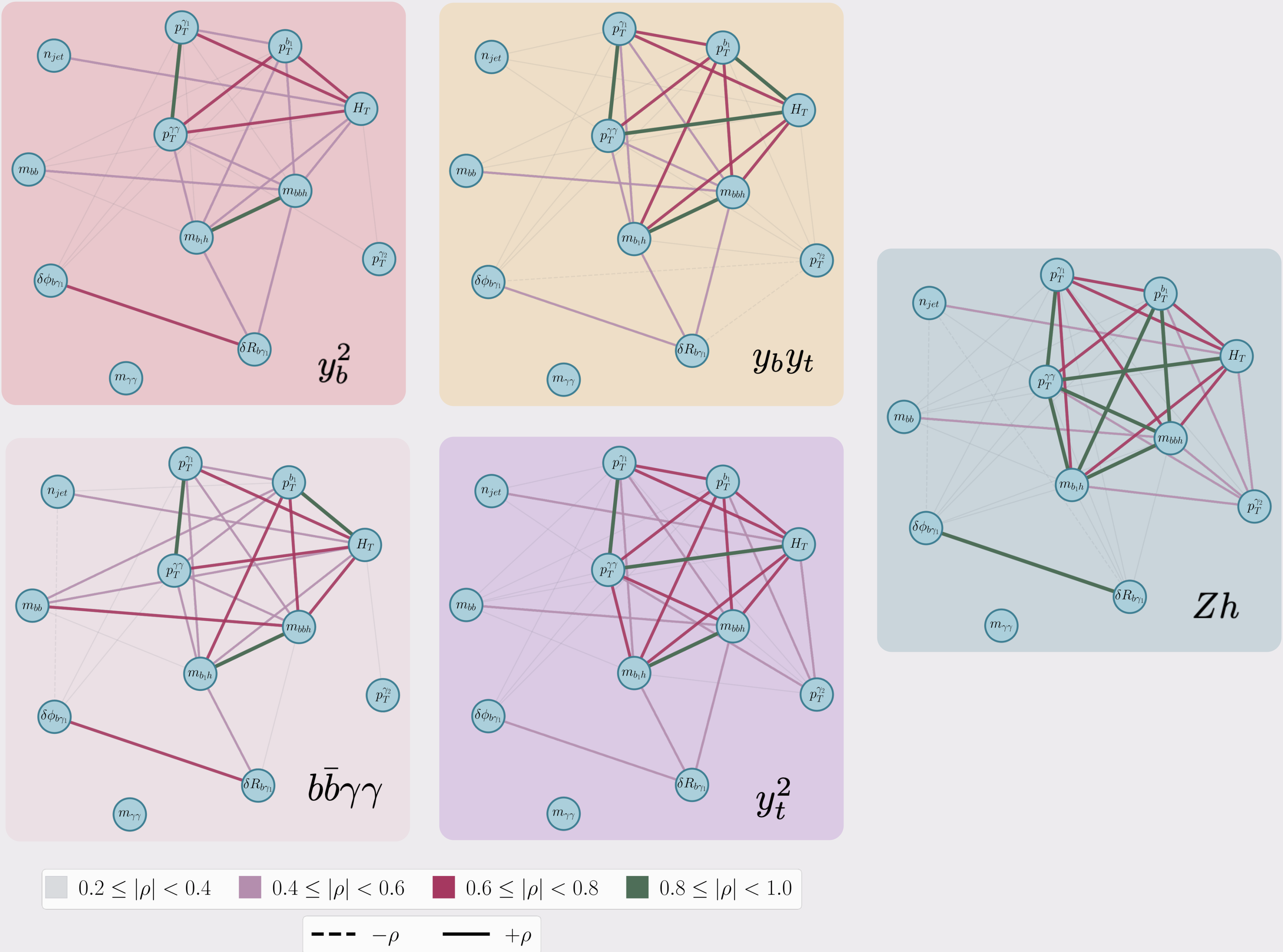
- We have selected the following list of observables similar to C. Grojean et al (2020):

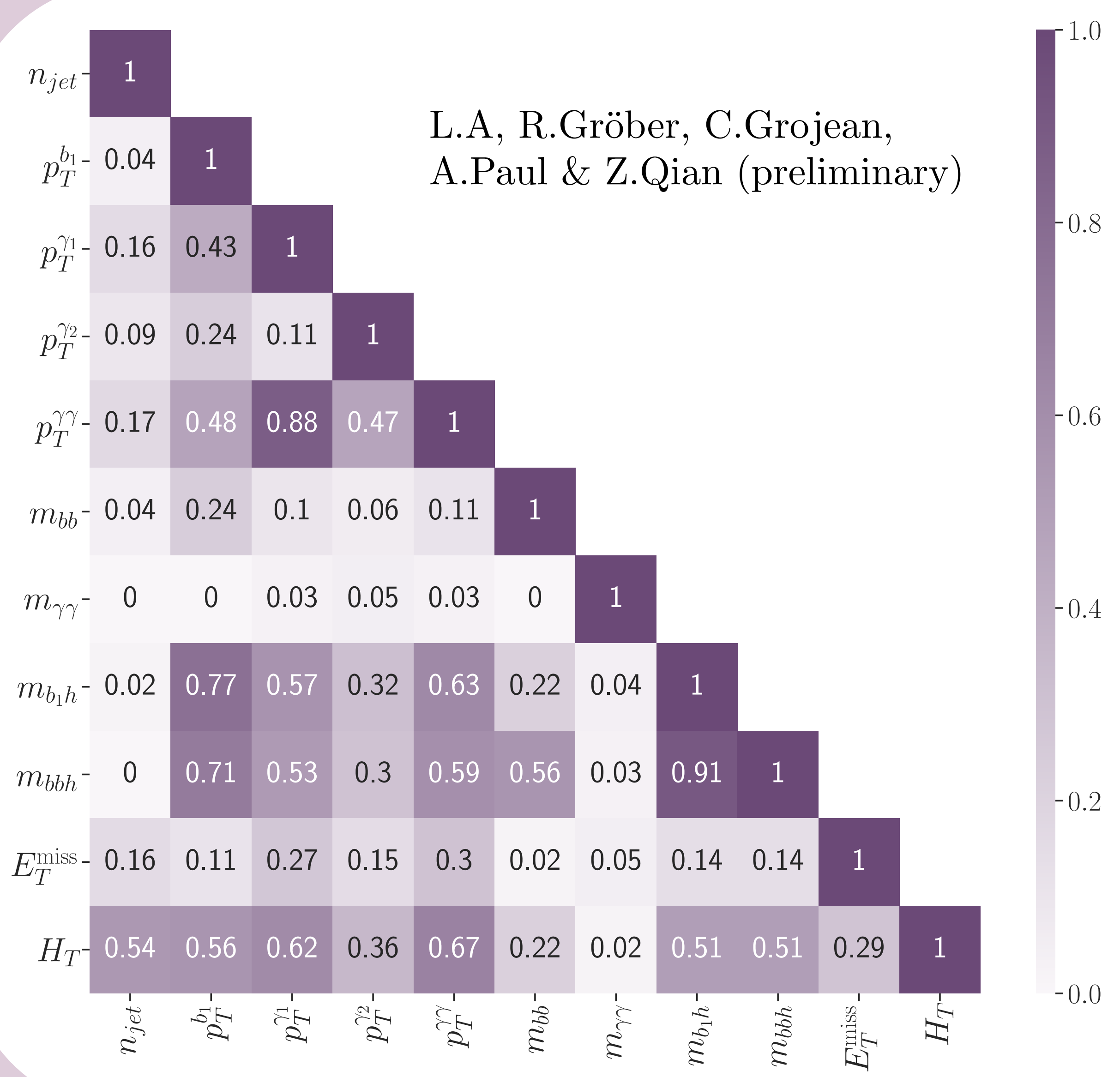
$$p_T^{b_1} p_T^{b_2}, p_T^{\gamma_1}, p_T^{\gamma\gamma}, \eta_{b_{j1}}, \eta_{b_{j2}}, \eta_{\gamma_1}, \eta_{\gamma\gamma}$$

$$n_{bjet}, n_{jet}, \Delta R^{b\gamma}_{\text{min}}, \Delta\phi^{bb}_{\text{min}}, m_{\gamma\gamma}, m_{bb}, m_{b_1h}, m_{b\bar{b}h}, H_T.$$

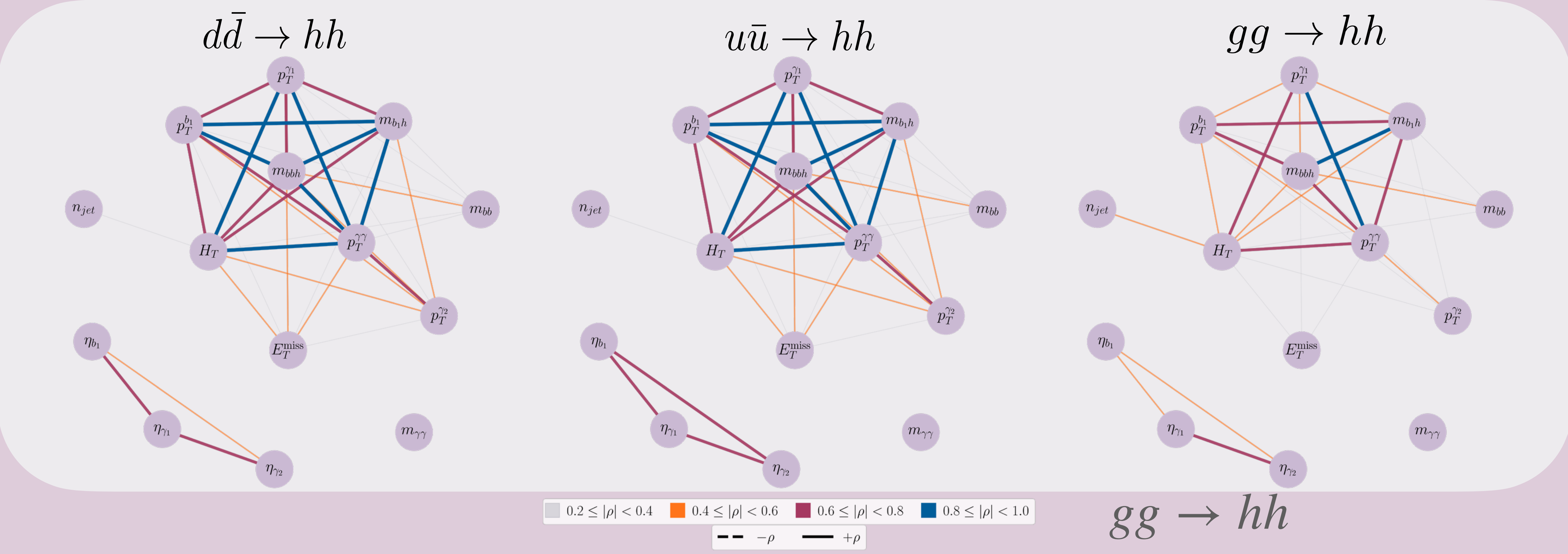
Cooperation in Physics

- 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





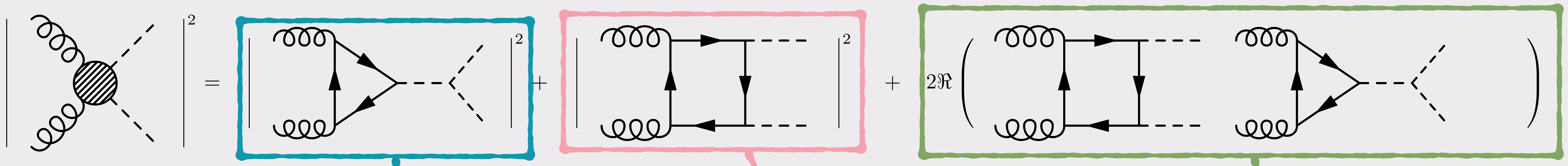
multivariate inherits correlations!



$gg \to hh$

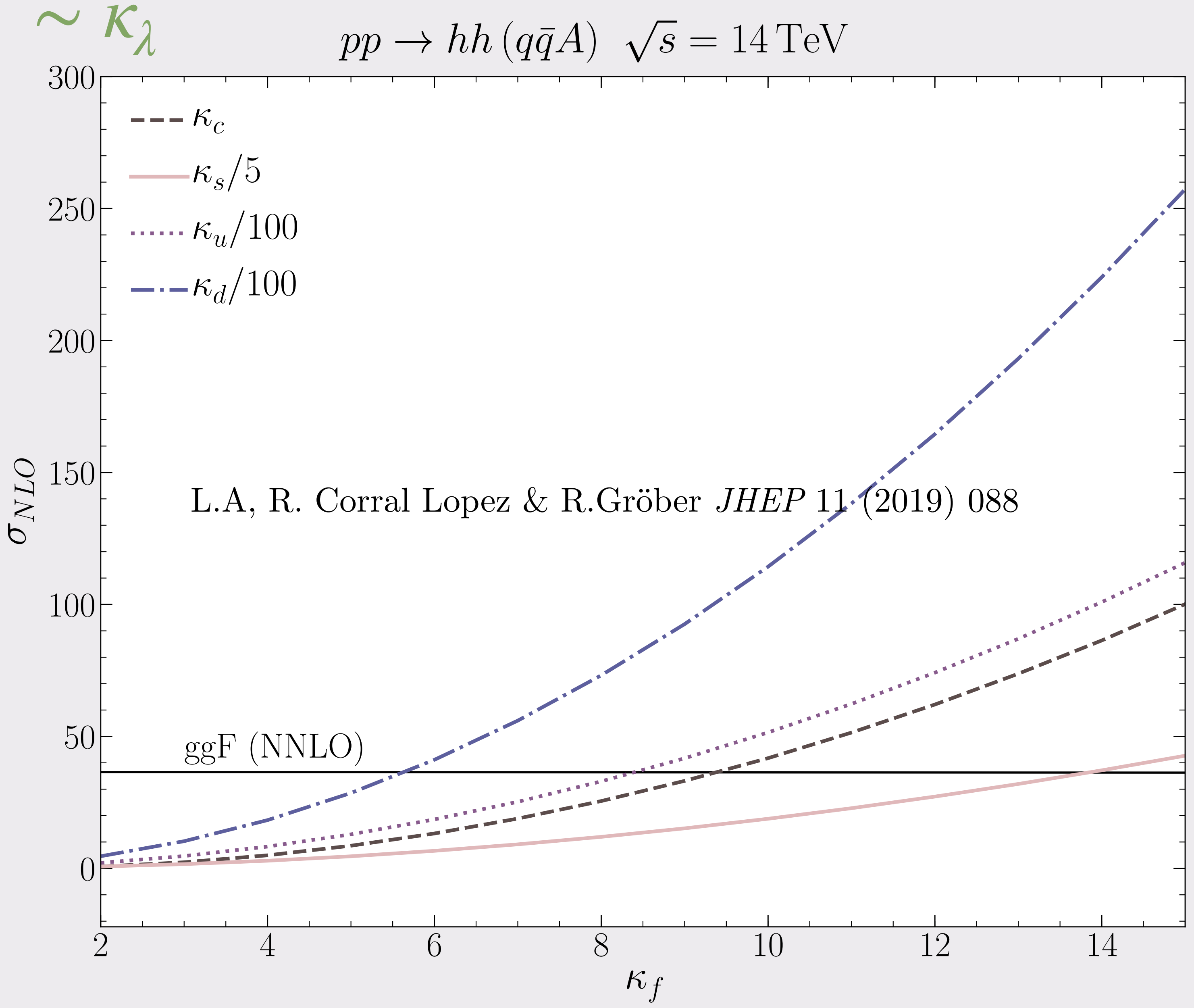
The analysis II

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



$\sim \kappa_\lambda^2$ no κ_λ dependence $\sim \kappa_\lambda$

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

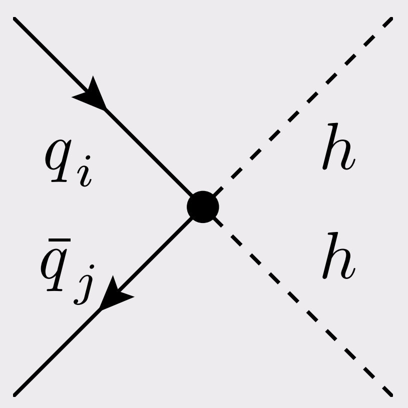


❖We adopt this notation

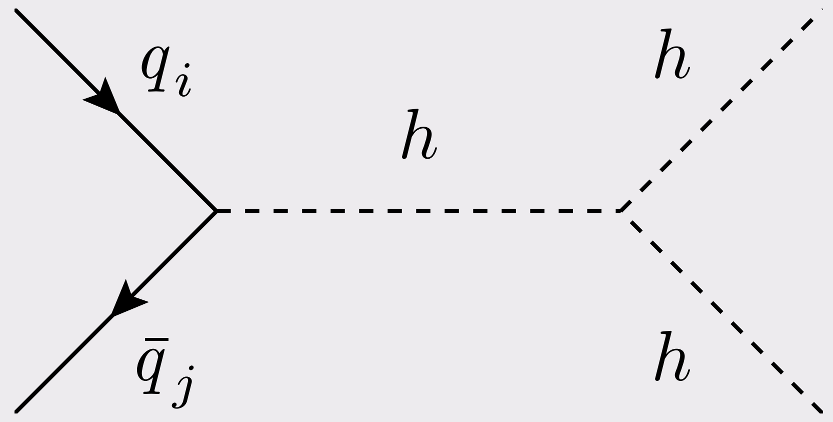
$$\kappa_q := \frac{g_{hq\bar{q}}}{g^{\mathrm{SM}}_{hq\bar{q}}}$$

Though, we work in SMEFT, so we also have

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

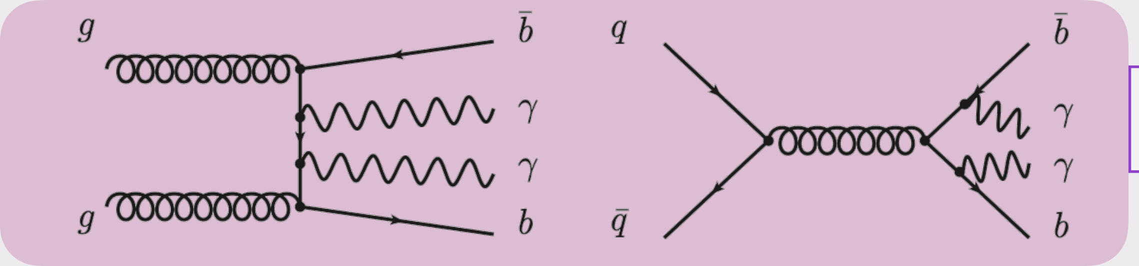


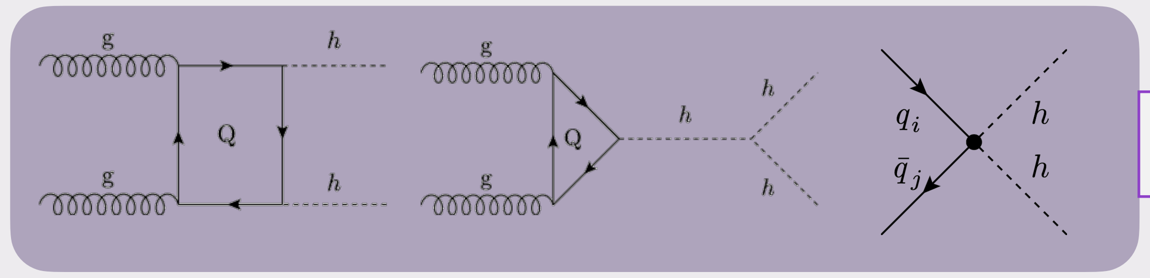
$\sim \kappa_q^2$

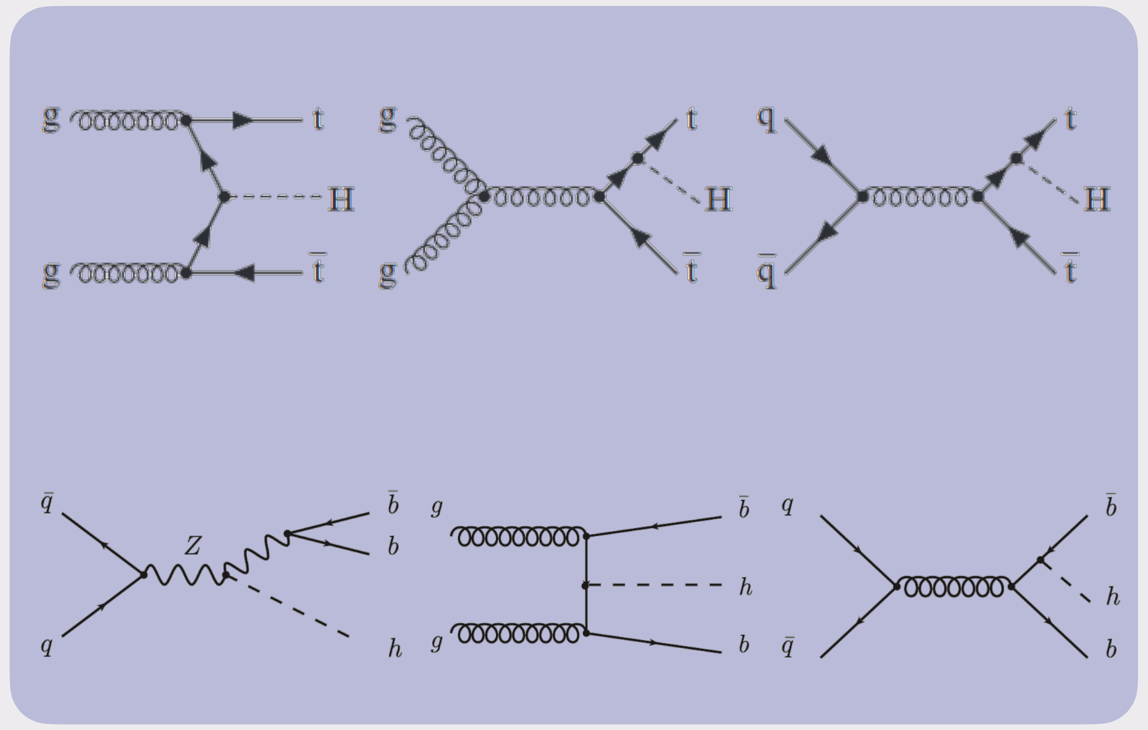


Analysis summery (Provided by Ayan Paul)

Interpretable Variables







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

QCD-QED Backgrounds

hh signal

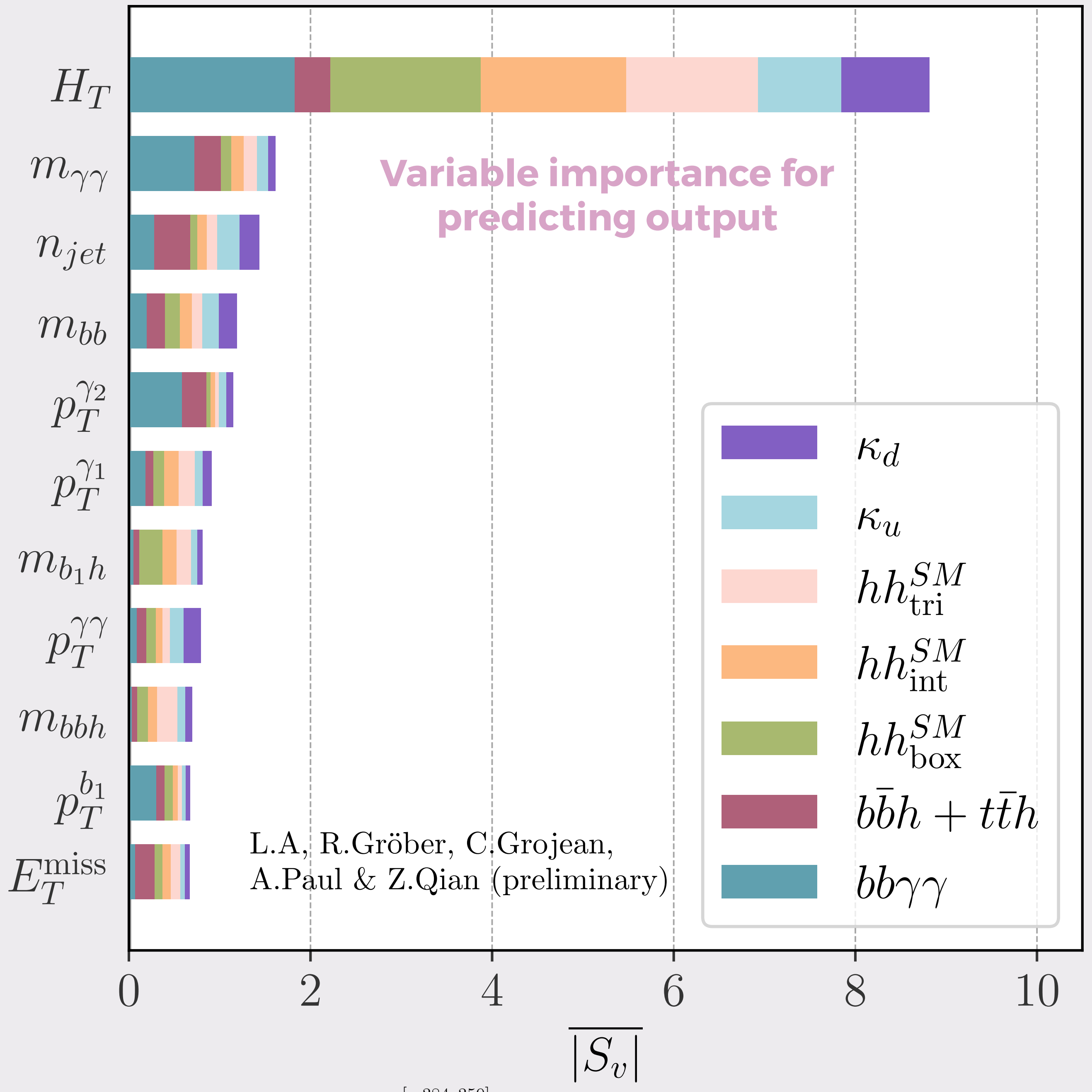
$b\bar{b}h + t\bar{t}h$ backgrounds

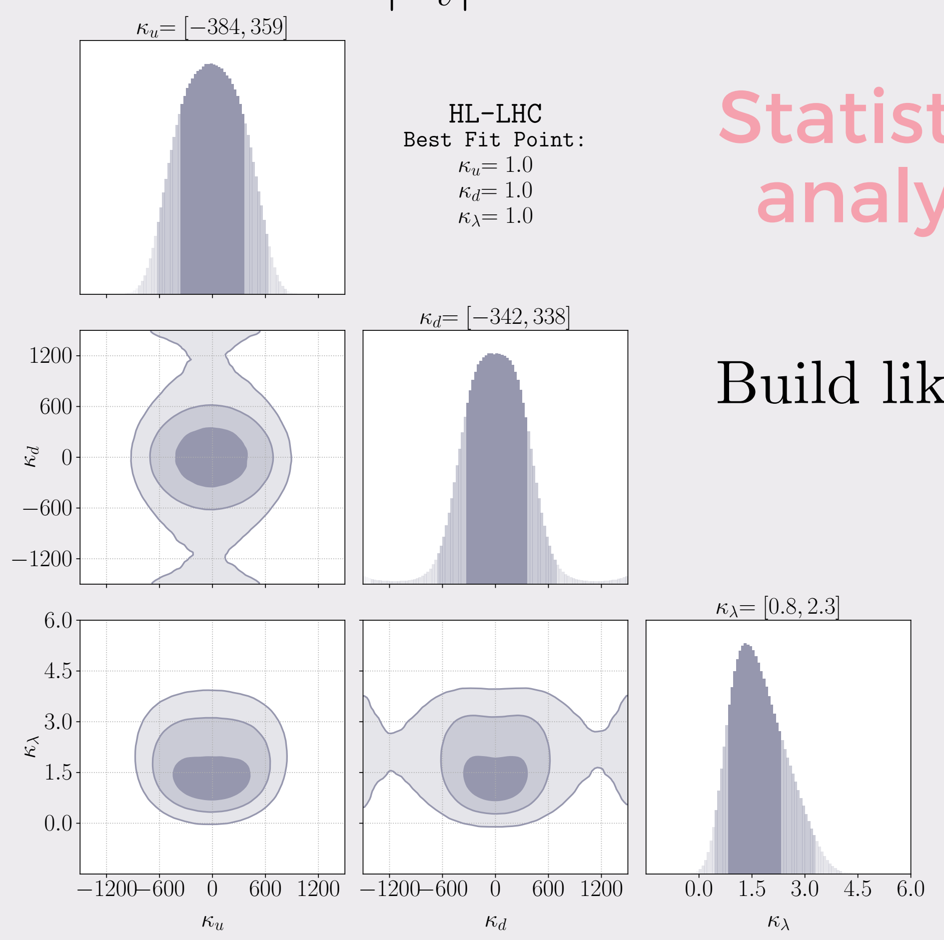
Construct high-level kinematic observables (features), with basic cuts

Shapley values + Physics Insights

Boosted Decision Trees + Signal Classification

Interpretable models



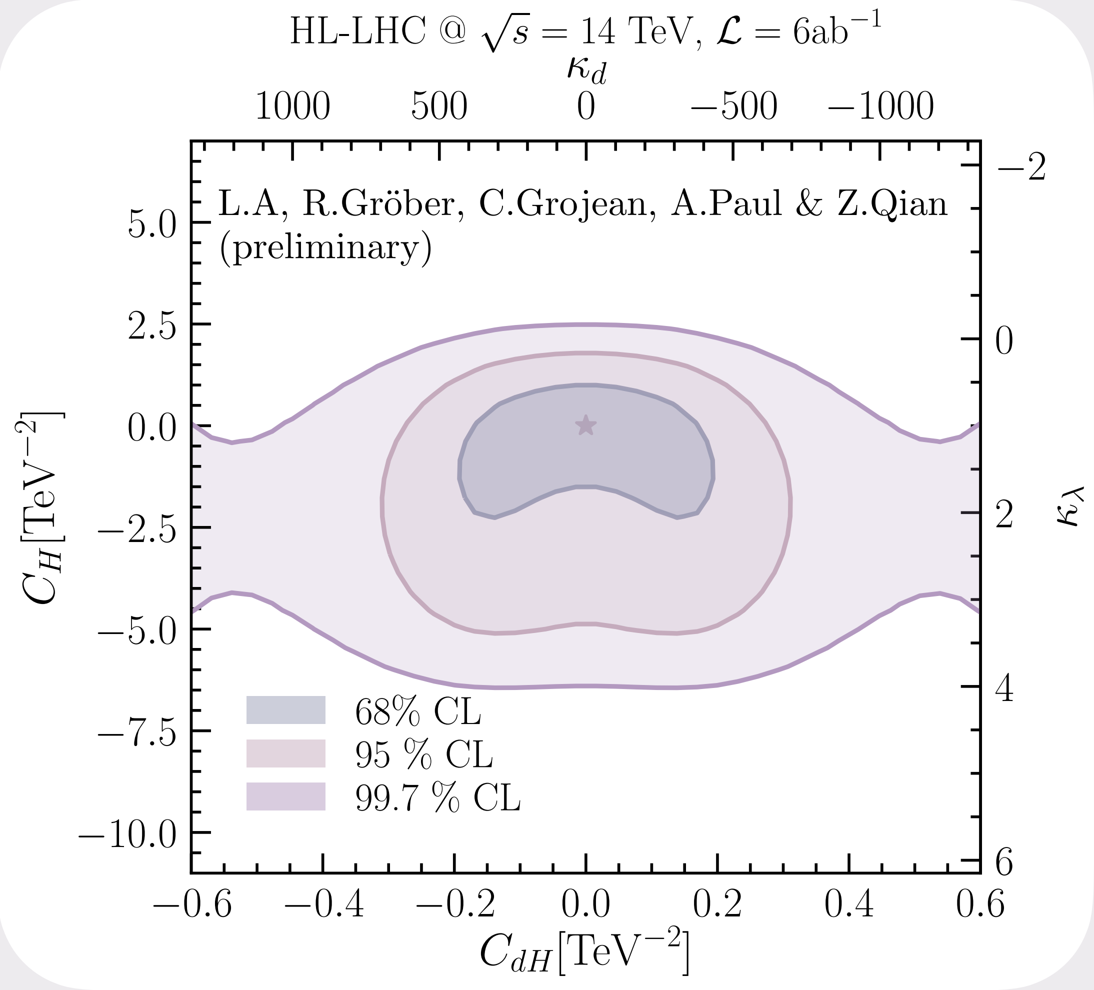


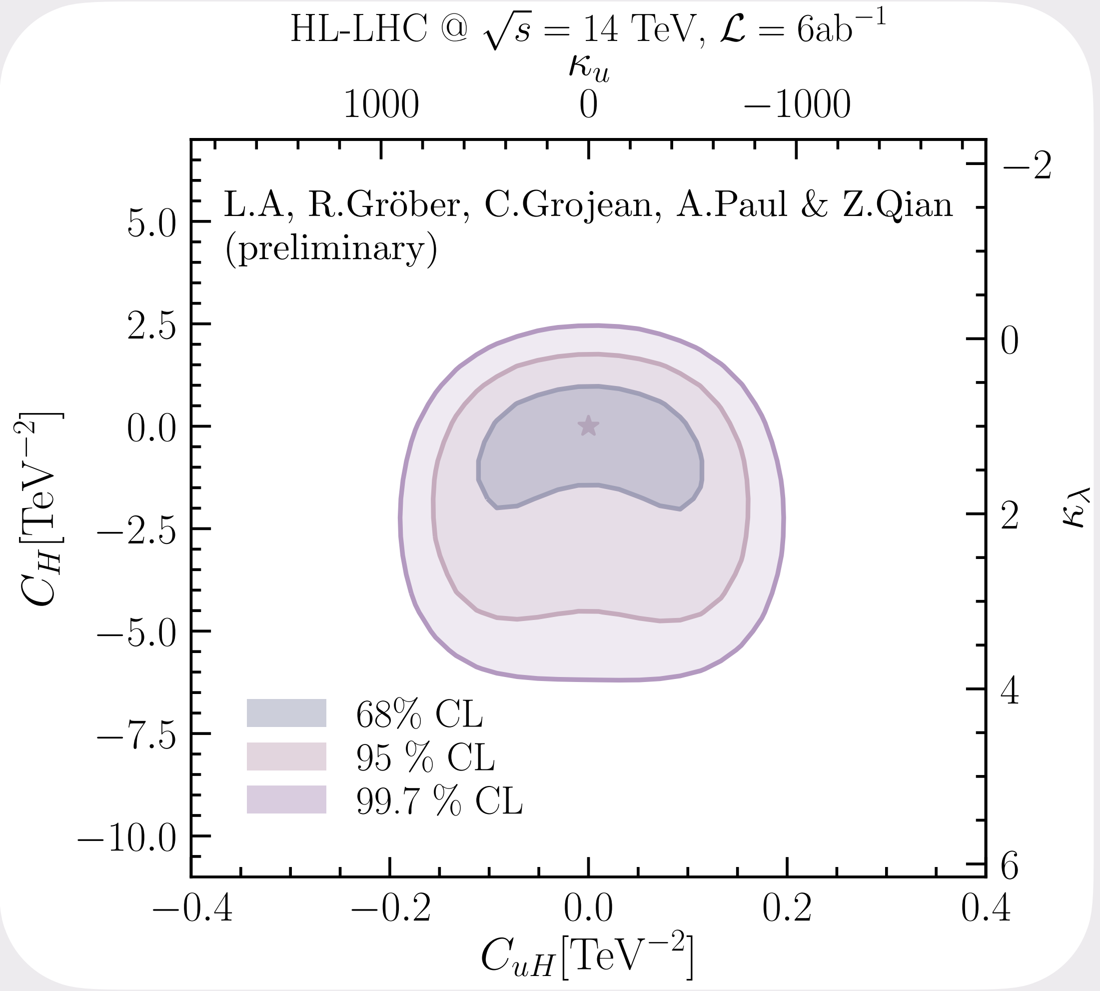
Statistical analysis

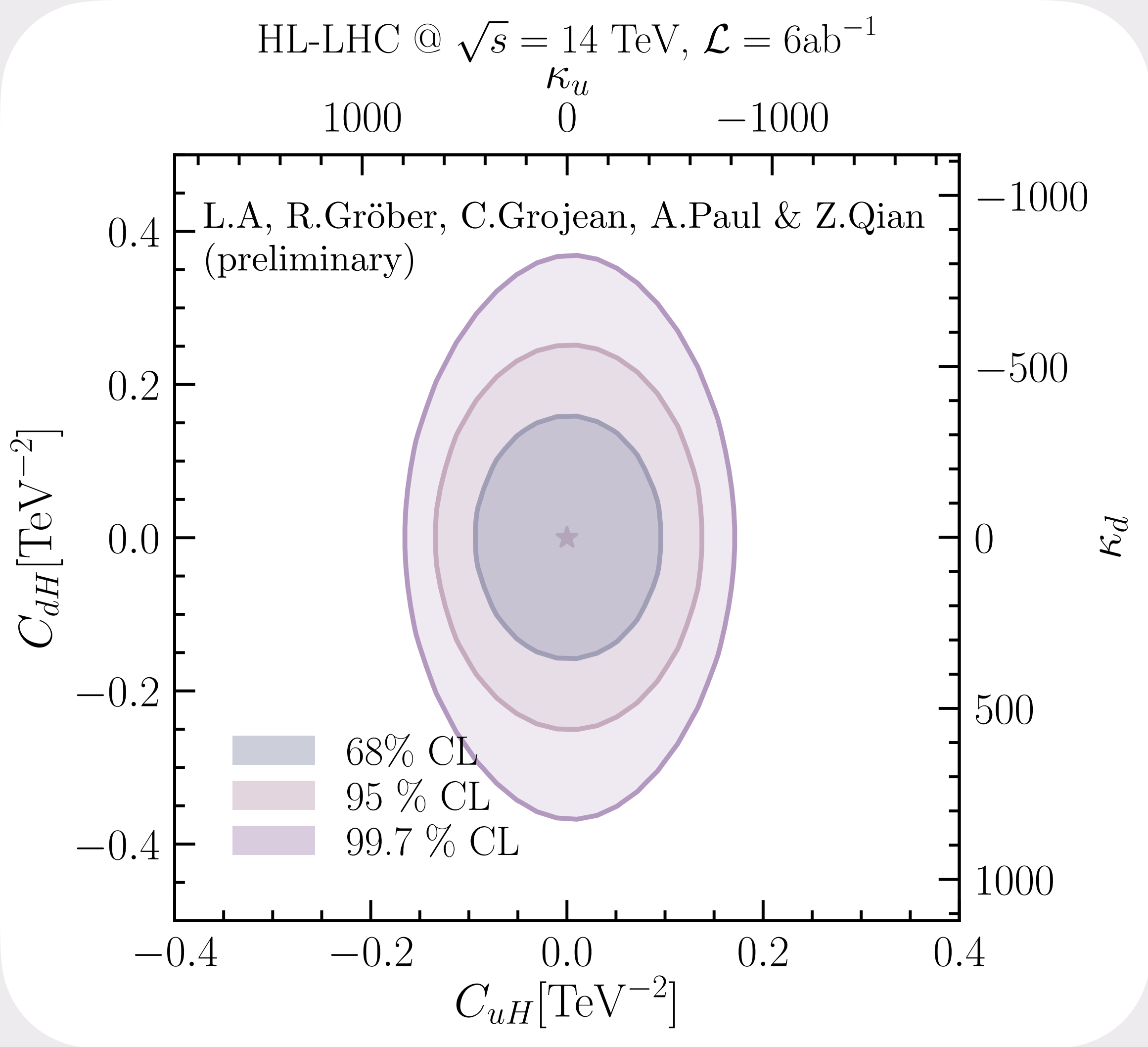
Build likelihoods

Results

Likelihood fits







- From the BDT output it is possible to construct the test-statistic G.Cowan et al (2010)

$$q_\mu = -2\ln(\lambda(\mu))\,\mu > \hat{\mu}$$

$$\lambda(\mu) = \frac{L(\mu, (\hat{\hat{\theta}}))}{L(\hat{\mu}, \hat{\theta})}$$

- We could also write the test-statistic in terms of the SMEFT Wilson-coefficients

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

$$\frac{C_{qH}}{\Lambda^2} = \frac{\sqrt{2}\,m_q}{v^3}(1-\kappa_q)$$

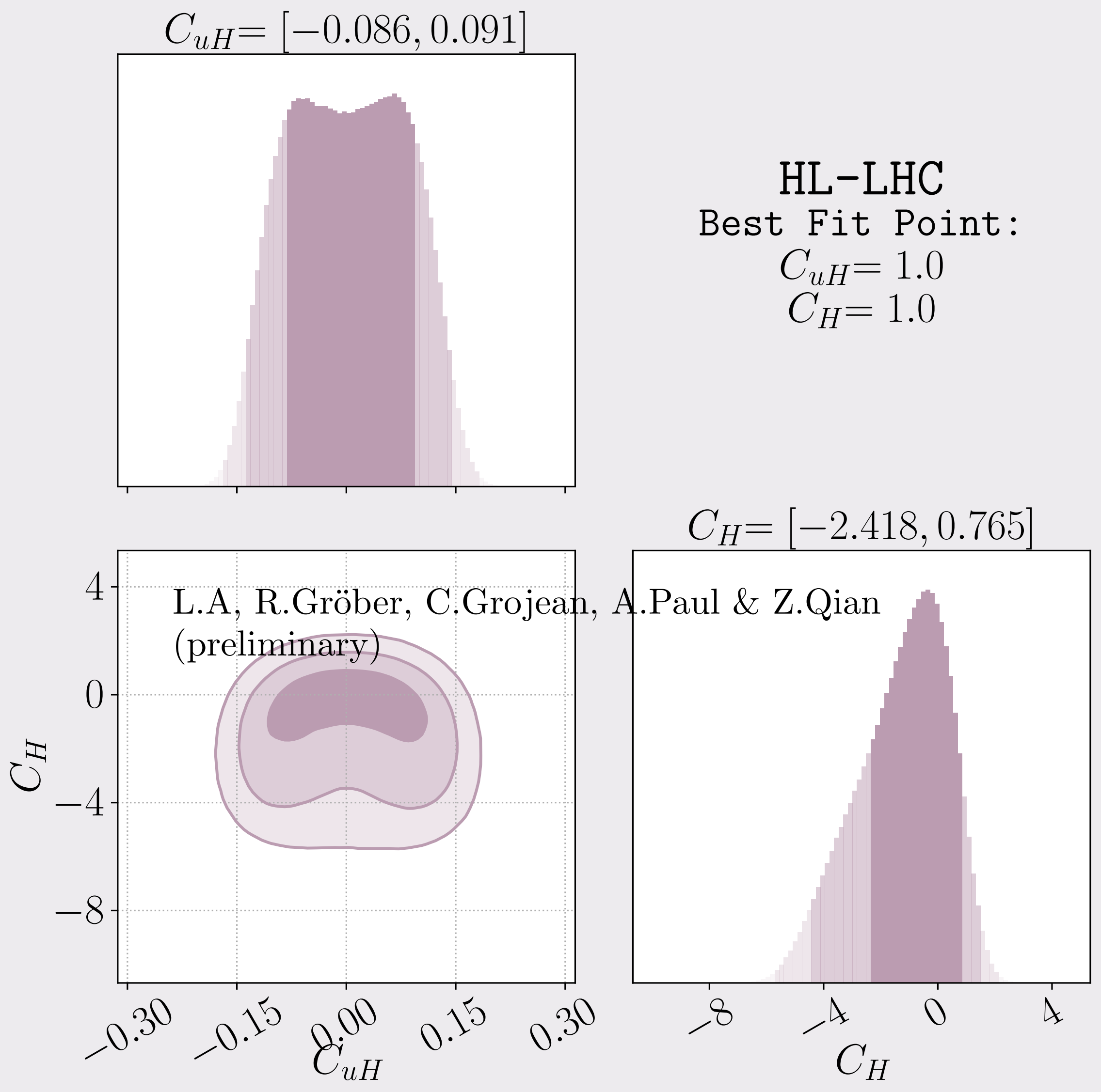
$$c^q_{ii} := C^{ii}_{qH}$$

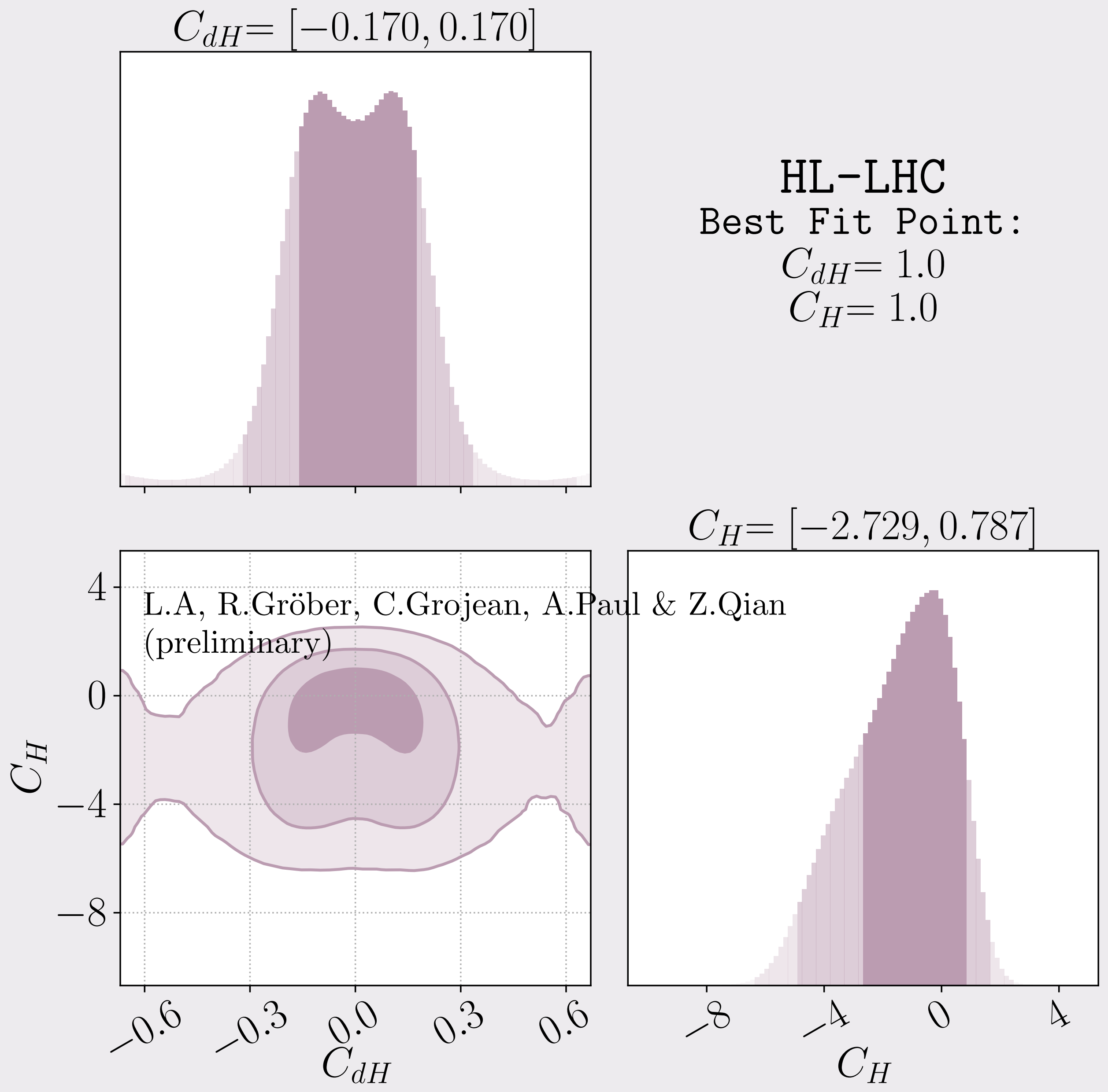
$$\mathcal{L}_{\text{SMEFT}} = C_{H,\Box}(H^\dagger H)\Box(H^\dagger H) + C_{H\,D}|(H^\dagger D_\mu H)|^2 + C_H(H^\dagger H)^3$$

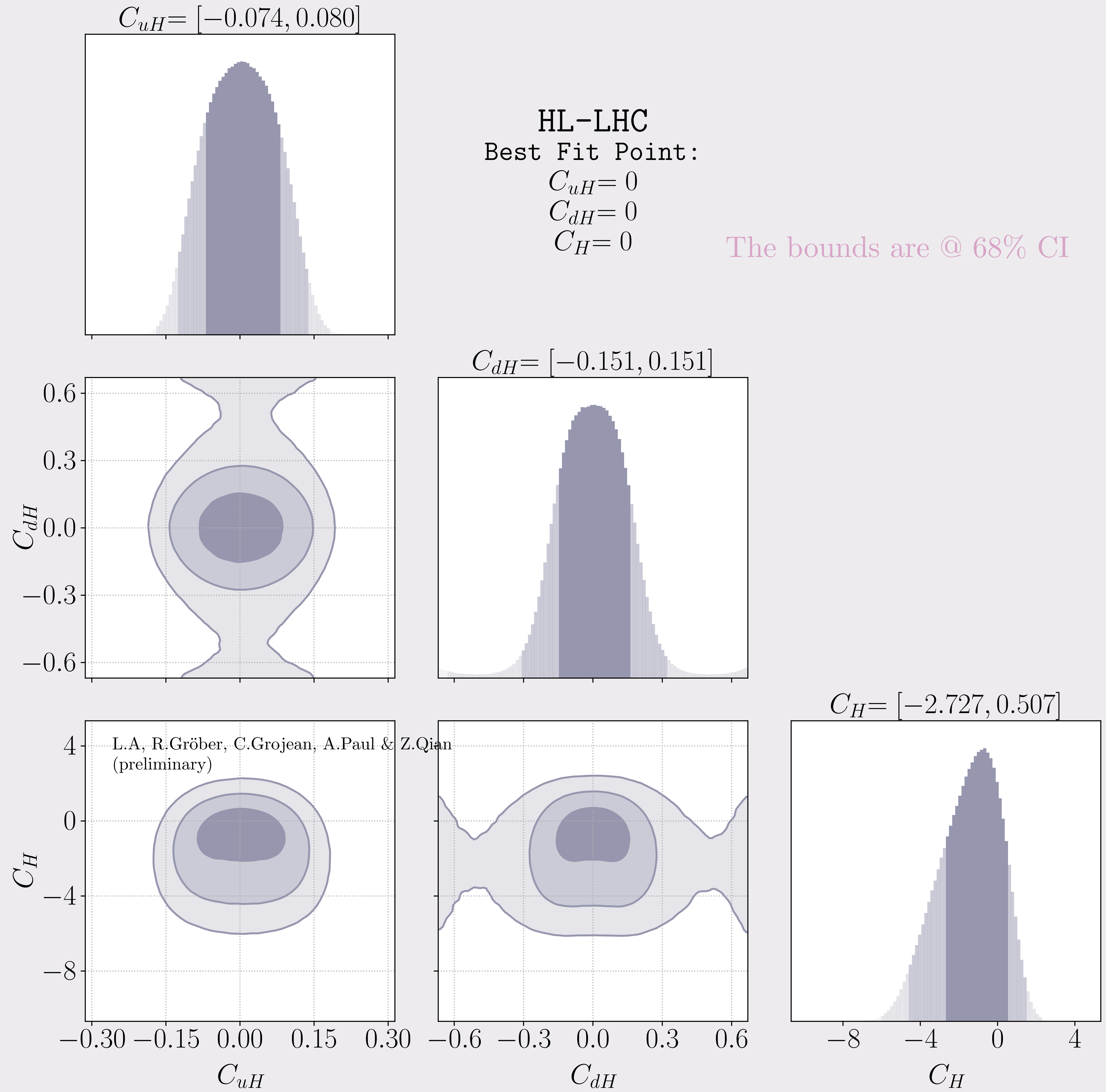
- We have not included systematics here, i.e. (stats. only)

- The fit was also done via a Bayesian method, and both results agreed.

Bounds Extraction (HL-LHC)



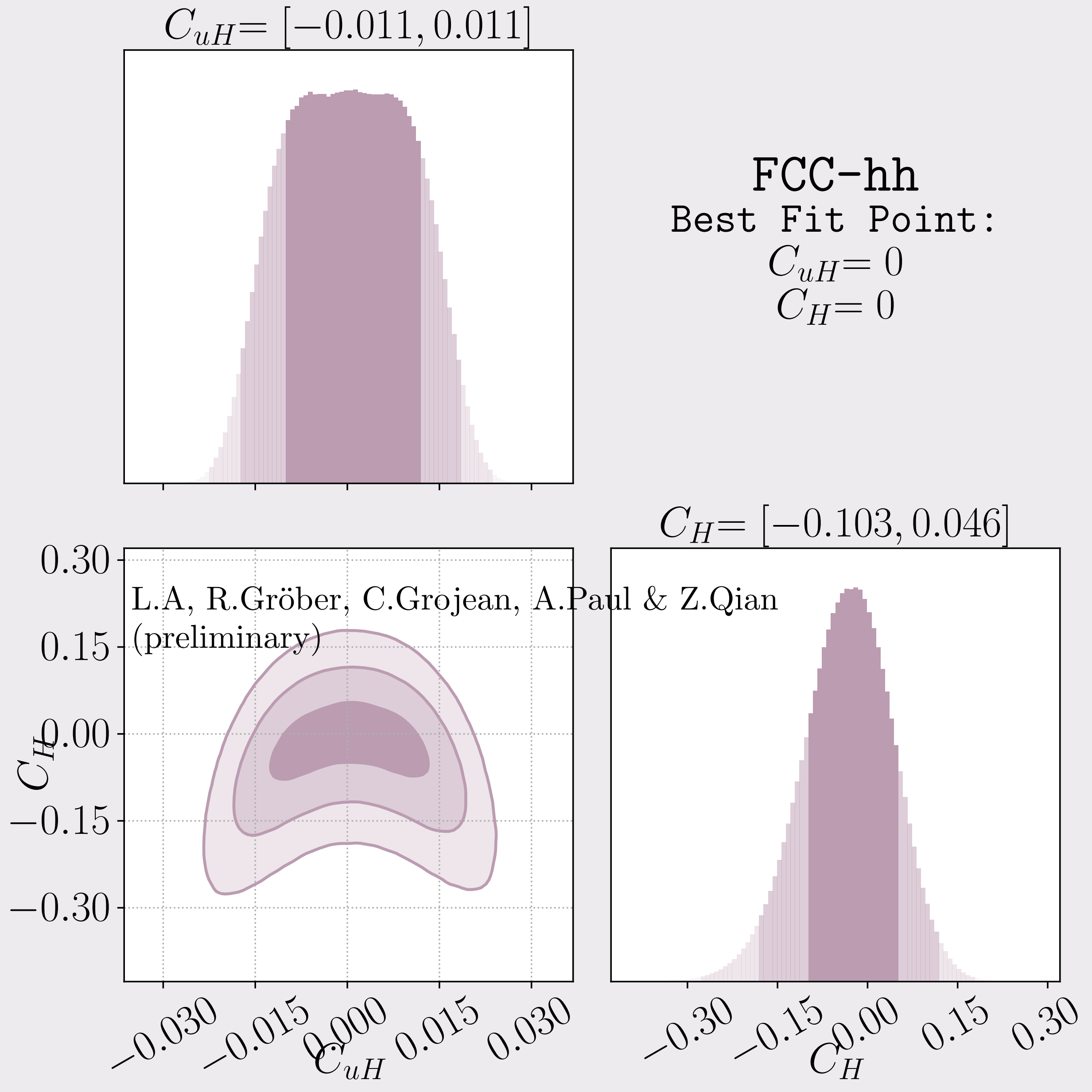


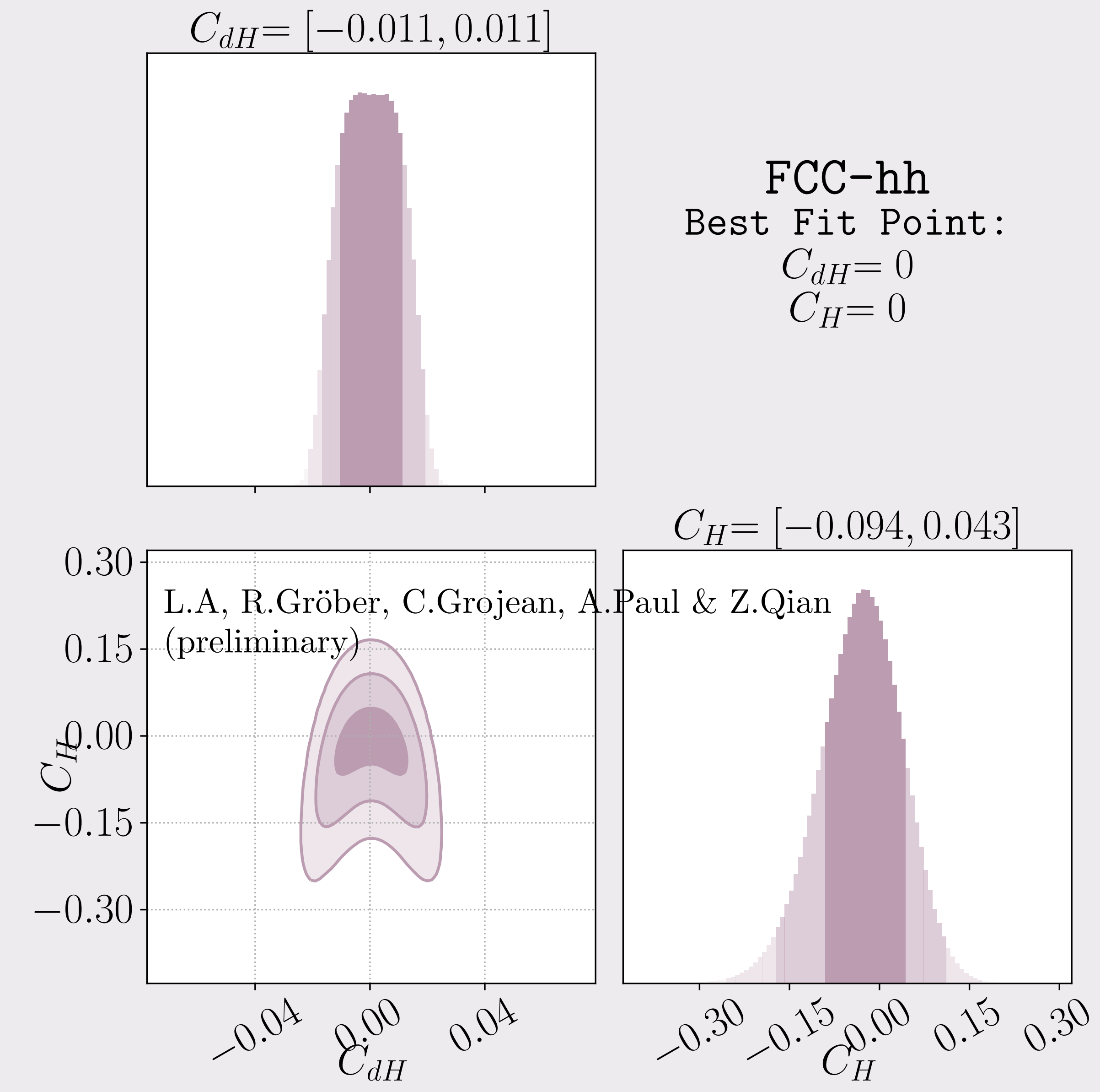


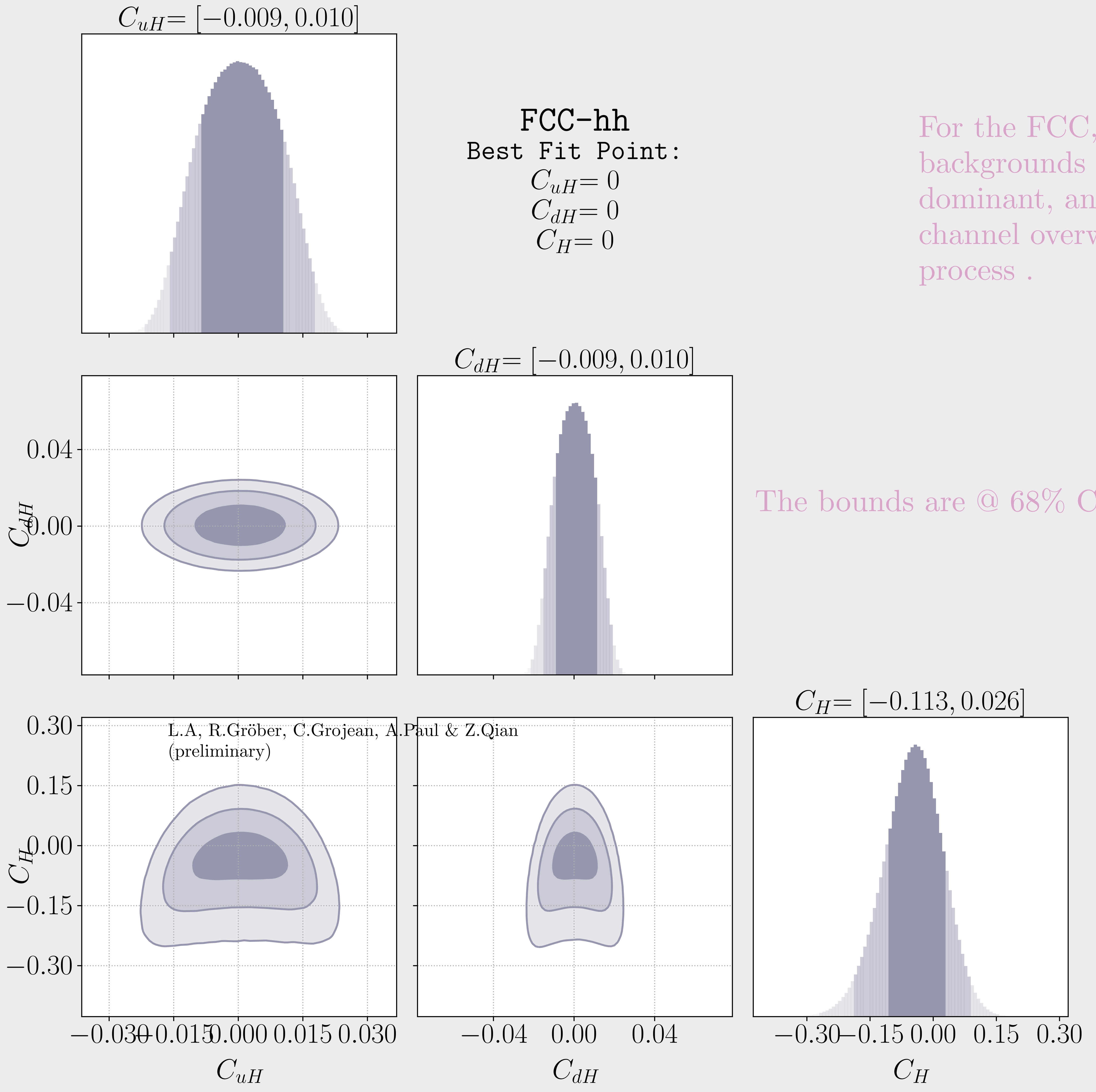
The bounds are @ 68% CI

Bounds Extraction outlook

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







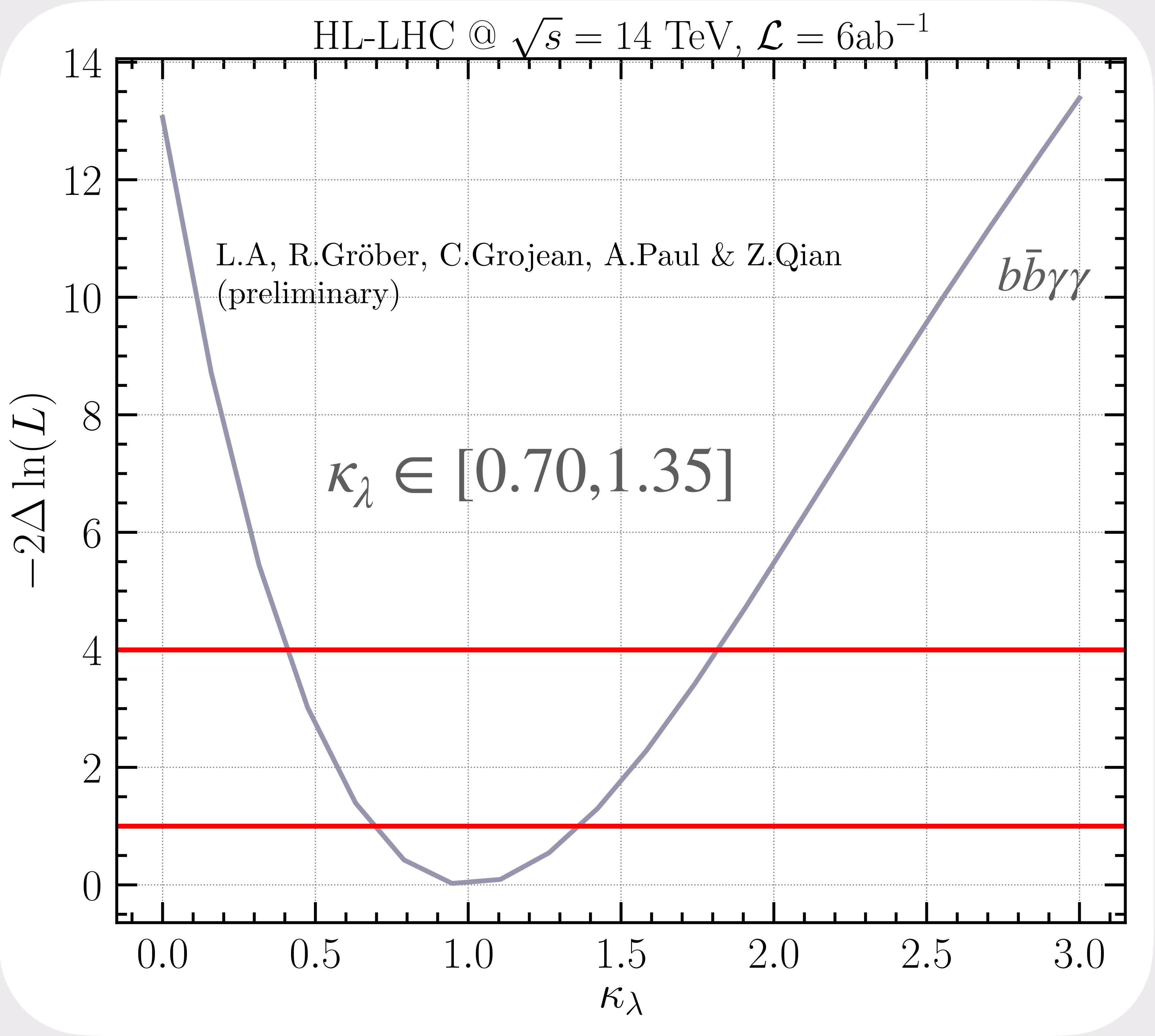
For the FCC, the backgrounds become more dominant, and gluon fusion channel overwhelms the process .

The bounds are @ 68% CL

Bounds on κ_λ alone

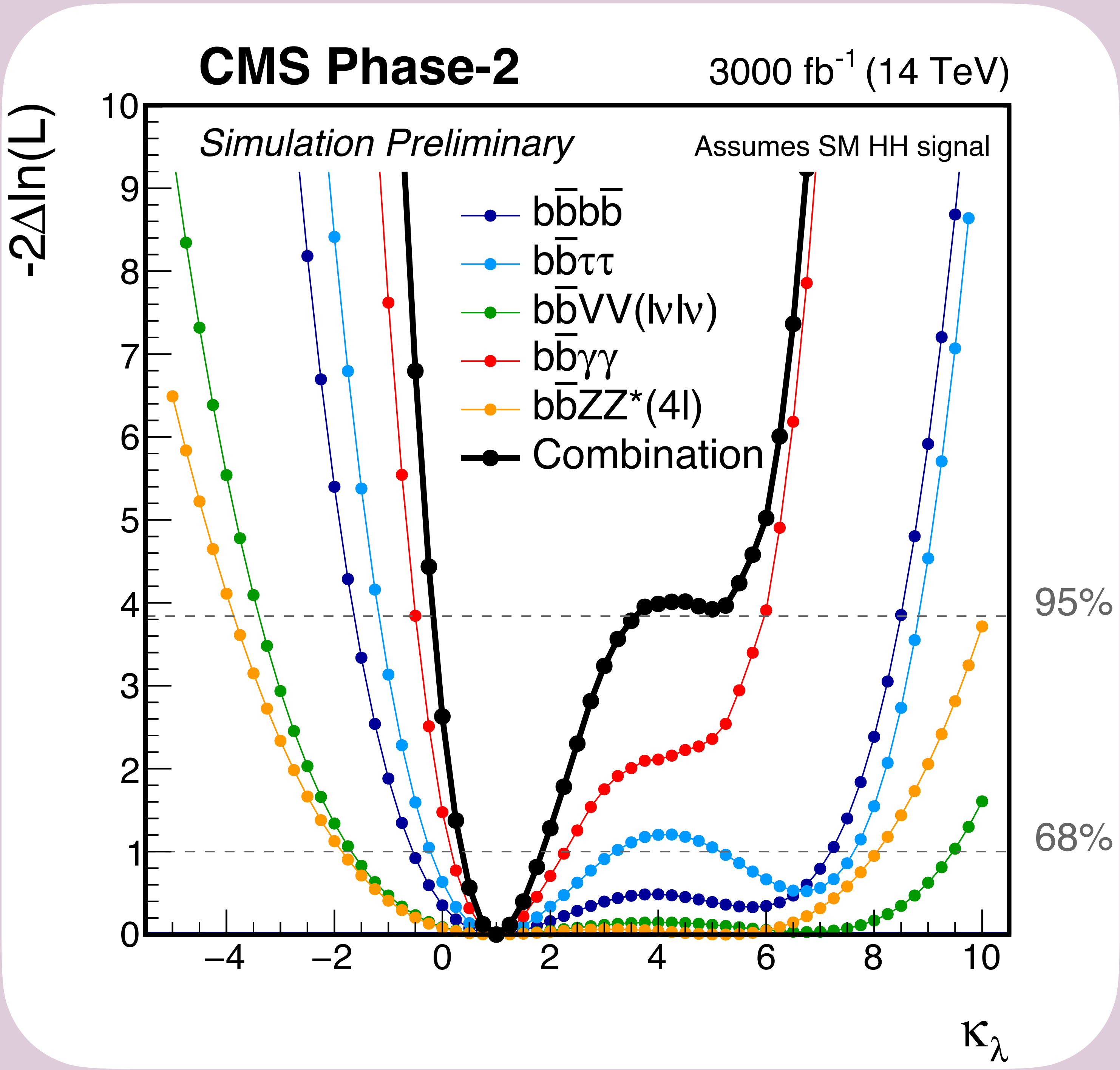
★In our analysis, we were able to achieve competitive sensitivity to the results coming from ATLAS and CMS.

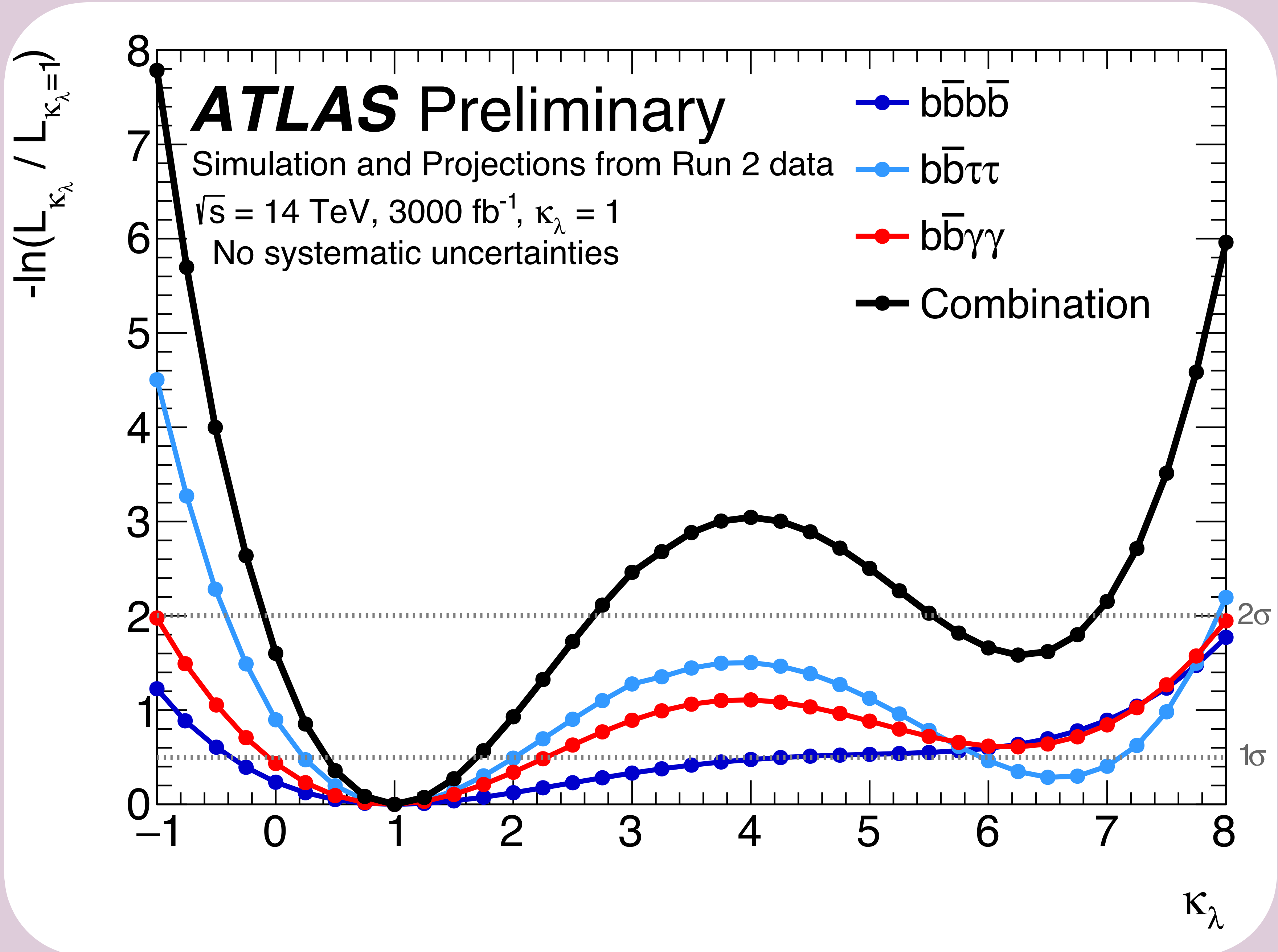
The bounds are @ 68% CL



ATLAS & CMS
average for $b\bar{b}\gamma\gamma$
rescaled for $\mathscr{L} = 6\,\mathrm{ab}^{-1}$

$\kappa_\lambda \in [0.88,1.41]$





Conclusion

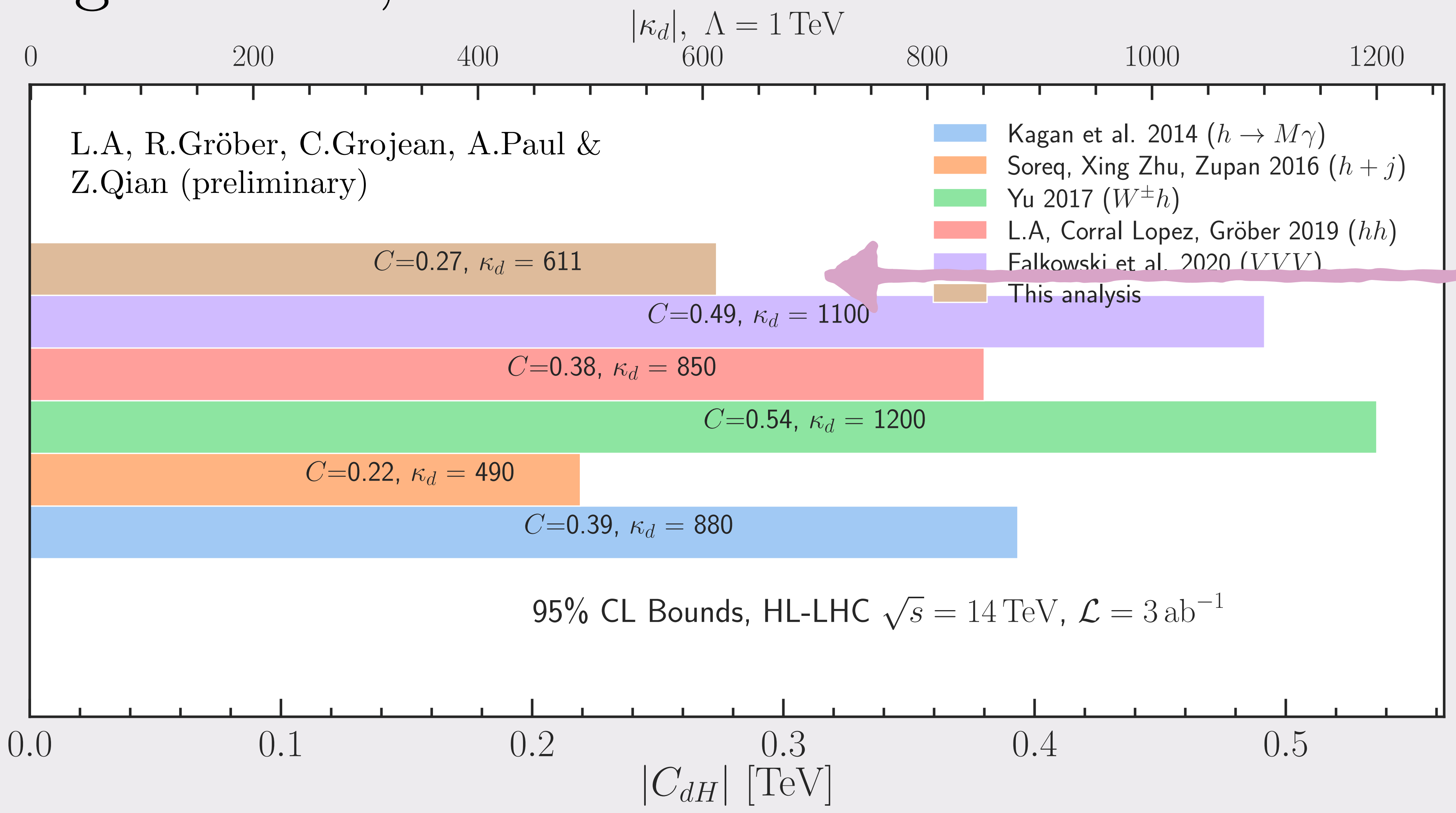
- It was possible to distinguish the signal for κ_λ, κ_u & κ_d in our ML-based analysis.

- The expected bounds on up Yukawa coupling modifications from this analysis are the *strongest model-independent* bounds from a single process, and 2nd best for down type.

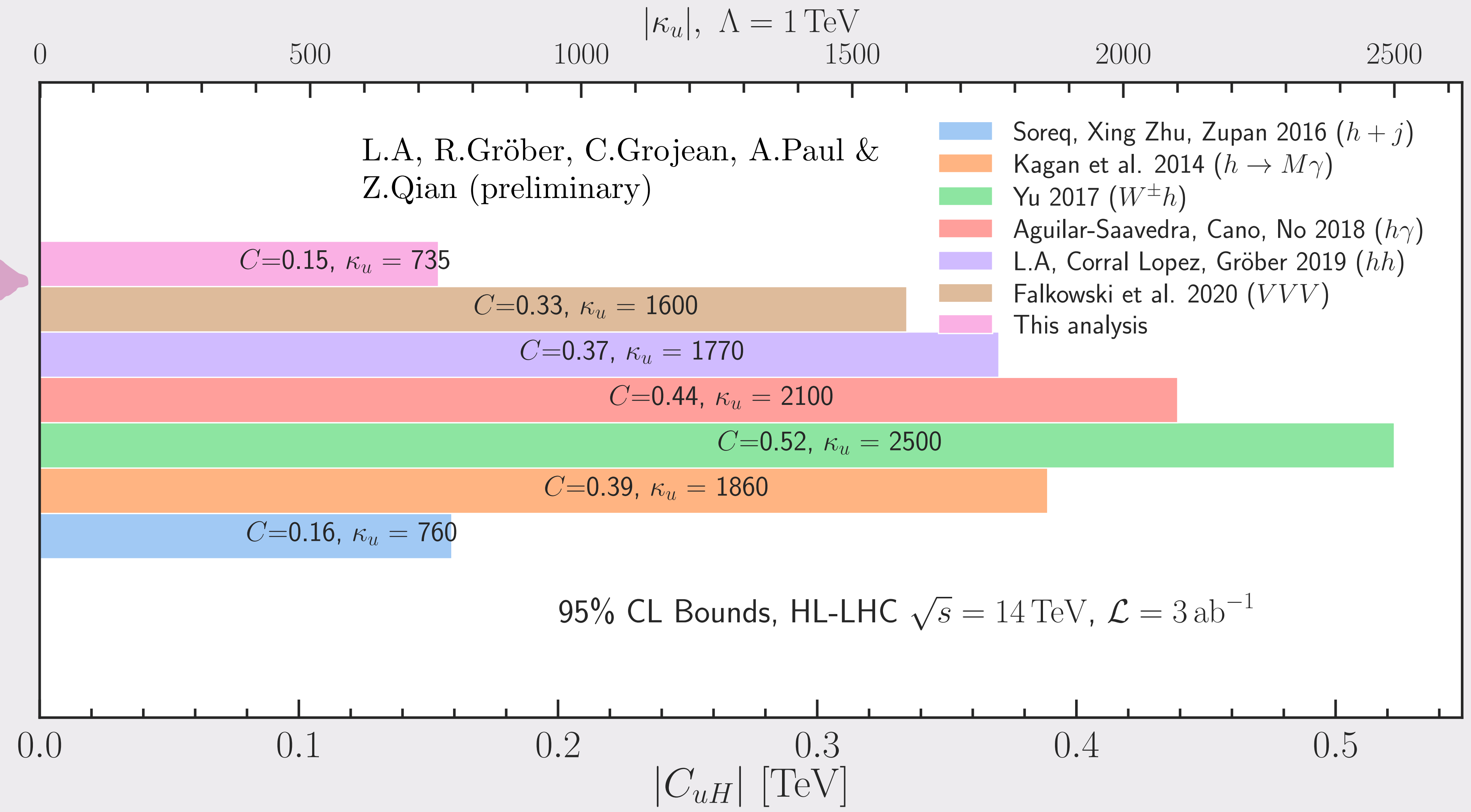
- The expected bound on κ_λ from HH has been improved, with plenty of room for improvement.

- 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.

- Models with aligned flavour violation (AFV) allow for large modifications to light Yukawa without having large FCNC, c.f. Bar-Shalom & Soni 18' .



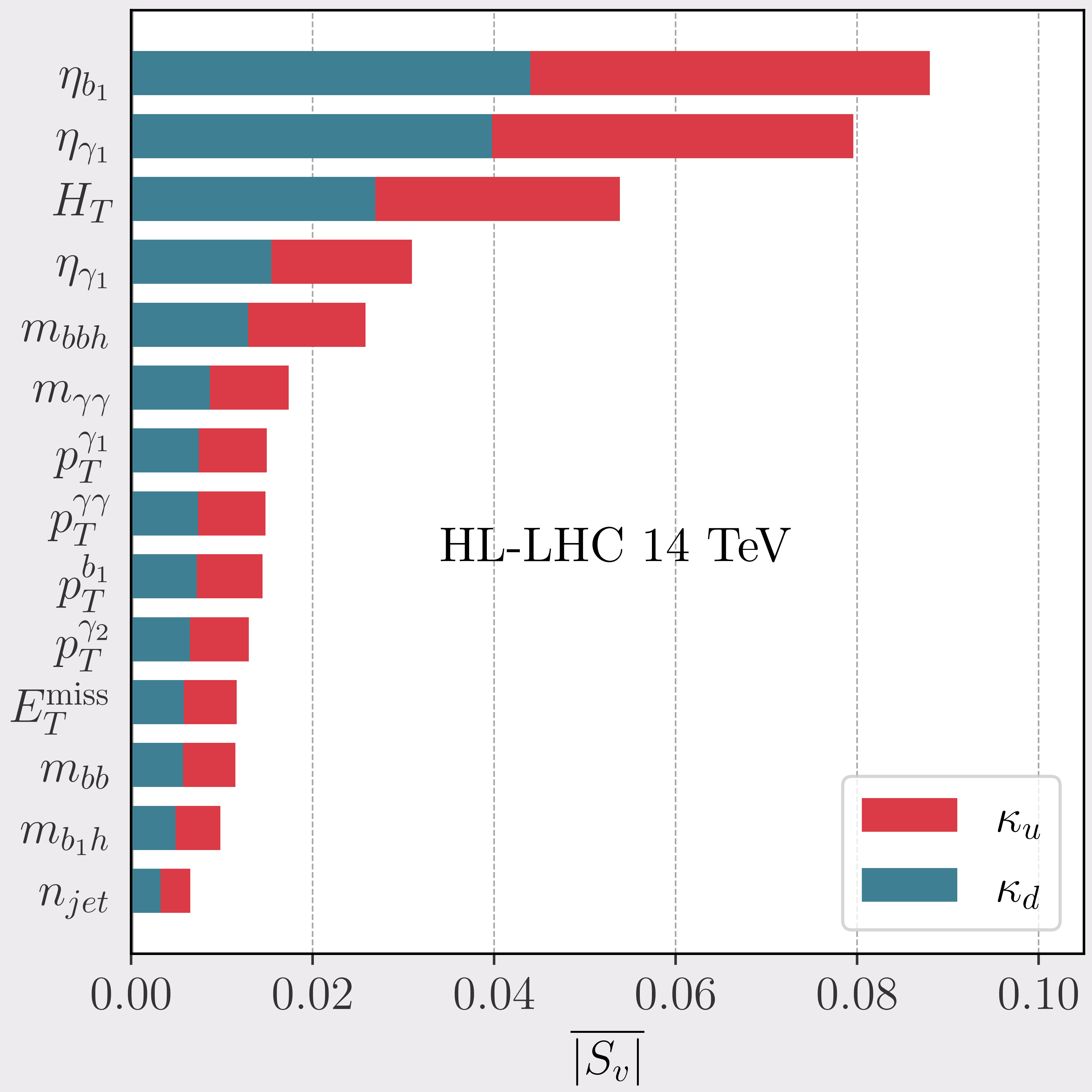
New bounds !

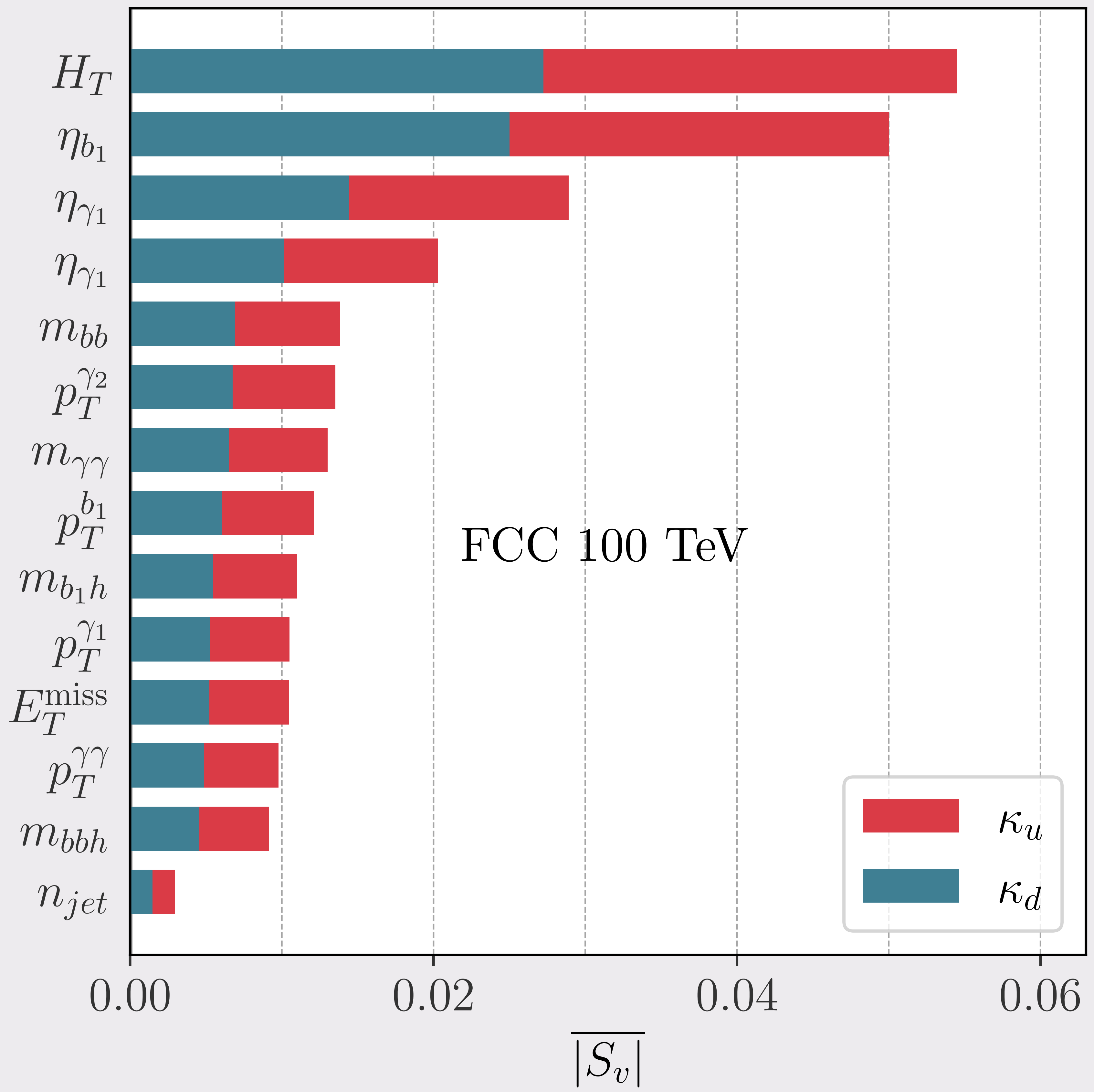


Thank you !

Backup

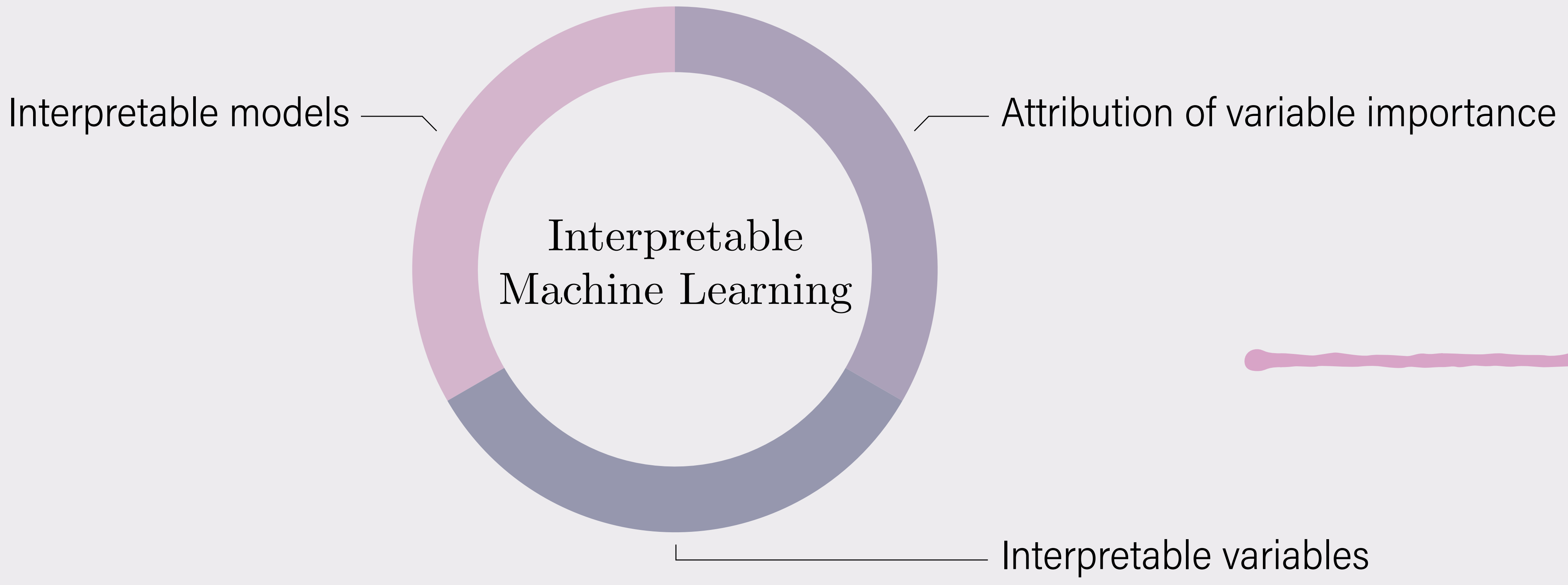
Disentangeling κ_u & κ_d

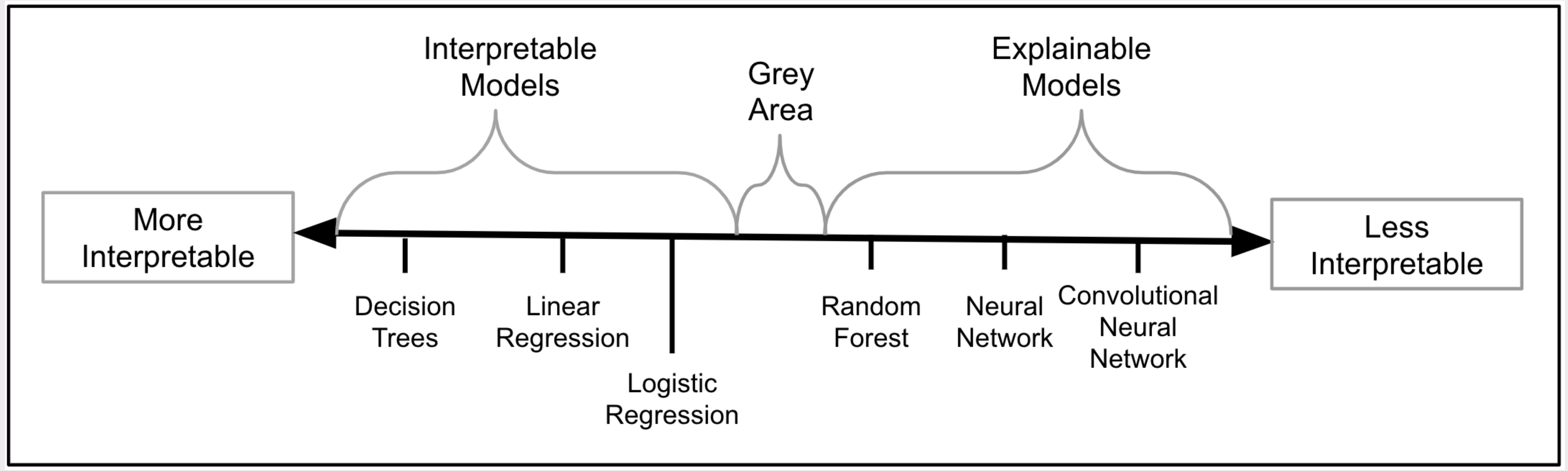




interpretable vs explainable ML

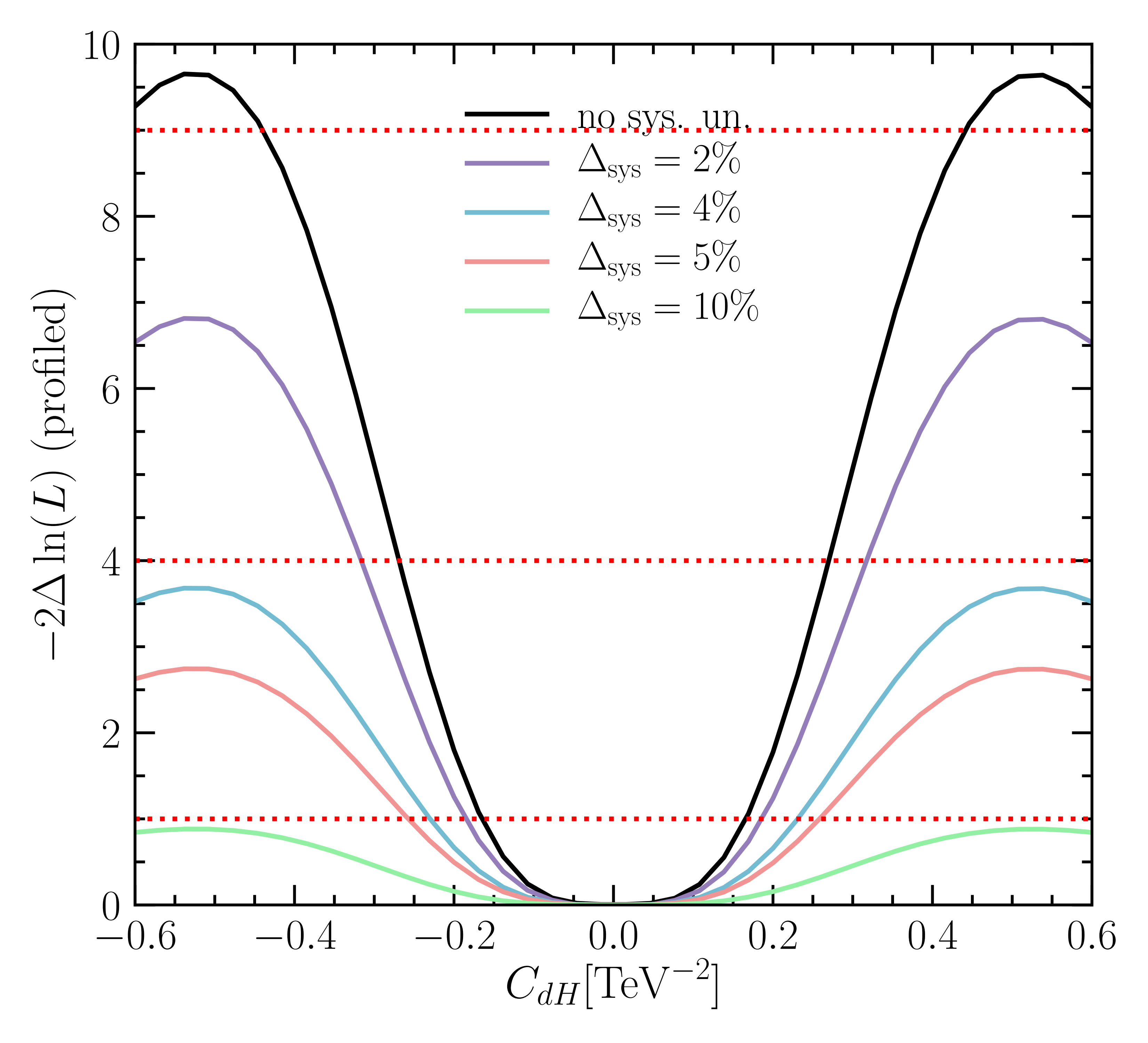
- Explainable models are not fully interpretable – proliferation of parameters can be a problem
- An interpretable model should be able to understandably map the input to the output
- Interpretability is important since an ML model should make the right decision for the right reasons.

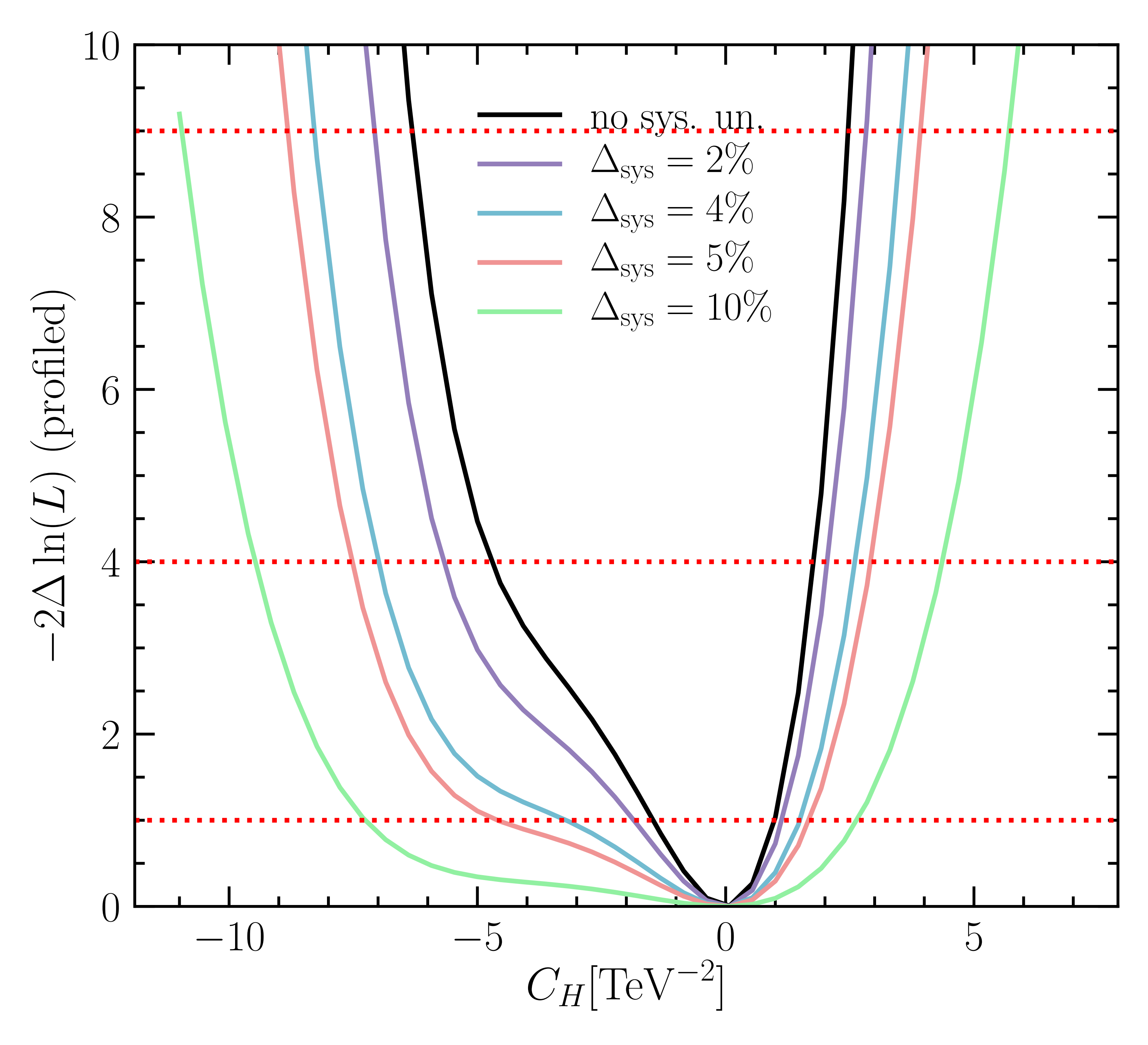


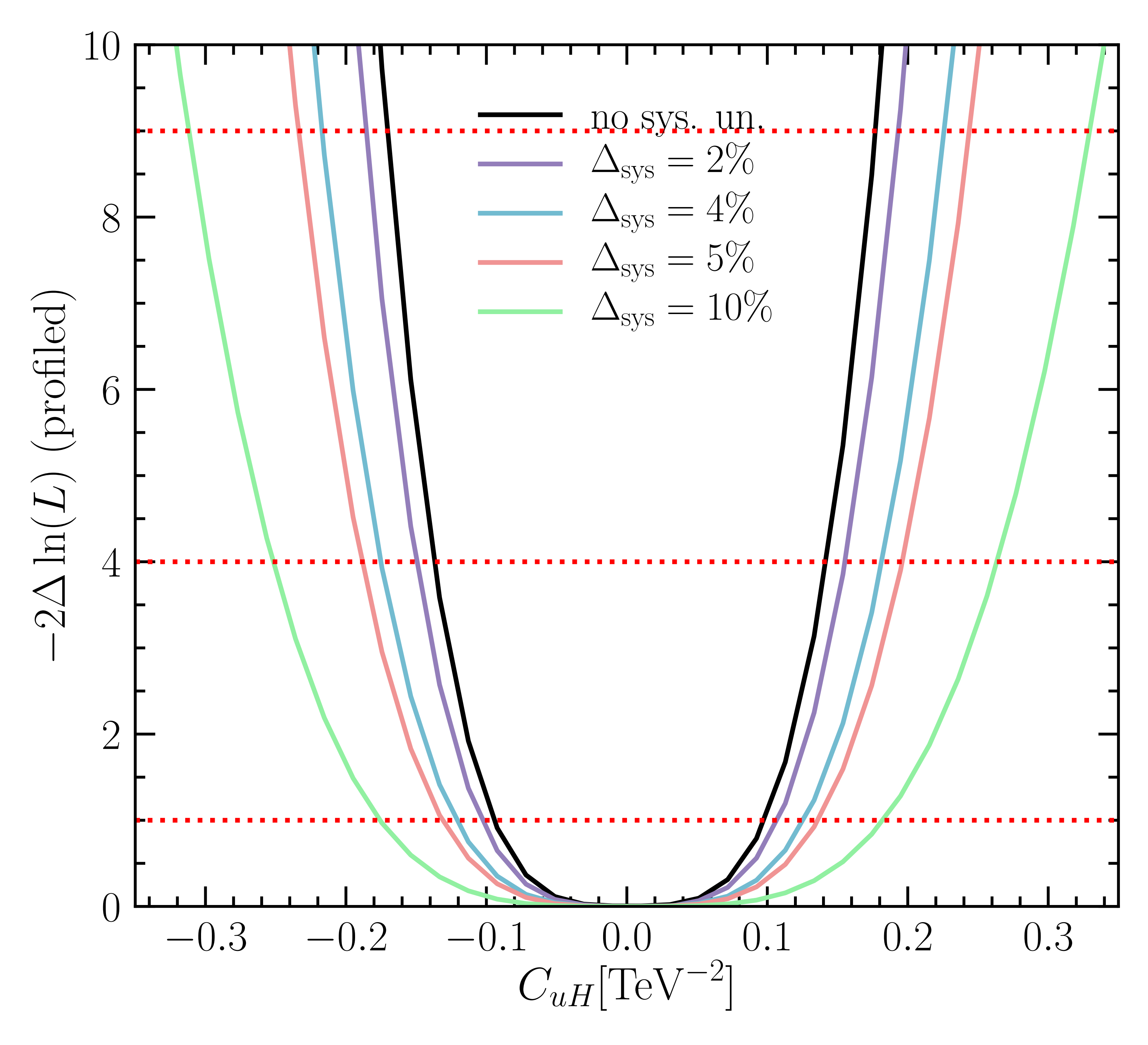


C. Rudin, *Stop explaining black box machine learning models for high stakes decisions and use interpretable models instead.* Nature Machine Intelligence 1, 206–215 (2019)

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

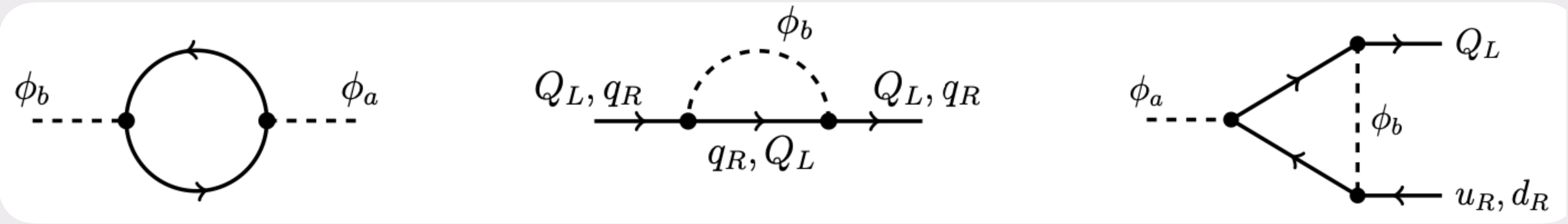
The bar notation correspond to a different matrix

Features and problems of (AFV)

✓AFV allows for flavourful new physics (including EFT's), while satisfying the flavour constraints. The simplest case is to just take the zeroth-order term in the FA expansion (i.e. $[y^q, k_q] = 0$) Nir & Seiberg 93'; Leurer, Nir, Seiberg 94' and Peuelas & Pich 17'.

✓All linear combinations, and tensor products of the flavour aligned NP spurions are also flavour aligned.

✓All radiative corrections only caused RGE running of the Alignment expansion coefficients elements, hence AFV is radiatively stable !



✗ There is typically no obvious symmetry that „predicts" AFV, hence it requires significant fine-tuning . Nir & Seiberg 93'; Leurer, Nir, Seiberg 94'; Branco, Grimus, and L. Lavoura 96' ;and Antaramian, Hall& Rasin 92'

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'

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

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

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

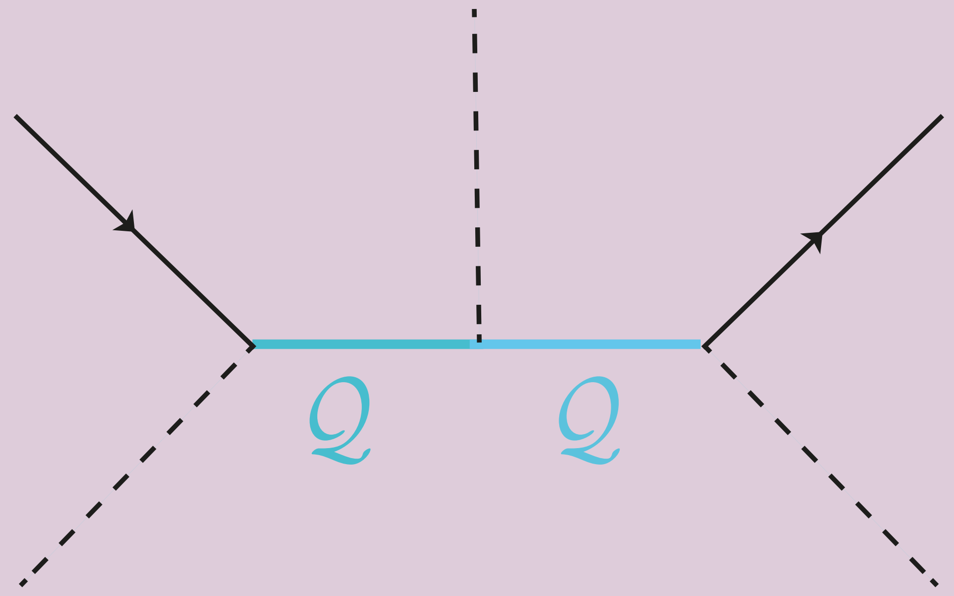
$$\hat{f}_{dH}, \hat{f}_{uH} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- 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.

Spontaneous flavour violation (SFV).

Egana-Ugrinovic Homiller & Meade 18'

- SFV provides a UV completion for a subset of AFV models which requires (almost) no fine-tuning.

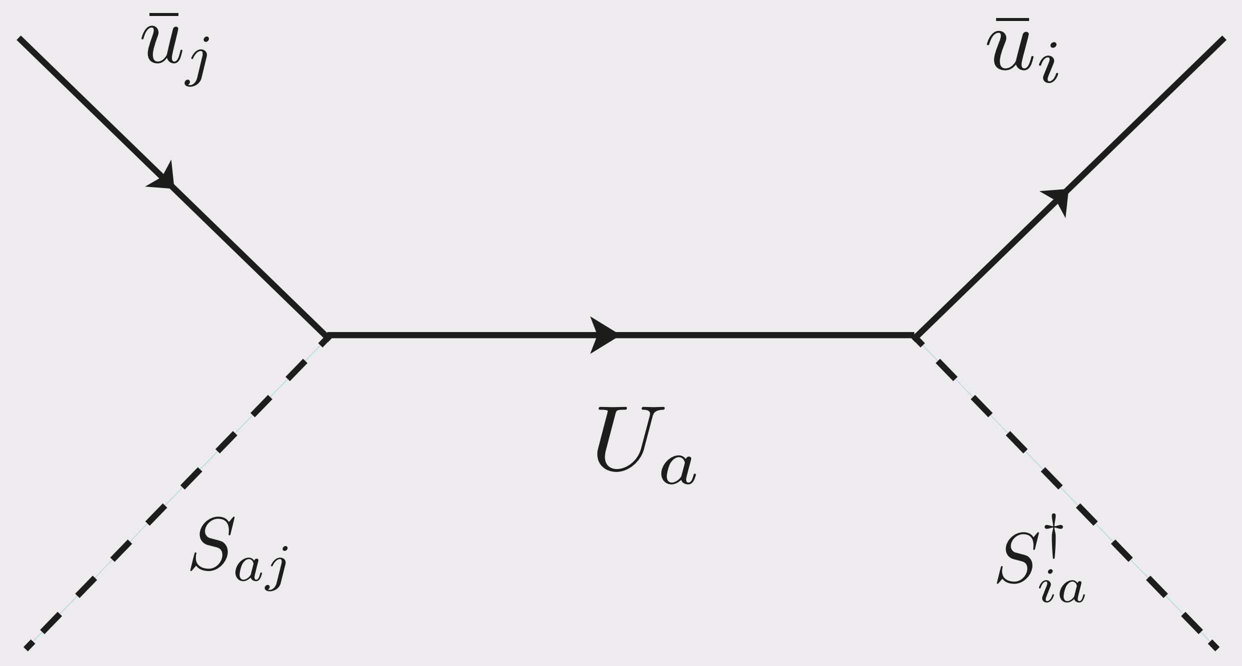
- SFV is realised if Λ_{NP} FCNC are introduced only via wave function renormalisation of RH quarks.

- The only interactions breaking $U^3(1)_f \otimes CP$ symmetry are CKM, and wave function renormalisation. (They are the only spurions breaking flavour and CP)

$$\begin{aligned} \mathcal{L} \supset \;& iZ^u_{ij}\bar{u}^\dagger_i\bar{\sigma}^\mu D_\mu u_j + i\bar{d}^\dagger_i\bar{\sigma}^\mu D_\mu d_i + i\bar{Q}^\dagger_i\bar{\sigma}^\mu D_\mu Q_i \\ - \;& \left[y^u_{ij}\;\bar{Q}_i H u_j - y^d_{ij}\bar{Q}_i\tilde{H} d_j + \text{h.c.}\right] + \mathcal{L}_{\text{BSM}} \end{aligned}$$

- The UV completion would compose of new scalars S_{iA} and VLQ's U_A,

$$\begin{aligned} \mathcal{L} \supset \;& M_{AB}U_A\bar{U}_B + \xi S_{iA}\bar{u}_i U_A \\ - \;& \left[y^u_{ij}\;\bar{Q}_i H u_j - y^d_{ij}\bar{Q}_i\tilde{H} d_j + \text{h.c.}\right] + \mathcal{L}_{\text{BSM}} \end{aligned}$$



Features and problems of (SFV)

✓Almost a natural schema for AFV .

✓Not stable under RGE, however, FCNC are still suppressed.

✓Provides FCNC suppression beyond CKM, which allows for more relaxed flavour bounds.

✗ Either up-type or down-type can have non-universal flavour alignment but not both

Not „so“ natural ..

This UV completion is not free from some tuning, like the inclusion of a discrete $\mathbb{Z}_2$ symmetry to forbid the VLQ from coupling to the SM d.o.f

Summery of flavourful models

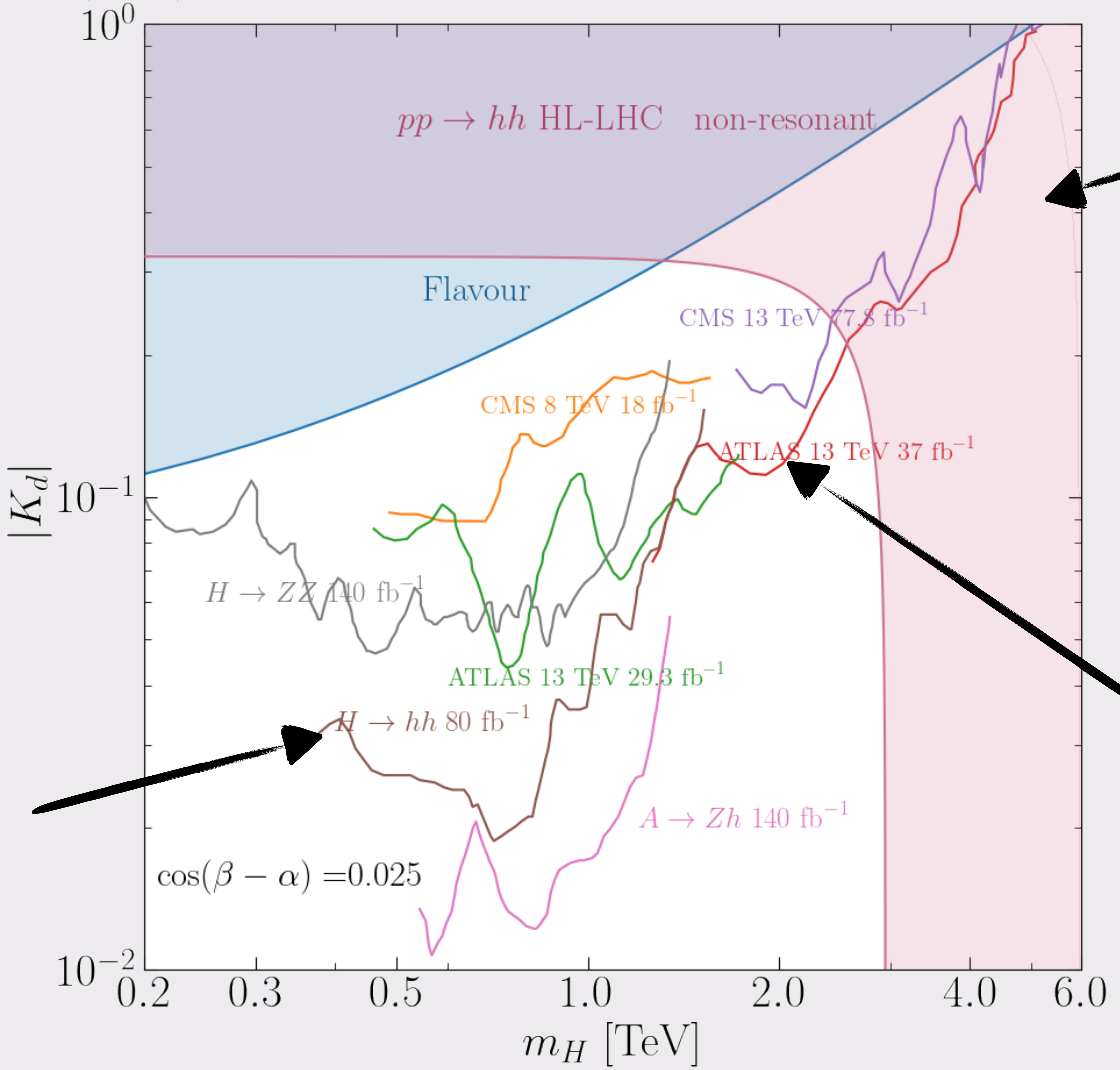
- This table contains a summery for the schema that flavourful models might have. Mainly theories with one or more extra Higgs doublets.

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'

Potential bounds on a 2HDM with SFV

- Higgs pair production offers one of most sensitive probes for flavourful models, we take here 2HDM as an example . à la Egana-Ugrinovic, Homiller & Meade 21’



Our current work

$H \to jj$ bounds

Triviality bounds

This plot is not complete, since 2HDM contain the term $\lambda_6 H_1^\dagger H_2 H_1^\dagger H_1$ it modifies the Higgs trilinear self-interaction. The running of this coupling after resumption will contain a Landau pôle somewhere in this plot

Resonant hh production (Egana-Ugrinovic, Homiller & Meade 21’)