Probing Higgs couplings to light quarks via Higgs pair production

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based on JHEP 11 (2019) 088 in collaboration with R. Corral Lopez and R. Gröber
and preliminary work with
R. Gröber, C. Grojean, A. Paul, and Z. Qian

Higgs and Effective Field Theory - HEFT 2021

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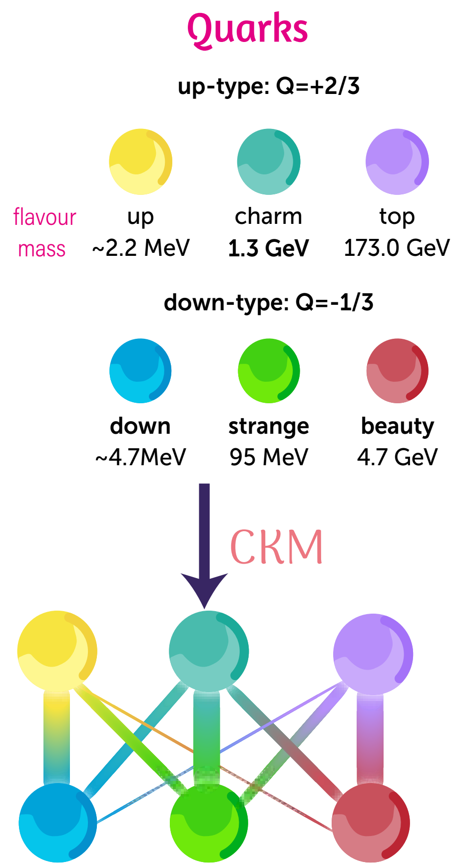
Higgs “flavour”

Higgs boson is the source of “ flavour” in the SM



- In the SM, all quarks couple to the Higgs via Yukawa term,

$$\mathcal{L} = \sum_{ij} y_u^{ij} \bar{Q}_L^i \tilde{H} u_R^j + y_d^{ij} \bar{Q}_L^i H d_R^j + \text{h.c}$$

- This is not only the source of quark masses, but also the source of flavour symmetry breaking, with the broken generators giving rise to the CKM matrix

$$SU(3)_Q \otimes SU(3)_u \otimes SU(3)_d \rightarrow U(1)_B$$

10 (free parameters = 6 (quark masses) + 3(CKM angles)+ 1 (CP phase)

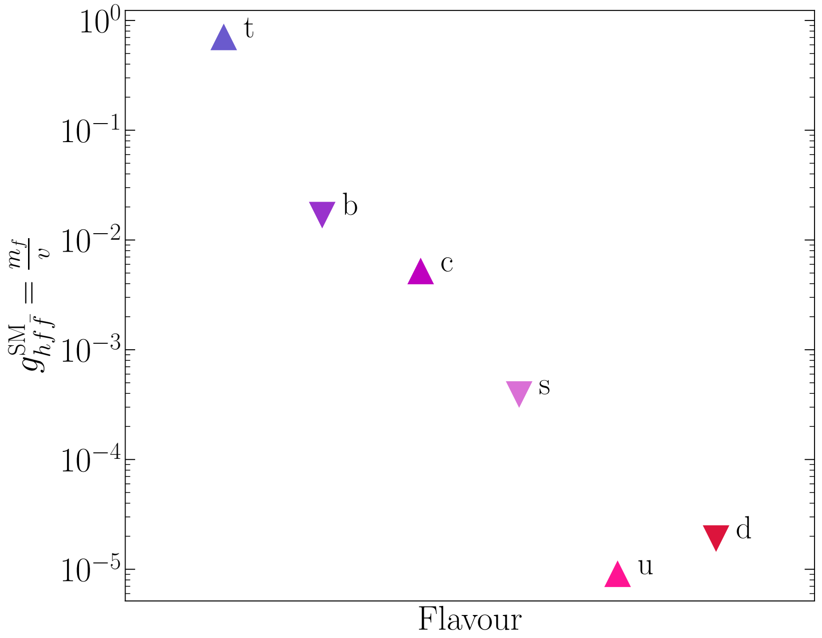
- The large hierarchy in the quark masses remains a puzzle in the SM known as the “old” flavour puzzle .

Why the Higgs couples so differently to different generations ?

- Higgs coupling to light quarks, i.e. 1st and 2nd generations are not measured and weakly constrained.

- For constraints on light Yukawa couplings, it is common to define:

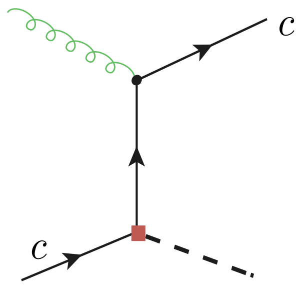
$$\bar{\kappa}_q = \frac{g_{hq\bar{q}}}{g_{hb\bar{b}}^{\text{SM}}} \qquad \kappa_q = \frac{g_{hq\bar{q}}}{g_{hq\bar{q}}^{\text{SM}}}$$



State of the art

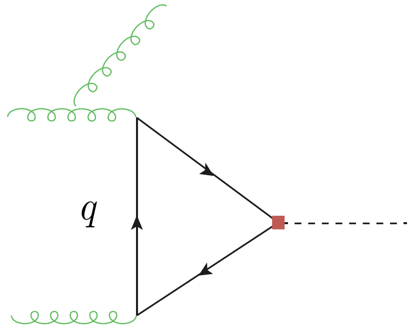
Direct probes of light Yukawa coupling

- H+c production Brivio, Isidori, Goertz (2015).



$\kappa_c \sim 1$ HL-LHC 14 TeV

- Kinematics of ggF production of H+j Bishara et al (2018)

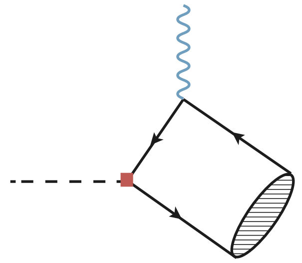


$\kappa_c \in (-1.4, 3.8)$ LHC run II 13 TeV

$\kappa_c \in (-0.6, 3.0)$ HL-LHC 14 TeV

- Higgs decay to mesons + γ

Bodwin et al (2013), Kagan et al (2014) and Konig, Neubert. (2015) ...



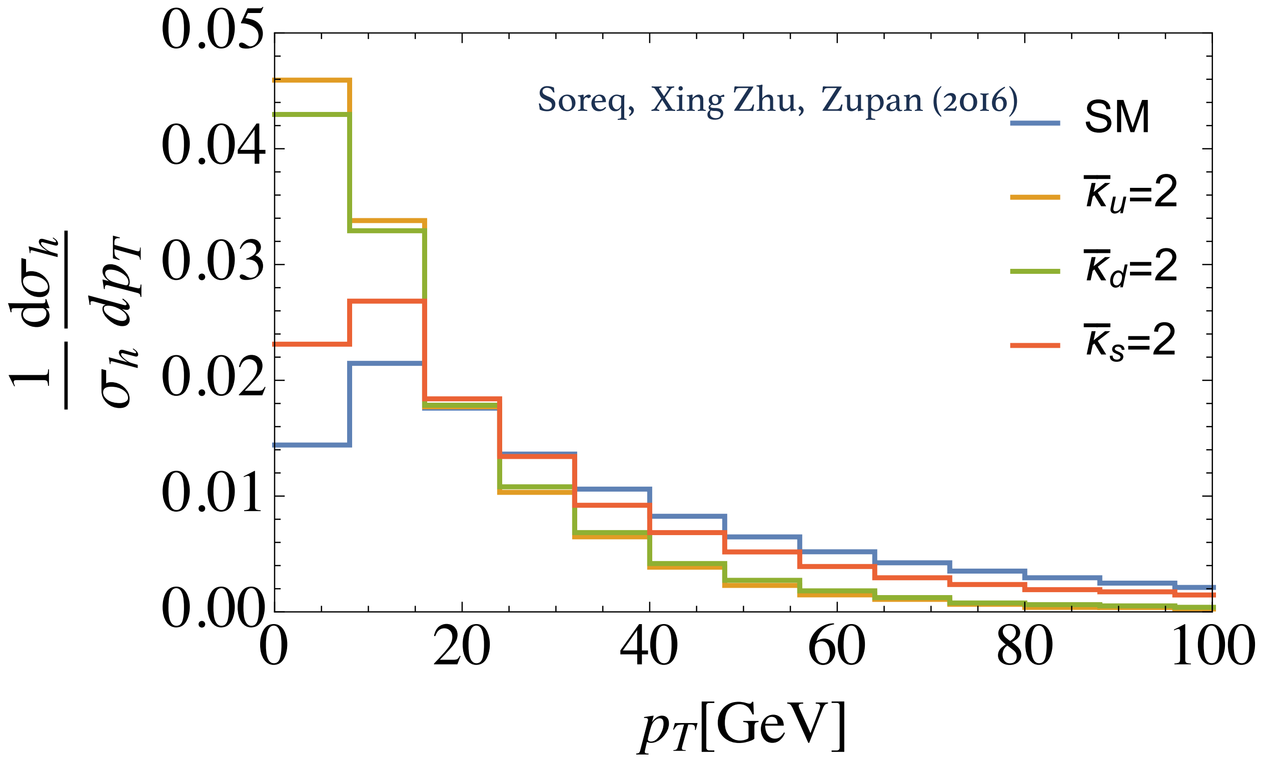
$\kappa_u < 1860$
$\kappa_d < 880$
$\kappa_s < 290$

single operator fit LHC run II 13 TeV

- Higgs kinematics (quark initiated) Soreq, Xing Zhu, Zupan (2016)

$\kappa_u < 760$
$\kappa_d < 490$

LHC @ 300 fb^{-1} 13 TeV

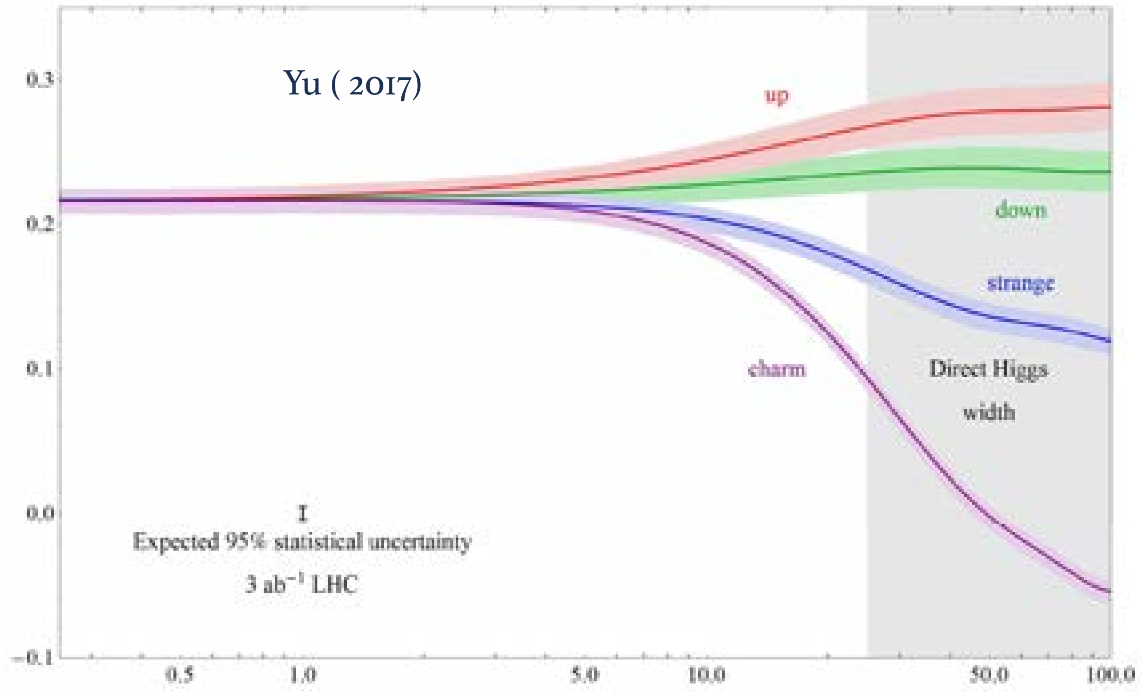


Approaches to probing light quarks Yukawa coupling

•WH production, charge asymmetry Yu (2017)

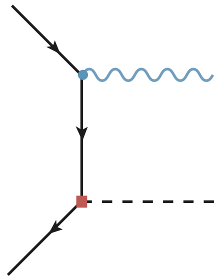
$$A = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h + \sigma(W^-h)}$$

$\kappa_d < 1200$ $\kappa_s < 430$ HL-LHC 14 TeV
$\kappa_u < 2500$



•Higgs + γ Aguilar-Saavedra, Cano, No. (2018).

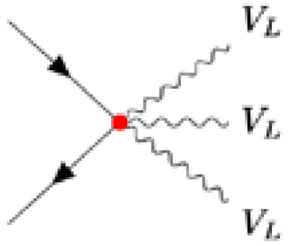
This can break the degeneracy between up and down type quarks



$\kappa_u < 2100$ HL-LHC 14 TeV

• Triple gauge bosons production Falkowski et al. (2020)

$\kappa_d < 1100$
$\kappa_s < 250$ HL-LHC 14 TeV from (WWW)
$\kappa_u < 1600$



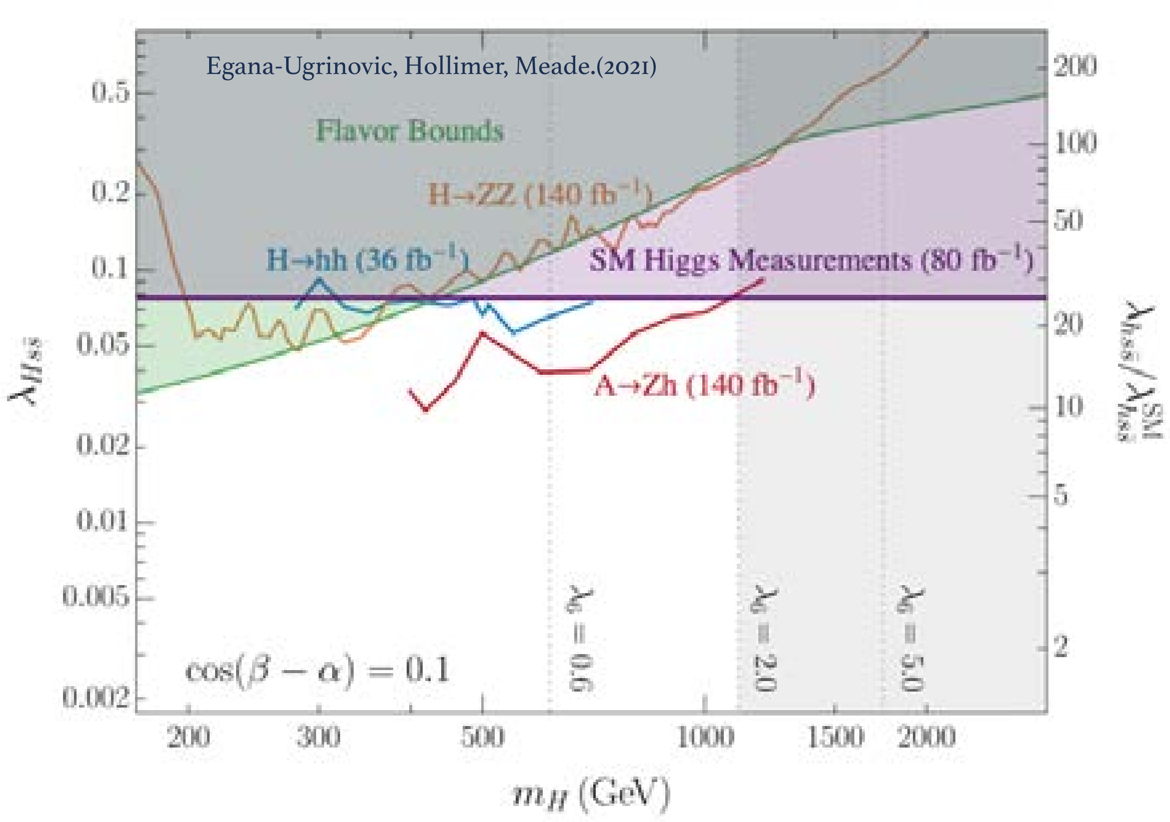
Stay tuned for Natascia Vignaroli's talk to learn more about this channel !

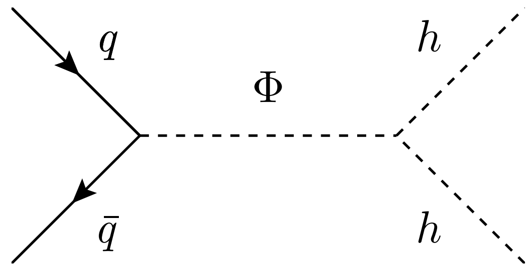
• b-mistagging (VBF, VH, ...) Perez, et al. (2015 and 2016) Kim & Park (2015)

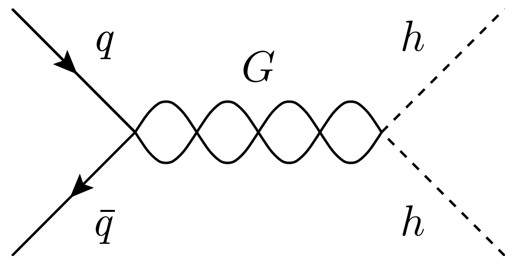
$\kappa_c < 6.1$ HL-LHC 14 TeV (We'll talk about this later)

Direct probes of light Yukawa coupling

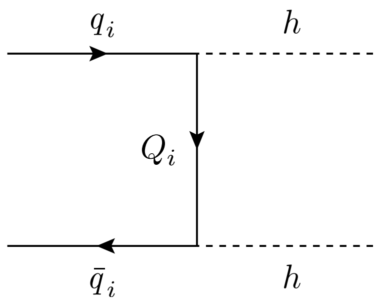
- Higgs pair production
  - Model independent   LA, Corral Lopez, Gröber. (2019)   Our work
  - Model dependent (2HDM)   Martin Bauer, Marcela Carena, Adrián Carmona(2018)   Egana-Ugrinovic, Hollimer, Meade.(2021)

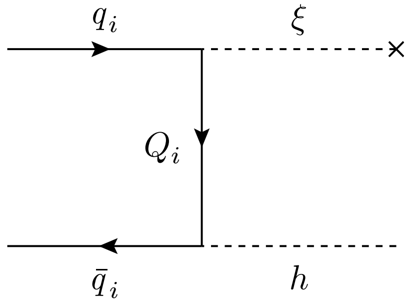






- Other model-dependent analysis :
  - Universally enhanced light Yukawa (VLQ's) Shaouly Bar-Shalom, Amarjit Soni (2019)
  - Randall-Sundrum like model Harling and Servant (2016)
  - ....





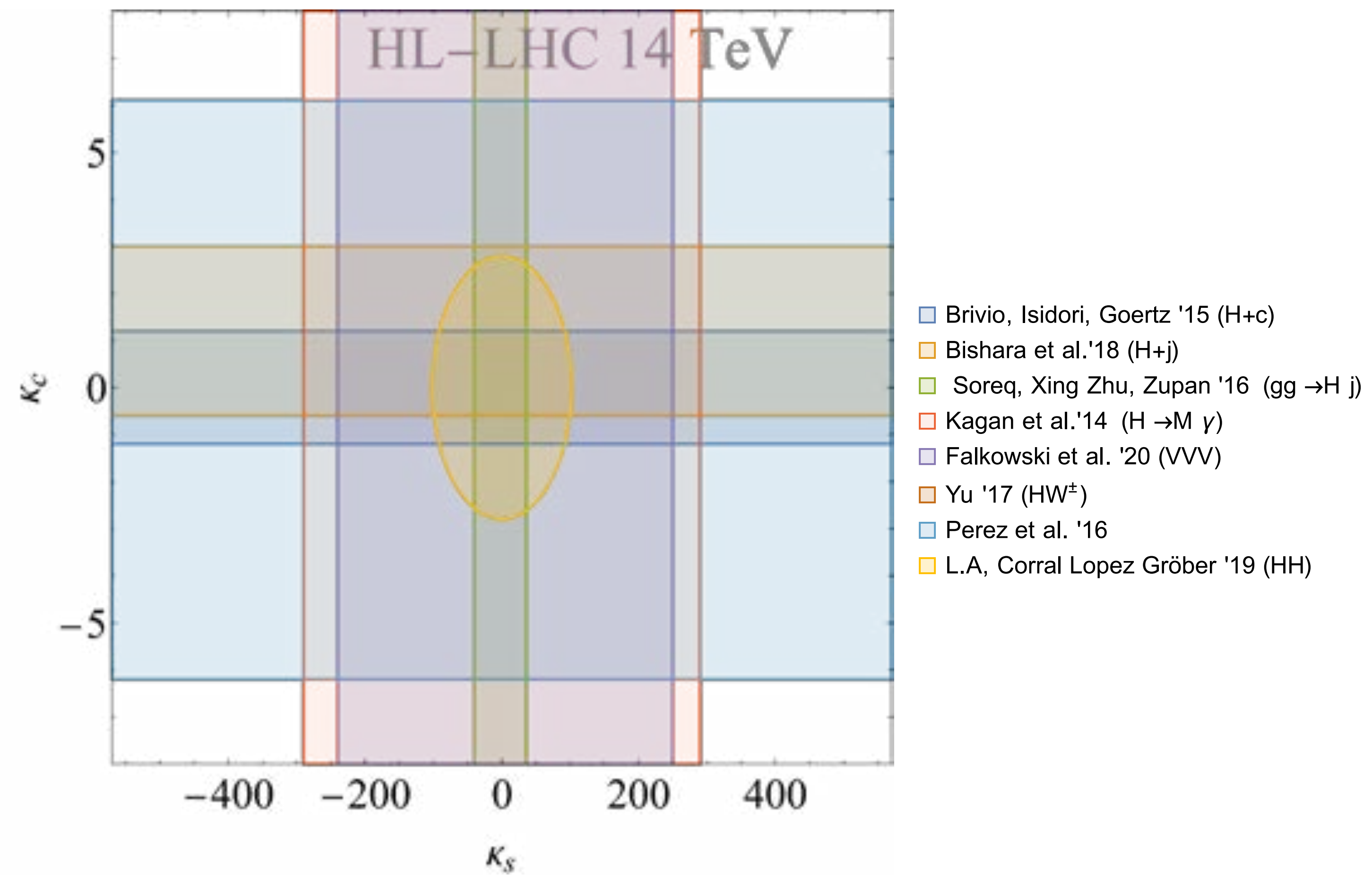
Summery of the current status

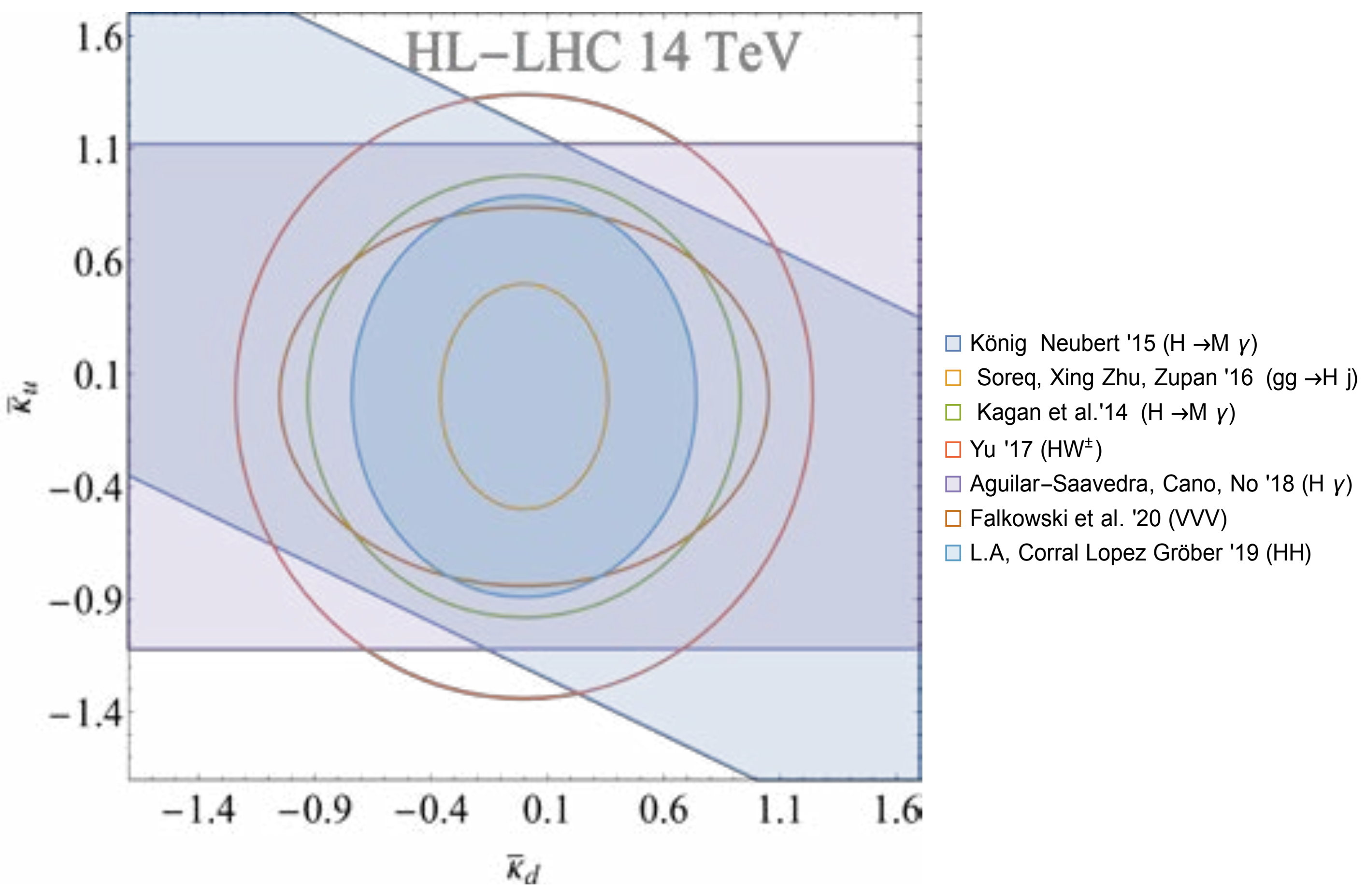
- Current approaches are *complementary* to each other.

  Each approach studies different combinations of couplings, some can break degeneracies between flavours and so on..

- The global fit, with assumptions on the Higgs width yields more strict bounds . de Blas et al. (2019)

$$|\kappa_u| < 570\,, \quad |\kappa_d| < 270\,, \quad |\kappa_s| < 13\,, \quad |\kappa_c| < 1.2\,.$$

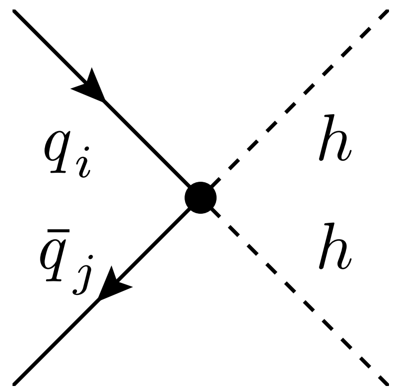




The assumptions made in each of these studies are generally different, so these plots should be taken with a grain of salt

Effective field theory for Light Yukawa & HH

- Usually, when looking at deviations from the SM in Yukawa couplings, the kappa formalism is used
- This is inaccurate when discussing Higgs pair production due to the presence of hhqq coupling.



- There are 2 EFT's one can look at:

-The chiral Lagrangian

This is what is meant by κ typically

$$-\mathcal{L} = \bar{q}_L \frac{m_q}{v}\left(v + c_q h + \frac{c_{qq}}{v} h^2 + \dots\right) q_R + h.c, \longrightarrow \quad g_{h\bar{q}_i q_i} = c_q g^{\rm SM}_{h\bar{q}_i q_i}\,, \qquad g_{hh\bar{q}_i q_i} = \frac{c_{qq} g^{\rm SM}_{h\bar{q}_i q_i}}{v}\,.$$

v= 246 GeV here

-SMEFT, with light quarks dim 6 operators

$$\Delta\mathcal{L}_y = \frac{H^\dagger H}{\Lambda^2}\left(c^u_{ij}\bar{Q}^i_L \tilde{H} u^j_R + c^d_{ij}\bar{Q}^i_L H d^j_R + h.c.\right)\,, \longrightarrow \quad g_{h\bar{q}_i q_j}: \quad \frac{m_{q_i}}{v}\delta_{ij} - \frac{v^2}{\Lambda^2}\frac{\tilde{c}^q_{ij}}{\sqrt{2}}\,, \qquad g_{hh\bar{q}_i q_j}: \quad -\frac{3}{2\sqrt{2}}\frac{v}{\Lambda^2}\tilde{c}^q_{ij}$$

One can abuse the kappa formalism and apply it to SMEFT, to get

$$\frac{C_{qH}}{\Lambda^2} = \frac{\sqrt{2}\,m_q}{v^3}(1-\kappa_q) \qquad \Rightarrow \qquad g_{h\bar{q}q} = \kappa_q\, g^{SM}_{h\bar{q}q}$$

$$c^q_{ii} := C^{ii}_{qH} \qquad\qquad g_{hh\bar{q}q} = -\frac{2}{2\sqrt{2}v}(1-\kappa_q) g^{SM}_{hh\bar{q}q}$$

- Effective field theories (like HEFT and SMEFT) need to include operators modifying light Yukawa in the fits.

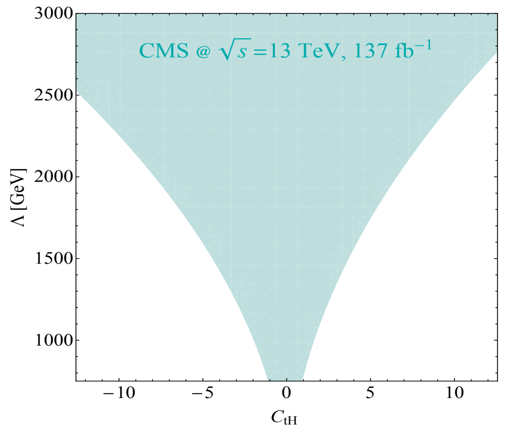
SMEFT prospective

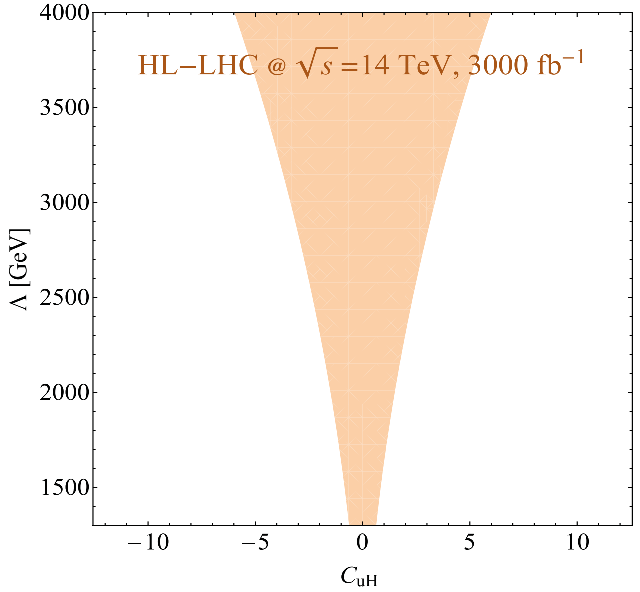
- If one looks strictly within SMEFT, the light quark-Higgs coupling operators are not that far behind !
- Compared to the top-Higgs coupling, both Wilson coefficients are constrained to ~O(0.1)

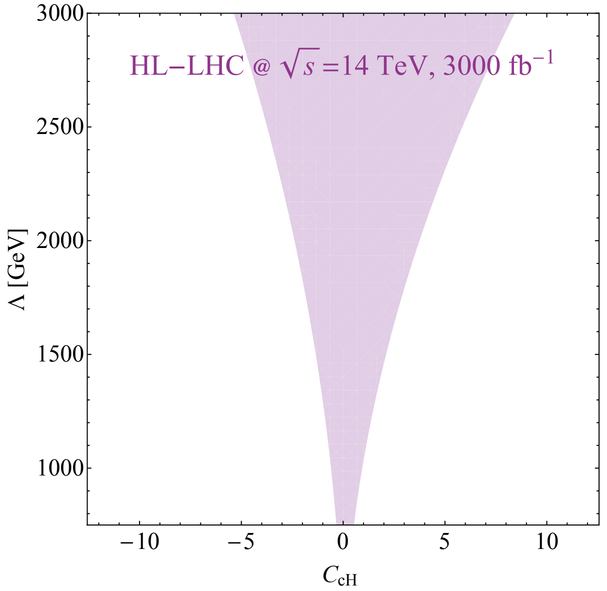
Any NP model that couples to the Light quarks in a" natural" way and have a small scale would modify light Yukawa couplings by a huge amount.

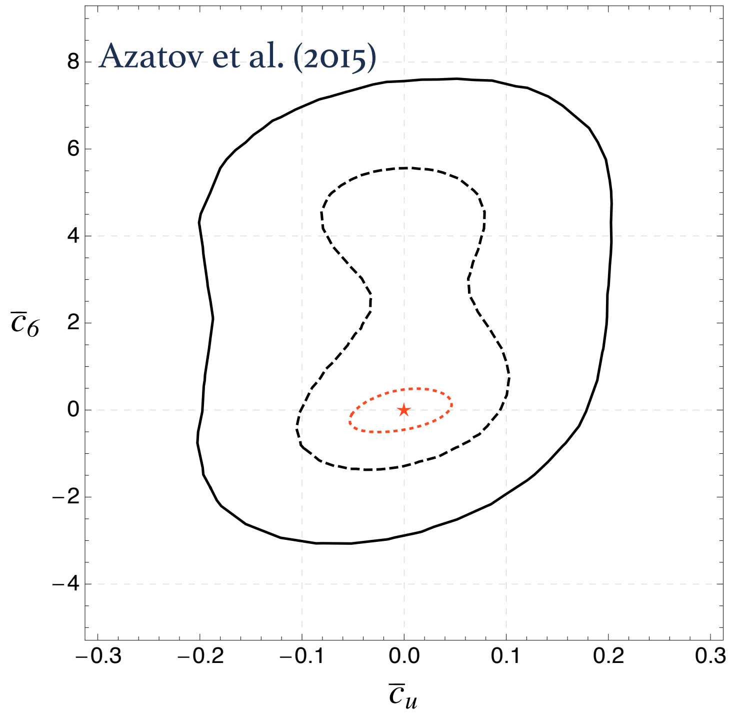
Such models would be excluded or almost excluded, pushing the scale of NP to few to several TeV.

flavour	$\frac{C_{qH}}{(1-\kappa_q)}$ $\Lambda = 1\text{TeV}$	$\frac{C_{qH}}{(1-\kappa_q)}$ $\Lambda = 5\text{TeV}$
up	2.25×10^{-4}	5.60×10^{-3}
down	4.39×10^{-4}	1.10×10^{-2}
strange	9.70×10^{-3}	2.42
charm	0.17	4.34
beauty	0.43	10.70
top	17.6	439.90









- UV complete models could be matched to SMEFT operator C_{qH} universally and still be safe from exclusion.

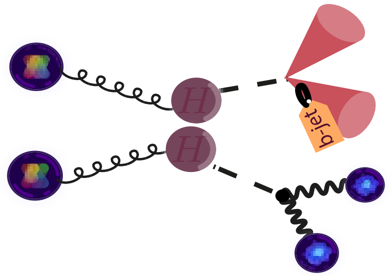
Inducing large modifications to light quarks.

However, the challenge is to prevent FCNC's from flavour non-diagonal C_{qH}, (MFV, SFV, AFV…) Egana-Ugrinovic, Homiller, Meade (2019)

Our Work

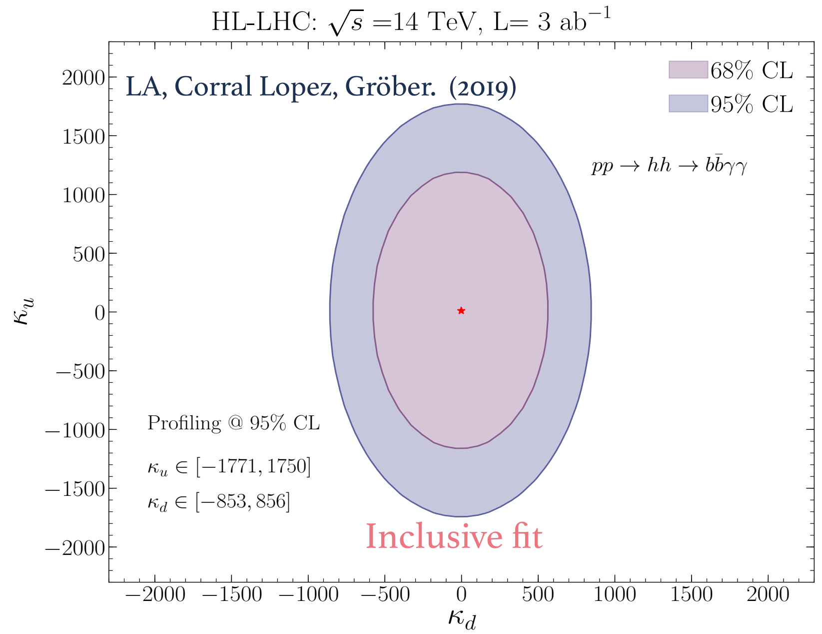
HL-LHC sensitivity:

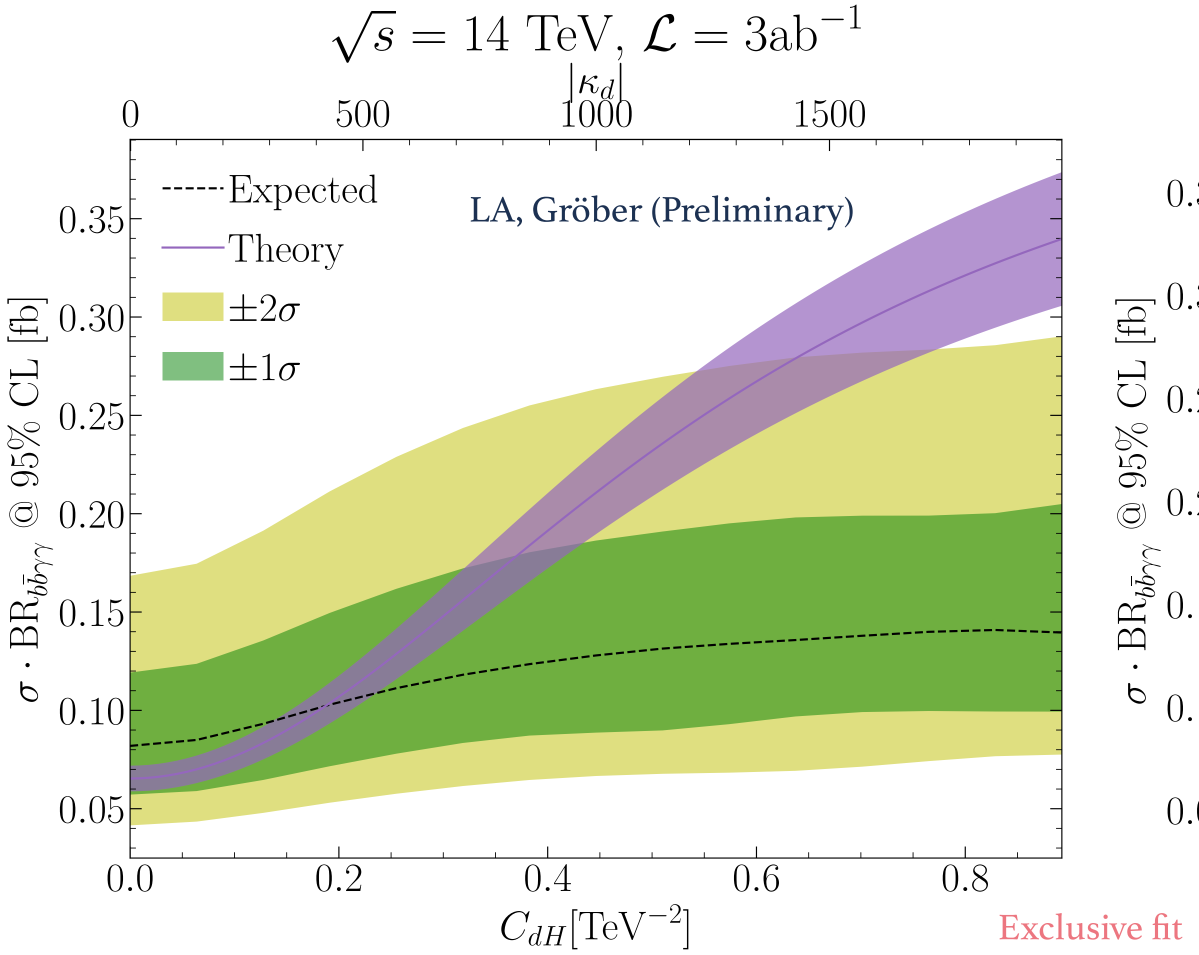
- We looked at the final state $pp \to hh \to b\bar{b}\gamma\gamma$

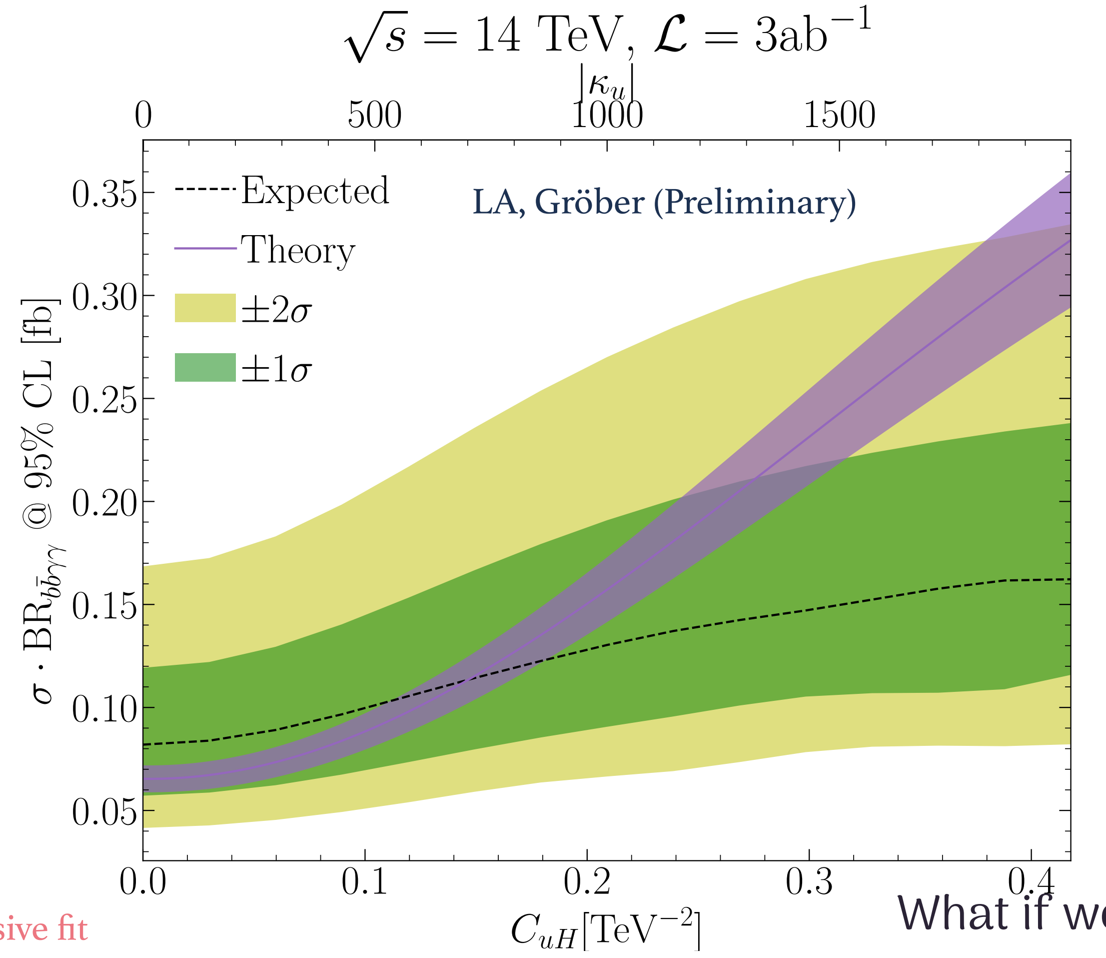


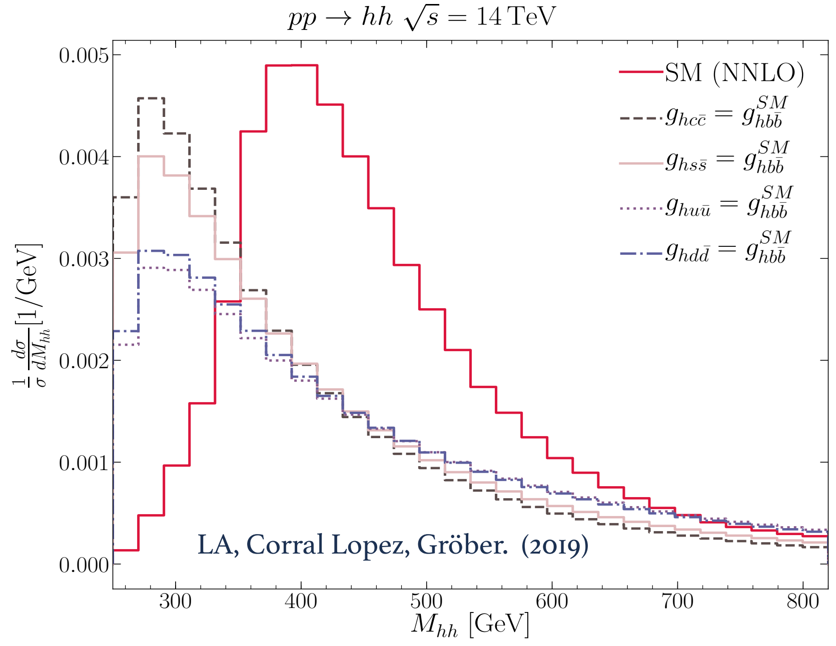
Bounds have improved significantly, by using 5 m_{hh} and 5 $p_{T,h}$ categories in an exclusive fit

$$\kappa_d \sim 600, \qquad \kappa_u \sim 1000$$

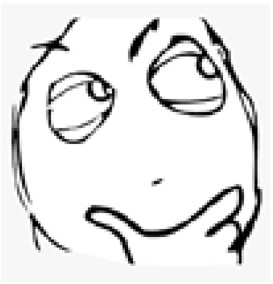






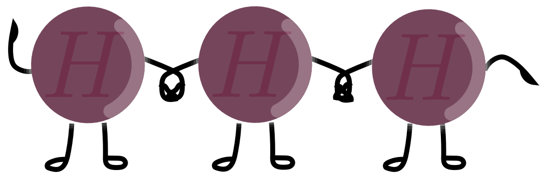


What if we could have more categories ?

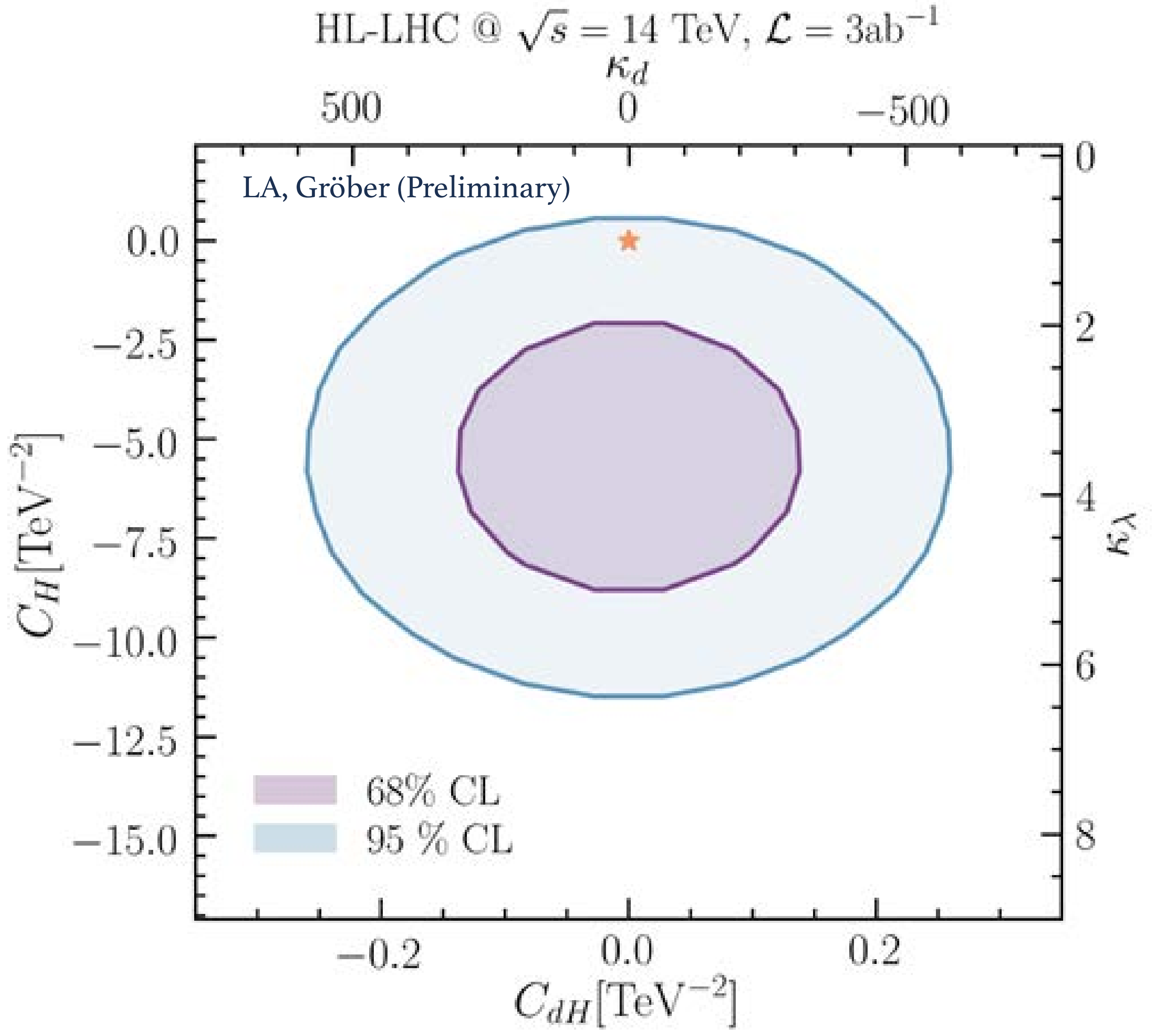


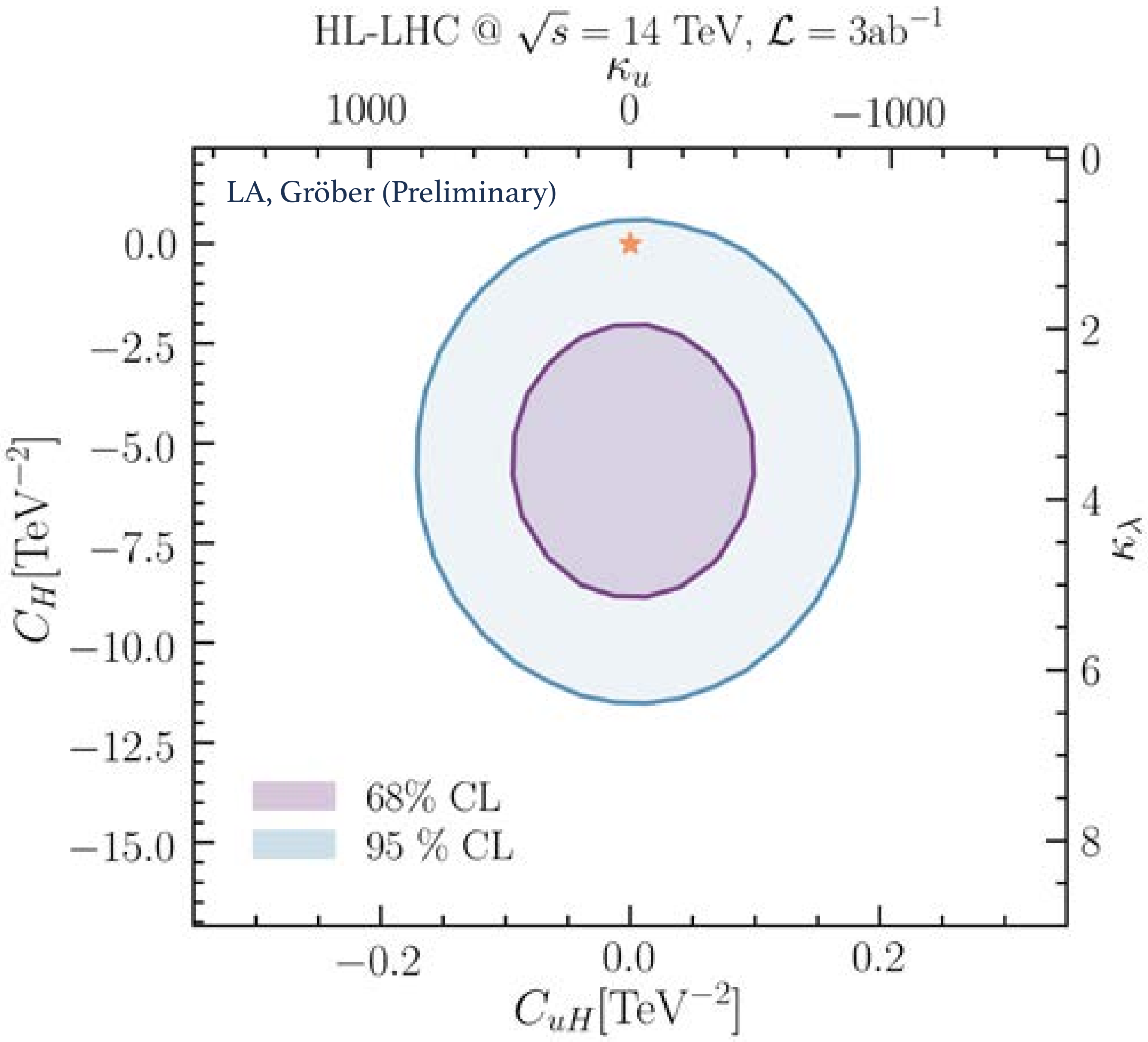
Bounds with trilinear coupling

- Combined likelihood fit with varying both light Yukawa and Higgs trilinear coupling



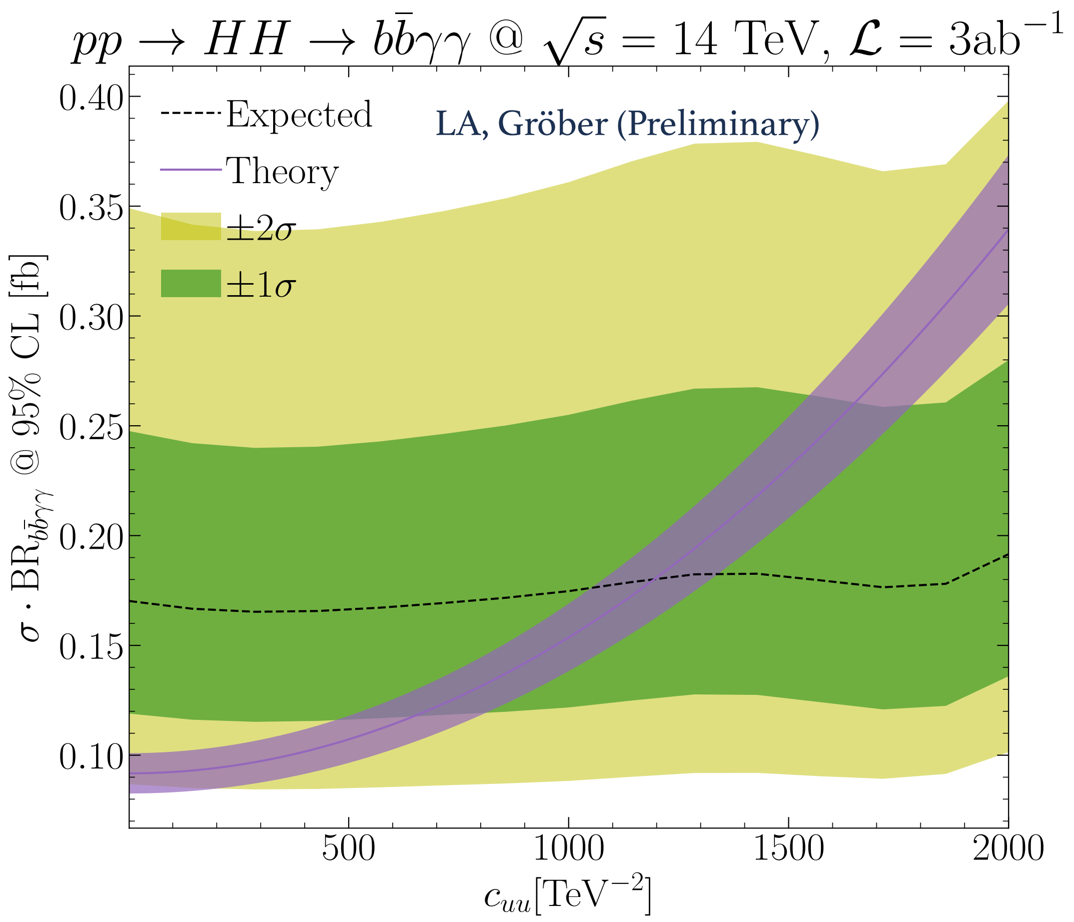
There is no significant correlation, however for an accurate measurement of the trilinear Higgs self-coupling we need to also make a combined fit.

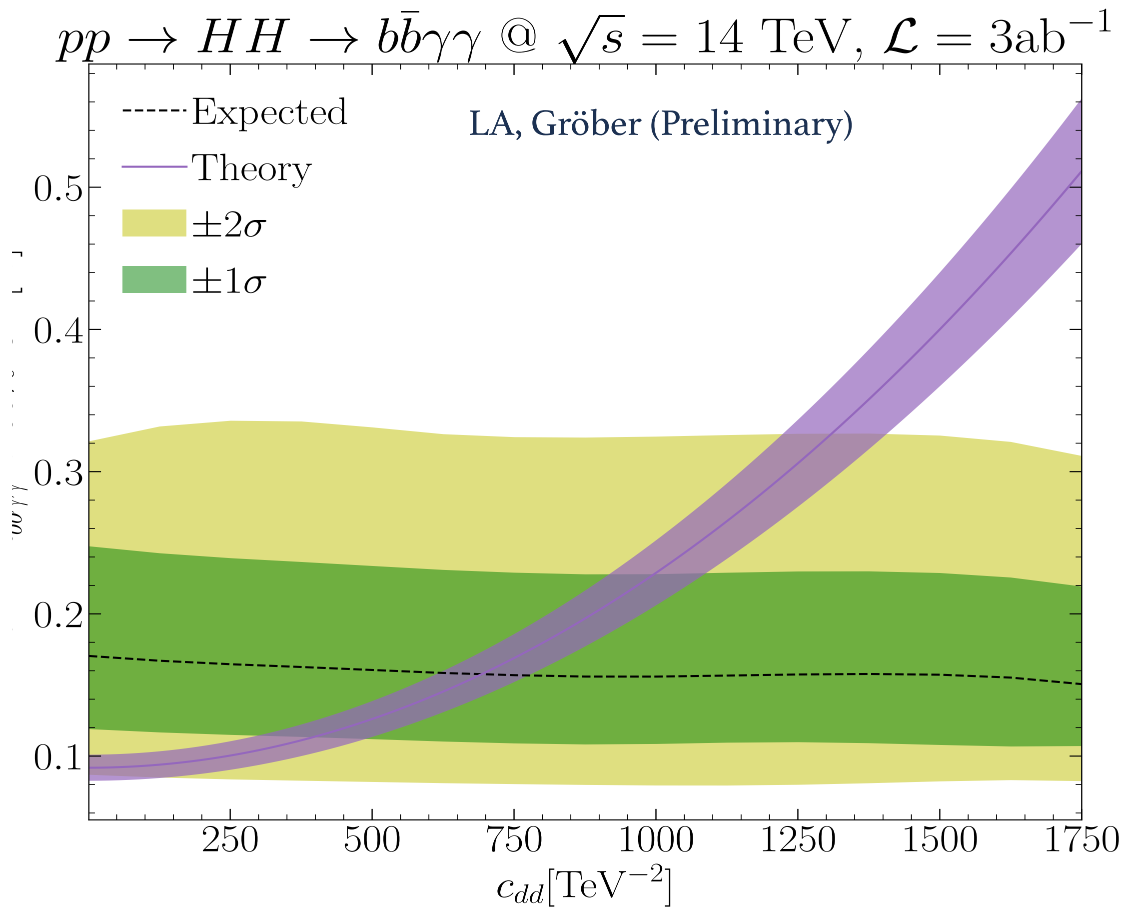




Bounds on Chiral Lagrangian

- One of the features of HH it could probe non-linear EFT Wilson coefficients.





However, the coupling c_q cannot be probed alone. :(

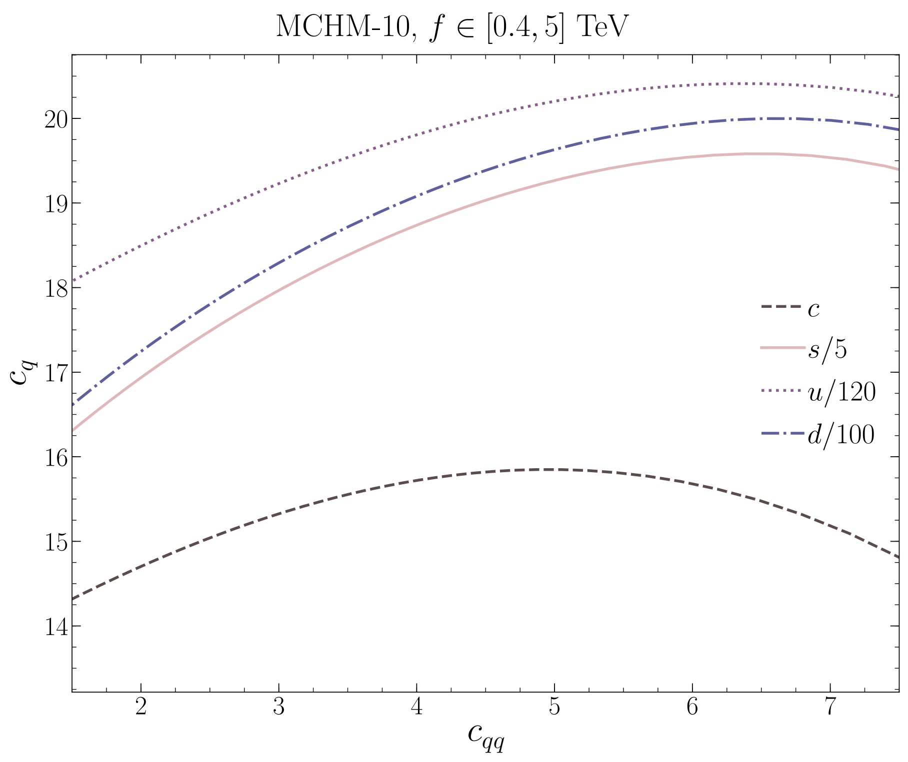
$$c_{dd} < 650, \qquad c_{uu} < 1100$$

Bounds on Chiral Lagrangian

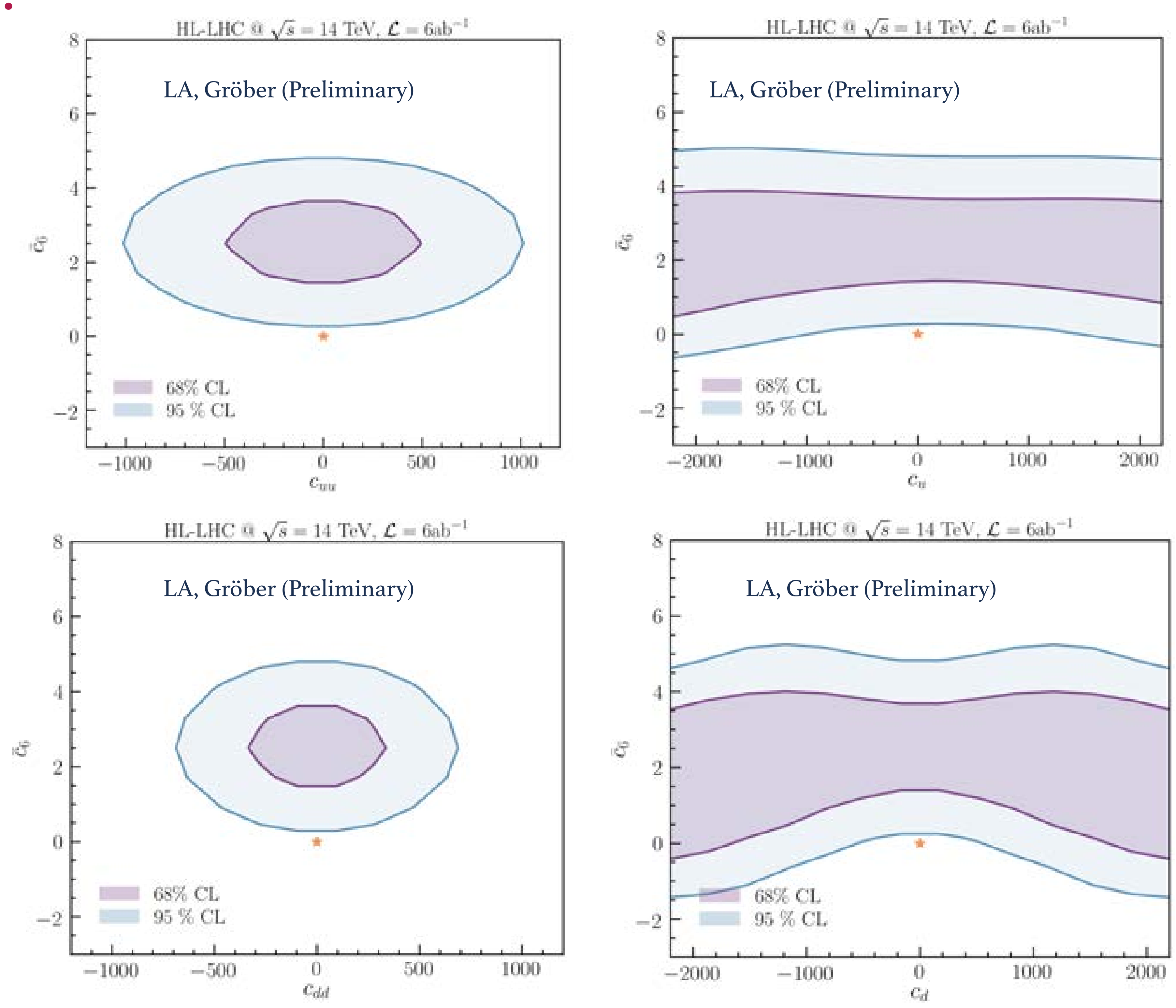
HL-LHC with combined ATLAS and CMS fits:

- Similar pattern is observed for the chiral Lagrangian, there is no correlation between the trilinear and c_{qq} and very weak one for c_q

- But HH can distinguish between c_{qq} and $c_{q.}$ even when the trilinear coupling is turned on.
- This could be useful in probing UV models having correlation between these couplings.



An example of non-trivial correlation between c_{qq} and c_q in a toy composite Higgs model based on Gillioz et al. (2013)

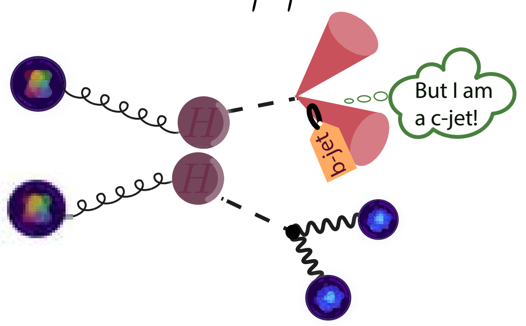


What about the 2nd generation ?

- The channel $pp \to hh \to b\bar{b}\gamma\gamma$ is not suitable to probe 2nd gen. Yukawa.

- However, it is possible to use the mistagging efficiency of c jets as b jets to access $pp \to hh \to c\bar{c}\gamma\gamma$

This method was developed and used by Perez, et al. (2015 and 2016) Kim & Park (2015) to probe charm Yukawa in Higgs decays to b quarks.



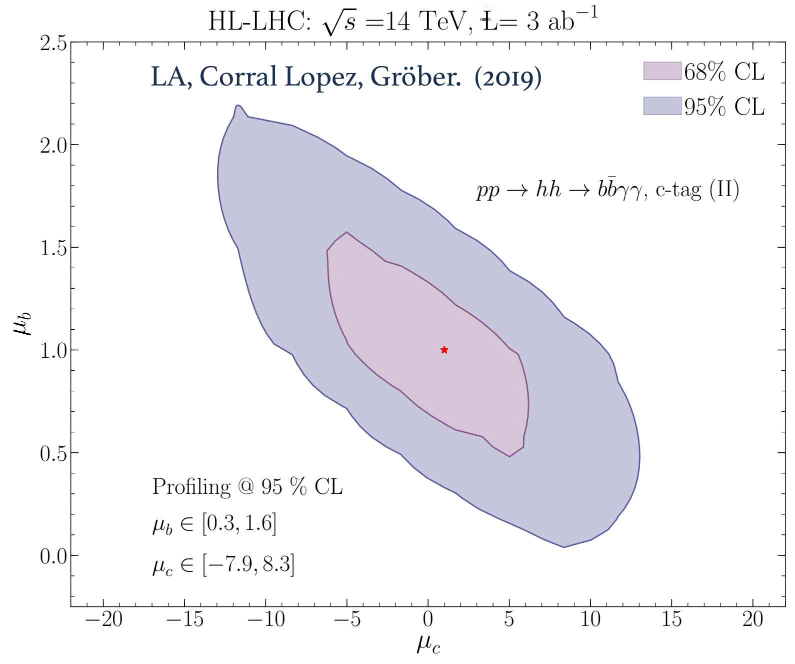
Including some c-tagging scheme , in order to break the degeneracy, it is possible to con-strains charm Yukawa using the same analysis for the $b\bar{b}\gamma\gamma$ final state.

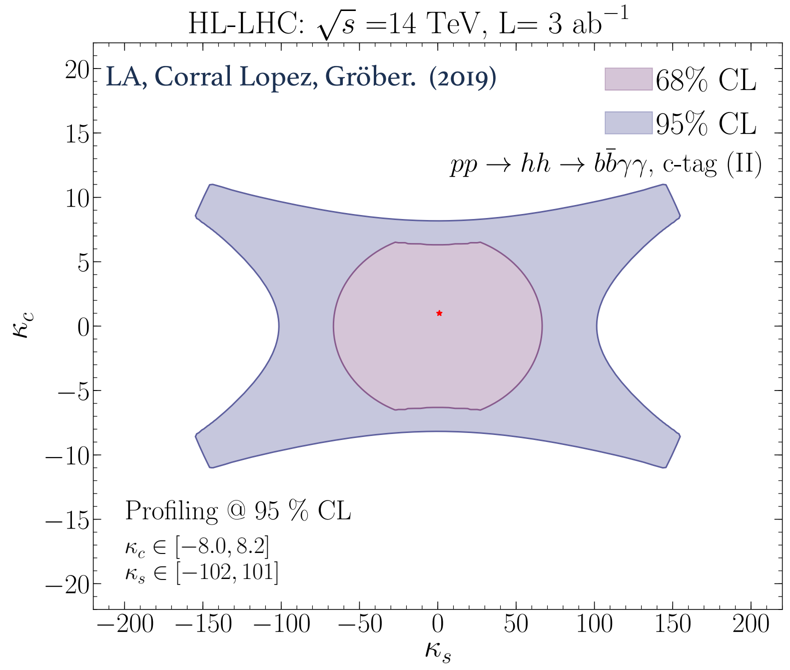
$$\hat{\mu} = \frac{\sigma_{hh}\,\mathcal{B}_b\,\epsilon_{b1}\,\epsilon_{b2}\,\epsilon_f + \sigma_{hh}\,\mathcal{B}_c\,\epsilon_{c1}\,\epsilon_{c2}\,\epsilon_f}{\sigma_{hh}^{\rm SM}\,\mathcal{B}_b^{\rm SM}\,\epsilon_{b1}\,\epsilon_{b2} + \sigma_{hh}^{\rm SM}\,\mathcal{B}_c^{\rm SM}\,\epsilon_{c1}\,\epsilon_{c2}},$$

where now ϵ_b is either ϵ_b or $\epsilon_{c\to b}$ and ϵ_c either ϵ_c or $\epsilon_{b\to c}$. This simplifies to

$$\hat{\mu} = \frac{\mu_b + 0.05\,\epsilon_{c/b}^2\,\mu_c}{1 + 0.05\,\epsilon_{c/b}^2}\,\epsilon_f\,.$$

c-tagging working point	ϵ_c	$\epsilon_{c\to b}$	μ_c(up) 95% CL
c-tag I	19%	13%	10.1
c-tag II	30%	20%	8.2
c-tag III	50%	20%	3.8





For the c-tagging working points from ATLAS see :
arXiv:1501.01325 [hep-ex].
ATLAS-CONF-2013-063,
ATLAS-TDR-19, 2010 and ATL-PHYS-PUB-2015-018, CERN,

Here, the strange Yukawa is probed via 2 channels as well, improving its bound.

Prospects for future collides

- A 27 TeV collider would be able to probe 1st gen. couplings to a great accuracy.
- A 100 TeV collider would be able to probe them all (or would it ?).

FCC

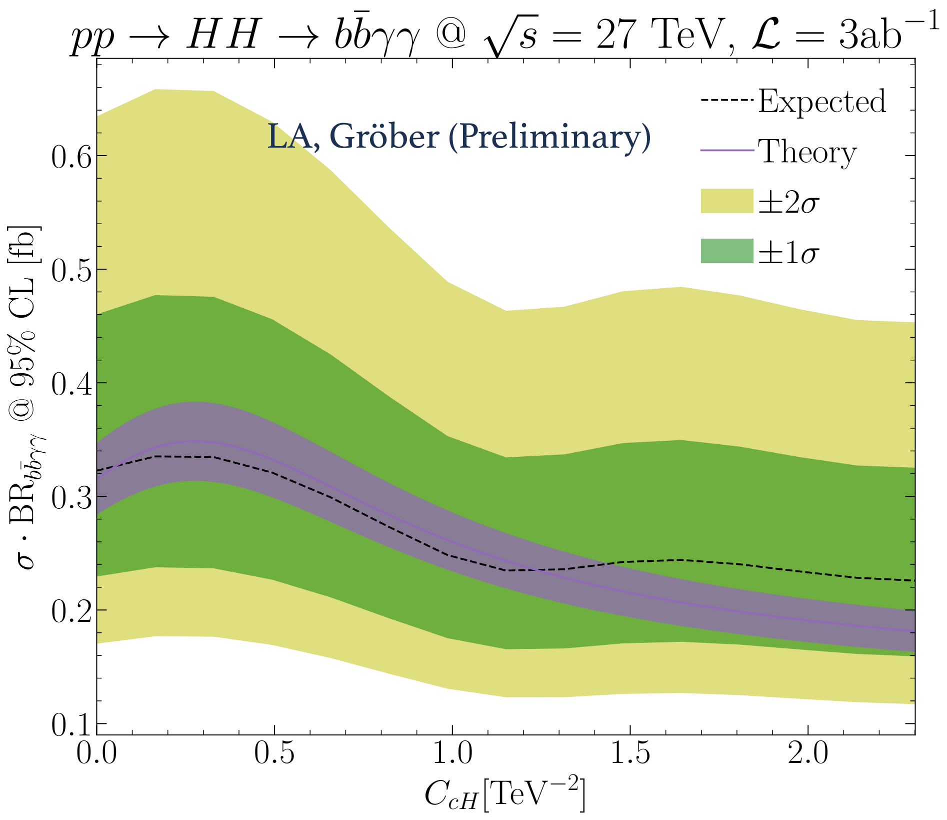
- For strange and charm, it would be plausible to start looking at flavour tagging.

There are already developments in flavour tagging to probe light Yukawa

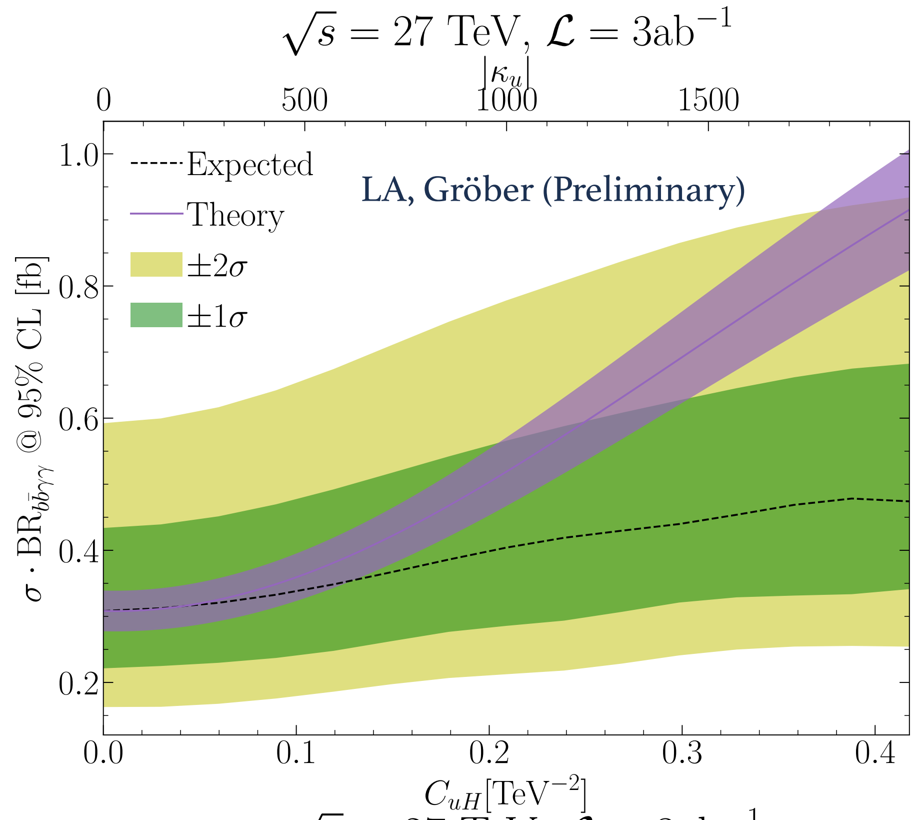
Perez, Soreq, Stamou, Tobioka (2015); Brivio, Goertz, Isidori (2015); ATLAS 1802.04329, CMS 1912.01662; Duarte-Campderros, Perez, Schlaffer, Soffer (2018)

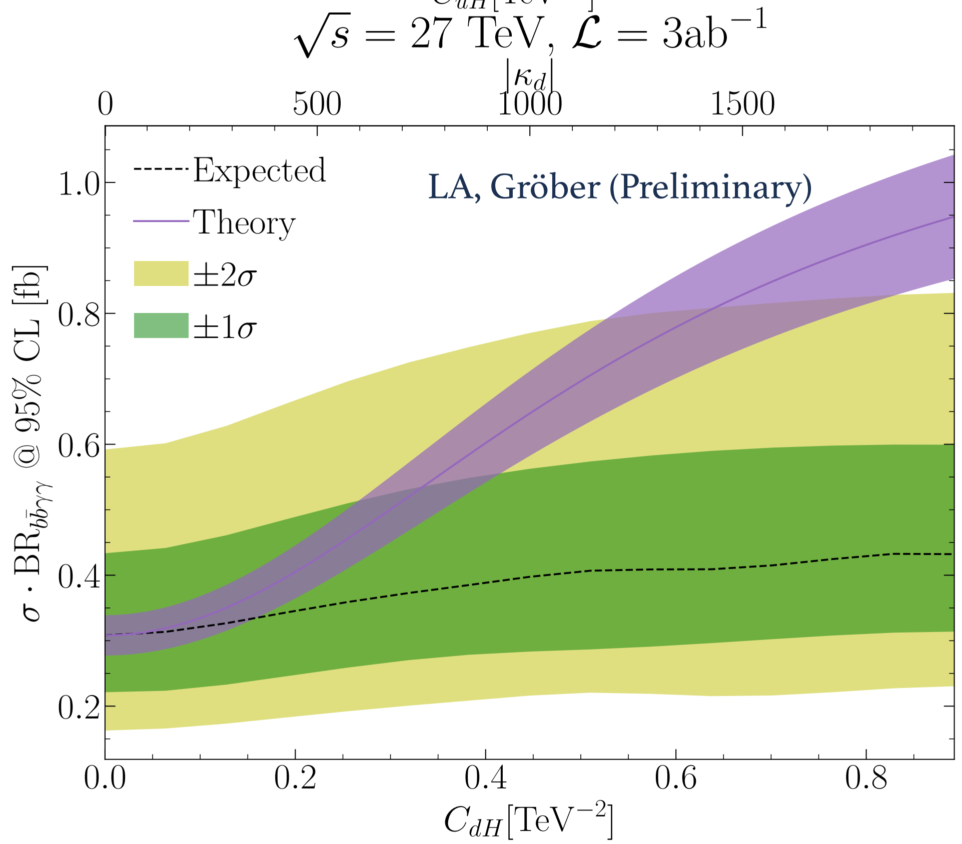
$\kappa_d \sim 70 \qquad \kappa_u \sim 200$

HE-LHC 27 TeV



For the charm, the bounds from this final states will remain weak.





Large uncertainty bands due to the ignorance of the detector performance of future colliders .

Outlook and open problems

• We saw that the fits were improved significantly with categories of 2 kinematic distributions.
It is possible to take this further using *interpretable machine learning* Grojean, Paul, Qian (2020)

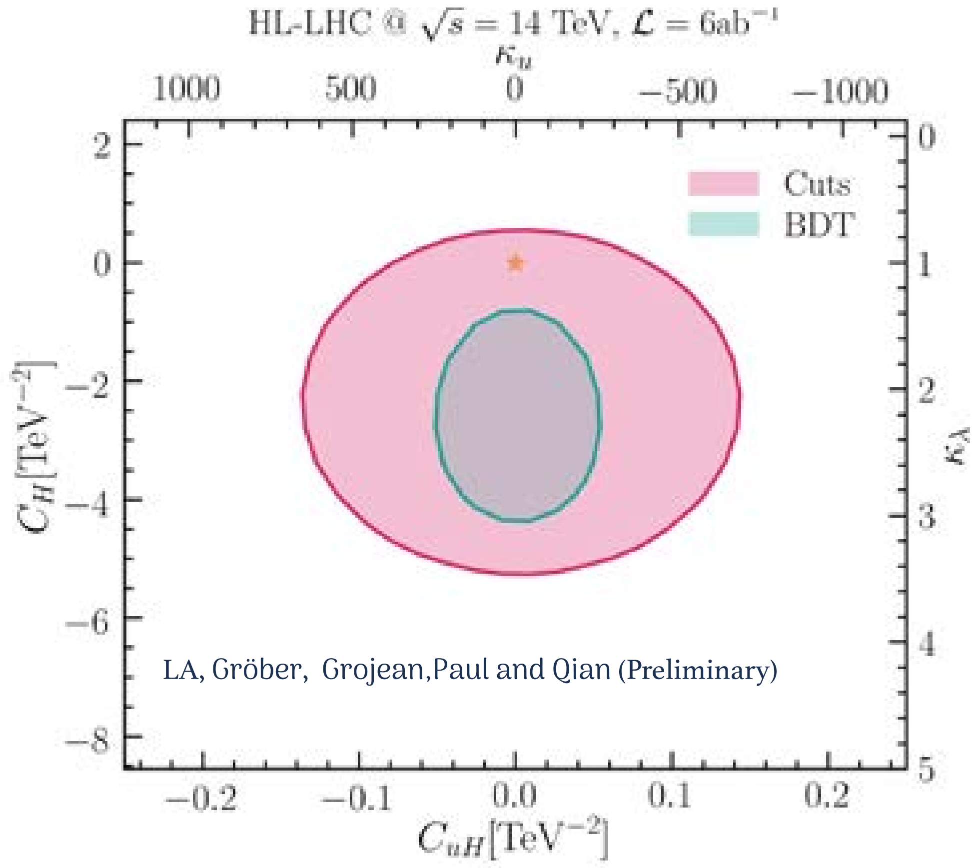
• Studying the flavour violating, and CP odd couplings still needs to be done.

•The light quark masses are not completely well defined, particularly the renormalisation scheme that should be used for them.

• More UV complete models that modify the light quark Yukawa and keep the flavour non-universal ones within currents bounds.

• In depth implementation of charm tagging and c- contamination of b-tagged jets.

• Is it possible to link the old flavour puzzle to the new flavour anomalies ?
for example see Bordone et al. (2017).



Thank You !