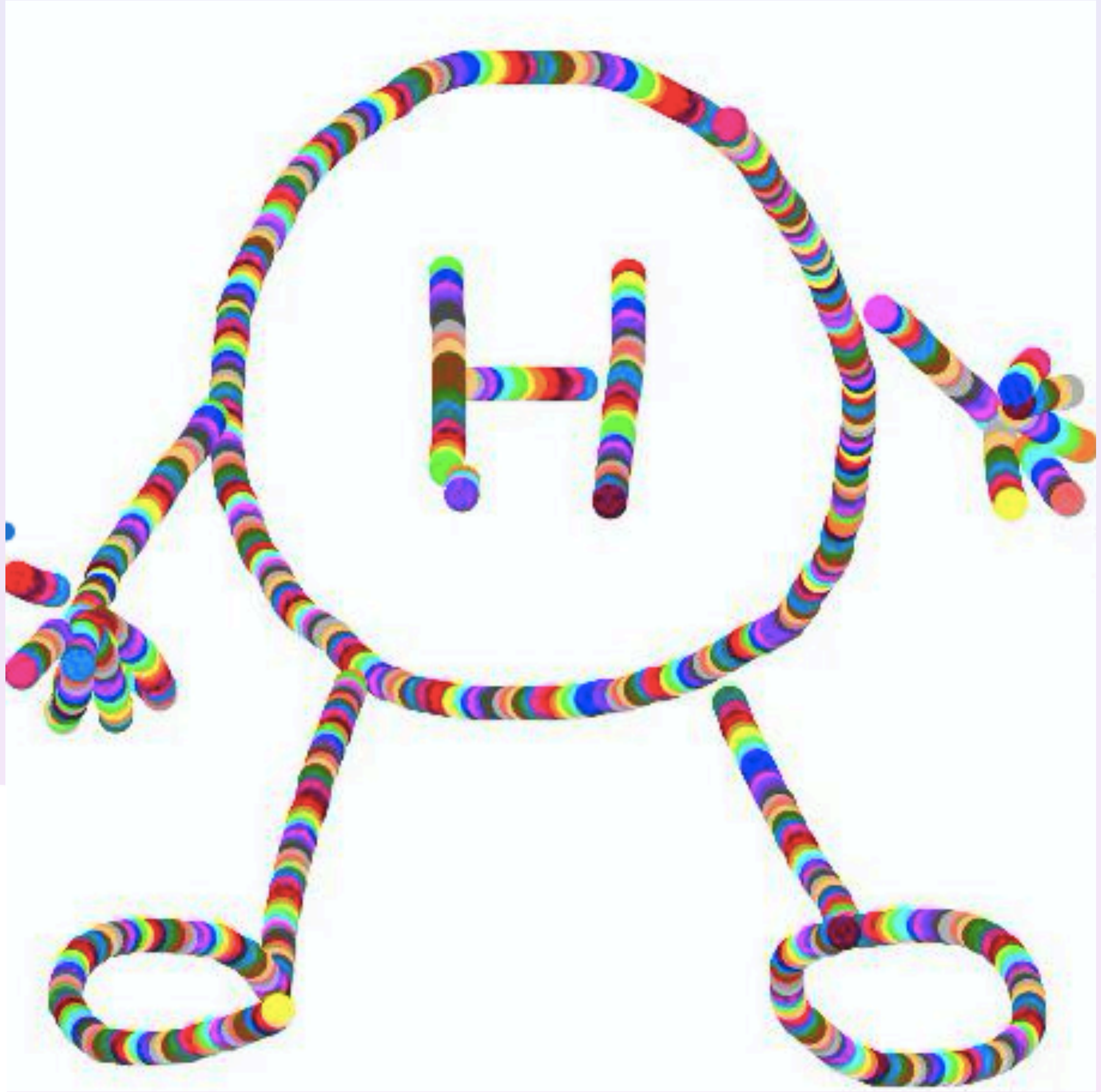
Light Yukawa couplings from off-shell Higgs production

Ramona Gröber

based on work with E. Balzani and M. Vitti
JHEP 10 (2023) 027



15/11/2023

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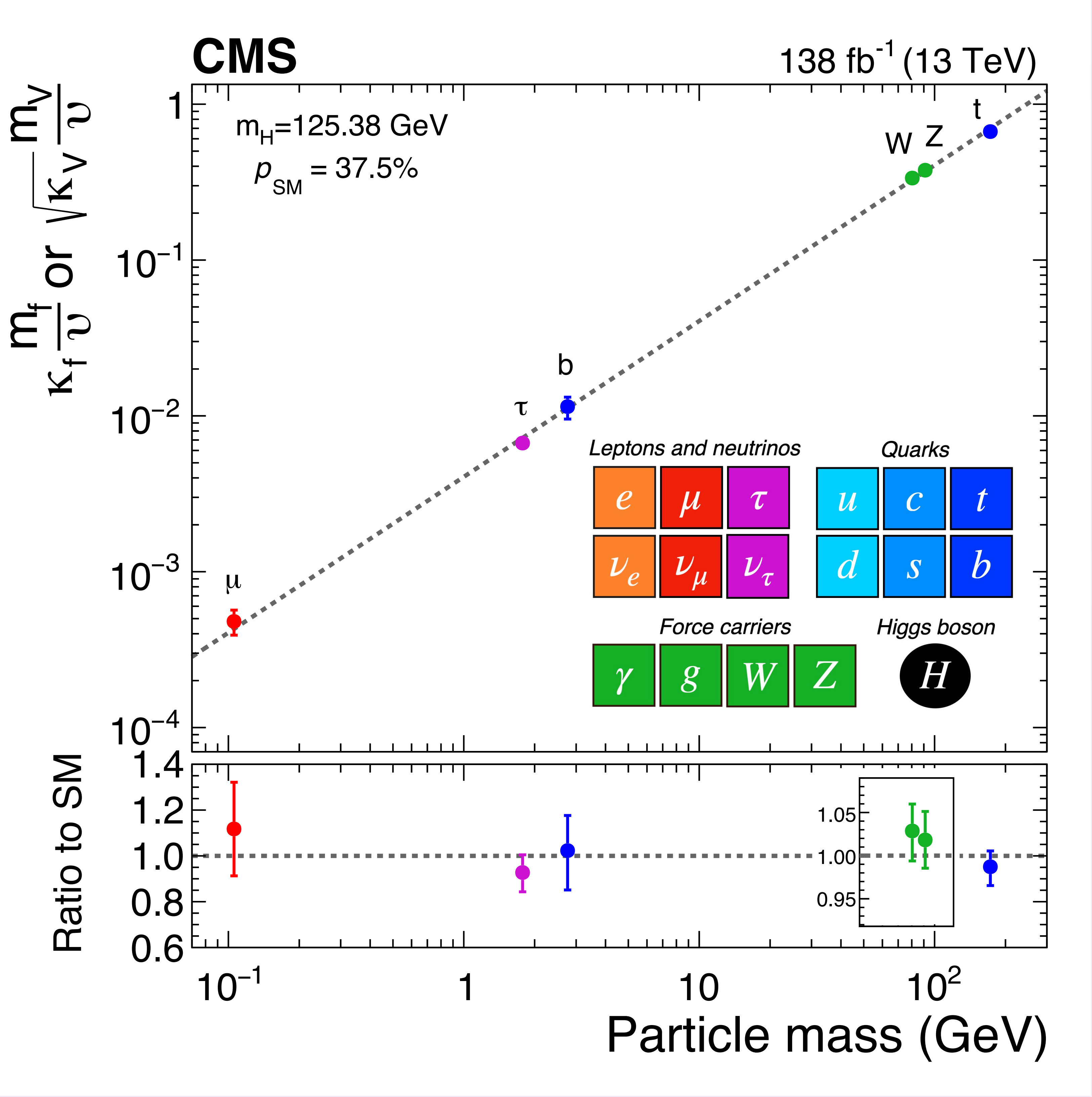
Higgs couplings



3rd generation fermion and gauge boson couplings to Higgs boson fairly good measured

2nd generation fermion couplings first results available

Higgs self-couplings?

First generation Yukawa couplings?

Light quark Yukawa couplings

HL-LHC prospects for measurement of 1st and 2nd generation quark Yukawa couplings
$\kappa = y_q / y_q^{SM}$

[de Blas, Cepeda, d'Hondt et al '19]

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

global fit, not completely model-independent

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Alternative ways:

- Higgs kinematics: Higgs+jet transverse momentum distribution
  [Bishara Haisch, Monni, Re '16; Soreq, Zhu, Zupan '16]
- Higgs decays to photon and vector mesons
  [Bodwin, Pietrello, Stoynev, Velasco '13; Kagan, Perez, Pietrello, Soreq, Stoynev, Zupan '14; Alte, König, Neubert '16 ATLAS 1712.02758, CMS 2007.05122]
- Charm tagging (strange tagging at lepton colliders)
  [Perez, Soreq, Stamou, Tobioka '15; Brivio, Goertz, Isidori '15; ATLAS 1802.04329, CMS 1912.01662; Duarte-Campderros, Perez, Schlaffer, Soffer '18]
- various other proposals [Yu '17, Aguilar-Saavedra, Cano, No '18, Falkowski et al. '20, Vignaroli '22]

Light quark Yukawa couplings

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In this talk: explore the potential of Higgs pair production and off-shell Higgs production for constraining first generation quarks

SMEFT

$$\mathcal{L}_{SM} \supset -y^u_{ij}\bar{Q}^i_L\tilde{\phi}u^j_R - y^d_{ij}\bar{Q}^i_L\phi d^j_R + h.c.$$

At dim-6 level the Higgs couplings to fermions are modified by the operator

$$\mathcal{L}_{dim\,6} \supset \frac{c^u_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{Q}^i_L\tilde{\phi}u^j_R + \frac{c^d_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{Q}^i_L\phi d^j_R + h.c.$$

mass eigenbasis:

$$\tilde{c}^q_{ij} = (V^L_q)^*_{ki}c^q_{kl}V^R_{lj}$$

Couplings:

$$g_{h\bar{q}_iq_j} = \frac{m_{q_i}}{v}\delta_{ij} - \frac{v^2}{\Lambda^2}\frac{\tilde{c}^q_{ij}}{\sqrt{2}}$$

$$g_{hh\bar{q}_iq_j} = -\frac{3}{2\sqrt{2}}\frac{v^2}{\Lambda^2}\tilde{c}^q_{ij}$$

direct coupling to Higgs pair

$$g_{G_0G_0\bar{q}_iq_j} = -\frac{1}{2\sqrt{2}}\frac{v^2}{\Lambda^2}\tilde{c}^q_{ij}$$

In the following consider only flavour diagonal case.

Notation:

$$g_{h\bar{q}q} = \kappa_q g^{SM}_{h\bar{q}q} \qquad g_{hh\bar{q}q} = -\frac{3}{2}\frac{1-\kappa_q}{v}g^{SM}_{h\bar{q}q}$$

SMEFT

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$$g_{G_0G_0\bar{q}_iq_j} = -\frac{1}{2\sqrt{2}}\frac{v^2}{\Lambda^2}\tilde{c}^q_{ij}$$

coupling to longitudinal Z bosons via Goldstone boson equivalence theorem

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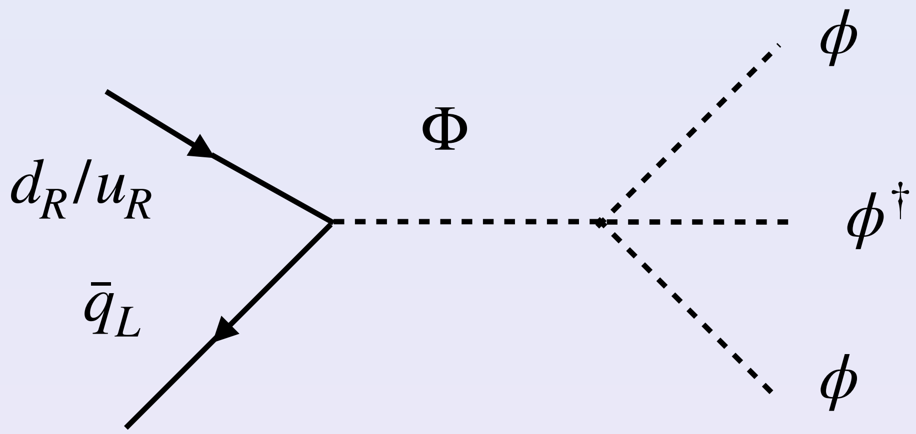
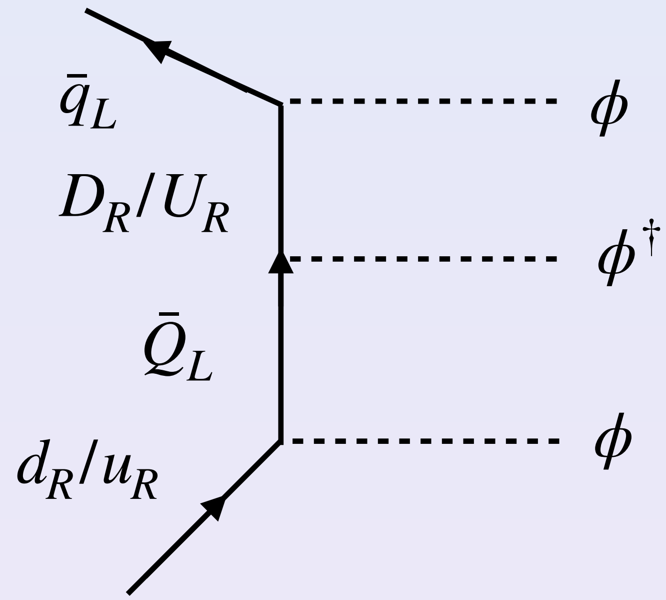
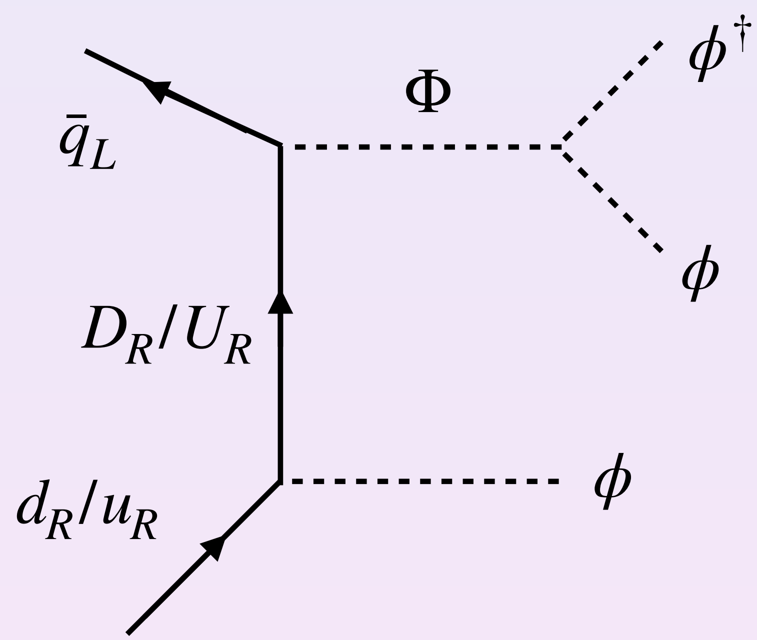
Large light quark Yukawas



heavy scalar



vectorlike quarks



vectorlike quark+ heavy scalar

concrete models:

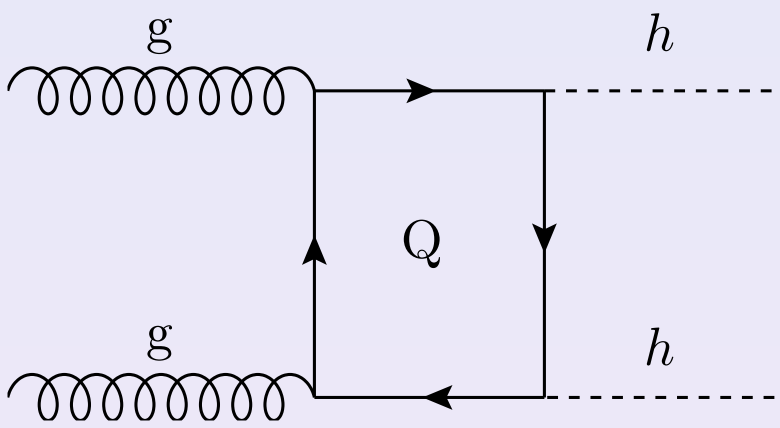
2HDM with spontaneous flavour violation [Egana-Ugrinovic, Homiller, Meade '18, '19]

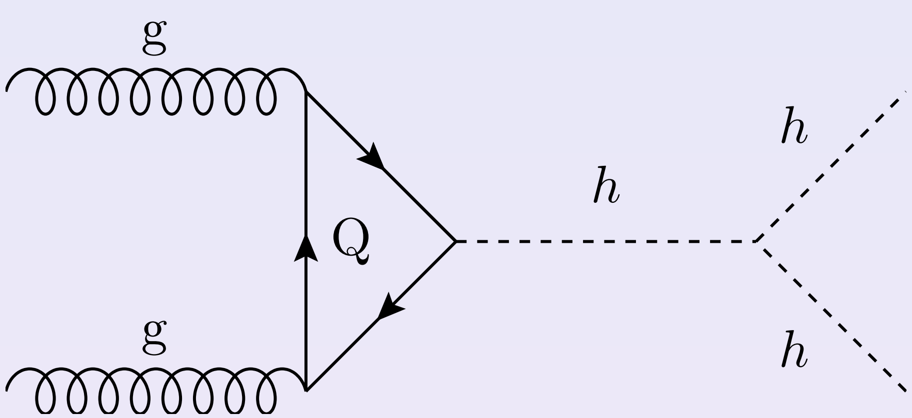
vector-like quarks + flavour symmetries [Bar-Shalom, Soni '18]

Higgs pair production

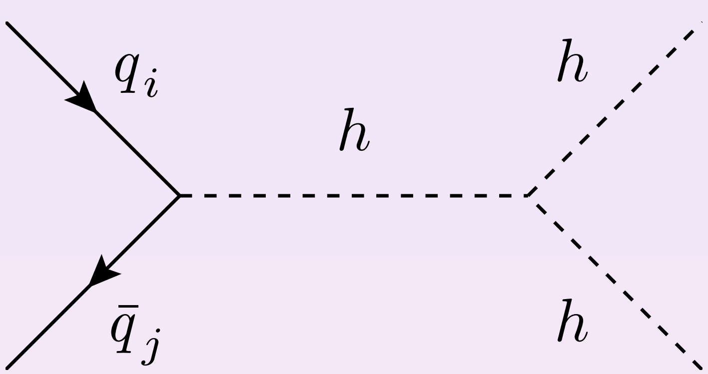
Higgs pair production

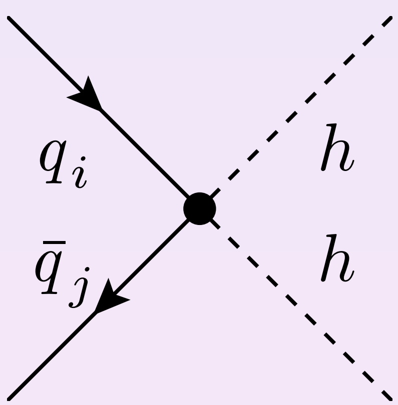
Higgs pair production in SM, gluon fusion dominated by heavy quark loops

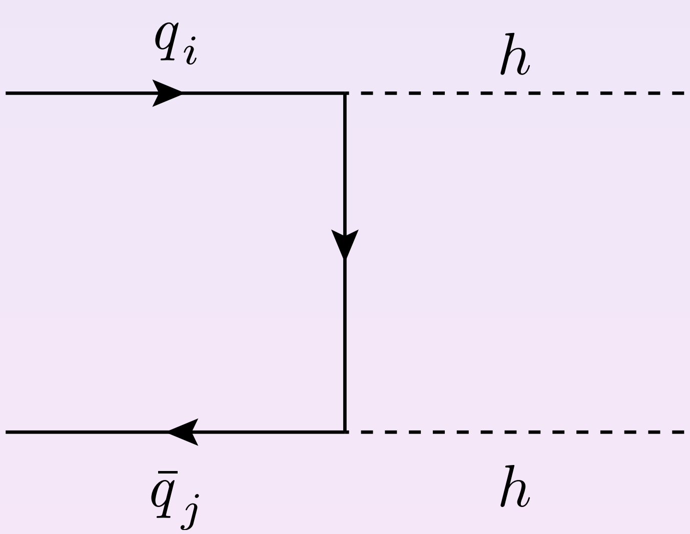




enhanced light Yukawa couplings

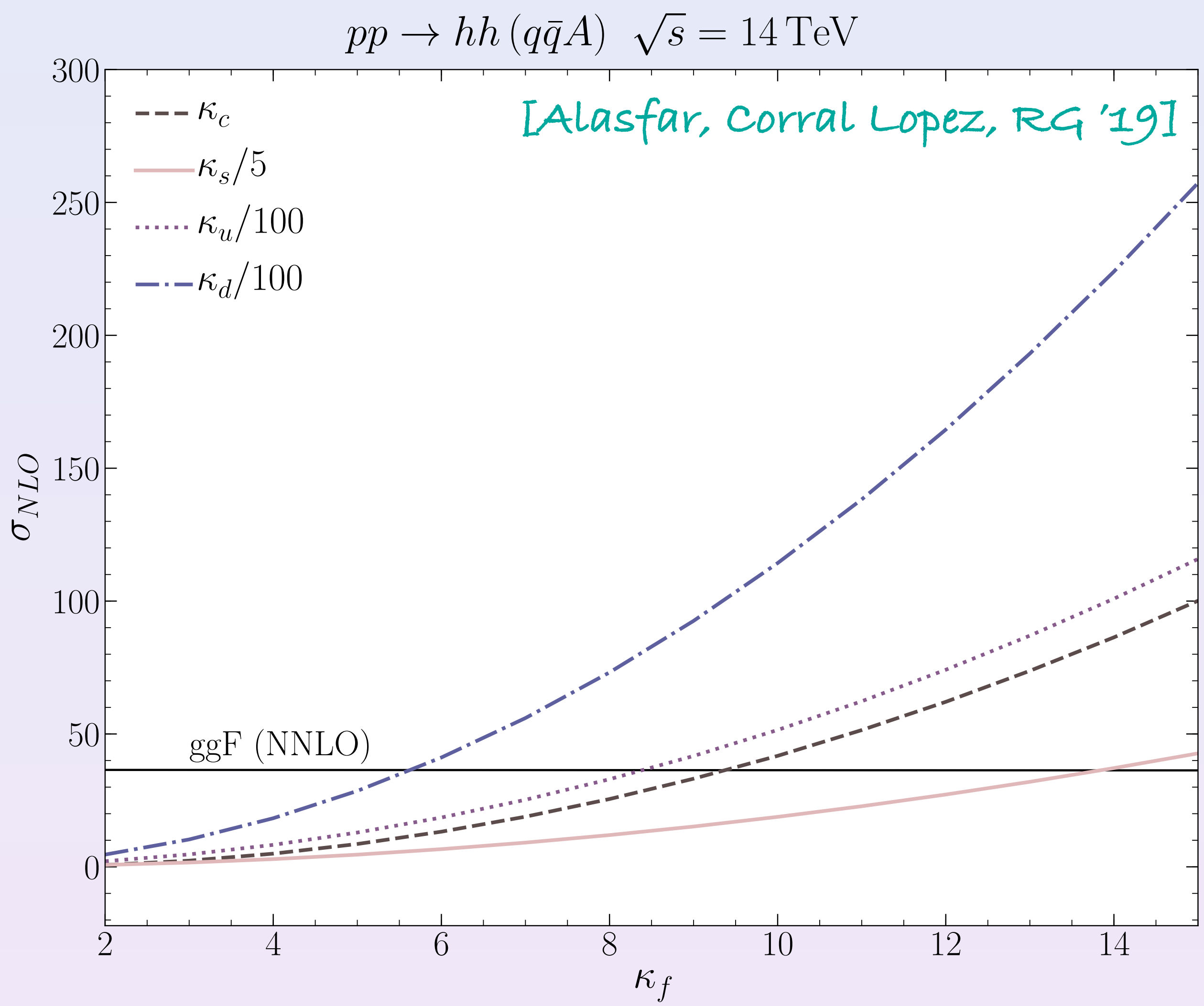


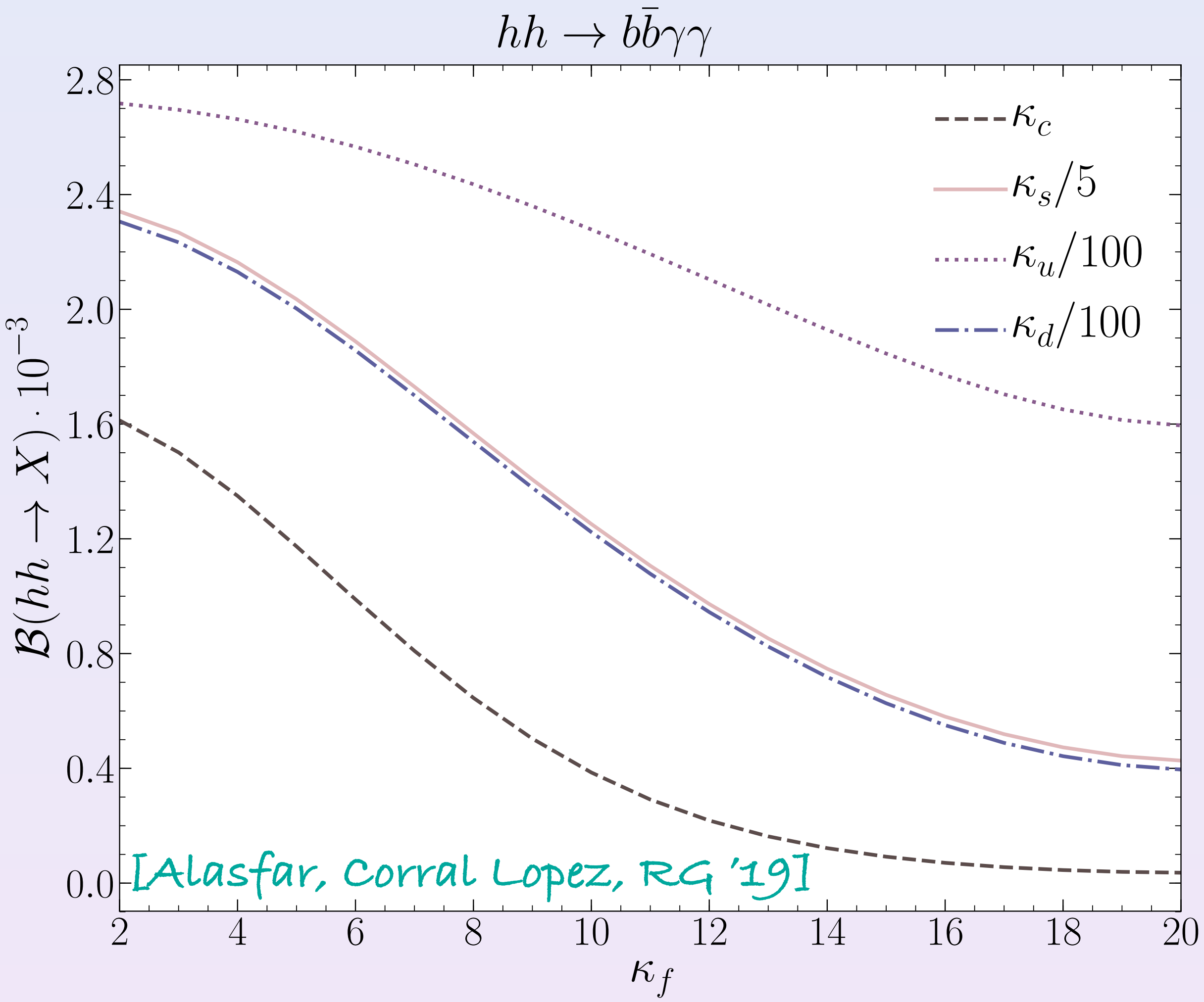




contribution most important for 1st generation (given the coupling limits)

Higgs pair production





increase of cross section,
(also modified distributions)

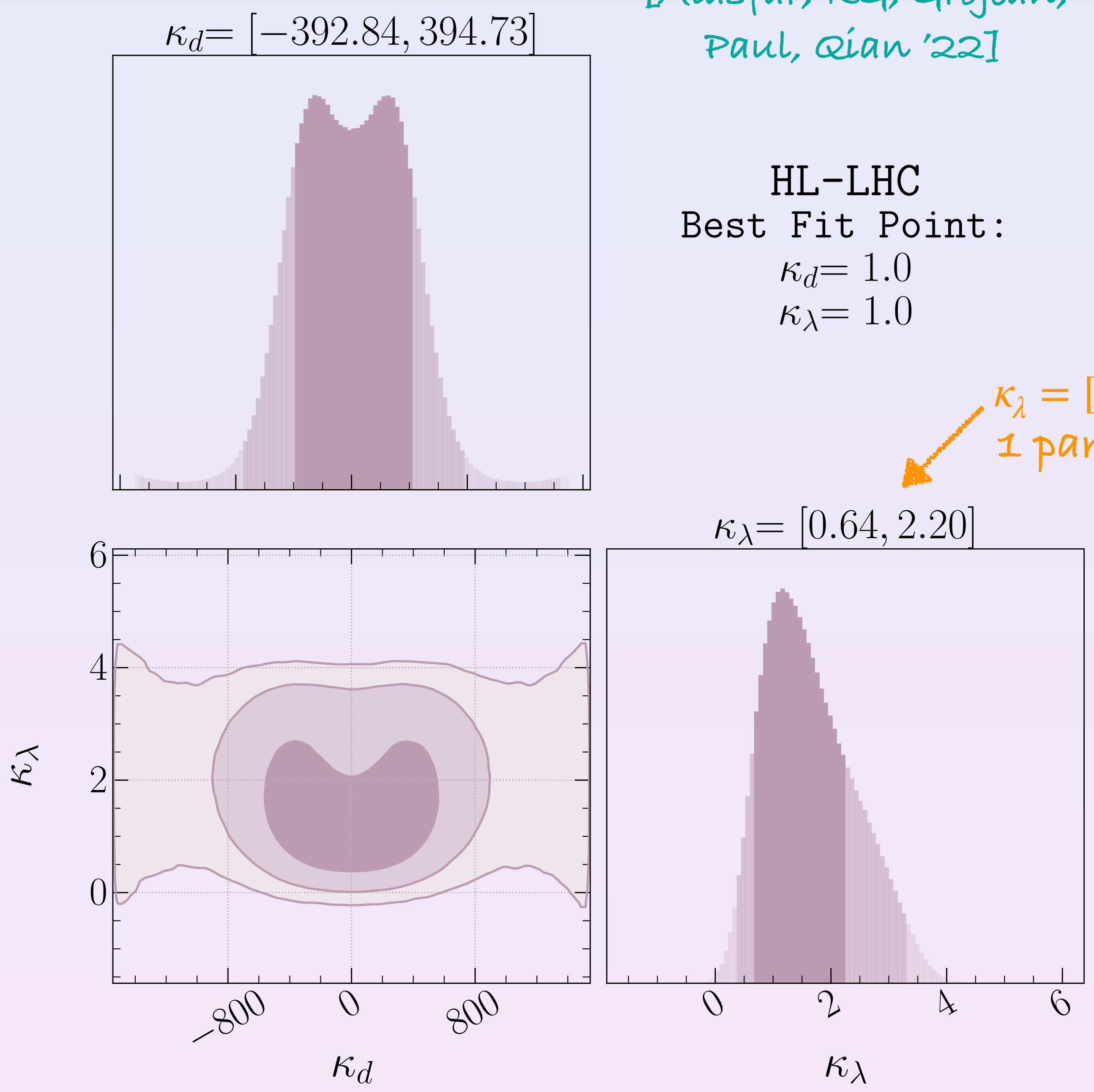
decrease of BR for typical di-Higgs final state

Cut and count analysis: $\kappa_u < 1251$, $\kappa_d < 610$

Higgs pair production results

using BDTs to learn the shapes

[Alasfar, RG, Grojean, Paul, Qian '22]

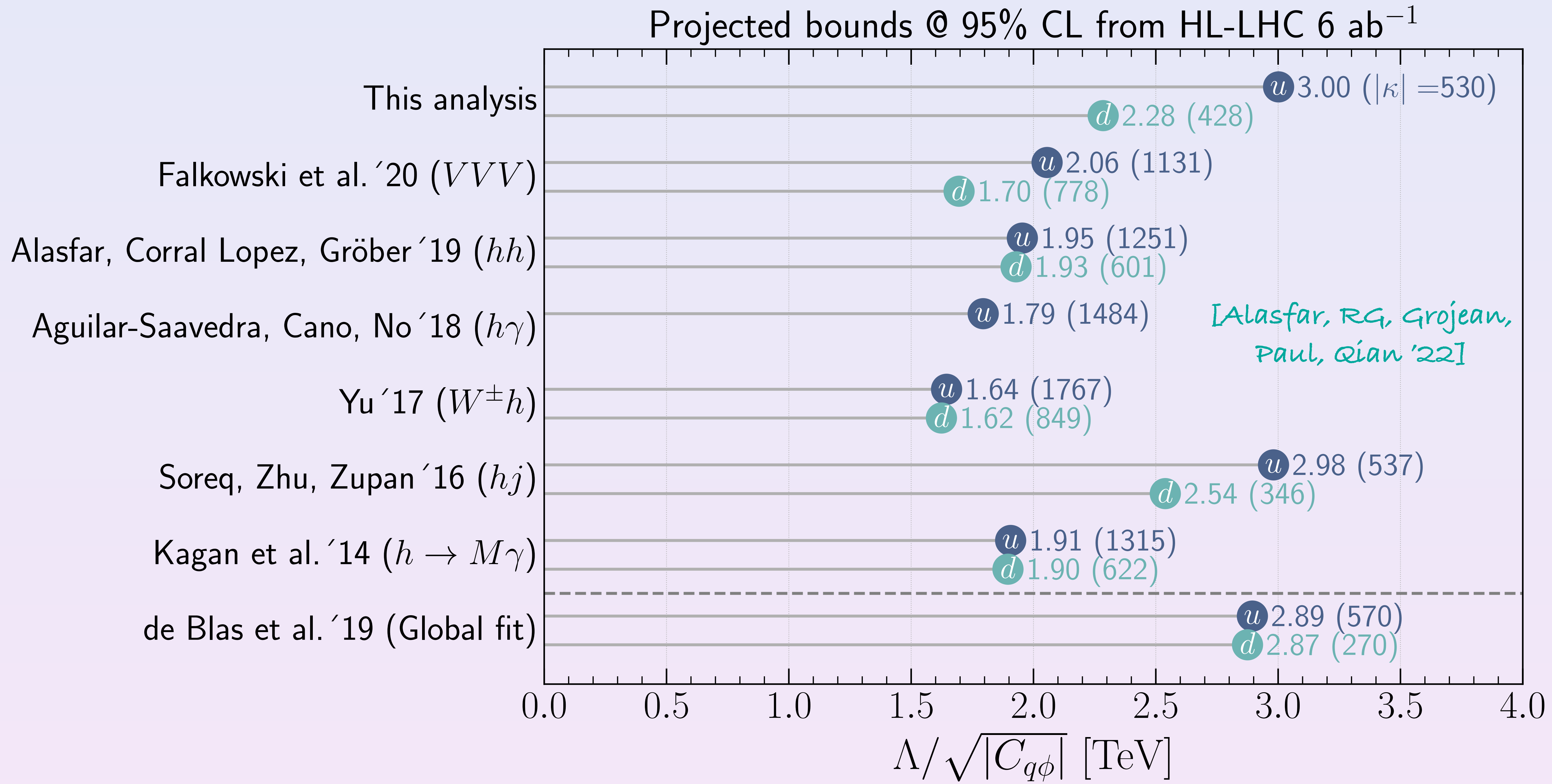


κ_λ = [0.53,1.73]
1 parameter fit

We performed several one-/two- and three-parameter fits

here we can see that the sensitivity on the trilinear Higgs self-coupling is diluted in two-parameter fit

Results



huge improvement over cut-and count analysis

Off-shell Higgs production

Off-shell Higgs production

Considered as probe of Higgs width

[Kauer, Passarino '12, Carla, Melnikov '13, Campbell, Ellis, Williams '13]

$$\frac{\mu_{on}}{\mu_{off}} \propto \frac{\kappa^2_{ggh}(m_h)\kappa^2_{hZZ}(m_h)}{\Gamma_h/\Gamma_h^{SM}} \frac{1}{\kappa^2_{ggh}(m_{4\ell})\kappa^2_{hZZ}(m_{4\ell})}$$

works for

[Englert, (Soreq), Spannowsky '14]

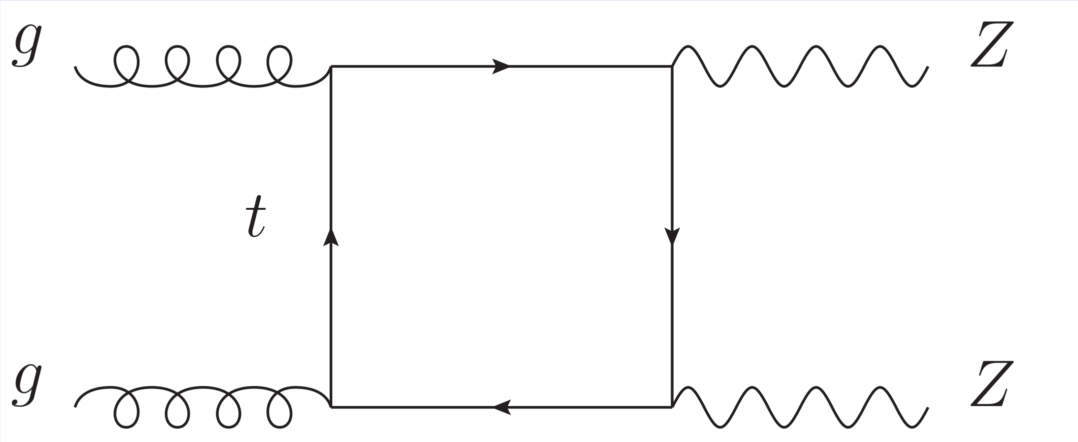
$$\kappa_{ggh}(m_h) = \kappa_{ggh}(m_{4\ell}) \qquad \kappa_{hZZ}(m_h) = \kappa_{hZZ}(m_{4\ell})$$

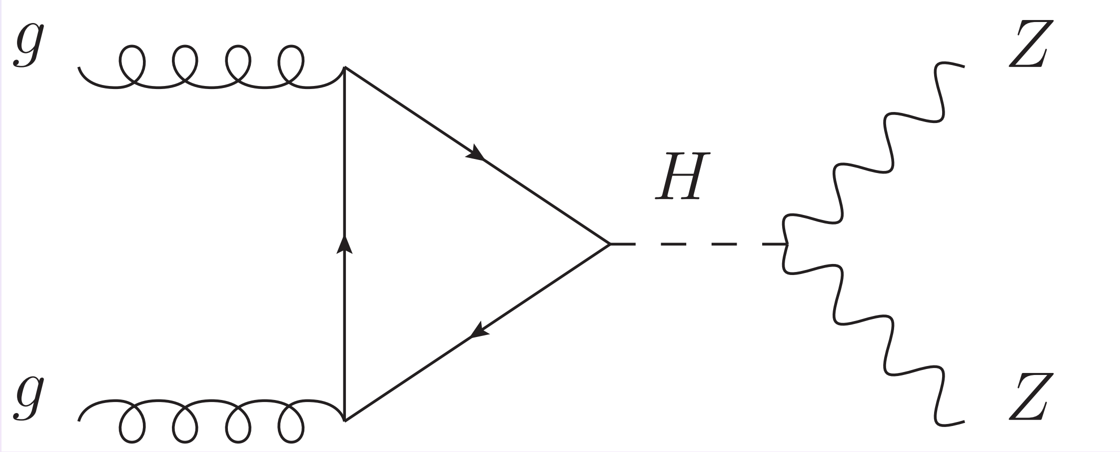
CMS: $3.2^{2.4}_{-1.7}$ MeV

[CMS in Nature 18 (2022) 1392]

ATLAS: $4.6^{2.6}_{-2.6}$ MeV

[ATLAS-CONF-2022-068]





For enhanced light quark Yukawa couplings it does not work:

new production channel to be added, spoils the "model-independence" of width measurement

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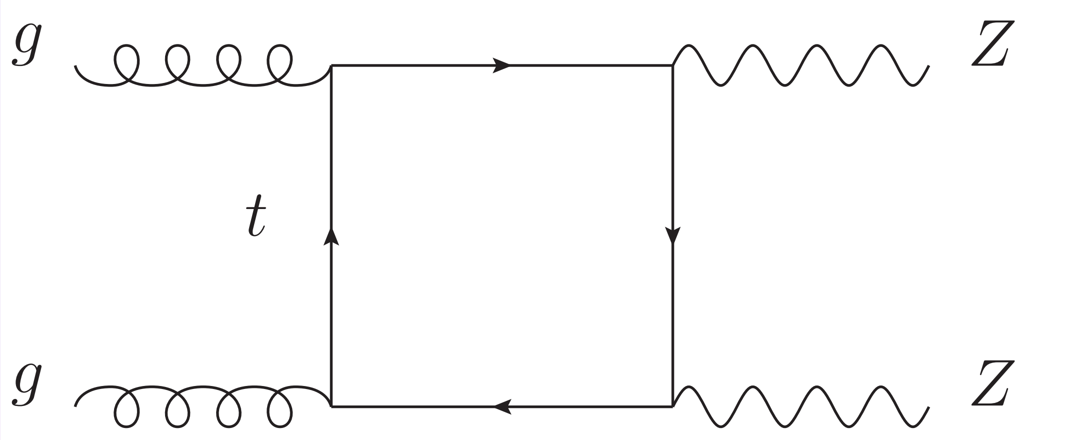
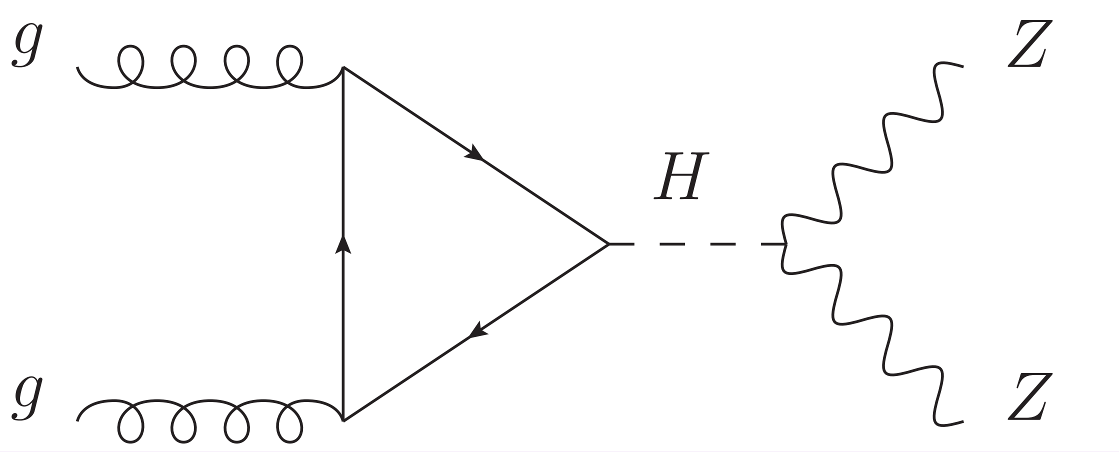




For enhanced light quark Yukawa couplings it does not work:

use instead kinematic properties of off-shell production

[works nicely also for other BSM scenarios see Haisch, Koole '21 '22, Haisch, Ruhrdorfer, Schmid, Weiler '23]

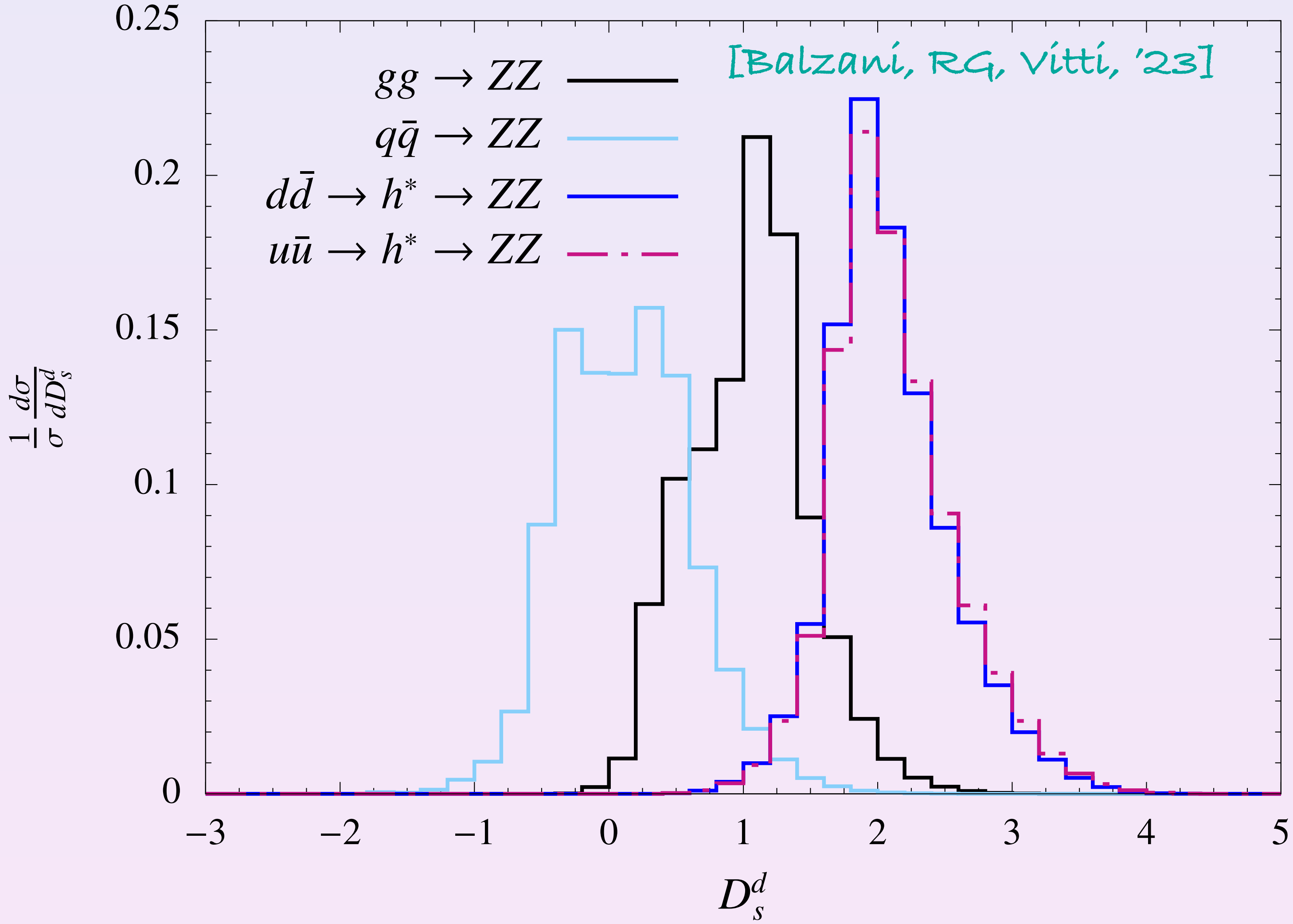
Kinematic discriminants

$$D_s^d = \log_{10}\left(\frac{P_{sig}^{d\bar{d}}}{P_{back}^{q\bar{q}} + P_{back}^{gg}}\right)$$

Poisson ratio of likelihoods

$$Z_i = \sqrt{2\left[(s_i+b_i)\ln\frac{(s_i+b_i)(b_i+\sigma_{b_i}^2)}{b_i^2+(s_i+b_i)\sigma_{b_i}^2} - \frac{b_i^2}{\sigma_{b_i}^2}\ln\left(1+\frac{s_i\sigma_{b_i}^2}{b_i(b_i+\sigma_{b_i}^2)}\right)\right]}$$

$$\sigma_{b_i} = \Delta_{b_i} b_i$$



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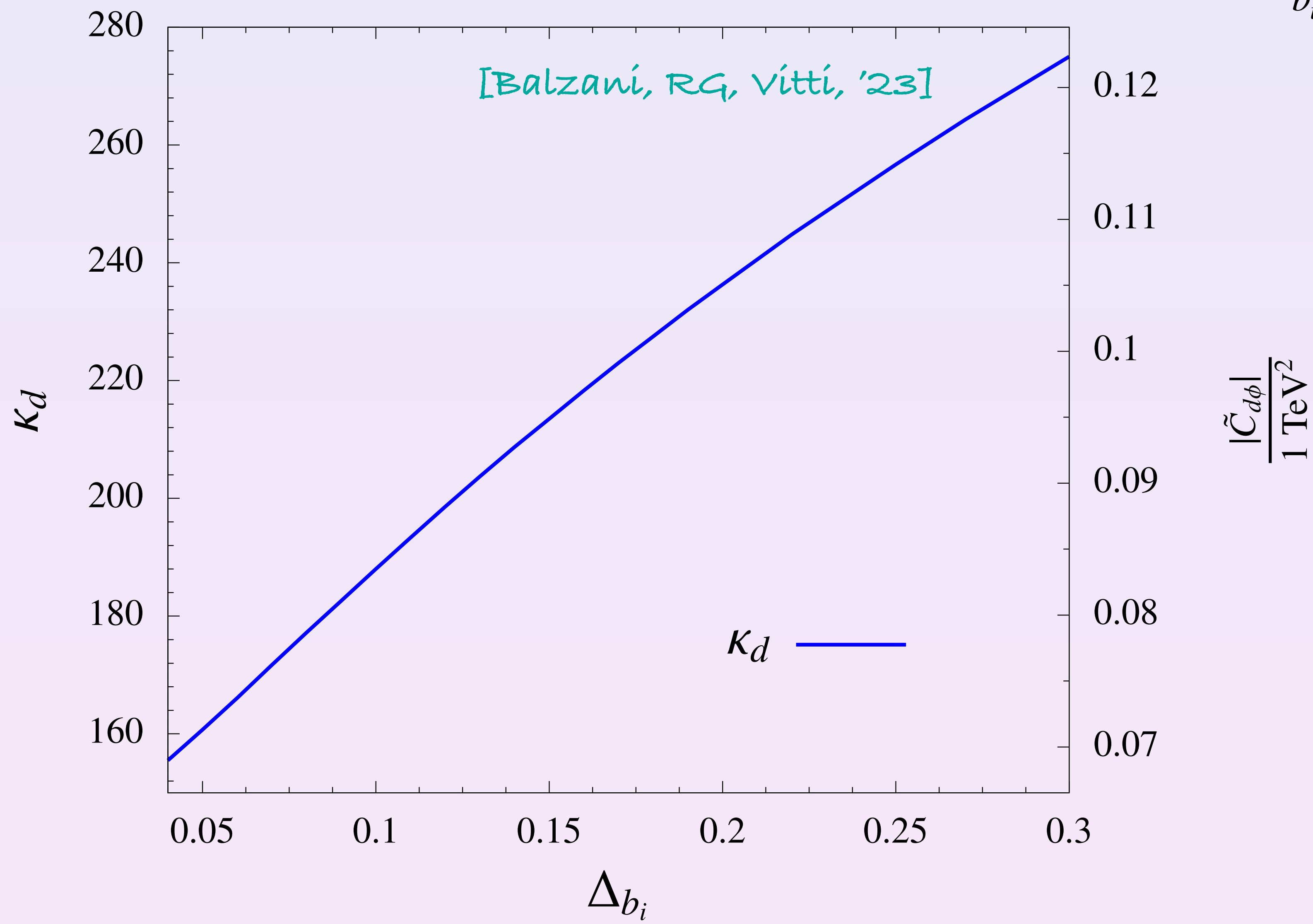
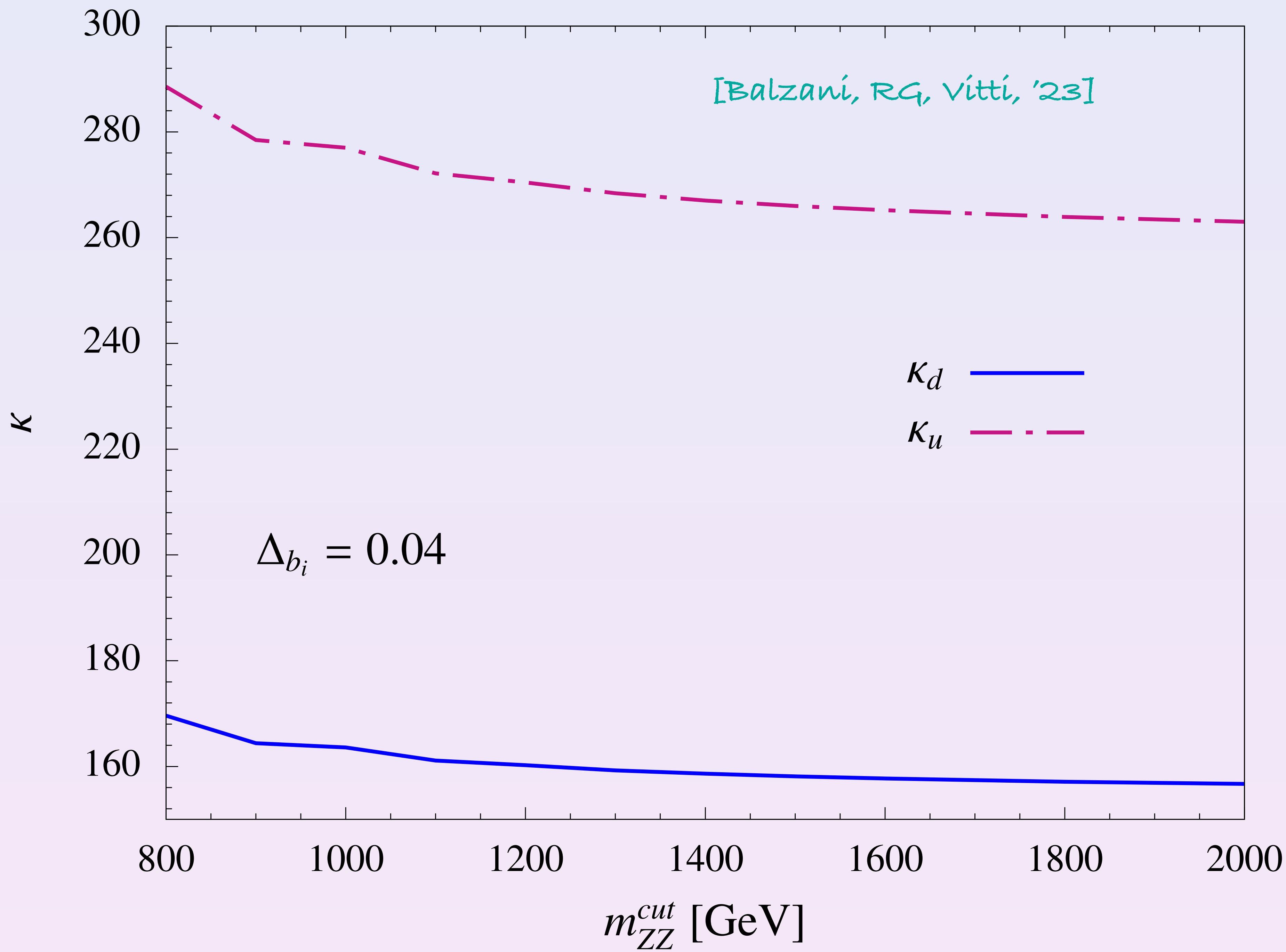
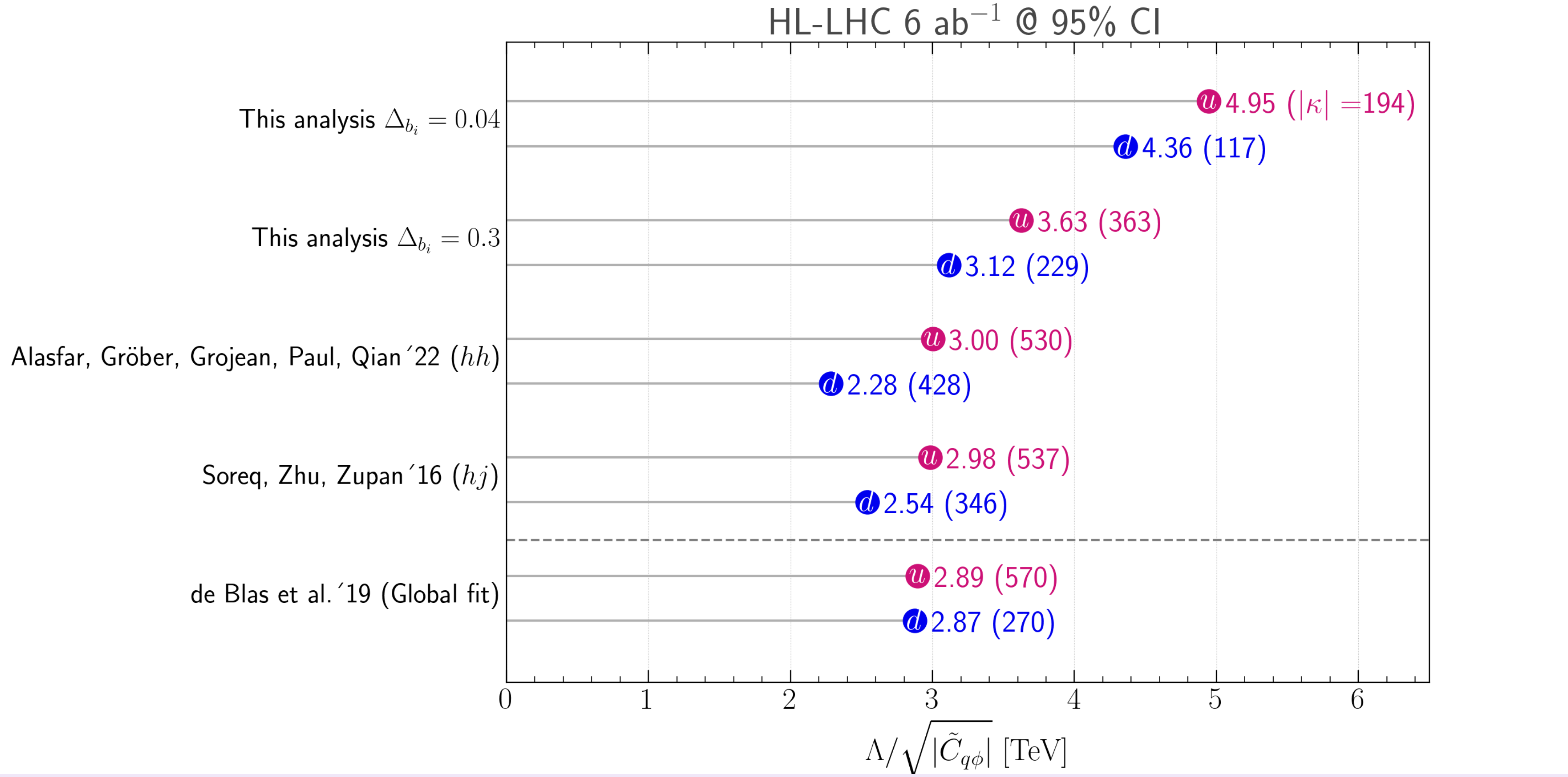


Best probe of first generation quark Yukawa couplings!

EFT validity



Conclusion



Higgs pair production: ML helps to improve on the sensitivity, possible to measure both trilinear and light quark Yukawa couplings at the HL-LHC

Off-shell Higgs: Kinematic discriminants extremely helpful to distinguish signal from background

Thanks for your attention!

Backup

Machine learning

Can extract both light quark Yukawas and trilinear Higgs self-coupling from di-Higgs?

We use Boosted Decision Trees and a comprehensive set of kinematic variables instead of four-momenta

$p_T^{b_1}, p_T^{b_2}, p_T^{\gamma_1}, p_T^{\gamma\gamma}$

$\eta_{b_{j1}}, \eta_{b_{j2}}, \eta_{\gamma_1}, \eta_{\gamma\gamma}$

$n_{bjet}, n_{jet}, \Delta R_{min}^{b\gamma}, \Delta\phi_{min}^{bb}$

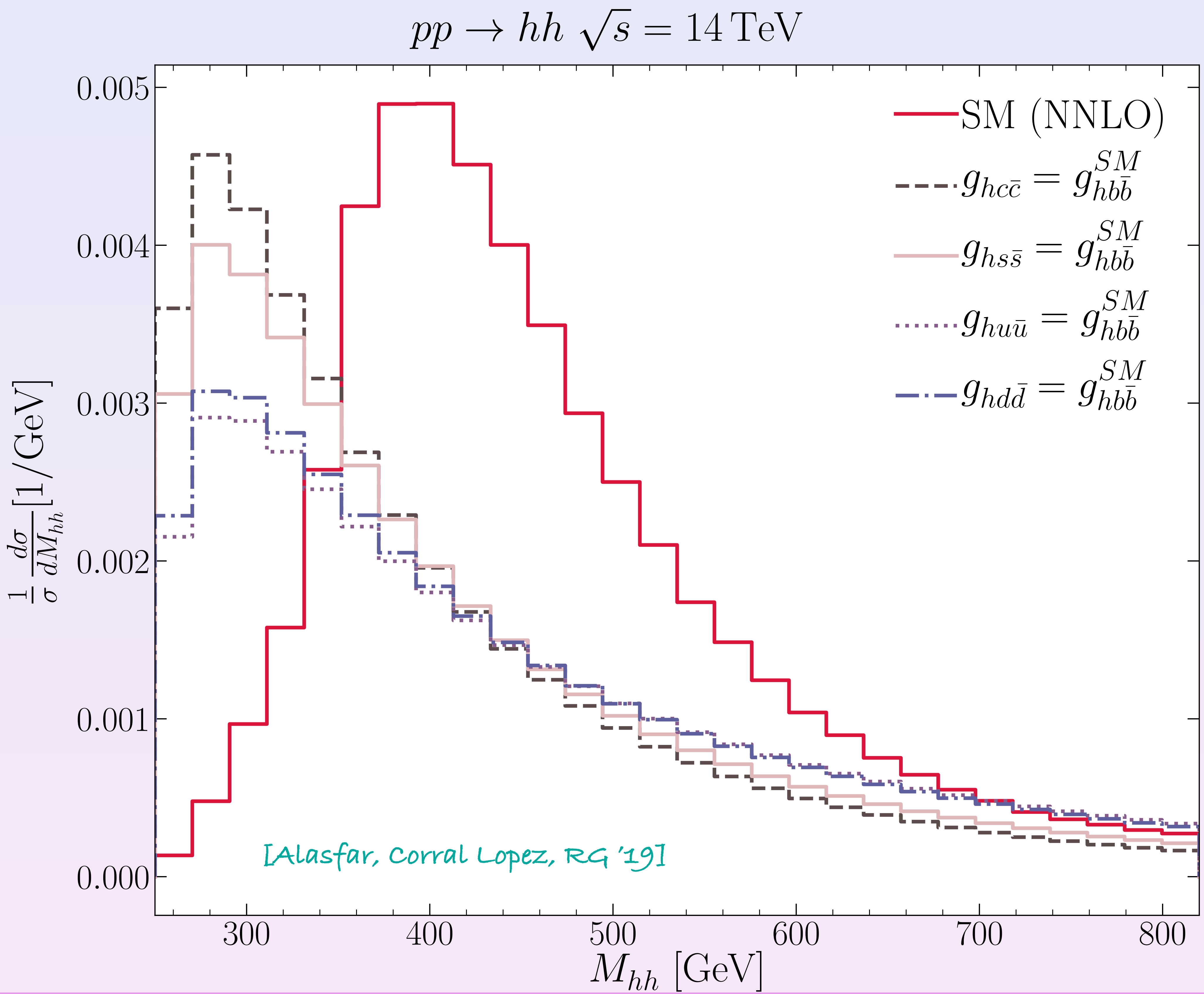
$m_{\gamma\gamma}, m_{bb}, m_{b_1,h}, m_{b\bar{b}h}, H_T$

we are interested in interpretability of our result

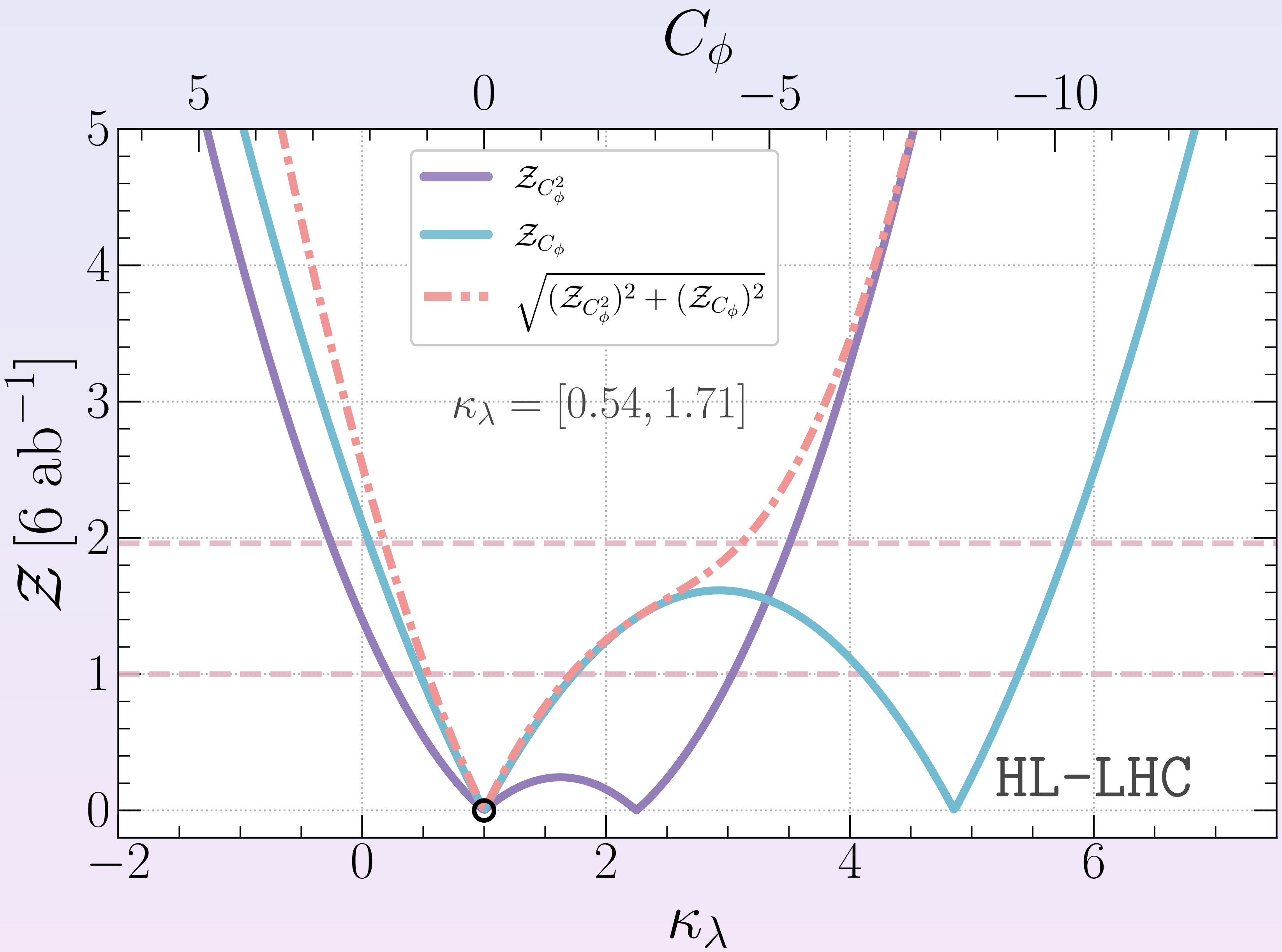
To learn the shapes of the various contributions we divide into several categories:

$Q\bar{Q}h = b\bar{b}h(h \to \gamma\gamma), t\bar{t}h(h \to \gamma\gamma)$	background
$b\bar{b}\gamma\gamma$	background
$d\bar{d}hh, u\bar{u}hh$	signal for enhanced light quark couplings
$hh_{tri}^{ggF}, hh_{int}^{ggF}$	signal for trilinear Higgs self-coupling
hh_{box}^{ggF}	background

Invariant mass distribution

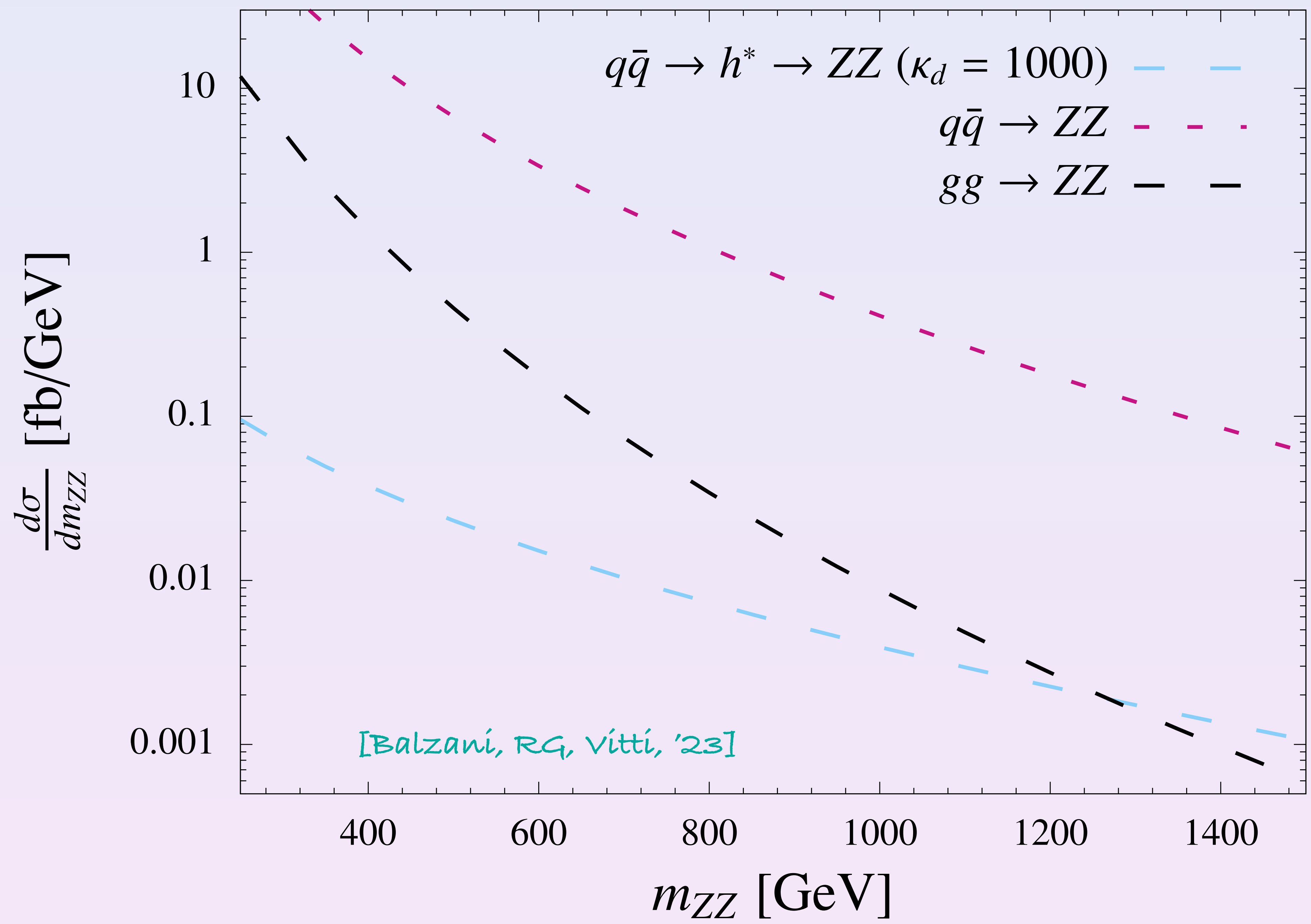


SMEFT trilinear bounds

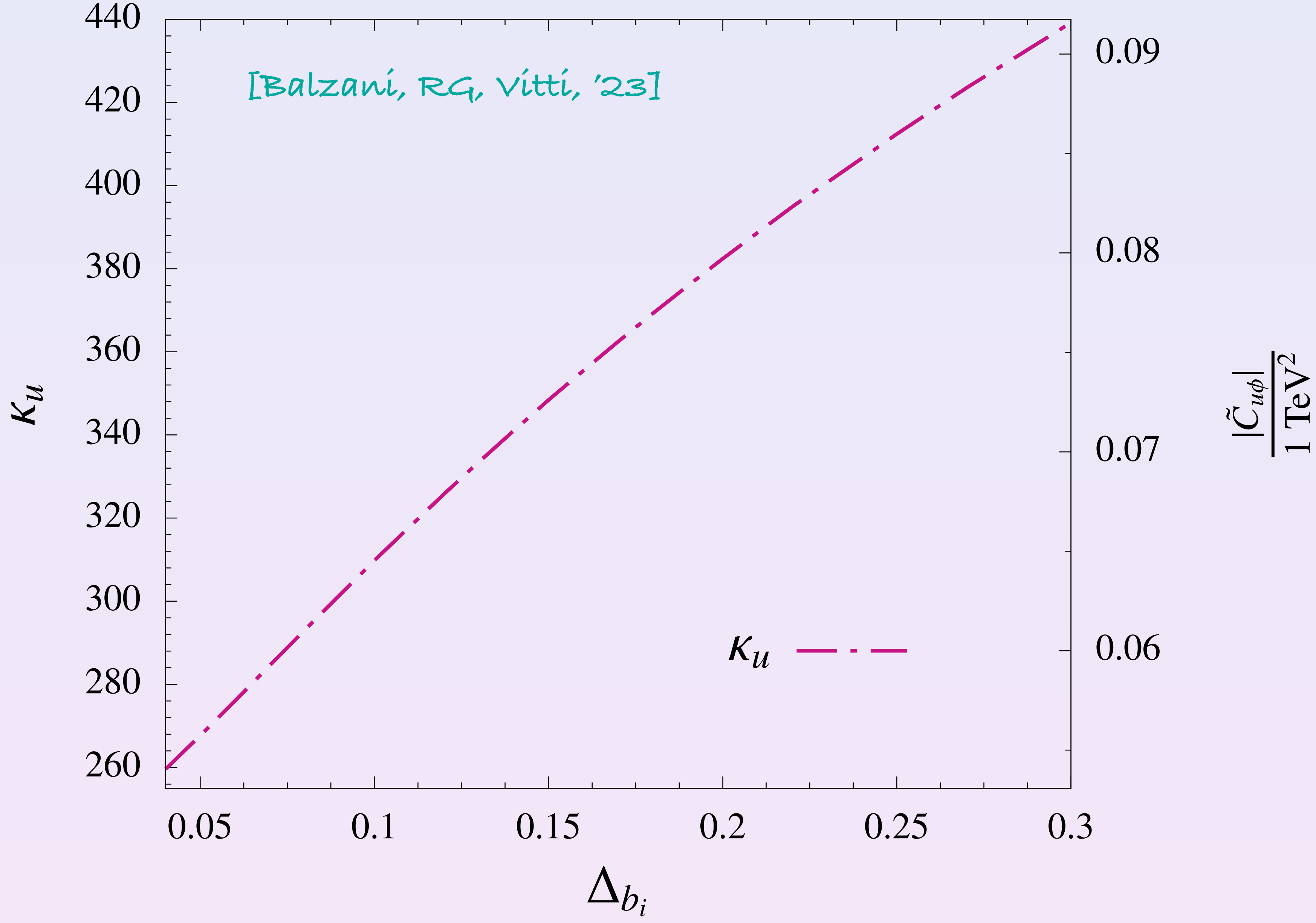


[Alasfar, RG, Grojean, Paul, Qian '22]

Invariant mass distribution ZZ



Up Yukawa coupling



BR to ZZ and single Higgs