Di-Higgs Production and the Higgs self-coupling

[ChatGPT on proposal of my daughter]

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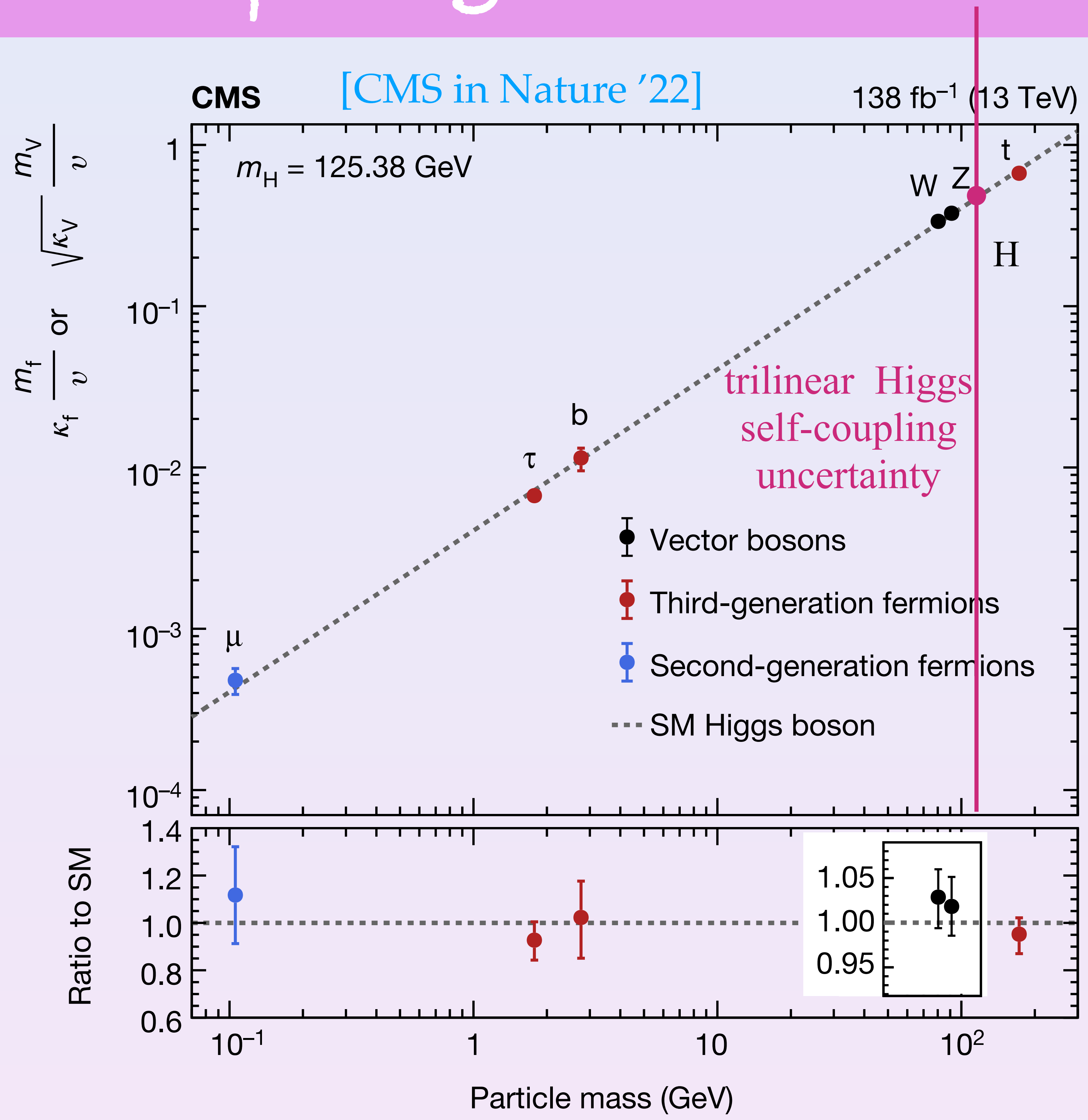
Higgs couplings

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

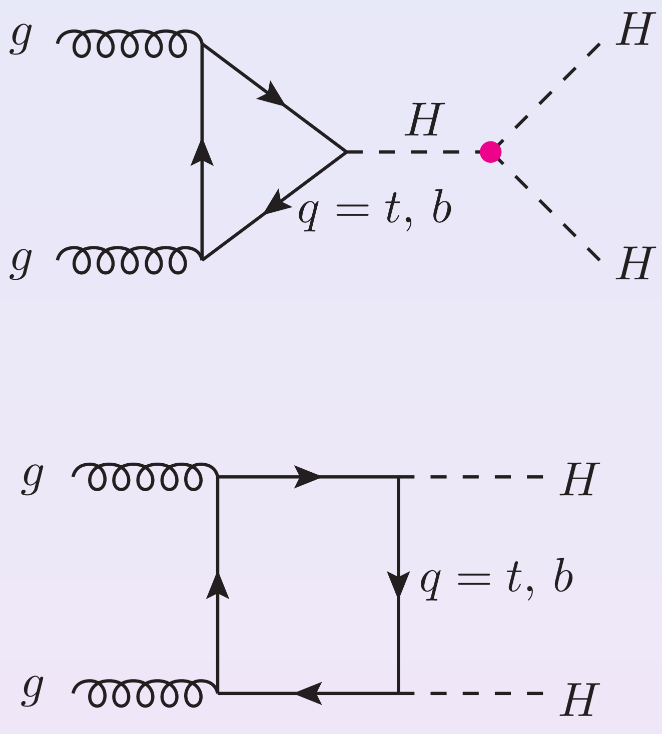
2nd generation fermion couplings first results available

Higgs self-couplings?

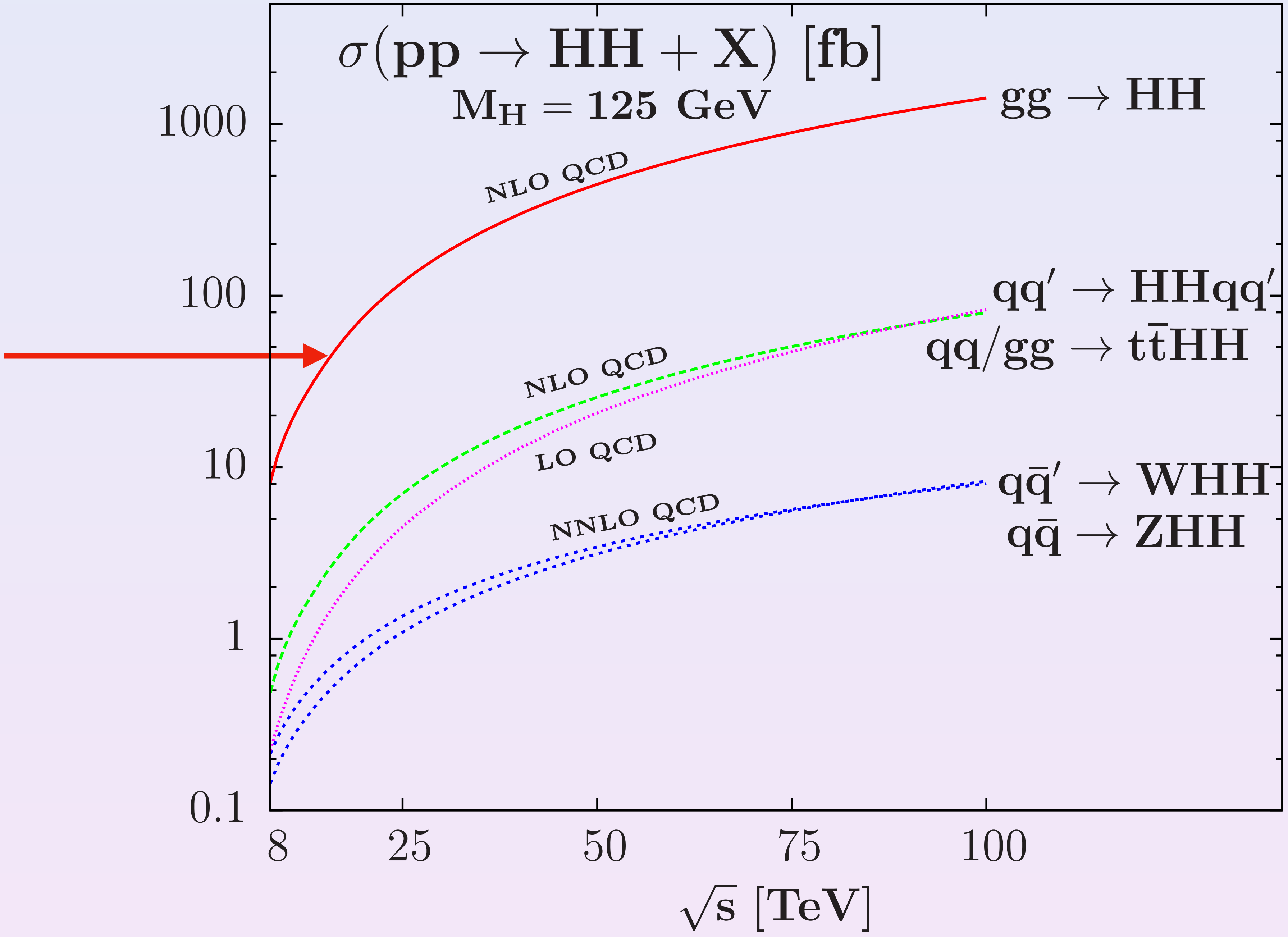


Higgs Pair Production

$gg \to HH$



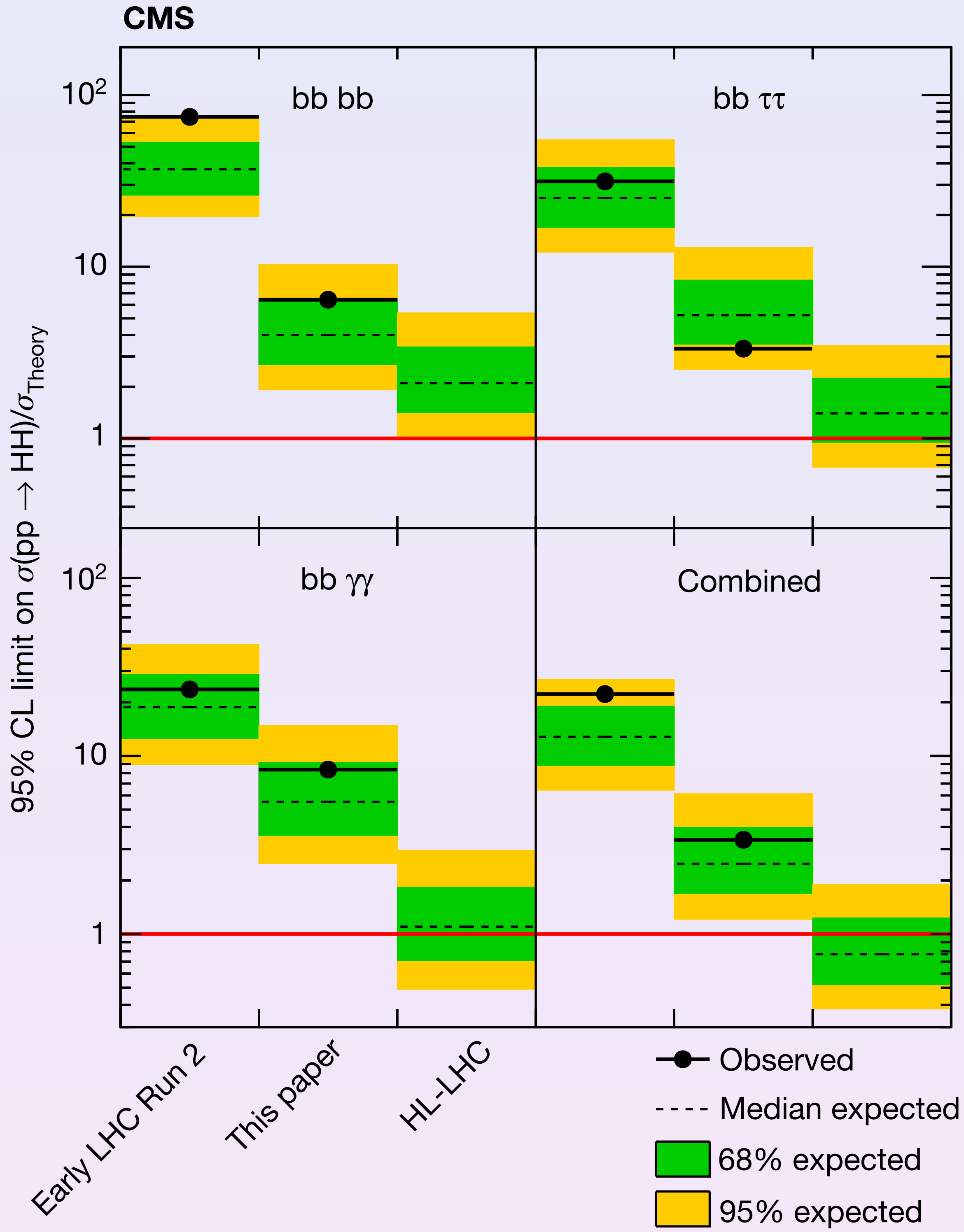
[Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12]



Small cross section

Difficult to measure

Higgs Pair Production



[CMS Nature '22]

$$-0.4 < \kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{SM} < 6.3$$

Theory status

Gluon fusion known up to N^{3}LO in the infinite top mass limit

[L.-B. Chen, H. T. Li, H.-S. Shao and J. Wang '19]

Higher order corrections extremely important (NLO/LO ~1.6)

Infinite top mass limit valid only in very small part of phase space

Full top mass dependence at NLO QCD computed *numerically* in [Borowka et al '16, Baglio et al '18]

large uncertainty from top mass renormalisation scheme choice [Baglio et al '18]

electroweak corrections O(-4%) [Bi, Huangx2, Ma, Yu '23; Heinrich, Jones, Kerner, Stone, Vestner '24]

Monte Carlo implementations:

POWHEG @ NLO QCD including also HEFT/SMEFT [Heinrich, Jones, Kerner, Luisoni, Vryonidou ' 17, Heinrich, Jones, Kerner, Scyboz '20, Heinrich, Lang, Scyboz '22]

Geneva @ NNLO QCD infinite top mass limit [Alioli et al. 22]

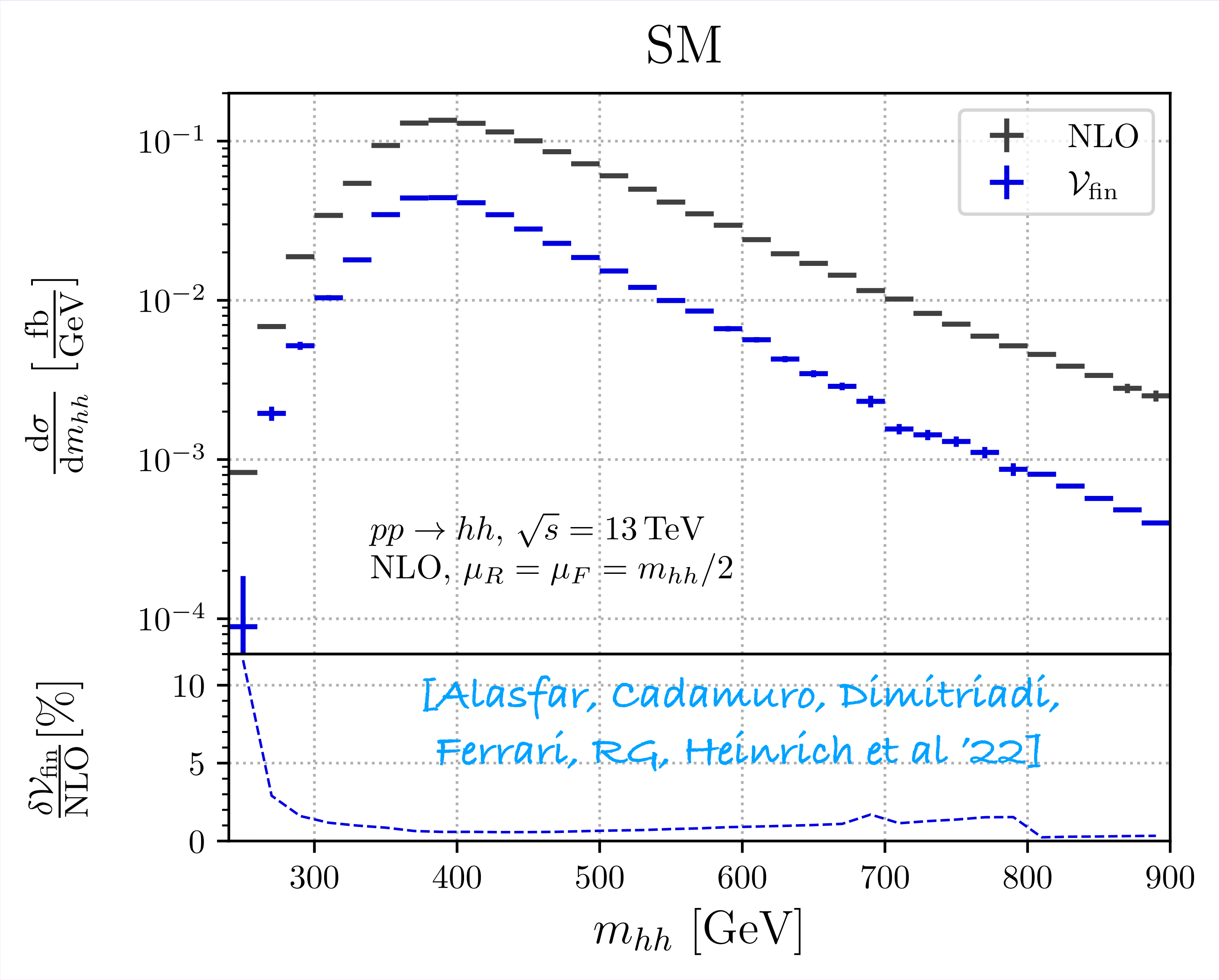
Numerical computation

Computation of virtuals numerical (i.e. input parameters fixed at early stage) in Monte Carlo implemented as a grid

Disadvantages:

input parameters cannot be changed ⟶ missing flexibility

with BSM: better numerics when SM-like



[Alasfar, Cadamuro, Dimitriadi, Ferrari, RG, Heinrich et al '22]

Can we describe analytically the relevant phase space?

Can this then be used for a Monte Carlo?

DiHiggs: a new POWHEG implementation

Idea

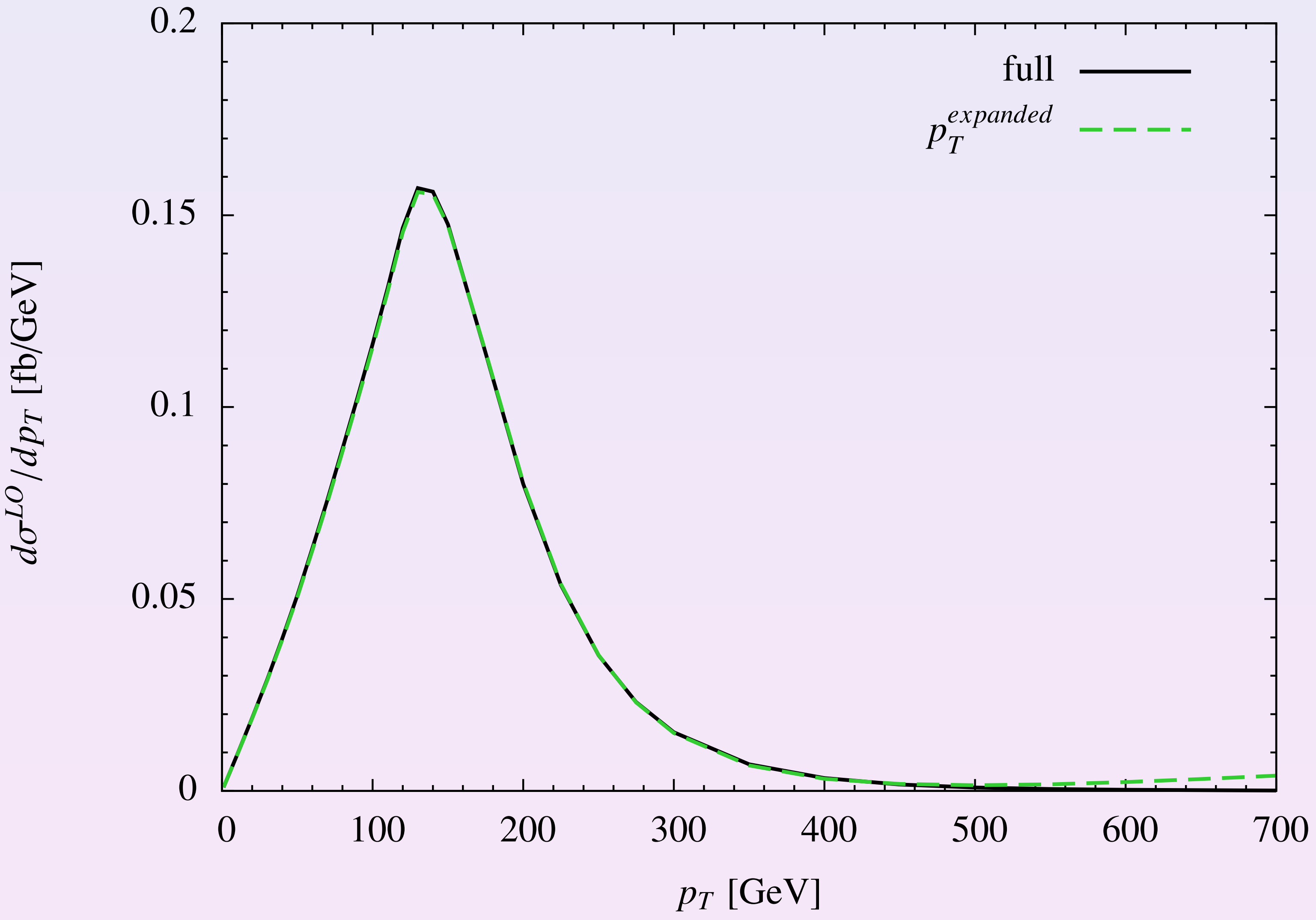
Idea:

Keep full s dependence

Reduces to one-scale problem

(Taylor) Expand the p_T and m_H dependence

[Bonciani, Degrassi, Giardino, RG '18]



$$m_H^2 \ll 4m_t^2$$

always true

$$p_T^2 \ll 4m_t^2$$

not always true, but for largest part of phase space

High-energy expansion

For a Monte Carlo we need to cover the full phase space...

Strategy: to combine with a high-energy expansion

$$\hat{s}, \hat{t}, \hat{u} \gg m_t^2 > m_{ext}^2$$

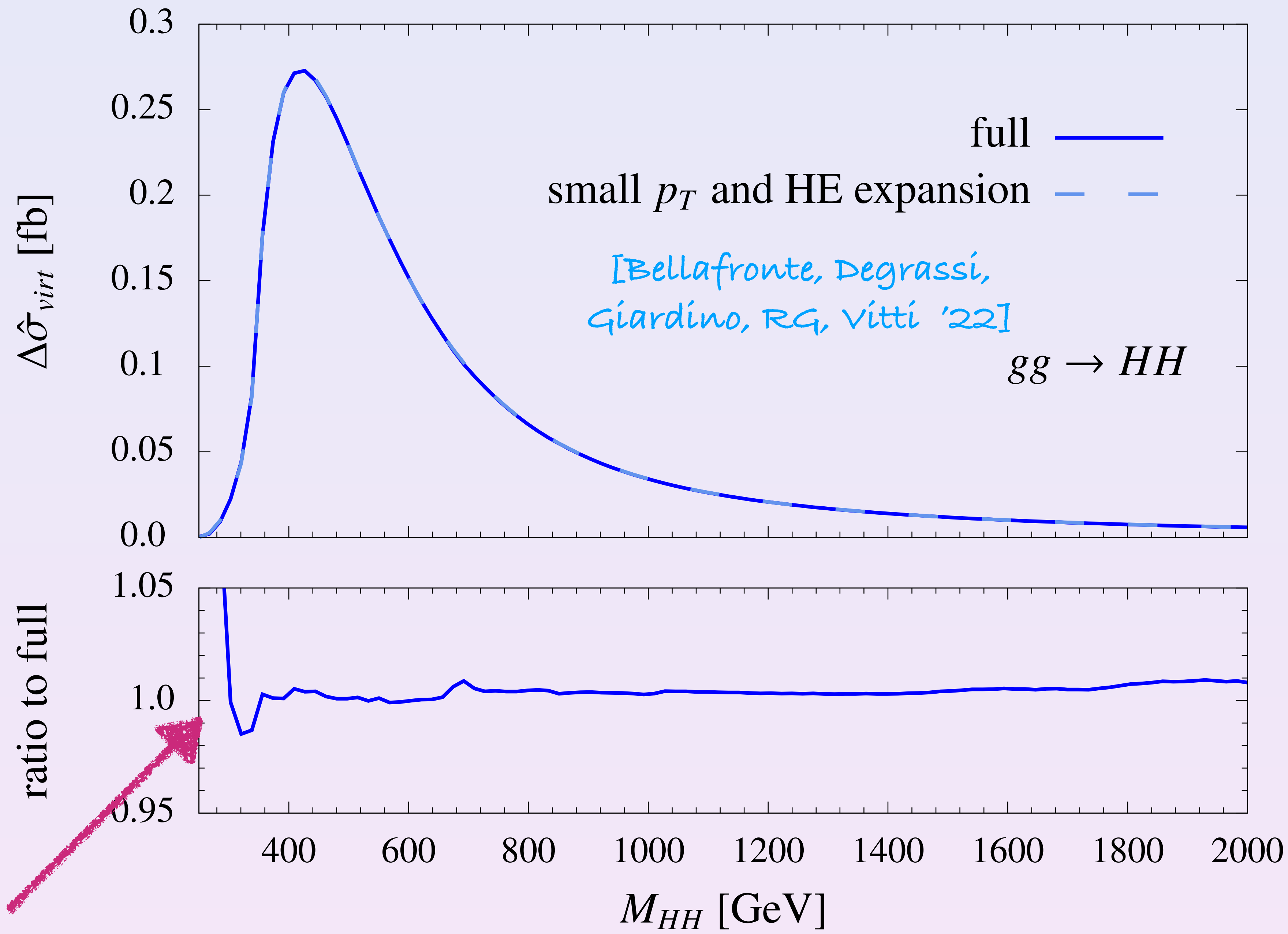
Results available up to high orders (16) in m_t^2

[Davies, Mishima, Steinhauser, Wellmann '18]

Combine the two expansions with Padé approximants

$$[n/m] = \frac{a_0 + a_1 x + \ldots + a_n x^n}{1 + b_1 x + \ldots b_m x^m}$$

Combination of expansions



[Bellafronte, Degrassi, Giardino, RG, Vitti '22]

few phase space points
in virtual grid of

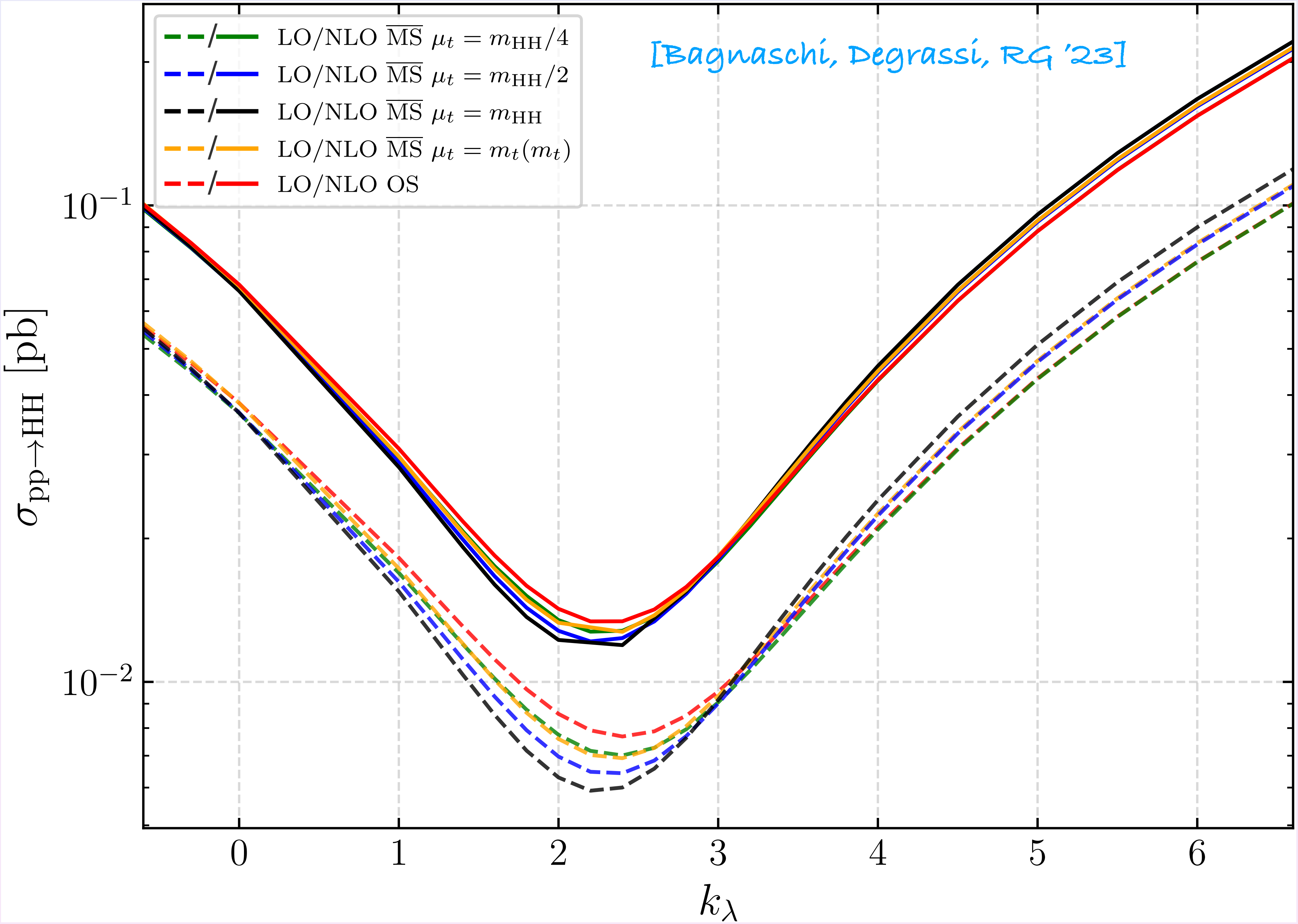
[Davies, Heinrich, Jones et al. '19]

Works incredibly well (difference < 1%)

New POWHEG implementation

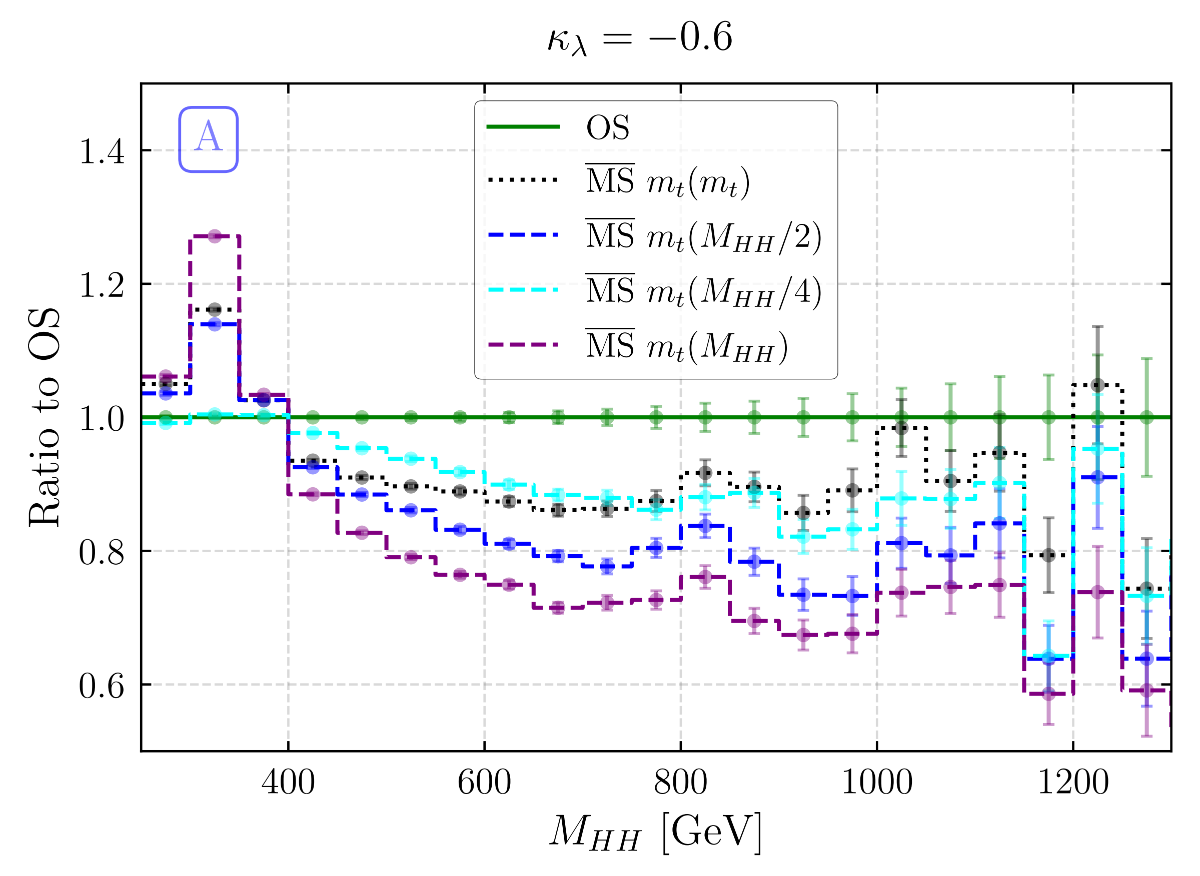
virtuals with expansion technique analytically

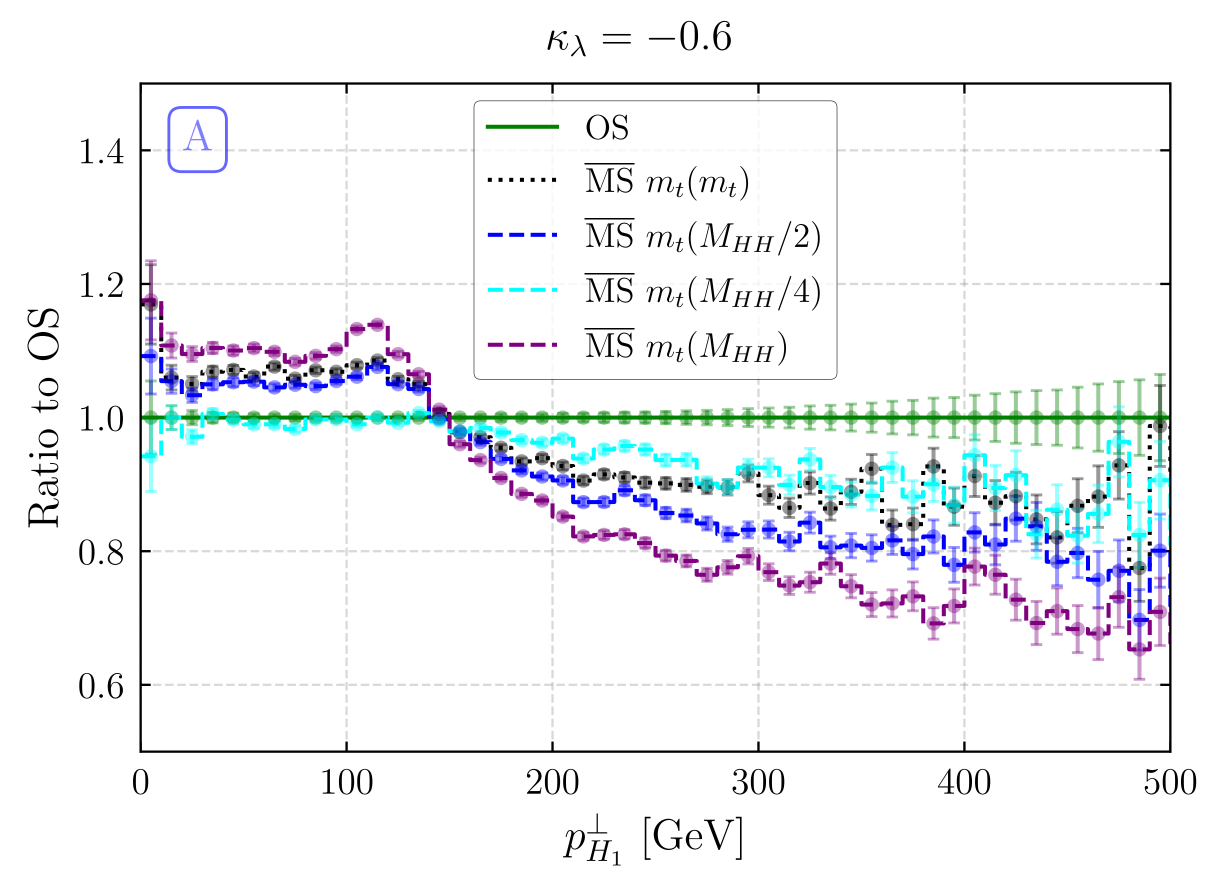
reals with MadLoop [Hirschi et al. '11]



New POWHEG implementation

[Bagnaschi, Degrassi, RG '23]

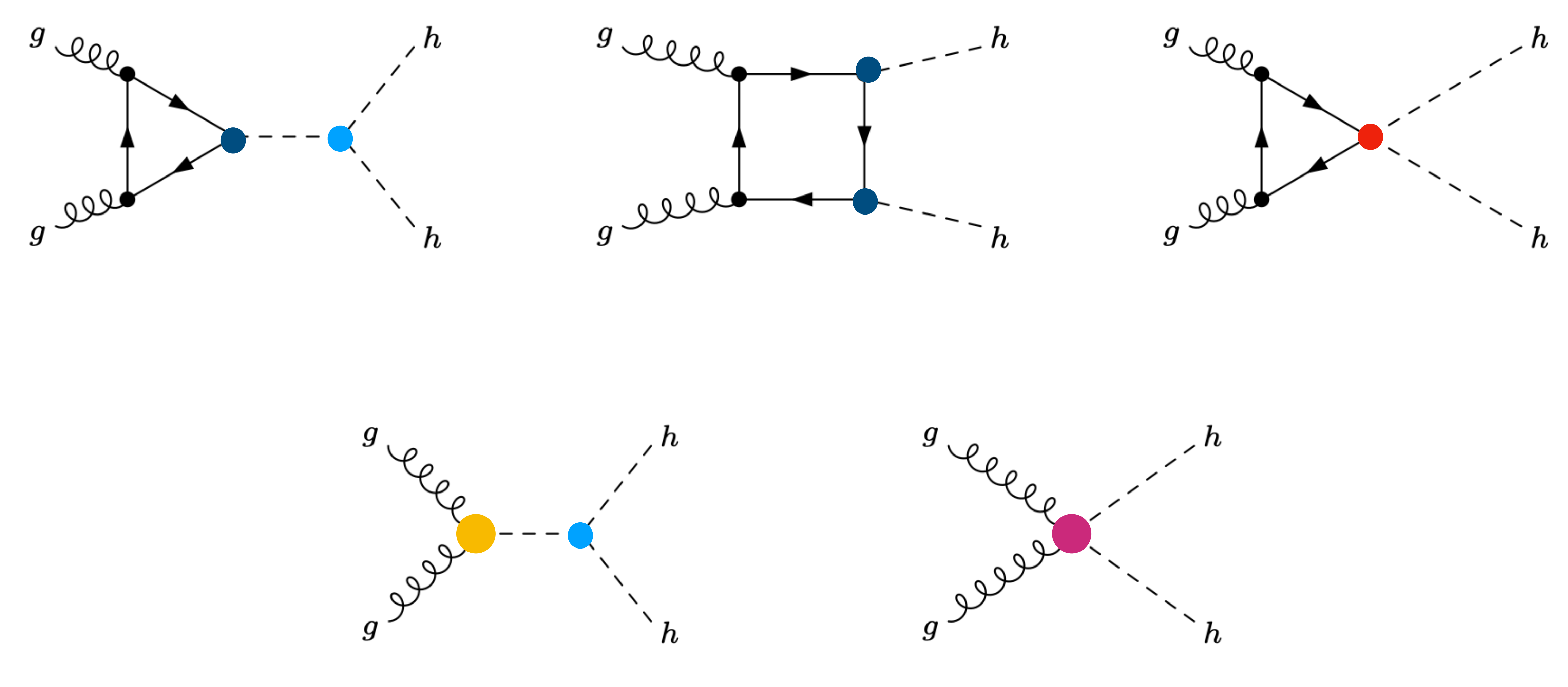




flexibility of analytic approach allows to vary top mass renormalisation scheme

Higgs pair production beyond the Standard Model

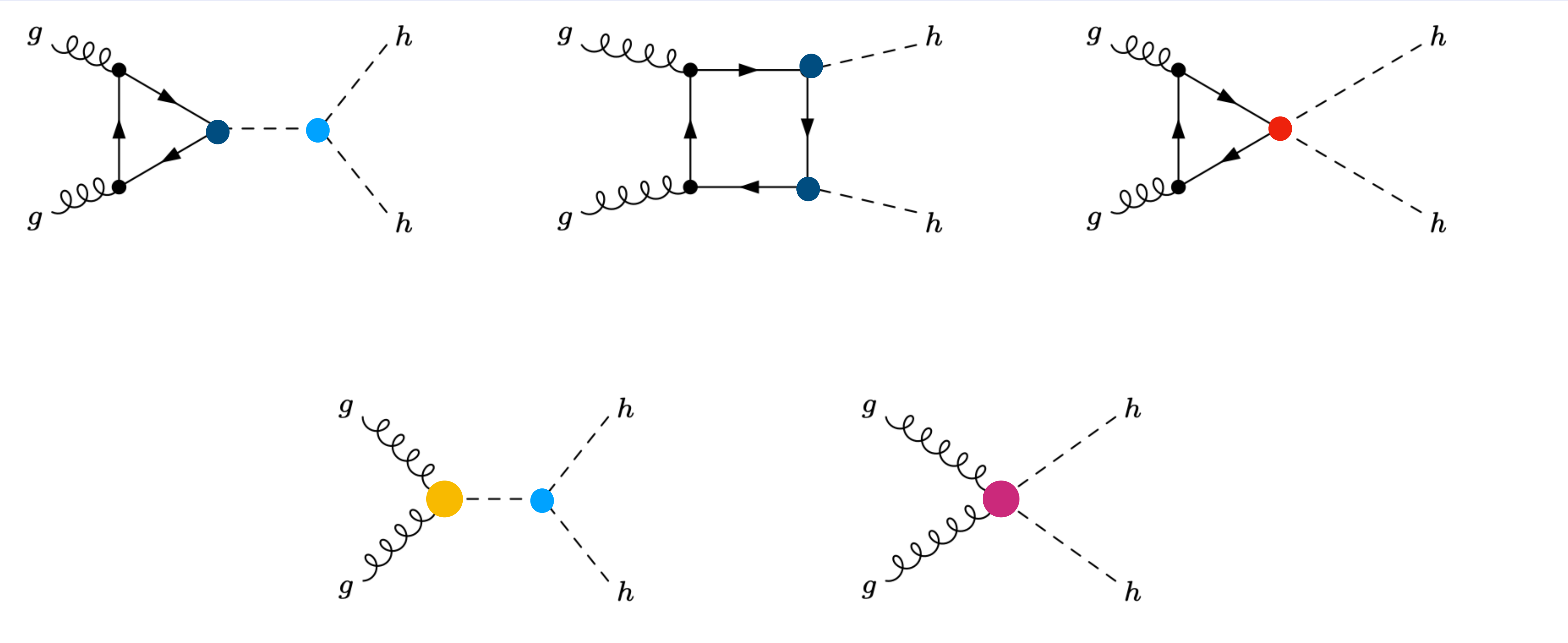
Effective Theory for HH



HEFT:

$$\mathcal{L} = -m_t \bar{t}t\left(c_t \frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right) + \frac{\alpha_s}{8\pi}\left(c_g \frac{h}{v} + c_{gg}\frac{h^2}{v^2}\right) G^{\mu\nu}G_{\mu\nu} + c_{hhh}\frac{m_h^2}{2v}h^3$$

Effective Theory for HH

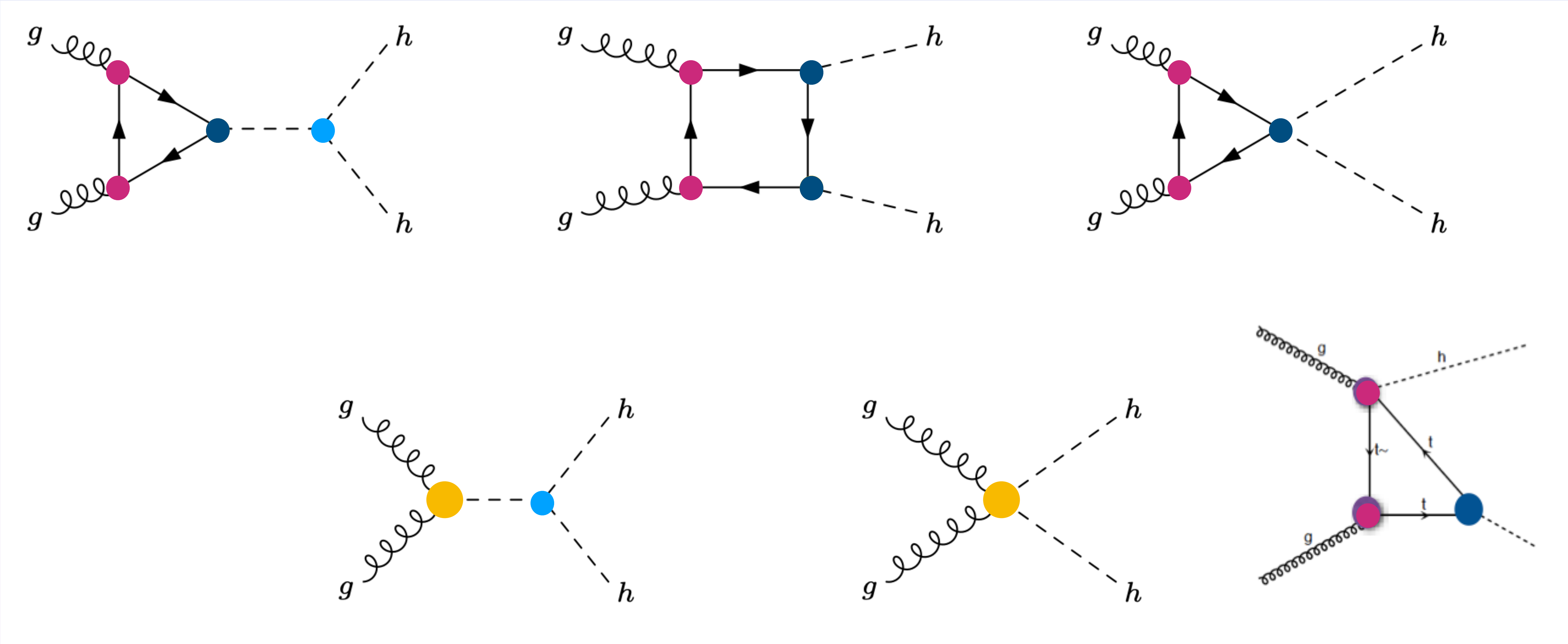


HEFT:

two Higgs couplings only to be probed in HH

$$\mathscr{L} = -m_t\bar{t}t\left(c_t\,\frac{h}{v} + c_{tt}\,\frac{h^2}{v^2}\right) + \frac{\alpha_s}{8\pi}\left(c_g\,\frac{h}{v} + c_{gg}\frac{h^2}{v^2}\right)G^{\mu\nu}G_{\mu\nu} + c_{hhh}\frac{m_h^2}{2v}h^3$$

Non-resonant HH production



SMEFT:

$$\mathscr{L} = C_{H,\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD} D_\mu(H^\dagger H) D^\mu(H^\dagger H)^* + C_H |H|^6 + C_{HG}|H|^2 G_{\mu\nu}G^{\mu\nu} + C_{uH}\bar{Q}_L\tilde{H}t_R|H|^2 + h.c. + C_{uG}\bar{Q}_L\sigma_{\mu\nu}T^a\tilde{H}t_R G^a_{\mu\nu} + h.c.$$

Warsaw basis

coefficients of $\mathcal{O}(1/\Lambda^2)$

HH production in SMEFT

Wilson coefficients depend on energy scale

$$\frac{dC_i}{d\ln\mu} = \gamma_{ij} C_j$$

in HH production we probe wide range of scales → this effect should be included

HH production in SMEFT

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in HH production we probe wide range of scales → this effect should be included

Attention: $C_{HG}|H|^2 G_{\mu\nu}G^{\mu\nu}$ enters at tree-level

is though generated at loop-level by weakly interacting models

[Arzt, Einhorn, Wudka '95;
Buchalla, Heinrich, Müller-Salditt, Prandler '22]

↓

necessitates computation of two-loop RGE contribution of tree-level generated operators

i.e. four-top operators

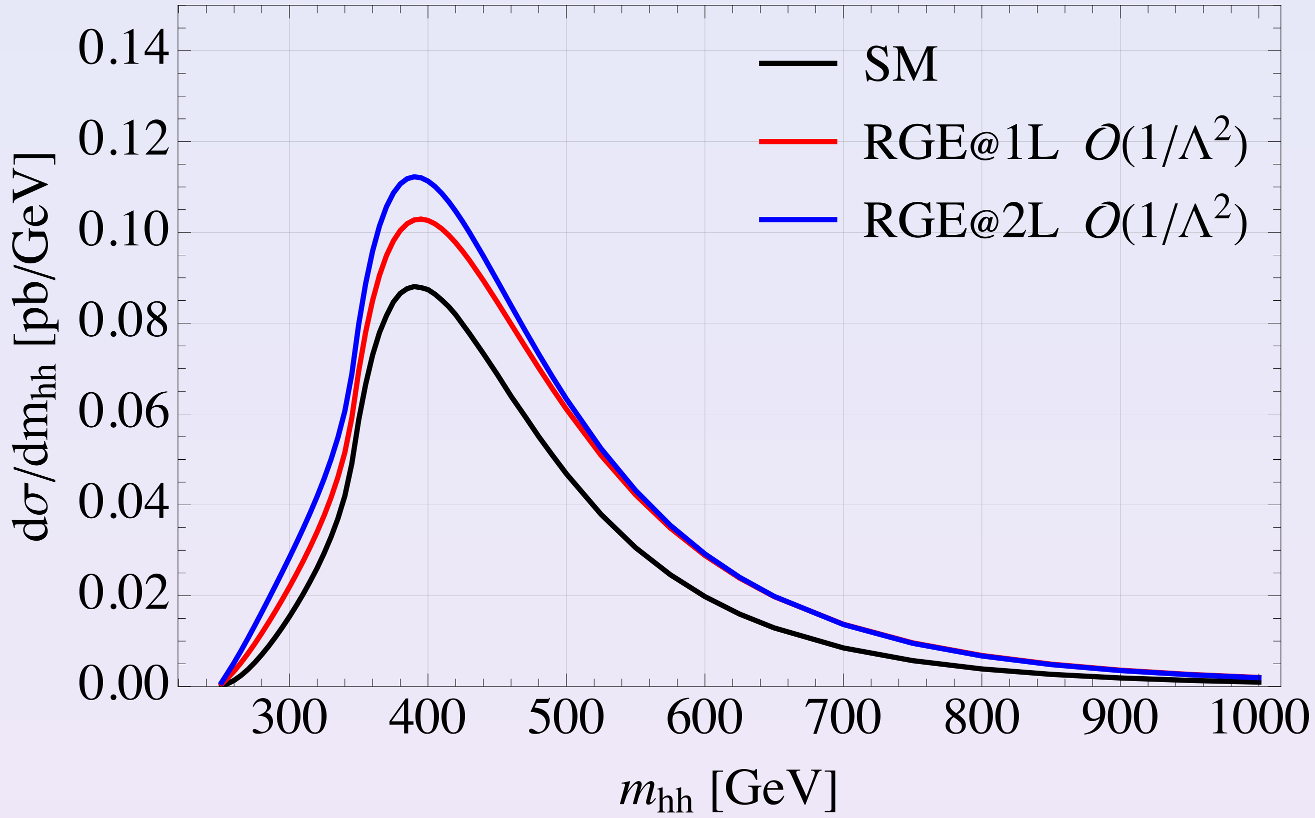
[Di Noi, RG, Heinrich, Lang, Vitti '23;
Heinrich, Lang '23]

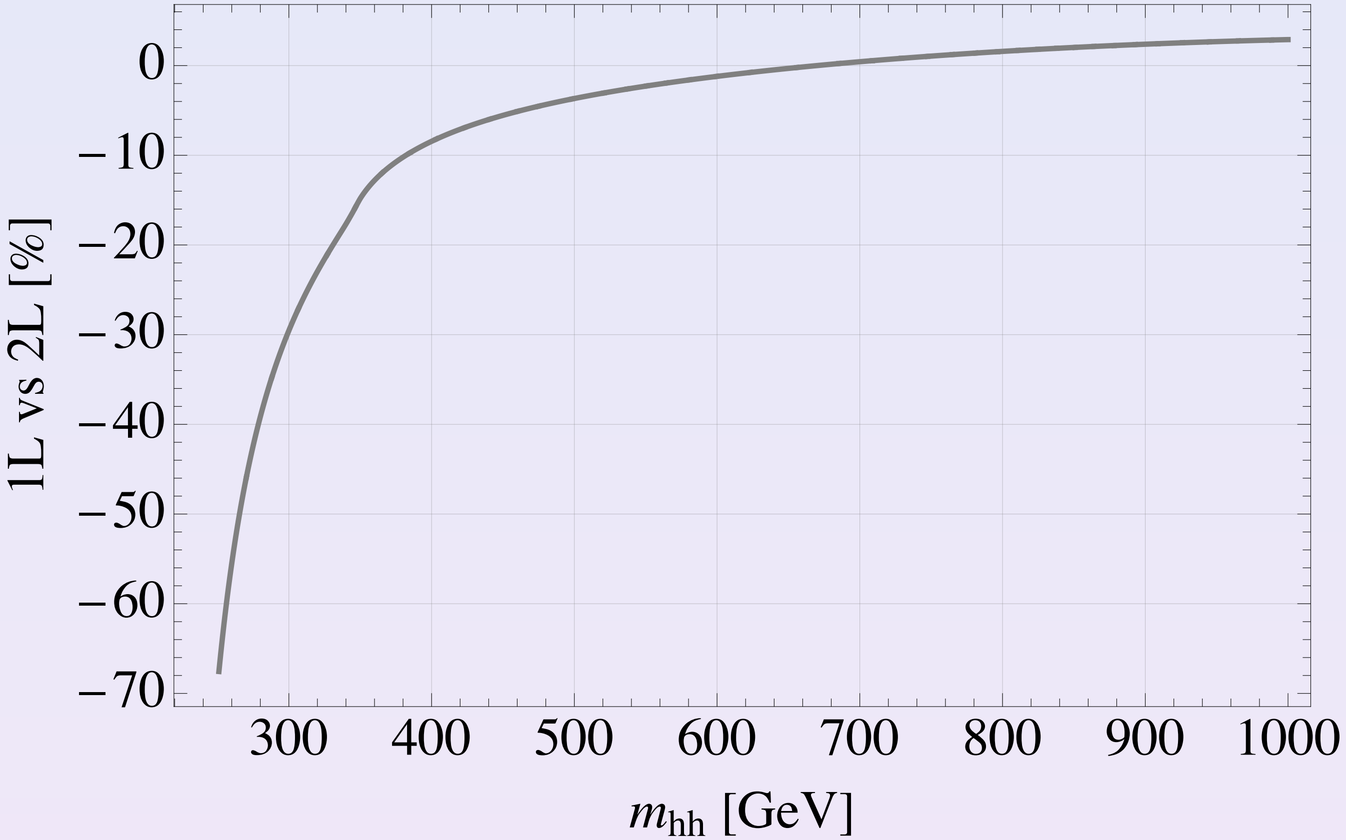
Yukawa-type operators

[Di Noi, RG, Mandal '24]

HH production in SMEFT

[Di Noi, RG, Mandal '24]





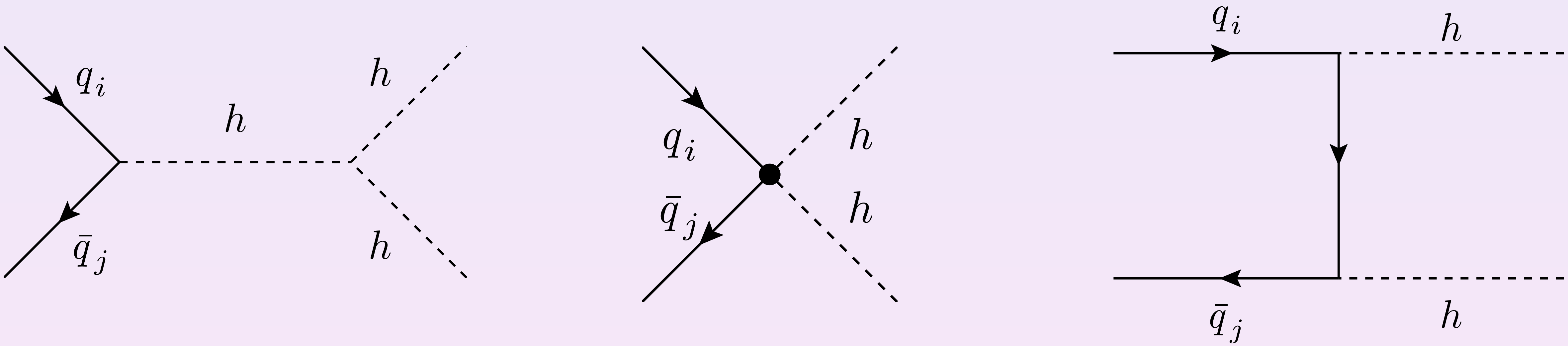
$$\text{S1}: \quad \mathcal{C}_{tH}(\Lambda)=1,\ \mathcal{C}_{HG}(\Lambda)=\frac{1}{16\pi^2},\ \mathcal{C}_{tG}(\Lambda)=-\frac{1}{16\pi^2},\ \mathcal{C}_{Qt(1,8)}(\Lambda)=-10,\ \mathcal{C}_{H}(\Lambda)=0.$$

including the (two-loop) running effects in the Wilson coefficients can sizeably affect the cross section

Light quark Yukawas in HH

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

enhanced light Yukawa couplings

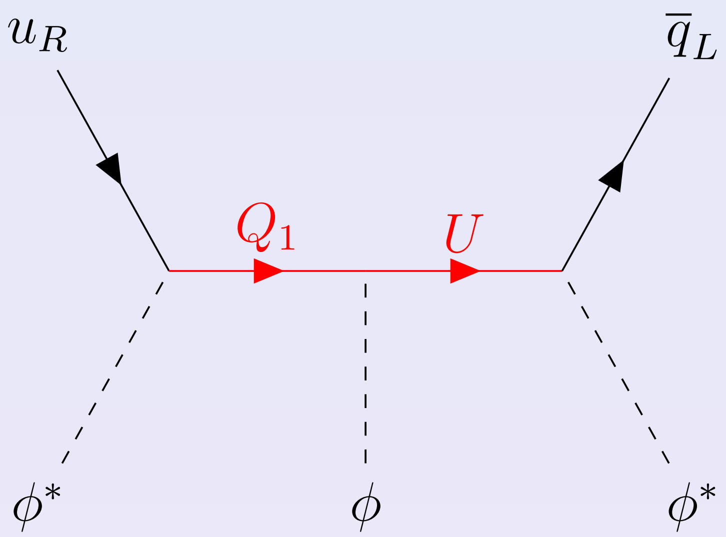


contribution most important for 1st generation (given the coupling limits)

Light quark Yukawa couplings

Models that generate light quark Yukawa deviations are for instance two representations of vector-like quarks

↓

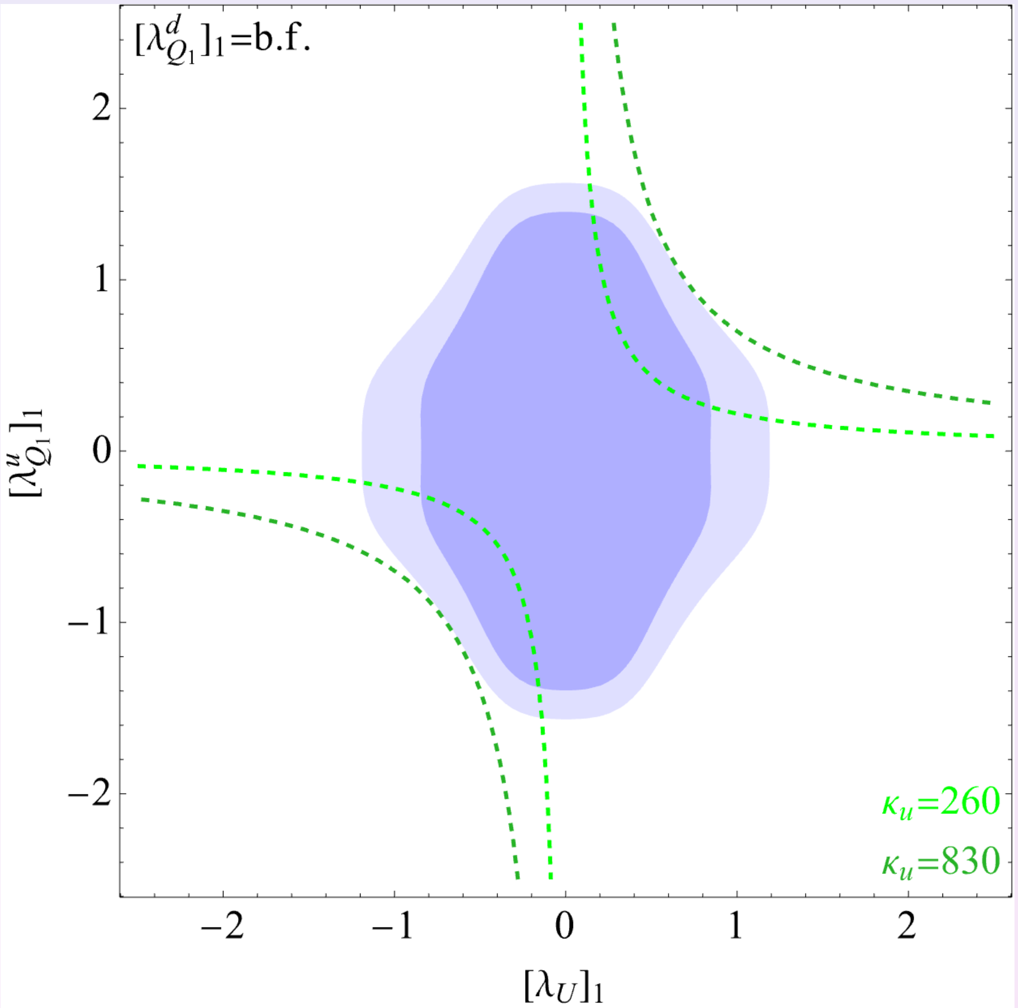


8 models, constrained by Higgs physics and EWPTs

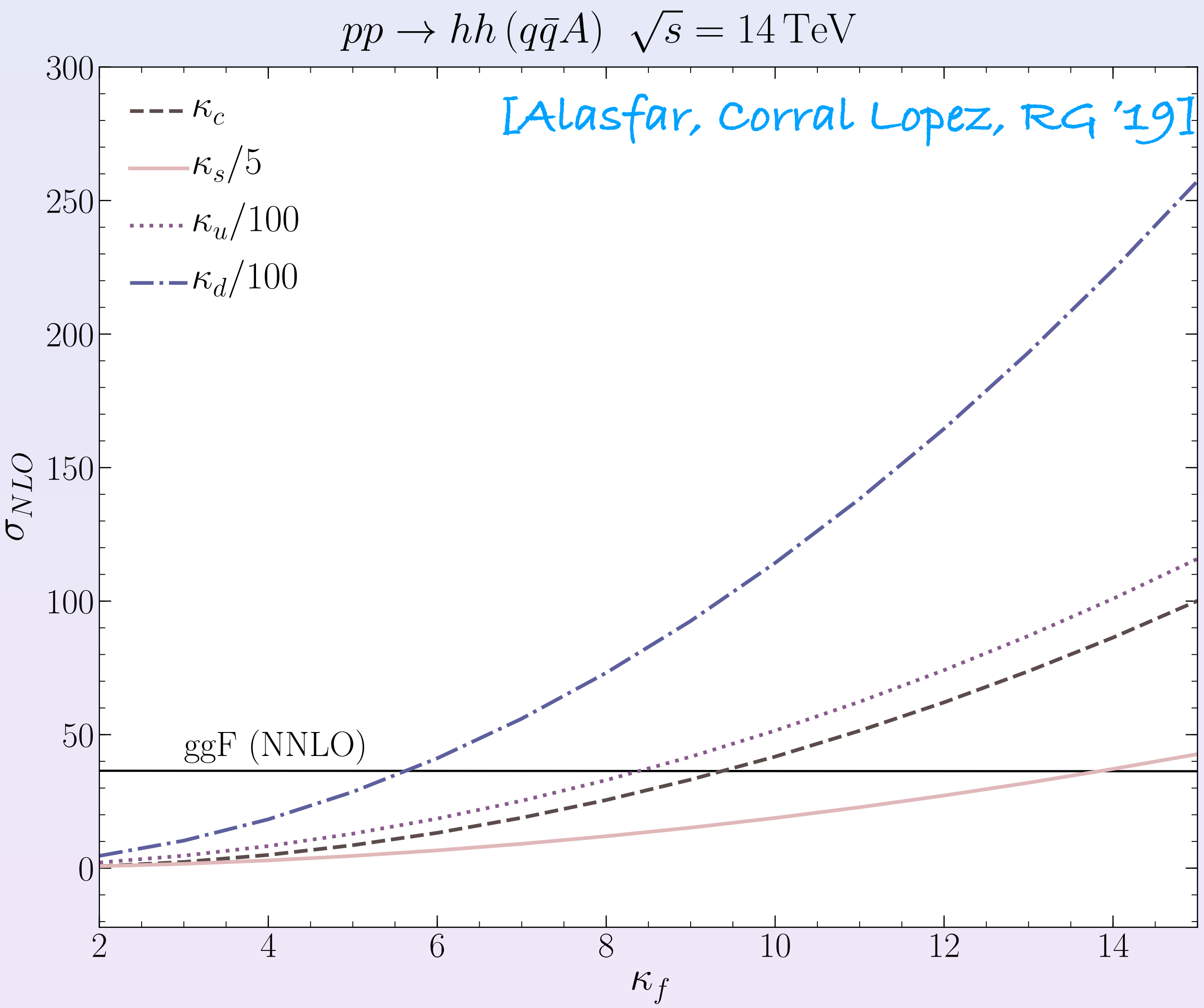
[Erdelyi, RG, Selimović; to appear]

adding a $Q = (3,2)_{1/6}$ and $U = (3,1)_{2/3}$

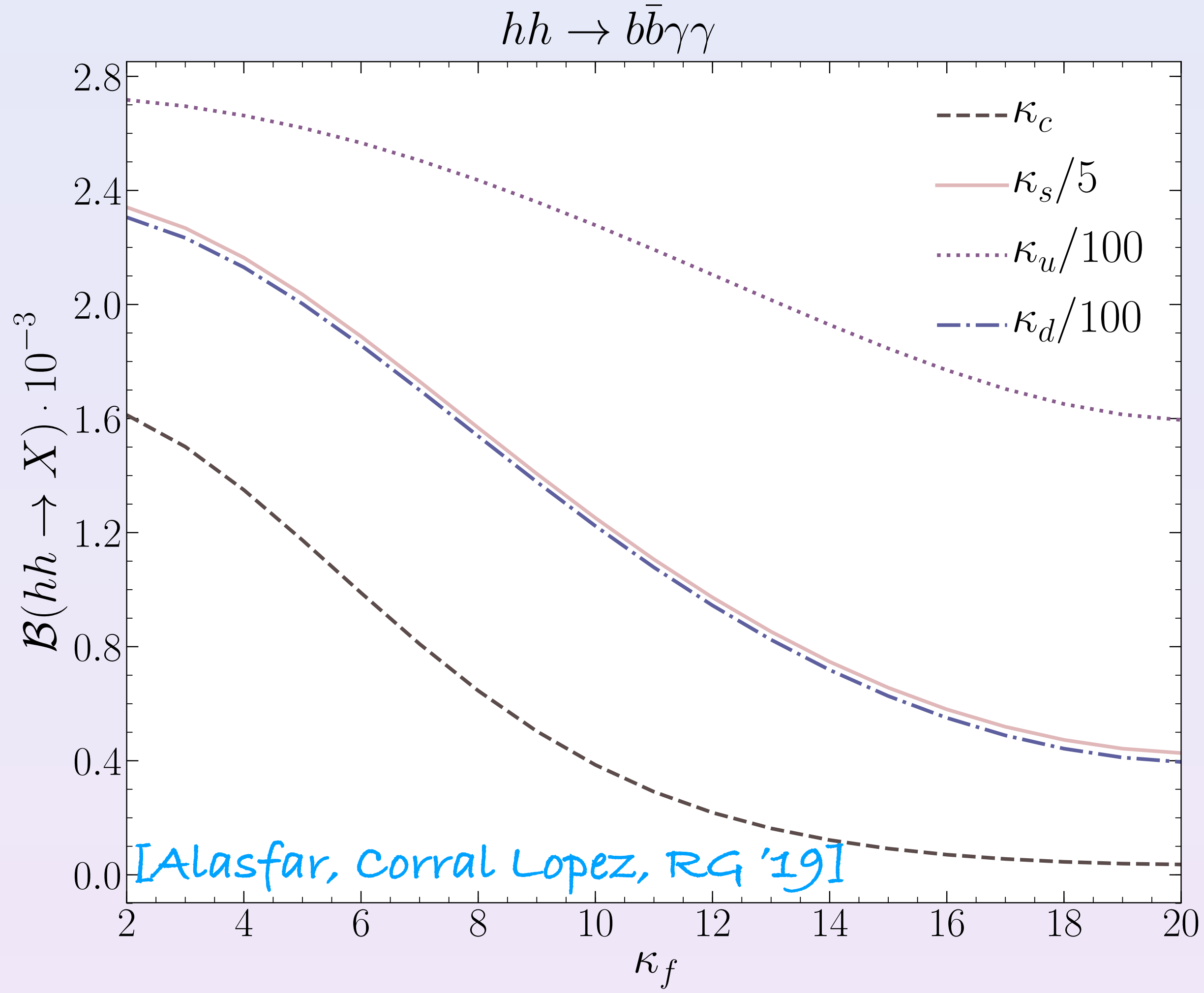
$$\kappa_u = 1 + \frac{v^3}{\sqrt{2} m_u M^2} \lambda^u_{Q_1} \lambda_U \lambda_{Q_1 U}$$



Higgs pair production



[Alasfar, Corral Lopez, RG '19]



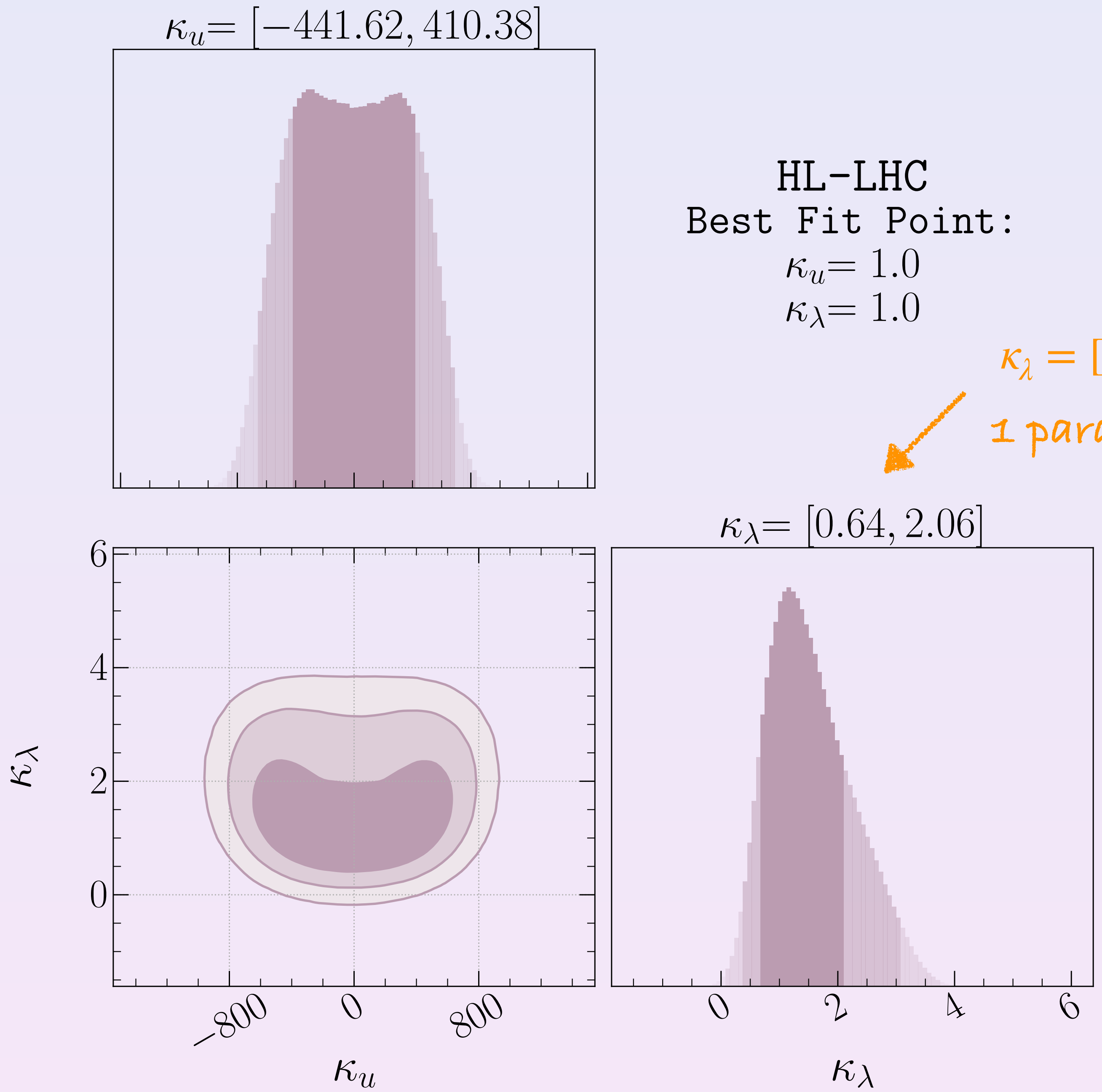
[Alasfar, Corral Lopez, RG '19]

increase of cross section,
(also modified distributions)

decrease of BR for typical di-Higgs final state

Light quark Yukawas in HH

[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

Conclusion

- Higgs pair production can give us lots of information on new physics (beyond just trilinear Higgs self-coupling)

  can probe SMEFT/HEFT, new resonances, light quark Yukawa couplings

- Requirement of precise predictions: not so simple, it is a multi-scale problem, still large uncertainties

  for Monte Carlo an analytic approach is useful and can be sufficiently precise

  approach is flexible (can be applied to BSM) and allows to compute top renormalisation scheme uncertainty

- Not in this talk: other Higgs pair production processes, new resonances, alternative probes of the trilinear Higgs self-coupling

Thanks for your attention!

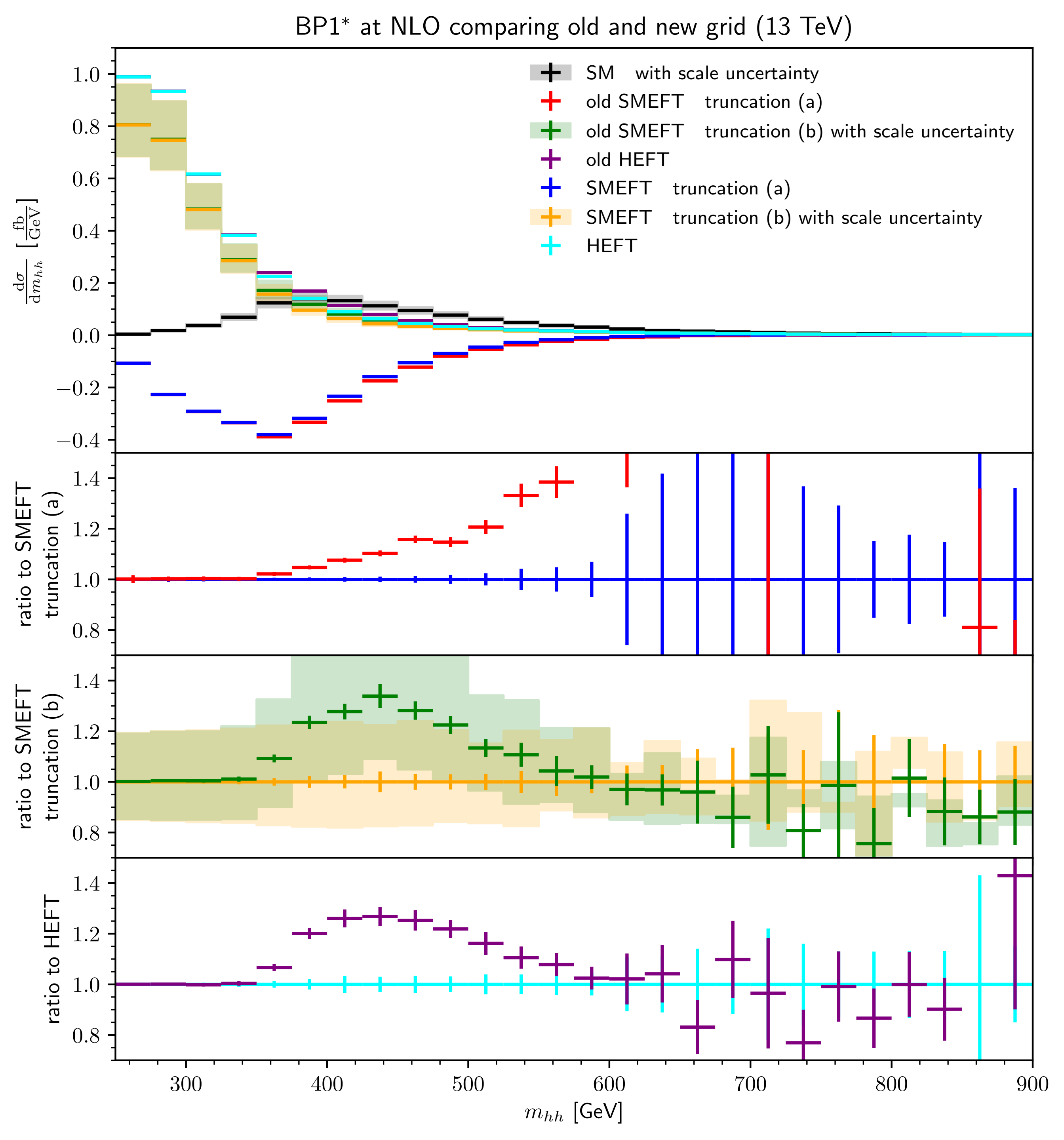
Backup

New POWHEG implementation

We had a discrepancy with respect to the POWHEG by [Heinrich et al '20 '22] when varying the trilinear Higgs self-coupling

BP1:

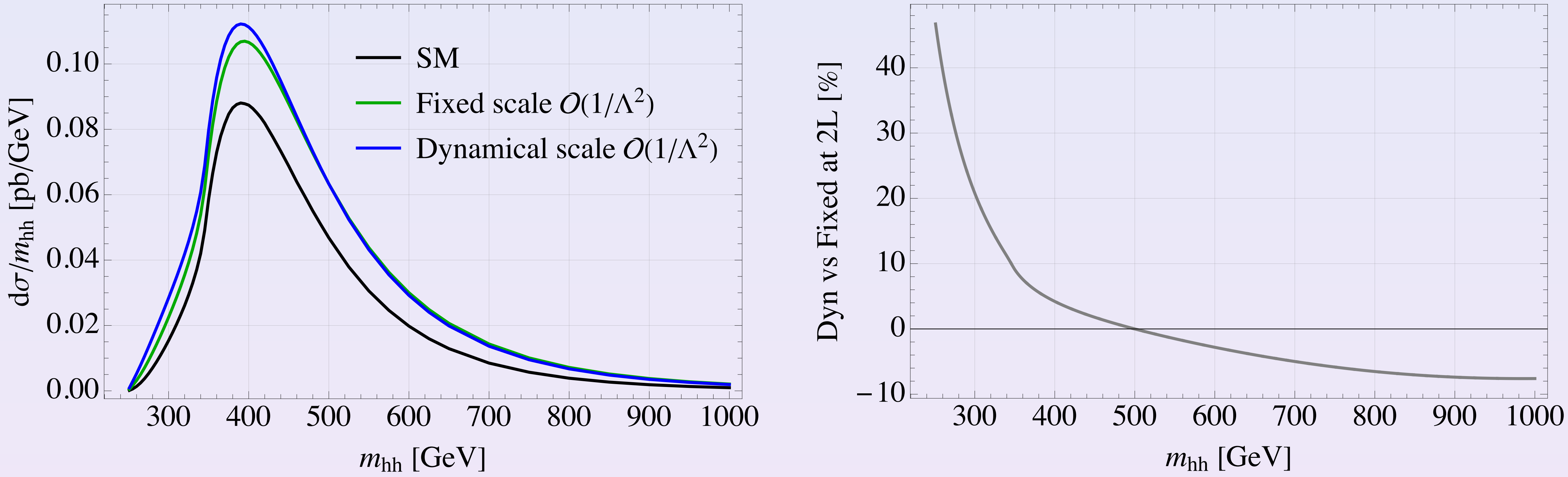
$c_{hhh} \approx 5.1, c_t = 1.1$



[Heinrich et al '22]

Importance RGE running

[Di Noi, RG, Mandal '24]



fixed scale: $\mu_R = 2m_H$

dynamical scale: $\mu_R = m_{HH}/2$

SMEFT

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

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

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

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

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

direct coupling to longitudinal modes of Z's

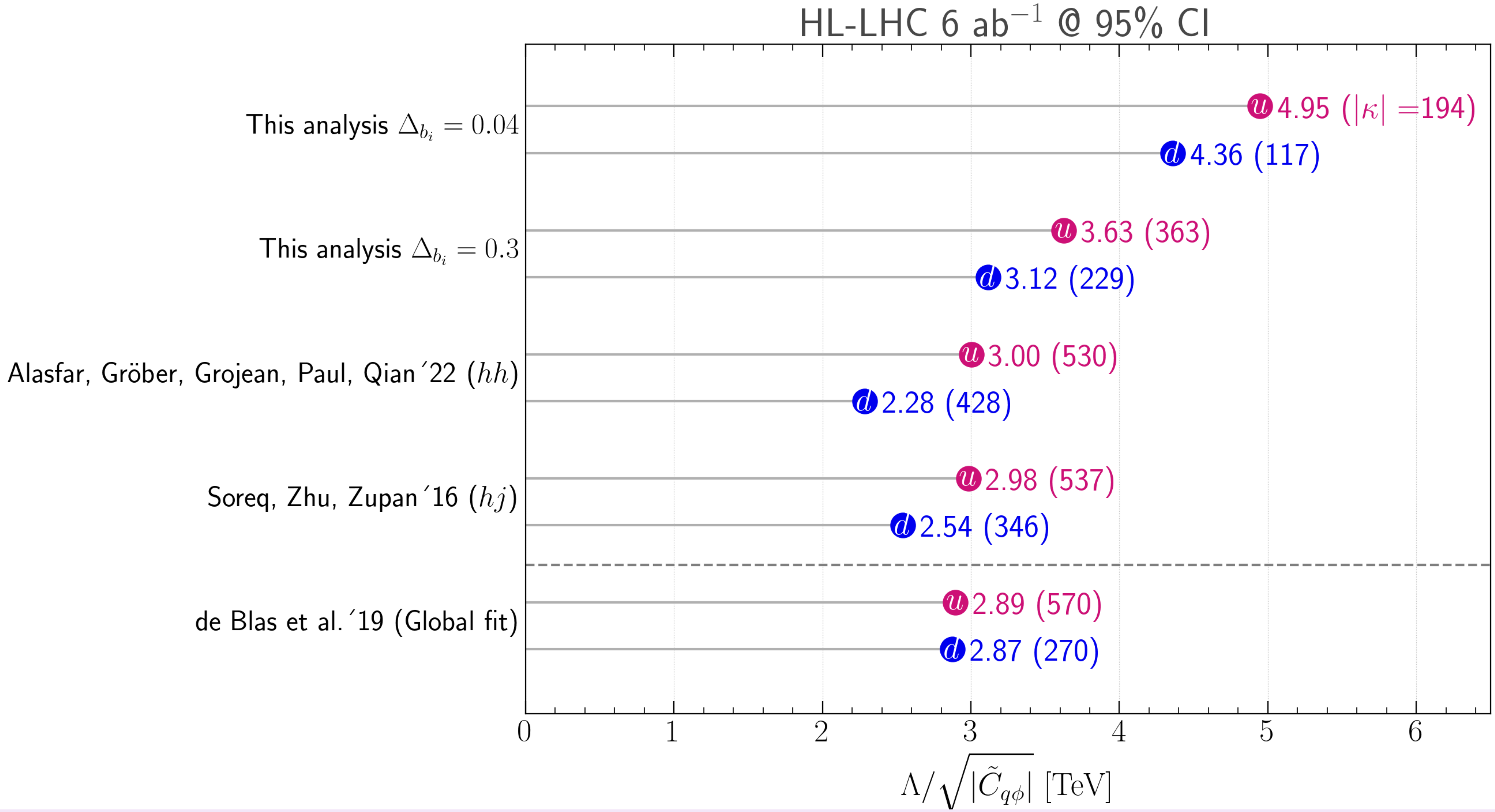
In the following consider only flavour diagonal case.

Notation:

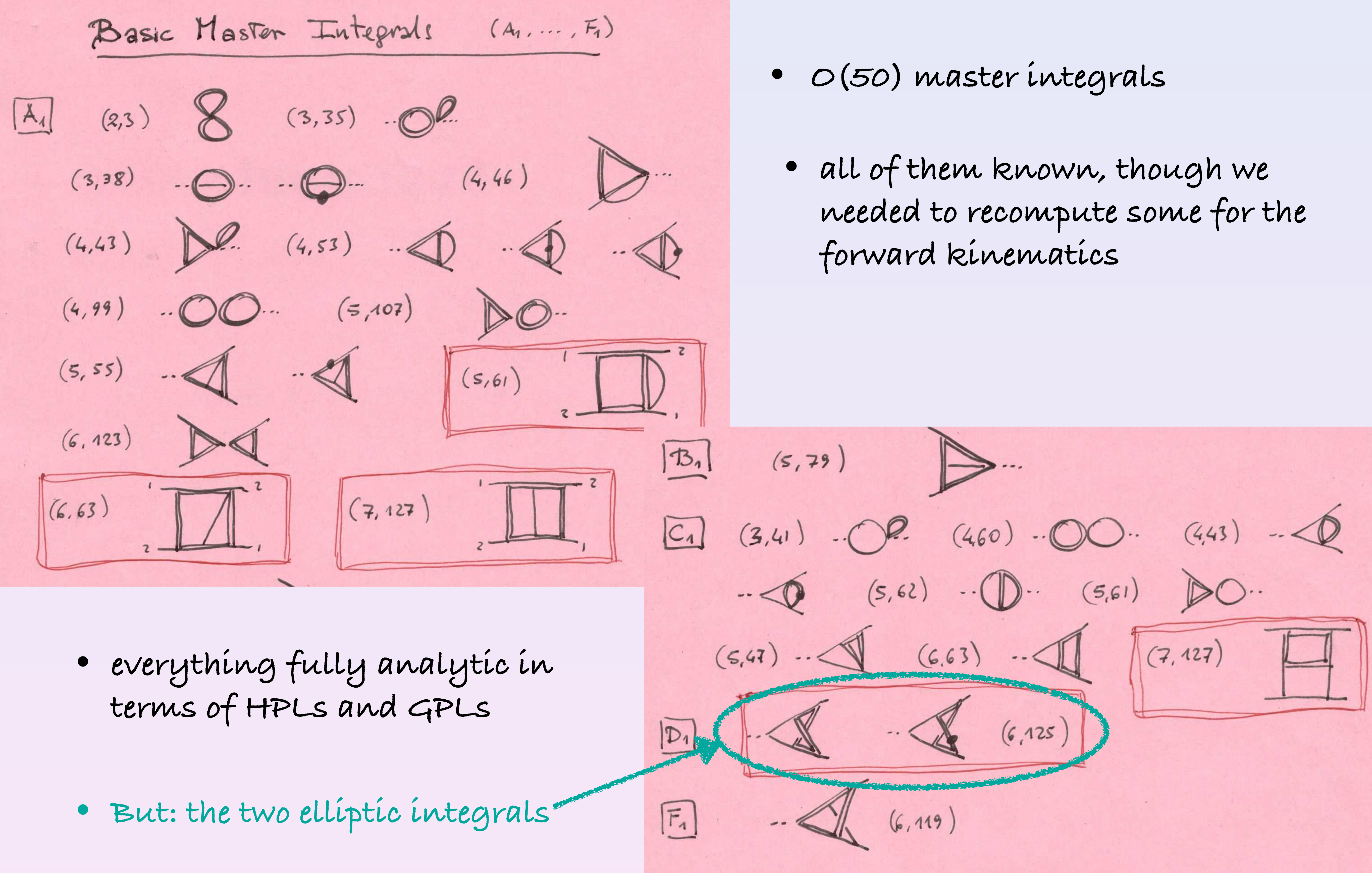
$$g_{h\bar{q}q} = \kappa_q g^{SM}_{h\bar{q}q} \qquad g_{hh\bar{q}q} = -\frac{3}{2}\frac{1-\kappa_q}{v}g^{SM}_{h\bar{q}q}$$

Summary light quark Yukawas

[Balzani, RG, Vitti '23]



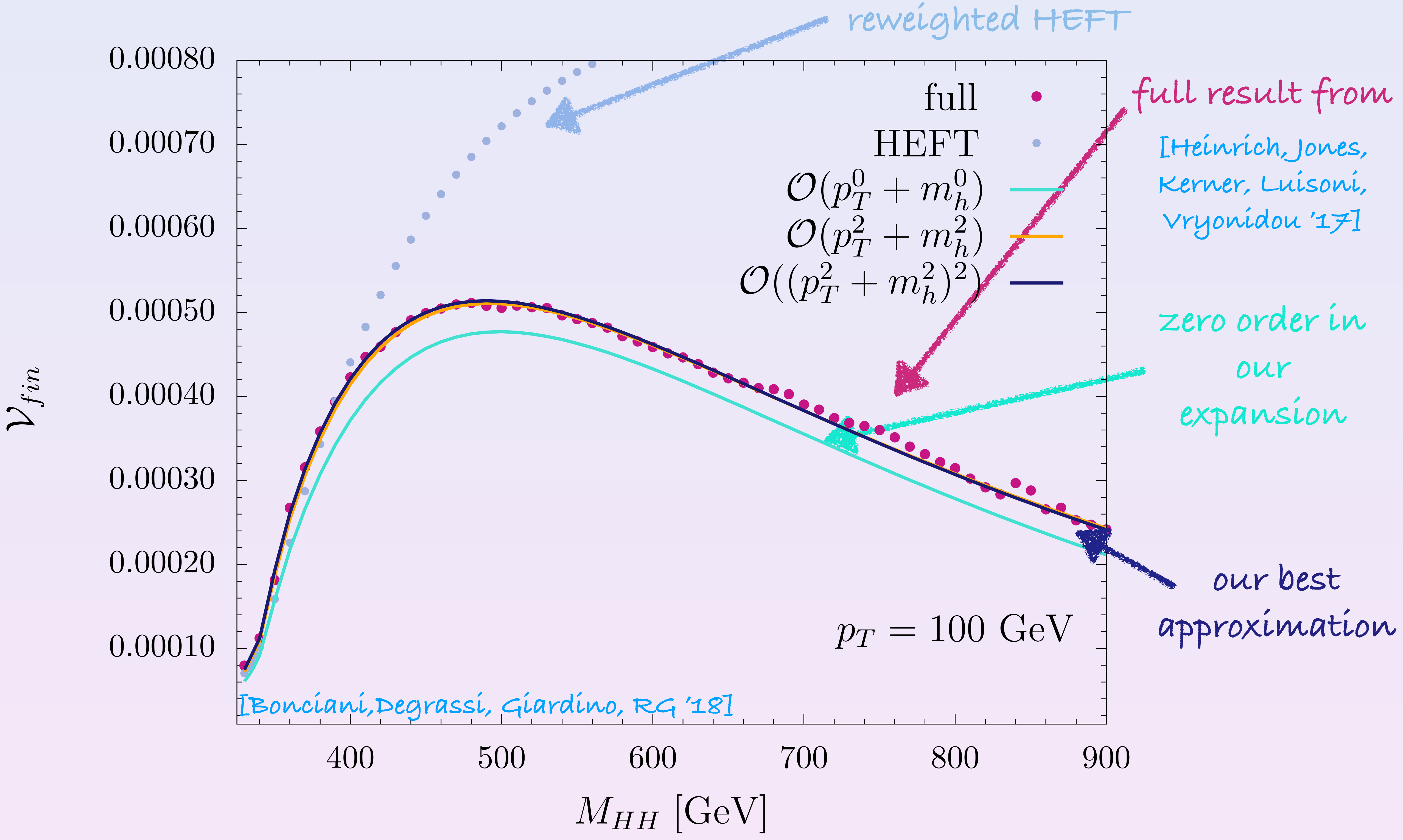
NLO expansion



- O(50) master integrals
  - all of them known, though we needed to recompute some for the forward kinematics

- everything fully analytic in terms of HPLs and GPLs
- But: the two elliptic integrals

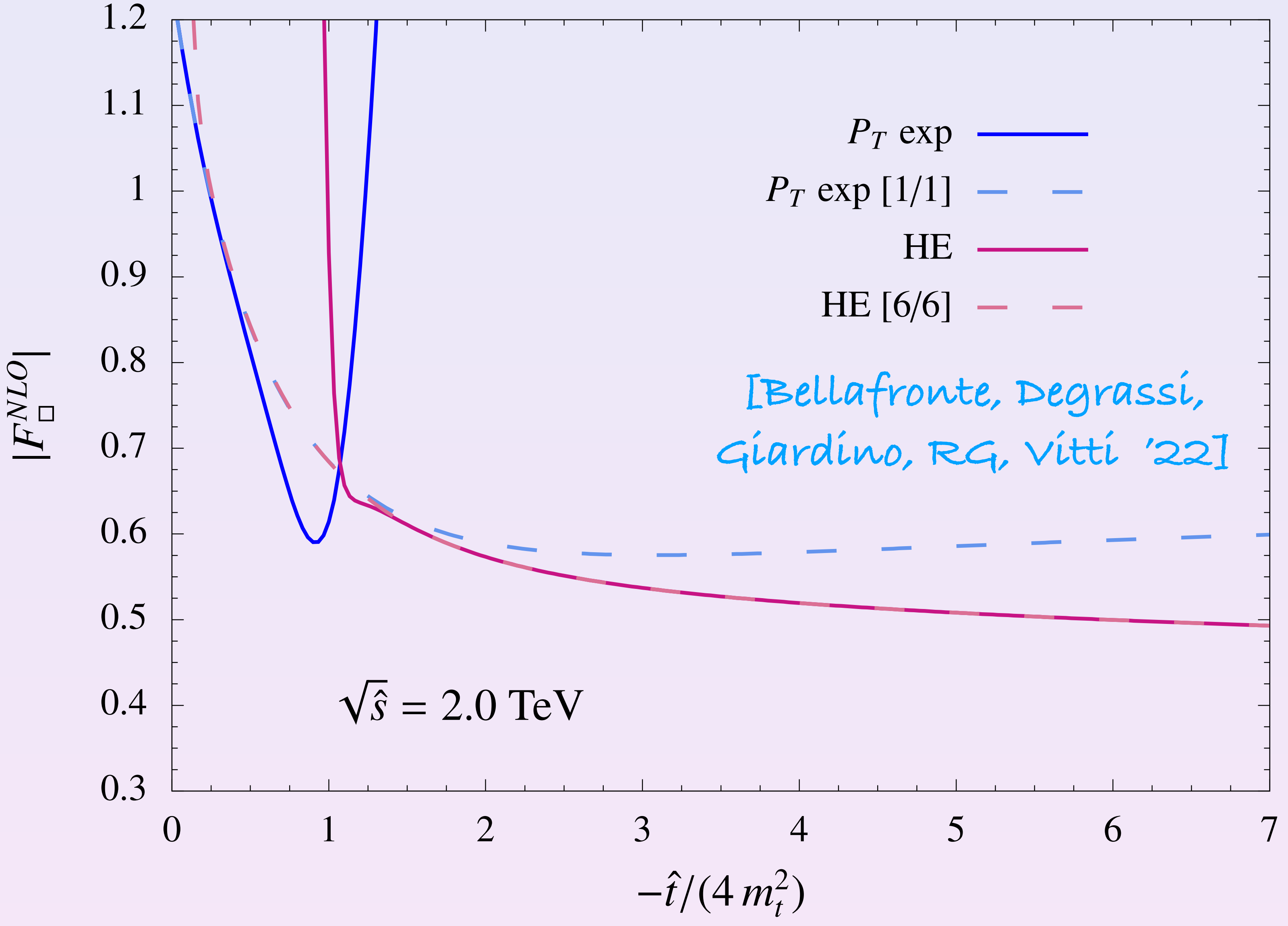
NLO results



Computing time ~0.2 s on MacBook per phase space point

Combination of expansions

Next-to Leading order form factor for Higgs pair production:



[Bellafronte, Degrassi, Giardino, RG, Vitti '22]