Double Higgs Production

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[ChatGPT on proposal of my daughter]

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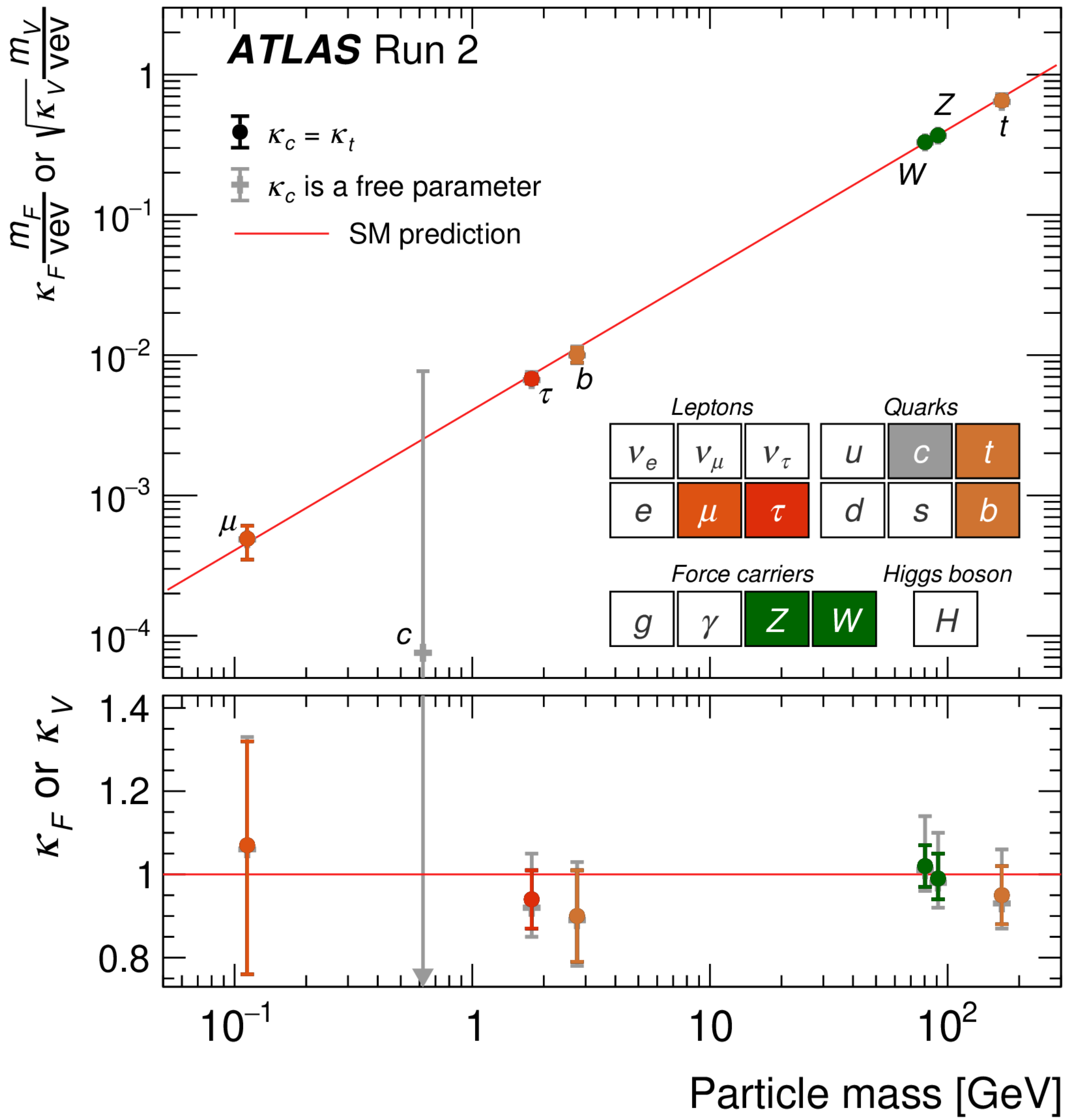
Higgs couplings



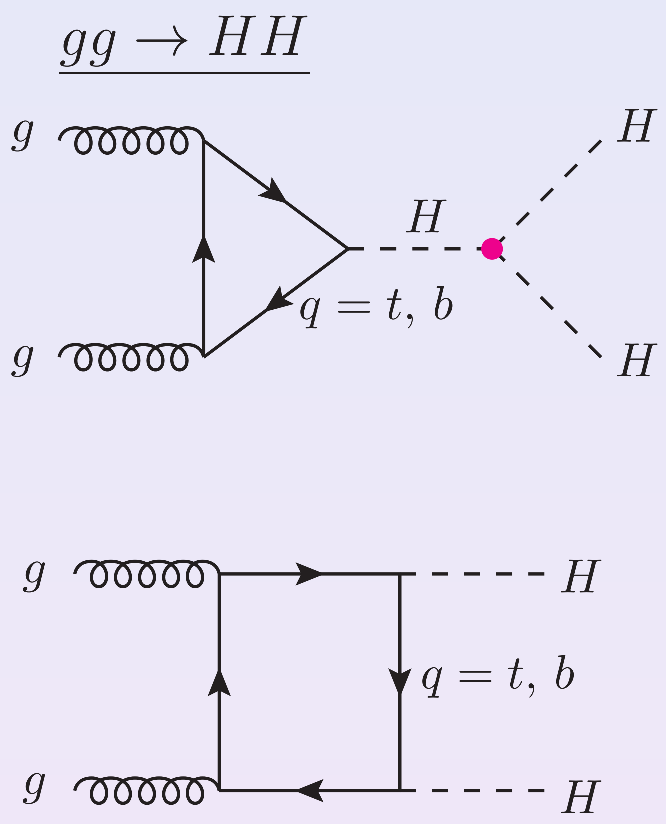
3rd generation fermion and gauge boson couplings to Higgs boson fairly good measured

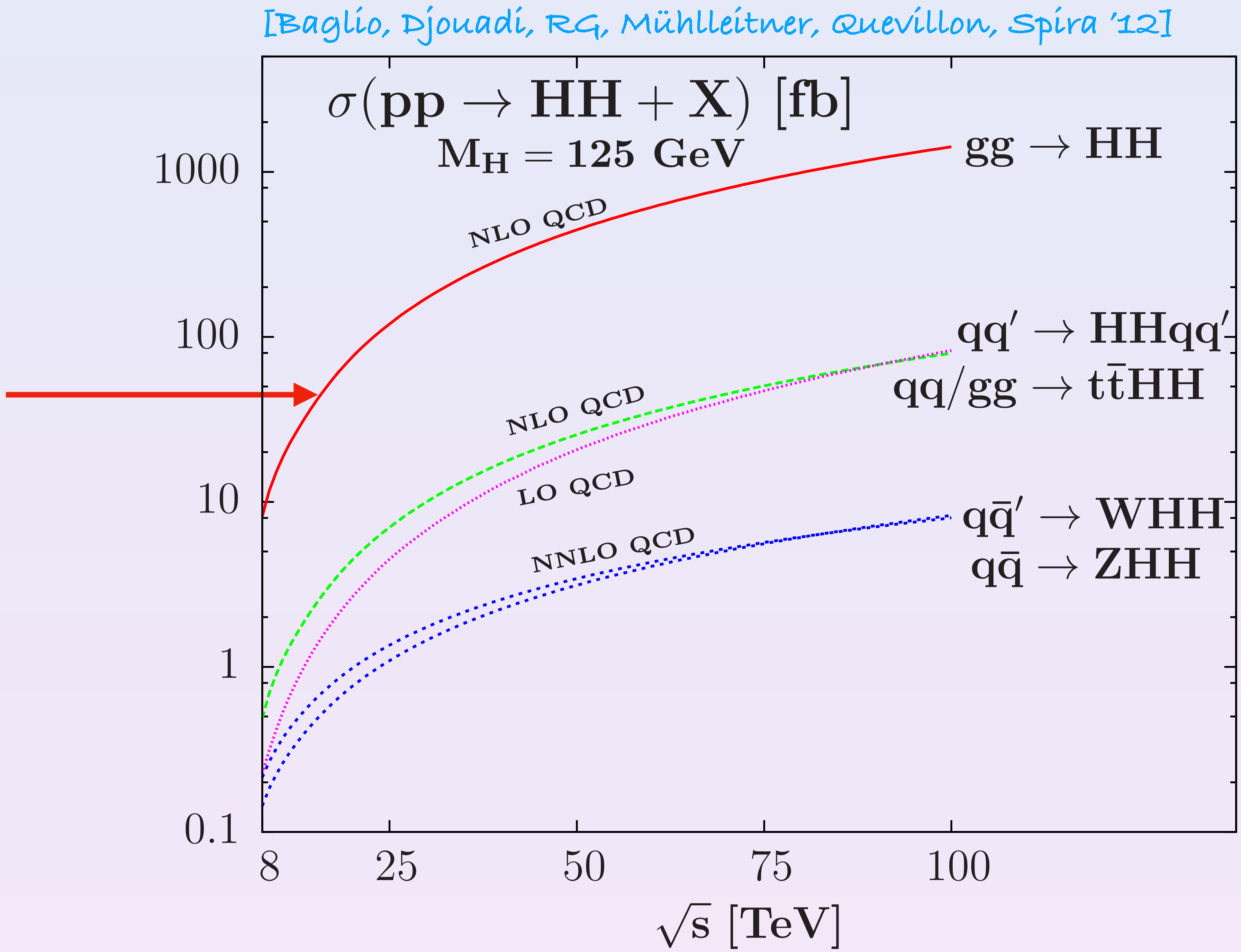
2nd generation fermion couplings first results available

Higgs self-couplings?

First generation Yukawa couplings?

Higgs Pair Production

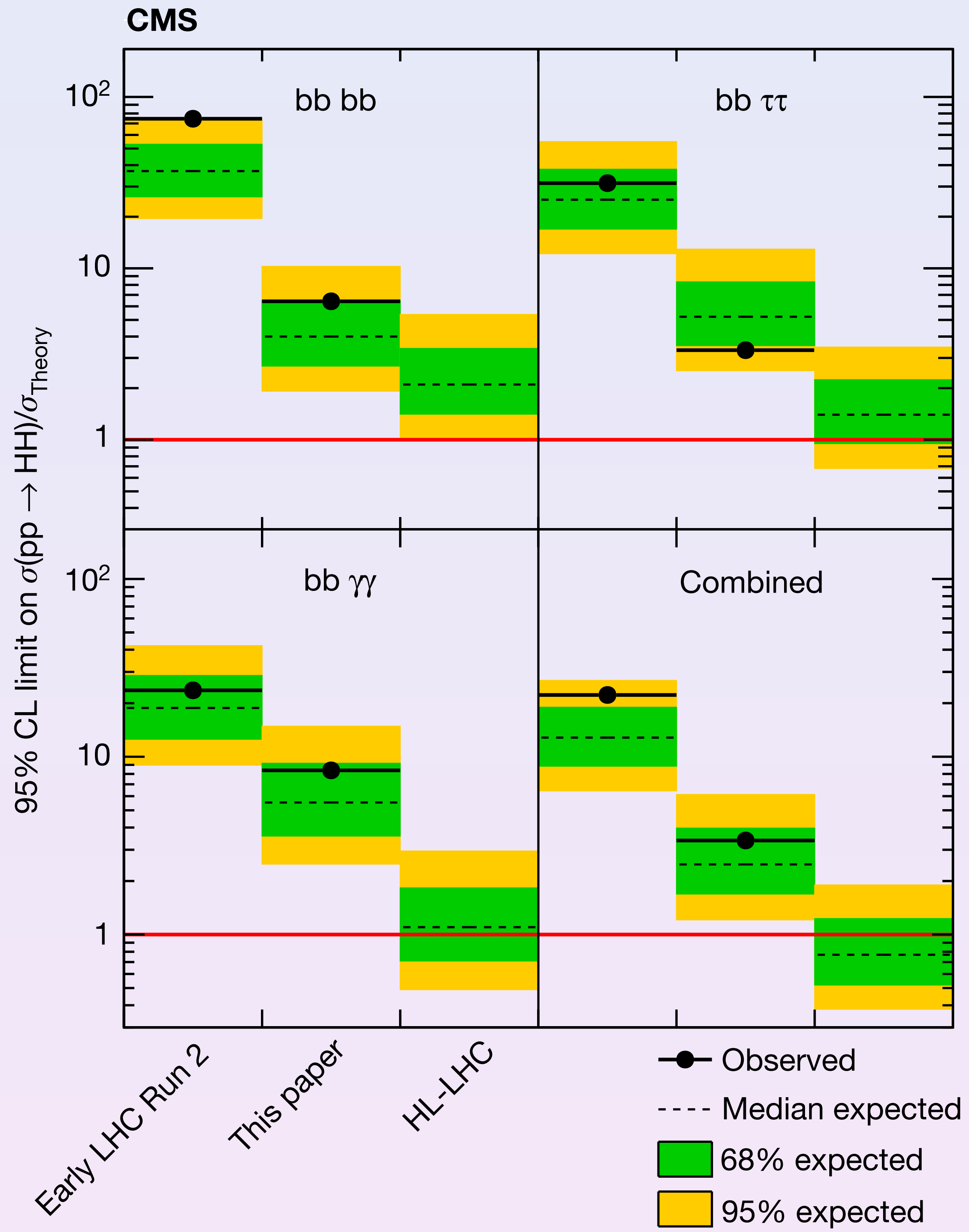




Small cross section

Difficult to measure

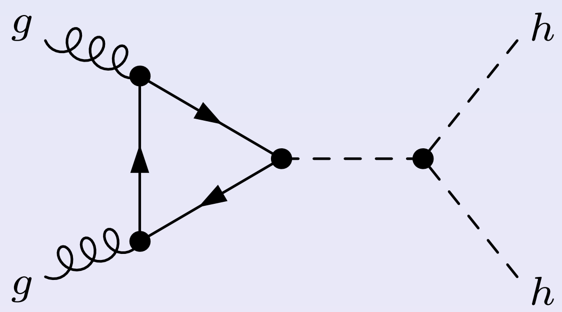
Higgs Pair Production

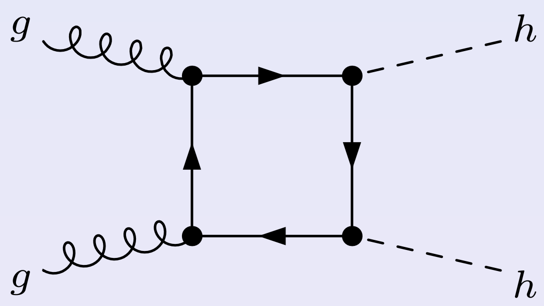


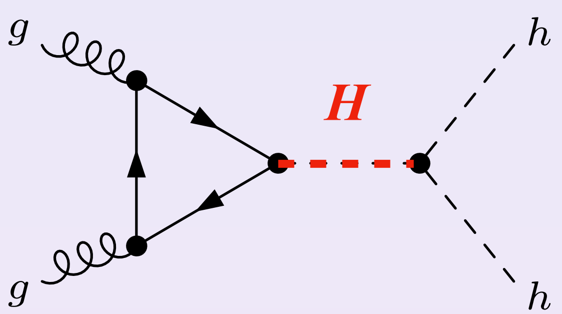
[CMS Nature '22]

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

Higgs Pair Production in BSM

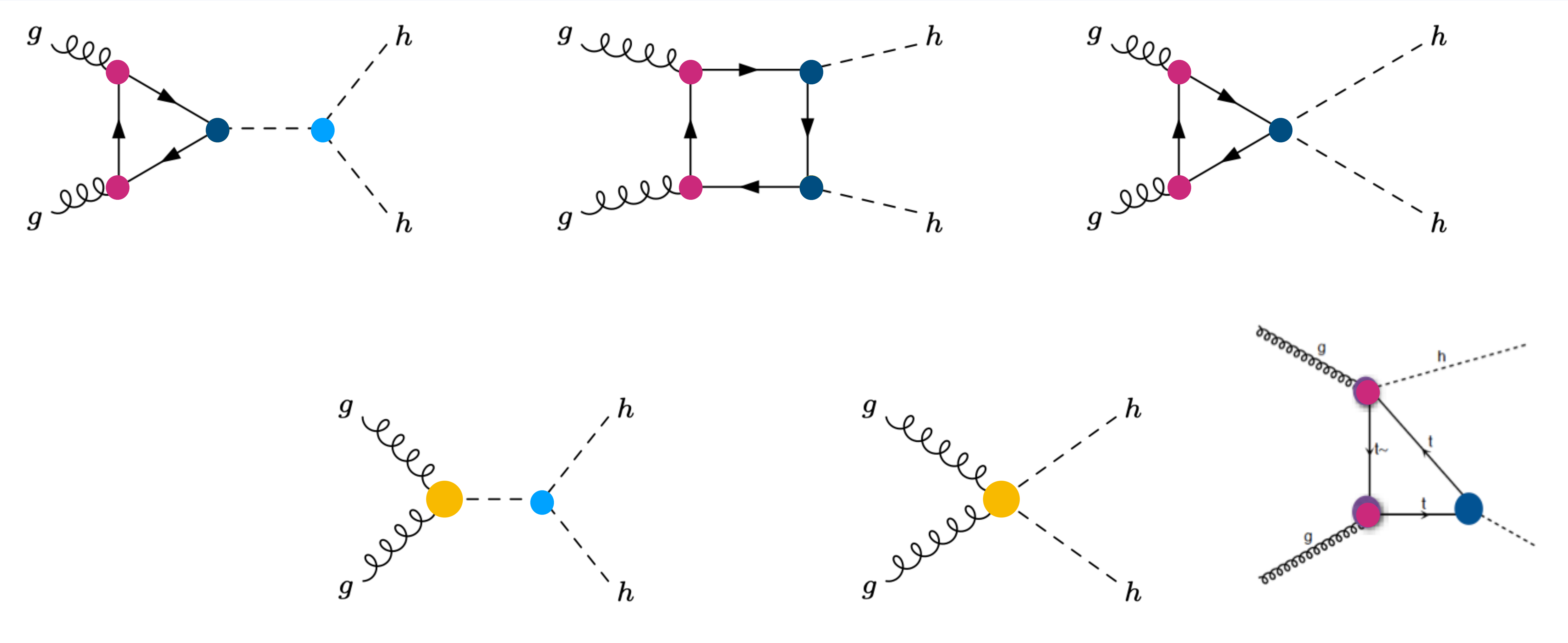






resonant Higgs pair production

Non-resonant HH production



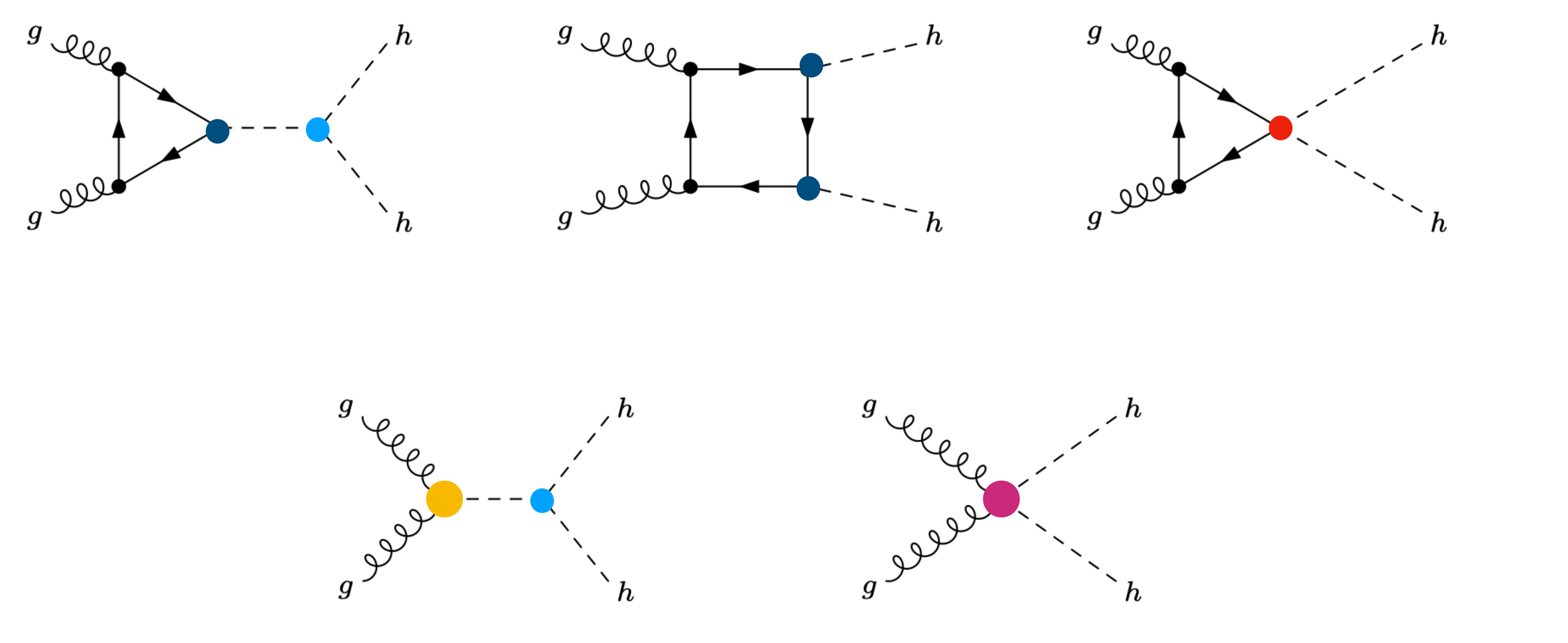
SMEFT:

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

Warsaw basis

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

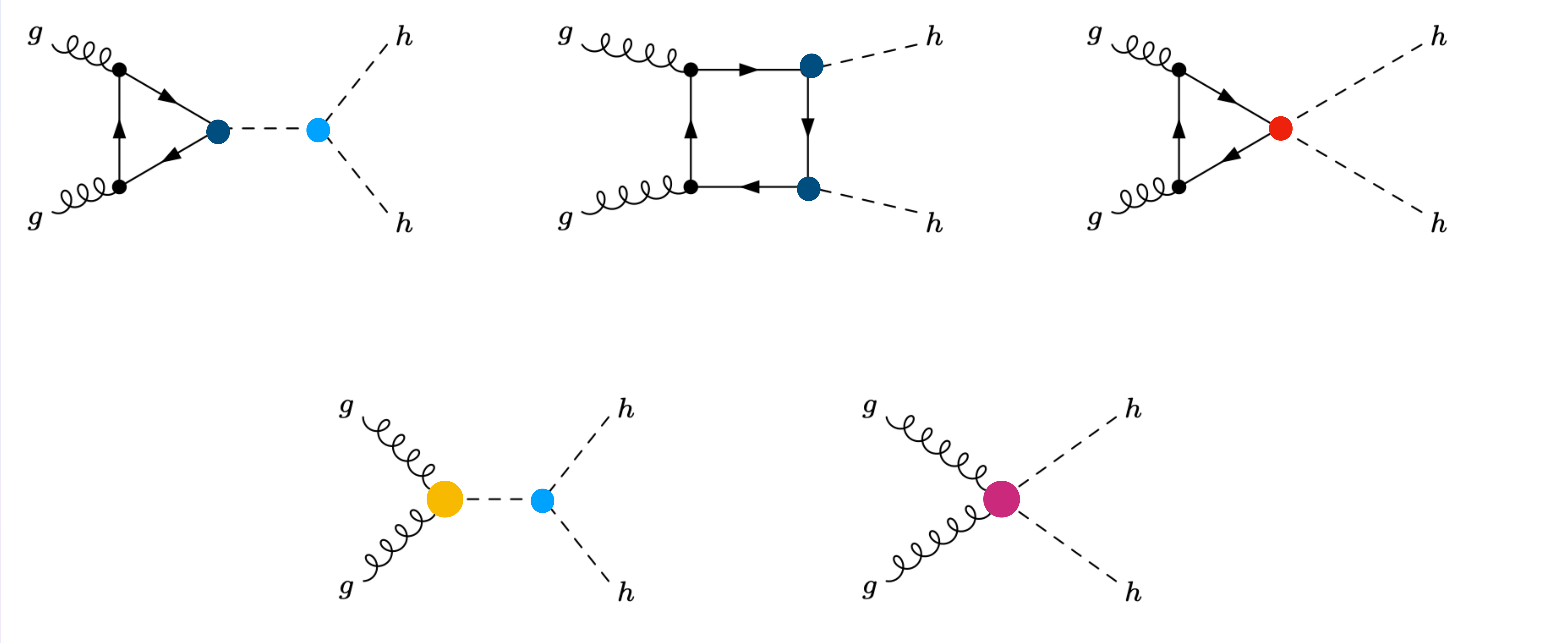
Effective Theory for HH



HEFT:

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

Effective Theory for HH



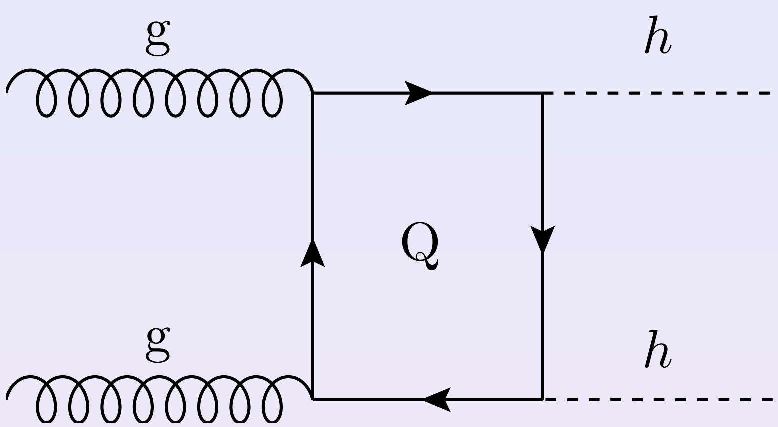
HEFT:

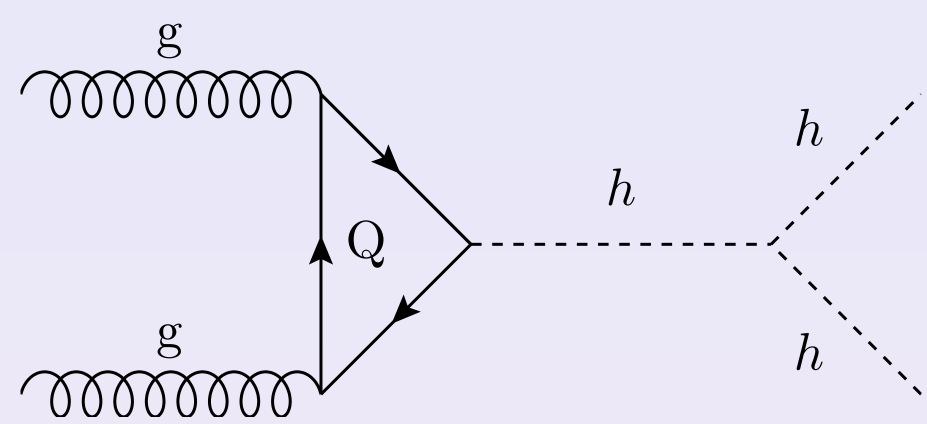
two Higgs couplings only to be probed in HH

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

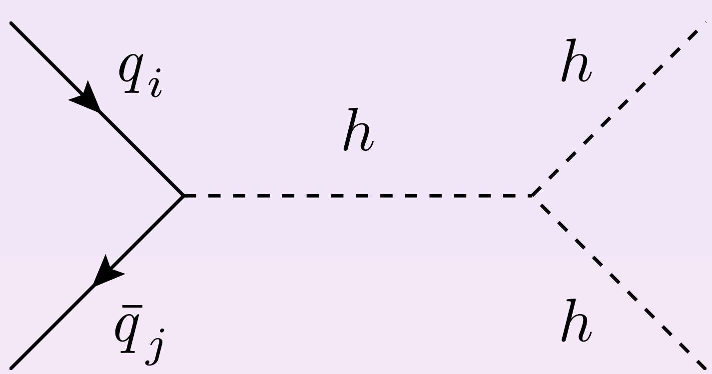
Light quark Yukawas in HH

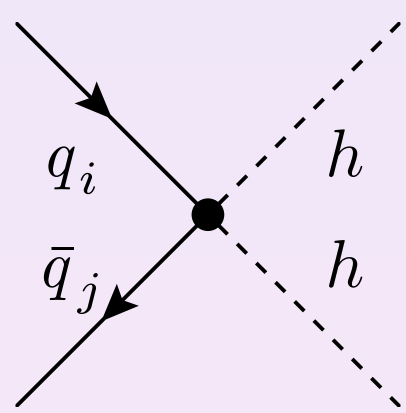
Higgs pair production in SM, gluon fusion dominated by heavy quark loops

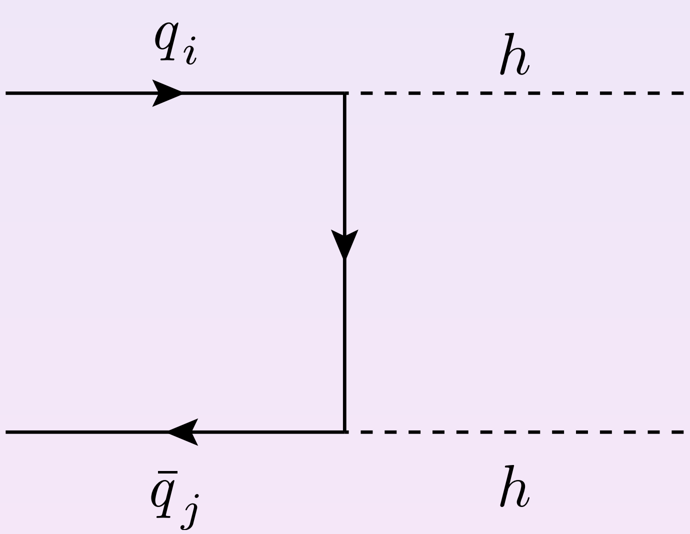




enhanced light Yukawa couplings

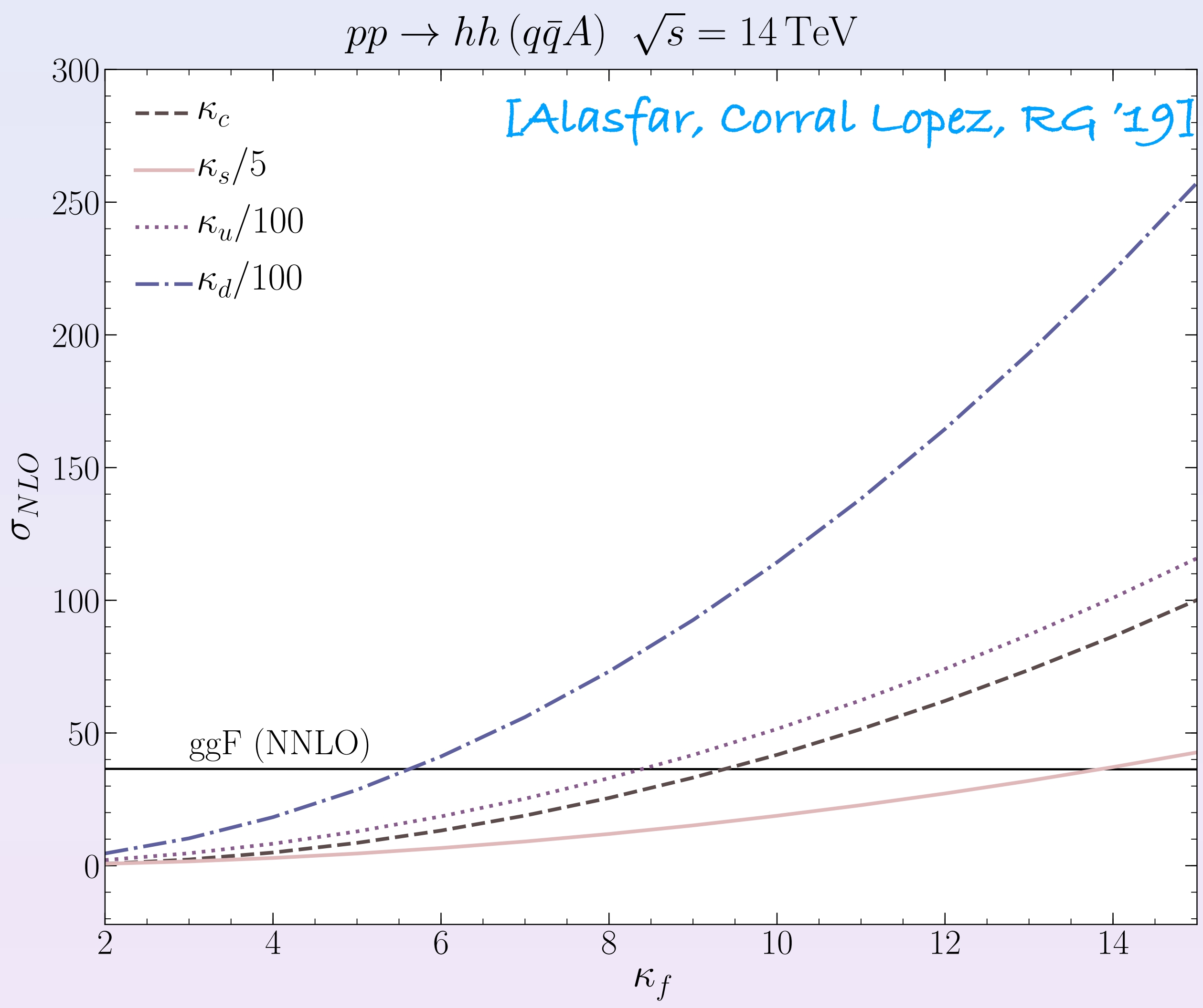


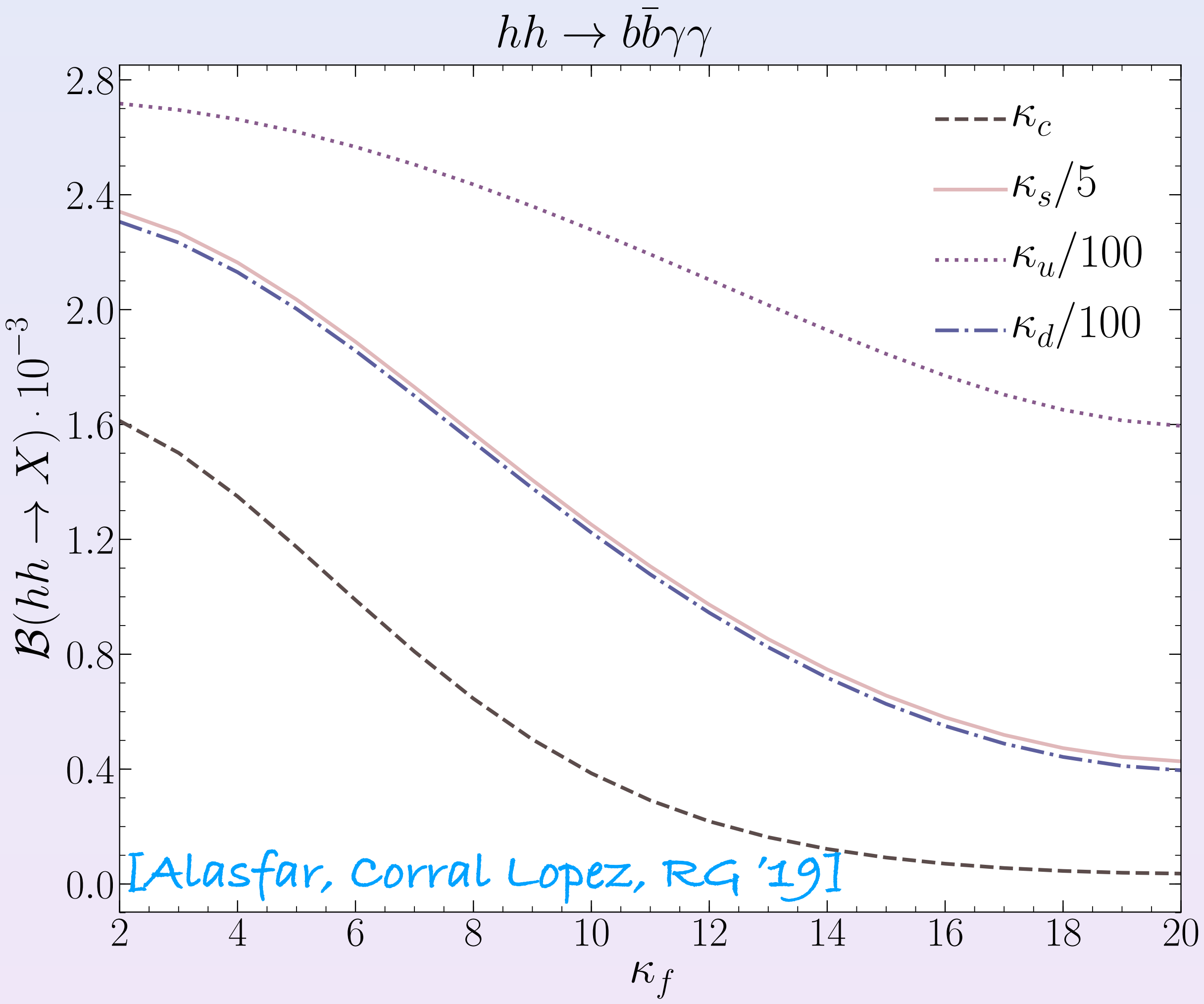




contribution most important for 1st generation (given the coupling limits)

Higgs pair production



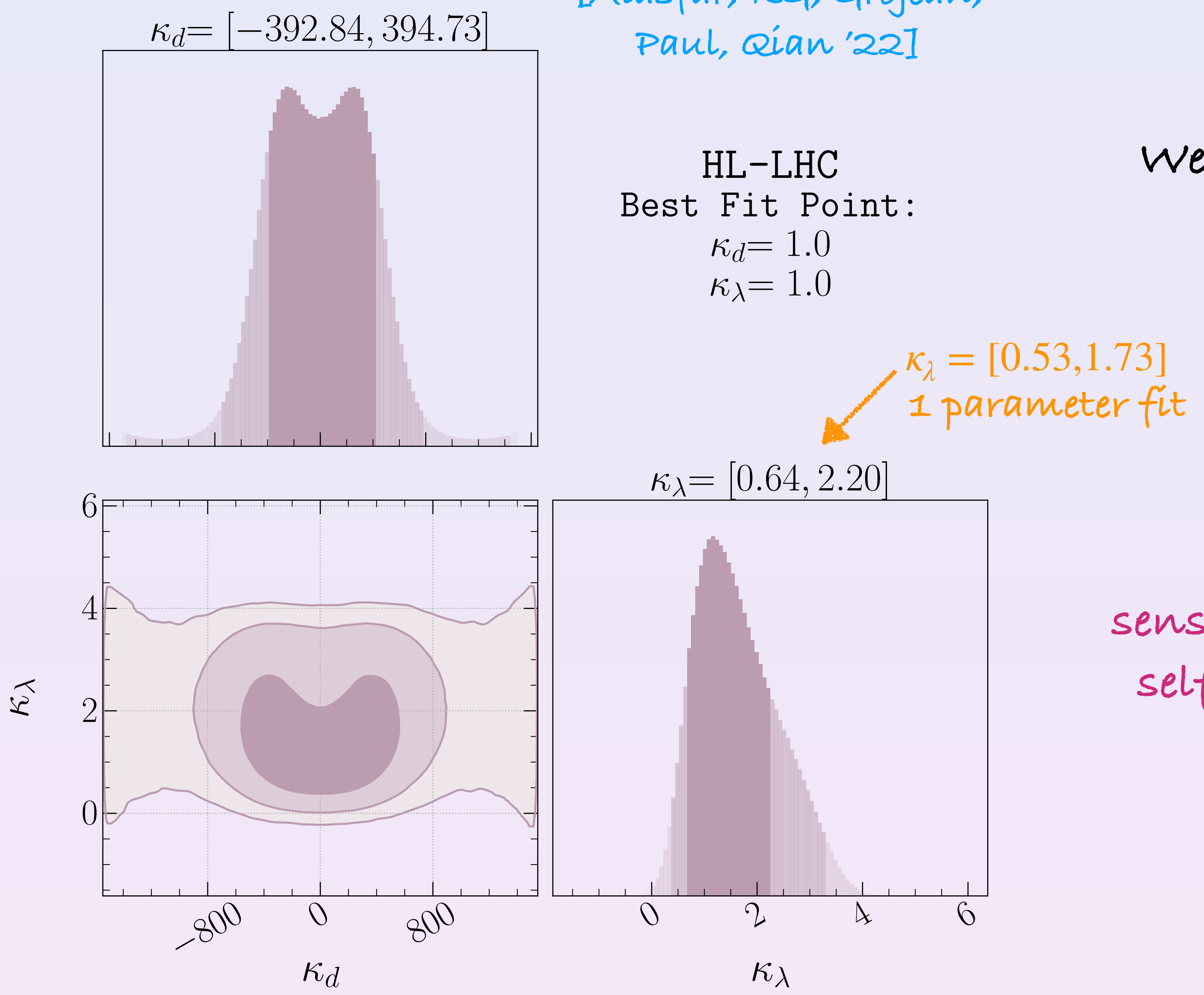


increase of cross section,
(also modified distributions)

decrease of BR for typical di-Higgs final state

Light quark Yukawas in HH

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



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

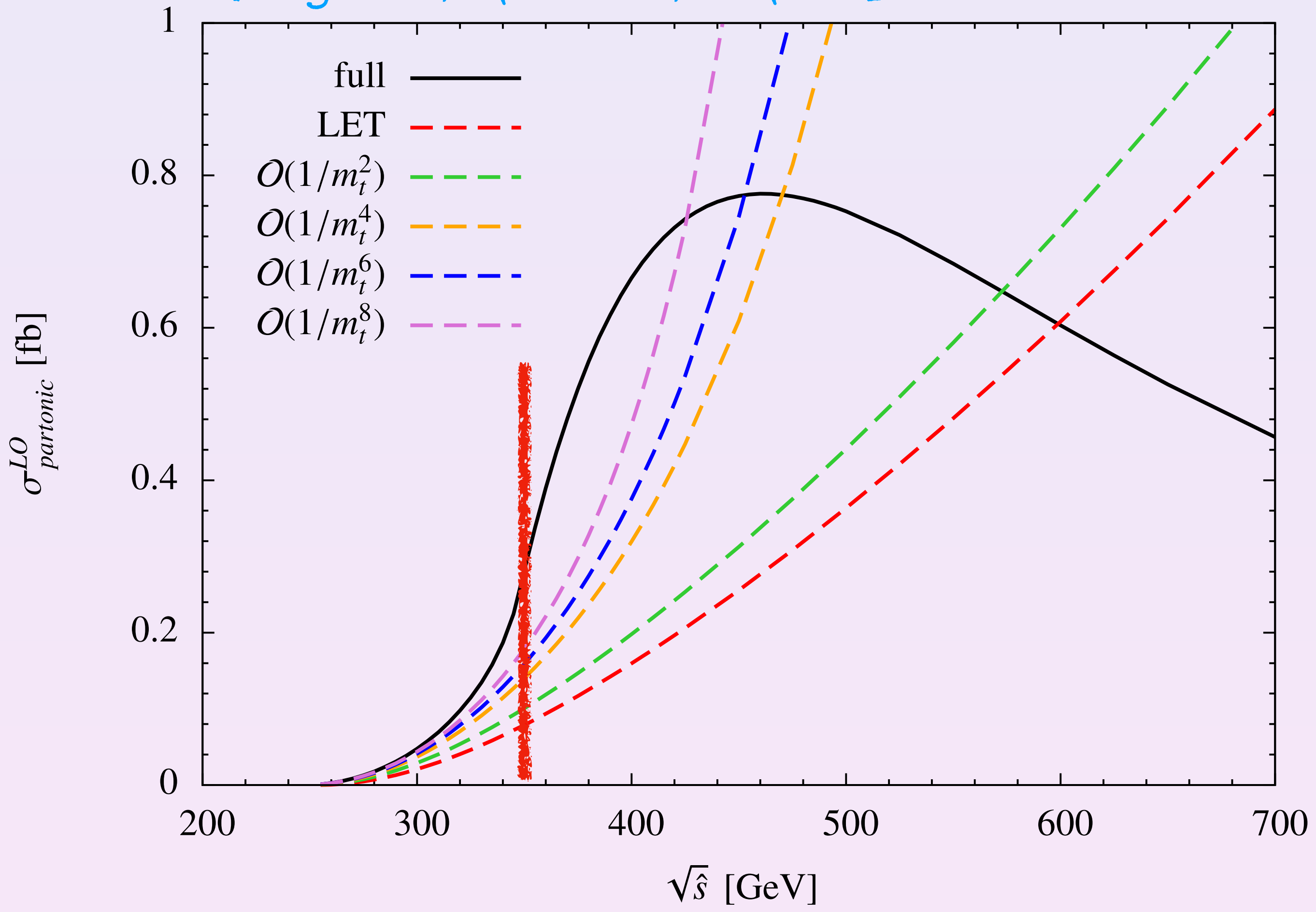
Theory status Higgs production production

Gluon fusion known up to N³LO 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

[Degrassi, Giardino, RG '16]



expansion valid for $\hat{s}, \hat{t}, \hat{u}, m_H^2 \ll 4m_t^2$

$$\frac{1}{(p+q)^2 - m^2} \approx \frac{1}{p^2 - m^2}\left(1 - \frac{2p\cdot q + q^2}{p^2 - m^2} + \ldots\right)$$

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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]

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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]

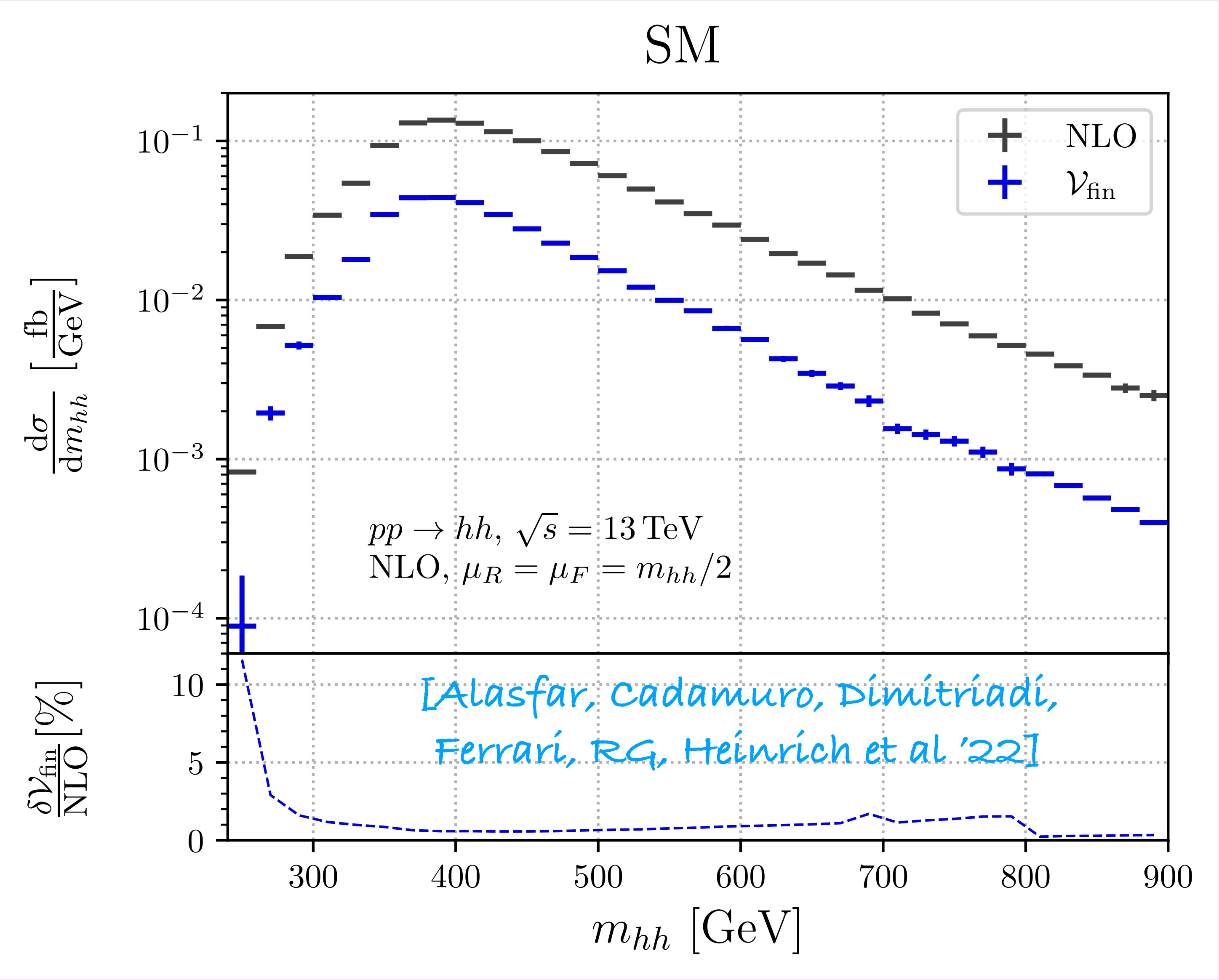
Geneva @ NNLO QCD infinite top mass limit [Alioli et al. 22]

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



Can we describe analytically the relevant phase space?

Can this then be used for a Monte Carlo?

DiHiggs: a new POWHEG implementation

Idea

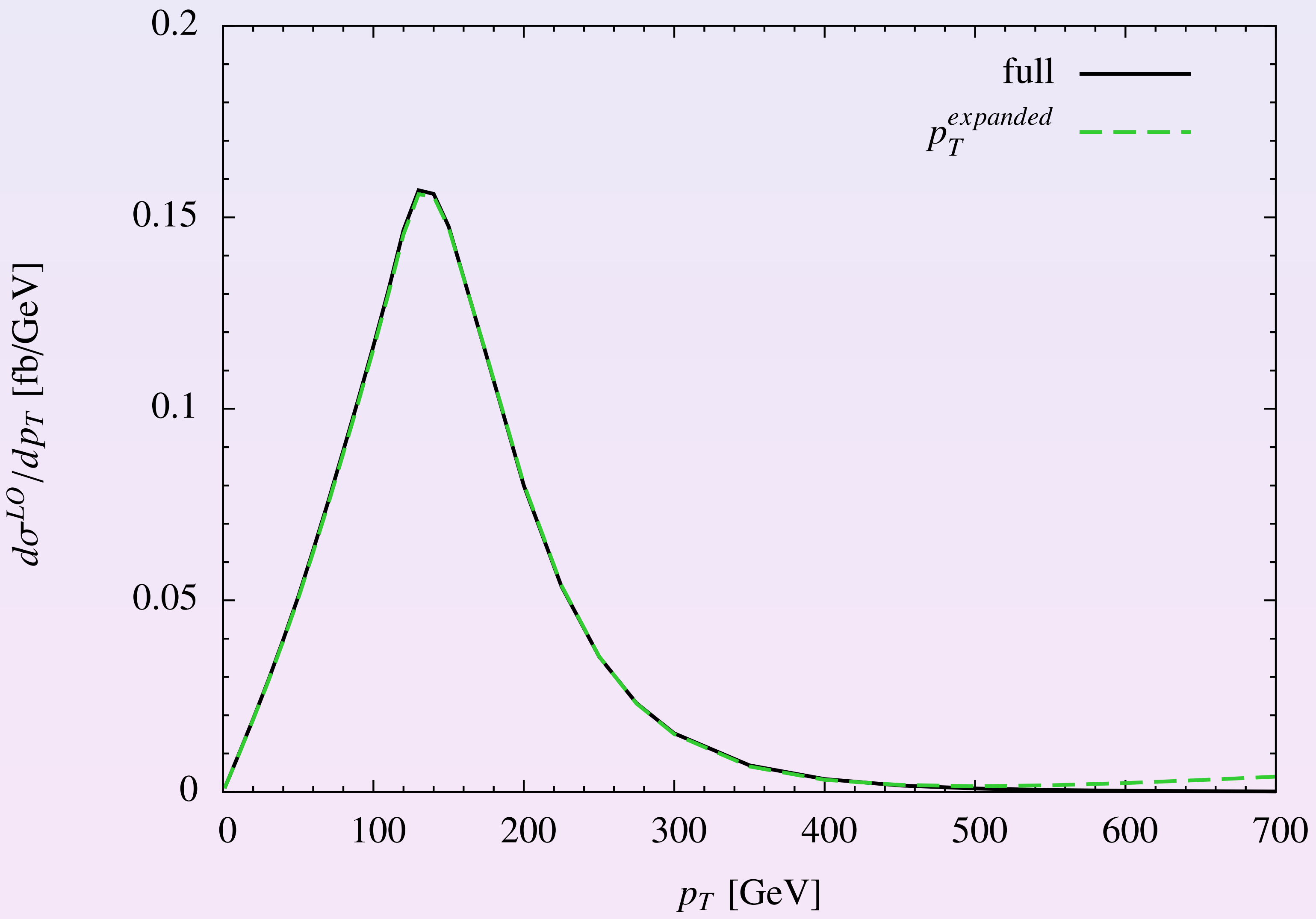
Idea:

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 base space...

High-energy expansion

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Strategy: to combine with a high-energy expansion

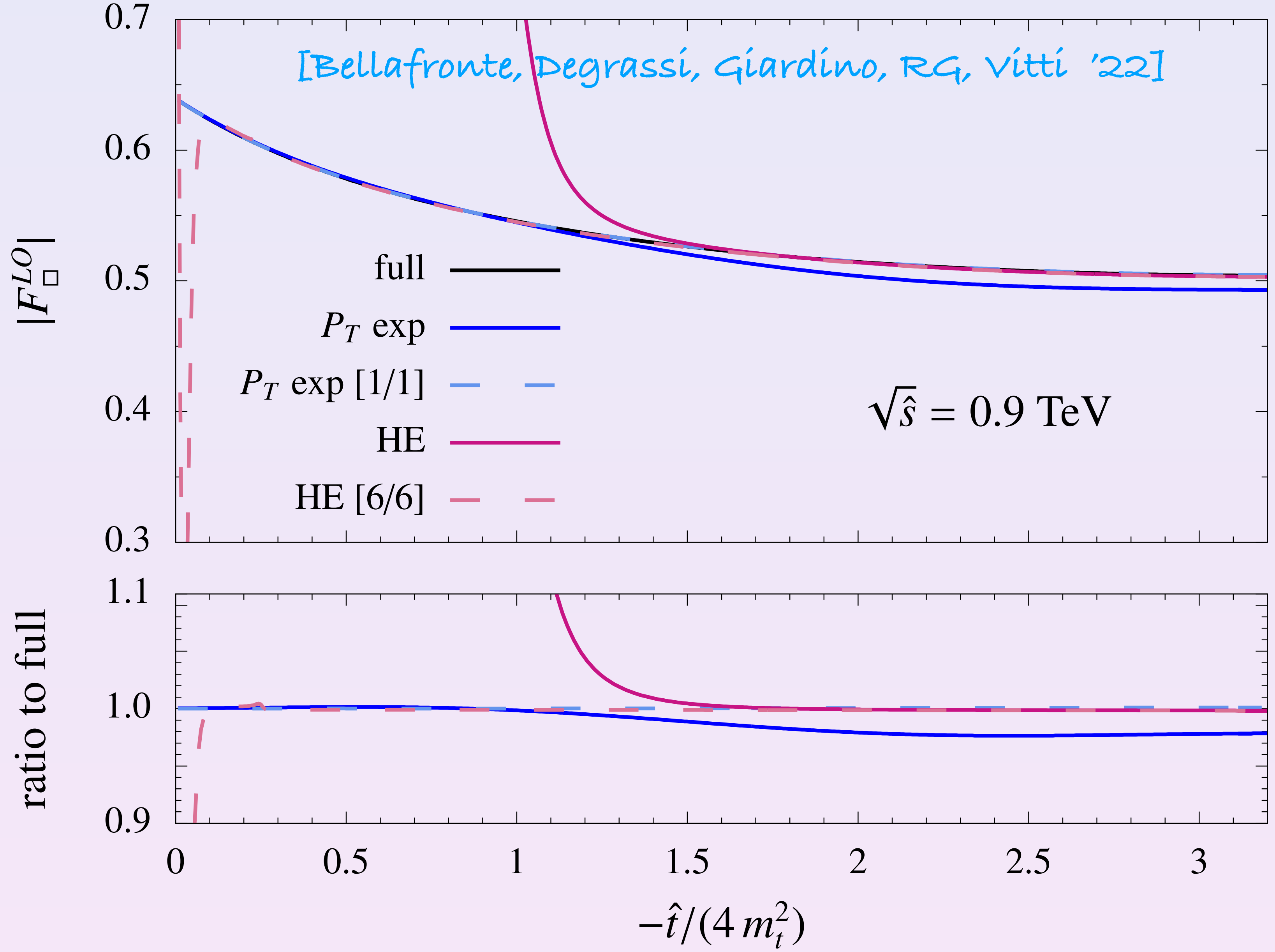
$$\hat{s}, \hat{t}, \hat{u} \gg m_t^2 > m_{ext}^2$$

Results available up to high orders (16) in m_t^2 [Davies, Mishima, Steinhauser, Wellmann '18]

Padé approximants can push validity down to $p_T \sim 150$ GeV

Combination of expansions

Leading order form factor for Higgs pair production:

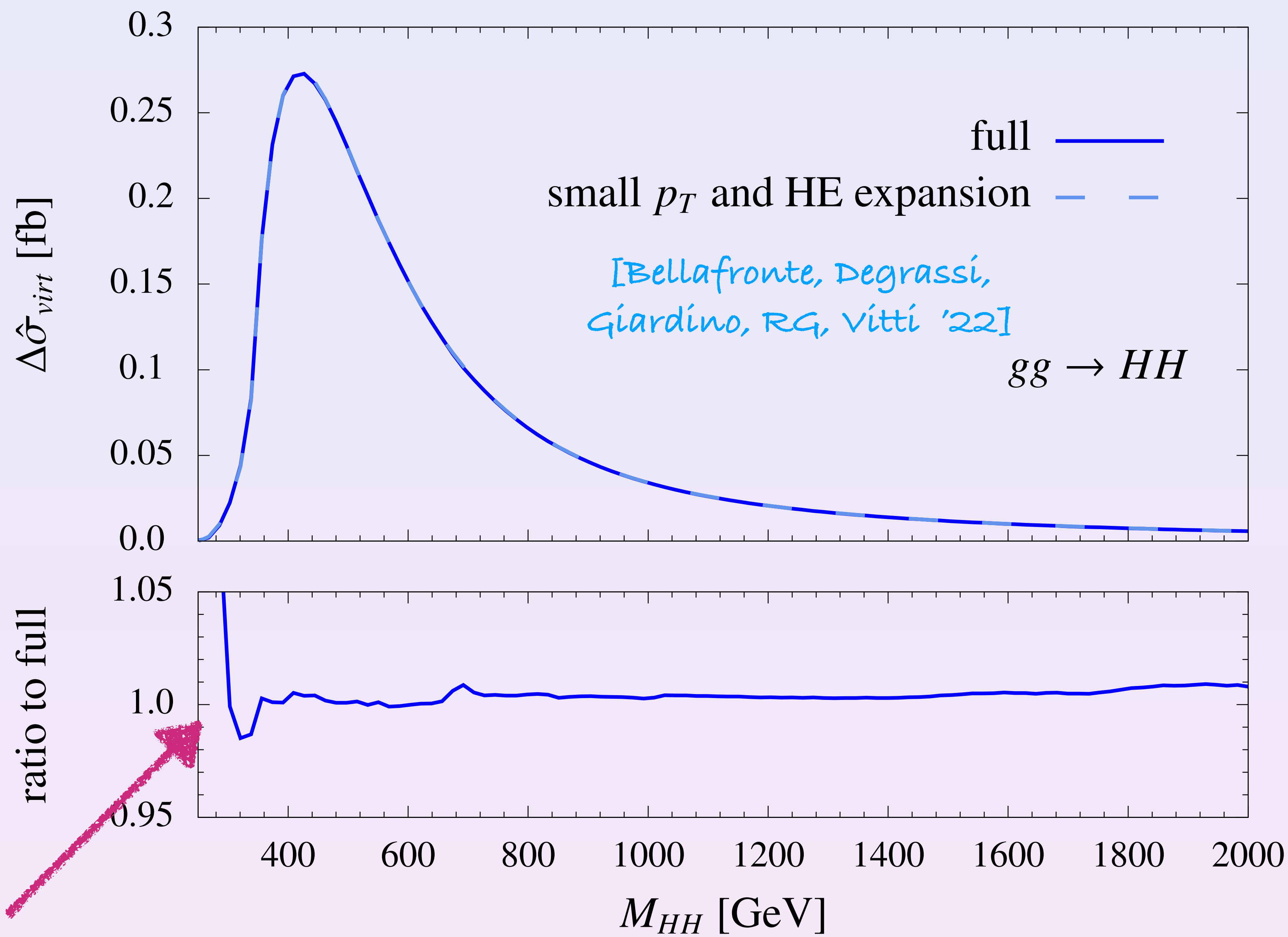


Padé approximant

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

Expansions are complementary, using Padé approximants one can increase convergence

Combination of expansions



few phase space points
in virtual grid of

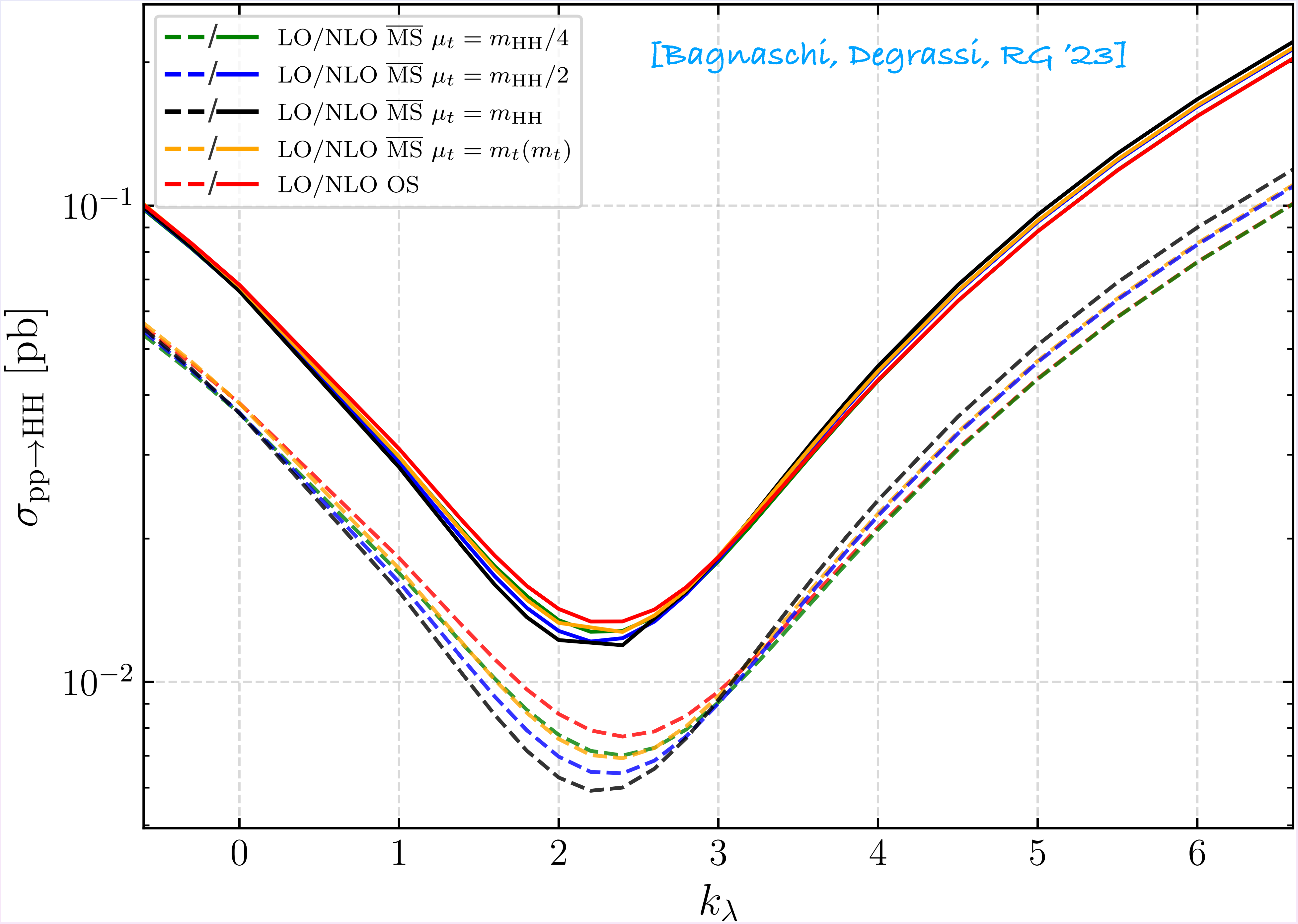
[Davies, Heinrich, Jones et al. '19]

Works incredibly well (difference < 1%)

New POWHEG implementation

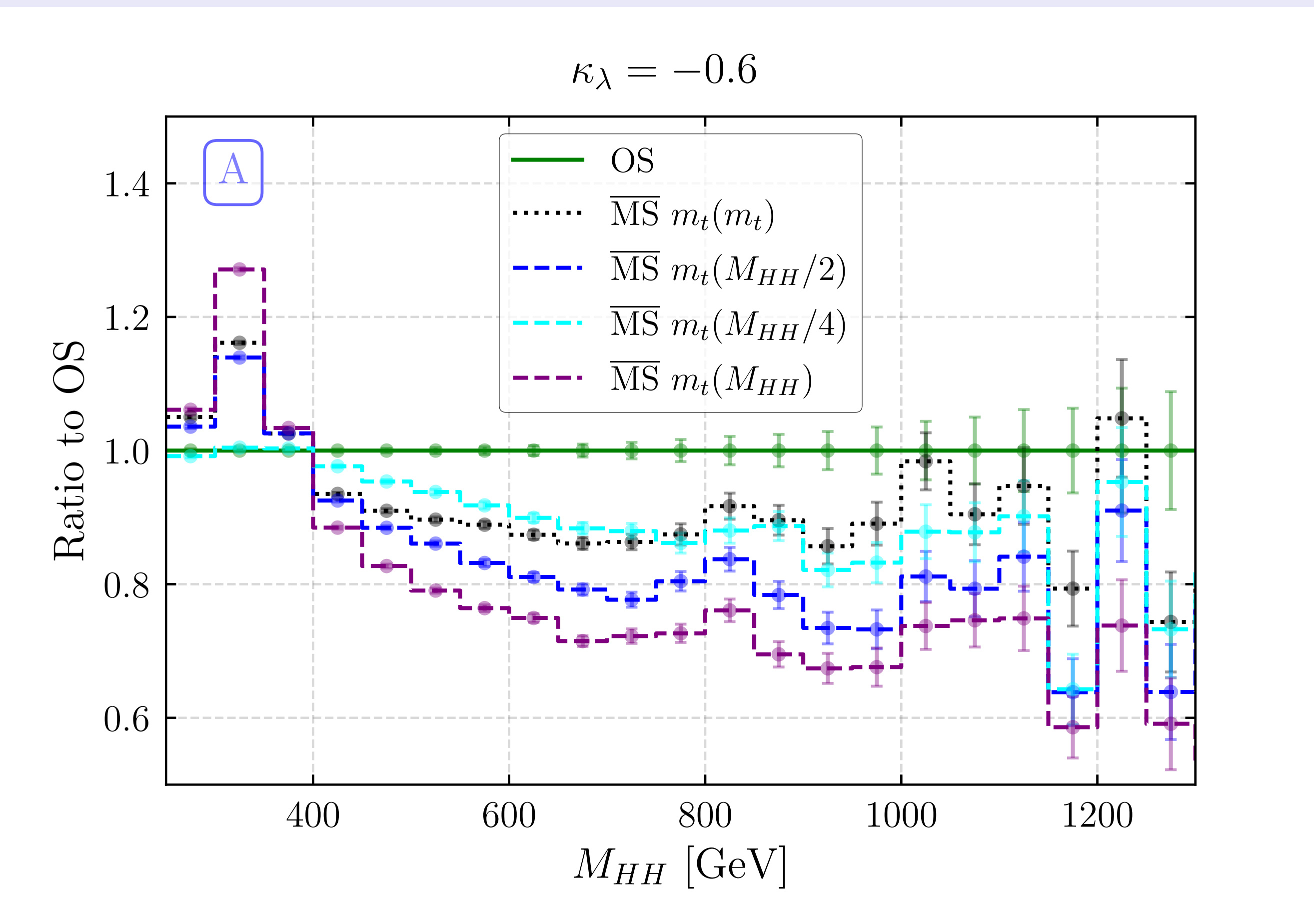
virtuals with expansion technique analytically

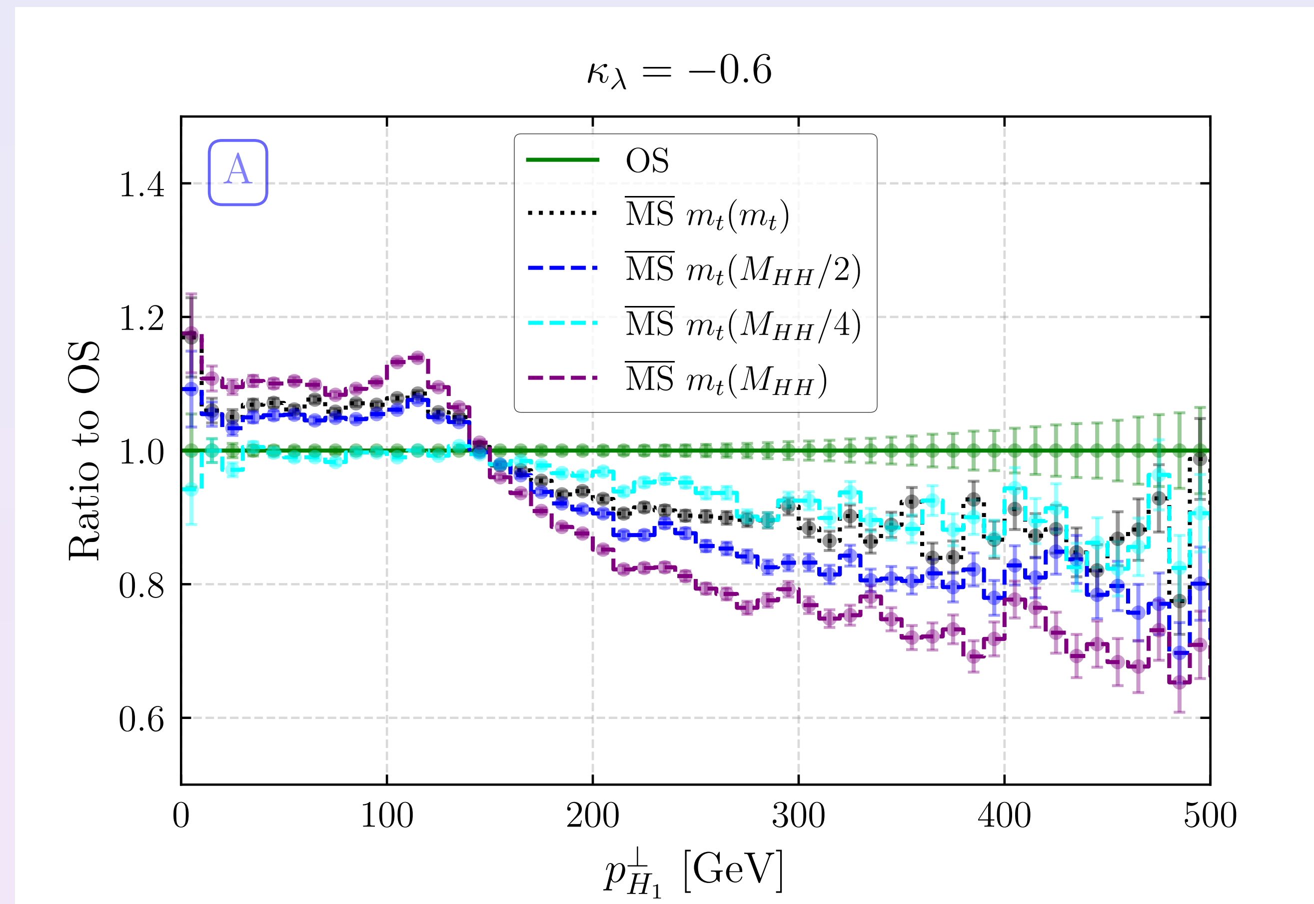
reals with MadLoop [Hirschi et al. '11]



New POWHEG implementation

[Bagnaschi, Degrassi, RG '23]





flexibility of analytic approach allows to vary top mass renormalisation scheme

Conclusion

- Higgs pair production can give us lots of information on new physics
- Requirement of precise predictions: for 2 -> 2 processes it's a multi-scale problem
- for Monte Carlo a analytic approach is useful and can be sufficiently precise
- Monte Carlo with analytic approach is very flexible and can be easily extended to BSM

Thanks for your attention!

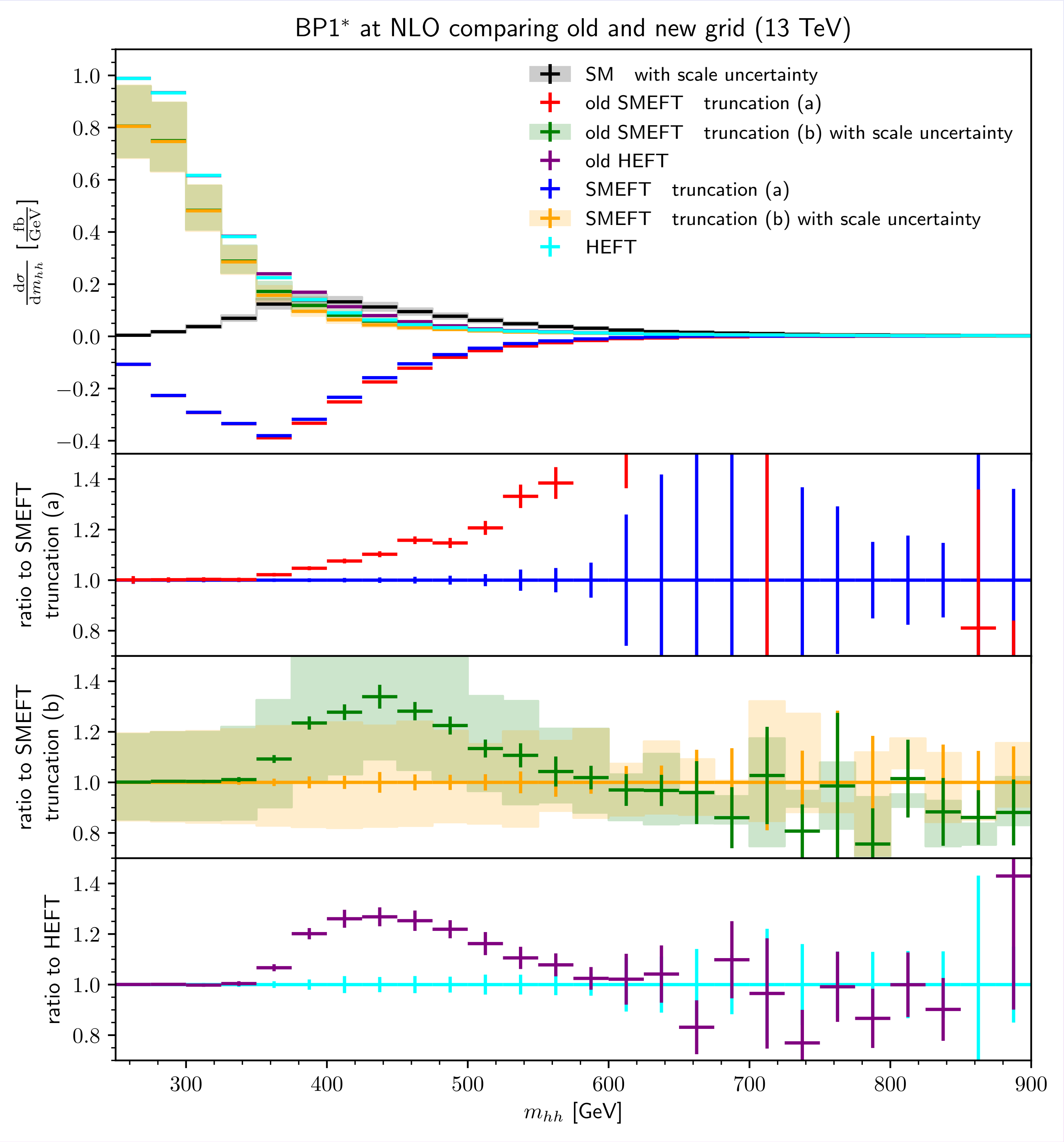
Backup

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]

Light quark couplings in Higgs pair production

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

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

direct coupling to longitudinal modes of Z's

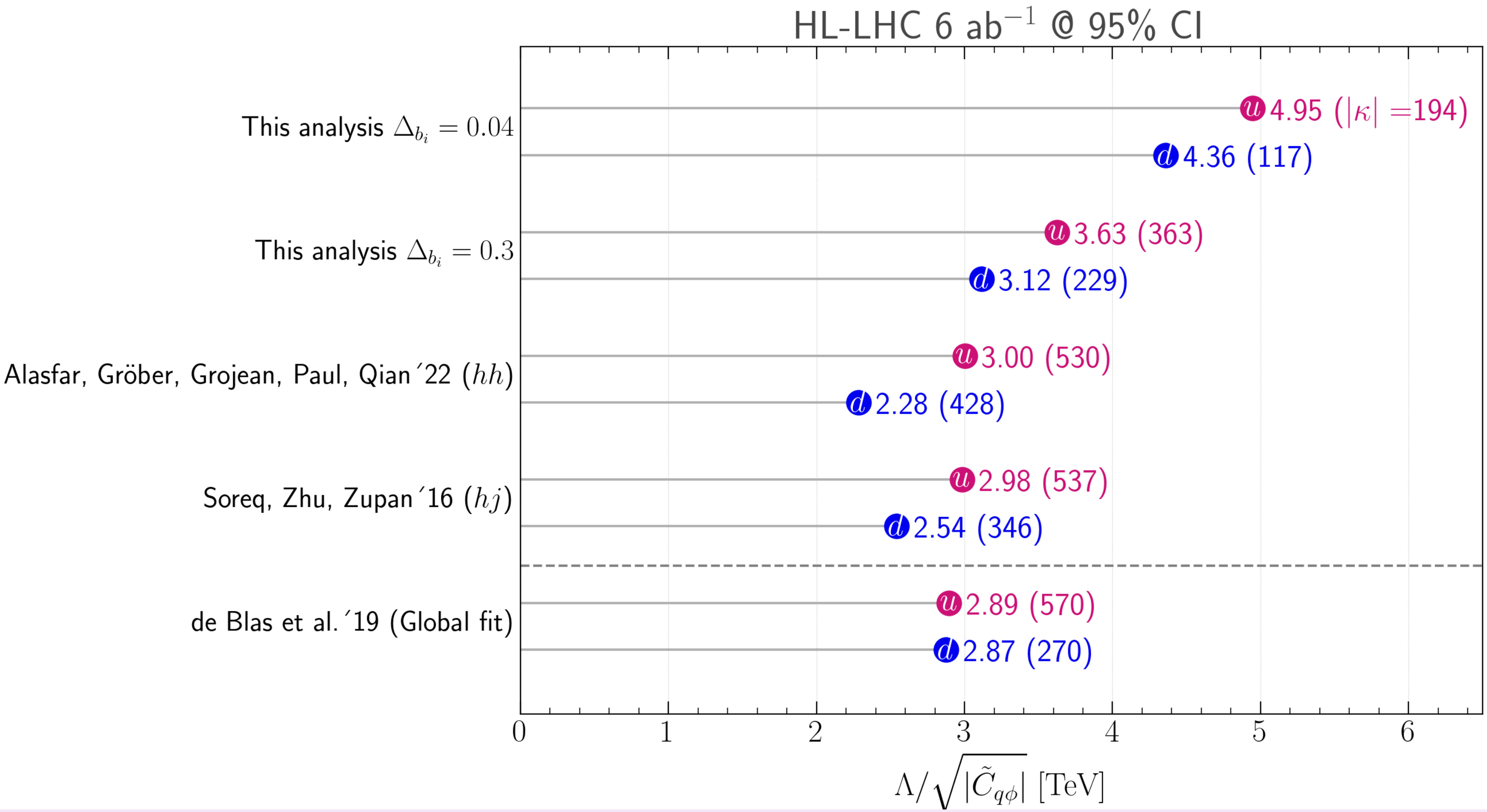
In the following consider only flavour diagonal case.

Notation:

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

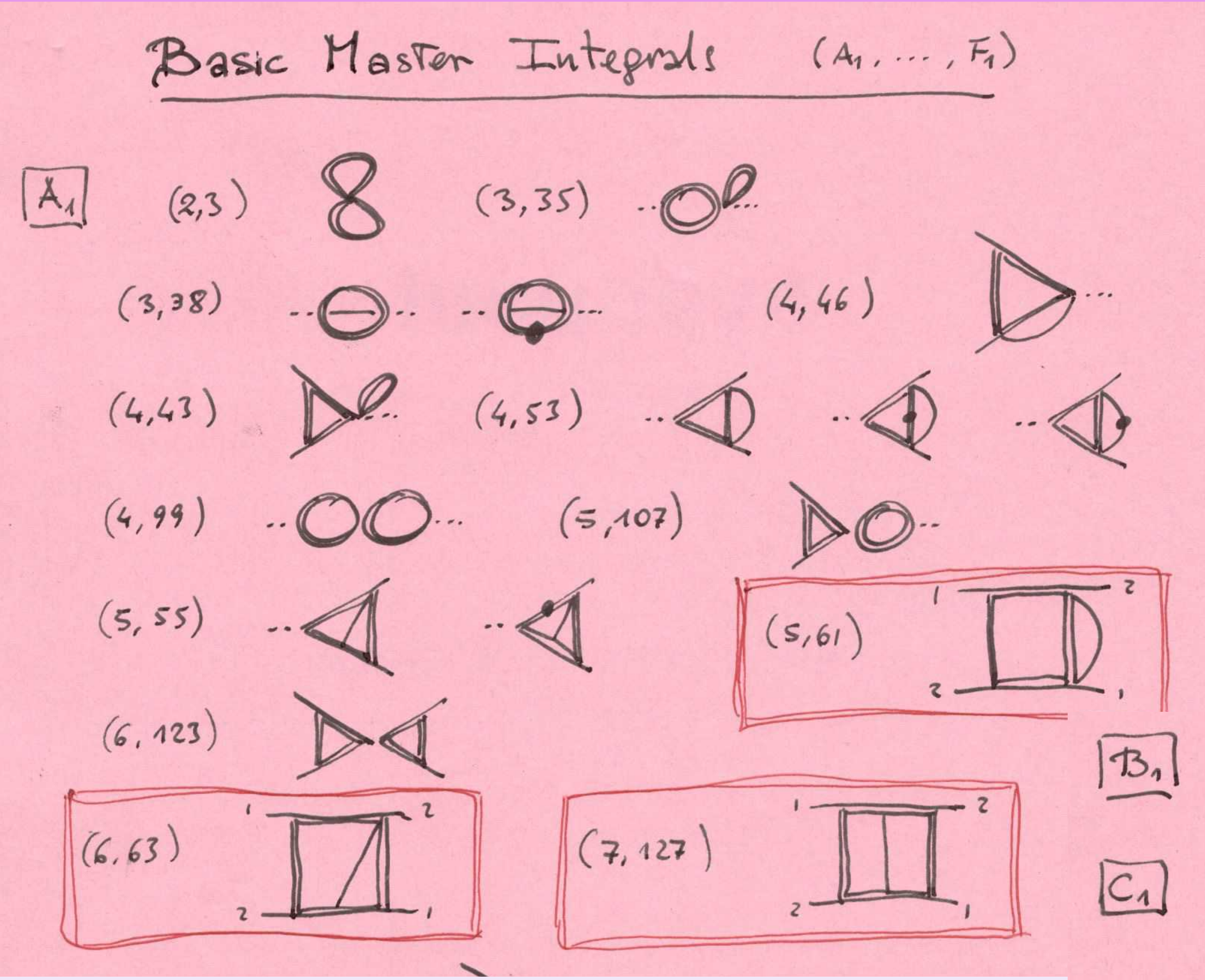
Summary

[Balzani, RG, Vitti '23]

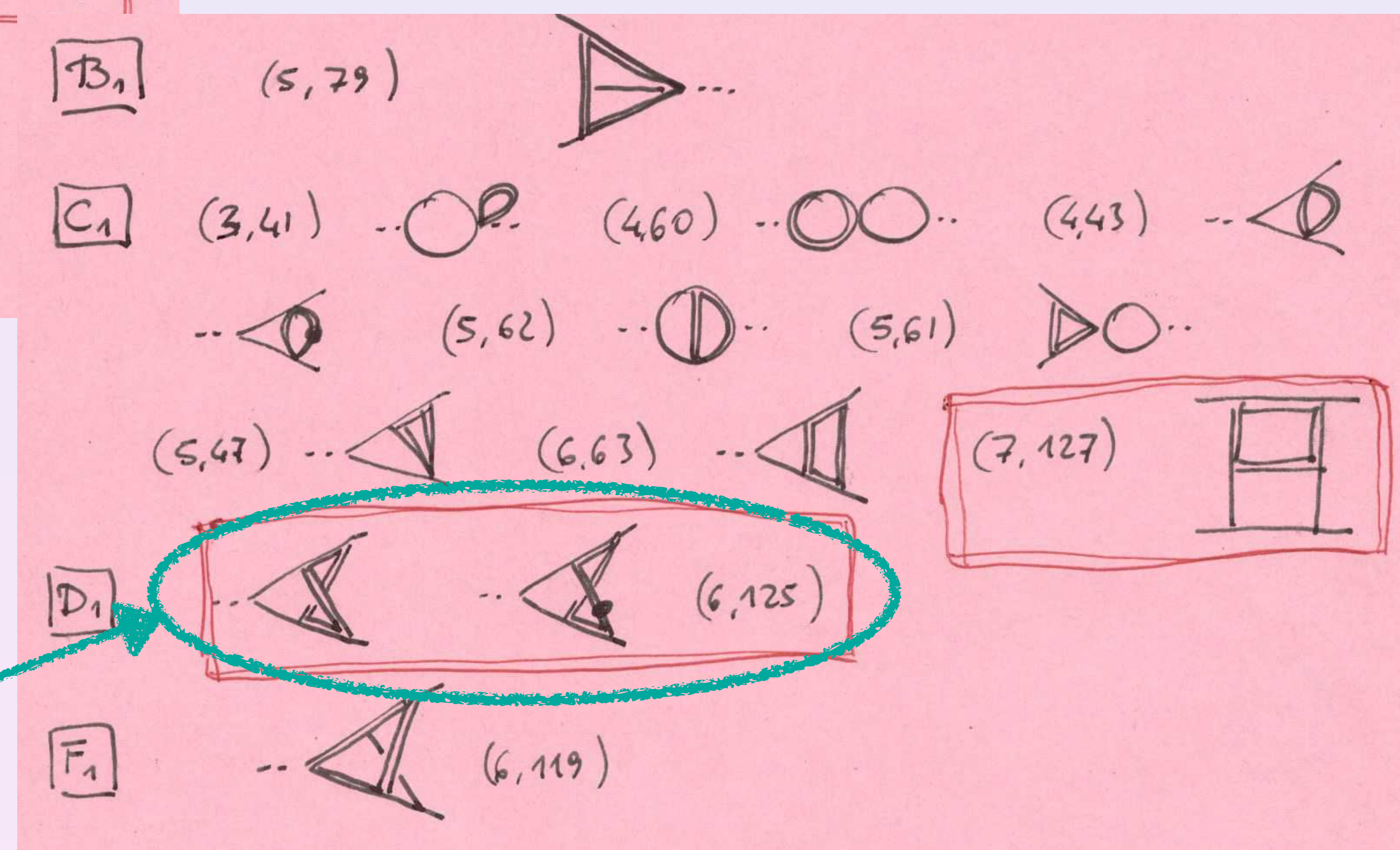


P_T expansion

NLO expansion

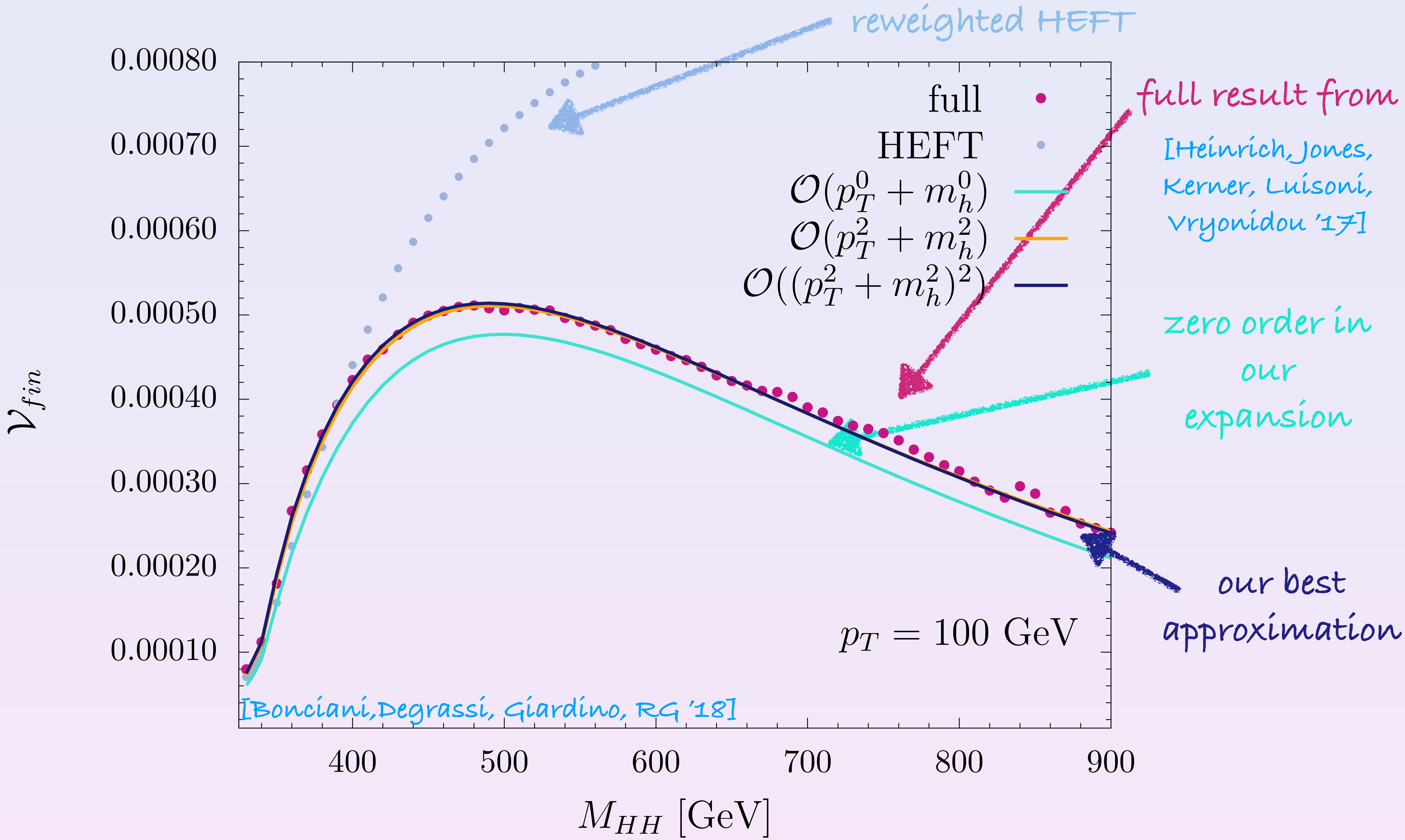


- O(50) master integrals
  - all of them known, though we needed to recompute some for the forward kinematics



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

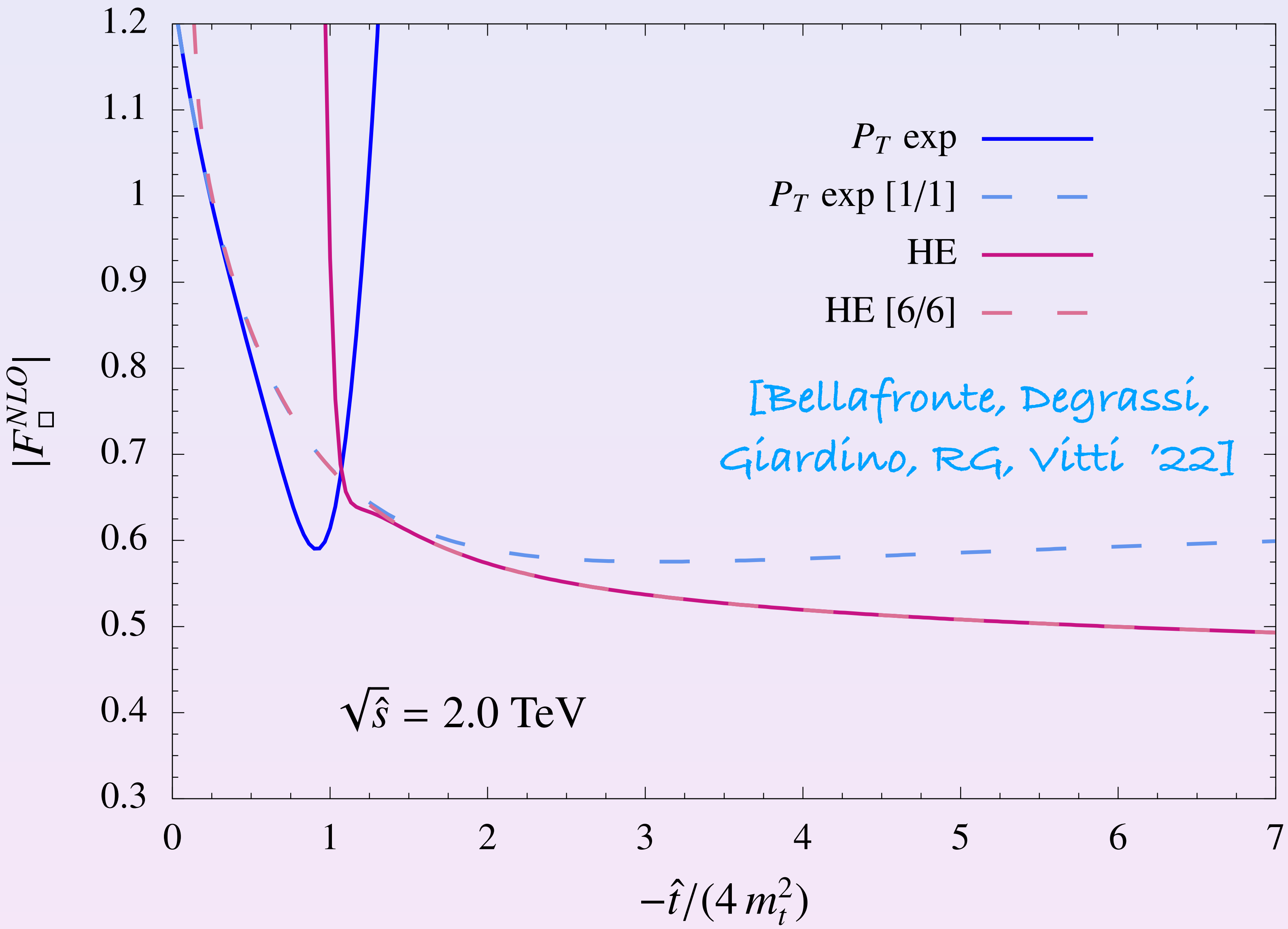
NLO results



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]