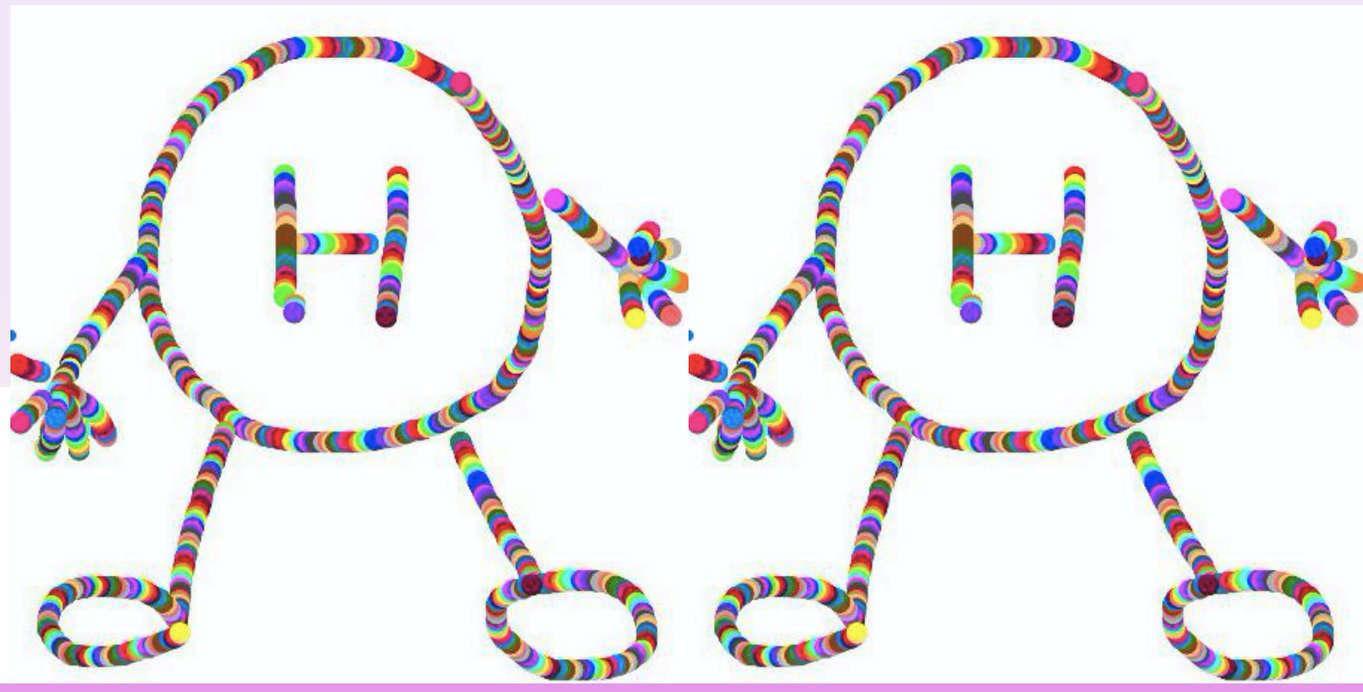
BSM effects in di-Higgs production

Ramona Gröber

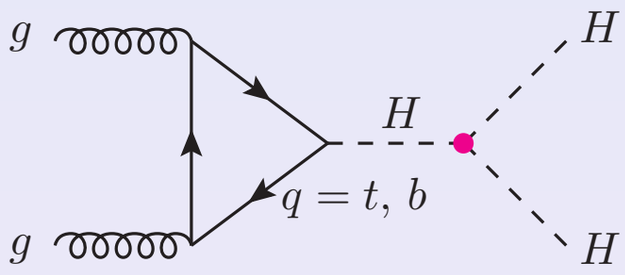
WIN2021

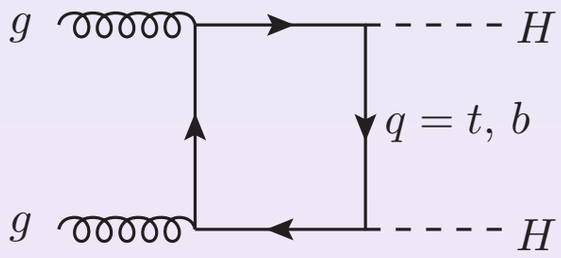
09/06/2021



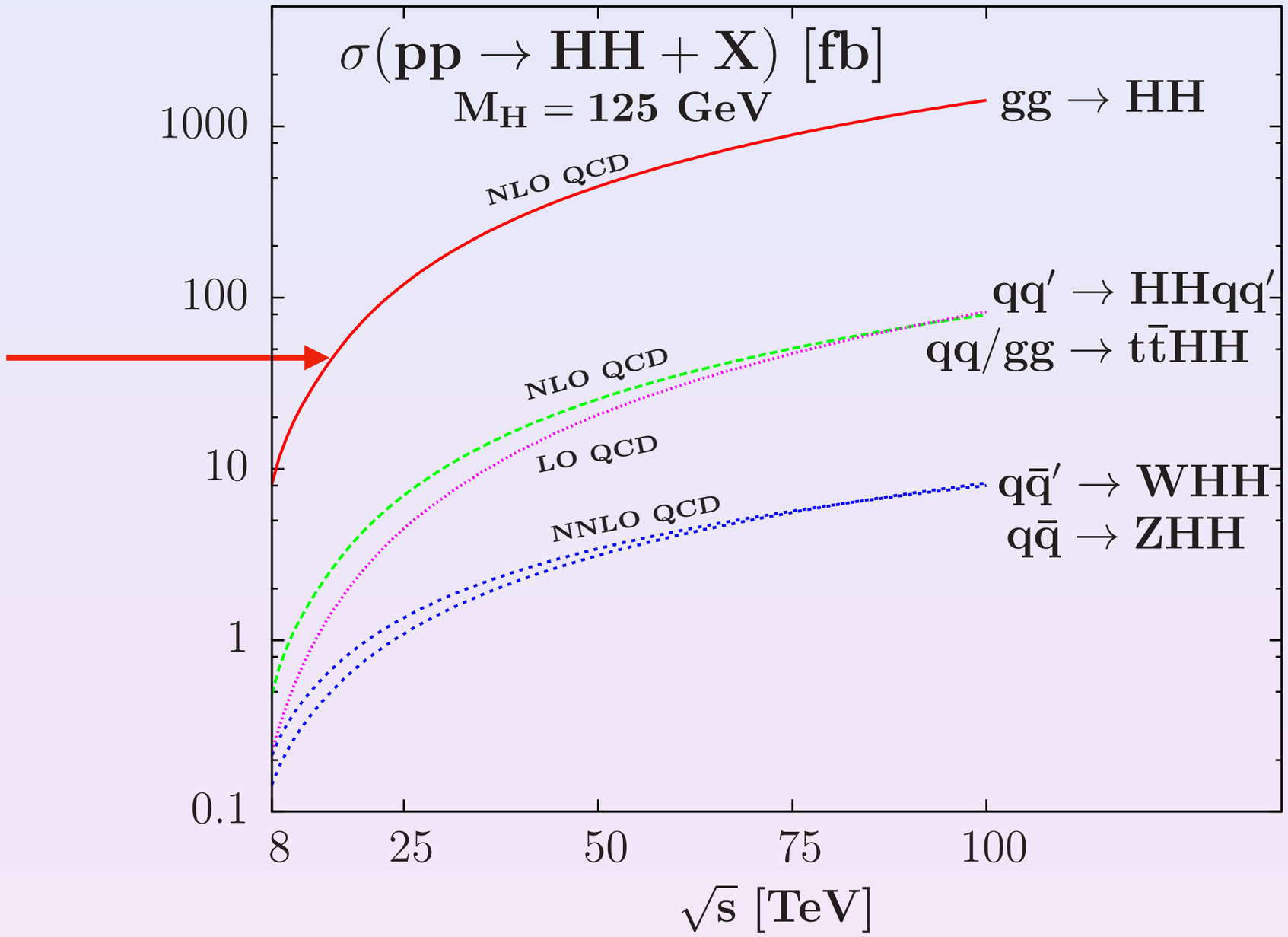
Higgs pair production in the SM

$gg \to HH$



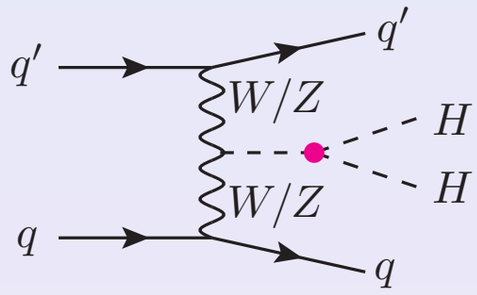


[Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12]

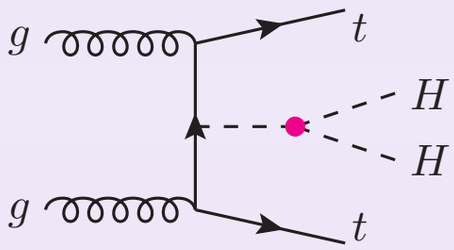


Higgs pair production in the SM

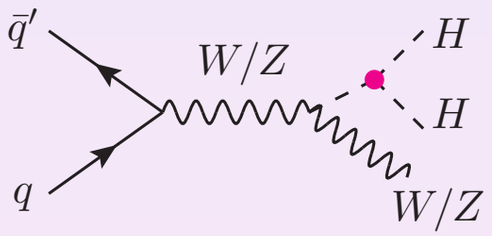
$qq' \to HHqq'$



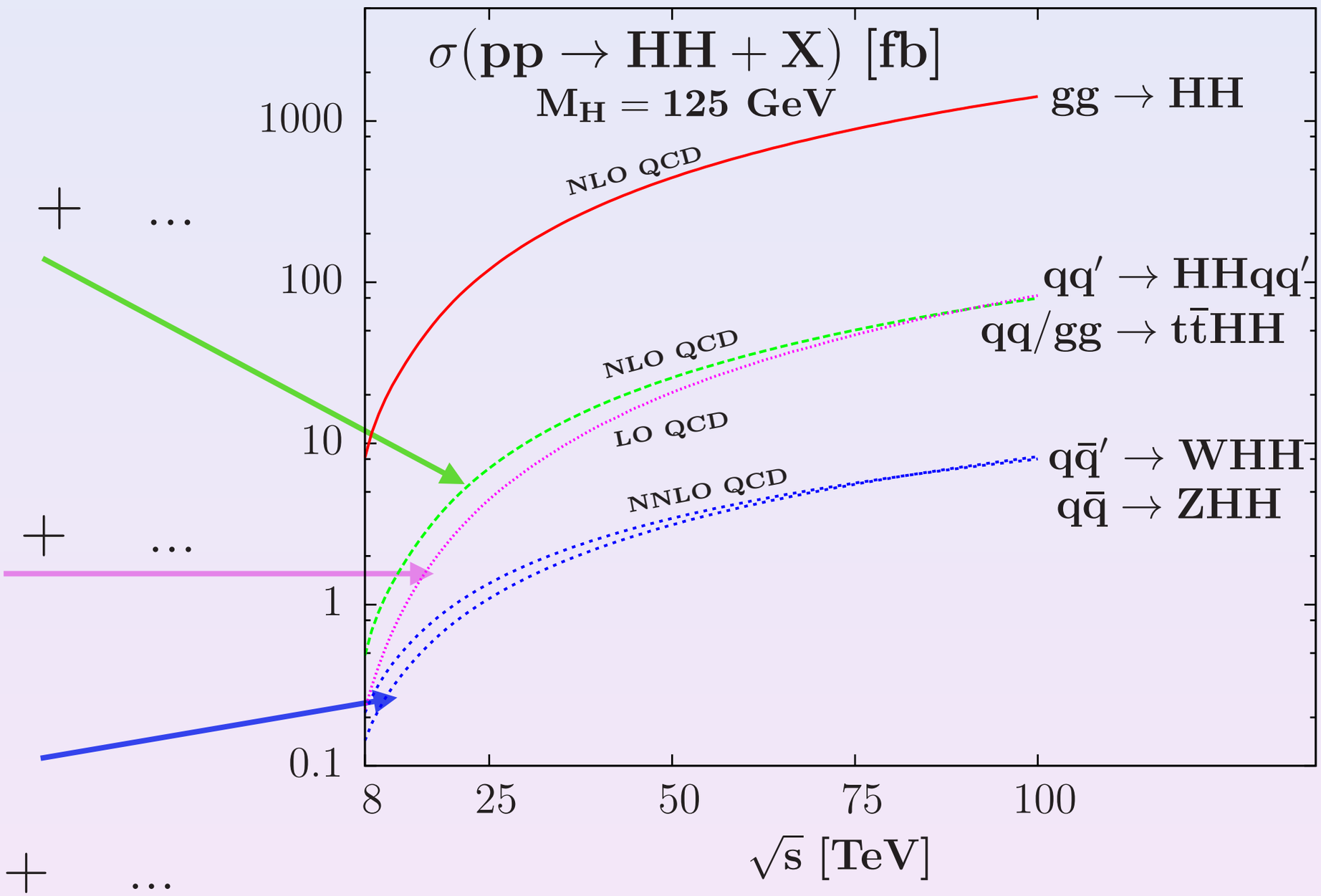
$q\bar{q}/gg \to t\bar{t}HH$



$q\bar{q}' \to ZHH/WHH$



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



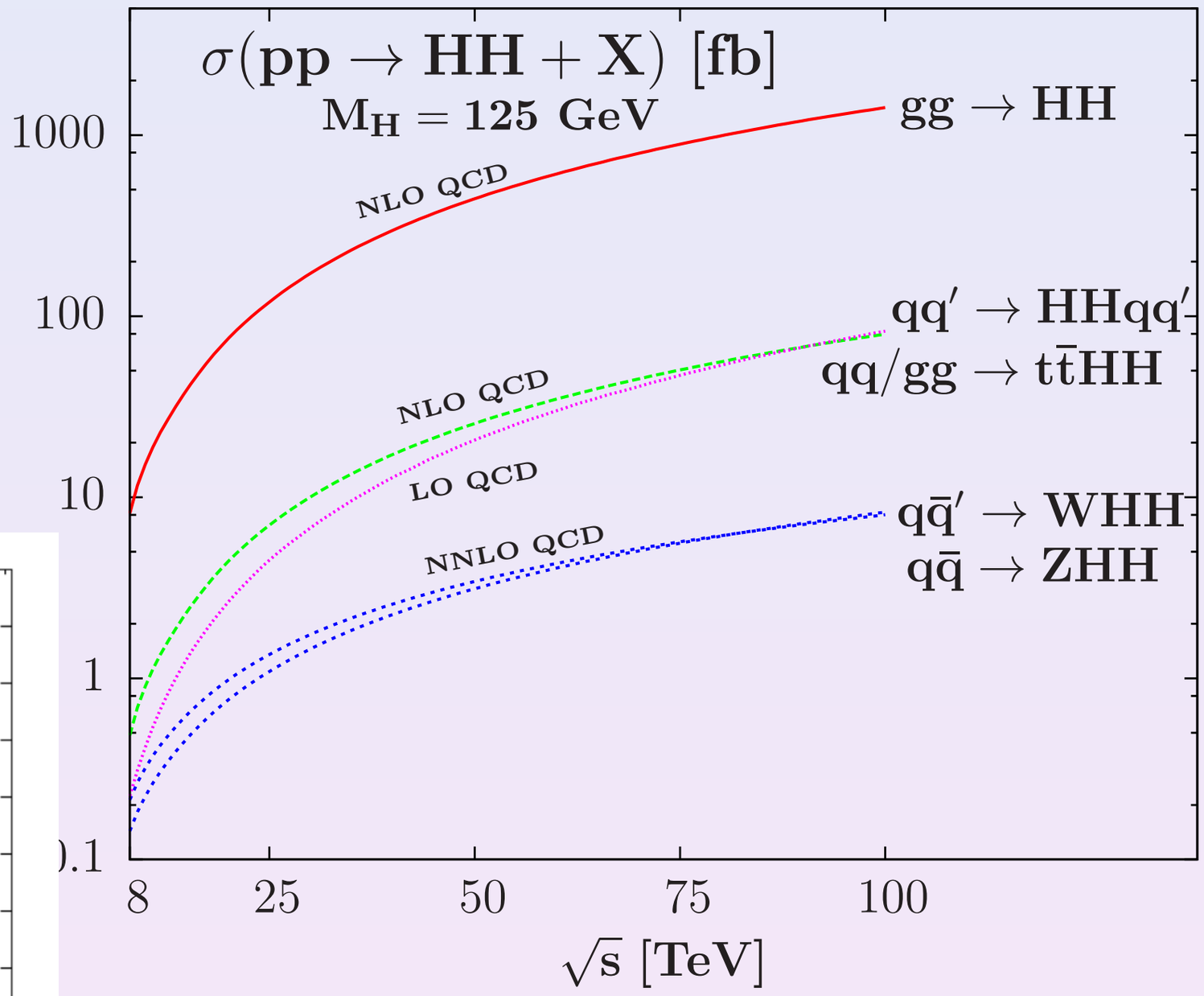
Higgs pair production in the SM

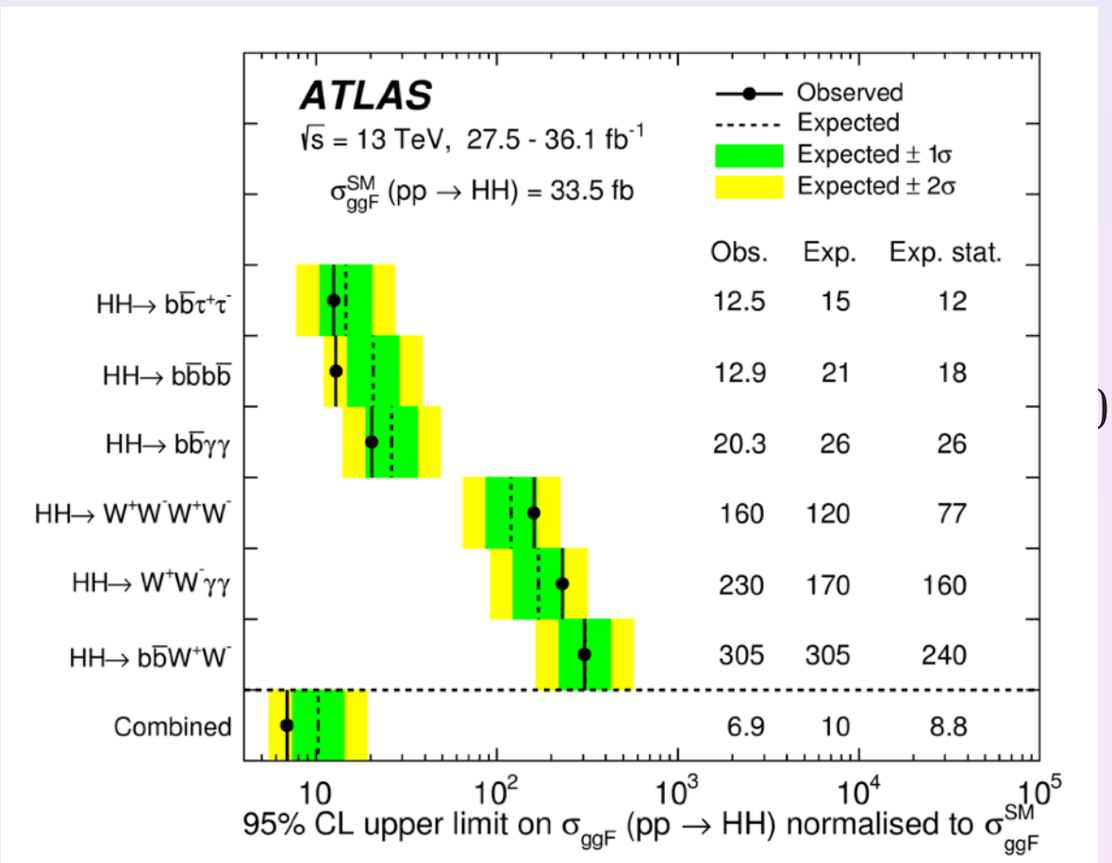
trilinear Higgs self-coupling accessible

Small cross section

Difficult to measure

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





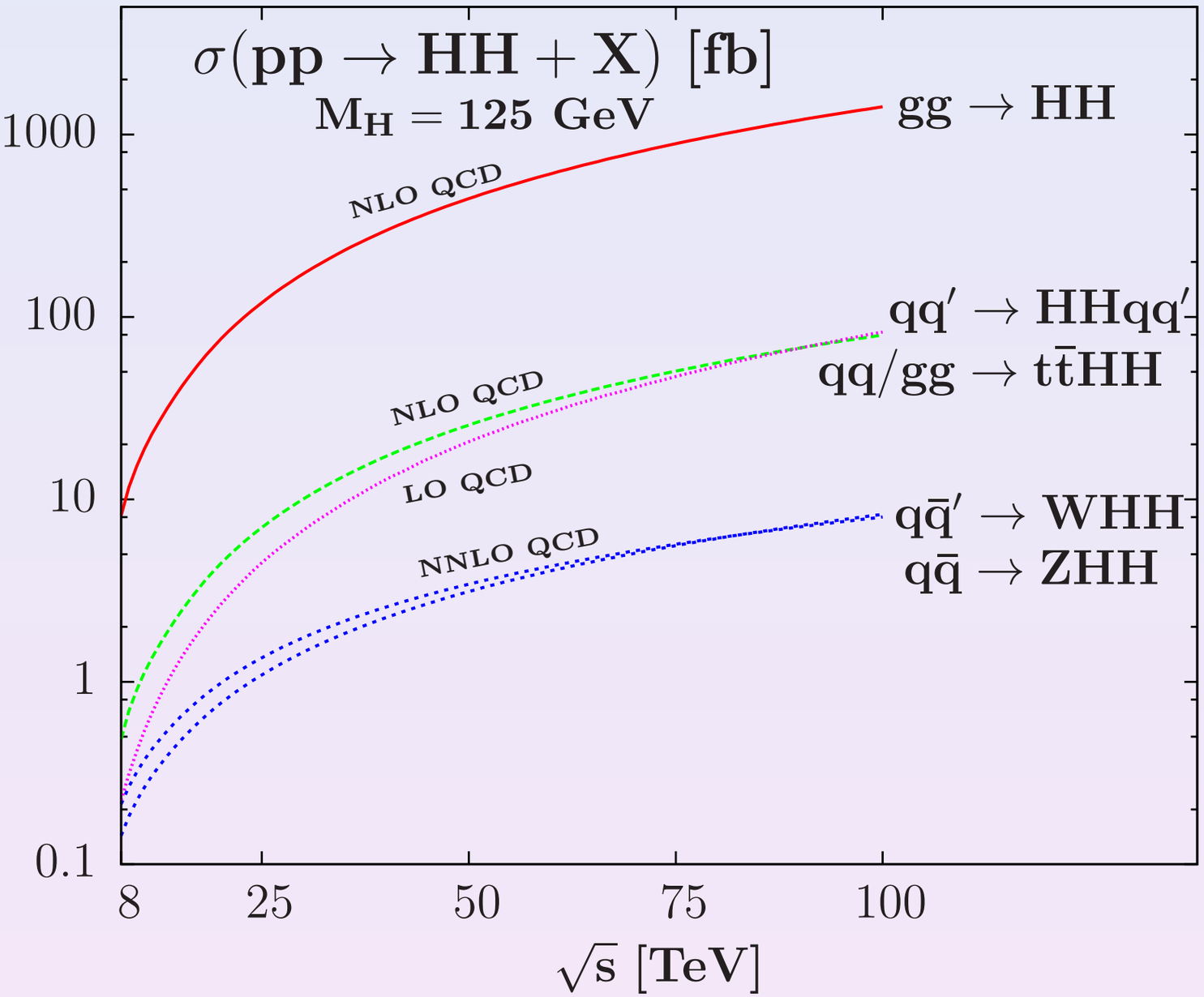
Higgs pair production in the SM

trilinear Higgs self-coupling accessible

Small cross section

Difficult to measure

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



other processes can also be promising

[Dolan, Englert, Greiner, Nordström, Spannowsky, '15, Englert, Krauss, Spannowksy, Thompson '14, Nordström, Papaefstathiou '18, Bishara, Rojo, Contino '16, Arganda, García-García, Herrero '18, ...]

Rest of the talk: gluon fusion

BSM in HH

- A Higgs pair can be resonantly produced

- Non-resonant production:

★ Probes Higgs non-linearities

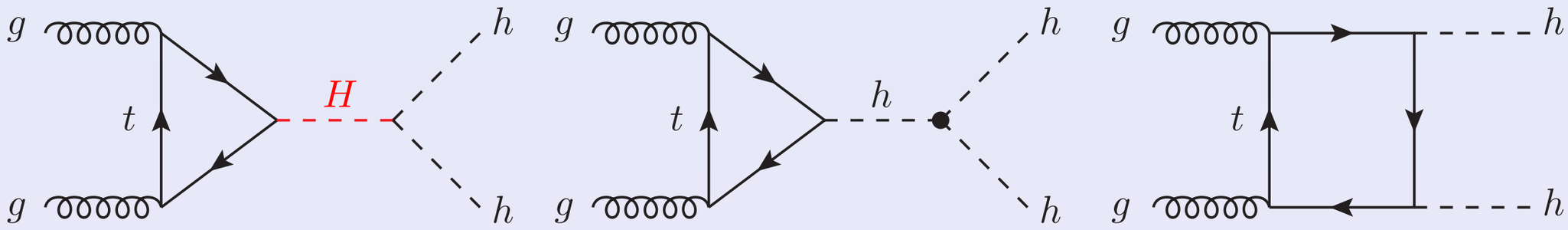
★ Probes the trilinear Higgs self-coupling

★ New particles in the loop

★ Probes light quark Yukawa couplings

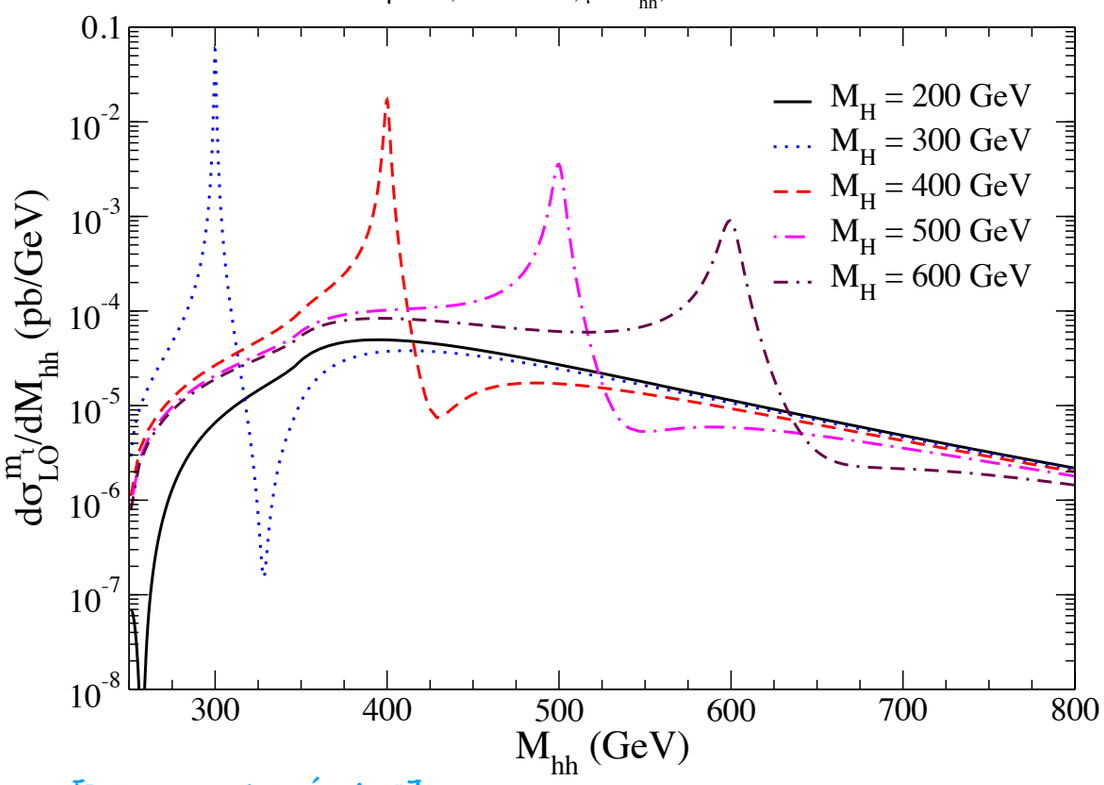
Resonant HH production

Resonant Higgs pair production



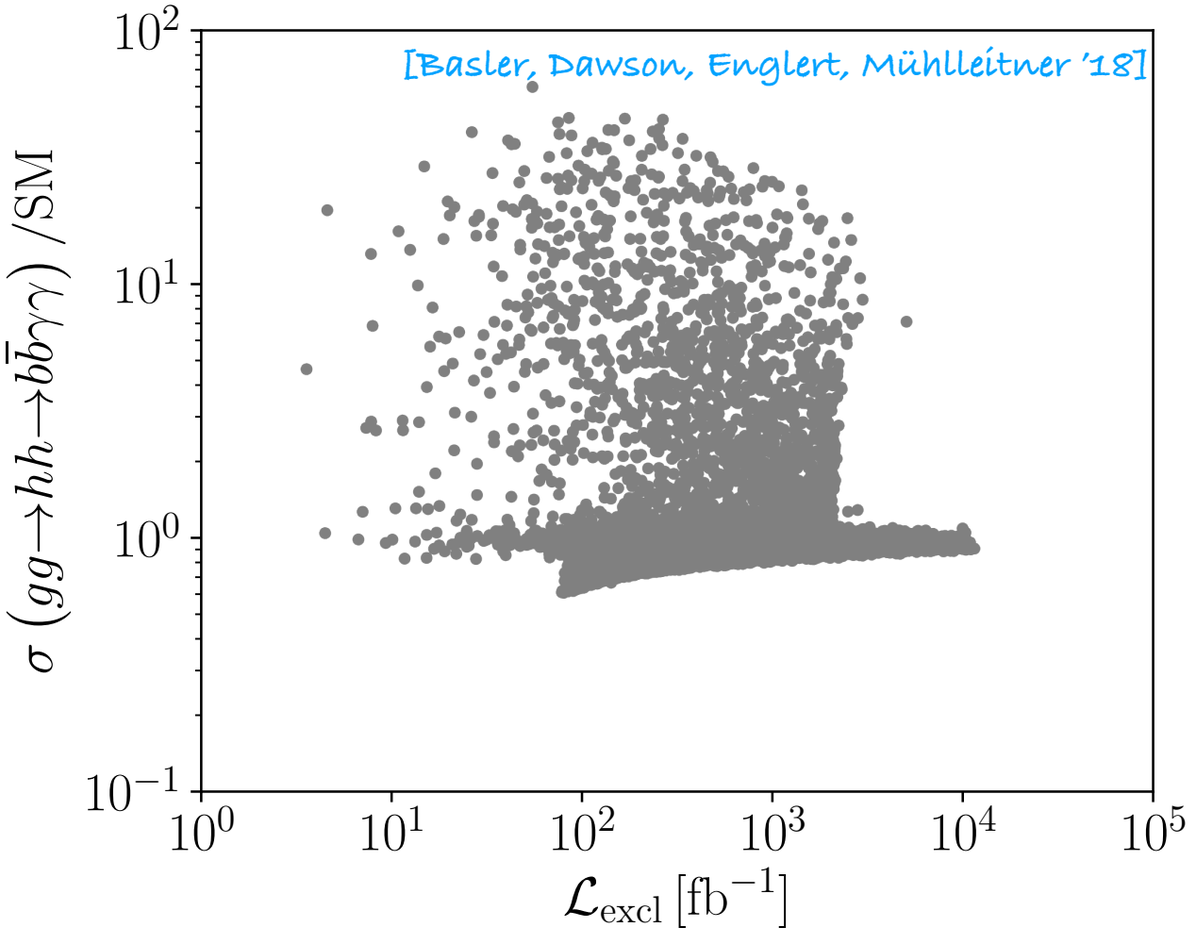
Typical signal in multi-Higgs models where the new Higgs is not too heavy.

E.g. singlet model, 2HDM, NMSSM, ...



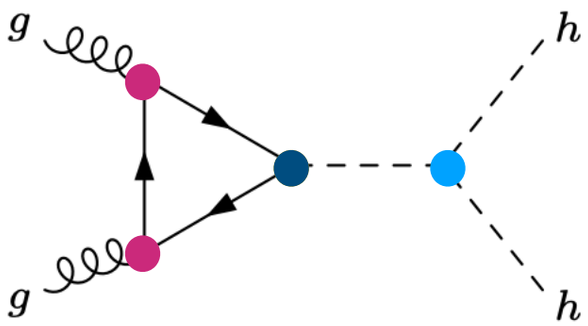
[Dawson, Lewis '14]

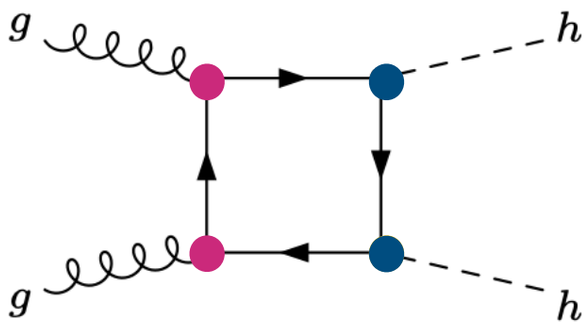
C2HDM

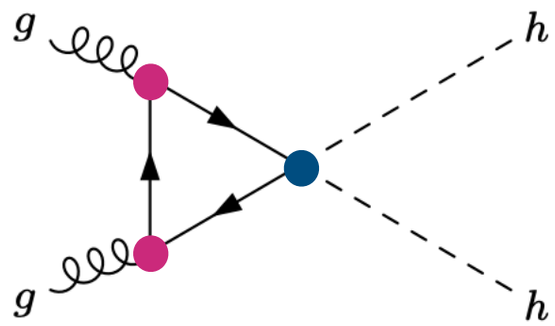


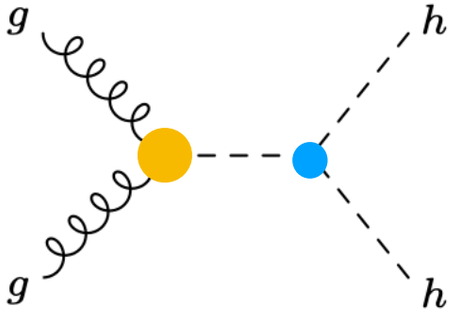
Higgs non-linearities and EFT

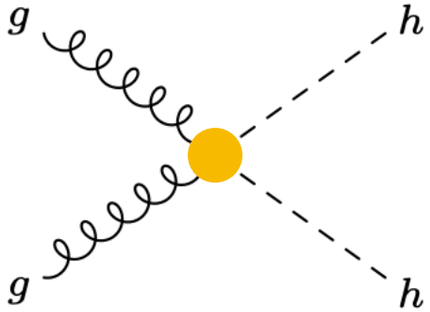
Non-resonant HH production

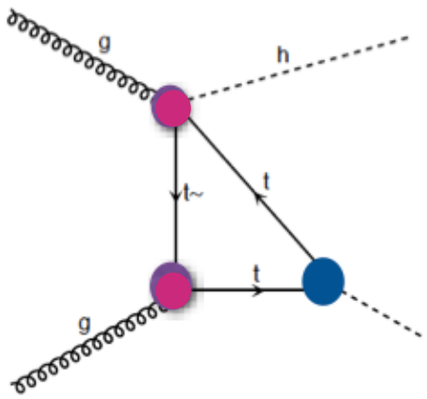








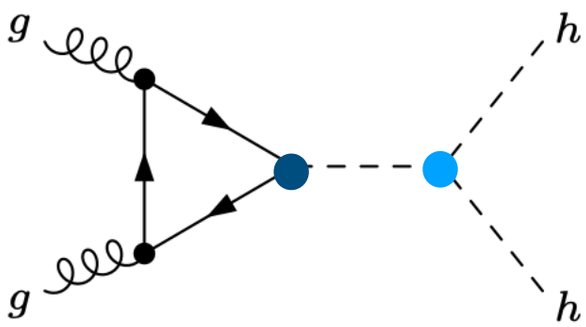


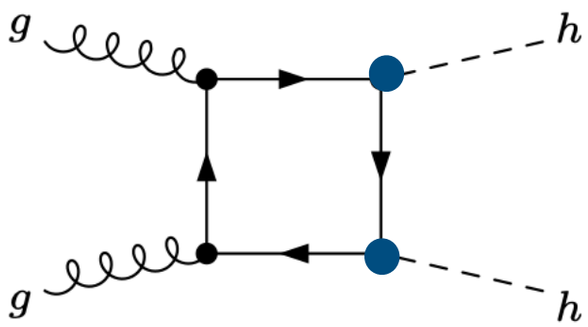


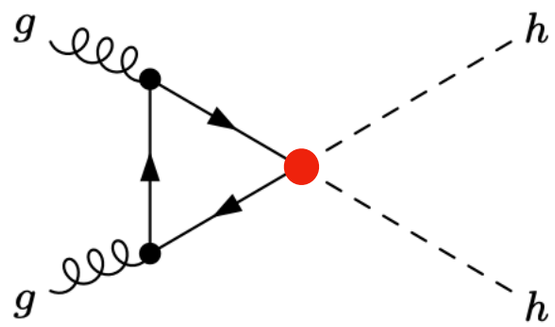
SMEFT:

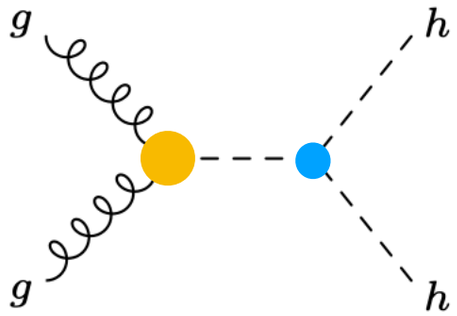
$$\mathscr{L} = \frac{c_H}{\Lambda^2}(H^\dagger \partial_\mu H)^2 + \frac{c_6}{\Lambda^2}|H|^6 + \frac{c_g}{\Lambda^2}|H|^2 G_{\mu\nu}G^{\mu\nu} + \frac{y_t c_y}{\Lambda^2}\bar{Q}_L \tilde{H} t_R |H|^2 + h.c. + \frac{c_{tG}}{\Lambda^2}\bar{Q}_L \sigma_{\mu\nu} T^a \tilde{H} t_R G^a_{\mu\nu} + h.c.$$

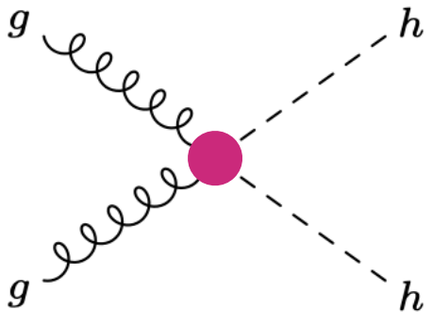
Effective Theory for HH







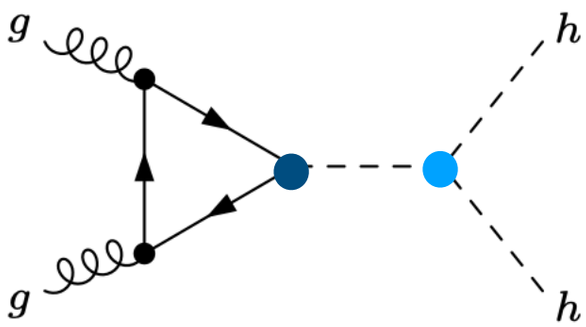


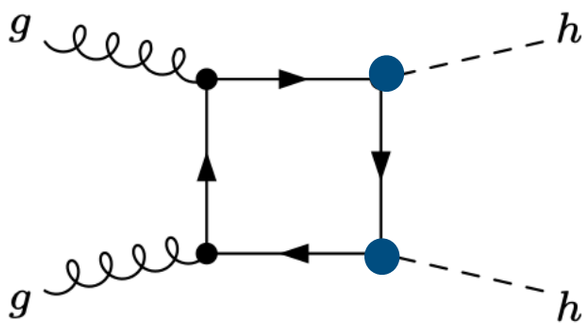


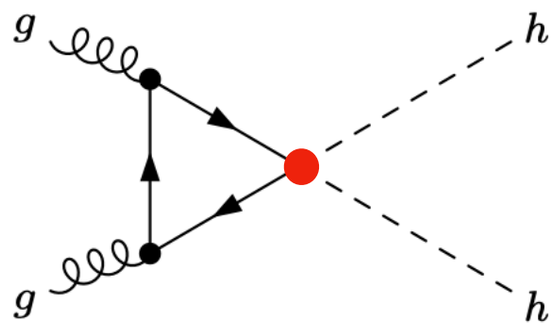
HEFT:

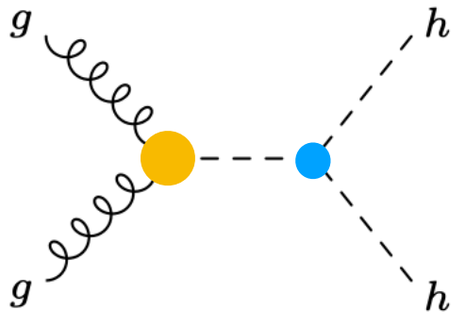
$$\mathscr{L} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) + \frac{\alpha_s}{8\pi} \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{v^2} \right) G^{\mu\nu} G_{\mu\nu} + c_{hhh} \frac{m_h^2}{2v} h^3$$

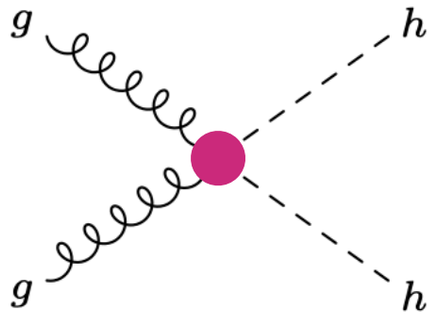
Effective Theory for HH











HEFT:

two Higgs couplings only to be probed in HH

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

HEFT/SMEFT for HH?

HEFT

strongly-interacting models, larger deviations from SM

⊕ di-Higgs is THE place to probe differences in one or two Higgs couplings

⊕ NLO results available

[Buchalla et al '18; Heinrich et al '20]

⊖ many more couplings only in HH: degeneracies?

⊖ UV models that don't linearise to SMEFT?

SMEFT

weakly coupled models, smooth deviation from SM

⊕ contains dipole operator (which by power counting is expected to be of higher order though)

⊕ Combination with single Higgs fits simpler

Trilinear Higgs self-coupling

Trilinear coupling

One of the primary goals of the HL-LHC

Probes the Higgs boson potential

$$V = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

EWSB

$$V(h) = \underbrace{\frac{1}{2} m_h^2}_{\mu^2} h^2 + \frac{1}{3!} \underbrace{\lambda_{hhh}}_{= \frac{3\, m_h^2}{v}} h^3 + \frac{1}{4!} \underbrace{\lambda_{hhhh}}_{= \frac{3\, m_h^2}{v^2}} h^4$$

Trilinear coupling

One of the primary goals of the HL-LHC

Probes the Higgs boson potential

$$V = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

EWSB

$$V(h) = \underbrace{\frac{1}{2} m_h^2}_{\mu^2} h^2 + \frac{1}{3!} \underbrace{\lambda_{hhh}}_{= \frac{3\, m_h^2}{v}} h^3 + \frac{1}{4!} \underbrace{\lambda_{hhhh}}_{= \frac{3\, m_h^2}{v^2}} h^4$$

strong 1st order ew phase transition usually predicts modified trilinear Higgs self-coupling

nightmare scenario: scalar singlet

[Curtin, Meade, Yu '15]

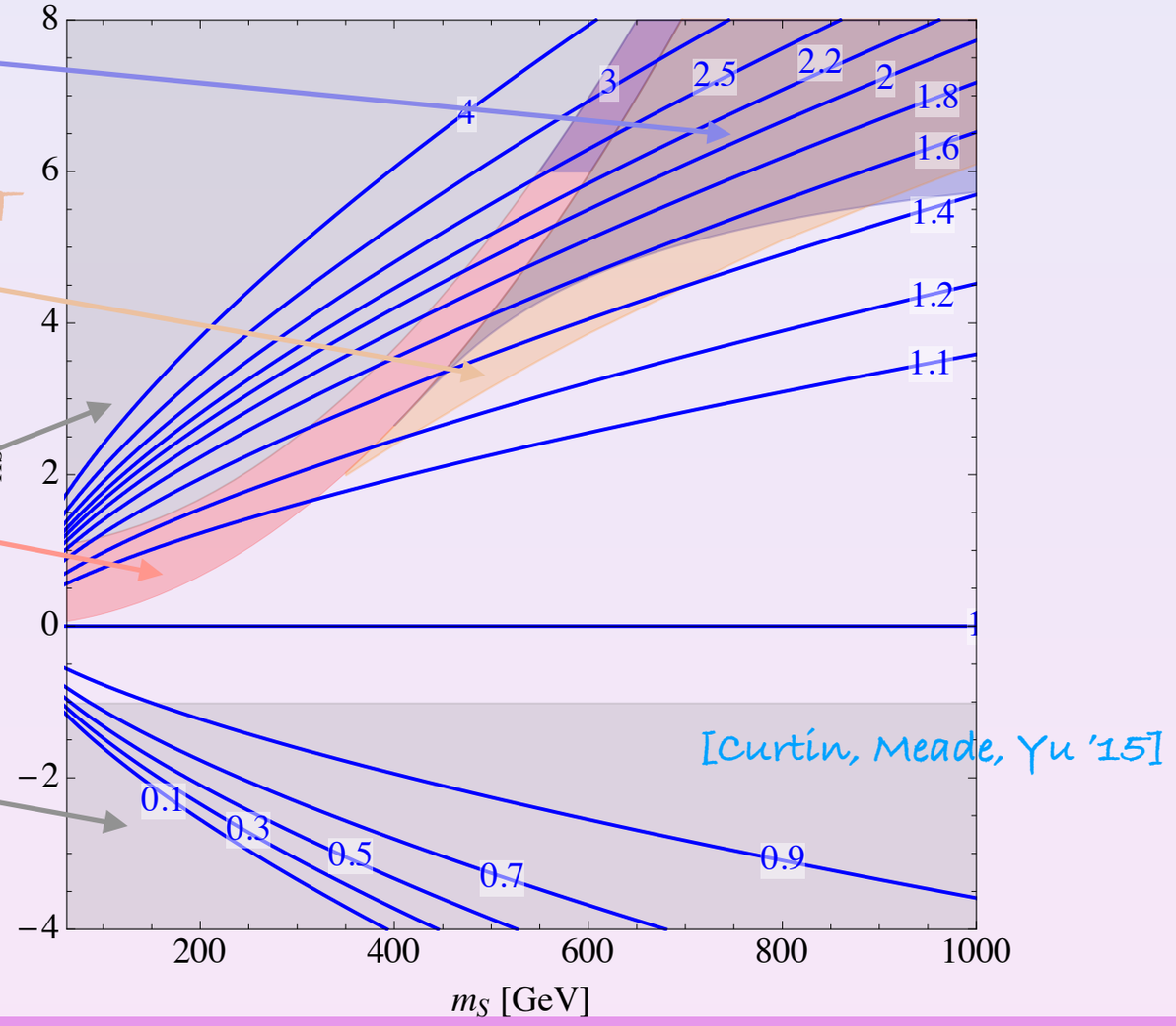
target for trilinear Higgs self-coupling: 20-30 %

one loop analysis unreliable

one step EWPT

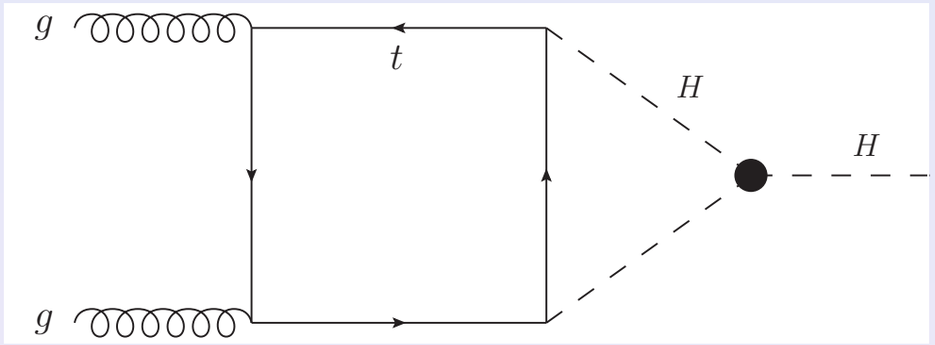
two step EWPT

non perturbative singlet quartic



Trilinear coupling: interplay with Single Higgs

Trilinear Higgs self-coupling enters via electroweak loops to single Higgs production



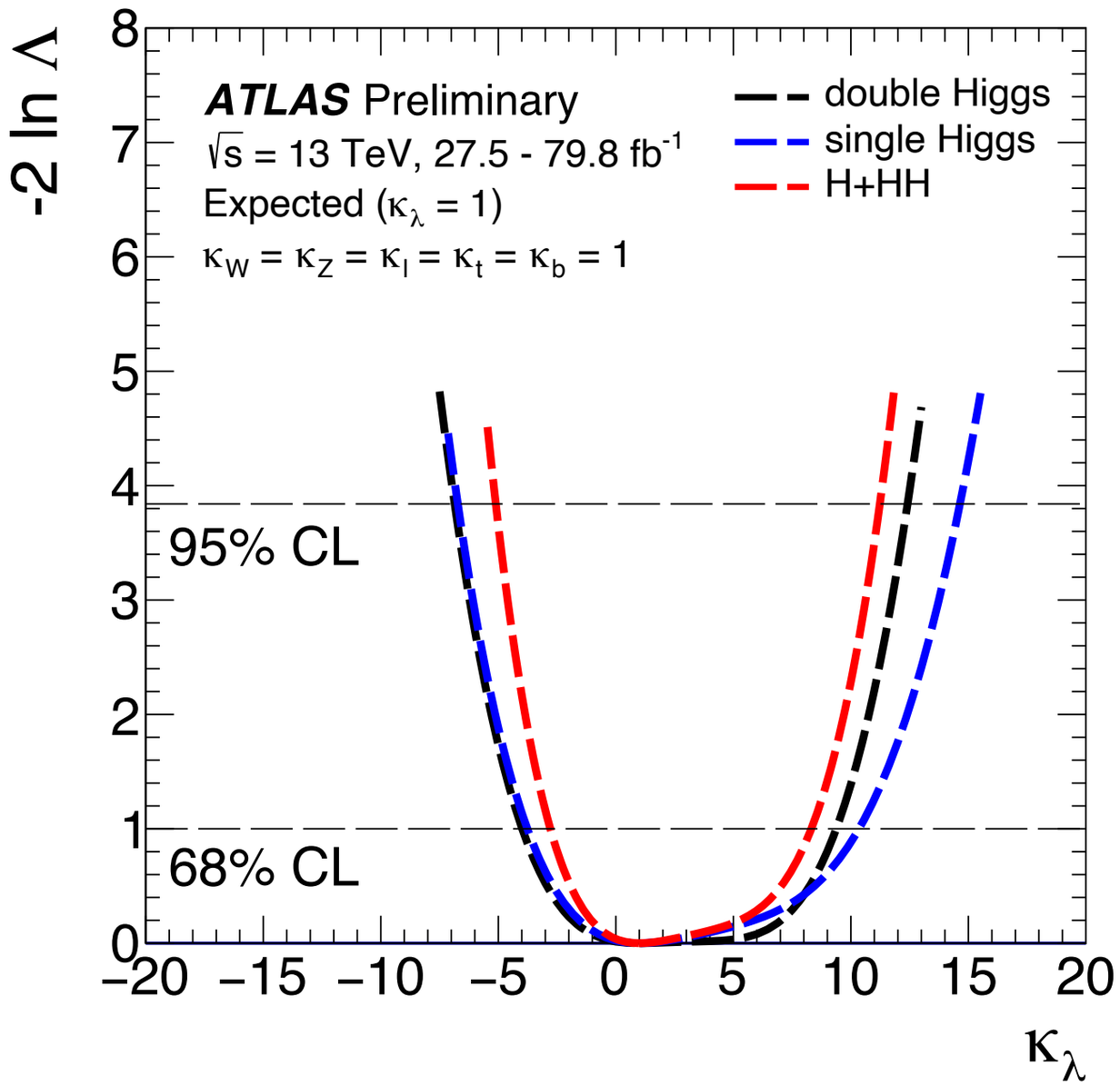
[McCullough '14, Gorbahn, Haisch '16, Degrassi, Giardino, Maltoni, Pagani '16, Bizon, Gorbahn, Haisch Zanderighi '16]

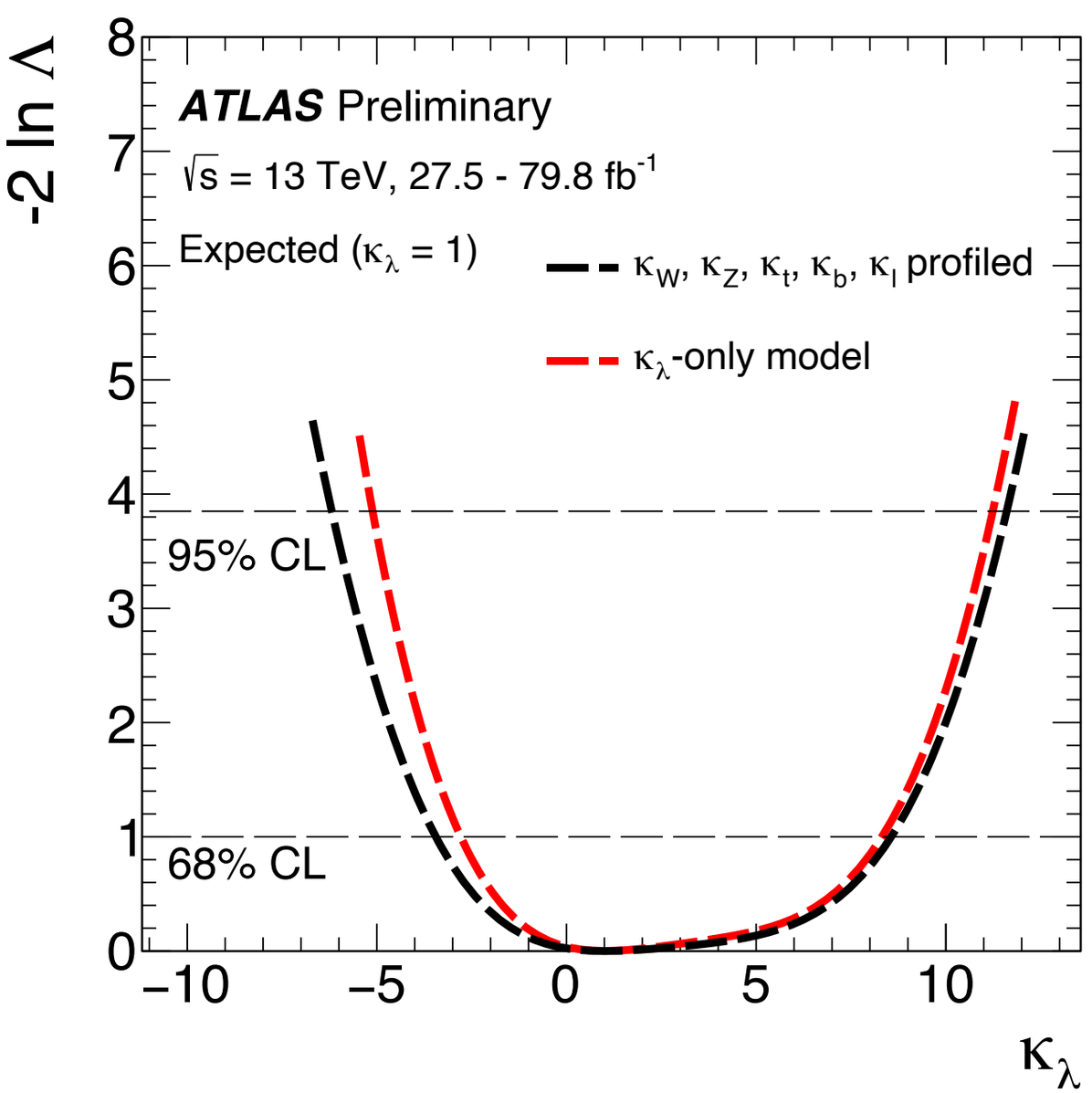
Global fit necessary, including HH and differential measurements to resolve degeneracies

[Di Vita, Grojean, Panico, Rimbau, Vantalon '17, Maltoni, Pagani, Shivaji, Zhao '18]

Trilinear coupling: interplay with Single Higgs

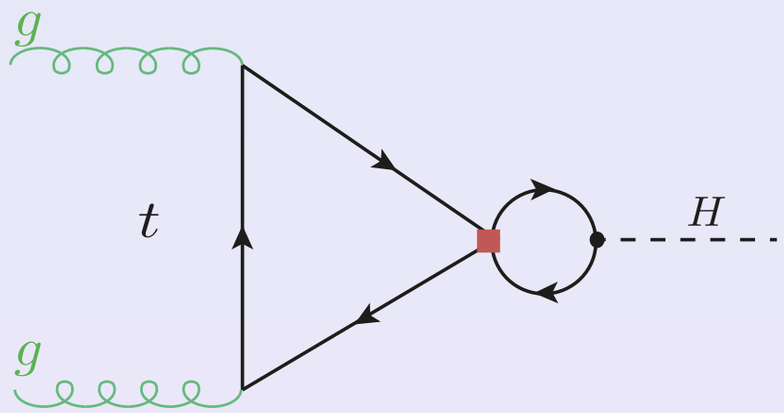
Trilinear Higgs self-coupling enters via electroweak loops to single Higgs production





Operators entering at NLO

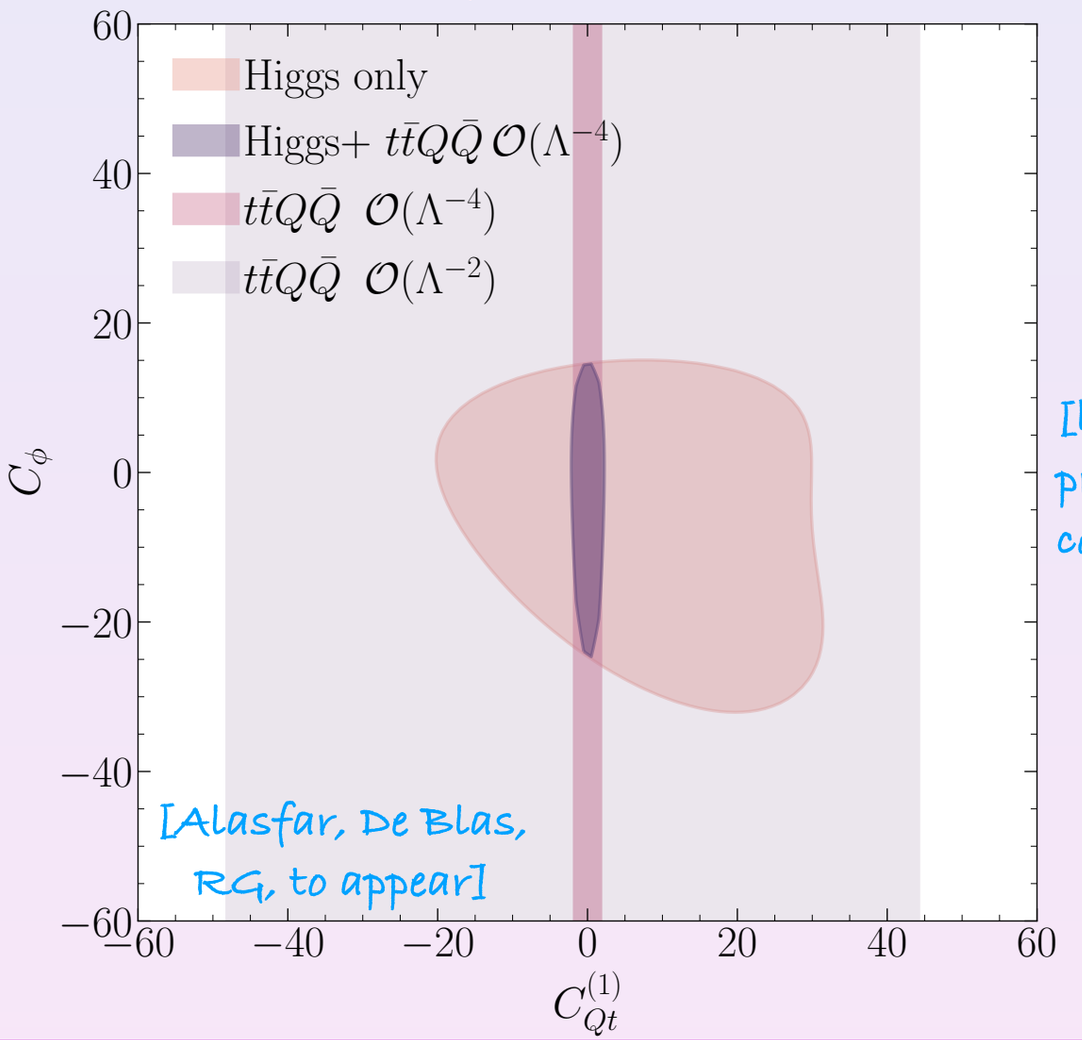
But is it enough to include the tree-level operators into the global fit?



E.g. poorly constrained four-fermion operators enter at NLO to single Higgs production and decay

[work in progress with L. Alasfar and J. De Blas]

$$\frac{C_\Phi}{\Lambda^2}|H|^6$$



[bounds from 4 top production from SMEFiT collaboration '21]

$$\frac{C_{Qt}^{(1)}}{\Lambda^2}(\bar{Q}_L\gamma_\mu Q_L)(\bar{t}_R\gamma^\mu t_R)$$

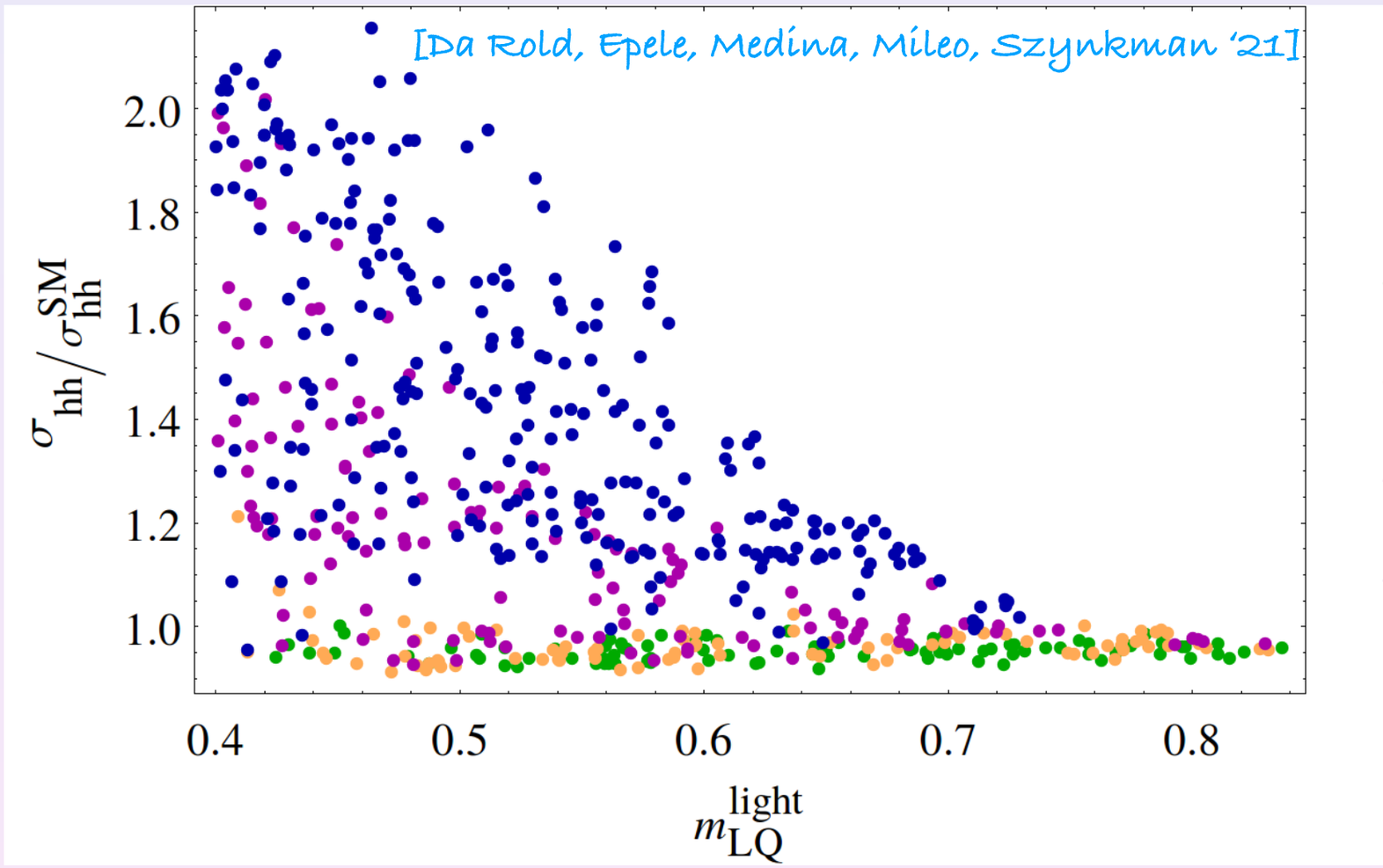
New particles in the loop

New particles in the loop

Vector-like quarks or colored scalars contribute to the gluon fusion loop

Difficult to get sizeable effects (where the EFT is not applicable) given exclusion limits on coloured new particles

Model with scalar leptoquarks



Light quark 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]

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

global fit, not completely model-independent

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; Nakai, Shih, Thomas '20]
- Associate Higgs production with photon [Aquilar-Saavedra, Cano, No '20]
- Tri-Boson [Falkowski et al '20]
- Di-Higgs production [Alasfar, Corral Lopez, RG '19]

SMEFT: Light Yukawa couplings

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

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

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

Couplings:

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

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

direct coupling to Higgs pair

In the following consider only flavour diagonal case.

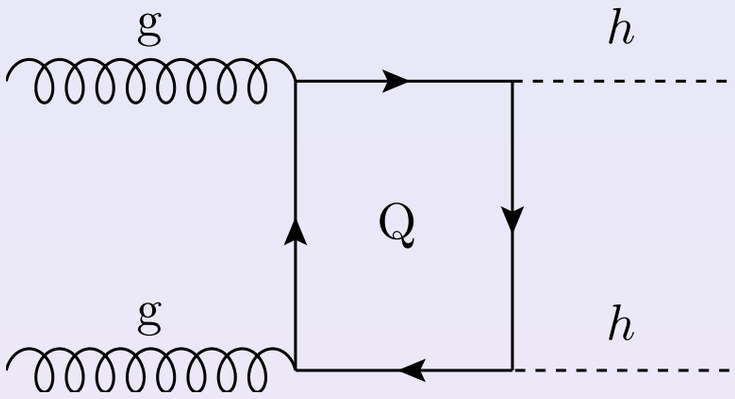
Notation:

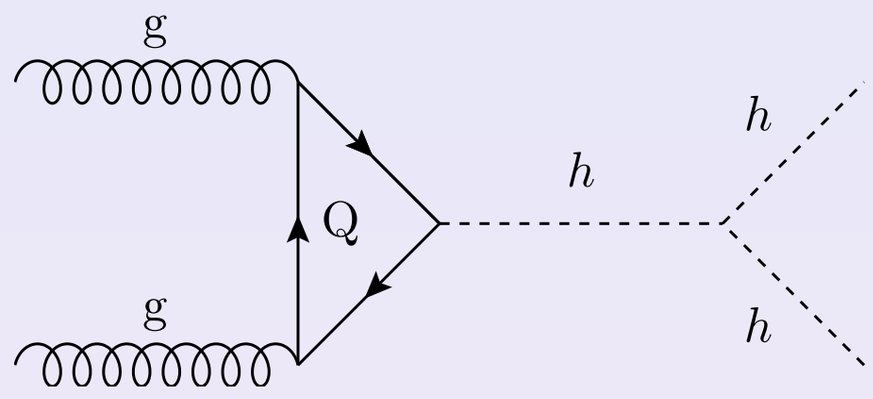
$$g_{h\bar{q}q} = \kappa_q g^{SM}_{h\bar{q}q}$$

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

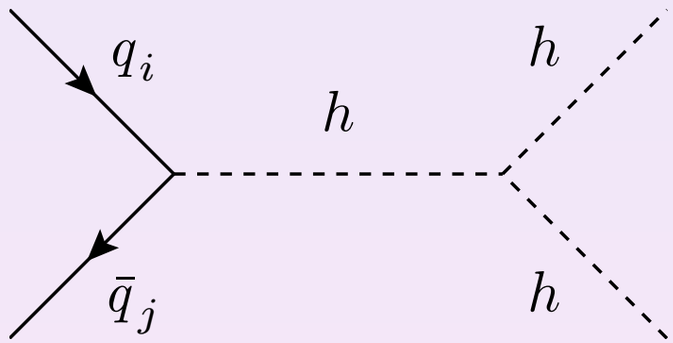
Higgs pair production

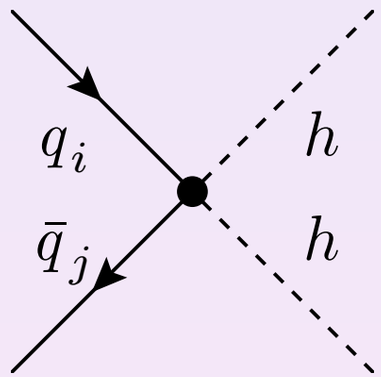
Higgs pair production in SM, gluon fusion dominated by heavy quark loops

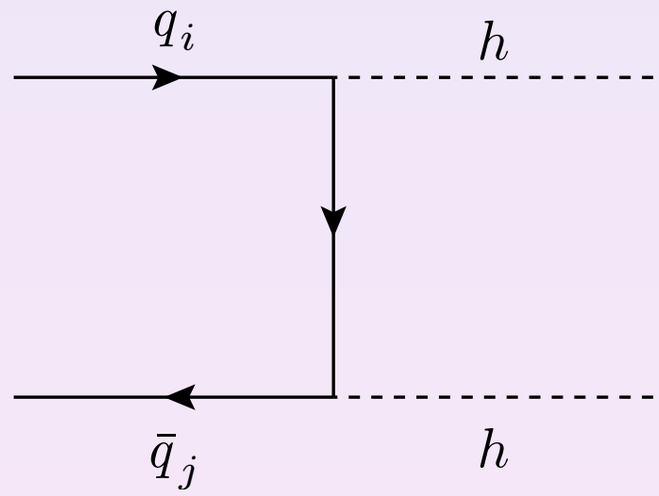




enhanced light Yukawa couplings

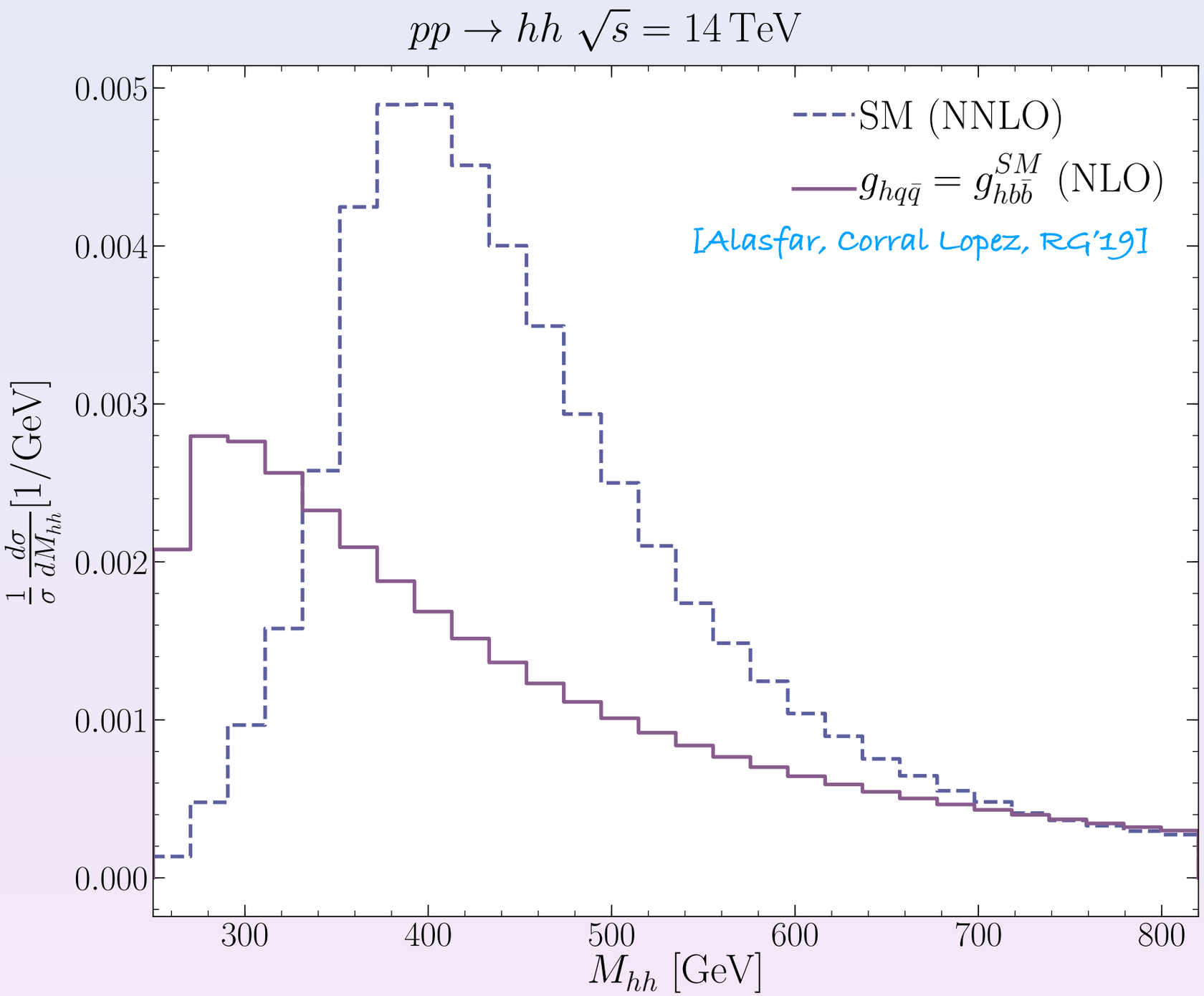






contribution most important for 1st generation (given the coupling limits)

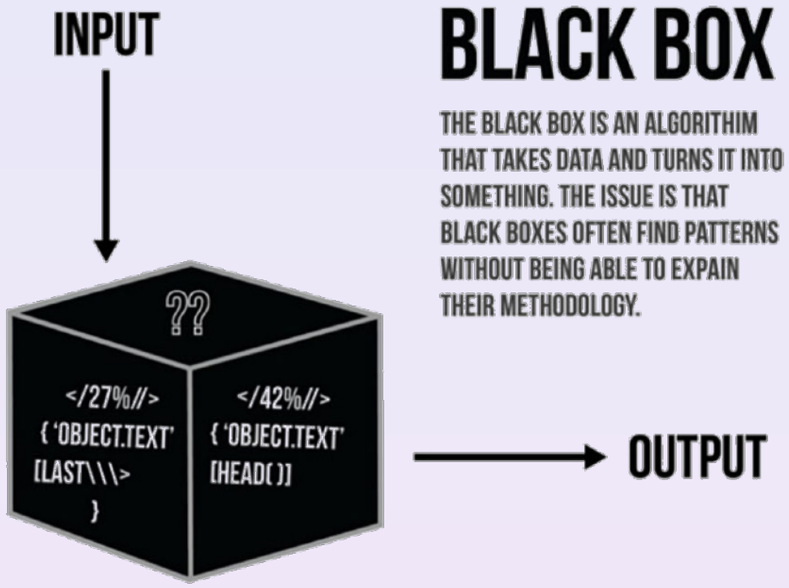
Distribution in invariant Higgs pair mass



kinematical distributions different?

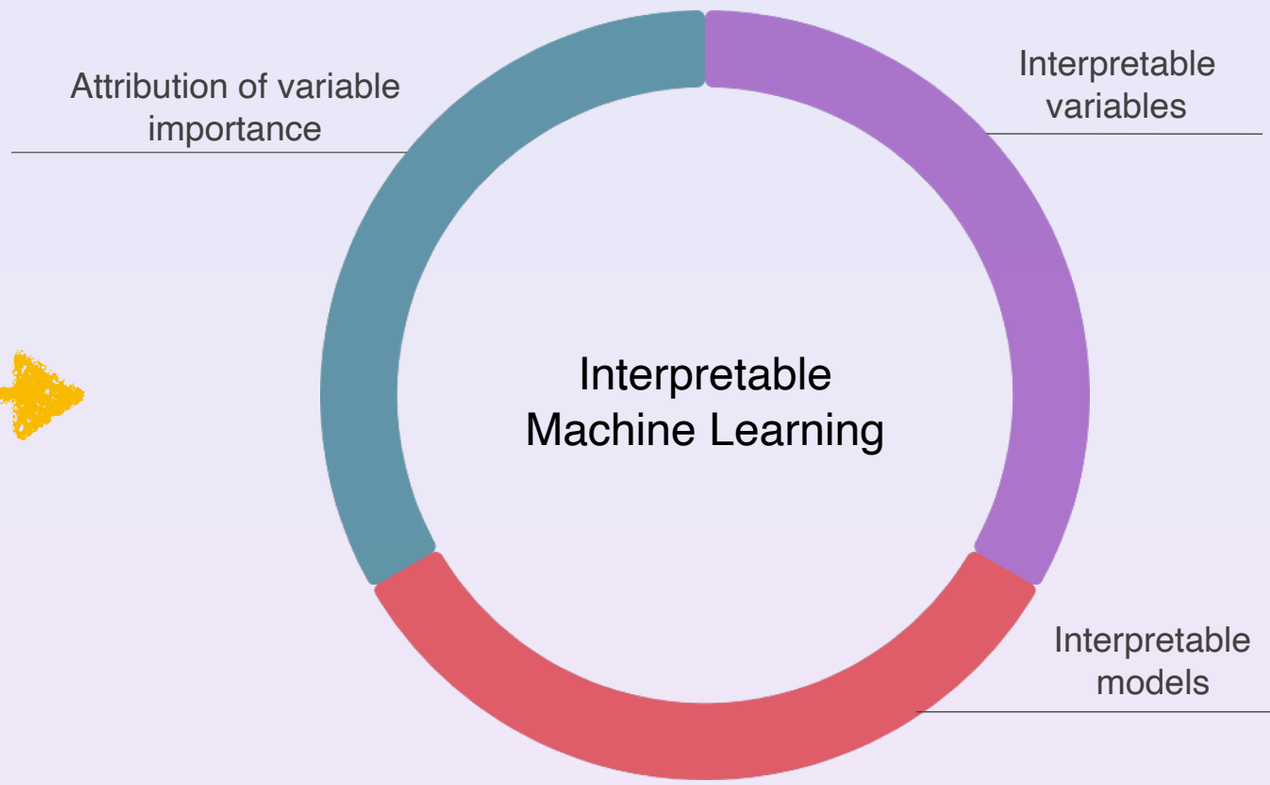
how can we get maximal information?
several EFT operators to constrain...

Interpretable Machine Learning



BLACK BOX

THE BLACK BOX IS AN ALGORITHIM THAT TAKES DATA AND TURNS IT INTO SOMETHING. THE ISSUE IS THAT BLACK BOXES OFTEN FIND PATTERNS WITHOUT BEING ABLE TO EXPAIN THEIR METHODOLOGY.

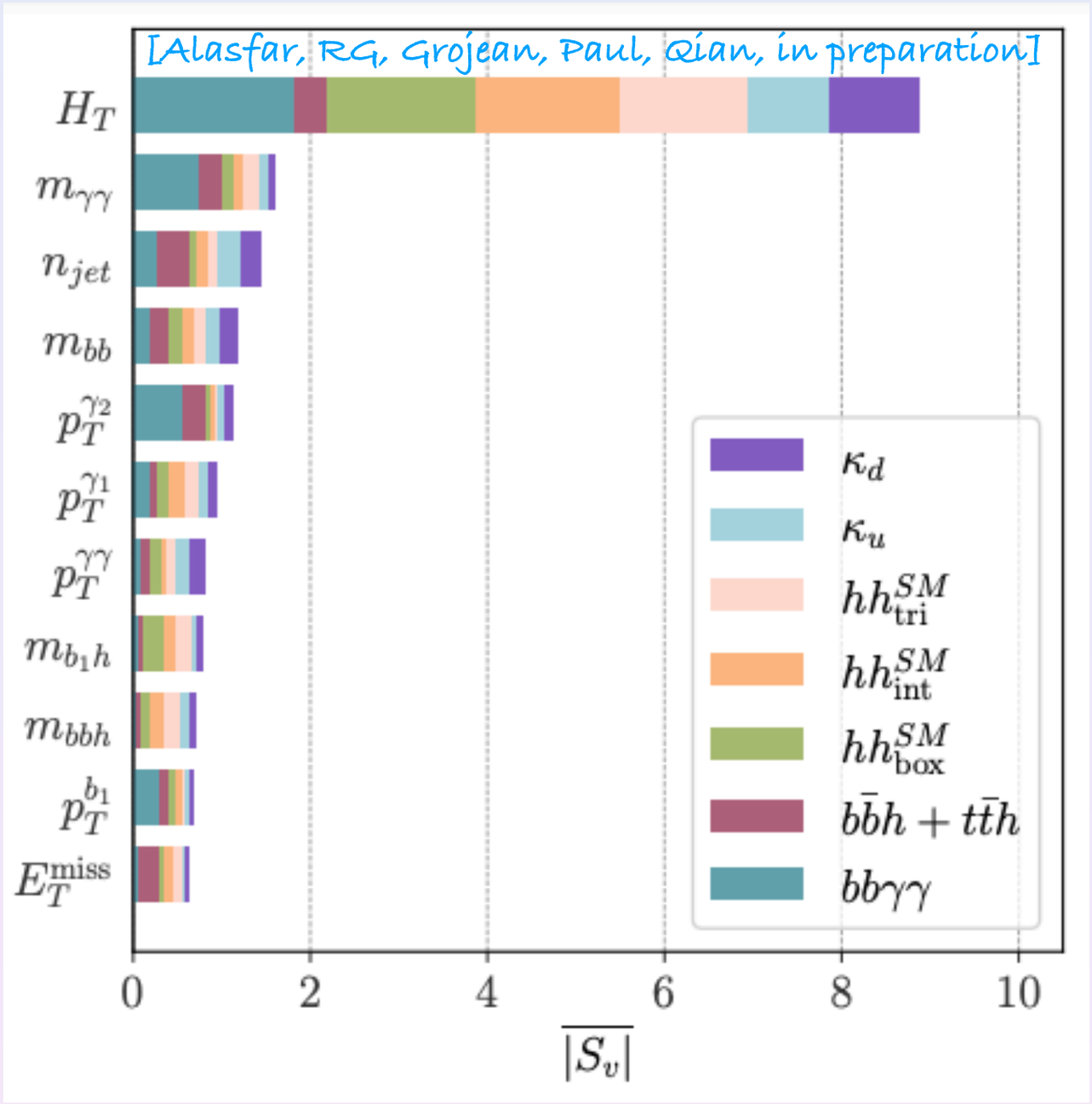


[thanks to A. Paul for the figures]

Shapley value borrowed from game theory, assign an importance to the various kinematic variables

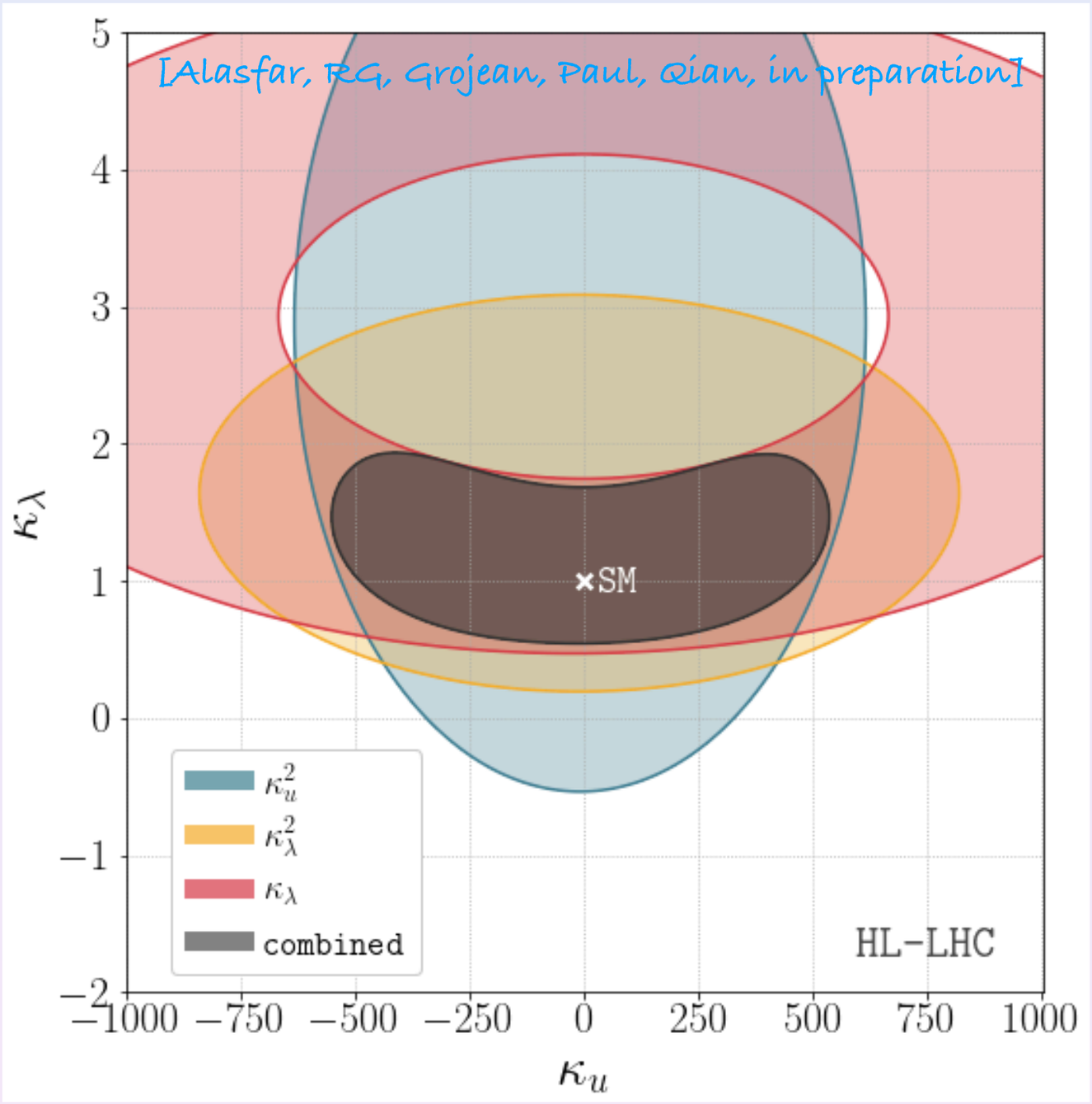
Interpretable Machine Learning

we treat box, interference and triangle separately



Shapley value assigns importance to the various kinematic variables

Results light Yukawa modifications



Bounds on κ_u very comparable to global fit

Conclusions

- In Di-Higgs production can discover a lot of new exciting physics
- multi-Higgs models can lead to striking new resonant signals
- Higgs non-linearities: Is SMEFT/HEFT right EFT description?
- for trilinear Higgs self-coupling extraction also single Higgs can help, but need to account for more operators entering at NLO
- Higgs production provides also a handle on the poorly constrained light quark Yukawa couplings

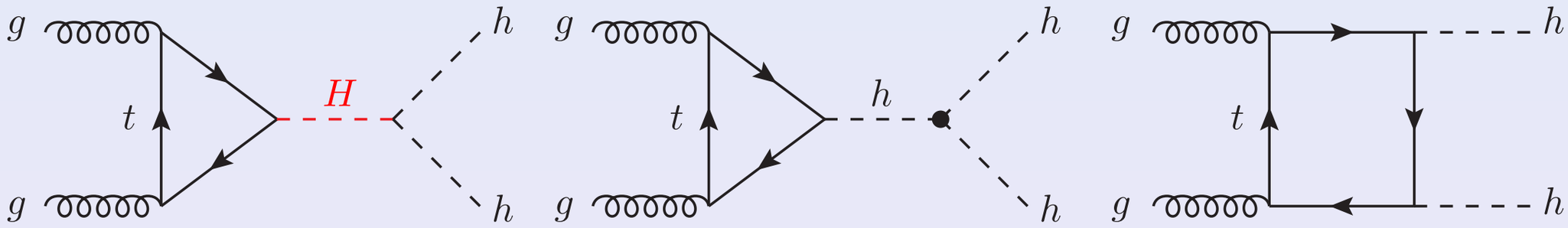
Conclusions

- In Di-Higgs production can discover a lot of new exciting physics
- multi-Higgs models can lead to striking new resonant signals
- Higgs non-linearities: Is SMEFT/HEFT right EFT description?
- for trilinear Higgs self-coupling extraction also single Higgs can help, but need to account for more operators entering at NLO
- Higgs production provides also a handle on the poorly constrained light quark Yukawa couplings

Thanks for your attention!

Backup

Resonant Higgs pair production



Typical signal in multi-Higgs models where the new Higgs is not too heavy.

E.g. singlet model, 2HDM, NMSSM, ...

Interference with SM-like triangle and box important? Model-dependence!

Classification of interferences

$$\eta = \int_{m_\phi-10\Gamma_\phi}^{m_\phi+10\Gamma_\phi} dm_F \left(\frac{d\sigma_S}{dm_F}+\frac{d\sigma_I}{dm_F}\right) \Big/ \int_{m_\phi-10\Gamma_\phi}^{m_\phi+10\Gamma_\phi} dm_F \left(\frac{d\sigma_S}{dm_F}\right)$$

$$\eta_- = \int_{m_\phi-10\Gamma_\phi}^{m_F^I} dm_F \left(\frac{d\sigma_S}{dm_F}+\frac{d\sigma_I}{dm_F}\right) \Big/ \int_{m_\phi-10\Gamma_\phi}^{m_F^I} dm_F \left(\frac{d\sigma_S}{dm_F}\right)$$

$$\eta_+ = \int_{m_F^I}^{m_\phi+10\Gamma_\phi} dm_F \left(\frac{d\sigma_S}{dm_F}+\frac{d\sigma_I}{dm_F}\right) \Big/ \int_{m_F^I}^{m_\phi+10\Gamma_\phi} dm_F \left(\frac{d\sigma_S}{dm_F}\right) .$$

[Bagnaschi, Carvalho, RG, Liebler, Quevillon]