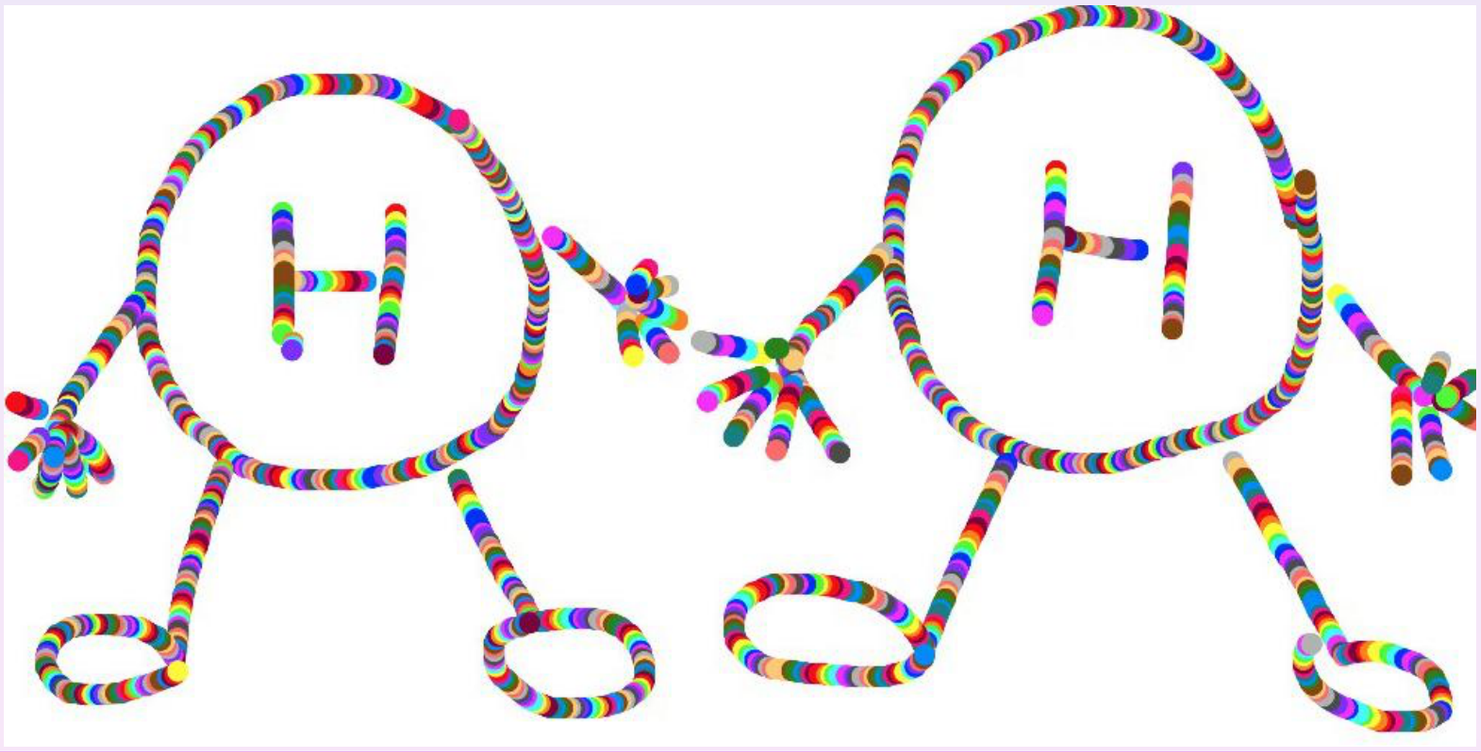
Probing the Higgs boson in pairs

Ramona Gröber

Humboldt-Universität zu Berlin



Seminar
IFT Madrid

03/12/2018

Outline

- Motivation

- Theoretical predictions for di-Higgs production

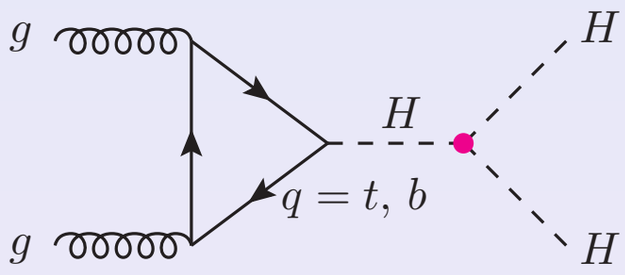
- Higgs pair production beyond the Standard Model

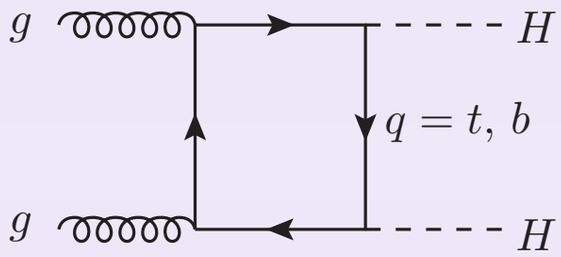
  - Trilinear Higgs self-coupling

  - Resonant Higgs pair production

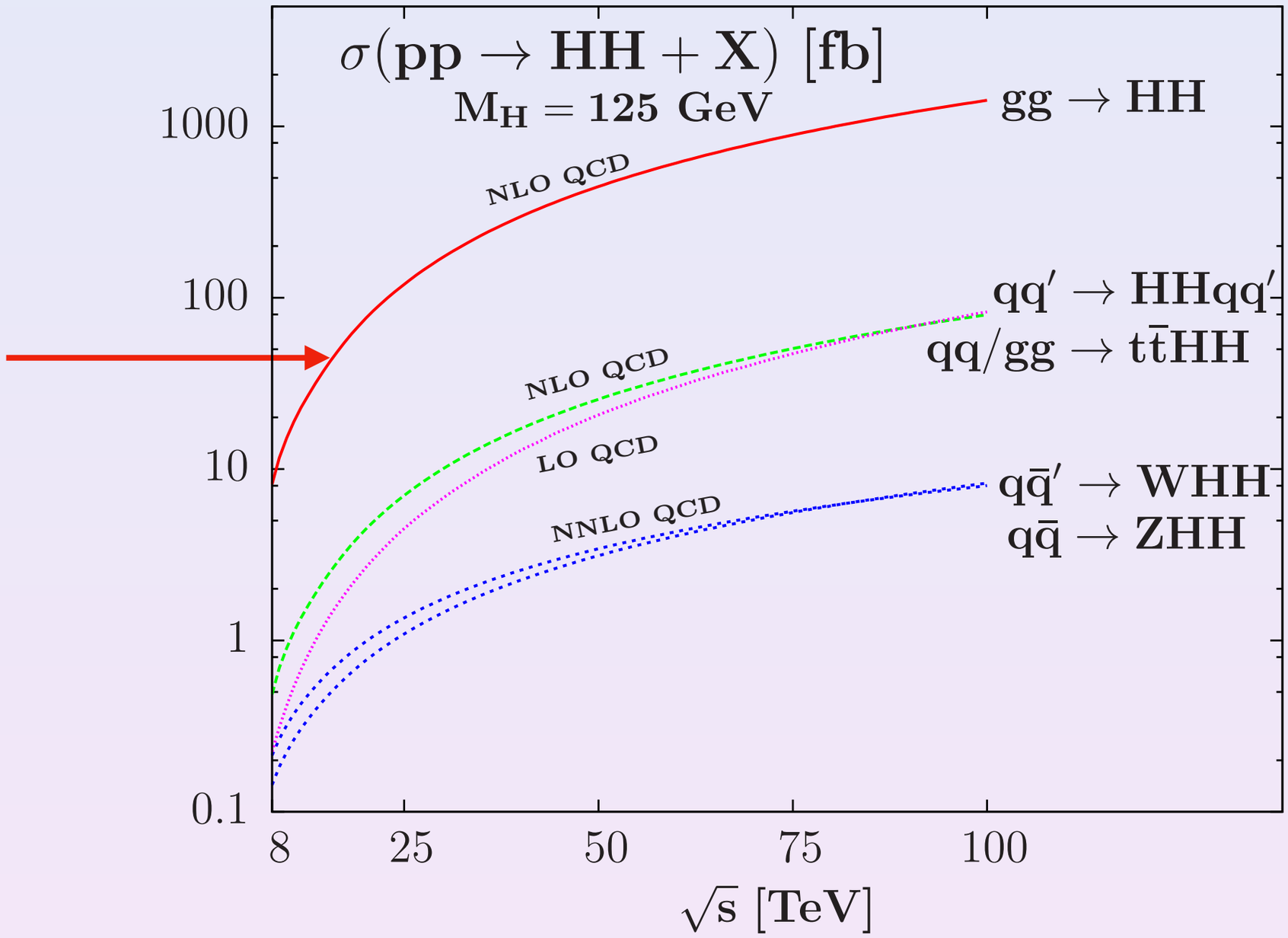
Higgs pair production

$gg \to HH$





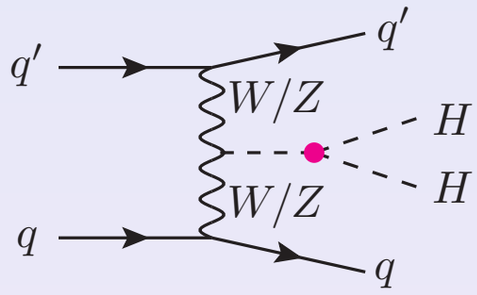
[Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12]



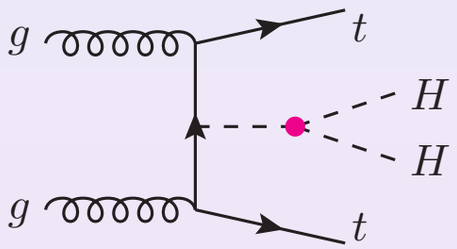
Higgs pair production

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

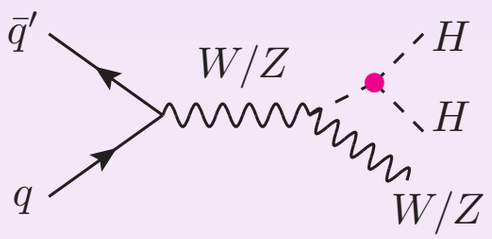
$qq' \to HHqq'$



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



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



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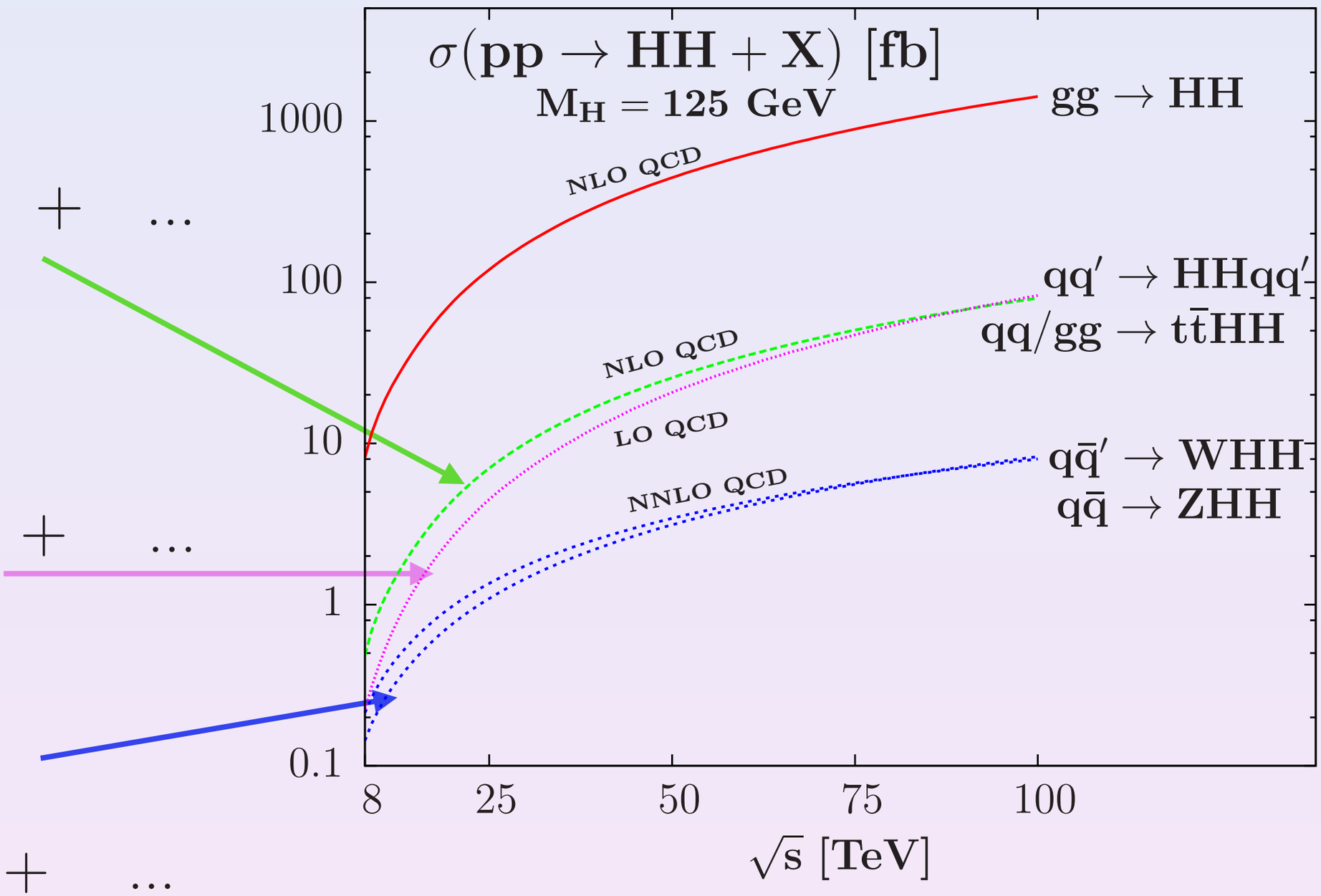

Higgs pair production

trilinear Higgs self-coupling accessible

Small cross section

Difficult to measure

Most promising final state is $b\bar{b}\gamma\gamma$

[Baur, Plehn, Rainwater '03, Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12, Yao '13, Barger et al '13, Azatov et al '15, Lu et al '15, Kling et al '16, Adhikary et al '17, Goncalves et al '18]

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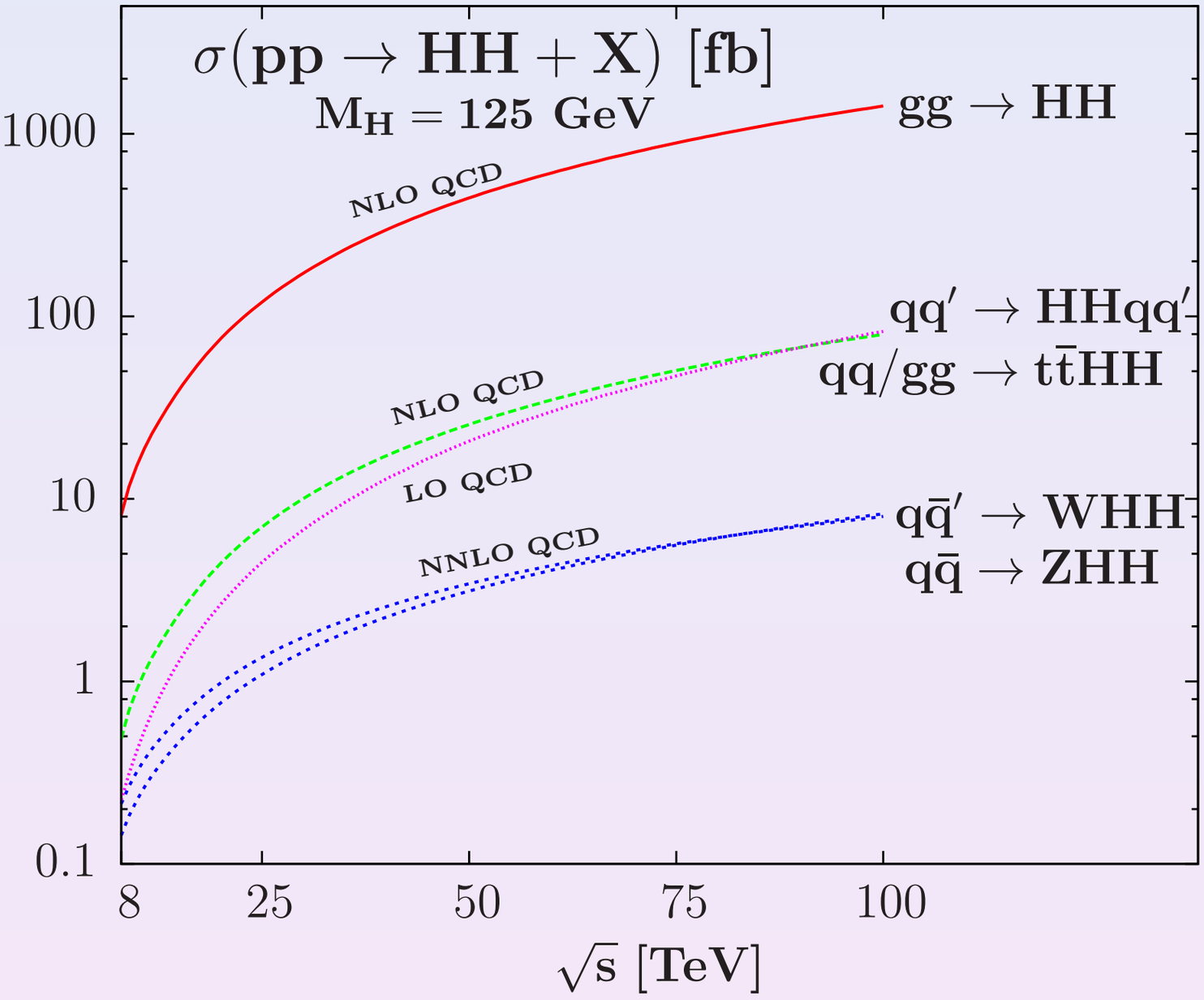

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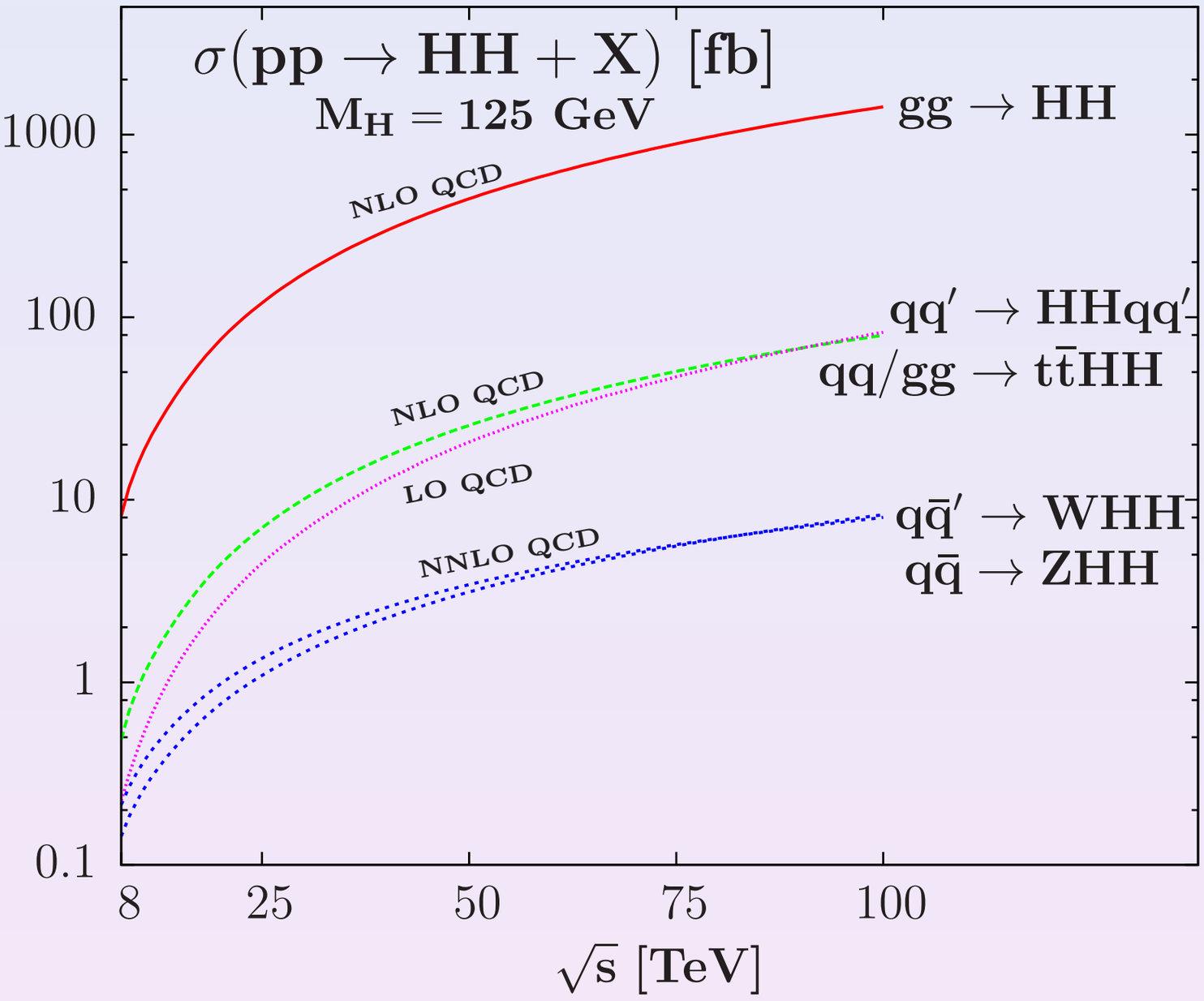
Rest of the talk: gluon fusion

[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, ...]

Theoretical predictions for Higgs pair via gluon fusion

Higgs pair production in the SM

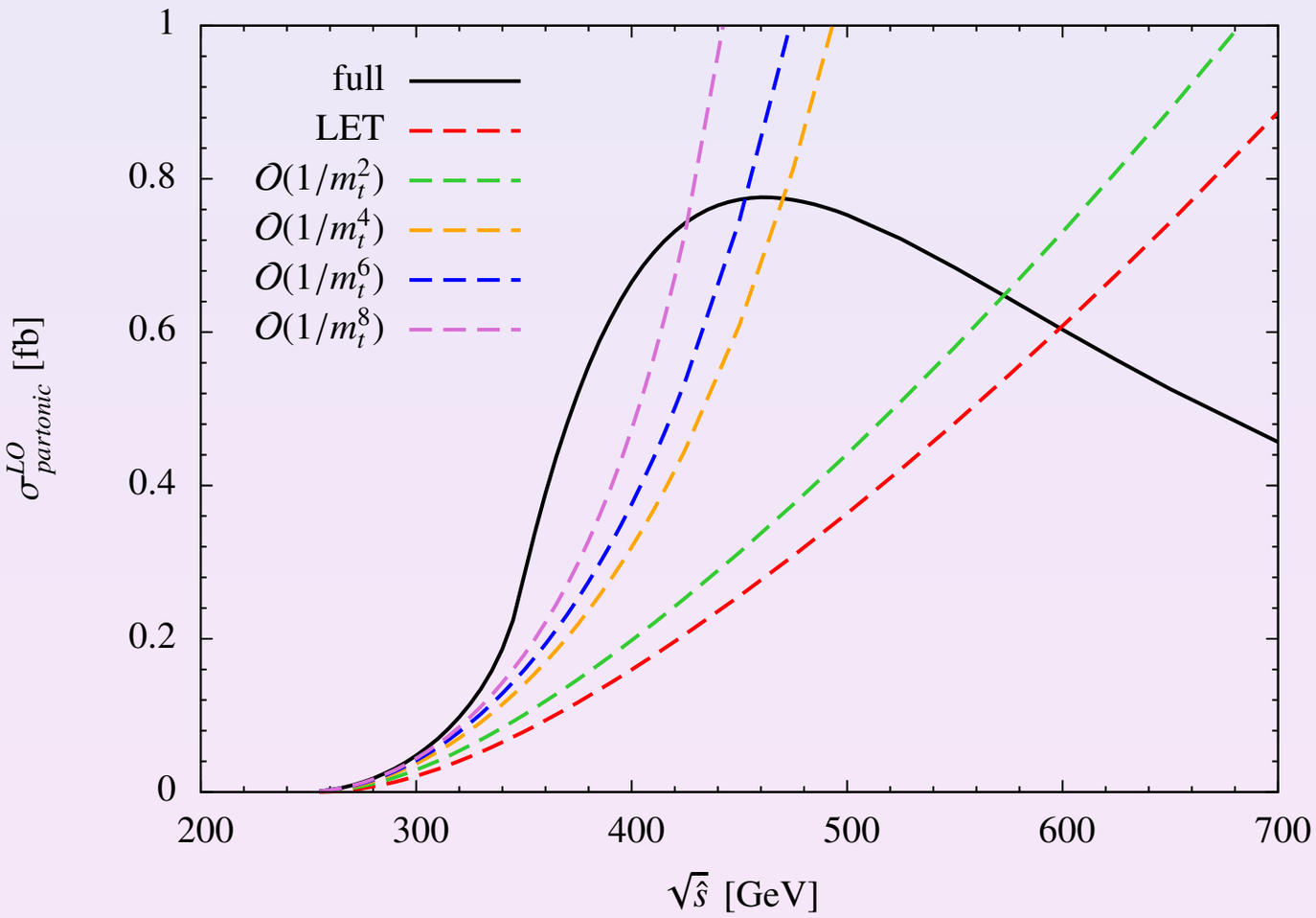
NLO QCD corrections large: K~1.9 [Dawson, Dittmaier, Spira '98]

Historically:

- NLO QCD corrections computed in large top mass limit [Dawson, Dittmaier, Spira '98]
  simplifies the integrals dramatically

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

[Degrassi, Giardino, RG '16]



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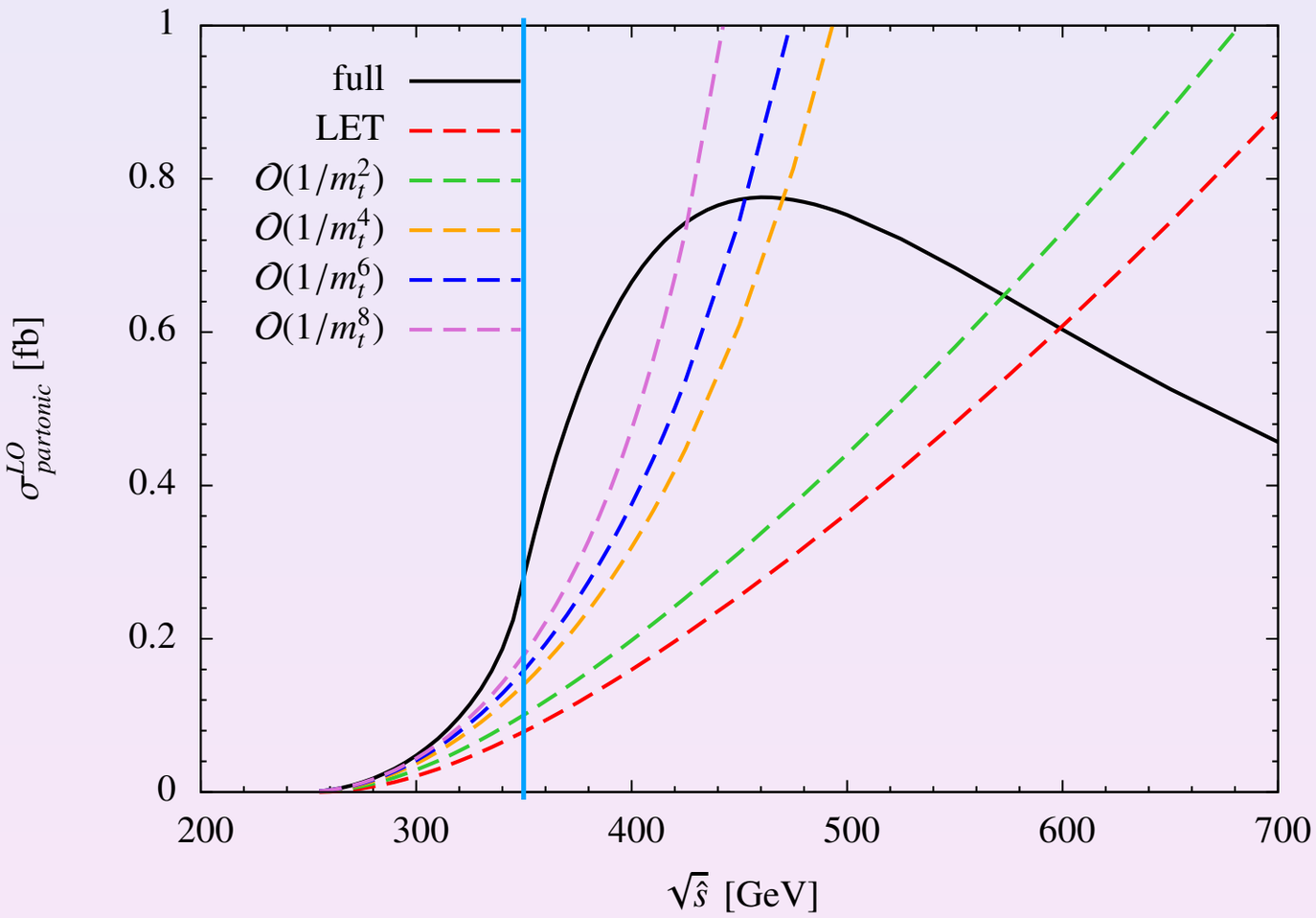

valid for $\hat{s}, \hat{t}, \hat{u}, m_H^2 \ll 4m_t^2$

improvement by reweighting with full LO cross section

Higgs pair production in the SM

Bottleneck = virtual corrections

Estimation of finite top mass effects

- real corrections in full mass dependence [Frederix, et al '14, Maltoni, Vryonidou, Zaro '14]
- higher orders in expansion in large m_t [Grigo, Hoff, Melnikov, Steinhauser '13, Grigo, Hoff, Steinhauser '15, Degrassi, Giardino, RG '16]

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- NLO result in full mass dependence fully numerical, available as a grid [Borowka et al '16, Baglio et al '18] [Heinrich, Jones, Kerner, Luisoni, Vryonidou '17]
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Can we obtain a (semi-) analytical result incorporating the top mass dependence?

Advantages: faster, application to other processes and BSM, cross-check, ...

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Can we obtain a (semi-) analytical result incorporating the top mass dependence?

Expansion in small p_T, m_H [Bonciani, Degrassi, Giardino, RG '18]

High-energy limit [Davies, Mishima, Steinhauser, Wellmann '18]

Expansion in small m_H [Xu, Yang '18]

Padé approximants for top mass effects

Combine several expansions by using Padé approximants

$$[n/m](\omega) = \frac{\sum_{i=0}^{n} a_i \omega^i}{1 + \sum_{j=1}^{m} b_j \omega^j}$$

Ingredients:

$$z = (\hat{s} + i0)/(4m_t^2)$$

- large mass expansion (around z=0) [from Degrassi, Giardino, RG '16]
- threshold expansion (around z=1) [computed in RG, Maier, Rauh '17]

- Form factor vanishes for $z \to \infty$

"Trick":

- Conformal mapping $z = \frac{4\omega}{(1+\omega)^2}$ [Tarasov, Fleischer '94]

Padé approximants for top mass effects

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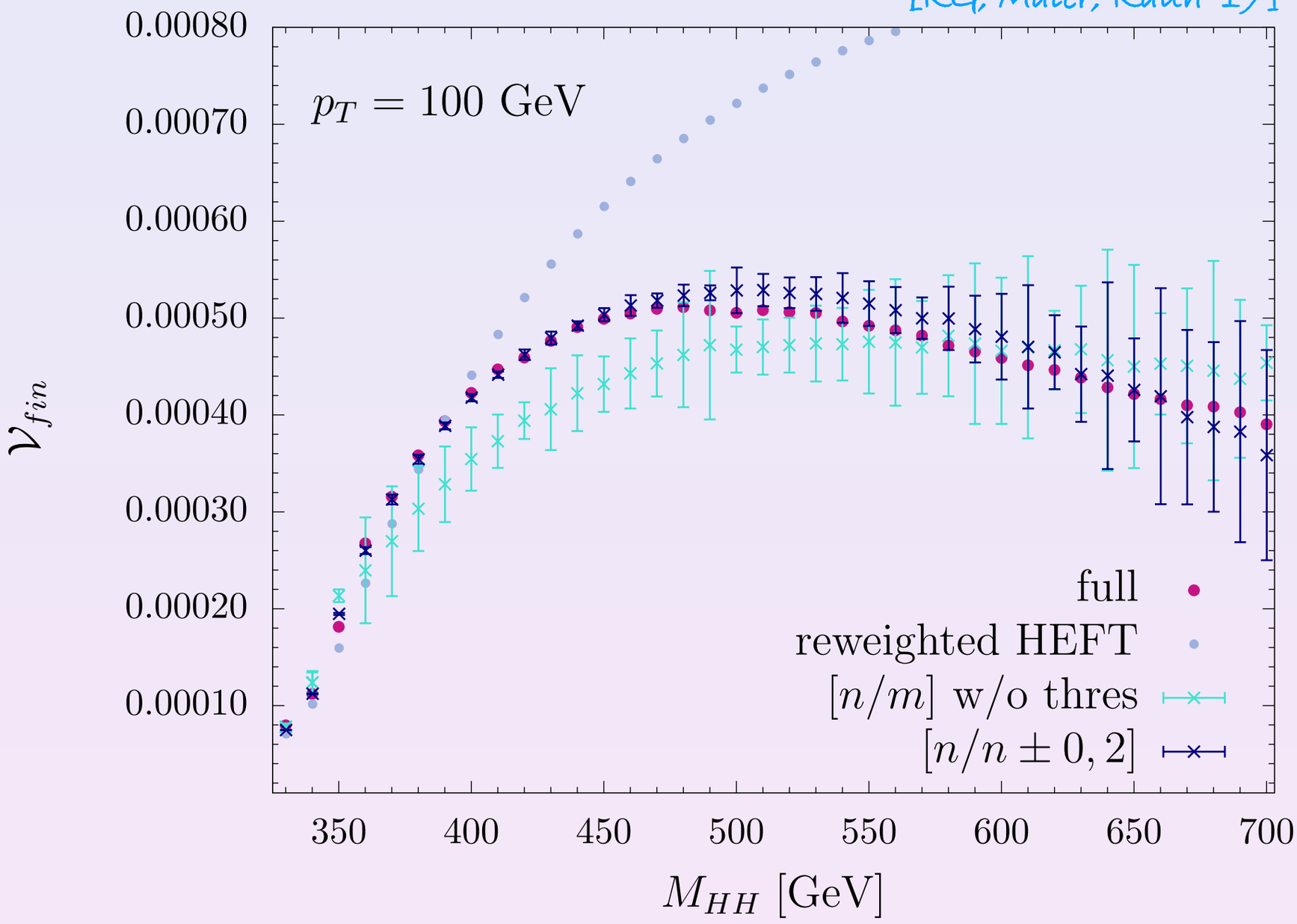
[RG, Maier, Rauh '17]



Comparison with grid from [Heinrich, Jones, Kerner, Luisoni, Vryonidou '17]

Higgs pair production beyond the Standard Model

Higgs pair production beyond the SM

1. measurement of trilinear Higgs self-coupling

probes the Higgs potential

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

EWSB

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

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Is there a correlation between couplings hXX and hhXX?

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3. probing particles in the gluon fusion loop

Gluon fusion loop can contain new colored particles

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i.e. heavy new scalar (or spin 2 particle) decaying to hh

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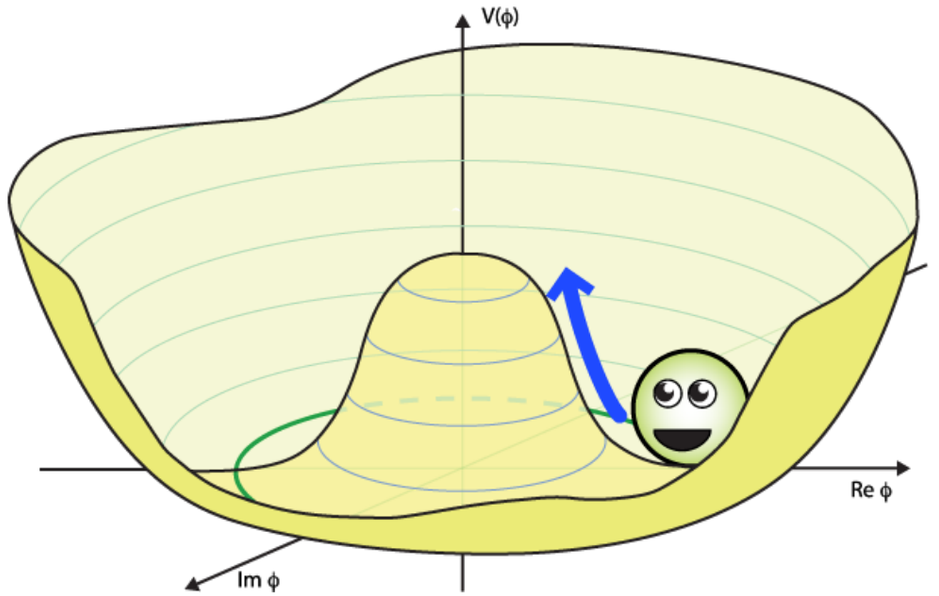
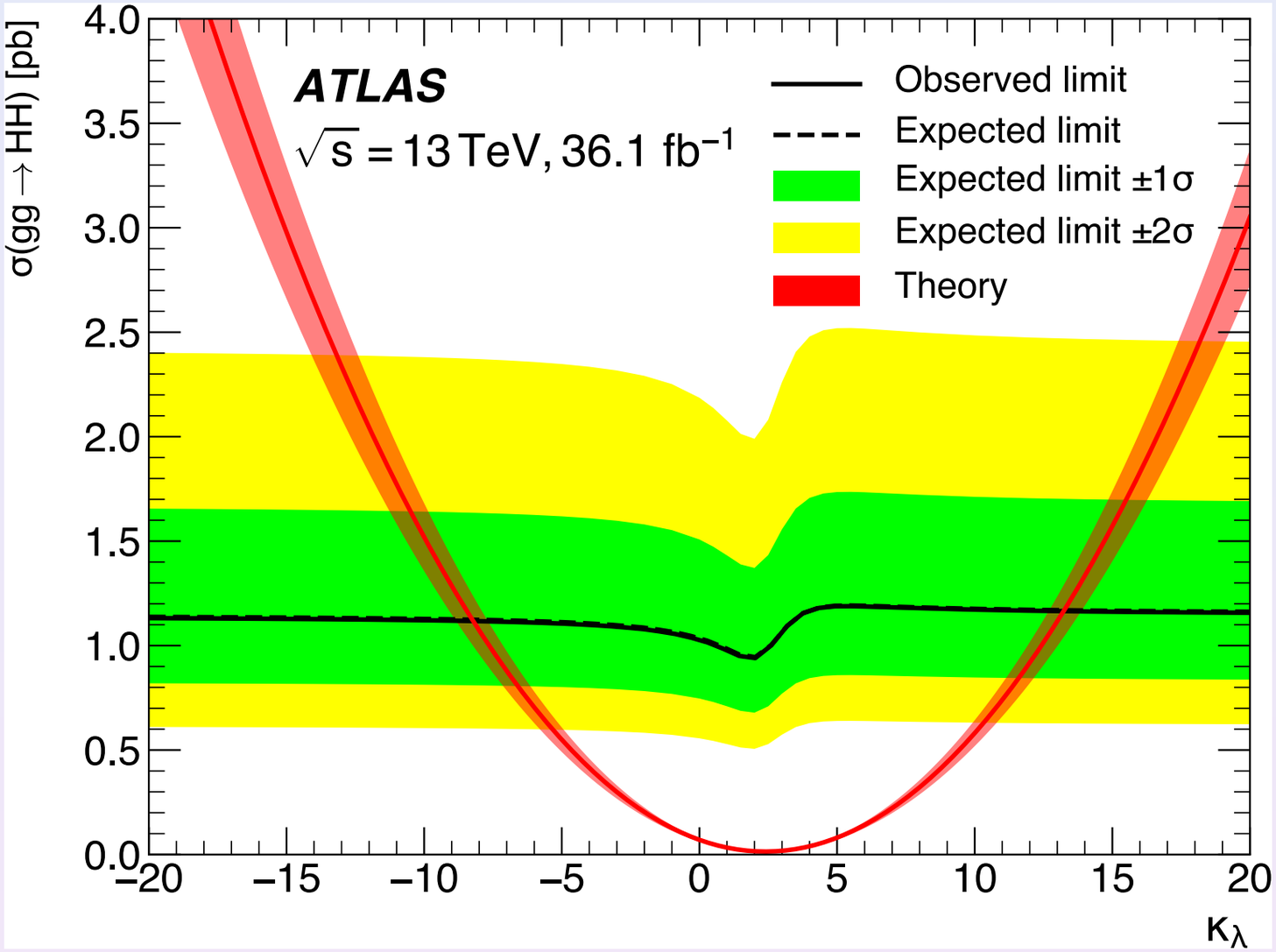
Probing the trilinear Higgs self-coupling

Measurement of trilinear Higgs self-coupling gives insight to the Higgs potential and hence electroweak symmetry breaking



[quantumdiaries.org]

Higgs pair production



Searches difficult,
require high luminosities

Current bounds $\mathcal{O}(\pm 10\lambda_{hhh}^{SM})$

[arXiv:1509.0467, arXiv: 1506.0028,
arXiv: 1603.0689]

Prospects at HL-LHC
for $b\bar{b}\gamma\gamma$ final state

$$-0.2 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 6.9$$

[talk by Delgove "Double-Higgs
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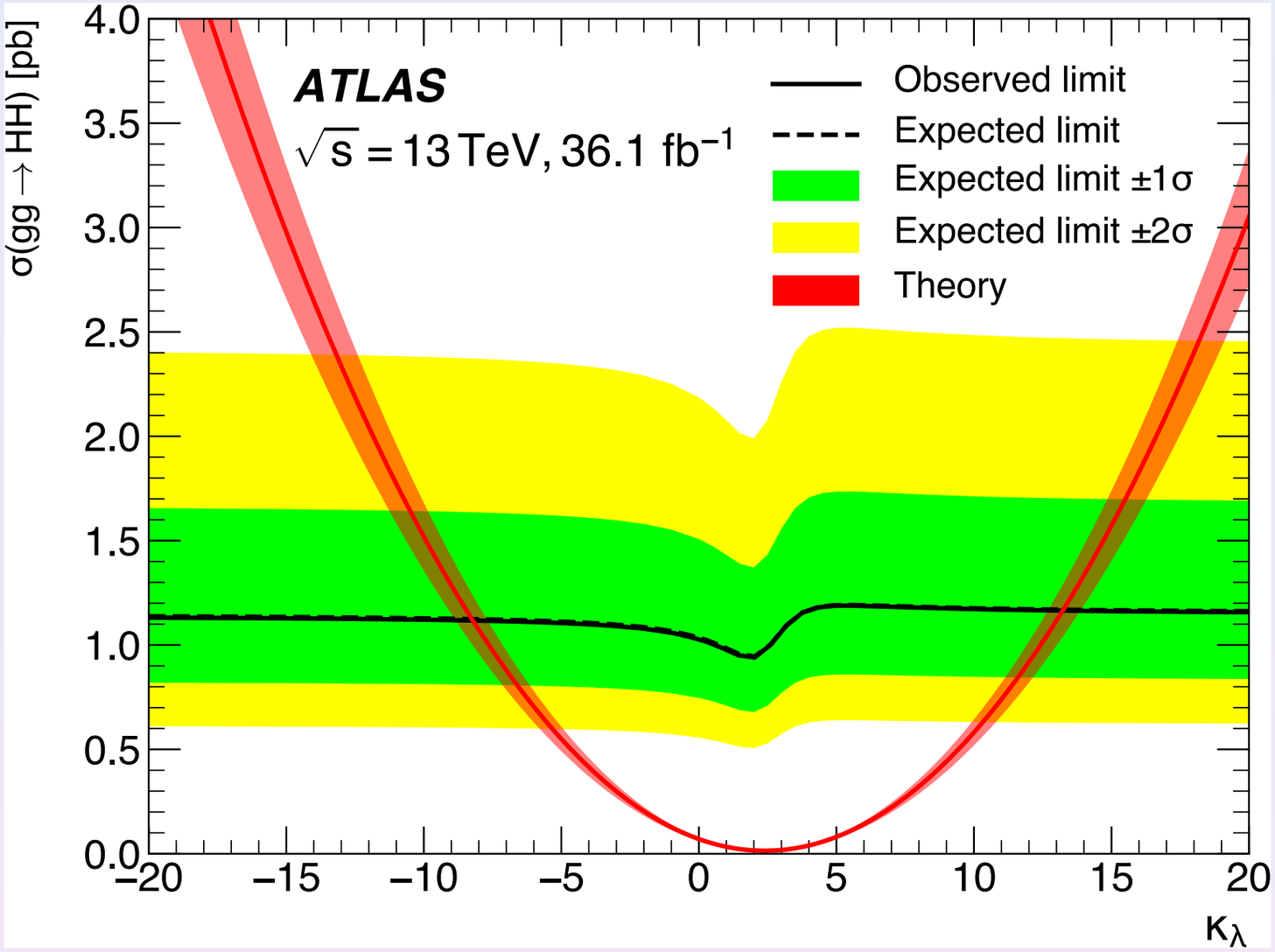
Higgs pair production



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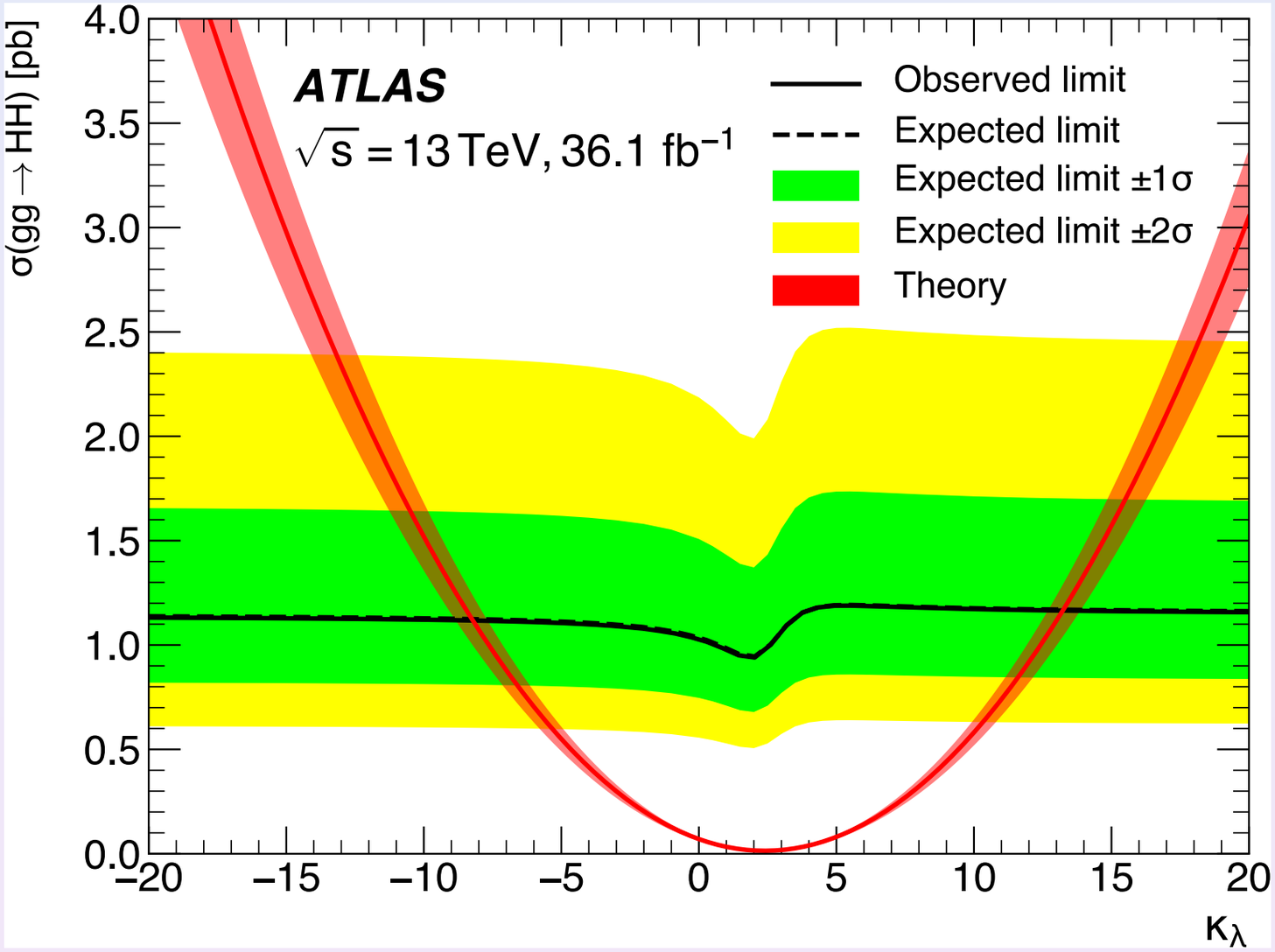
Single Higgs to constrain trilinear Higgs self-coupling:

Enters in electroweak corrections to single Higgs

$$-9.4 < (\lambda_{hhh}/\lambda_{hhh}^{SM})_{2\sigma} < 17$$

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

Higgs pair production



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Single Higgs to constrain trilinear Higgs self-coupling:

Global fit, taking into account differential measurements

$$0.1 < (\lambda_{hhh}/\lambda_{hhh}^{SM})_{1\sigma} < 2.3$$

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

Trilinear Higgs self-coupling

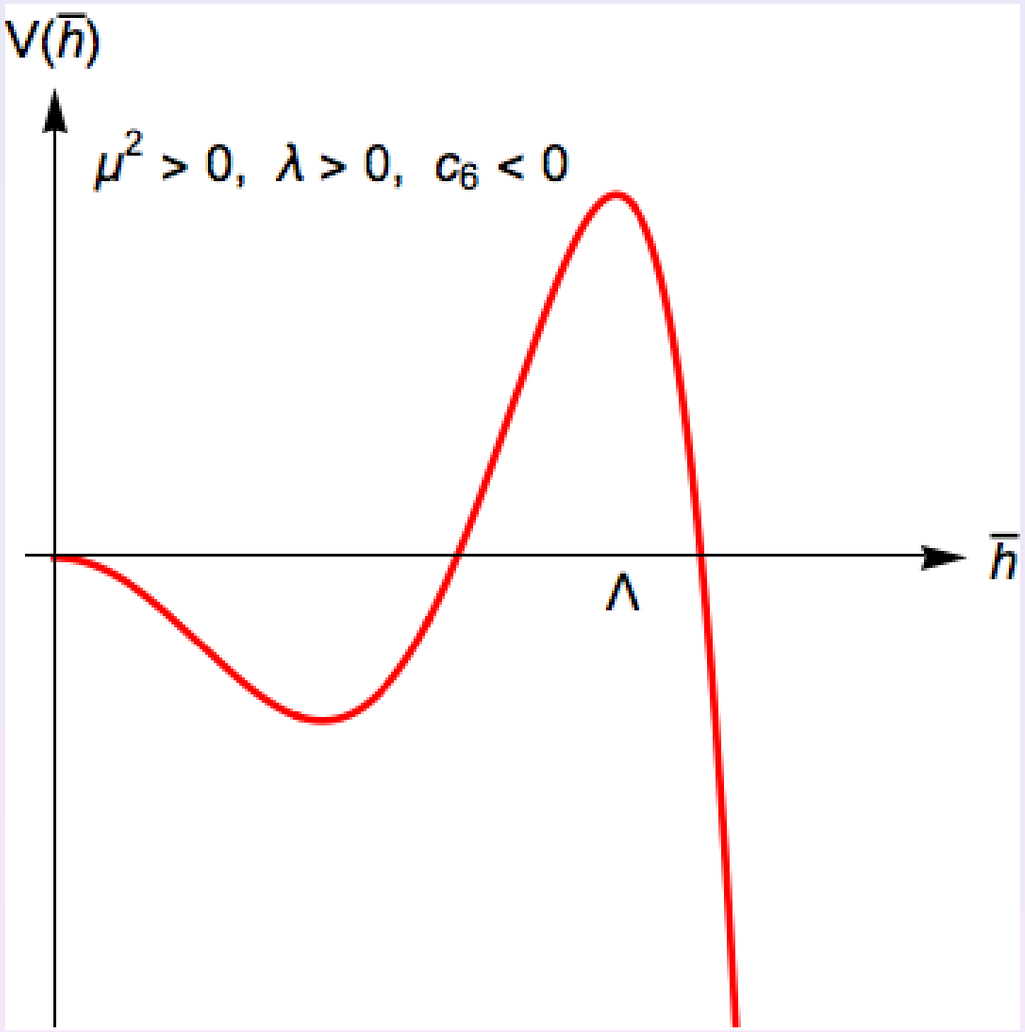
Can the trilinear Higgs self-coupling be constraint theoretically?

And how large can it be in concrete models?

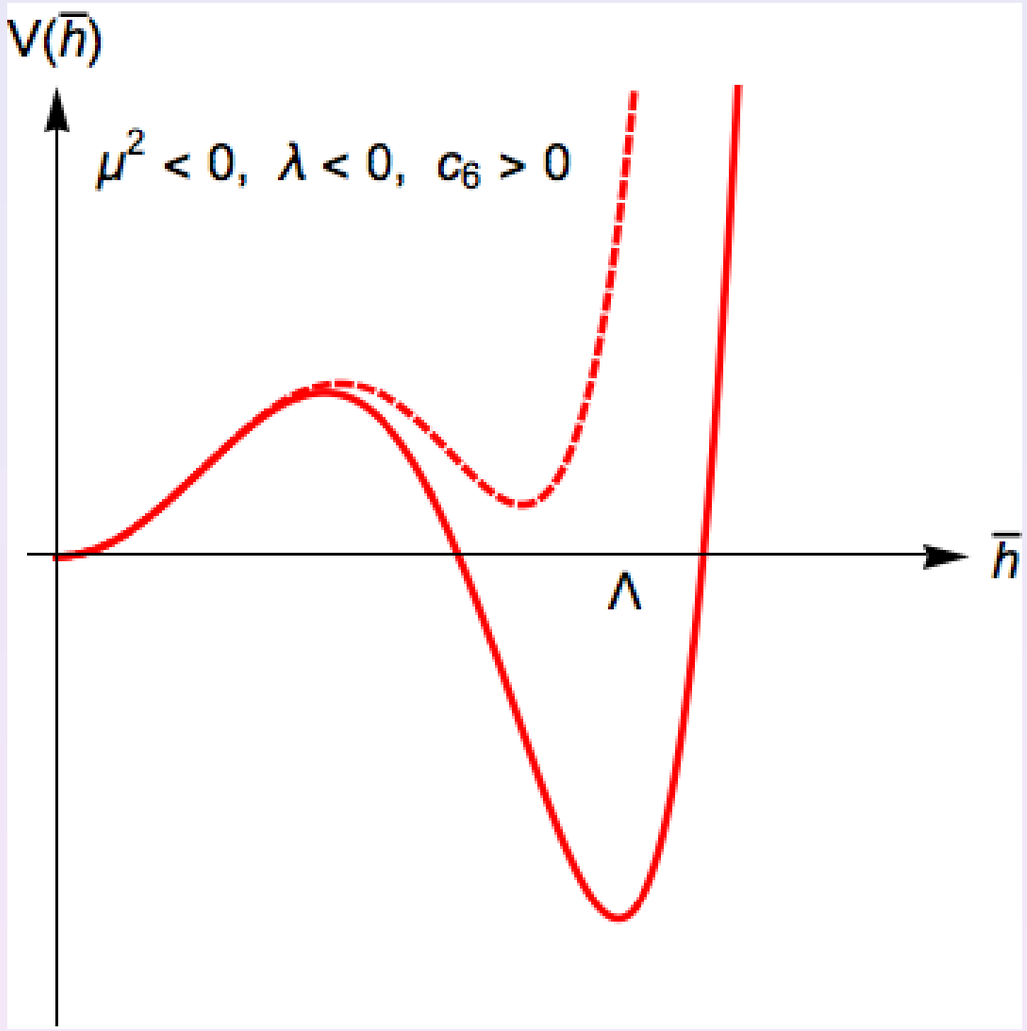
Vacuum stability

$$V^{(6)} = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{c_6}{v^2} |H|^6$$

large field instability



small field instability



turns out that none of those instabilities can set bound on trilinear Higgs self-coupling deviations

Large field instability

Toy model

[for a similar argument see Burgess, Di Clemente, Espinosa '02]

$$V(h,\phi) = -\frac{1}{2}\mu^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}M^2\phi^2 + \xi h^3\phi + \kappa h^2\phi^2 + \frac{1}{4}\lambda'\phi^4$$

Electroweak vacuum is absolutely stable if

$$\kappa > 0 \qquad \text{and} \qquad \lambda > \frac{\xi^2}{\kappa} \qquad \text{and} \qquad \lambda' > 0$$

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Integrating out ϕ and expanding in large M^2

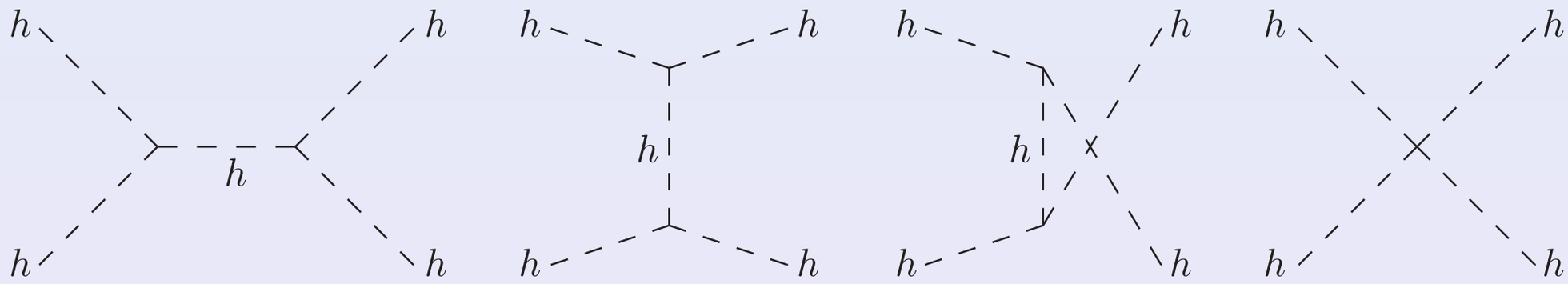
$$V_{EFT}(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 - \frac{1}{2}\frac{\xi^2}{M^2}h^6 + \frac{\xi^2\kappa}{M^4}h^8 + \dots$$

h^6 operator makes potential seem unstable!

for vacuum instability analysis full tower of EFT operators necessary

full models

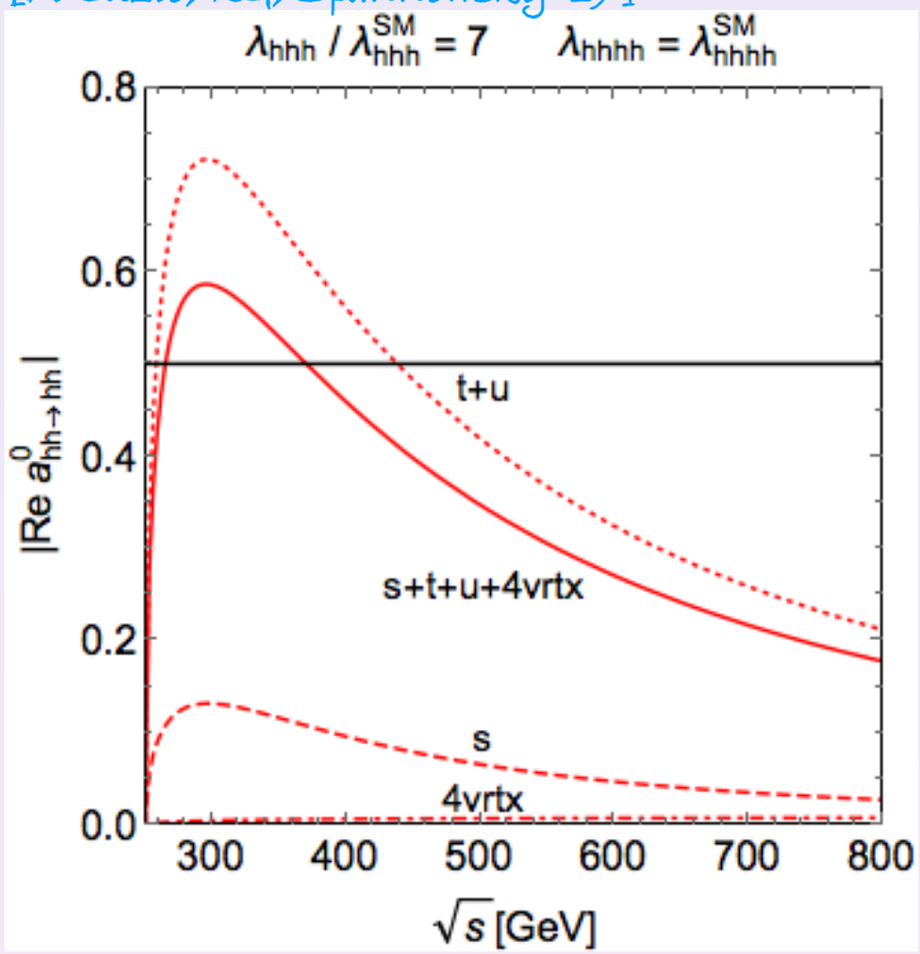
Perturbative unitarity bound

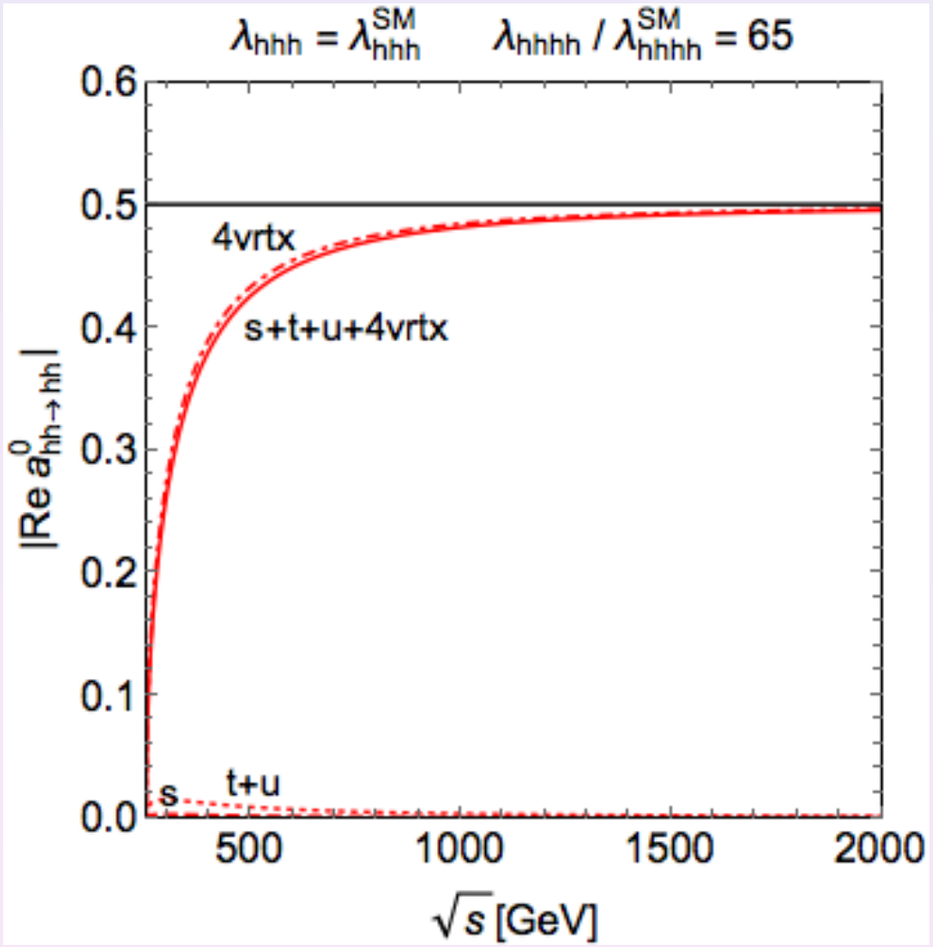


Perturbative unitarity bound from partial wave analysis

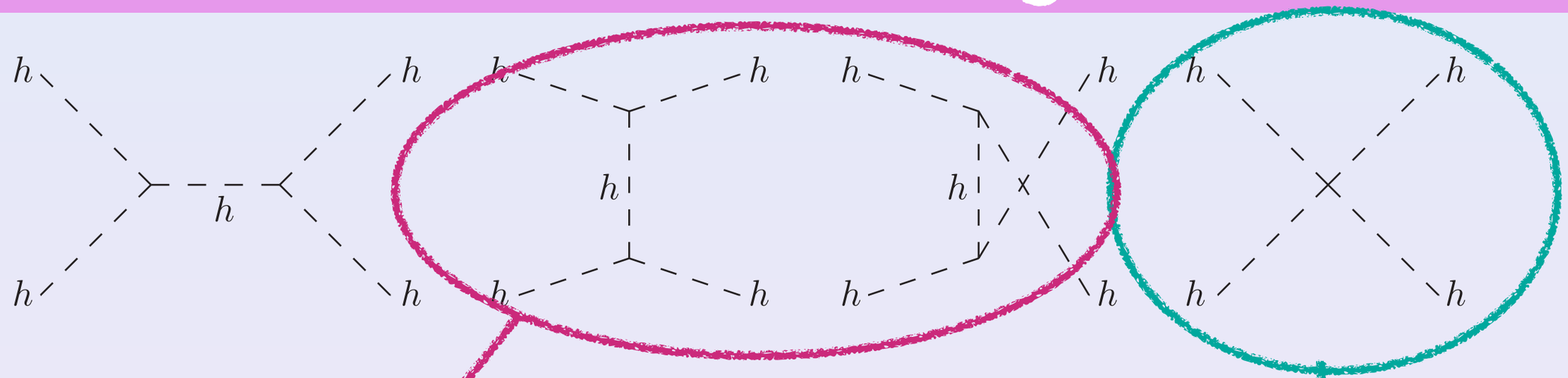
$$|\text{Re } a^0_{hh\to hh}| < 1/2$$

[Di Luzio, RG, Spannowsky '17]





Perturbative unitarity bound



Perturbative unitarity bound from partial wave analysis

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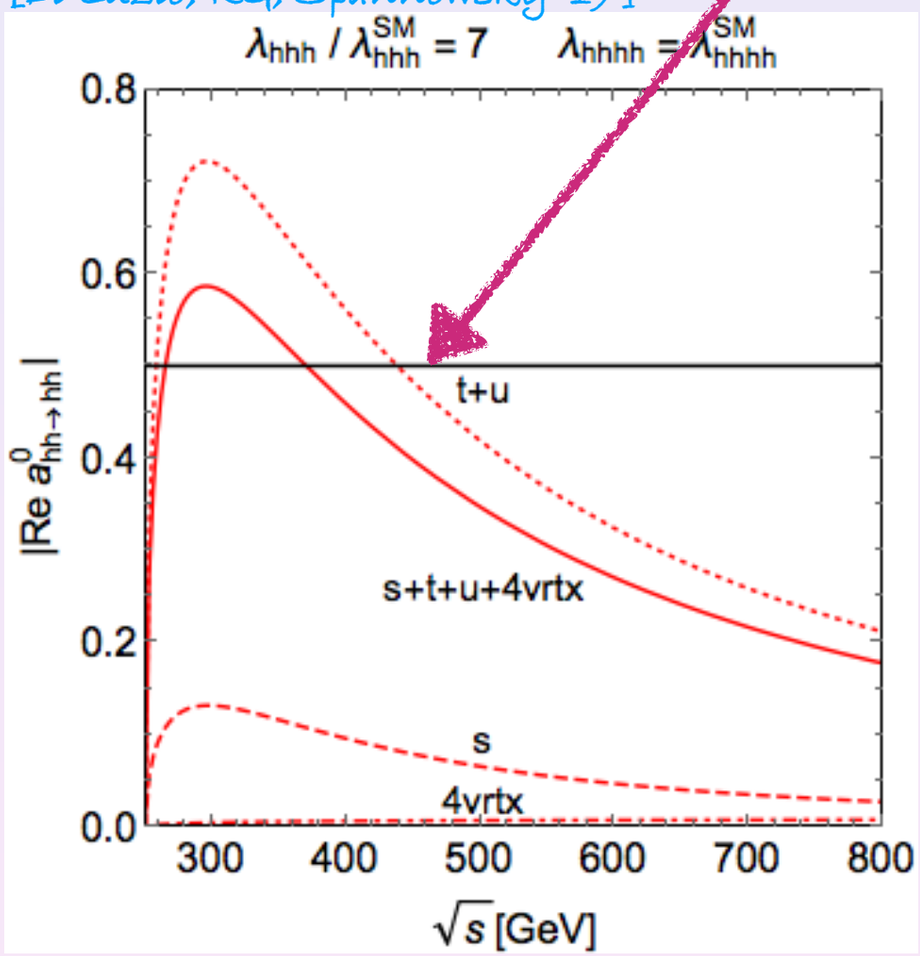
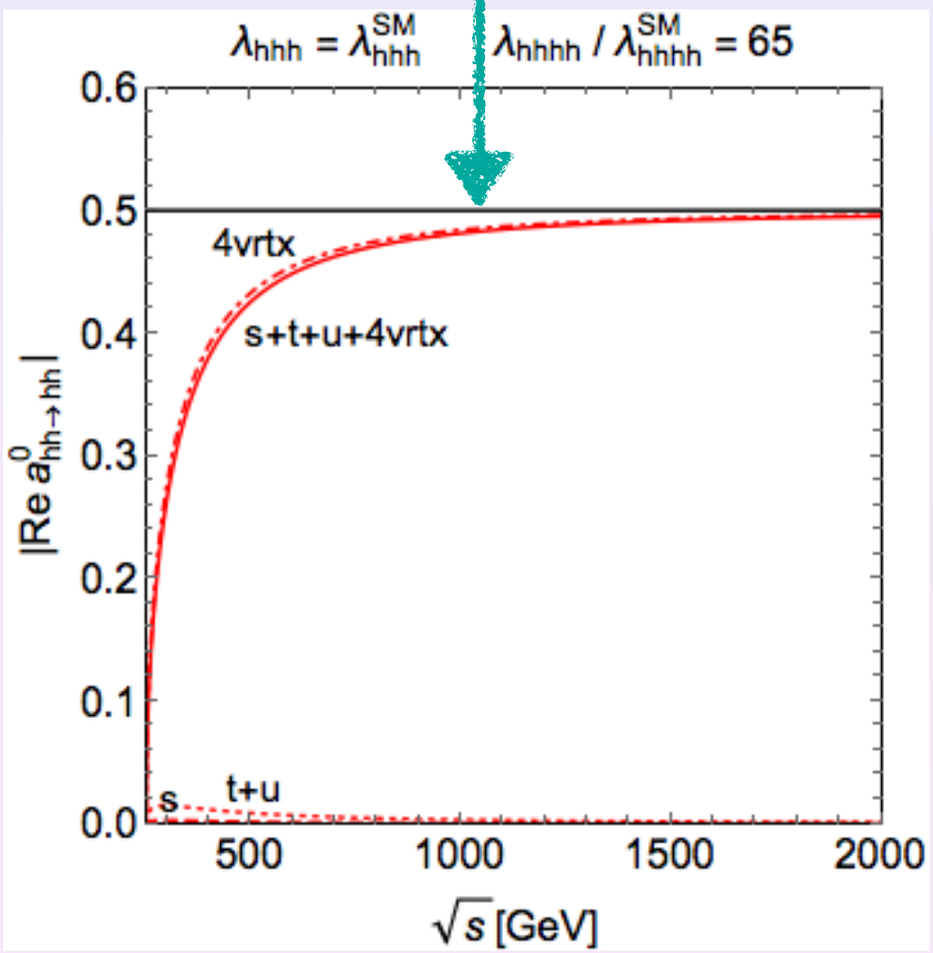
bounds at low s

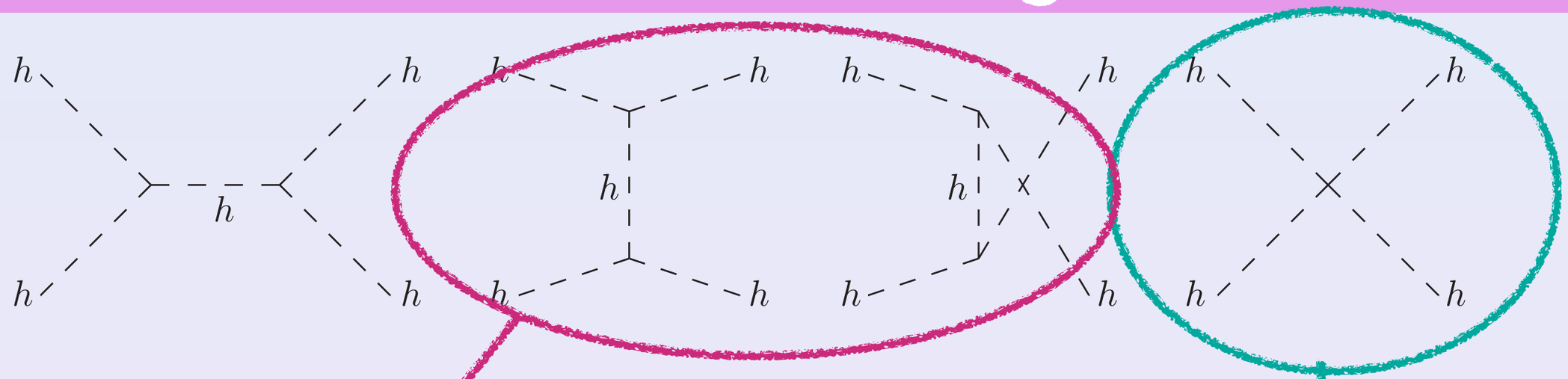
[Di Luzio, RG, Spannowsky '17]



bounds at large s



Perturbative unitarity bound



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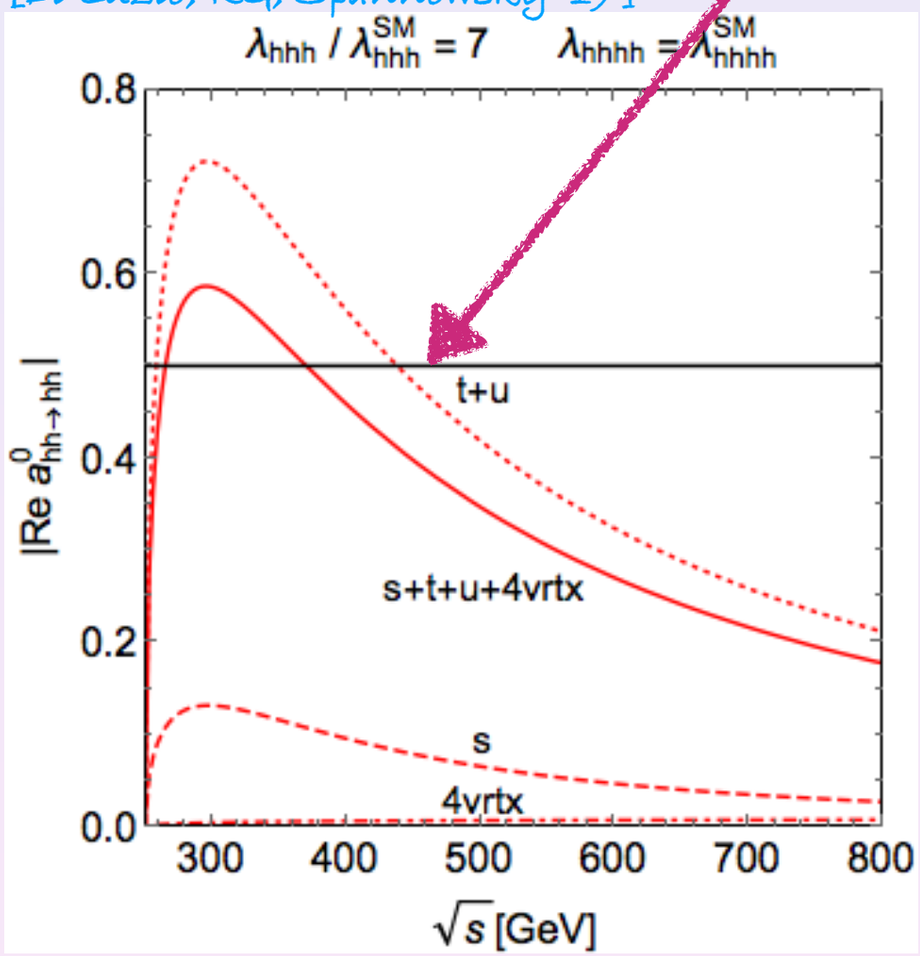
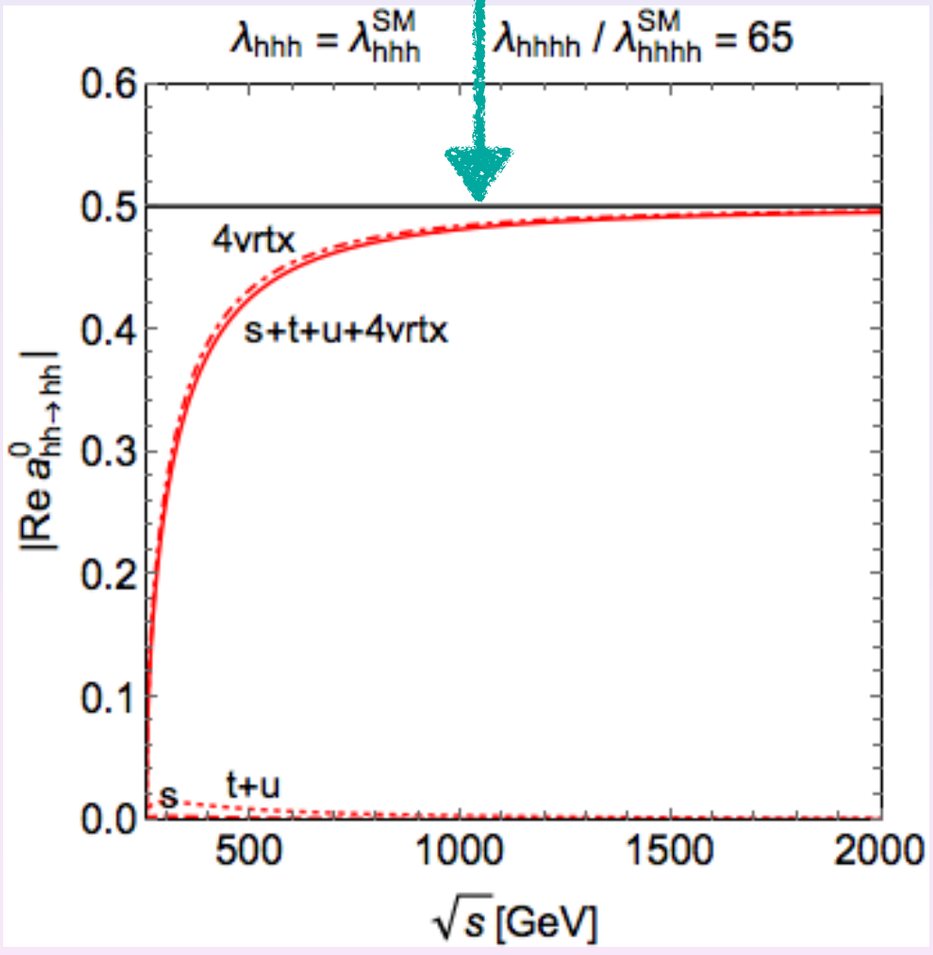


Perturbative unitarity bound

$$\left|\lambda_{hhh}/\lambda^{\rm SM}_{hhh}\right| \lesssim 6.5$$

$$\left|\lambda_{hhhh}/\lambda^{\rm SM}_{hhhh}\right| \lesssim 65$$

bounds at large s

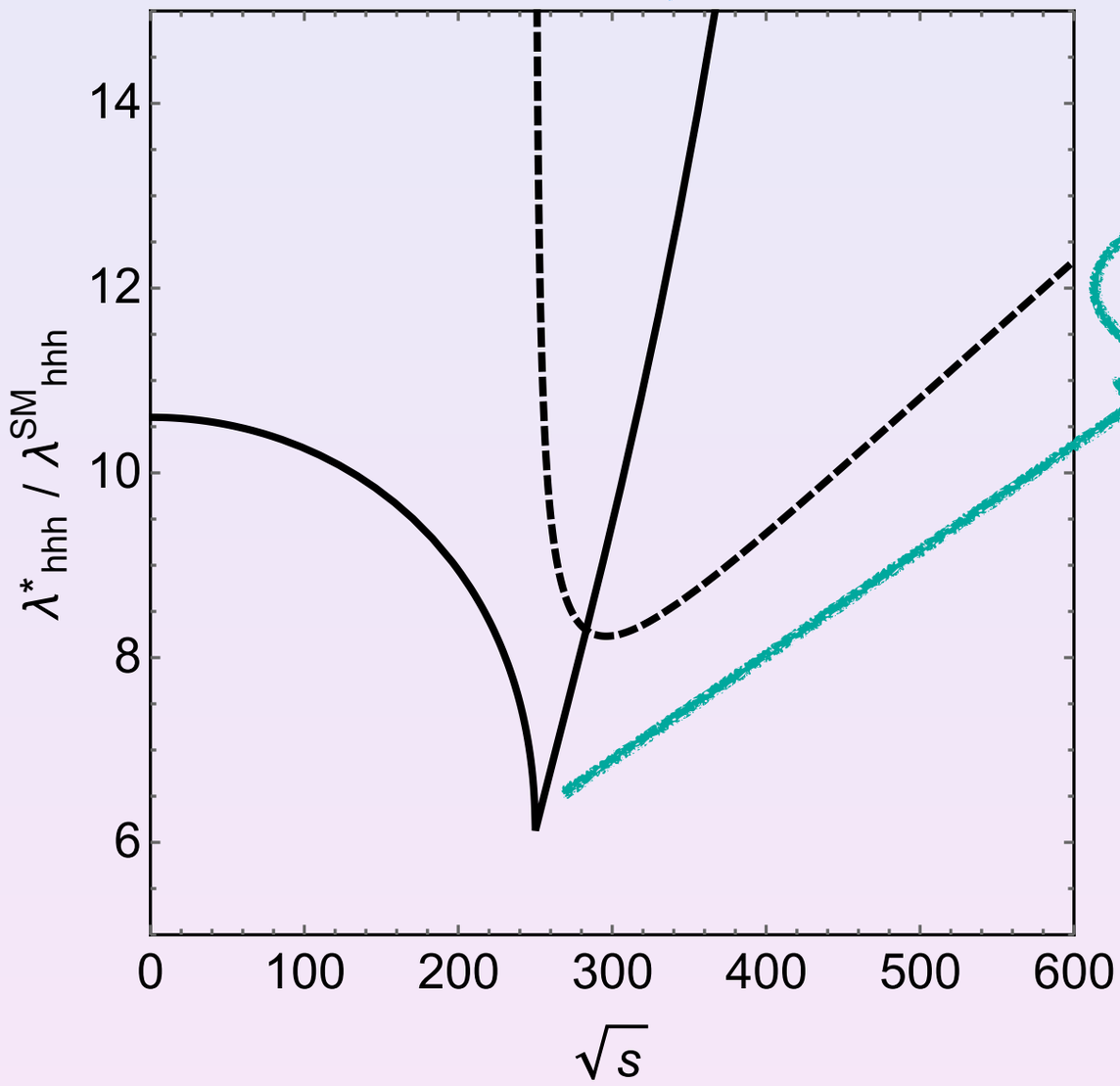


Perturbativity bound

Similar bound obtained by requesting that

$$|\lambda_{hhh}^{1loop}| < |\lambda_{hhh}^{tree}|$$

[Di Luzio, RG, Spannowsky '17]



$$|\lambda_{hhh}/\lambda_{hhh}^{SM}| < 6$$

How large can λ_{hhh} be?

In which models do we expect largest deviation?

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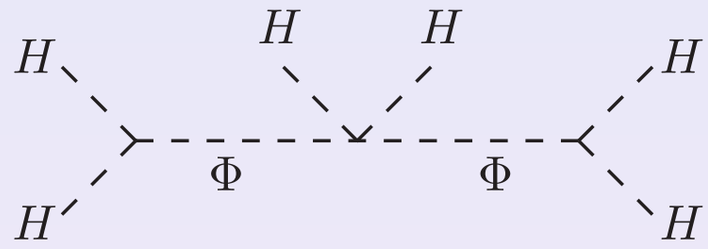
In which models do we expect largest deviation?

If there is a tree-level contribution to $\mathcal{L}_6 = \frac{c_6}{\Lambda^2}|H|^6$

In models with new scalars that couple with

$$\mathcal{L} = HH\Phi \quad \text{or} \quad \mathcal{L} = HHH\Phi$$



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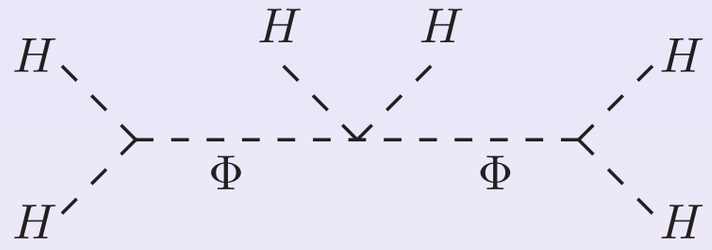

Φ	$\mathcal{O}_\Phi$
$(1,1,0)$	$\Phi H H^\dagger$
$(1,2,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1,3,0)$	$\Phi H H^\dagger$
$(1,3,1)$	$\Phi H^\dagger H^\dagger$
$(1,4,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
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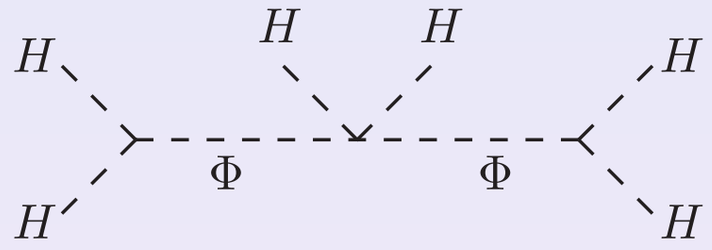

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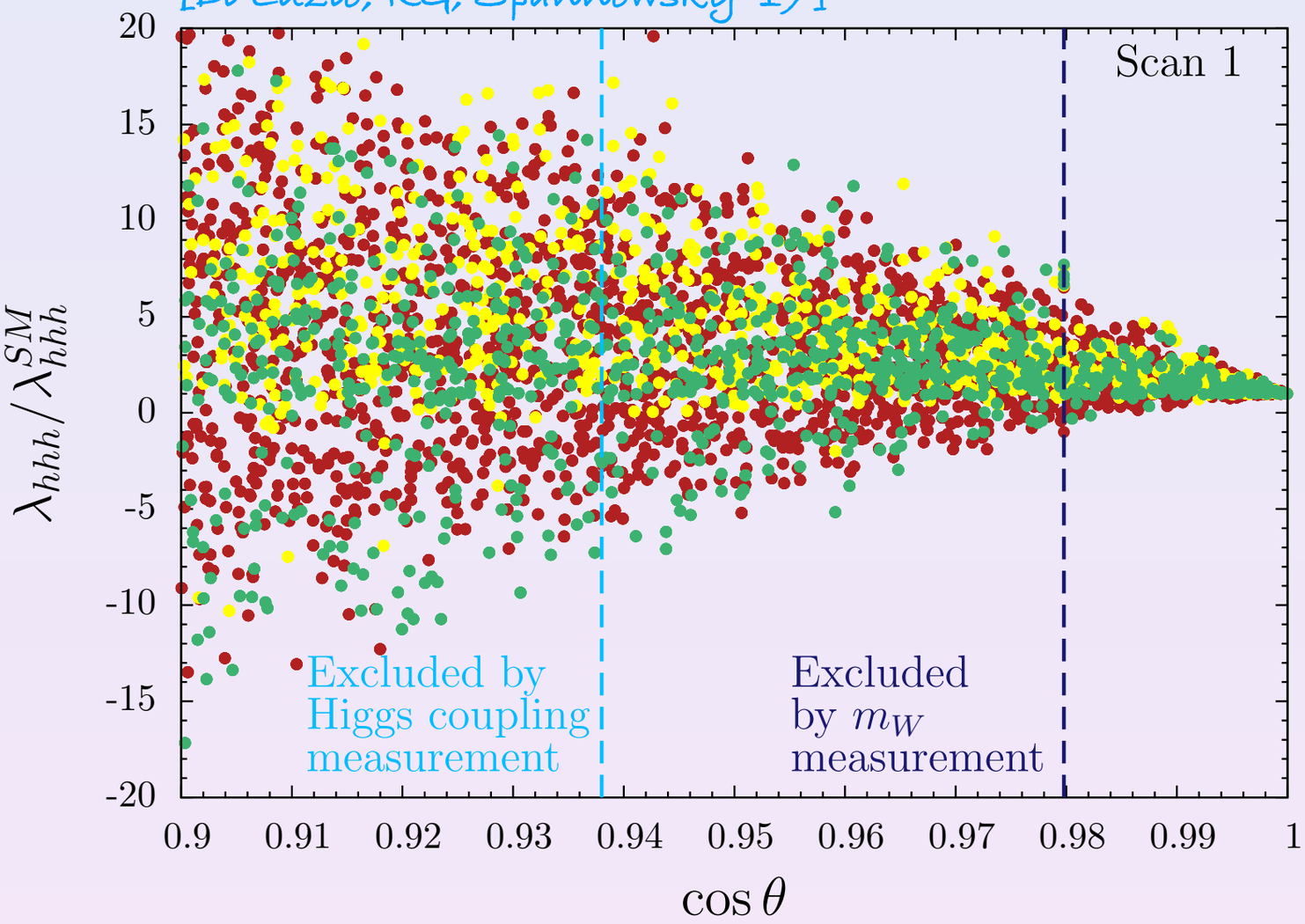
$(1,4,\frac{3}{2})$	$\Phi H^\dagger H^\dagger H^\dagger$

How large can λ_{hhh} be, taking into account indirect constraints?

Singlet model

$$V(H,\Phi) = \mu_1^2|H|^2 + \lambda_1|H|^4 + \frac{1}{2}\mu_2^2\Phi^2 + \mu_4|H|^2\Phi + \frac{1}{2}\lambda_3|H|^2\Phi^2 + \frac{1}{3}\mu_3\Phi^3 + \frac{1}{4}\lambda_2\Phi^4$$

[Di Luzio, RG, Spannowsky '17]



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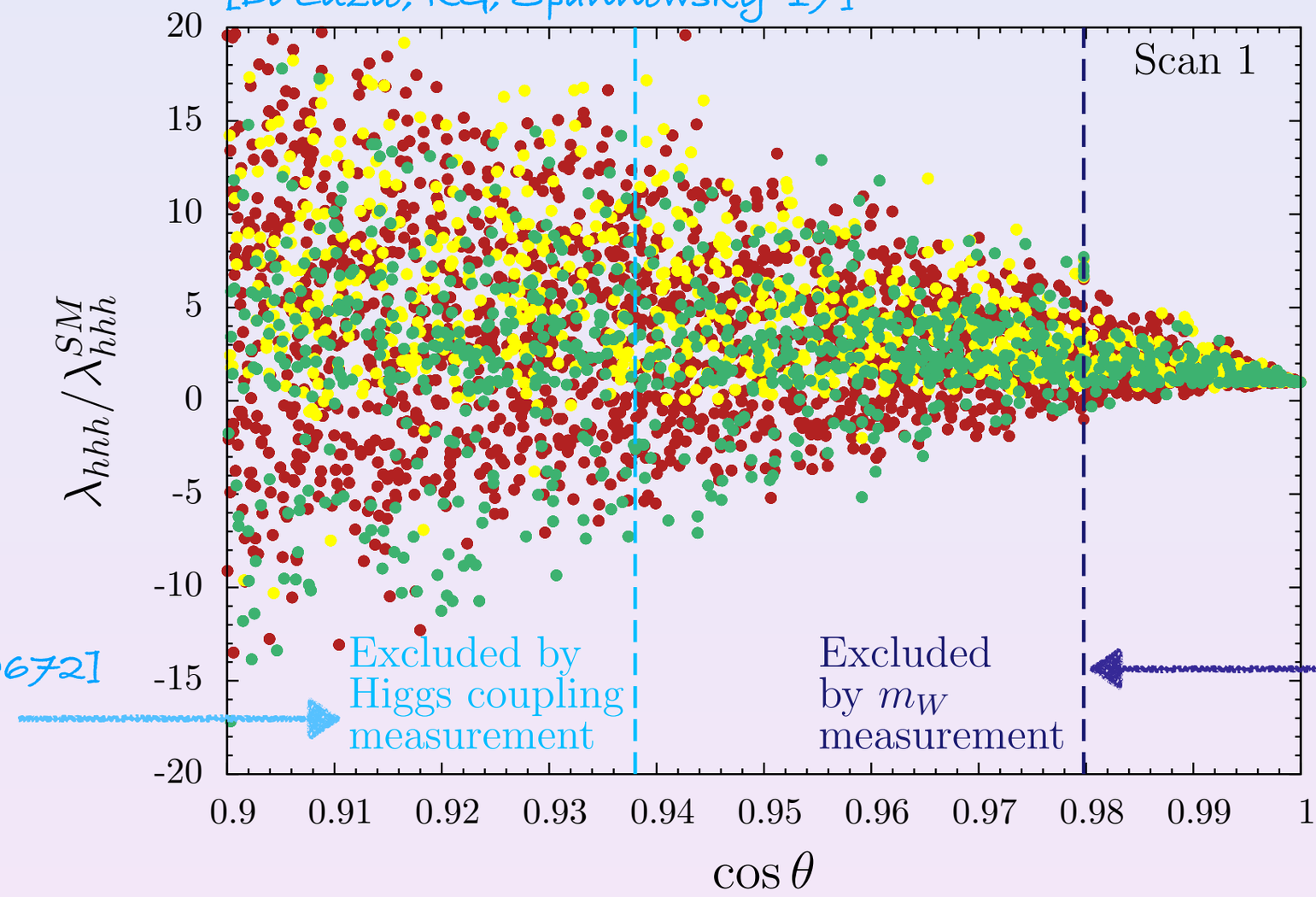
[Di Luzio, RG, Spannowsky '17]



[ATLAS 1509.006721] →

← [Lopez-Val, Robens '14]

Color code: electroweak vacuum is stable, metastable, unstable

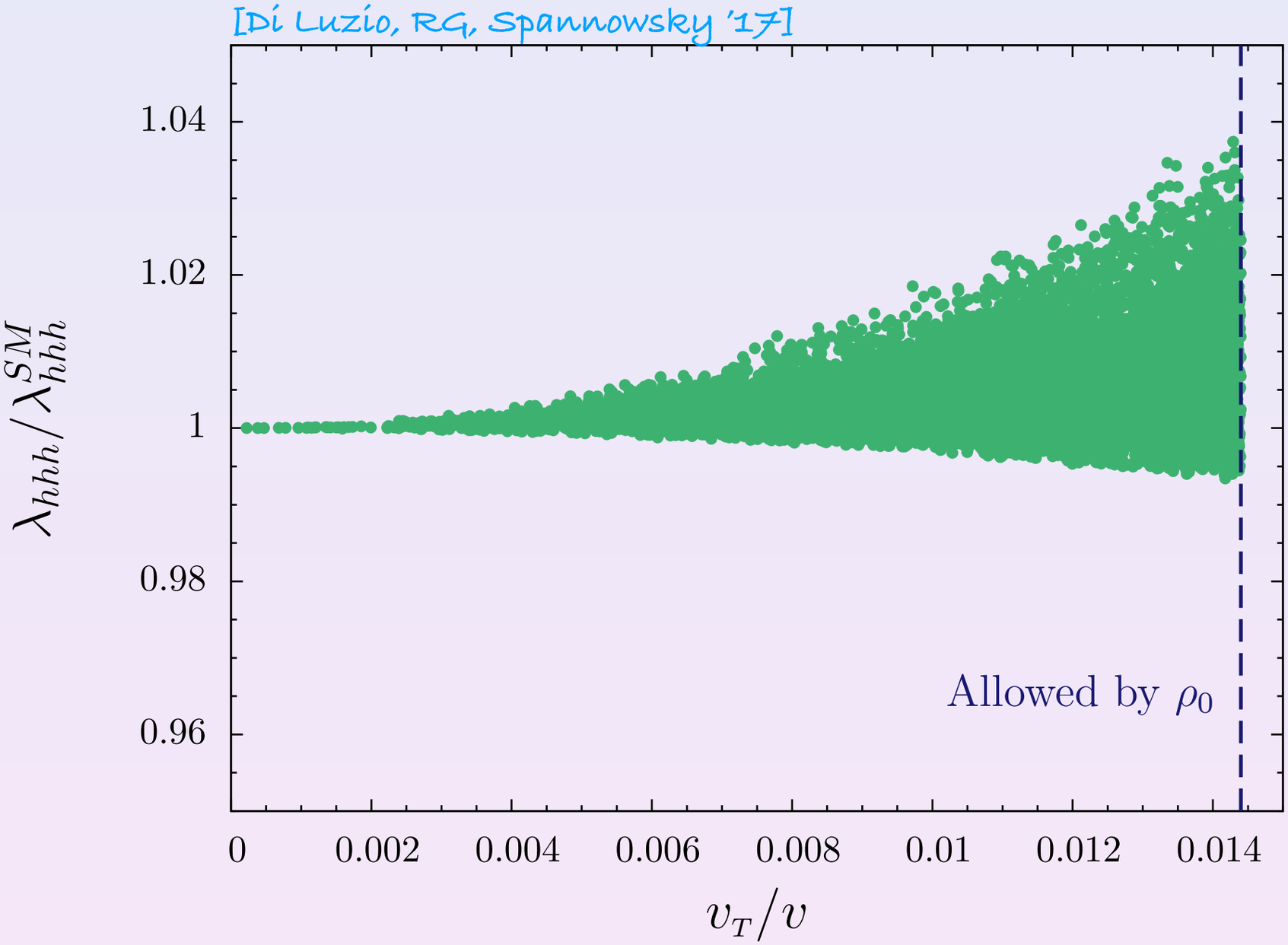
Singlet model allows for deviations of

$$-1.5 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 8.7$$

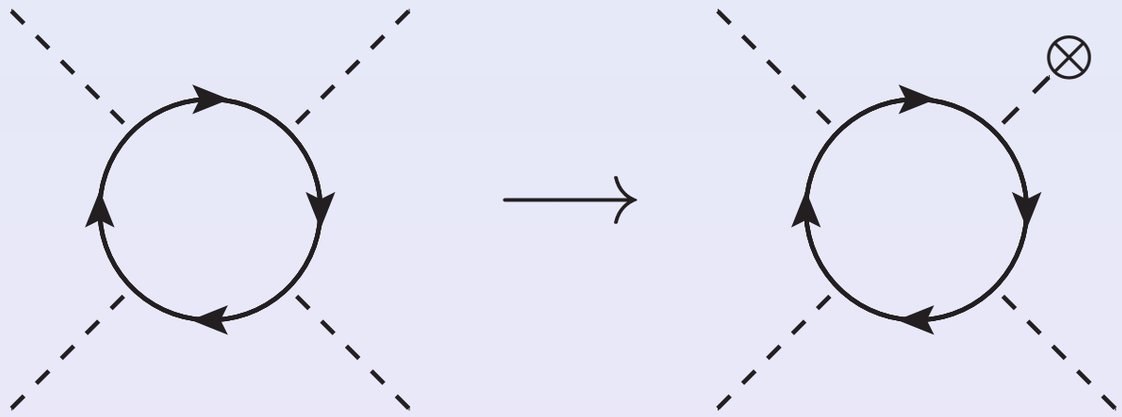
Triplet model

$$V(H,\Phi) = \mu_1^2 |H|^2 + \frac{1}{2}\mu_2^2 |\Phi|^2 + \lambda_1 |H|^4 + \frac{1}{4}\lambda_2 |\Phi|^4 + \frac{1}{2}\lambda_3 |H|^2 |\Phi|^2 + \mu_4 H^\dagger \sigma^\alpha H \Phi^\alpha$$

[Di Luzio, RG, Spannowsky '17]



Loop induced λ_{hhh} modification



Connection vacuum stability

trilinear Higgs self-coupling

study case of fermonic singlets

RH neutrinos, inverse see-saw

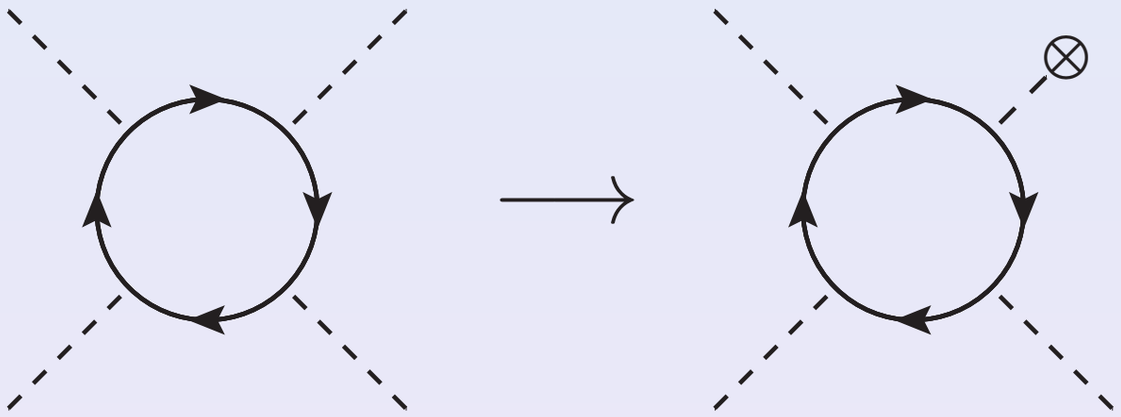
[Mohapatra, (Valle)'86, Bernabeu et al '87]

$$\mathscr{L}_{ISS} = -Y_\nu^{ij}\bar{L}_i\tilde{\phi}\nu_{R,j} + M_{ij}\bar{\nu}_{R,i}X_j + \mu_X^{ij}\bar{X}_i^C X_j + h.c.$$

common mass scale M=10 TeV

and $Y_\nu = |y_\nu| I_3$ [Baglio, Weiland '16]

Loop induced λ_{hhh} modification



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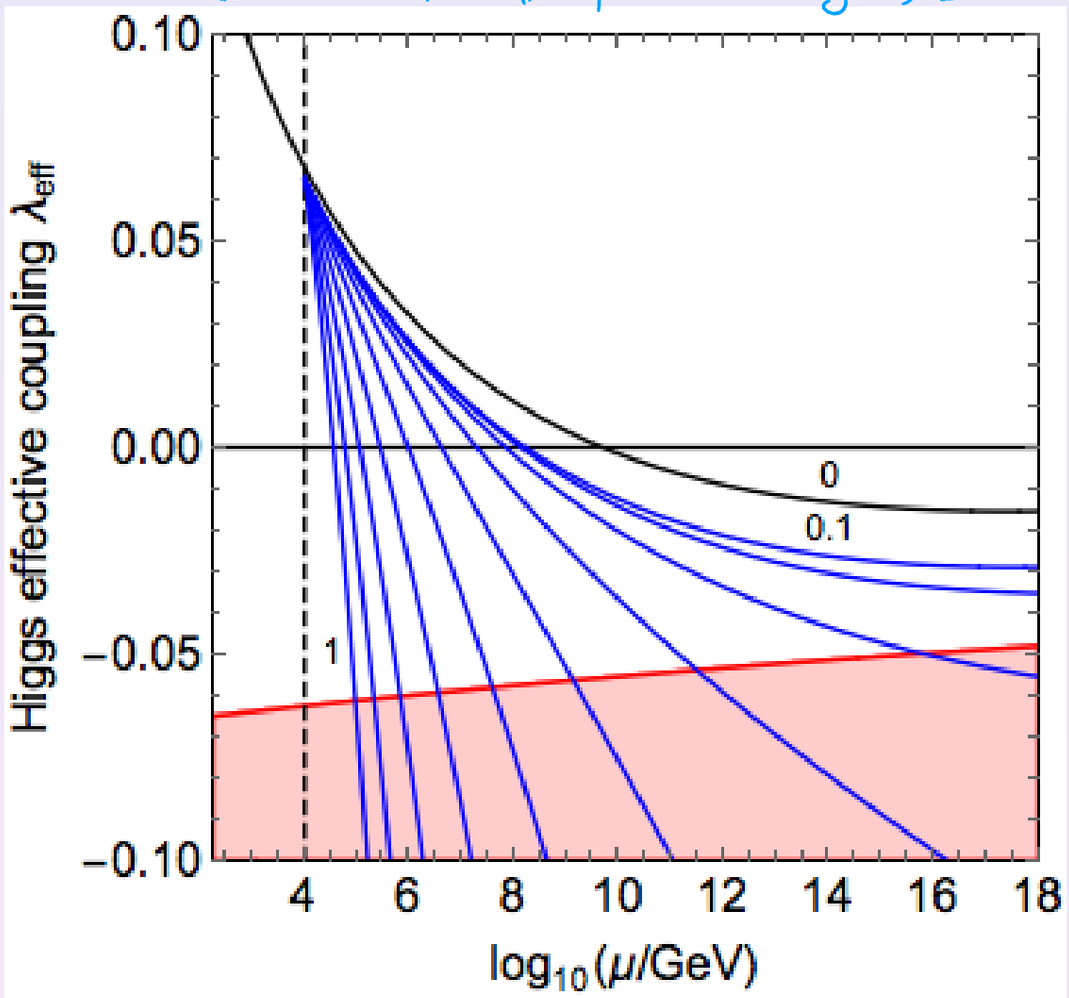
$y_\nu = 0.8$ requires UV-completion within 2 orders of magnitude due to instability [see also Delle Rose, Marzo, Urbano '15]

Connection vacuum stability

trilinear Higgs self-coupling

[Di Luzio, RG, Spannowsky '17]



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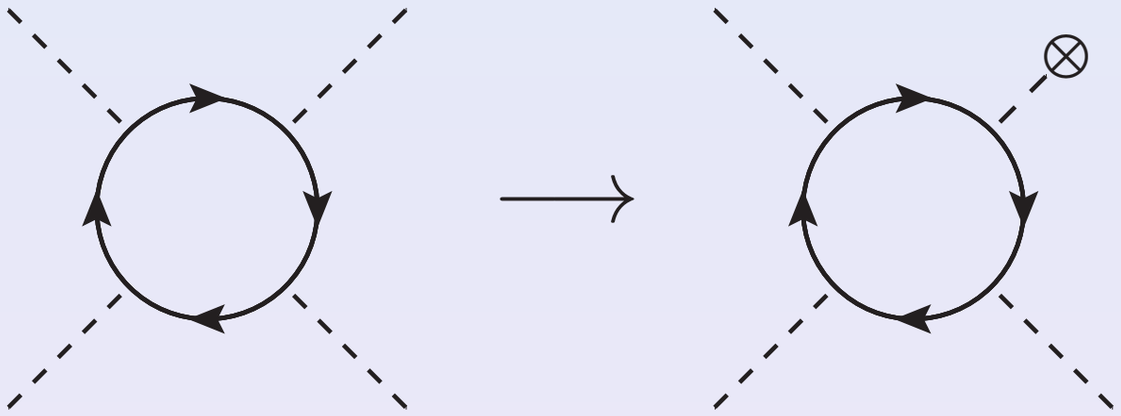


modification of trilinear Higgs self-coupling

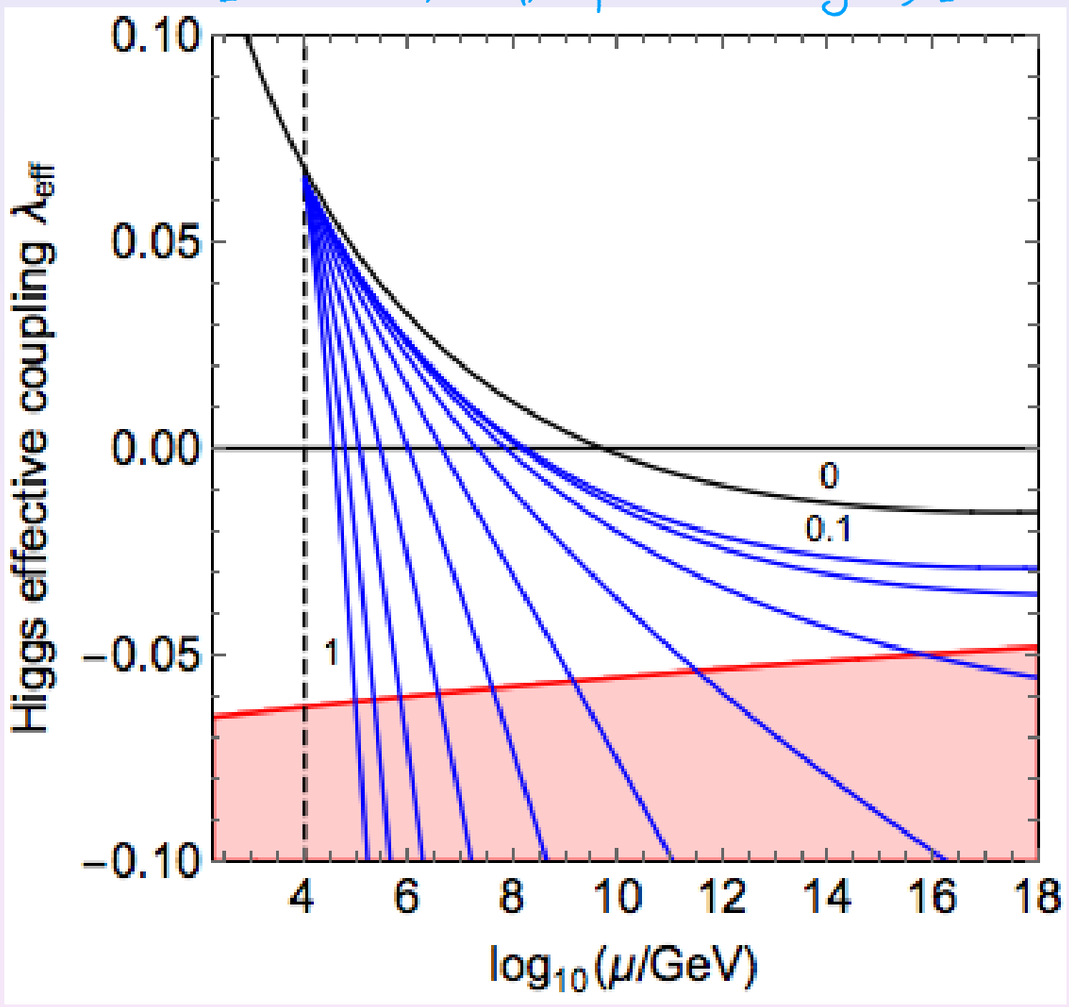
$$|\lambda_{hhh}/\lambda_{hhh}^{SM}| < 0.1\,\%$$

non-observable

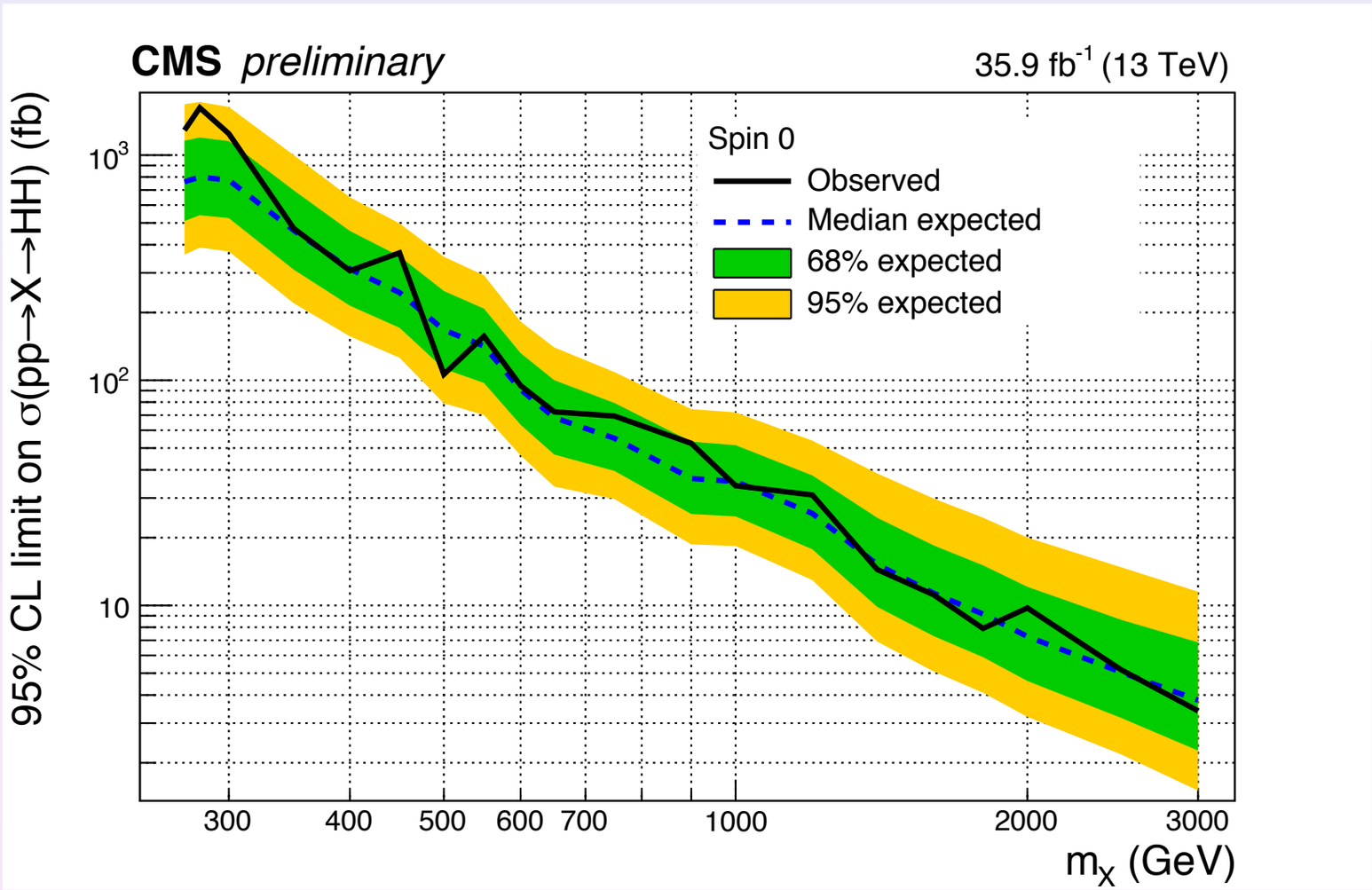
Connection vacuum stability

trilinear Higgs self-coupling

[Di Luzio, RG, Spannowsky '17]



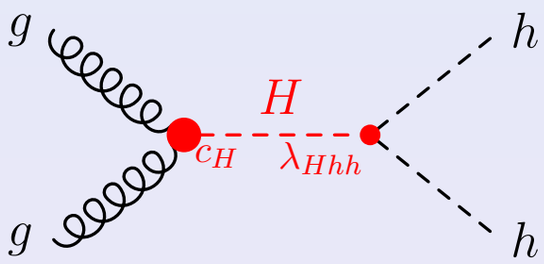
Resonant di-Higgs production



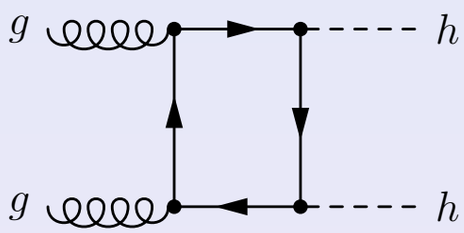
[many works in different models, e.g. Chen, Dawson, Lewis '14, Martin Lonzano, Moreno, Park '15, Huang et al '17, ...]

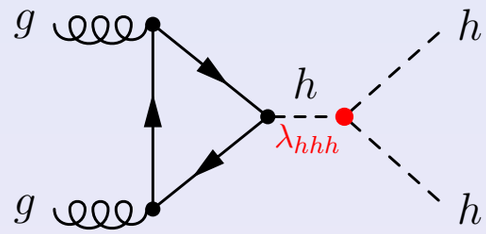
Resonant production of a new scalar

Signal



Background





$$\mathscr{L} = \frac{\alpha_s}{12\pi v} c_H H G_{\mu\nu} G^{\mu\nu}$$

parameters $|c_H|, \phi_{c_H}, \Gamma_H, \lambda_{hhh}$

When is the interference between signal and background relevant?

Not considered in experimental searches

Resonant production of a new scalar

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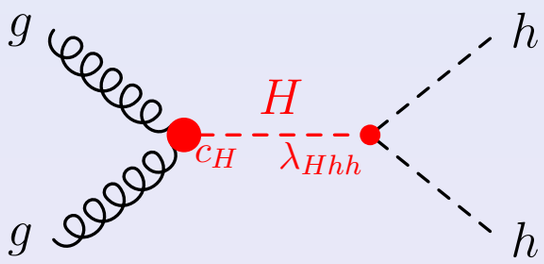

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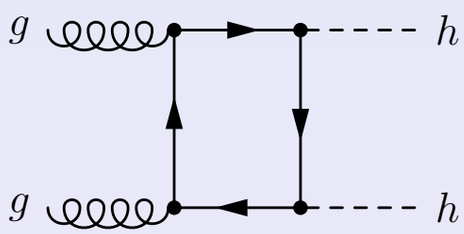

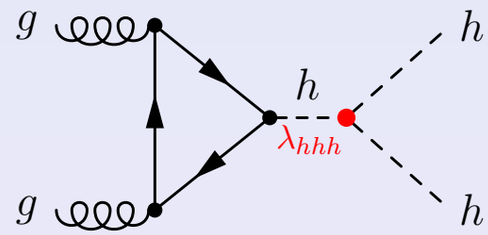

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$$\frac{d\sigma}{dm_{hh}} = \frac{d\sigma_S}{dm_{hh}} + \frac{d\sigma_I}{dm_{hh}} + \frac{d\sigma_B}{dm_{hh}}$$

Resonant production of a new scalar

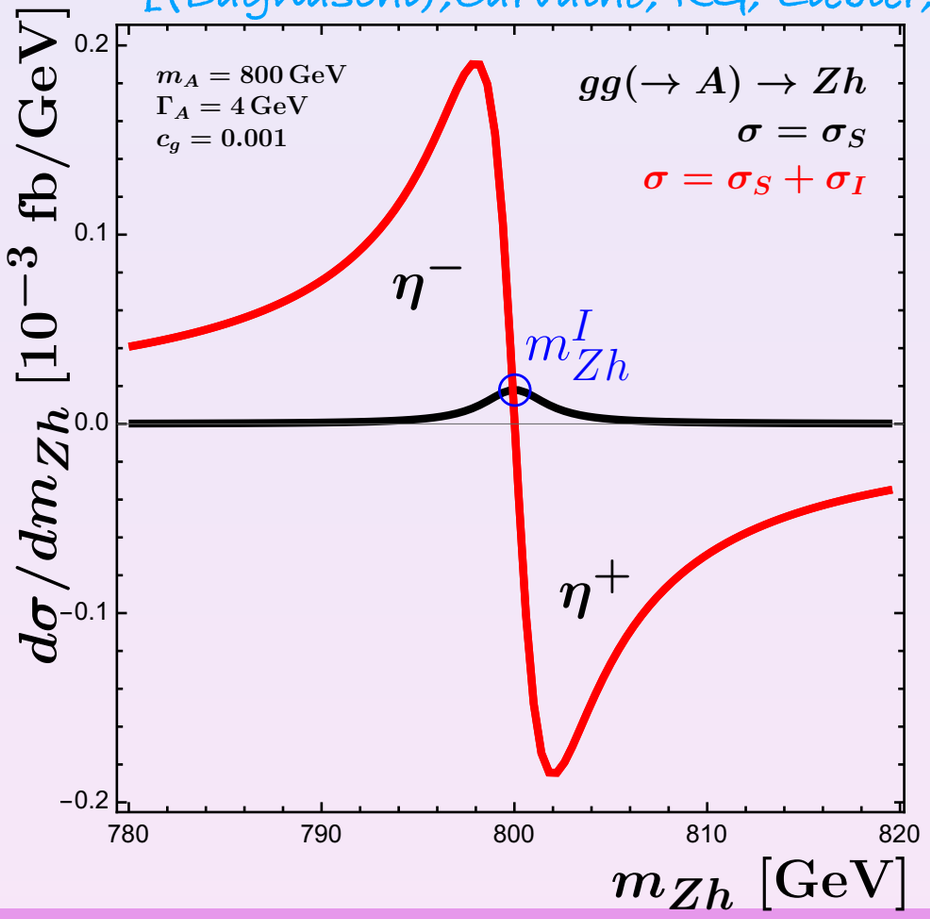
Classification of interferences

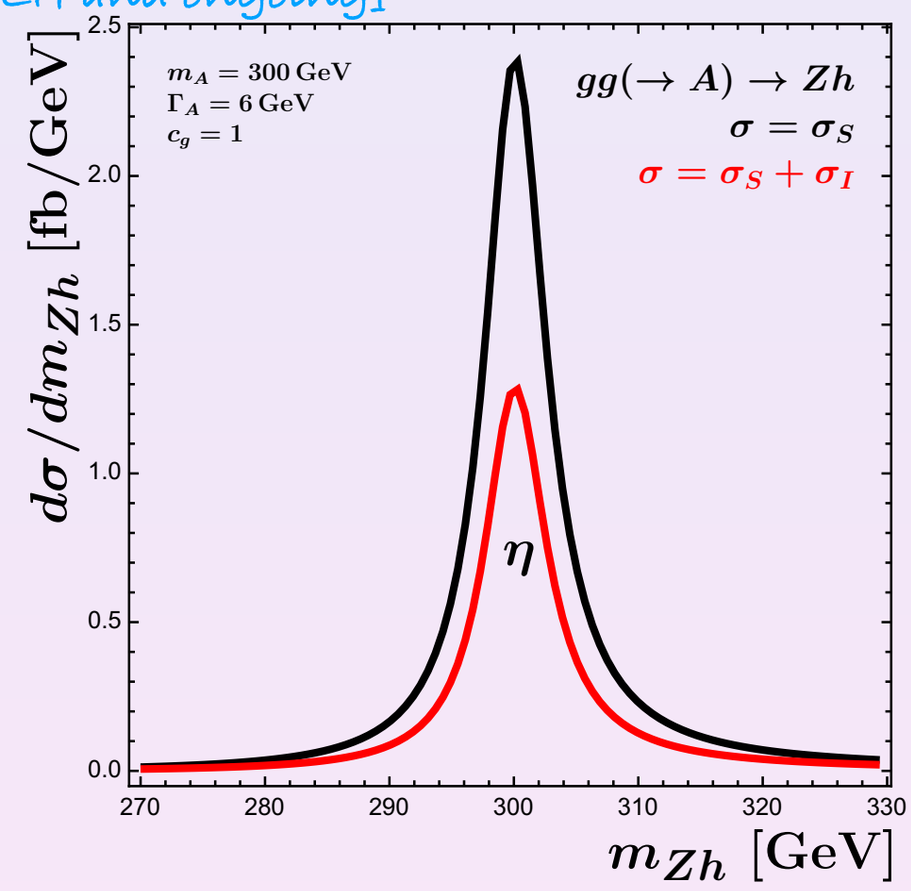
$$\eta = \int_{m_\phi-10\Gamma_\phi}^{m_\phi+10\Gamma_\phi} dm_F \left(\frac{d\sigma_S}{dm_F}+\frac{d\sigma_I}{dm_F}\right) \Big/ \int_{m_\phi-10\Gamma_\phi}^{m_\phi+10\Gamma_\phi} dm_F \left(\frac{d\sigma_S}{dm_F}\right)$$

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

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

[(Bagnaschi),Carvalho, RG, Liebler, Quevillon @LH and ongoing]



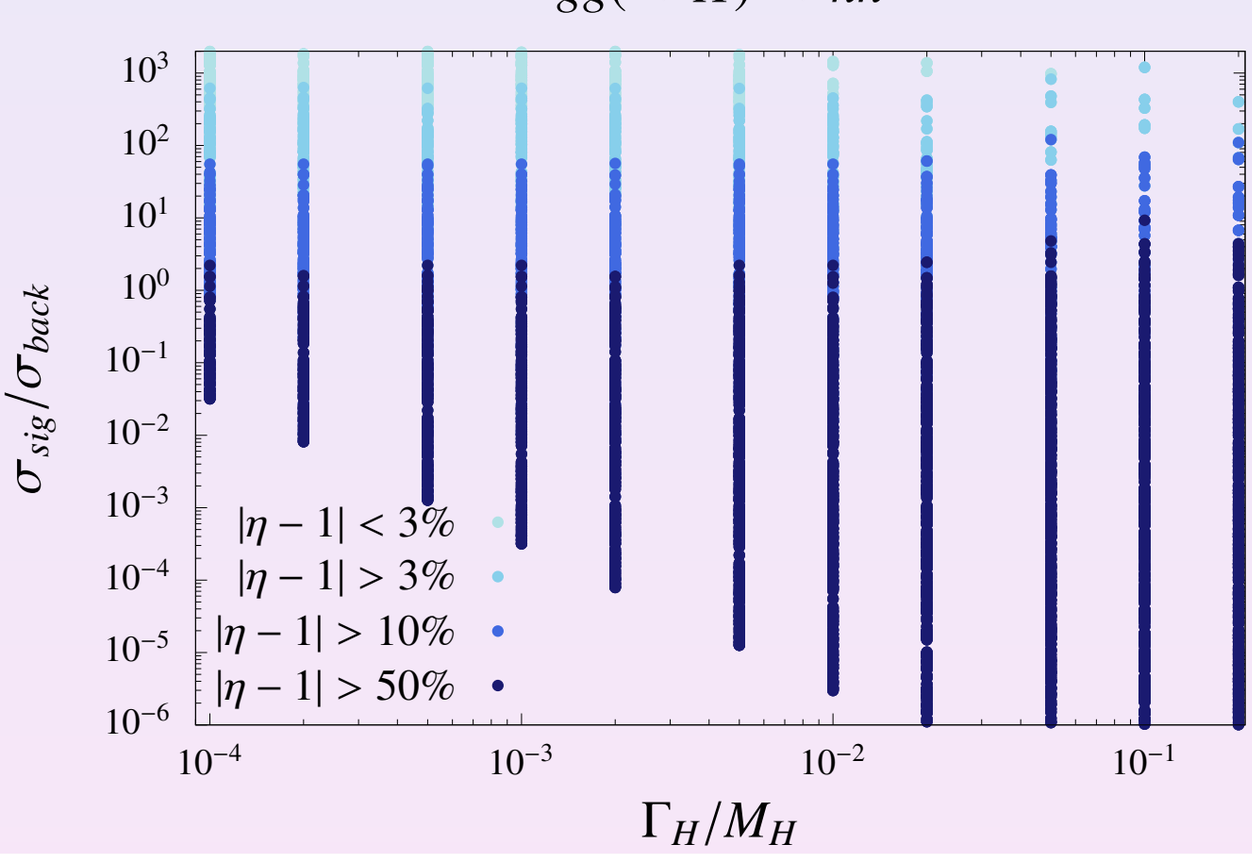


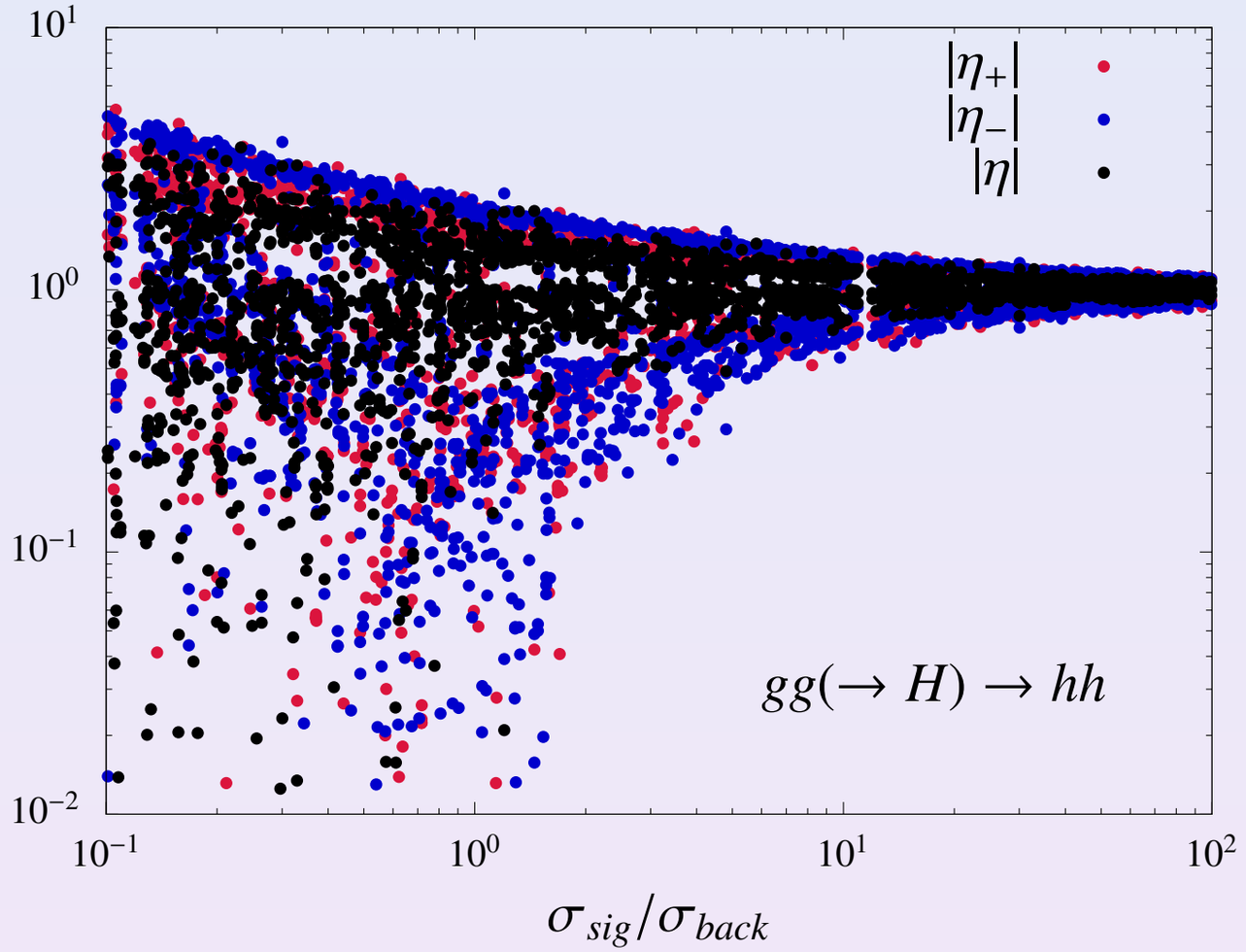
Resonant production of a new scalar

When is the interference between signal and background relevant?

Interference sizeable if

$\sigma_{sig}/\sigma_{back}$ O(10) or smaller





I(Bagnaschi),Carvalho, RG, Liebler, Quevillon @LH and ongoing]

Conclusion

- Higgs pair production measurement allows to probe exciting new physics

  Higgs potential: probes trilinear self-coupling

  discovery channel for new Higgs bosons

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  Concrete models can have deviations in trilinear Higgs self-coupling by a factor of a few

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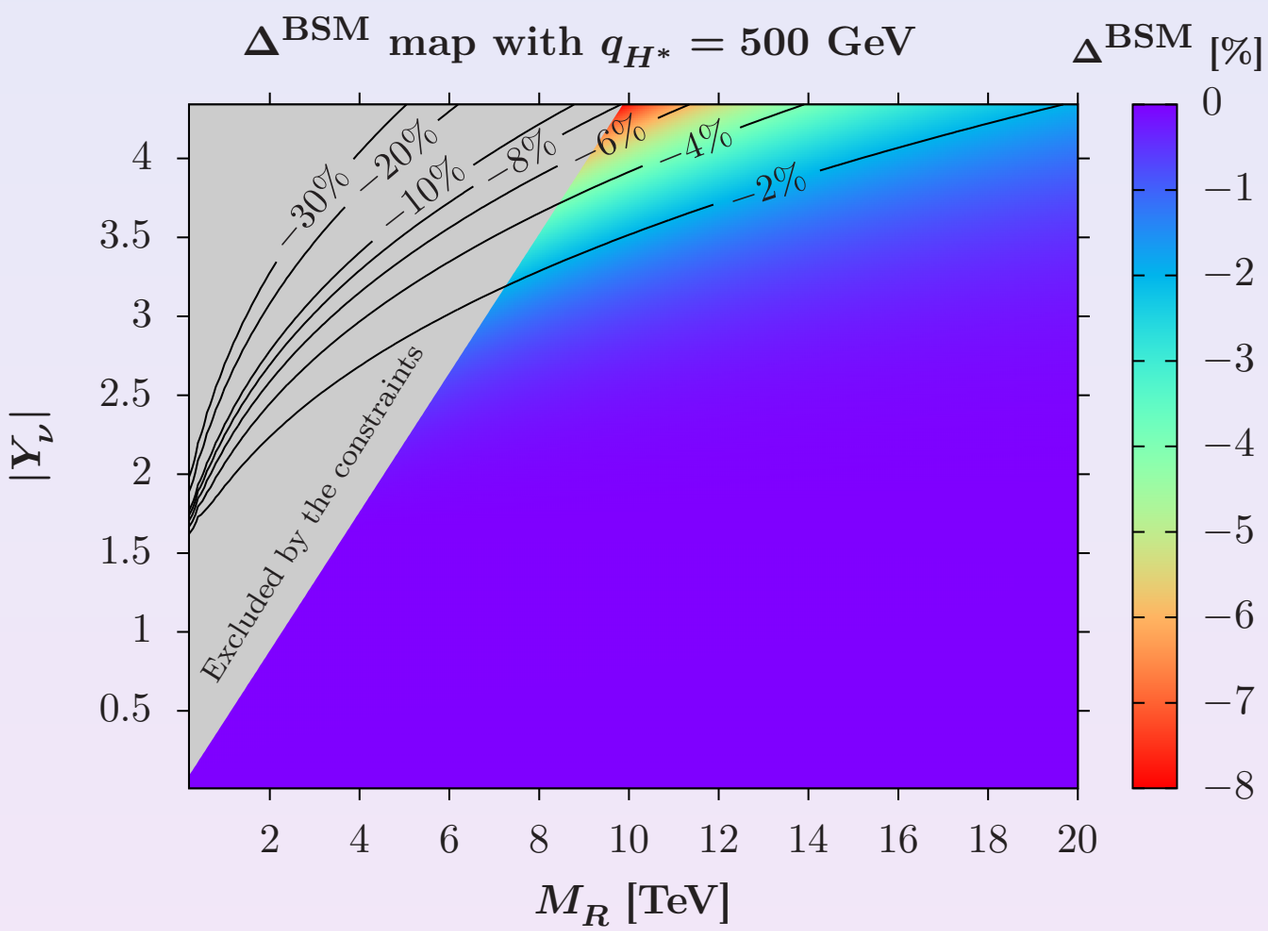
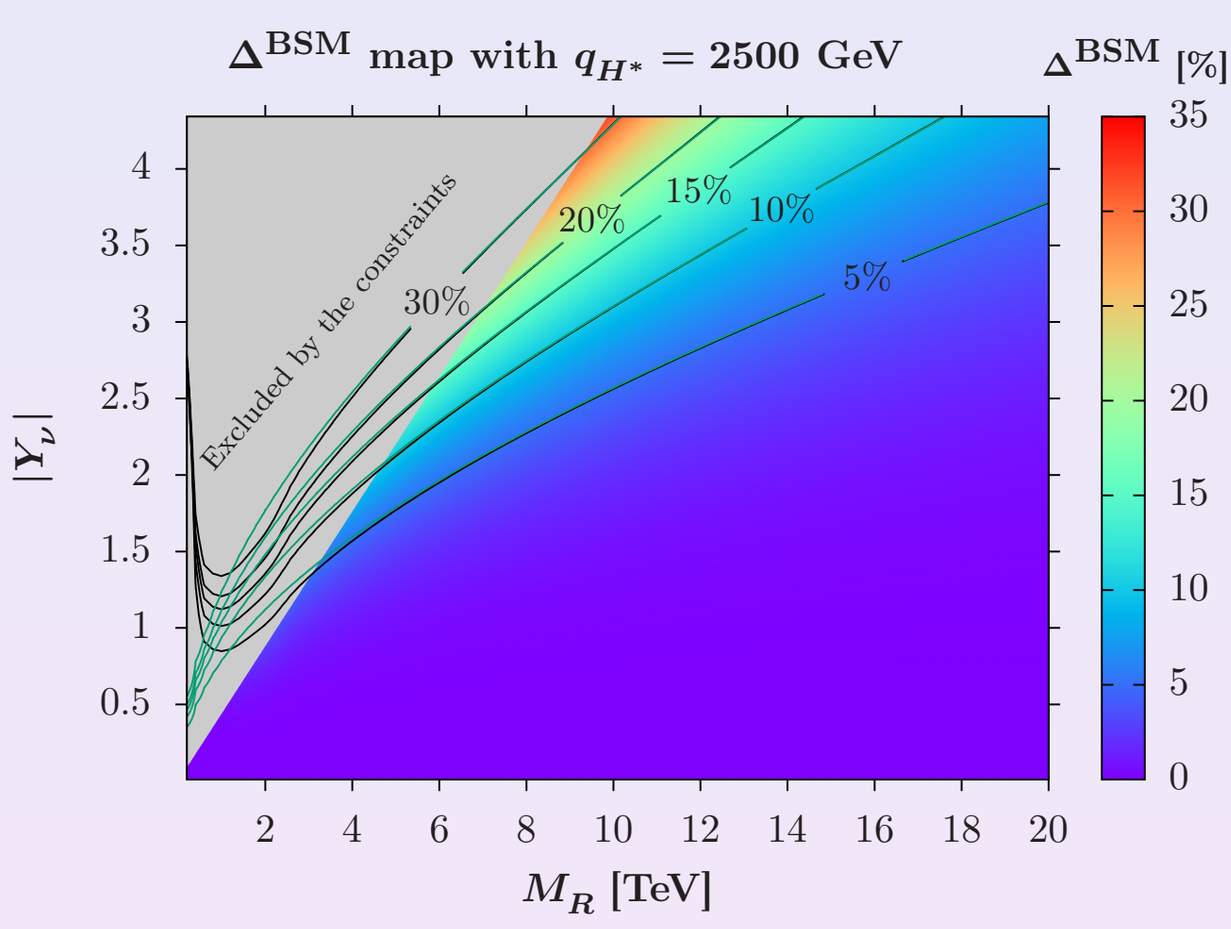
Thanks for your attention!

Bounds on neutrino model

[plots form Baglio, Weiland '16]





constraints from LFV decays, non-unitarity of PMNS matrix, Planck and neutrino oscillation data

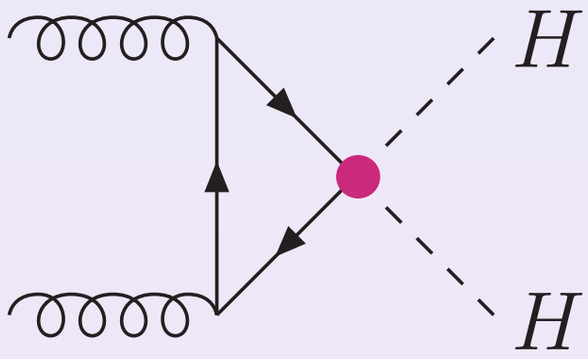
Higgs non-linearities

$$\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{2v^2}\right)-c_3\frac{1}{6}\left(\frac{3M_h^2}{v}\right)h^3+\frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{2v^2}\right)$$

not independent in SMEFT

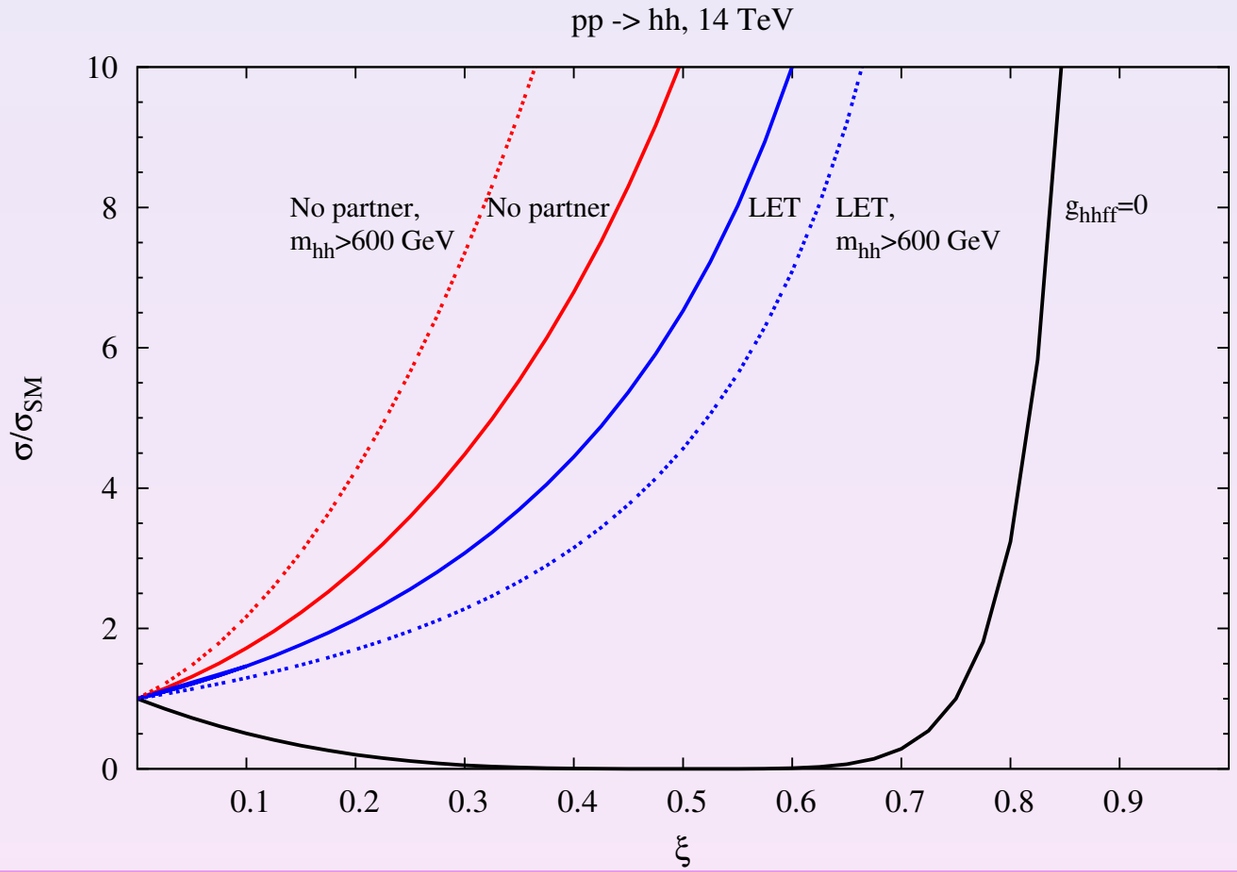
not independent in SMEFT

needs to be probed in multi-Higgs final states

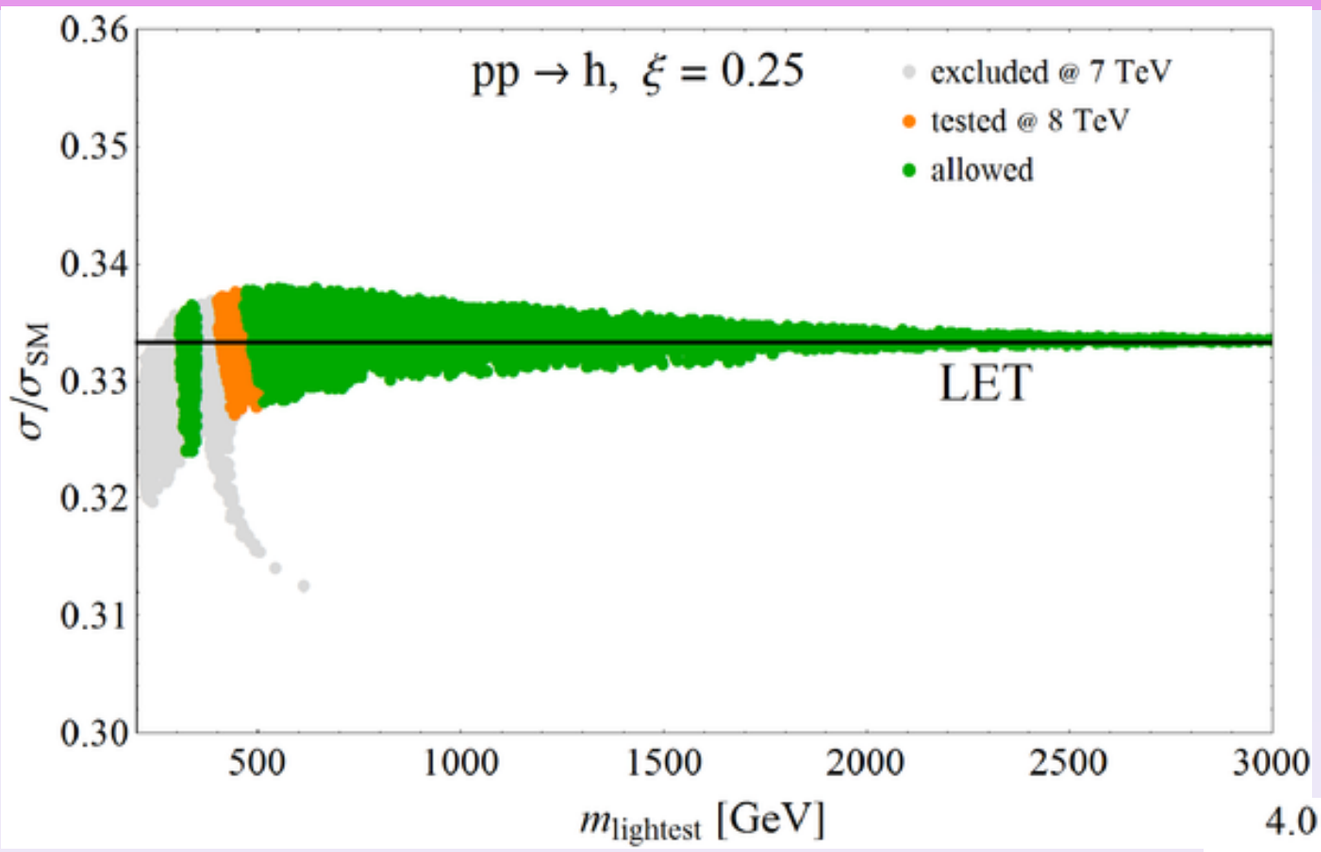


[Gillioz, RG, Grojean, Mühlleitner, Salvioni '12]

appears e.g. in Composite Higgs Models [RG, Mühlleitner '10]
leads to a large increase of cross section



Probing new particle in the loop



Single Higgs

Possible degeneracy of shift in top Yukawa coupling and effective coupling to gluons

Example: [Falkowski '07, Low, Vichi '10, ...]

Composite Higgs Models, dependence only on ξ

[Gillioz, RG, Grojean, Mühlleitner, Salvioni '12]

Double Higgs

Can resolve degeneracy

In CHMs: dependence on spectrum of vector-like quarks