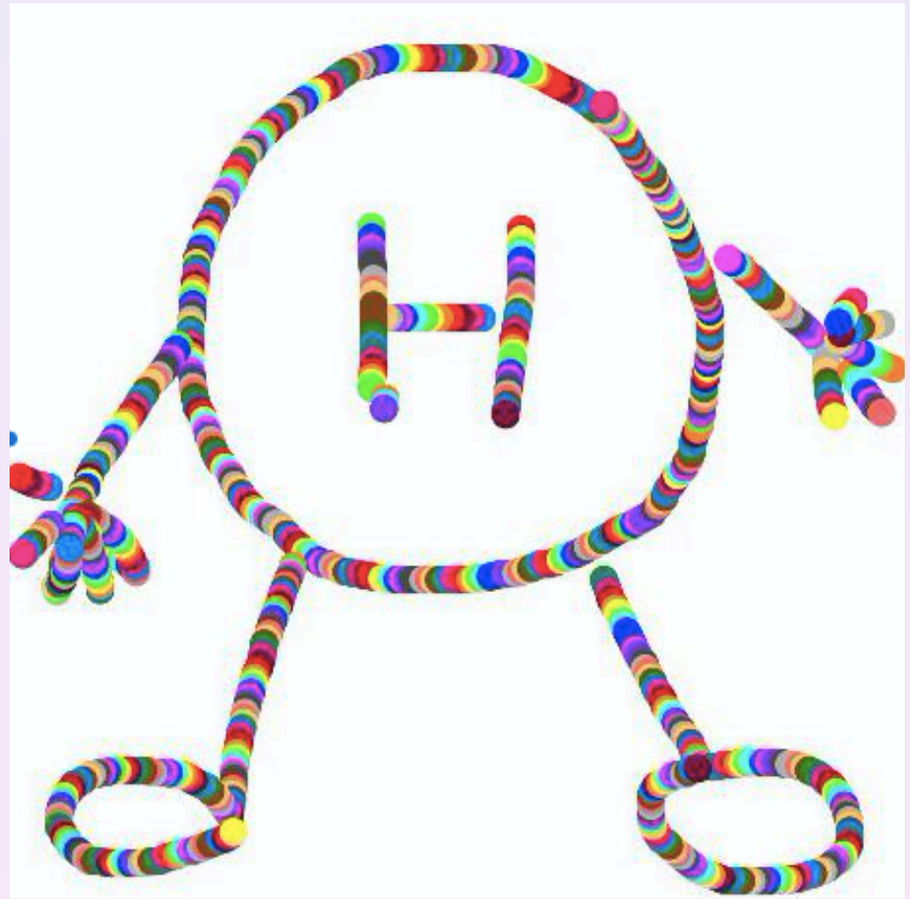
SM and BSM Higgs properties

Ramona Gröber

IPPP,
Durham University

Invisibles 2018

07/09/2018



The Higgs boson discovery...

With the Higgs boson the last missing ingredient of the Standard Model is found ...

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...but is it the only Higgs boson?
Is the Higgs sector really as predicted by the SM?

Why Higgs physics at Invisibles '18?

Why am I here? What is the connection to Invisibles?

Why Higgs physics at Invisibles '18?

Connections to the "Invisibles":

- Higgs as a portal

$$\mathcal{L} = \lambda(\phi^\dagger\phi)(H^\dagger H)$$ to scalars: "dark sector"

$$\mathcal{L} = yL^\dagger HN$$ neutrino portal

[see e.g. also Arsenii's talk on Monday, Anastasiia, Nicolas' and Sarif's talk yesterday]

- Higgs decays to invisibles

Higgs boson measurements of invisible width can limit light invisible states

- connection of hierarchy problem with other open issues of SM

e.g. dark matter? → could there be a connection to the Higgs sector?

matter-antimatter asymmetry of the universe → could there be a connection to the Higgs sector?

The Higgs boson at Invisibles '18

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  Higgs boson measurements of invisible width can limit light invisible states

- connection of hierarchy problem with other open issues of SM

  e.g. dark matter? → many models address both, e.g. SUSY

  matter-antimatter asymmetry of the universe → electroweak baryogenesis, modification of trilinear Higgs self coupling

The Higgs boson - what do we know?

width

couplings

mass

spin

CP

The Higgs boson – what do we know?

width

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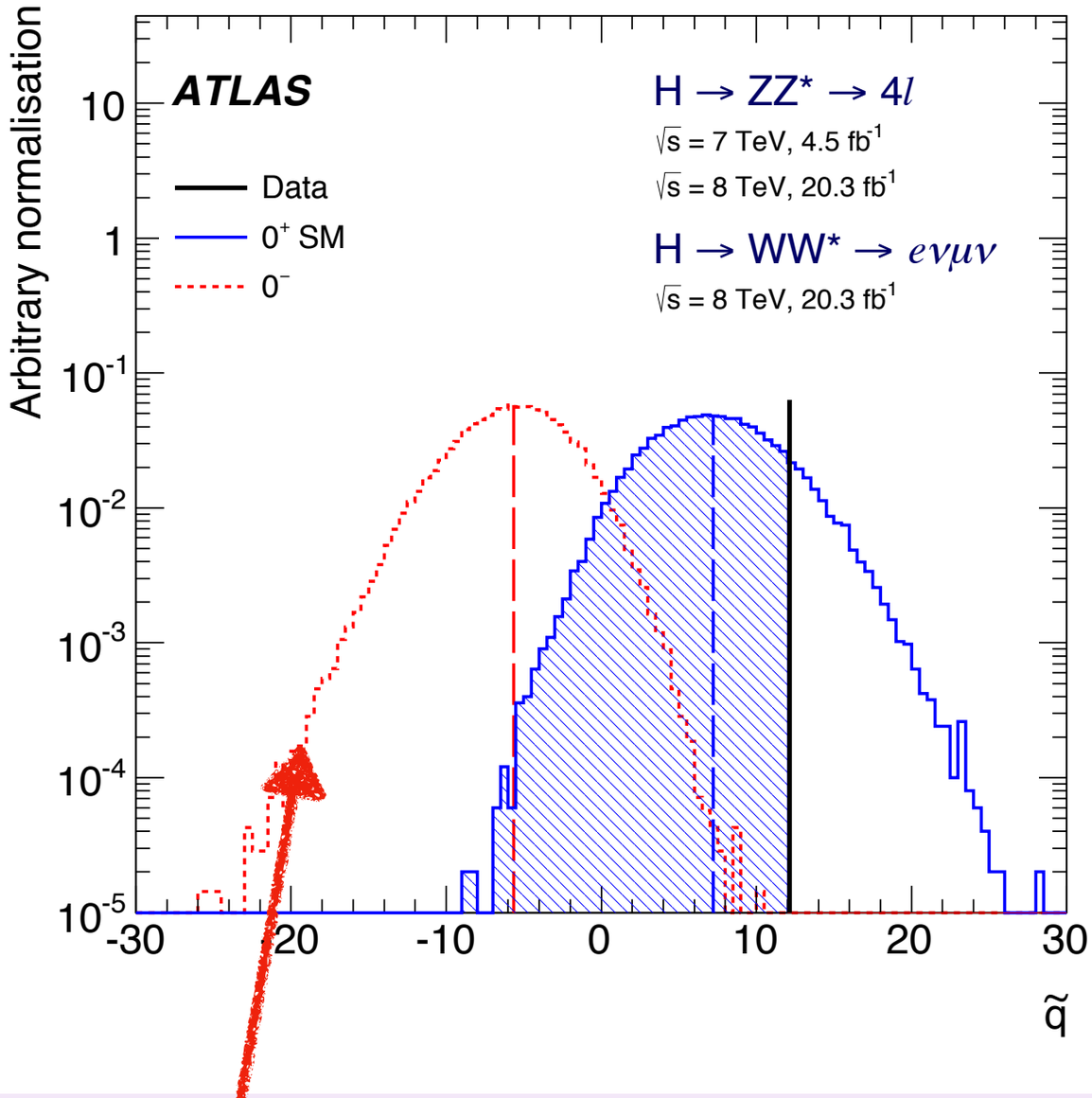
spin

$$m_H = 124.97 \pm 0.24 \text{ GeV}$$

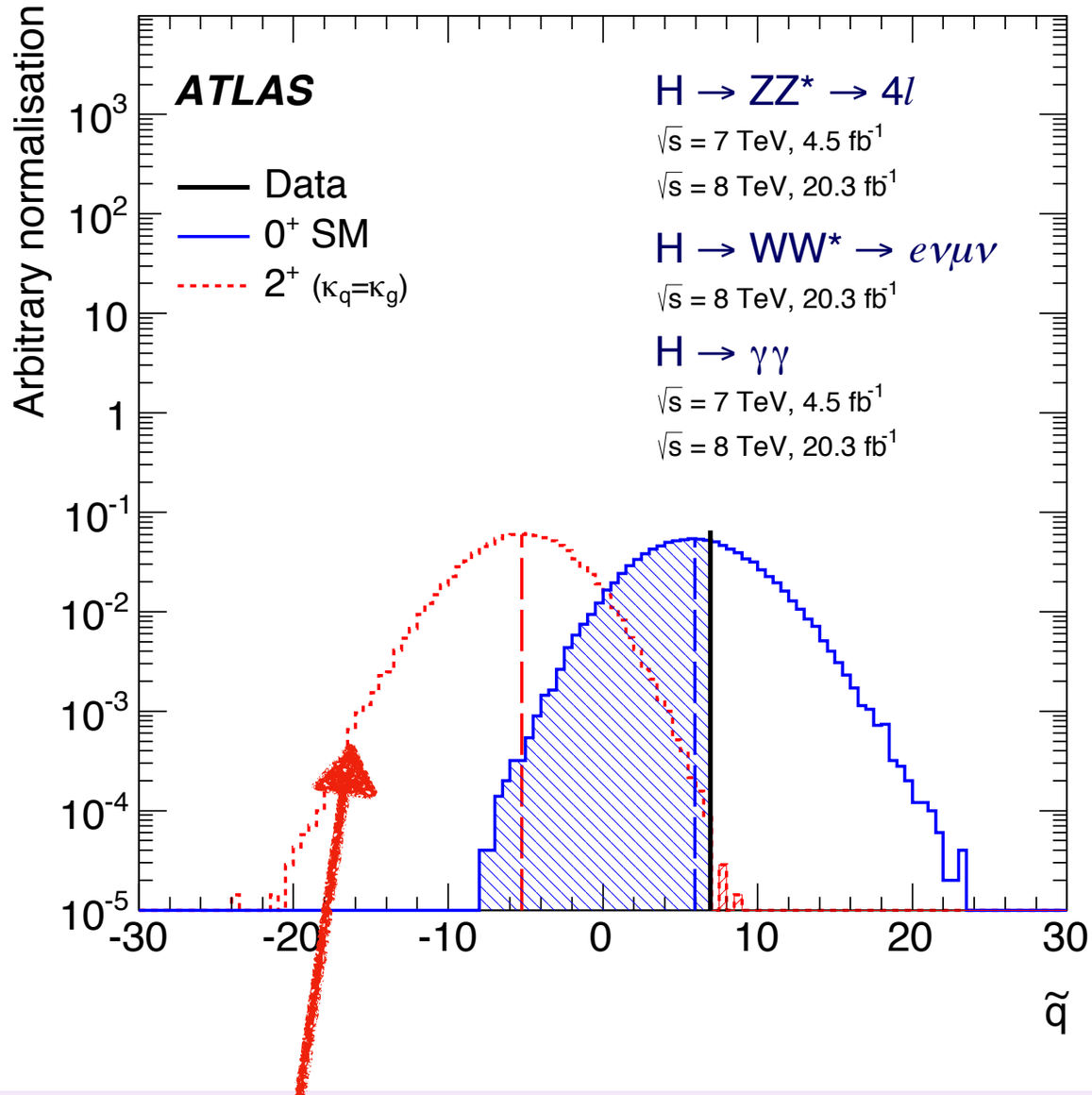
[ATLAS, 1806.00242]

CP

CP/Spin

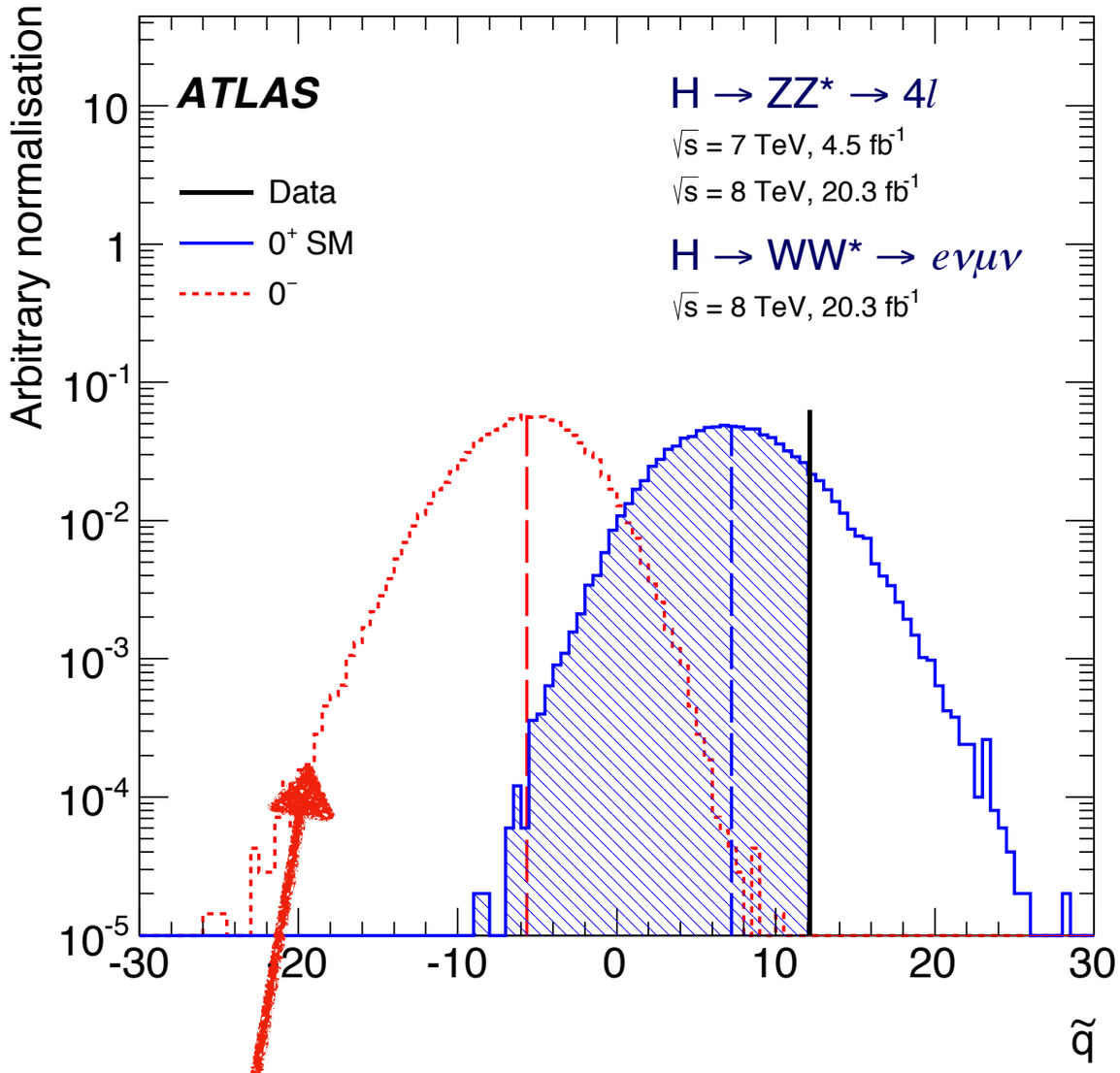


purely CP-odd



spin 2

CP/Spin



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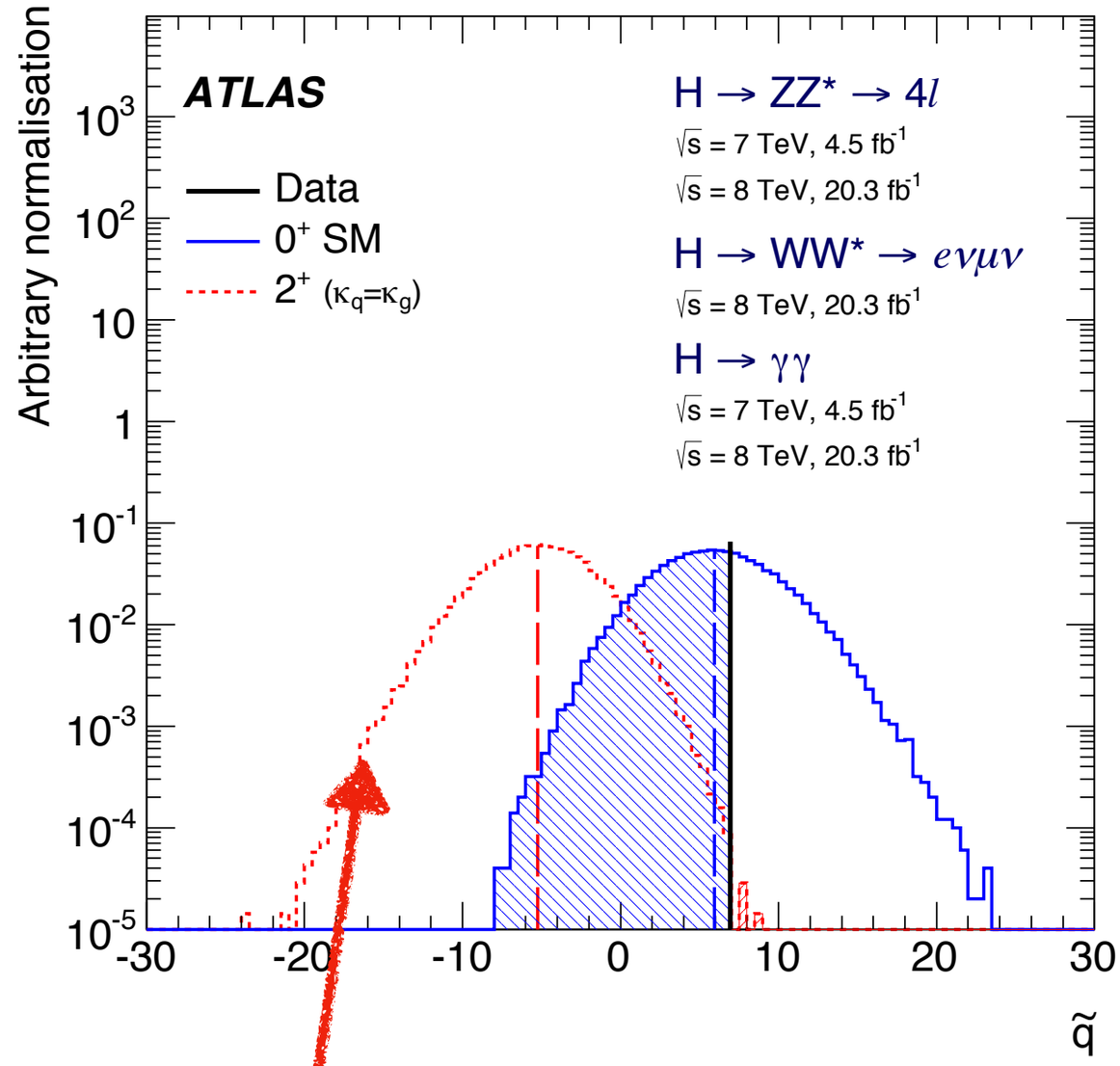
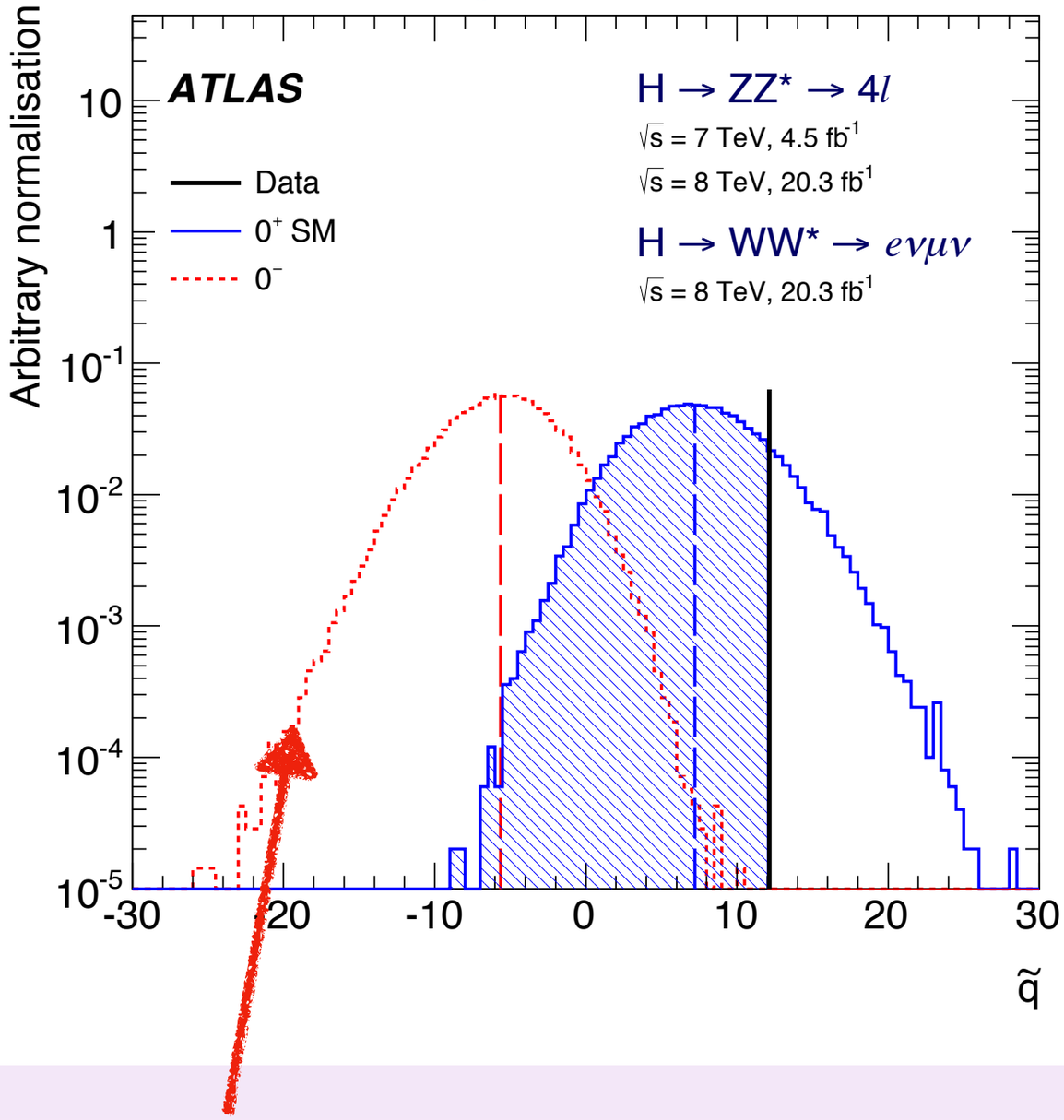


spin 2

spin 2/ purely CP-odd Higgs disfavoured

CP/Spin

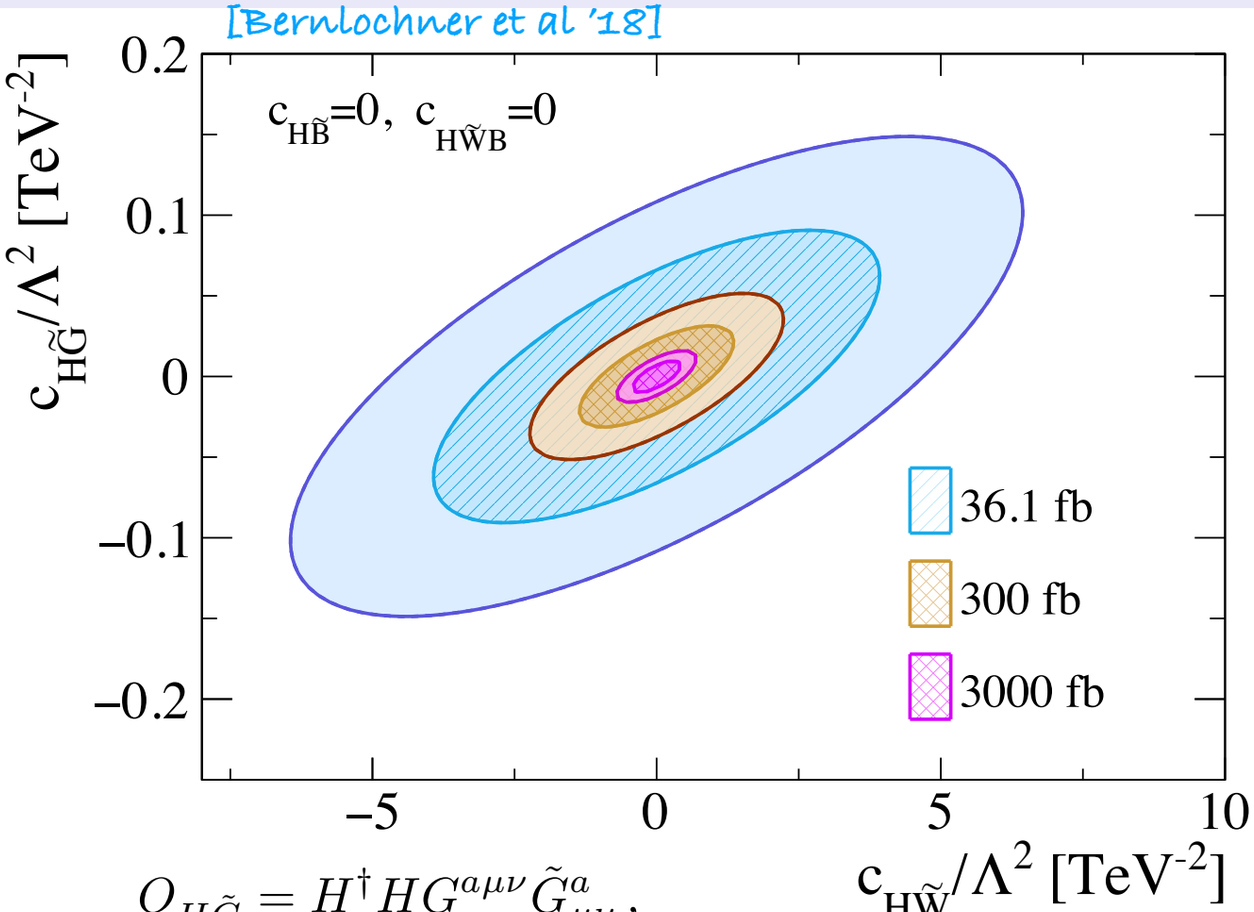
[ATLAS 1506.05669]



purely CP-odd

This does not mean though there can be no CP-violation in the Higgs sector!

[Bernlochner et al '18]



$$O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu}\tilde{G}^a_{\mu\nu}\,,$$

$$O_{H\tilde{W}} = H^\dagger H W^{a\mu\nu}\tilde{W}^a_{\mu\nu}$$

spin 2/ purely CP-odd Higgs disfavoured

Higgs width

$$\Gamma_H = \Gamma_{vis} + \Gamma_{inv} + \Gamma_{untagged}$$

the "usual" SM decays

decays to invisible final states, e.g. DM current limits

BR<0.24

[CMS 1610.09218]

visible but yet not searched for exotic final states

no direct measurement possible at the LHC

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sizeable destructive interference of h->ZZ with background [Kauer Passarino '12]

measurement of off- and on shell couplings allows to extract width

[Caola, Melnikov '13]

$$\mu_{ZZ}^{\rm on} \equiv \frac{\sigma_h \times {\rm BR}(h \to ZZ \to 4\ell)}{[\sigma_h \times {\rm BR}(h \to ZZ \to 4\ell)]_{\rm SM}} \sim \frac{\kappa_{ggh}^2\, \kappa_{hZZ}^2}{\Gamma_h/\Gamma_h^{\rm SM}}\,,$$

$$\mu_{ZZ}^{\rm off} \equiv \frac{{\rm d}\overline{\sigma}_h}{[{\rm d}\overline{\sigma}_h]_{\rm SM}} \sim \kappa_{ggh}^2(\hat{s})\, \kappa_{hZZ}^2(\hat{s})\,,$$

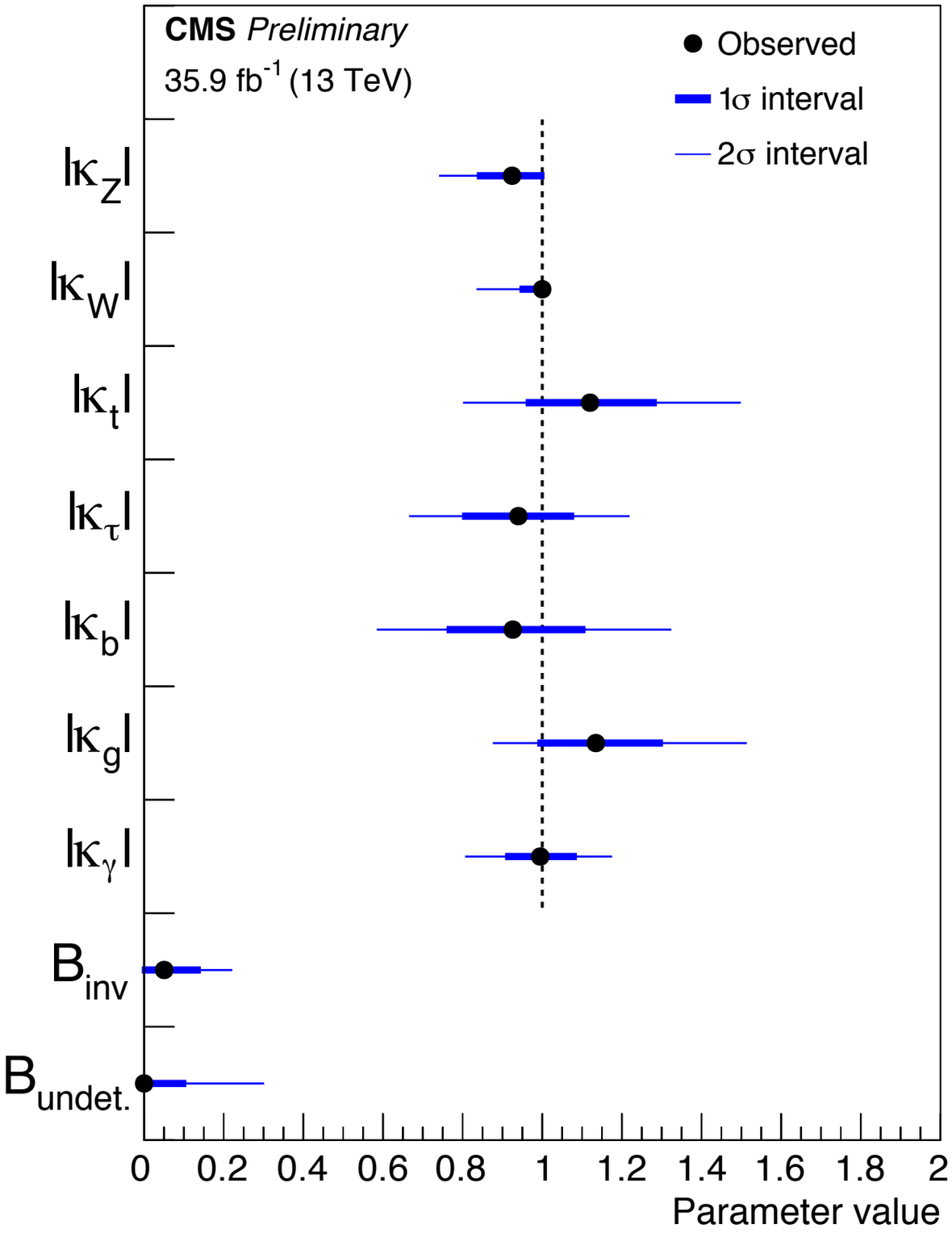
Caveat for width determination:

$$\kappa_{ggh}(\hat{s}) = {\rm const}, \quad \kappa_{hZZ}(\hat{s}) = {\rm const}$$

$$\Gamma_H/\Gamma_{SM} < 3.5$$

[ATLAS 1808.0011911]

Higgs couplings



So far everything SM-like

higher precision might still reveal a surprise

Missing:

- Higgs self-couplings
- couplings to 1st and 2nd generation

Higgs couplings

$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} = & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\left(D^\mu H\right)^\dagger\sigma^i\left(D^\nu H\right)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right)B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{F_1} = & \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\
& + \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& + \left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right) \\
& + \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\
& + \frac{i\bar{c}_{Hl}}{v^2}\left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right),
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{F_2} = & \frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L\sigma^i H^c\sigma^{\mu\nu}u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu} \\
& + \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L\sigma^i H\sigma^{\mu\nu}d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu} \\
& + \frac{\bar{c}_{lB}\,g'}{m_W^2}\,y_l\,\bar{L}_L H\sigma^{\mu\nu}l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\,y_l\,\bar{L}_L\sigma^i H\sigma^{\mu\nu}l_R\,W^i_{\mu\nu} + h.c.
\end{aligned}
$$

[operators from Contino, Ghezzi, Grojean, Mühlleitner, Spira '14]

So far everything SM-like

higher precision might still reveal a surprise

Missing:

- Higgs self-couplings
- couplings to 1st and 2nd generation
- more generally: constrain dim-6 effective Lagrangian

The Higgs boson – what do we know?

width

only under certain assumption, SM width not yet reached

couplings

lot of progress made after Higgs discovery

the more precise the better

couplings still to be measured

mass ✓ ★

the more precise the better

spin ✓

CP ✓ ★

CP-mixed state still possible

The future in Higgs physics

- Precision measurements of couplings:

  Many models predictably only small deviations in couplings in absence of new light states

- Couplings yet unexplored

  light Yukawa couplings, Higgs self-couplings, in general: exploration of dim-6 Higgs operators

- Exotic Higgs decay channels

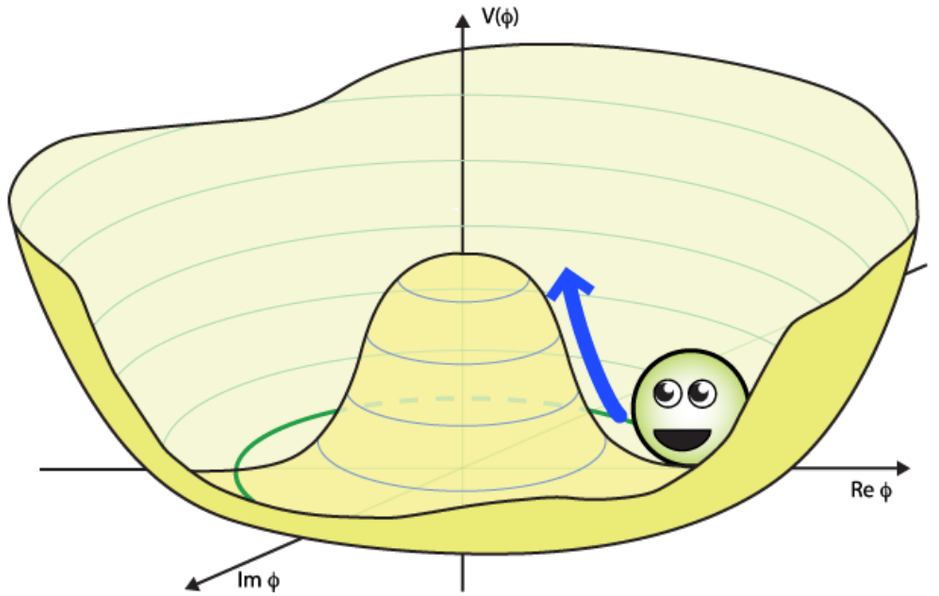
  in extensions of the SM exotic decays are possible

- Searches for additional Higgs bosons

  the Higgs might not come alone...

Probing the trilinear Higgs self-coupling

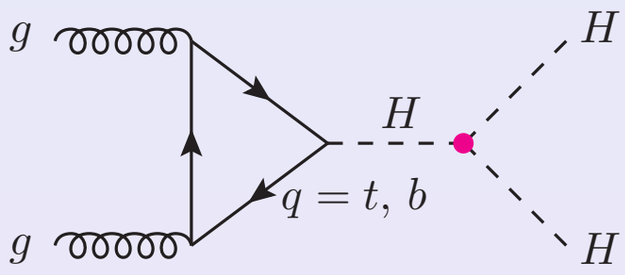
Measurement of trilinear Higgs self-coupling gives insight to the Higgs potential and hence electroweak symmetry breaking

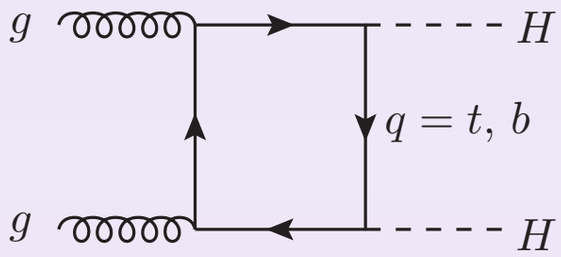


[quantumdiaries.org]

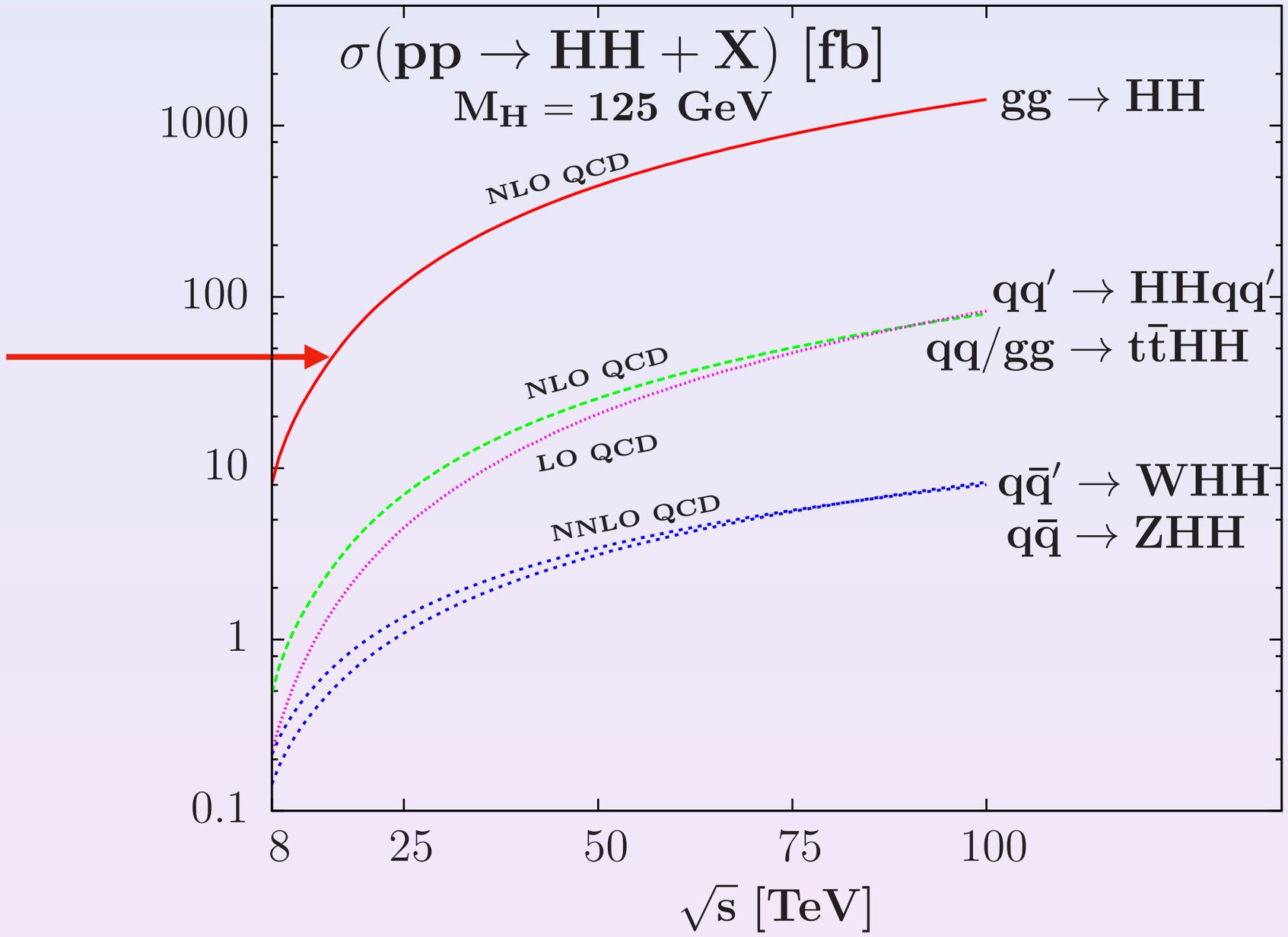
Higgs pair production

$gg \to HH$





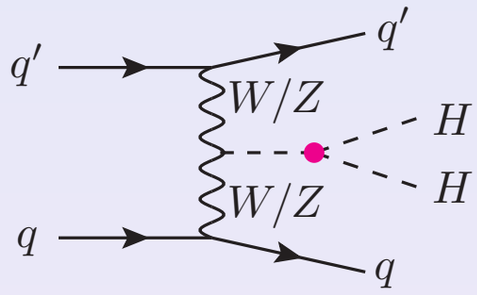
[Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12]



Higgs pair production

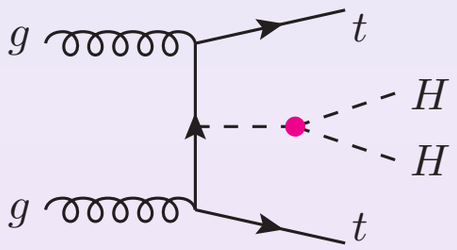
[Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12]

$qq' \to HHqq'$



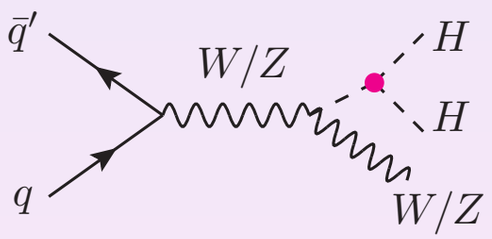
$+ \quad \dots$

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



$+ \quad \dots$

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



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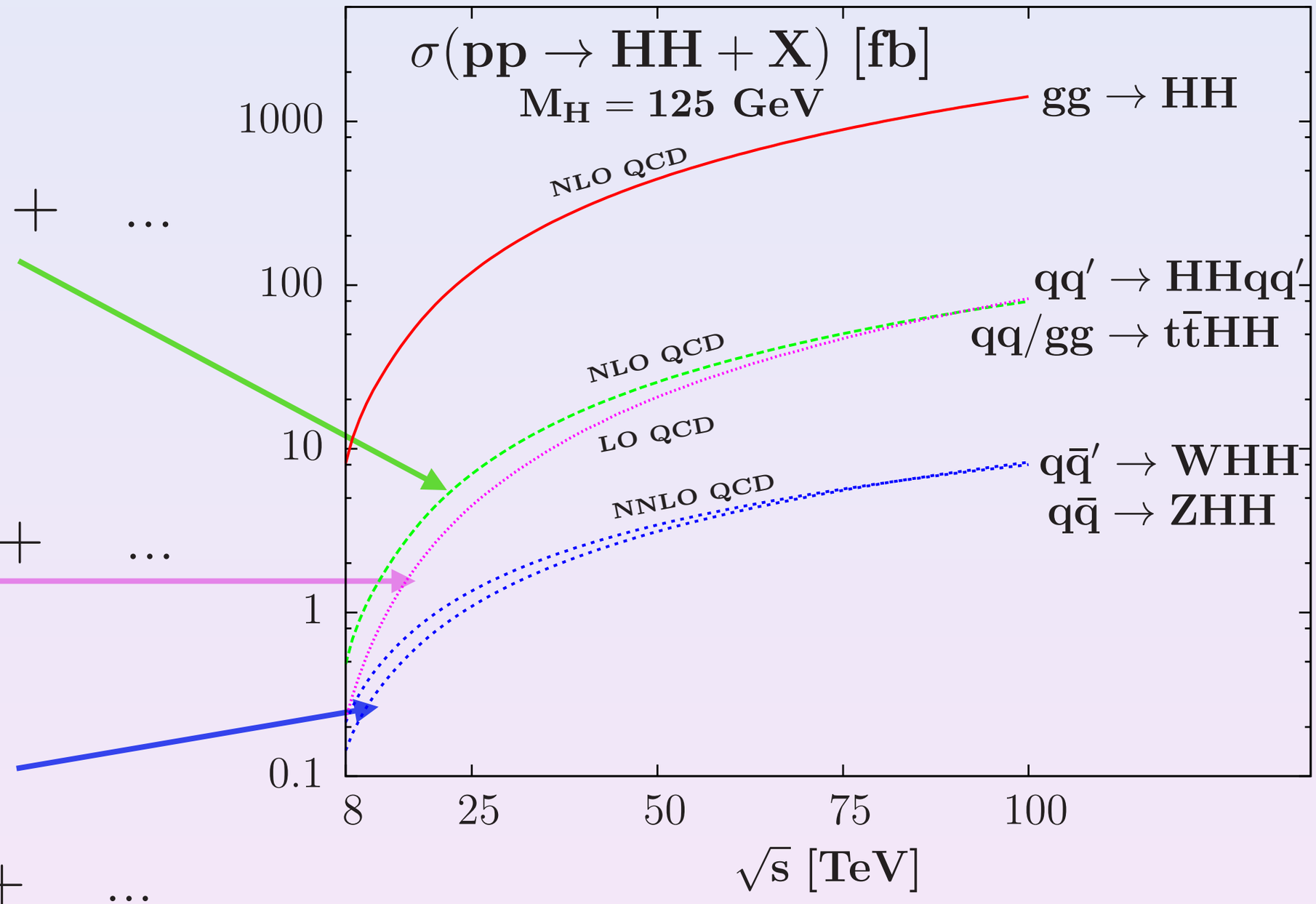


Higgs pair production

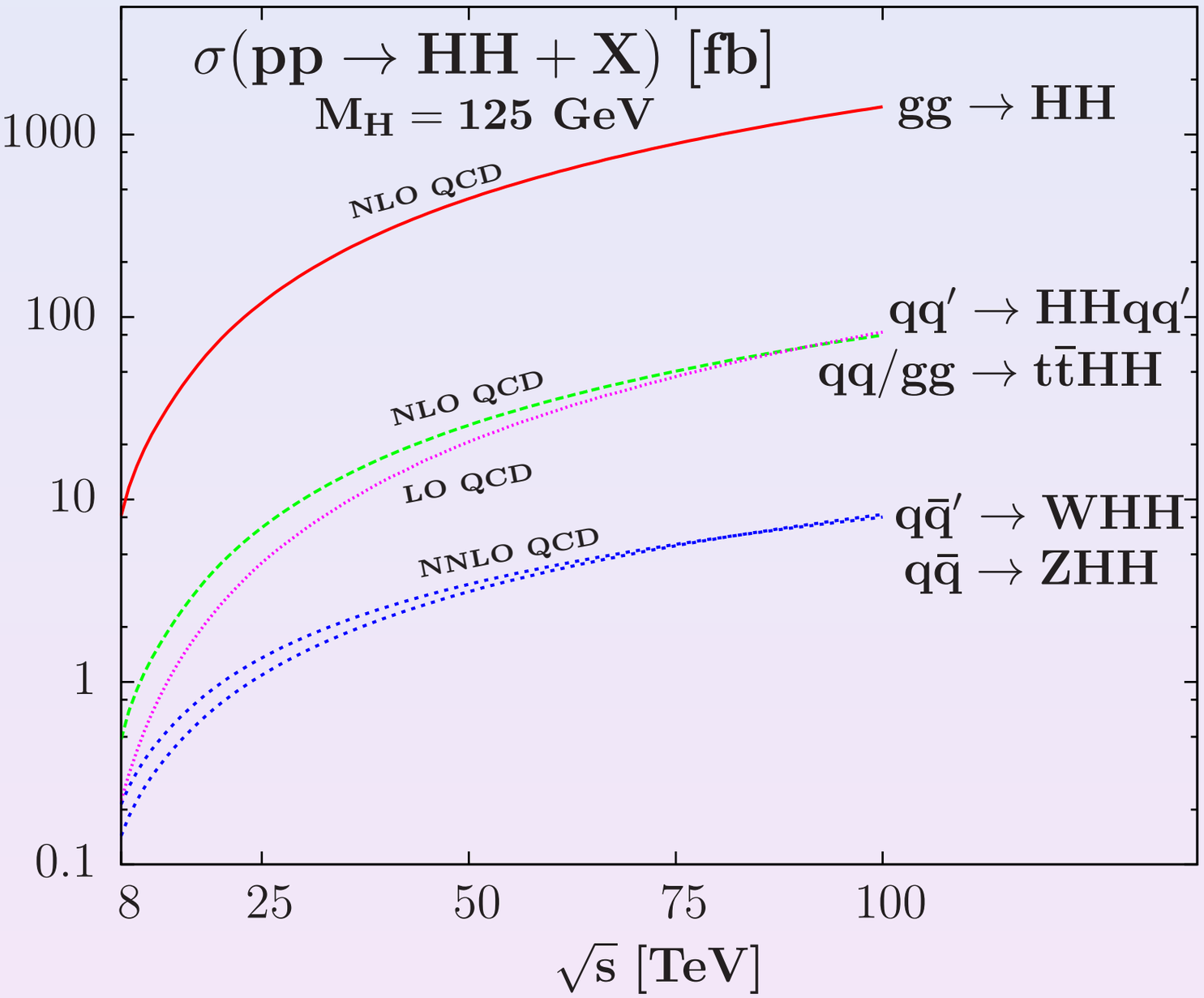
Small cross section

Difficult to measure

Most promising final state is $b\bar{b}\gamma\gamma$ (significance ~ 1.5)

[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]

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



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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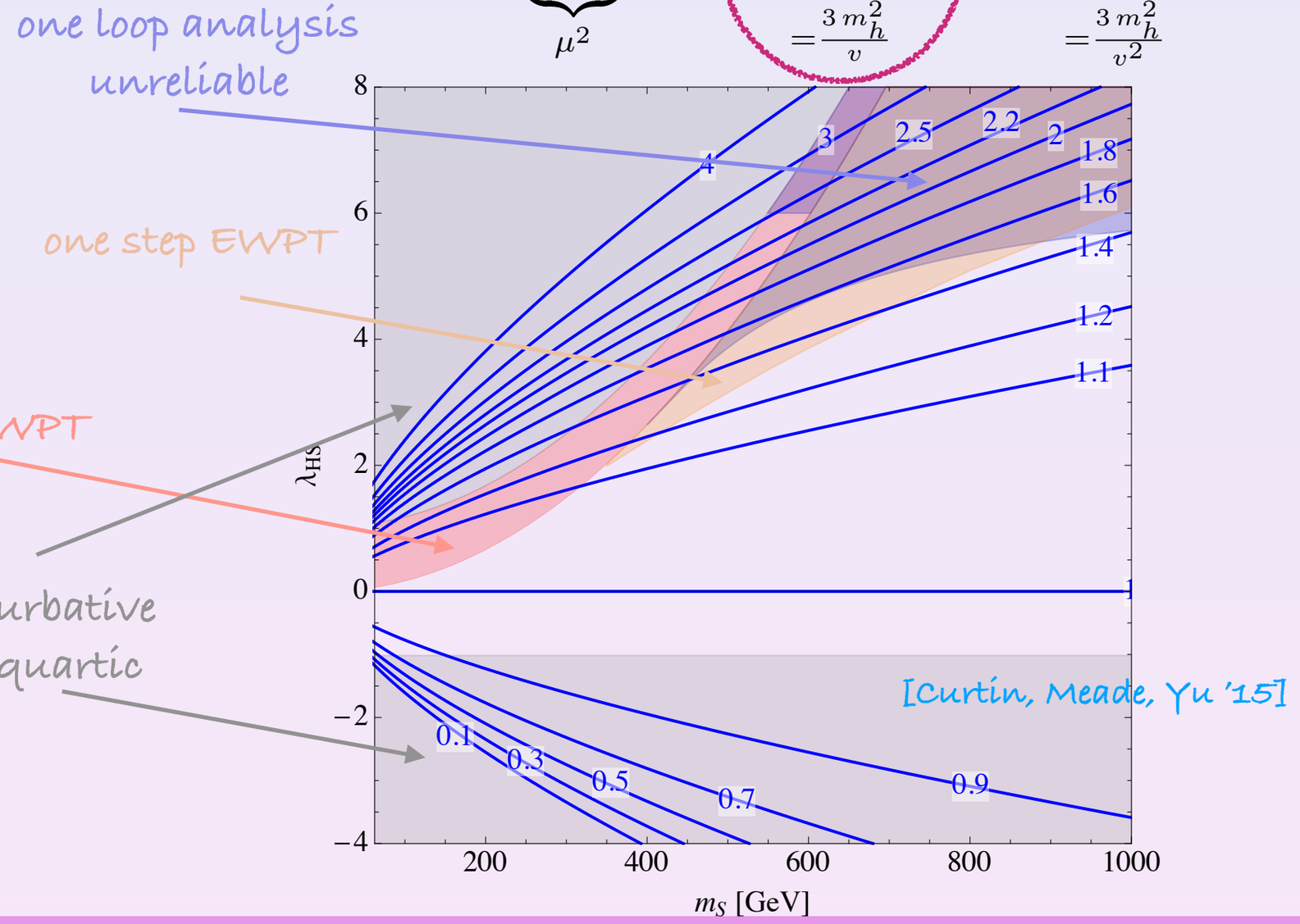
probes the Higgs potential

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 %



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2. does the Higgs boson couple non-linearly?

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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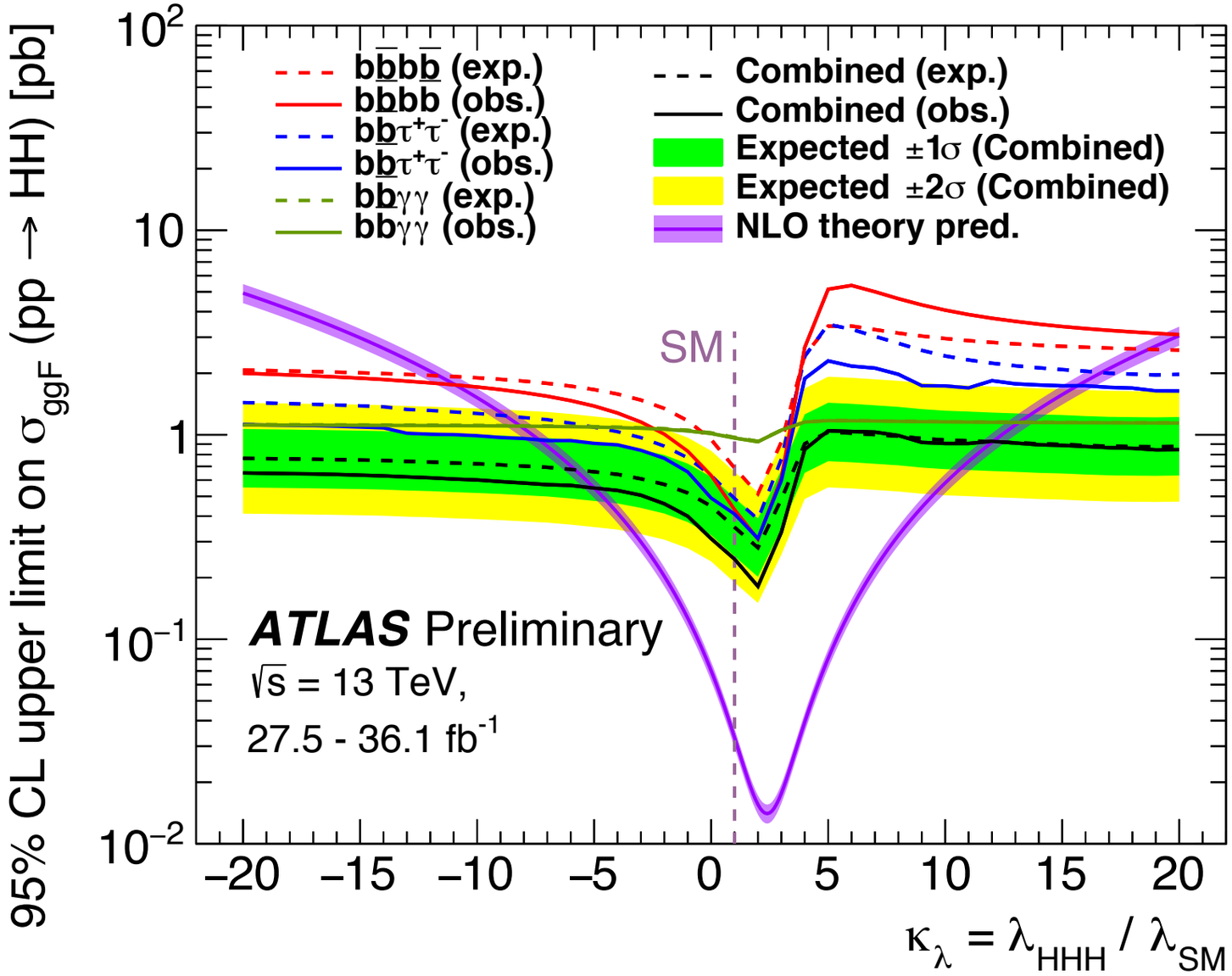
Gluon fusion loop can contain new colored particles

4. discovery mode for new resonances decaying to hh

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

Higgs pair production



Searches difficult,
require high luminosities

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

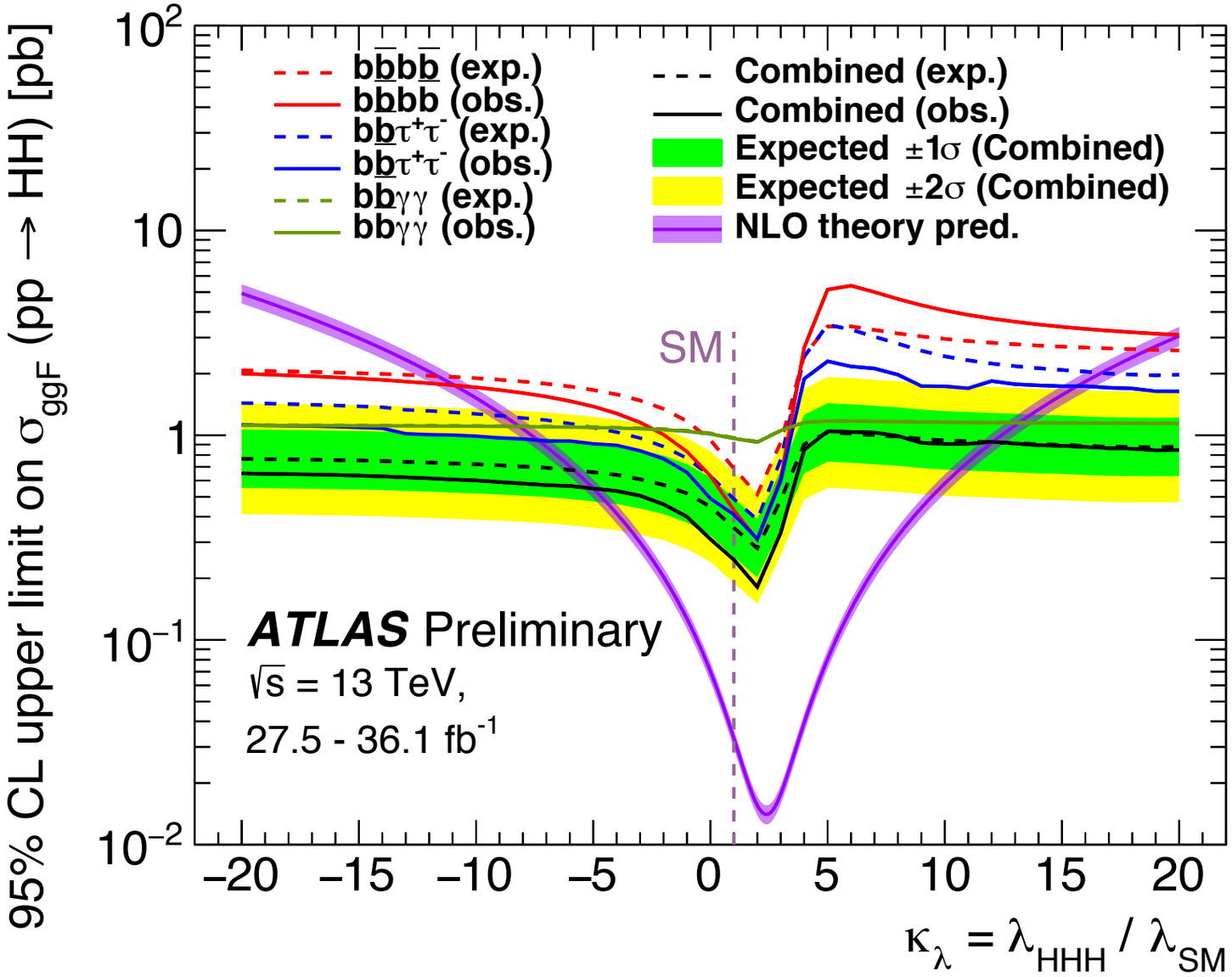
[arXiv:1509.0467, arXiv: 1506.0028,
arXiv: 1603.0689]

Prospects at HL_LHC
for $b\bar{b}\gamma\gamma$ final state

$$-0.8 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 7.7$$

[ATL-PHYS-PUB-2017-001]

Higgs pair production



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[ATL-PHYS-PUB-2017-001]

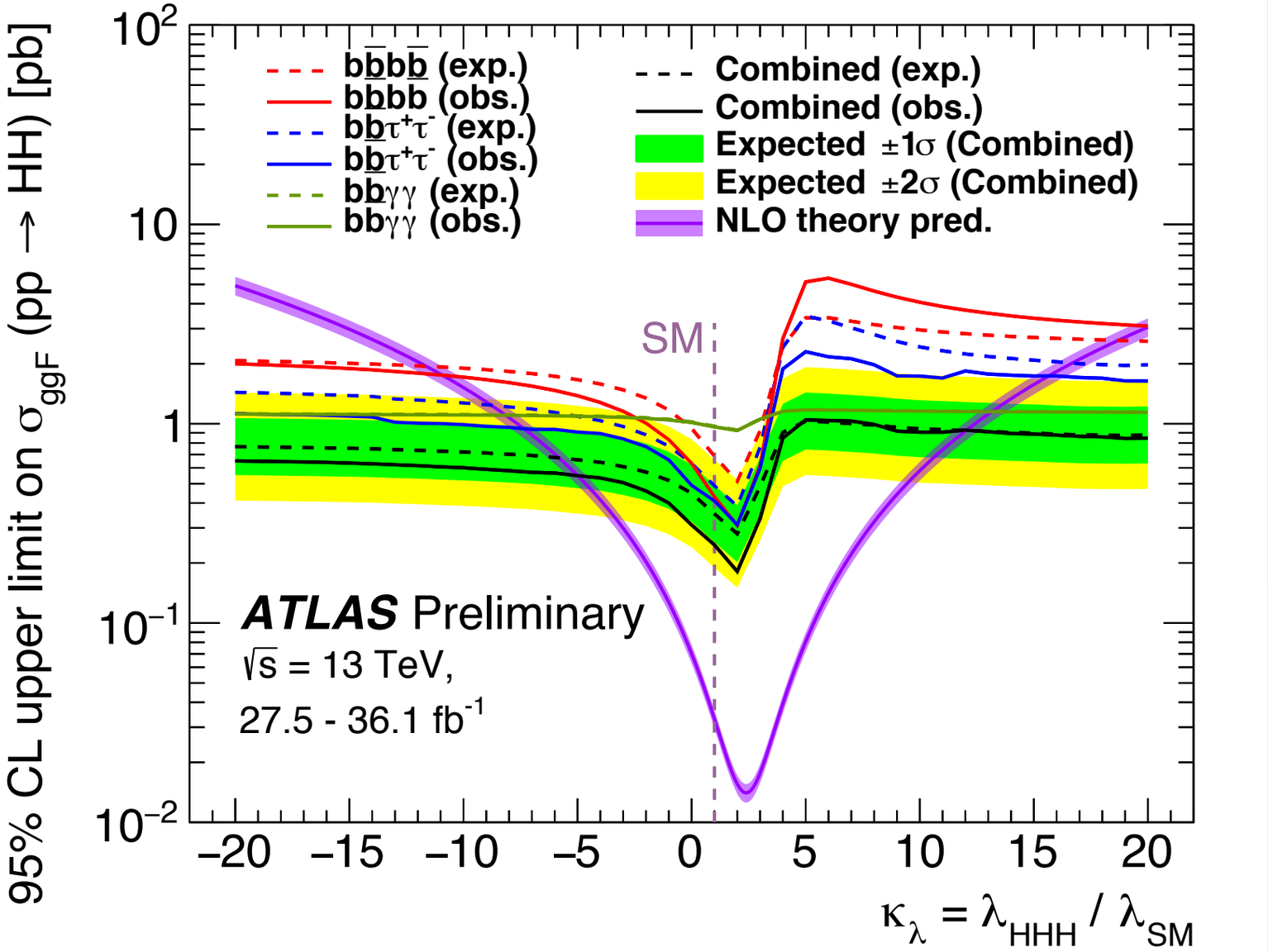
Single Higgs to constrain trilinear Higgs self-coupling:

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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Prospects at HL_LHC for $b\bar{b}\gamma\gamma$ final state

$$-0.8 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 7.7$$

[ATL-PHYS-PUB-2017-001]

Single Higgs to constrain trilinear Higgs self-coupling:

Global fit, taking into account differential measurements

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

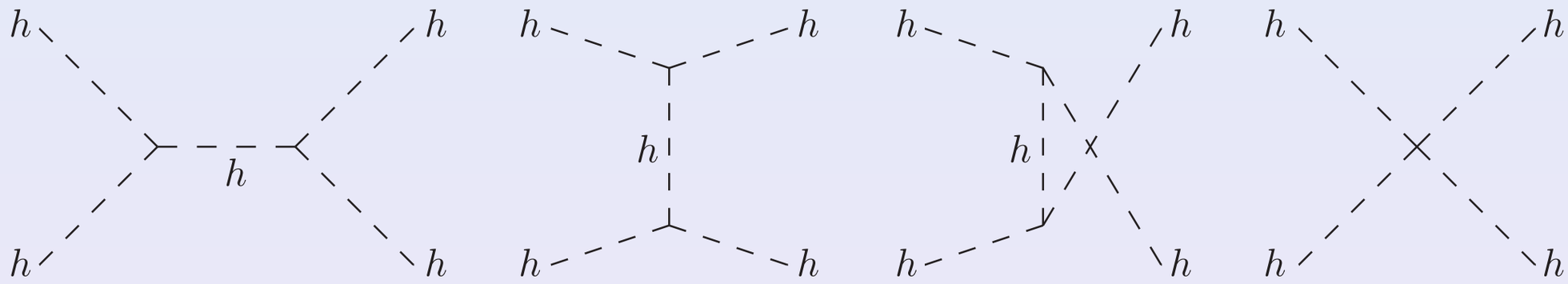
[Di Vita, Grojean, Panico, Rimbau, Vantalon '17 see also: Maltoni, Pagani, Shivaji, Zhao '18]

Trilinear Higgs self-coupling

Can the trilinear Higgs self-coupling be constraint theoretically?

And how large can it be in concrete models?

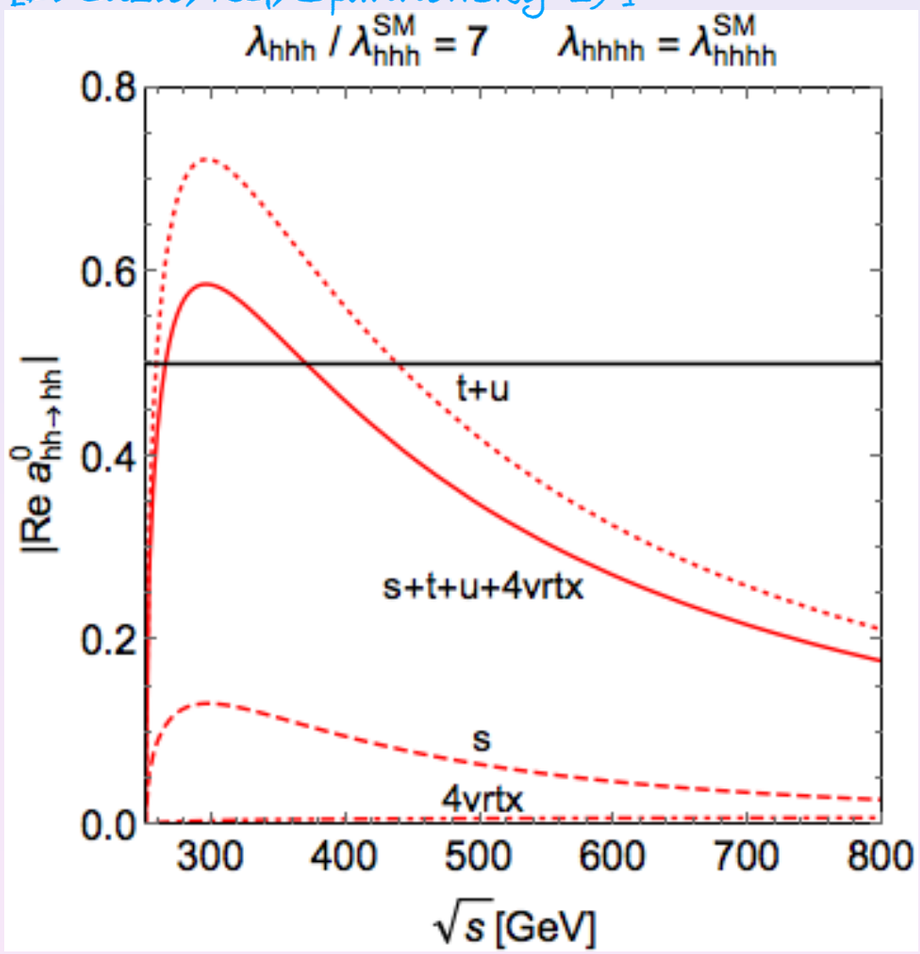
Perturbative unitarity bound

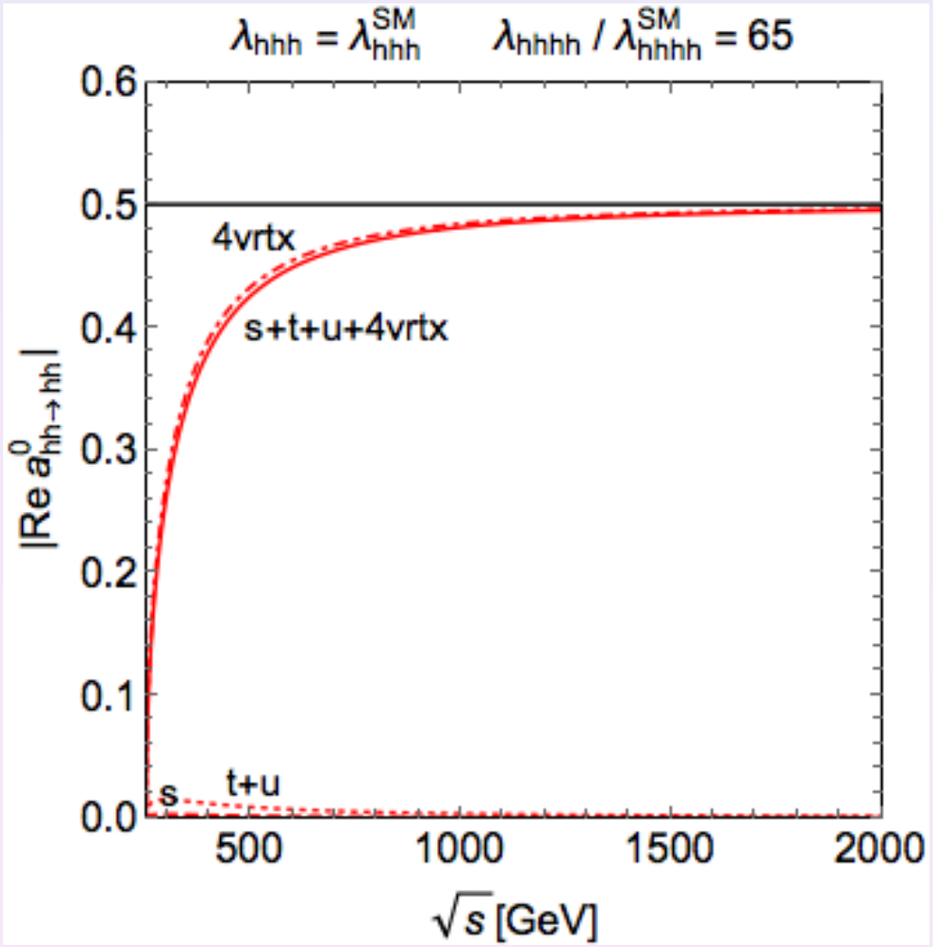


Perturbative unitarity bound from partial wave analysis

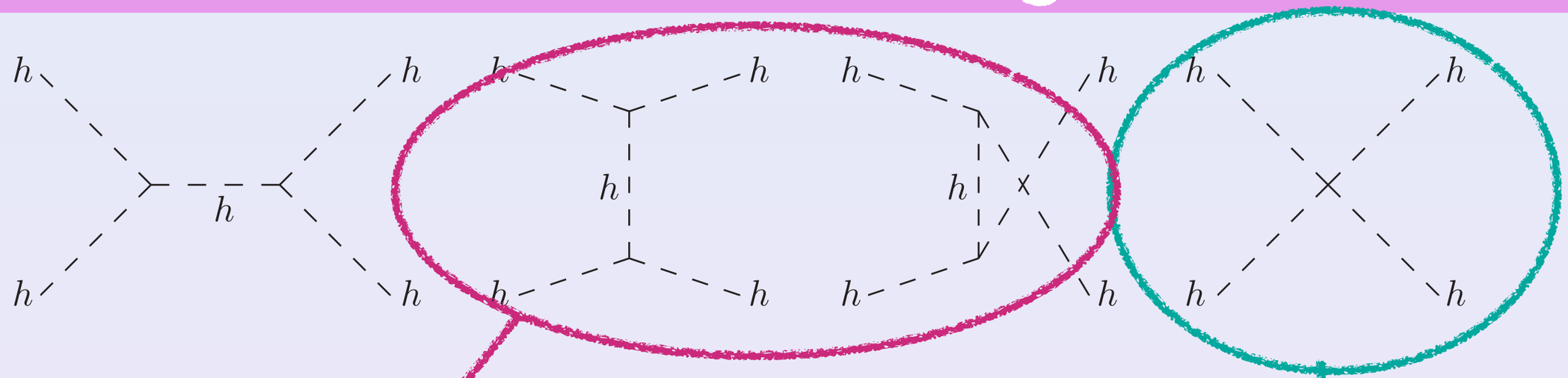
$$|\text{Re } a^0_{hh\to hh}| < 1/2$$

[Di Luzio, RG, Spannowsky '17]





Perturbative unitarity bound



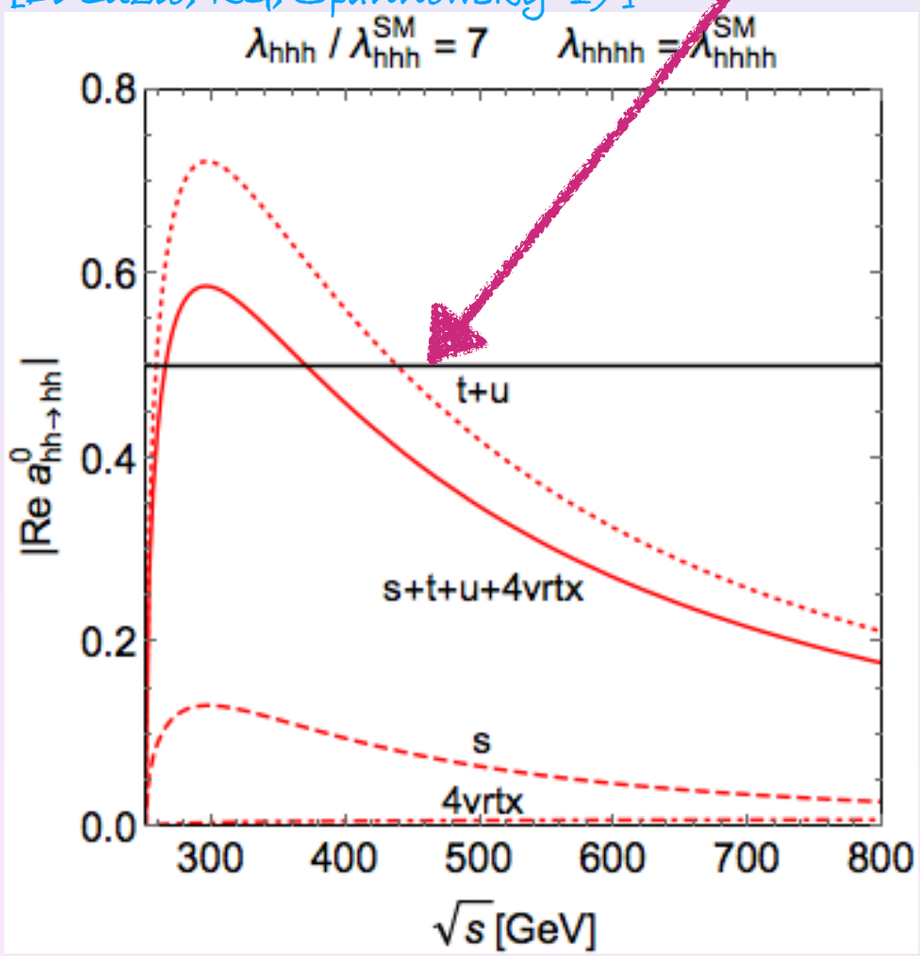
Perturbative unitarity bound from partial wave analysis

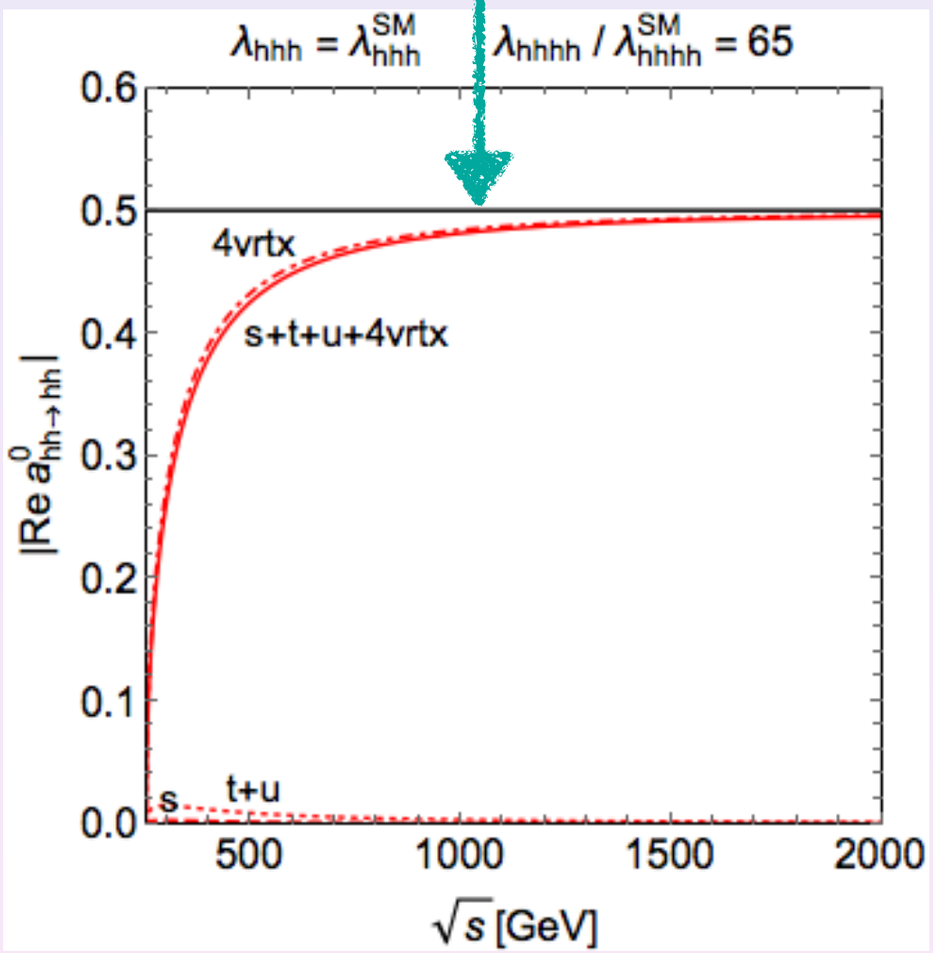
$$|\text{Re } a^0_{hh\to hh}| < 1/2$$

bounds at low s

bounds at large s

[Di Luzio, RG, Spannowsky '17]





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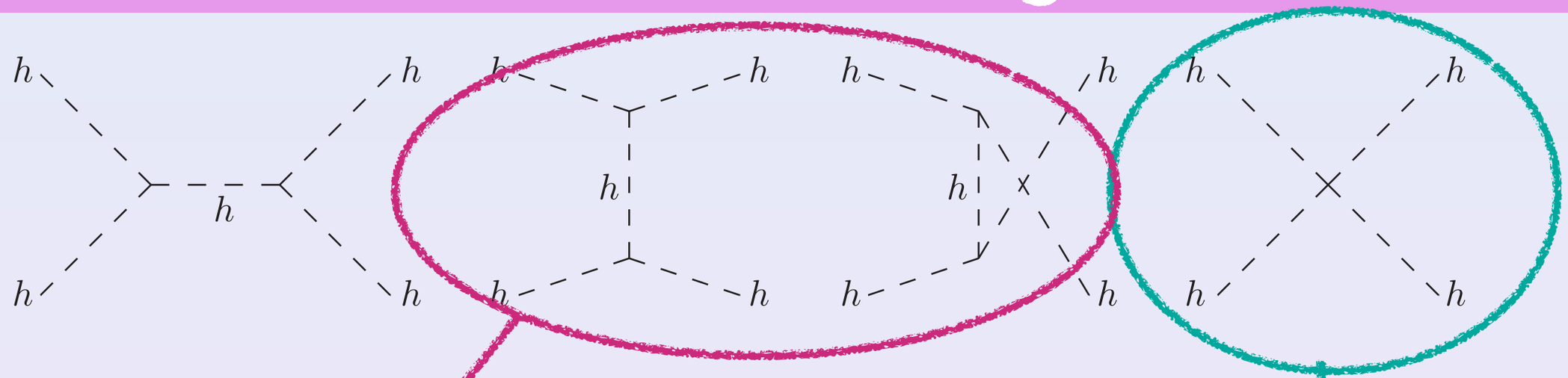

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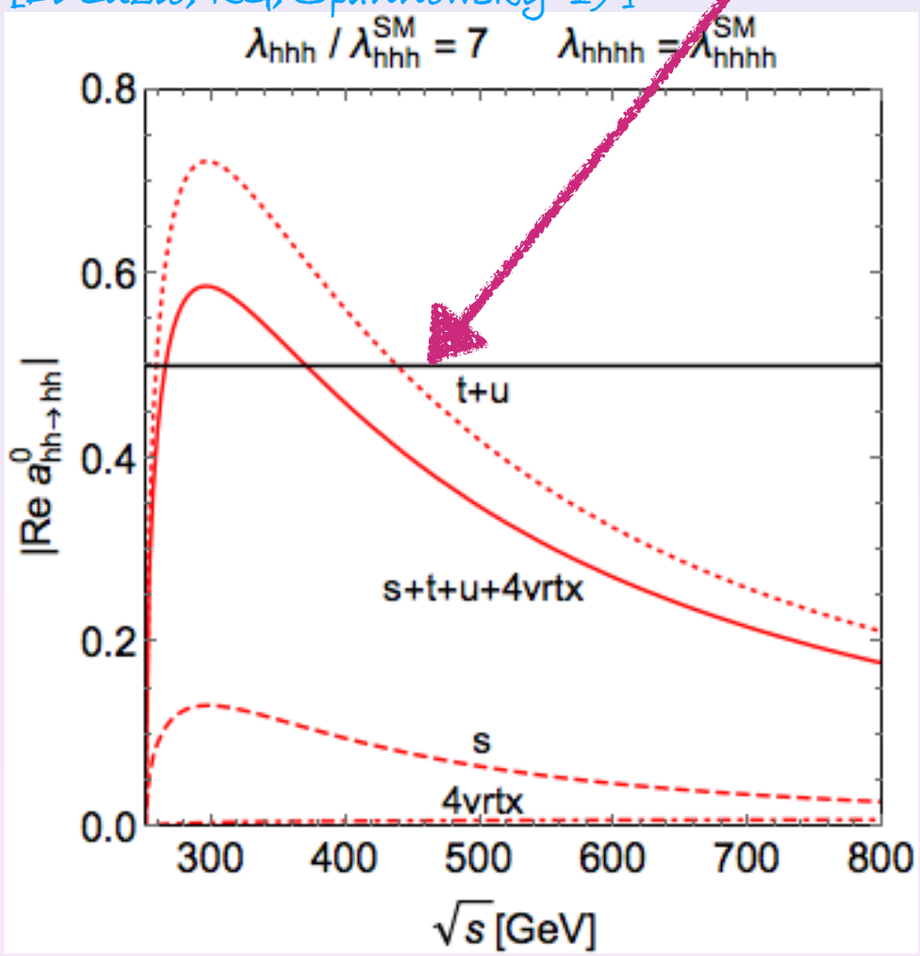
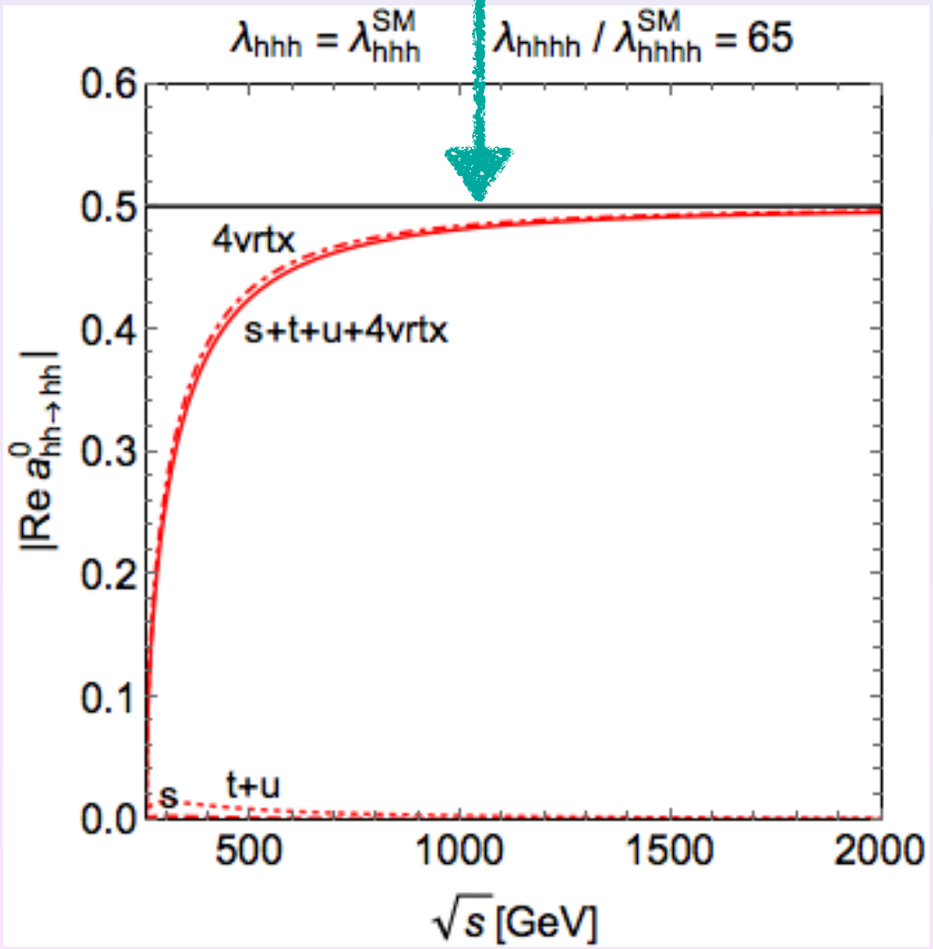


Perturbative unitarity bound

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

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

bounds at large s



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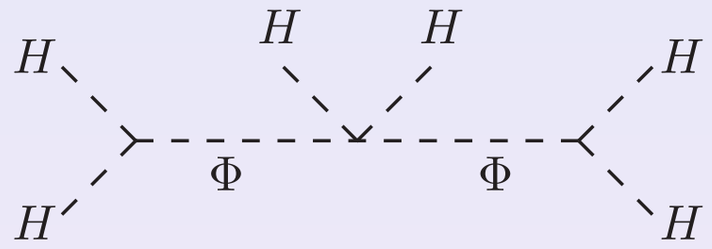
In models with new scalars that couple with

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



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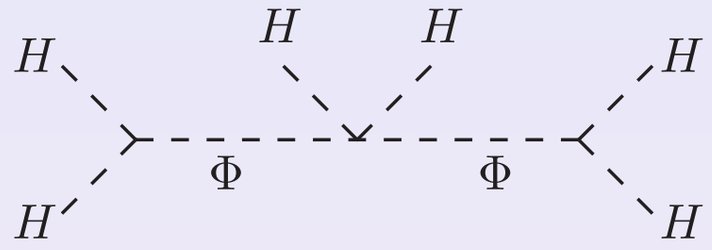

Φ	$\mathcal{O}_\Phi$
$(1,1,0)$	$\Phi H H^\dagger$
$(1,2,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
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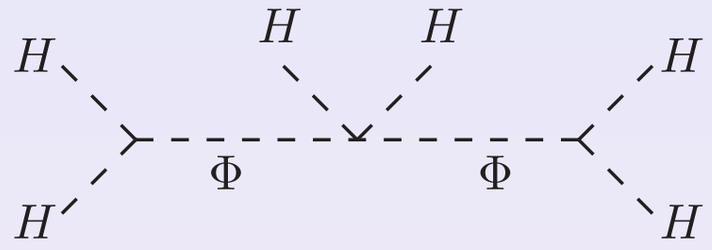

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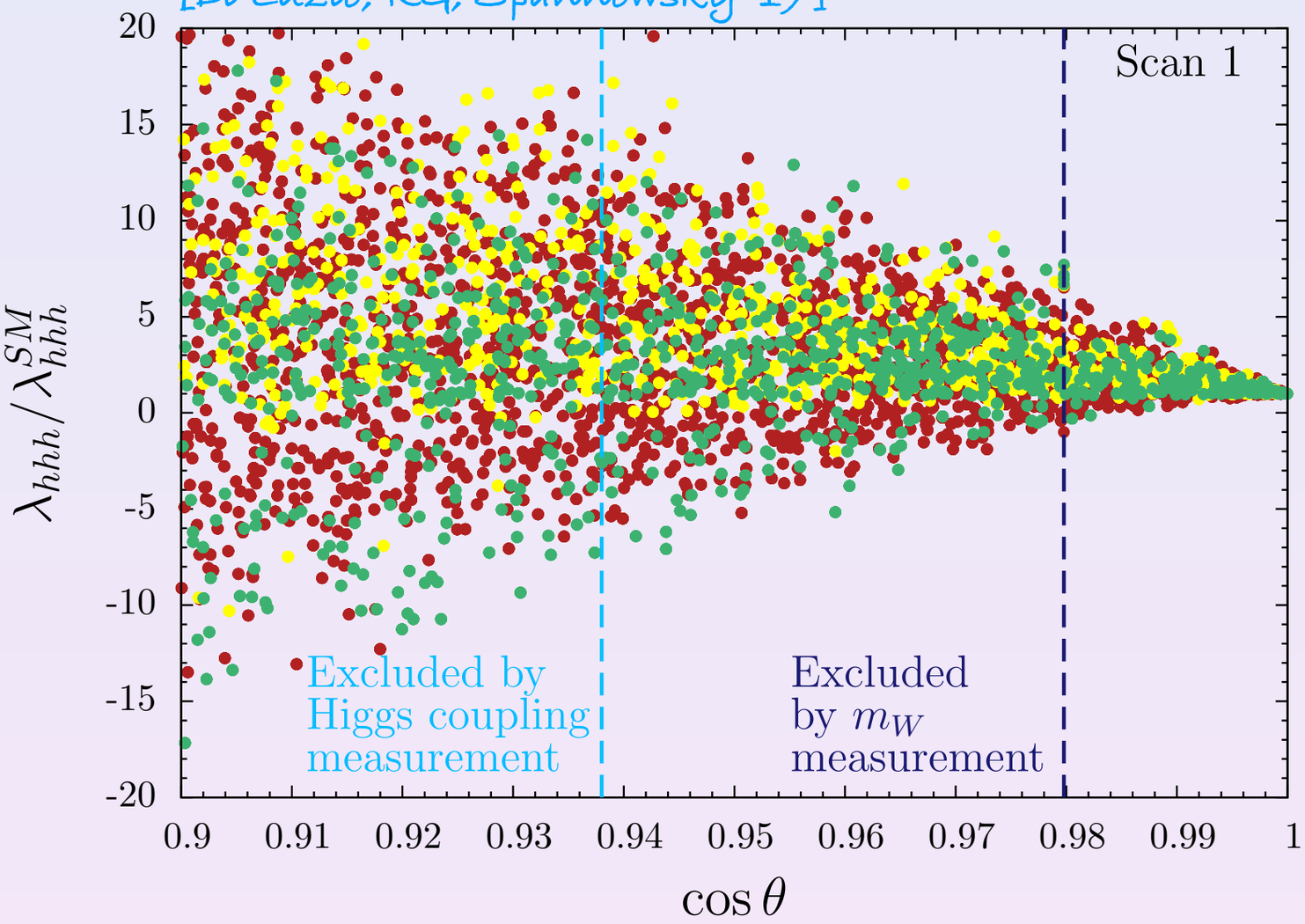
How large can λ_{hhh} be, taking into account indirect constraints?

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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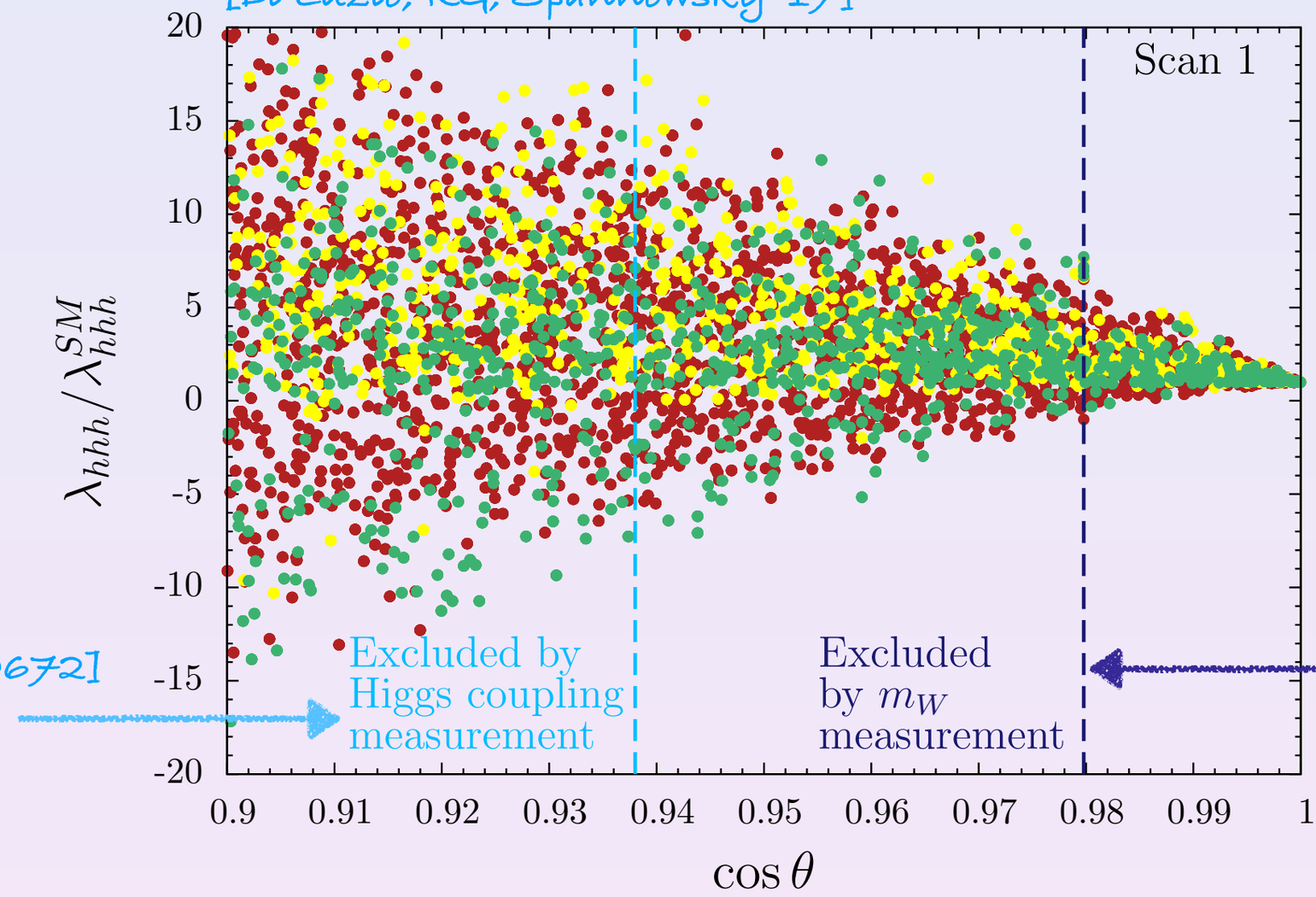


[ATLAS 1509.006721] → Excluded by Higgs coupling measurement

Excluded by m_W measurement ← [Lopez-Val, Robens '14]

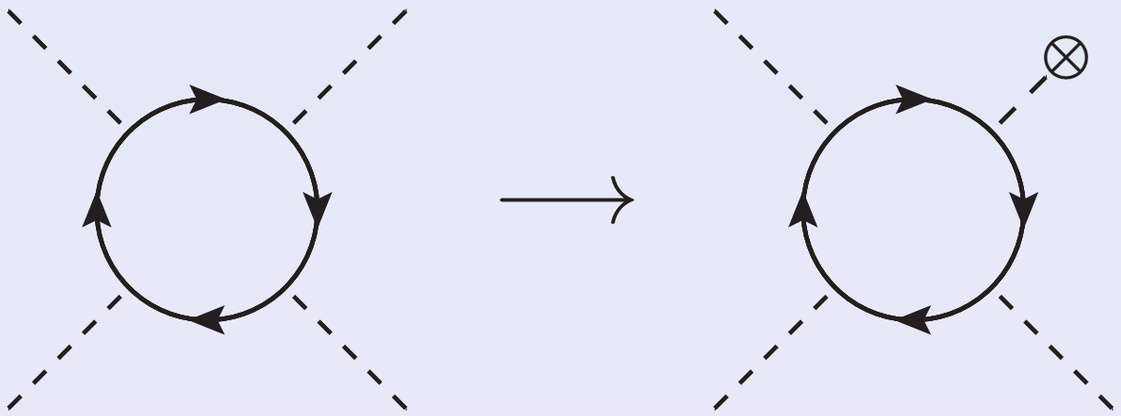
Color code: electroweak vacuum is stable, metastable, unstable

Singlet model allows for deviations of

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

Vacuum instability analysis does not constrain the trilinear Higgs self coupling

Loop induced λ_{hhh} modification



Connection vacuum stability

trilinear Higgs self-coupling

RH neutrinos, inverse see-saw

$$\mathcal{L}_{\rm ISS} = -Y_\nu \overline{L}\tilde{H}\nu_R - M_R\overline{\nu^c}X - \frac{1}{2}\mu_X\overline{X^c}X + \text{h.c.}\,,$$

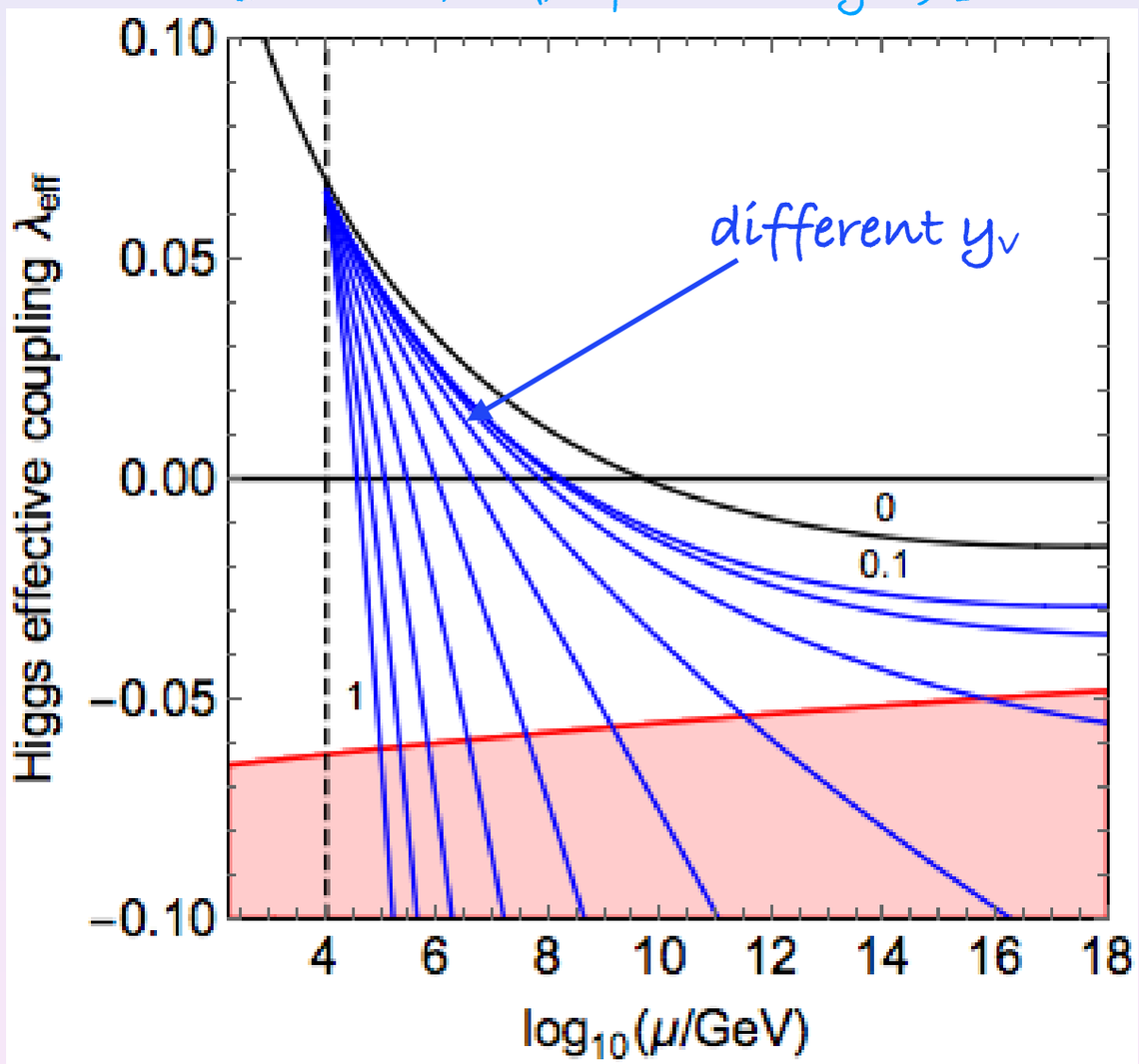
common mass scale M_R=10 TeV

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

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

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

[Di Luzio, RG, Spannowsky '17]



Conclusion

- Many measurements in Higgs physics still outstanding

- Trilinear Higgs self-coupling measurement important probes Higgs potential information on electroweak baryogenesis

- Current limits not strong yet and above bounds from perturbative unitarity

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

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Thanks for your attention!

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]