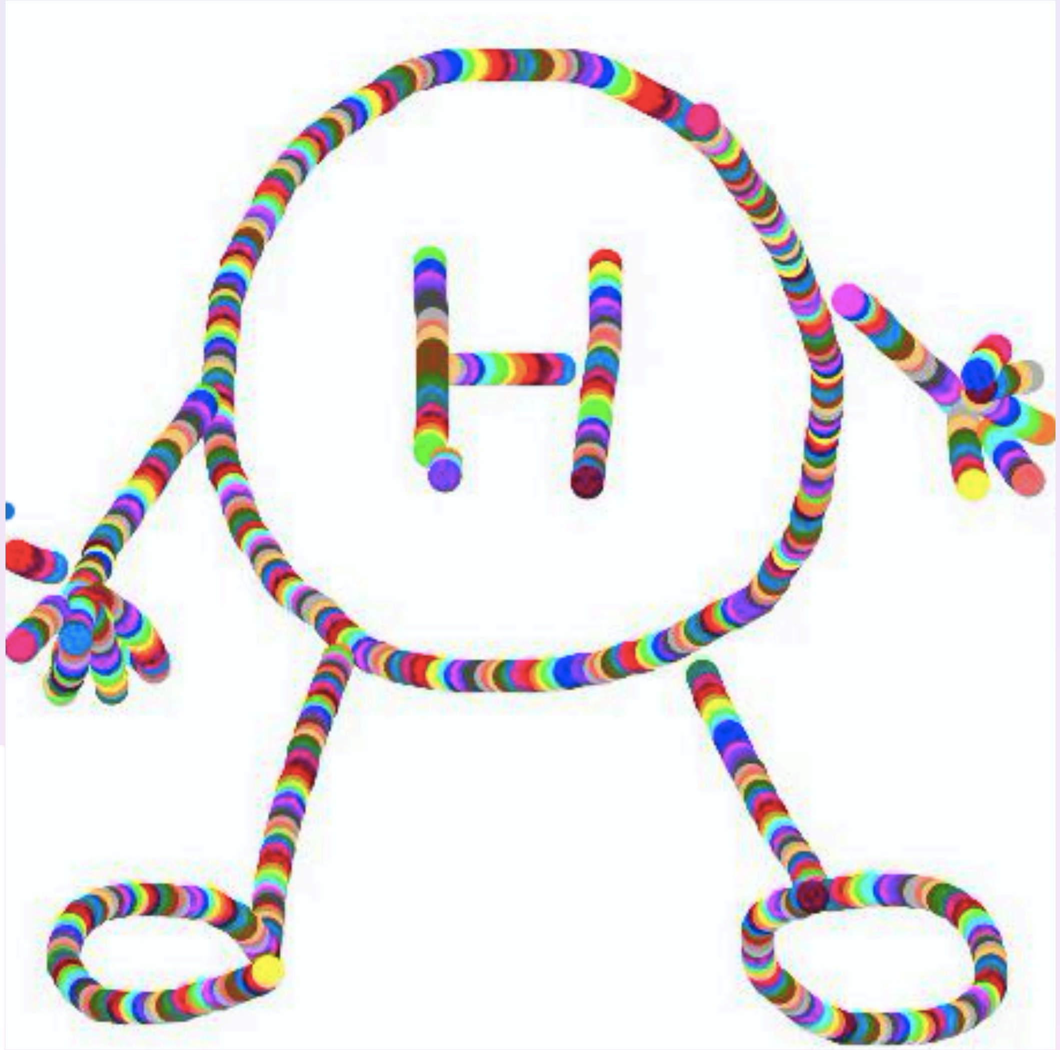
Quo vadis, Higgs?

Ramona Gröber

Deutsche Physikerinnen Tagung, 2022

27/11/2022



Discovery of the Higgs boson...

A bit more than 10 years ago

With the Higgs boson the last missing ingredient of the Standard Model was discovered...

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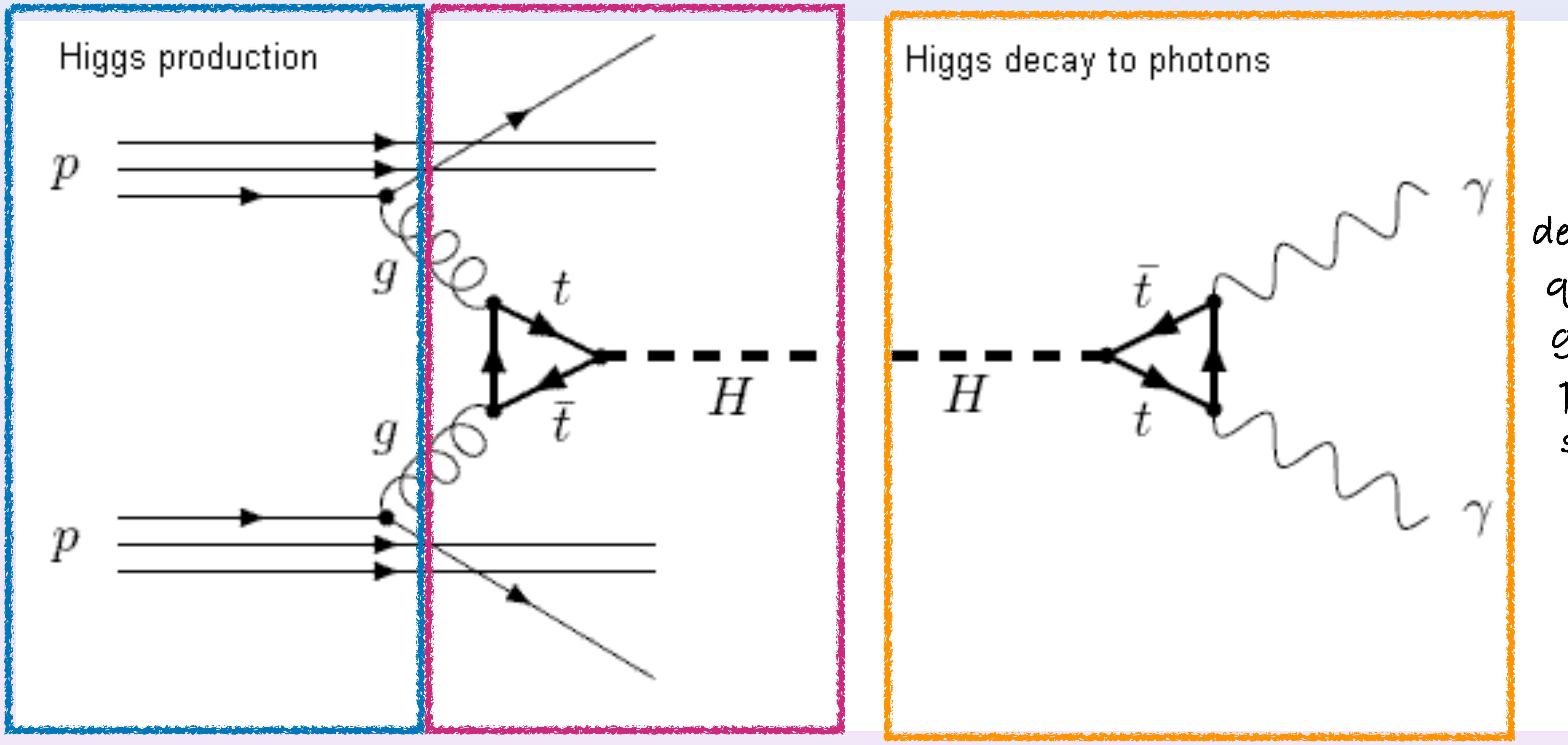
With the Higgs boson the last missing ingredient of the Standard Model was discovered...

But many questions remain: e.g. Are there other Higgs bosons? What is dark matter? Why there is more matter than anti-matter in the universe?...

Outline

- What was needed for the Higgs discovery?
- What do we know about the Higgs boson?
- What should we still learn?
- Summary and Outlook

Production of a Higgs boson



decays in quarks/ gluons: parton shower

Parton distribution function

Higgs production: Calculated in perturbation theory, mediated by top quark loop

Higgs decay (Branching ratio)

What we know about the Higgs...

Life time (width)

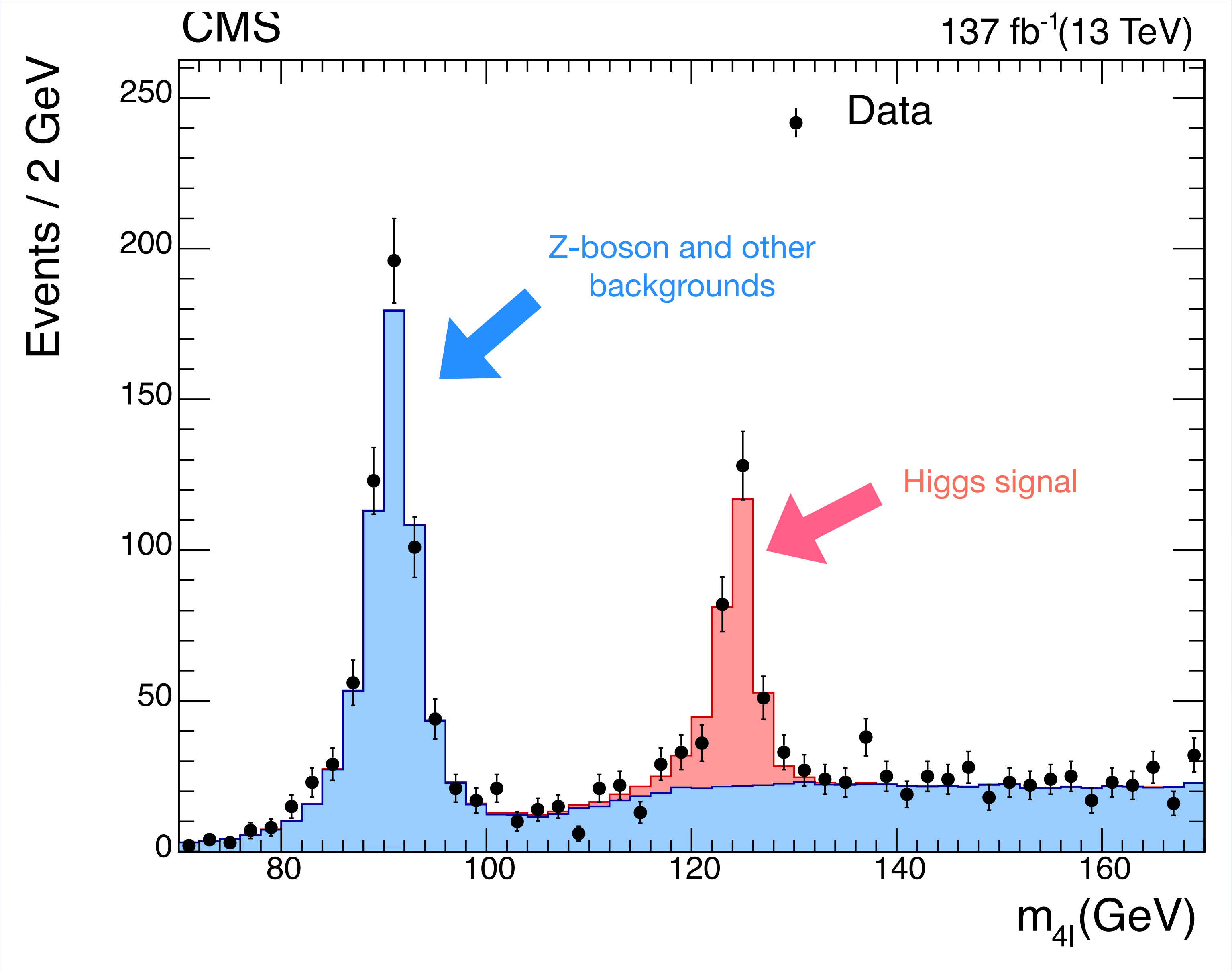
Couplings

Mass

Spin

CP

What we know about the Higgs...



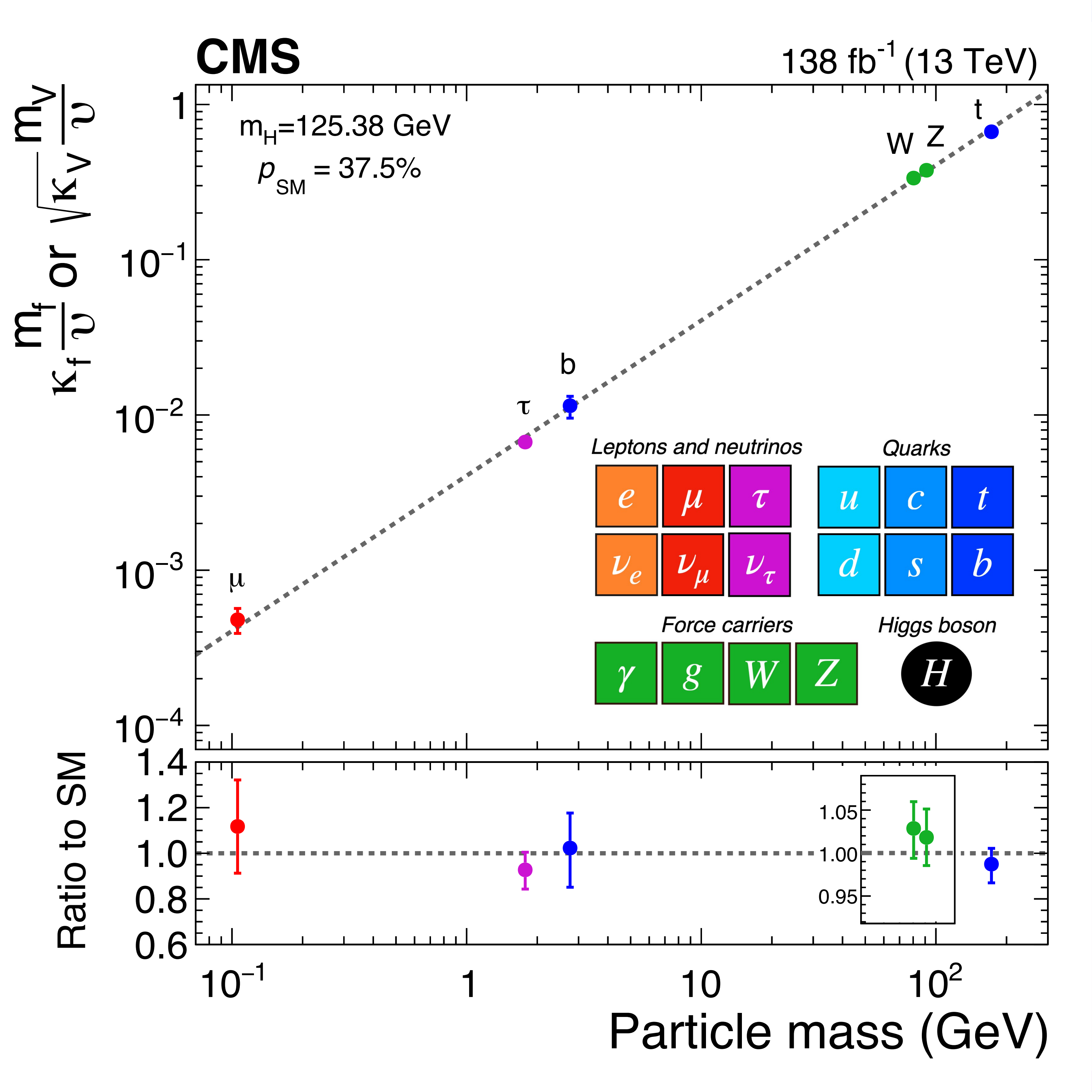
Peak above background: existence of a particle ... the Higgs boson

Position of peak: mass

Number of events at peak: interaction strength

CP and spin by looking at angular distributions

Higgs couplings



Higgs couplings to the most massive particles of the Standard Model measured remarkably well

But what about 1st and 2nd generation? What about the Higgs self-coupling?

What we know about the Higgs...

Life time (width)

more about that later

Couplings

more about the "missing" ones later

Mass

$124.99 \pm 0.18 \pm 0.04$ GeV

[ATLAS Run2]

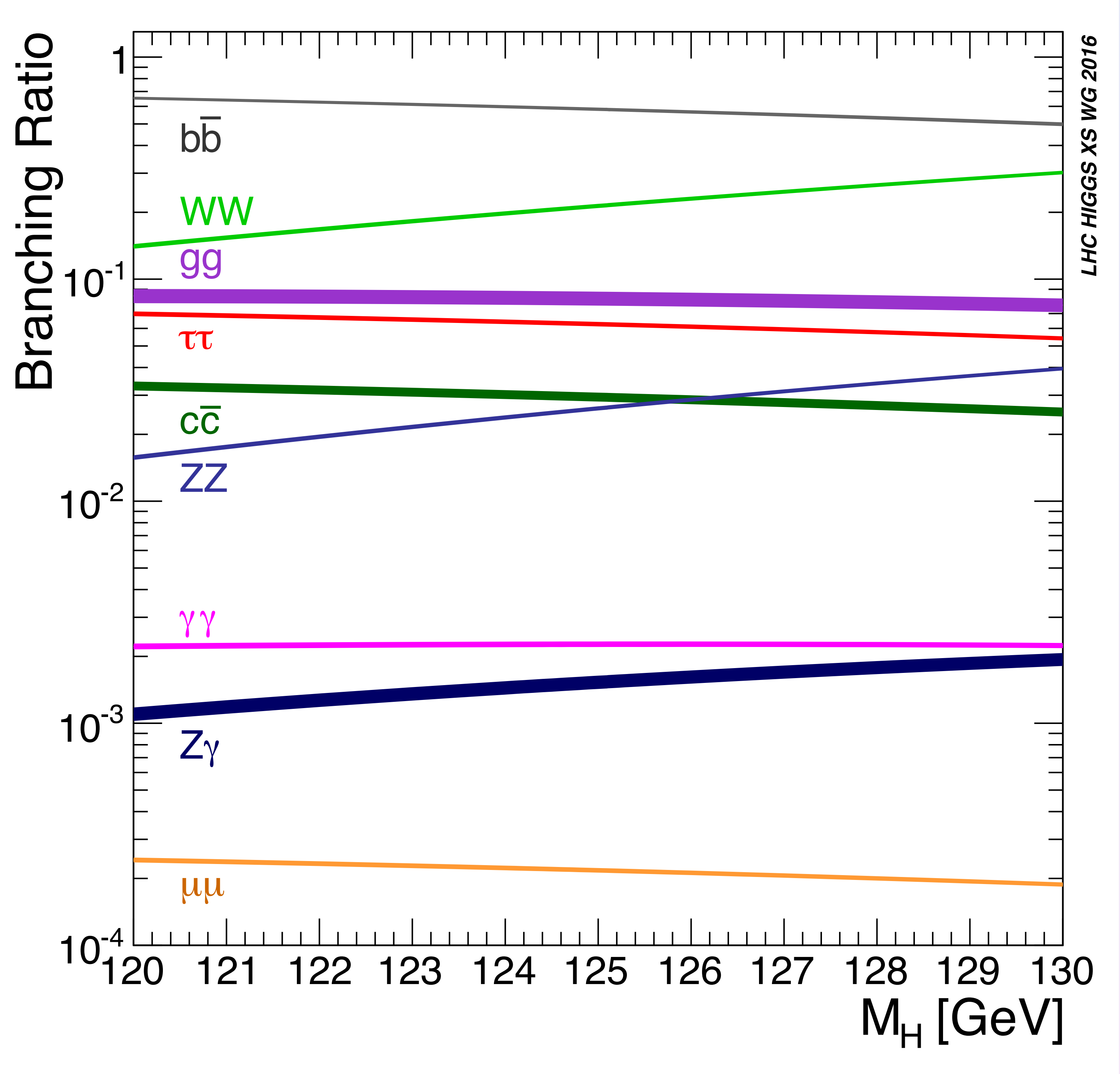
Spin

angular distributions in decays to vector bosons

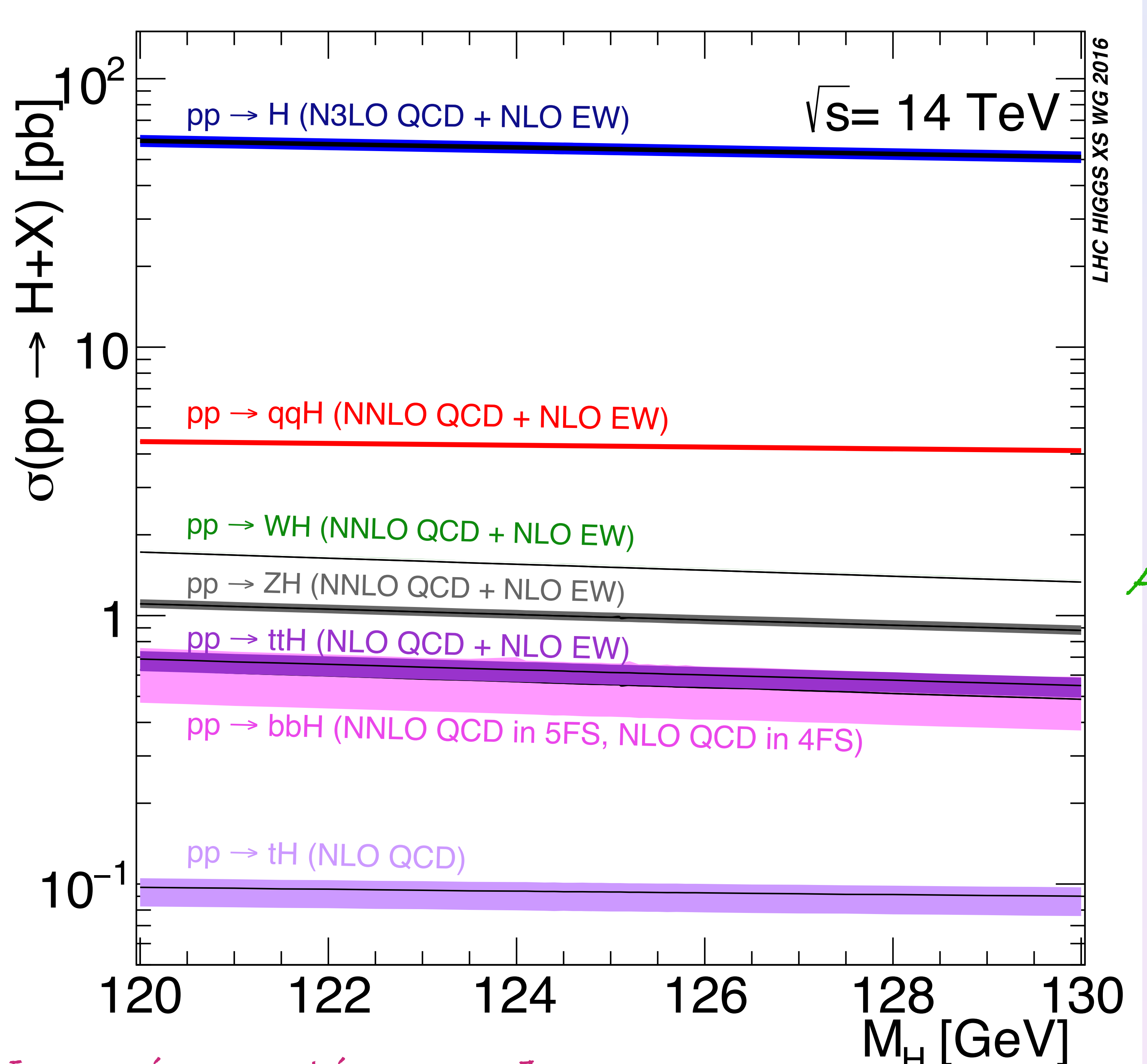
CP

well established that Higgs boson is spin-0 and (mostly) CP-even as predicted in SM

Higgs decays

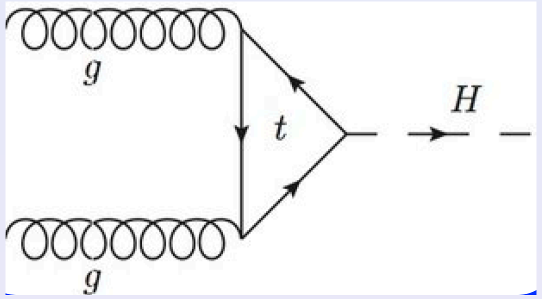


Higgs production and theory input

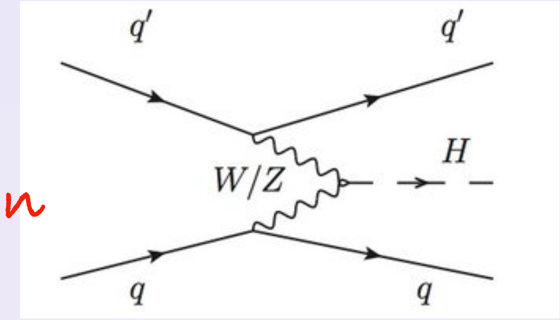


[LHC Higgs working group]

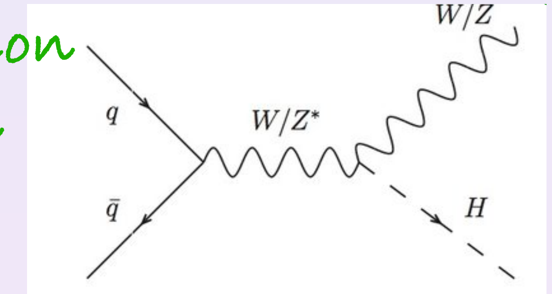
Gluon fusion



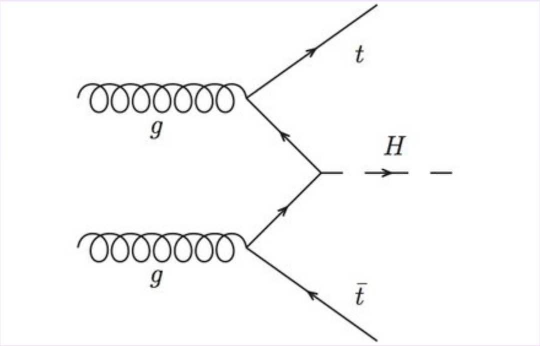
Vector boson fusion



Associated production with vector boson

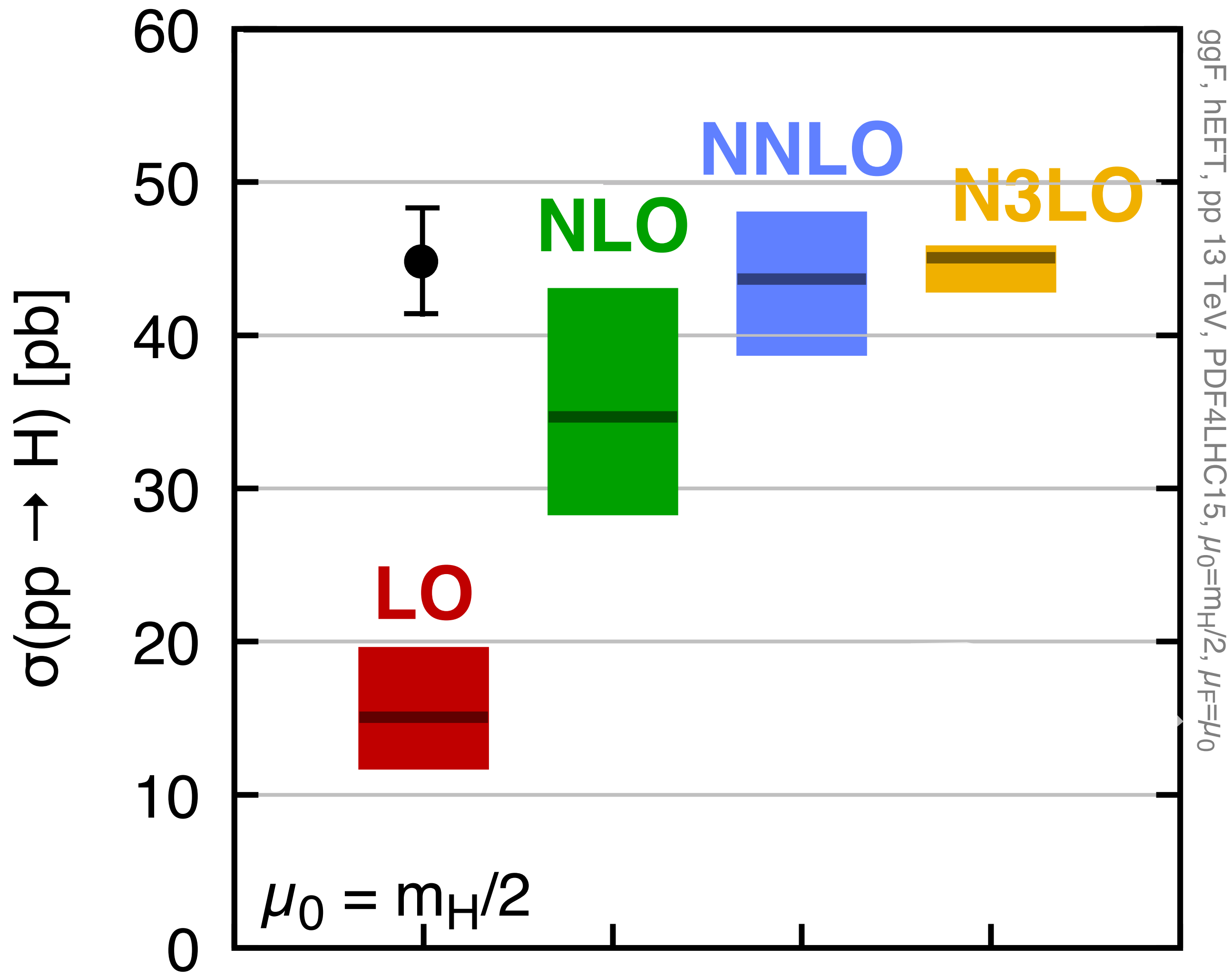


ttH production



Precise Theoretical predictions

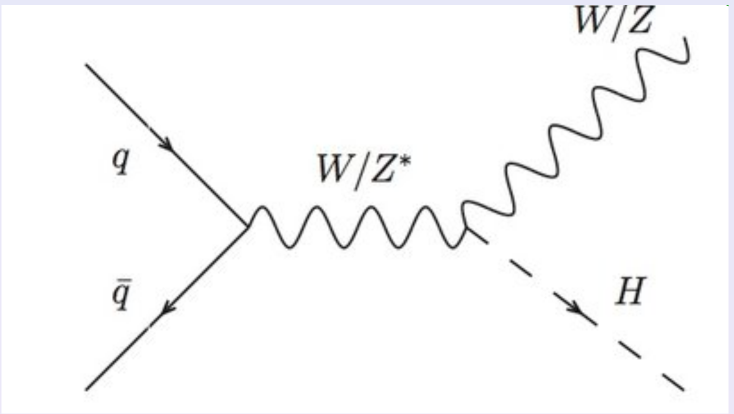
Higgs production in gluon fusion

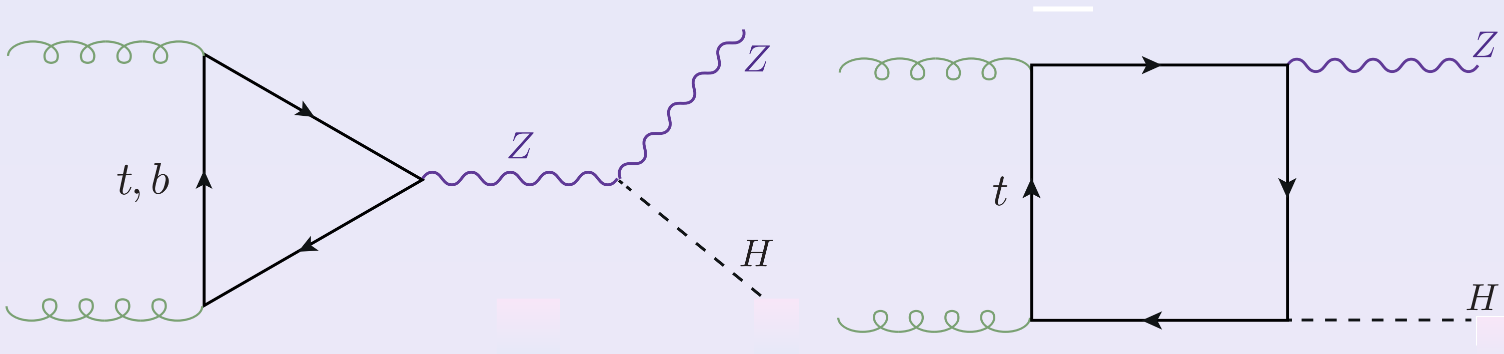


[fig. by Giulia Zanderighi, Higgs 2022]

Precise predictions necessary to match experimental error!

Higgs production in association with a vector boson





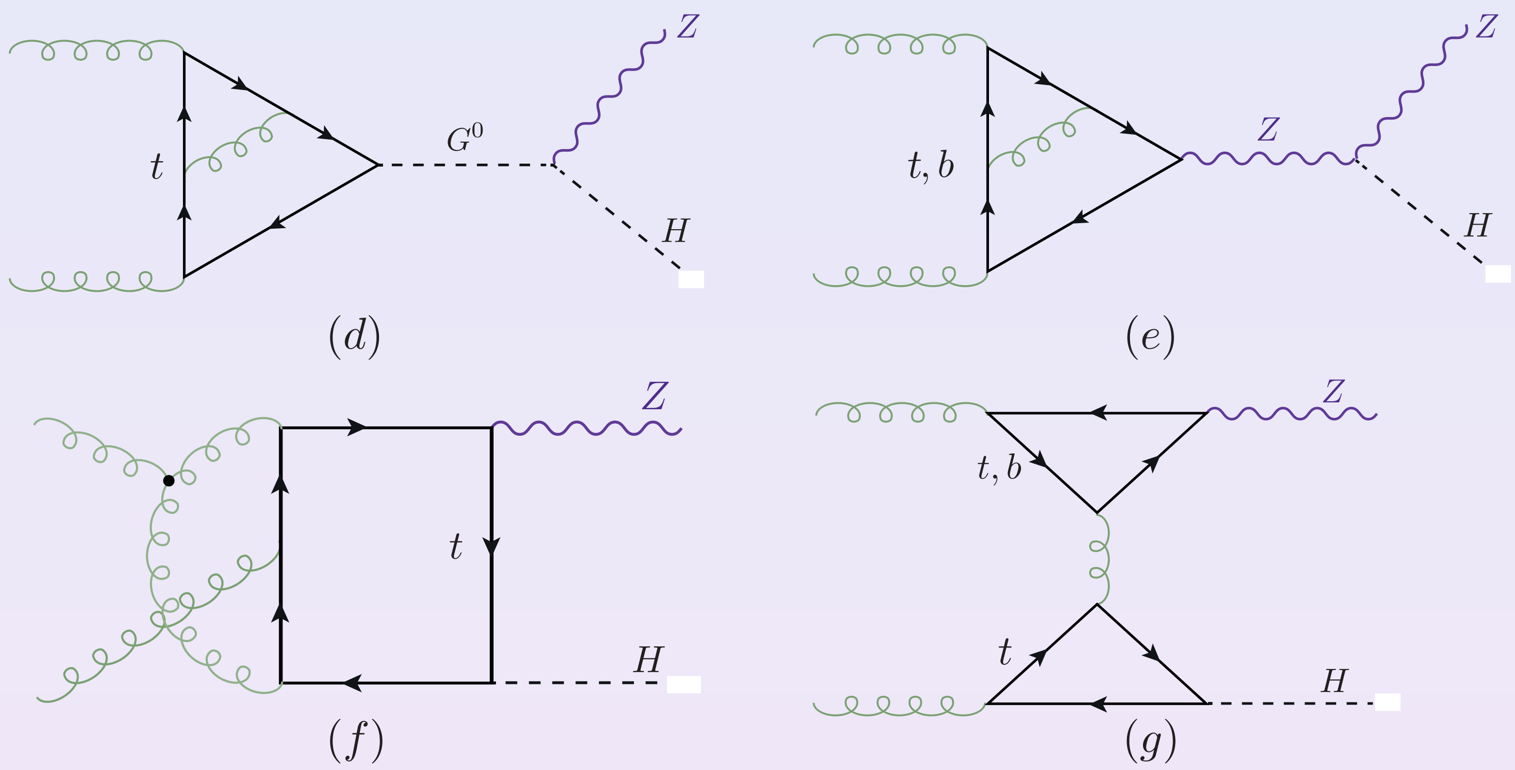
computed at N3LO by

[Baglio, Duhr, Mistlberger, Szafron '22]

NLO difficult to compute in full dependence of top quark mass due to several mass scales that lead to complicated expressions and integrals

[Degrassi, RG, Vitti, Zhao '22; Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser, '22]

Precise Theoretical predictions



Bottleneck are the genuine two loop diagrams, leading to two loop integrals

Strategies:

- Numerically, fixing values of Higgs, Z and top quark mass [Chen, Heinrich, Jones, Kerner, Klappert, Schlenk '20]
- Analytically, using approximations valid in certain part of the phase space [Altenkamp, Dittmaier, Harlander, Rzehak, Zirke '12] [Hasselhuhn, Luthe, Steinhauser, '16] [Davies, Mishima, Steinhauser, '20] [Alasfar, Degrassi, Giardino, RG, Vitti '21]

Precise Theoretical predictions

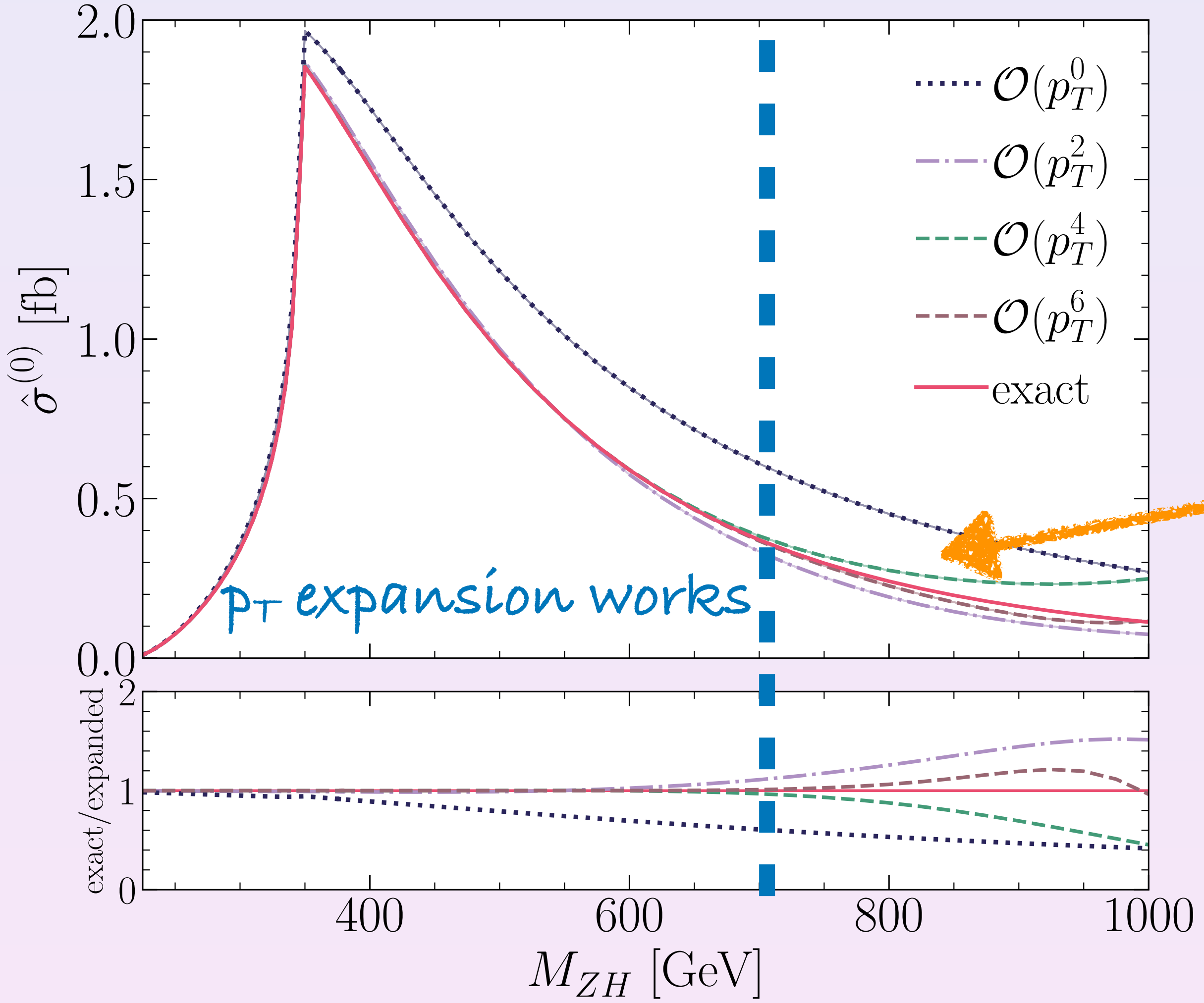
Expressions and integrals become simpler when dividing in small and large scales

p_T expansion: [Bonciani, Degrassi, Giardino, RG '18, Alasfar, Degrassi, Giardino, RG, Vitti '21]

$$p_T^2, m_h^2, m_Z^2 \ll m_t^2, s$$

in this variable can be Taylor expanded

[Alasfar, Degrassi, Giardino, RG, Vitti '21]



high energy expansion necessary

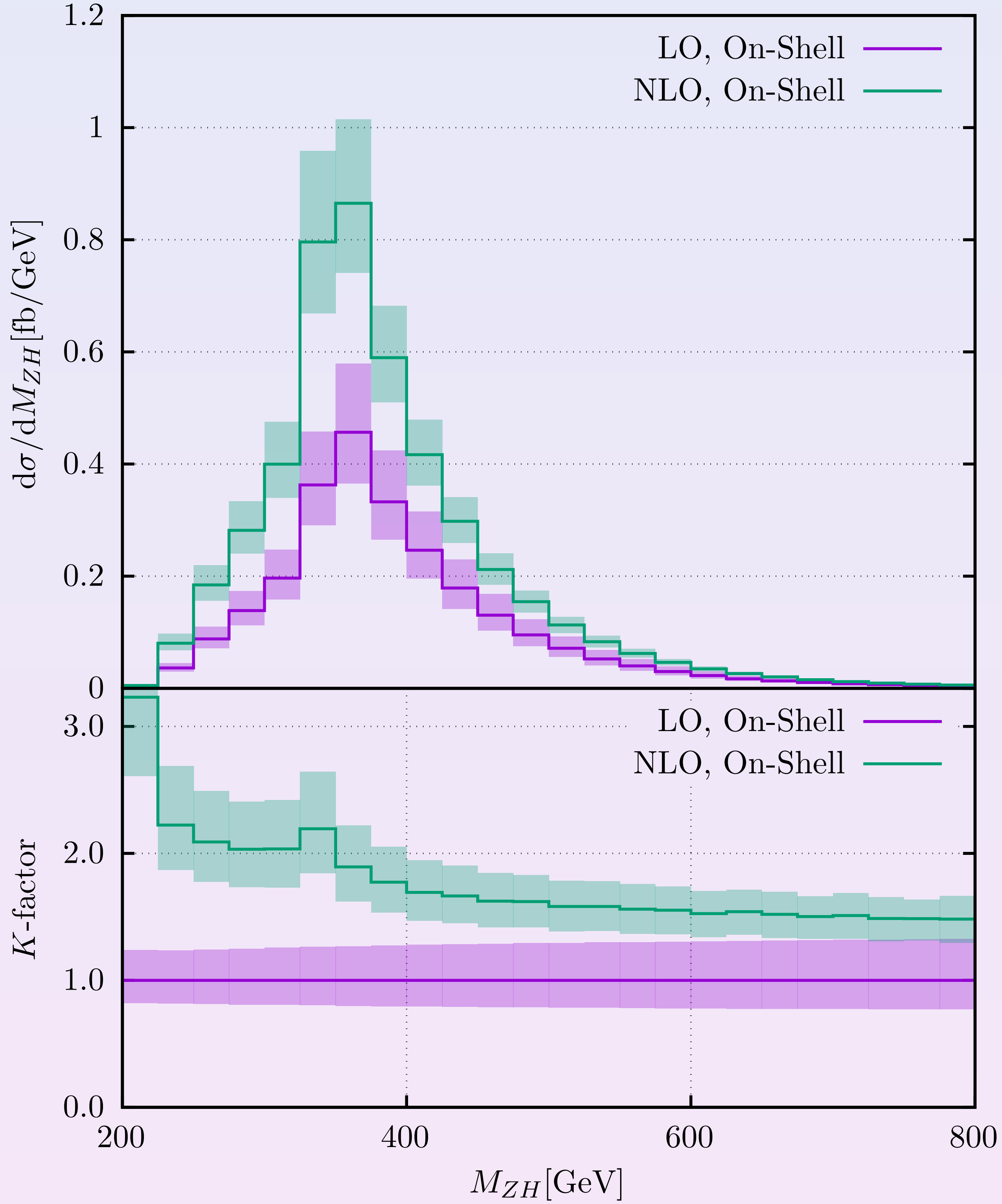
[Davies, Mishima, Steinhauser, '20]

expansions combined in

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

Precise Theoretical predictions

[Degrassi, RG, Vitti, Zhao '22]



large NLO corrections

theoretical uncertainty reduced but still large

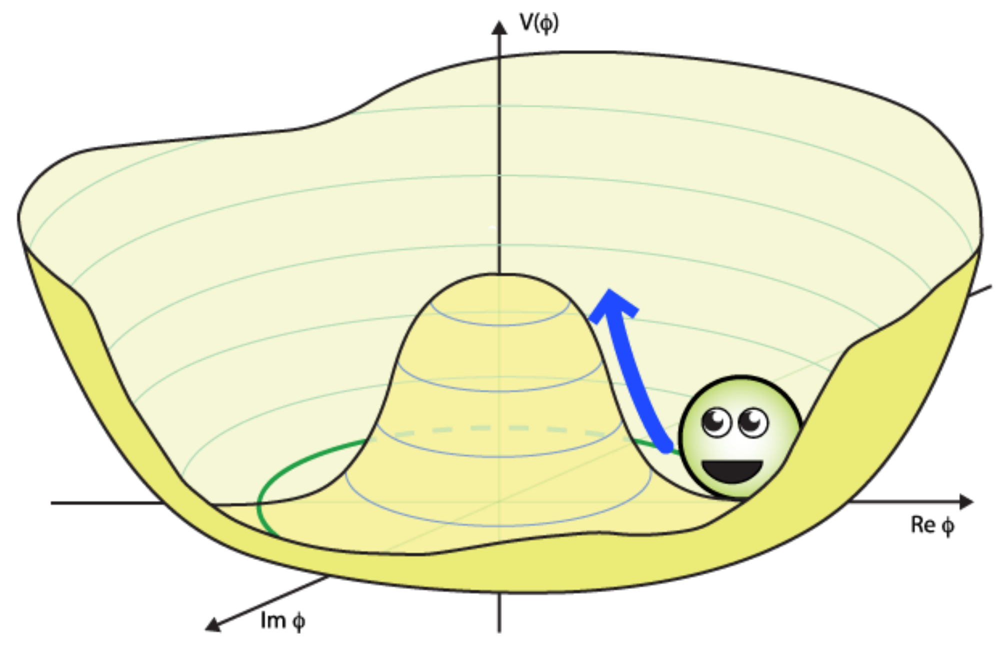
What we don't know yet about the Higgs boson:
1.) Higgs potential

Measurement of Higgs self-couplings gives access to Higgs potential

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

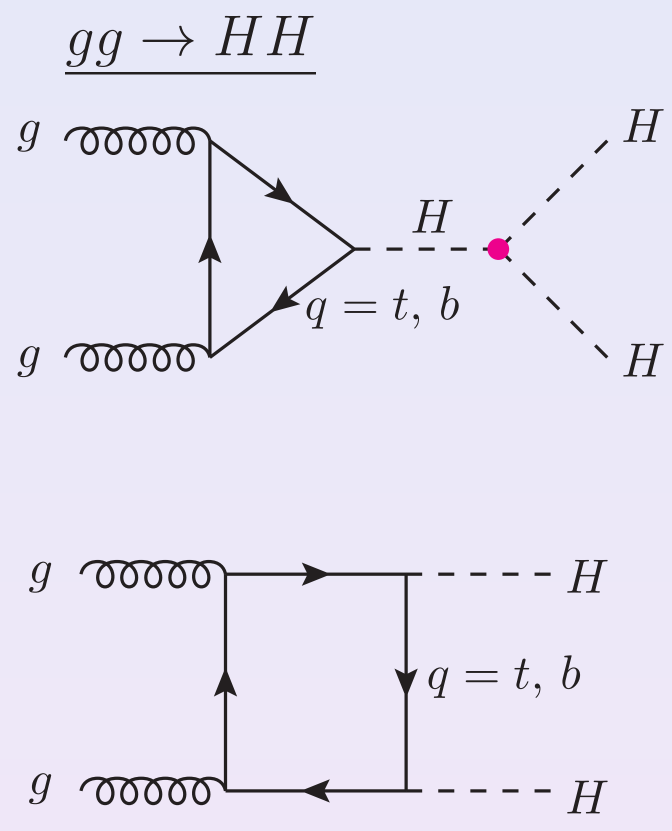
$$\Big\downarrow \text{ EWSB}$$

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

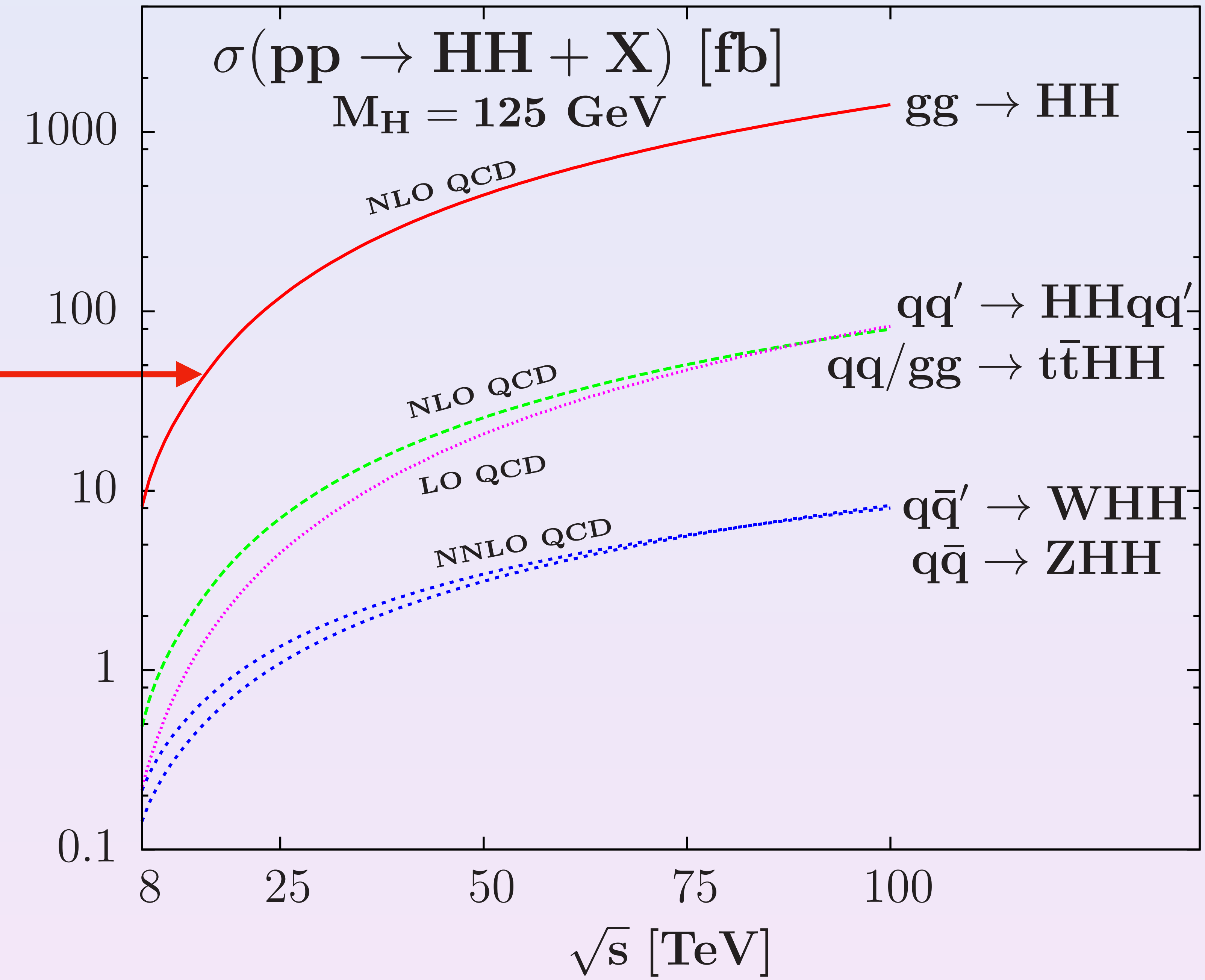


[quantumdiaries.org]

Higgs Pair Production



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



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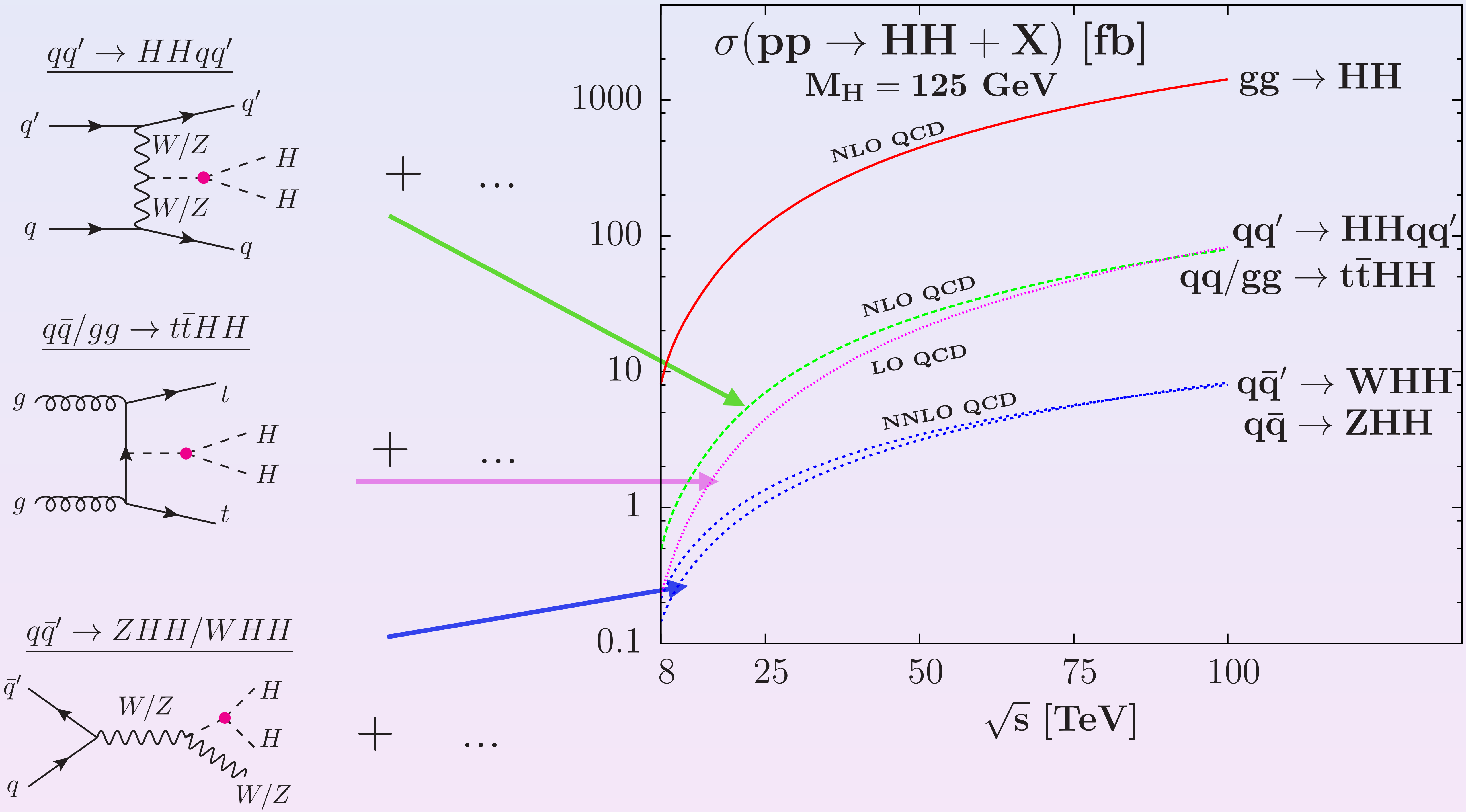
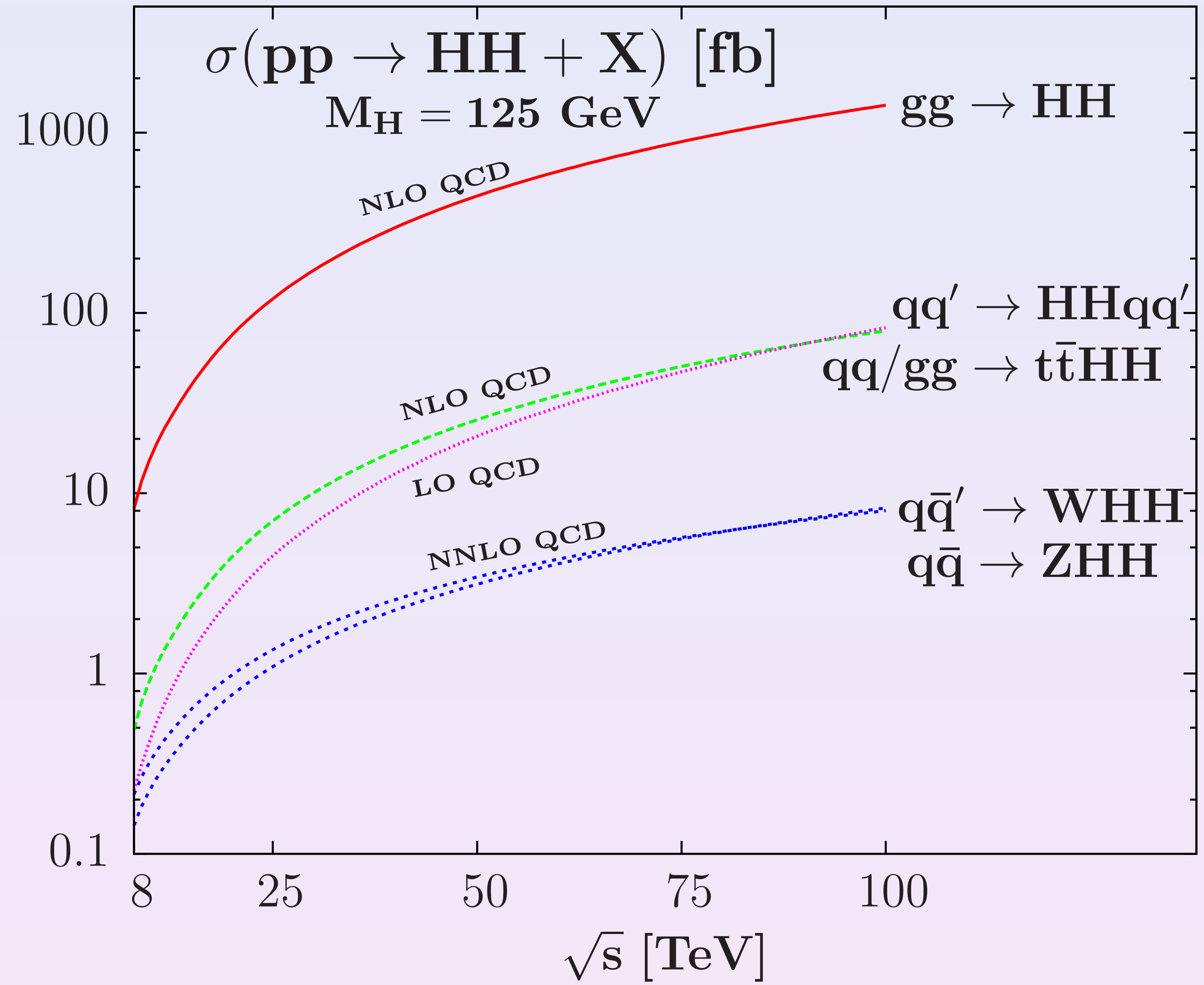


Higgs Pair Production

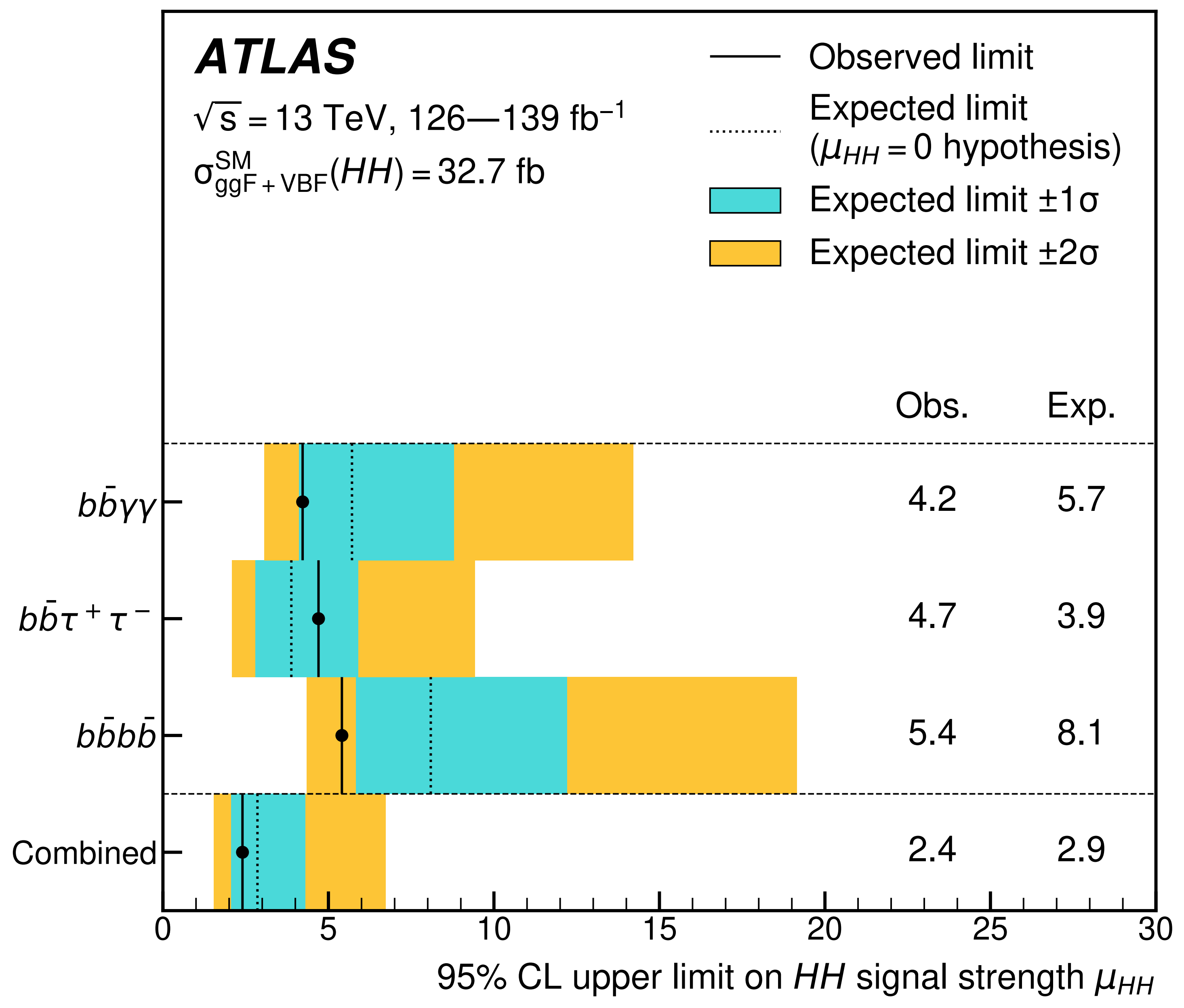
Small cross section

Difficult to measure

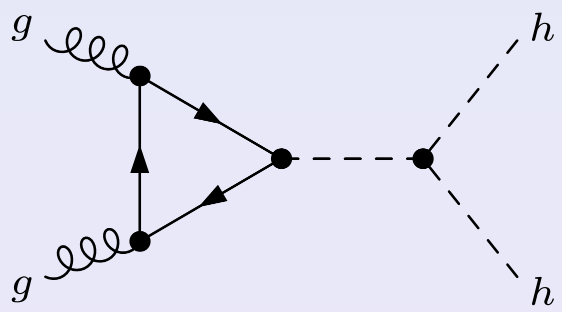
[Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12]

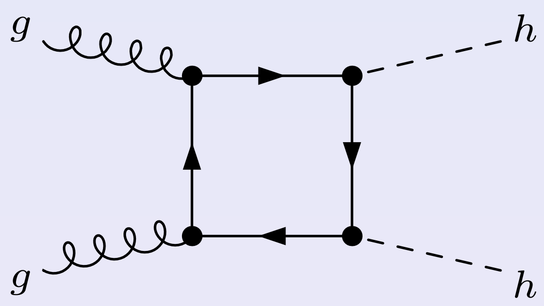


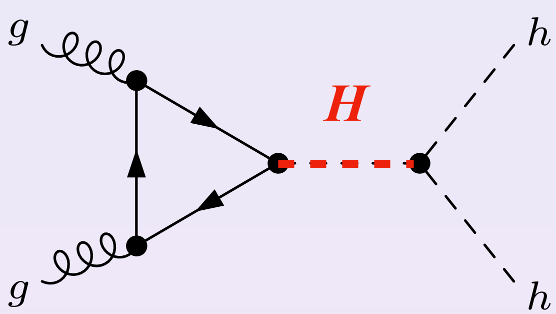
Higgs Pair Production



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

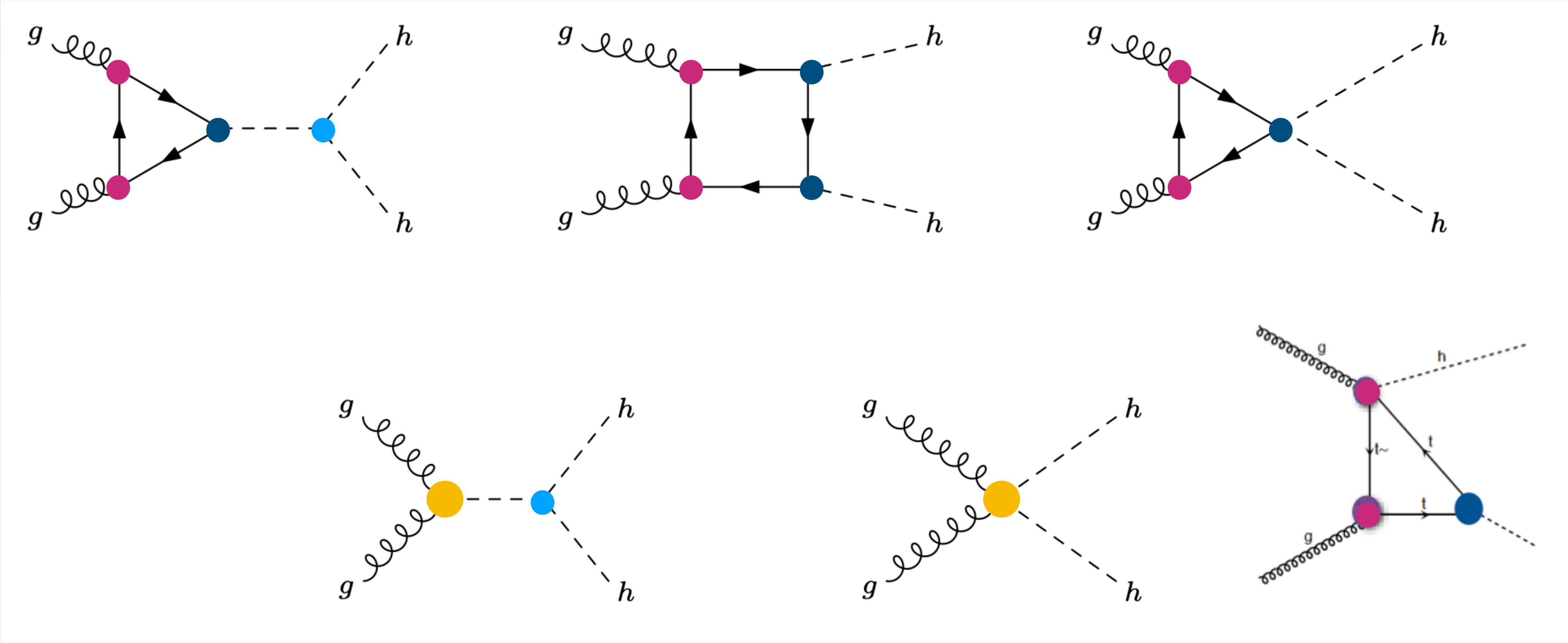






resonant Higgs pair production

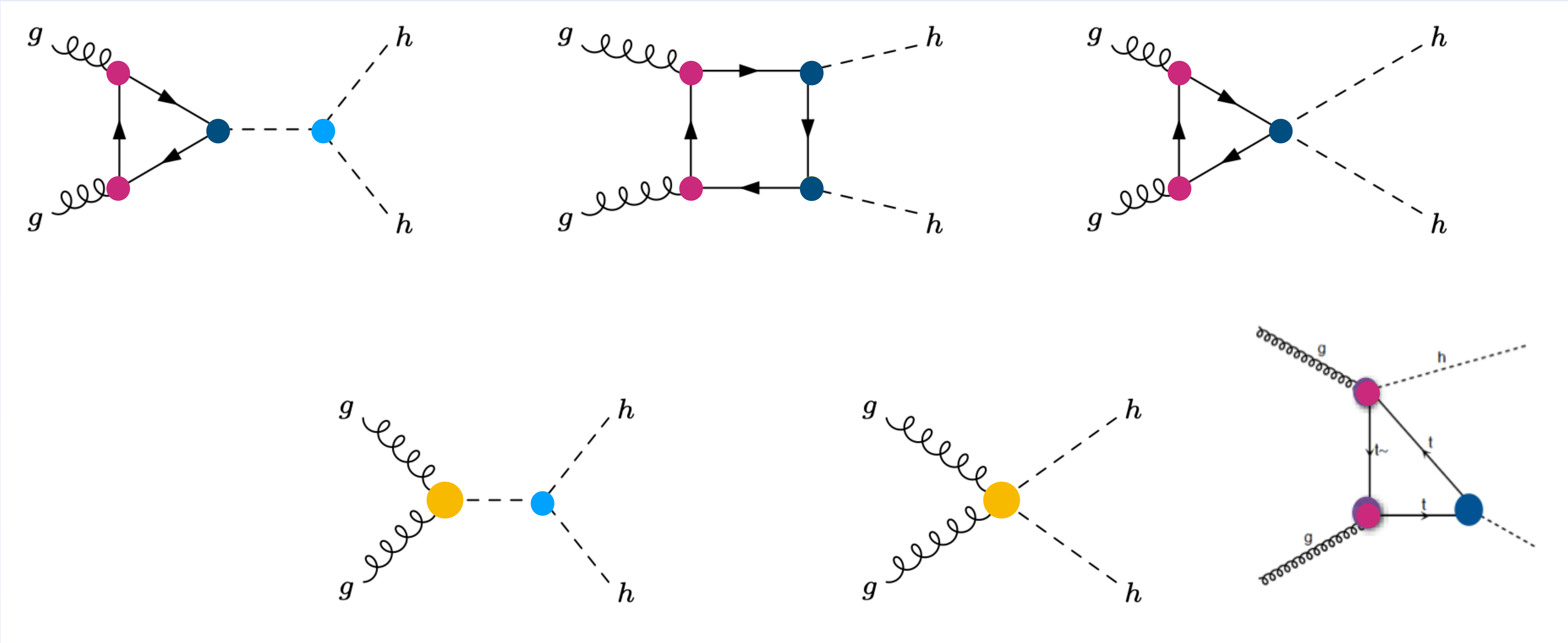
Non-resonant HH production



Standard Model Effective Field Theory (SMEFT):

$$\mathscr{L} = \frac{\bar{c}_H}{v^2}(H^\dagger \partial_\mu H)^2 - \frac{\bar{c}_6 \lambda}{v^2}|H|^6 + \frac{\bar{c}_g g_s^2}{m_W^2}|H|^2 G_{\mu\nu}G^{\mu\nu} + \frac{\bar{c}_u}{v^2}\bar{Q}_L \tilde{H} t_R |H|^2 + h.c. + \frac{c_{tG}\alpha_s}{v^2}\bar{Q}_L \sigma_{\mu\nu} T^a \tilde{H} t_R G^a_{\mu\nu} + h.c.$$

Non-resonant HH production

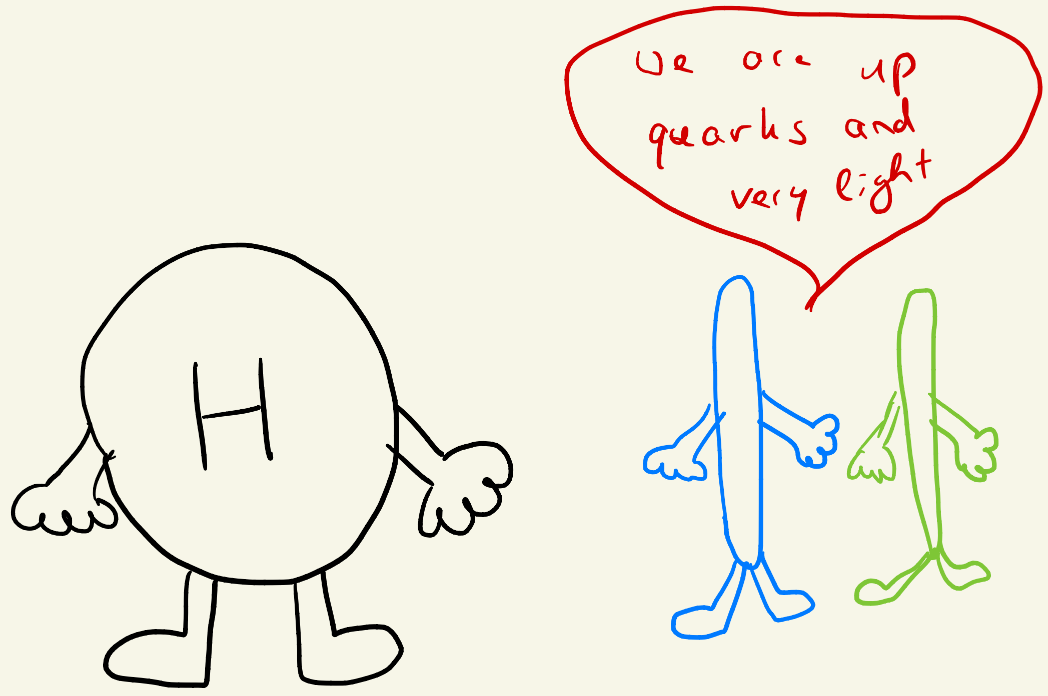


Standard Model Effective Field Theory (SMEFT):

but the equivalent for light quarks?

$$\mathscr{L} = \frac{\bar{c}_H}{v^2}(H^\dagger \partial_\mu H)^2 - \frac{\bar{c}_6 \lambda}{v^2}|H|^6 + \frac{\bar{c}_g g_s^2}{m_W^2}|H|^2 G_{\mu\nu}G^{\mu\nu} + \frac{\bar{c}_u}{v^2}\bar{Q}_L \tilde{H} t_R |H|^2 + h.c. + \frac{c_{tG}\alpha_s}{v^2}\bar{Q}_L \sigma_{\mu\nu} T^a \tilde{H} t_R G^a_{\mu\nu} + h.c.$$

What we don't know yet about the Higgs boson:
2.)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]

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

global fit, not completely model-independent

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global fit, not completely model-independent

Alternative ways:

- Higgs kinematics: Higgs+jet transverse momentum distribution [Bishara Haisch, Monni, Re '16; Soreq, Zhu, Zupan '16]
- VVV production [Falkowski et al '20]
- Higgs+photon [Aguilar-Saavedra, Cano, No '18]
- Wh [Yu'17]

And in Higgs pair production?

Standard Model Effective Field Theory

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

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

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

Couplings:

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

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

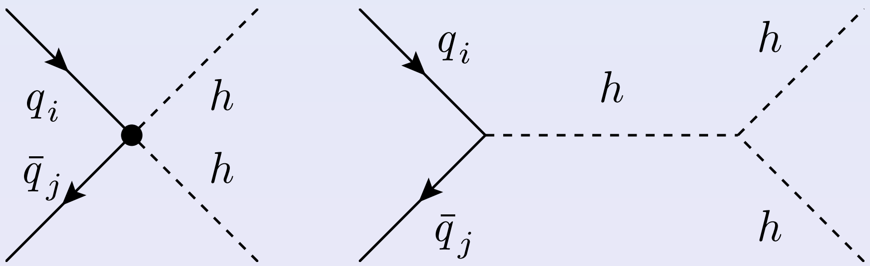
direct coupling to Higgs pair

In the following consider only flavour diagonal case.

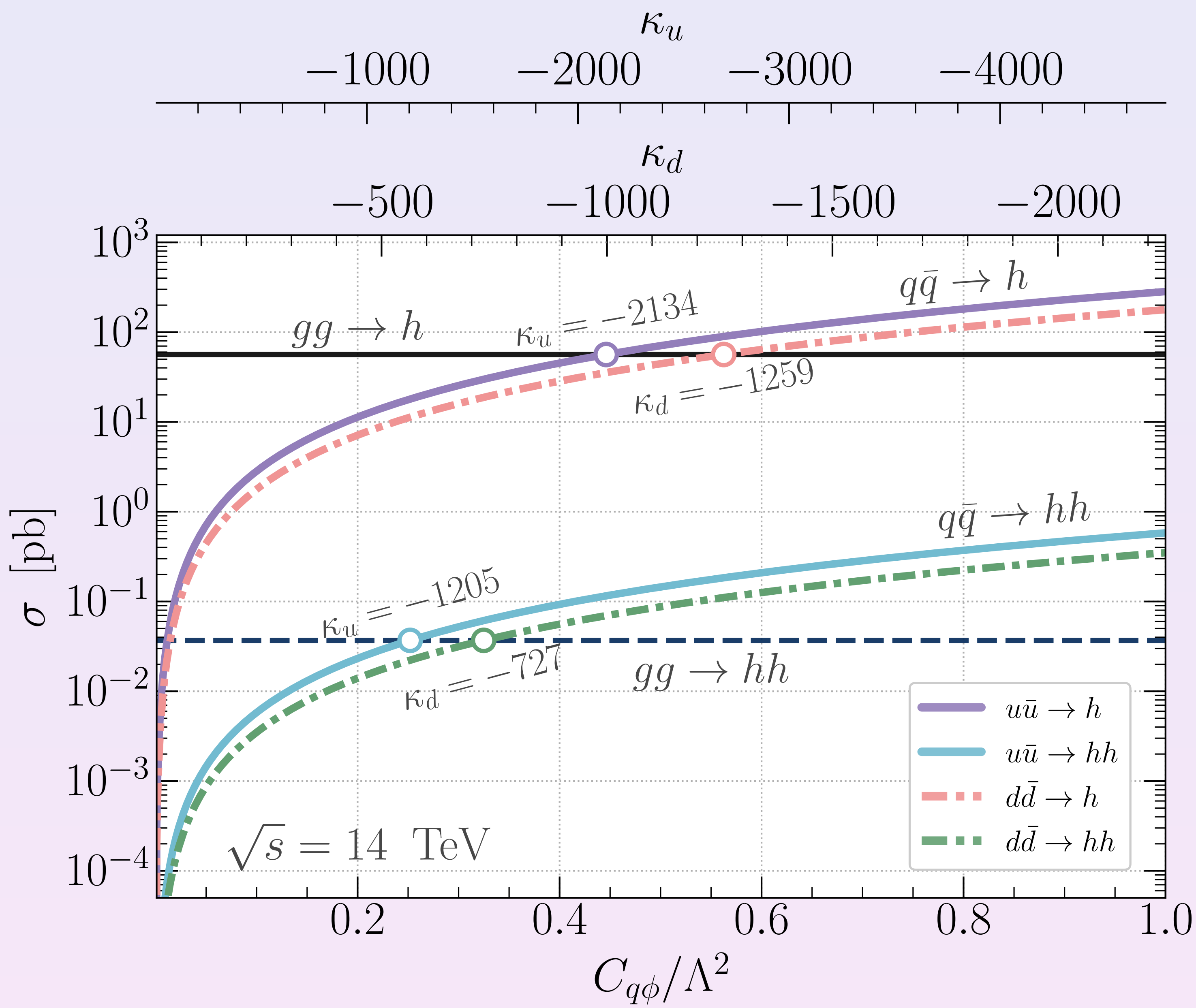
Notation:

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

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



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

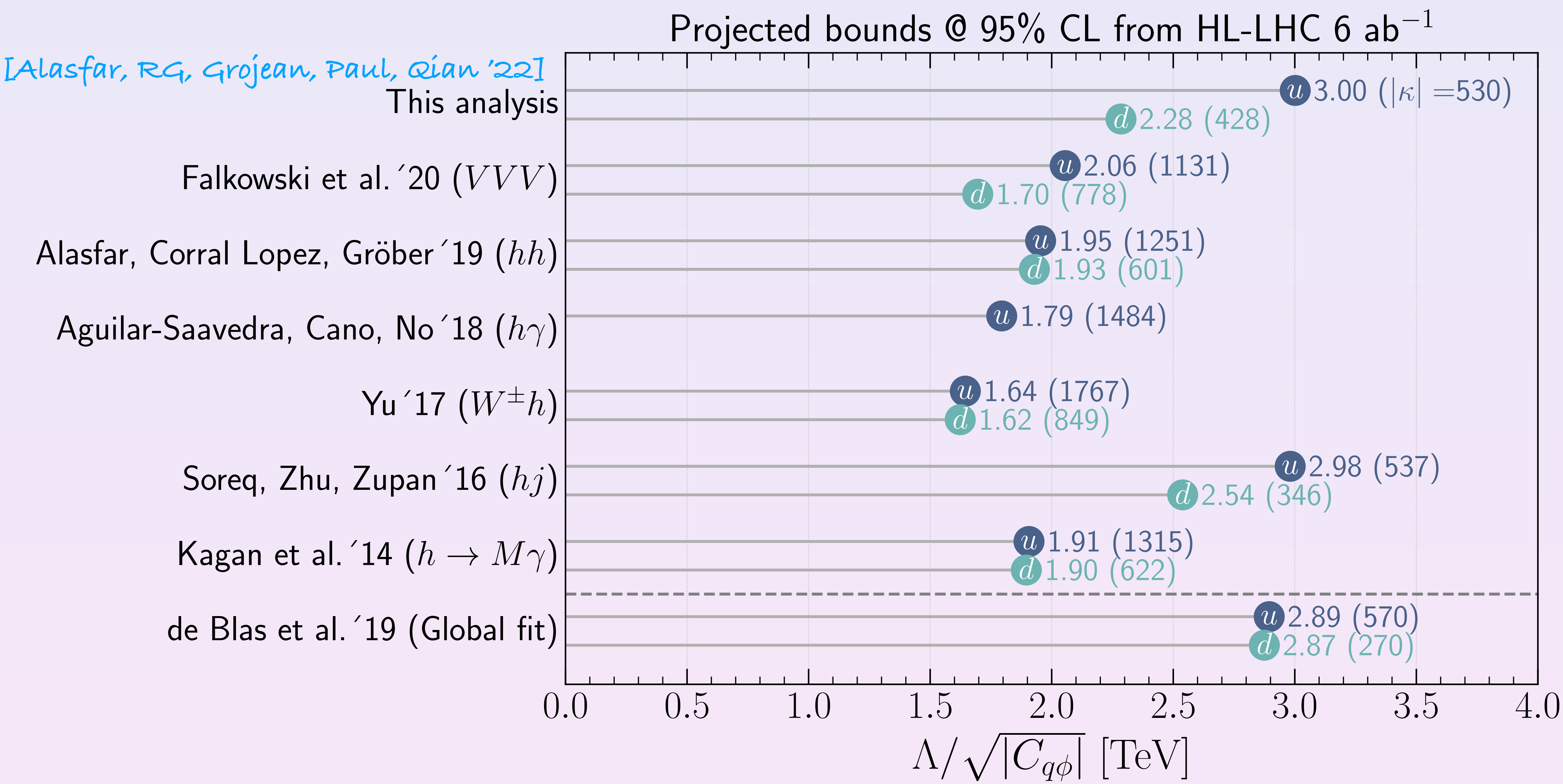


Light quark Yukawa couplings in HH

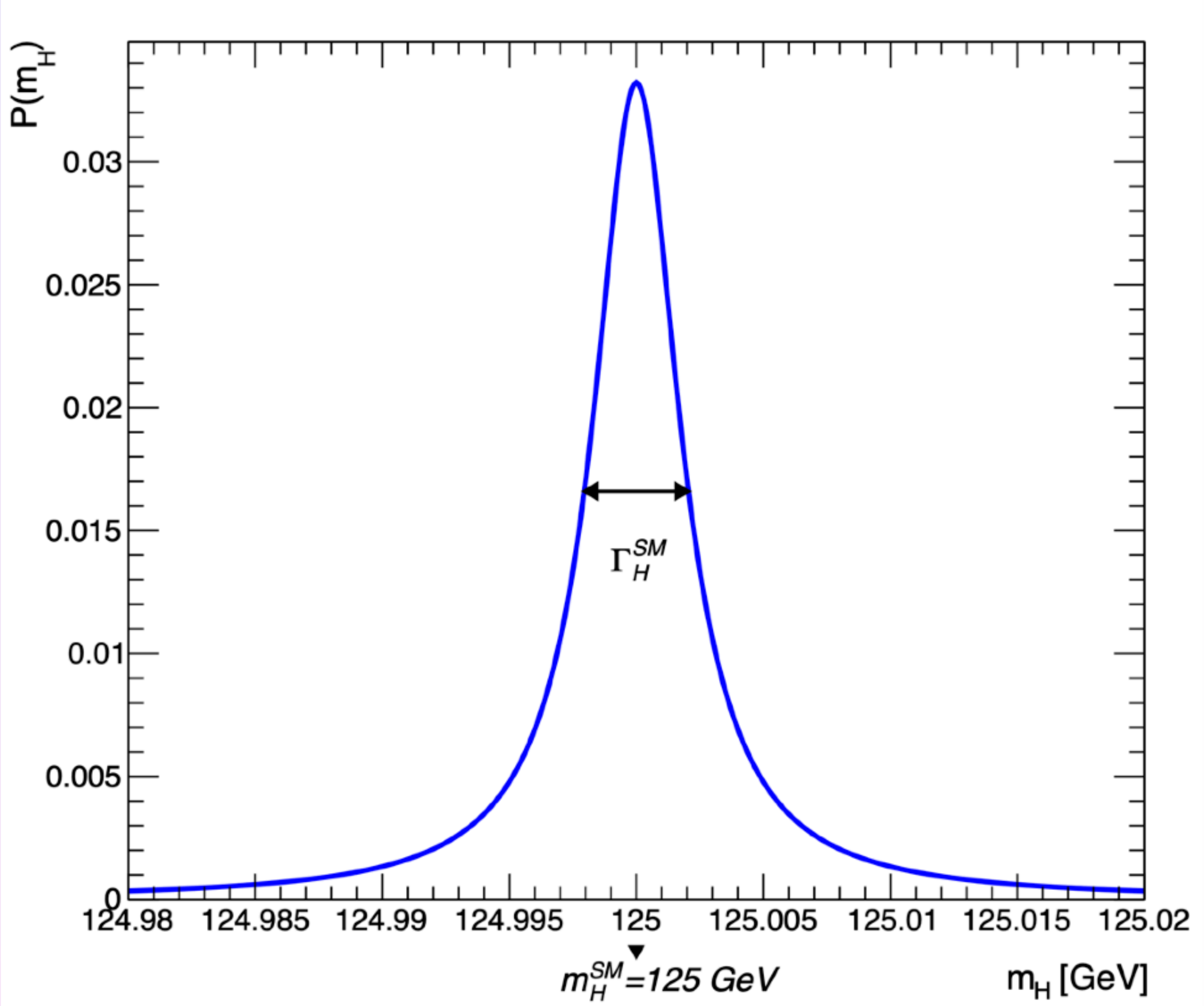
Fit on trilinear Higgs self-coupling becomes worse if light quark Yukawa deviations are considered

[0.53,1.7] ⟶ [0.79,2.3] (1 sigma, HL-LHC)

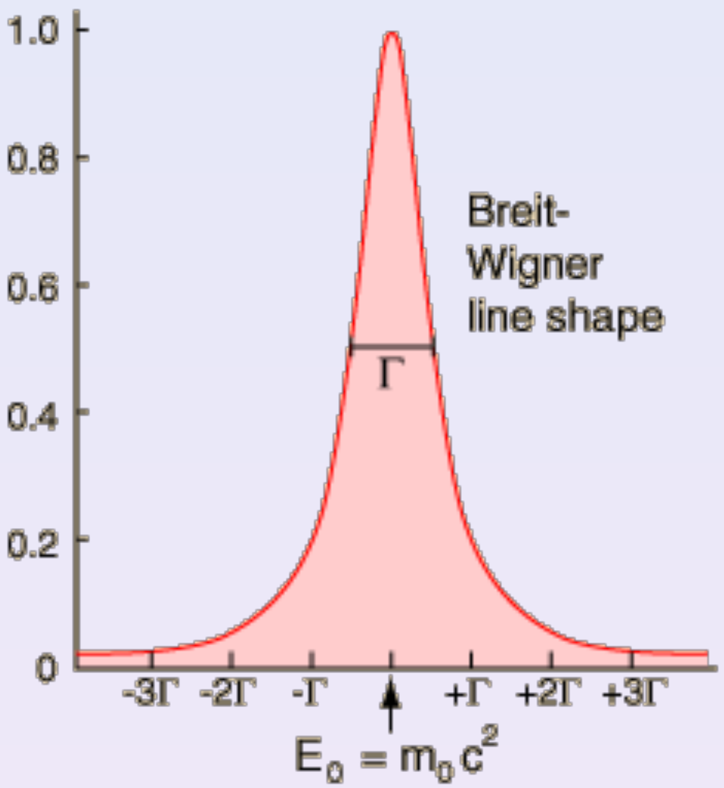
[Alasfar, RG, Grojean, Paul, Qian '22]



What we don't know yet about the Higgs boson:
3.) Higgs width



Higgs decay width (life time)



$$\frac{1}{p^2 - m^2 + im\Gamma}$$

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

"usual" SM decays

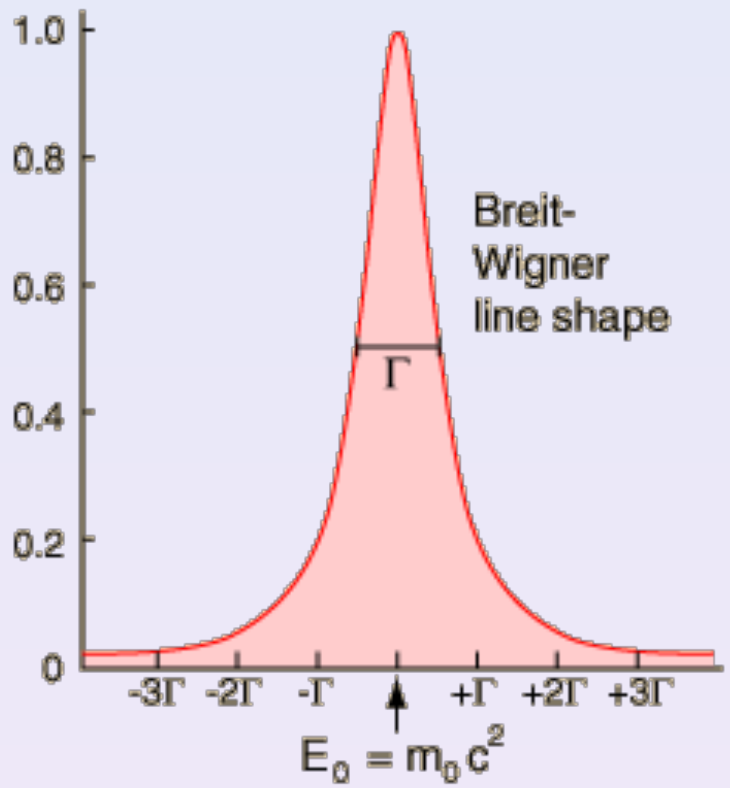
decays in invisible final states e.g. Dark Matter, current limit BR<0.145

visible but exotic and hence not searched for

[ATLAS 2202.07953]

no direct measurement possible at LHC

Higgs decay width (life time)



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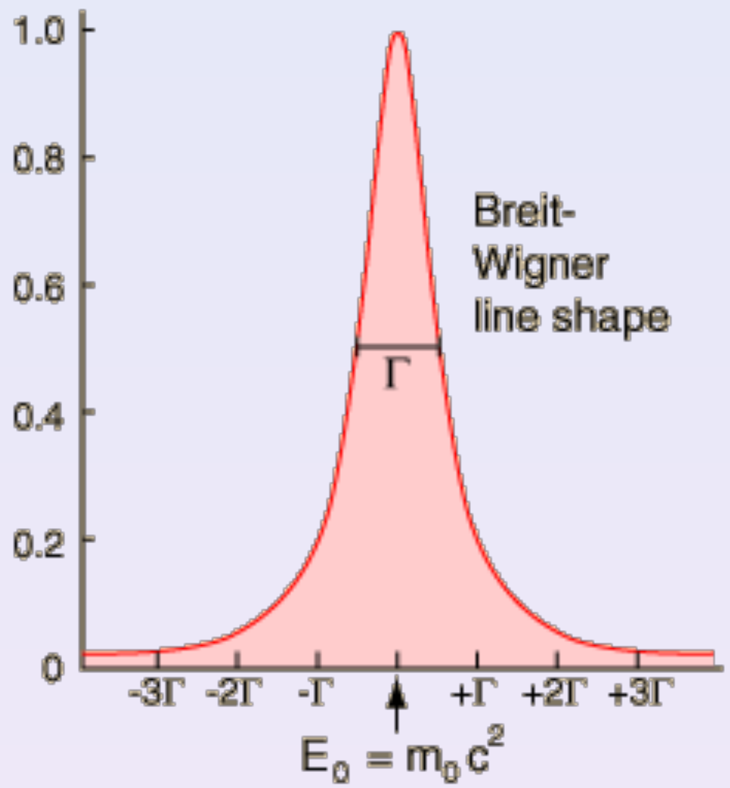
Measurement of off-and on-shell rates to extract width

[Kauer, Passarino '12; Caola, Melnikov '13; Campell, Ellis, Willams '13]

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

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

Higgs decay width (life time)



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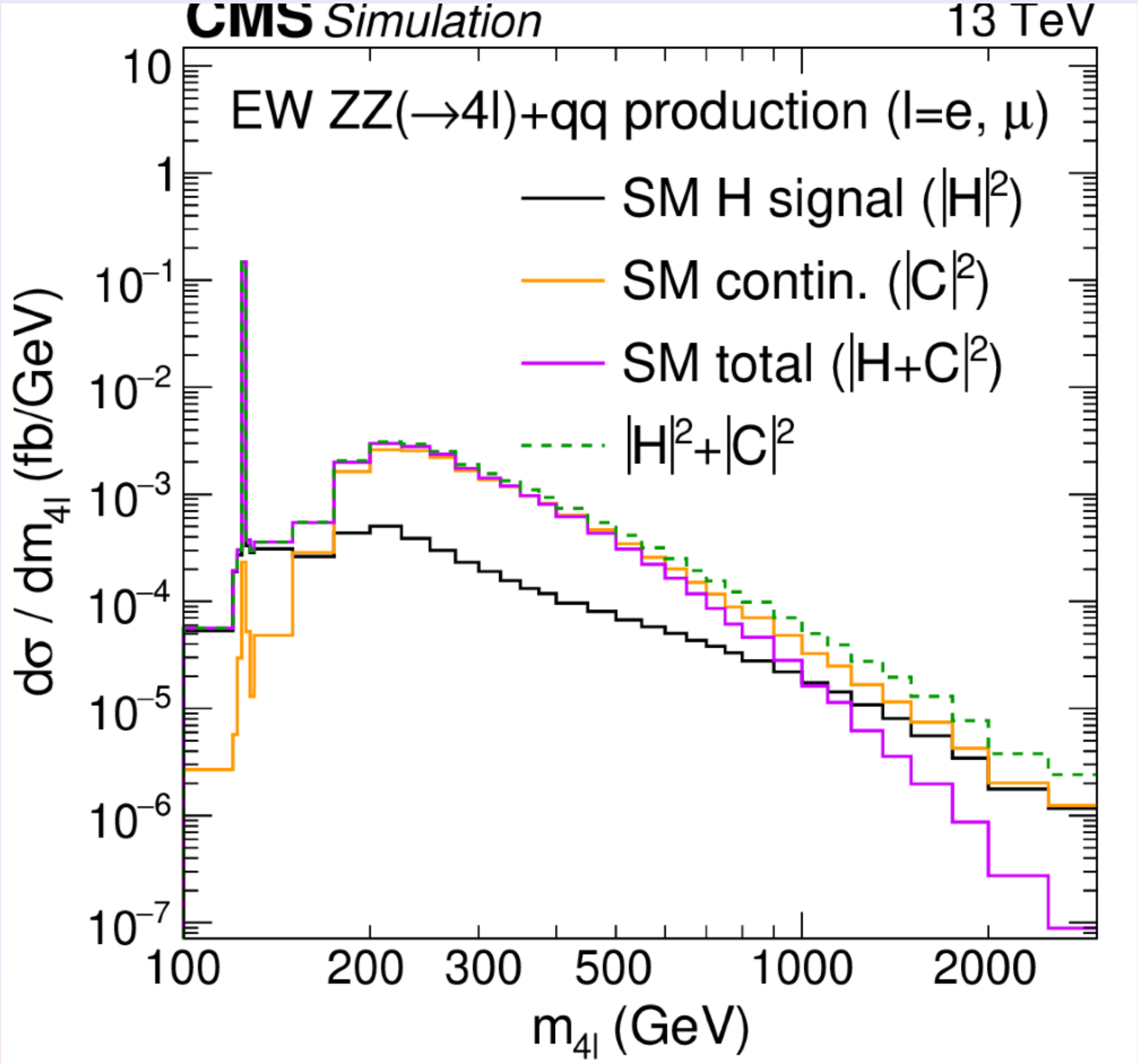
$$\mu_{ZZ}^{\text{off}} \equiv \frac{\text{d}\overline{\sigma}_h}{[\text{d}\overline{\sigma}_h]_{\text{SM}}} \sim \kappa_{ggh}^2(\hat{s})\, \kappa_{hZZ}^2(\hat{s})$$

One though needs to assume that

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

Higgs decay width (life time)

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$ (consistent with SM) [CMS' 22]



But...

Coming back to the scenario with large light Yukawa couplings:

$$\mu_{on} = \frac{(\sigma_{q\bar{q}} + \sigma_{gg}) \cdot \frac{\Gamma^{SM}_{h->ZZ}}{\Gamma^{SM}_{tot} + \Gamma_{q\bar{q}}}}{\sigma_{gg} \cdot \frac{\Gamma^{SM}_{h->ZZ}}{\Gamma^{SM}_{tot}}}$$

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direct interpretation from width not possible

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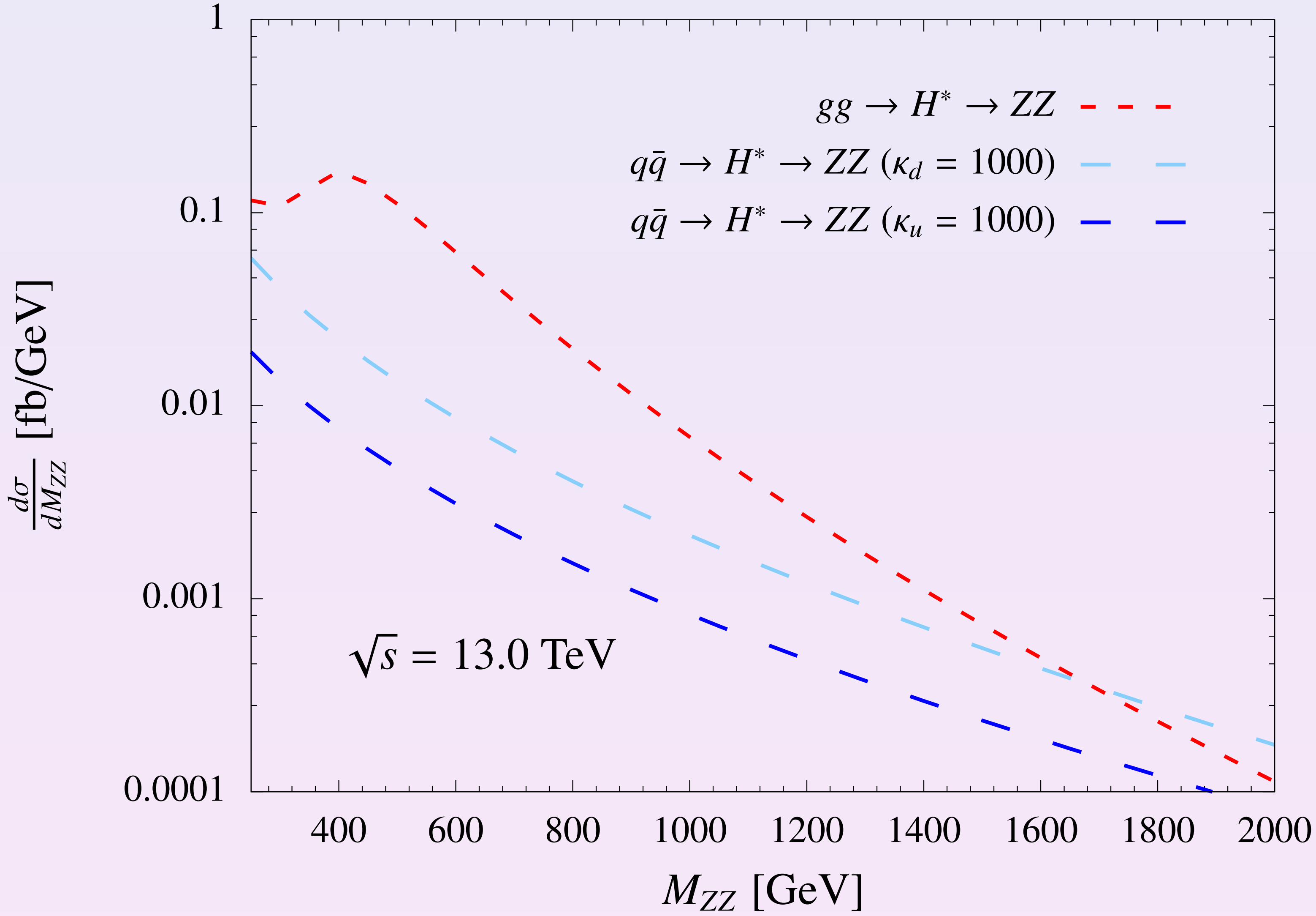

[Balzani, RG, Vitti in preparation]

$$S1 : \kappa_u > 1390, \kappa_d > 830$$

$$S2 : \kappa_u > 1270, \kappa_d > 750$$

numbers based on invariant mass distribution only, improvements with matrix element method?

[HL-LHC systematic uncertainties: ATL-PHYS-PUB-2018-054]

Conclusion

Even though the Higgs boson is now 10 years old there still remains a lot to be learned about!

Theory challenges:

- precision predictions for Higgs (an background) processes

  this is not: let's sit down and compute another order in perturbation theory but requires lots of new ideas and to tackle technical challenges

- where can new physics hide? How can we test it?

  connections to the open questions of the Standard Model?

- And... in case a deviation is found, how can it be interpreted?

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Thanks for your attention!

About myself

2011-2014: PhD at KIT

2012: discovery of Higgs boson

2014-2016: Post-doc at Instituto Nazionale di Fisica Nucleare, Rome 3, Italy

2016-2018: Post-doc at Institute of Particle Physics Phenomenlogy, Durham University, UK

2018-2019: W2-Professor at Humboldt-University, Berlin (financed by the Berliner Gleichstellungsfonds, 5 year position)

2019-2022: Tenure-Track Assistant Professor (Ricercatrice a Tempo determinato tipo B) at the University of Padova, Italy

2020: birth of my daughter

Since Oct 2022: Associate Professor in Padova

2022: birth of my son

Gender equality at UniPD

Physics department (2019)

Students∼ 33% are female

Researcher (=Assistant Professor): 29 % women

Associate Professor: 14 % women

Full Professor: 14 % women

[thanks to Leila Zoia for pointing me to these numbers]