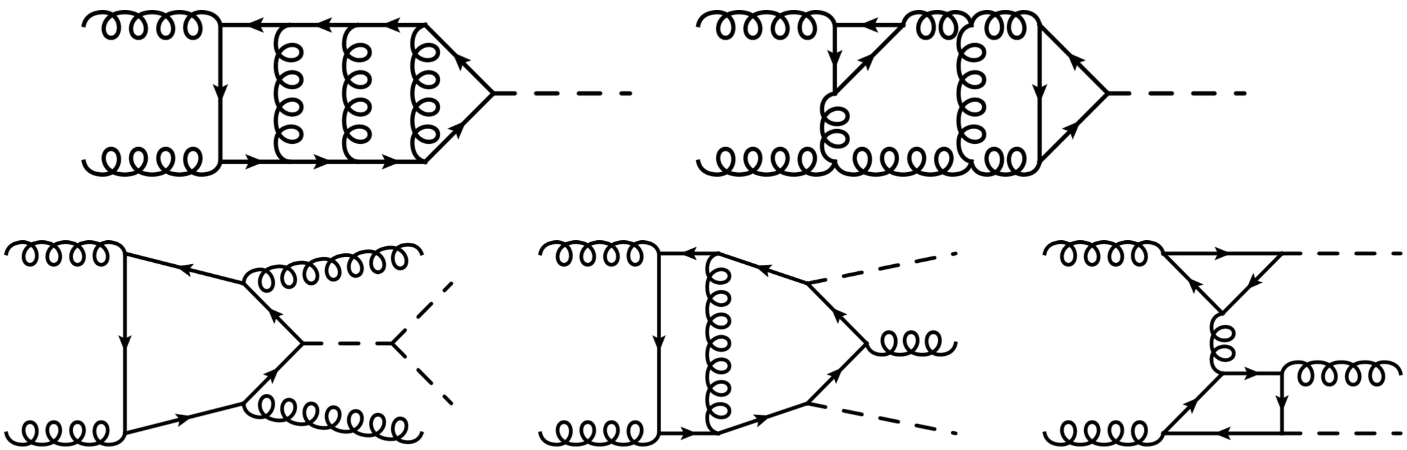
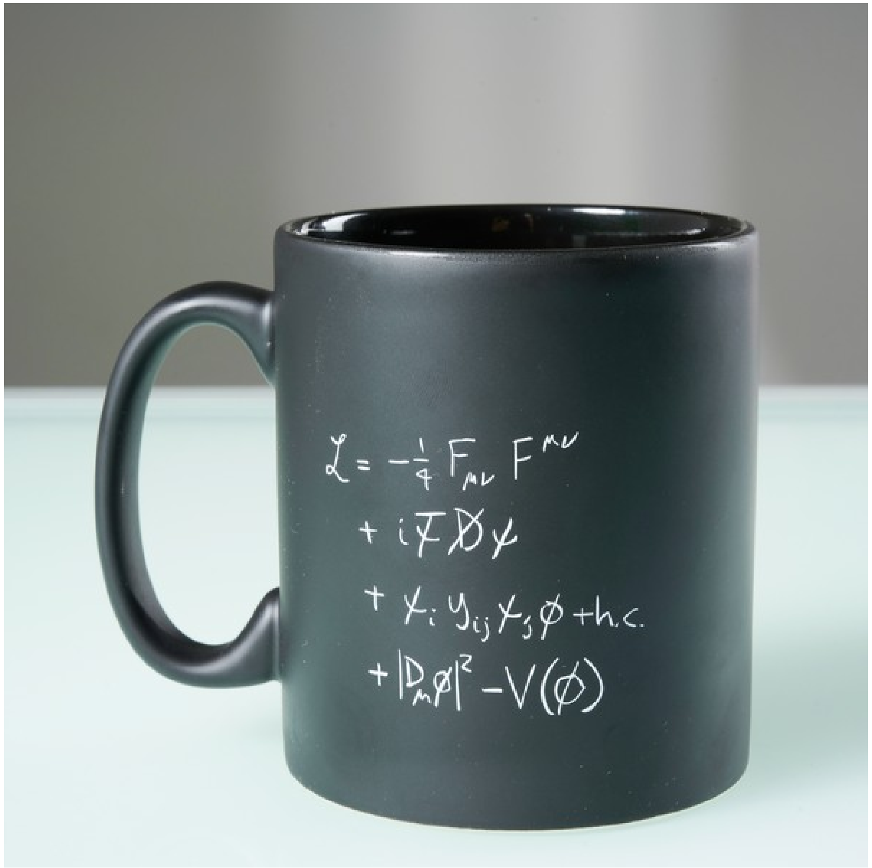
Higgs Boson Production at the LHC

Florian Herren - Institute for Theoretical Particle Physics



Why are we interested in the Higgs Boson?

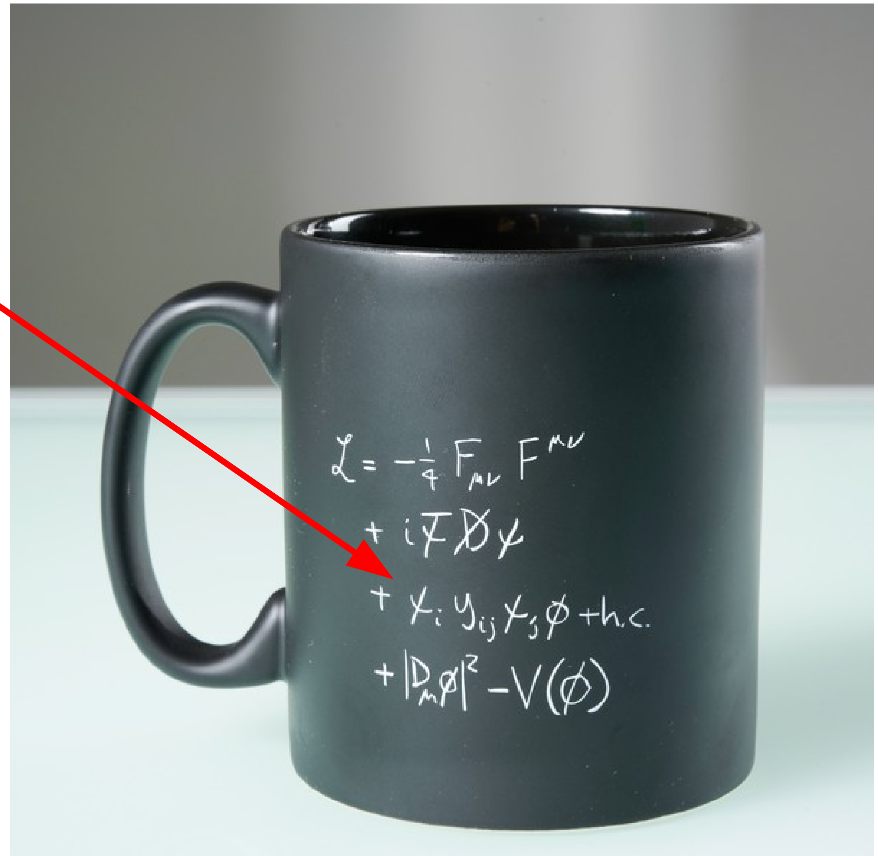


(Image: CERN)

Why are we interested in the Higgs Boson?

Yukawa sector

- Higgs-Fermion interactions
- Fermion masses
- Flavour structure
- CP-violation



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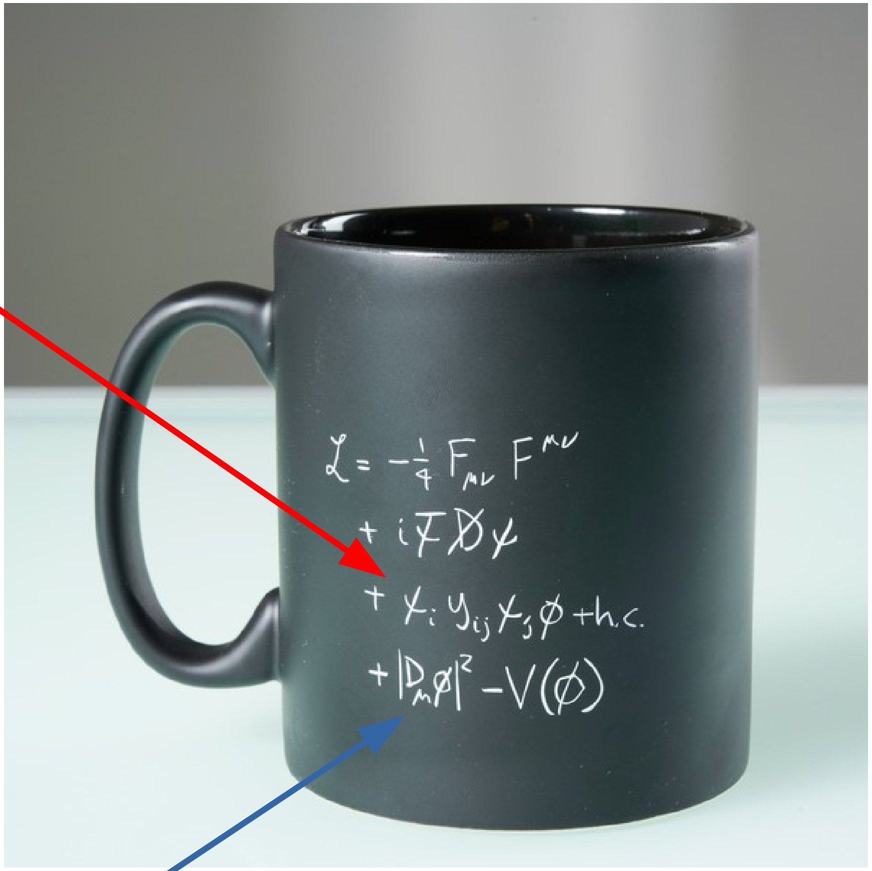

Gauge-Kinetic term

- Higgs-Gauge-Boson interactions
- Gauge boson masses

Why are we interested in the Higgs Boson?

Karlsruhe Institute of Technology

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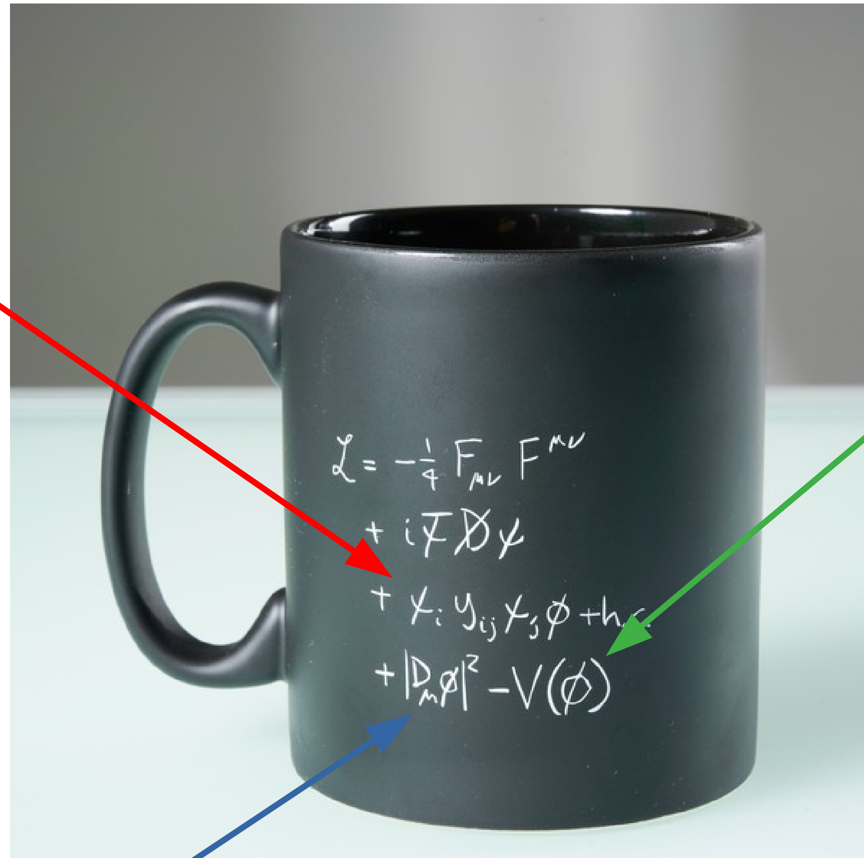

Higgs potential
- Higgs boson mass
- Multi-Higgs interactions

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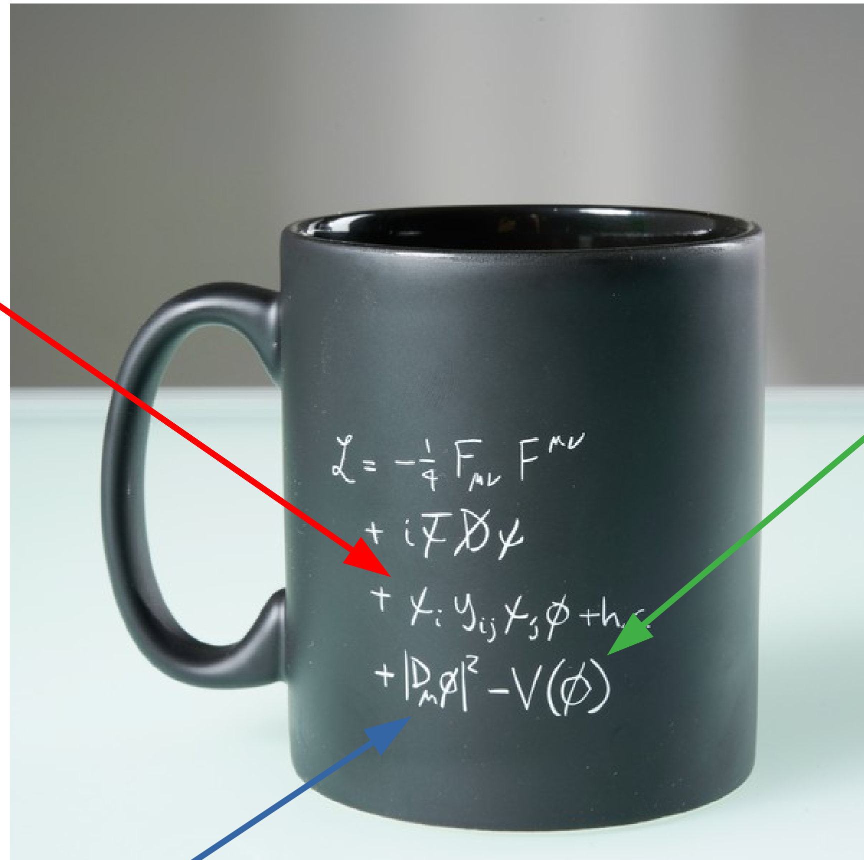

Higgs potential
- Higgs boson mass
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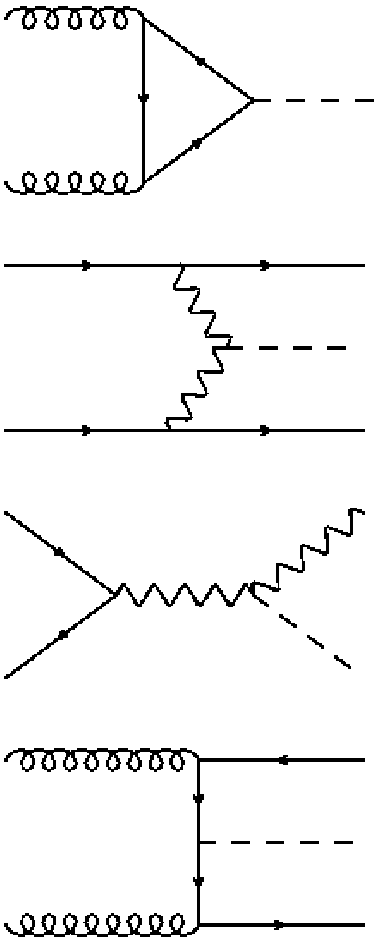
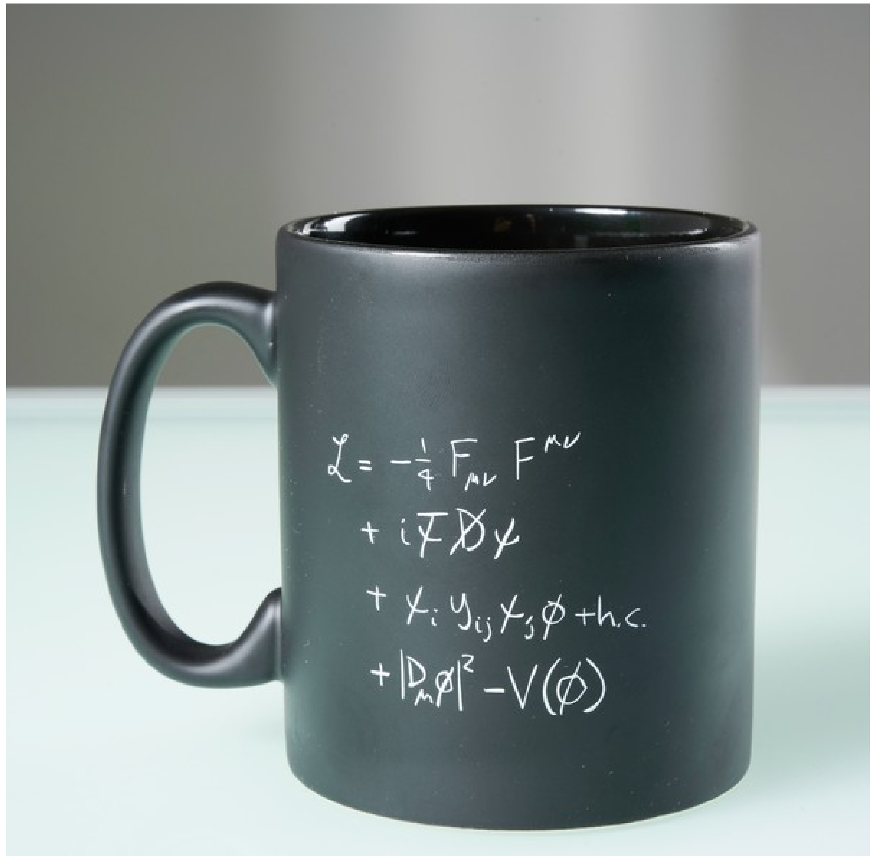
Gauge-Kinetic term
- Higgs-Gauge-Boson interactions
- Gauge boson masses

➡ The Higgs boson plays a central role in the SM

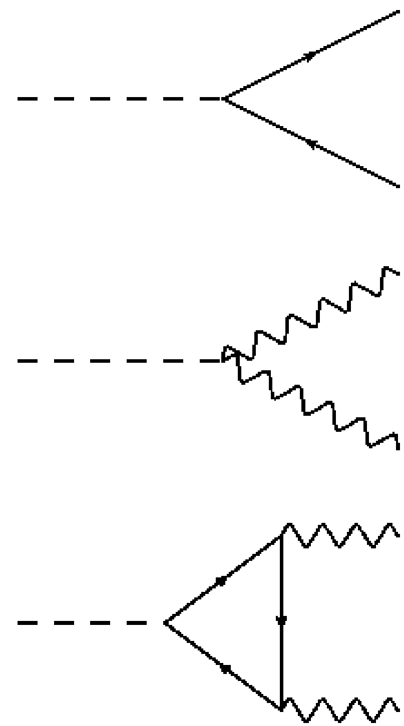
How can we study the different sectors?

Production





Decay



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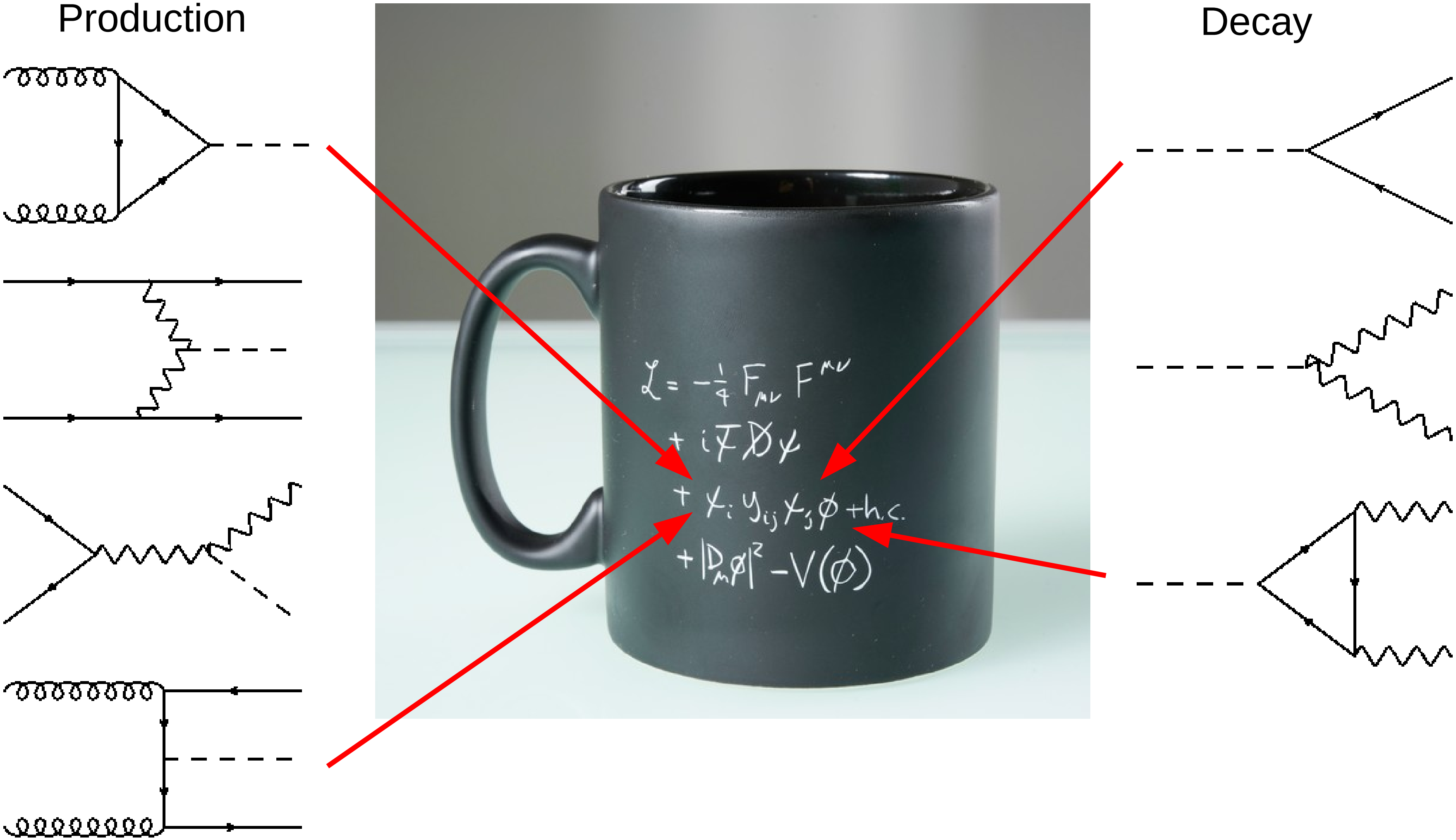
Production

Decay



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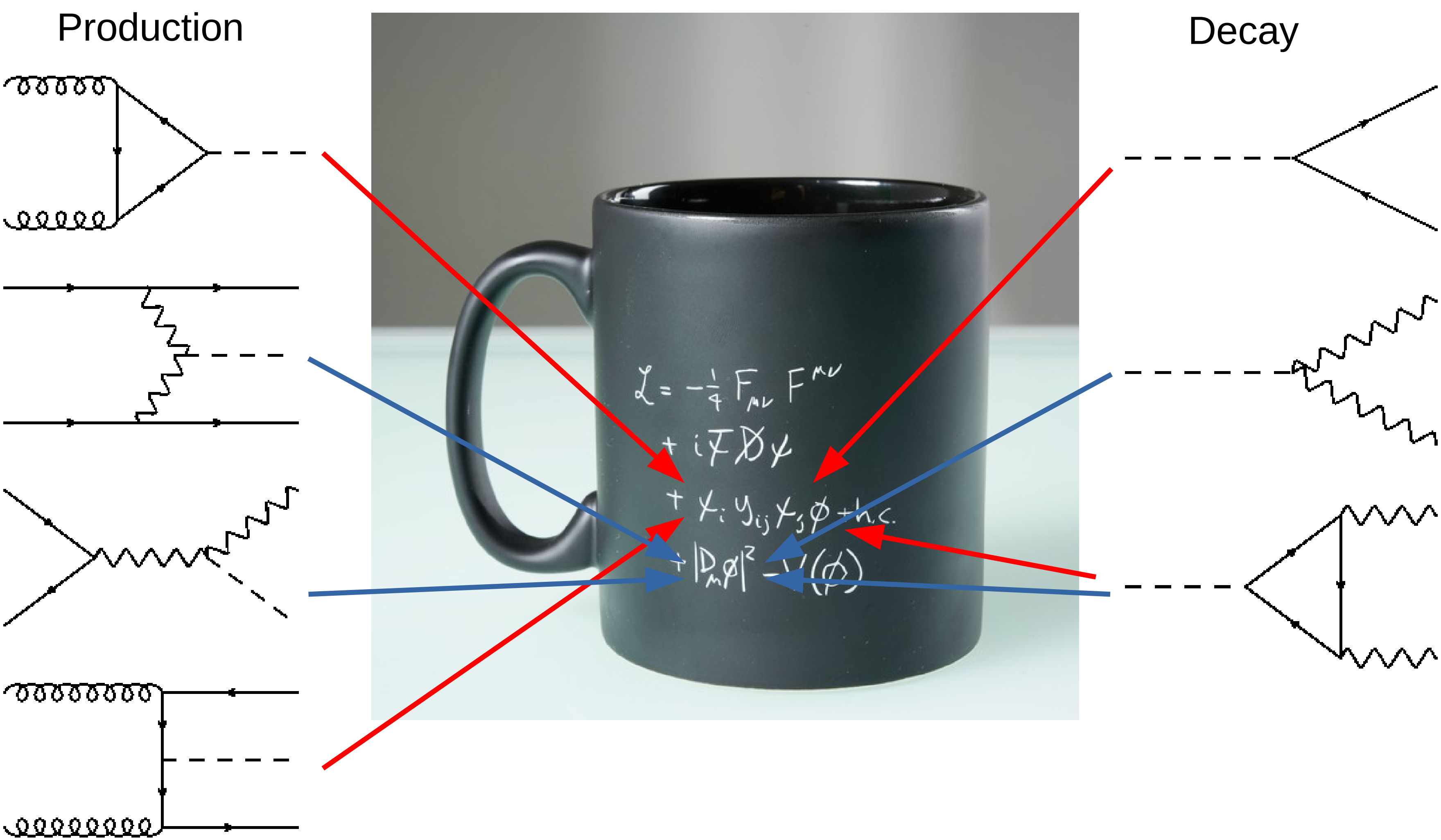

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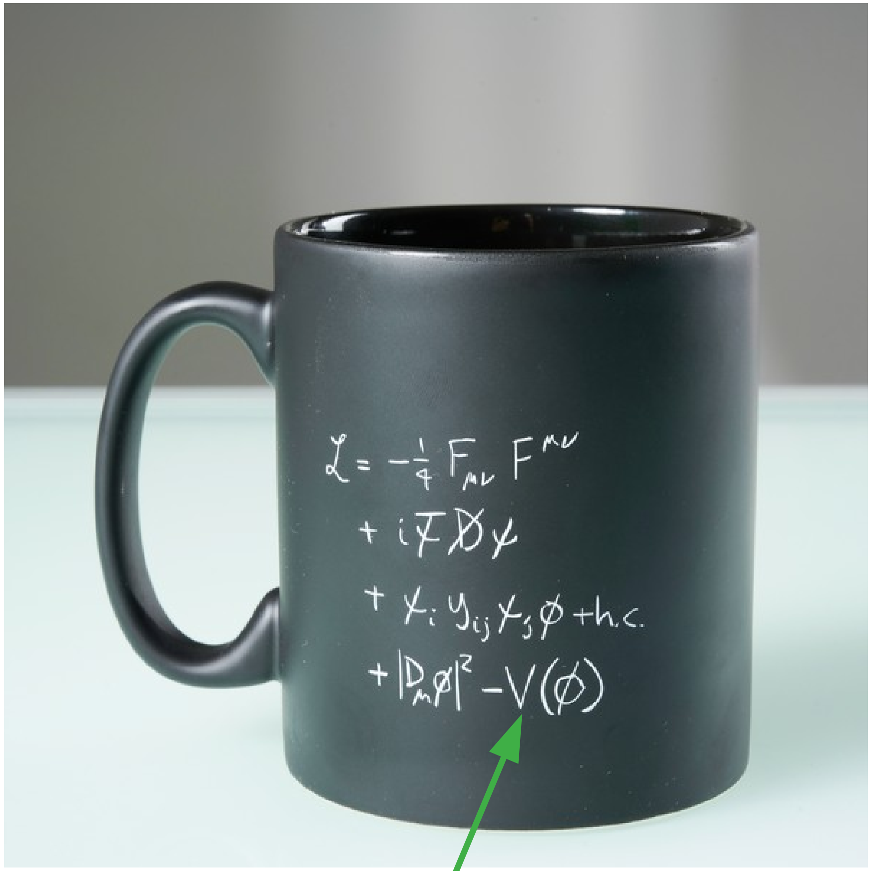

How can we study the potential?

The Higgs potential

$$\mathrm{V}(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

Electroweak symmetry breaking $\big\downarrow$ $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$

$$\mathrm{V}(H) = \tfrac{1}{2} m_H^2 H^2 + v\lambda H^3 + \tfrac{\lambda}{4} H^4$$

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$$\mathrm{m}_H = 125.10 \ \mathrm{GeV}$$
$$v = 246.26 \ \mathrm{GeV}$$

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$$\mathrm{m}_H = 125.10 \text{ GeV}$$

$$v = 246.26 \text{ GeV}$$

$$\lambda = \frac{2 m_H^2}{v^2} \approx 0.13$$

The Higgs potential

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2 + \ldots.$$

Electroweak symmetry breaking $\Big\downarrow$ $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$

$$V(H) = \tfrac{1}{2} m_H^2 H^2 + v\lambda_3 H^3 + \frac{\lambda_4}{4} H^4 + \ldots$$

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$$\lambda_4 = \ ?$$

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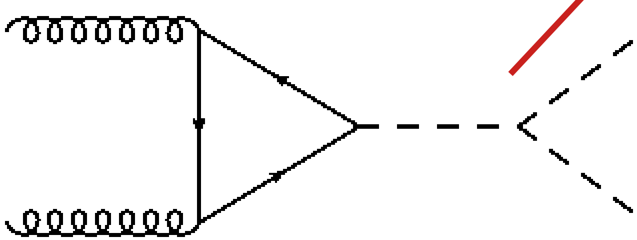
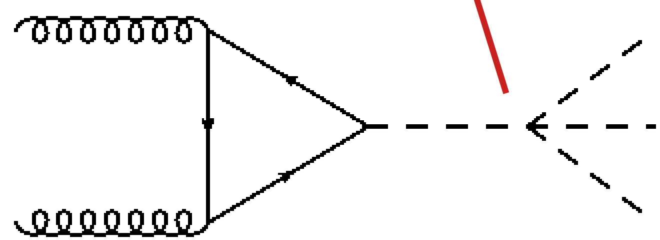
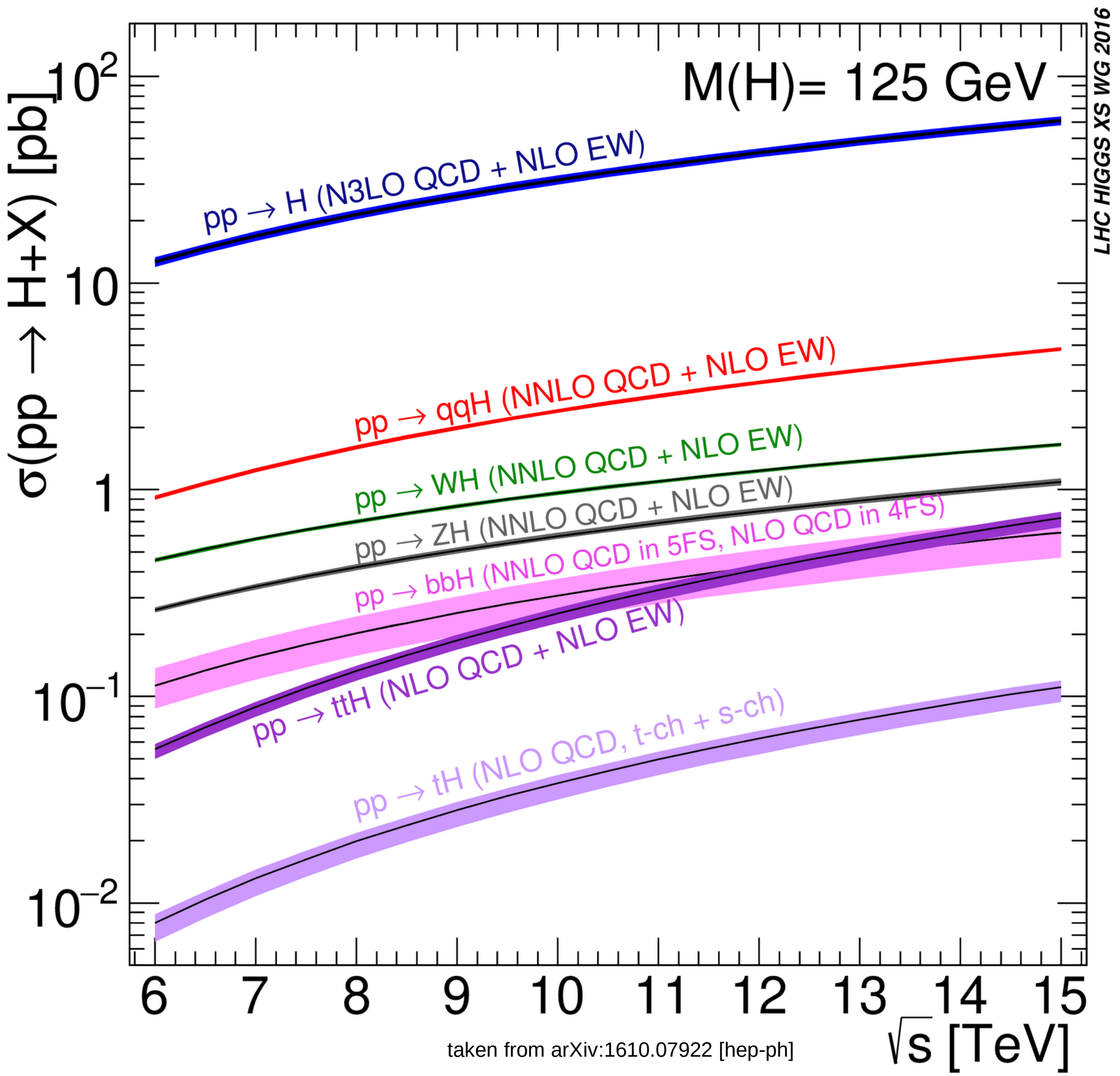


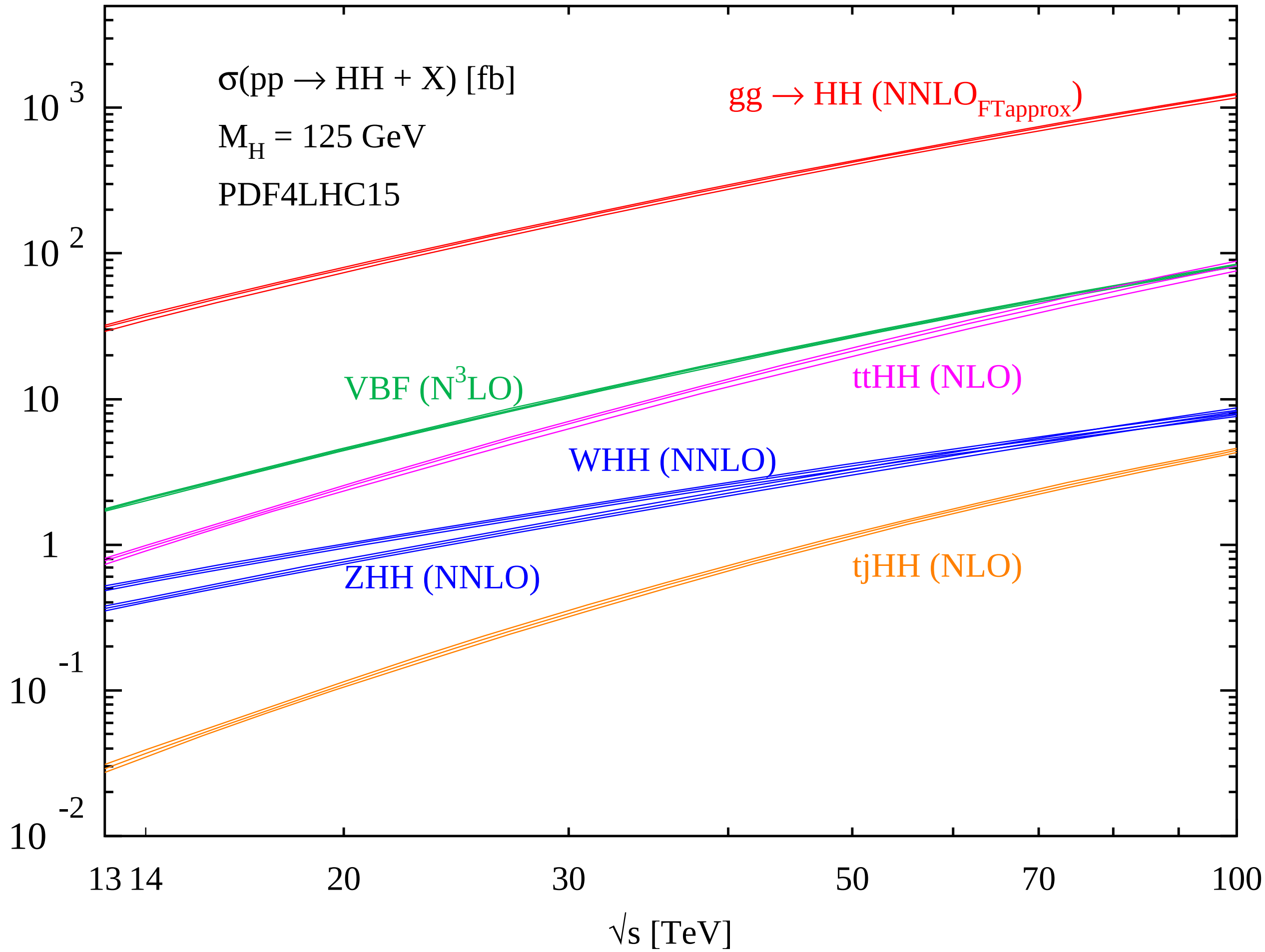


Production cross sections: H + X



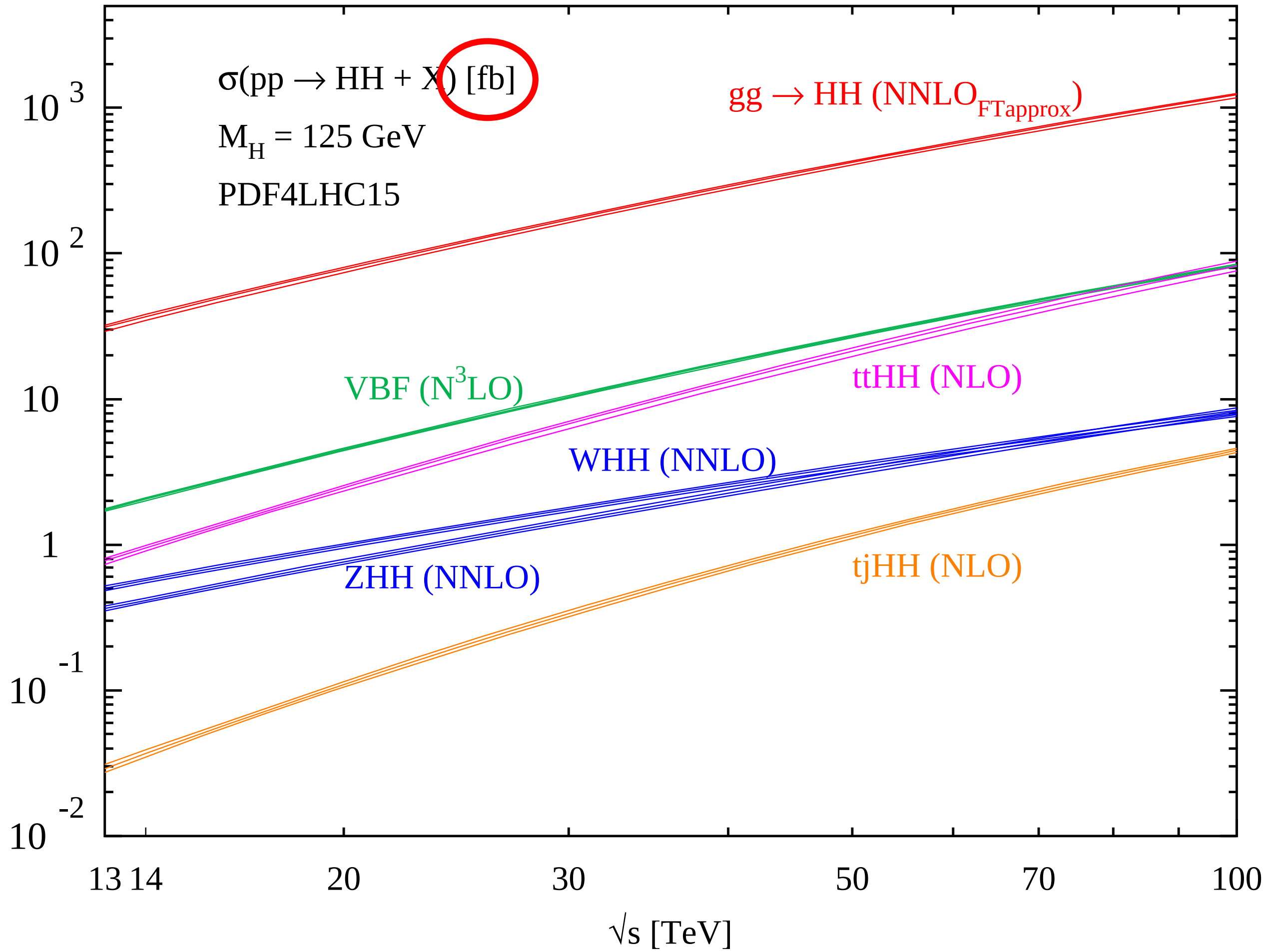
taken from arXiv:1610.07922 [hep-ph]

Production cross sections: HH + X



taken from arXiv:1910.00012 [hep-ph]

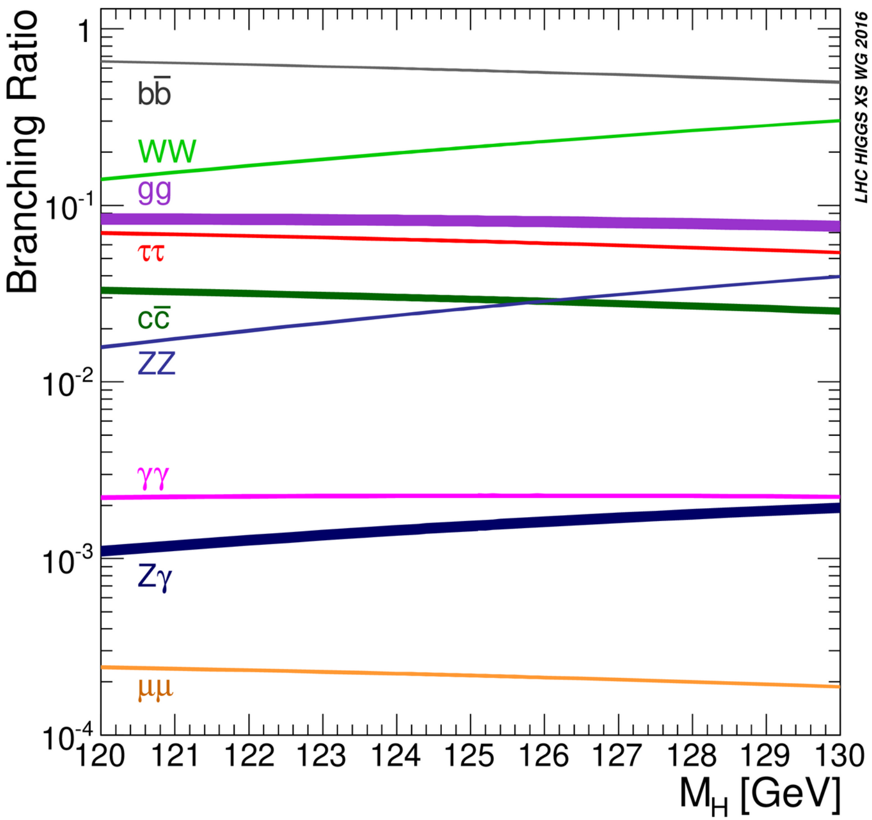
Production cross sections: HH + X



$$\sigma_{gg\to HH+X}\,(13\mathrm{TeV}) \approx 31\mathrm{fb}$$

Branching ratios

Single Higgs



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Branching ratios

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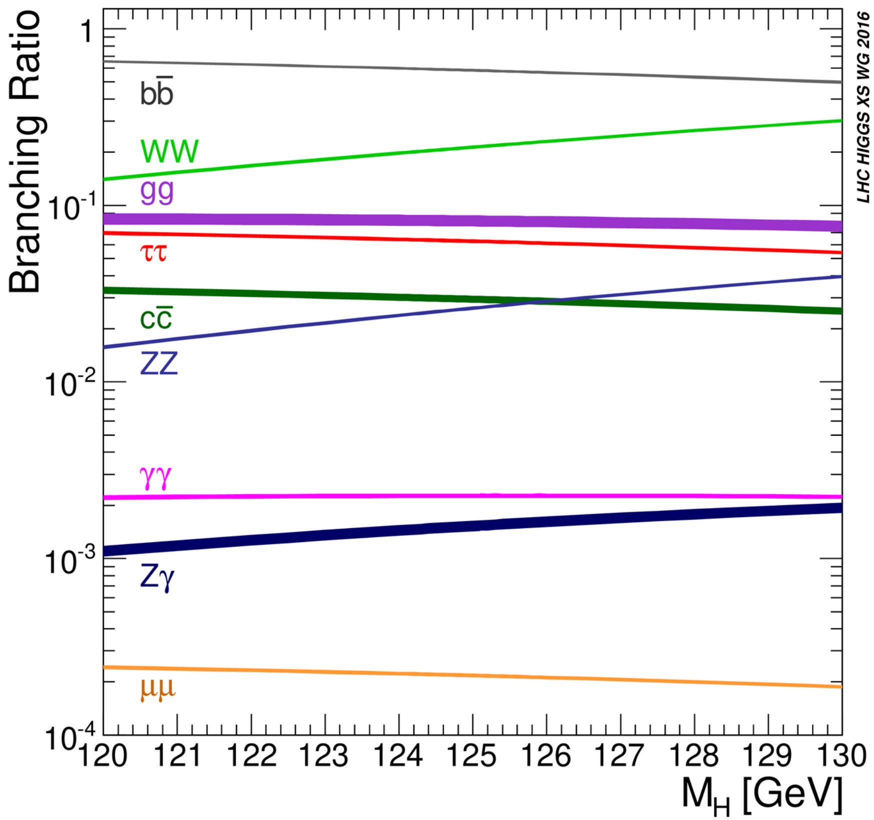

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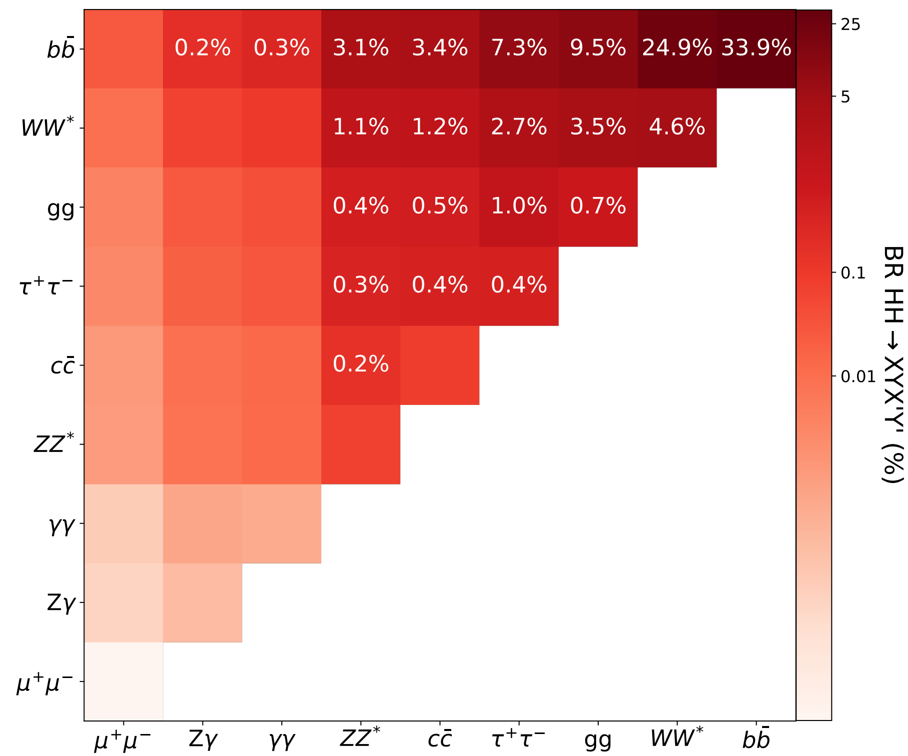
Di-Higgs



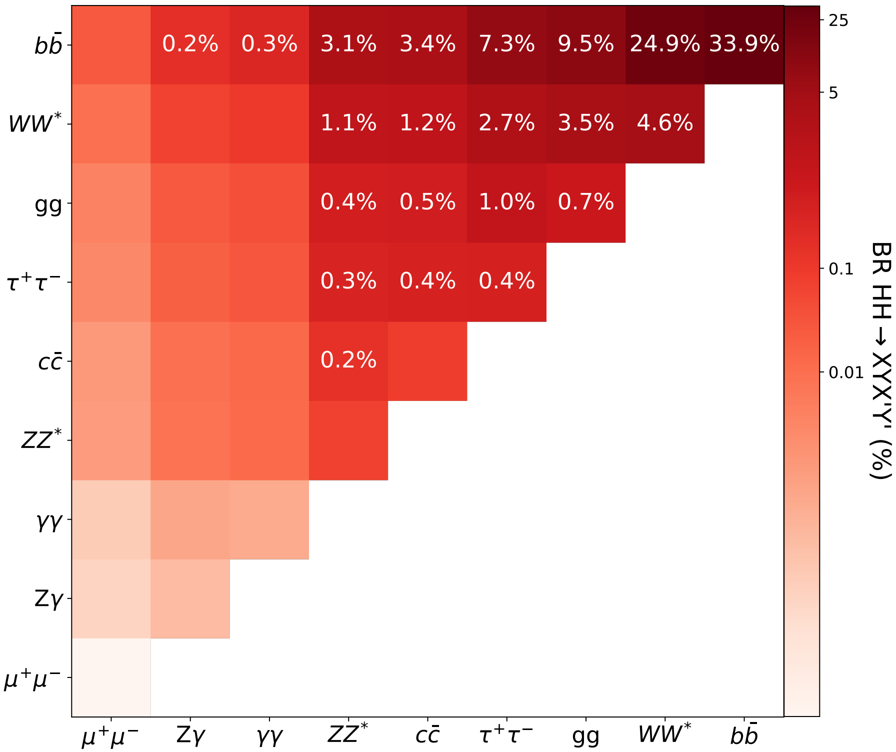
taken from arXiv:1910.00012 [hep-ph]

Branching ratios

ATLAS and CMS searched in 36 fb^{-1}:

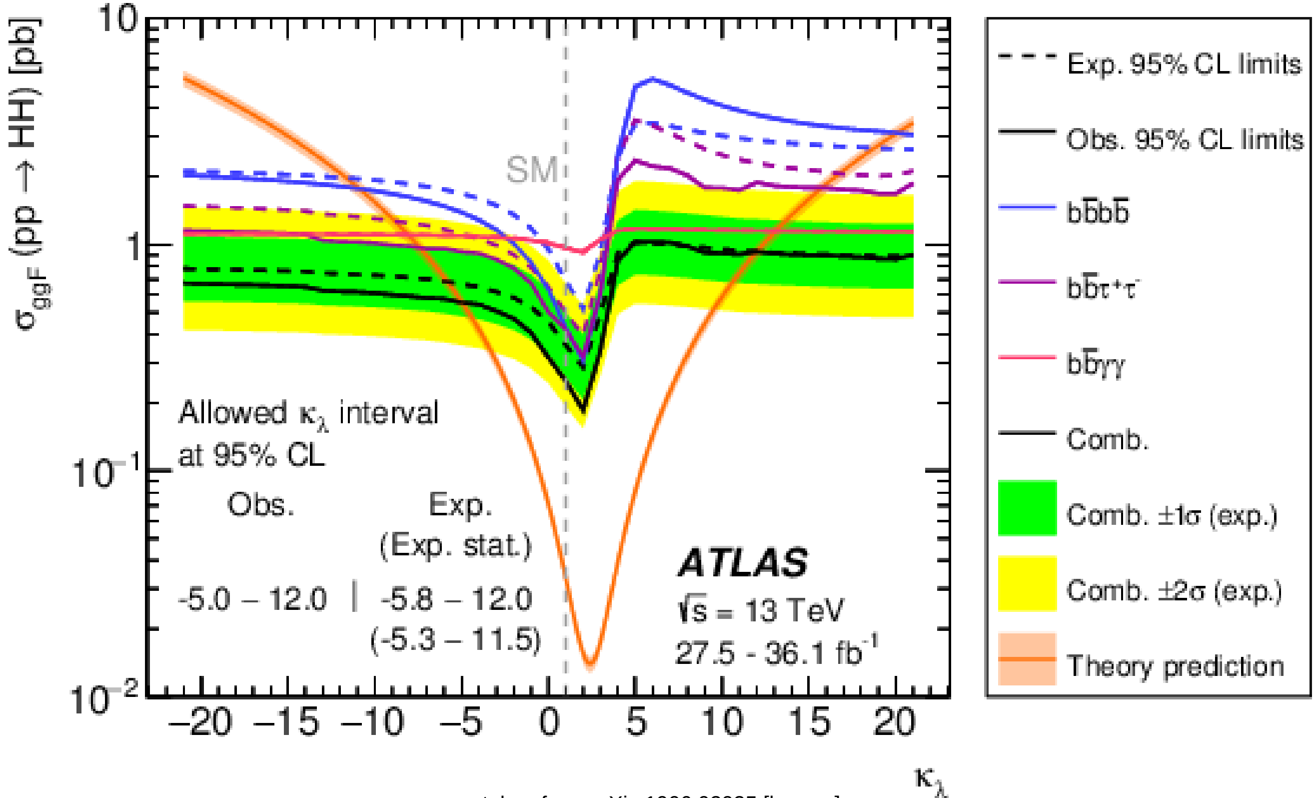
$\rightarrow b\bar{b}b\bar{b}$ ~370
$\rightarrow b\bar{b}\tau^+\tau^-$ ~80
$\rightarrow b\bar{b}\gamma\gamma$ ~3
$\rightarrow b\bar{b}VV^*$ ~310
$\rightarrow \gamma\gamma WW^*$ ~1
$\rightarrow WW^*WW^*$ ~50
$\rightarrow \tau^+\tau^-\tau^+\tau^-$ ~4

Di-Higgs



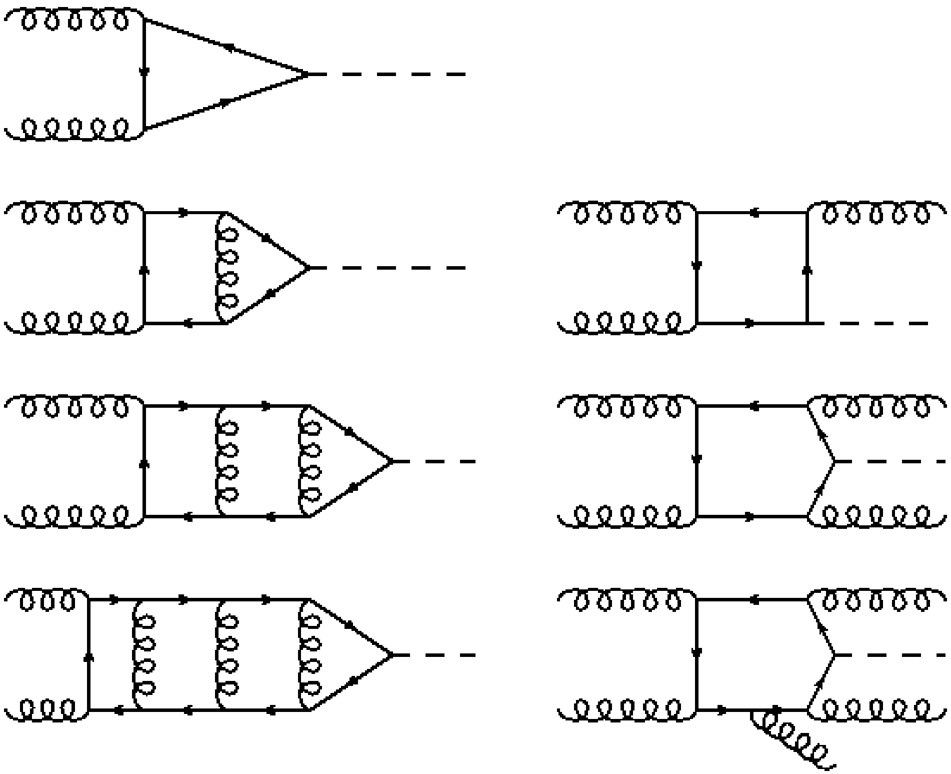
taken from arXiv:1910.00012 [hep-ph]

Experimental Status: HH + X



taken from arXiv:1906.02025 [hep-ex]

Theoretical Status: H + X



$\text{exact (analytical)}$

Georgi, Glashow, Machacek, Nanopoulos ‘78

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Djouadi, Spira, Zerwas ‘91; Dawson ‘91
Spira, Djouadi, Graudenz, Zerwas ‘95

$$s/m_t^2 \ll 1$$

Harlander, Kilgore ‘02; Anastasiou, Melnikov ‘02;
Ravindran, Smith, van Nerven ‘03; Harlander, Ozeren ‘09;
Pak, Rogal, Steinhauser ‘09

$$m_t \to \infty$$

Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog,
Lazopoulos, Mistlberger ‘16; Mistlberger ‘18

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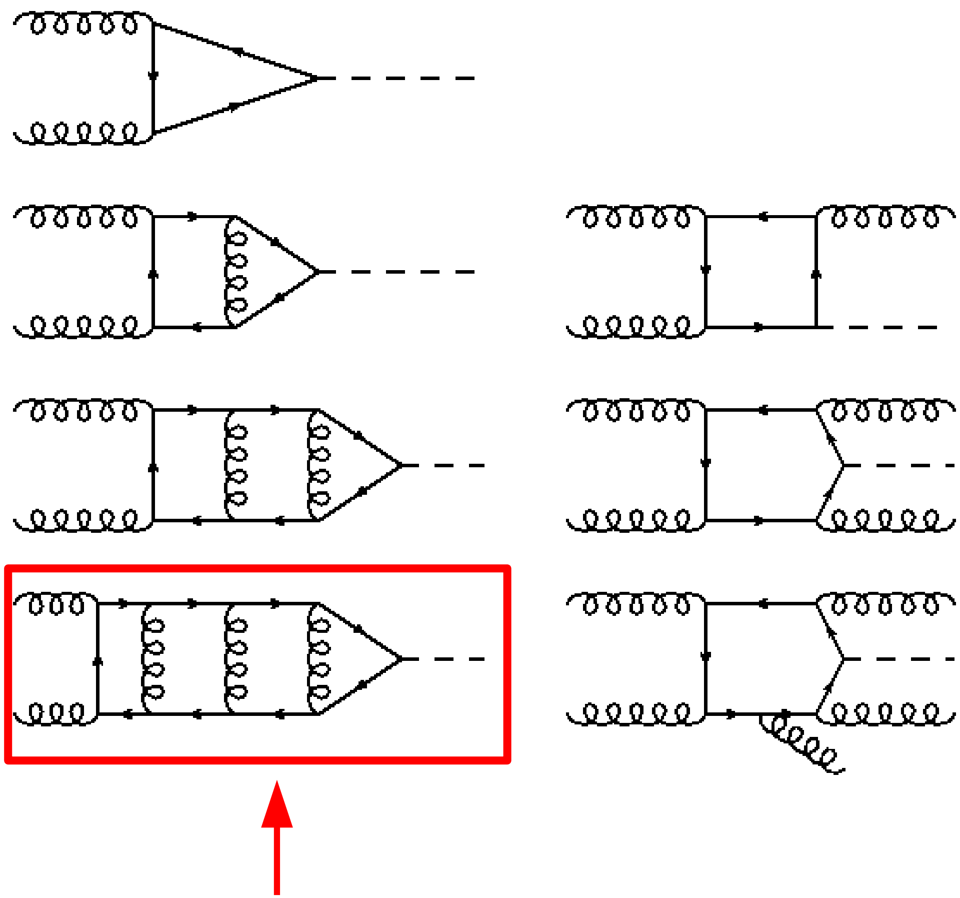

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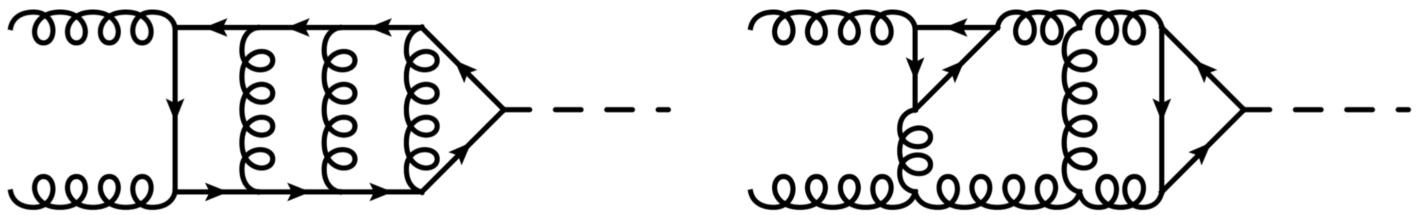
Computation of top mass corrections

Davies, FH, Steinhauser ‘19

Top Quark mass effects in Higgs production

N³LO corrections to inclusive Higgs Boson production only known in the approximation of an infinitely heavy top quark

→ Take into account finite top quark mass, start with virtual corrections



→ Need to evaluate 4-loop 3-point functions with an internal mass, this only recently was accomplished numerically at 3 loops

Davies, Gröber, Maier, Rauh, Steinhauser '19;
Czakon, Niggetiedt '20

Method: Large mass expansion

Exploit the fact that our problem only depends on 2 scales: m_t and $s = m_h^2$

→ $\mathcal{A}\left(m_t, m_h\right) \propto \tilde{\mathcal{A}}\left(\rho\right)$ with $\rho = \frac{m_h^2}{m_t^2} \approx 0.5$

→ Expand in small parameter

Take for example

$$F\left(a\right) = \int_0^\infty \frac{\mathrm{d}x}{\left(x+a+1\right)^2} = \frac{1}{1+a} \approx 1 - a + a^2 + \mathcal{O}\left(a^3\right)$$

We can expand before integration

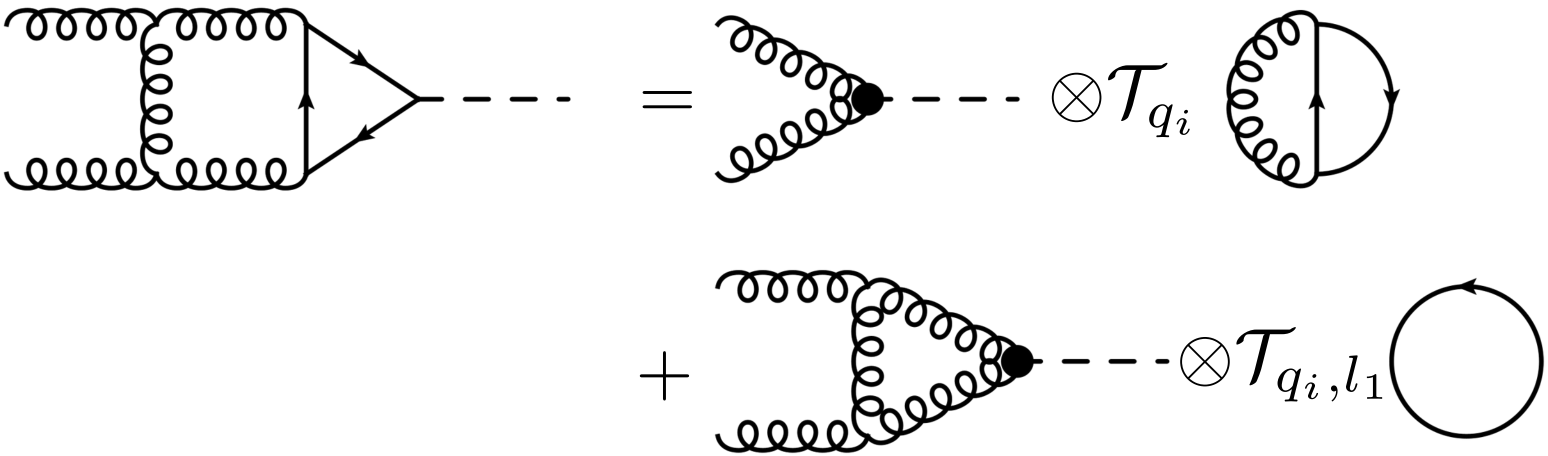
$$F\left(a\right) \approx \int_0^\infty \frac{\mathrm{d}x}{\left(x+1\right)^2} - 2a\int_0^\infty \frac{\mathrm{d}x}{\left(x+1\right)^3} + 3a^2\int_0^\infty \frac{\mathrm{d}x}{\left(x+1\right)^4} + \mathcal{O}\left(a^3\right) = 1 - a + a^2 + \mathcal{O}\left(a^3\right)$$

→ We trade a single, complicated integral for multiple simpler ones

Method: Large mass expansion

In reality we are dealing with asymptotic series: $F(a) = \sum_{i,j} c_{i,j} a^i \ln^j(a)$

For the case of a large internal mass and small external momenta we can employ the method of expansion by subgraph:



2-loop, two scale $\longrightarrow$ 2-loop tadpole $+$ 1-loop form factor and 1-loop tadpole

$\longrightarrow$ Systematic expansion in large top quark mass

Top Quark mass effects in Higgs production

Karlsruhe Institute of Technology

At 4-loop order we have to evaluate 3-loop form factor integrals and 4-loop tadpoles instead of more complicated 4-loop 3-point functions

→ Expanded up to ρ^2

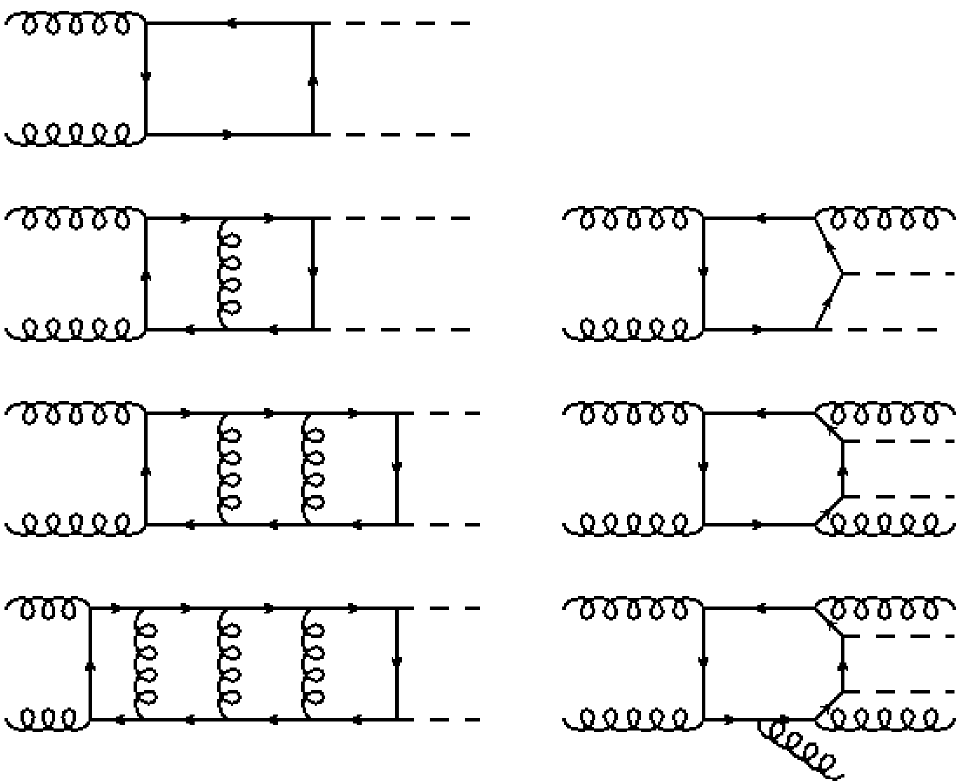
→ Finite part of gluon-Higgs amplitude recieves
10% correction at $\mathcal{O}\left(\rho^1\right)$
another 1% correction at $\mathcal{O}\left(\rho^2\right)$

→ Computationally very challenging:
> 40 million 4-loop tadpole integrals
> 1 million 3-loop form factor integrals

→ First building block including top quark mass effects at N^3LO

→ Read more in: arXiv:1911.10214

Theoretical Status: HH + X



exact

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exact (numerical)

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke ‘16; Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher ‘18; Davies, Heinrich Jones, Kerner, Mishima, Steinhauser, Wellmann ‘19

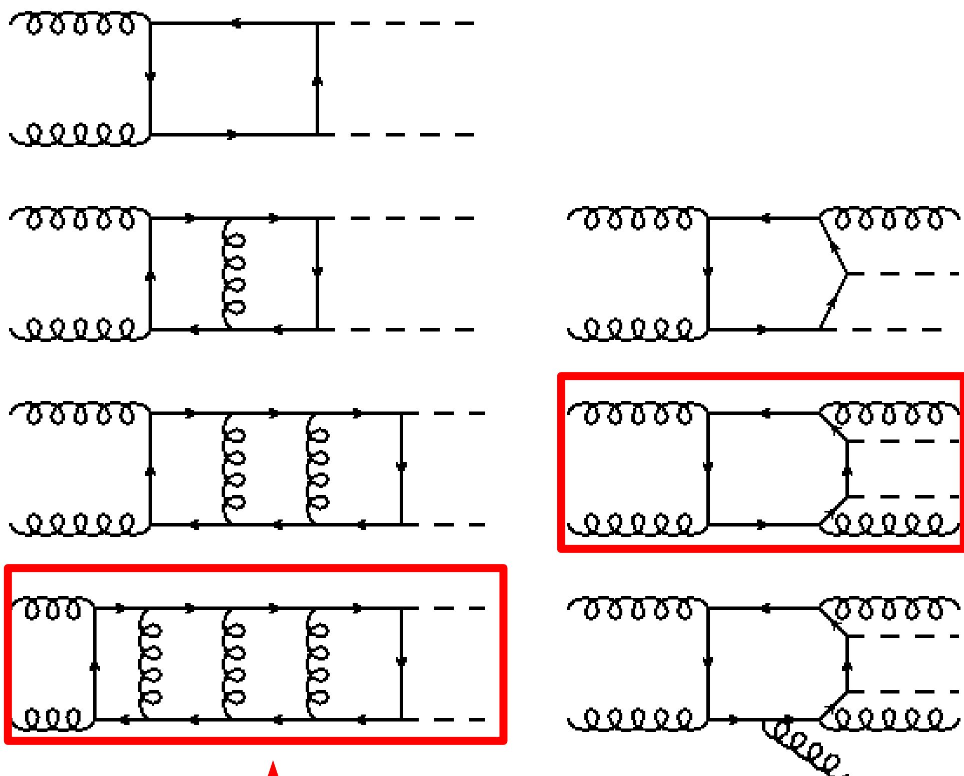
partial $\mathrm{s}/\mathrm{m}_t^2 \ll 1$

De Florian, Mazzitelli ‘13; Grigo, Melnikov, Steinhauser ‘14; Grigo, Hoff, Steinhauser ‘14; Davies, Steinhauser ‘19; Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli ‘18

$\mathrm{m}_t \rightarrow \infty$

Chen, Li, Shao Wang ‘19 & ‘20

Theoretical Status: HH + X



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$$m_t \to \infty$$

Chen, Li, Shao Wang '19 & '20

Compute two-Higgs-gluon coupling

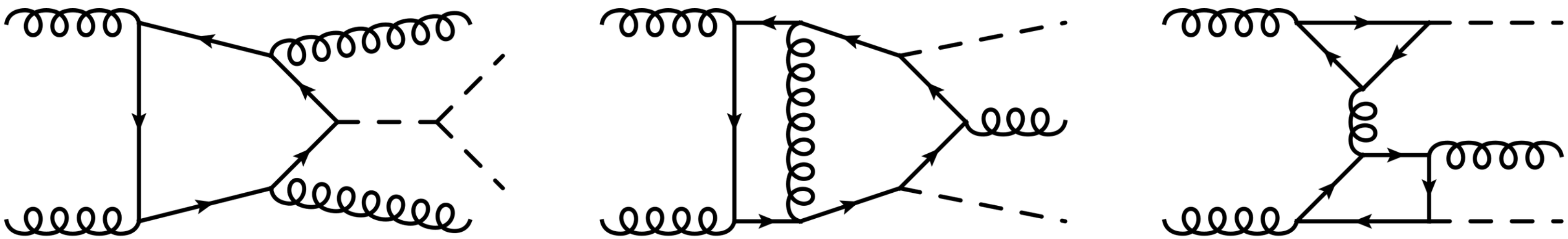
Spira '16; Gerlach, FH, Steinhauser '18

Compute top mass corrections to real and real-virtual contributions

Davies, FH, Mishima, Steinhauser '19 & WIP

Higgs boson pair production at NNLO

Our goal is to compute real emission corrections to the inclusive Higgs boson pair production cross-section at NNLO



We use the large mass expansion, but is it even valid?

$$2m_h = \sqrt{s}_{\mathrm{min}} > m_t$$

Due to the analytic structure of the integrals involved, we expect convergence for

$$2m_h = \sqrt{s}_{\mathrm{min}} \leq \sqrt{s} < 2m_t$$

→ Expansion good for low energies

Method: Differential equations

To obtain the total cross-section we need to integrate over the final state phase space after expanding in the top quark mass

- Use linear relations among phase space integrals to reduce them to a set of master integrals $\vec{I}\left(m_h^2/s,\epsilon\right)$
- Take derivative w.r.t to $x = m_h^2/s$ and use linear relations once more to obtain first-order ODE

$$\partial_x \vec{I} = M\left(x,\epsilon\right)\vec{I}$$

- Technically, the solution can be easily written down:

$$\vec{I}\left(x\right) = U\left(x,x_0\right)\vec{I}\left(x_0\right)$$
$$U\left(x,x_0\right) = \mathcal{T}e^{\int_{x_0}^{x}\mathrm{d}yM\left(y,\epsilon\right)} = 1 + \int_{x_0}^{x}\mathrm{d}yM\left(y,\epsilon\right) + \int_{x_0}^{x}\mathrm{d}y\int_{x_0}^{y}\mathrm{d}zM\left(y,\epsilon\right)M\left(z,\epsilon\right) + \ldots$$

Method: Differential equations

In practice this is not really helpful, unless we find a basis of integrals

$$\vec{J} = T^{-1}(x,\epsilon)\,\vec{I}$$

such that

$$T^{-1} M(x,\epsilon)\, T - T^{-1}\partial_x T = \epsilon \overline{M}(x) \longrightarrow \partial_x \vec{J} = \epsilon \overline{M}(x)\, \vec{J}$$

The evolution operator now takes the form

$$\overline{U}(x,x_0) = 1 + \epsilon \int_{x_0}^{x} \mathrm{d}y \overline{M}(y) + \epsilon^2 \int_{x_0}^{x} \mathrm{d}y \int_{x_0}^{y} \mathrm{d}z \overline{M}(y)\, \overline{M}(z) + \ldots.$$

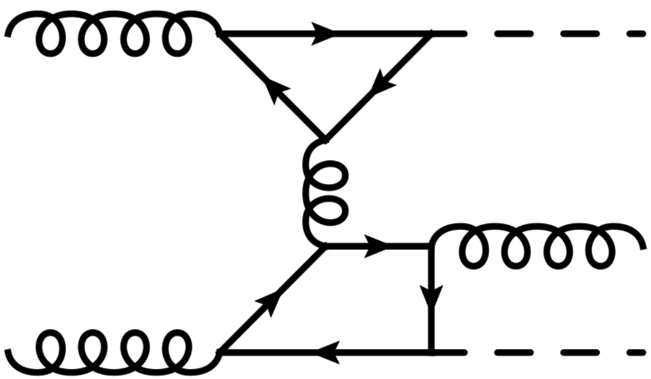
which can be computed order by order in ϵ

Finding this change of basis is highly non-trivial and sometimes not even possible

Higgs boson pair production at NNLO

We expand the total cross-section for large top quark mass
and compute all required phase space master integrals analytically

- → Expanded up to ρ^4
- → Master integrals computed exact in x, also appear in other pair production processes
- → Combine them with available virtual corrections
- → Subset already done: arXiv:1904.11998



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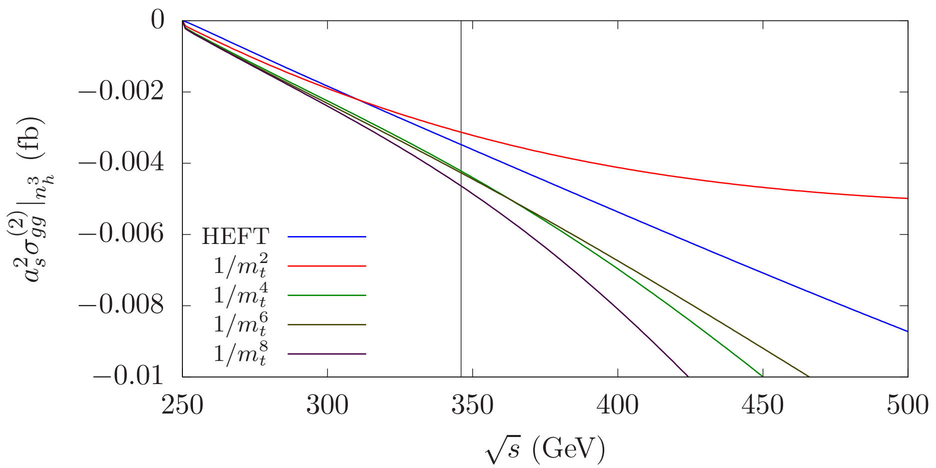


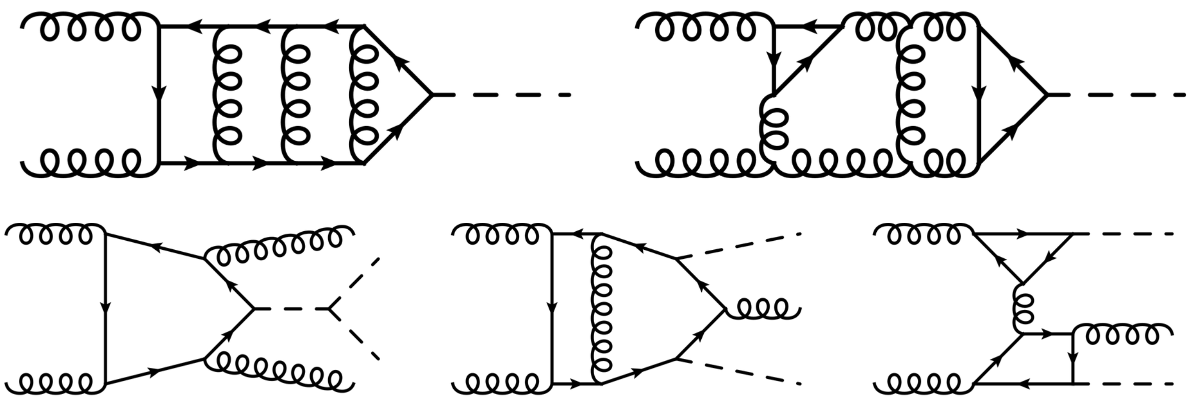
Summary

Hopefully I could convince you that,

- there is still a lot left to explore in the Higgs sector of the SM
- Higgs Boson pair production is particularly interesting
- to improve theoretical predictions approximations are necessary
- often rather simple concepts, like expanding in a small parameter or ODEs, are helpful

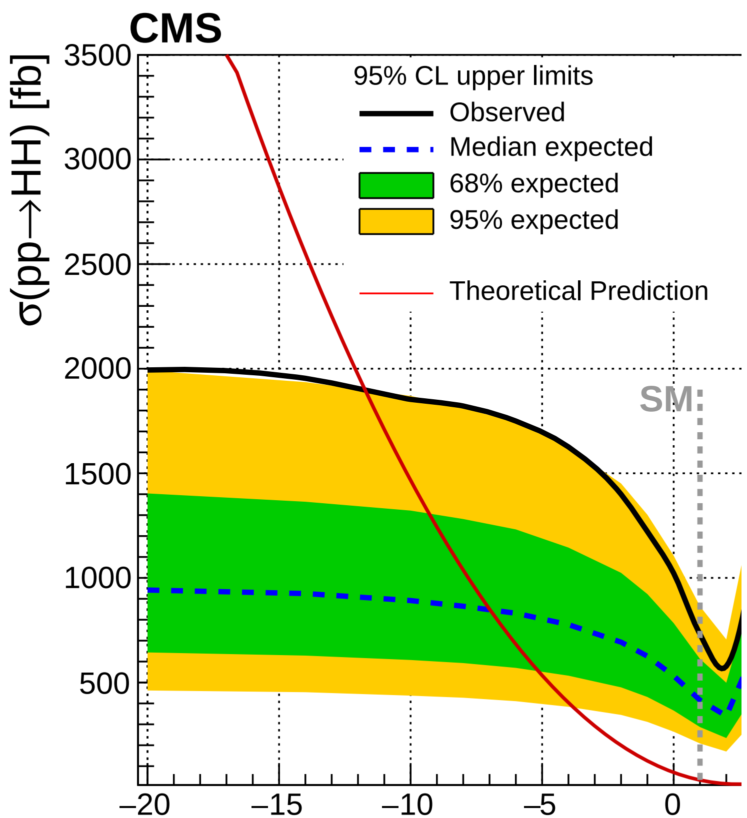
My work includes the computation of

- the effective di-Higgs-gluon coupling at four loops
- Top quark mass contributions to single Higgs production at N^3LO
- Top quark mass contributions to Higgs pair production at NNLO



Backup

Experimental Status: HH + X



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