Higgs Pair Production and Perturbative Corrections

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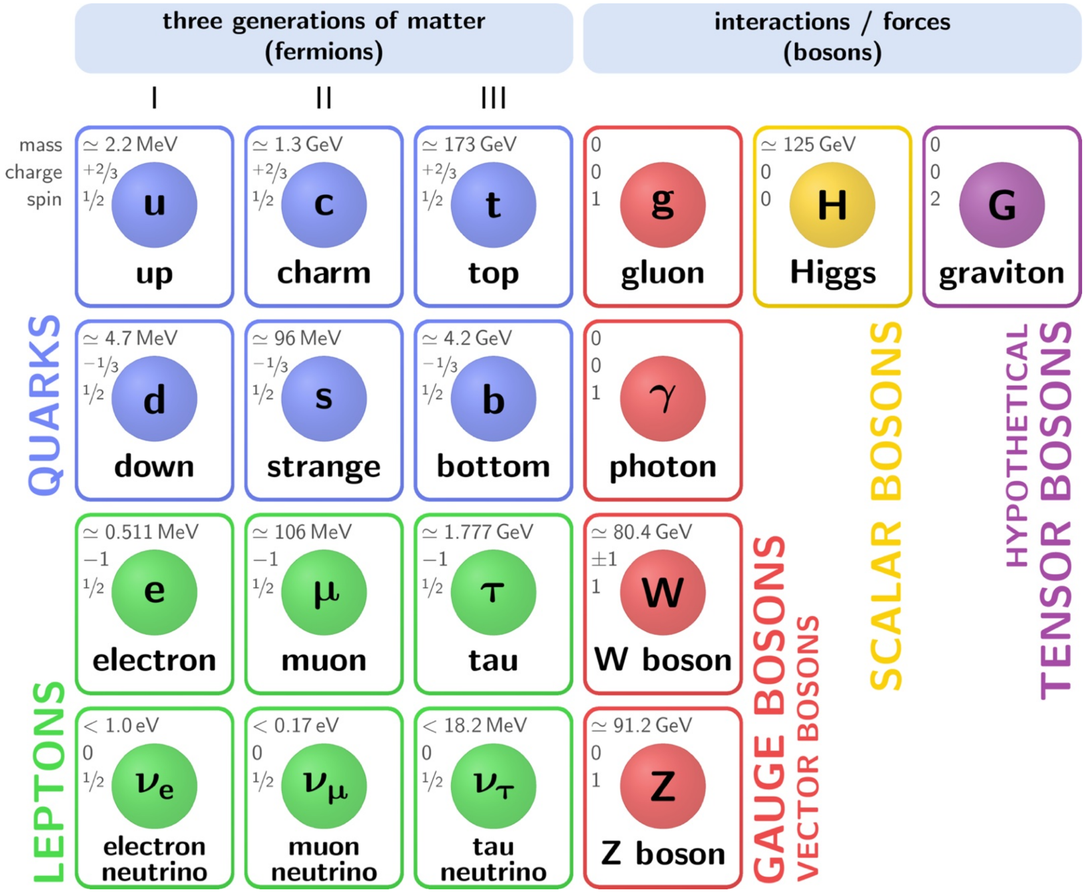
HTL, Si, Wang, Zhang, Zhao, CPC, arXiv:2407.14716
HTL, Si, Wang, Zhang, Zhao, JHEP, arXiv:2402.00401
Chen, HTL, Shao, Wang, JHEP, arXiv:1912.13001
Chen, HTL, Shao, Wang, PLB, arXiv:1909.06808

KIAS-IBS-CKC Joint Workshop on Particle, String and Cosmology
High1 Resort, Jan. 17 2025

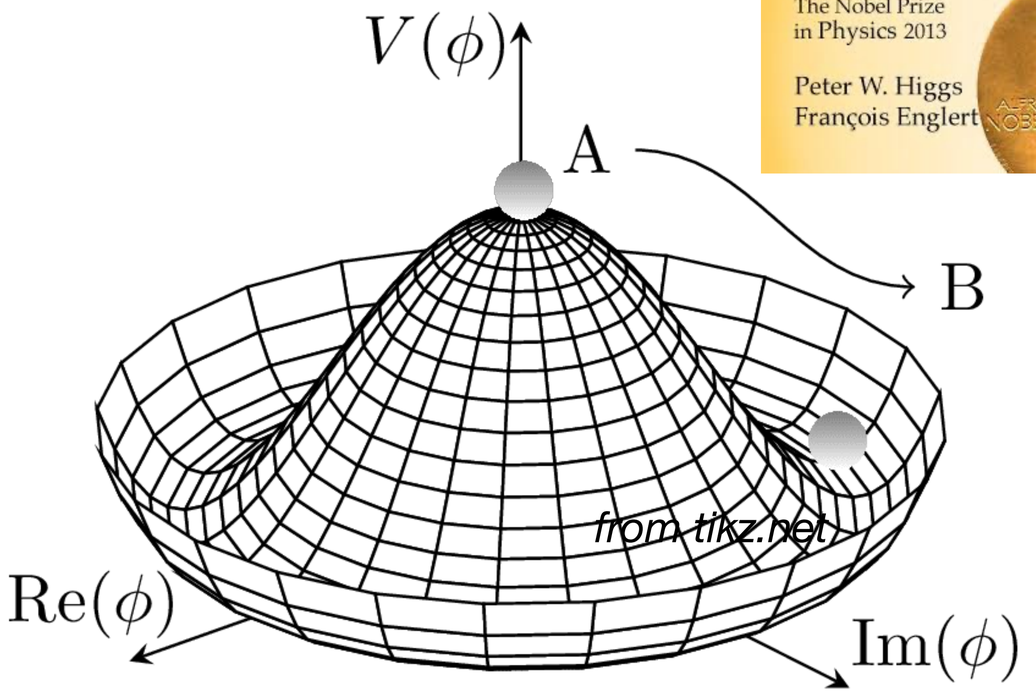
Outline

- Introduction
- QCD corrections to HH production
- EW corrections to HH production
- Conclusion

Introduction



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



Introduction

Measurements are crucial for refining our understanding of Higgs mechanism

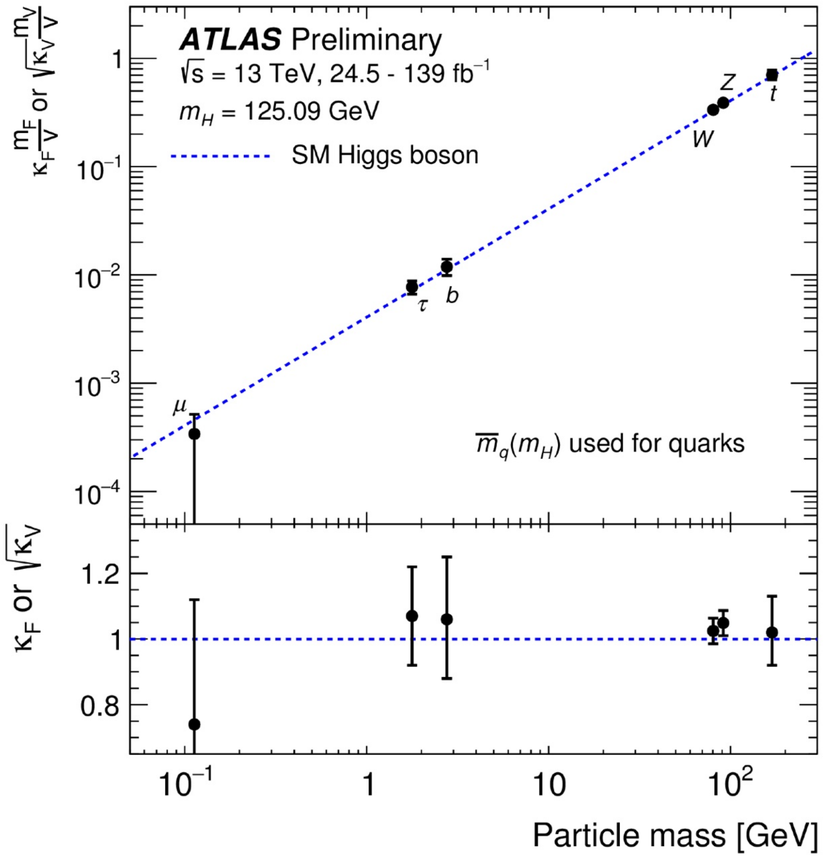
Higgs Boson properties

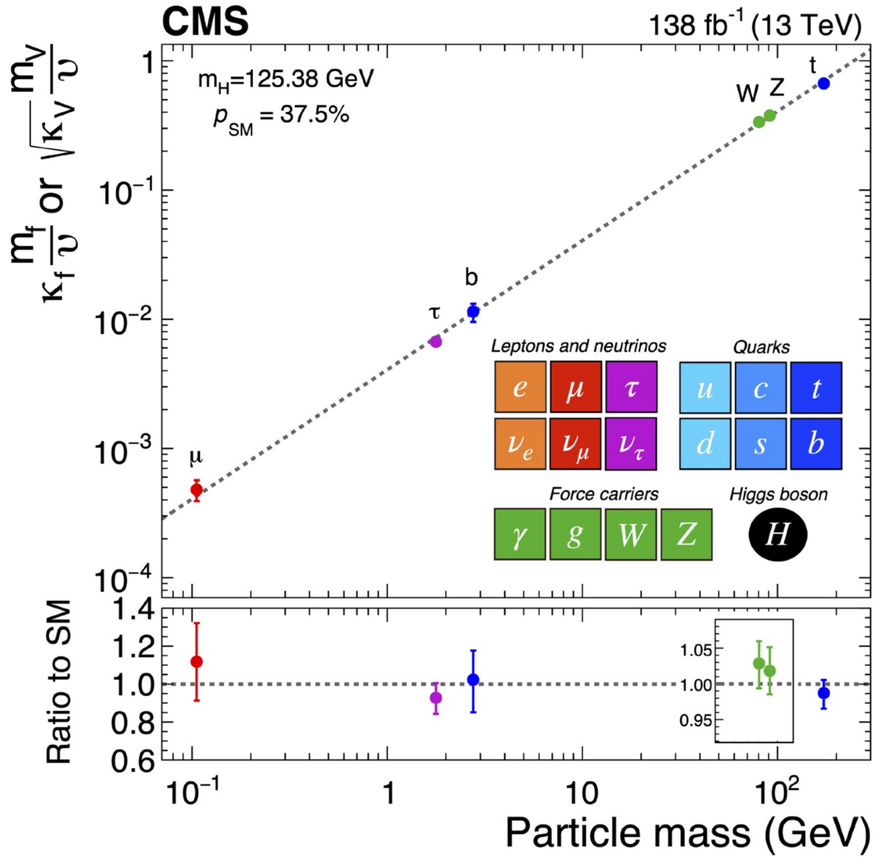
ATLAS, Run1+Run2

$m_H = 125.22 \pm 0.14\mathrm{GeV}$

$\Gamma_H = 4.5^{+3.3}_{-2.5}\mathrm{MeV}$

CP even





Introduction

Higgs self-coupling is a crucial parameter for Higgs potential and electroweak symmetry

$$V(H) = -\mu^2 H^\dagger H + \lambda^{\mathrm{SM}} \left(H^\dagger H\right)^2 \qquad \lambda_{\mathrm{SM}} = \frac{m_h^2}{2v^2}$$

Shape of the potential connected to the phase transition of the early universe from the unbroken to the broken electroweak symmetry

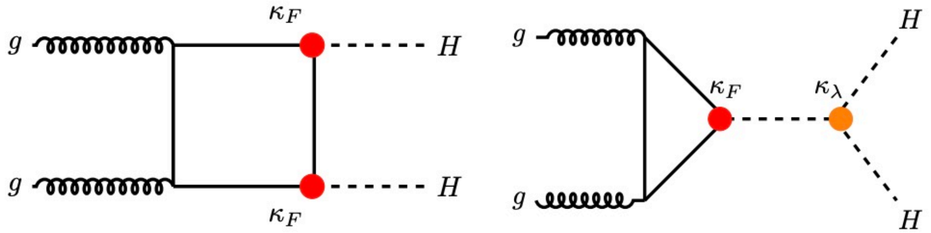
A deviation of the potential from the SM would directly point to new physics

- **with additional scalar particles (SUSY, additional singlets, etc)**
- **whether the Higgs is composite**
- **with first-order electroweak phase transition**

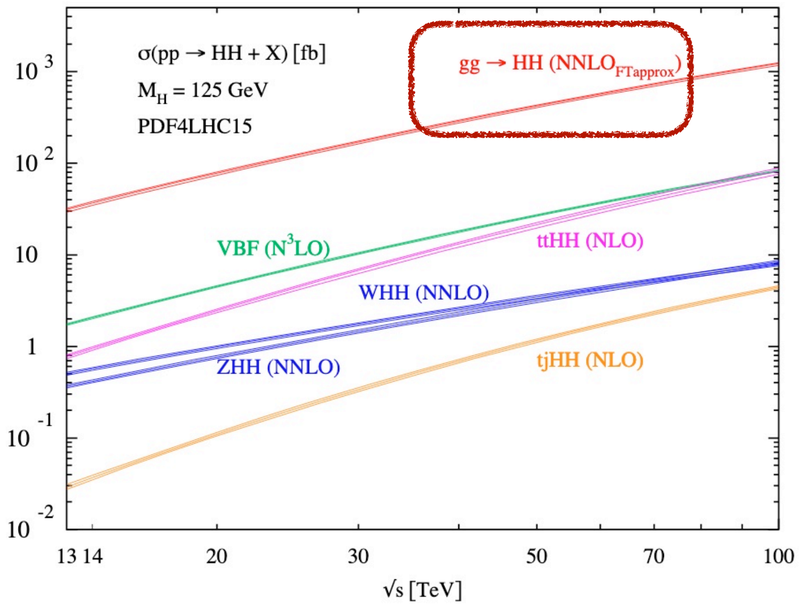
The precise measurement of the Higgs self-coupling is one of top priorities of the current and future high-energy collider experiments

Introduction

Higgs Self-coupling can be directly studied
via HH production processes



- **gluon fusion to Higgs pair**
  talk about this later
- **vector boson fusion to Higgs pair**
  the structure-function approach (NNNLO)
- **double Higgs strahlung process (VHH)**
  total and differential cross section (NNLO)
- **associated production of Higgs pair with top quark pair**
  NLO



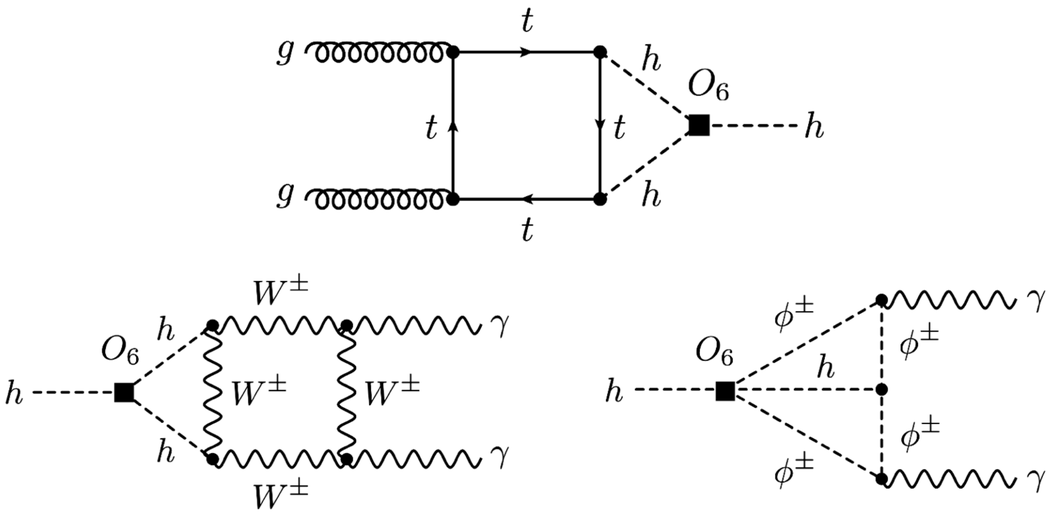
For VHH production at NNLO, see arXiv:1607.06382 and arXiv:1710.02464 by HTL, C.S.Li and J.Wang

Micco, Gouzevitch,Vernieri, Alison, arXiv:1910.00012

Introduction

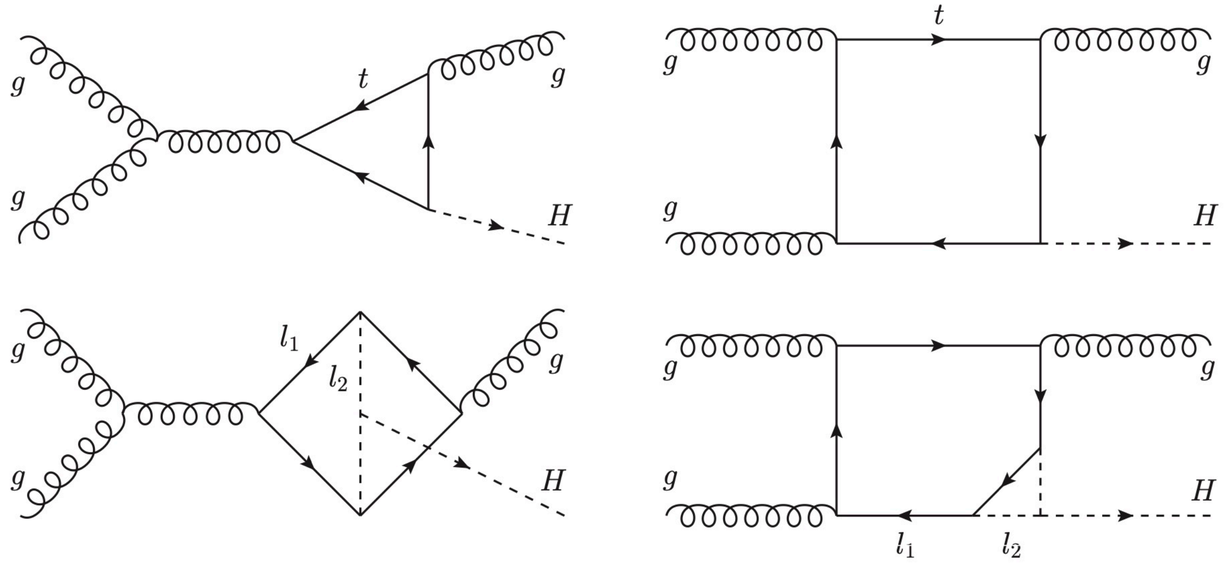
Higgs self-coupling can be measured indirectly (loop effects, HVV coupling, et al)

McCullough, arXiv:1312.3322
Gorbahn ,Haisch, arXiv:1607.03773
Degrassi, Giardino, Maltoni, Pagani, arXiv:1607.04251
Huang, Long, Wang, arXiv:1608.06619
Bizon, Gorbahn, Haisch, Zanderighi, arXiv:1610.05771
Gao, Shen, Wang, Yang, Zhou, arXiv:2302.04160



Single Higgs production and decay

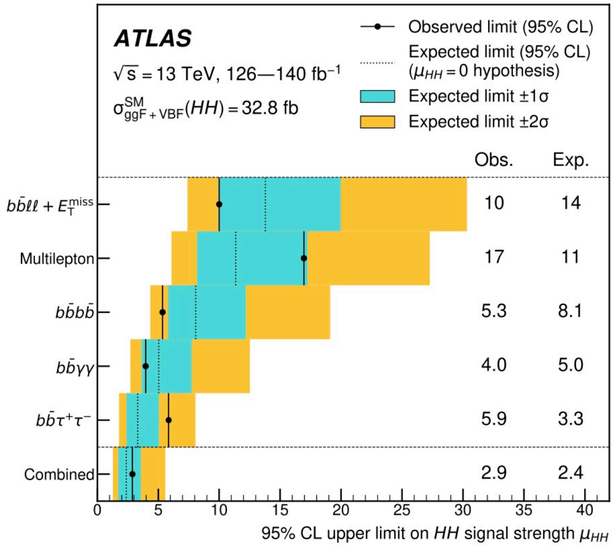
arXiv:1607.04251

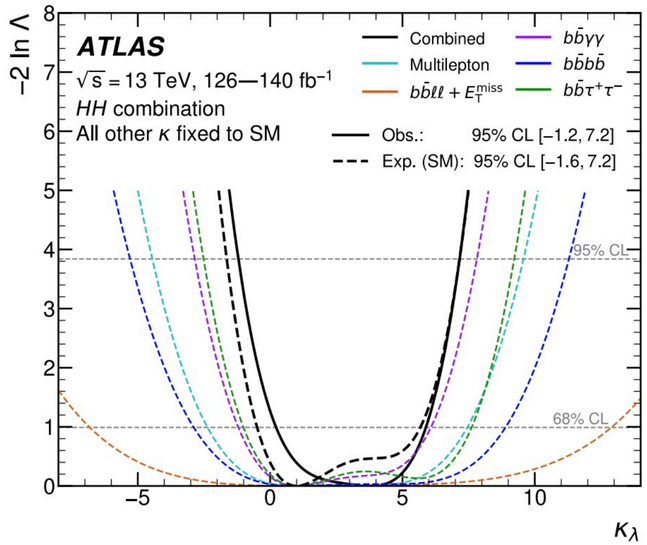


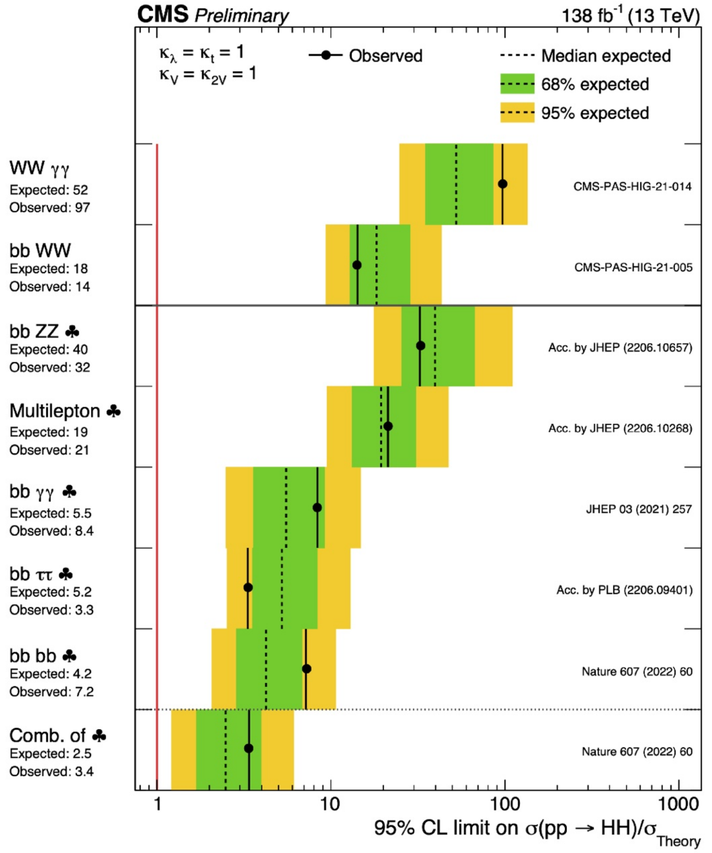
H+jet production *arXiv:2302.04160*

Introduction

At the LHC







explored in the ggF and VBF HH production processes.

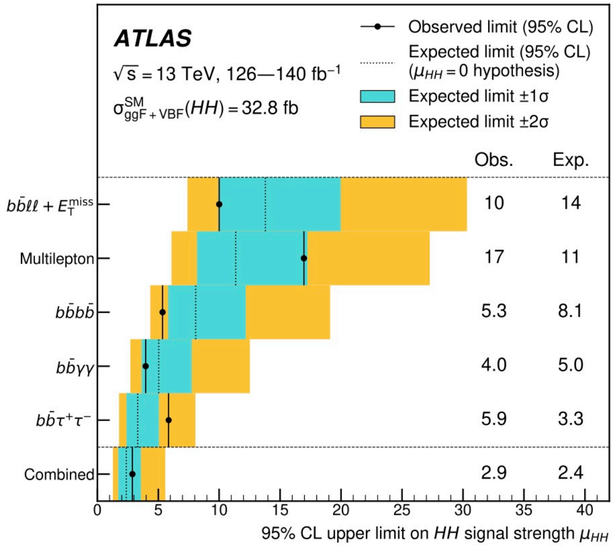
ATLAS, arXiv: 2406.09971

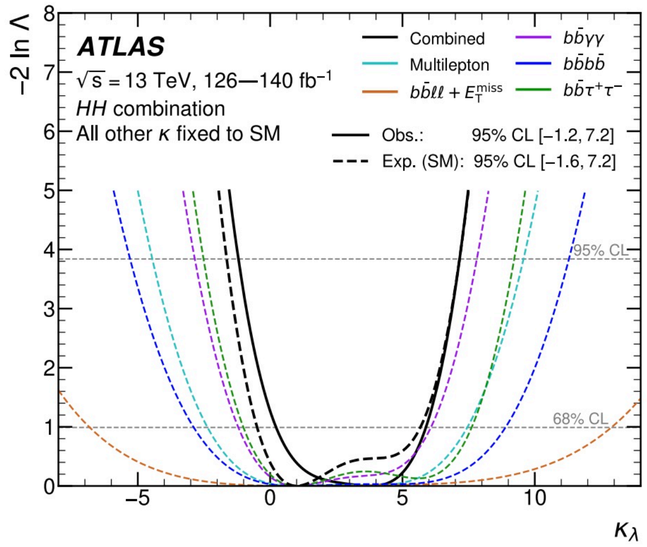
combination of single and double Higgs boson production

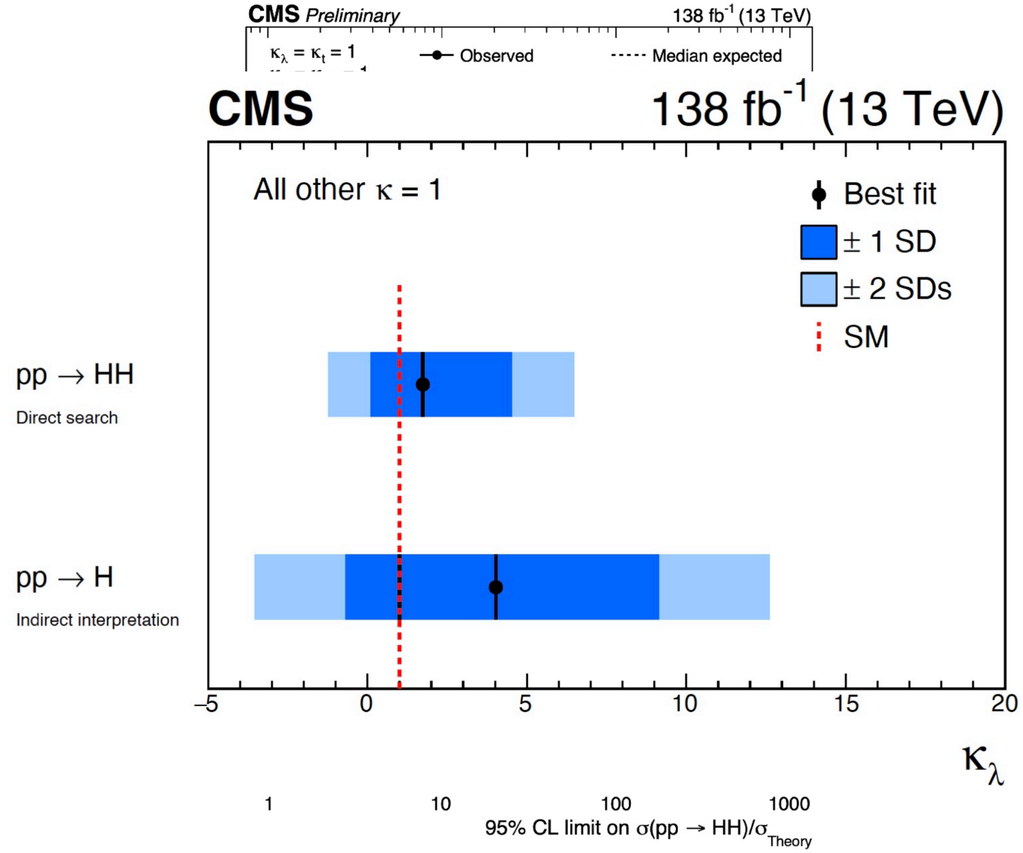
CMS, arXiv: 2407.13554

Introduction

At the LHC







explored in the ggF and VBF HH production processes.

ATLAS, arXiv: 2406.09971

combination of single and double Higgs boson production

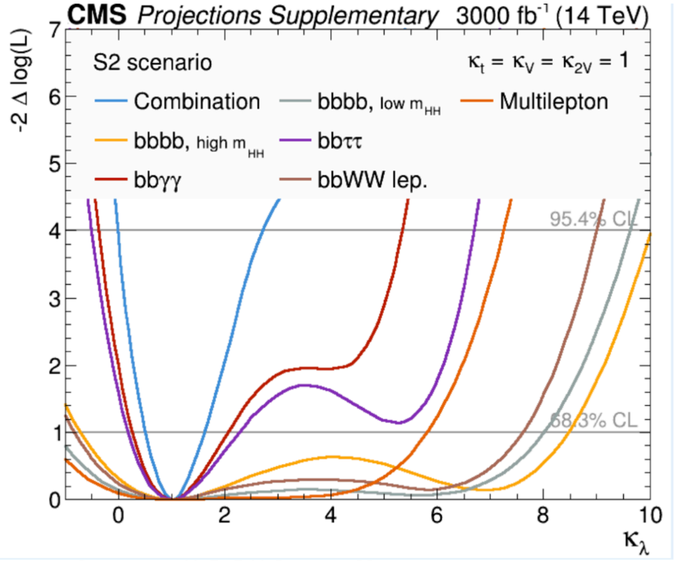
CMS, arXiv: 2407.13554

Introduction

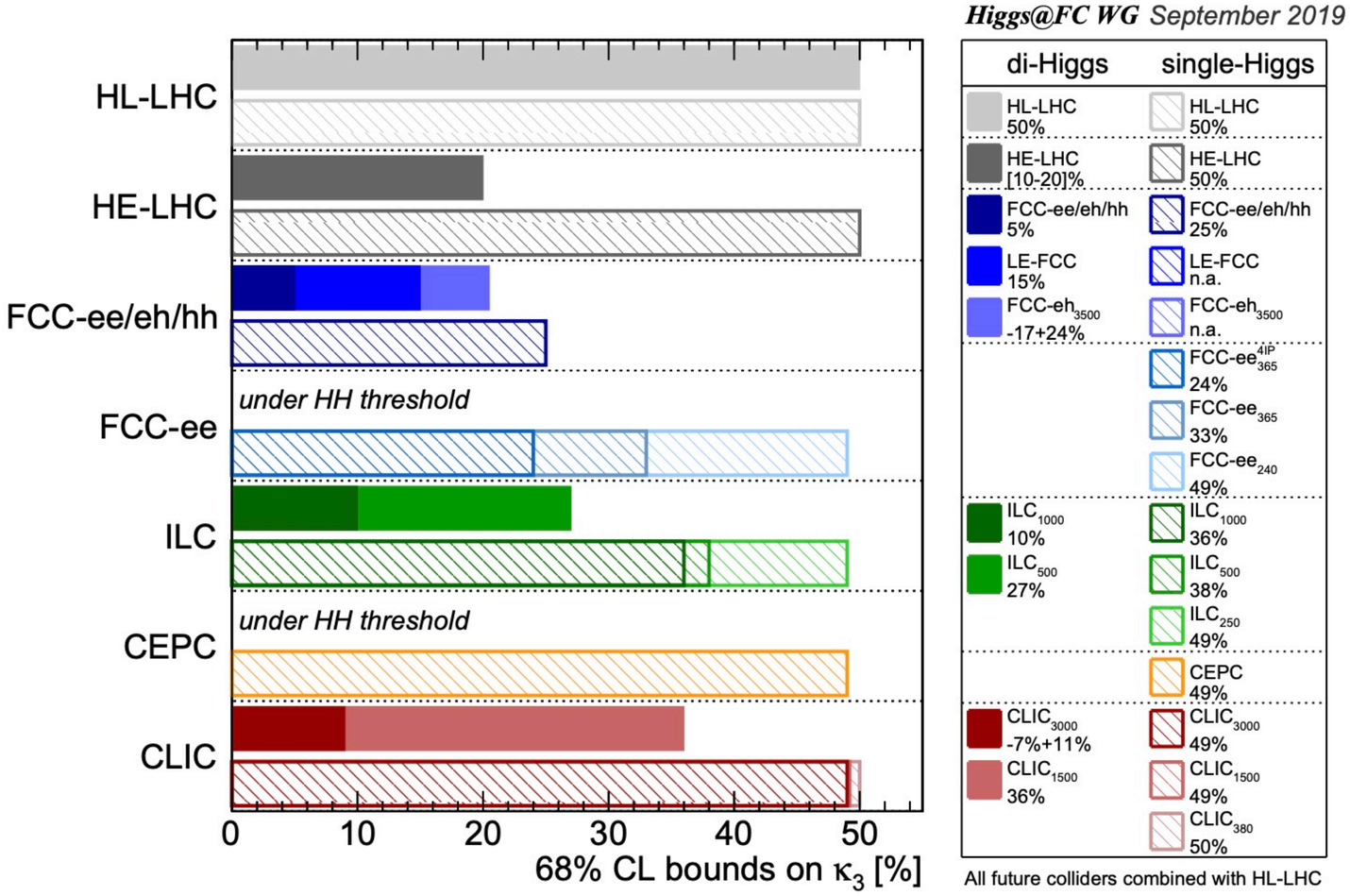
At future colliders

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.1, 2.6]	[-0.5, 6.4]
Baseline	[-0.5, 6.1]	[-1.6, 7.5]
Theoretical unc. halved	[-1.2, 6.9]	[-2.6, 8.5]
Run 2 syst. unc.	[-1.2, 6.9]	[-2.8, 8.5]

ATL-PHYS-PUB-2022-053



from CMS's talk



arXiv:1905.03764

Perturbative corrections

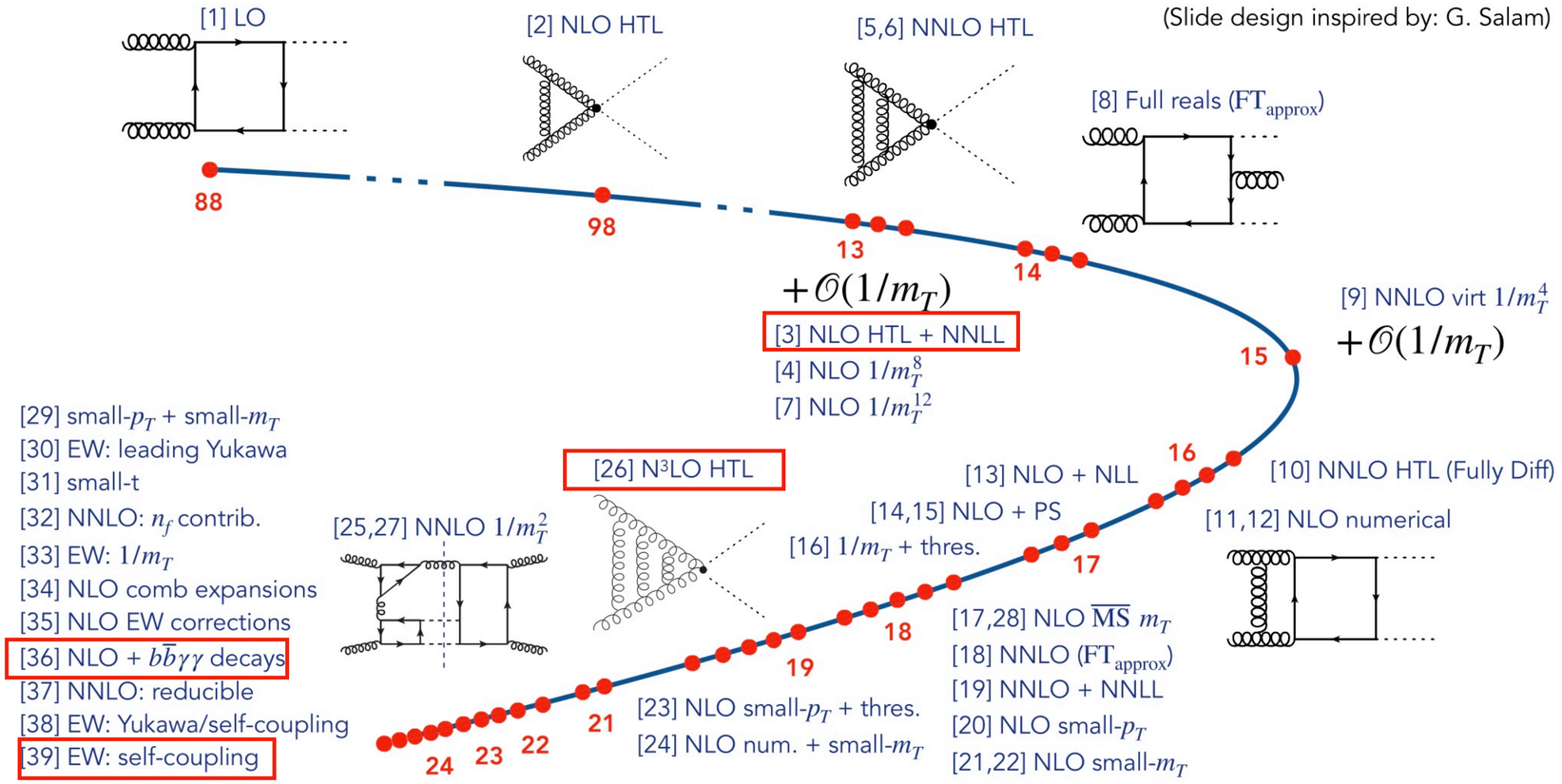
gg2HH

Process	Theory	σ_{th} [pb]	δ_{th} [%]	δ_{PDF} [%]	δ_{α_s} [%]	Run 2 $\delta_{\mu}^{\text{tot}}$ [%]	HL-LHC $\delta_{\mu}^{\text{tot}}$ (δ_{μ}^{th}) [%]
$ggF\ HH$	$\text{N}^3\text{LO}_{\text{HTL}}$ NLO_{QCD}	0.03105	$^{+2.2}_{-5.0}$	± 2.1	± 2.1	$-1.0 < \lambda/\lambda_{\text{SM}} < 6.6$	$0.5 < \lambda/\lambda_{\text{SM}} < 1.5$

Jones, LHEP 2023 (2023) 442

Perturbative corrections

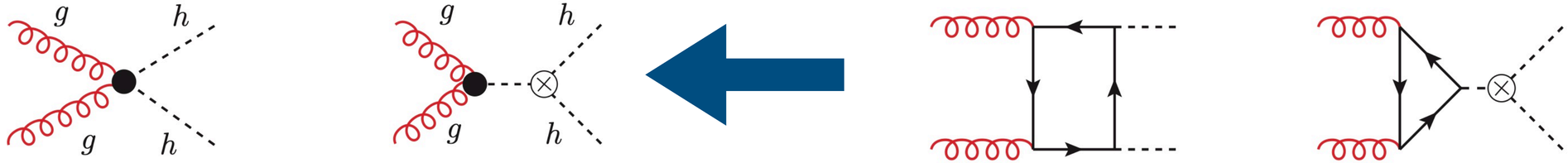
gg2HH

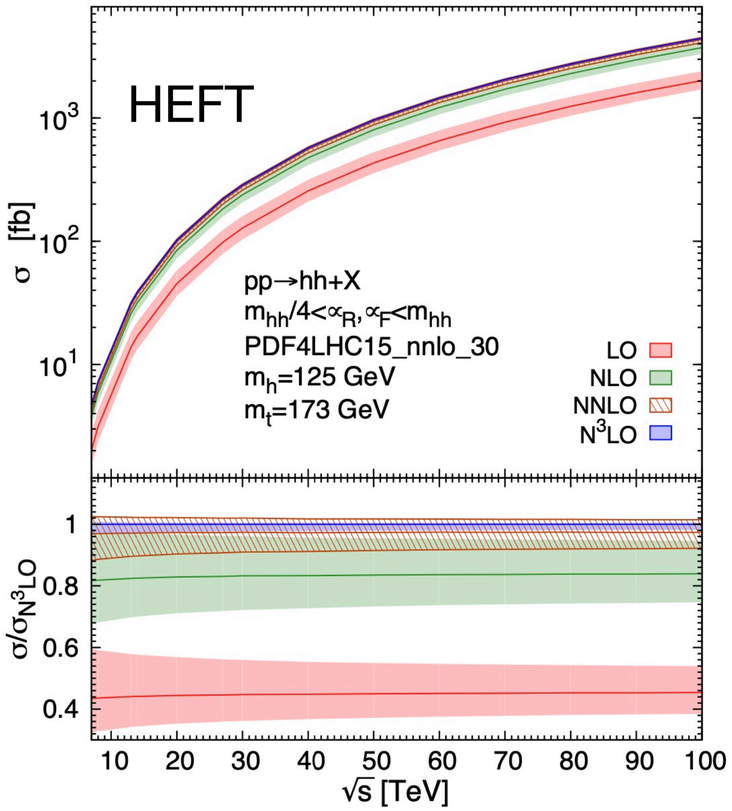


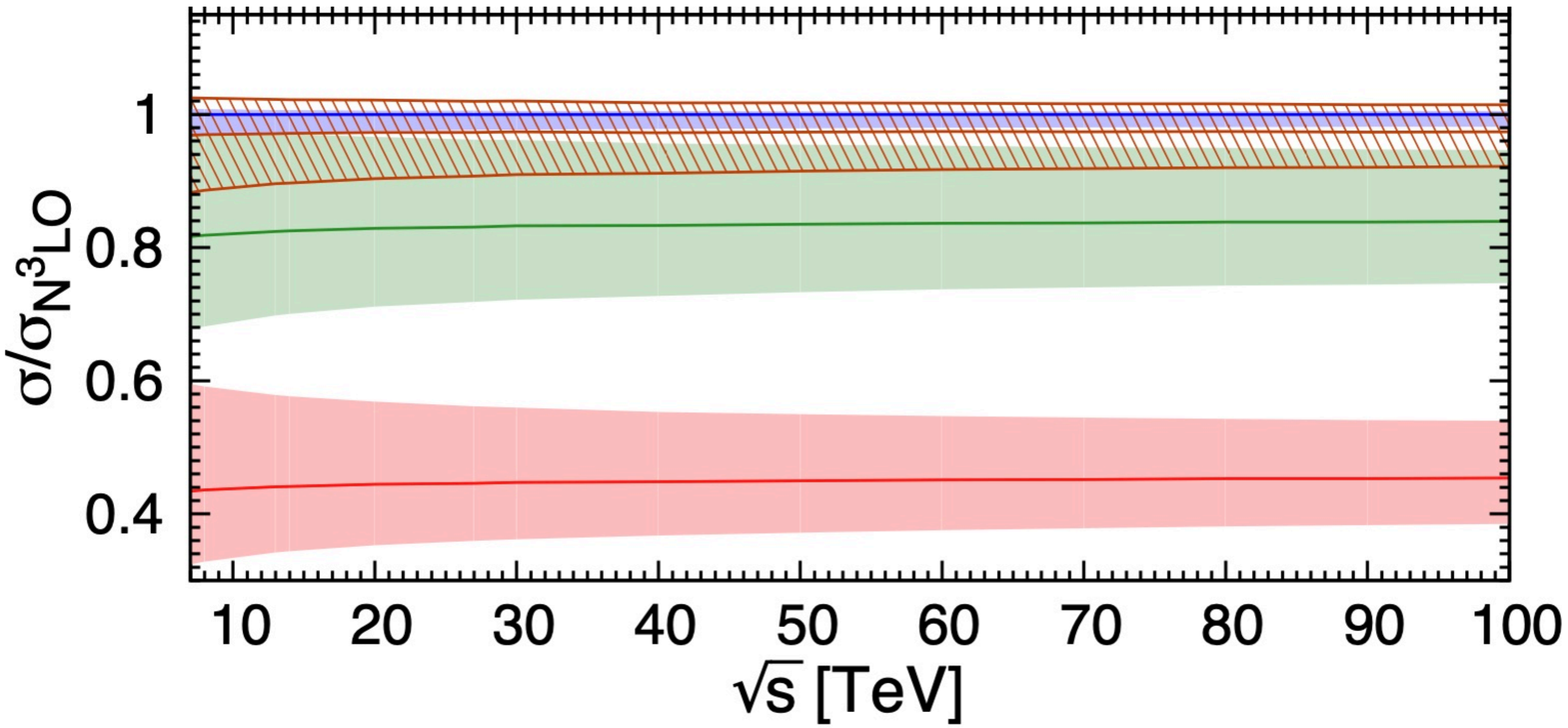
[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Davies, Mishima, Schönwald, Steinhauser 23; [32] Davies, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser, Zhang 23; [34] Bagnaschi, Degrassi, Gröber 23; [35] Bi, Huang, Huang, Ma Yu 23; [36] Li, Si, Wang, Zhang, Zhao 24; [37] Davies, Schönwald, Steinhauser, Vitti 24; [38] Heinrich, SPJ, Kerner, Stone, Vestner; [39] Li, Si, Wang, Zhang, Zhao 24

taken from Spira's talk at Higgs 2024

QCD corrections

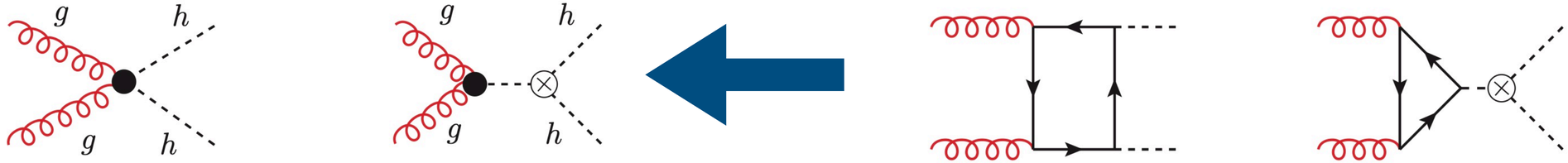


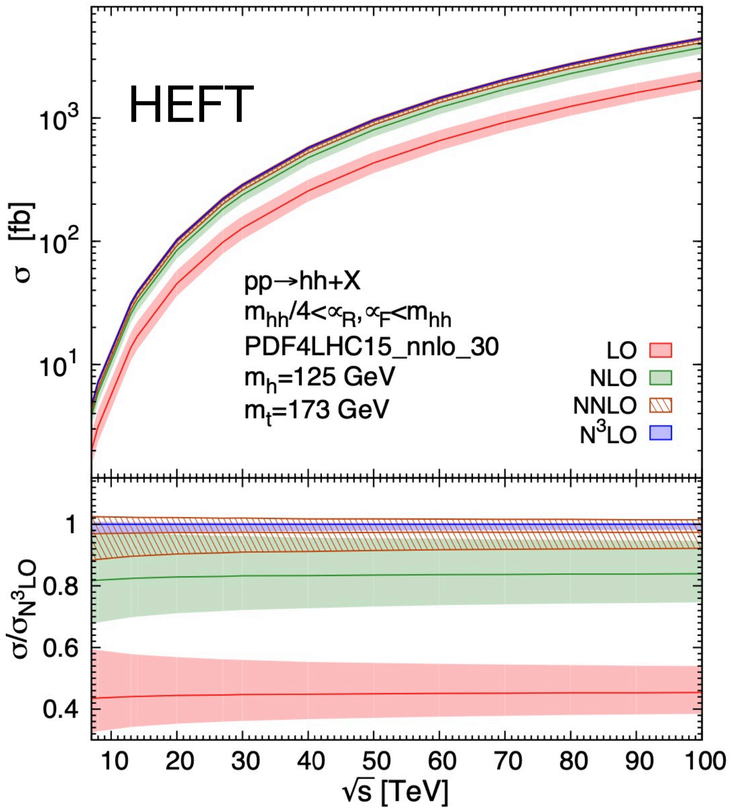




Chen, HTL, Shao, Wang, arXiv:1909.06808, arXiv:1912.13001

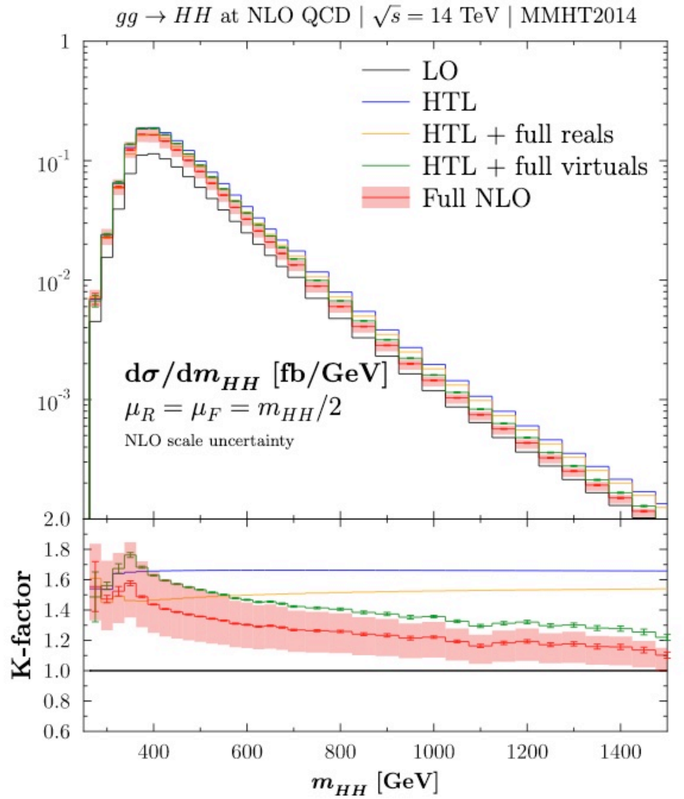
QCD corrections





Improving results by matching

- replace the EFT tree amplitude to one-loop ones in full theory
- reweight loop amplitudes with the ratio of tree ones



large top quark mass effects

Chen, HTL, Shao, Wang, arXiv:1909.06808, arXiv:1912.13001

QCD corrections

Schemes by reweighing the differential cross section

☑ $N^kLO \oplus N^lLO_{m_t}$: **add the difference**

$$d\sigma^{\mathrm{N^kLO}\oplus\mathrm{N^lLO_{m_t}}} = d\sigma^{\mathrm{N^lLO}}_{m_t} + \Delta\sigma^{k,l}_{m_t\to\infty}$$

☑ $N^kLO_{B-i} \oplus N^lLO_{m_t}$: **weighted by LO_{m_t} cross section**

$$d\sigma^{\mathrm{N^kLO_{B-i}}\oplus\mathrm{N^lLO_{m_t}}} = d\sigma^{\mathrm{N^lLO}}_{m_t} + \Delta\sigma^{k,l}_{m_t\to\infty}\frac{d\sigma^{\mathrm{LO}}_{m_t}}{d\sigma^{\mathrm{LO}}_{m_t\to\infty}}$$

☑ $N^kLO \otimes N^lLO_{m_t}$: **weighted by $N^lLO_{m_t}$ cross section**

$$d\sigma^{\mathrm{N^kLO}\otimes\mathrm{N^lLO_{m_t}}} = d\sigma^{\mathrm{N^lLO}}_{m_t}\frac{d\sigma^{\mathrm{N^kLO}}_{m_t\to\infty}}{d\sigma^{\mathrm{N^lLO}}_{m_t\to\infty}} = d\sigma^{\mathrm{N^lLO}}_{m_t} + \Delta\sigma^{k,l}_{m_t\to\infty}\frac{d\sigma^{\mathrm{N^lLO}}_{m_t}}{d\sigma^{\mathrm{N^lLO}}_{m_t\to\infty}}\,.$$

inclusive total cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO_{m_t}	$27.56^{+14\%}_{-13\%}$	$32.64^{+14\%}_{-12\%}$	$126.2^{+12\%}_{-10\%}$	$1119^{+13\%}_{-13\%}$
$\mathrm{NNLO}\oplus\mathrm{NLO}_{m_t}$	$32.16^{+5.9\%}_{-5.9\%}$	$38.29^{+5.6\%}_{-5.5\%}$	$157.3^{+3.0\%}_{-4.7\%}$	$1717^{+5.8\%}_{-12\%}$
$\mathrm{NNLO_{B-i}}\oplus\mathrm{NLO}_{m_t}$	$33.08^{+5.0\%}_{-4.9\%}$	$39.16^{+4.9\%}_{-5.0\%}$	$150.8^{+4.6\%}_{-5.7\%}$	$1330^{+4.0\%}_{-7.2\%}$
$\mathrm{NNLO}\otimes\mathrm{NLO}_{m_t}$	$32.47^{+5.3\%}_{-7.8\%}$	$38.42^{+5.2\%}_{-7.6\%}$	$147.6^{+4.8\%}_{-6.7\%}$	$1298^{+4.2\%}_{-5.3\%}$
$\mathrm{N^3LO}\oplus\mathrm{NLO}_{m_t}$	$33.06^{+2.1\%}_{-2.9\%}$	$39.40^{+1.7\%}_{-2.8\%}$	$163.3^{+4.0\%}_{-8.3\%}$	$1833^{+14\%}_{-20\%}$
$\mathrm{N^3LO_{B-i}}\oplus\mathrm{NLO}_{m_t}$	$34.17^{+1.9\%}_{-4.6\%}$	$40.44^{+1.9\%}_{-4.7\%}$	$155.5^{+2.3\%}_{-5.0\%}$	$1372^{+2.8\%}_{-5.0\%}$
$\mathrm{N^3LO}\otimes\mathrm{NLO}_{m_t}$	$33.43^{+0.66\%}_{-2.8\%}$	$39.56^{+0.64\%}_{-2.7\%}$	$151.7^{+0.53\%}_{-2.4\%}$	$1333^{+0.51\%}_{-1.8\%}$

Larger difference with different approaches due to larger invariant mass

For total cross section, the difference is about a few percent

Chen, HTL, Shao, Wang, arXiv:1909.06808, arXiv:1912.13001

QCD corrections

Di-Higgs decay with a measurement function F_J

$$\Gamma_{\rm dec} \equiv \int d\Gamma_{H_1} \int d\Gamma_{H_2}\ F_J$$

Cross section for Di-Higgs production and decay

$$\sigma^{(n)}_{\rm pro+dec(X_1,X_2)} = \left(\sigma_{\rm pro} \frac{1}{\Gamma_{H_1\to X_1}} \frac{1}{\Gamma_{H_2\to X_2}} \Gamma_{\rm dec(X_1,X_2)} \Big|_{\rm expanded\ to\ } \alpha_s^n \right) \times R(H_1 \to X_1) R(H_2 \to X_2)\,.$$

expanded in series of α_s

NLO corrections as sum of corrections to production and decay individually

$$\sigma^{(1)}_{\rm pro+dec(b\bar{b},\gamma\gamma)} = \sigma^{\rm pro(1)}_{\rm pro+dec(b\bar{b},\gamma\gamma)} + \sigma^{\rm dec(1)}_{\rm pro+dec(b\bar{b},\gamma\gamma)}$$

production part

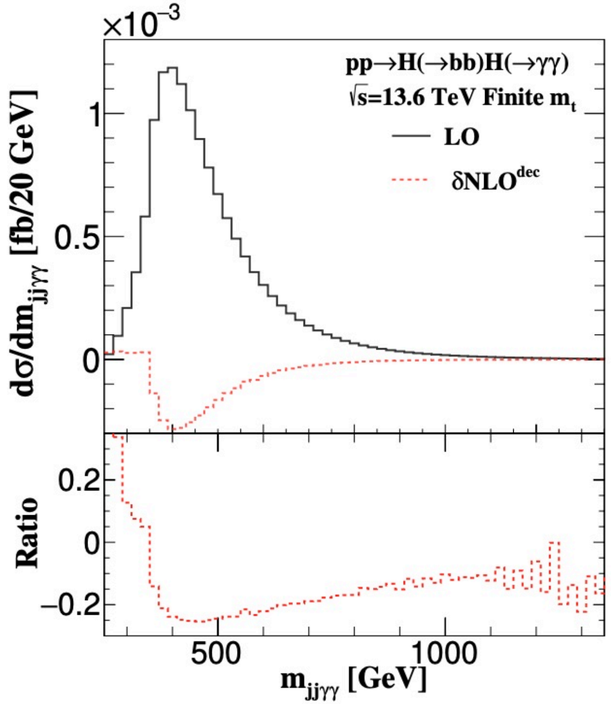
$$\sigma^{\rm pro(1)}_{\rm pro+dec(b\bar{b},\gamma\gamma)} = \sigma^{(1)}_{\rm pro} \frac{1}{\Gamma^{(0)}_{H_1\to b\bar{b}}} \frac{1}{\Gamma^{(0)}_{H_2\to\gamma\gamma}} \Gamma^{(0)}_{\rm dec(b\bar{b},\gamma\gamma)} \times R(H_1 \to b\bar{b}) R(H_2 \to \gamma\gamma)$$

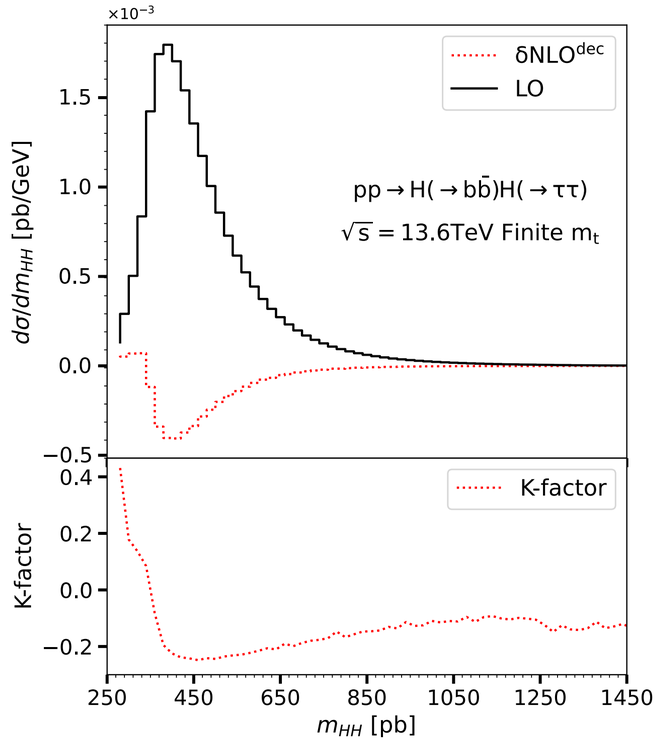
HTL, Si, Wang, Zhang, Zhao, JHEP 04 (2024) 002

QCD corrections

$$\sigma^{\mathrm{dec}(1)}_{\mathrm{pro+dec}(b\bar{b},\gamma\gamma)} = \sigma^{(0)}_{\mathrm{pro}} \frac{1}{\Gamma^{(0)}_{H_1\to b\bar{b}}} \frac{1}{\Gamma^{(0)}_{H_2\to\gamma\gamma}} \Gamma^{(0)}_{\mathrm{dec}(b\bar{b},\gamma\gamma)} \left(\frac{\int d\Gamma^{(1)}_{H_1\to b\bar{b}} F_J}{\int d\Gamma^{(0)}_{H_1\to b\bar{b}} F_J} - \frac{\Gamma^{(1)}_{H_1\to b\bar{b}}}{\Gamma^{(0)}_{H_1\to b\bar{b}}} \right) \times R(H_1 \to b\bar{b}) R(H_2 \to \gamma\gamma)$$

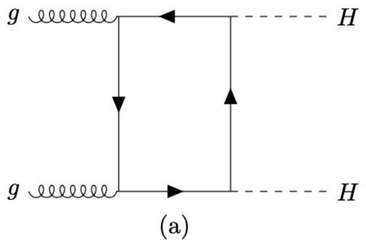
	without decays	with decays but no cuts		with decays and cuts	
		$\mathrm{LO}^{\mathrm{dec}}$	$\delta\mathrm{NLO}^{\mathrm{dec}}$	$\mathrm{LO}^{\mathrm{dec}}$	$\delta\mathrm{NLO}^{\mathrm{dec}}$
$\mathrm{LO}^{\mathrm{pro}}_{\infty}$	$17.07^{+31\%}_{-22\%}$	$0.02257^{+31\%}_{-22\%}$	0	$0.01257^{+30\%}_{-22\%}$	$-0.00175^{+42\%}_{-28\%}$
$\mathrm{LO}^{\mathrm{pro}}_{m_t}$	$19.85^{+28\%}_{-20\%}$	$0.02624^{+28\%}_{-20\%}$	0	$0.01395^{+27\%}_{-20\%}$	$-0.00261^{+39\%}_{-27\%}$
$\delta\mathrm{NLO}^{\mathrm{pro}}_{\infty}$	$14.86^{+6\%}_{-7\%}$	$0.01964^{+6\%}_{-7\%}$	–	$0.01064^{+6\%}_{-7\%}$	–
$\delta\mathrm{NLO}^{\mathrm{pro}}_{m_t}$	$13.08^{+4\%}_{-8\%}$	$0.01729^{+4\%}_{-8\%}$	–	$0.00914^{+4\%}_{-8\%}$	–
Full NLO result					
NLO_{∞}	$31.93^{+18\%}_{-15\%}$	$0.04221^{+18\%}_{-15\%}$		$0.02146^{+15\%}_{-14\%}$	
NLO_{m_t}	$32.93^{+14\%}_{-13\%}$	$0.04354^{+14\%}_{-13\%}$		$0.02047^{+10\%}_{-11\%}$	

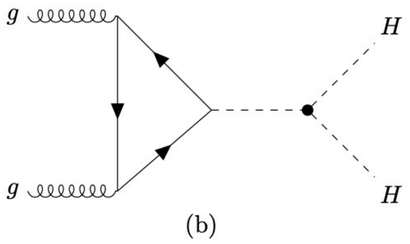




HTL, Si, Wang, Zhang, Zhao, arXiv:2402.00401 and in preparation

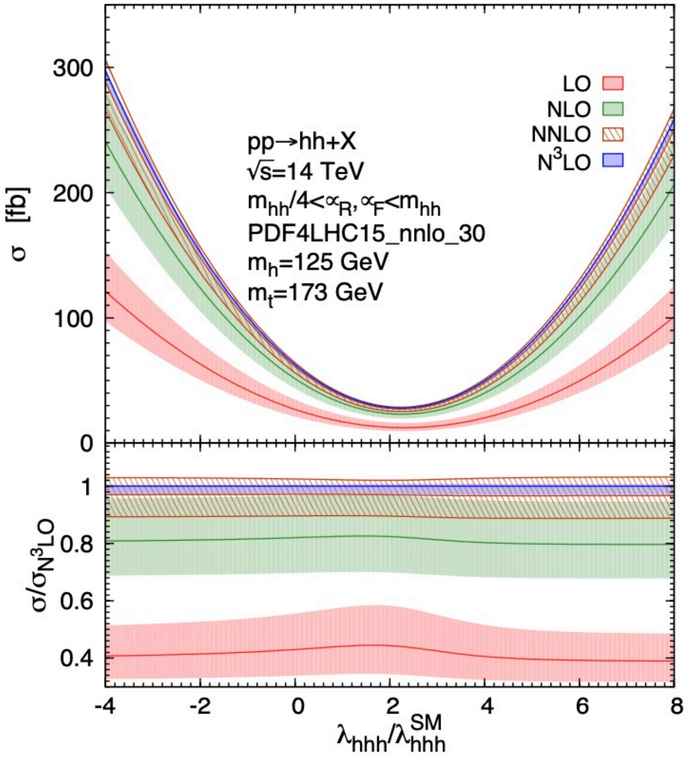
EW corrections

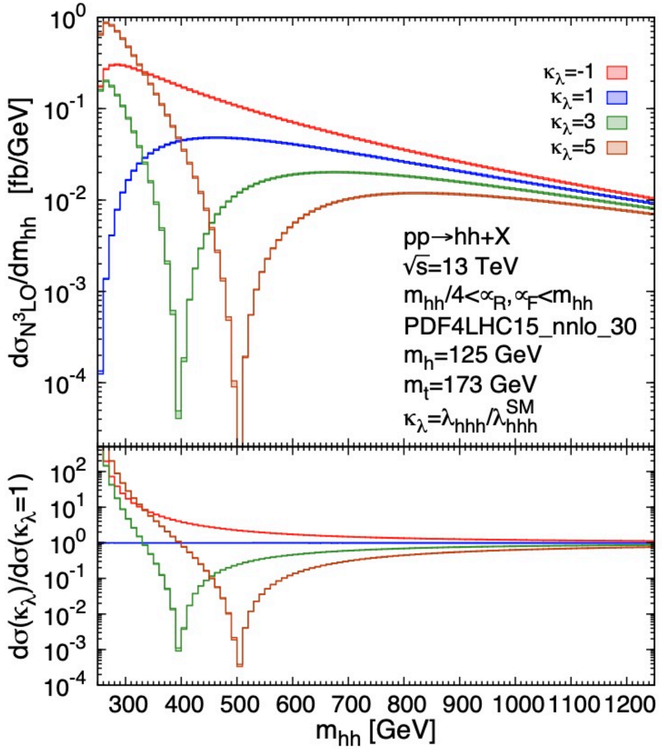




$$\sigma^{\kappa_\lambda}_{\mathrm{ggF,NNLO-FT}} = (\ 10.8\ \kappa^2_{\lambda_{3H}} - 49.6\ \kappa_{\lambda_{3H}} + 70.0\ )\ \ \mathrm{fb},$$

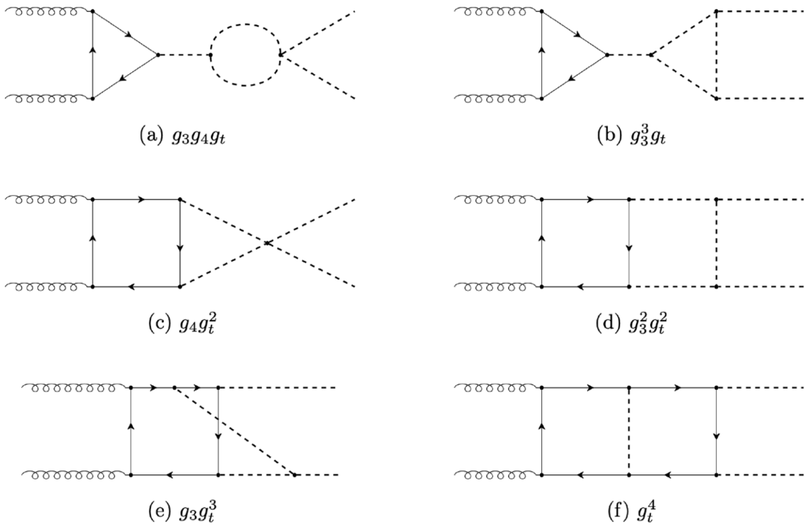
Higgs self coupling can be extracted from





EW corrections

Top-Yukawa-induced and Higgs self coupling-induced corrections



Muhlleitner, Schlenk, Spira arXiv:2207.02524
Davies, Mishima, Schonwald, Steinhauser, Zhang arXiv:2207.02587
Heinrich, Jones, Kerner, Stone, Vestner, arXiv:2407.04653

complete EW corrections obtained numerically

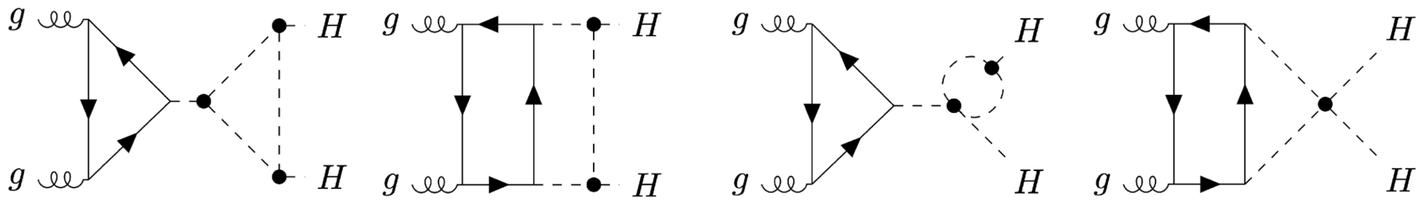
μ	$M_{HH}/2$	$\sqrt{p_T^2+m_H^2}$	m_H
LO	19.96(6)	21.11(7)	25.09(8)
NLO	19.12(6)	20.21(6)	23.94(8)
$\mathcal{K}$ factor	0.958(1)	0.957(1)	0.954(1)

Bi, Huang, Huang, Ma, Yu, PRL, 2024

EW correction with $1/m_t$ expansion

Davies, Schönwald, Steinhauser, Zhang, 2308.01355

EW corrections



$$\delta\sigma_{\rm EW} = \delta_A + \delta_B\lambda + \delta_C\lambda^2 + \delta_D\lambda^3 + \delta_E\lambda^4$$

- Higher-order EW corrections include Feynman diagrams with one or more triple Higgs or quadruple Higgs vertices.

- These corrections exhibit a distinct functional dependence on the Higgs self-coupling.

EFT approach

$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

$$V^{\rm NP}(\Phi) \equiv \sum_{n=3}^{\infty} \frac{c_{2n}}{\Lambda^{2n-4}} \left(\Phi^\dagger\Phi - \frac{1}{2}v^2\right)^n$$

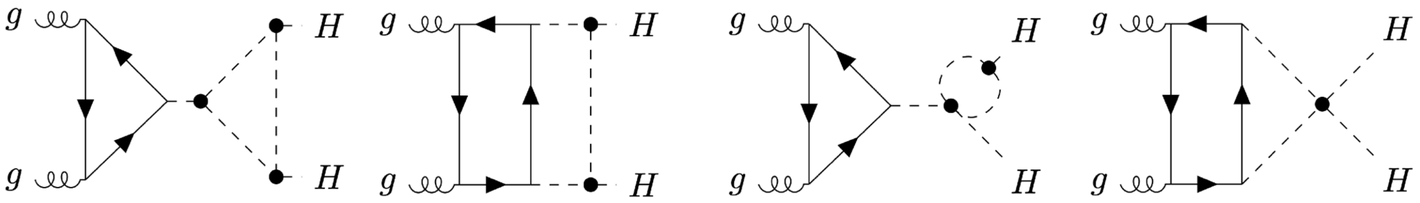
If one count the power exactly, cross section only depends on κ_3 and κ_4 linearly

$$\kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}} = 1 + \frac{c_6 v^2}{\lambda\Lambda^2} \equiv 1 + \bar{c}_6,$$

$$\kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{\rm SM}} = 1 + \frac{6c_6 v^2}{\lambda\Lambda^2} + \frac{4c_8 v^4}{\lambda\Lambda^4} \equiv 1 + 6\bar{c}_6 + \bar{c}_8\,.$$

Davies, Mishima, Schonwald, Steinhauser and Zhang arXiv:2207.02587

EW corrections



$$\delta\sigma_{\rm EW} = \delta_A + \delta_B\lambda + \delta_C\lambda^2 + \delta_D\lambda^3 + \delta_E\lambda^4$$

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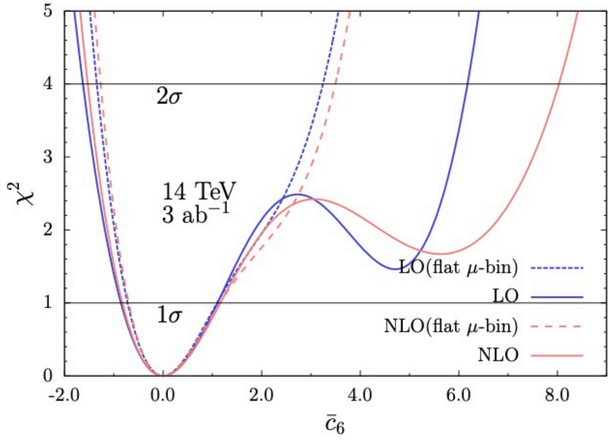
EFT approach

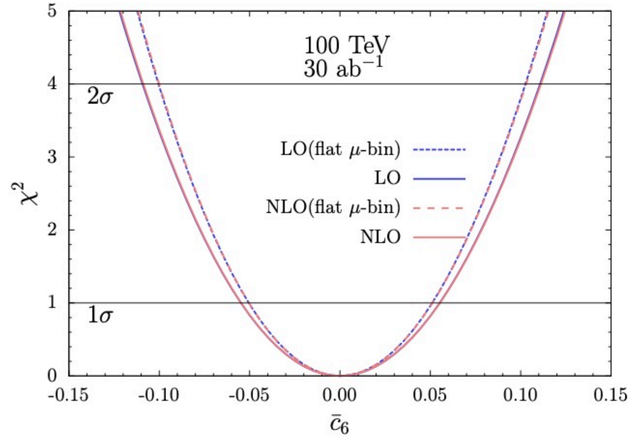
$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda$$

$$V^{\rm NP}(\Phi) \equiv \sum_{n=3}^{\infty} \frac{c_{2n}}{\Lambda^{2n-4}} \left(\Phi^\dagger \mathfrak{q}\right.$$

$$\kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}} = 1 + \frac{c_6 v^2}{\lambda\Lambda^2} \equiv 1 + \bar{c}_6,$$

$$\kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{\rm SM}} = 1 + \frac{6c_6 v^2}{\lambda\Lambda^2} + \frac{4c_8 v^4}{\lambda\Lambda^4} \equiv 1 + 6\bar{c}_6 + \bar{c}_8\,.$$





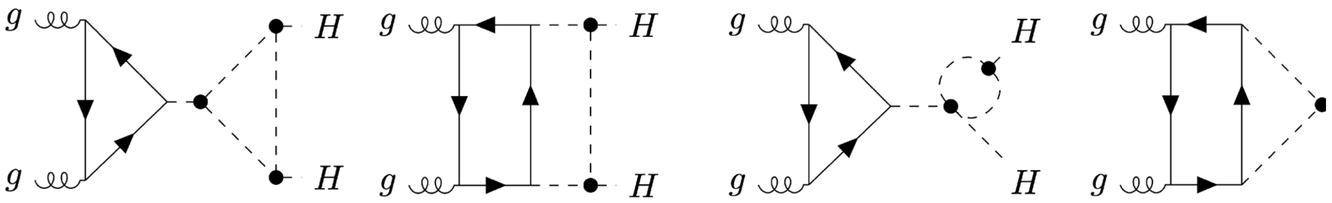
Davies, Mishima, Schonwald, Steinhauser and Zhang arXiv:2207.02587

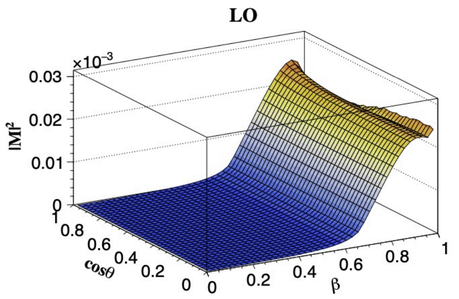
EW corrections

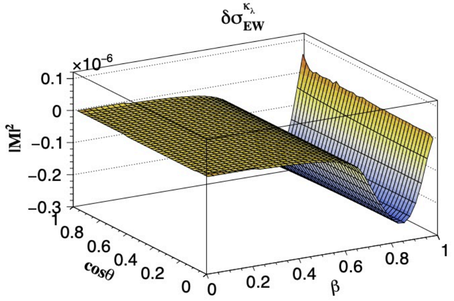
$$\mathcal{L}_{\rm H} = (D_\mu\phi_0)^\dagger(D^\mu\phi_0) + \mu_0^2(\phi_0^\dagger\phi_0) - \lambda_0(\phi_0^\dagger\phi_0)^2, \qquad \phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ H + Z_v v \end{pmatrix}$$

$$\mathcal{L}_{\rm H} = \frac{1}{2}Z_\phi(\partial_\mu H)^2 - \left(-\frac{1}{2}Z_{\mu^2}Z_\phi Z_v^2\mu^2 v^2 + \frac{1}{4}Z_\lambda Z_\phi^2 Z_v^4\lambda v^4\right) - (Z_\lambda Z_\phi^2 Z_v^3\lambda v^3 - Z_{\mu^2}Z_\phi Z_v\mu^2 v)H$$
$$- \left(\frac{3}{2}Z_\lambda Z_\phi^2 Z_v^2\lambda v^2 - \frac{1}{2}Z_{\mu^2}Z_\phi\mu^2\right)H^2 - \boxed{Z_{\kappa_{3\rm H}}Z_\lambda Z_\phi^2 Z_v\lambda_{3\rm H} v H^3} - \boxed{\frac{1}{4}Z_{\kappa_{4\rm H}}Z_\lambda Z_\phi^2\lambda_{4\rm H}H^4} + \cdots,$$

$\lambda_{3H} \to \kappa_3\lambda_{3H}$ $\lambda_{4H} \to \kappa_4\lambda_{4H}$



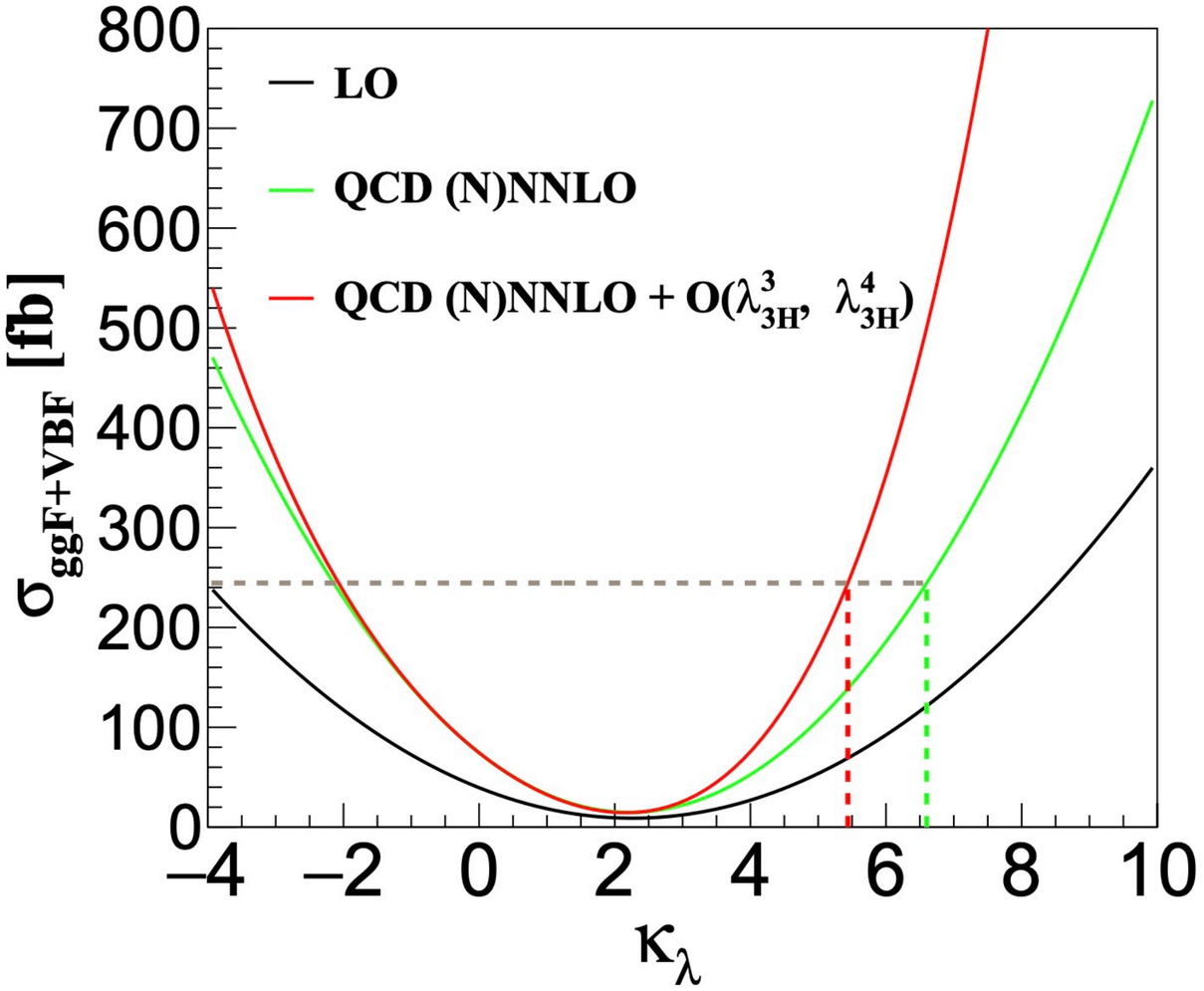




$$\delta\sigma^{\kappa_\lambda}_{\rm ggF,EW} = (0.075\kappa^4_{\lambda_3} - 0.158\kappa^3_{\lambda_3} - 0.006\kappa^2_{\lambda_3}\kappa_{\lambda_4} - 0.058\kappa^2_{\lambda_3} + 0.070\kappa_{\lambda_3}\kappa_{\lambda_4} - 0.149\kappa_{\lambda_4}) \ \ \text{fb}$$

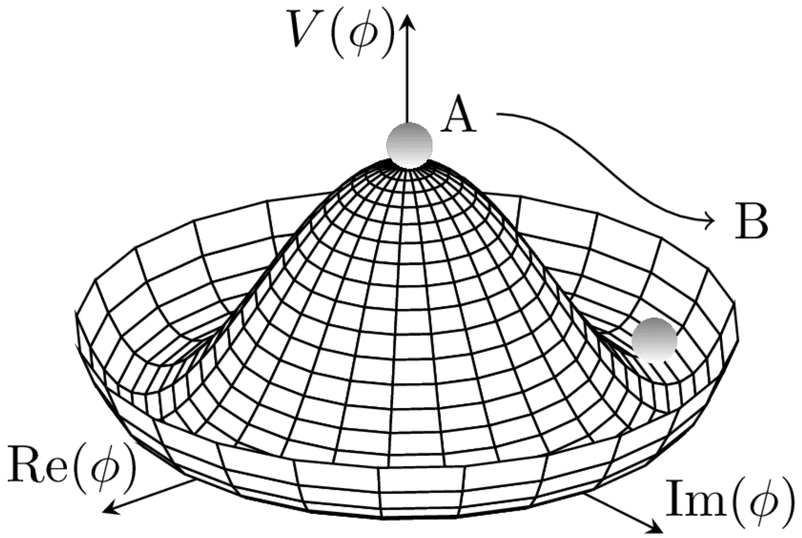
$$\delta\sigma^{\kappa\lambda}_{\rm VBF,EW} = (0.0215\kappa^4_{\lambda_3} - 0.0324\kappa^3_{\lambda_3} - 0.0019\kappa^2_{\lambda_3}\kappa_{\lambda_4} - 0.0043\kappa^2_{\lambda_3} + 0.0151\kappa_{\lambda_3}\kappa_{\lambda_4} - 0.0211\kappa_{\lambda_4})\,\text{fb}$$

EW corrections



- EW corrections include higher order terms in κ_λ
- Large effects observed for large κ_λ
- The upper limit by the ATLAS and CMS collaboration on κ_λ is 6.6 and 6.49
- With EW correction, the , the upper limit is narrowed down to 5.4 and 5.37

Conclusion



- Measurement about Higgs self-coupling is a cornerstone for understanding electroweak symmetry breaking and probing new physics.
- A precision study for HH production and decay is required
- A method proposed to extract the κ_λ dependence in the cross section
- A better constraint obtained after considering EW corrections

Thank you!!