Higgs boson pair production and decay to $b\bar{b}\gamma\gamma$ at NLO in QCD

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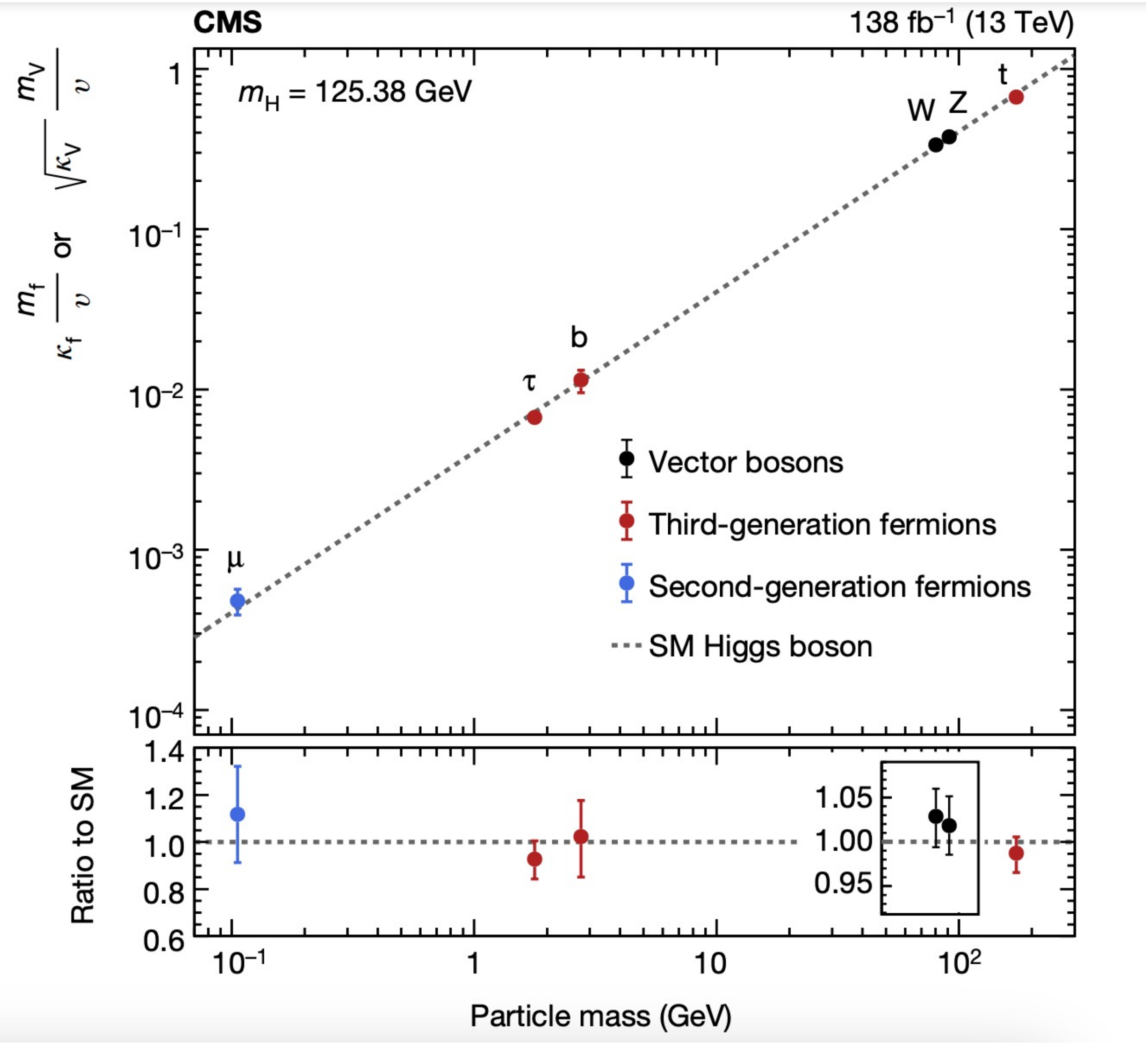
OUTLINE

1. Introduction and motivation
2. Framework
3. Numerical result
4. Summary

Introduction

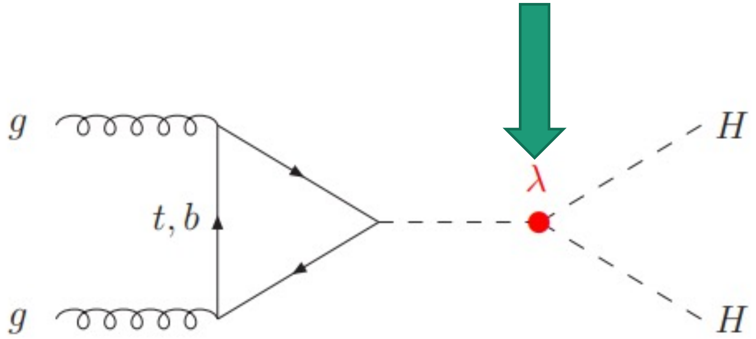


[CMS, Nature 607, 60–68 (2022)]

Why we study Higgs boson pair production?

Higgs pair production is a key to probing Higgs self-coupling!

$$V(h) = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

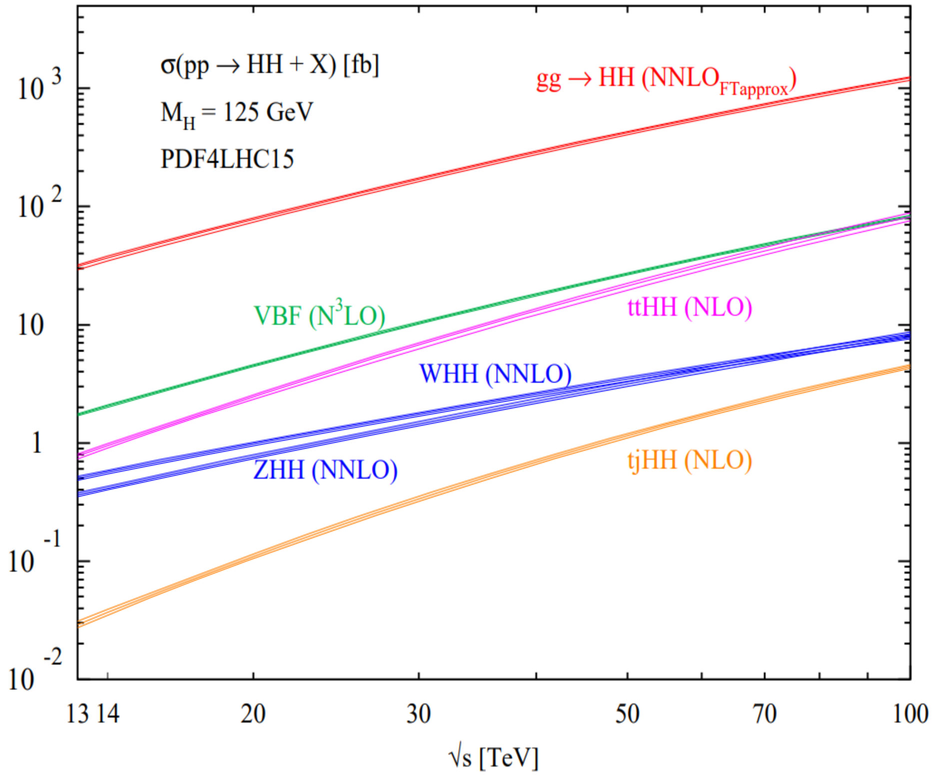


The trilinear Higgs self-coupling λ is important for examing the shape of Higgs potential and understanding EWSB.

Introduction

Higgs pair production by ggF: Theoretical (partial) Status

Main production channel



[Biagio Di Micco *et al*, arXiv:1910.00012]

Heavy top limit:

N3LO+N3LL: [Ajjath, Shao, arXiv:2209.03914]

N3LO: [Chen, Li ,Shao,Wang , arXiv:1909.06808]

NNLO: [de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev,arXiv:1606.09519]

NLO+NNLL: [Shao, Li ,Li ,Wang, arXiv:1301.1245]

Finite mt dependence:

$\mathrm{NNLO}_{\mathrm{FTapprox}}$ +NNLL: [De Florian, Mazzitelli,arXiv:1807.03704]

$\mathrm{NNLO}_{\mathrm{FTapprox}}$: [Grazzini, Heinrich, Jones, Kallweit, Kerner, ArXiv:1803.02463](applyed by CMS and ATLAS)

NLO+NLL: [Feerera, Pires,arXiv:1609.01691]

NLO: [Borowka, *et al* ,arXiv:1608.14798, arXiv:1604.06477]

NLO EW: [Davies, Schonwald , Steinhauserc ,Zhang, arXiv:2308.01355]

NNLO: [Mazzitelli,arXiv:2206.14667]
[Czakon, Harlander, Klappert, Niggetiedt,arXiv:2105.04436]

NLO: [Baglio, Campanario, Glaus, Muhlleitner, Spira, Streicher, arXiv:1811.05692]

[See Xuan Chen's and talk]

Introduction

$\kappa_\lambda = \frac{\lambda_{HHH}^{EXP}}{\lambda_{HHH}^{SM}}$ $\kappa - framework$ [CERN-2013-004 (CERN, 2013)]

$$\sigma(gg \to HH) \sim \frac{\sigma(gg \to H)}{1000}$$

$HH \to b\bar{b}\gamma\gamma$ has the highest S/B.

$HH \to b\bar{b}b\bar{b}$ has the highest branching ratio.

$HH \to b\bar{b}\tau\tau$ has middle S/B and branching ratio.

ATLAS:

Final states	Obs.	Exp.
$b\bar{b}b\bar{b}$	[-3.5,11.3]	[-5.4,11.4]
$b\bar{b}\gamma\gamma$	[-1.5,6.7]	[-2.4,7.7]
$b\bar{b}\tau\tau$	[-2.4,9.2]	[-2.0,9.0]
Combine	[-0.6,6.6]	[-2.1,7.8]

[ATLAS,arXiv:2301.03212]
[ATLAS,arXiv:2112.11876]
[ATLAS-CONF-2021-052]
[ATLAS,PLB 843(2023)137745]

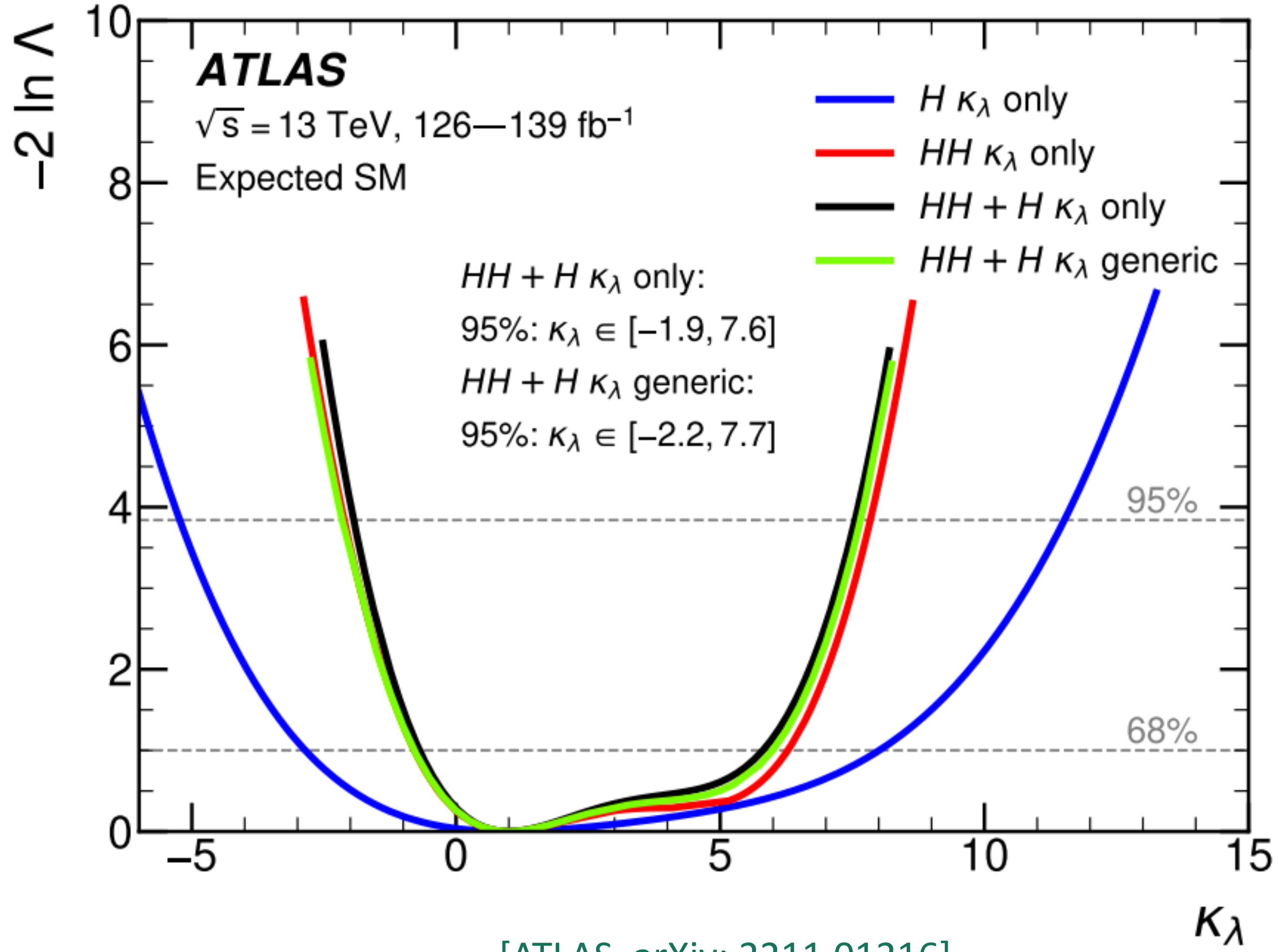
[See Yihui Lai and Marco Valente's talk]

CMS:

Final states	Obs.	Exp.
$b\bar{b}b\bar{b}$	[-2.3,9.4]	[-5.0,12.0]
$b\bar{b}\gamma\gamma$	[-3.3,8.5]	[-2.5,8.2]
$b\bar{b}\tau\tau$	[-1.7,8.7]	[-2.9,9.8]
Combine	[-1.2,7.0]	[-2.3,8.0]

[CMS,arXiV:2202.09617]
[CMS,arXiv:2011.12373]
[CMS,arXiv:2206.09401]
[CMS-PAS-HIG-23-006]

Introduction



[ATLAS, arXiv: 2211.01216]

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

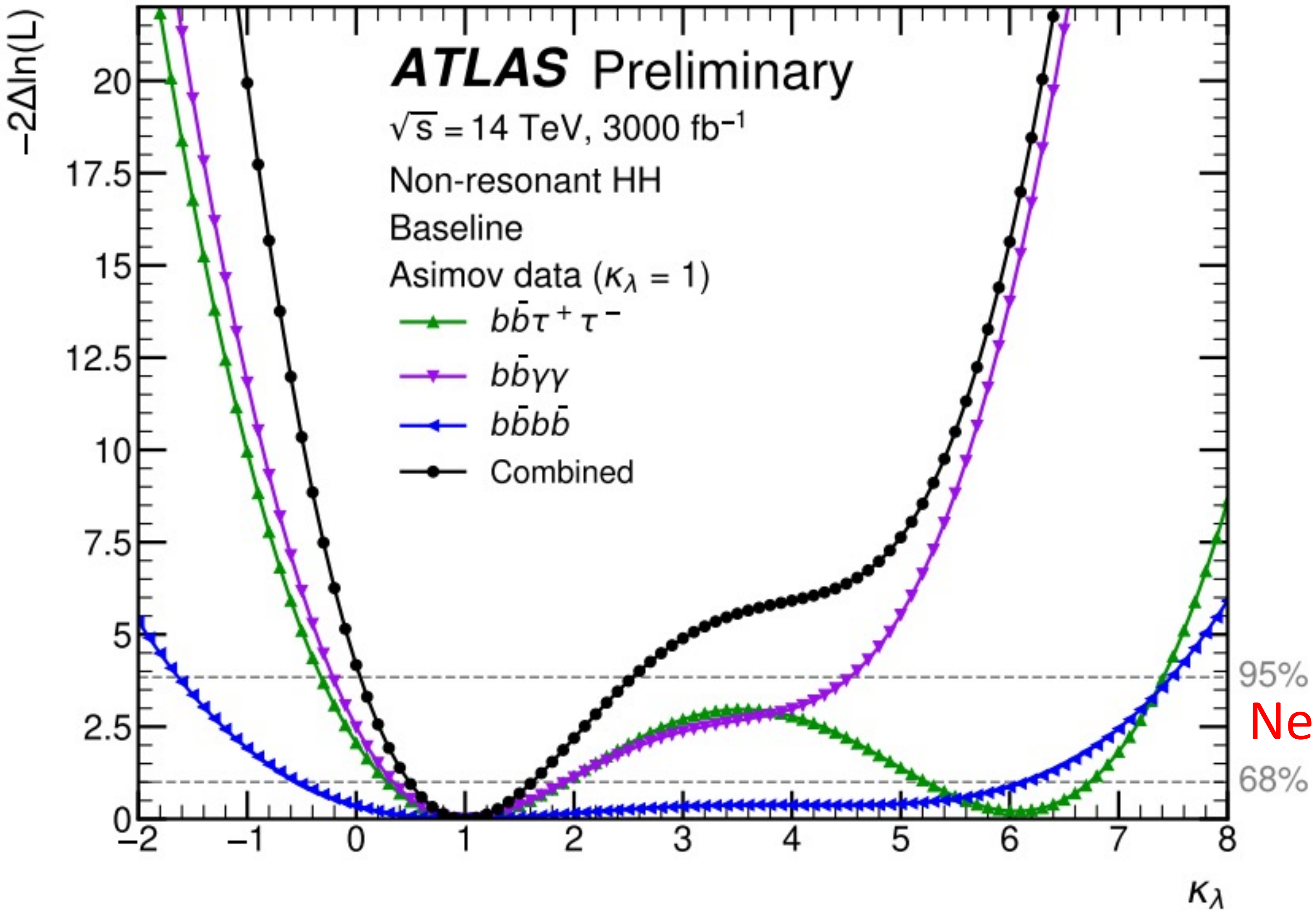
Expected self-coupling modifier at 95% C.L.

Single- and di-Higgs combination:

Run 2: $\kappa_\lambda \in [-1.9\,, 7.6]$

Constraint is still loose.

Introduction



$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

Expected self-coupling modifier at 95% C.L.

HL-LHC projection : $\kappa_\lambda \in [0.0\,, 2.5]$

Need more precise theoretical prediction.

[ATL-PHYS-PUB-2022-053]

Framework

- For the specific Higgs pair decay model $H_1 \to X_1, H_2 \to X_2$, in the frame of narrow width approximation, we have,

$$\sigma_{pro+dec}(X_1, X_2) = \sigma_{pro} \frac{\int d\Gamma_{H_1\to X_1}}{\Gamma_{H_1\to X_1}} \frac{\int d\Gamma_{H_2\to X_2}}{\Gamma_{H_2\to X_2}} \times R(H_1 \to X_1) R(H_2 \to X_2).$$

The cross-section can be expanded in a series of strong coupling,

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

$$\sigma^{pro(1)}_{pro+dec(\bar{b}b,\gamma\gamma)} = \sigma^{(1)}_{pro} \frac{\int d\Gamma^{(0)}_{H_1\to b\bar{b}}}{\Gamma^{(0)}_{H_1\to b\bar{b}}} \frac{\int d\Gamma^{(0)}_{H_2\to\gamma\gamma}}{\Gamma^{(0)}_{H_2\to\gamma\gamma}} \times R\left(H_1 \to b\bar{b}\right) R(H_2 \to \gamma\gamma). \qquad \delta NLO^{pro} \times LO^{dec}$$

Framework

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

Numerator expanding

$$-\sigma^{(0)}_{pro} \frac{\Gamma^{(1)}_{H_1\to b\bar{b}}}{(\Gamma^{(0)}_{H_1\to b\bar{b}})^2} \frac{1}{\Gamma^{(0)}_{H_2\to\gamma\gamma}} \int d\Gamma^{(0)}_{H_1\to b\bar{b}} \int d\Gamma^{(0)}_{H_2\to\gamma\gamma} \times R(H_1 \to b\bar{b}) R(H_2 \to \gamma\gamma)$$

Denominator expanding

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

$LO^{pro} \times \delta NLO^{dec}$

This contribution is 0 in the total cross-section.

Why we consider its correction effects ?

Why we ignore the $H_2 \to \gamma\gamma$ NLO QCD correction ?

$$\ldots \left(\frac{\int d\Gamma^{(1)}_{H_2\to\gamma\gamma}}{\int d\Gamma^{(0)}_{H_2\to\gamma\gamma}} - \frac{\Gamma^{(1)}_{H_2\to\gamma\gamma}}{\Gamma^{(0)}_{H_2\to\gamma\gamma}} \right) \ldots \overset{\text{Cut}}{=} 0$$

Numerical result

	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	$0.01257^{+30\%}_{-22\%}$	$-0.001750^{+42\%}_{-28\%}$
$\mathrm{LO}^{\mathrm{pro}}_{m_t}$	$19.85^{+28\%}_{-21\%}$	$0.02624^{+28\%}_{-20\%}$	0	$0.01395^{+27\%}_{-20\%}$	$-0.002613^{+39\%}_{-27\%}$
$\delta\mathrm{NLO}^{\mathrm{pro}}_{\infty}$	$14.86^{+6\%}_{-7\%}$	$0.01964^{+6\%}_{-7\%}$	–	$0.01064^{+6\%}_{-7\%}$	–
$\delta\mathrm{NLO}^{\mathrm{pro}}_{m_t}$	$13.08^{+4\%}_{-8\%}$	$0.01729^{+4\%}_{-8\%}$	–	$0.009142^{+4\%}_{-8\%}$	–
		Full NLO result			
NLO_{∞}	$31.93^{+18\%}_{-15\%}$	$0.04221^{+18\%}_{-15\%}$		$0.02146^{+15\%}_{-14\%}$	
NLO_{m_t}	$32.93^{+14\%}_{-13\%}$	$0.04354^{+14\%}_{-13\%}$		$0.02047^{+10\%}_{-11\%}$	

$\sqrt{s} = 14$ TeV
$m_t = 173$ GeV
$m_H = 125$ GeV
PDF4LHC15_nlo_100_pdfas

$\mu_R, \mu_F \in \frac{m_{HH}}{2}\left(\frac{1}{2}, 1, 2\right)$ and $\frac{\mu_R}{\mu_F} = \frac{1}{4}$ or 4 are excluded (7-point).

$LO_{m_t} / LO_{\infty} = 16\%$ → $NLO_{m_t}/NLO_{\infty} = 3\%$

$\delta NLO_{\infty} / LO_{\infty} = 87\%$ → $\delta NLO_{m_t} / LO_{m_t} = 66\%$

Agree with [arXiv:1909.06808] (HTL) and [arXiv:1608.14798] (SM)

Numerical result

	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	$0.01257^{+30\%}_{-22\%}$	$-0.001750^{+42\%}_{-28\%}$
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Full NLO result					
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NLO_{m_t}	$32.93^{+14\%}_{-13\%}$	$0.04354^{+14\%}_{-13\%}$		$0.02047^{+10\%}_{-11\%}$	

In numerical data:

$$R(H \to b\bar{b}) \times R(H \to \gamma\gamma) = 58.24\% \times 0.227\% = 0.13\%$$

$$LO^{pro}LO^{dec} = LO^{pro} \times R(H \to b\bar{b}) \times R(H \to \gamma\gamma)$$

$$\delta NLO^{pro}LO^{dec} = \delta NLO^{pro} \times R(H \to b\bar{b}) \times R(H \to \gamma\gamma)$$

$$LO^{pro}\delta NLO^{dec} = \cdots \left(\frac{\int d\Gamma^{(1)}_{H_1 \to b\bar{b}}}{\int d\Gamma^{(0)}_{H_1 \to b\bar{b}}} - \frac{\Gamma^{(1)}_{H_1 \to b\bar{b}}}{\Gamma^{(0)}_{H_1 \to b\bar{b}}} \right) \ldots = 0$$

Confirm the validity of our numerical program.

Numerical result

	without decays	with decays but no cuts		with decays and cuts	
		LO^{dec}	δNLO^{dec}	LO^{dec}	δNLO^{dec}
LO^{pro}_{∞}	$17.07^{+31\%}_{-22\%}$	$0.02257^{+31\%}_{-22\%}$	0	$0.01257^{+30\%}_{-22\%}$	$-0.001750^{+42\%}_{-28\%}$
$LO^{pro}_{m_t}$	$19.85^{+28\%}_{-21\%}$	$0.02624^{+28\%}_{-20\%}$	0	$0.01395^{+27\%}_{-20\%}$	$-0.002613^{+39\%}_{-27\%}$
$\delta NLO^{pro}_{\infty}$	$14.86^{+6\%}_{-7\%}$	$0.01964^{+6\%}_{-7\%}$	–	$0.01064^{+6\%}_{-7\%}$	–
$\delta NLO^{pro}_{m_t}$	$13.08^{+4\%}_{-8\%}$	$0.01729^{+4\%}_{-8\%}$	–	$0.009142^{+4\%}_{-8\%}$	–
Full NLO result					
NLO_{∞}	$31.93^{+18\%}_{-15\%}$	$0.04221^{+18\%}_{-15\%}$		$0.02146^{+15\%}_{-14\%}$	
NLO_{m_t}	$32.93^{+14\%}_{-13\%}$	$0.04354^{+14\%}_{-13\%}$		$0.02047^{+10\%}_{-11\%}$	

$p_T^j, p_T^\gamma > 25$ GeV
$|\eta^j|, |\eta^\gamma| < 2.5$
$\Delta R_{jj,j\gamma,\gamma\gamma} > 0.4$
$90 < m_{jj} < 190$ GeV

$$\ldots\left(\frac{\int d\Gamma^{(1)}_{H_1\to b\bar b}}{\int d\Gamma^{(0)}_{H_1\to b\bar b}} - \frac{\Gamma^{(1)}_{H_1\to b\bar b}}{\Gamma^{(0)}_{H_1\to b\bar b}}\right)\ldots = 0 \quad \xrightarrow{\text{CUT}} \quad \ldots\left(\frac{\int d\Gamma^{(1)}_{H_1\to b\bar b}}{\int d\Gamma^{(0)}_{H_1\to b\bar b}} - \frac{\Gamma^{(1)}_{H_1\to b\bar b}}{\Gamma^{(0)}_{H_1\to b\bar b}}\right)\ldots \neq 0$$

$$\left(LO^{pro}_{m_t}\,\delta NLO^{dec} / LO^{pro}_{m_t}\,LO^{dec}\right) \overset{Cut}{\Longrightarrow} -19\%$$

$$\left(LO^{pro}_{\infty}\,\delta NLO^{dec} / LO^{pro}_{\infty}\,LO^{dec}\right) \overset{Cut}{\Longrightarrow} -14\%$$

Larger than N^3LO QCD correction (~+6%)
[Chen,Li,Shao,Wang, arXiv:1910.00012]

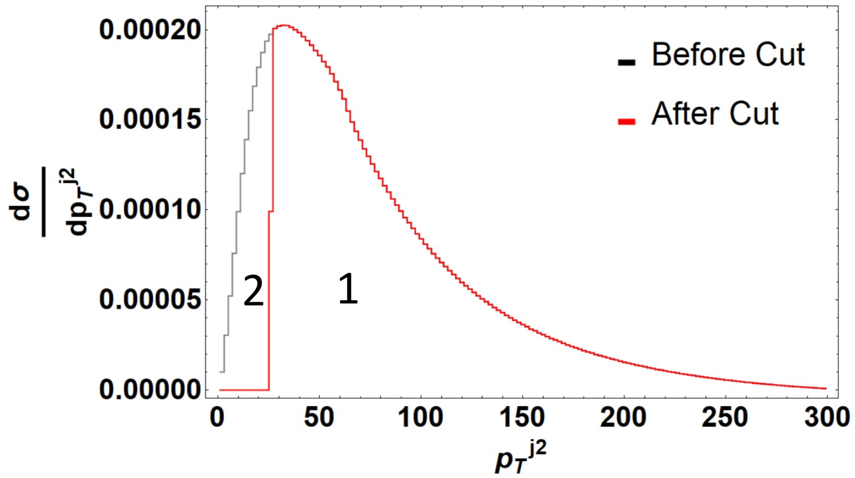
Numerical result

	without decays	with decays but no cuts		with decays and cuts	
		$\mathrm{LO}^{\mathrm{dec}}$	$\delta\mathrm{NLO}^{\mathrm{dec}}$	$\mathrm{LO}^{\mathrm{dec}}$	$\delta\mathrm{NLO}^{\mathrm{dec}}$
$\mathrm{LO}_{\infty}^{\mathrm{pro}}$	$17.07^{+31\%}_{-22\%}$	$0.02257^{+31\%}_{-22\%}$	0	$0.01257^{+30\%}_{-22\%}$	$-0.001750^{+42\%}_{-28\%}$
$\mathrm{LO}_{m_t}^{\mathrm{pro}}$	$19.85^{+28\%}_{-21\%}$	$0.02624^{+28\%}_{-20\%}$	0	$0.01395^{+27\%}_{-20\%}$	$-0.002613^{+39\%}_{-27\%}$
$\delta\mathrm{NLO}_{\infty}^{\mathrm{pro}}$	$14.86^{+6\%}_{-7\%}$	$0.01964^{+6\%}_{-7\%}$	–	$0.01064^{+6\%}_{-7\%}$	–
$\delta\mathrm{NLO}_{m_t}^{\mathrm{pro}}$	$13.08^{+4\%}_{-8\%}$	$0.01729^{+4\%}_{-8\%}$	–	$0.009142^{+4\%}_{-8\%}$	–
Full NLO result					
NLO_{∞}	$31.93^{+18\%}_{-15\%}$	$0.04221^{+18\%}_{-15\%}$		$0.02146^{+15\%}_{-14\%}$	
NLO_{m_t}	$32.93^{+14\%}_{-13\%}$	$0.04354^{+14\%}_{-13\%}$		$0.02047^{+10\%}_{-11\%}$	

-49%

-53%

$p_T^j, p_T^\gamma > 25$ GeV
$|\eta^j|, |\eta^\gamma| < 2.5$
$\Delta R_{jj,j\gamma,\gamma\gamma} > 0.4$
$90 < m_{jj} < 190$ GeV

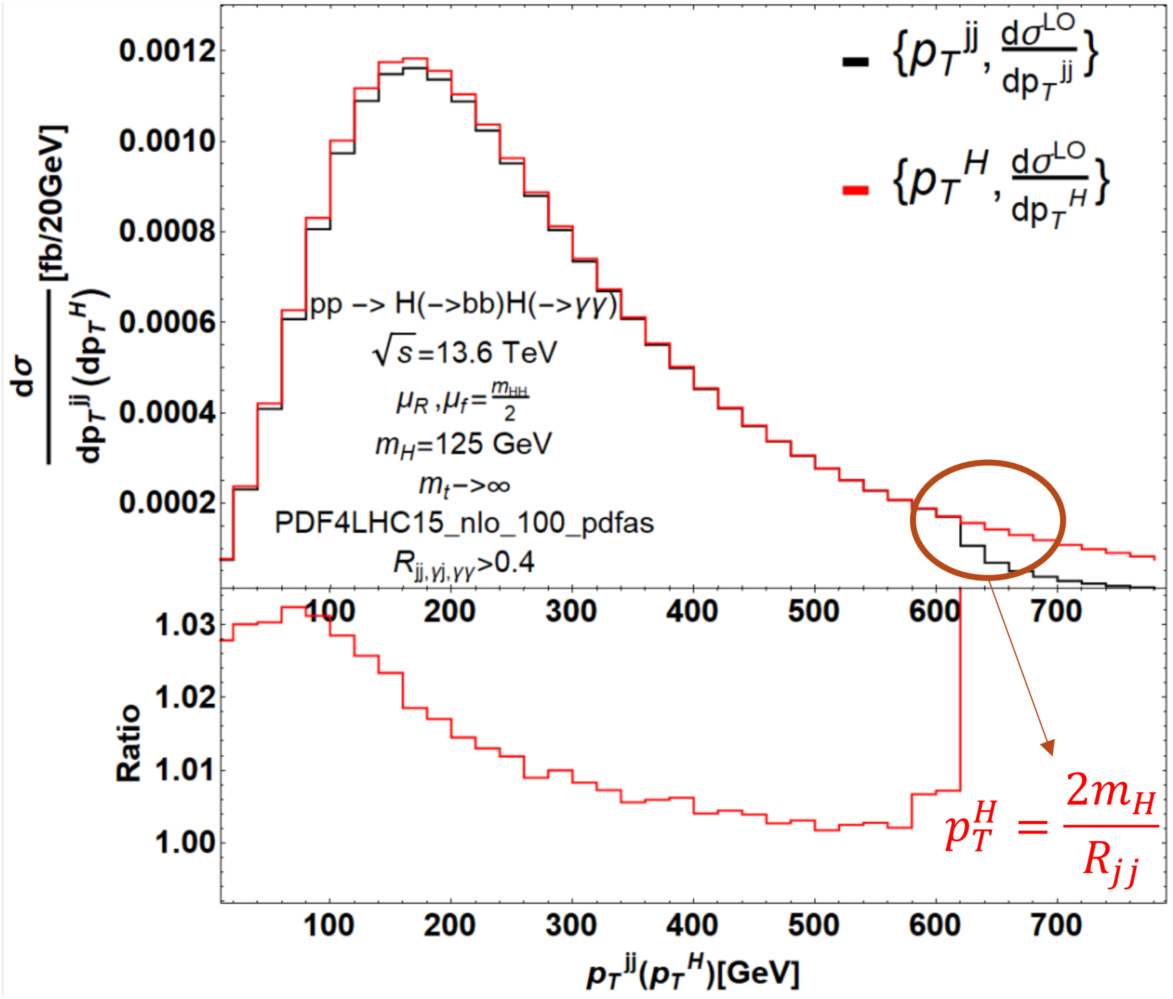


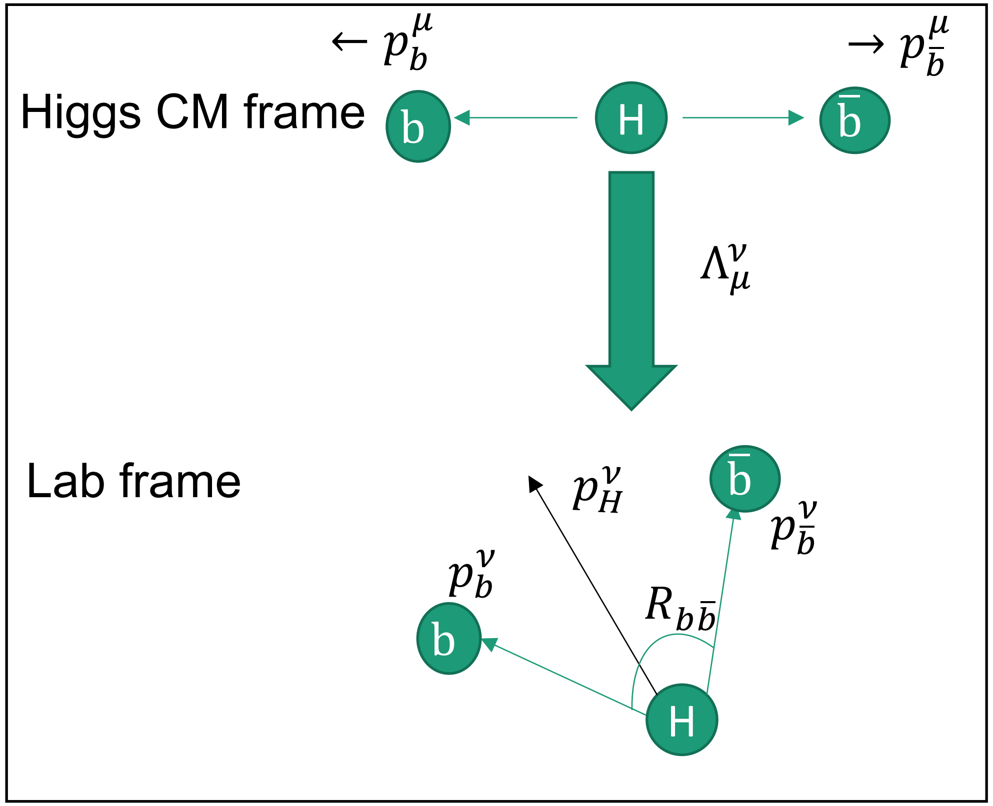
$$\frac{Region1}{Region2} \sim \frac{4}{1}$$

The cross-section with low p_T is cut.

Numerical result

Reconstructed Higgs is different from intermediate Higgs



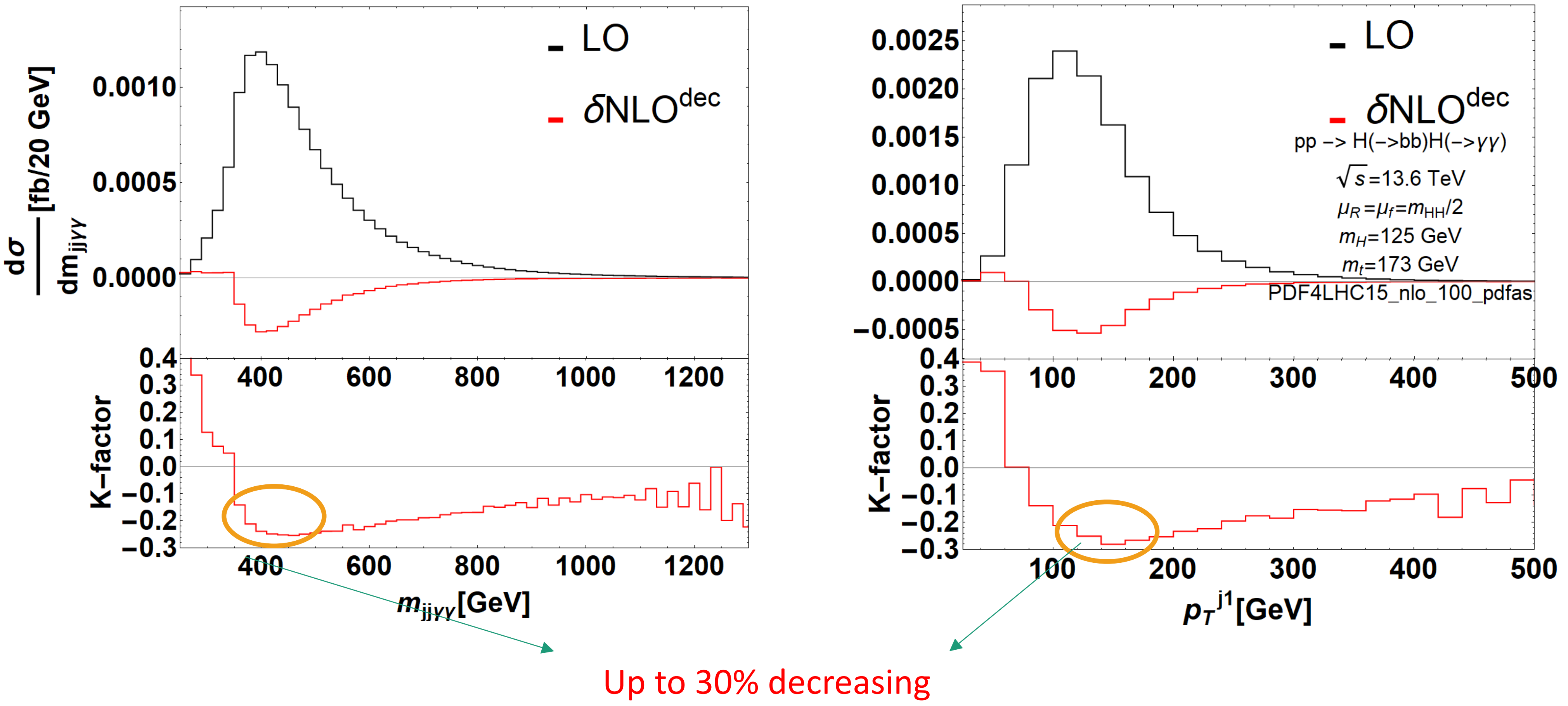


$$p_H^\nu = \left(p_H^0, \overrightarrow{p_T^H}\right) \quad |\overrightarrow{p_b}| = z\left|\overrightarrow{p_T^H}\right|, |\overrightarrow{p_{\bar{b}}}| = \bar{z}\left|\overrightarrow{p_T^H}\right|$$

$$p_b^\nu = (|\overrightarrow{p_b}|, \overrightarrow{p_b})$$

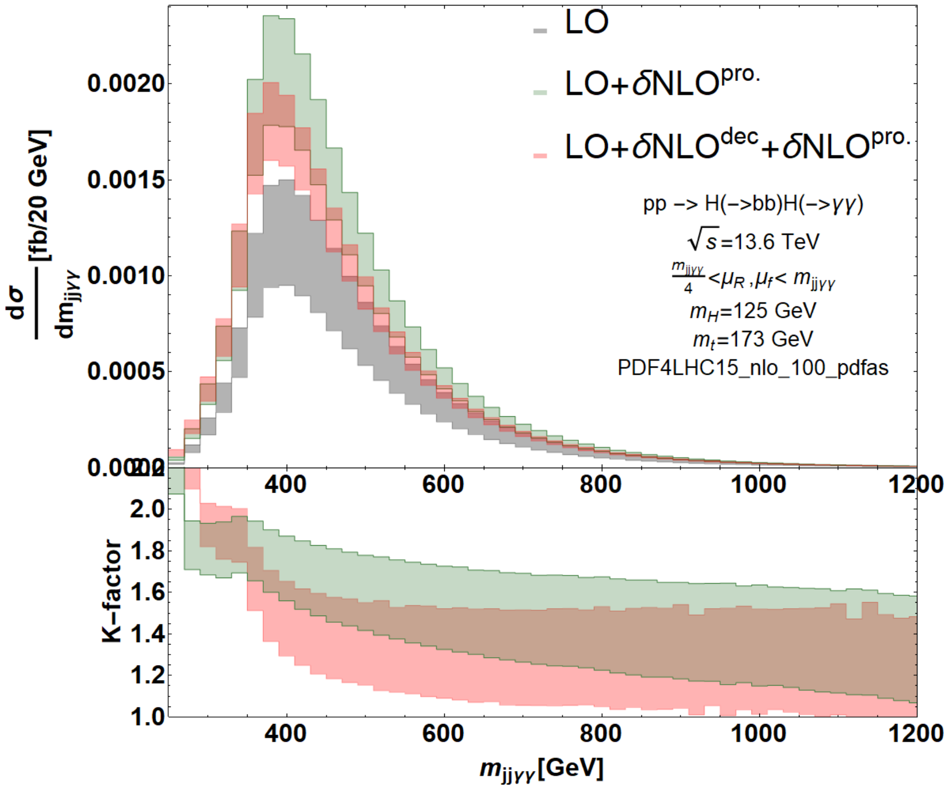
$$p_{\bar{b}}^\nu = (|\overrightarrow{p_{\bar{b}}}|, \overrightarrow{p_{\bar{b}}}) \qquad m_H^2 = z\bar{z}\left(\left|\overrightarrow{p_T^H}\right|\right)^2 R^2$$

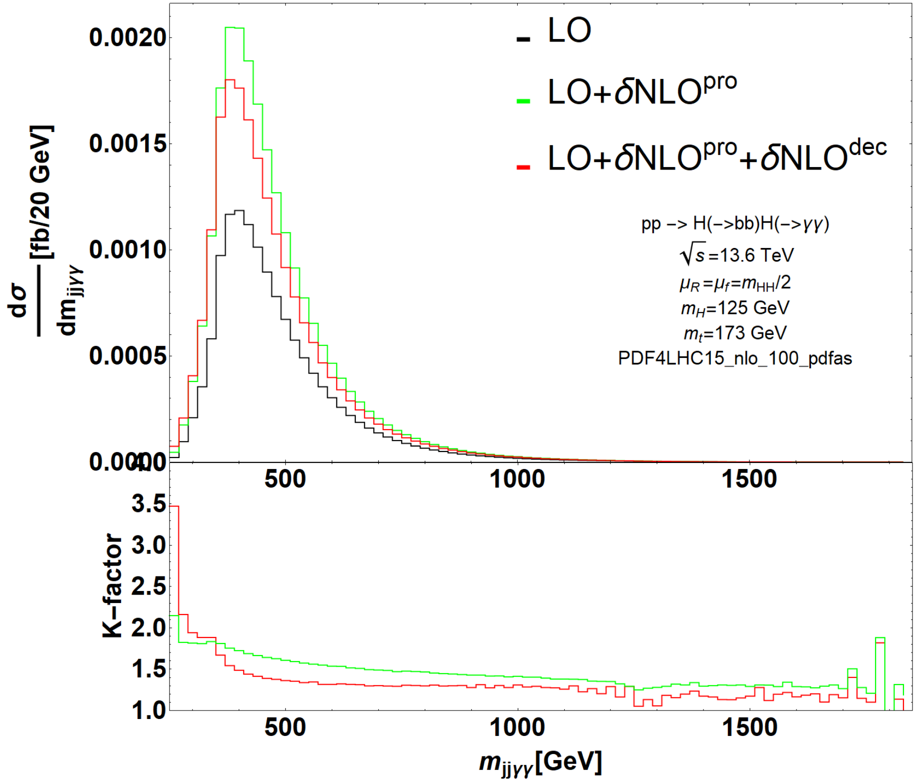
Numerical result



In the peak region, the QCD correction is as large as about -30%.

Numerical result





- The NLO decay correction is negative but in some region is still positive.

- The K-factor is not constant.

Summary

- Higgs self-coupling λ_{HHH} is important for the SM and the best way to directly measure λ_{HHH} is from Higgs pair production.
- So far, only the higher-order QCD corrections in the production processes have been studied.
- The QCD correction in decay is significant especially for cross-sections after cut.
- $\delta\mathrm{NLO}^{\mathrm{dec}}$ ~ up to -30%(-19%) for distributions(total cross-section) with respect to LO

Thank you !