

Precise prediction for Higgs productions and decays

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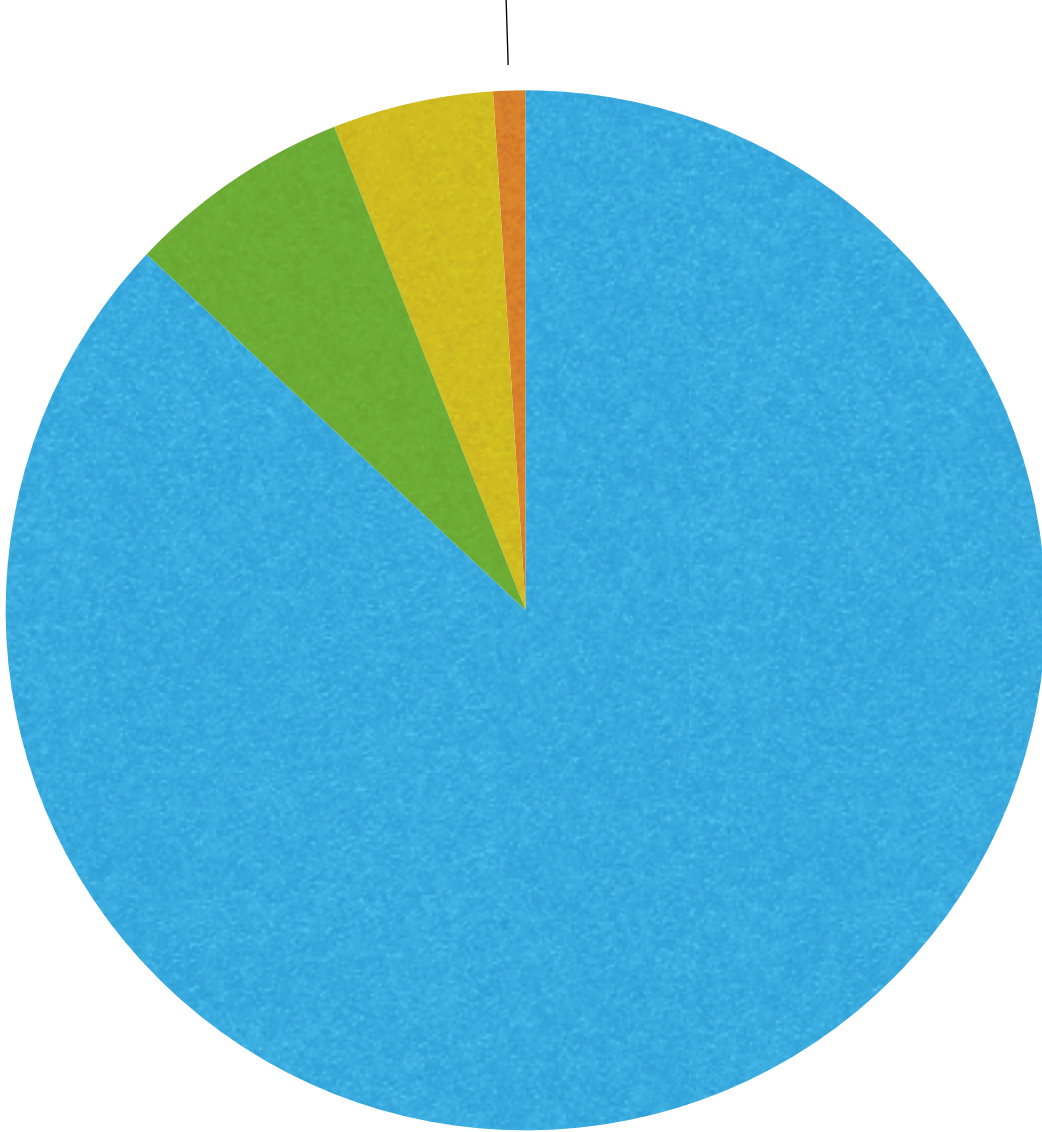
2nd TeV and 33rd LHC mini-Workshop, 2026 Sep. 18-20, Beijing

Outline

- 1. Higgs productions**
- 2. Higgs decays**
- 3. Summary**

Single Higgs production

● gg fusion ● W/Z fusion ● VH ● ttH



Expected exp. accuracy: 3%

Les Houches 2019, 2003.01700

Cross-section	Measurement (pb)	SM prediction (pb)	Ratio to SM
ggF + <i>bbH</i>	47.0 ^{+3.1} _{-2.7}	44.8 ± 2.6	1.05 ^{+0.07} _{-0.06}
VBF	3.6 ± 0.4	3.50 ± 0.07	1.04 ^{+0.12} _{-0.11}
<i>WH</i>	1.17 ± 0.18	1.216 ± 0.024	0.96 ± 0.15
<i>ZH</i>	0.80 ± 0.14	0.796 ± 0.029	1.00 ^{+0.18} _{-0.17}
<i>ttH</i> + <i>tH</i>	0.57 ^{+0.09} _{-0.08}	0.58 ± 0.05	0.97 ^{+0.15} _{-0.14}

ATLAS-CONF-2025-006

NNNLO QCD prediciton in Heavy Top Limit

Mistlberger '18

13 TeV	48.68 pb	^{+2.07pb} _{-3.16pb} $\left(\begin{smallmatrix} +4.26\% \\ -6.48\% \end{smallmatrix} \right)$	± 0.89 pb (± 1.85%)	^{+1.25pb} _{-1.26pb} $\left(\begin{smallmatrix} +2.59\% \\ -2.62\% \end{smallmatrix} \right)$
14 TeV	54.80 pb	^{+2.34pb} _{-3.54pb} $\left(\begin{smallmatrix} +4.28\% \\ -6.46\% \end{smallmatrix} \right)$	± 1.00 pb (± 1.86%)	^{+1.40pb} _{-1.42pb} $\left(\begin{smallmatrix} +2.60\% \\ -2.62\% \end{smallmatrix} \right)$



Scale



PDF



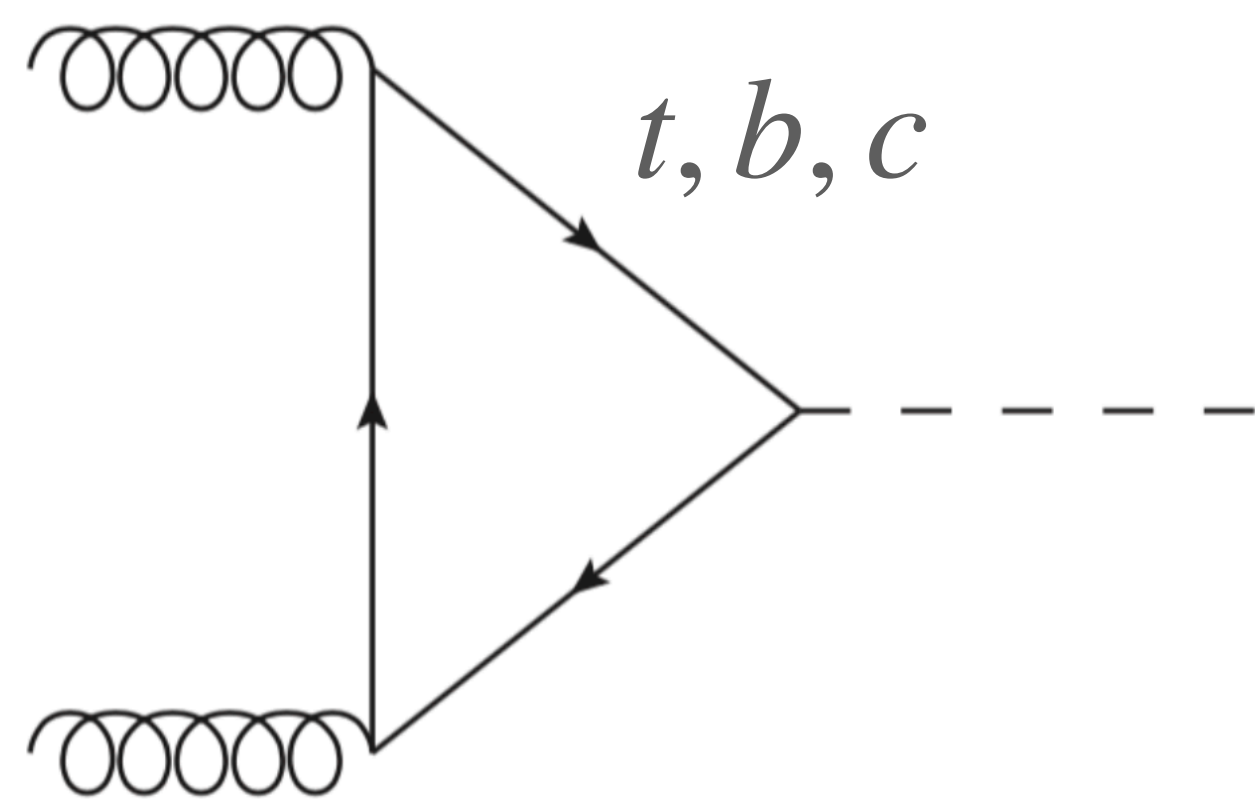
α_s

Finite top quark mass effects are found to be less than 1%.

Harlander, Ozeren '09; Pak, Rogal, Steinhauser '09

Single Higgs production

Light quark in the loop:



	$\overline{\text{MS}}$	OS	$\delta\sigma^{sc}$
$\sigma_{ex;t}^{LO}$	16.00 pb	16.04 pb	0.25%
$\sigma_{ex;t+b}^{LO}$	14.94 pb	14.24 pb	-4.8%
$\sigma_{ex;t+b+c}^{LO}$	14.83 pb	13.81 pb	-6.9%
$\sigma_{ex;t}^{NLO}$	36.60 pb	36.63 pb	0.08%
$\sigma_{ex;t+b}^{NLO}$	34.96 pb	34.49 pb	-1.3%
$\sigma_{ex;t+b+c}^{NLO}$	34.77 pb	34.04 pb	-2.1%

$$\delta\sigma^{sc} = (\sigma^{\text{OS}}/\sigma^{\overline{\text{MS}}} - 1) \times 100\%$$

Anastasiou et al,'16

The light quark contributions are around -7% at LO and -5% at NLO in MSbar scheme.

Their effects become more significant in OS scheme, and can be reduced after including higher orders.

The large logarithms $\ln(m_H^2/m_q^2)$ have been evaluated to all orders, giving (-0.34, 0.08)pb.

Anastasiou, Penin, '20

Three loop form factor has been obtained semi-numerically and analytically for leading color or massless quark loop .

Czakon, Niggetiedt, '20

In the two-loop one real corrections, master integrals have been known.

Frellesvig et al, '19

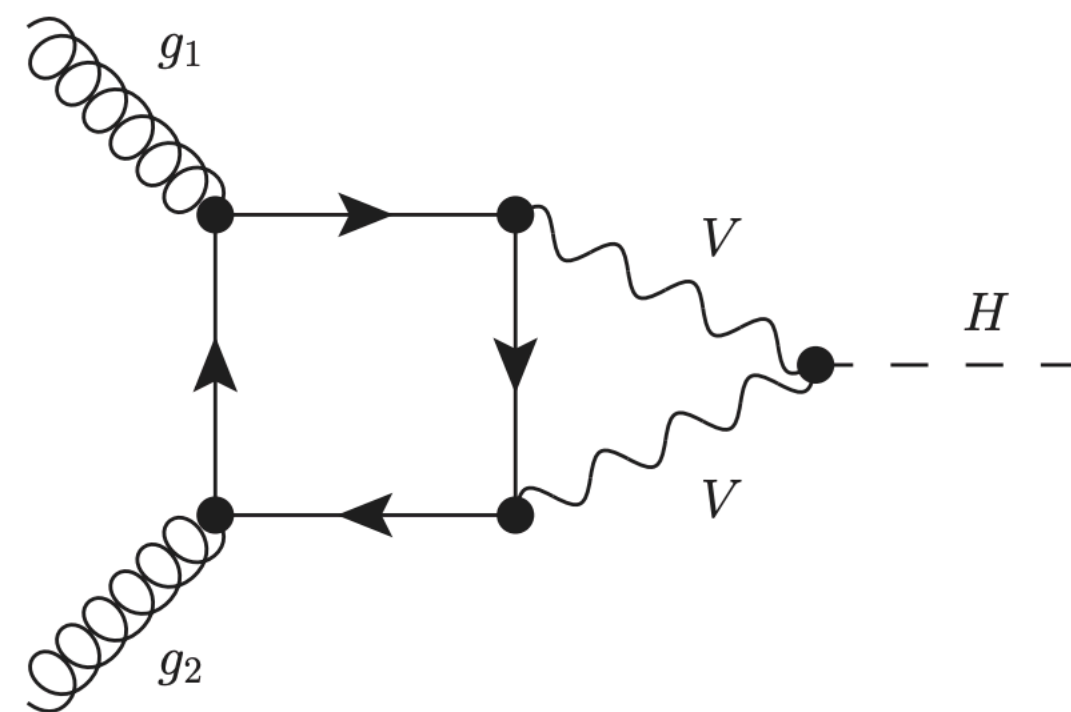
Harlander, Prausa, Usovitsch,'19,'20

Soft gluon effects at N4LO are found to be around -0.1%.

Das, Moch, '25

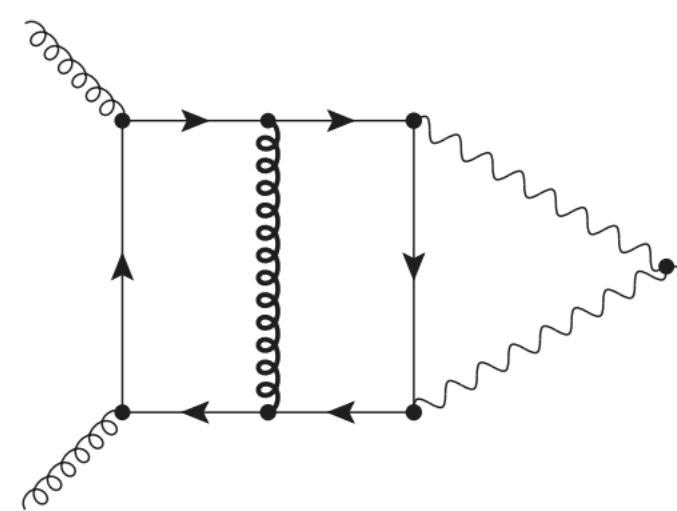
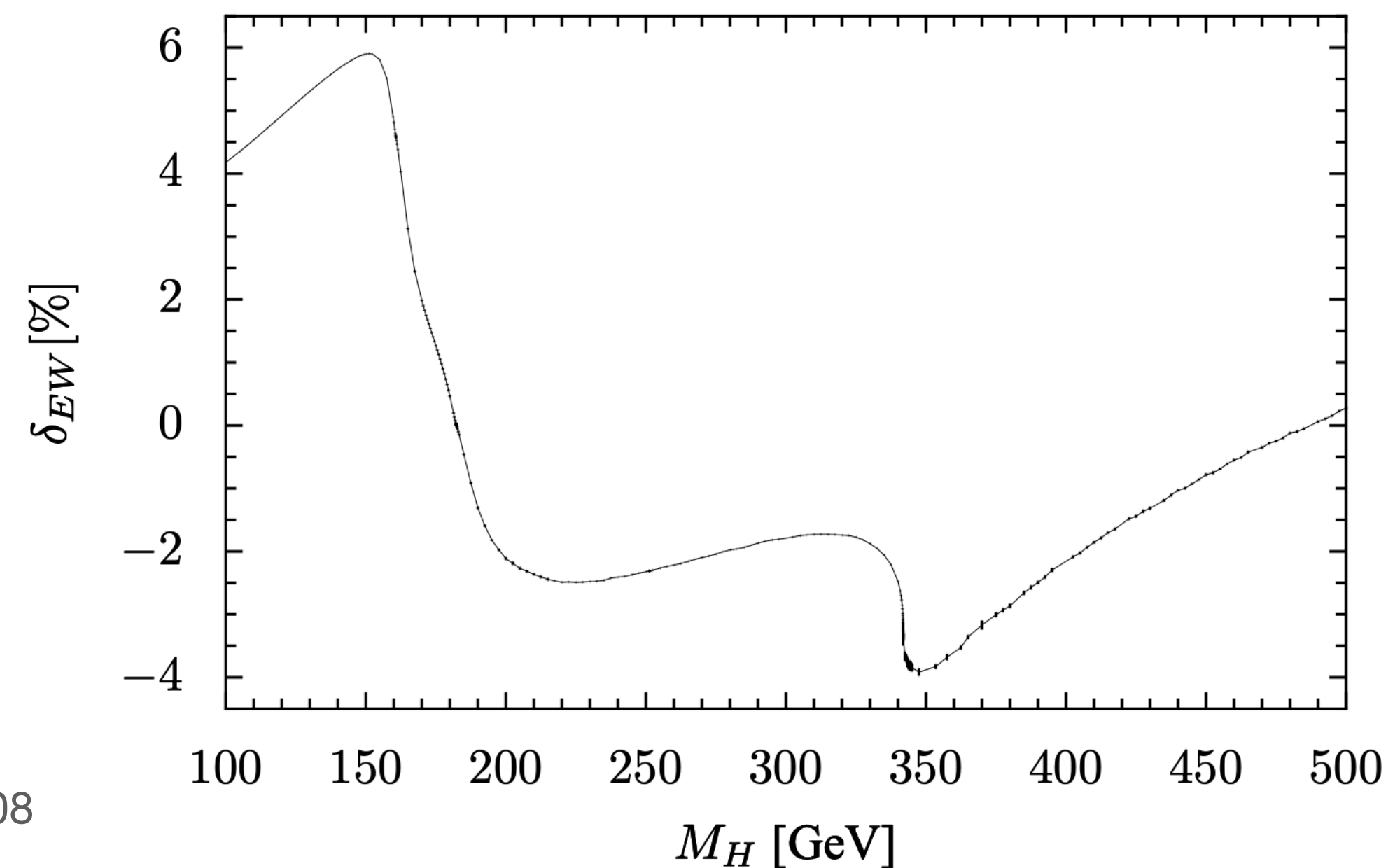
Single Higgs production

W/Z in the loop:



The EW correction is around +5%.

Actis et al, '08



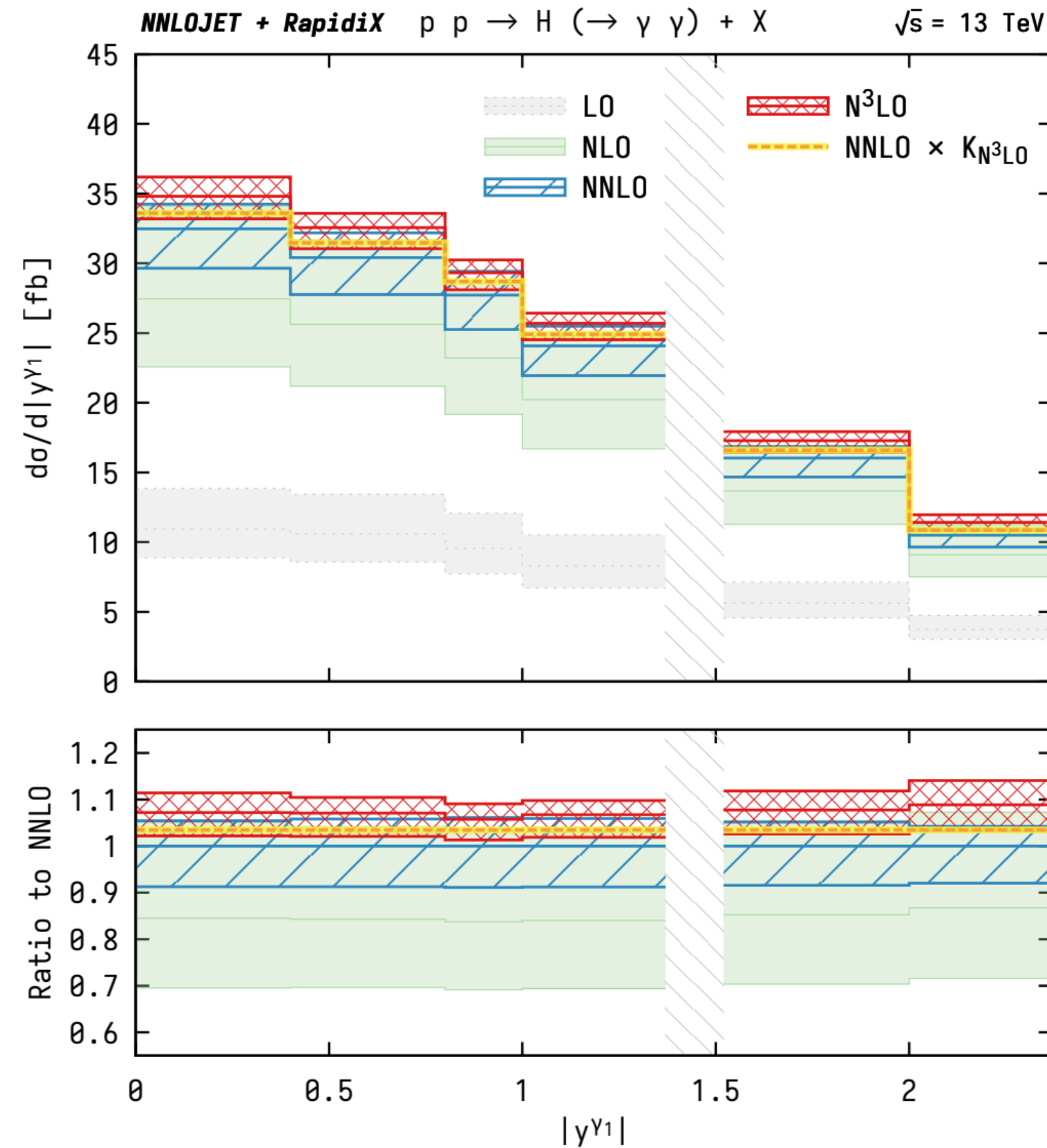
+ soft gluon approximation in real correction gives ~5% corrections to the NLO QCD result.

Bonetti et al, '18

Full real and NLO corrections have been obtained.

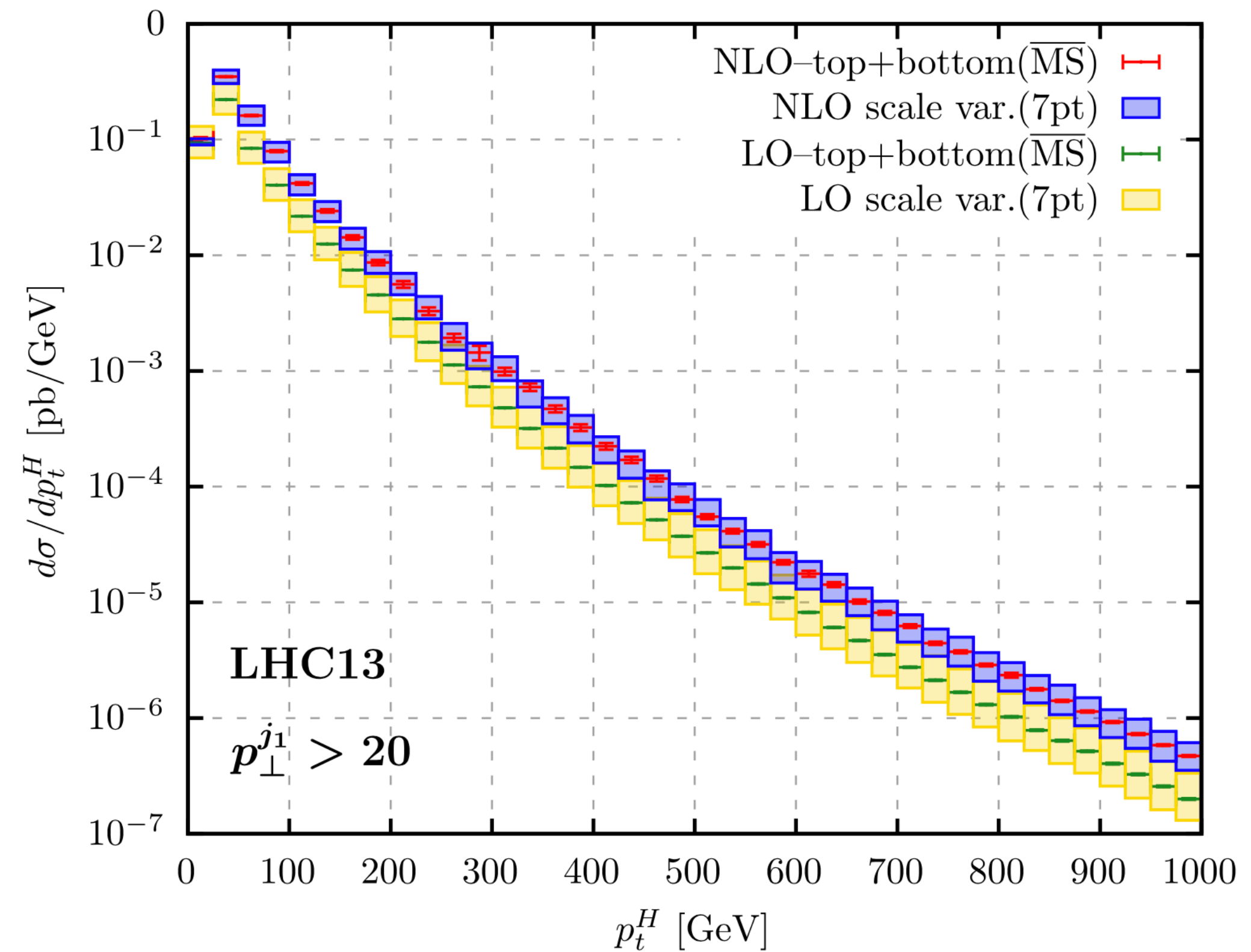
Bonetti et al, '20; Becchetti et al, '20

Single Higgs production



N3LO result lies outside the NNLO band.
N3LO corrections reduce the scale uncertainty.

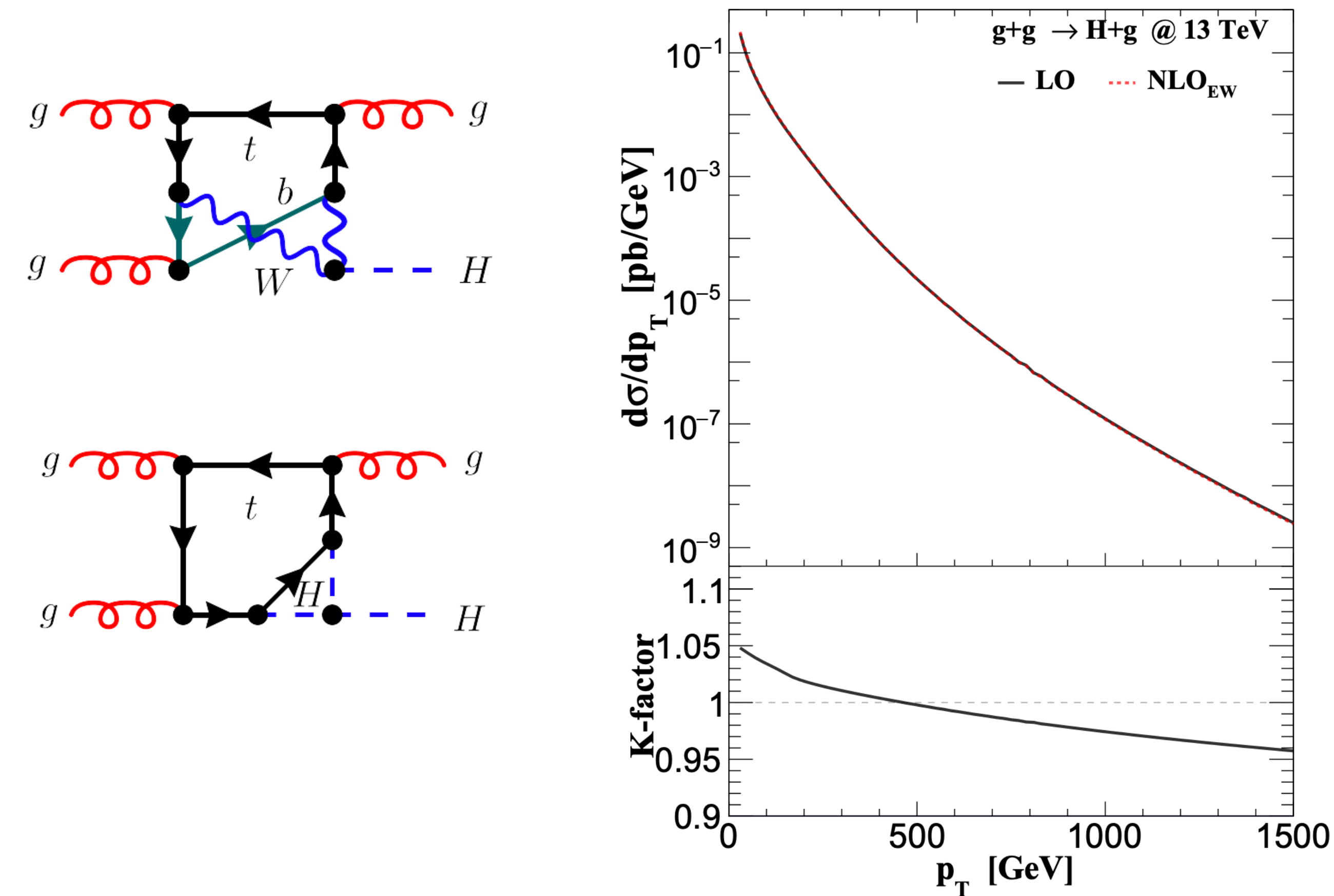
Chen et al, '21



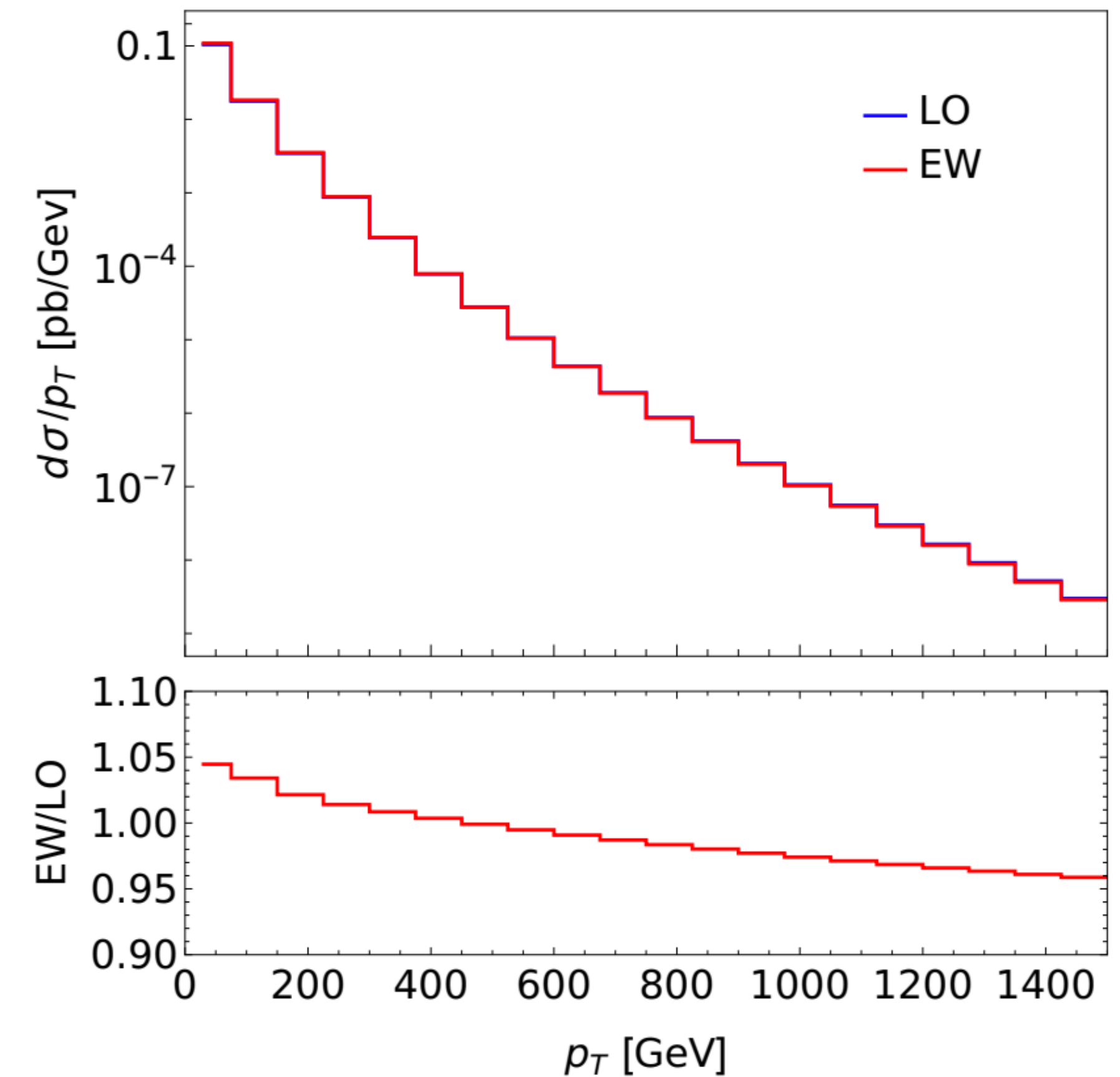
The NLO QCD correction to p_T spectrum is over 100%.
The heavy top quark limit is not valid at large p_T .

Bonciani et al, '23

Single Higgs + jet production



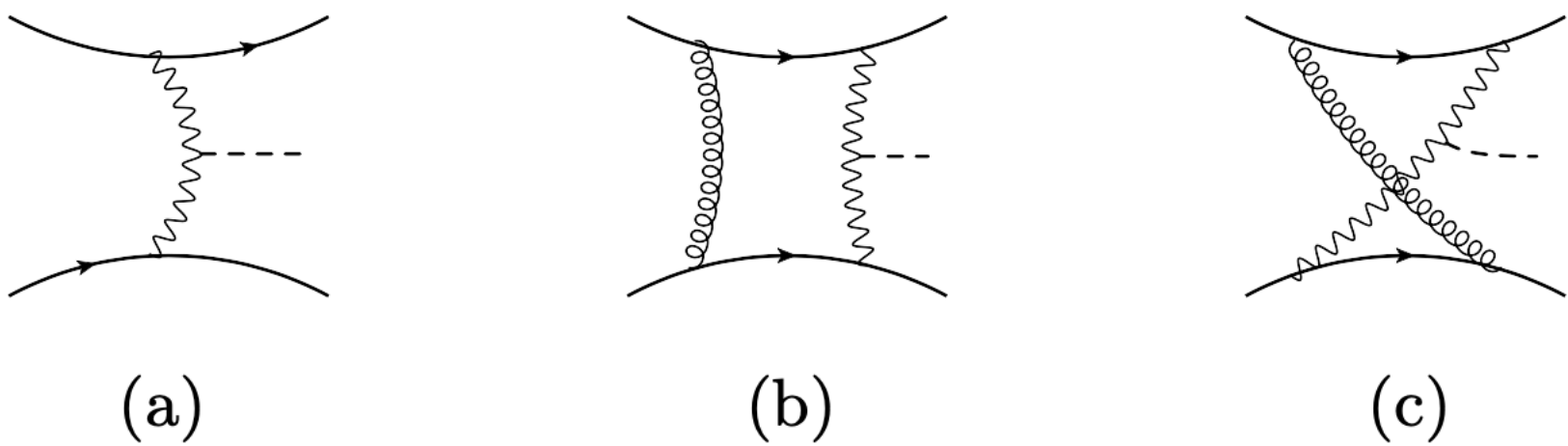
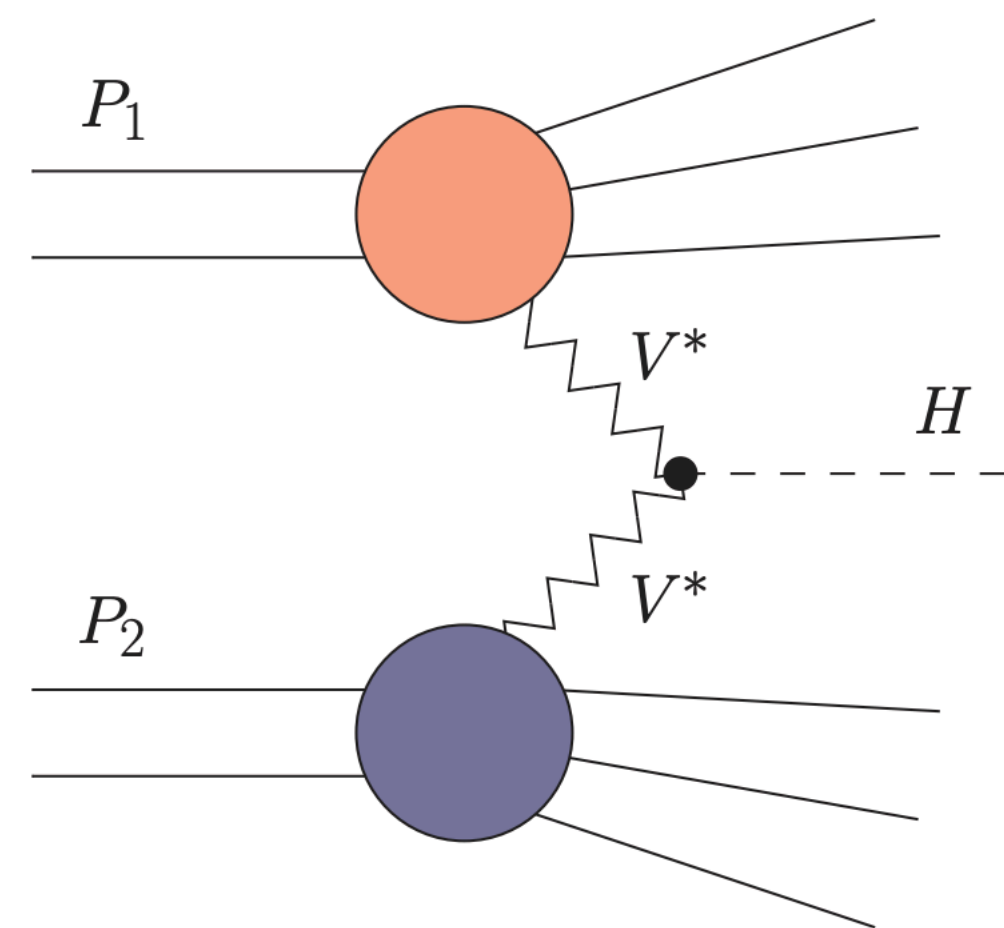
Chen, Li, Sang, '25



Bi, Ma, Du, '25

The EW correction changes the p_T spectrum by 5%.

VBF Higgs production



In the eikonal approximation Liu, Melnikov, Penin,19'

NNNLO QCD prediciton in structure function Dreyer, Karlberg,16'

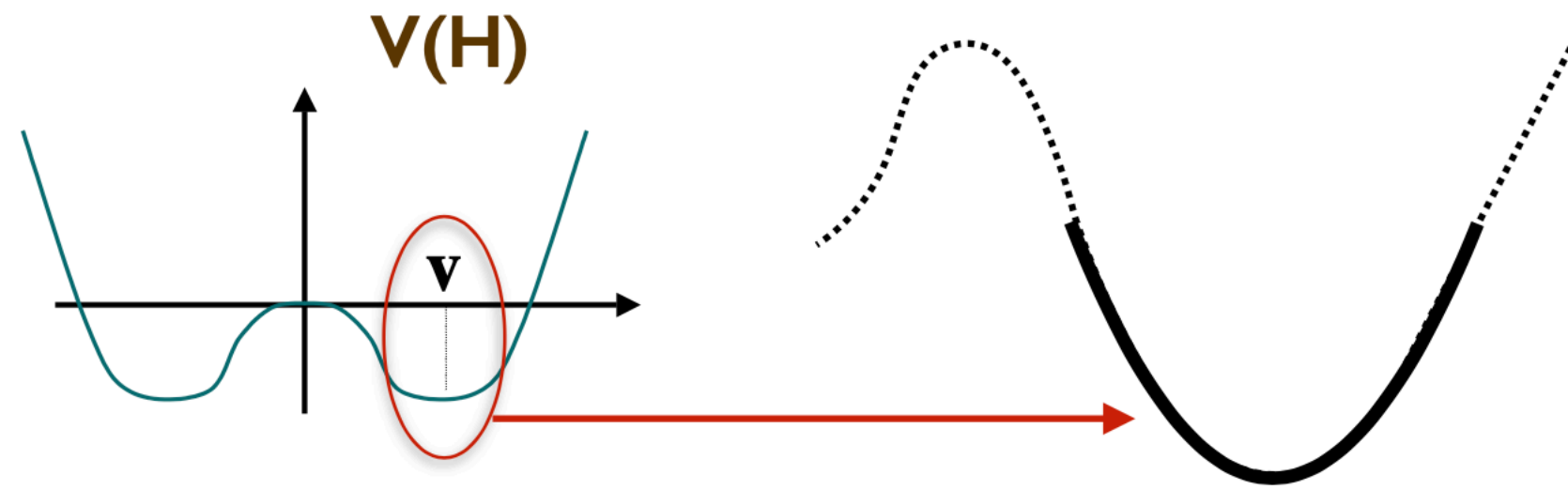
	$\sigma^{(13 \text{ TeV})} \text{ [pb]}$	$\sigma^{(14 \text{ TeV})} \text{ [pb]}$	$\sigma^{(100 \text{ TeV})} \text{ [pb]}$
LO	$4.099^{+0.051}_{-0.067}$	$4.647^{+0.037}_{-0.058}$	$77.17^{+6.45}_{-7.29}$
NLO	$3.970^{+0.025}_{-0.023}$	$4.497^{+0.032}_{-0.027}$	$73.90^{+1.73}_{-1.94}$
NNLO	$3.932^{+0.015}_{-0.010}$	$4.452^{+0.018}_{-0.012}$	$72.44^{+0.53}_{-0.40}$
N ³ LO	$3.928^{+0.005}_{-0.001}$	$4.448^{+0.006}_{-0.001}$	$72.34^{+0.11}_{-0.02}$

$$\Delta_{\text{NF}} = \frac{\sigma_{\text{VBF}}^{\text{NNLO,NF}}}{\sigma_{\text{VBF}}^{\text{LO}}} \times 100\% = -0.39\%$$

The eikonal approximation has been checked. With typical selection cuts, the non-factorizable NNLO corrections are small. For full inclusive phase space, they are of the same order as the NNLO factorisable ones.

Dreyer, Karlberg, Tancredi,20'

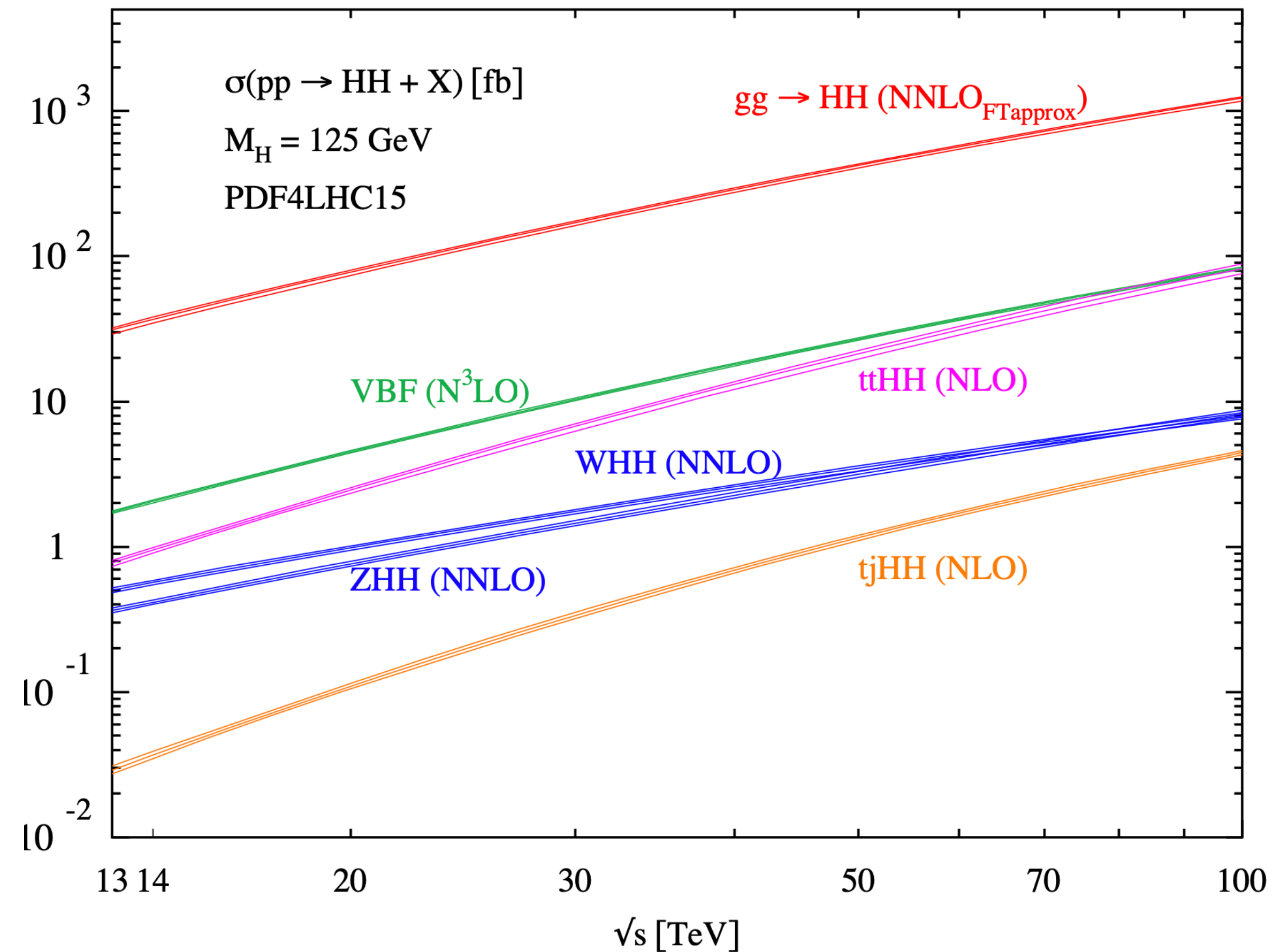
Double Higgs production



Higgs pair production is a process to access the trilinear Higgs Boson self-coupling.

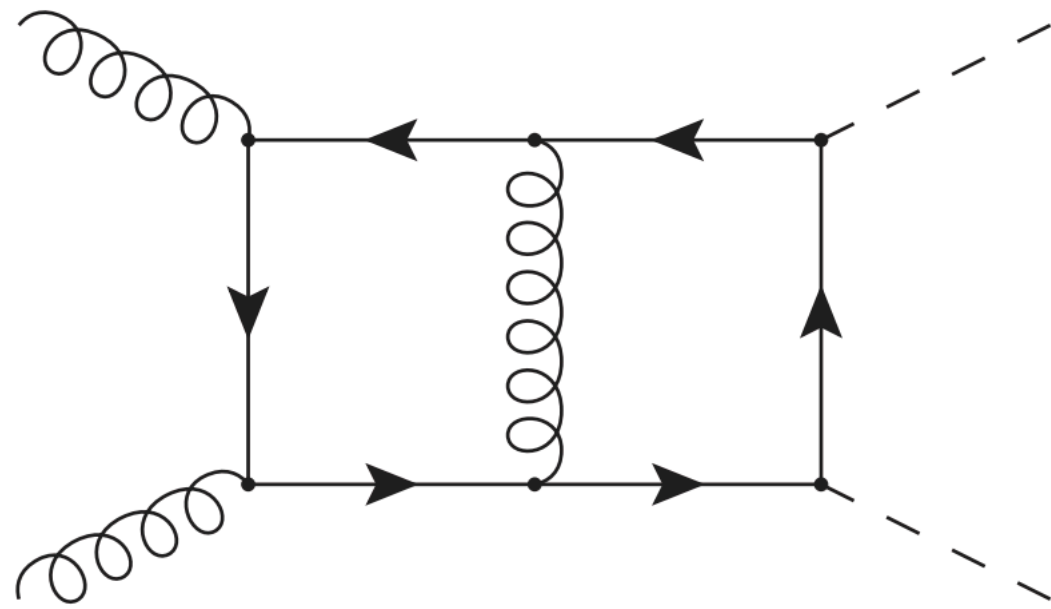
Expected accuracy:
~50% at HL-LHC,
~5% at FCC-hh @ 100 TeV

1902.00134
Mangano et al, '20



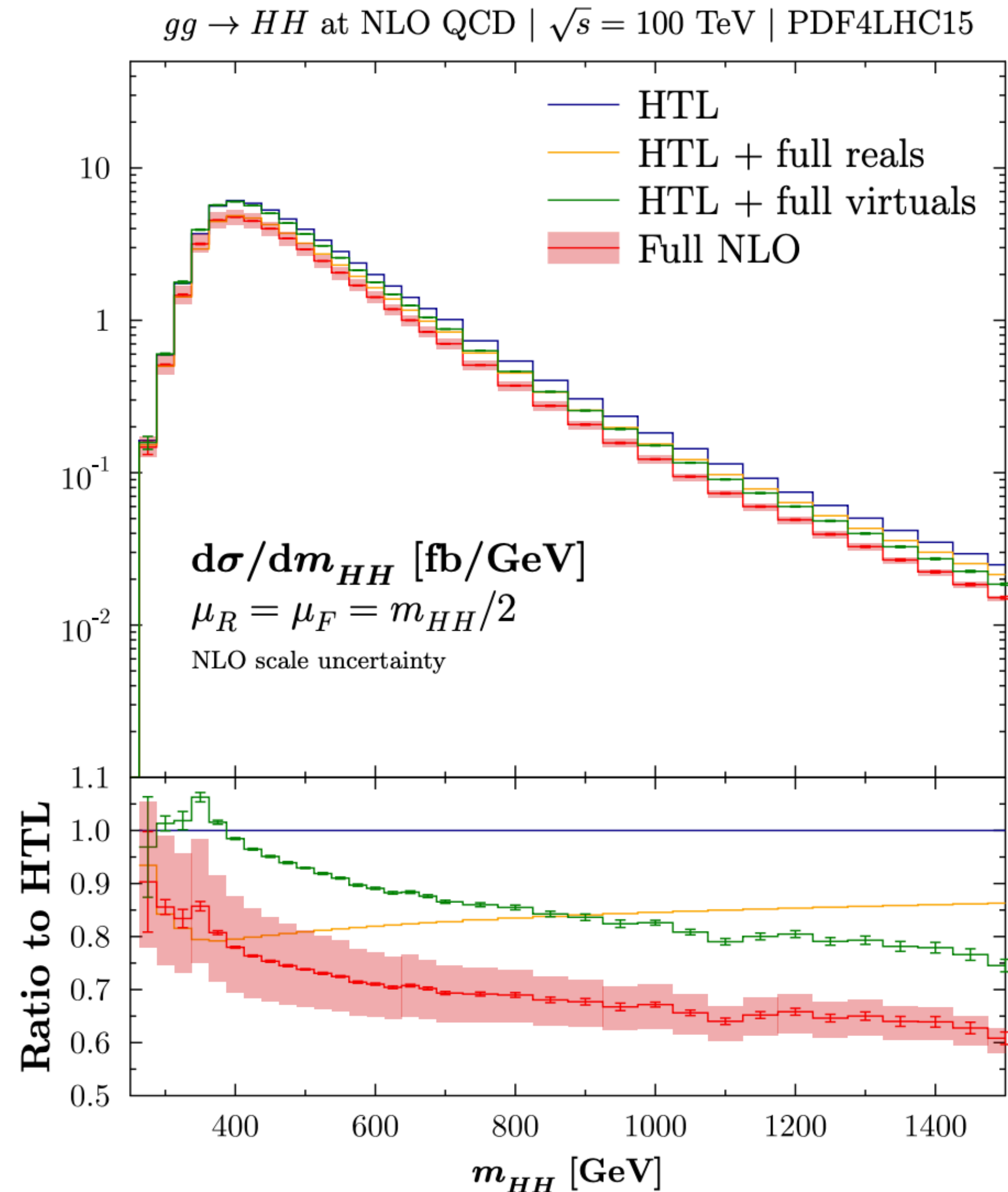
Handbook of LHC Higgs XS, 1610.07922

Double Higgs production



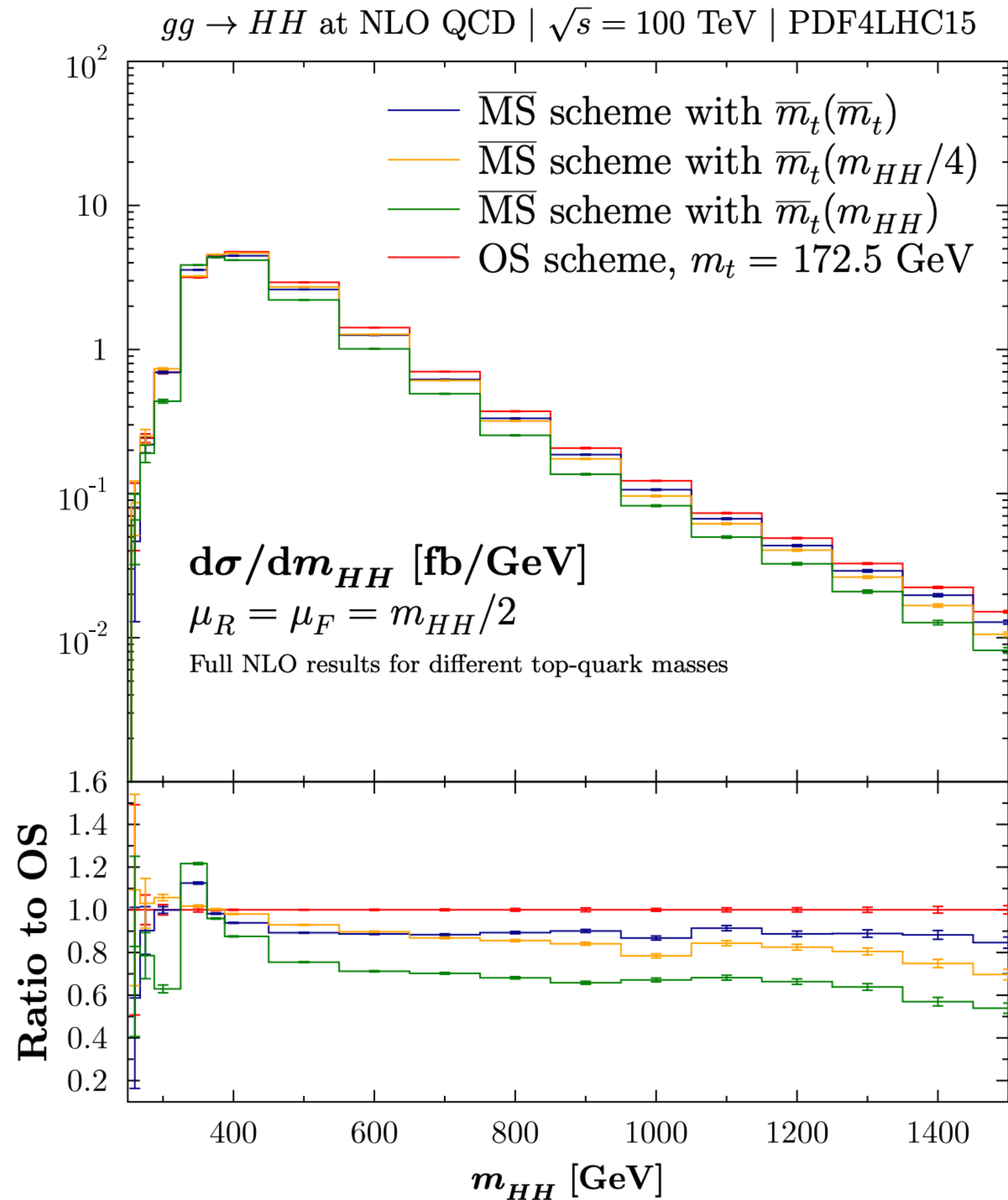
Full NLO QCD corrections:

1. Sector decomposition Borowka et al,'16
2. Contour deformation + Richardson extrapolation Baglio et al,'18, '20
3. Quasi-Monte Carlo Z. Li, JW, Q.-S.Yan, X.Zhao,'16



The HTL overshoots the full NLO by 10-40%.

Double Higgs production



Scale uncertainties:

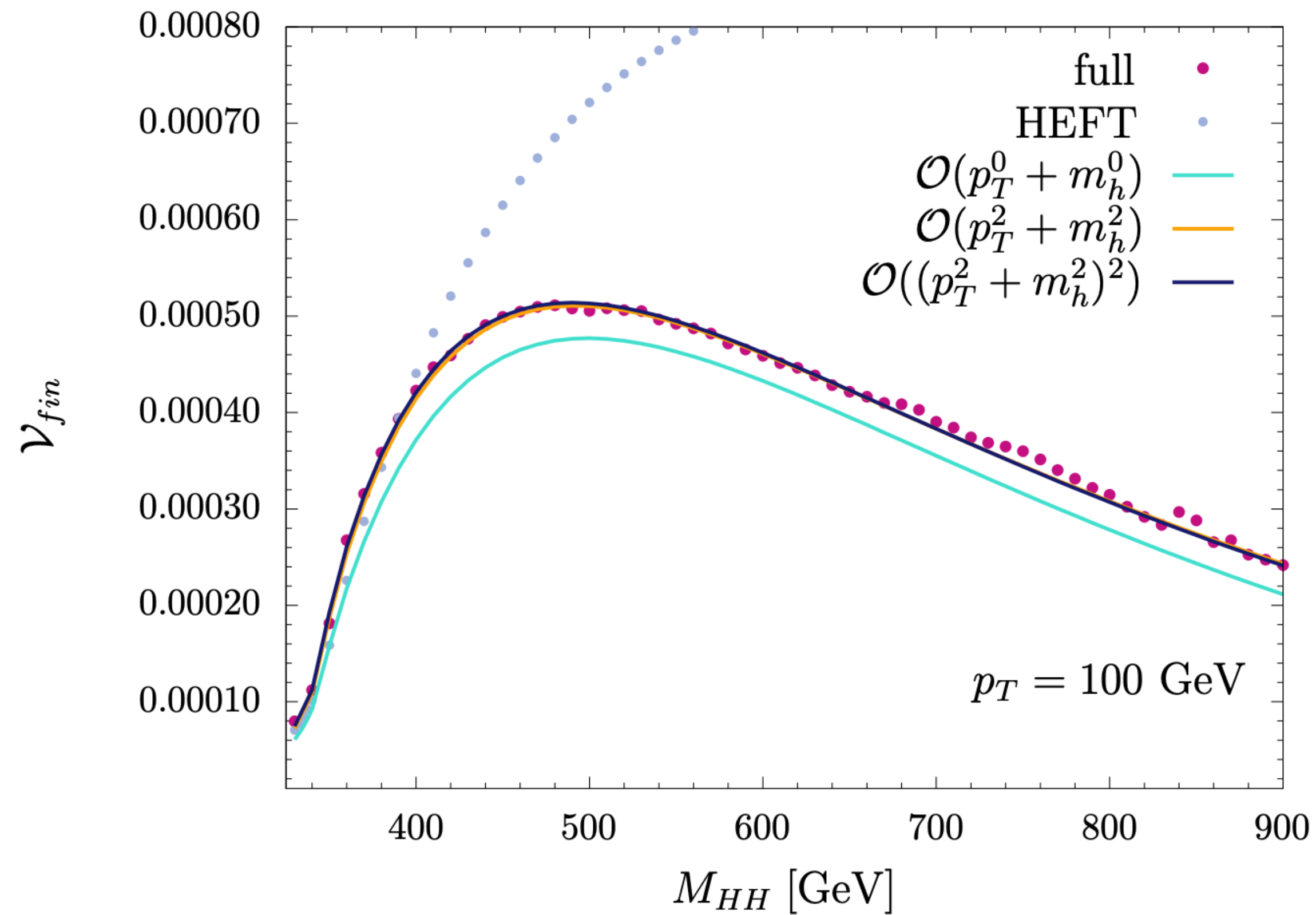
$$\begin{aligned}
 \sqrt{s} = 13 \text{ TeV} : \quad & \sigma_{tot} = 27.73(7)^{+13.8\%}_{-12.8\%} \text{ fb}, \\
 \sqrt{s} = 14 \text{ TeV} : \quad & \sigma_{tot} = 32.81(7)^{+13.5\%}_{-12.5\%} \text{ fb}, \\
 \sqrt{s} = 27 \text{ TeV} : \quad & \sigma_{tot} = 127.0(2)^{+11.7\%}_{-10.7\%} \text{ fb}, \\
 \sqrt{s} = 100 \text{ TeV} : \quad & \sigma_{tot} = 1140(2)^{+10.7\%}_{-10.0\%} \text{ fb},
 \end{aligned}$$

Top mass scheme uncertainties:

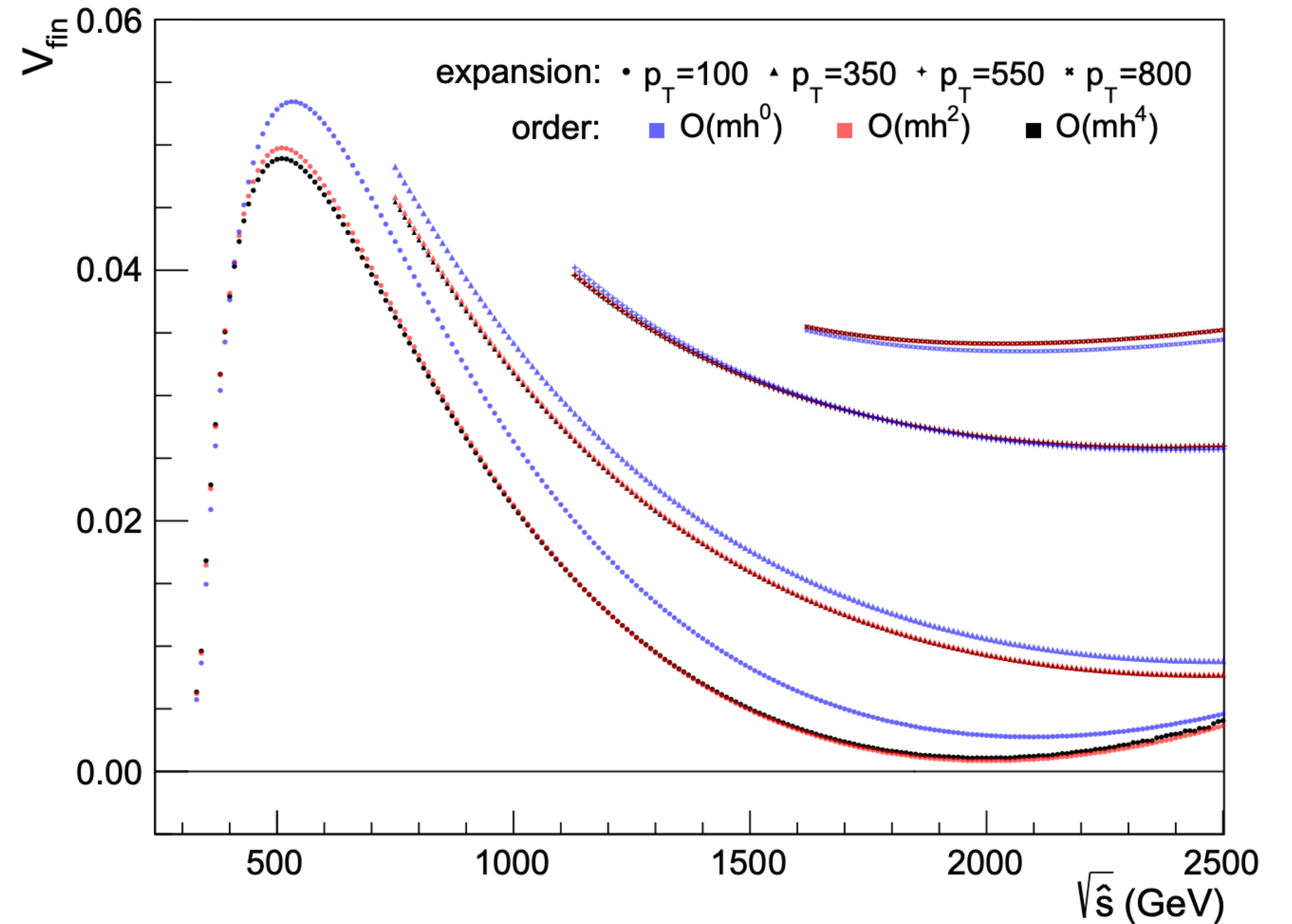
$$\begin{aligned}
 \sqrt{s} = 13 \text{ TeV} : \quad & \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%} \text{ fb}, \\
 \sqrt{s} = 14 \text{ TeV} : \quad & \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%} \text{ fb}, \\
 \sqrt{s} = 27 \text{ TeV} : \quad & \sigma_{tot} = 127.0(2)^{+4\%}_{-18\%} \text{ fb}, \\
 \sqrt{s} = 100 \text{ TeV} : \quad & \sigma_{tot} = 1140(2)^{+3\%}_{-18\%} \text{ fb}
 \end{aligned}$$

Double Higgs production

Analytical approach:



Bonciani et al,'18

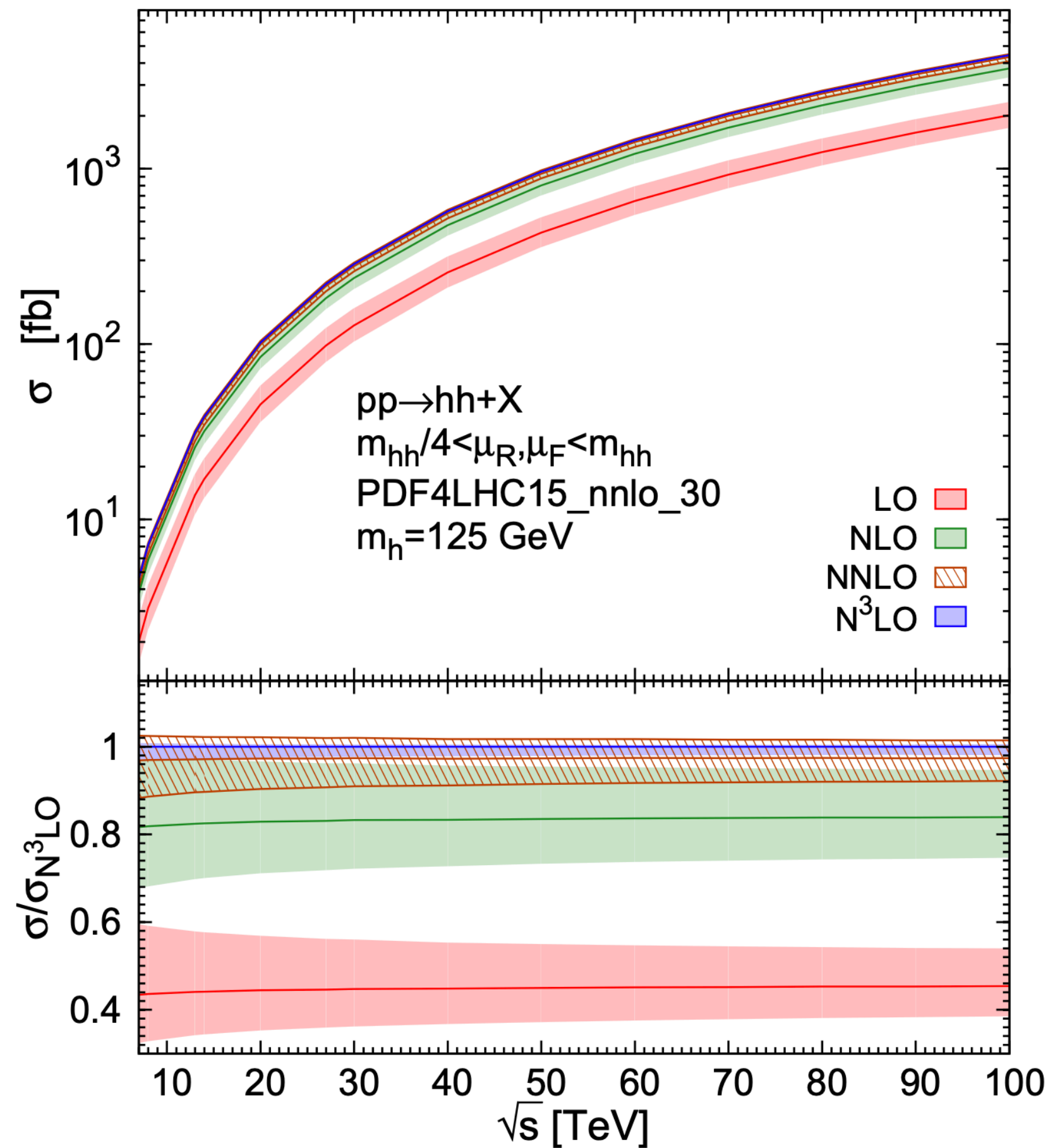
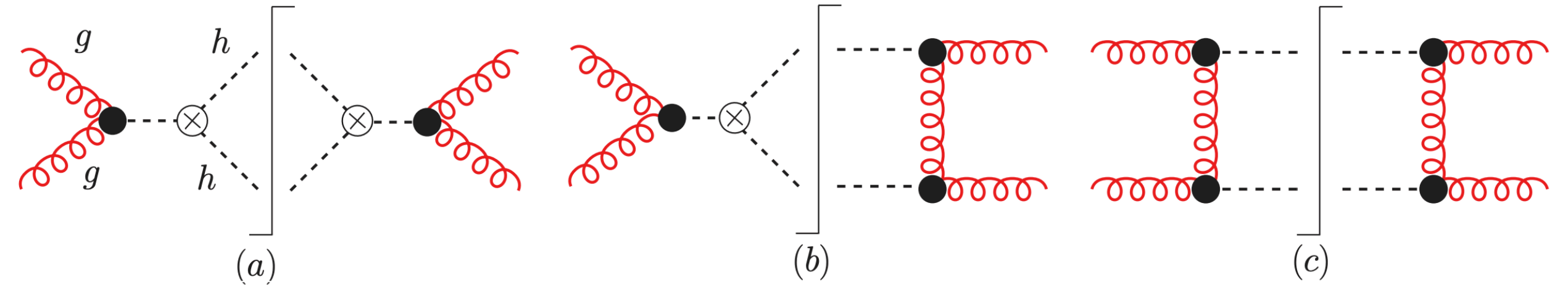


Xu, Yang '18; Wang et al,'20

Double Higgs production

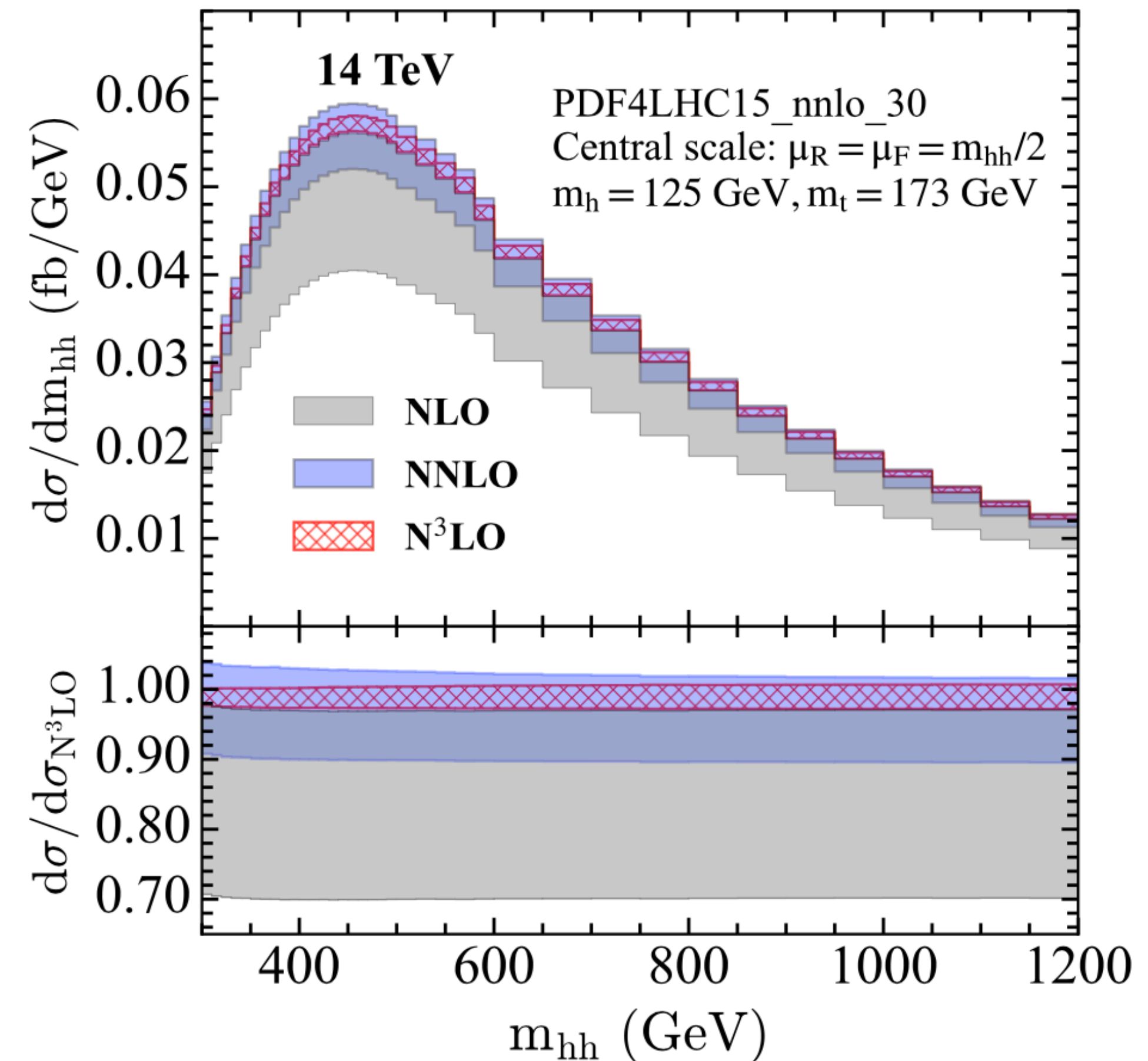
NNNLO QCD corrections in HTL

Chen, Li, Shao, JW, '19, '20



$$\frac{\sigma_{\text{NNNLO}}}{\sigma_{\text{NNLO}}} \sim 3\%$$

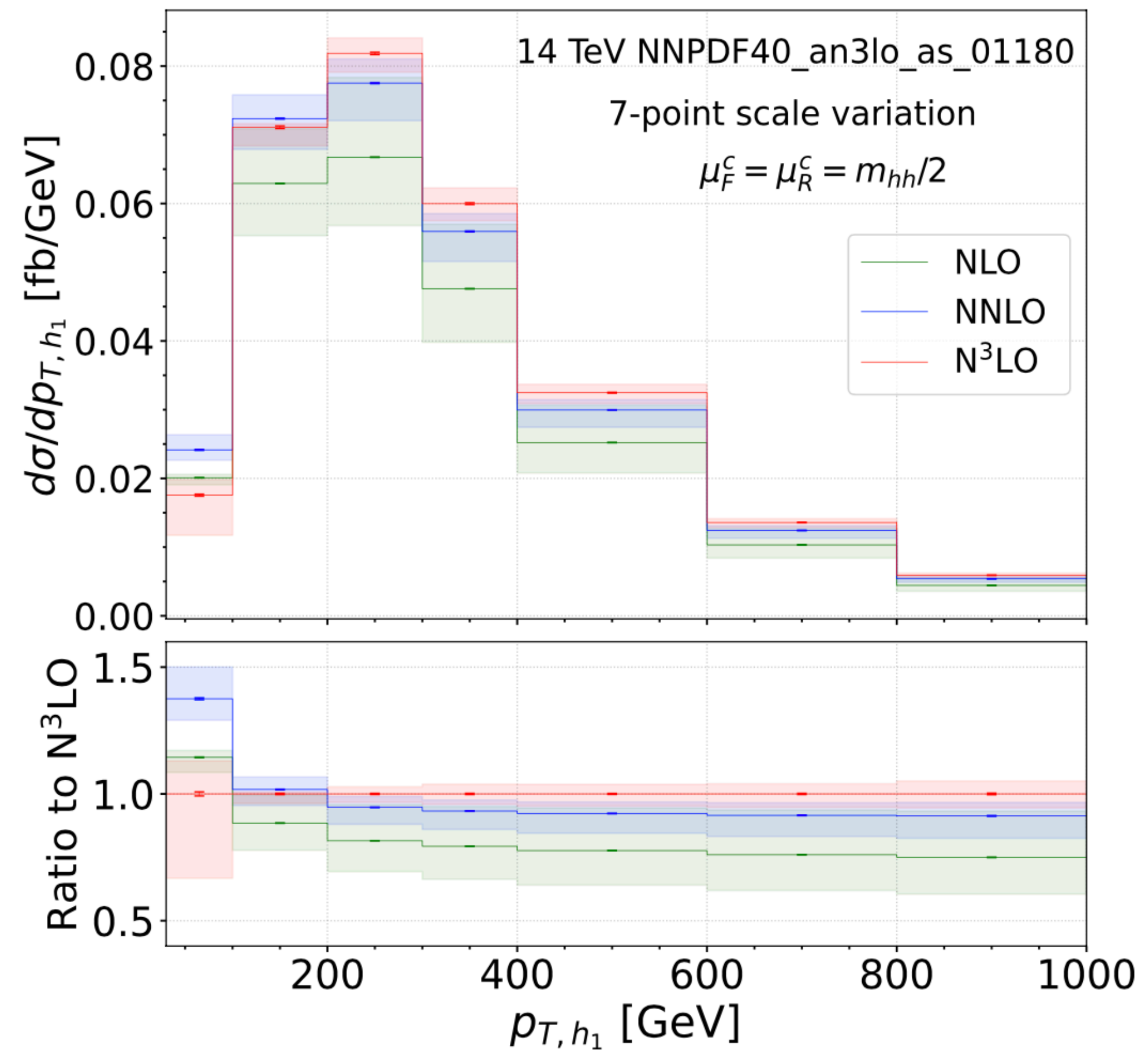
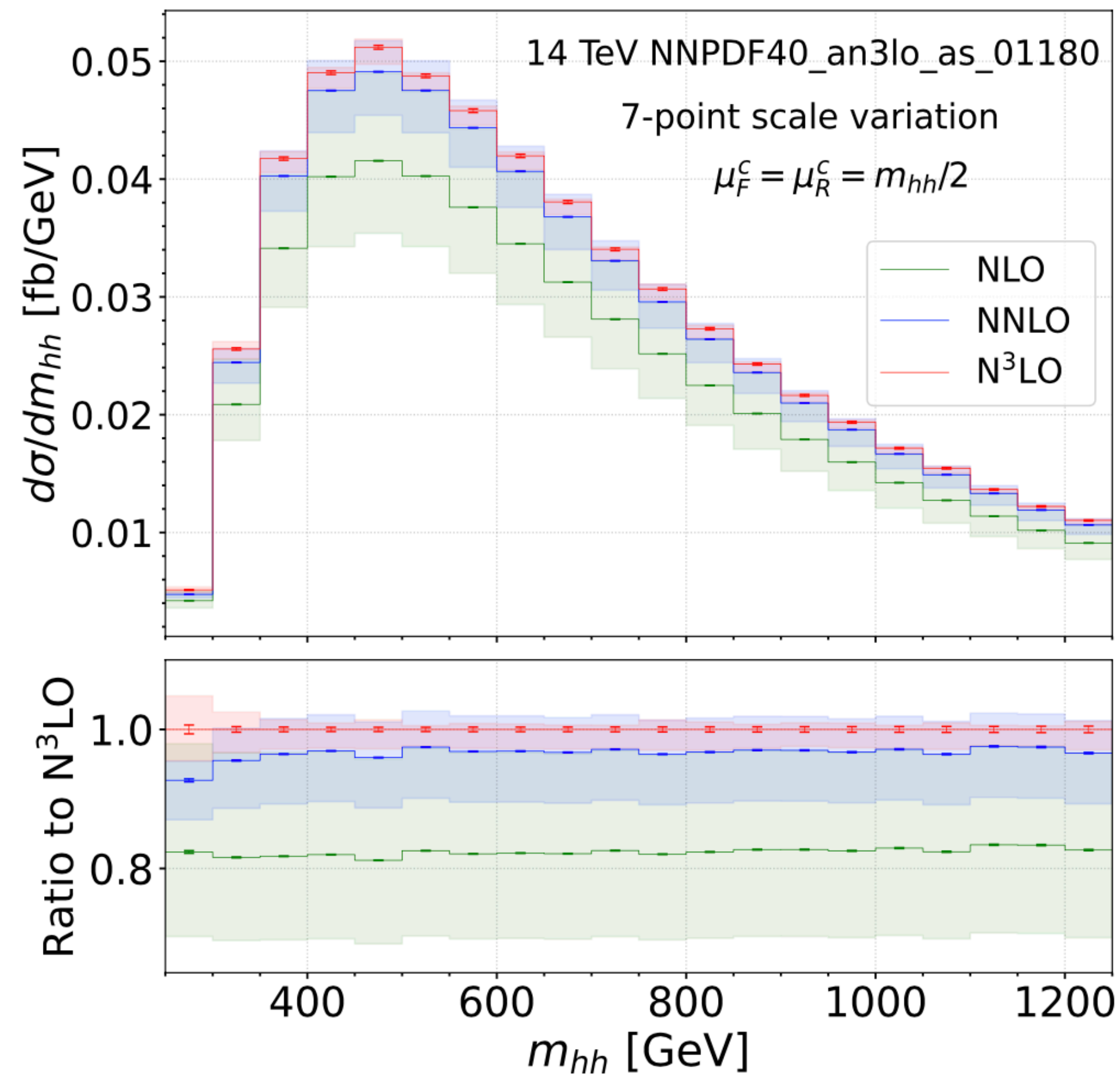
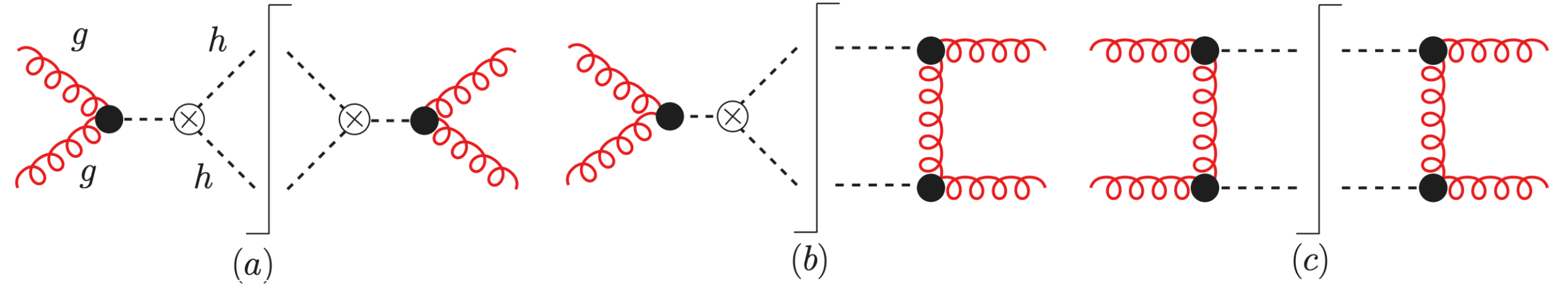
Scale unc.
 NNLO: 7%
 NNNLO: 3%



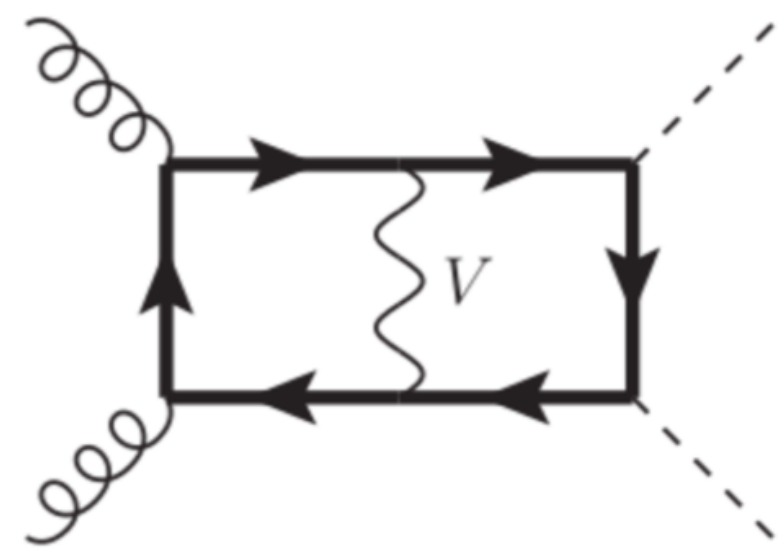
Double Higgs production

NNNLO QCD corrections in HTL

Chen, Dai, Li, Li, Shao, JW, '26

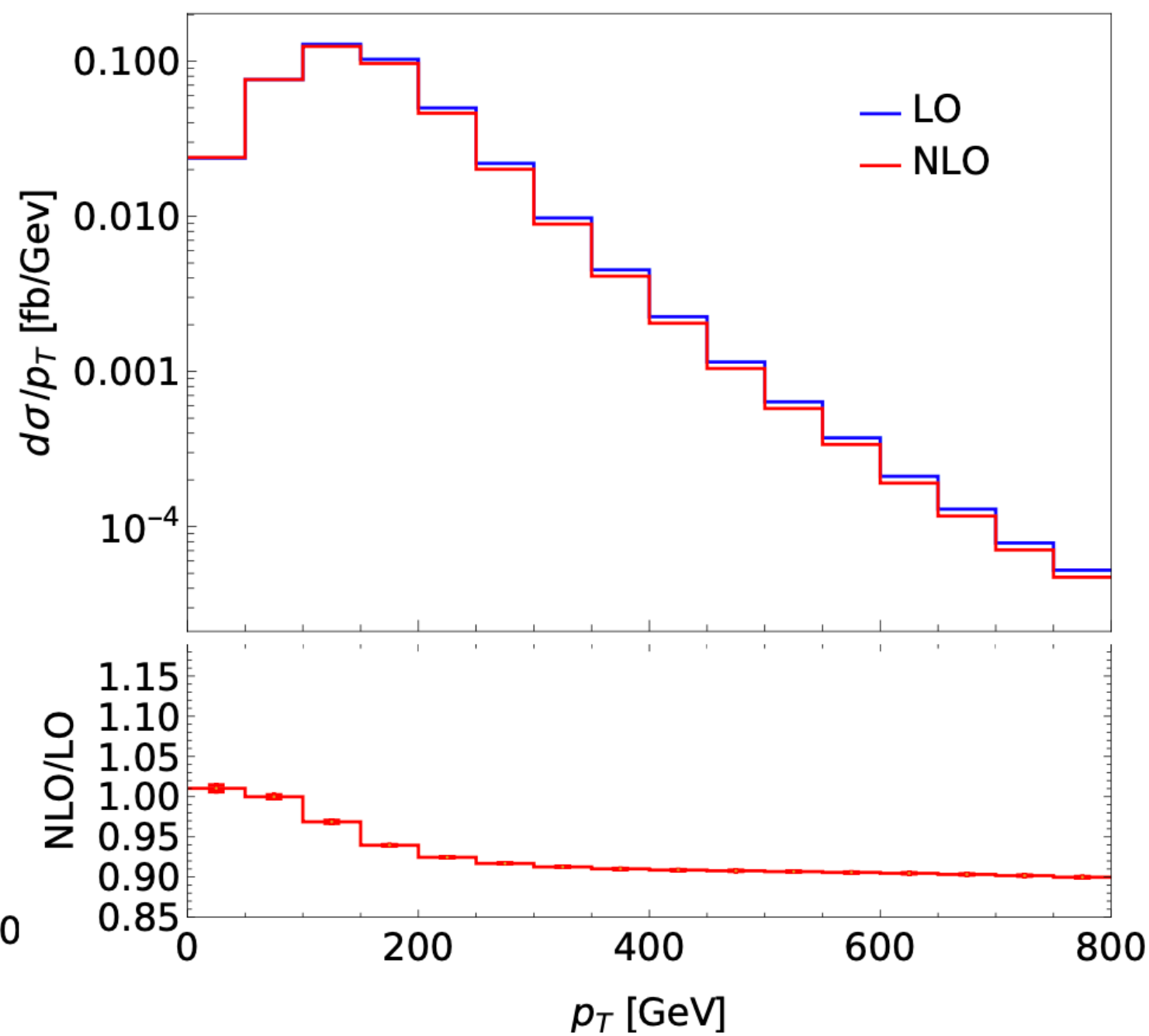
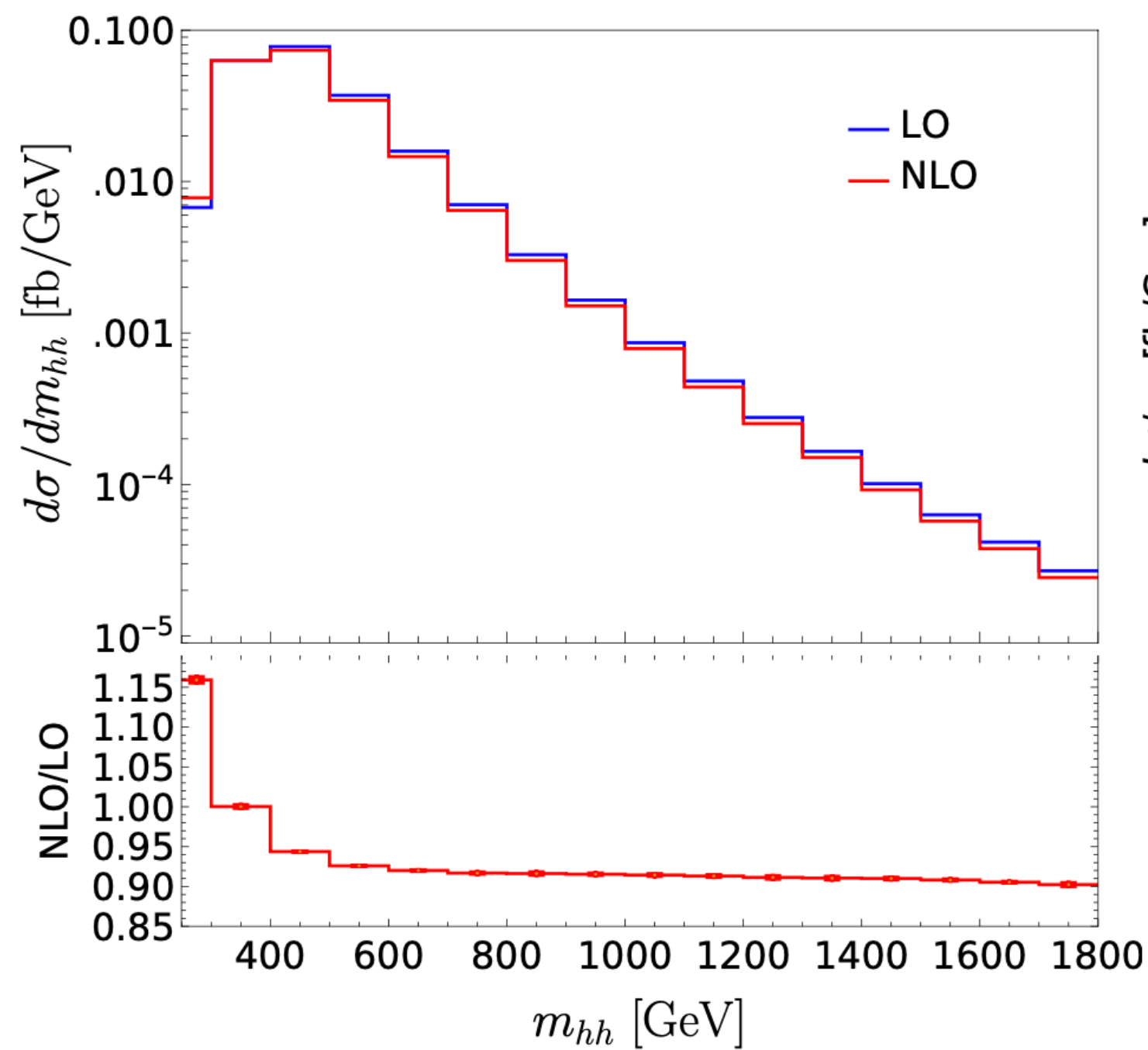


Double Higgs production



schemes	G_μ	α_0	α_{m_Z}
LO	19.96	18.84	21.28
NLO	19.12	19.19	19.03
$\mathcal{K}$ -factor	0.958	1.019	0.894

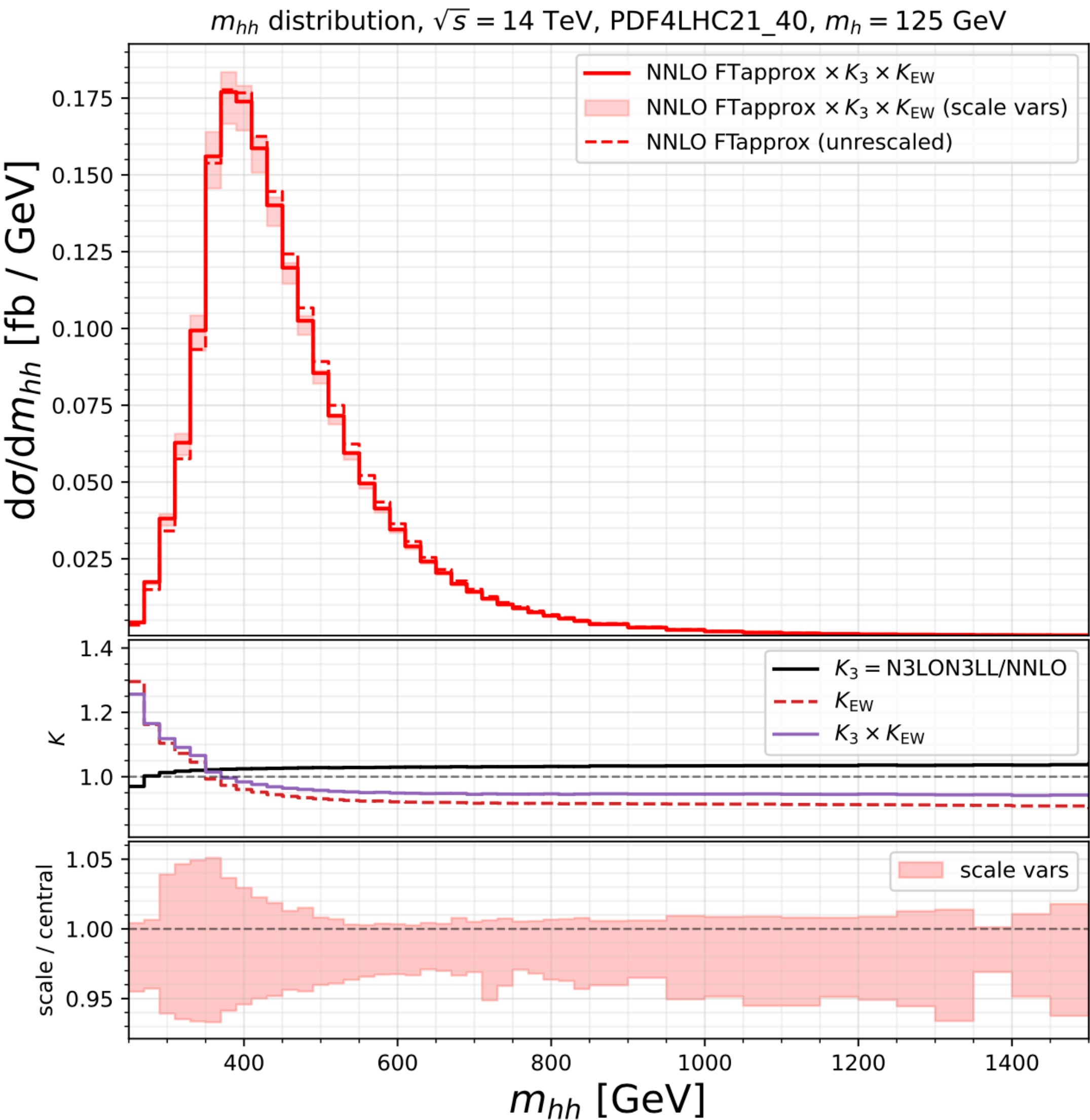
Scheme uncertainty ~13% at LO,
Reduced to ~1% at NLO in EW.



NLO EW corrections increase the cross section
by ~15% near threshold.

Large negative corrections at high pT region.

Double Higgs production



LHCHWG Recommendation for future analyses

$\sqrt{s}$ [TeV]	13	13.6	14
$\sigma_{\text{rec.}}$ [fb]	30.40	33.62	35.81
$\pm$ PDF unc. [%]	1.96	1.92	1.89
$\pm \alpha_s$ unc. [%]	1.51	1.49	1.47
$\pm$ PDF + α_s unc. [%]	2.47	2.43	2.39
QCD scale unc. [%]	+2.11 −4.98	+2.07 −4.85	+2.01 −4.78
m_t scheme unc. [%]	+5 −16	+5 −16	+5 −16
$\pm$ TH _{num} [%]	0.14	0.19	0.21
Scale + TH _{num} + m_t scheme unc. [%]	+7.25 −21.12	+7.26 −21.04	+7.22 −20.99

m_h [GeV]	$\sigma_{\text{rec.}}$ [fb]		
	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 13.6$ TeV	$\sqrt{s} = 14$ TeV
124.8	30.48	33.68	35.90
125	30.40	33.62	35.81
125.2	30.29	33.54	35.68

Double Higgs production

The Higgs self-couplings have not been determined. They can be taken as free parameters.

$$\mathcal{L} \supset m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu - \frac{1}{2} m_H^2 H^2 - \kappa_3 v \lambda H^3 - \kappa_4 \frac{\lambda}{4} H^4$$

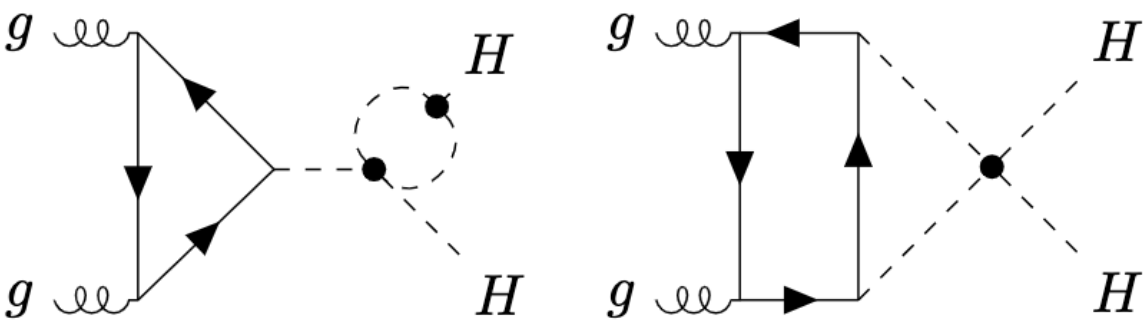
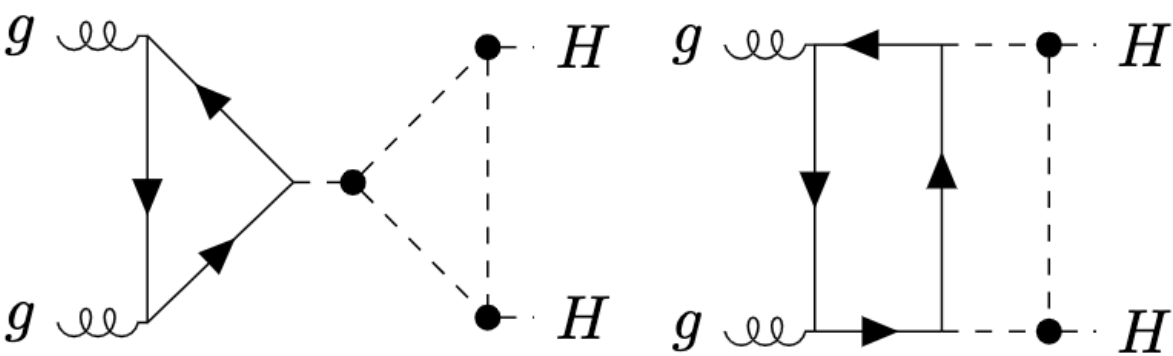
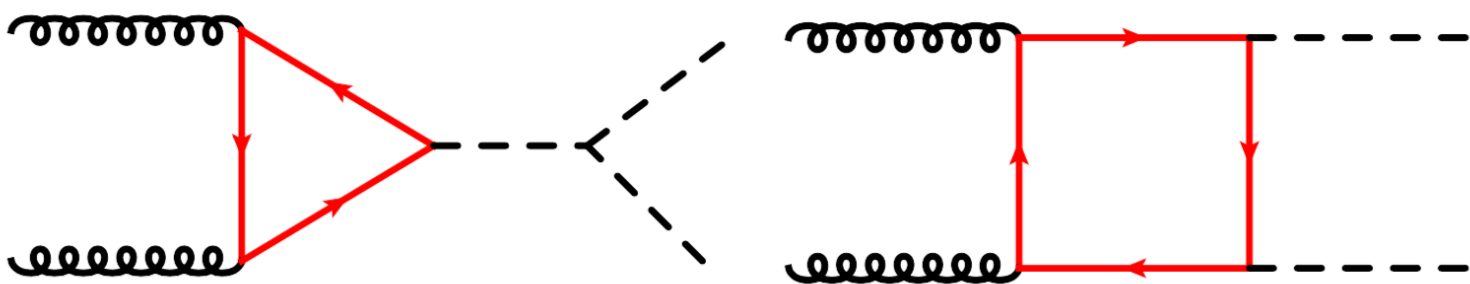
$$\sigma_{HH} = A + B\kappa_3 + C\kappa_3^2$$

computation	A [fb]	A/A(LO)	B [fb]	B/B(LO)	C [fb]	C/C(LO)
LO m_t fin	35.0		-23.0		4.73	
NLO m_t fin	62.6	1.79	-44.4	1.93	9.64	2.04
NLO m_t fin $\times$ NNLO SM FTApprox	70.0	2.00	-49.6	2.16	10.8	2.28
NNLO + NNLL $m_t \rightarrow \infty \times$ NNLO+NLL SM (partial m_t fin)	71.3	2.04	-47.7	2.08	9.93	2.10

1910.00012

$$\sigma_{HH} = A + B\kappa_3 + C\kappa_3^2 + D\kappa_3^3 + E\kappa_3^4 + F\kappa_3^2\kappa_4 + G\kappa_3\kappa_4 + H\kappa_4 + \dots$$

Higher power terms may increase the sensitivity.



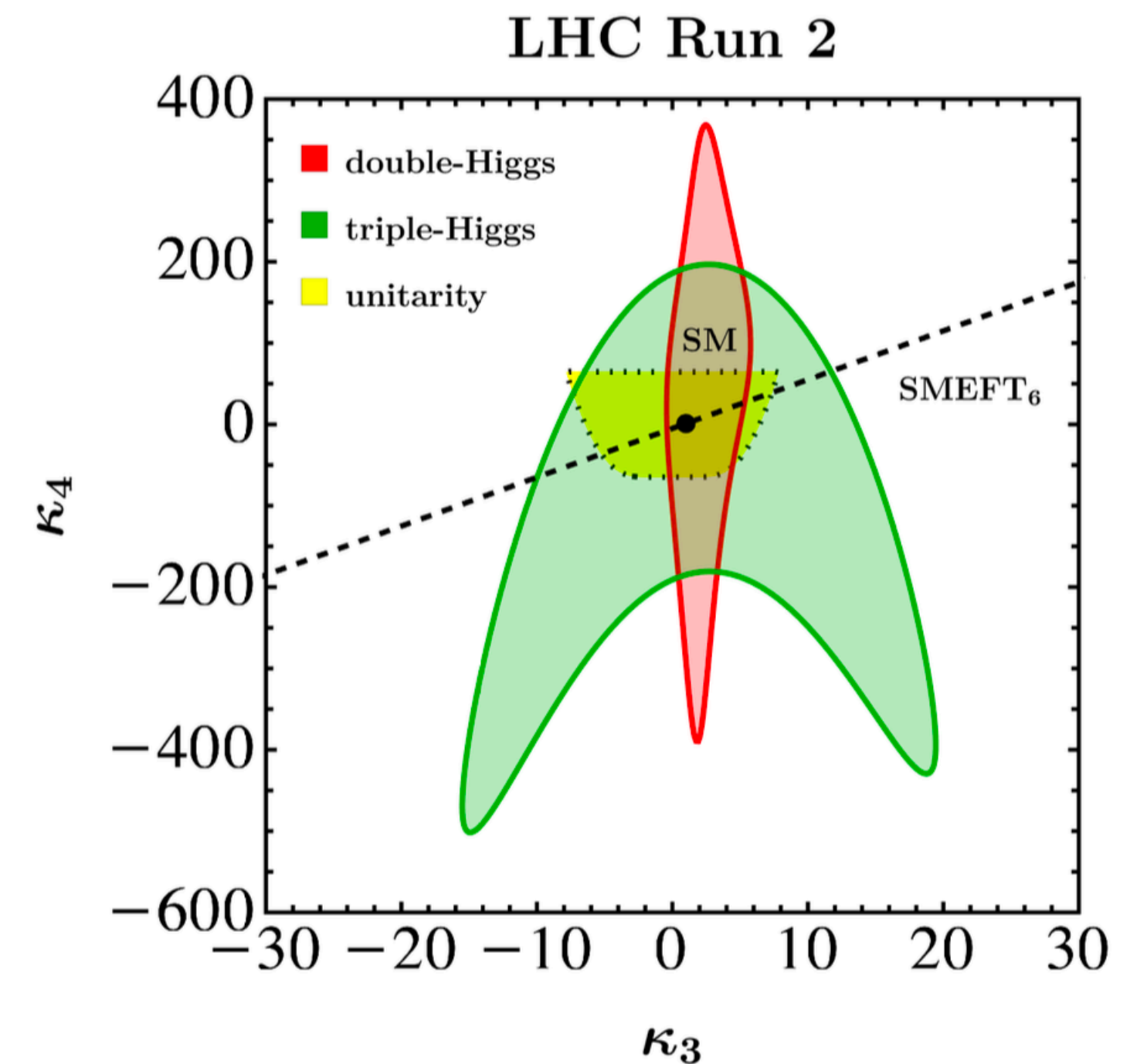
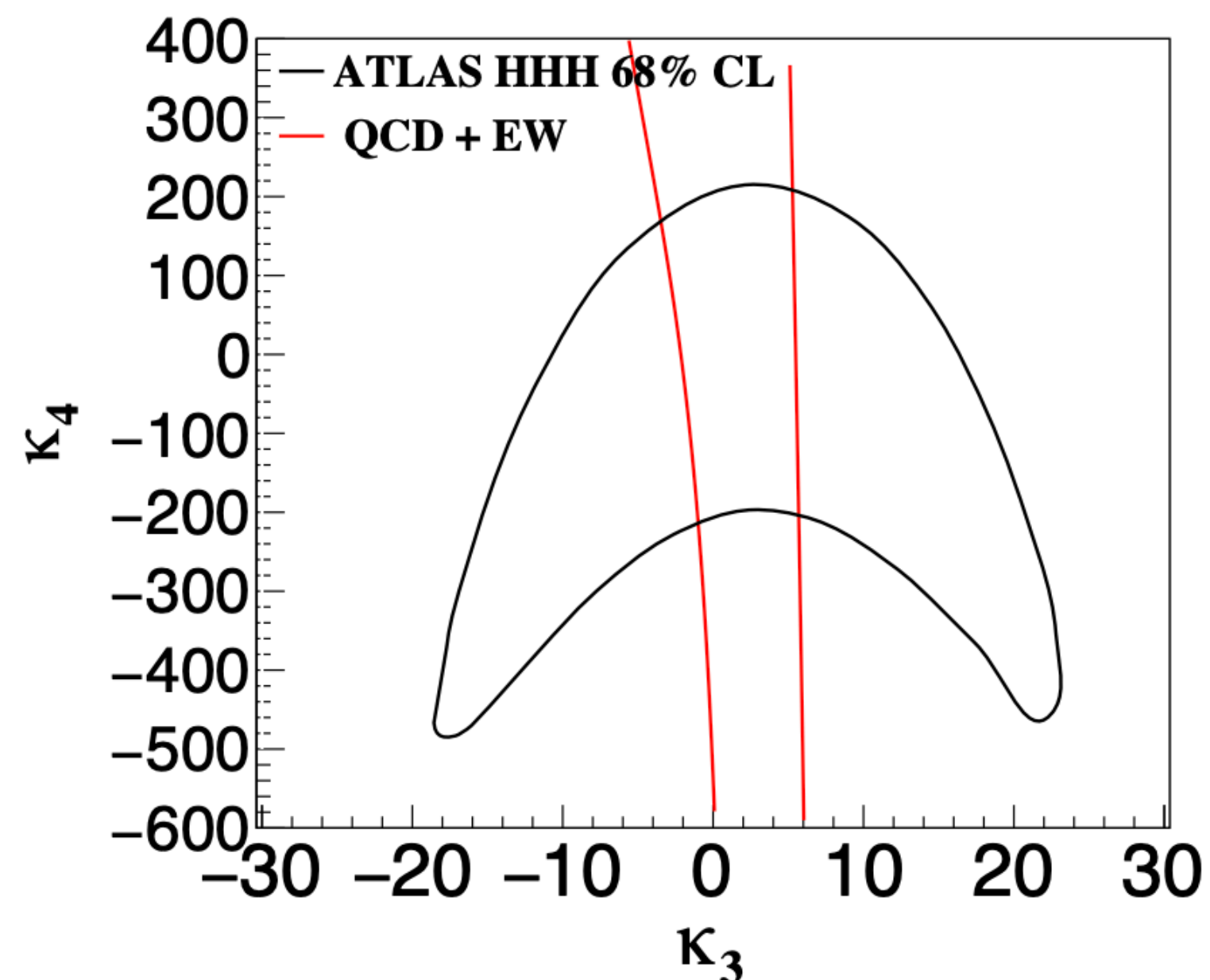
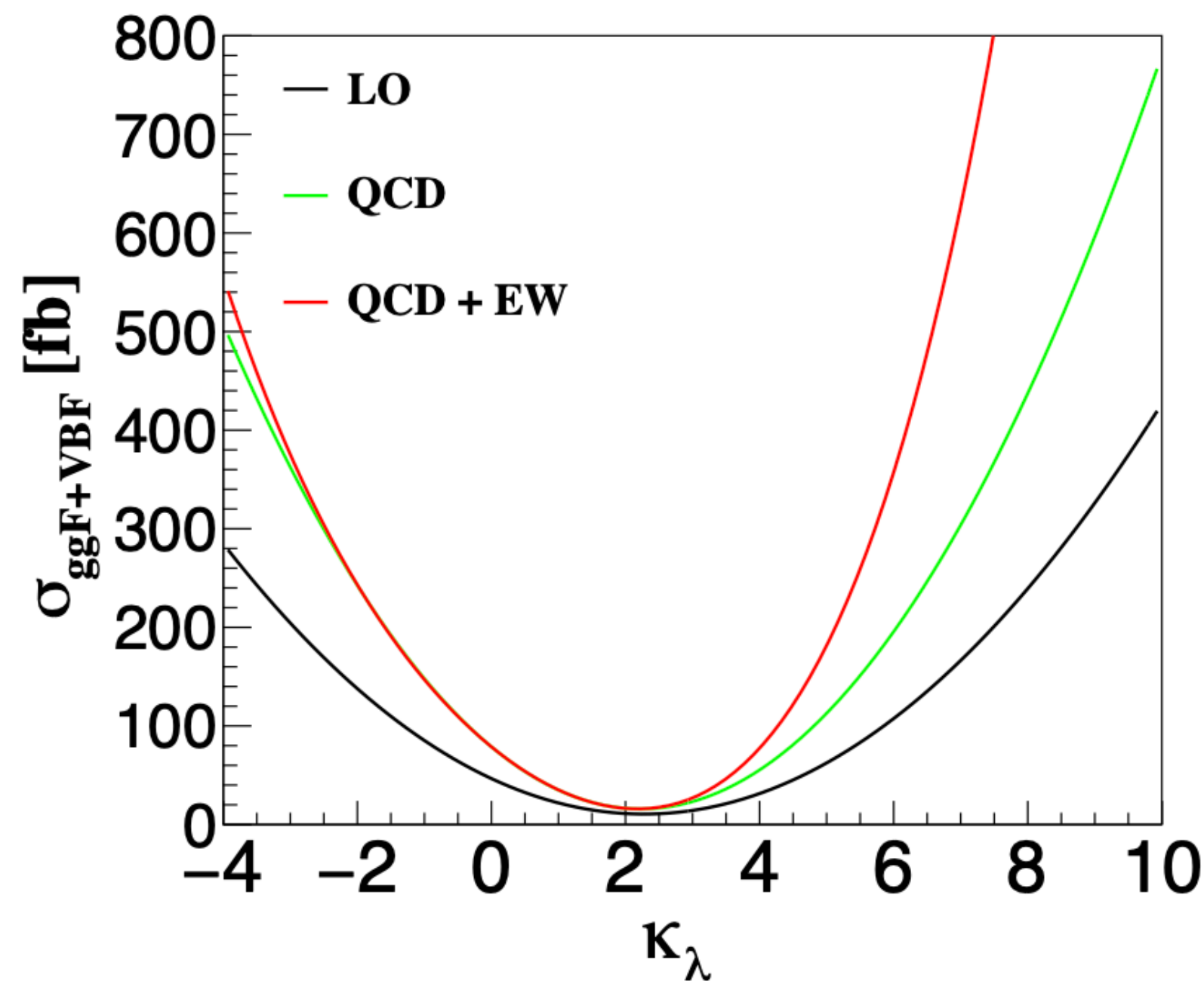
Double Higgs production

The λ dependent corrections are

LHCHWG Recommendation for future analyses

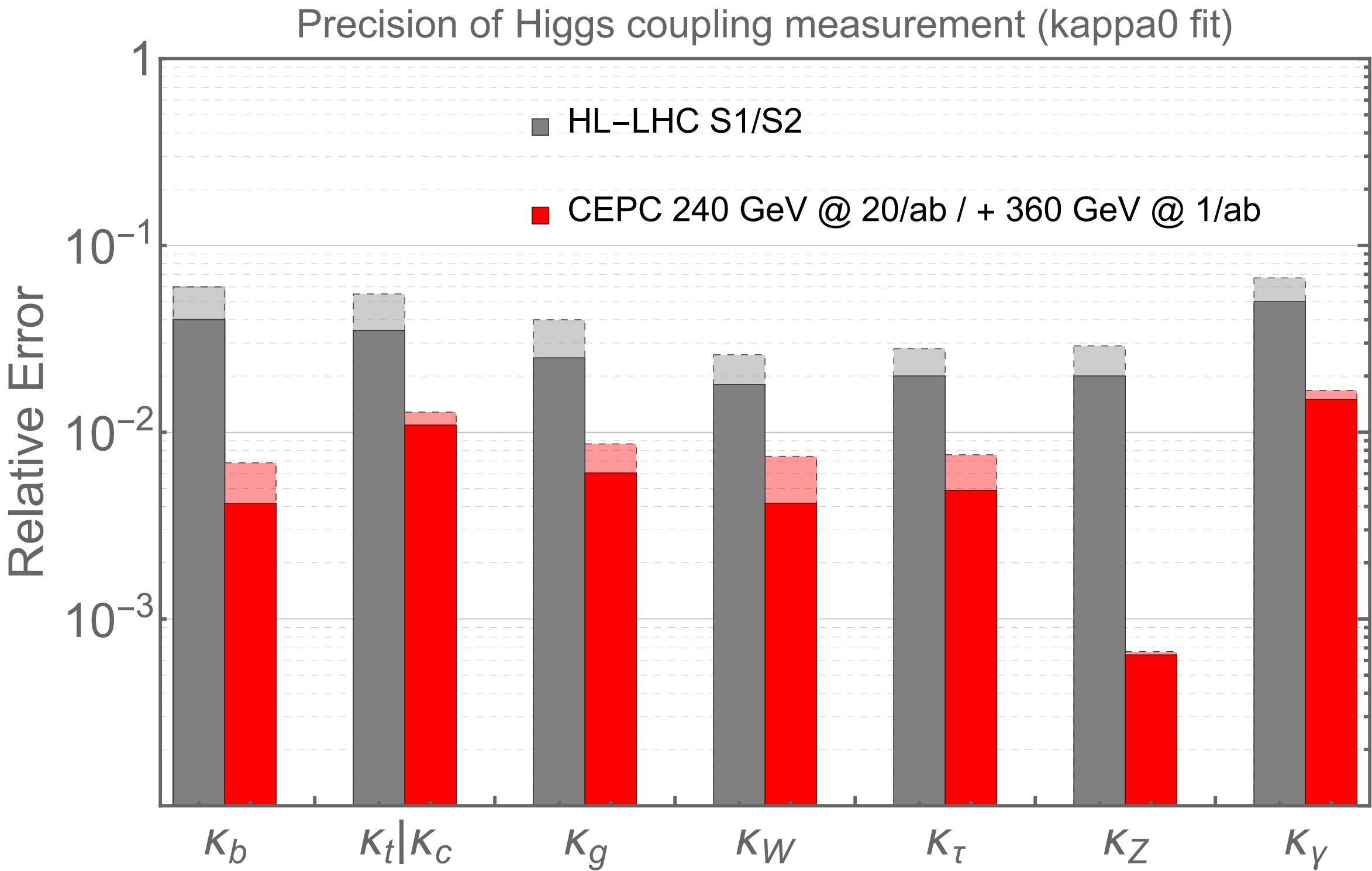
$$\sigma_{\text{ggF,EW}_{\text{II}}}^{13.6 \text{ TeV}} = (0.074\kappa_3^4 - 0.114\kappa_3^3 - 0.006\kappa_3^2\kappa_4 - 0.185\kappa_3^2 + 0.077\kappa_3\kappa_4 - 0.163\kappa_4) \text{ fb},$$

$$\sigma_{\text{VBF,EW}_{\text{II}}}^{13.6 \text{ TeV}} = (2.11\kappa_3^4 - 2.00\kappa_3^3 - 0.44\kappa_3^2\kappa_4 - 3.76\kappa_3^2 + 3.35\kappa_3\kappa_4 - 3.56\kappa_4) \cdot 10^{-2} \text{ fb},$$



Higgs decay

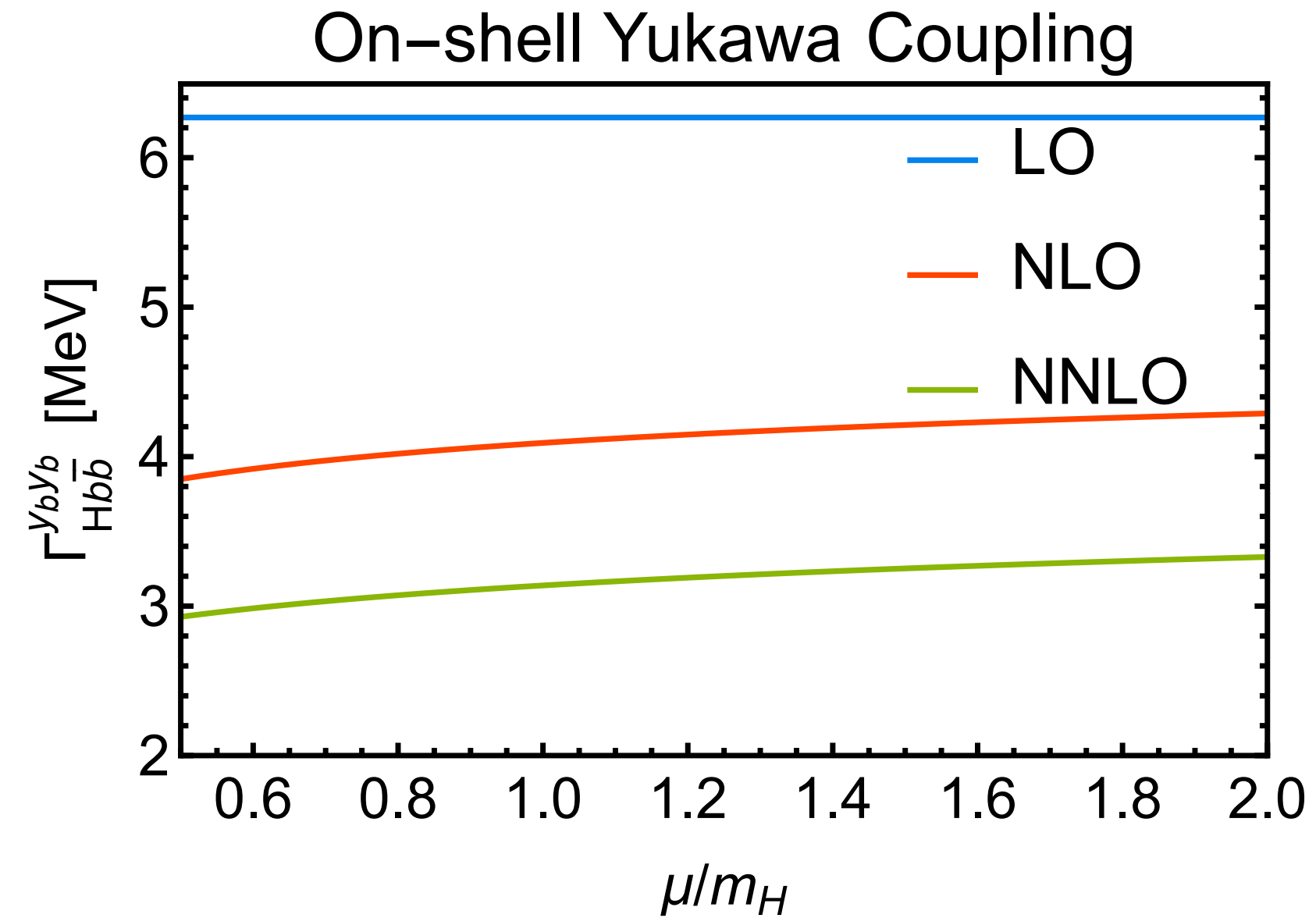
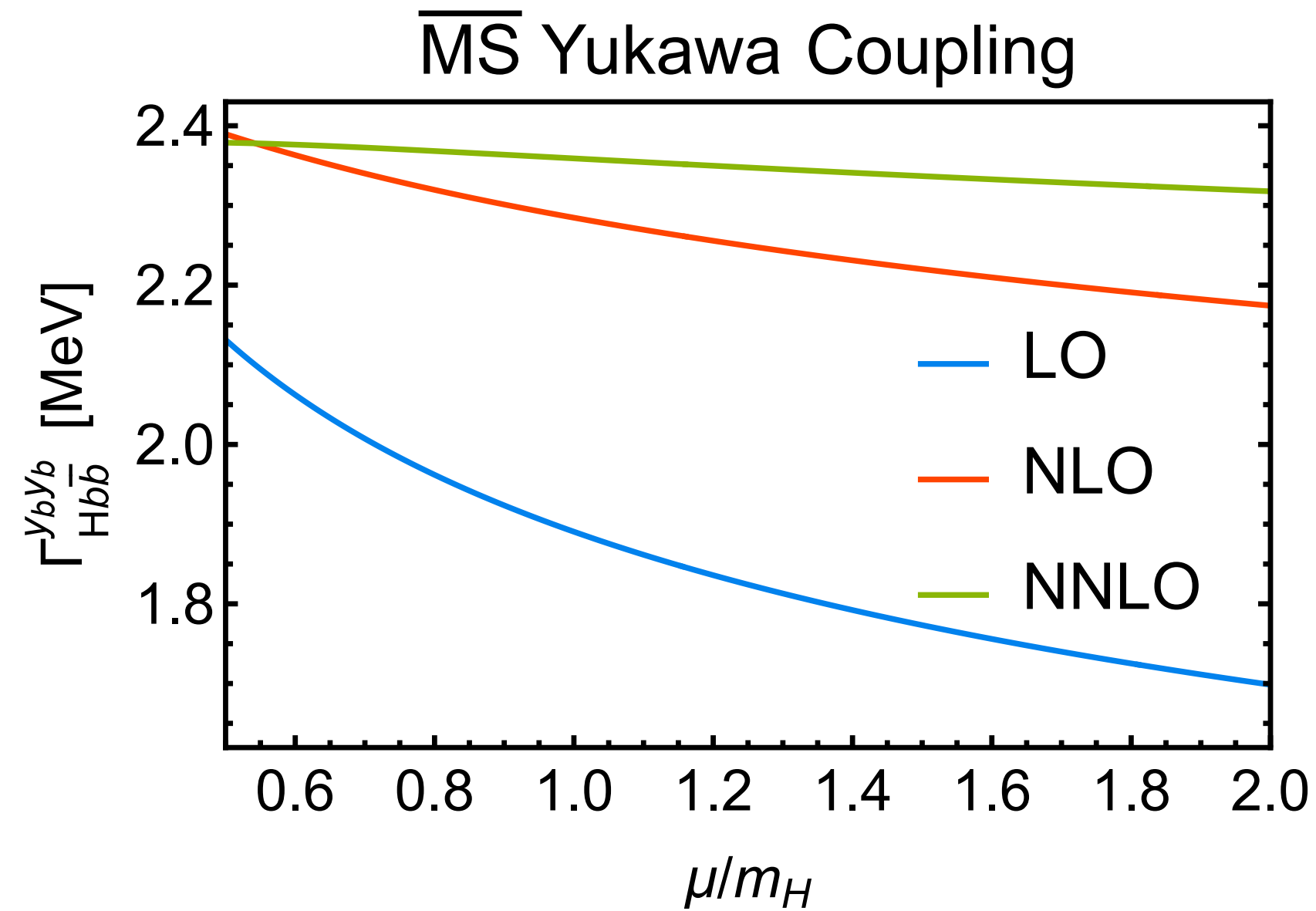
	240 GeV, 20 ab ⁻¹		360 GeV, 1 ab ⁻¹		
	ZH	vvH	ZH	vvH	eeH
inclusive	0.26%		1.40%	\	\
H→bb	0.14%	1.59%	0.90%	1.10%	4.30%
H→cc	2.02%		8.80%	16%	20%
H→gg	0.81%		3.40%	4.50%	12%
H→WW	0.53%		2.80%	4.40%	6.50%
H→ZZ	4.17%		20%	21%	
$H \rightarrow \tau\tau$	0.42%		2.10%	4.20%	7.50%
$H \rightarrow \gamma\gamma$	3.02%		11%	16%	
$H \rightarrow \mu\mu$	6.36%		41%	57%	
$H \rightarrow Z\gamma$	8.50%		35%		
$\text{Br}_{upper}(H \rightarrow inv.)$	0.07%				
Γ_H	1.65%		1.10%		



2205.08553

Higgs decay rates and couplings can be measured at (sub-)percent level.

Higgs decay

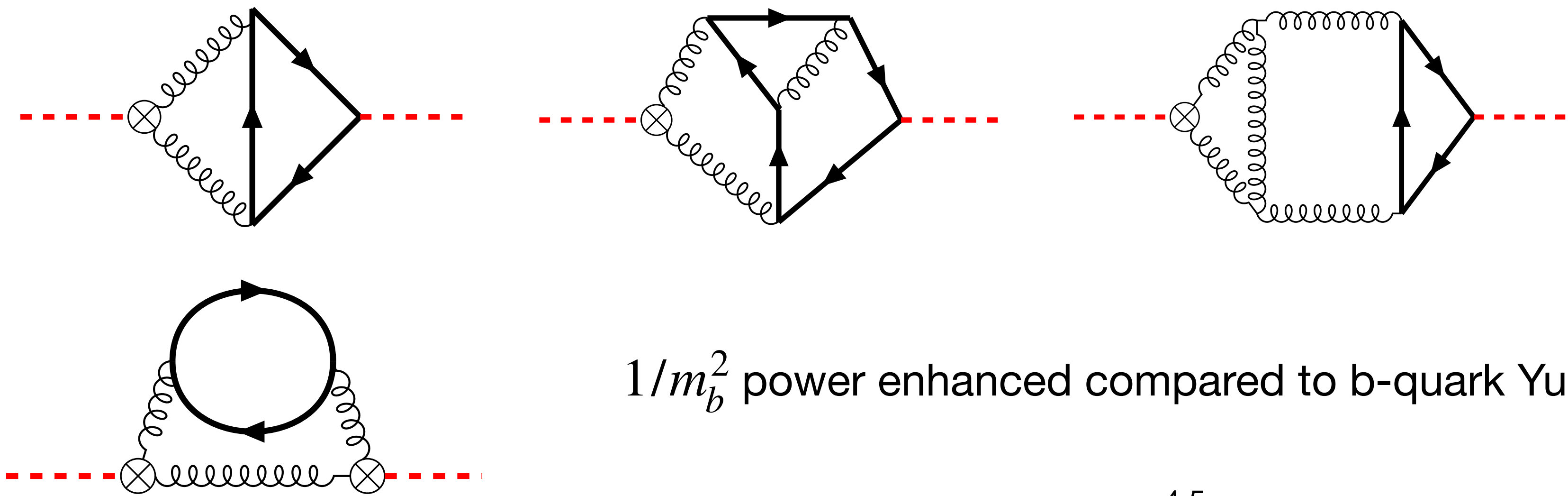


width	LO	NLO	NNLO(y_b^2)	NNLO($y_b y_t$)	NNNLO(y_b^2)	NNNNLO(y_b^2)
$\overline{\text{MS}}$	$1.891^{+0.241}_{-0.192}$	$2.285^{+0.105}_{-0.110}$	$2.359^{+0.020}_{-0.041}$	$2.376^{+0.026}_{-0.046}$	$2.379^{+0.005}_{-0.015}$	$2.377^{+0.006}_{-0.006}$
on-shell	6.269	$4.092^{+0.197}_{-0.242}$	$3.138^{+0.191}_{-0.210}$	$3.193^{+0.181}_{-0.197}$	$2.804^{+0.112}_{-0.096}$	$2.649^{+0.065}_{-0.049}$

In MSbar scheme, the perturbative expansion is more stable.

The corrections beyond NNLO are only 0.7%.

Higgs decay

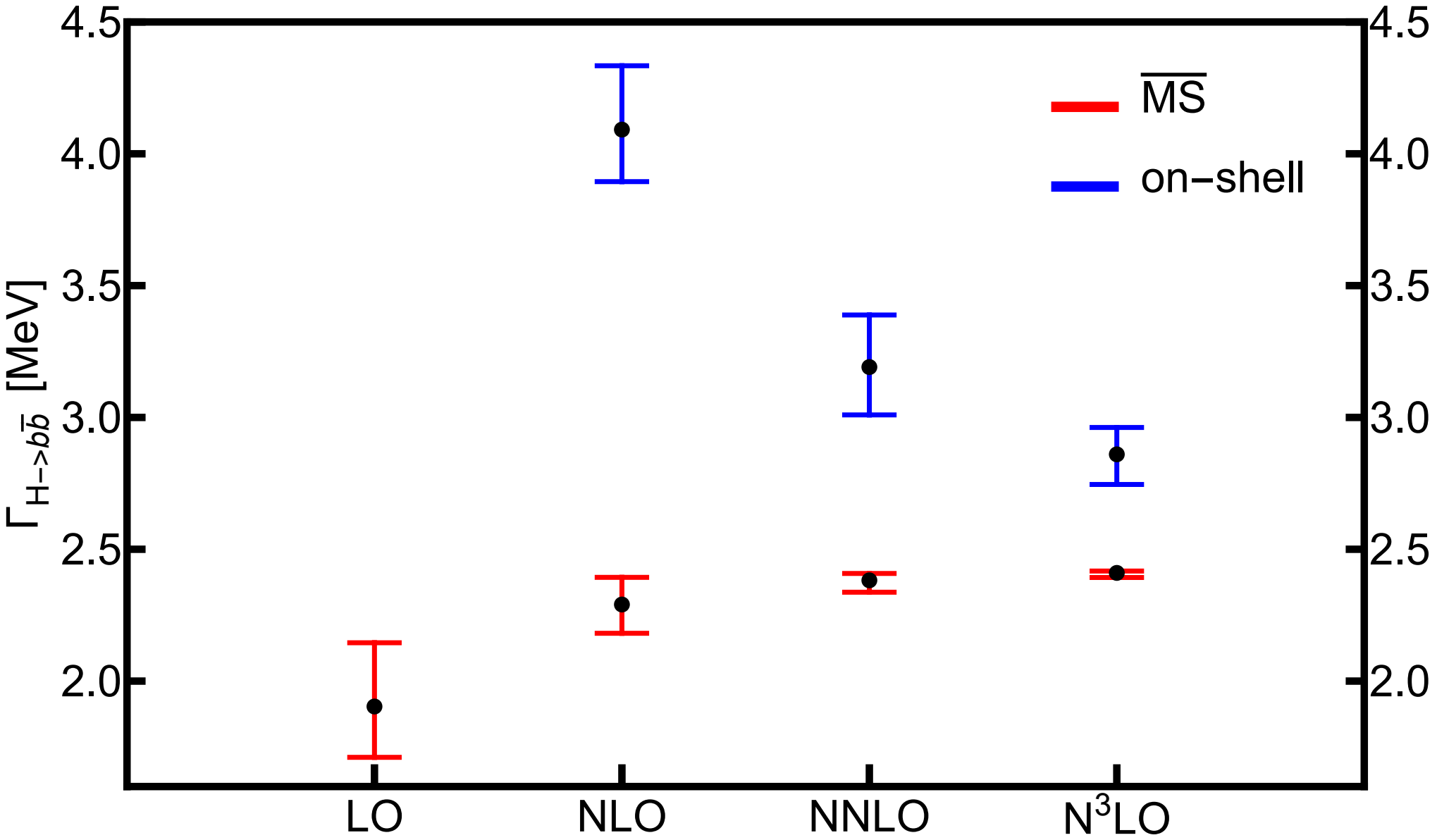


$\ln^2(m_H^2/m_b^2)$ enhanced

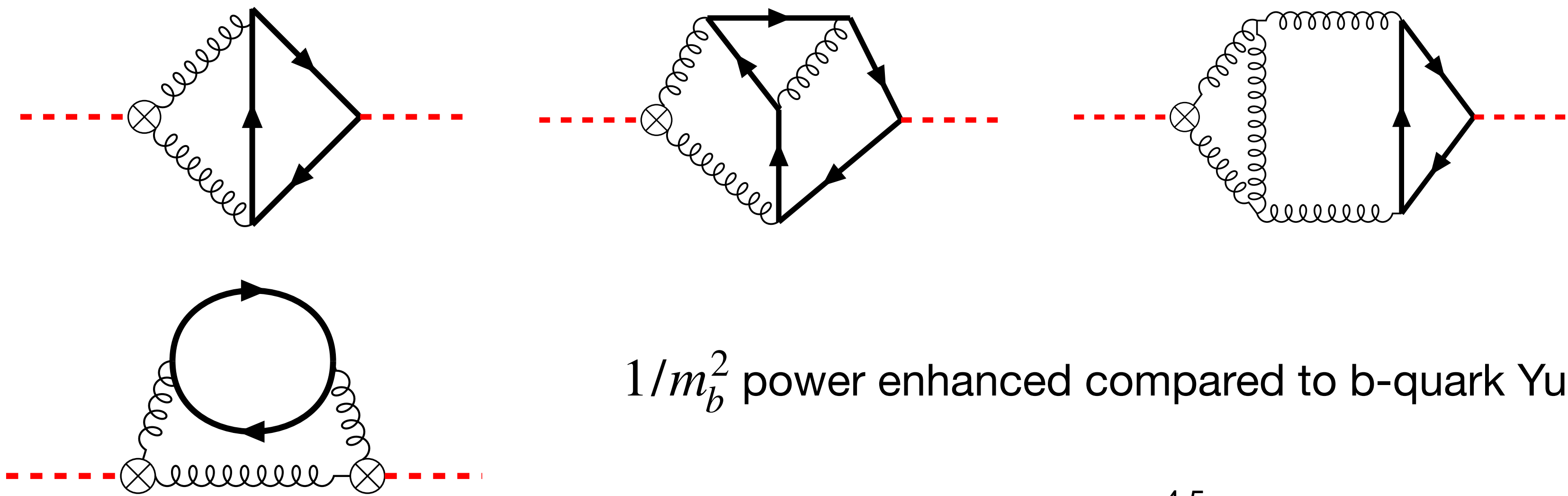
$1/m_b^2$ power enhanced compared to b-quark Yukawa induced decay.

	[MeV]	$\mu = \frac{1}{2}m_H$	$\mu = m_H$	$\mu = 2m_H$
$\mathcal{O}(\alpha_s^0)$	$\Gamma_{Hb\bar{b}}^{C_2C_2}$	2.1314	1.8905	1.6985
$\mathcal{O}(\alpha_s^1)$	$\Gamma_{Hb\bar{b}}^{C_2C_2}$	0.25813	0.39409	0.47563
$\mathcal{O}(\alpha_s^2)$	$\Gamma_{Hb\bar{b}}^{C_2C_2}$	-0.0043084	0.076819	0.143670
	$\Gamma_{Hb\bar{b}}^{C_1C_2}$	0.027078	0.024746	0.022608
$\mathcal{O}(\alpha_s^3)$	$\Gamma_{Hb\bar{b}}^{C_2C_2}$	-0.015360	0.0048336	0.038198
	$\Gamma_{Hb\bar{b}}^{C_1C_2}$	0.010314	0.013585	0.015170
	$\Gamma_{Hb\bar{b}}^{C_1C_1}$	0.0088676	0.0064617	0.0048595

over 1 %



Higgs decay

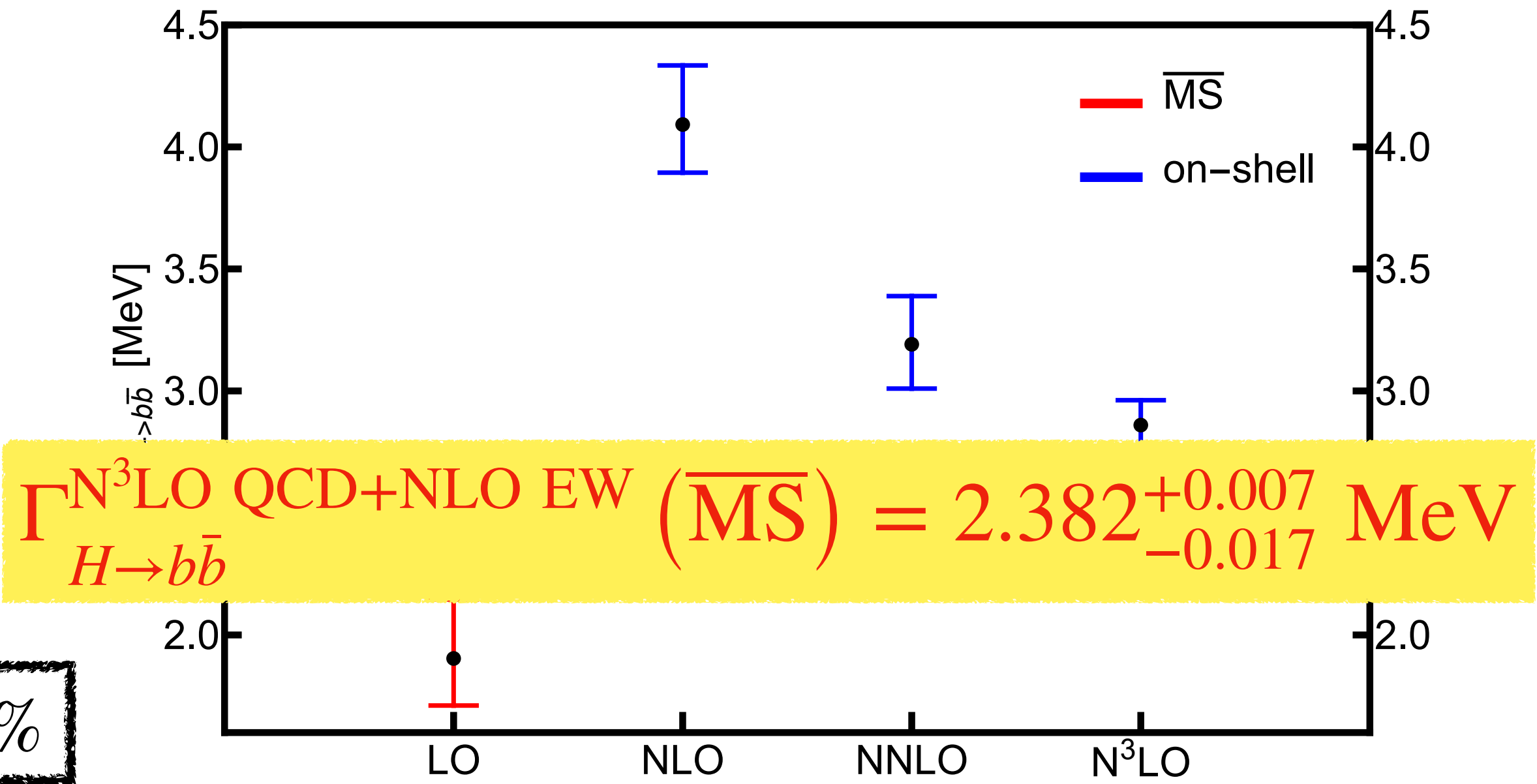


$\ln^2(m_H^2/m_b^2)$ enhanced

$1/m_b^2$ power enhanced compared to b-quark Yukawa induced decay.

	[MeV]	$\mu = \frac{1}{2}m_H$	$\mu = m_H$	$\mu = 2m_H$
$\mathcal{O}(\alpha_s^0)$	$\Gamma_{Hb\bar{b}}^{C_2C_2}$	2.1314	1.8905	1.6985
$\mathcal{O}(\alpha_s^1)$	$\Gamma_{Hb\bar{b}}^{C_2C_2}$	0.25813	0.39409	0.47563
$\mathcal{O}(\alpha_s^2)$	$\Gamma_{Hb\bar{b}}^{C_2C_2}$	-0.0043084	0.076819	0.143670
	$\Gamma_{Hb\bar{b}}^{C_1C_2}$	0.027078	0.024746	0.022608
$\mathcal{O}(\alpha_s^3)$	$\Gamma_{Hb\bar{b}}^{C_2C_2}$	-0.015360	0.0048336	0.038198
	$\Gamma_{Hb\bar{b}}^{C_1C_2}$	0.010314	0.013585	0.015170
	$\Gamma_{Hb\bar{b}}^{C_1C_1}$	0.0088676	0.0064617	0.0048595

over 1 %



Summary

- With the accumulating data at the LHC, the experimental errors become less and less, requiring high precise predictions from theory.
- The single and double Higgs production rates have been computed up to N3LO in QCD and NLO in EW. The remaining uncertainties in the single Higgs production are from scales, PDFs and input parameters.
- The uncertainty in double Higgs production is also affected by the m_t scheme.
- Higgs decay to $b\bar{b}$ is calculated up to N3LO including top quark contributions.
- In the future, after scrutinizing the data with highest precise theory, we are looking forward to some new physics discovery.