Precise predictions for Higgs boson pair production and decay

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希格斯物理研讨会

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CCAST，北京

Higgs self-coupling

★ Mass generations of gauge bosons: Higgs mechanism

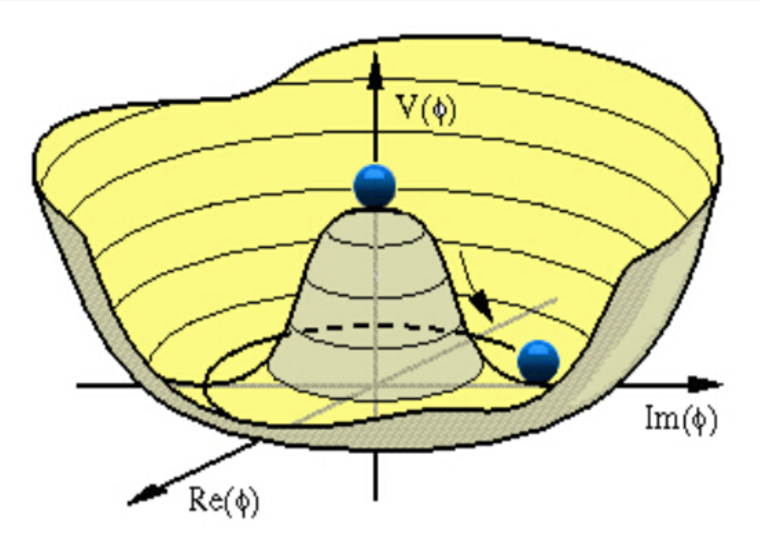
★ Mass generations of fermions: Higgs mechanism & Yukawa couplings

★ Mass generations of scalars?

$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

$$M_H = \sqrt{2}m = \sqrt{2\lambda}v$$

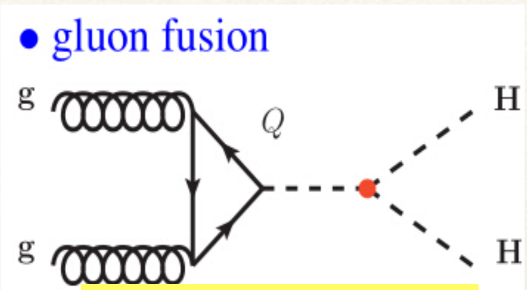
$$\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{M_H^2}{v}H^3 + \frac{1}{8}\frac{M_H^2}{v^2}H^4$$



In some new physics models, the trilinear Higgs self-coupling may change by O(100)%, while the couplings with gauge bosons and fermions are still in agreement with SM.

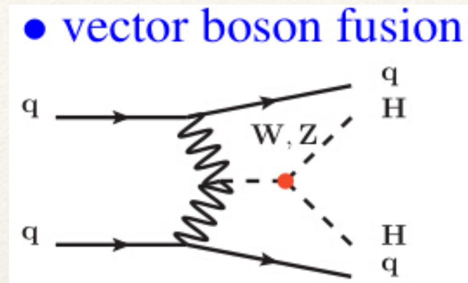
We need to measure the trilinear self coupling directly.

Higgs pair production



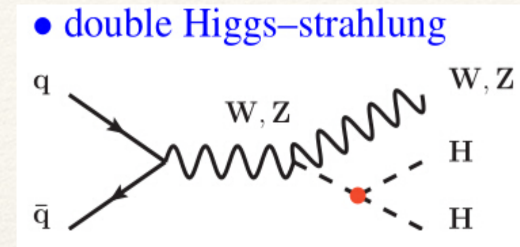
(NN)NLO QCD
~100000 events

Borowka,et al,PRL117,012001
Baglio, et al, EPJC, 79, 459
Chen,Li, Shao,**JW**, PLB 803,135292
JHEP,2003,072



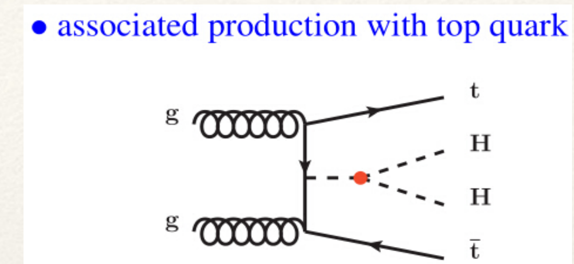
(N)NNLO QCD
~6000 events

Ling,Zhang,Ma,Guo,Li,Li,
PRD89,073001
Dreyer,Karlberg, PRD98,114016,
PRD99,074028



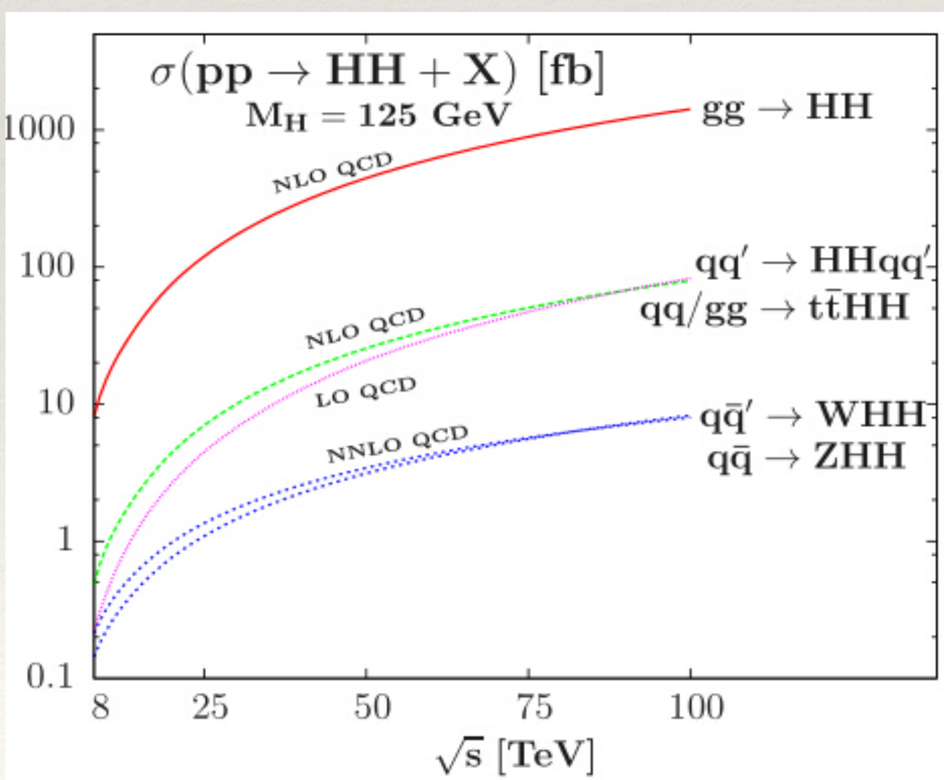
NNLO in QCD
~3200 events

Baglio,et al, JHEP1304,151
Li,Li,**JW**, PRD97,074026, PLB765,265



NLO in QCD
~3000 events

Englert,et al, PLB743,93
Liu, Zhang, 1410.1855
Frederix,et al, PLB 732,142



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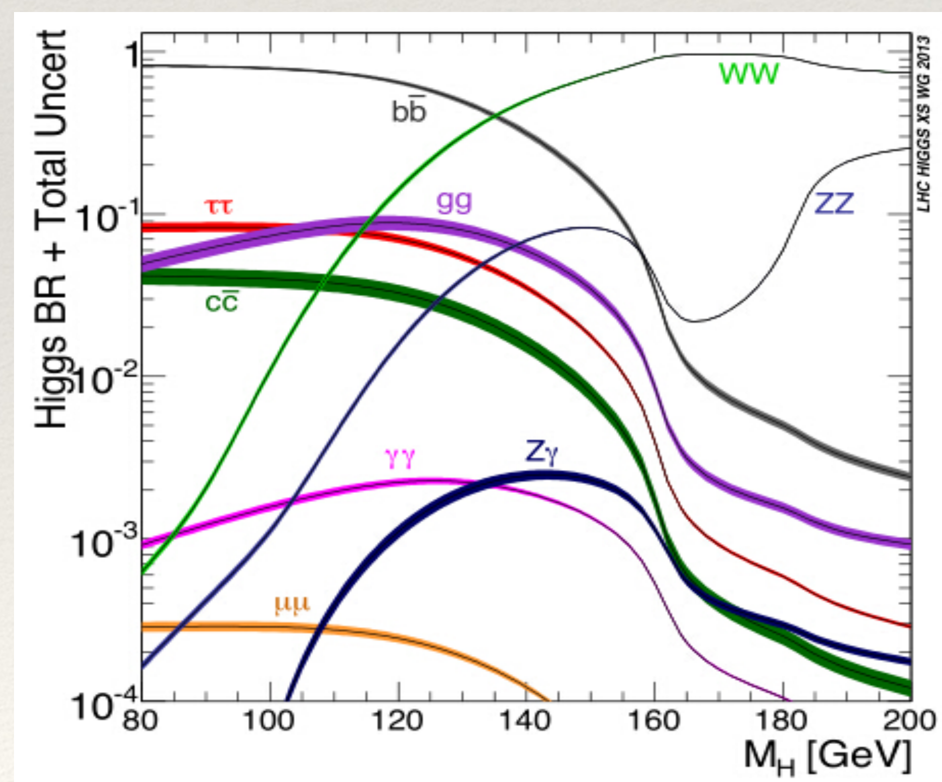
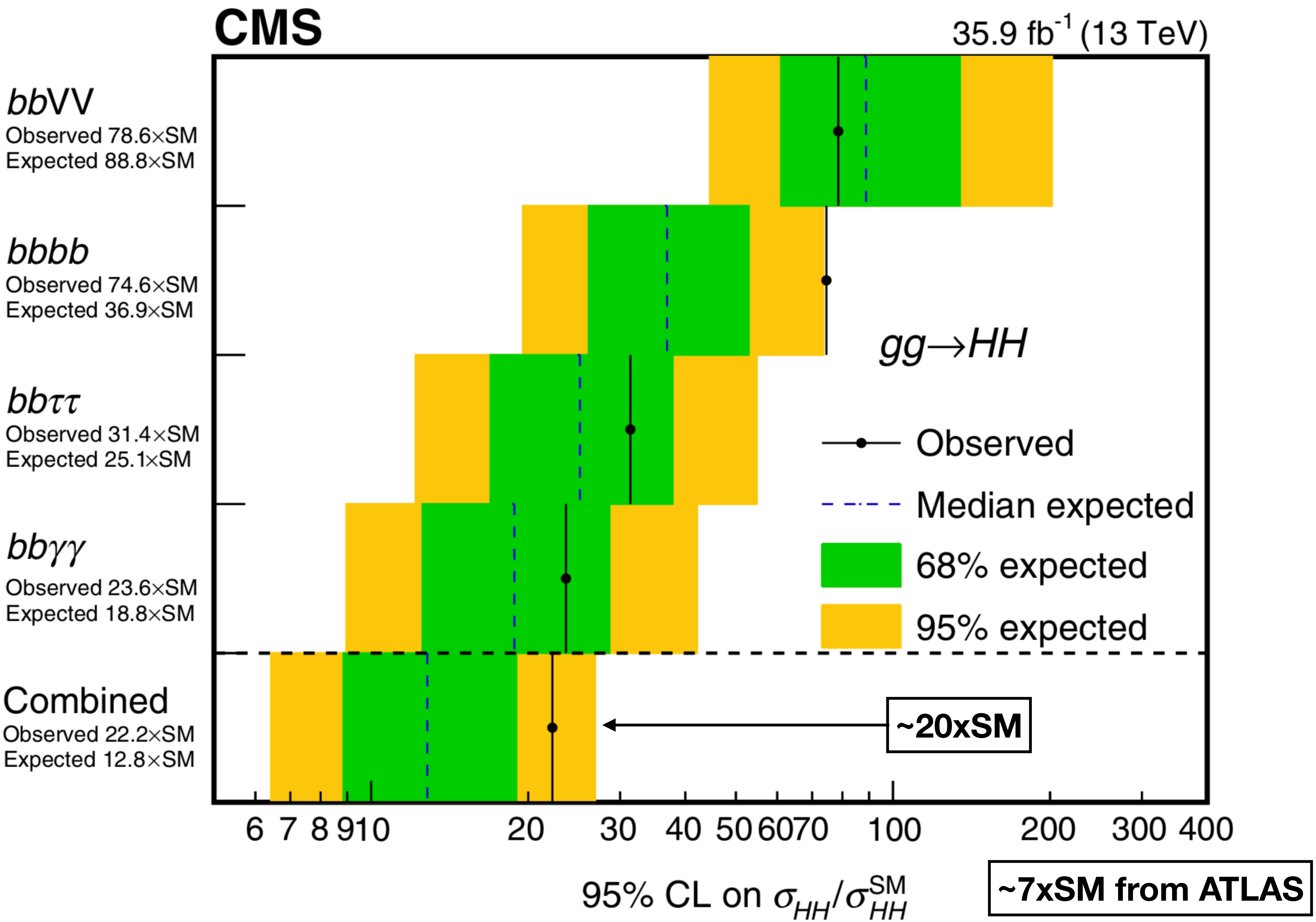


=

$b\bar{b}WW$
$b\bar{b}\gamma\gamma$
$b\bar{b}\tau\tau$
$Wb\bar{b}b\bar{b}$
$t\bar{t}b\bar{b}b\bar{b}$
……



Phys.Rev.Lett. 122, 121803 (2019)

Non-resonant HH production at 13 TeV with about 36 fb^{-1}

Final state	collaboration	allowed κ_λ interval at 95% CL	
		observed	expected
$b\bar{b}b\bar{b}$	ATLAS	-11 – 20	-12 – 19
	CMS	-23 – 30	-15 – 23
$b\bar{b}\tau^+\tau^-$	ATLAS	-7.3 – 16	-8.8 – 17
	CMS	-18 – 26	-14 – 22
$b\bar{b}\gamma\gamma$	ATLAS	-8.1 –13	-8.2 – 13
	CMS	-11 – 17	-8.0 – 14
Combined	ATLAS	-5.0 – 12	-5.8 – 12
	CMS	-12 – 19	-7.1 – 14
Our combination	Both experiments	-6.8 – 14	-4.6 – 11

Micoo et al, 1910.00012

Why do we need precise prediction?

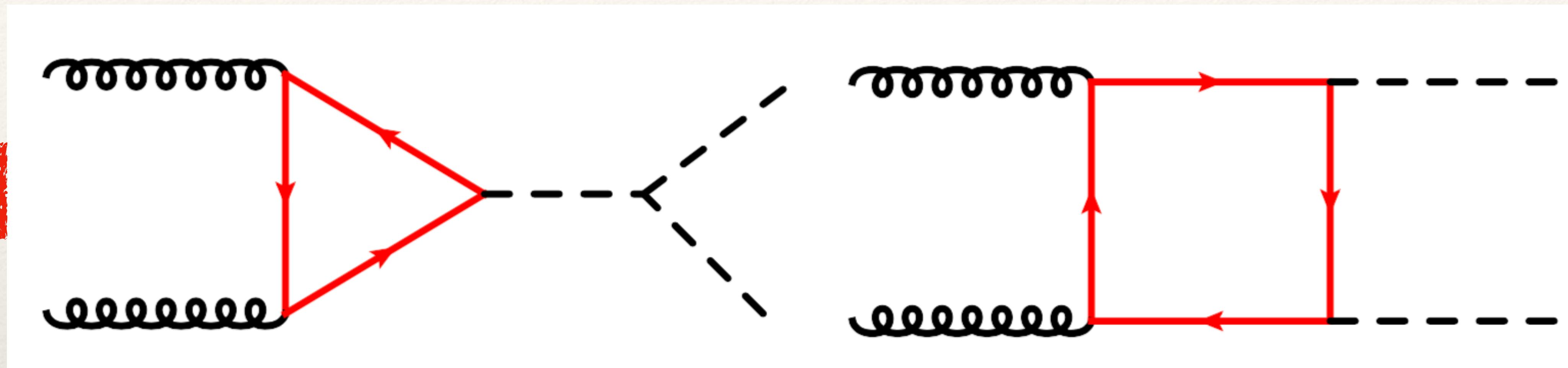
1. The measured events numbers do not depend on the theoretical prediction, but the interpretation does.

2. As time goes by, the experimental uncertainties will reduce. Theoretical uncertainties will reduce only after we calculate higher-order corrections.

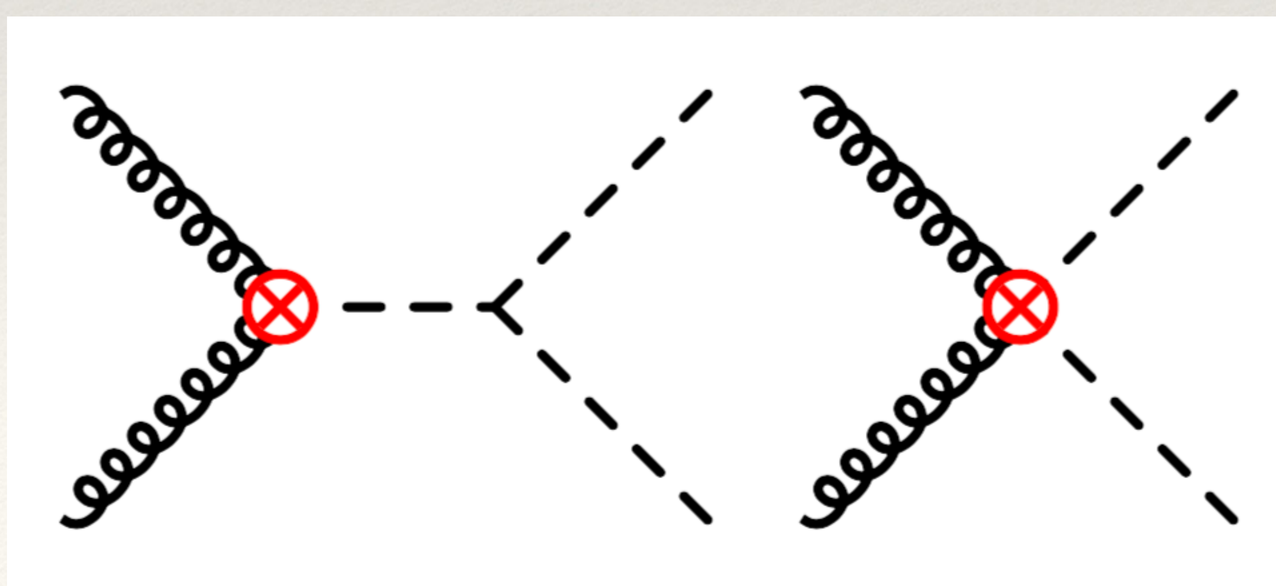
3. Renormalization and factorization scale uncertainties are sizable, especially for Higgs productions.

gg>HH

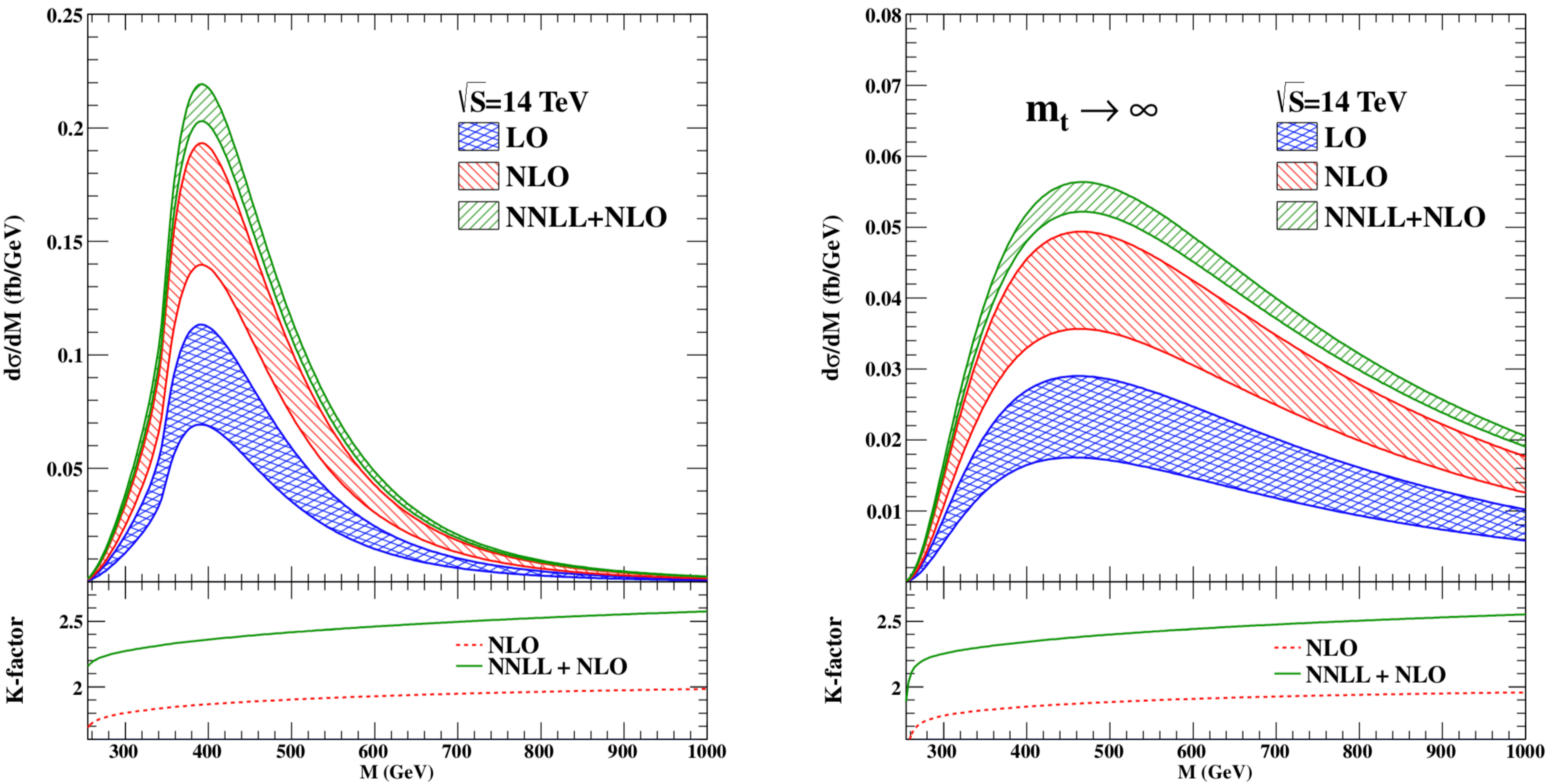
LO in SM



Heavy top quark limit

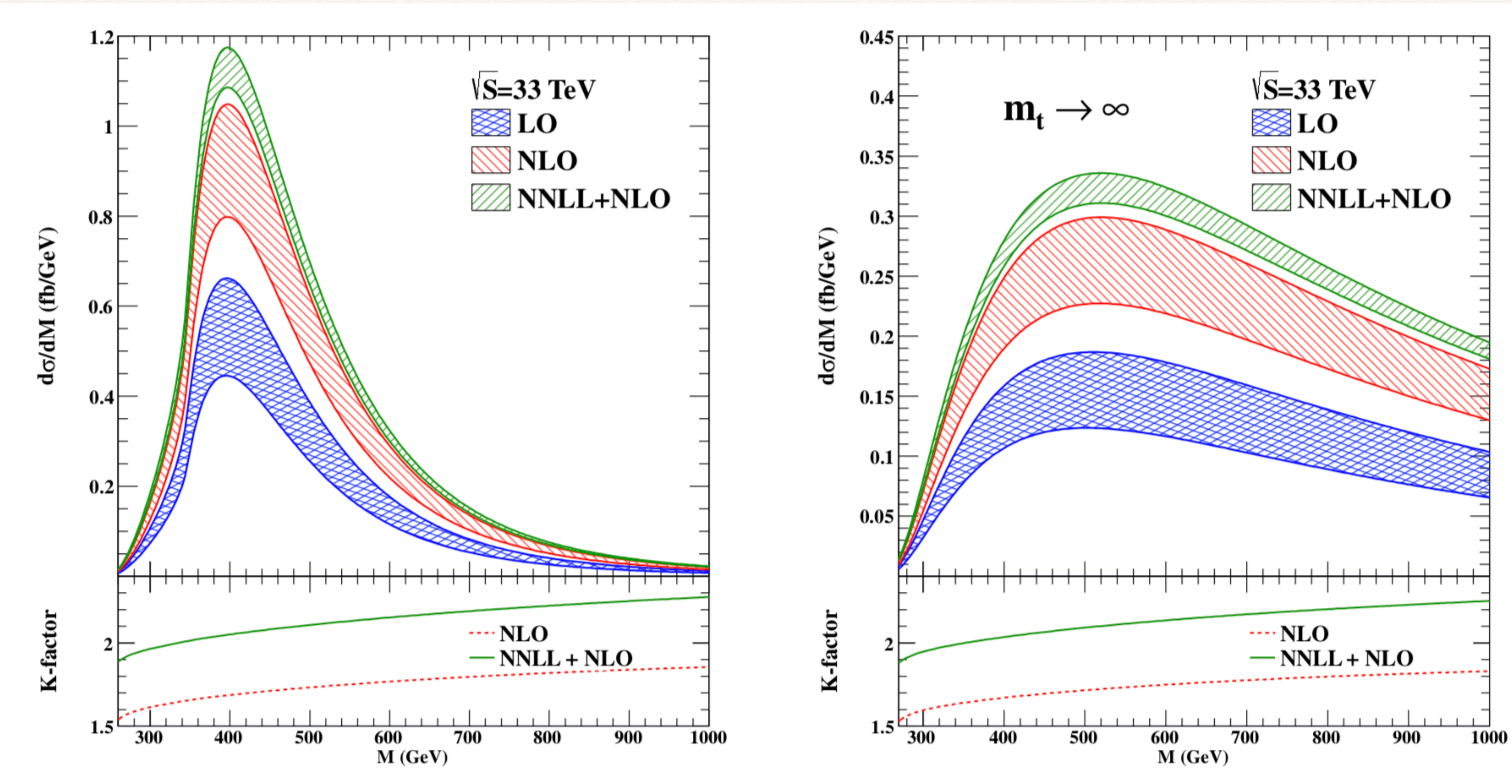


Q:How well is the approximation?



D.Y.Shao, C.S.Li, H.T.Li, JW, JHEP07(2013)169

gg>HH@NNLL



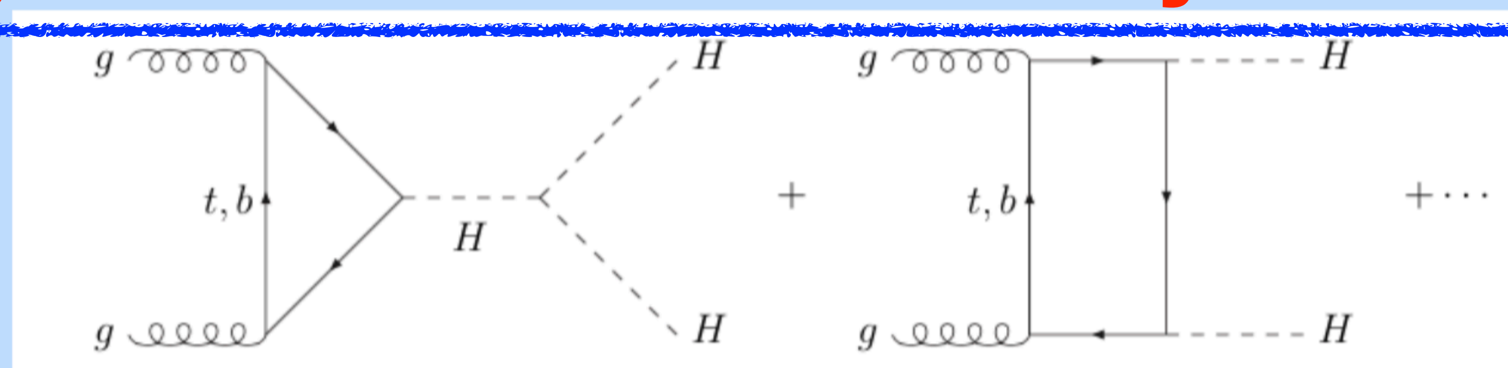
D.Y.Shao, C.S.Li, H.T.Li, JW, JHEP07(2013)169

gg>HH@NLO with full mt dep.

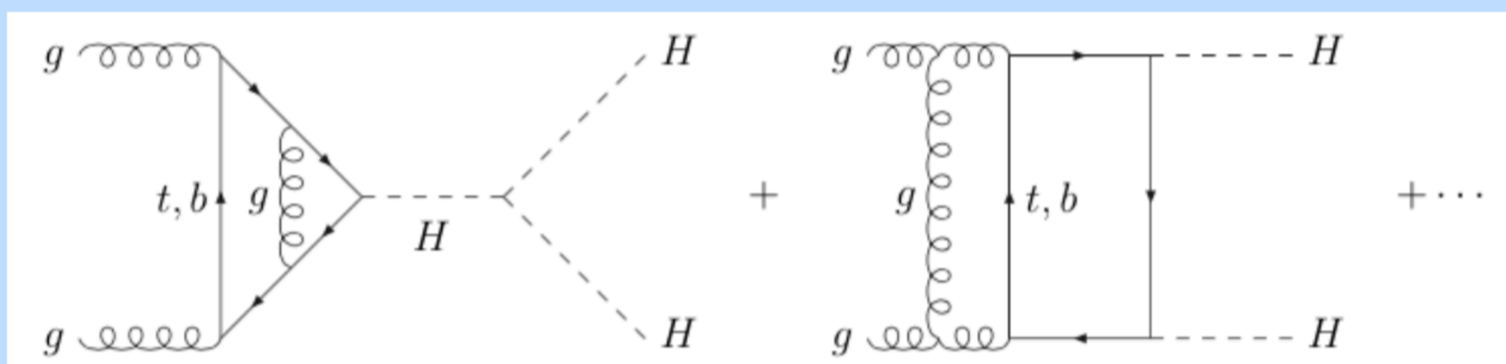
$$\sigma_{NLO}(pp \to HH + X) = \sigma_{LO} + \Delta\sigma_{virt} + \Delta\sigma_{gg} + \Delta\sigma_{qg} + \Delta\sigma_{q\bar{q}},$$

Very difficult to obtain analytical results

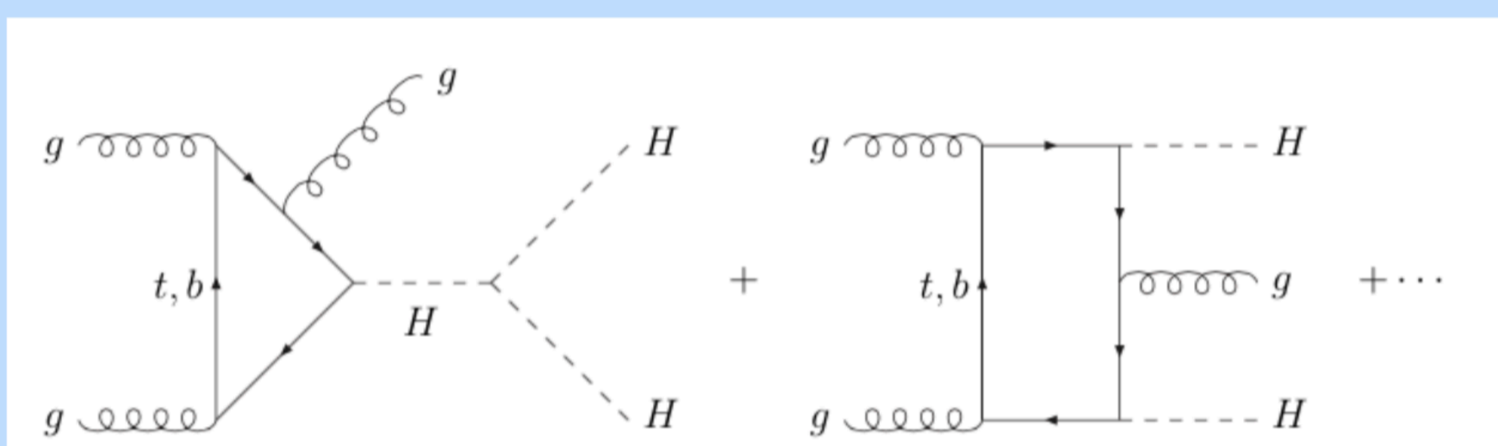
σ_{LO}:



$\Delta\sigma_{virt}$:

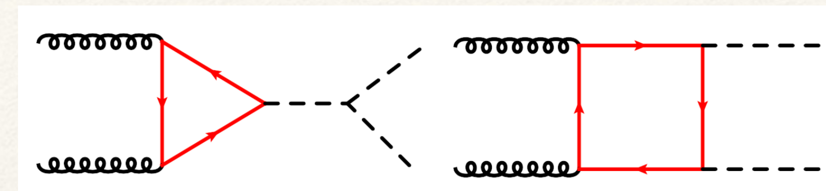


$\Delta\sigma_{ij}$:

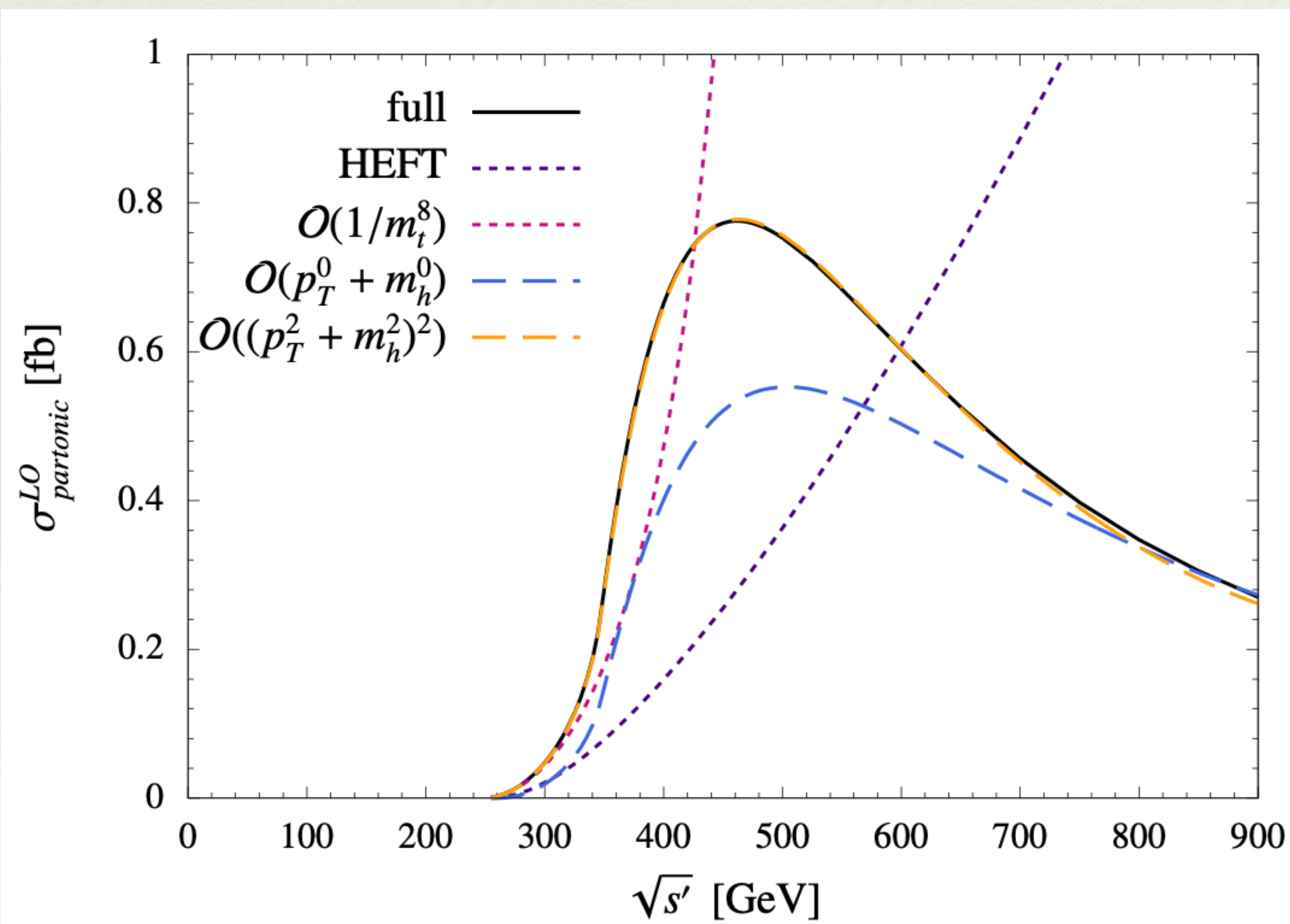


gg>HH@NLO with full mt dep.

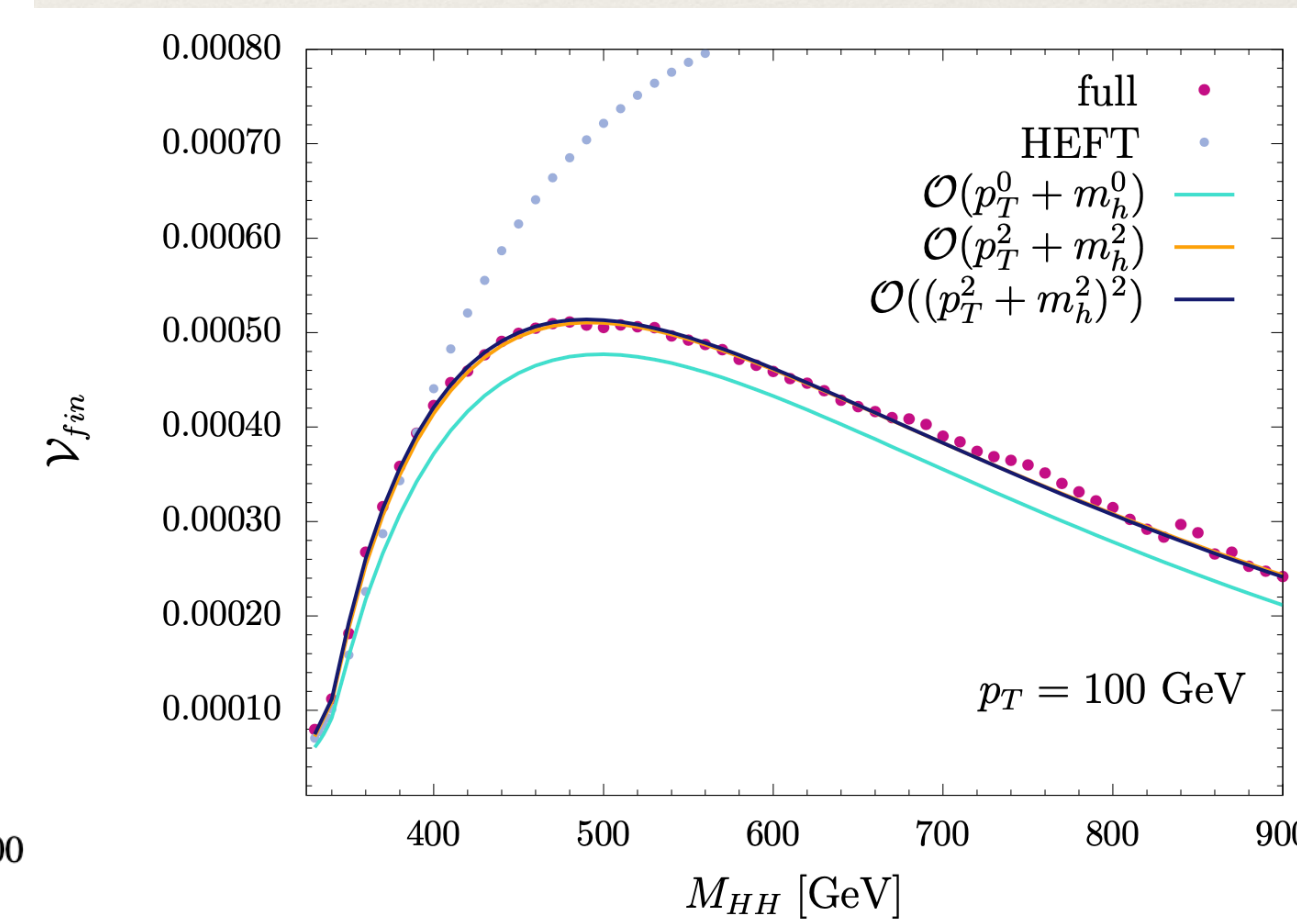
Expand in pT



One-loop



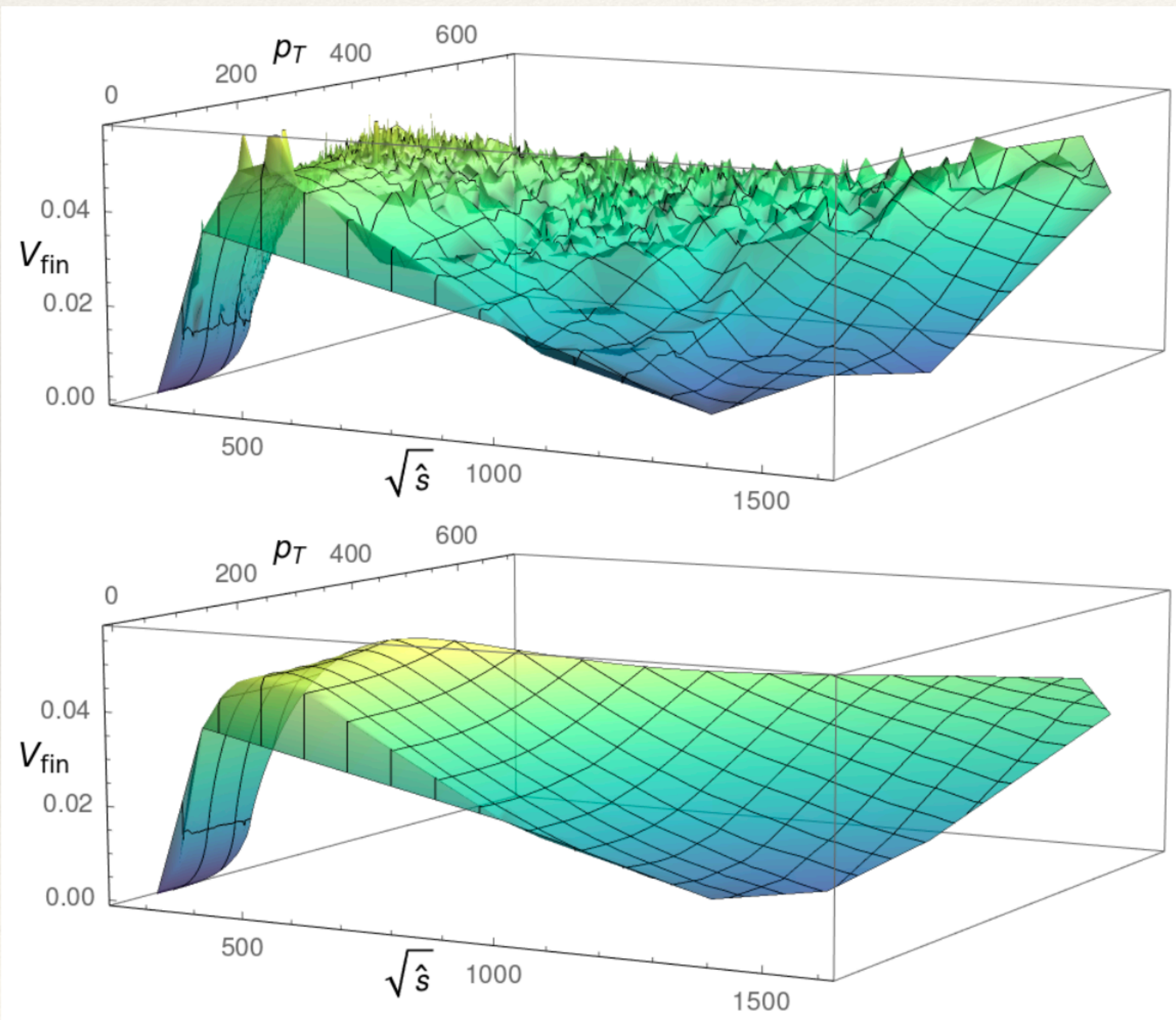
Two-loop

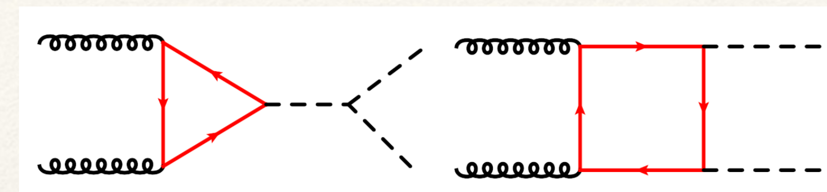


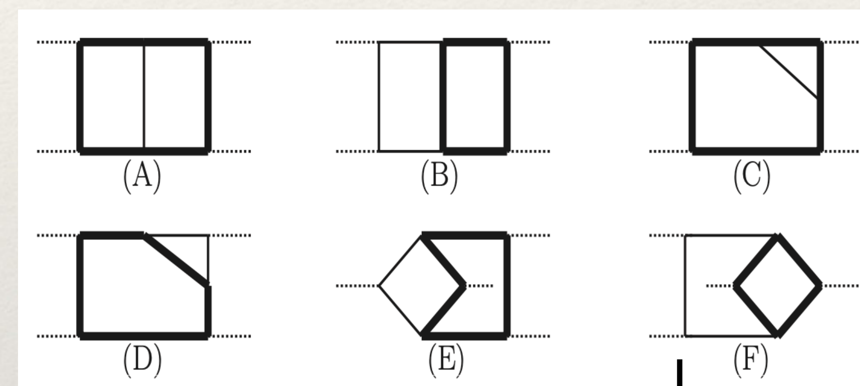
Bonciani, Degrassi, Giardino, Grober, PRL 121, 162003 (2018)

gg>HH@NLO with full mt dep.

Expand in mH







elliptic Feynman integrals

Xu and Yang, JHEP 1901, 211
Wang, Wang, Xu, Xu, Yang, PRD104,051901

gg>HH@NLO with full mt dep.

Numerical method: sector decomposition

$$I = \int_0^1 dx \int_0^1 dy x^{-1-\epsilon} y^{-\epsilon} (x + y - xy)^{-1}$$

$$I_1 = \int_0^1 dx x^{-1-\epsilon} \int_0^1 dt t^{-\epsilon} (1 + t - xt)^{-1},$$

$$I_2 = \int_0^1 dy y^{-1-2\epsilon} \int_0^1 dt t^{-1-\epsilon} (1 + t - yt)^{-1}.$$

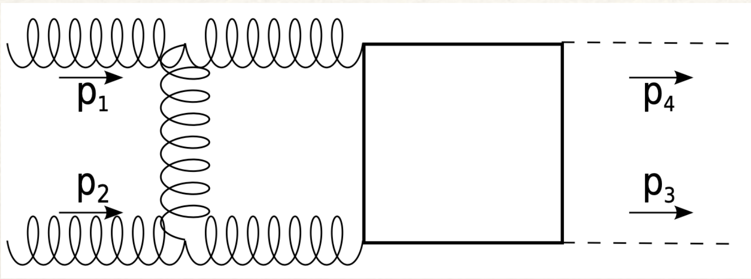
$$x^{-1+n\epsilon} = \frac{\delta(x)}{n\epsilon} + \left(\frac{1}{x}\right)_+ + n\epsilon \left(\frac{\ln x}{x}\right)_+ + \frac{(n\epsilon)^2}{2!} \left(\frac{\ln^2 x}{x}\right)_+ + O(\epsilon^3)$$

The QMC methods were born in the 1950s and 1960s from the desire to achieve faster

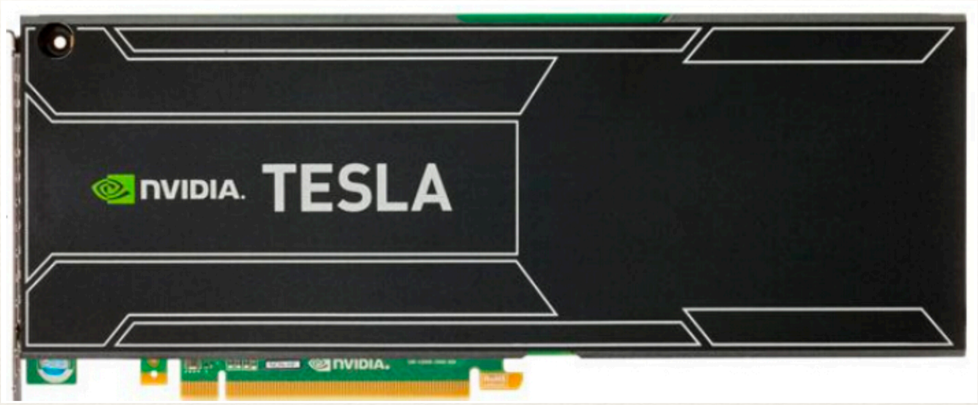
convergence than the MC rate of O(1/ n), and can achieve a convergence rate of order O(1/n) for very smooth functions.

Binoth and Heinrich, NPB, 585, 741

gg>HH@NLO with full mt dep.



$$I_B = e^{-2\epsilon\gamma_E} s^{-3-2\epsilon} \sum_{i=0}^{i=4} \frac{P_i}{\epsilon^i}$$

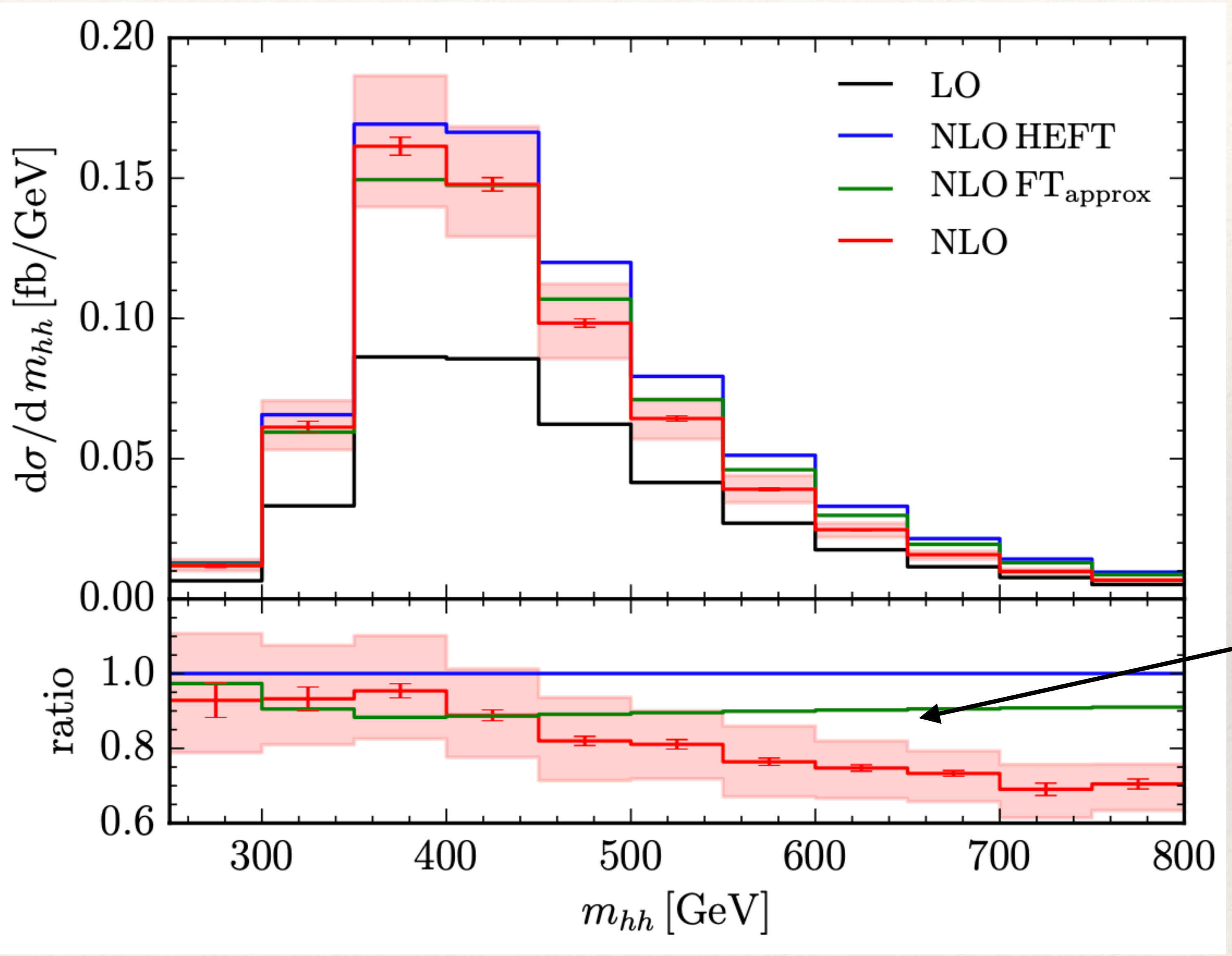


	Vegas/CPU	QMC/GPU
P_2	$-7.959 \pm 0.009 - 10.586i \pm 0.009i$	$-7.949 \pm 0.003 - 10.585i \pm 0.005i$
P_1	$3.9 \pm 0.1 - 28.1i \pm 0.1i$	$3.831 \pm 0.005 - 28.022i \pm 0.005i$
P_0	$-3.9 \pm 0.8 + 92.3i \pm 0.8i$	$-4.63 \pm 0.07 + 92.13i \pm 0.07i$
Time	45540s (12.7h)	19s

Li, JW, Yan, Zhao, *Chin.Phys.C*40, 033103

This method was soon adopted by the SecDec group in their code, and used in various calculations. https://pypi.org/project/pySecDec/

gg>HH@NLO with full mt dep.



20-30% reduction after including top quark mass effects

Borowka, et al, PRL **117**, 012001

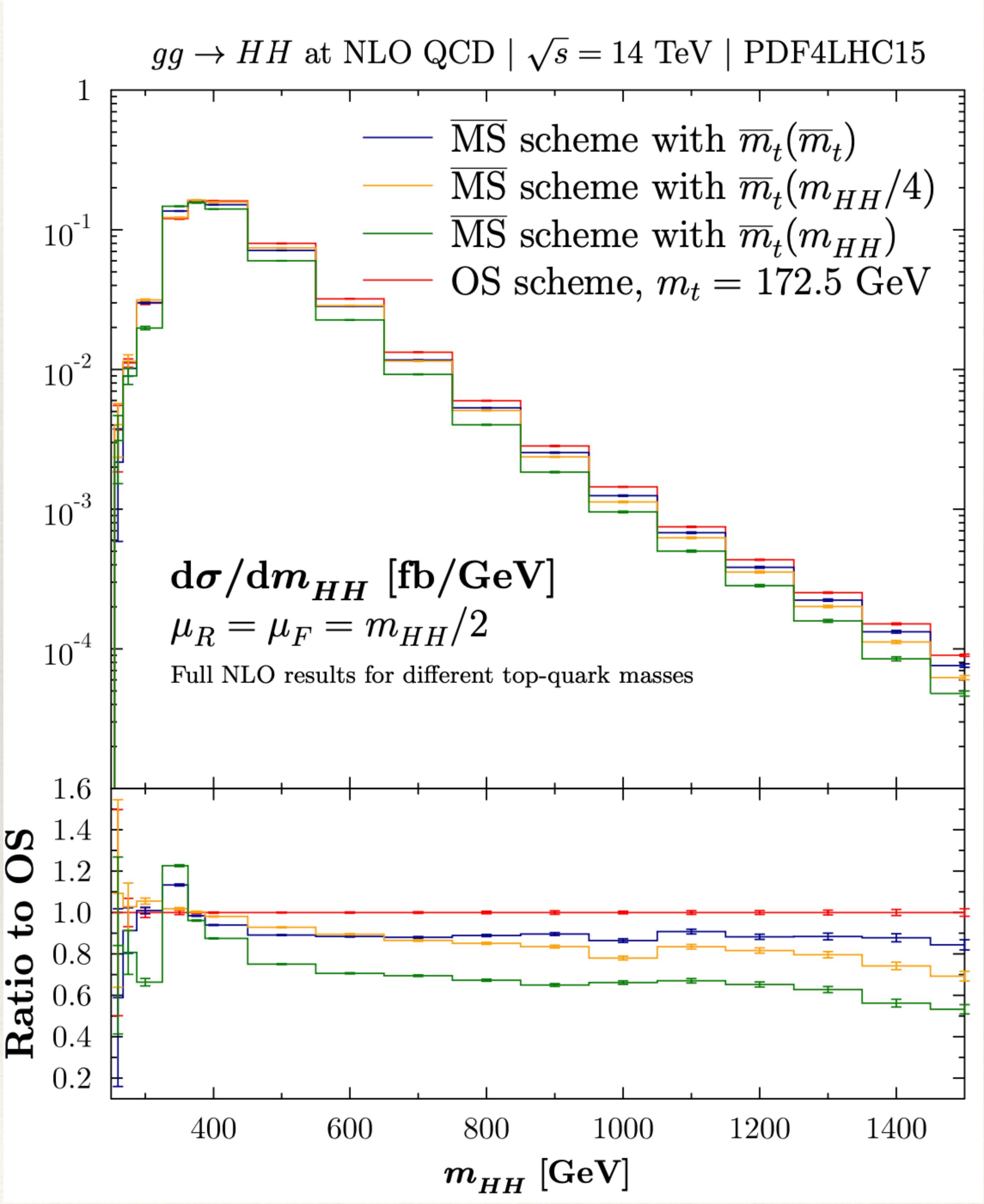
gg>HH@NLO: Full mt dependence

	PDF4LHC15	MMHT2014
σ_{LO}	19.80 fb	23.75 fb
	+95%	+66%
σ_{NLO}^{HTL}	38.66 fb	39.34 fb
	-15%	-15%
σ_{NLO}	32.78(7) fb	33.33(7) fb

$$\sigma(gg \to HH) = 32.78(7)^{+13.5\%}_{-12.5\%} \quad (\mathrm{PDF4LHC15})$$

Borowka, Greiner, Heinrich, et al, Phys.Rev.Lett.117,012001(2016),
Baglio, Campanario,Spira, et al, 1811.05692

gg>HH@NLO: Full mt dependence



$$\left.\frac{d\sigma_{NLO}}{dQ}\right|_{Q=300\ \text{GeV}} = 0.02978(7)^{+6\%}_{-34\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma_{NLO}}{dQ}\right|_{Q=400\ \text{GeV}} = 0.1609(4)^{+0\%}_{-13\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma_{NLO}}{dQ}\right|_{Q=600\ \text{GeV}} = 0.03204(9)^{+0\%}_{-30\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma_{NLO}}{dQ}\right|_{Q=1200\ \text{GeV}} = 0.000435(4)^{+0\%}_{-35\%}\ \text{fb/GeV}.$$

$$\sqrt{s} = 13\ \text{TeV}: \quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}\ \text{fb},$$

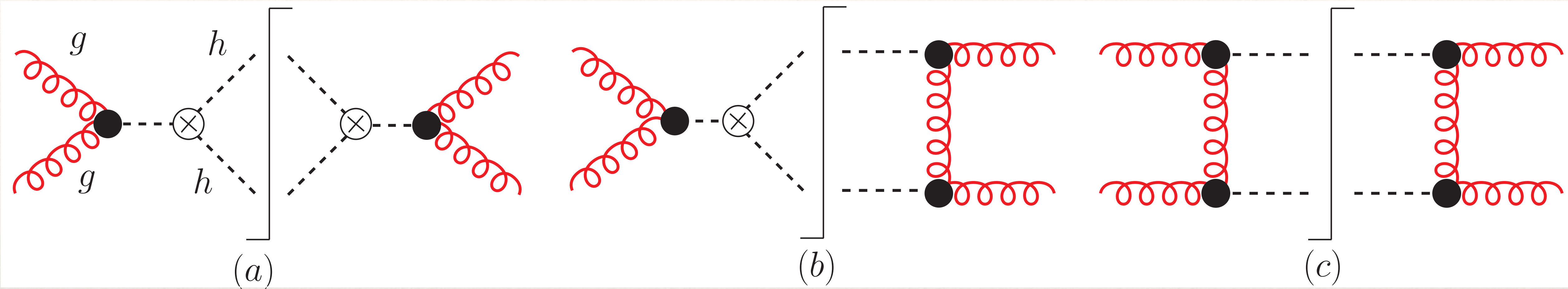
$$\sqrt{s} = 14\ \text{TeV}: \quad \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%}\ \text{fb},$$

$$\sqrt{s} = 27\ \text{TeV}: \quad \sigma_{tot} = 127.8(2)^{+4\%}_{-18\%}\ \text{fb},$$

$$\sqrt{s} = 100\ \text{TeV}: \quad \sigma_{tot} = 1140(2)^{+3\%}_{-18\%}\ \text{fb}$$

Baglio, Campanario,Spira, et al, 1811.05692, 2003.03227

gg>HH@NNNLO



NNNLO | **NNLO** | **NLO**

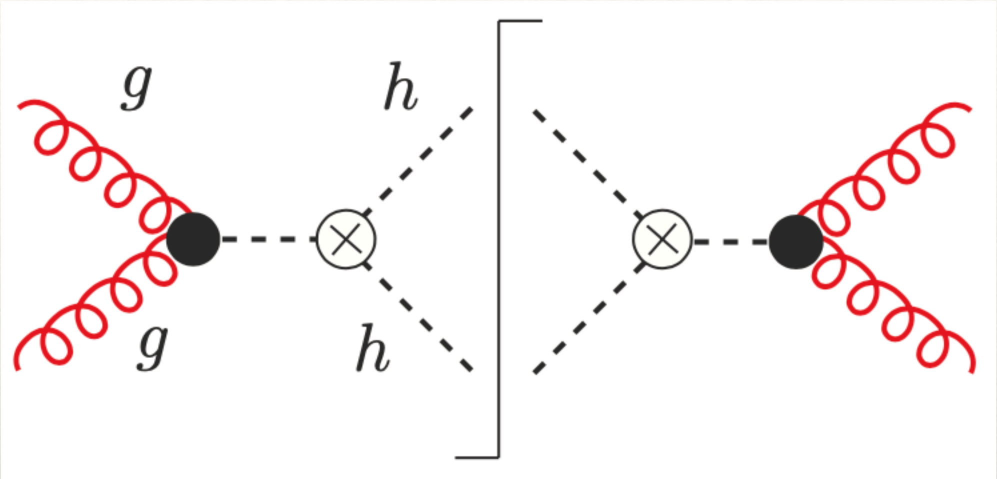
Similar to single Higgs | qT subtraction | Standard methods

Many checks:

1. Self consistency (gauge invariance, poles cancellation, RG equations)
2. Reproduce single Higgs xs up to NNLO
3. Reproduce double Higgs xs up to NNLO

L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

Class-(a)

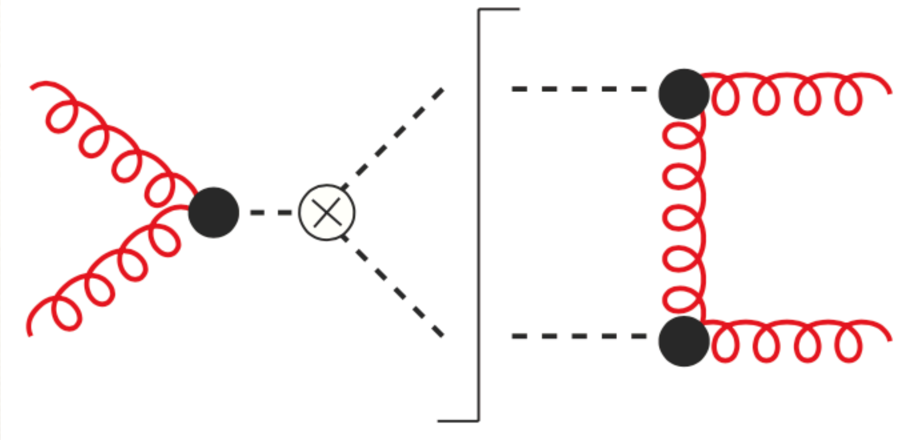


$$\frac{d\sigma^a_{hh}}{dm_{hh}} = f_{h\to hh}\left(\frac{C_{hh}}{C_h} - \frac{6\lambda_{hhh}v^2}{m^2_{hh}-m^2_h}\right)^2 \times \left(\sigma_h\big|_{m_h\to m_{hh}}\right)$$

$$f_{h\to hh} = \frac{\sqrt{m^2_{hh}-4m^2_h}}{16\pi^2 v^2}$$

Dulat, Lazopoulos, Mistlberger iHixs, 1802.00827

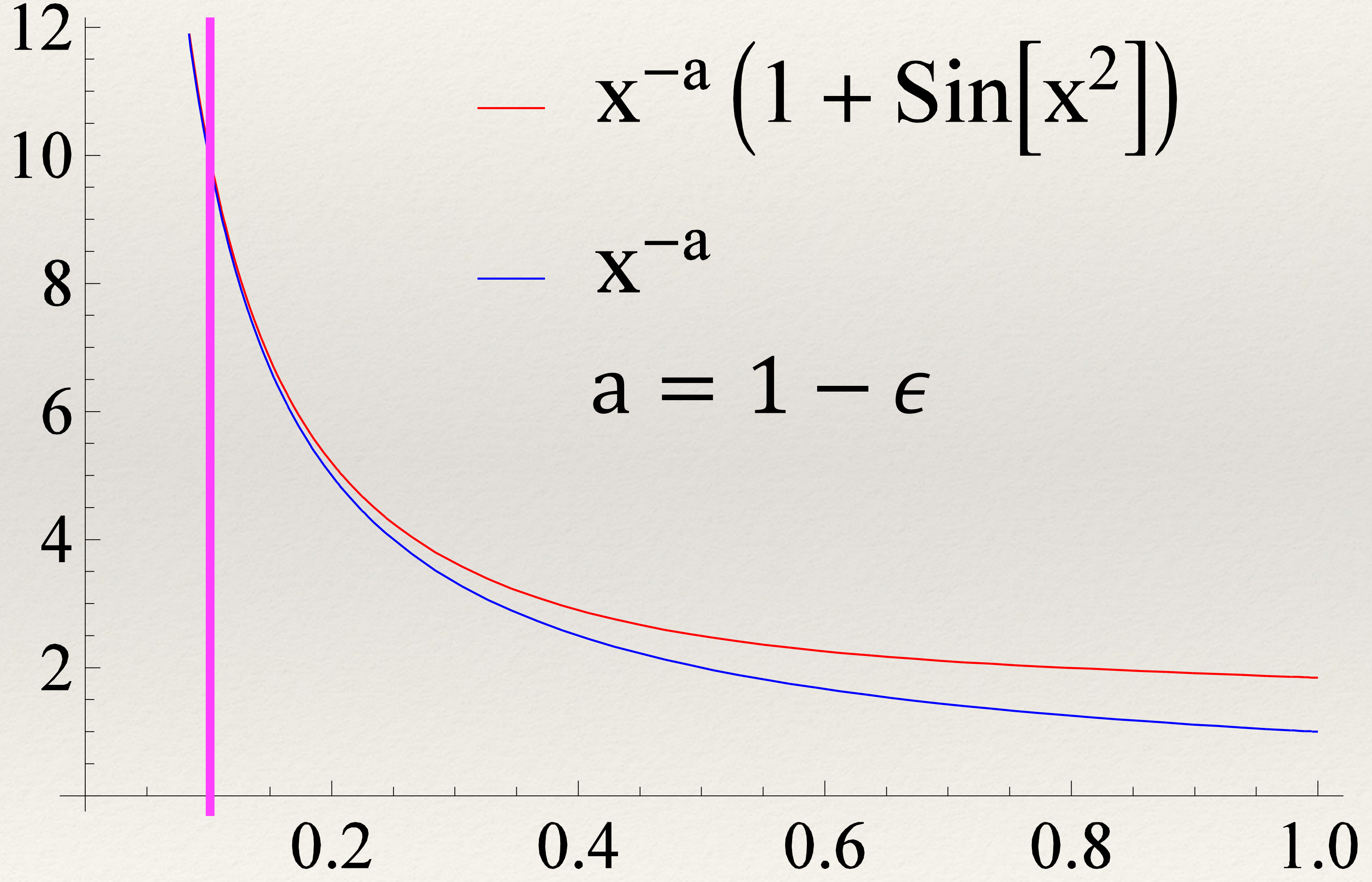
Class-(b)



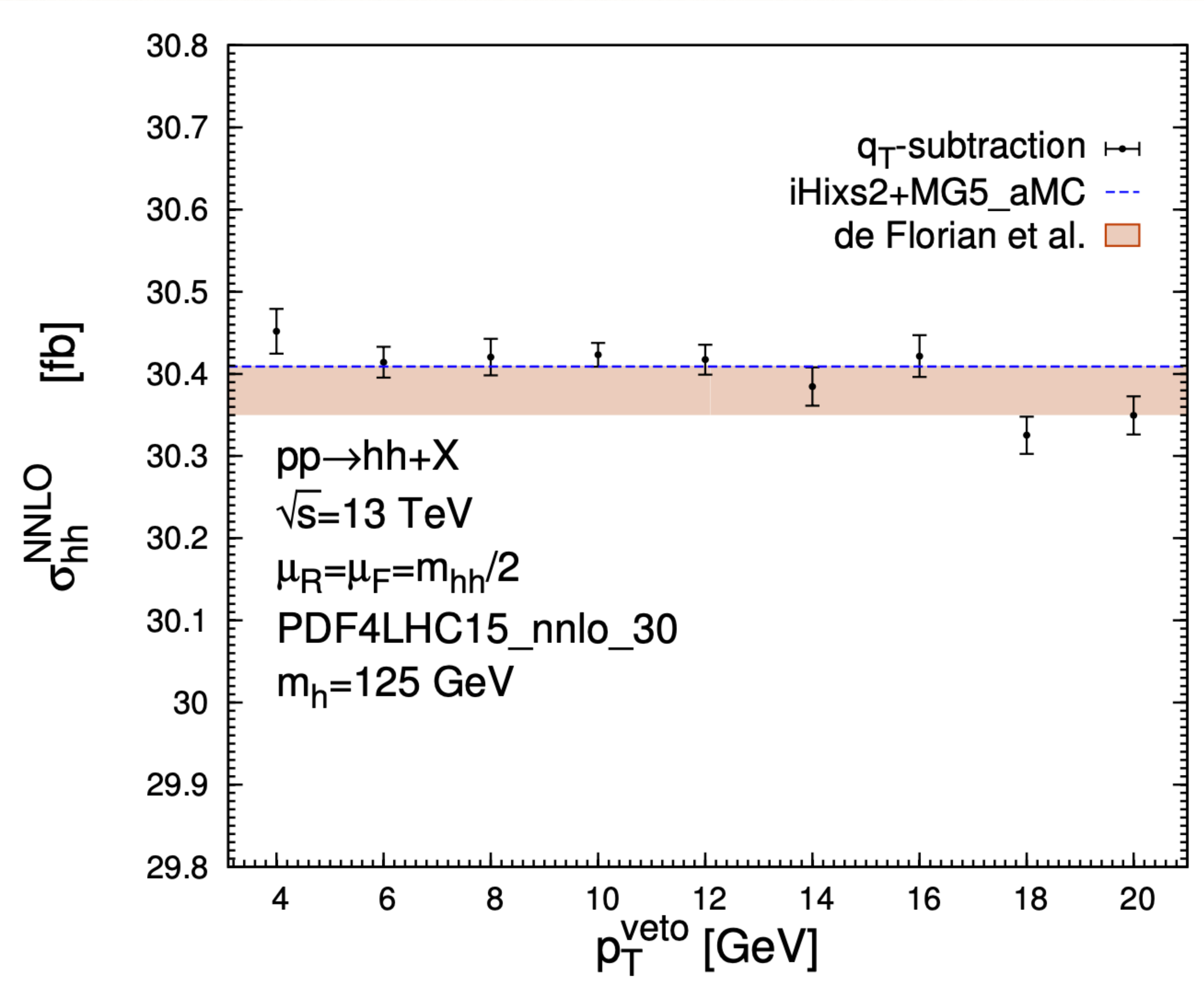
$$d\sigma^b_{hh} = d\sigma^b_{hh}\Big|_{p_T^{hh} < p_T^{\text{veto}}} + d\sigma^b_{hh}\Big|_{p_T^{hh} > p_T^{\text{veto}}}$$

$$\frac{d\sigma^b_{hh}}{dp_T^{hh}} = H^b \otimes B_g \otimes B_g \otimes S \times \left(1 + \mathcal{O}\left(\frac{\left(p_T^{hh}\right)^2}{Q^2}\right)\right)$$

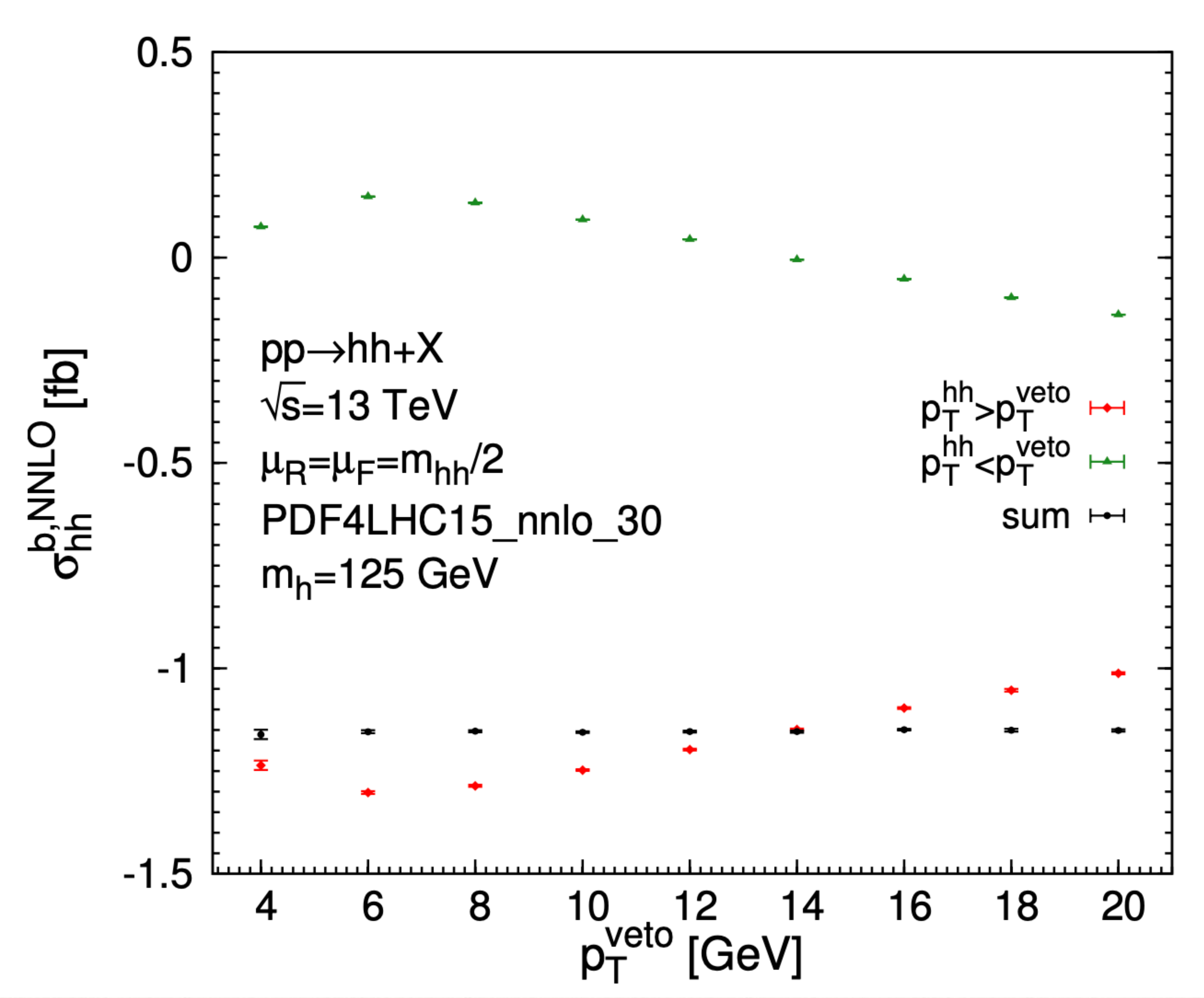
The idea of qT subtraction



Validation of qT subtraction



Validation of qT subtraction



How large are NNNLO corrections?

order \ $\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
$\mathrm{N^3LO}$	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4438^{+0.51\%}_{-1.8\%}$

87%

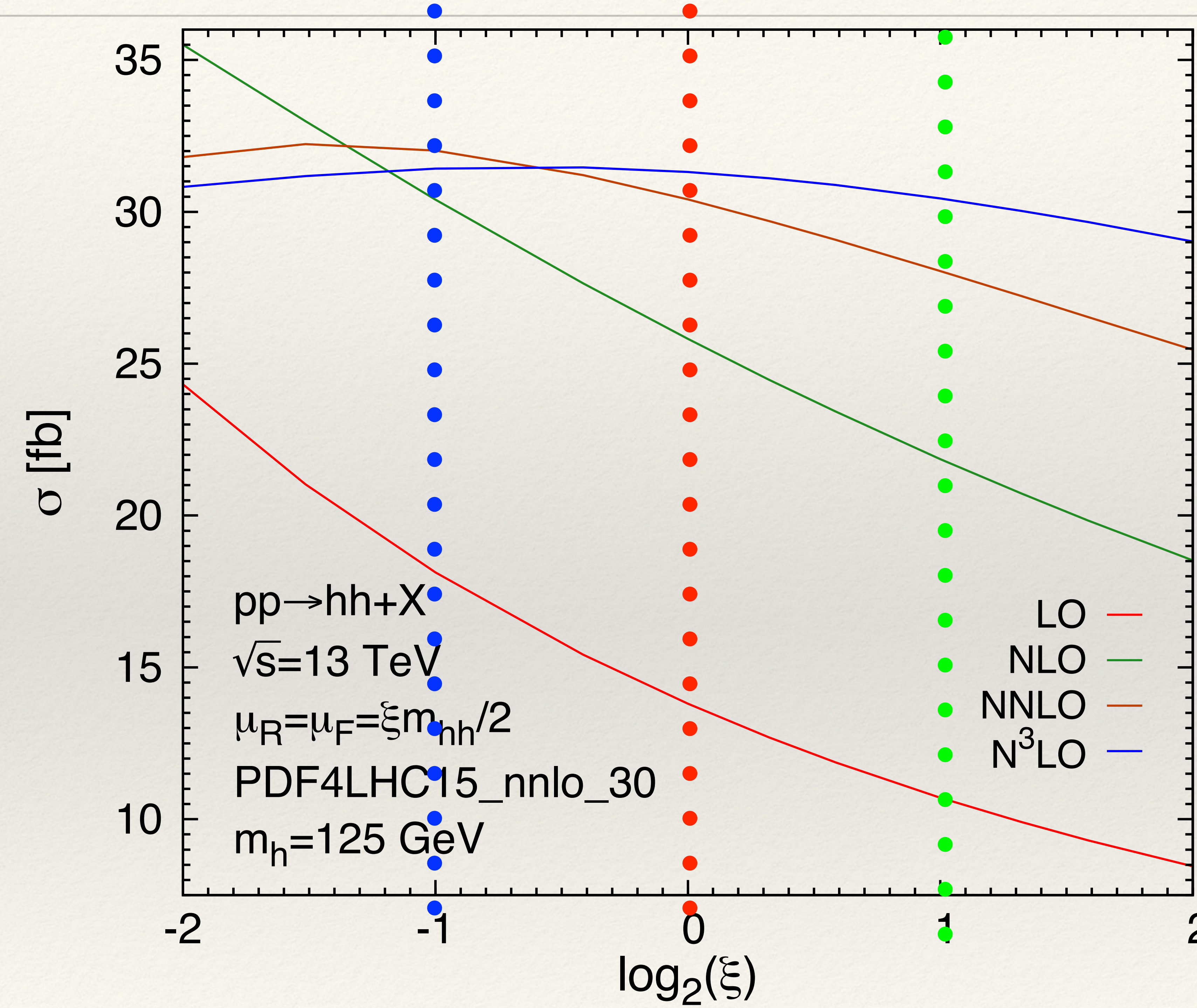
18%

3%

Scale uncer. less than PDF uncer. 3.3% now !

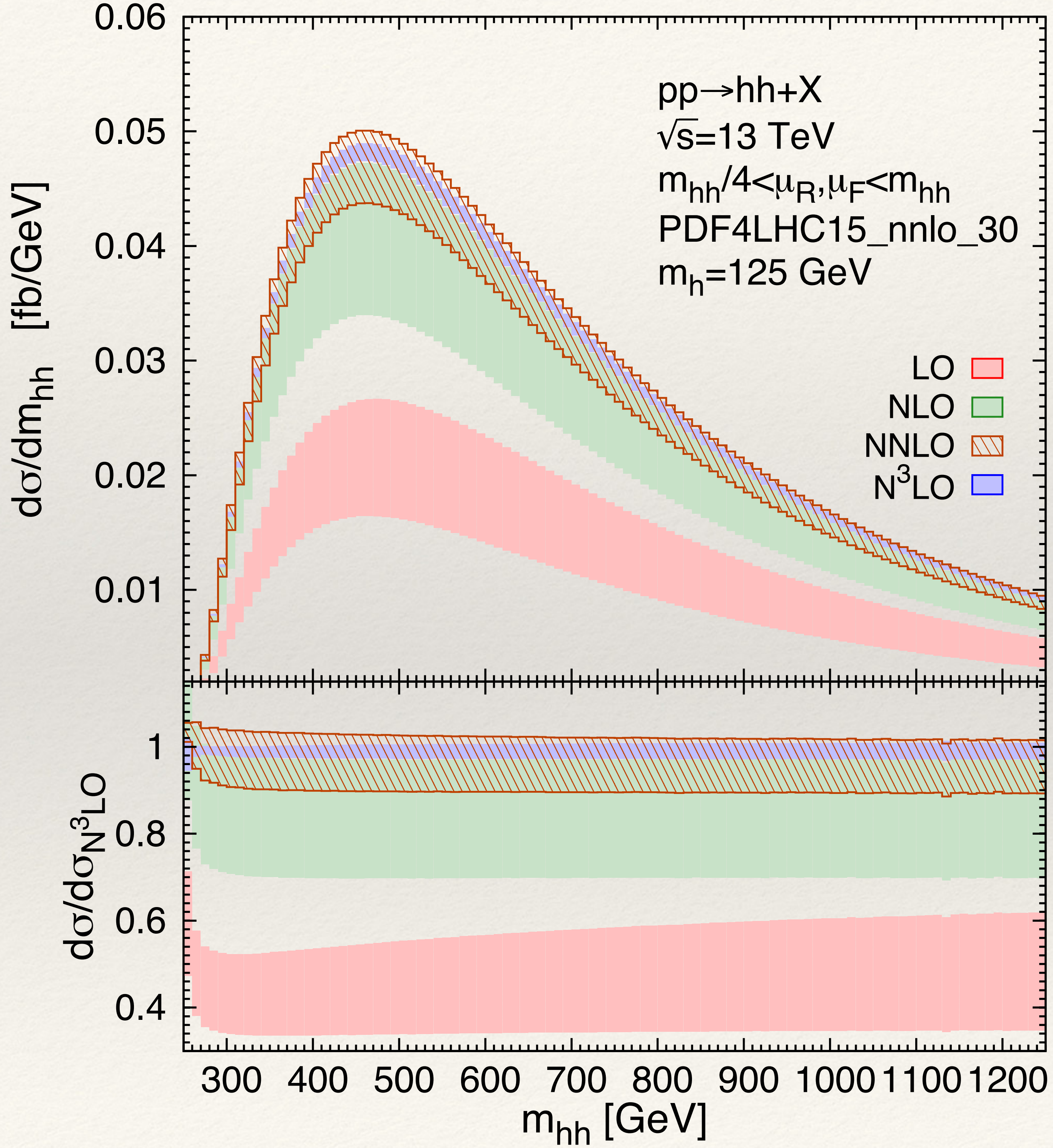
L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

How to choose a scale?

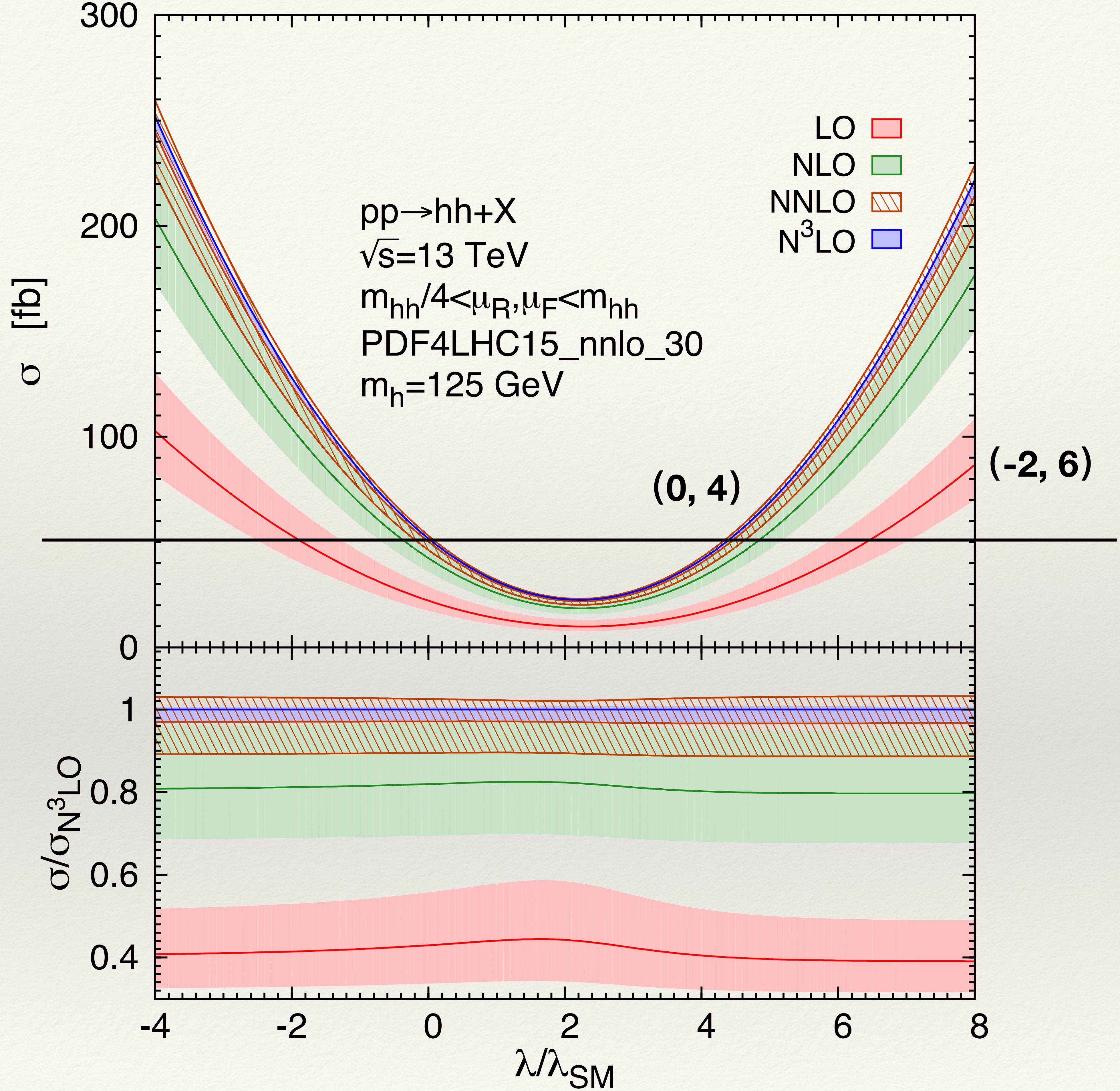


L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

Invariant mass of Higgs pair



L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072



L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

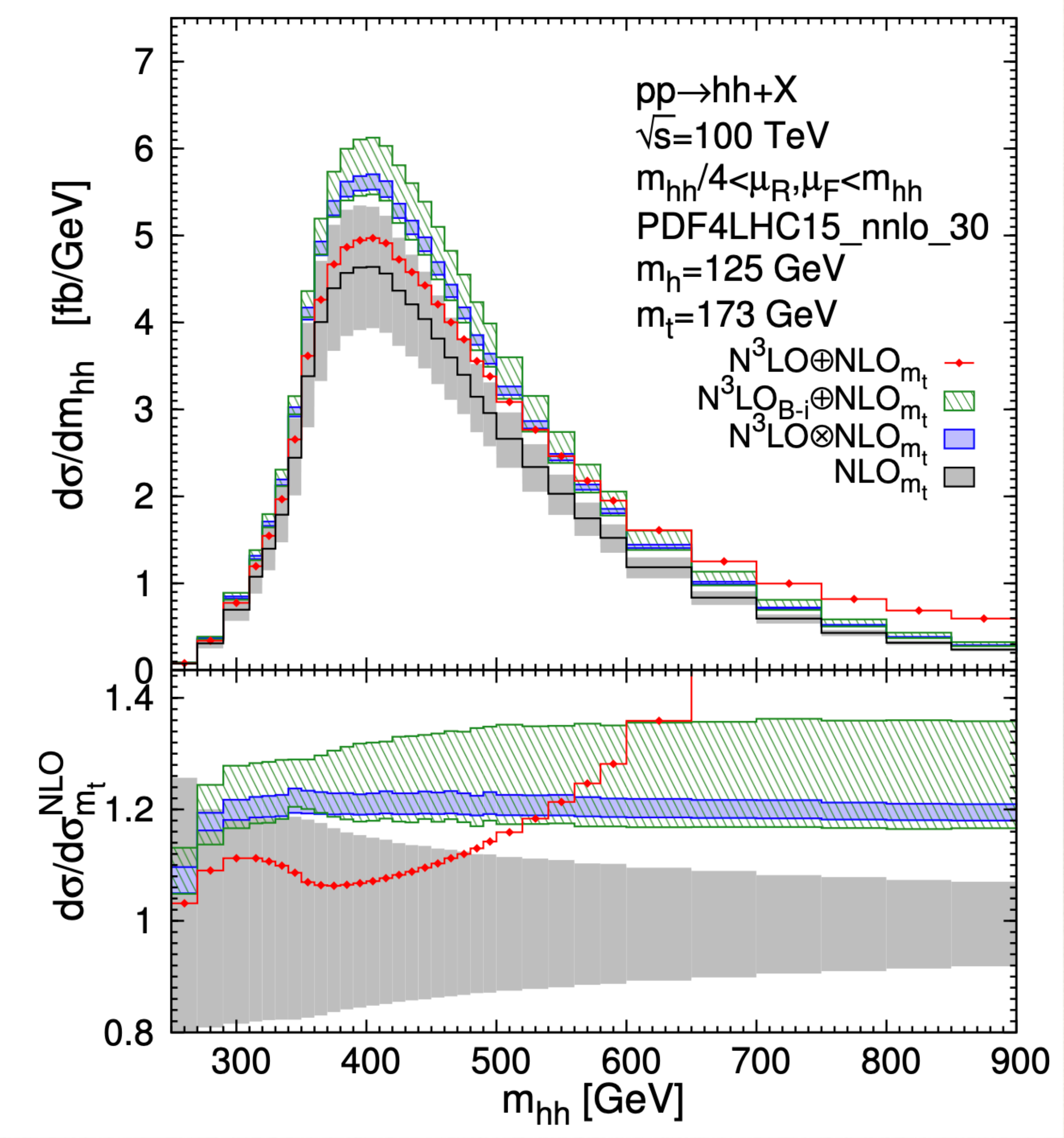
Top quark mass effects

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

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

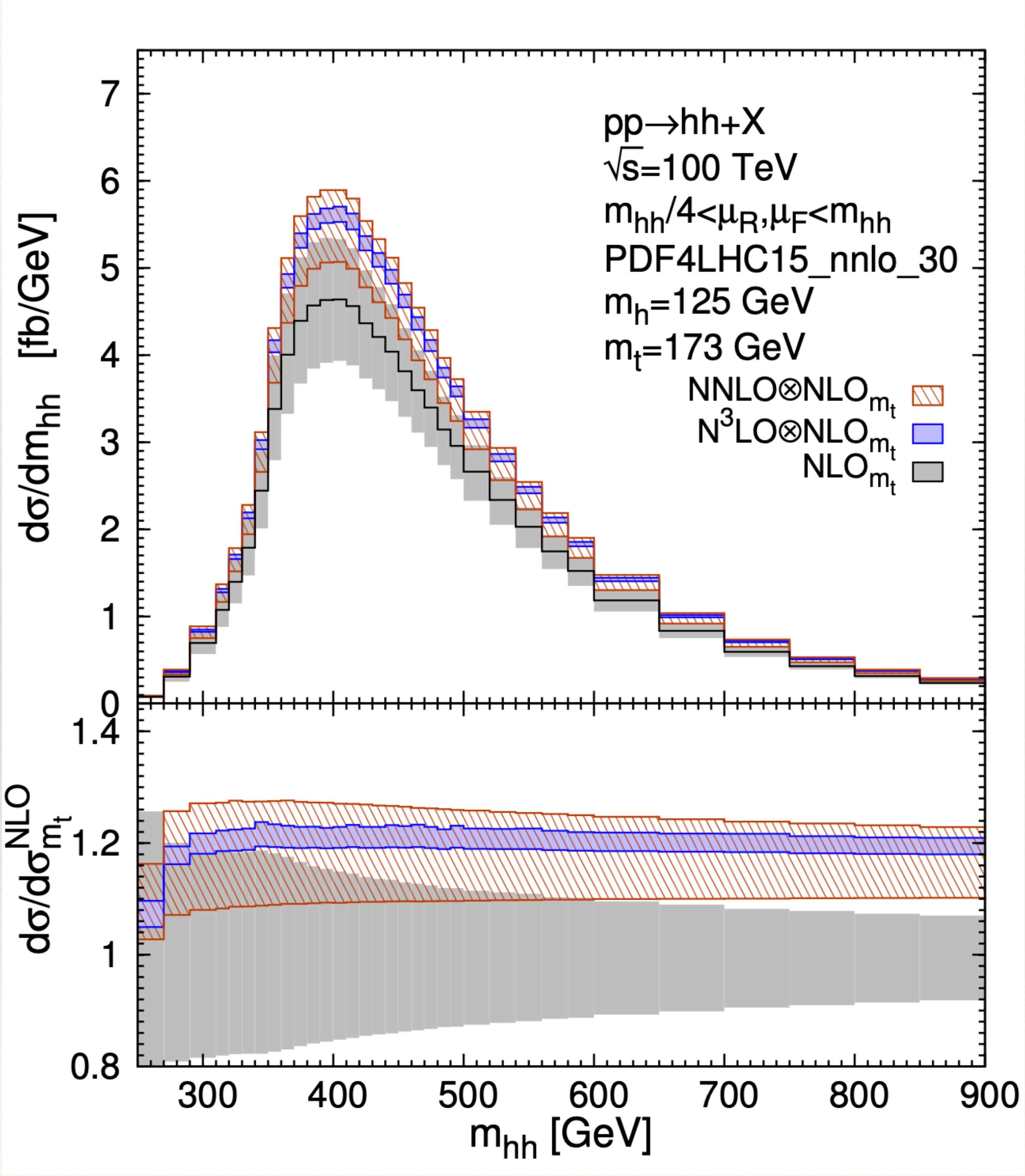
$$d\sigma^{\mathbf{N^kLO\otimes N^lLO_{m_t}}} = d\sigma^{\mathrm{N^lLO}}_{m_t}\frac{d\sigma^{\mathrm{N^kLO}}_{m_t\to\infty}}{d\sigma^{\mathrm{N^lLO}}_{m_t\to\infty}} = d\sigma^{\mathrm{N^lLO}}_{m_t} + \Delta\sigma^{k,l}_{m_t\to\infty}\frac{d\sigma^{\mathrm{N^lLO}}_{m_t}}{d\sigma^{\mathrm{N^lLO}}_{m_t\to\infty}}$$

gg→HH@NNNLO



L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

gg→HH@NNNLO



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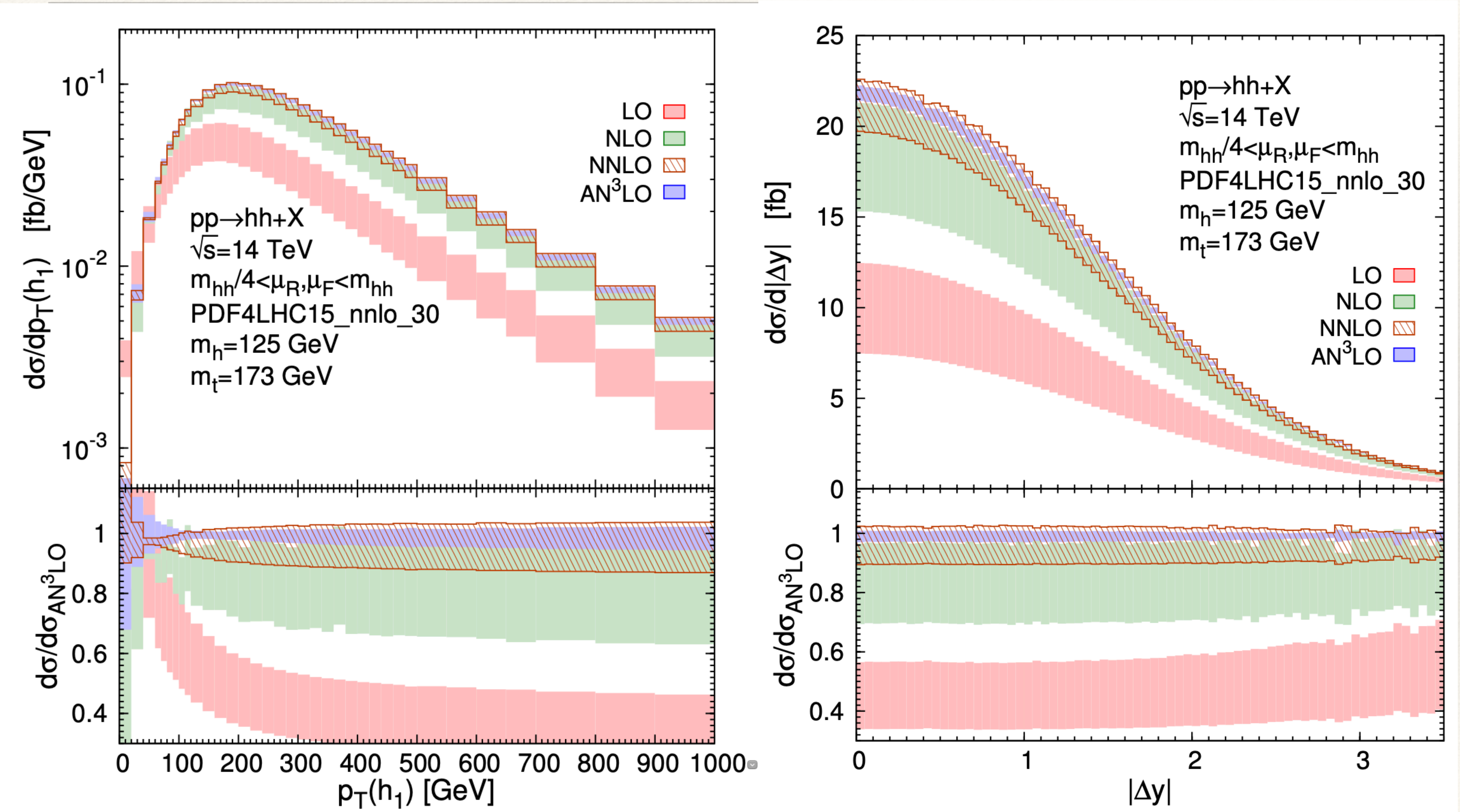
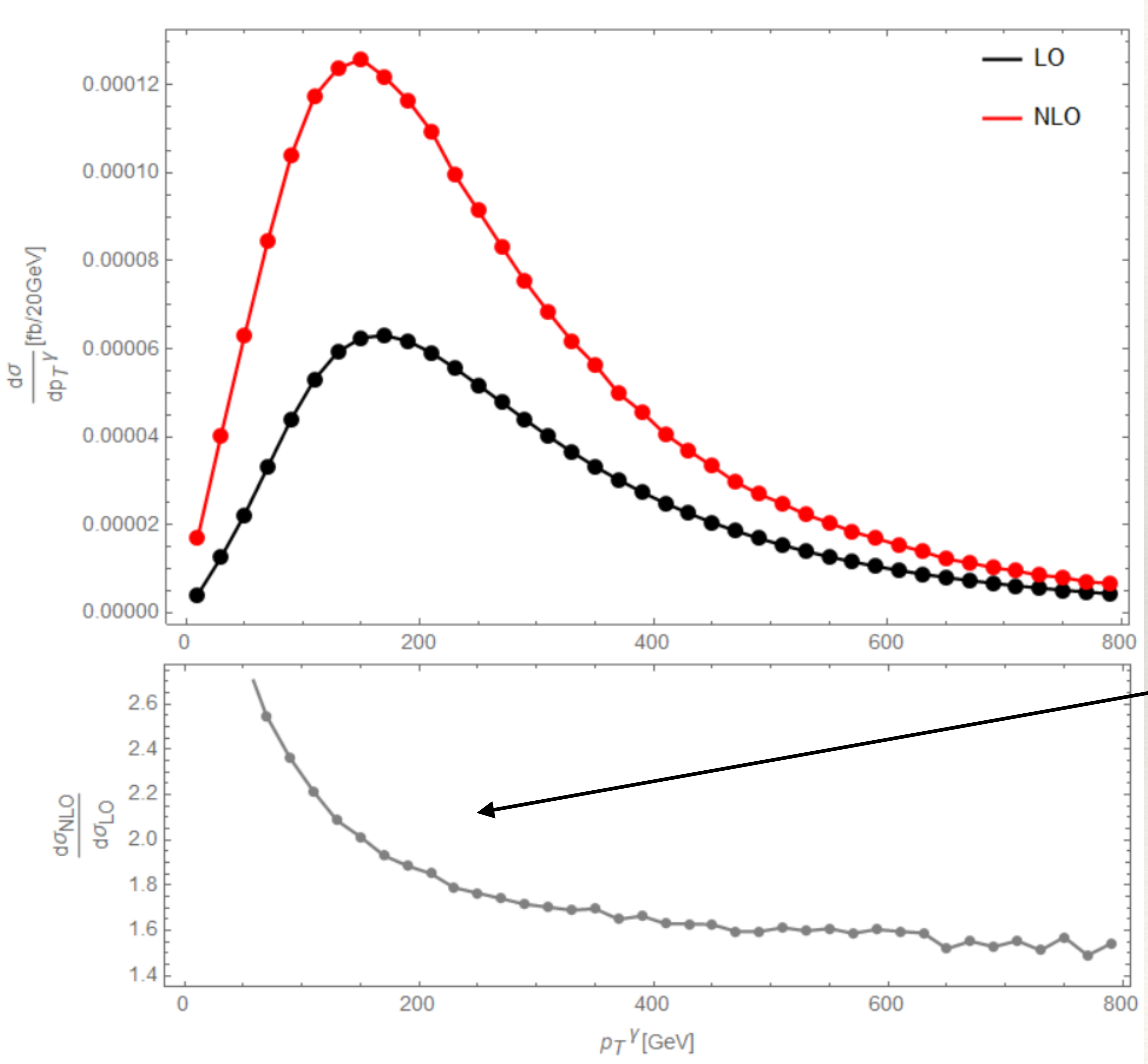


L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

gg→HH including decay



NLO prod. & LO decay

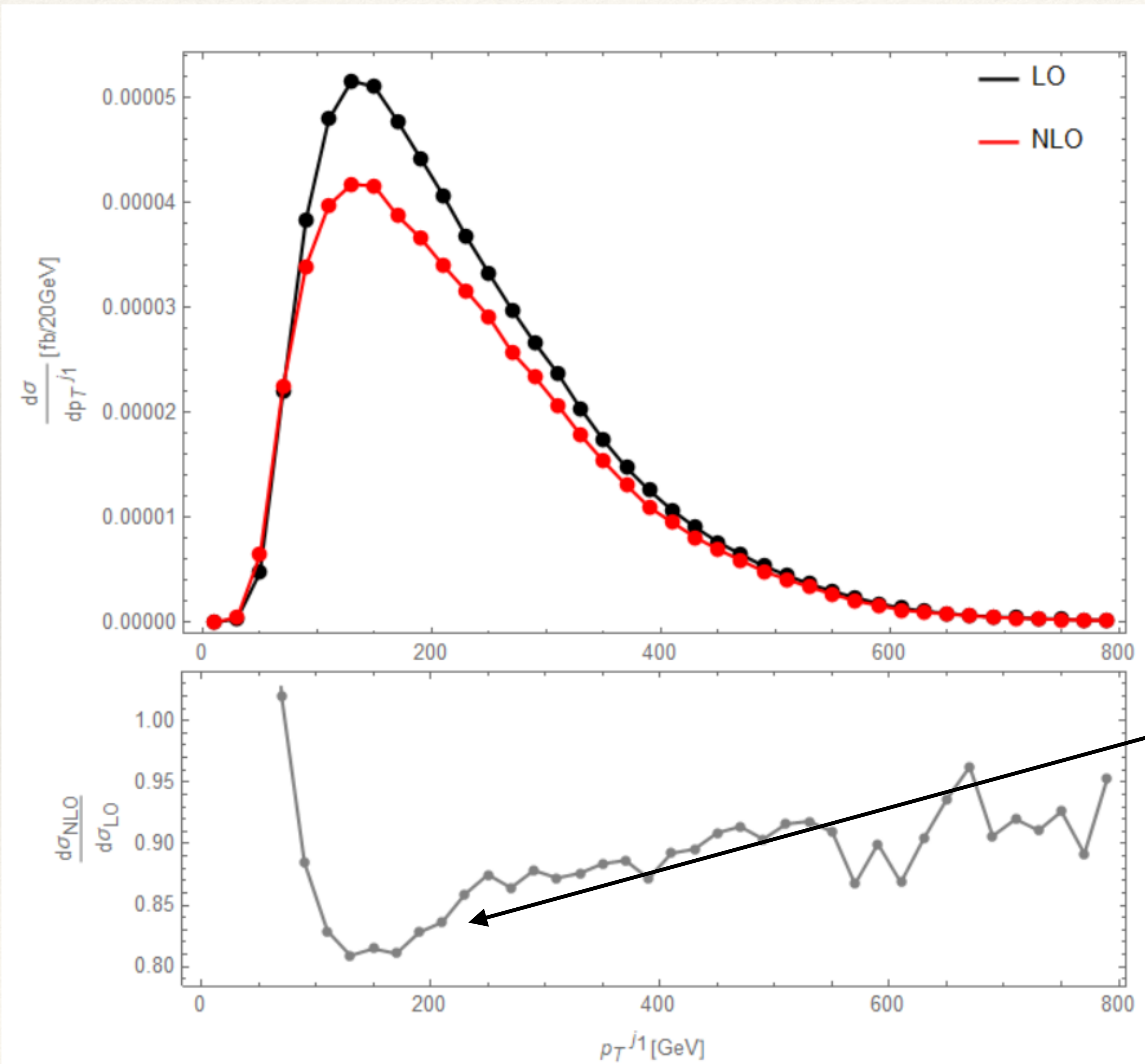
Non-constant enhancement

H.T.Li, JW, X.Zhang, D.Zhao, 2304.xxxxx

gg→HH including NLO decay

LO prod. & NLO decay

$p_j^T, p_\gamma^T > 25$ GeV
$|\eta_j|, |\eta_\gamma| < 2.5$
$\Delta R_{jj,\gamma j,\gamma\gamma} > 0.4$
$90\text{GeV} < m_{jj} < 190\text{GeV}$



Up to 20% reduction

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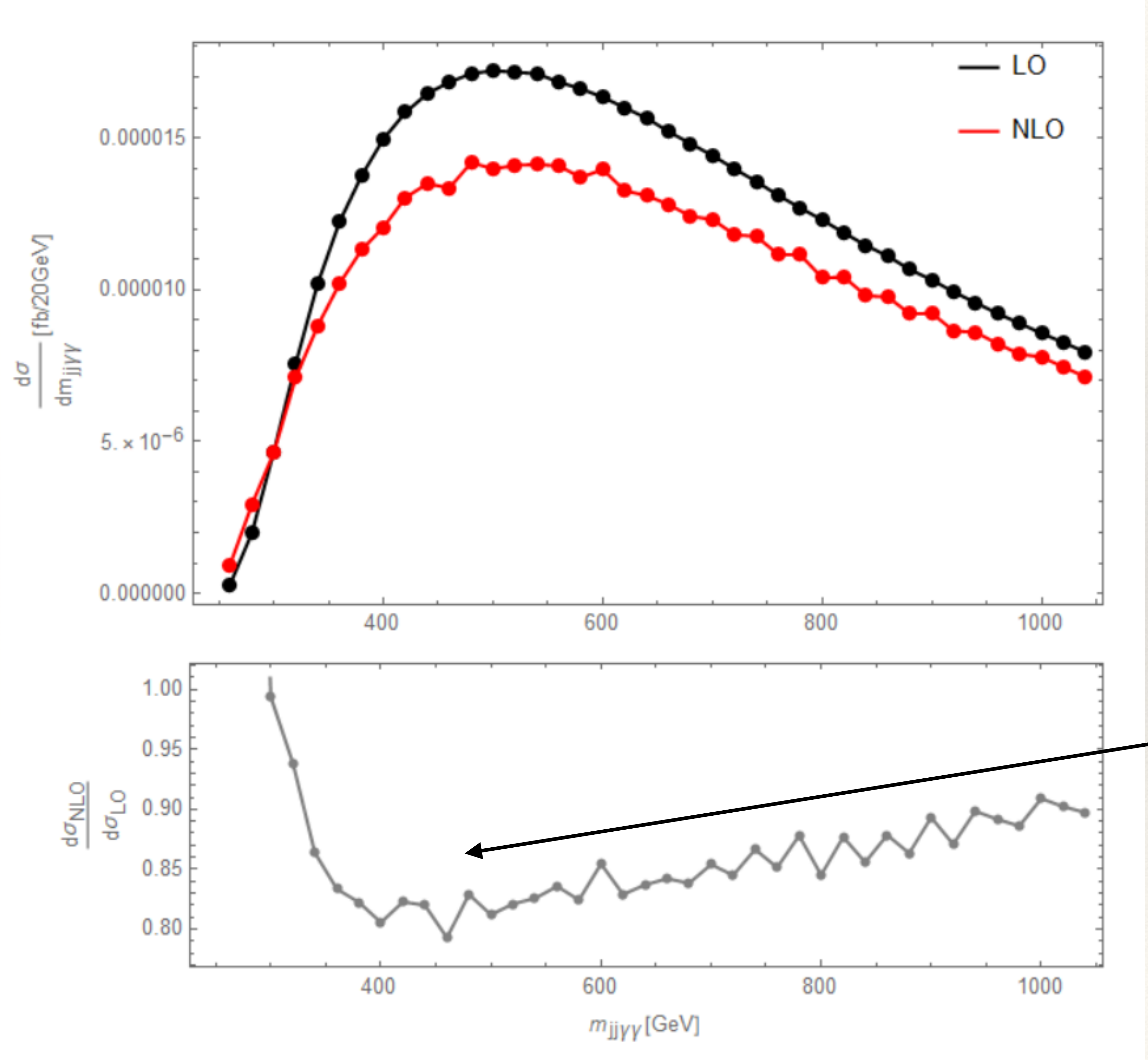
gg→HH including decay



LO prod. & NLO decay

$p_j^T, p_\gamma^T > 25$ GeV
$|\eta_j|, |\eta_\gamma| < 2.5$
$\Delta R_{jj,\gamma j,\gamma\gamma} > 0.4$
$90\text{GeV} < m_{jj} < 190\text{GeV}$

Up to 20% reduction

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Conclusion

- Measuring Higgs self-couplings is of great importance in the future.
- Precise theoretical prediction is needed to properly interpret the data.
- The dominant channel gg>HH has been calculated up to NLO/NNNLO in the finite/infinite mt scheme.
- The higher order effects in decay should also be considered for a detailed study.

Thank you!