Higgs boson pair production via gluon fusion at N3LO in QCD

王健
山东大学

第十五届TeV物理工作组学术研讨会
北京，2021-7-19

Higgs self-coupling

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★ Mass generations of gauge bosons: Higgs mechanism

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- ★ Mass generations of fermions: Higgs mechanism & Yukawa couplings

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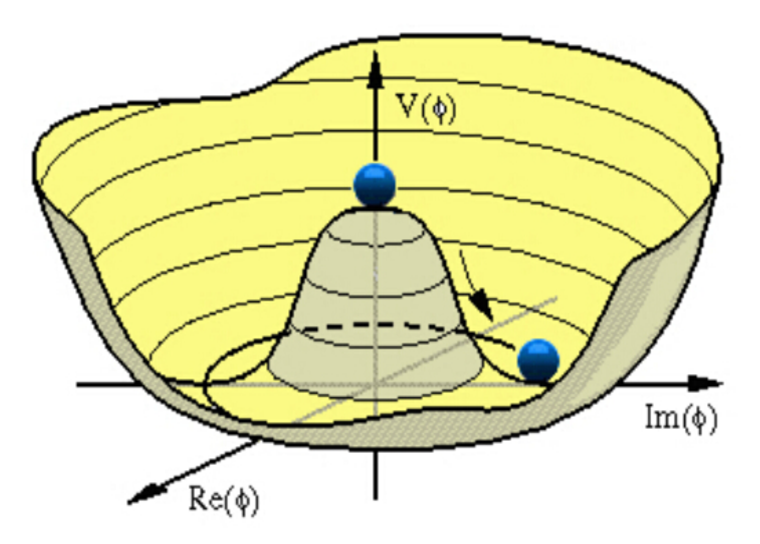
$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

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

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



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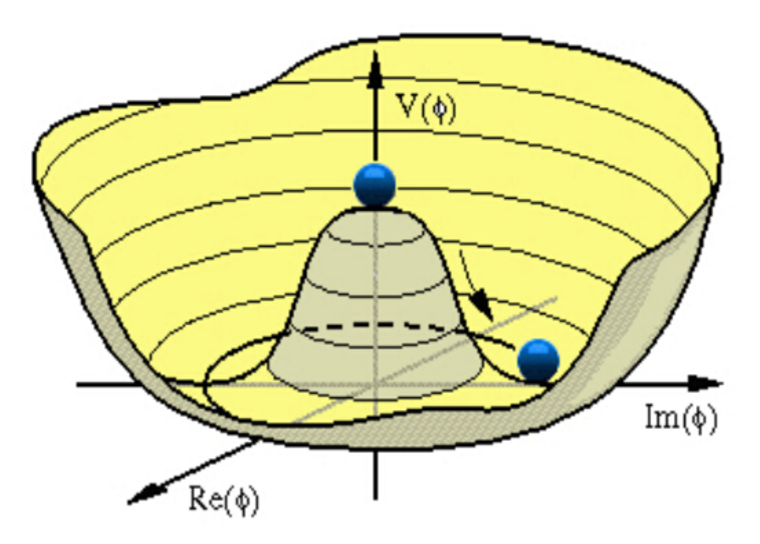

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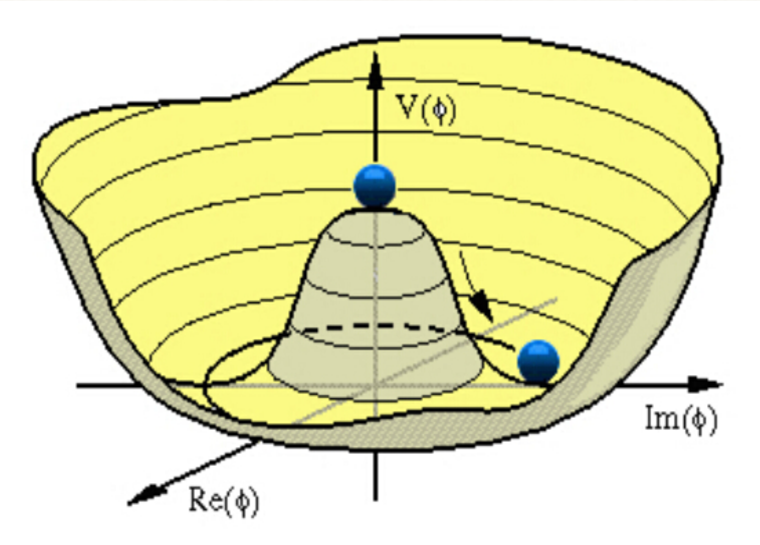
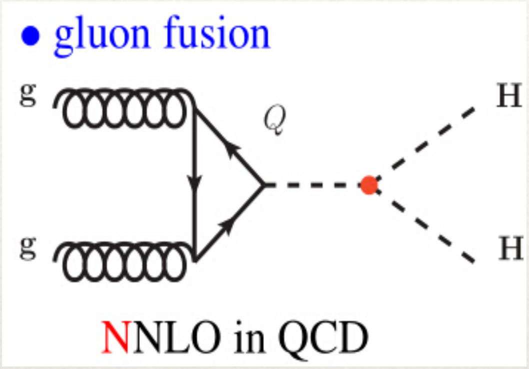
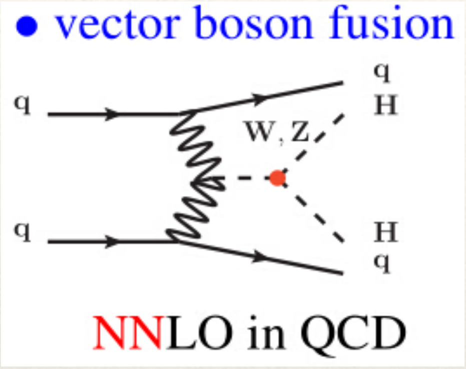


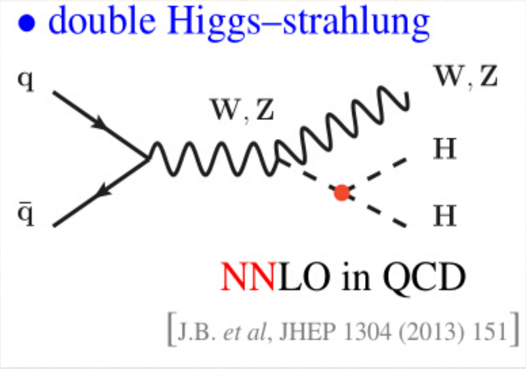
In some new physics models, the trilinear Higgs self-coupling may change by O(100)%, while the couplings with gauge bosons and fermions are still in agreement with SM.

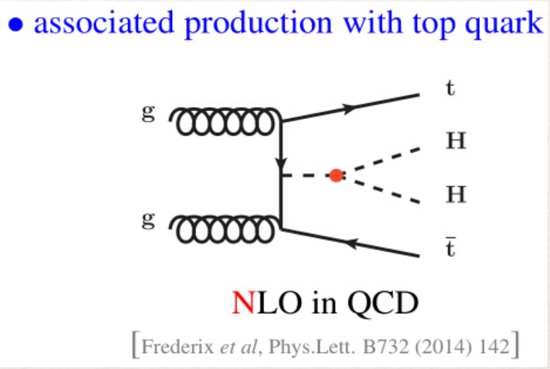
We need to measure the trilinear self coupling directly.

Higgs pair production

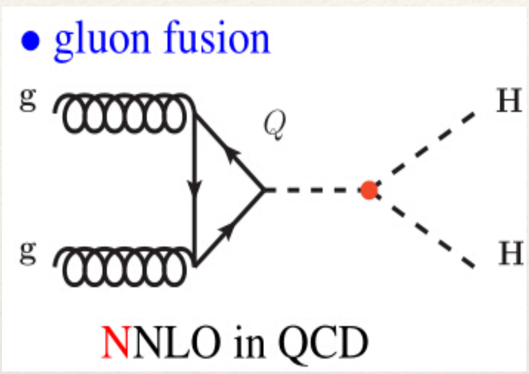


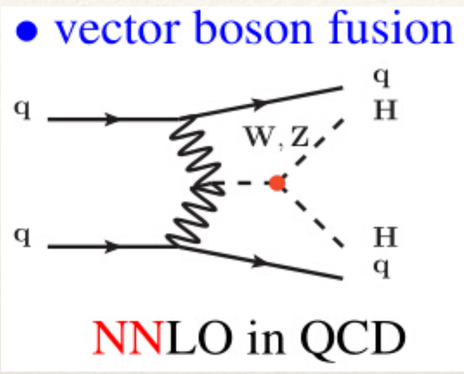


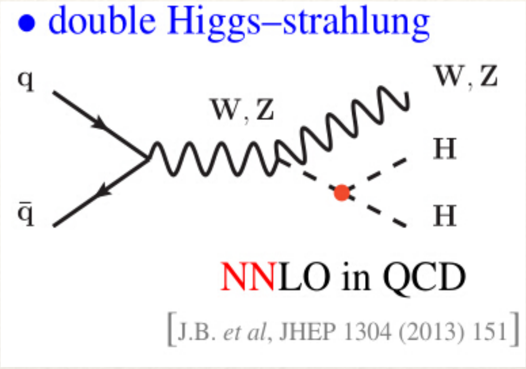


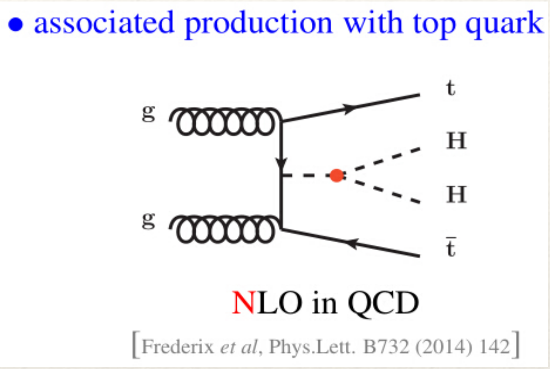


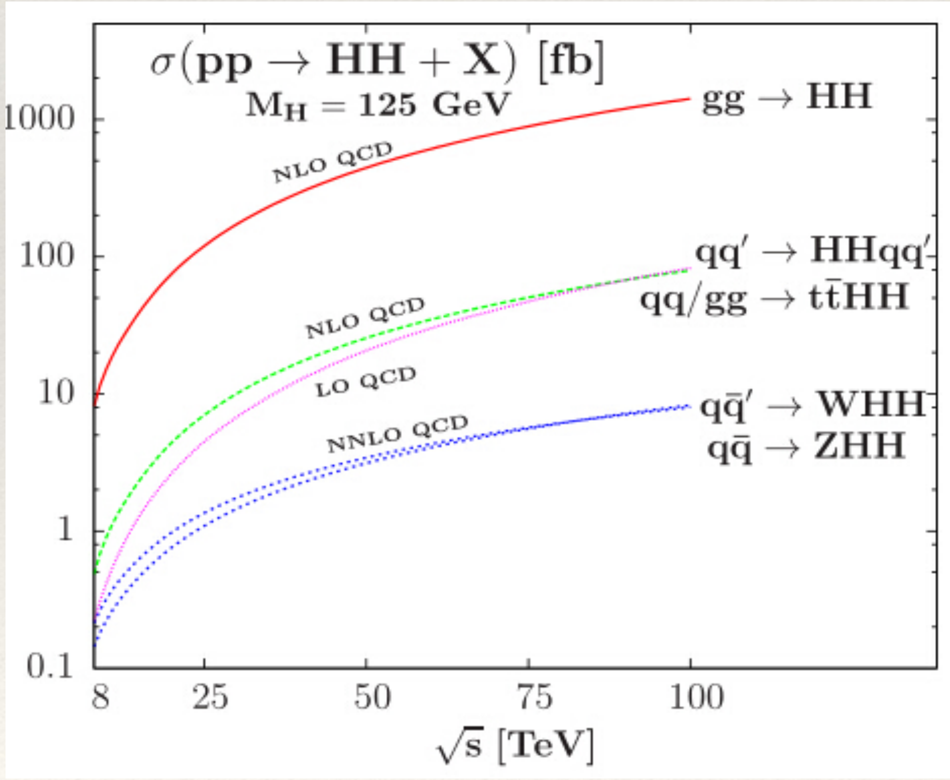
Higgs pair production



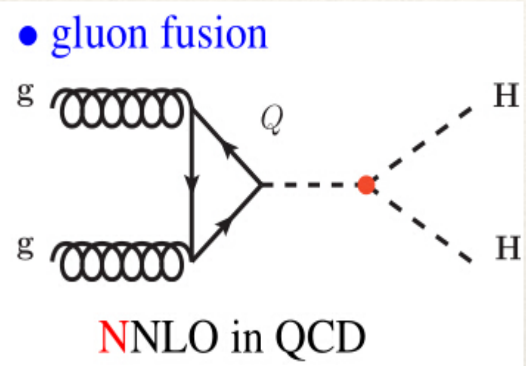


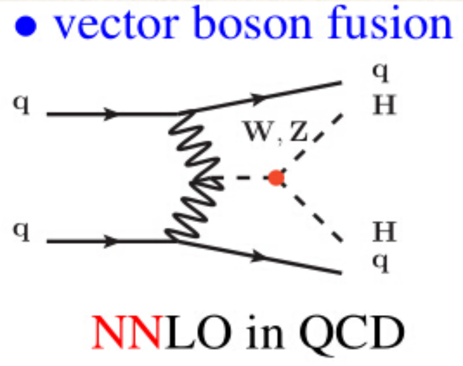


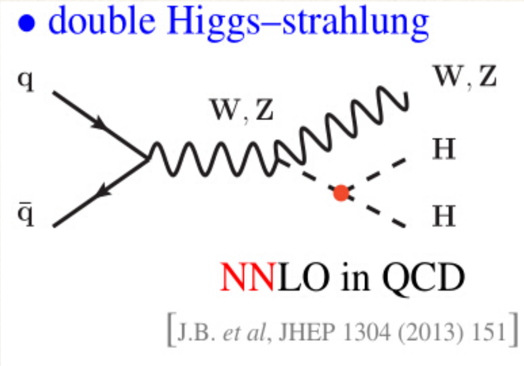


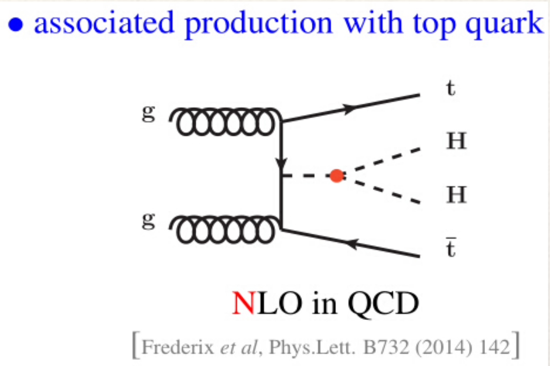


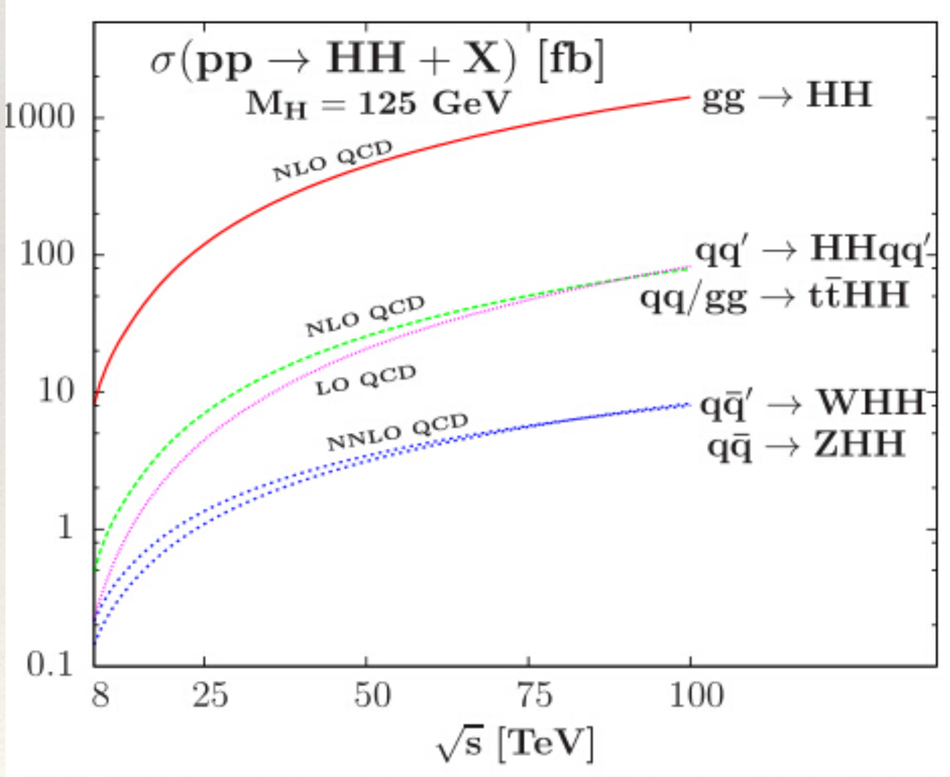
Higgs pair production

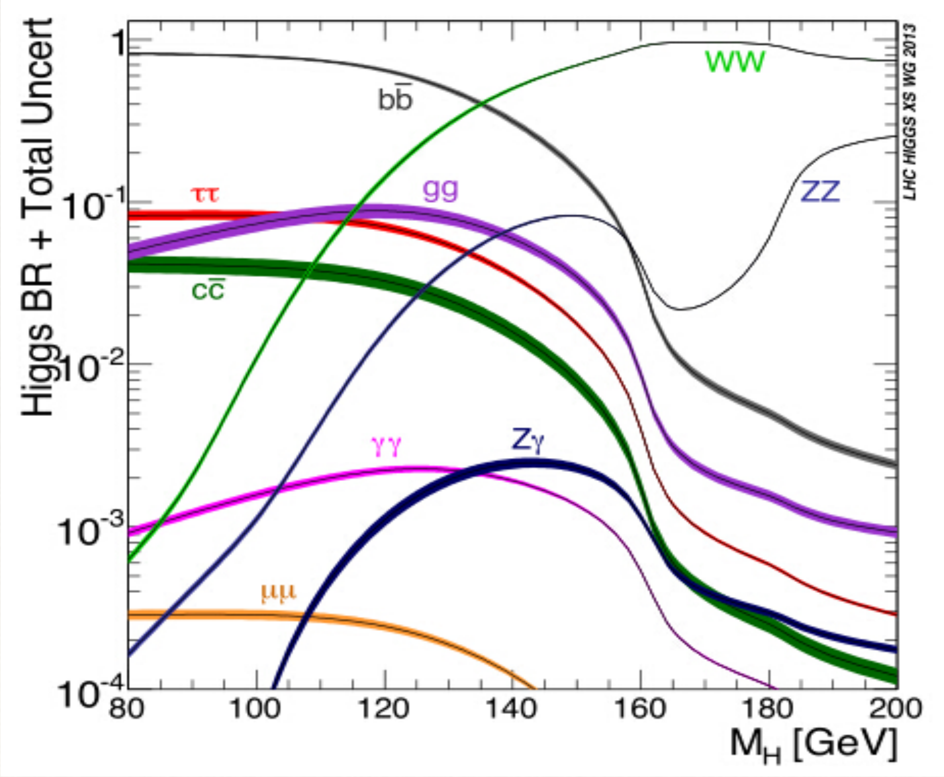












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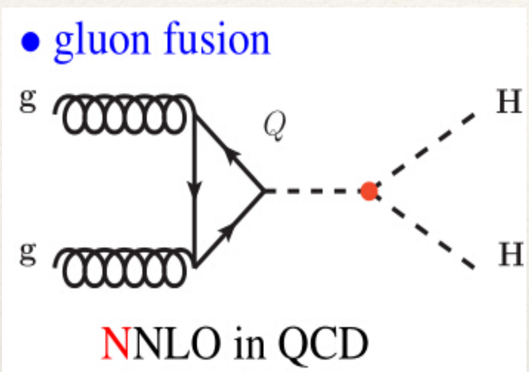

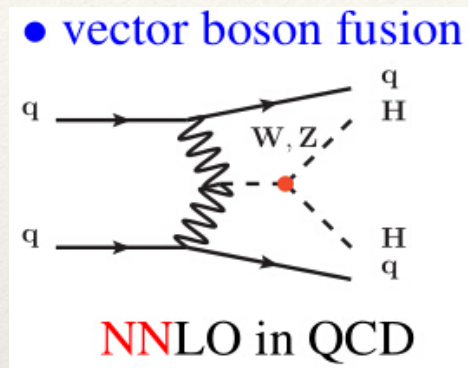

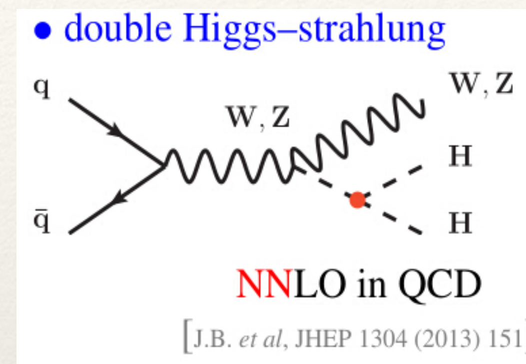

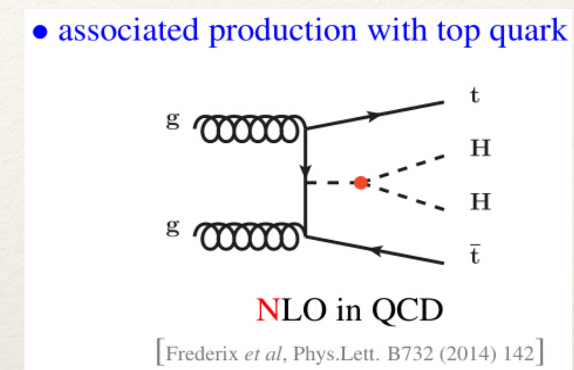

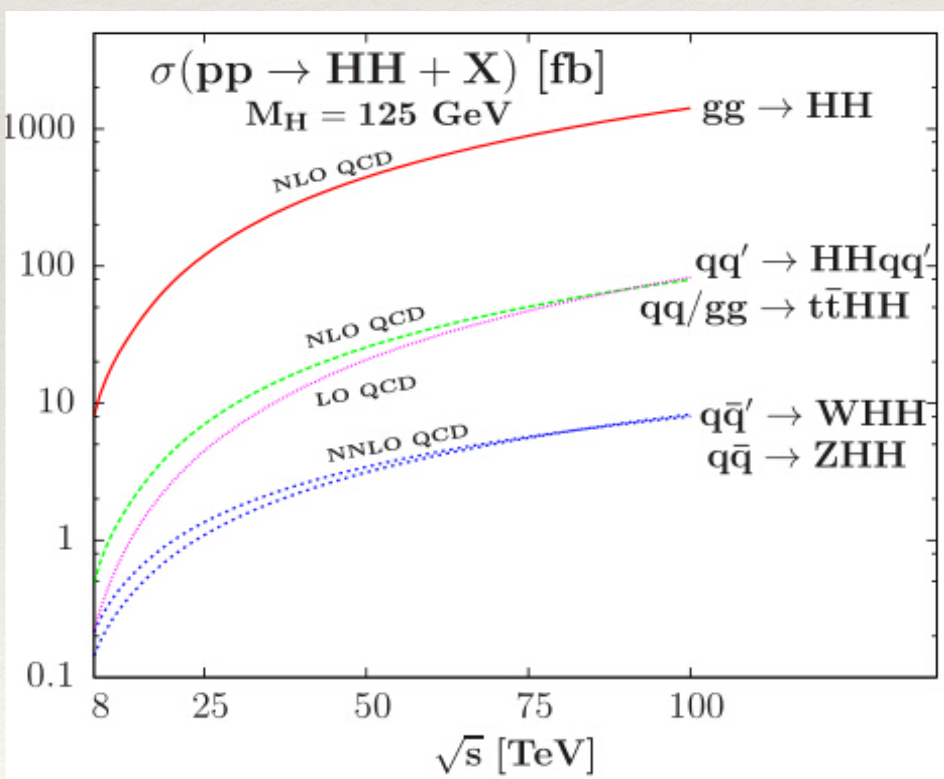

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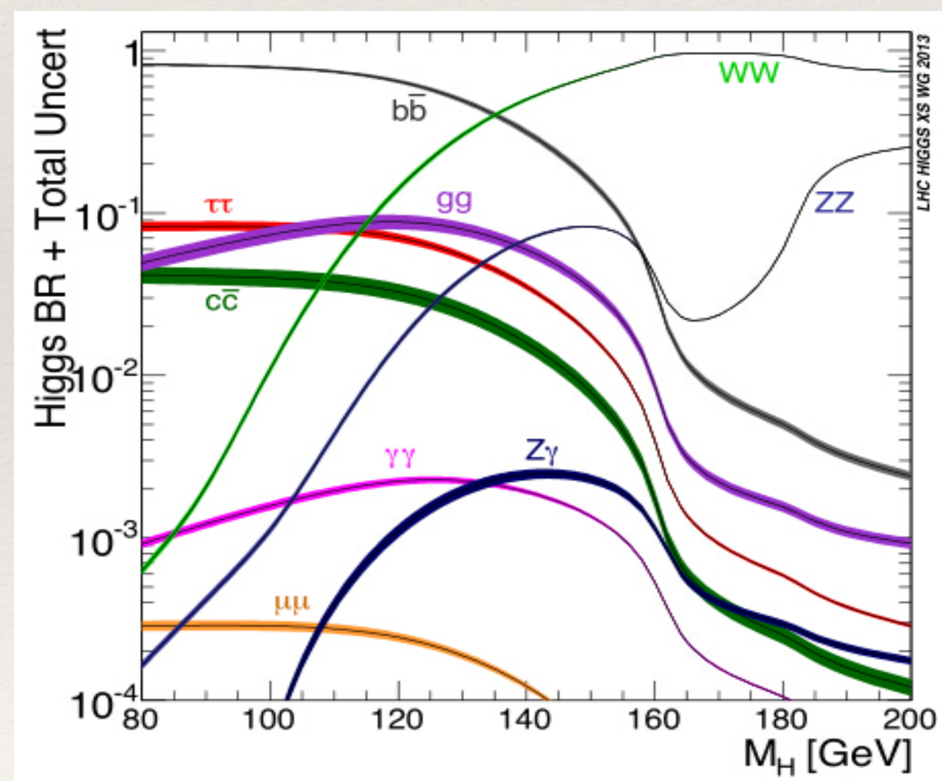
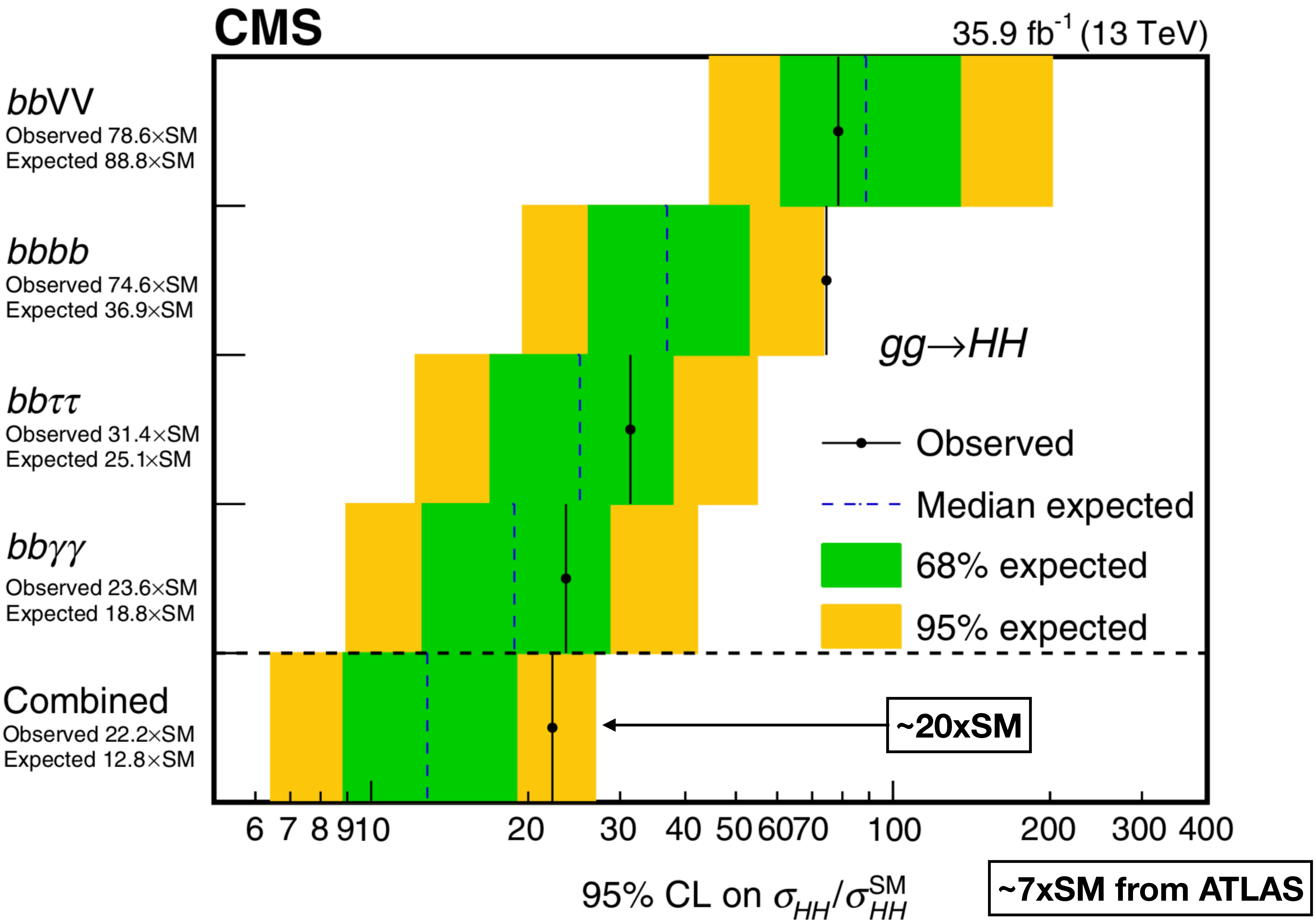


=

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



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 care about precision?

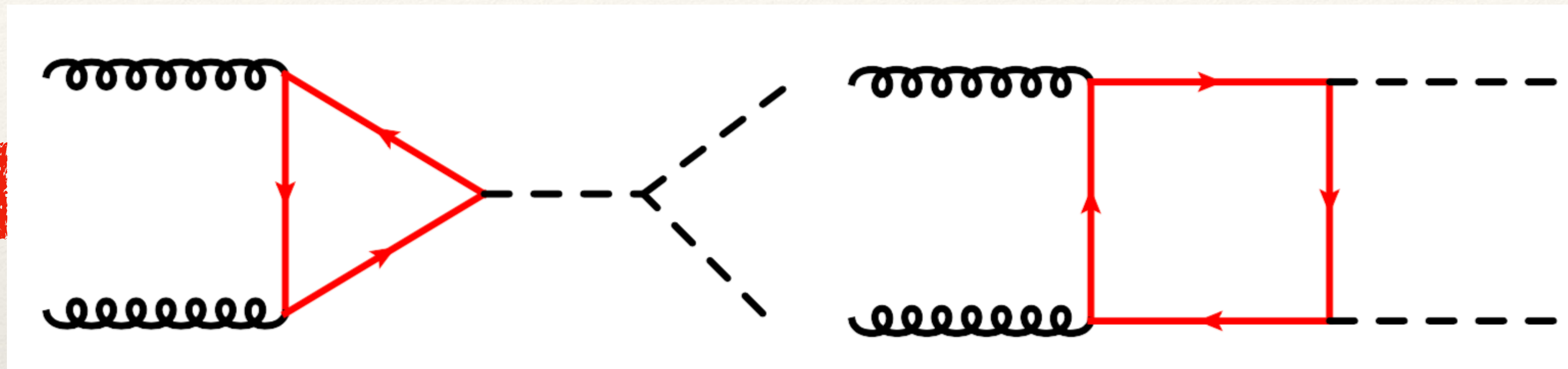
1. The measured numbers do not depend on the theoretical prediction, but the interpretation does.

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

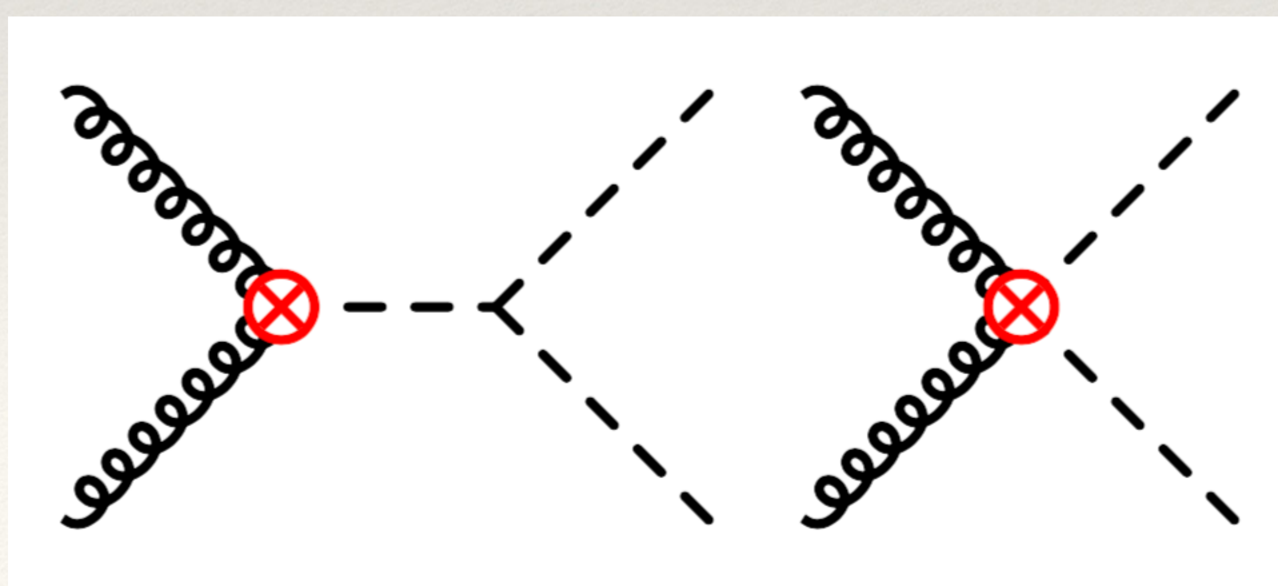
3. Renormalization and factorization scale uncertainties are intrinsic, especially for Higgs productions. How do we distinguish new physics signal from these theoretical uncertainties?

gg>HH

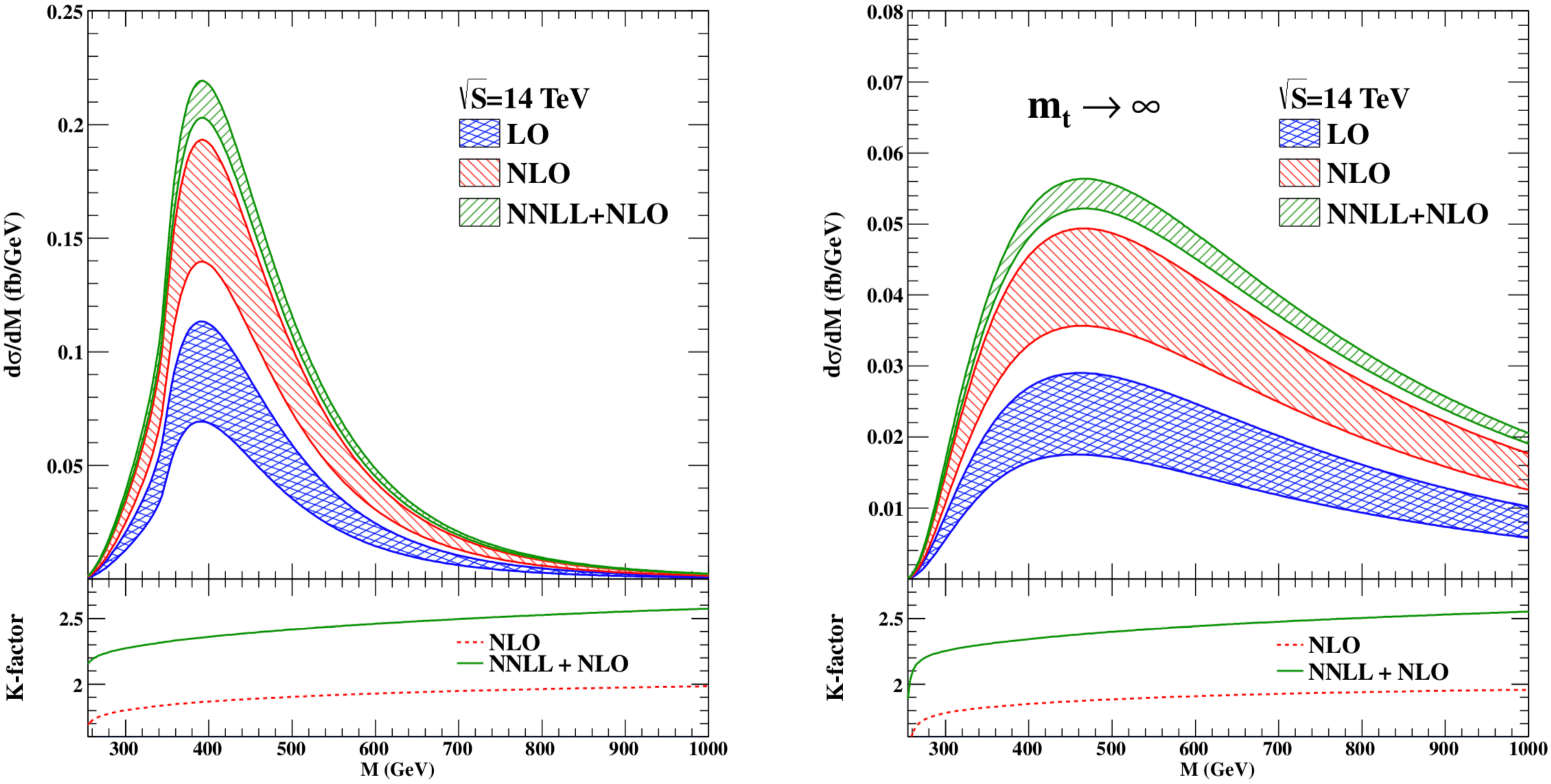
LO in SM



Heavy top quark limit

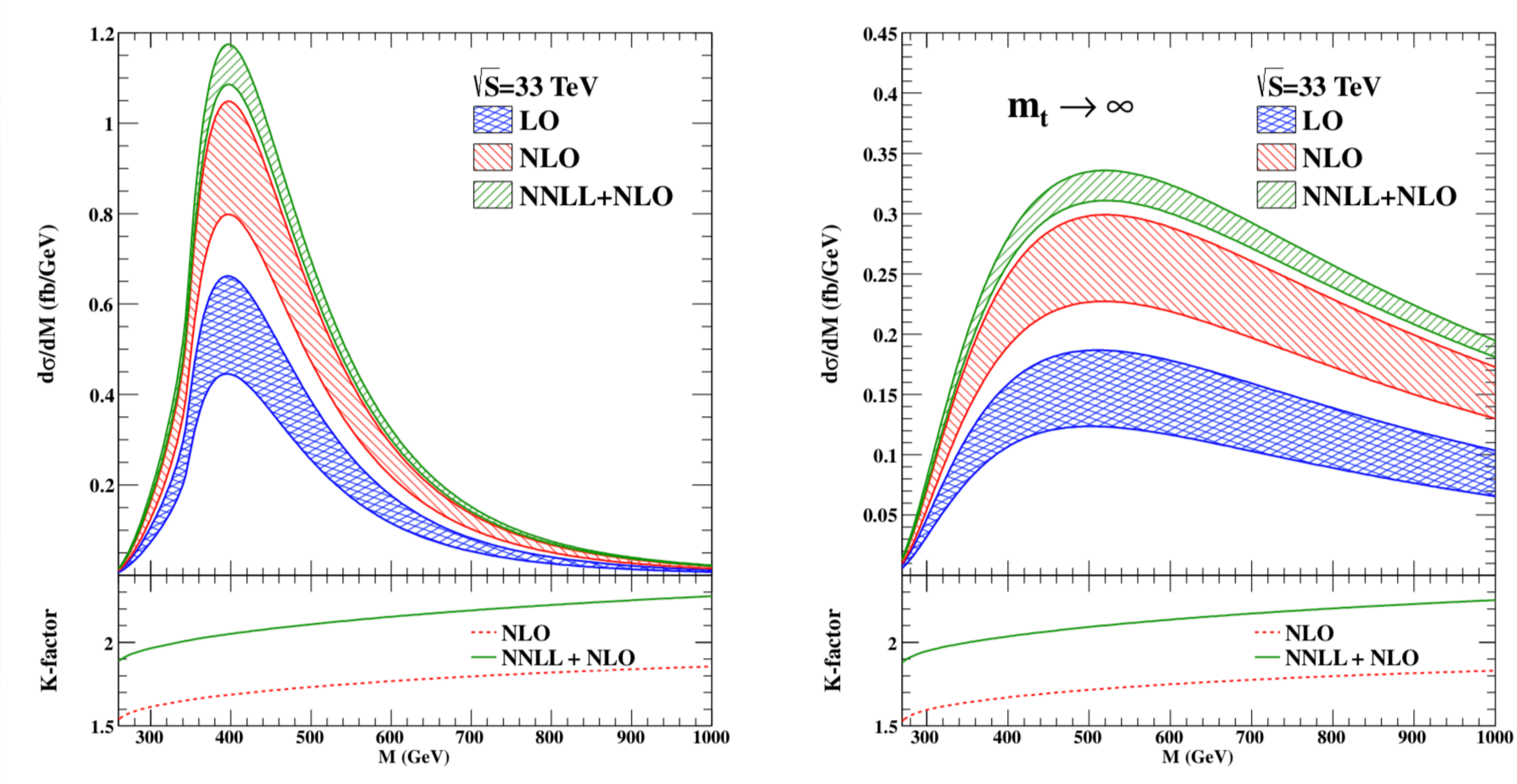


Q:How well is the approximation?



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

$\lambda/\lambda_{\rm SM}$	$\sqrt{S} = 33$ TeV		
	NLO [fb]	NLO + NNLL [fb]	K-factor
-1	$725.6^{+109.8+45.5\,(+19.4)}_{-89.7-41.7\,(-17.4)}$	$881.4^{+54.2+55.4\,(+30.8)}_{-16.5-52.4\,(-21.3)}$	1.21
-0.8	$655.3^{+99.1+41.0\,(+17.4)}_{-81.1-37.6\,(-15.8)}$	$796.0^{+48.9+50.0\,(+27.8)}_{-14.9-47.3\,(-19.3)}$	1.21
-0.6	$589.0^{+89.1+36.9\,(+15.7)}_{-72.9-33.7\,(-14.1)}$	$715.6^{+43.9+44.9\,(+24.9)}_{-13.4-42.5\,(-17.3)}$	1.21
-0.4	$526.9^{+79.8+32.9\,(+14.0)}_{-65.2-30.1\,(-12.6)}$	$640.2^{+39.2+40.2\,(+22.3)}_{-12.0-38.0\,(-15.5)}$	1.22
-0.2	$468.8^{+71.0+29.3\,(+12.5)}_{-58.1-26.8\,(-11.2)}$	$569.7^{+34.9+35.8\,(+19.8)}_{-10.6-33.8\,(-13.8)}$	1.22
0	$414.9^{+62.9+25.9\,(+11.0)}_{-51.5-23.6\,(-9.9)}$	$504.3^{+30.8+31.6\,(+17.5)}_{-9.4-30.0\,(-12.2)}$	1.22
0.2	$365.2^{+55.4+22.7\,(+9.7)}_{-45.4-20.8\,(-8.7)}$	$443.8^{+27.1+27.9\,(+15.4)}_{-8.3-26.3\,(-10.8)}$	1.22
0.4	$319.5^{+48.5+19.8\,(+8.5)}_{-39.8-18.1\,(-7.6)}$	$388.4^{+23.7+24.4\,(+13.4)}_{-7.2-23.0\,(-9.4)}$	1.22
0.6	$277.9^{+42.2+17.2\,(+7.4)}_{-34.7-15.7\,(-6.6)}$	$337.9^{+20.5+21.2\,(+11.6)}_{-6.3-20.0\,(-8.2)}$	1.22
0.8	$240.5^{+36.5+14.9\,(+6.4)}_{-30.0-13.5\,(-5.7)}$	$292.4^{+17.7+18.3\,(+10.1)}_{-5.4-17.3\,(-7.1)}$	1.22
1	$207.2^{+31.5+12.8\,(+5.5)}_{-25.9-11.6\,(-4.9)}$	$252.0^{+15.2+15.8\,(+8.6)}_{-4.7-14.9\,(-6.1)}$	1.22
1.2	$178.0^{+27.1+11.0\,(+4.7)}_{-22.3-10.0\,(-4.2)}$	$216.5^{+13.1+13.6\,(+7.4)}_{-4.0-12.8\,(-5.3)}$	1.22
1.4	$152.9^{+23.3+9.4\,(+4.0)}_{-19.2-8.5\,(-3.6)}$	$186.0^{+11.2+11.7\,(+6.3)}_{-3.4-11.0\,(-4.6)}$	1.22
1.6	$131.9^{+20.1+8.1\,(+3.5)}_{-16.6-7.3\,(-3.1)}$	$160.5^{+9.6+10.1\,(+5.5)}_{-3.0-9.5\,(-3.9)}$	1.21
1.8	$115.0^{+17.6+7.1\,(+3.0)}_{-14.5-6.4\,(-2.7)}$	$139.9^{+8.4+8.8\,(+4.8)}_{-2.6-8.3\,(-3.4)}$	1.22
2	$102.3^{+15.7+6.3\,(+2.7)}_{-12.9-5.7\,(-2.4)}$	$124.4^{+7.4+7.8\,(+4.2)}_{-2.3-7.4\,(-3.1)}$	1.22

0.8	$240.5^{+36.5+14.9\,(+6.4)}_{-30.0-13.5\,(-5.7)}$	$292.4^{+17.7+18.3\,(+1}_{-5.4-17.3\,(-7.1}$
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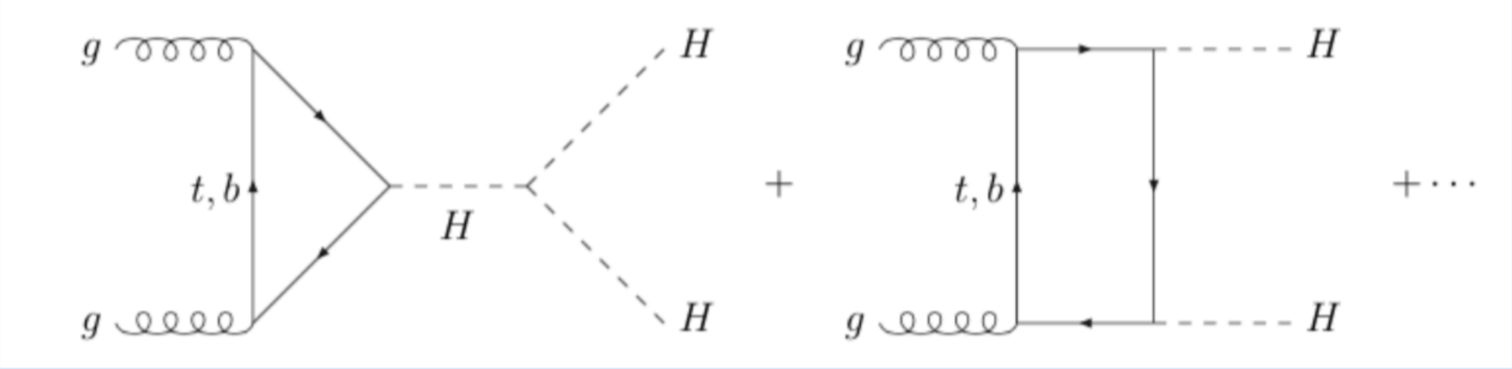
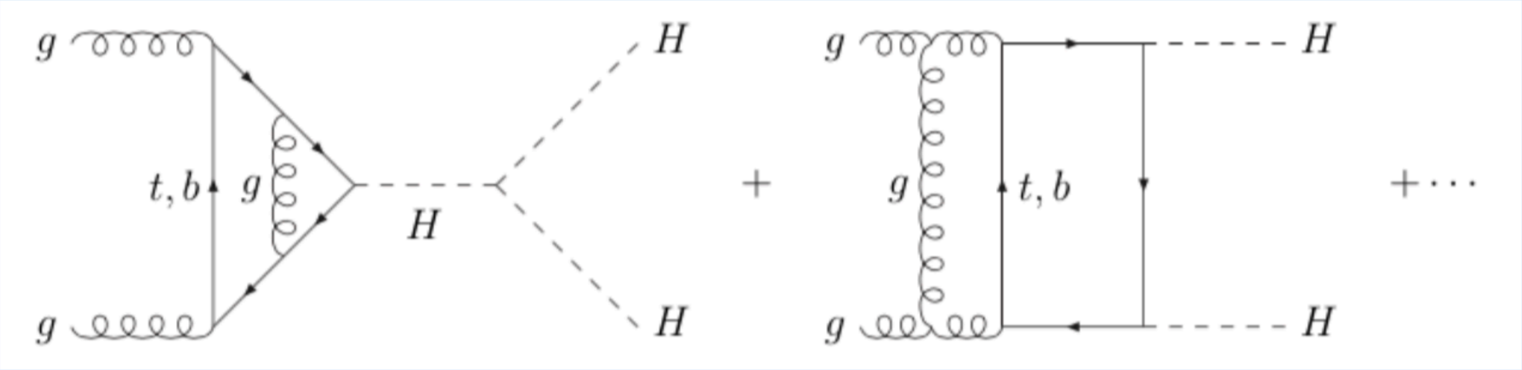
gg>HH@NLO

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

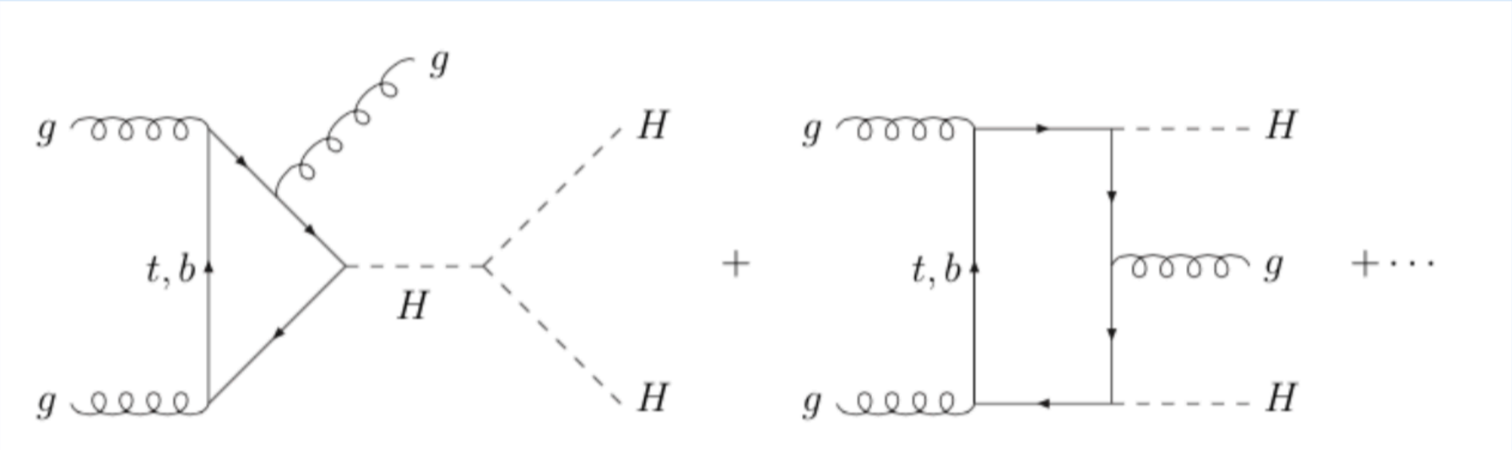
σ_{LO}:



$\Delta\sigma_{virt}$:



$\Delta\sigma_{ij}$:

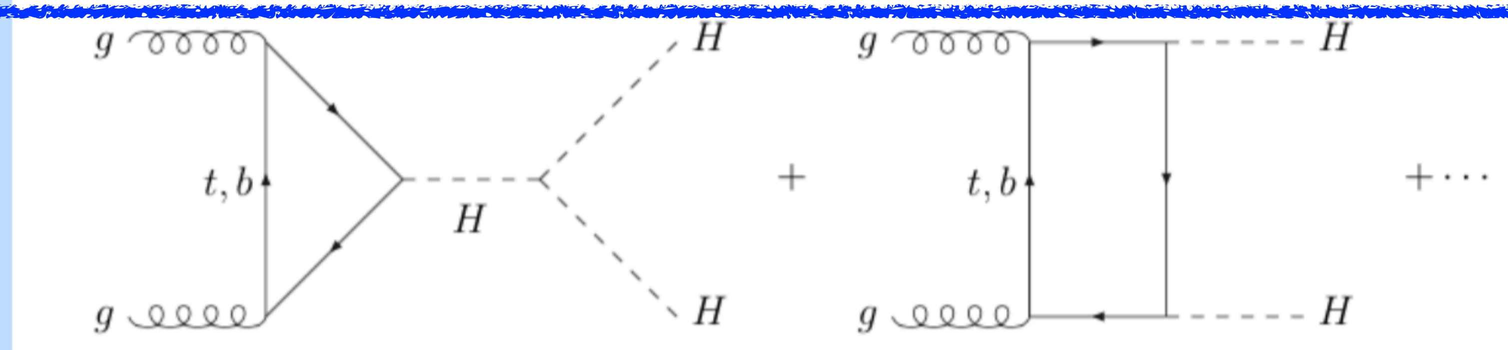


gg>HH@NLO

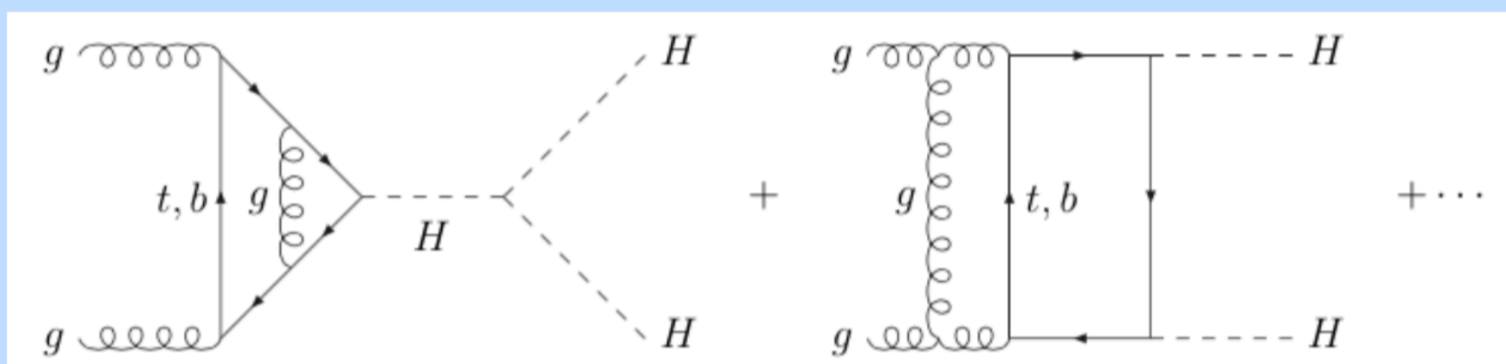
$$\sigma_{\rm NLO}(pp \to HH + X) = \sigma_{\rm LO} + \Delta\sigma_{\rm virt} + \Delta\sigma_{gg} + \Delta\sigma_{qg} + \Delta\sigma_{q\bar{q}},$$

Very difficult to obtain analytical results

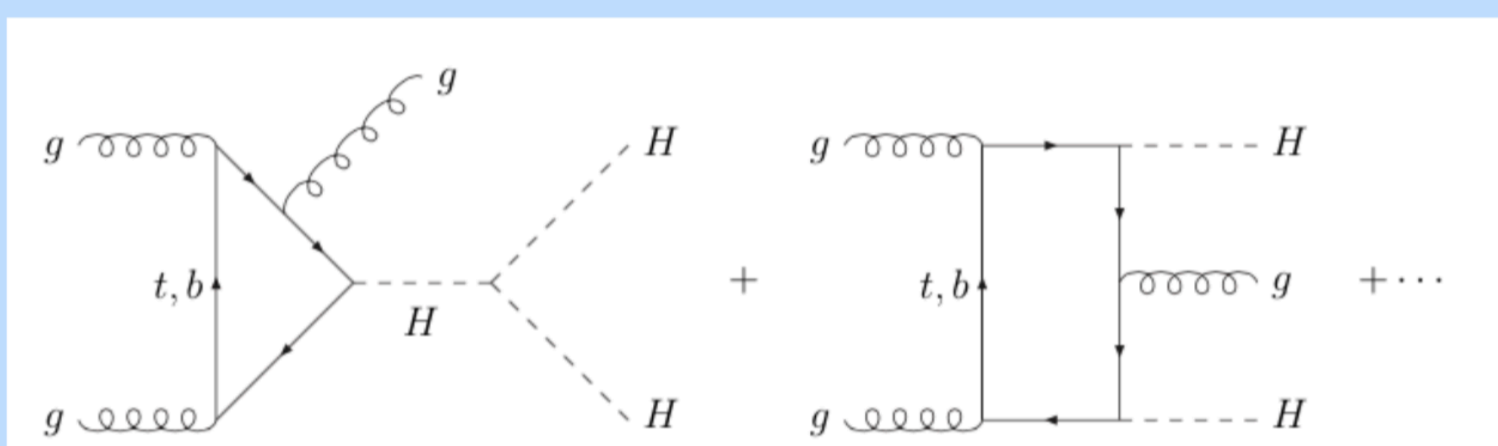
σ_{LO}:



$\Delta\sigma_{virt}$:



$\Delta\sigma_{ij}$:



gg>HH@NLO: Full mt dependence

	PDF4LHC15	MMHT2014
σ_{LO}	19.80 fb	23.75 fb
σ_{NLO}^{HTL}	38.66 fb	39.34 fb
σ_{NLO}	32.78(7) fb	33.33(7) fb

-15%

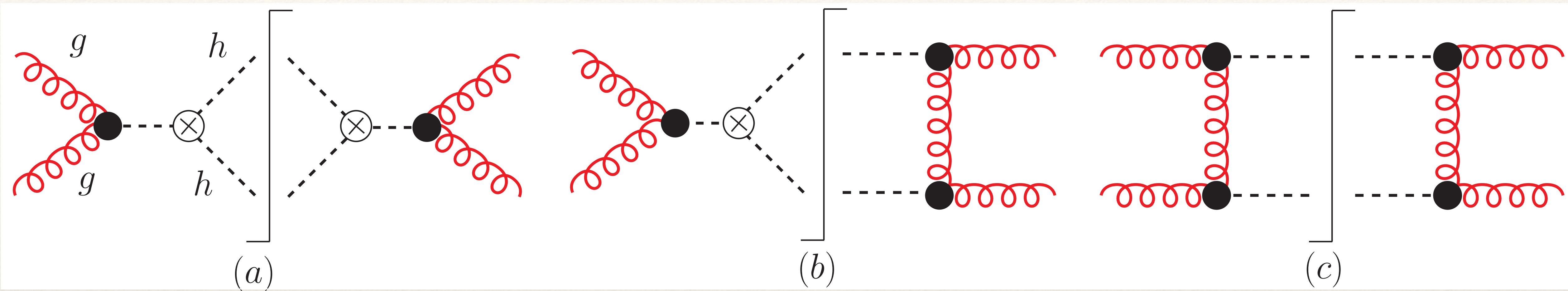
$$\sigma(gg \to HH) = 32.78(7)^{+13.5\%}_{-12.5\%} \quad \text{(PDF4LHC15)}$$

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

Frontiers: NNNLO

2015	2016	2017	2018	2019	2020
ggH x-sec (thres. exp.)	VBF H	ggH diff (thres. exp.)	ggH x-sec ggH pT-dist. ggH Y (approx) VBF HH	bbH	DY
Anastasiou, Duhr, Dulat, Herzog, Mistlberger	Dreyer Karlberg	Dulat, Mistlberger, Pelloni	Mistlberger, Cieri, Chen, Gehrmann, Gloveer, Huss Pelloni, Dreyer, Karlberg	Duhr, Dulat, Mistlberger	

gg>HH@NNNLO



NNNLO **NNLO** **NLO**

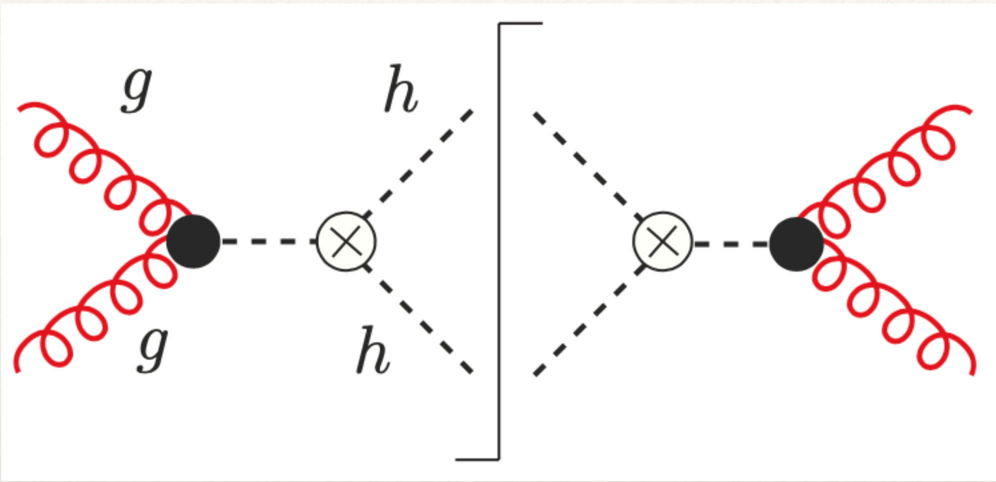
Similar to single Higgs **qT subtraction** **Standard methods**

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)

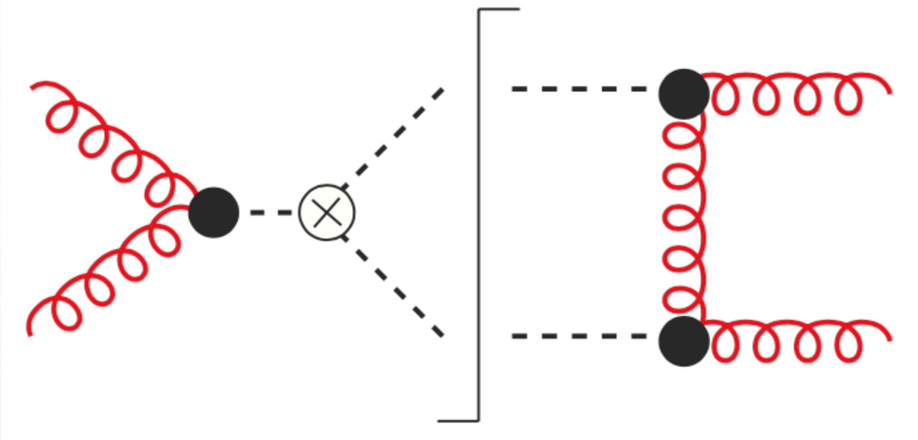


$$\frac{d\sigma^a_{hh}}{dm_{hh}} = f_{h\to hh}\left(\frac{C_{hh}}{C_h} - \frac{6\lambda_{hhh}v^2}{m_{hh}^2 - m_h^2}\right)^2 \times \left(\sigma_h\big|_{m_h\to m_{hh}}\right)$$

$$f_{h\to hh} = \frac{\sqrt{m_{hh}^2 - 4m_h^2}}{16\pi^2 v^2}$$

Dulat, Lazopoulos, Mistlberger iHixs, 1802.00827

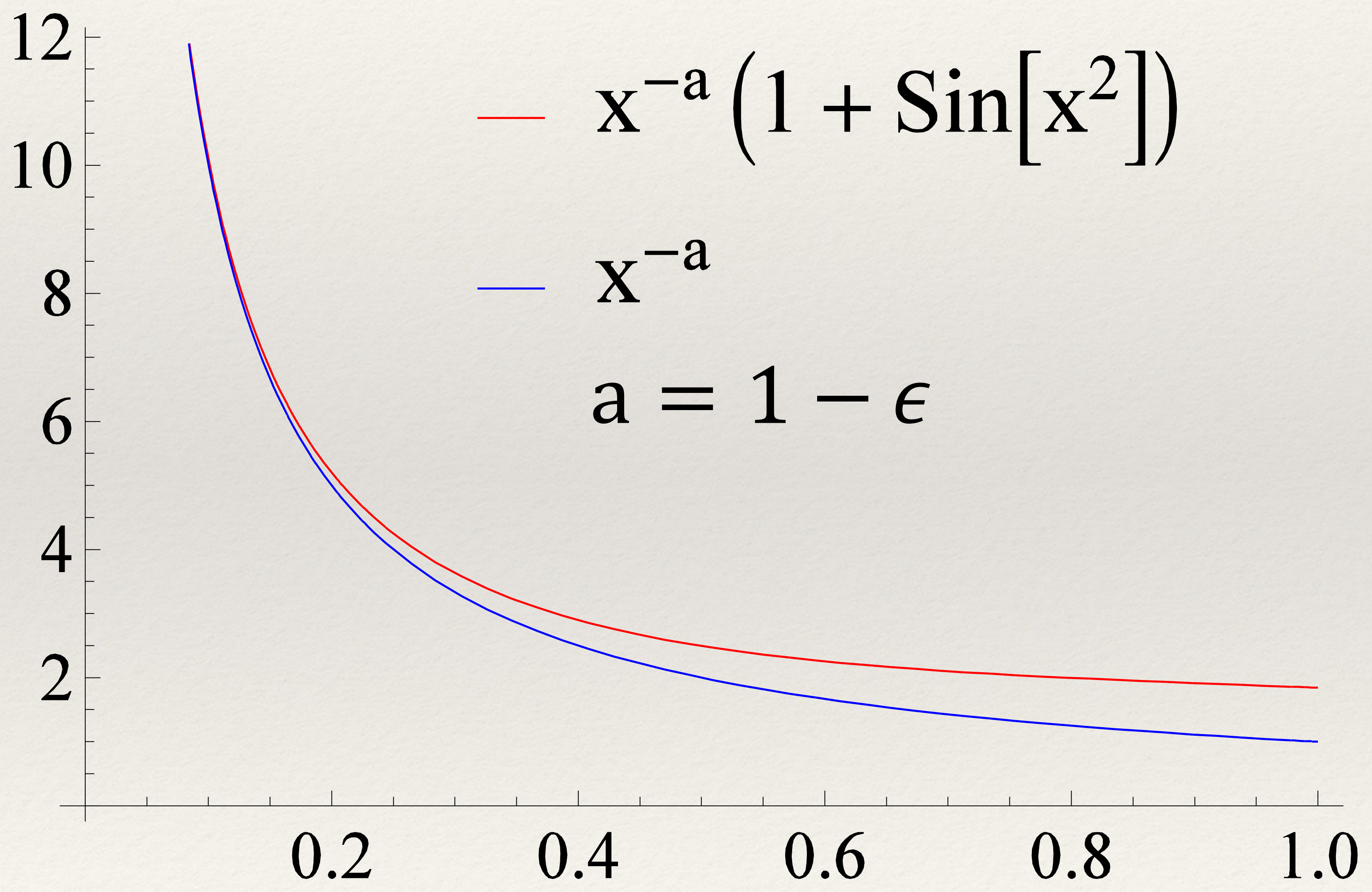
Class-(b)



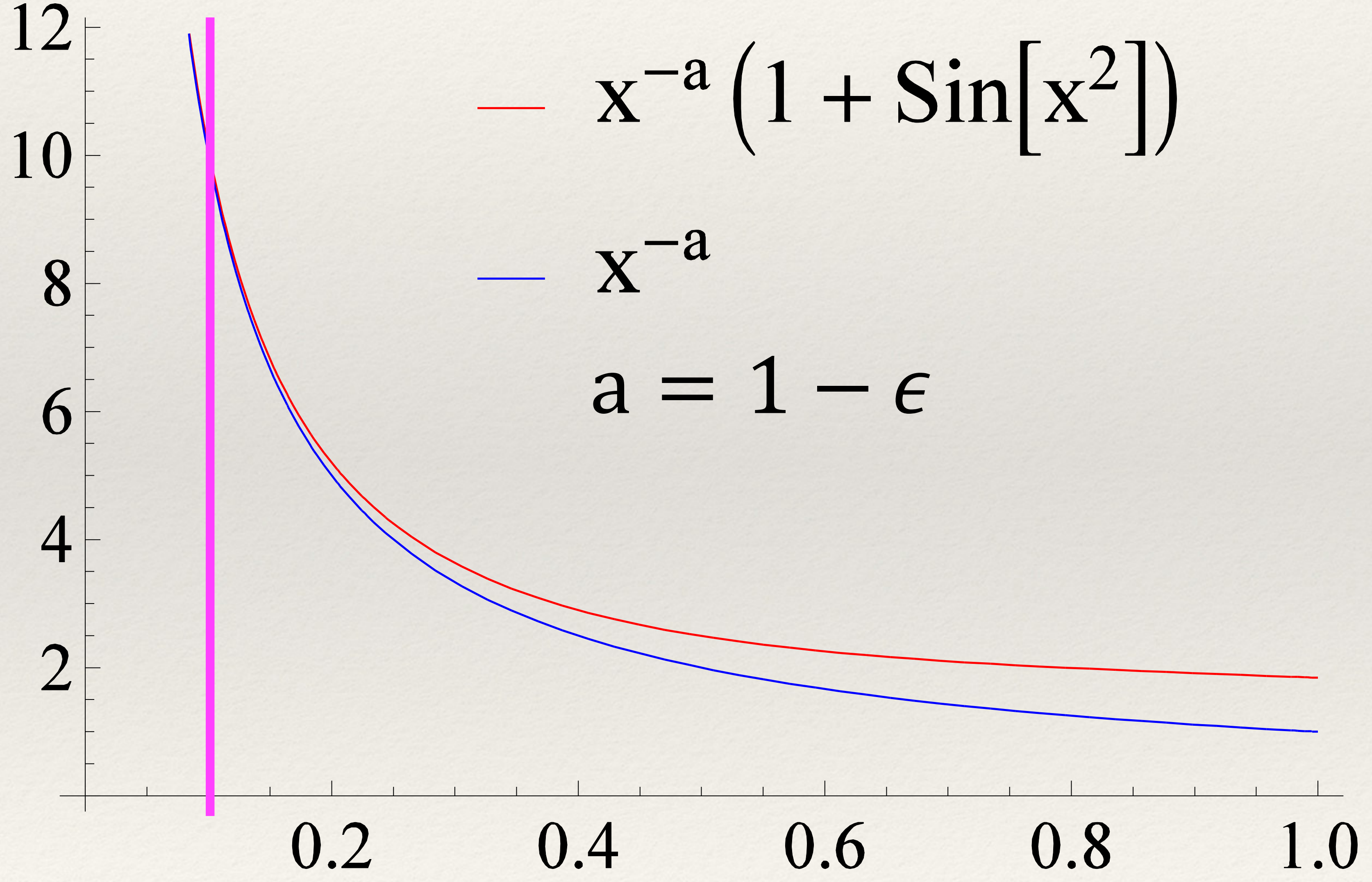
$$d\sigma_{hh}^{b} = d\sigma_{hh}^{b}\Big|_{p_T^{hh} < p_T^{\rm veto}} + d\sigma_{hh}^{b}\Big|_{p_T^{hh} > p_T^{\rm veto}}$$

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

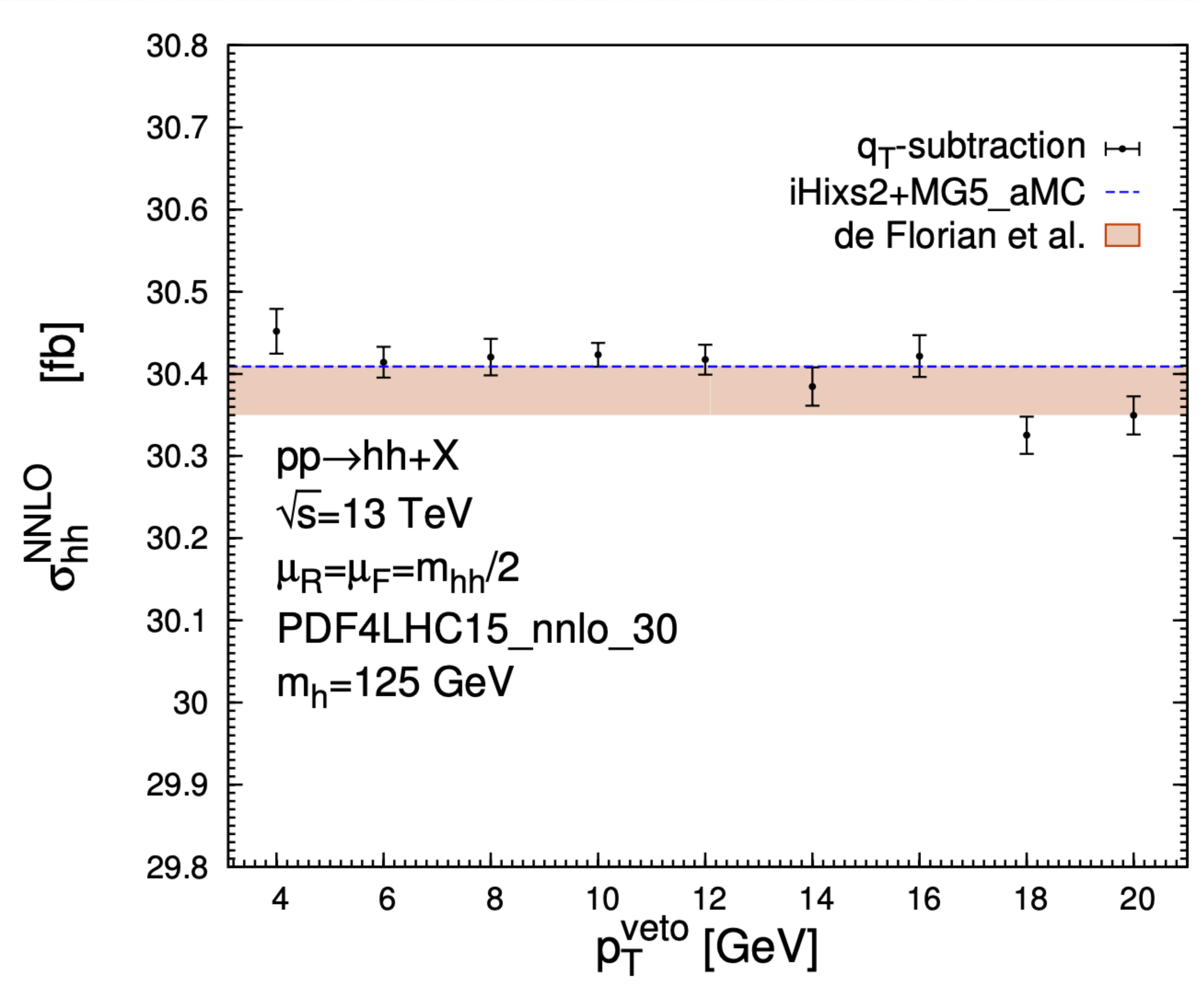
The idea of qT subtraction



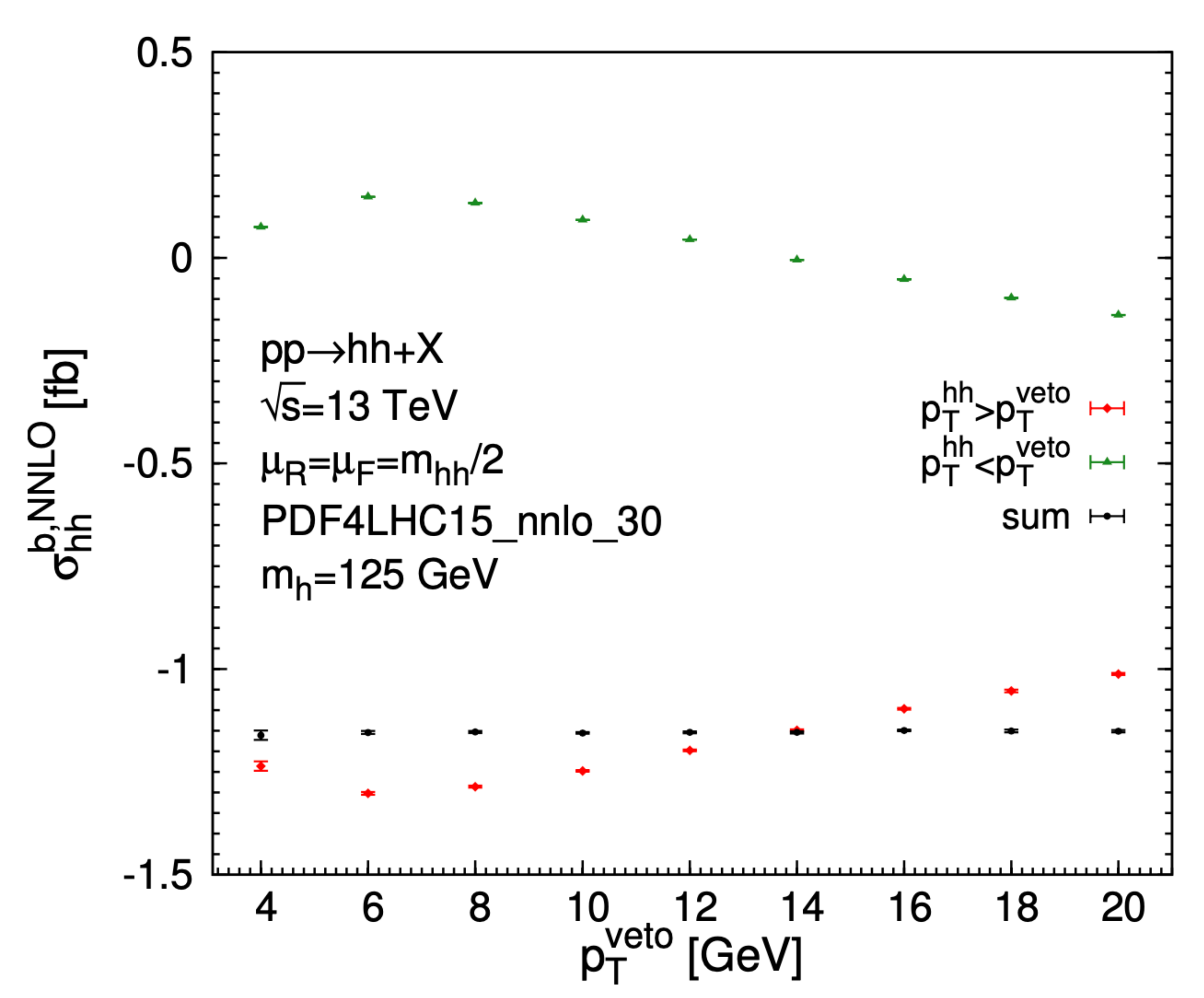
The idea of qT subtraction



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	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
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 !

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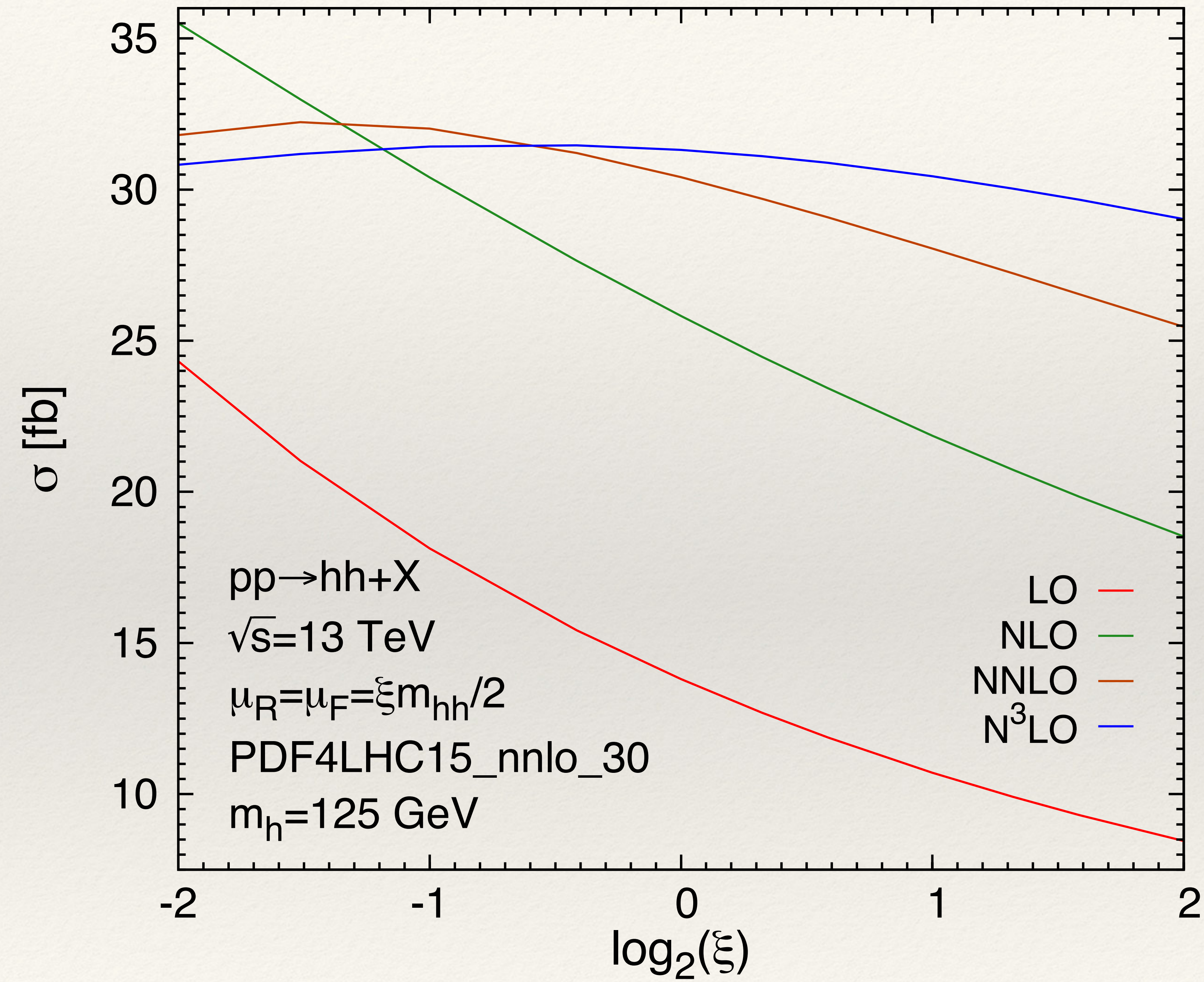
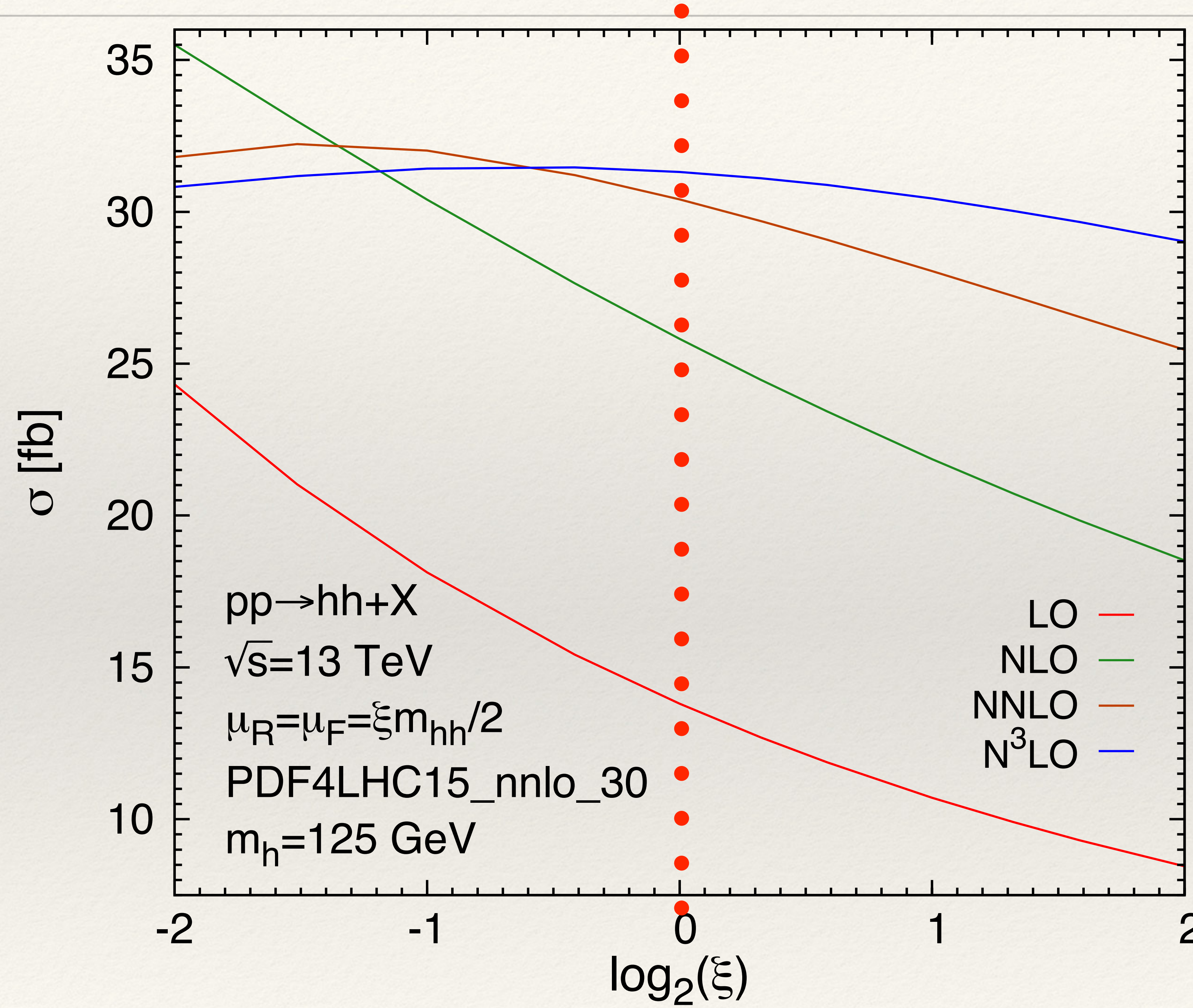
How to choose a scale?



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

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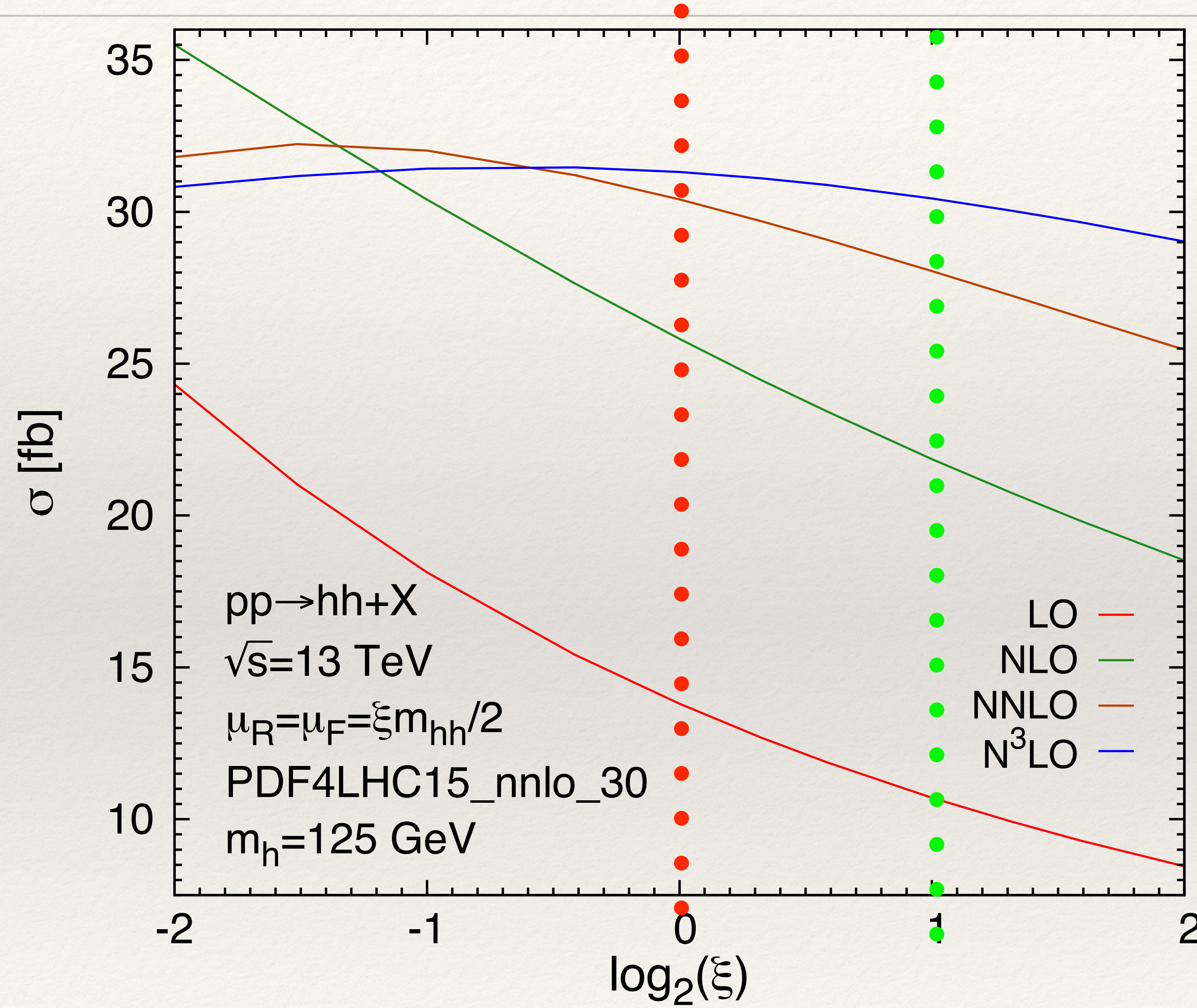
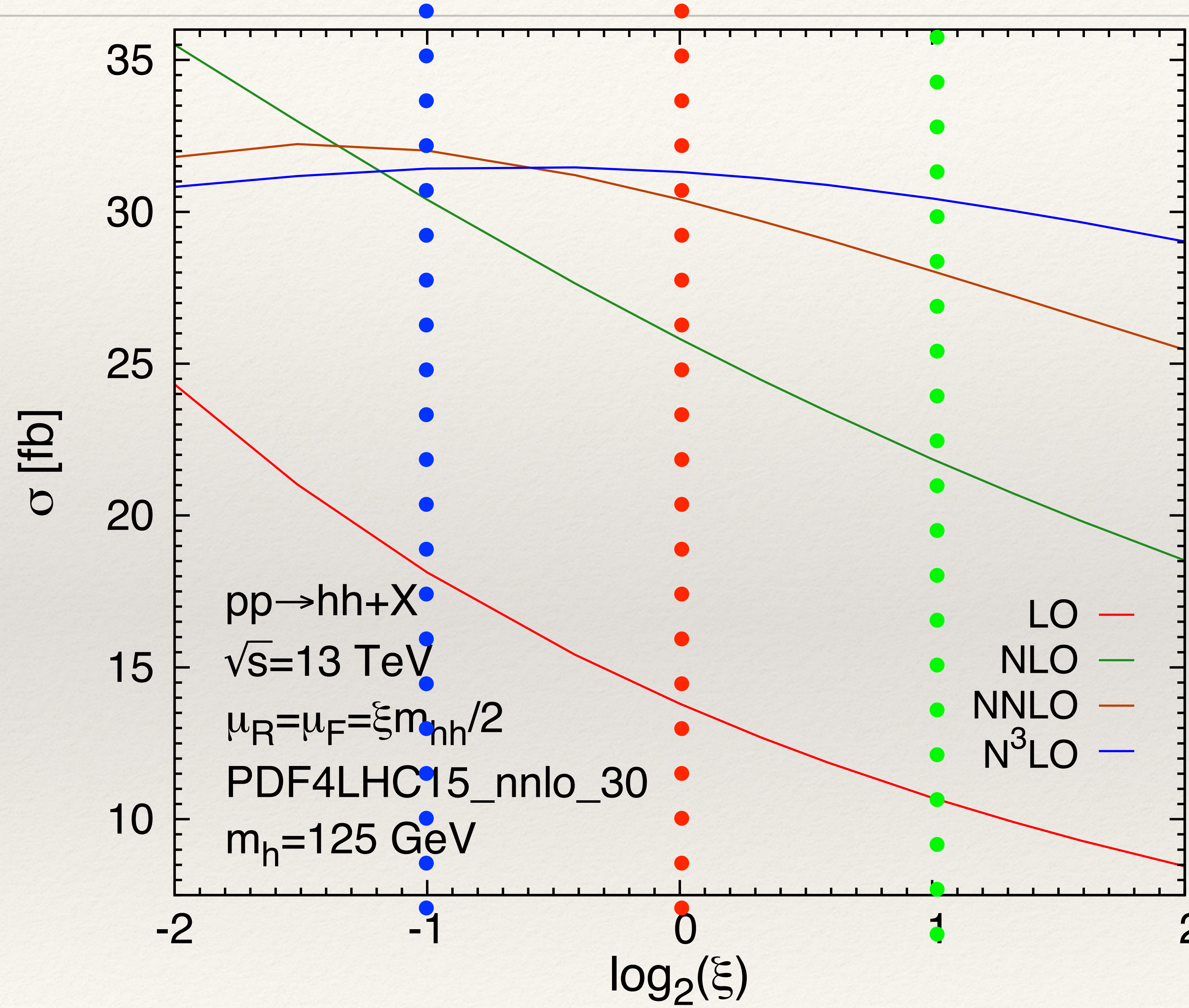


L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

How to choose a scale?



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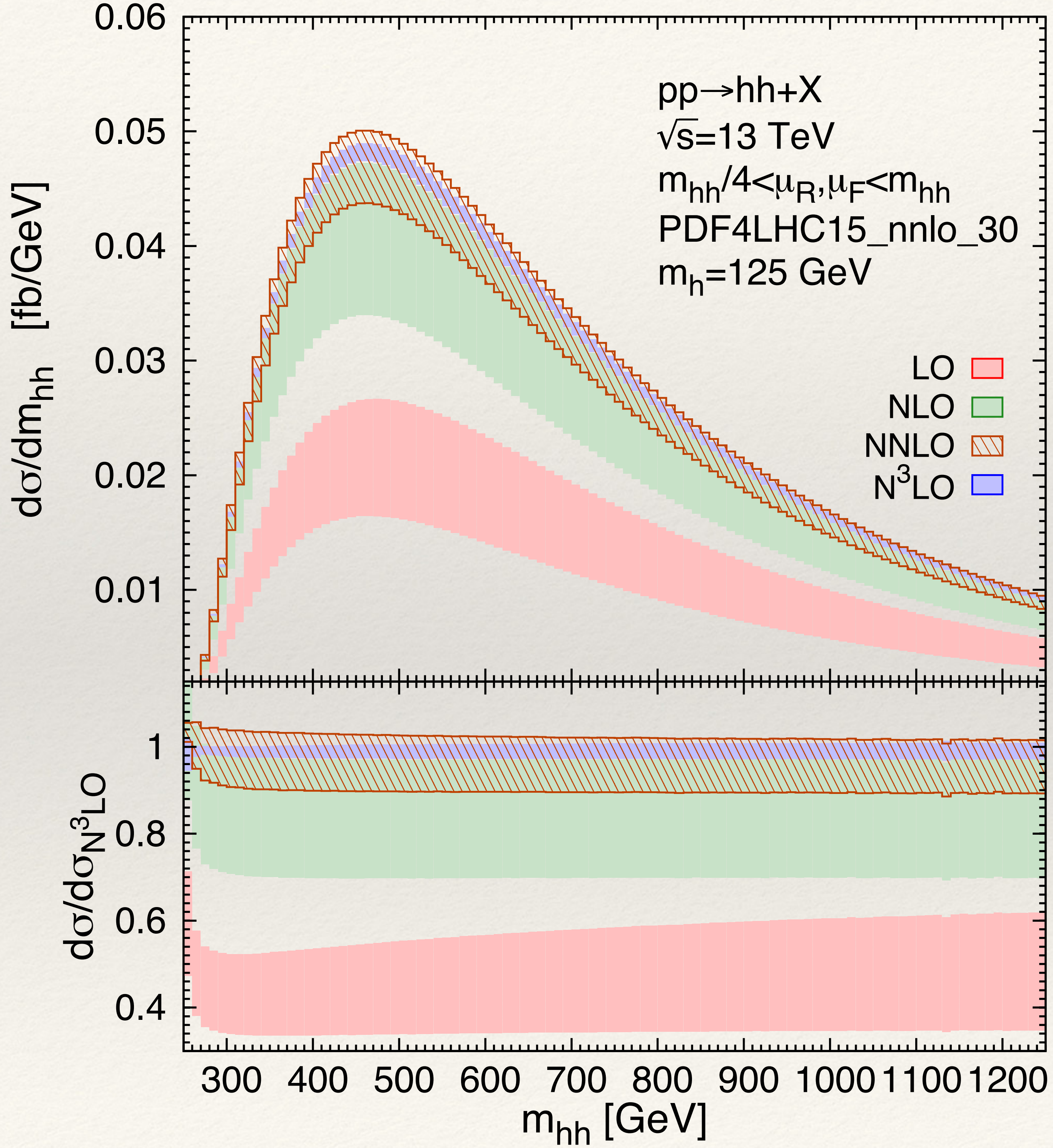
Invariant mass of Higgs pair



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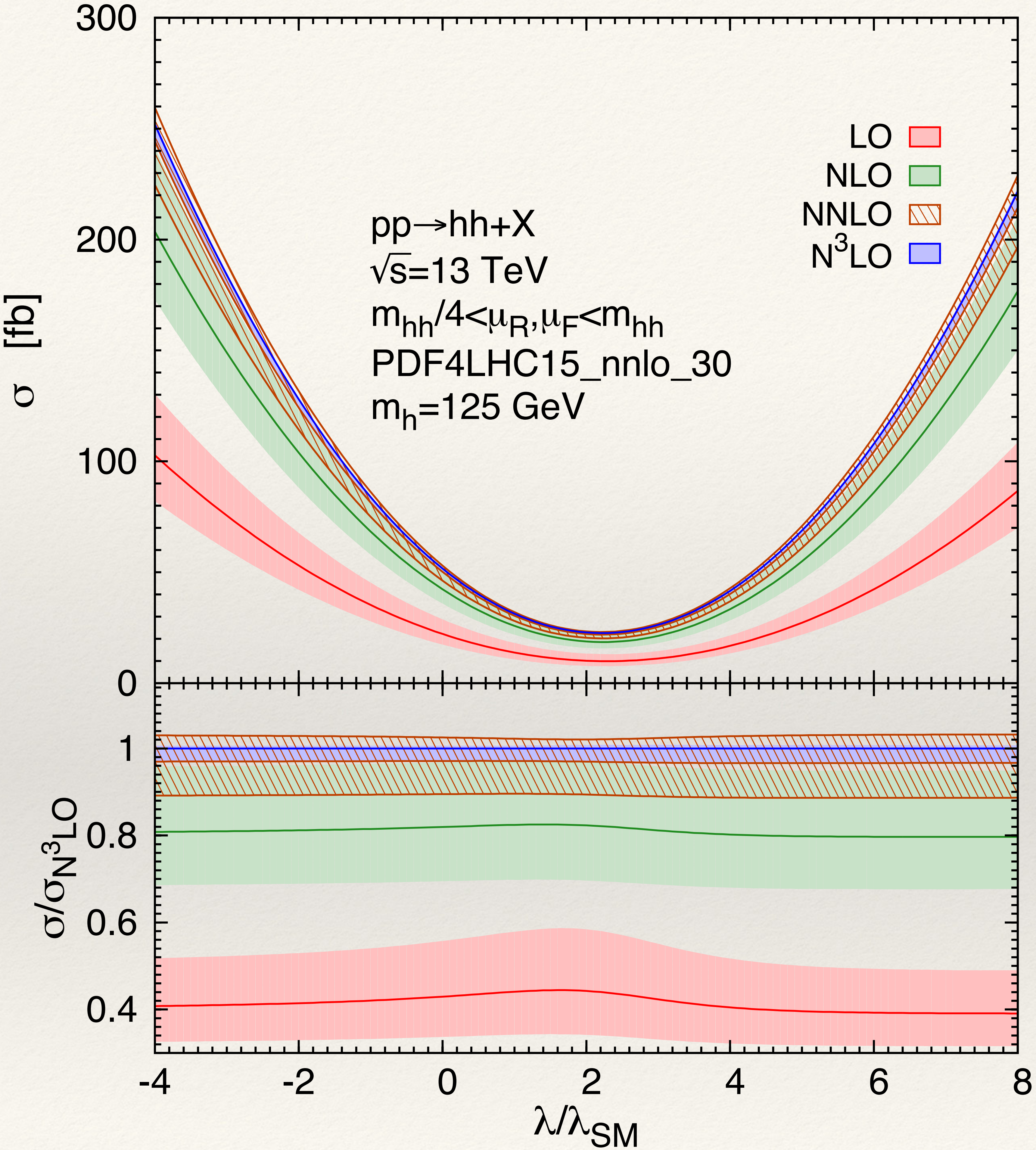

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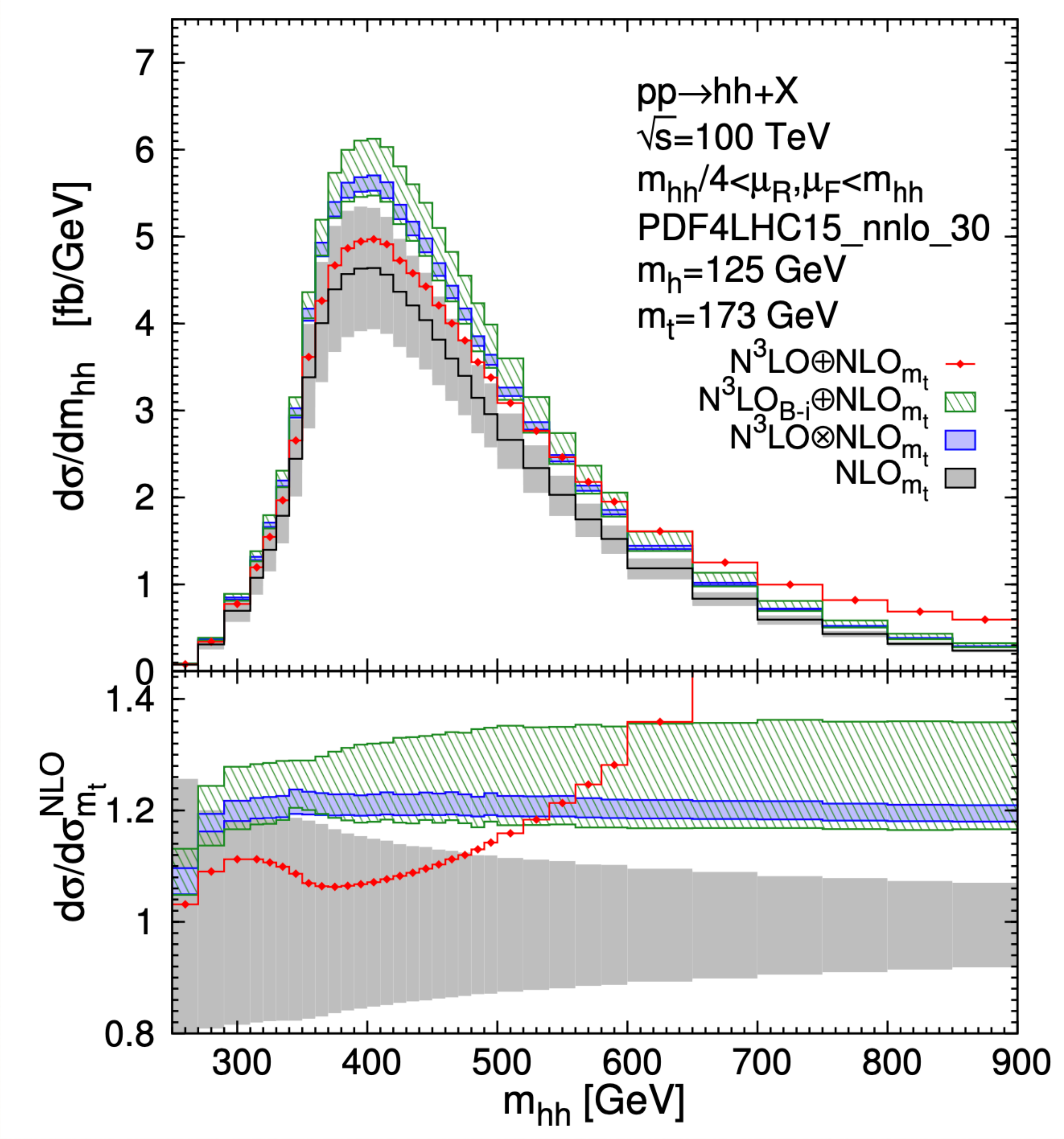
Top quark mass effects

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

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

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

gg→HH@NNNLO



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

Thank you!