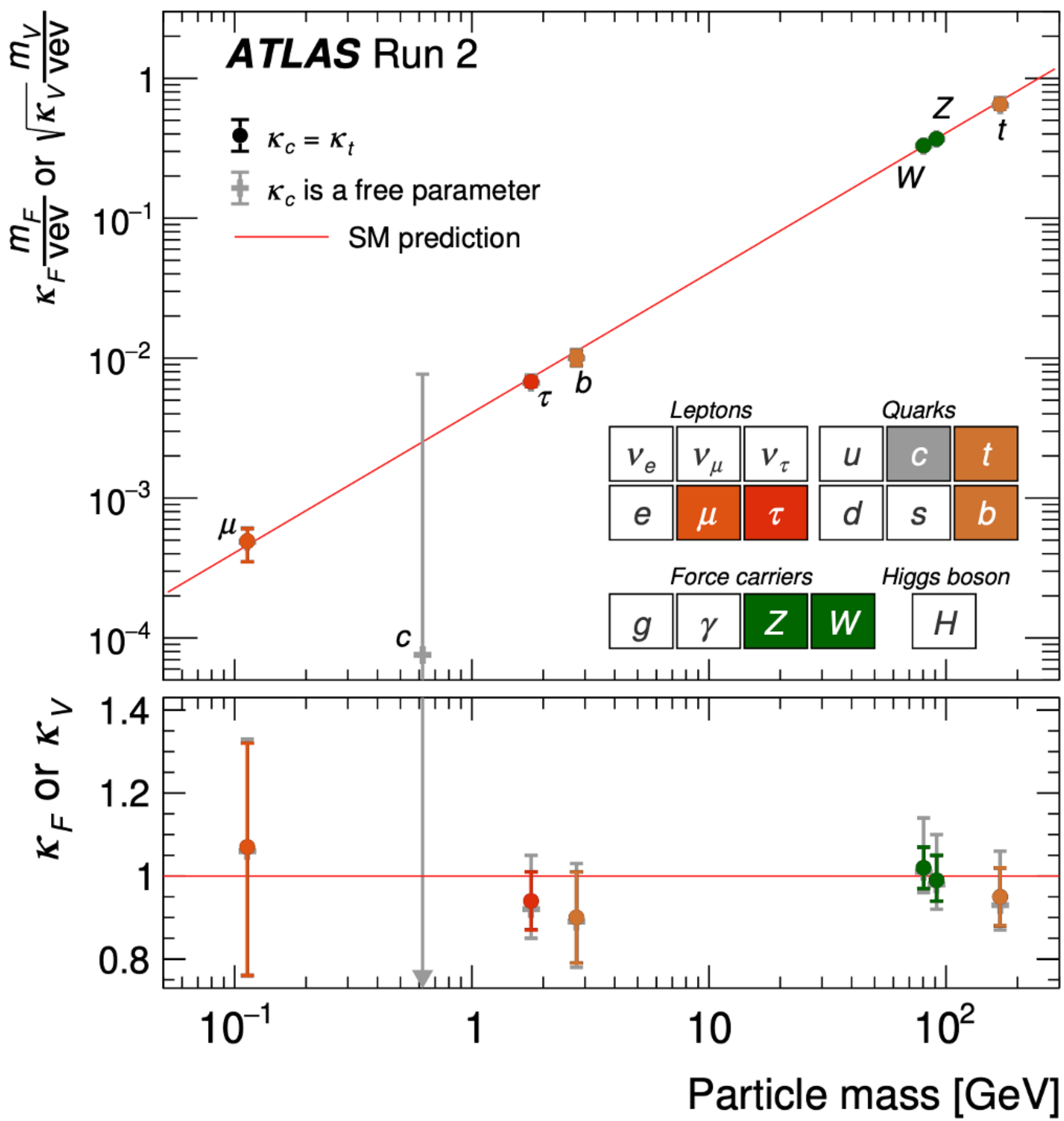
Precise predictions for Higgs boson pair production and decay

Jian Wang

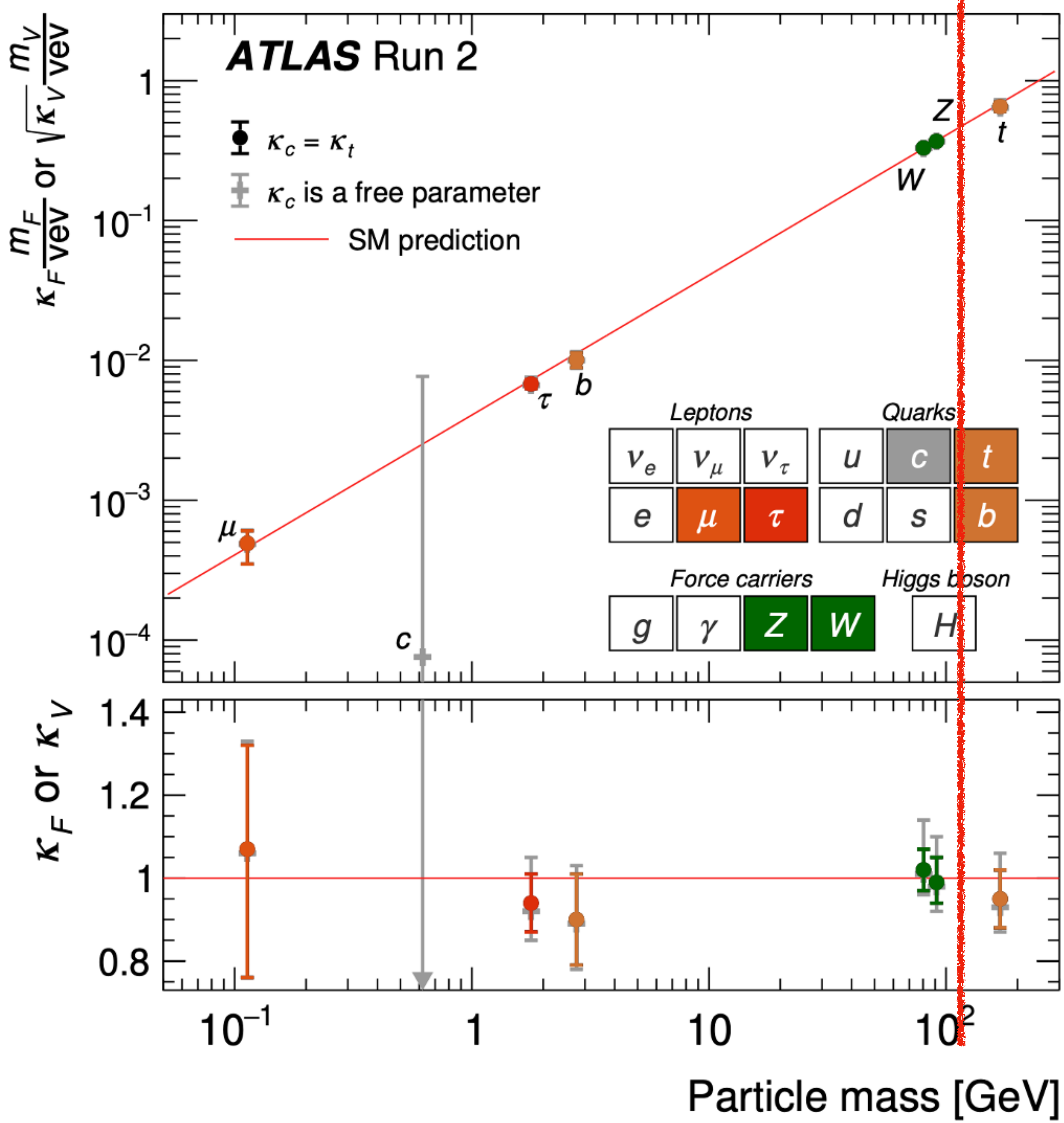
Shandong University

HPNP 2023

Osaka University



Nature 607(2022)52



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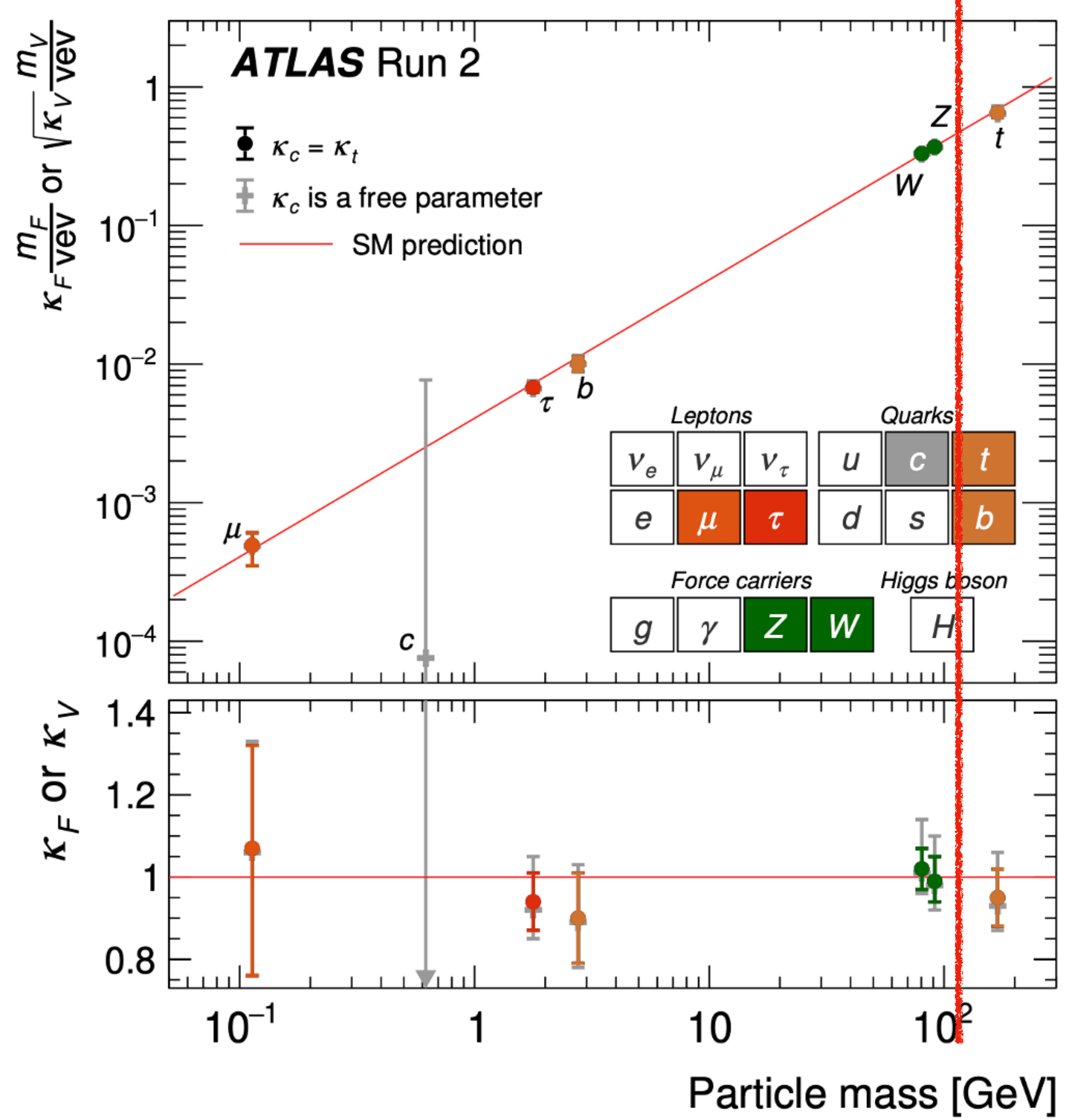


How about the coupling to Higgs boson?

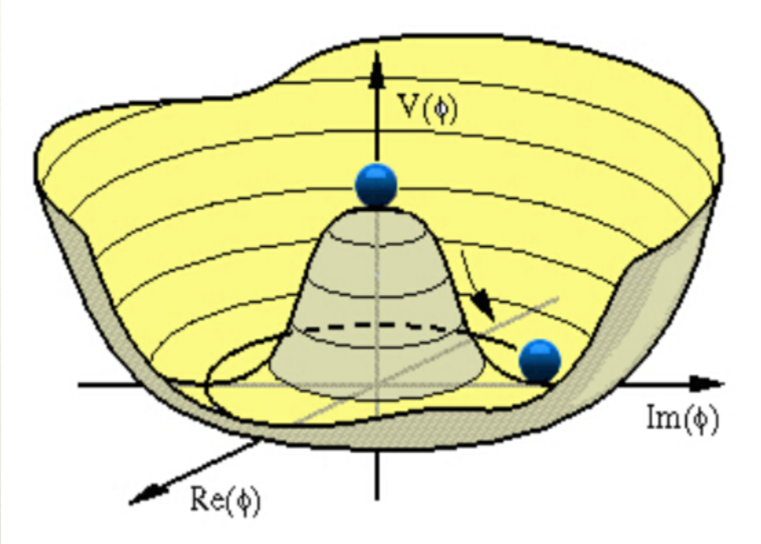
Nature 607(2022)52

Higgs self-coupling in the SM

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$V(h) = \tfrac{1}{2}m_h^2 h^2 + \sqrt{\tfrac{\lambda}{2}}m_H h^3 + \tfrac{1}{4}\lambda h^4$$



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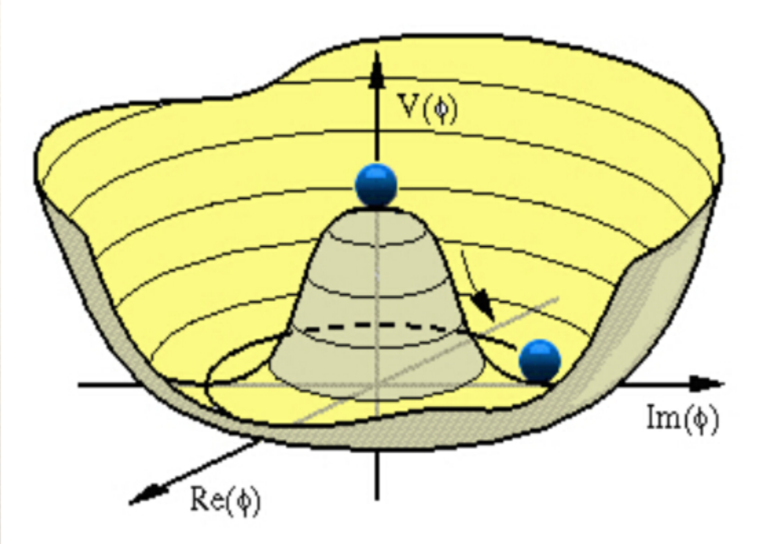

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S.Kanemura, et al, PLB558,157

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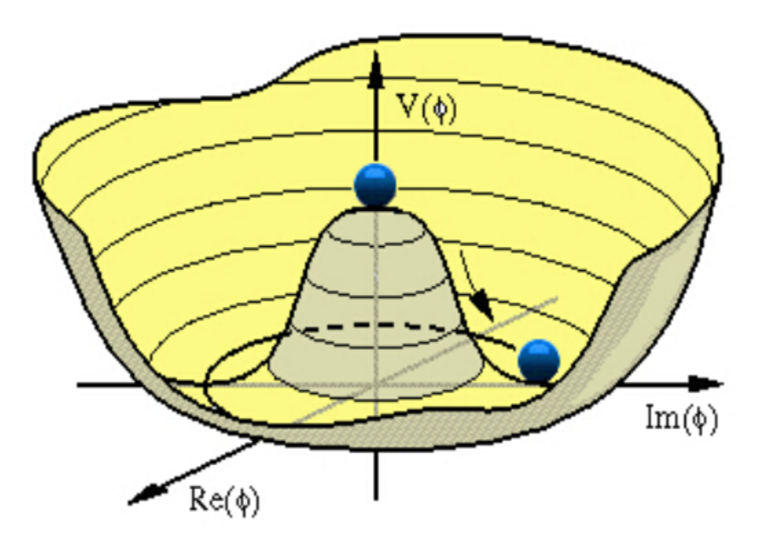

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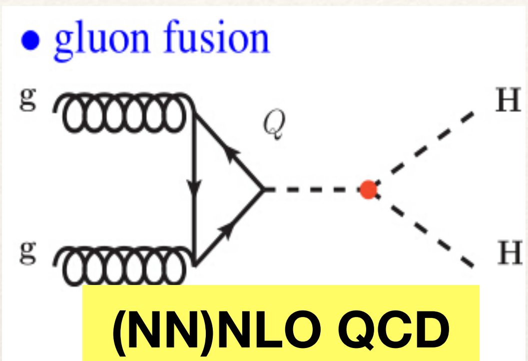
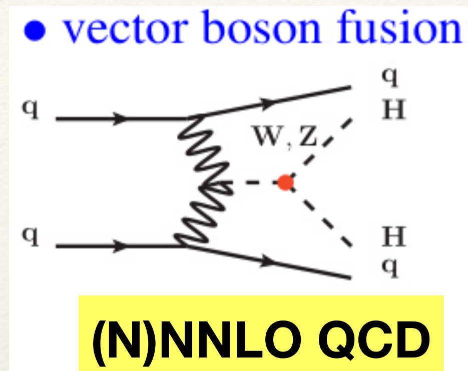
We need to measure the trilinear self coupling directly.

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



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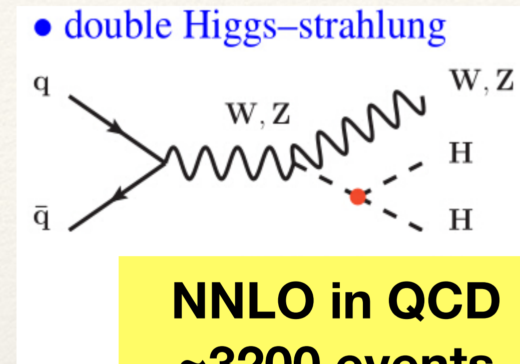

NNLO in QCD
~3200 events

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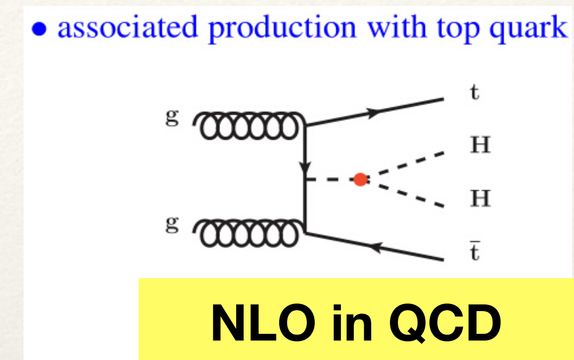

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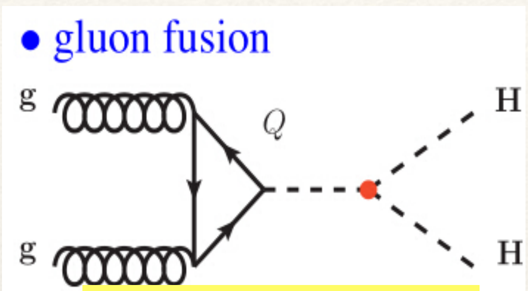

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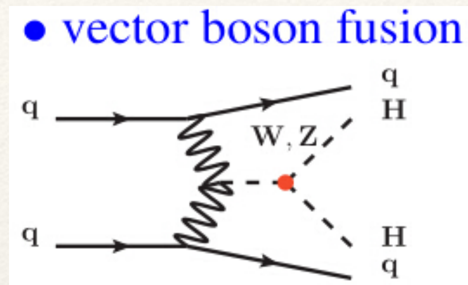

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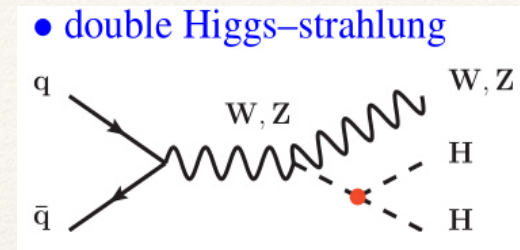

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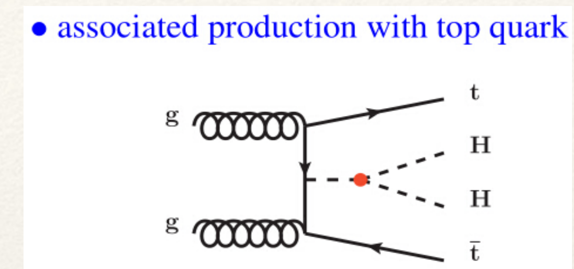

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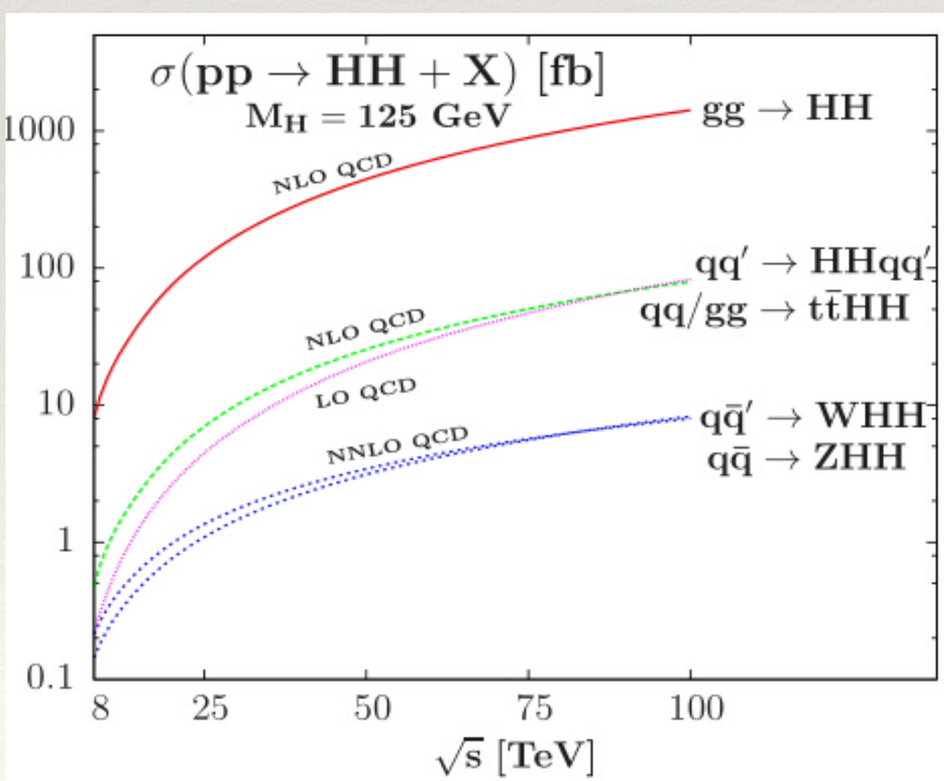

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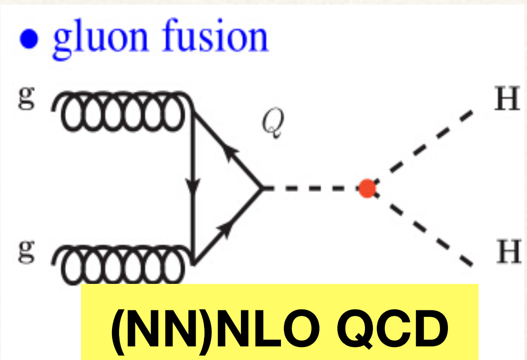

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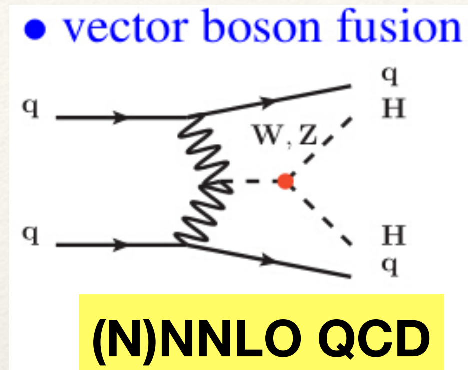

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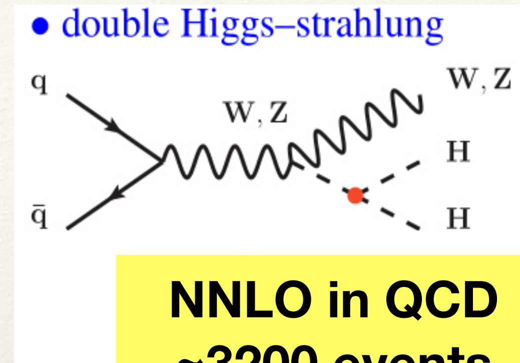

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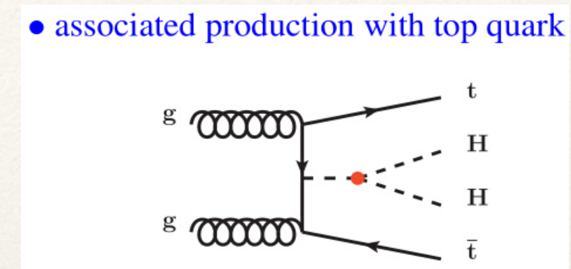

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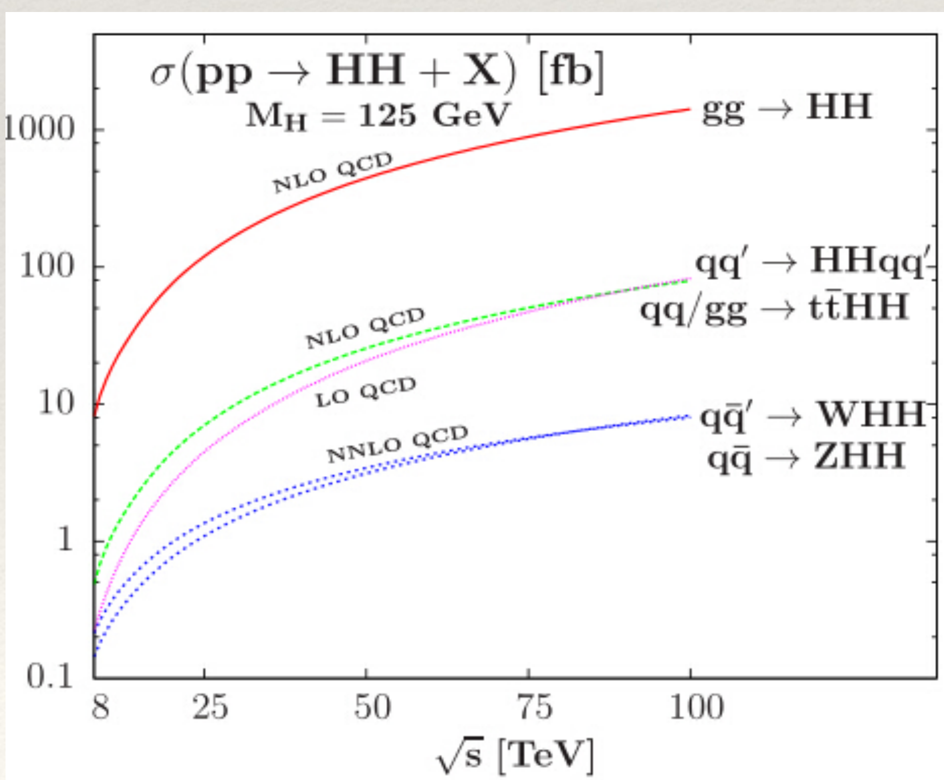

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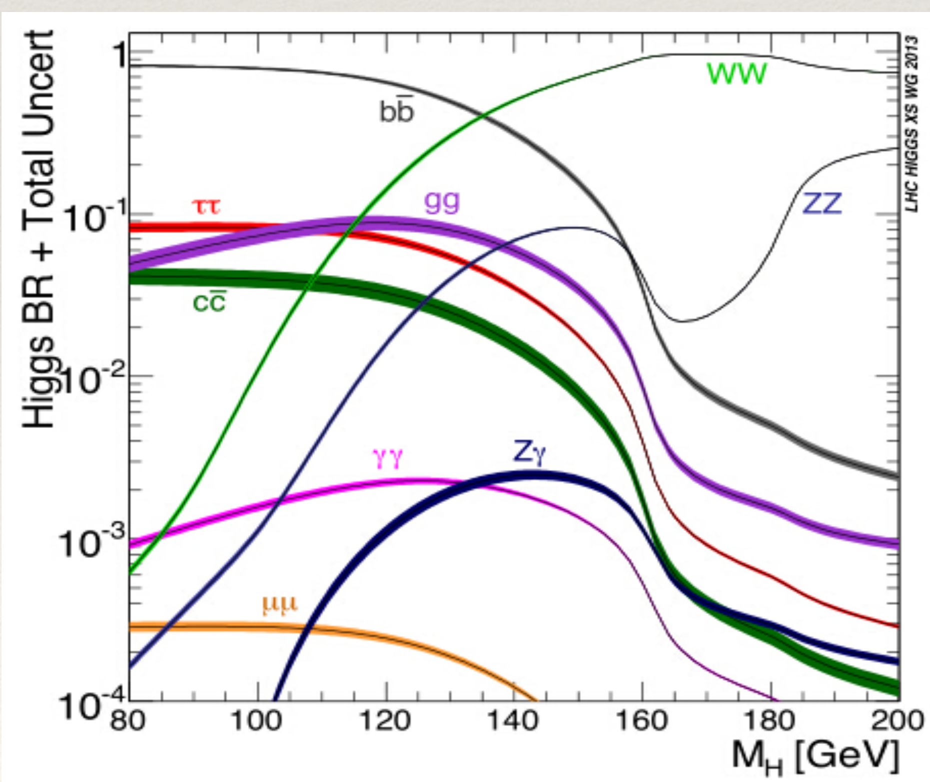

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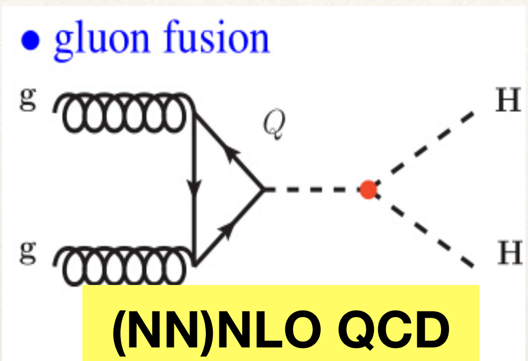

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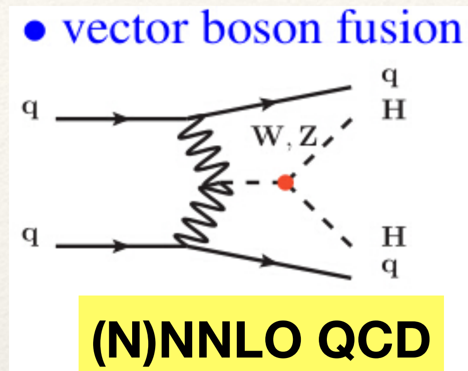

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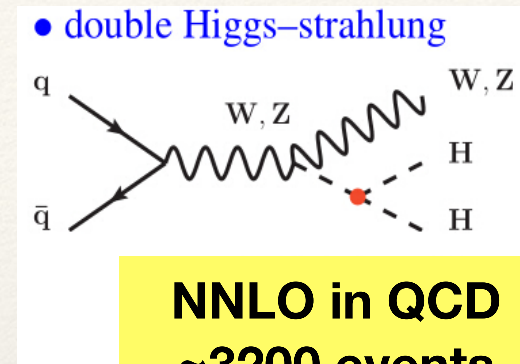

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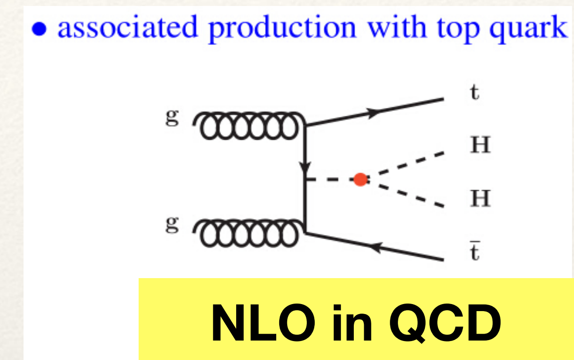

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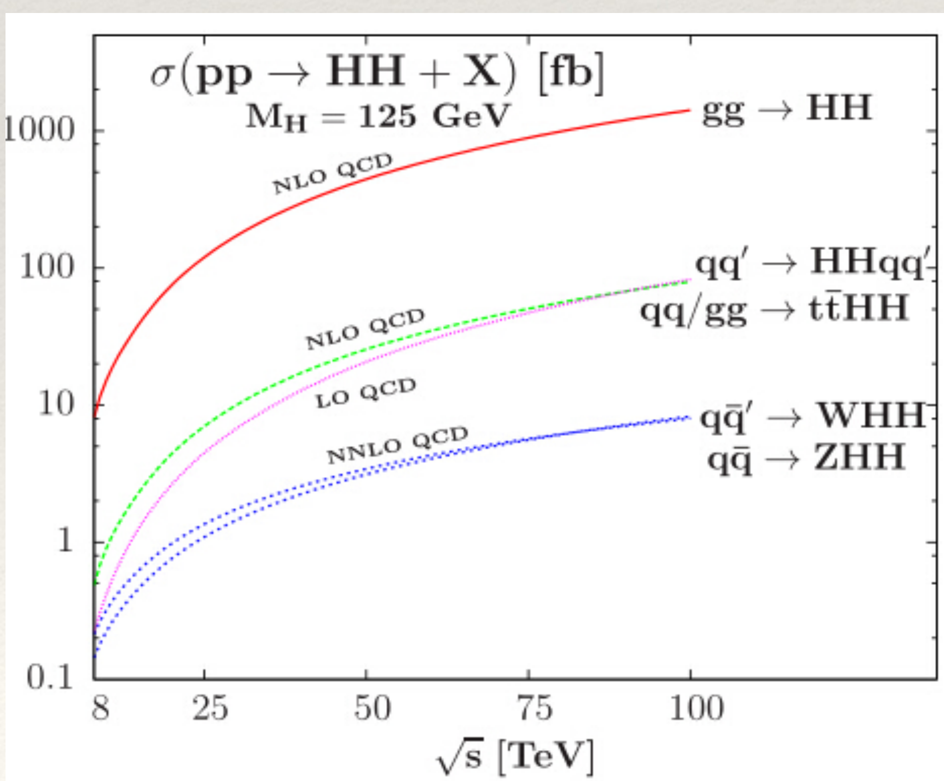

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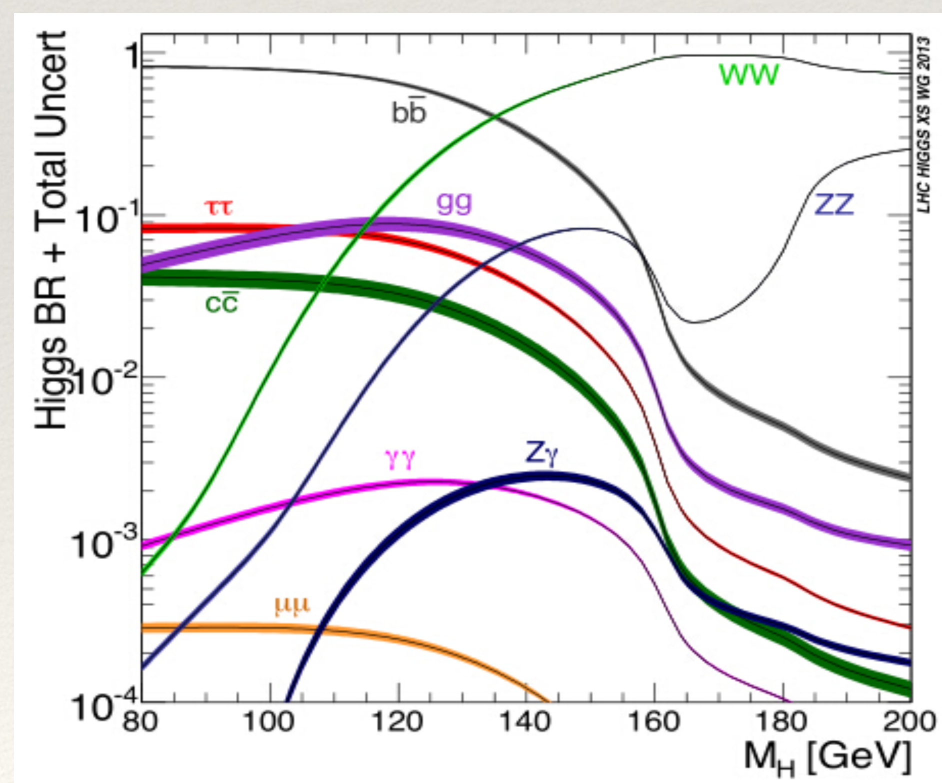
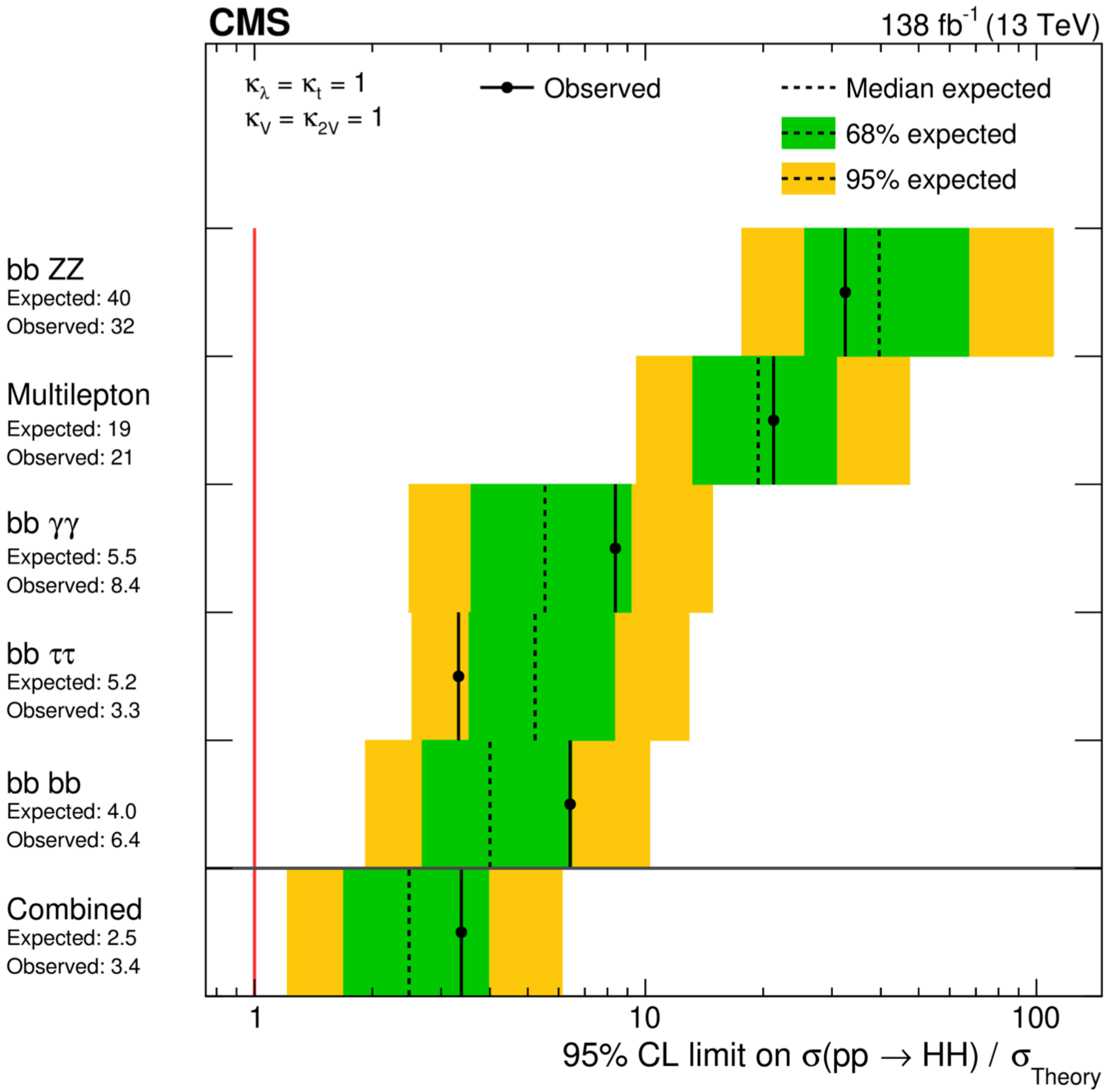


=

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



See the talks by Sanmay and Xiaohu

$$-1.2 < \kappa_\lambda < 6.5$$

Nature 607(2022)60

Why do we need precise prediction?

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

2. As more data are accumulated, 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.

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↓

the more precise the cross section is

gg>HH

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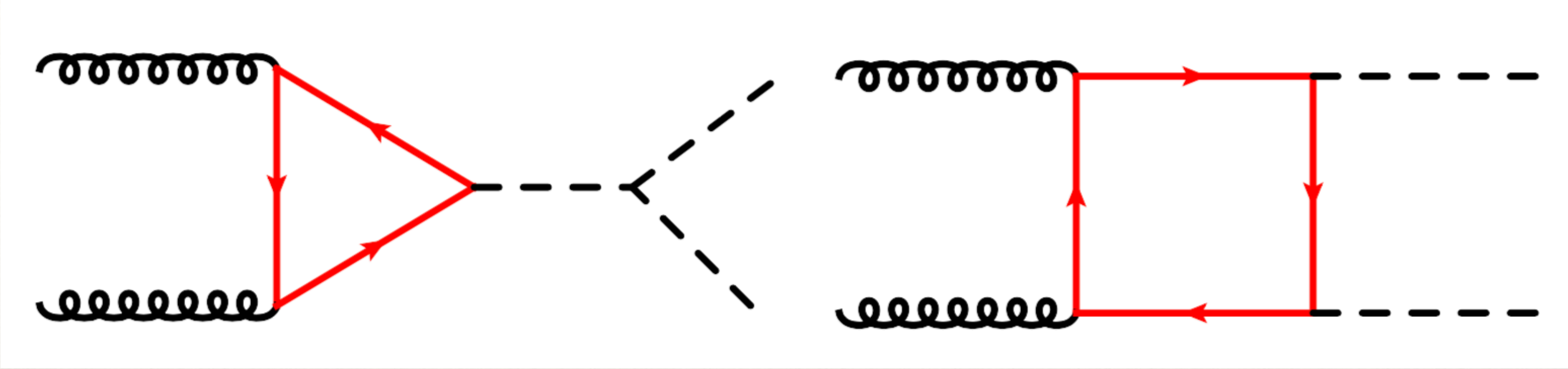
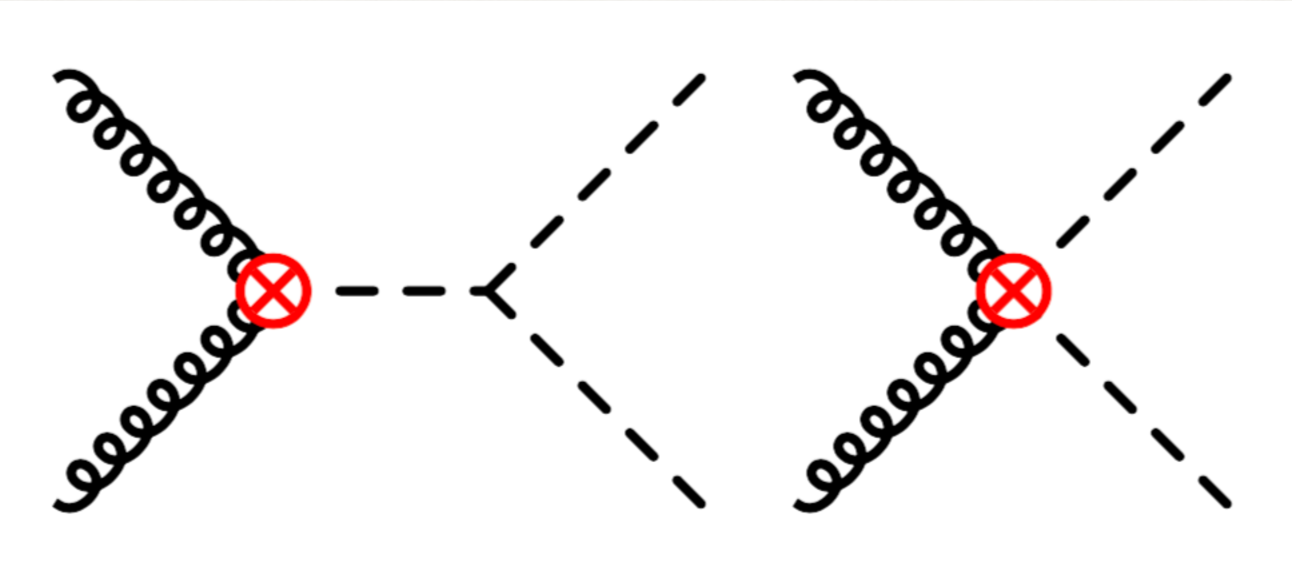


Heavy top quark limit



gg>HH

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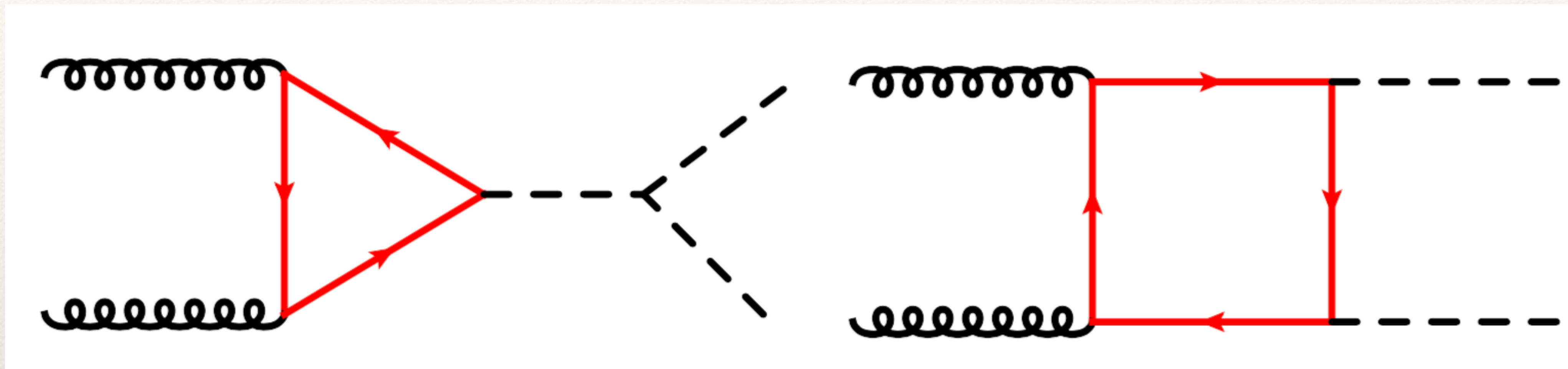

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Borowka, et al, PRL **117**, 012001

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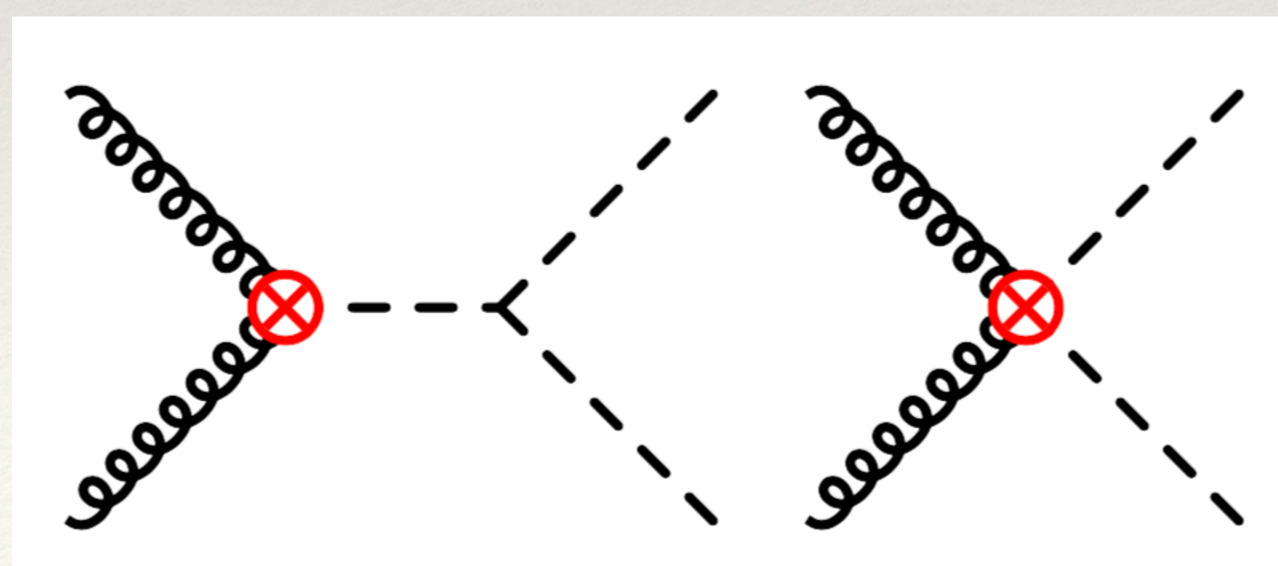

gg>HH

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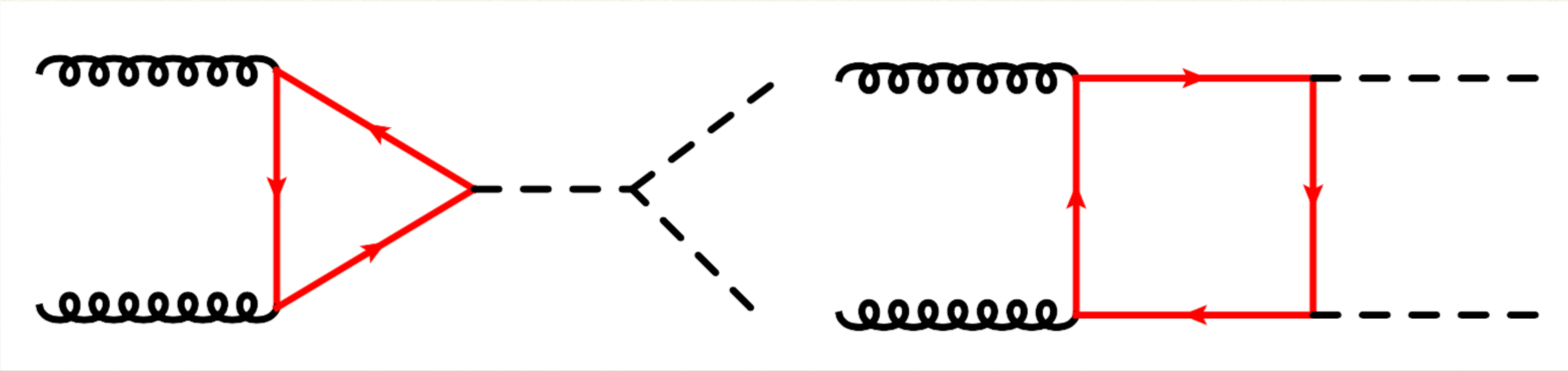

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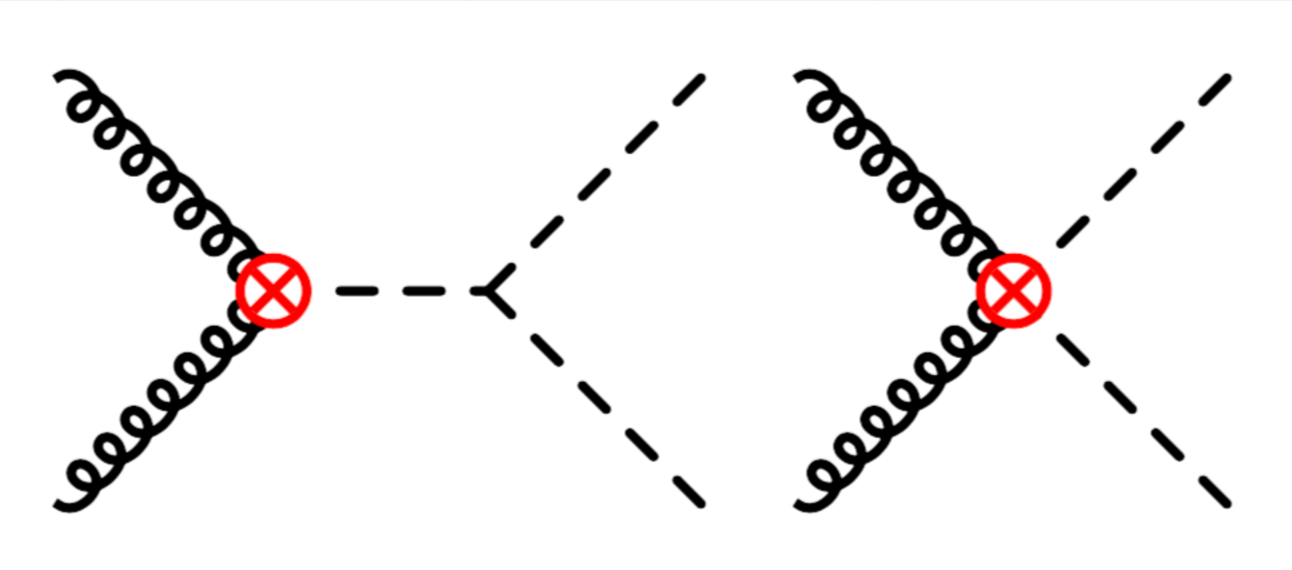

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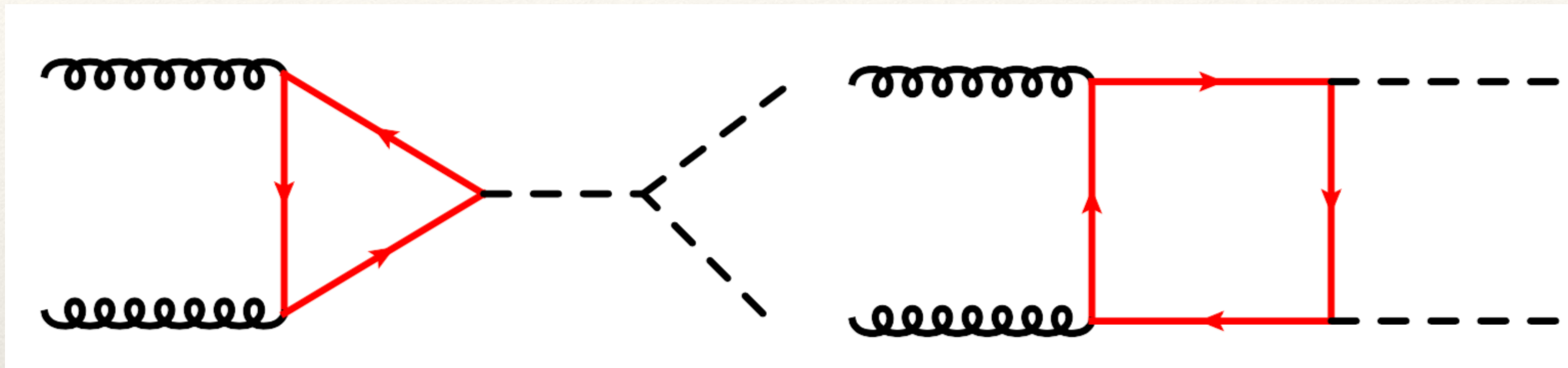

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$$LO_{\infty} \quad 17.07^{+30\%}_{-22\%} \; fb$$
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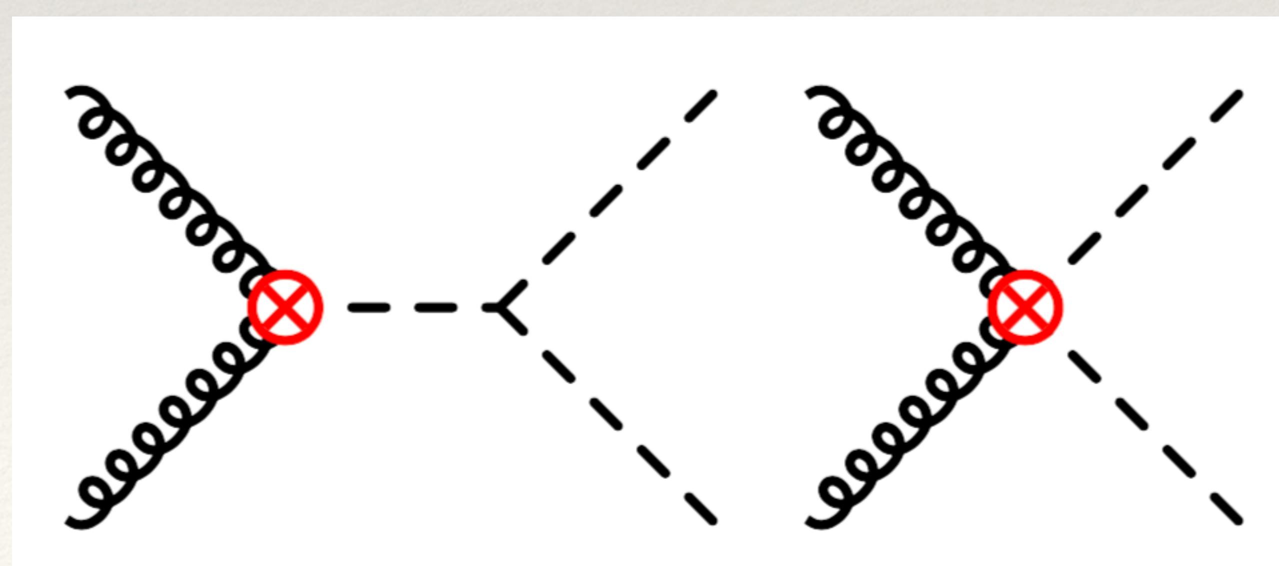
Dawson, Dittmaier, Spira, PRD58,115012



gg>HH

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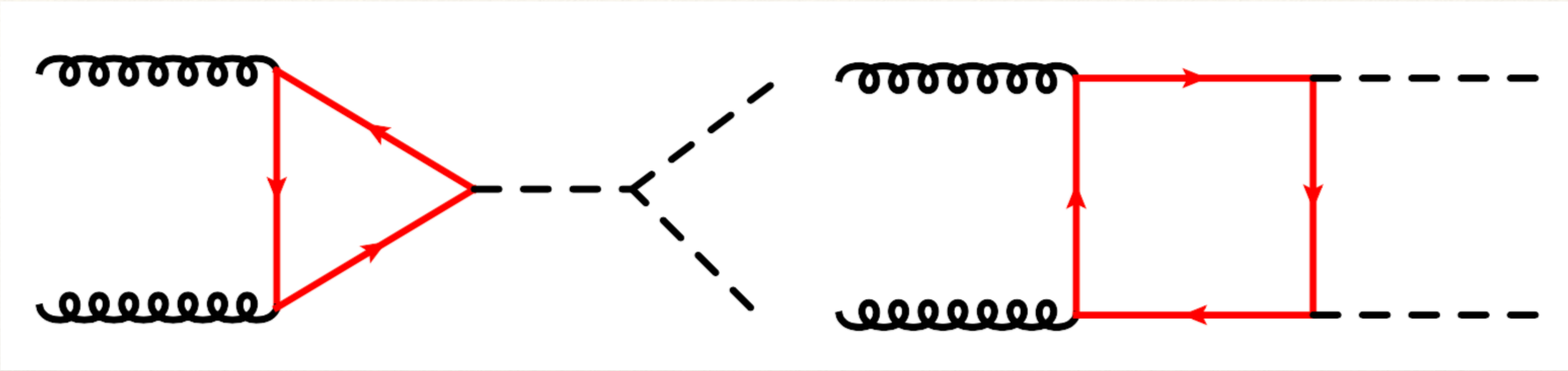

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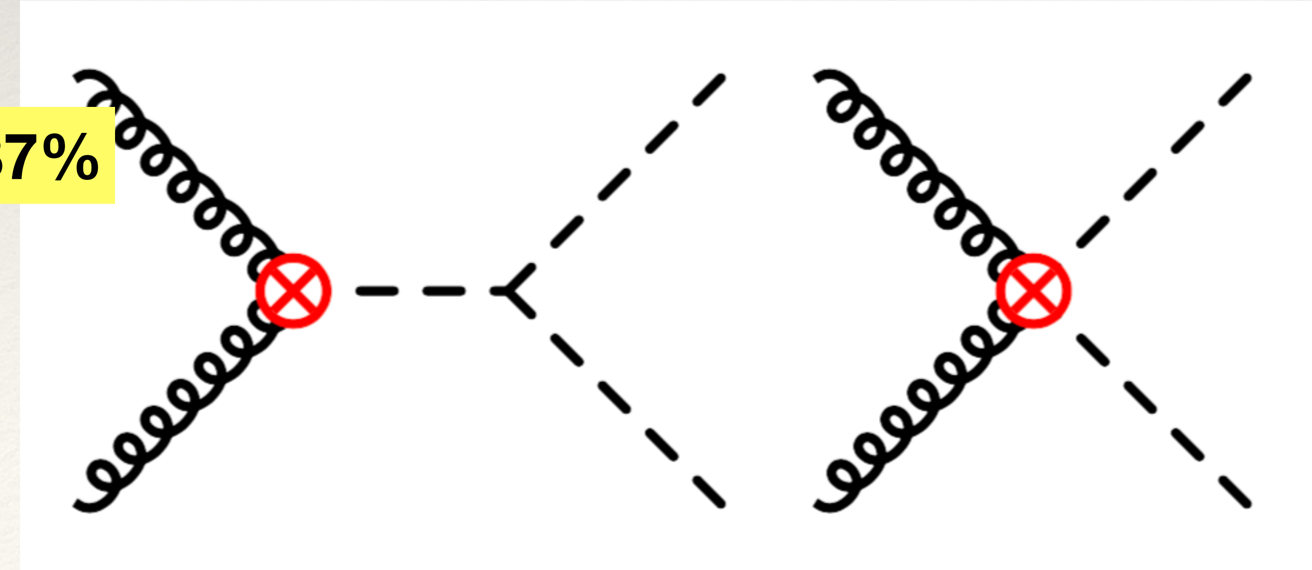

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+87%

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gg>HH

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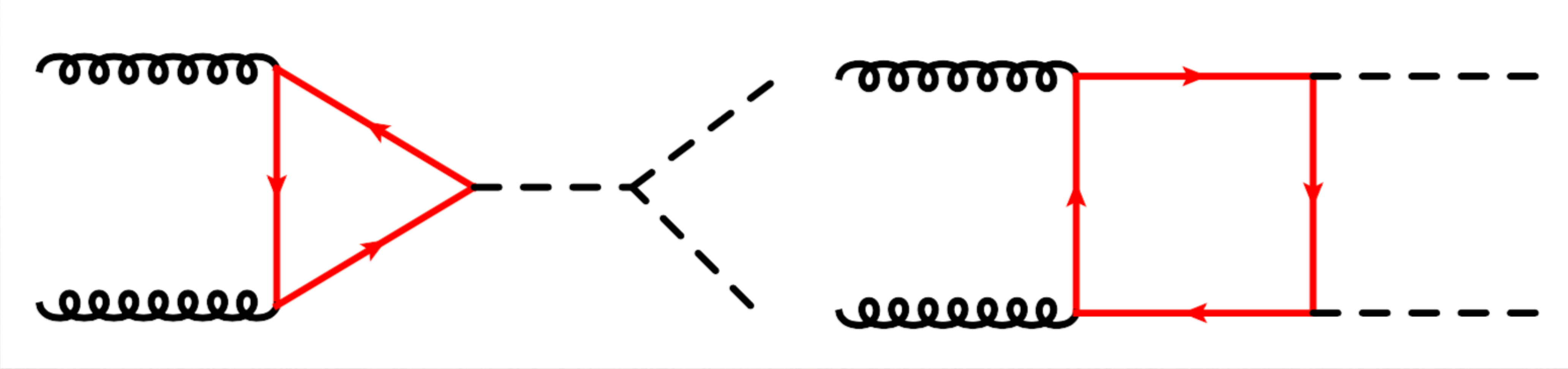

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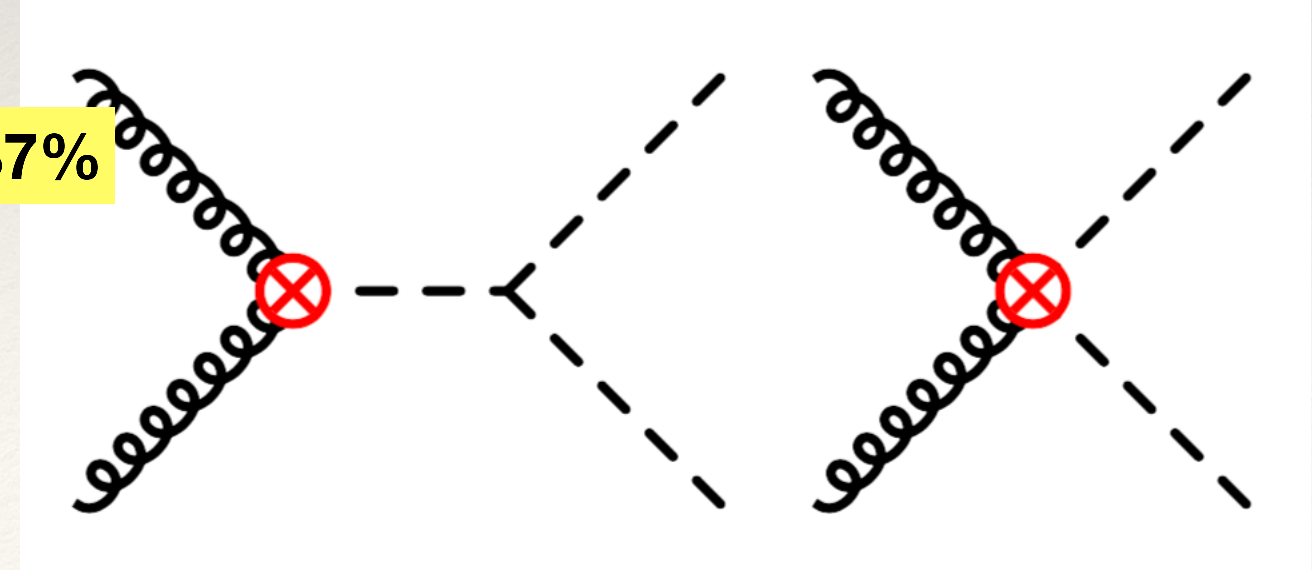

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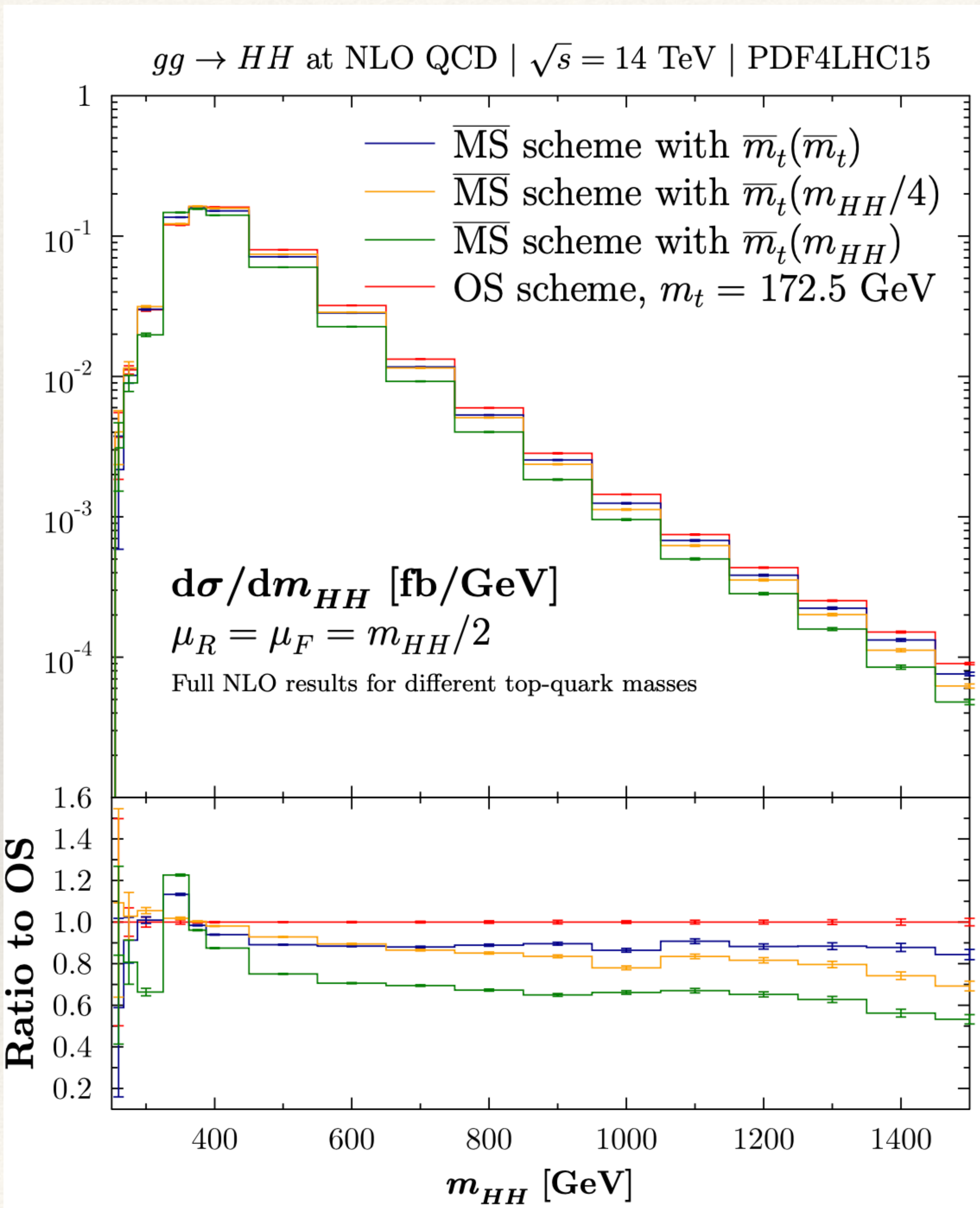
difference: 16% at LO to 3% at NLO

gg>HH@NLO: Full mt dependence



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

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

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

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

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

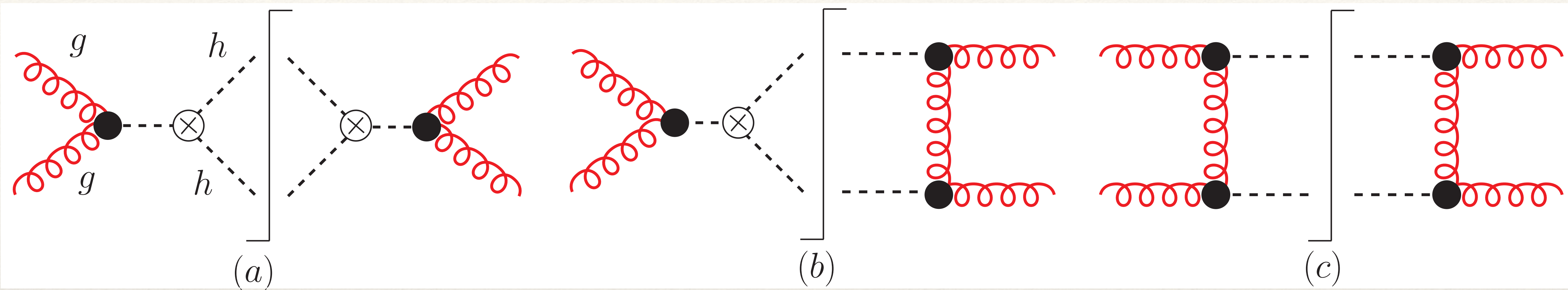
$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%} \text{ fb},$$

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

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

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

gg>HH@NNNLO



NNNLO — **Similar to single Higgs**

NNLO — **qT subtraction**

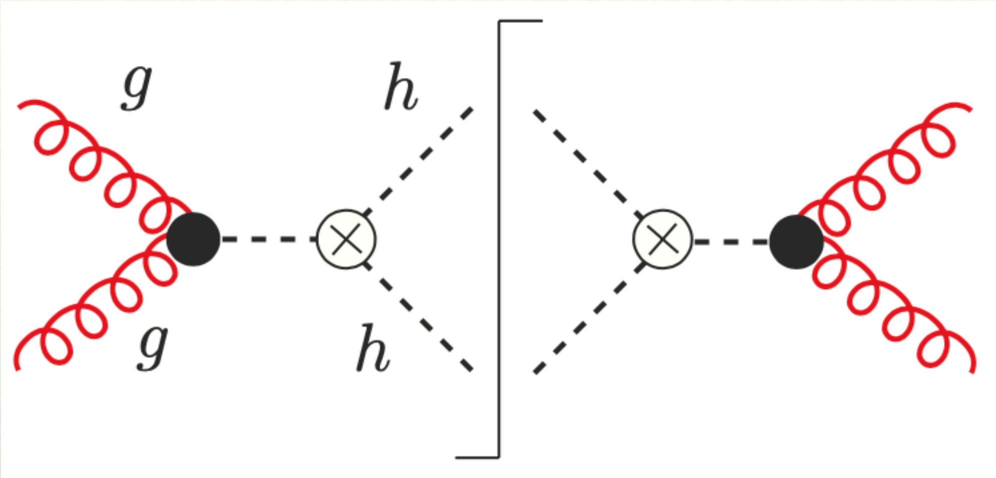
NLO — **Standard methods**

Many checks:

1. **Self consistency (gauge invariance, poles cancellation)**
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)

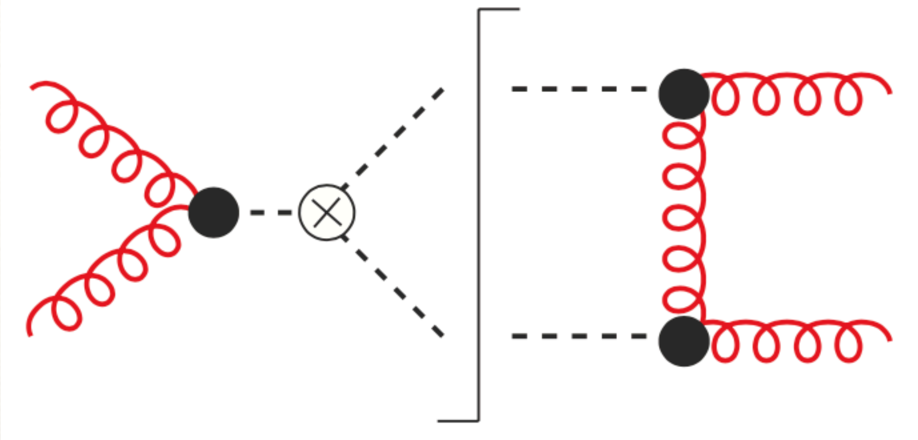


$$\frac{d\sigma^{a}_{hh}}{dm_{hh}} = f_{h\to hh}\left(\frac{C_{hh}}{C_h} - \frac{6\lambda_{hhh}v^2}{m_{hh}^2 - m_h^2}\right)^2 \times \left(\sigma_h\Big|_{m_h\to m_{hh}}\right)$$

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

Dulat, Lazopoulos, Mistlberger iHixs, 1802.00827

Class-(b)

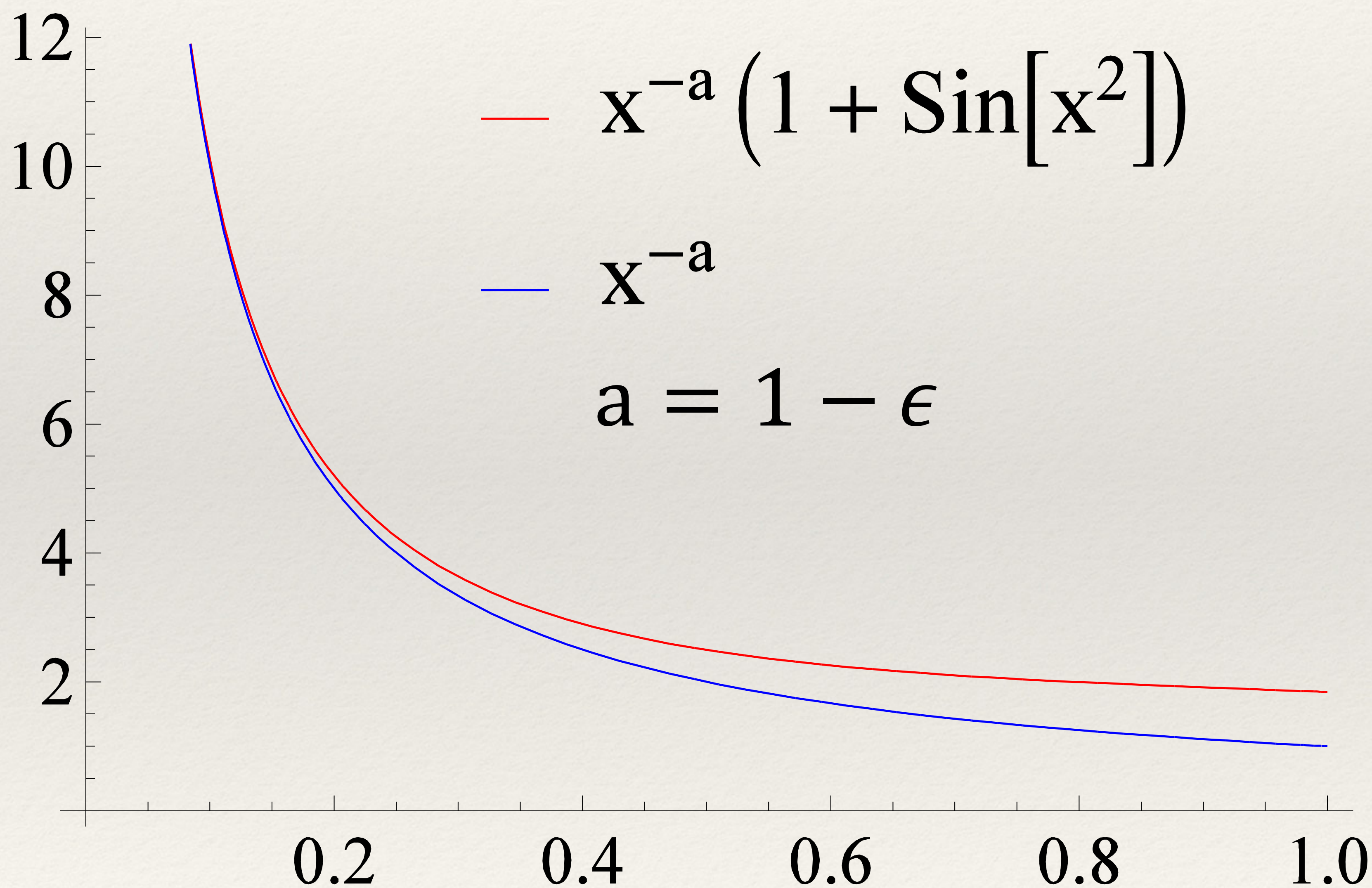


$$d\sigma^b_{hh} = d\sigma^b_{hh}\Big|_{p_T^{hh} < p_T^{\rm veto}} + d\sigma^b_{hh}\Big|_{p_T^{hh} > p_T^{\rm veto}}$$

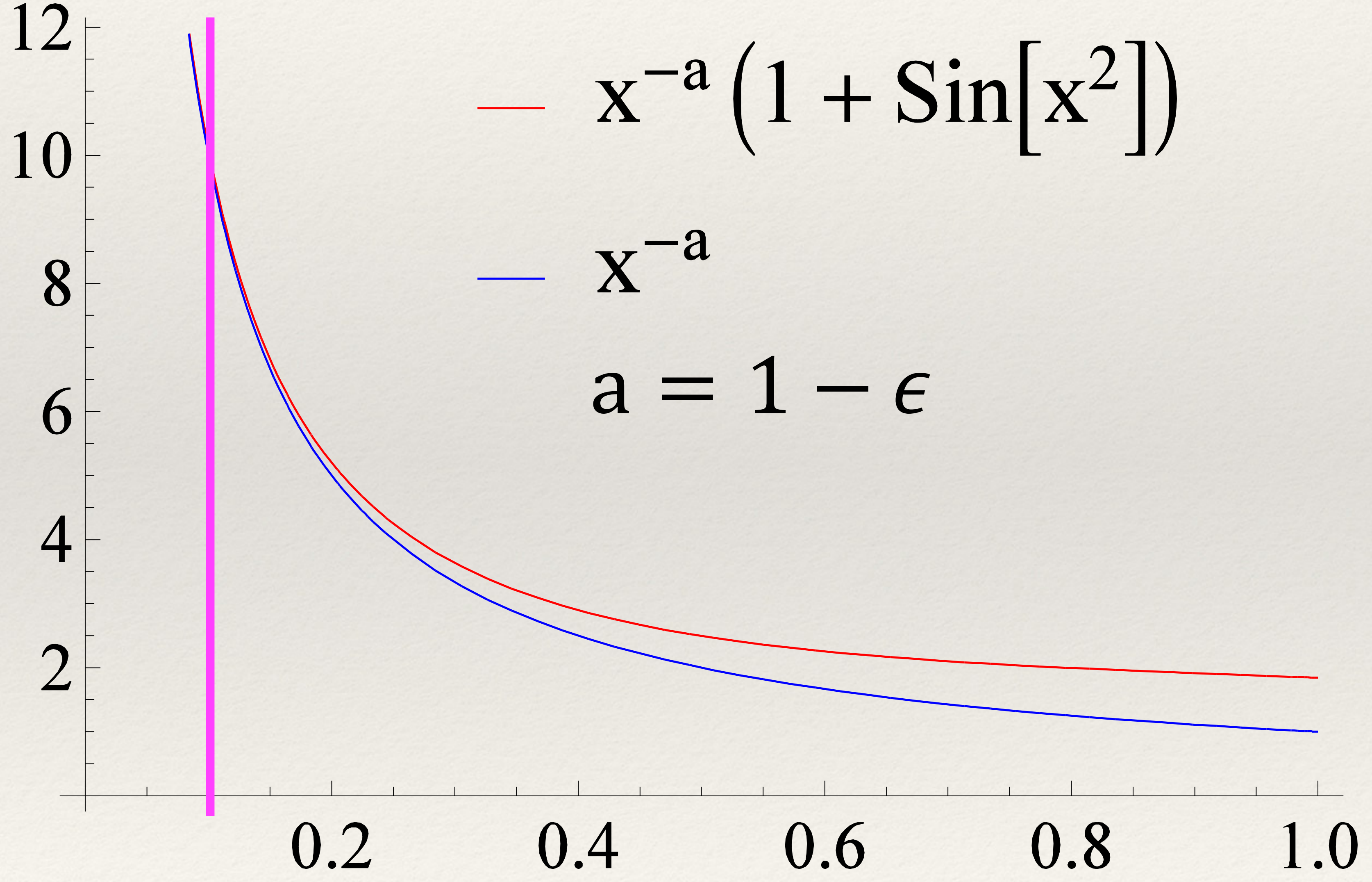
Catani, Grazzini, PRL98,222002

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

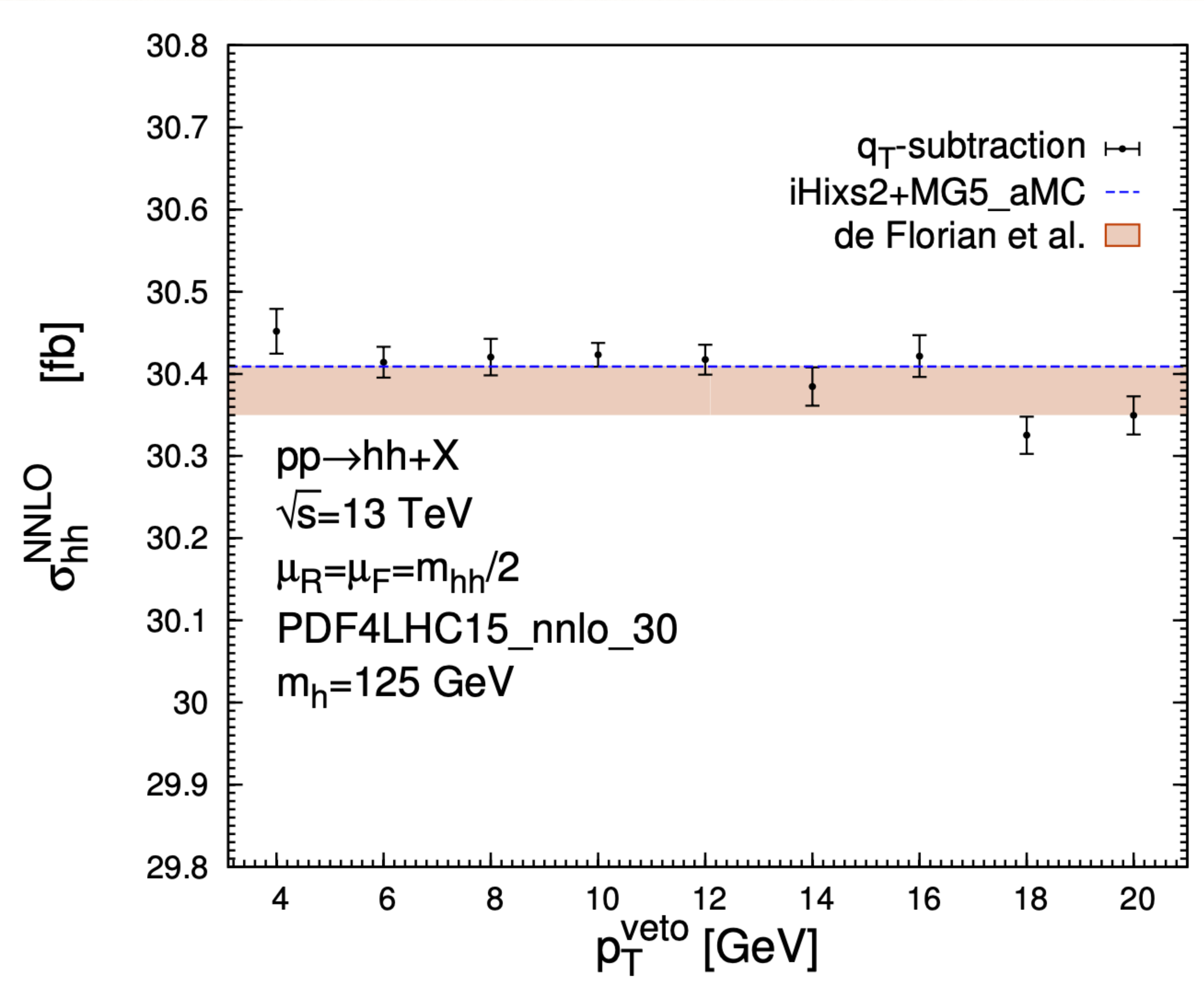
The idea of qT subtraction



The idea 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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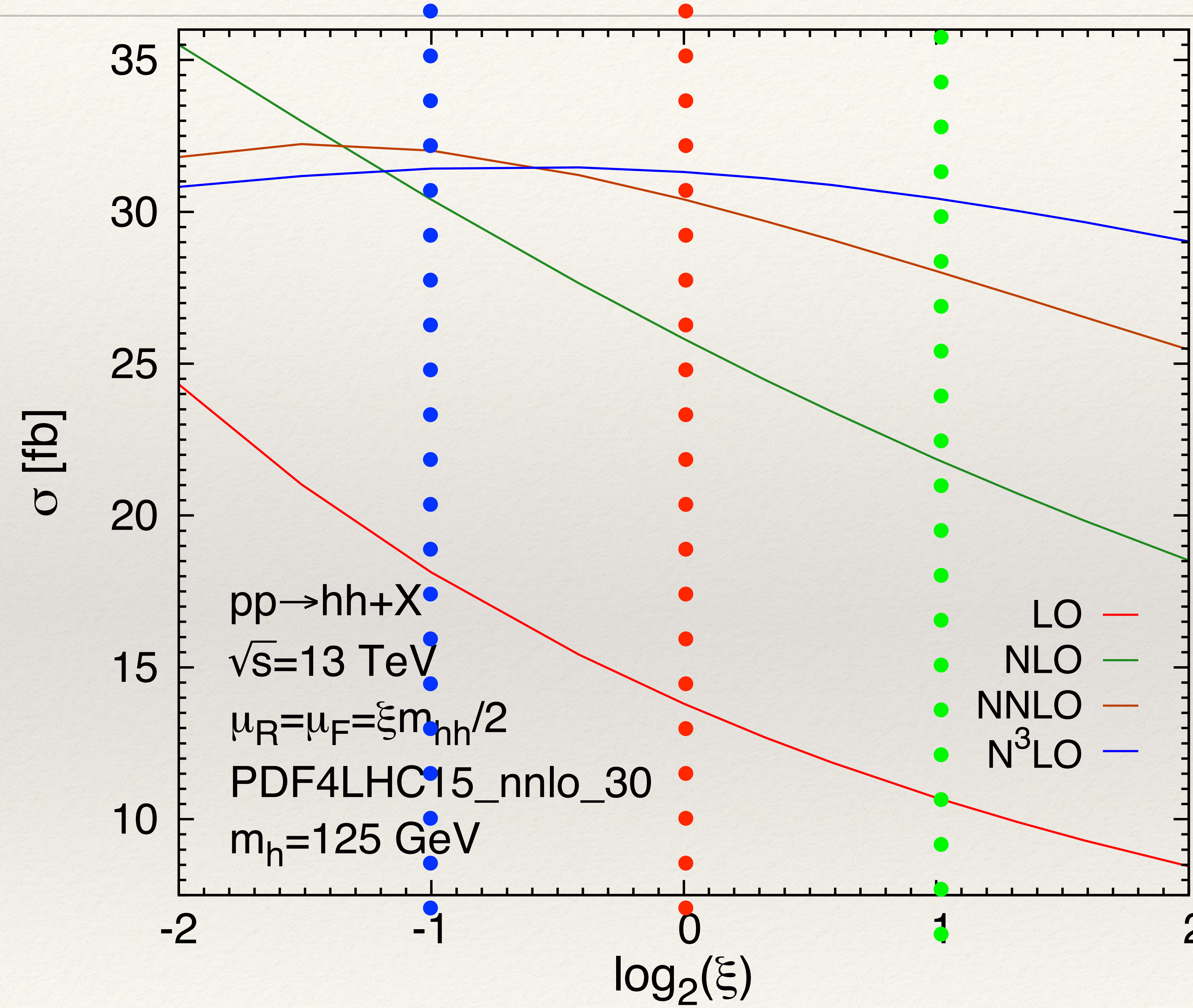
How to choose a scale?



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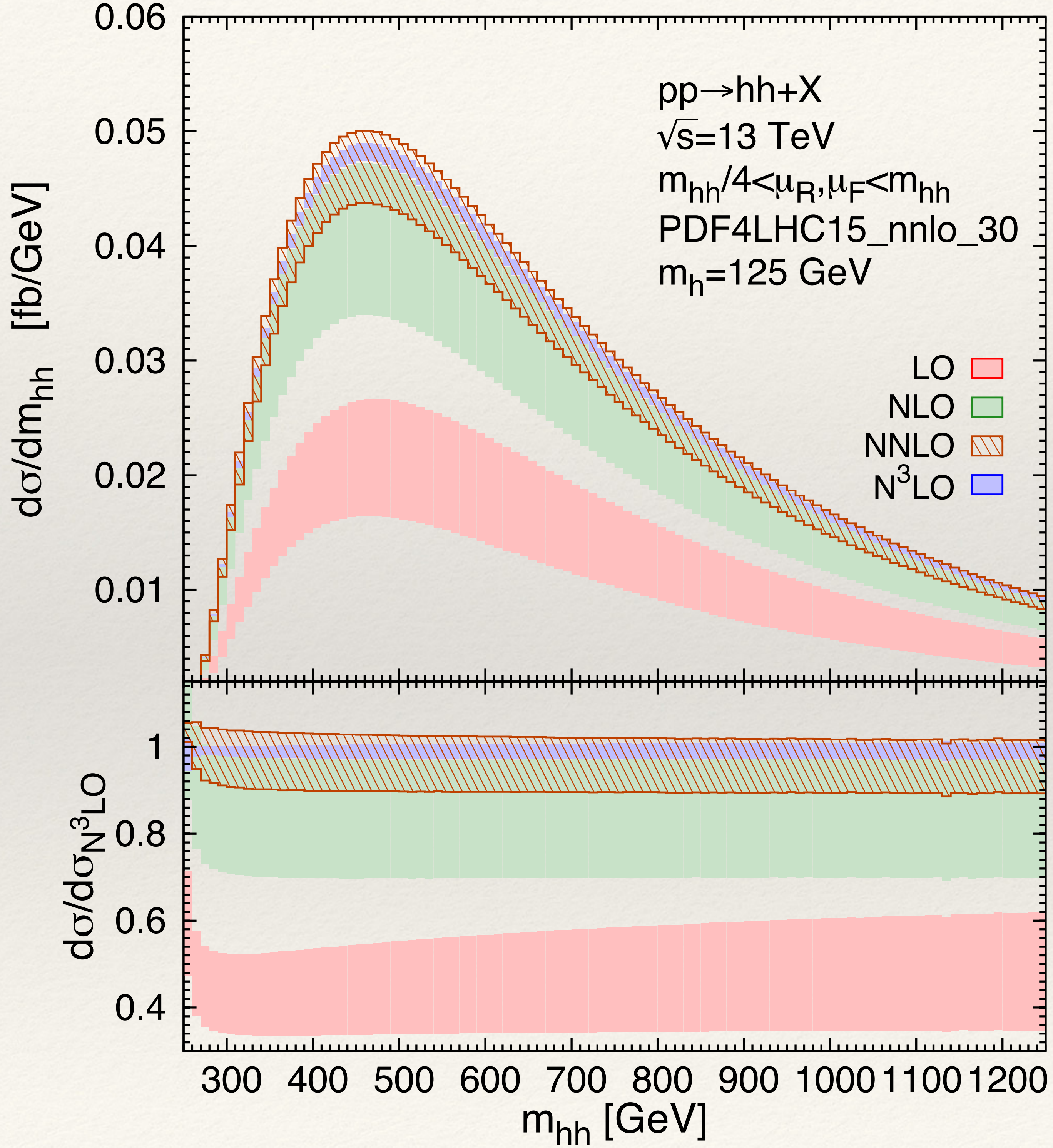
Invariant mass of Higgs pair



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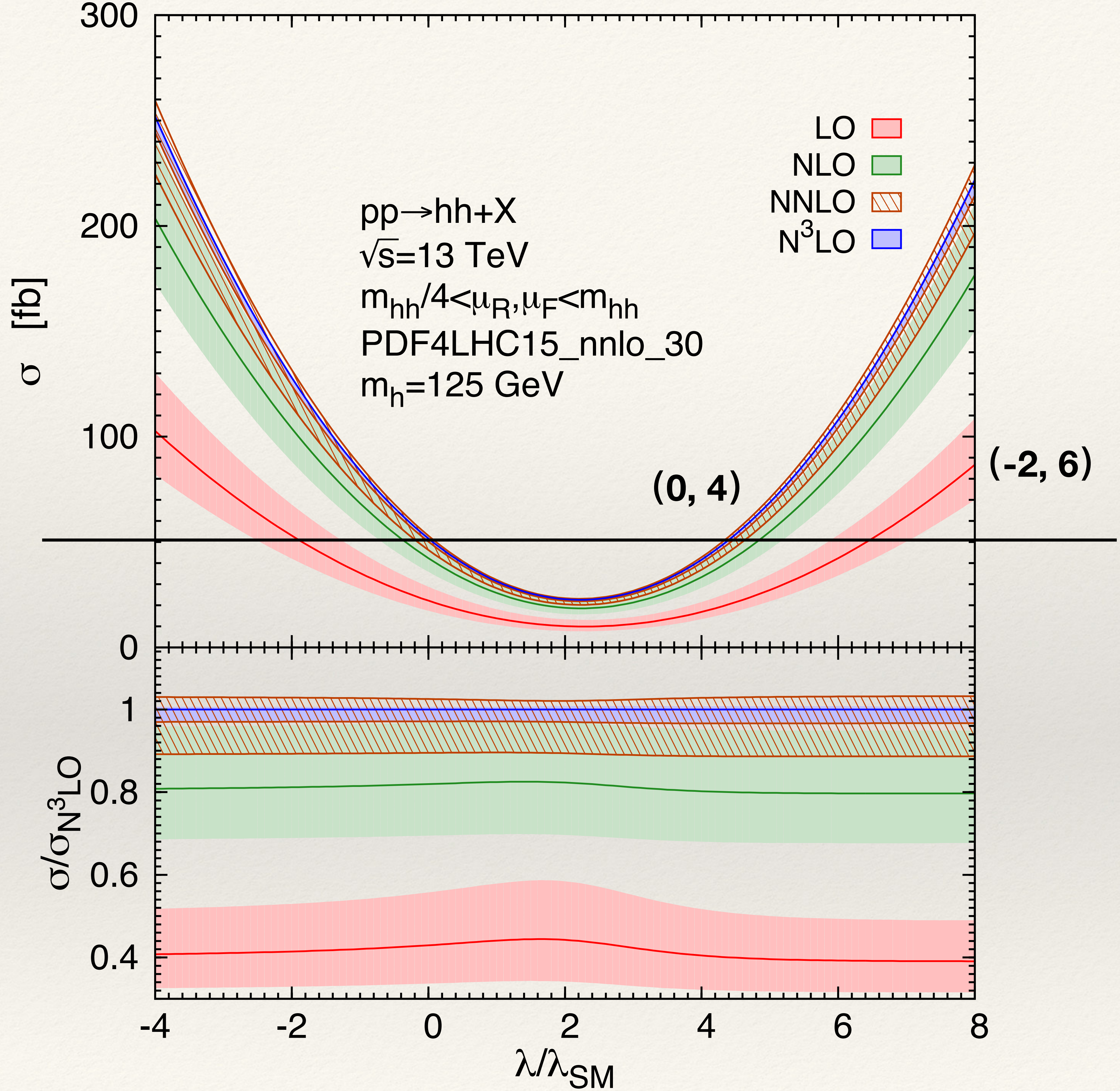
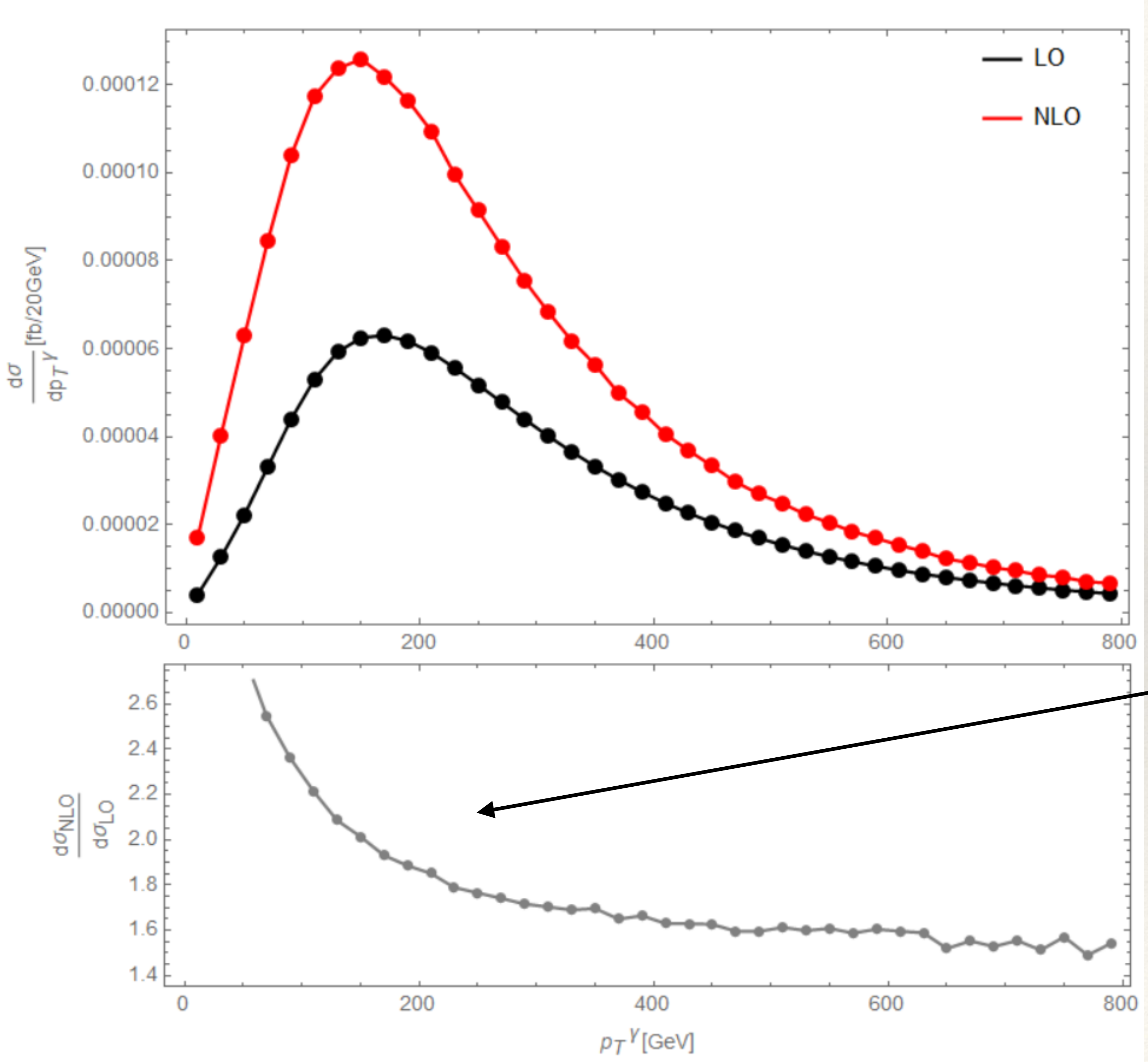


L.B.Chen, H.T.Li, H.S.Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

gg→HH including decay

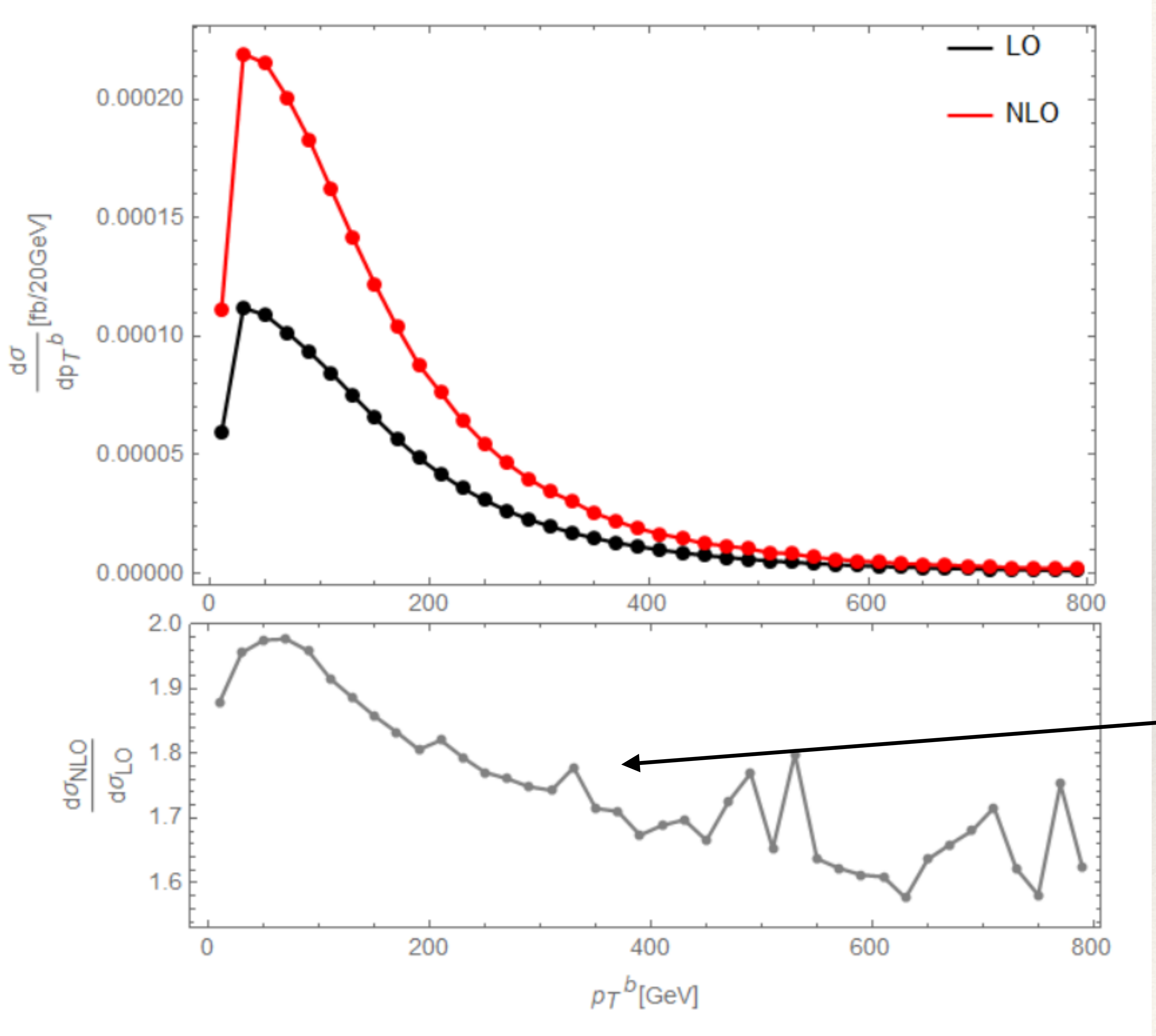


LO prod. & LO decay vs.
NLO prod. & LO decay

Non-constant enhancement

H.T.Li, JW, X.Zhang, D.Zhao, to appear

gg→HH including decay

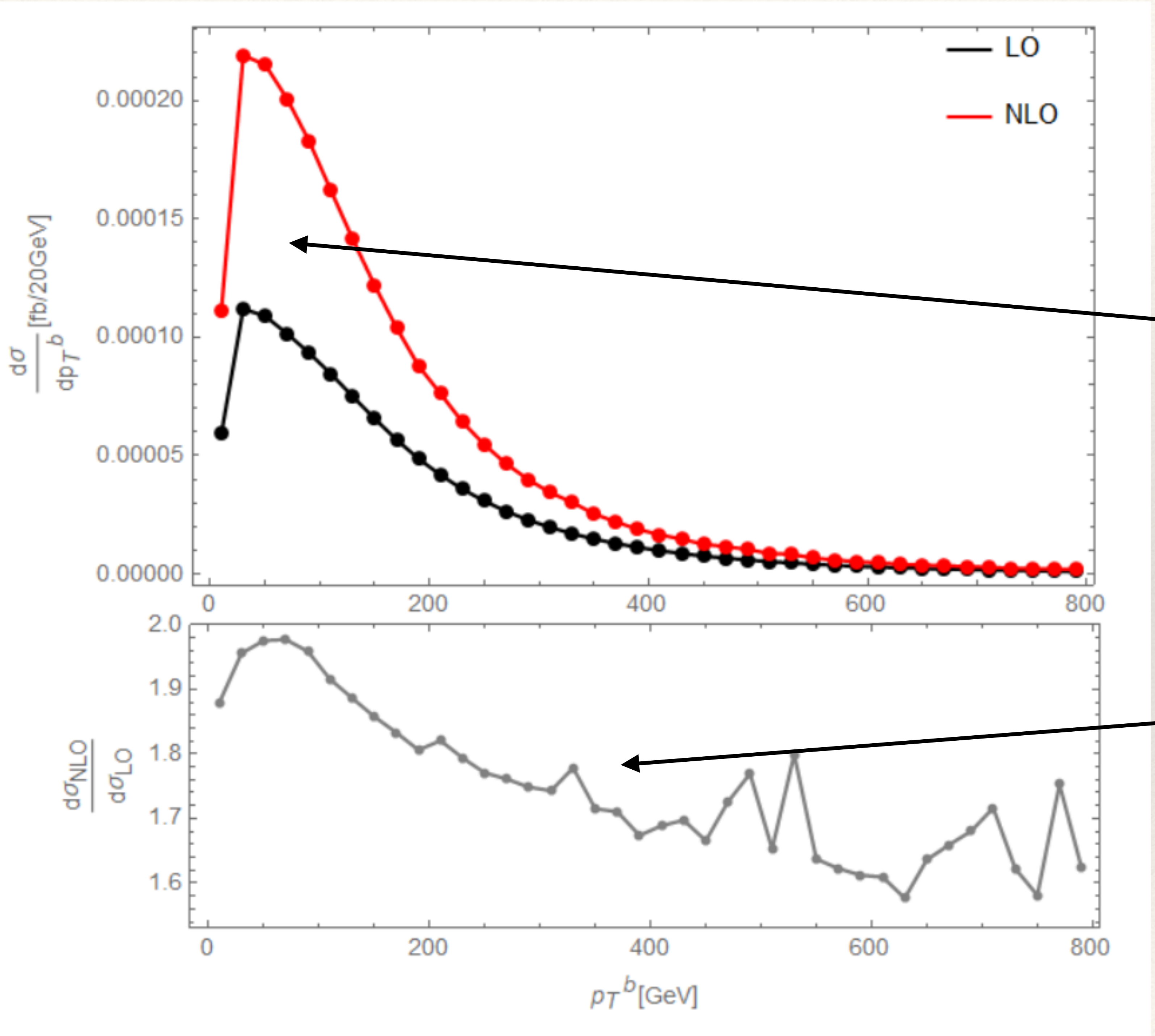


LO prod. & LO decay vs. NLO prod. & LO decay

Non-constant enhancement

H.T.Li, JW, X.Zhang, D.Zhao, to appear

gg→HH including decay



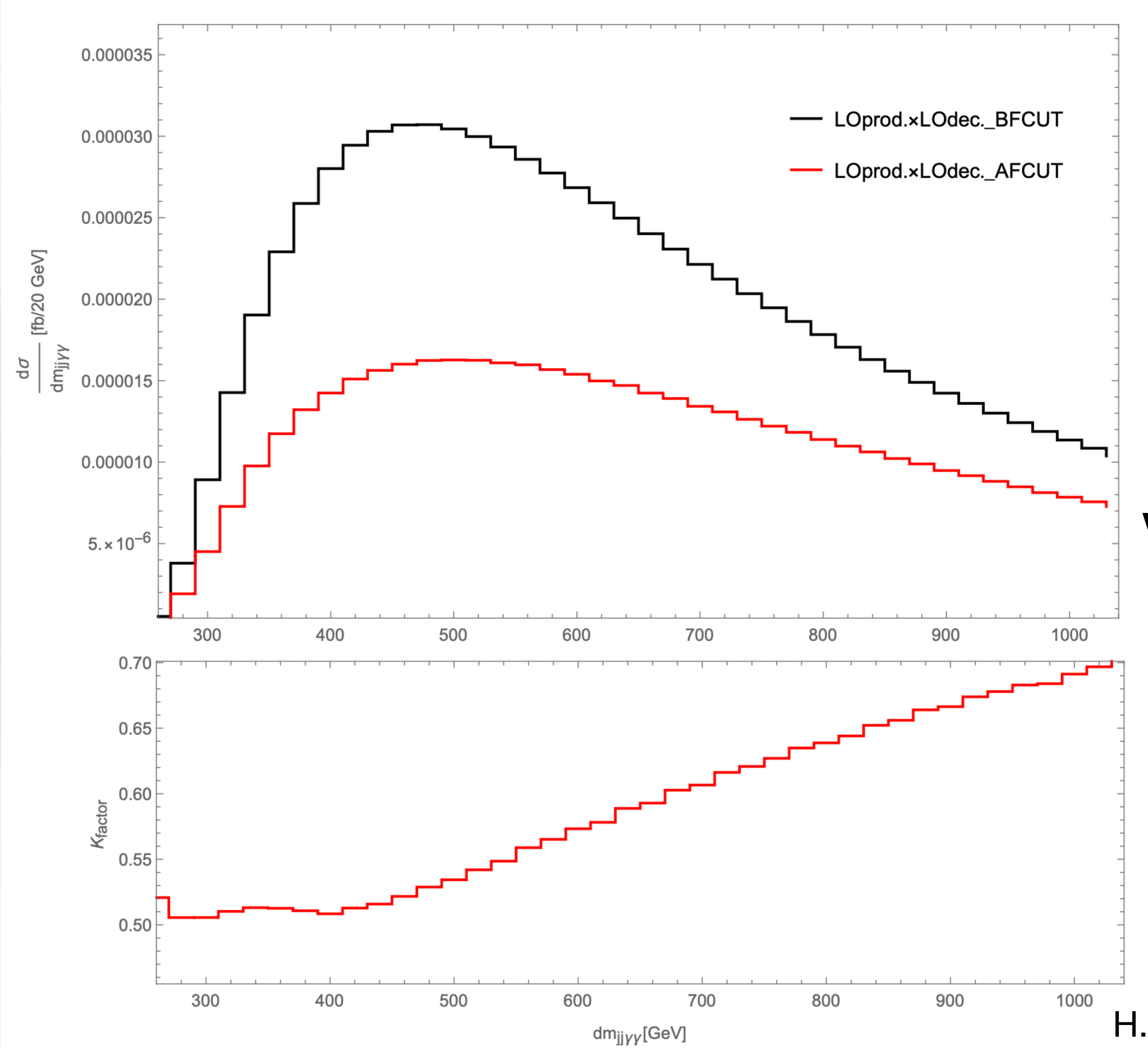
LO prod. & LO decay vs. NLO prod. & LO decay

Peak at ~30 GeV

Non-constant enhancement

H.T.Li, JW, X.Zhang, D.Zhao, to appear

gg→HH including decay



$p_j^T, p_\gamma^T > 25$ GeV

$|\eta_j|, |\eta_\gamma| < 2.5$

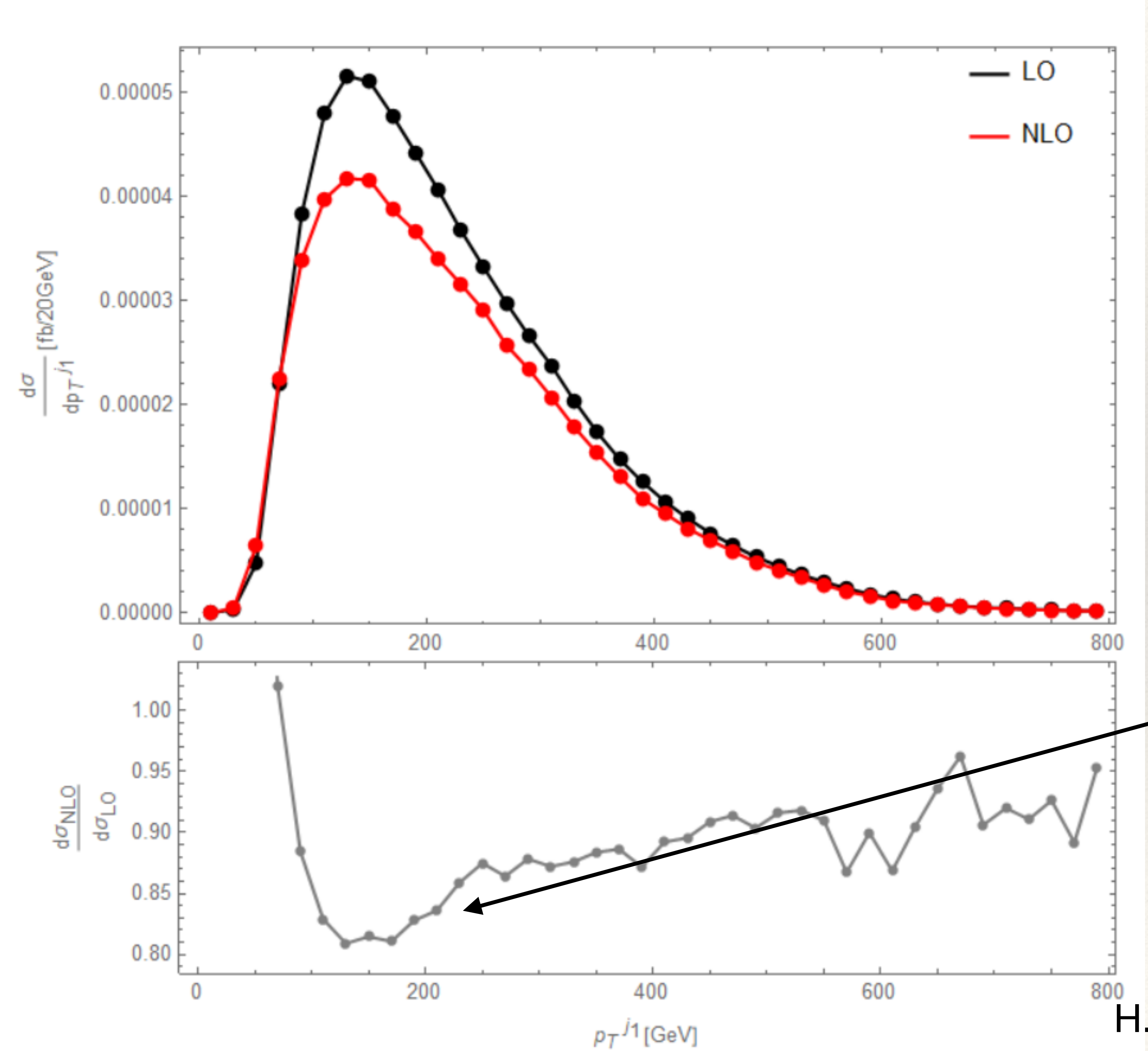
$\Delta R_{jj,\gamma j,\gamma\gamma} > 0.4$

$90\text{GeV} < m_{jj} < 190\text{GeV}$

Very loose cuts decrease the x-section significantly!

H.T.Li, JW, X.Zhang, D.Zhao, to appear

gg→HH including NLO decay



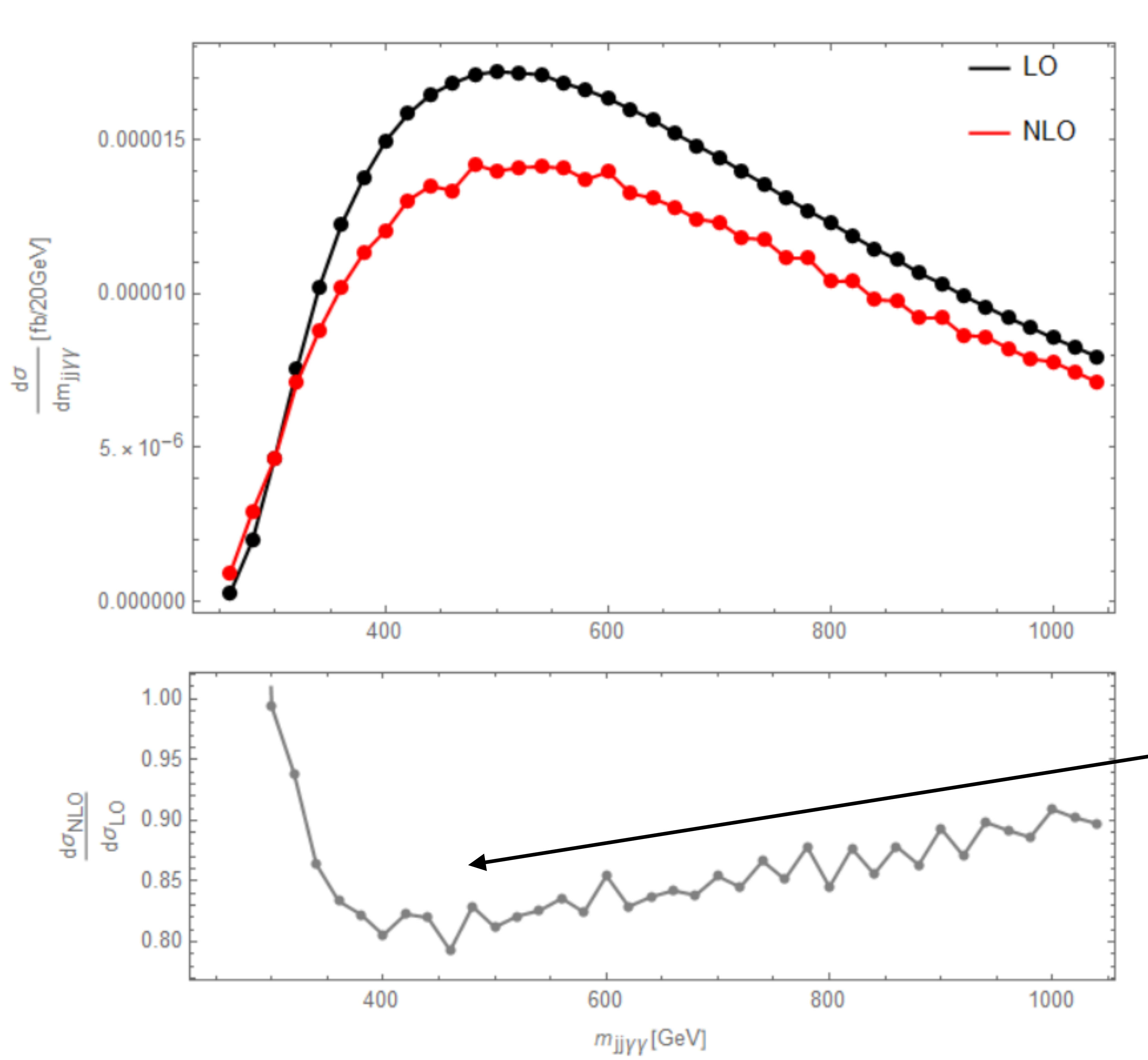
LO prod. & LO decay vs.
LO prod. & NLO decay

$p_j^T, p_\gamma^T > 25$ 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

H.T.Li, JW, X.Zhang, D.Zhao, to appear

gg→HH including NLO decay



LO prod. & LO decay vs.
LO prod. & NLO decay

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$|\eta_j|, |\eta_\gamma| < 2.5$
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Up to 20% reduction

H.T.Li, JW, X.Zhang, D.Zhao, to appear

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 cut effects and higher order corrections in decay are also significant, and thus should be considered for a detailed study.

Thank you!

Back-up slides

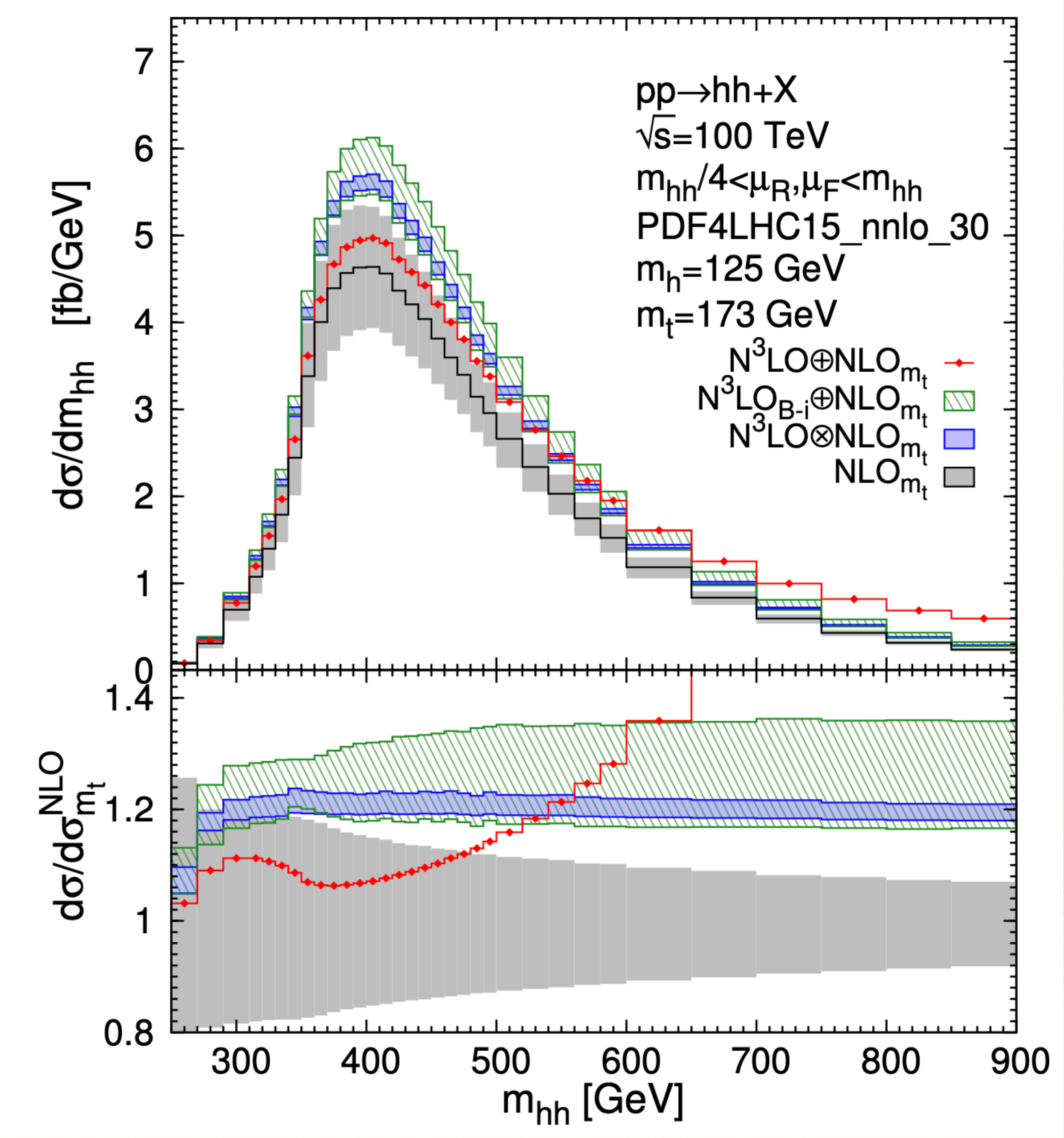
Top quark mass effects

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

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

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

gg→HH@NNNLO



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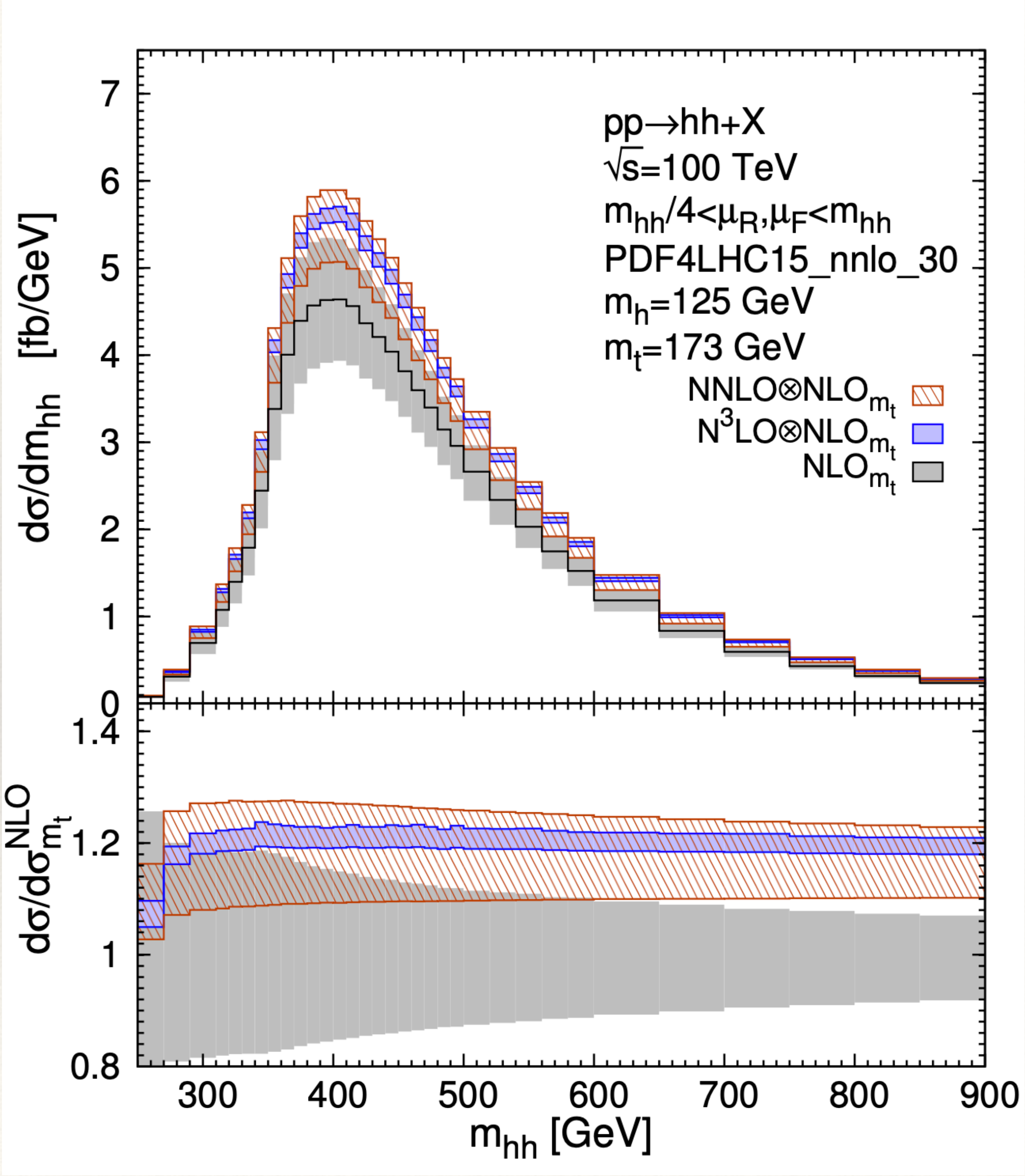
gg→HH@NNNLO



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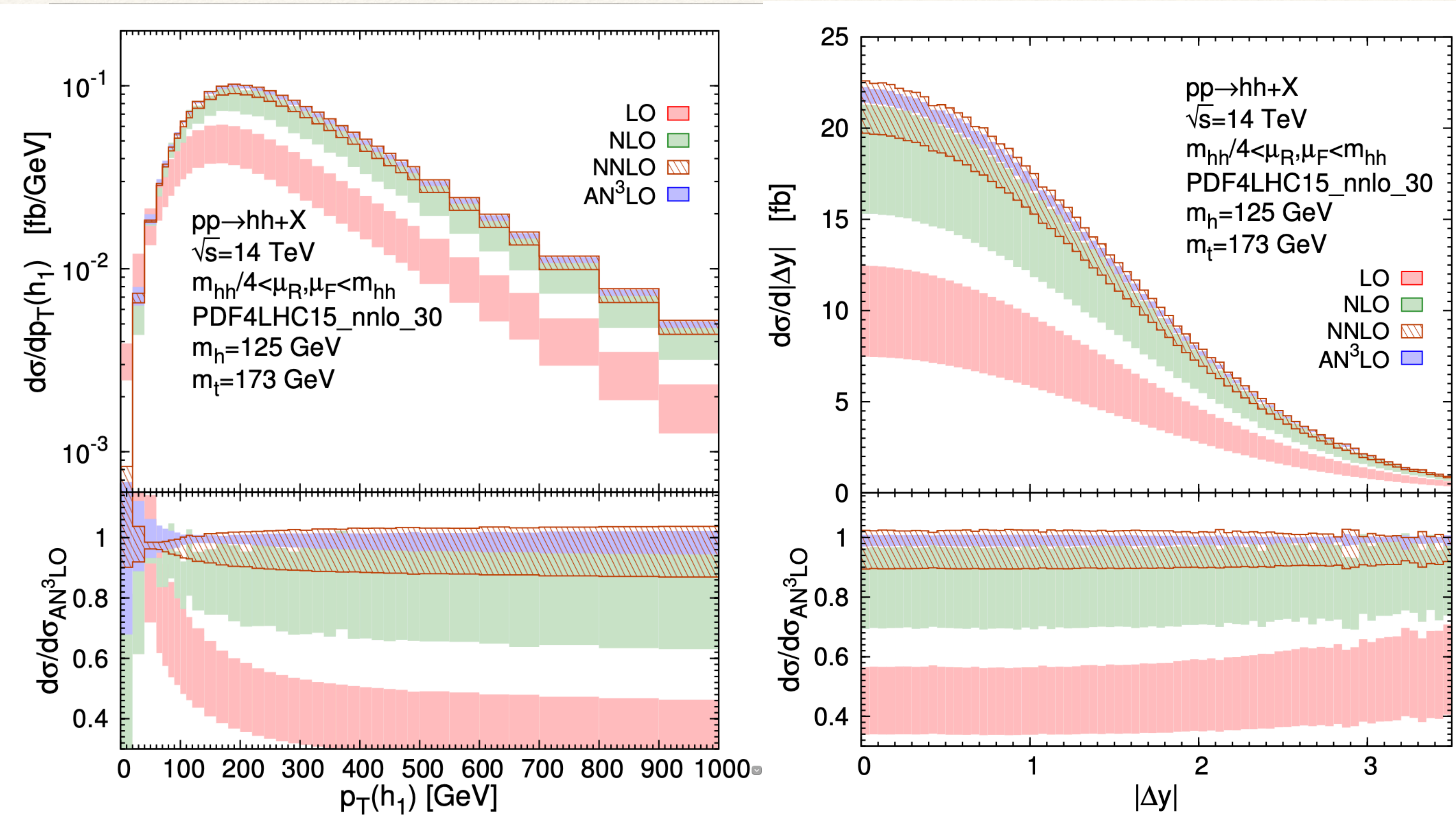
gg→HH@NNNLO



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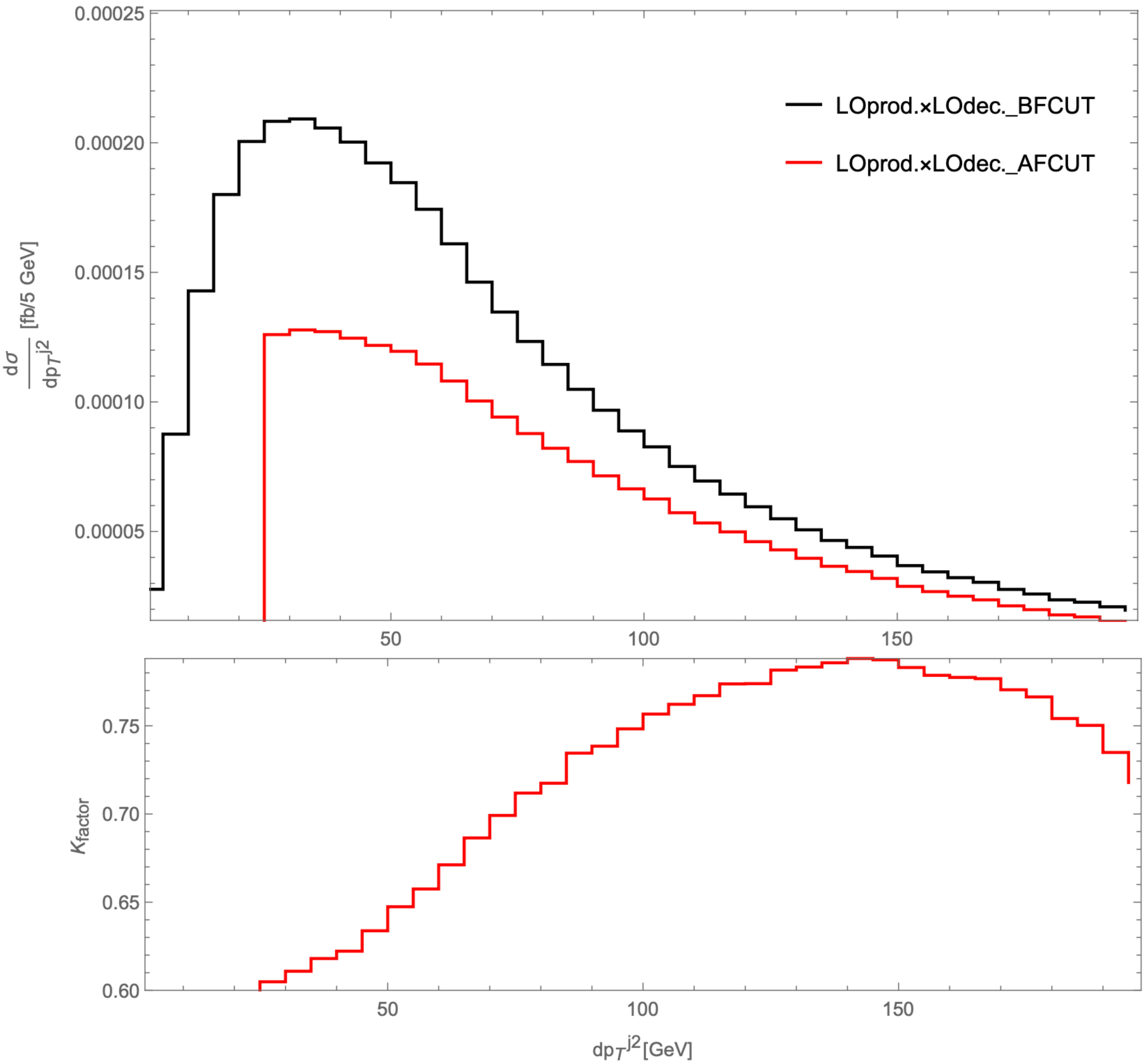

0.00025
0.00020
0.00015
0.00010
0.00005
dσ / dp_T^j2 [fb/5 GeV]
LOprod.×LOdec._BFCUT
LOprod.×LOdec._AFCUT
50
100
150
0.75
0.70
0.65
0.60
K_factor
50
100
150
dp_T^j2[GeV]