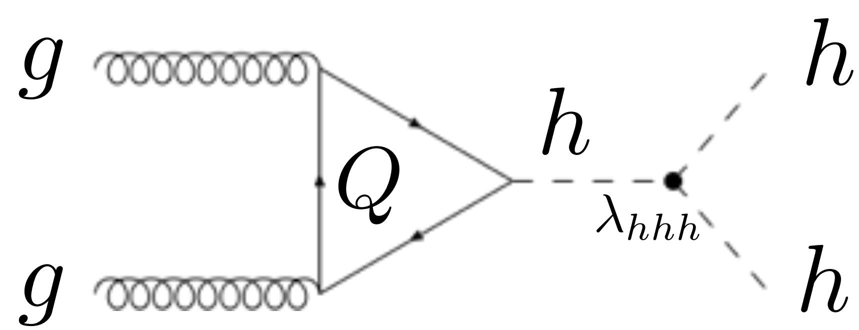
Higgs boson pair production at N³LO QCD



Hua-Sheng Shao

Work with L.-B. Chen, H.T. Li and J. Wang (1909.06808, 1912.13001)

2nd FCC-France Workshop
20 January 2021

HIGGS SELF COUPLINGS

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  - Unique way to understand the Higgs potential

⟹ *EW symmetry breaking*

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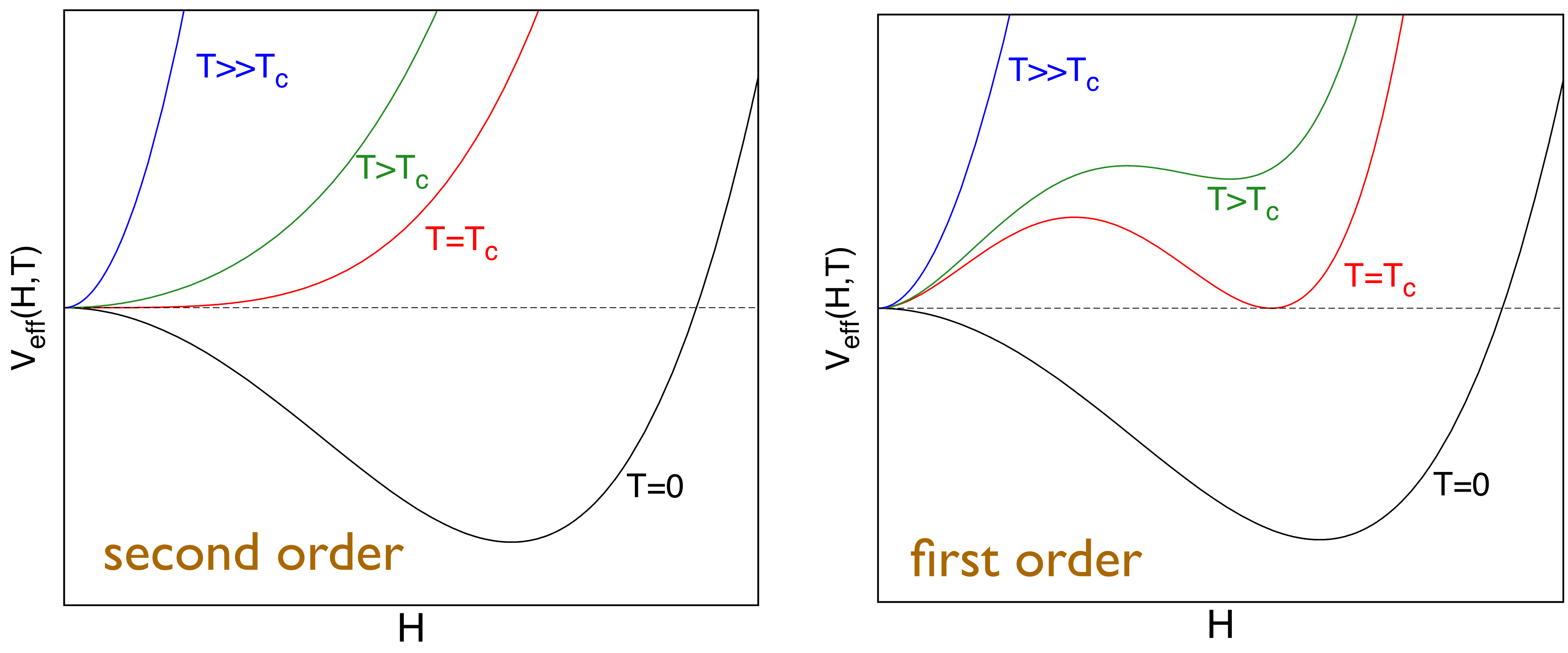

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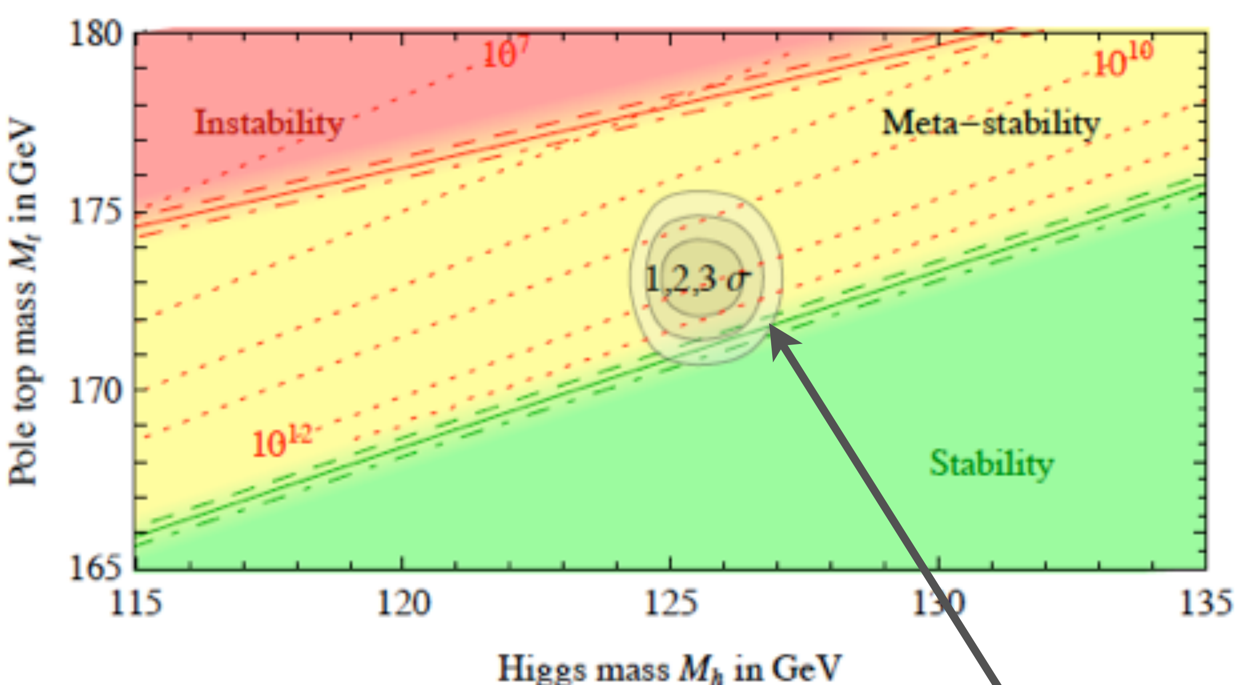
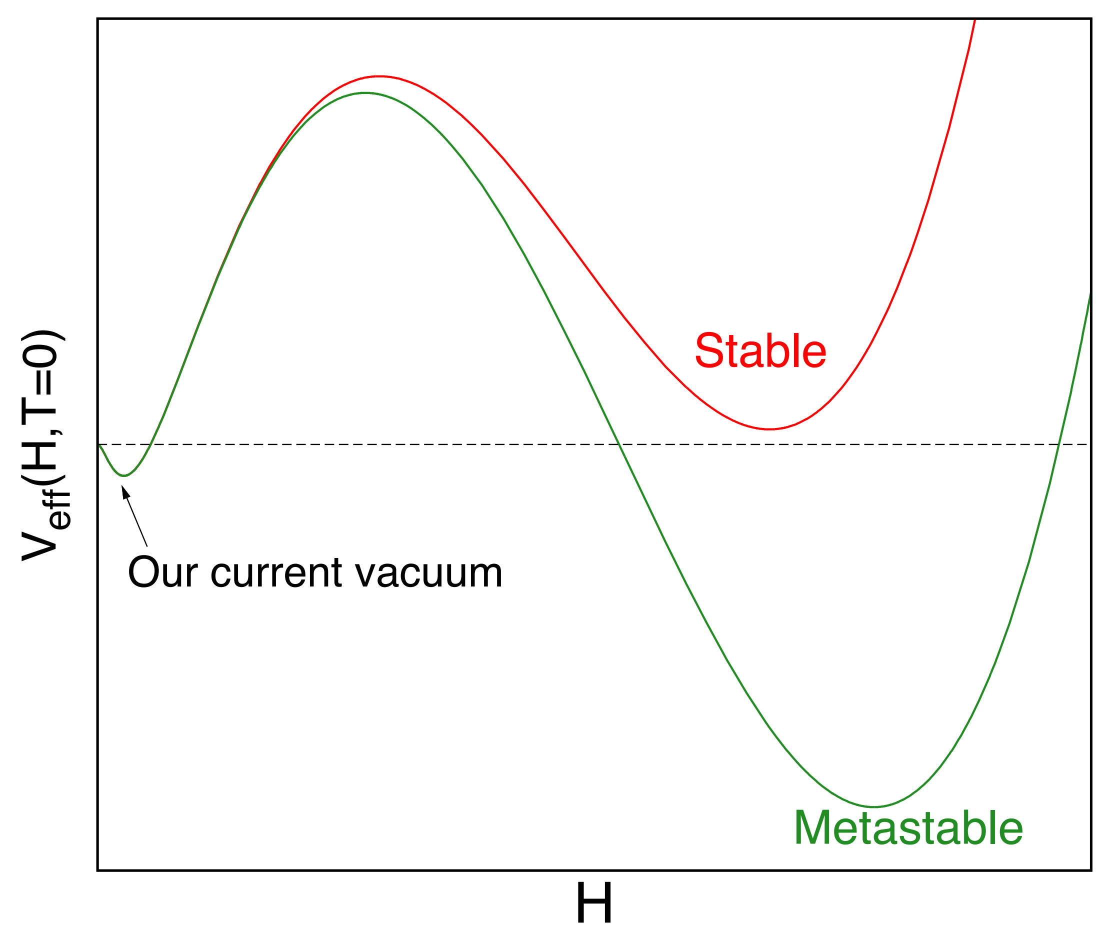


Degrassi et al. (2012)



Tuesday, January 19, 21

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LPTHE Laboratoire de Physique Théorique et Hautes Energies

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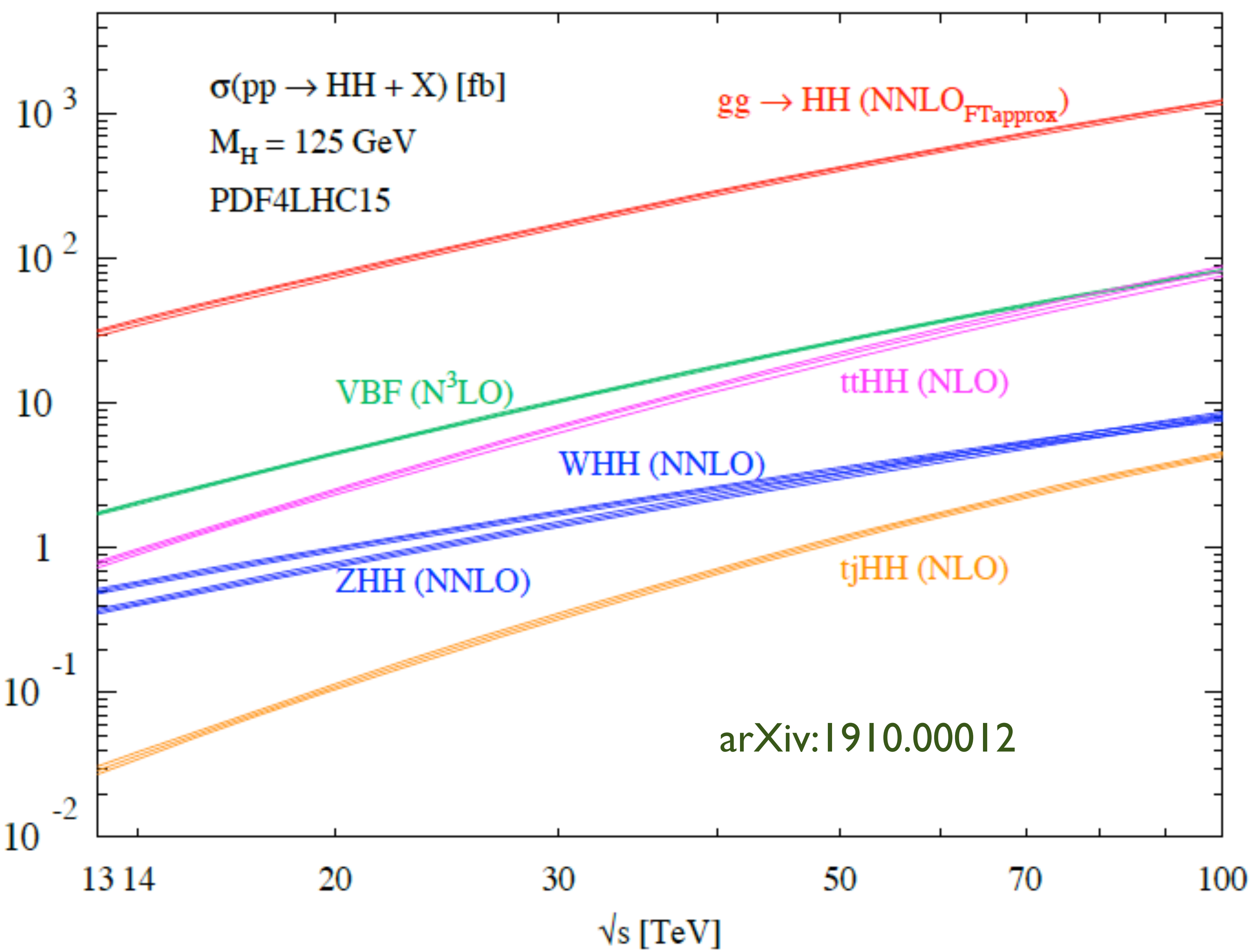
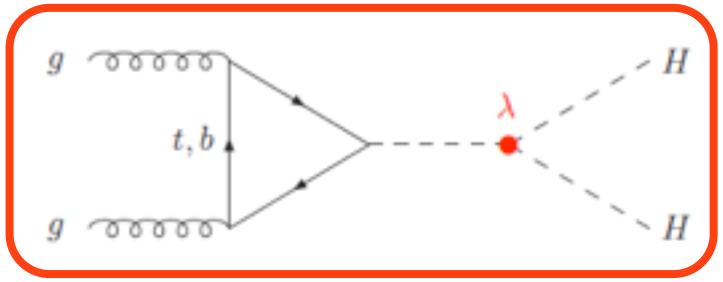
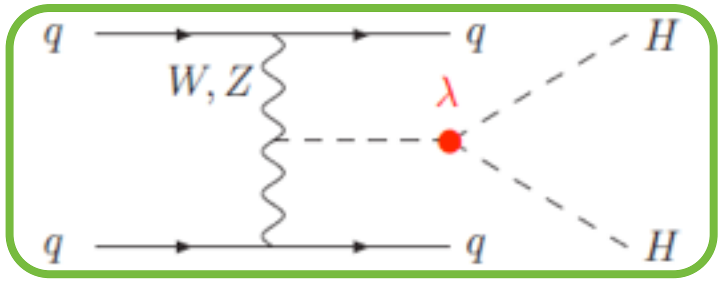
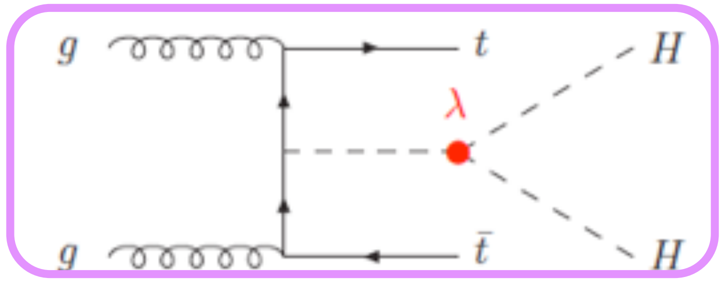
Perturbation theory breaks at scale $\frac{13\ \mathrm{TeV}}{|\delta\lambda_{hhh}|}$ Chang et al. (2019)

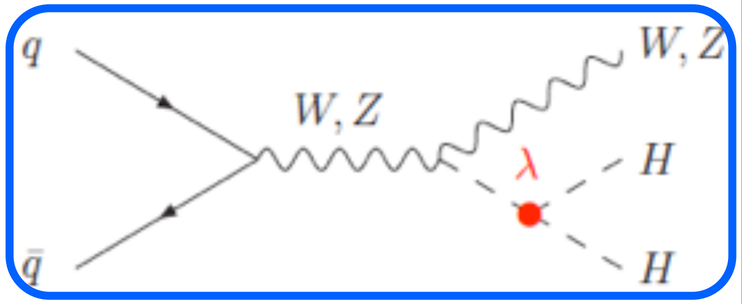
HIGGS BOSON PAIR PRODUCTION











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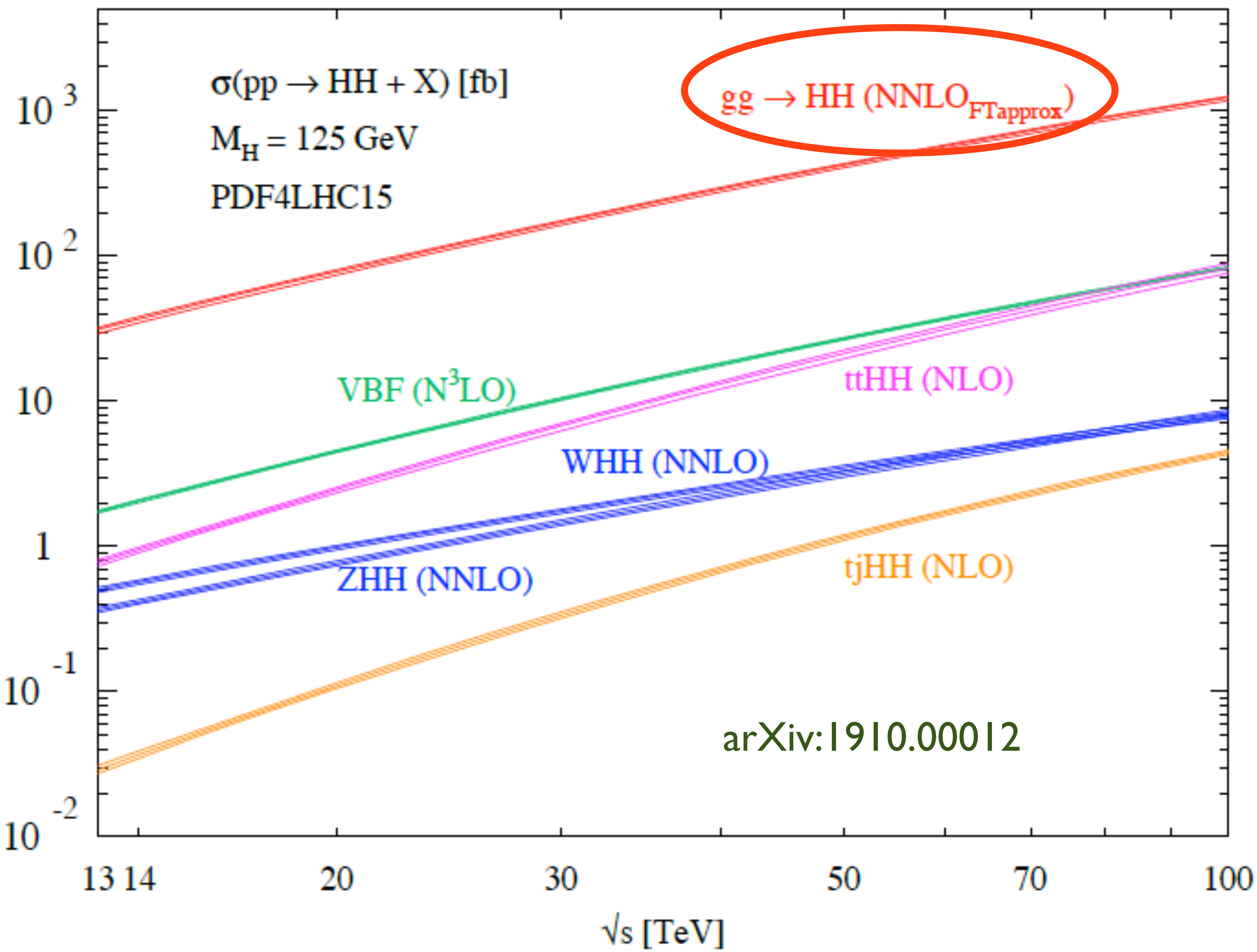

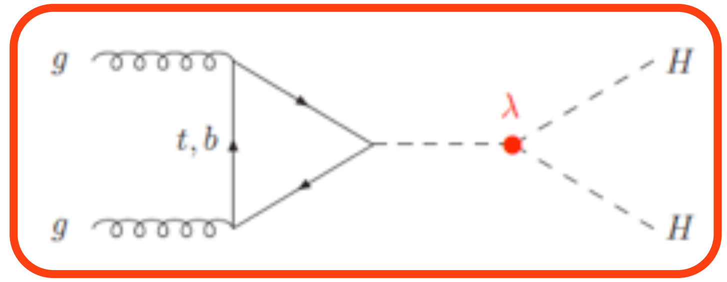

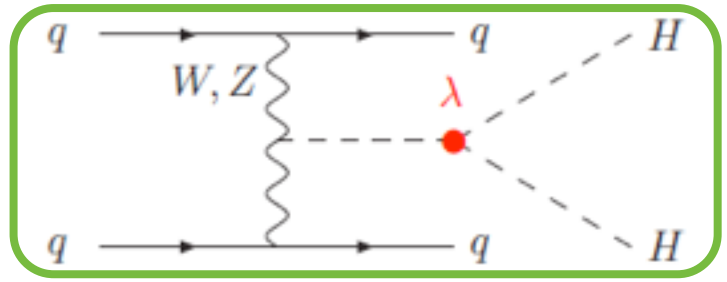

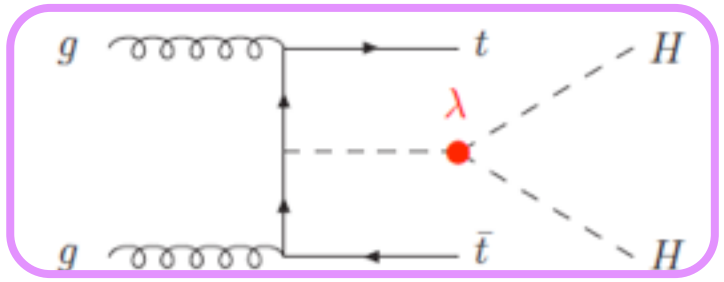

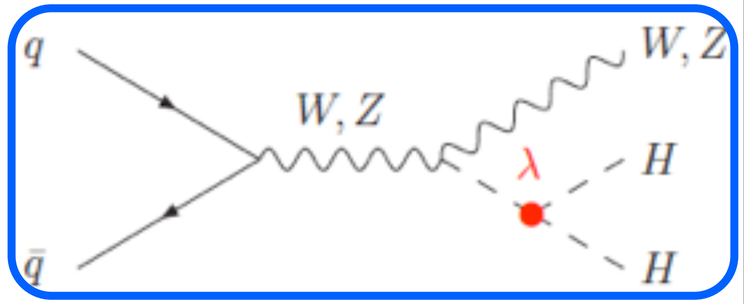

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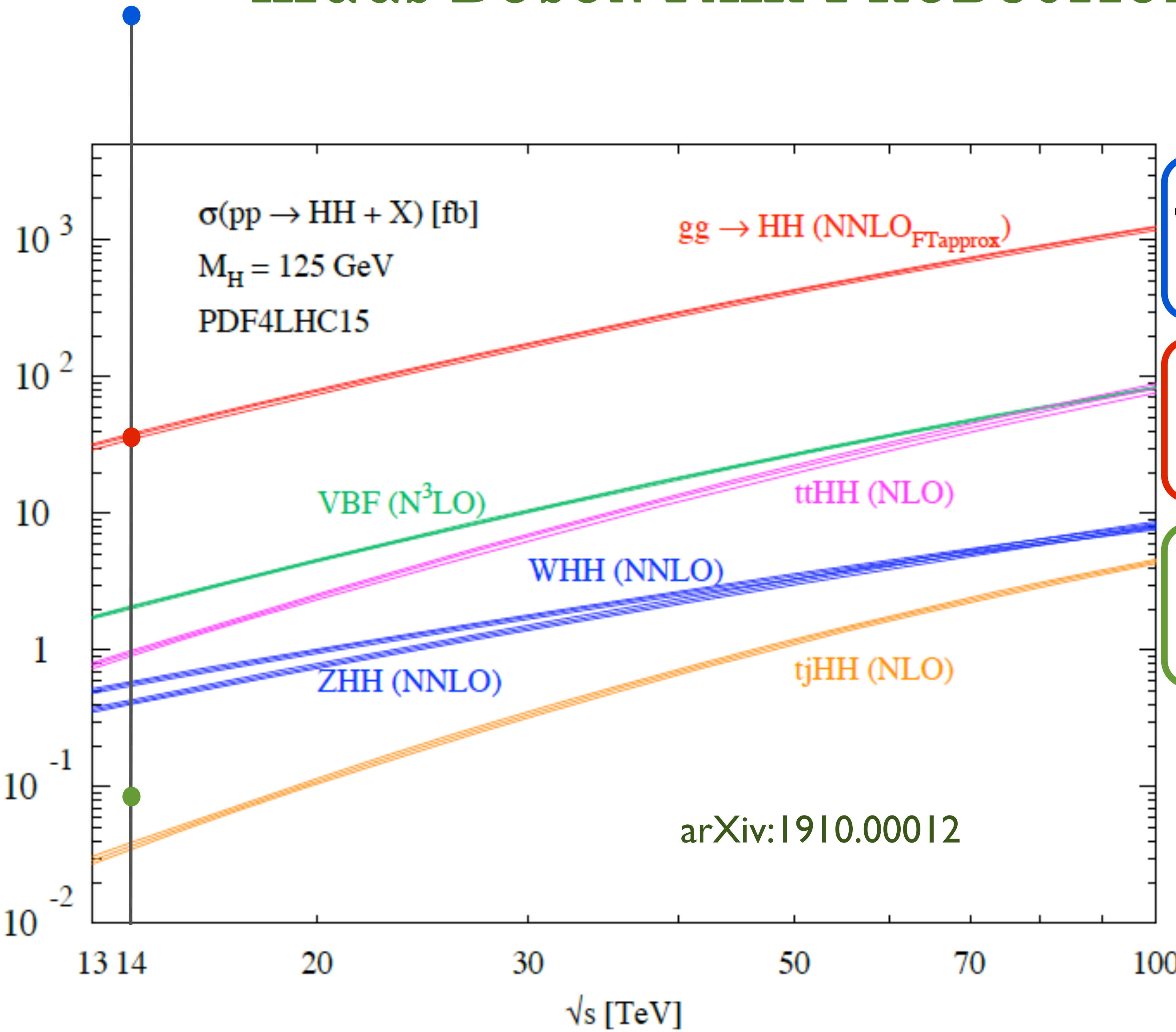


At 14 TeV:

$\sigma_h^{N^3LO} = 54.72$ pb

arXiv:1902.00134

$\sigma_{hh}^{NNLO_{FTapprox}} = 36.69$ fb

arXiv:1910.00012

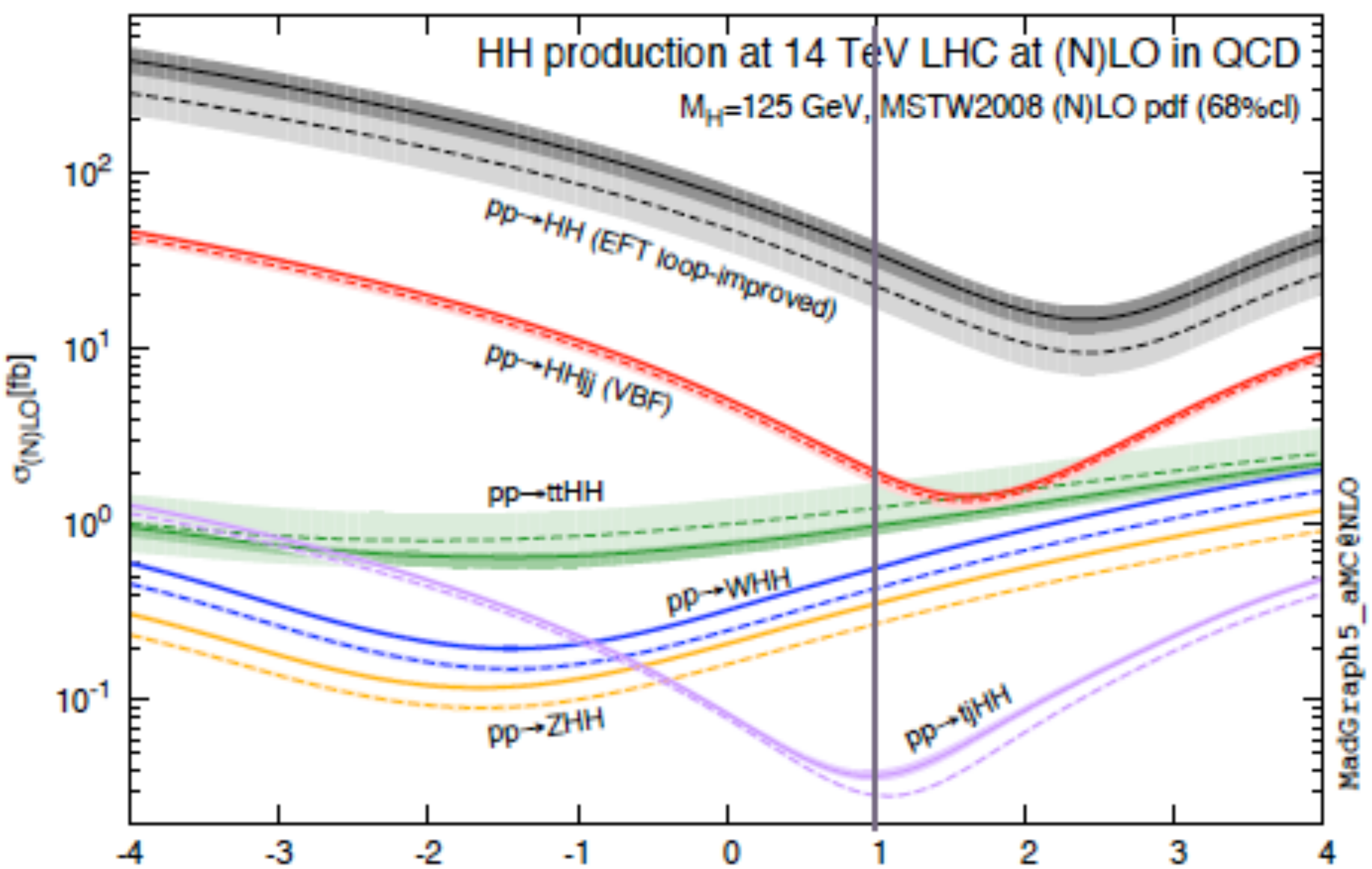
$\sigma_{hhh}^{NLO_{FTapprox}} = 89.4$ ab

arXiv:1408.6542

Cross sections for hh(h) increase by a factor of 20 (60) at 100 TeV

PROBING HIGGS SELF COUPLING

arXiv:1401.7340



- The self-coupling value can be extracted by measuring the cross sections.

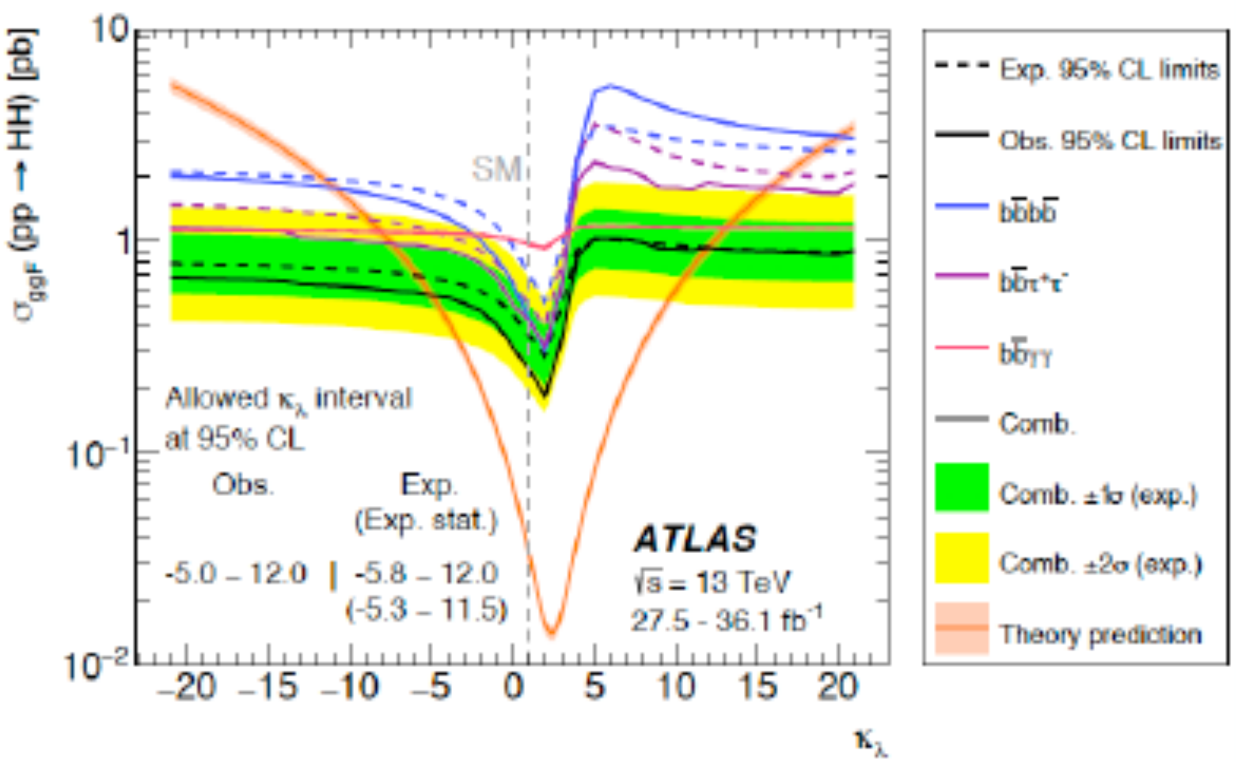
However:

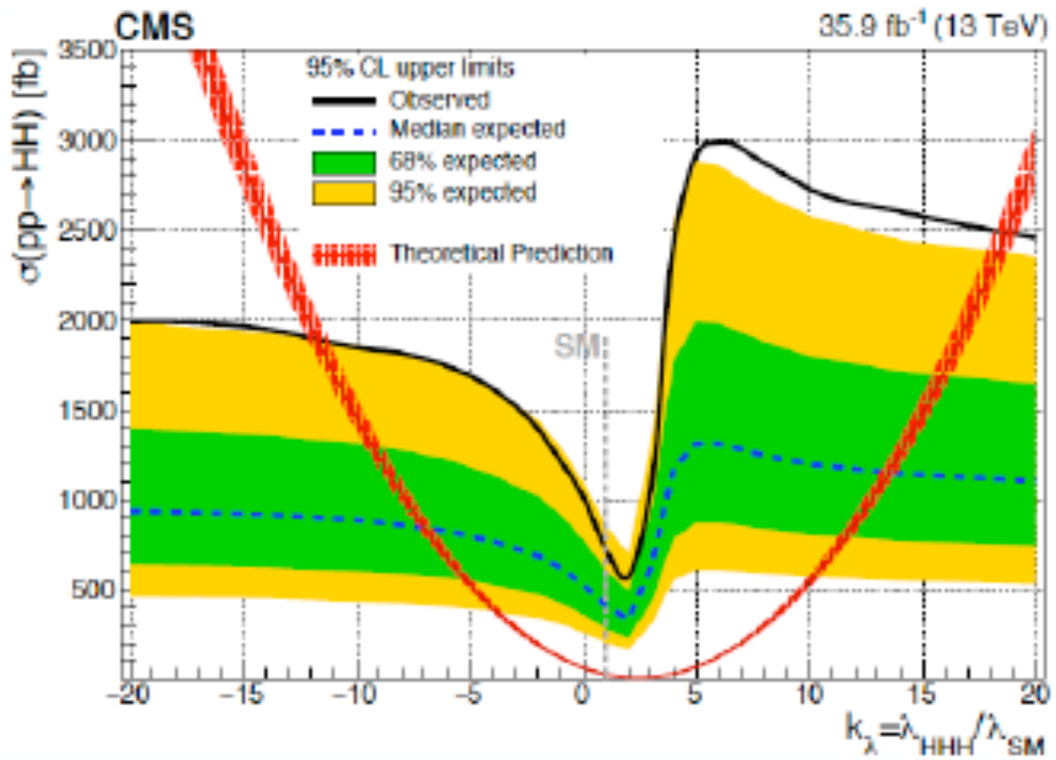
- Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
- The most commonly assumption is only changing the value of λ_{hhh}, which leads to (differential) cross section variations

$$\sigma = \sigma_{\rm SM}[1 + (\kappa_\lambda - 1)A_1 + (\kappa_\lambda^2 - 1)A_2]$$

THE MEASUREMENTS

$$\kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}}$$



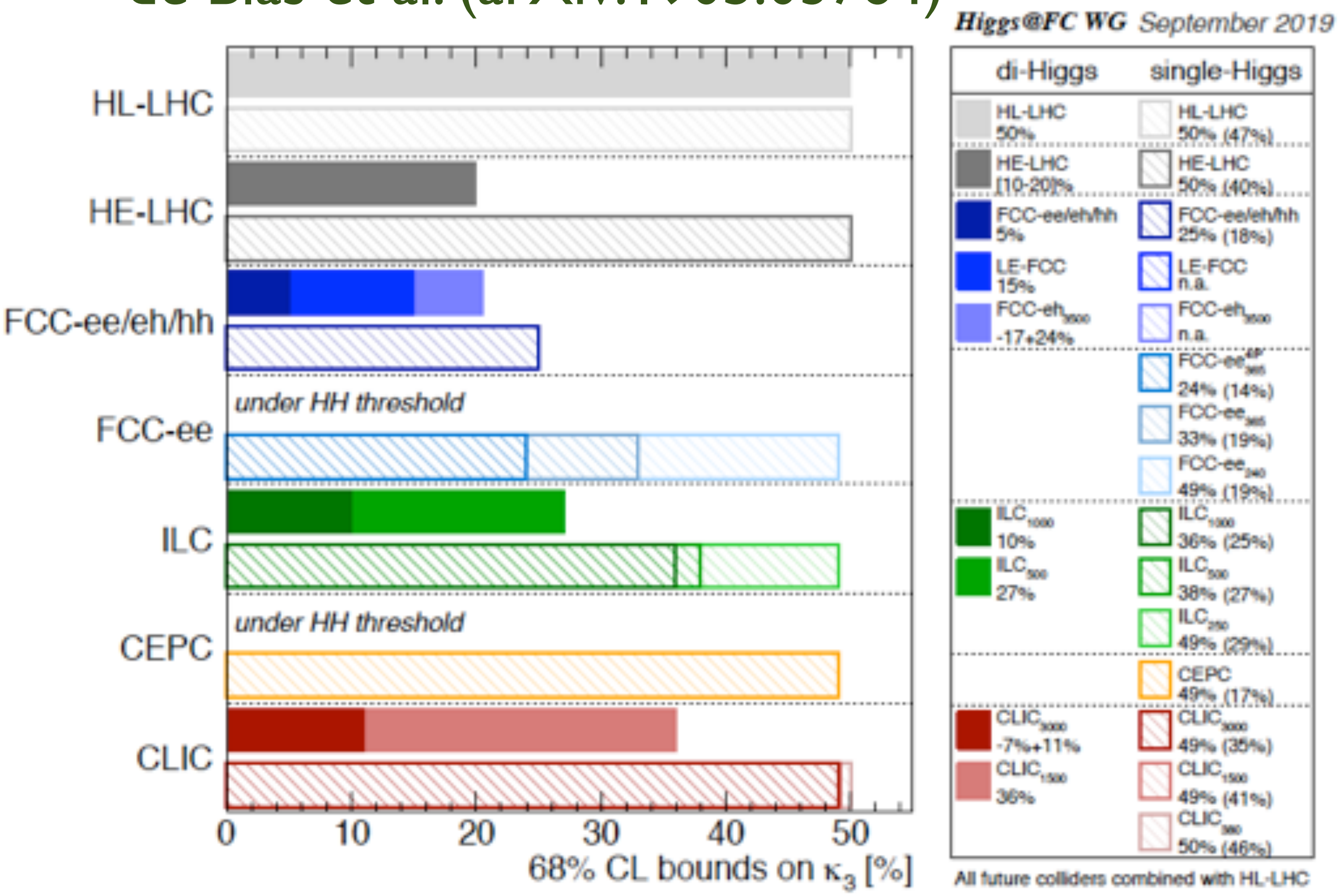


$$-5.0 < \kappa_\lambda < 12 \qquad\qquad -11.8 < \kappa_\lambda < 18.8$$

- Strong shape effects with κ_λ variations
- Soft spectra for $\kappa_\lambda \approx 5$ → difficult to constrain anomalous positive values

A QUICK INTRODUCTION

de Blas et al. (arXiv:1905.03764)



Caterina Vernieri (Snowmass21EF meeting)

collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
CEPC_{240}	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
CLIC_{380}	50%	–	50%
CLIC_{1500}	49%	36%	29%
CLIC_{3000}	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

50% accuracy (HL-LHC): sensitive to BSM with the largest new physics effects

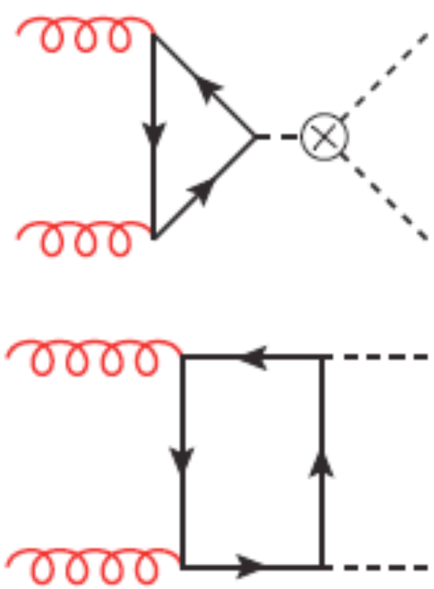
20% accuracy (future e+e-): discovery of SM-like λ_{hhh}

5% accuracy (FCC-hh): sensitive to BSM loop corrections

→ Ultimate precision machine !

Mangano et al. (arXiv:2004.03505)

- **Full top-quark mass dependence**
  - Leading order (LO) is a loop-induced process



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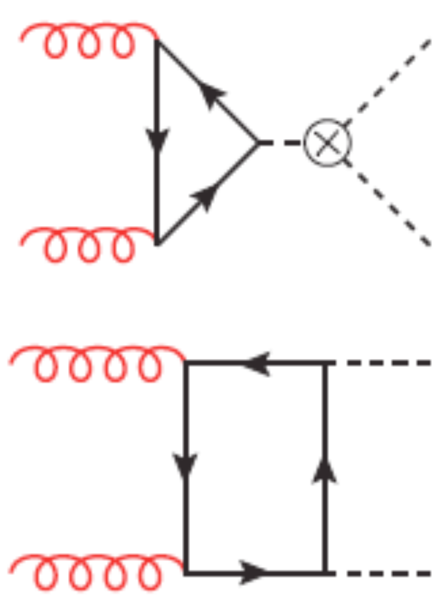

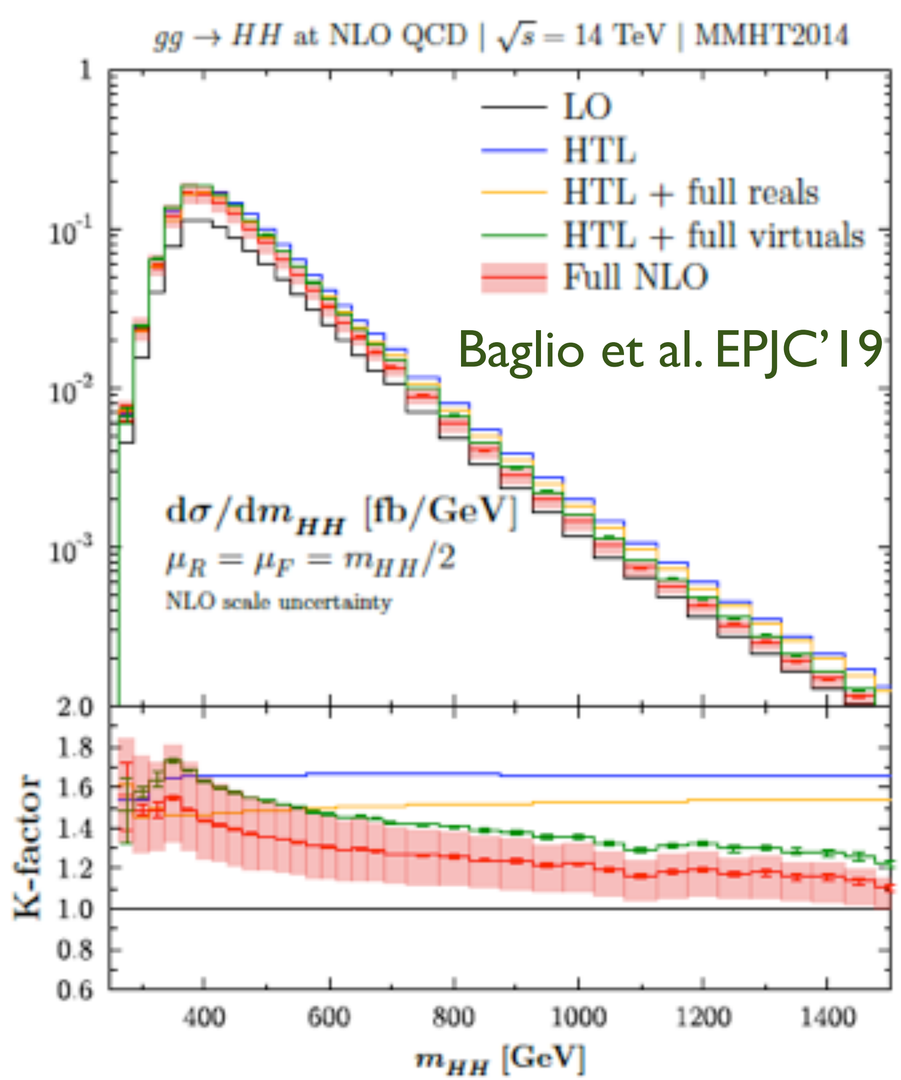

Reasonable approximations to extend $1/m_t$ result (rescaled exact Born, include exact real radiation) can fail the true K factor significantly.

virtual is so crucial, which is remaining to be understood

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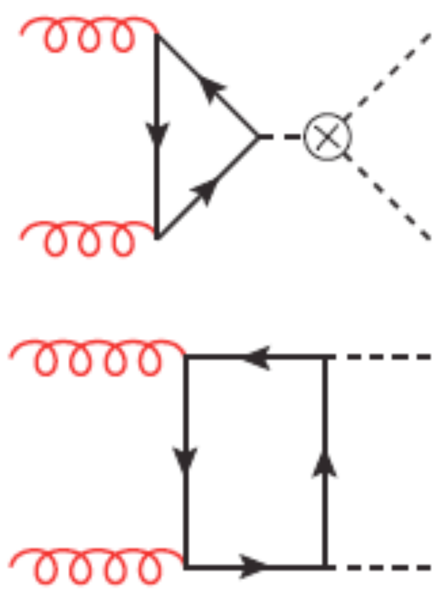

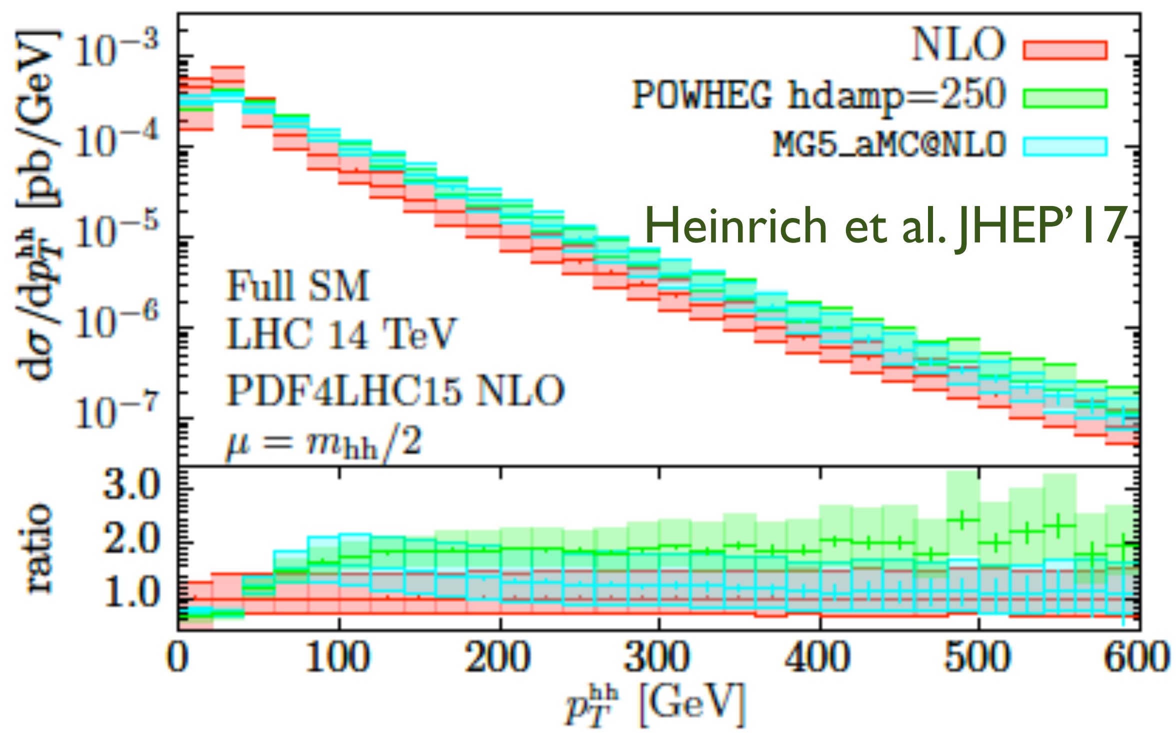

Matching scheme dependence starts to be significant at large p_T^{hh}

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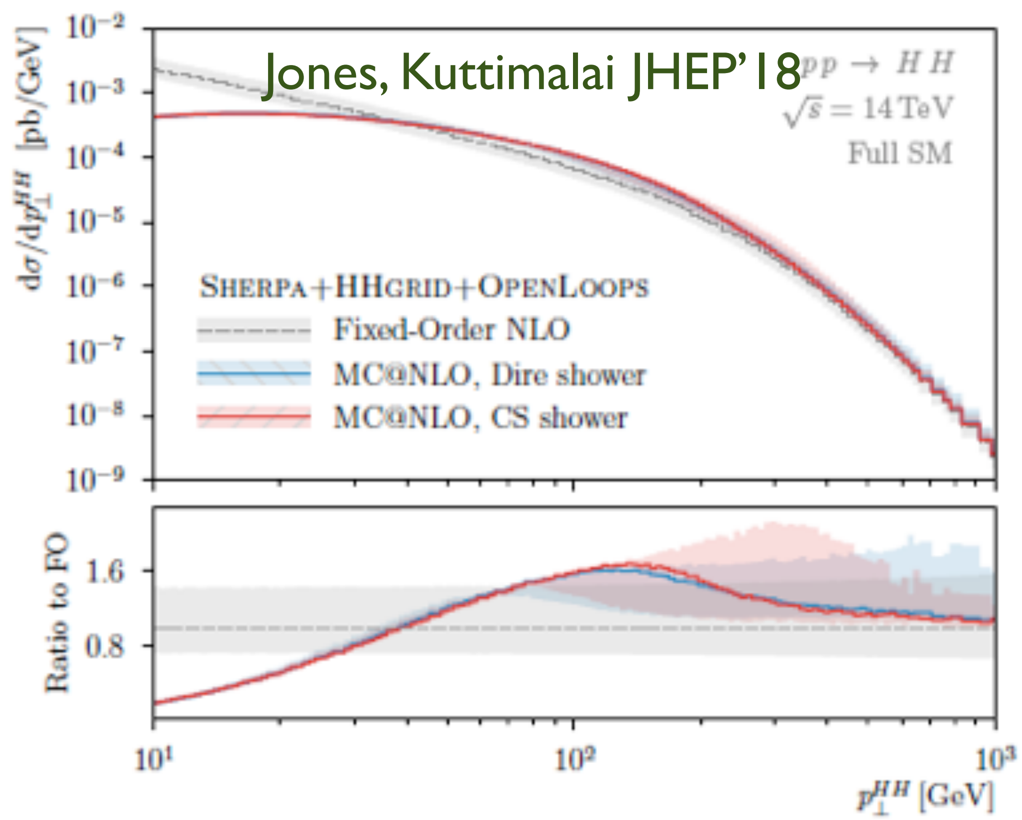

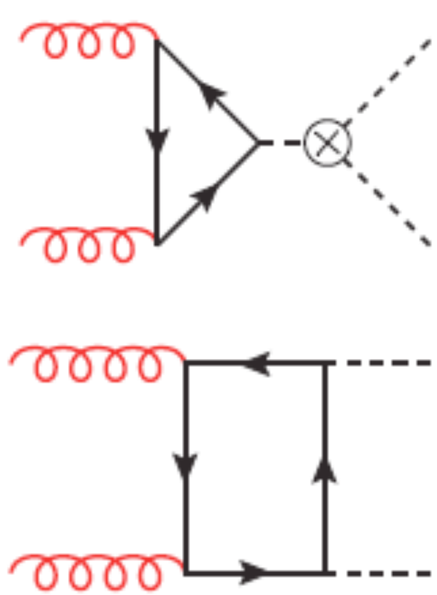

Shower scale uncertainty is also significant at large p_T^{hh}

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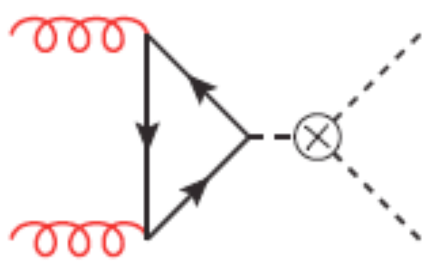
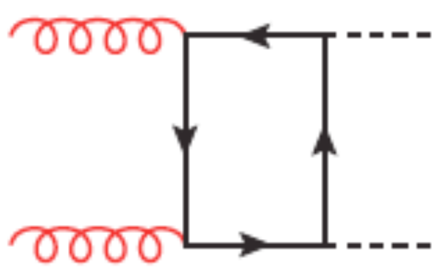
  - Scale unc. (>10%)

Energy	13 TeV	14 TeV	27 TeV	100 TeV
NLO	$27.78^{+13.8\%}_{-12.8\%}$ fb	$32.88^{+13.5\%}_{-12.5\%}$ fb	$127.7^{+11.5\%}_{-10.4\%}$ fb	$1147^{+10.7\%}_{-9.9\%}$ fb





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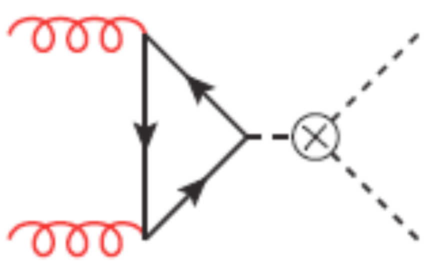

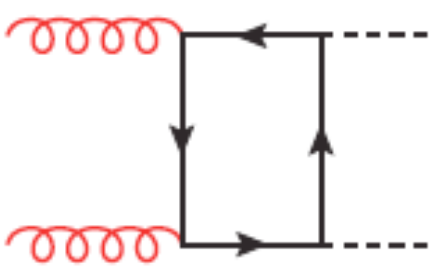

$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=300\text{ GeV}} = 0.02978(7)^{+6\%}_{-34\%}\text{ fb/GeV},$$
$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=400\text{ GeV}} = 0.1609(4)^{+0\%}_{-13\%}\text{ fb/GeV},$$
$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=600\text{ GeV}} = 0.03204(9)^{+0\%}_{-30\%}\text{ fb/GeV},$$
$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=1200\text{ GeV}} = 0.000435(4)^{+0\%}_{-35\%}\text{ fb/GeV}$$

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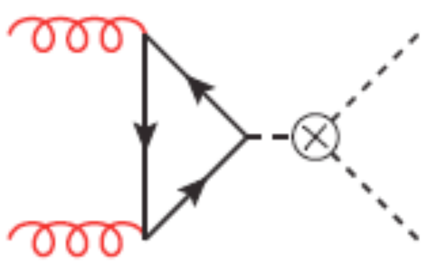
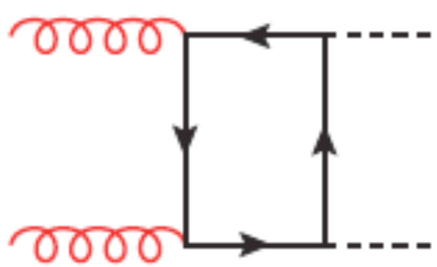
  - Scale unc. (>10%)
  - ... and large top-quark mass scheme dependence
  - A lot of analytical approximations (well-motivated to deepen understanding)

    Grigo et al. NPB'13, NPB'15; Degrassi EPJC'16;, Davies et al. JHEP'18,JHEP'19; Bonciani et al. PRL'18; Xu and Yang JHEP'19; Davies and Steinhauser (1909.01361)

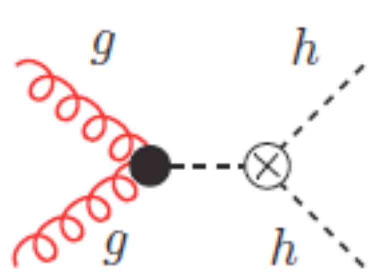


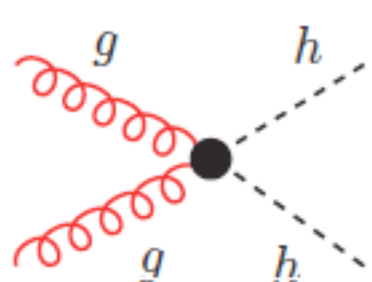


HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**

$$\mathcal{L}_{\rm eff} = -\frac{1}{4}G^a_{\mu\nu}G^{a\ \mu\nu}\left(C_h\frac{h}{v} - C_{hh}\frac{h^2}{2v^2}\right)$$





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  - The Wilson coefficients C_h and C_{hh} are known up to 4 loops

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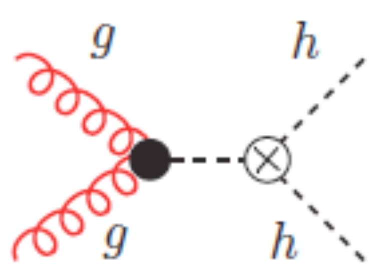

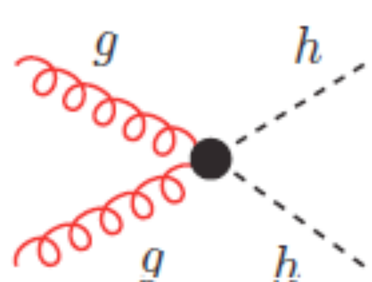

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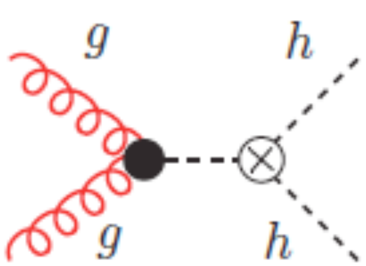
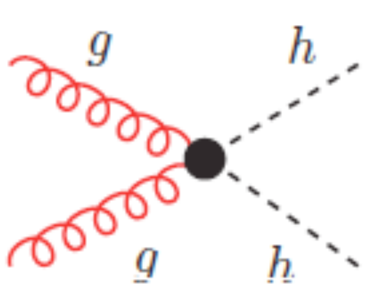
    - Threshold resummation Shao et al. JHEP'13; Florian and Mazzitelli JHEP'15, JHEP'18
    - $\text{NLO}_{\text{FTapprox}}$: NLO plus full top quark mass in Born and real Frederix et al. PLB'14; Maltoni et al. JHEP'14
    - Combine NNLO with full top-quark mass NLO Grazzini et al. JHEP'18





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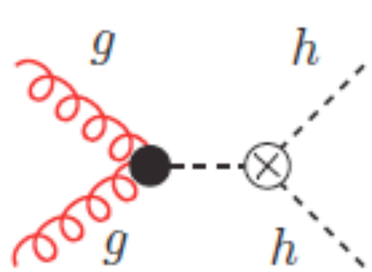
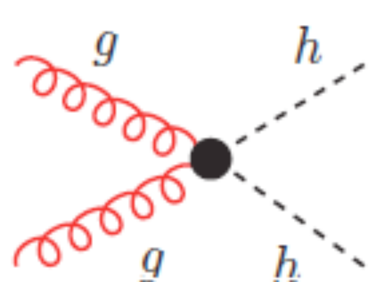


Our aim is to push the calculation to N^3LO !



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- **Infinite top-quark mass limit**

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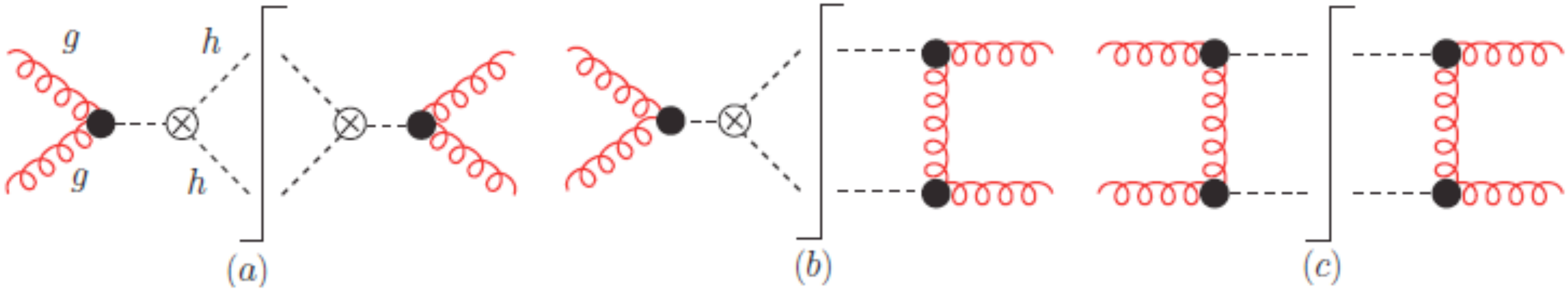

Chen, Li, HSS, Wang (PLB'20, JHEP'20)

	LO	NLO	NNLO	N^{3}LO
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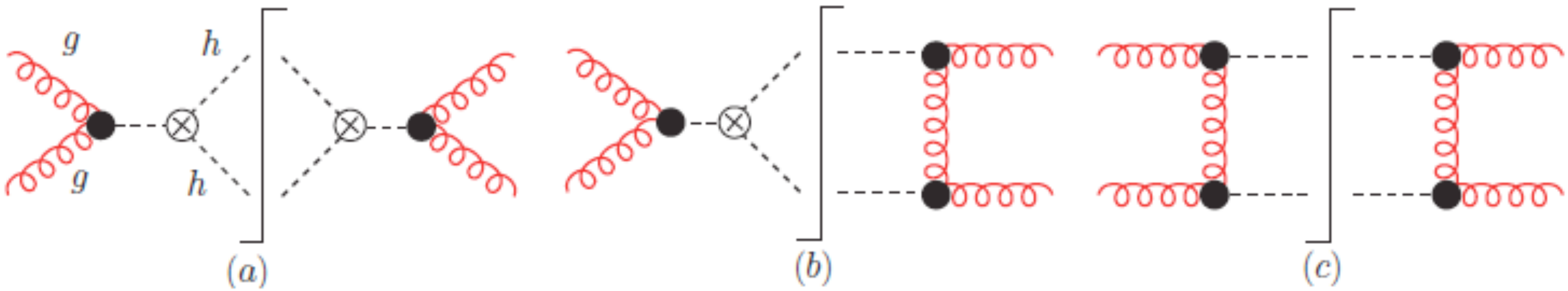

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- class-a: same topology as ggH

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

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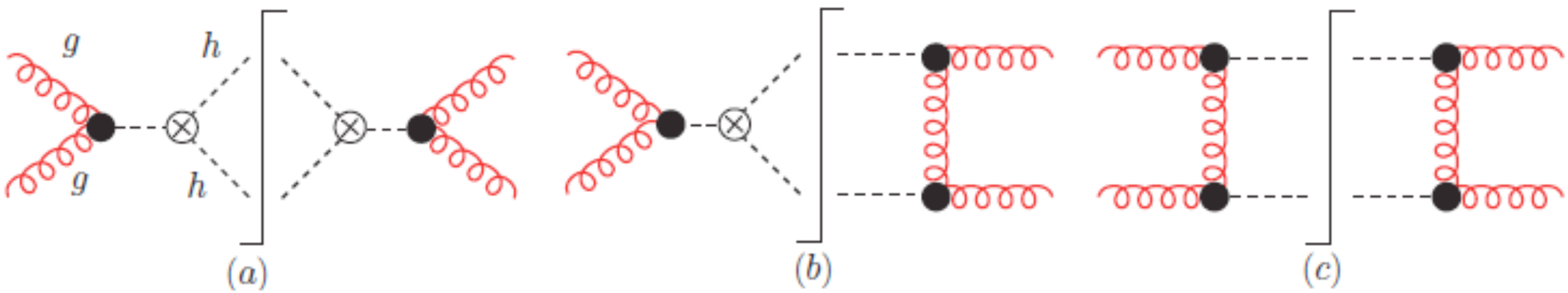

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From iHixs2

Dulat et al. CPC'18

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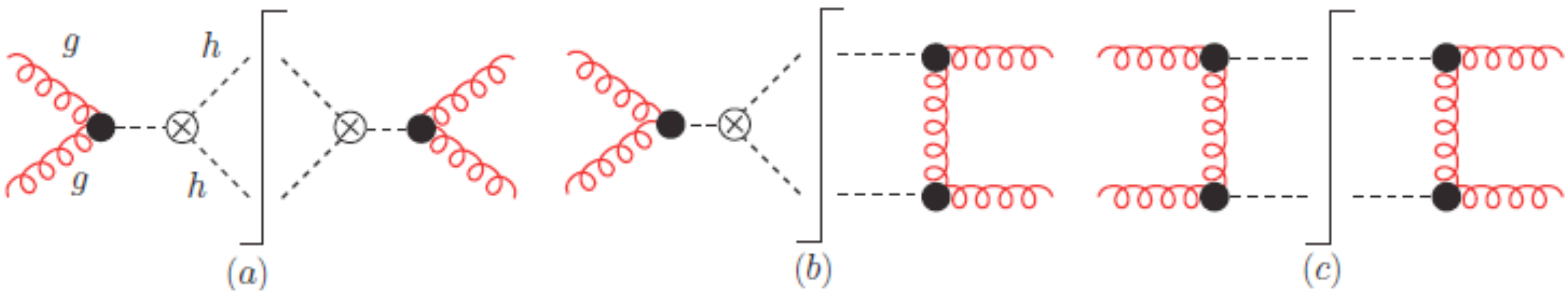

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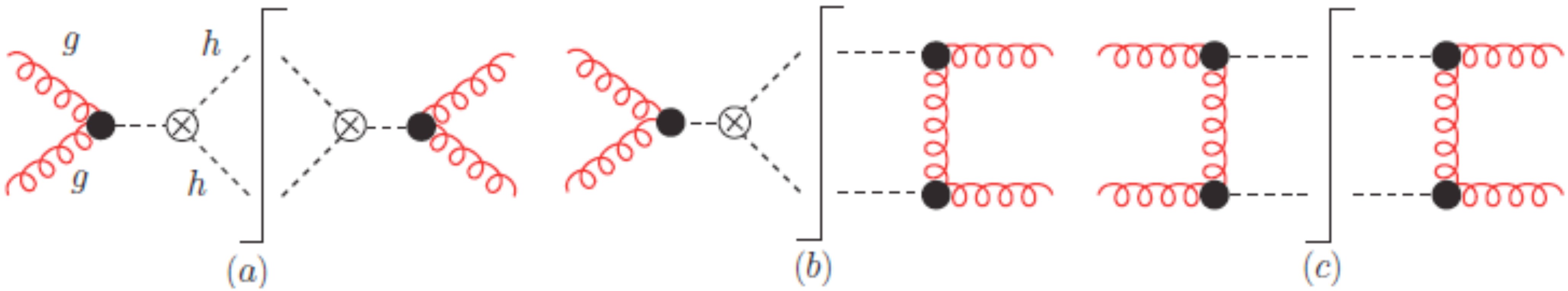

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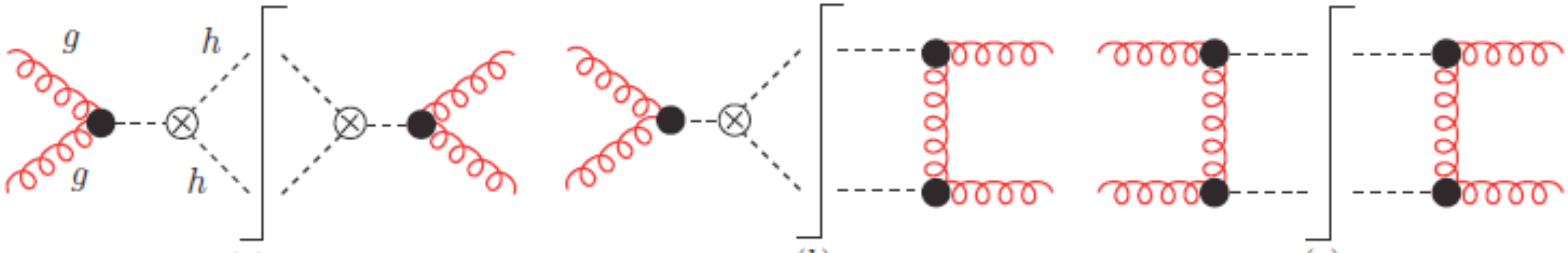

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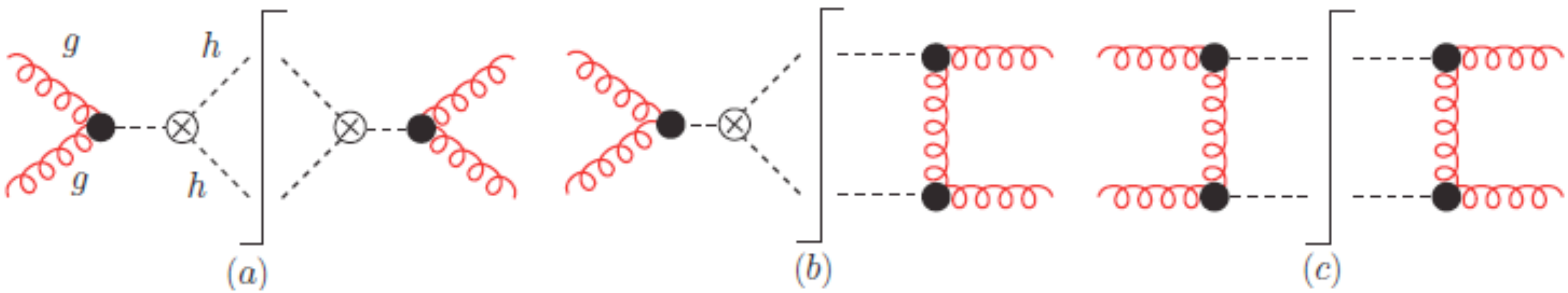

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$\mathcal{H}$ hard function

two-loop amplitude

Banerjee et al., JHEP'18

new one-loop amplitude

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LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

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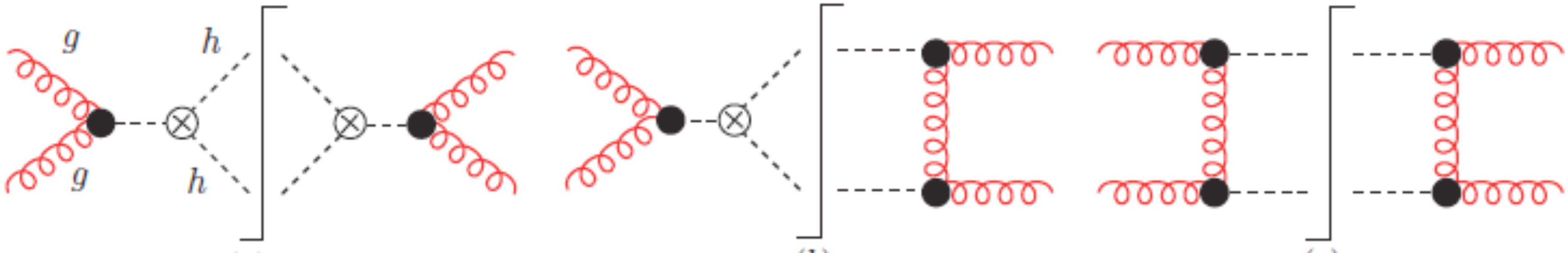

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$\mathcal{B}_i$ TMD beam function

two-loop exp. known

Gehrmann et al.PRL'12, JHEP'14; Luebbert et al., JHEP'16; Echevarria et al. JHEP'16; Luo et al., '19

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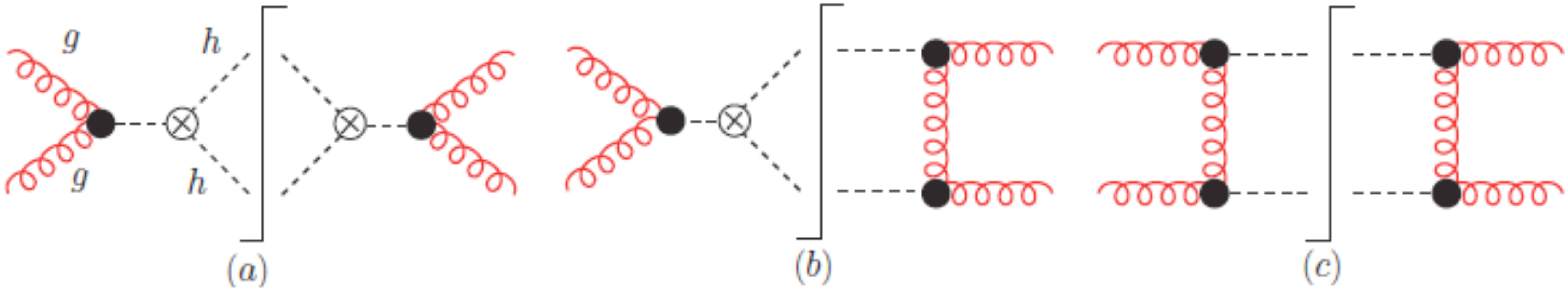

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MG5_aMC: $d\sigma^{b,\text{NNLO}}_{hh}\Big|_{p_T^{hh} > p_T^{\text{veto}}} = d\sigma^{b,\text{NLO}}_{hh+j}$

New and validated NLO model

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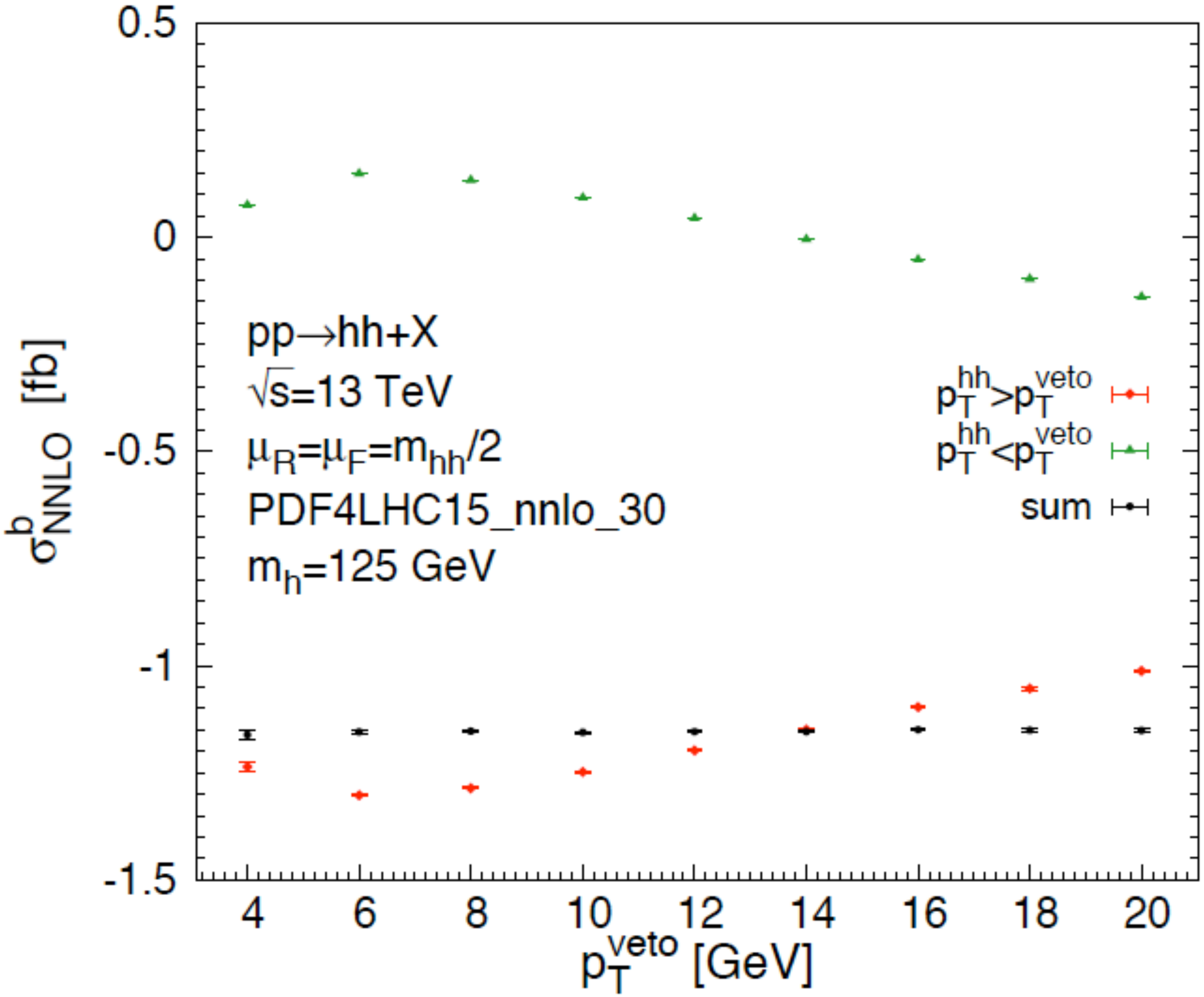

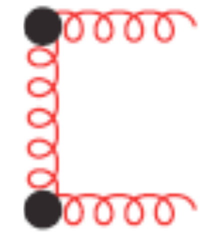

tot

a

b

c

ng (PLB'20, JHEP;20)

$d\sigma^b_{hh} + d\sigma^c_{hh}$

- class-

ni & Grazzini PRL'07)

d

l validated NLO

model

MG5_aMC: $d\sigma_{hh}|_{p_T^{hh}>p_T^{veto}} - d\sigma_{hh+j}$

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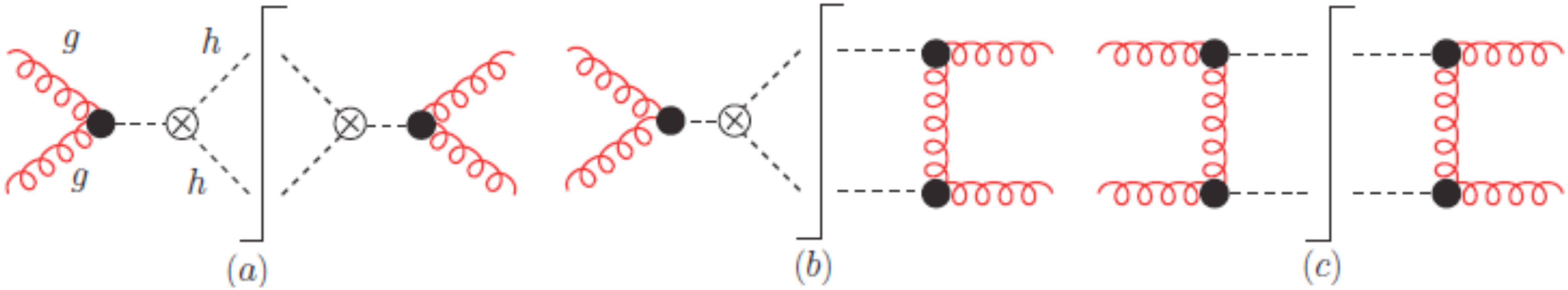

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- class-c: need NLO (full fledged)

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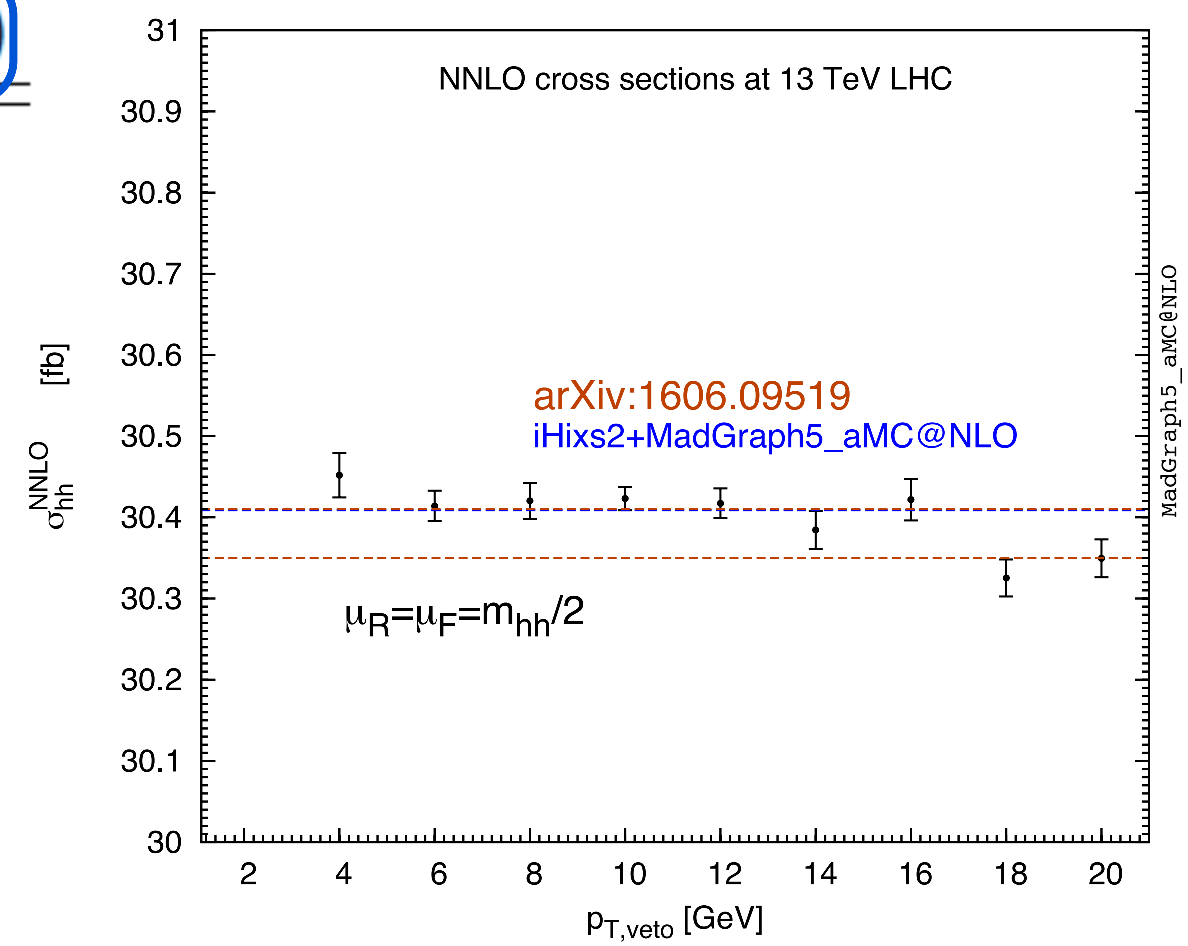
√ At least two independent calculations



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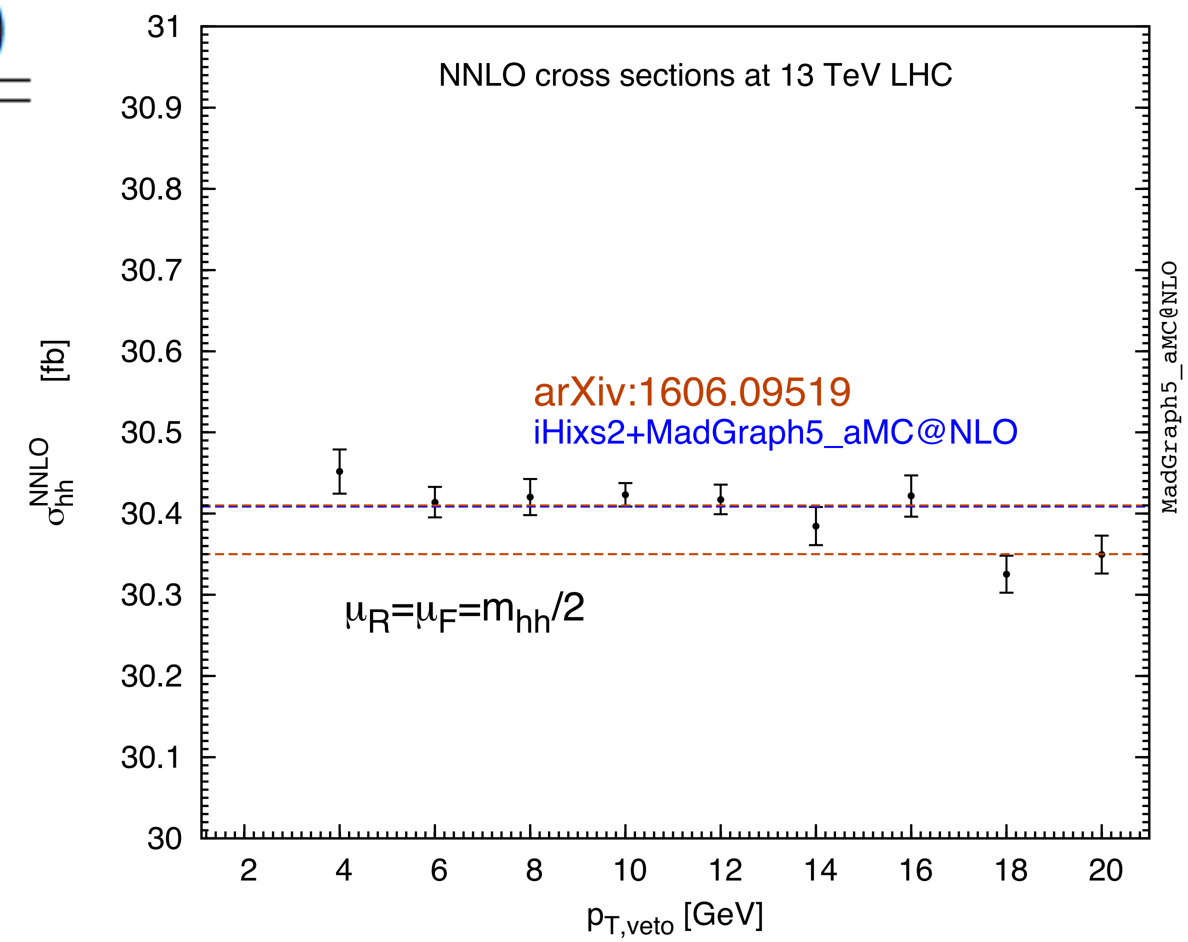

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$\surd$ Orthogonal check with NNLO ggHH

$\surd$ Check piece-by-piece

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c	0	0	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$

√ At least two independent calculations

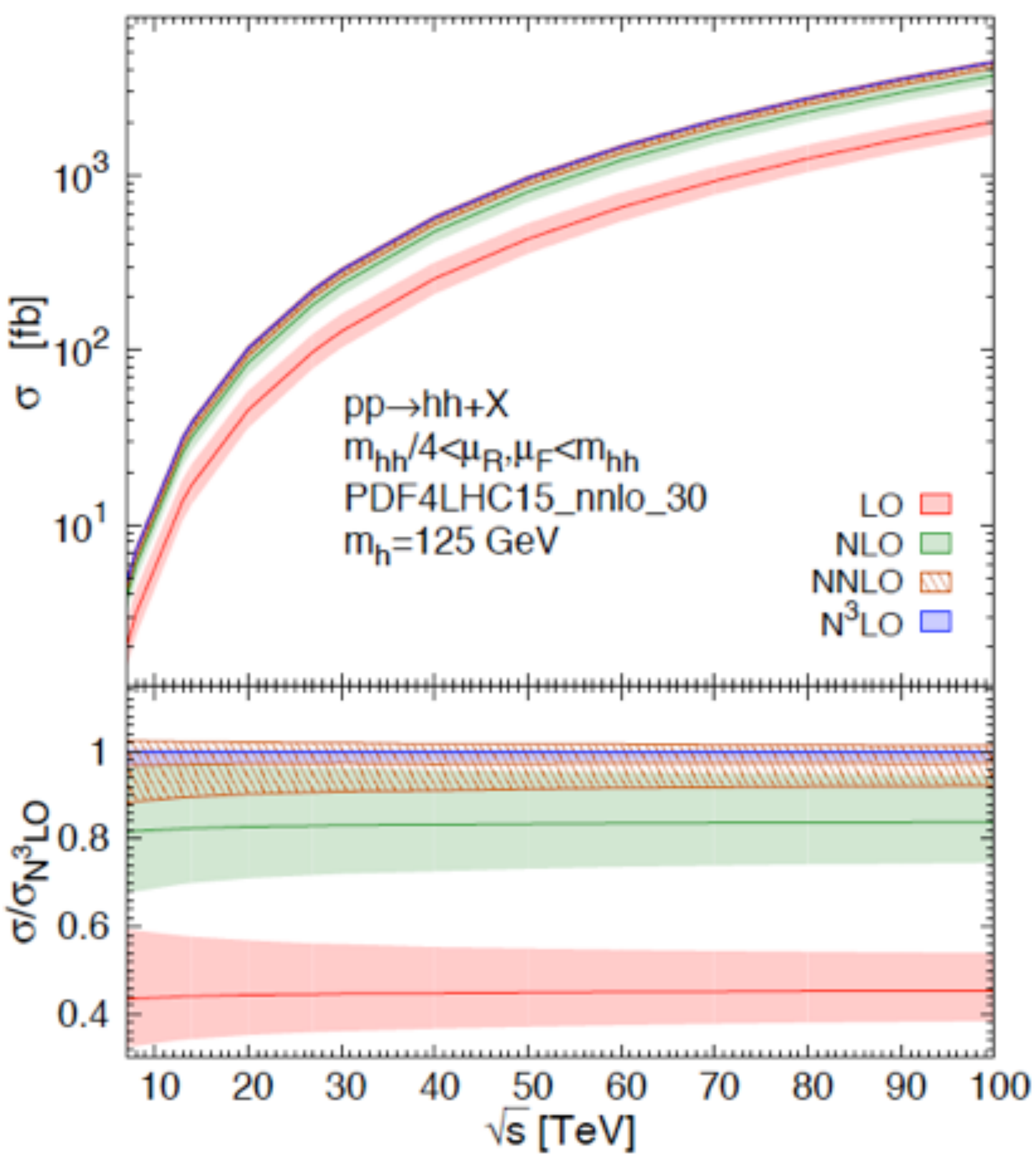
√ Orthogonal check with NNLO ggHH

√ Check piece-by-piece

	NLO	NNLO	N^{3}LO
order	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
a	iHixs2 q_T-subtraction MG5_aMC	iHixs2 q_T-subtraction	iHixs2
b	-	q_T-subtraction MG5_aMC	q_T-subtraction
c	-	-	q_T-subtraction MG5_aMC

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
  - N^3LO cross sections



in unit of fb

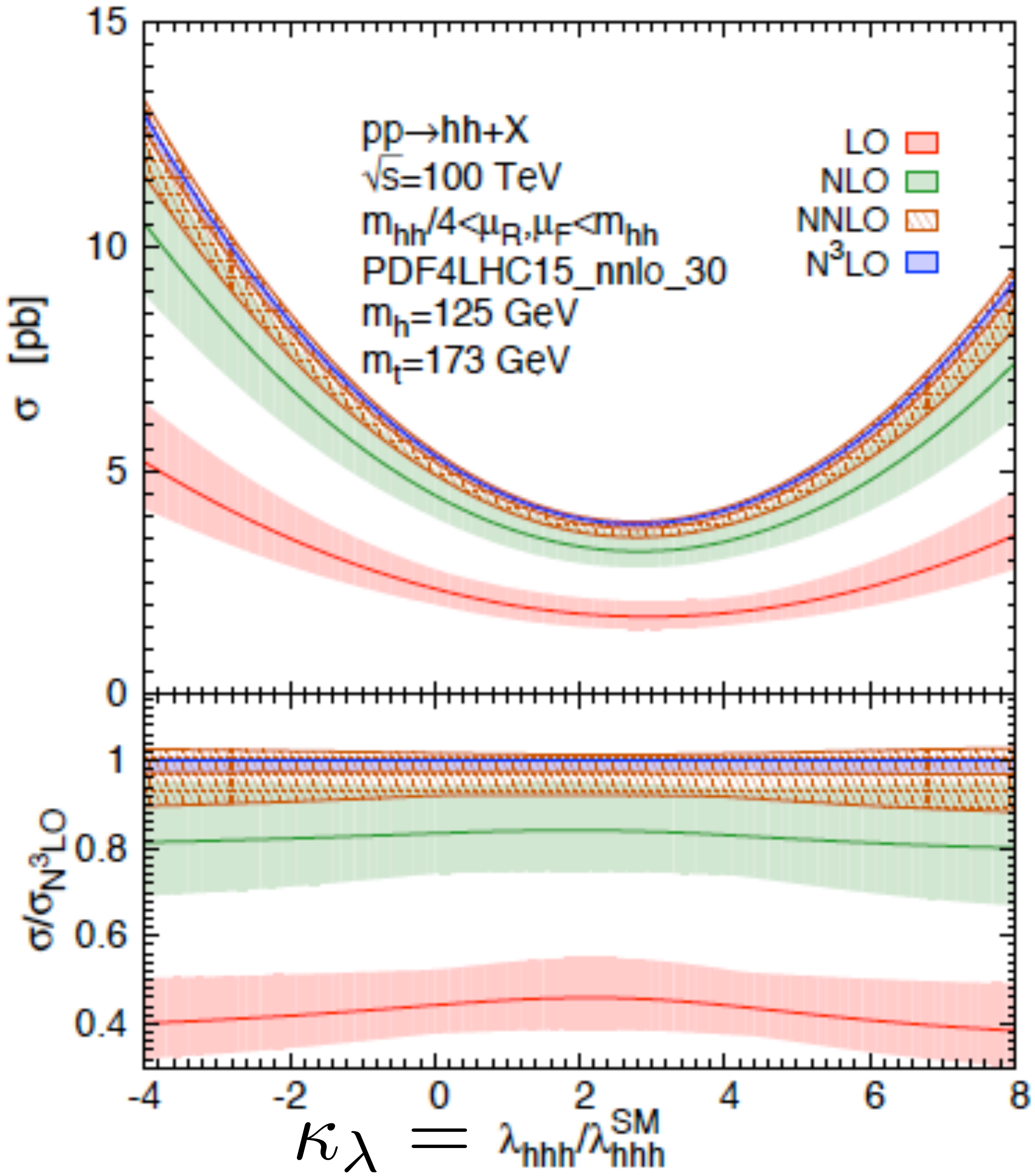
Chen, Li, HSS, Wang (PLB'20)

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	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4438^{+0.51\%}_{-1.8\%}$

- Scale unc. is significantly reduced !
- PDF unc. > scale unc. now !
- Good (asymptotic) perturbative convergence !

- **Infinite top-quark mass limit**
  - N^3LO cross sections

Chen, Li, HSS, Wang (JHEP'20)

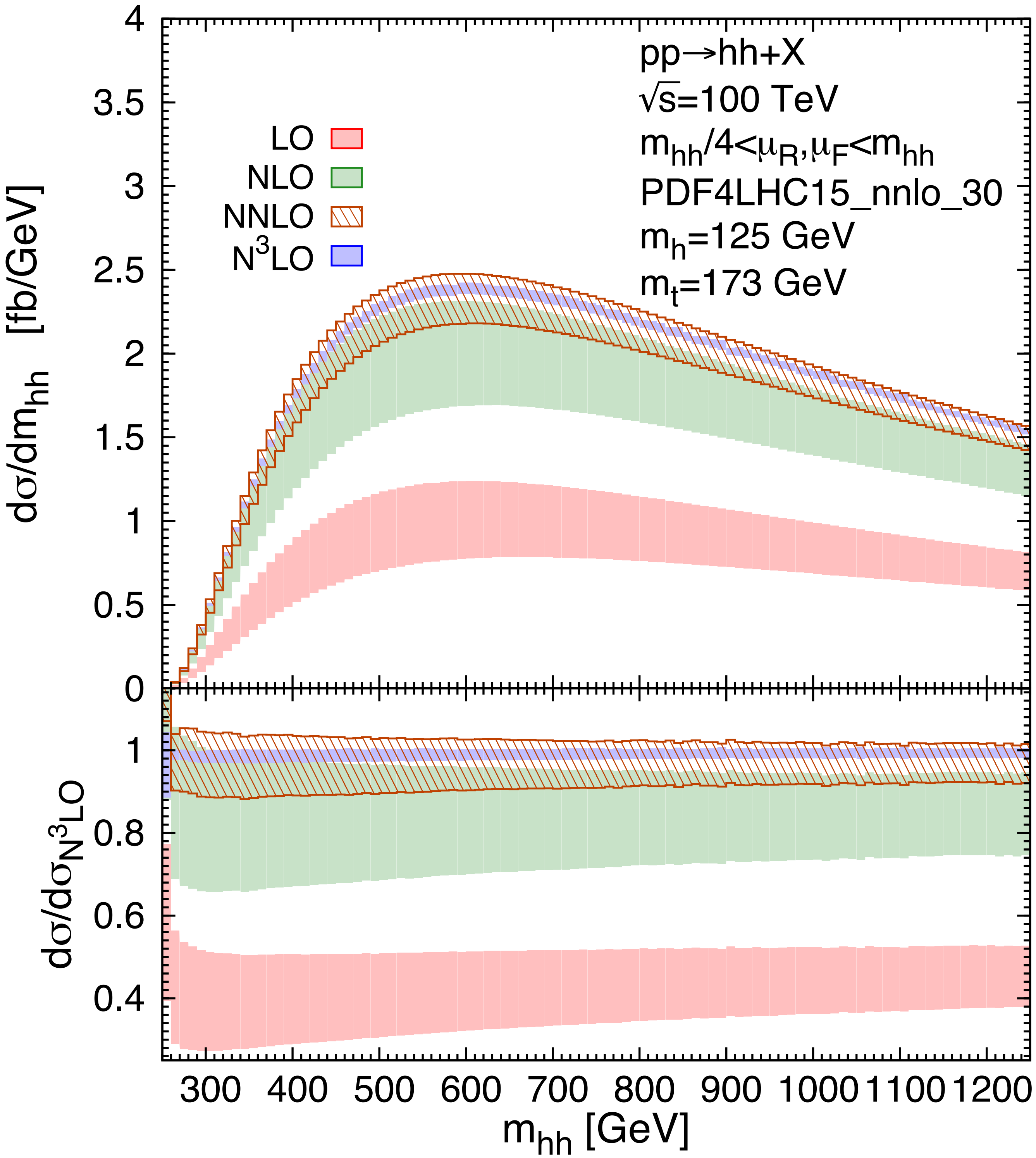


- Shapes change from LO to NLO and from NLO to NNLO
- The shape variation from NNLO to N^3LO is quite invisible

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
  - A N^3LO differential distribution

Chen, Li, HSS, Wang (JHEP'20)



- Scale unc. is significantly reduced !
- Very good (asymptotic) perturbative convergence !
- $N^3LO/NNLO$ is quite flat

TOP QUARK MASS APPROXIMATIONS

LPTHE
Laboratoire de Physique Théorique et Hautes Energies

Chen, Li, HSS, Wang (JHEP'20)

- **Several approximations:**

assuming we have $\begin{cases} \text{N}^k\text{LO} & \text{infinite top-quark mass limit} \\ \text{N}^l\text{LO} & \text{full top-quark mass dependence} \end{cases}$ $k > l$

- $\mathbf{N}^k\mathbf{LO}\oplus\mathbf{N}^l\mathbf{LO}_{m_t}$

$$d\sigma^{\mathrm{N^kLO\oplus N^lLO_{m_t}}} = d\sigma^{\mathrm{N^lLO}}_{m_t} + \left(d\sigma^{\mathrm{N^kLO}}_{m_t=\infty} - d\sigma^{\mathrm{N^lLO}}_{m_t=\infty}\right)$$

missing top mass in correction

The best !

- $\mathbf{N}^k\mathbf{LO}\otimes\mathbf{N}^l\mathbf{LO}_{m_t}$

$$d\sigma^{\mathrm{N^kLO\otimes N^lLO_{m_t}}} = d\sigma^{\mathrm{N^lLO}}_{m_t}\frac{d\sigma^{\mathrm{N^kLO}}_{m_t=\infty}}{d\sigma^{\mathrm{N^lLO}}_{m_t=\infty}}$$

Same K factor for mass correction

- $\mathbf{N}^k\mathbf{LO}_{\mathrm{B-i}}\oplus\mathbf{N}^l\mathbf{LO}_{m_t}$

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

Born mass improved for correction

TOP QUARK MASS RESULTS

LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

- **Top-quark mass dependent results** NLO_{mt} from Powheg, arXiv:1903.08137
  - N^3LO cross sections Chen, Li, HSS, Wang (JHEP'20)

in unit of fb

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO_{m_t}	$27.56^{+14\%}_{-13\%}$	$32.64^{+14\%}_{-12\%}$	$126.2^{+12\%}_{-10\%}$	$1119^{+13\%}_{-13\%}$
$\mathrm{NNLO}\oplus\mathrm{NLO}_{m_t}$	$32.16^{+5.9\%}_{-5.9\%}$	$38.29^{+5.6\%}_{-5.5\%}$	$157.3^{+3.0\%}_{-4.7\%}$	$1717^{+5.8\%}_{-12\%}$
$\mathrm{NNLO}_{\mathrm{B-i}}\oplus\mathrm{NLO}_{m_t}$	$33.08^{+5.0\%}_{-4.9\%}$	$39.16^{+4.9\%}_{-5.0\%}$	$150.8^{+4.6\%}_{-5.7\%}$	$1330^{+4.0\%}_{-7.2\%}$
$\mathrm{NNLO}\otimes\mathrm{NLO}_{m_t}$	$32.47^{+5.3\%}_{-7.8\%}$	$38.42^{+5.2\%}_{-7.6\%}$	$147.6^{+4.8\%}_{-6.7\%}$	$1298^{+4.2\%}_{-5.3\%}$
$\mathrm{N^3LO}\oplus\mathrm{NLO}_{m_t}$	$33.06^{+2.1\%}_{-2.9\%}$	$39.40^{+1.7\%}_{-2.8\%}$	$163.3^{+4.0\%}_{-8.3\%}$	$1833^{+14\%}_{-20\%}$
$\mathrm{N^3LO}_{\mathrm{B-i}}\oplus\mathrm{NLO}_{m_t}$	$34.17^{+1.9\%}_{-4.6\%}$	$40.44^{+1.9\%}_{-4.7\%}$	$155.5^{+2.3\%}_{-5.0\%}$	$1372^{+2.8\%}_{-5.0\%}$
$\mathrm{N^3LO}\otimes\mathrm{NLO}_{m_t}$	$33.43^{+0.66\%}_{-2.8\%}$	$39.56^{+0.64\%}_{-2.7\%}$	$151.7^{+0.53\%}_{-2.4\%}$	$1333^{+0.51\%}_{-1.8\%}$

- N^3LO enhances NNLO by 3% but enhances NLO by 20%
- N^3LO reduces scale unc. to 3%
- The missing top quark mass uncer. at N^3LO is around 5%
- The top mass scheme uncer. is unknown (not expected to be improved)

TOP QUARK MASS RESULTS

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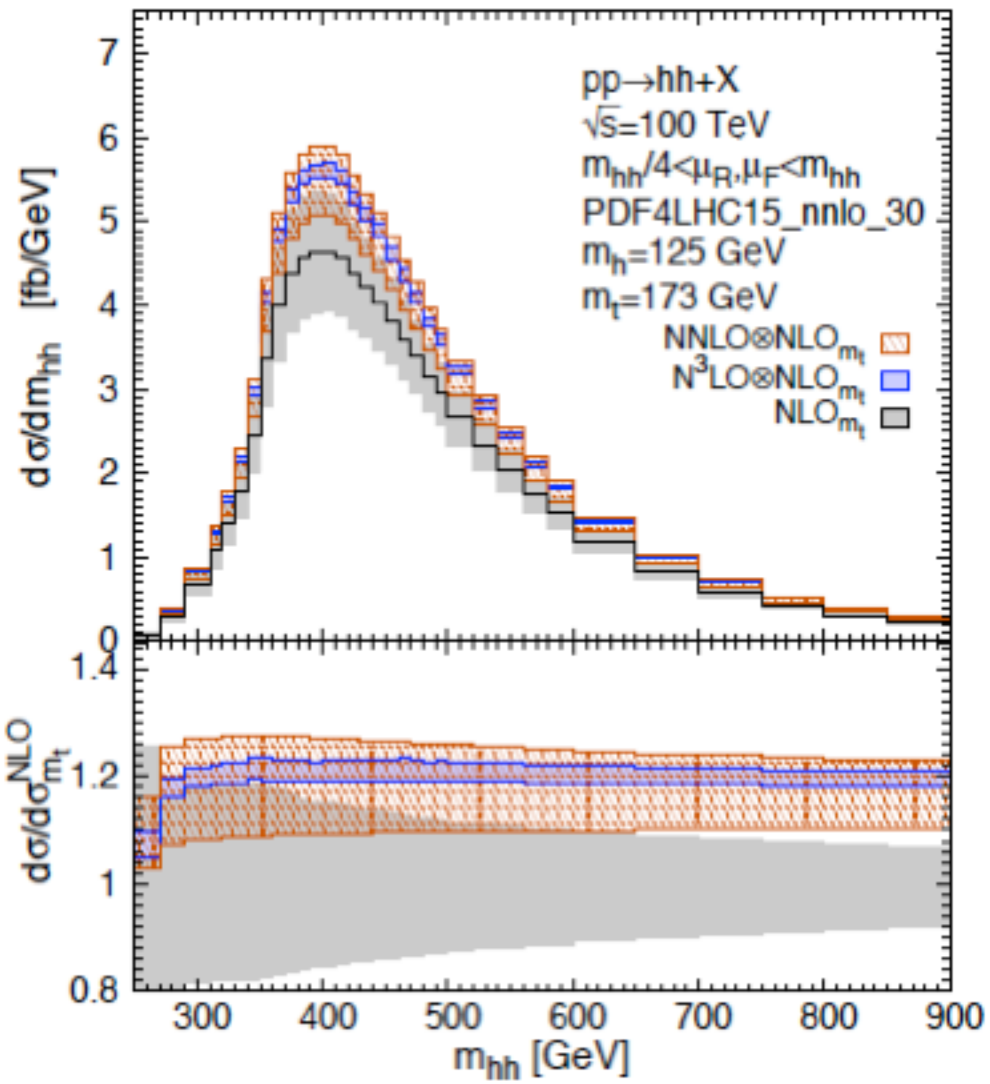
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

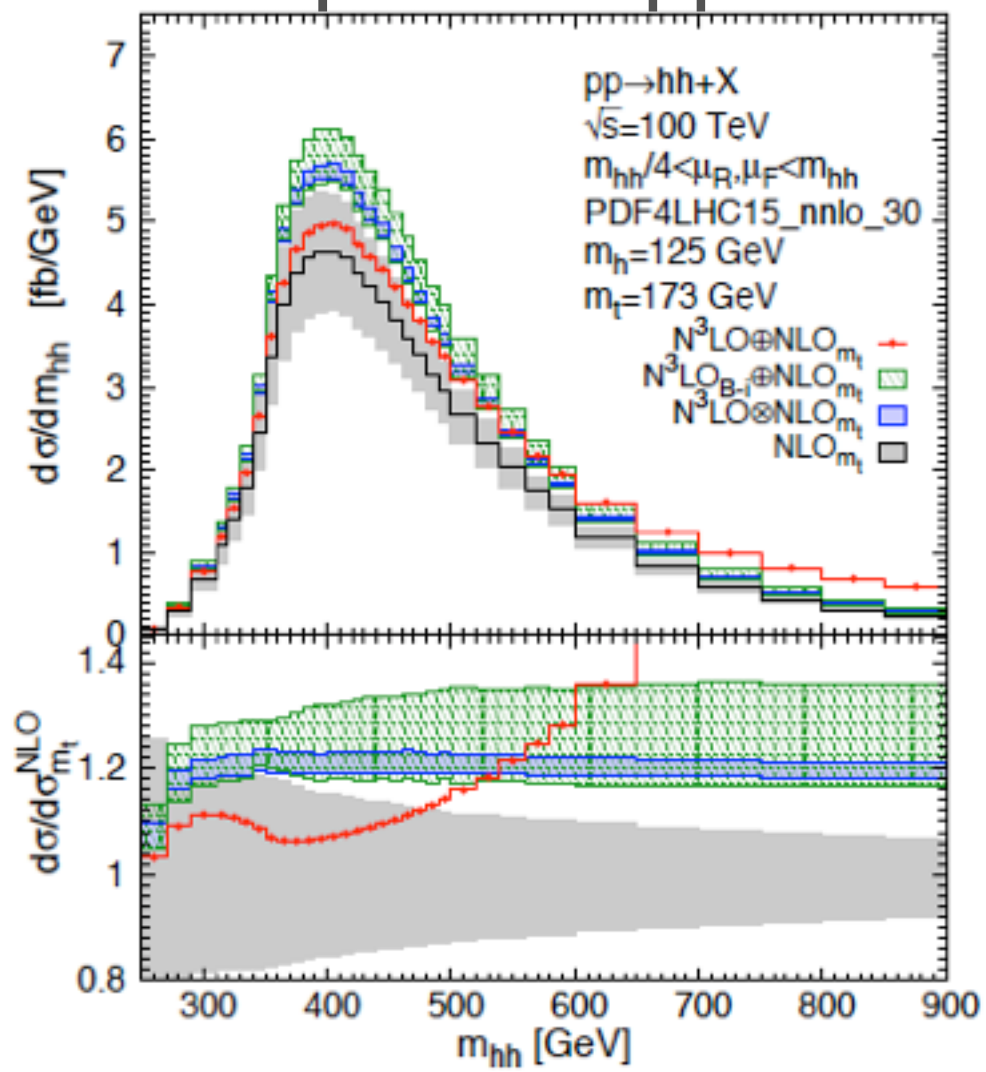
- **Top-quark mass dependent results** NLO_{mt} from Powheg, arXiv:1903.08137
  - N^3LO distributions

Chen, Li, HSS, Wang (JHEP'20)

NNLO vs N^3LO



3 top mass approx.



- Scale is again significantly reduced from NNLO to N^3LO
- Missing top-quark mass effect at large m_{hh} is very bad (red)

CONCLUSIONS

- We have carried out N^3LO calculations for Higgs pair production in the gluon fusion channel with the infinite top-quark mass limit.
- The scale uncertainty is significantly reduced to be below 2% at 100 TeV. PDF param. uncertainty is bigger than scale uncertainty.
- The asymptotic perturbative convergence in the process shows pretty good at N^3LO.

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  - How to further improve the finite top quark mass corrections ?
  - Other theoretical uncertainties (e.g. EW corr., parameterical errors) ?

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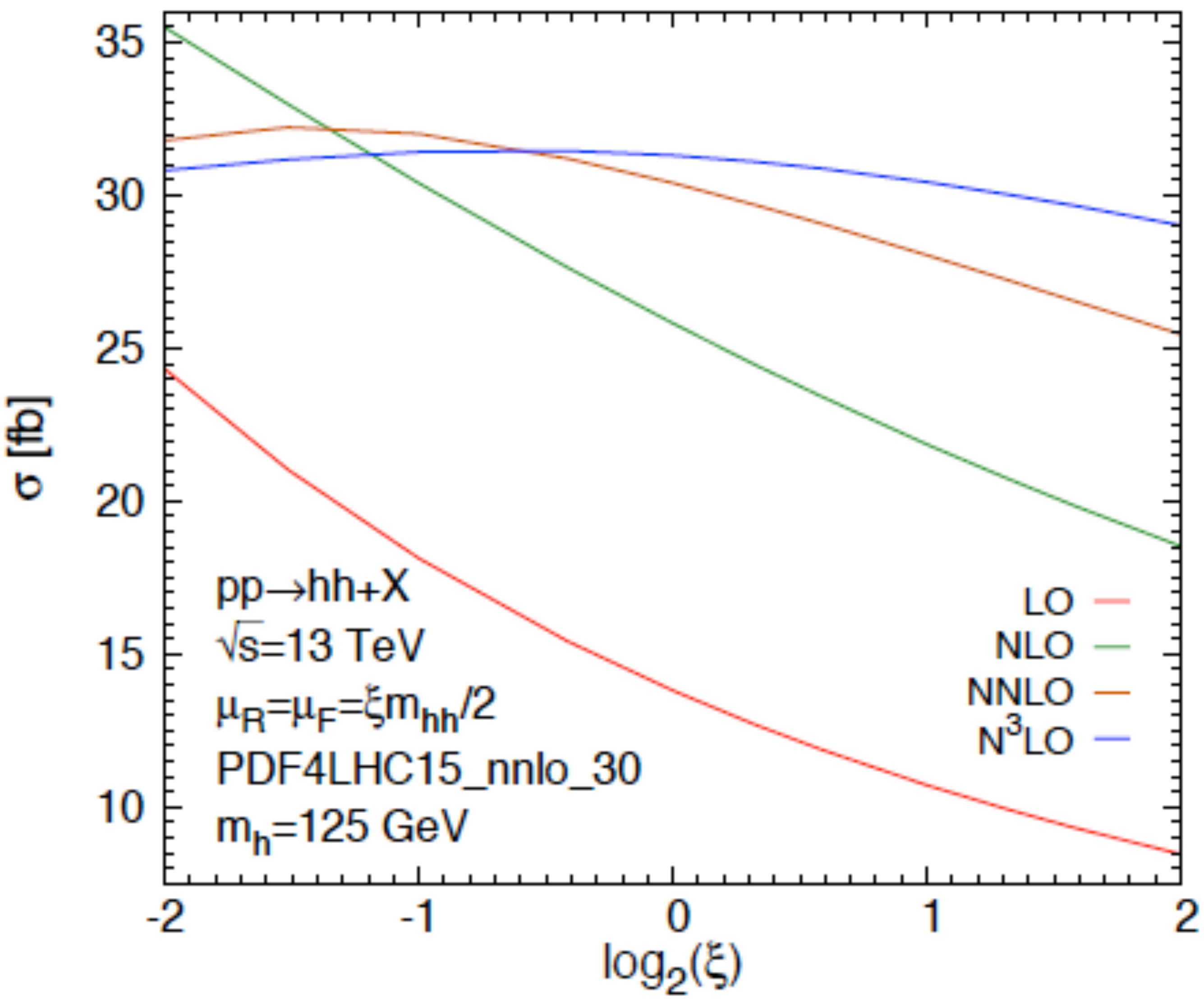
Thank you for your attention !

Backup

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
  - Assessment of central scale choice

Chen, Li, HSS, Wang (PLB'20)

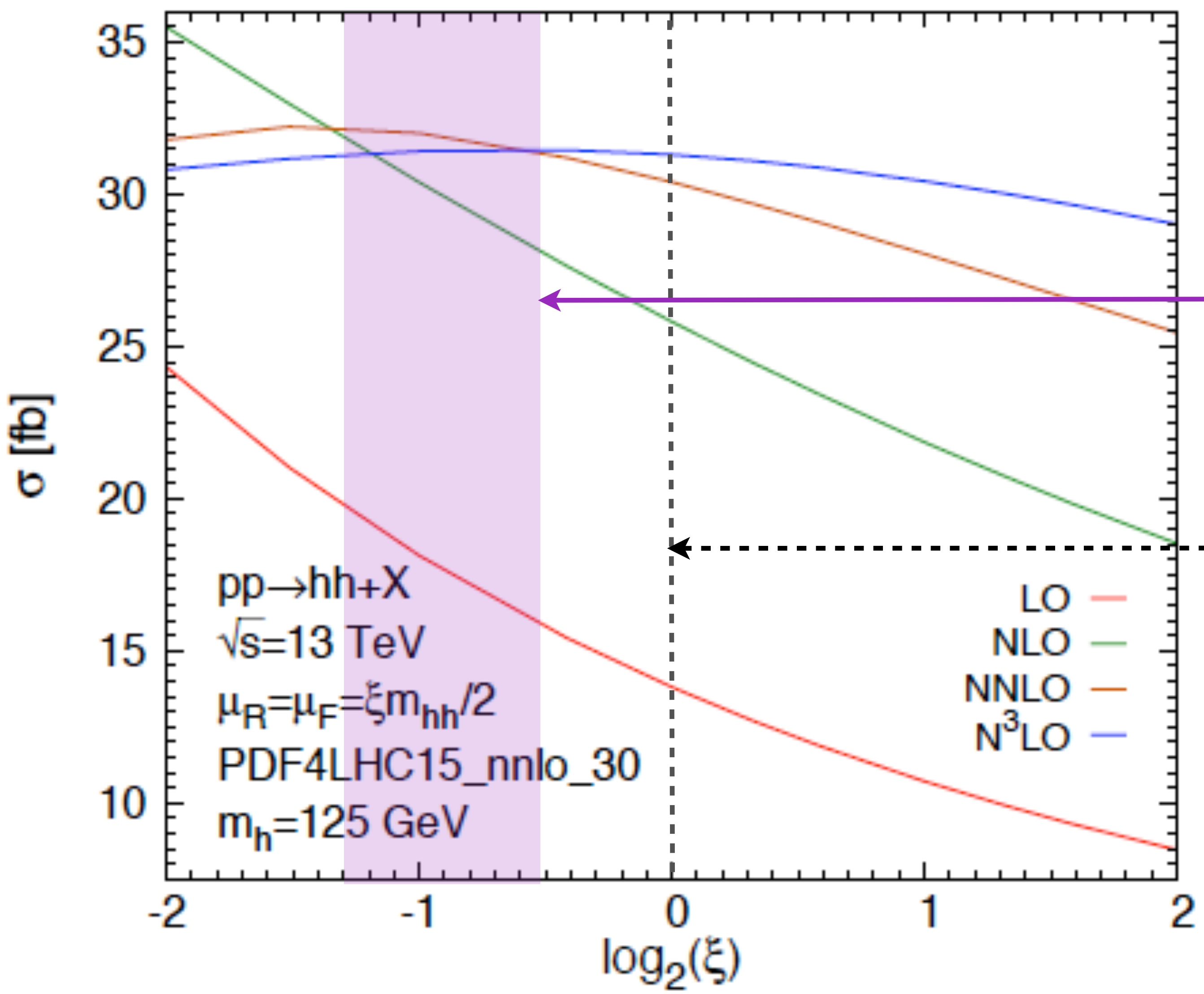


$$\mu_R = \mu_F = \xi \frac{m_{hh}}{2}$$

Tuesday, January 19, 21

- **Infinite top-quark mass limit**
  - Assessment of central scale choice

Chen, Li, HSS, Wang (PLB'20)



Faster convergent scale

Widespread scale choice

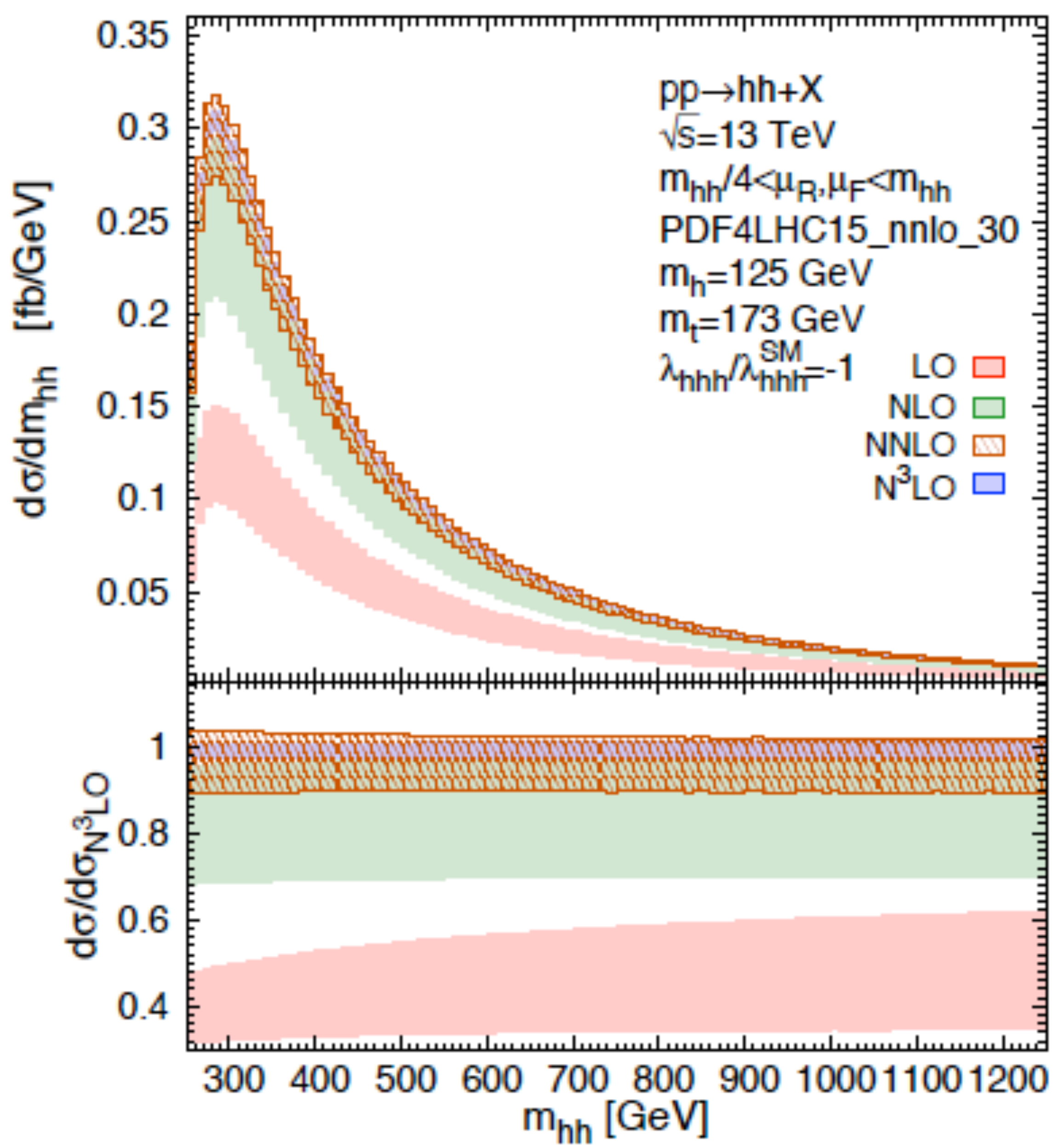
$$\mu_R = \mu_F = \xi \frac{m_{hh}}{2}$$

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
  - A N^3LO differential distribution

Chen, Li, HSS, Wang (JHEP'20)

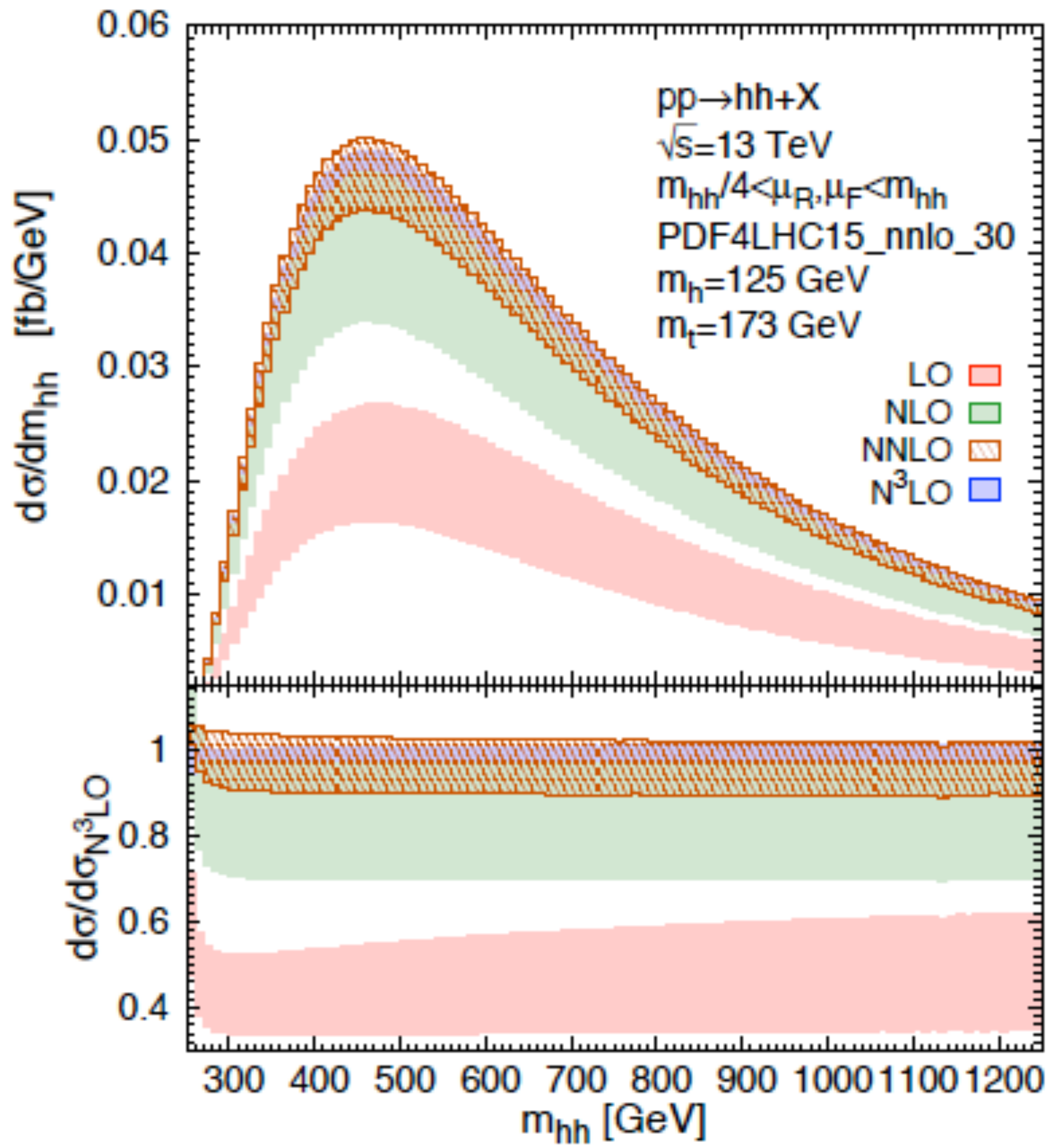
$$\kappa_\lambda = -1$$



- **Infinite top-quark mass limit**
  - A N^{3}LO differential distribution

Chen, Li, HSS, Wang (JHEP'20)

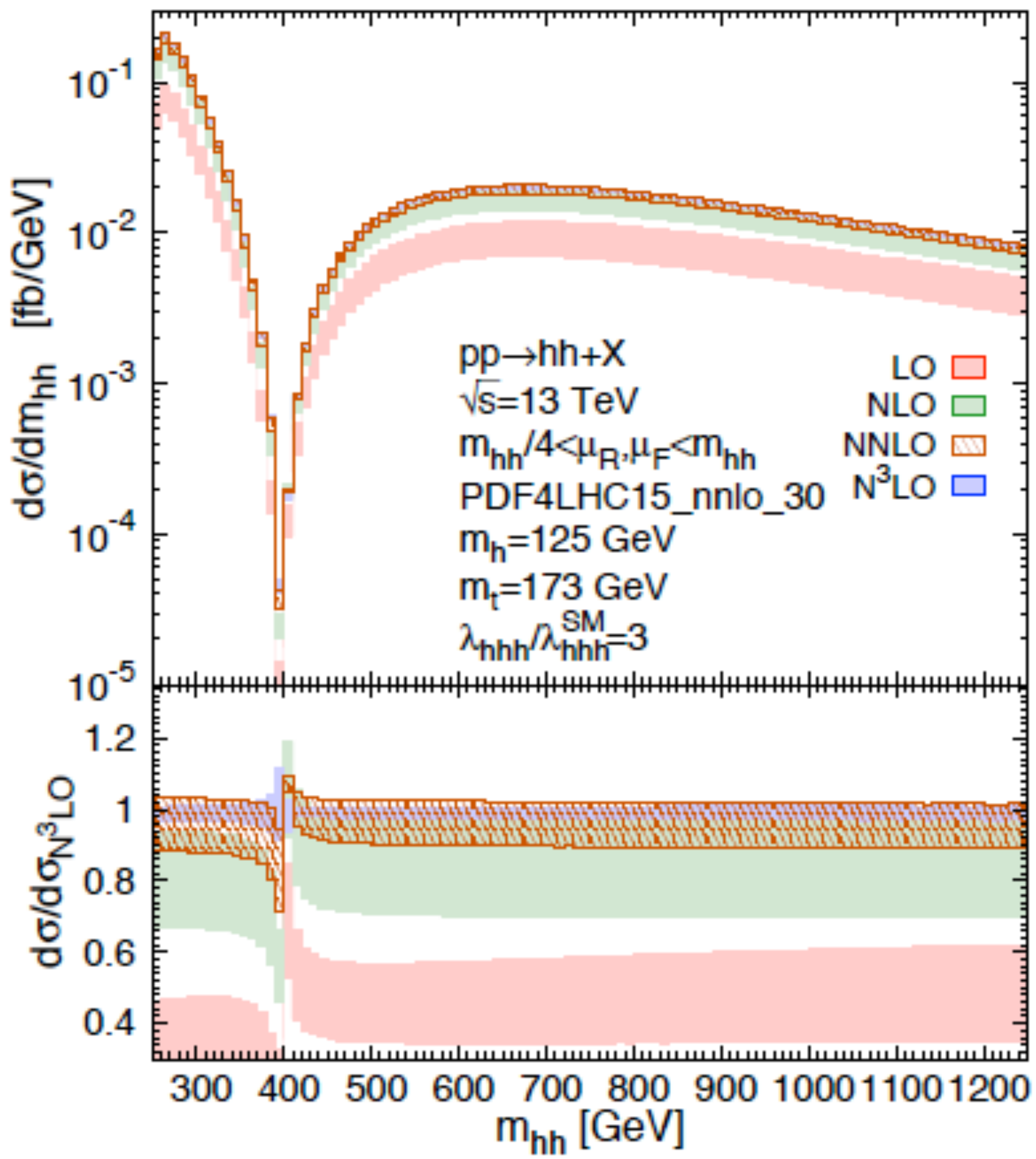
$$\kappa_\lambda = 1$$



- **Infinite top-quark mass limit**
  - A N[3]LO differential distribution

Chen, Li, HSS, Wang (JHEP'20)

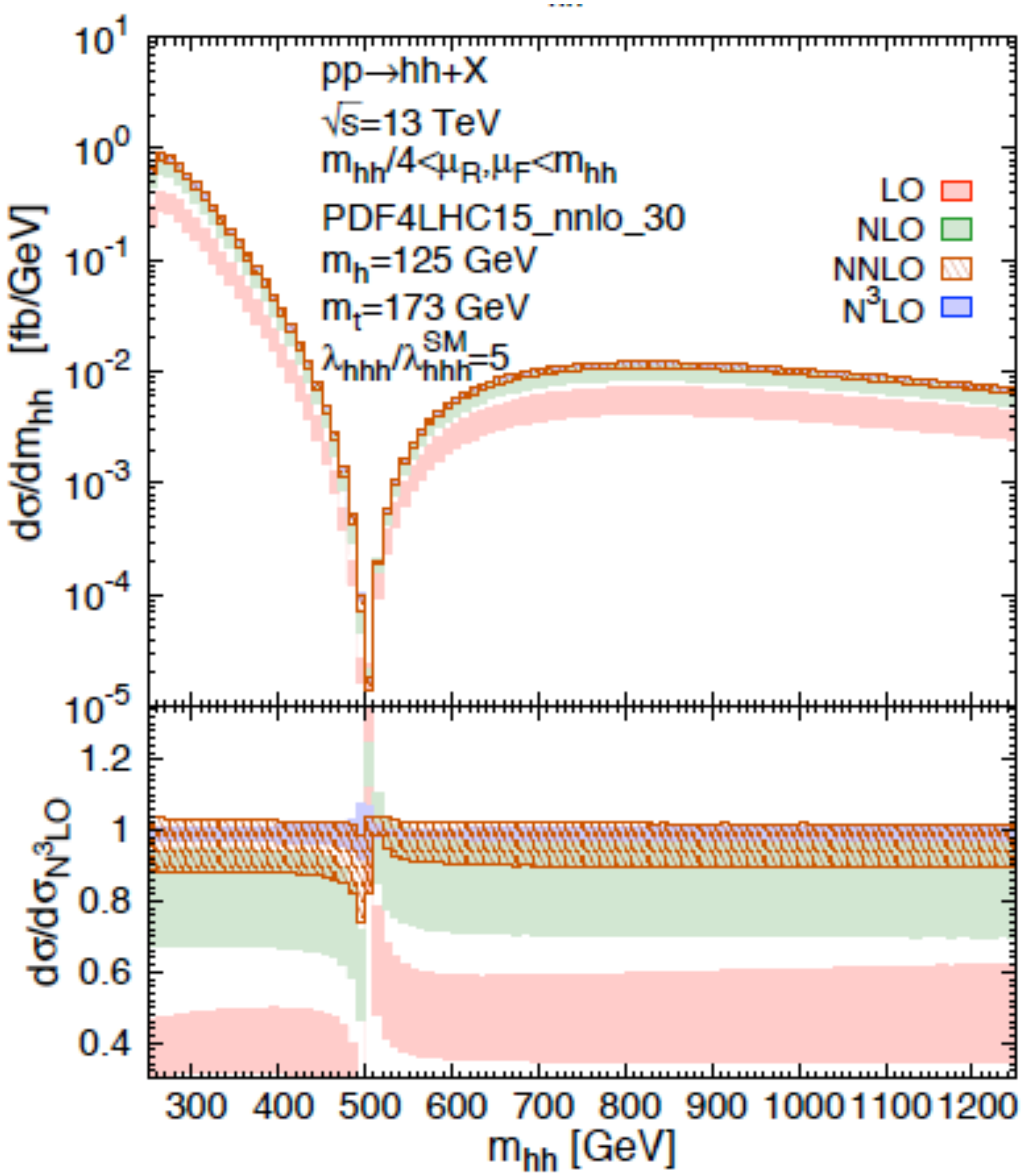
$$\kappa_\lambda = 3$$



- **Infinite top-quark mass limit**
  - A N^3LO differential distribution

Chen, Li, HSS, Wang (JHEP'20)

$$\kappa_\lambda = 5$$



HIGGS PAIR GLUON FUSION PRODUCTION

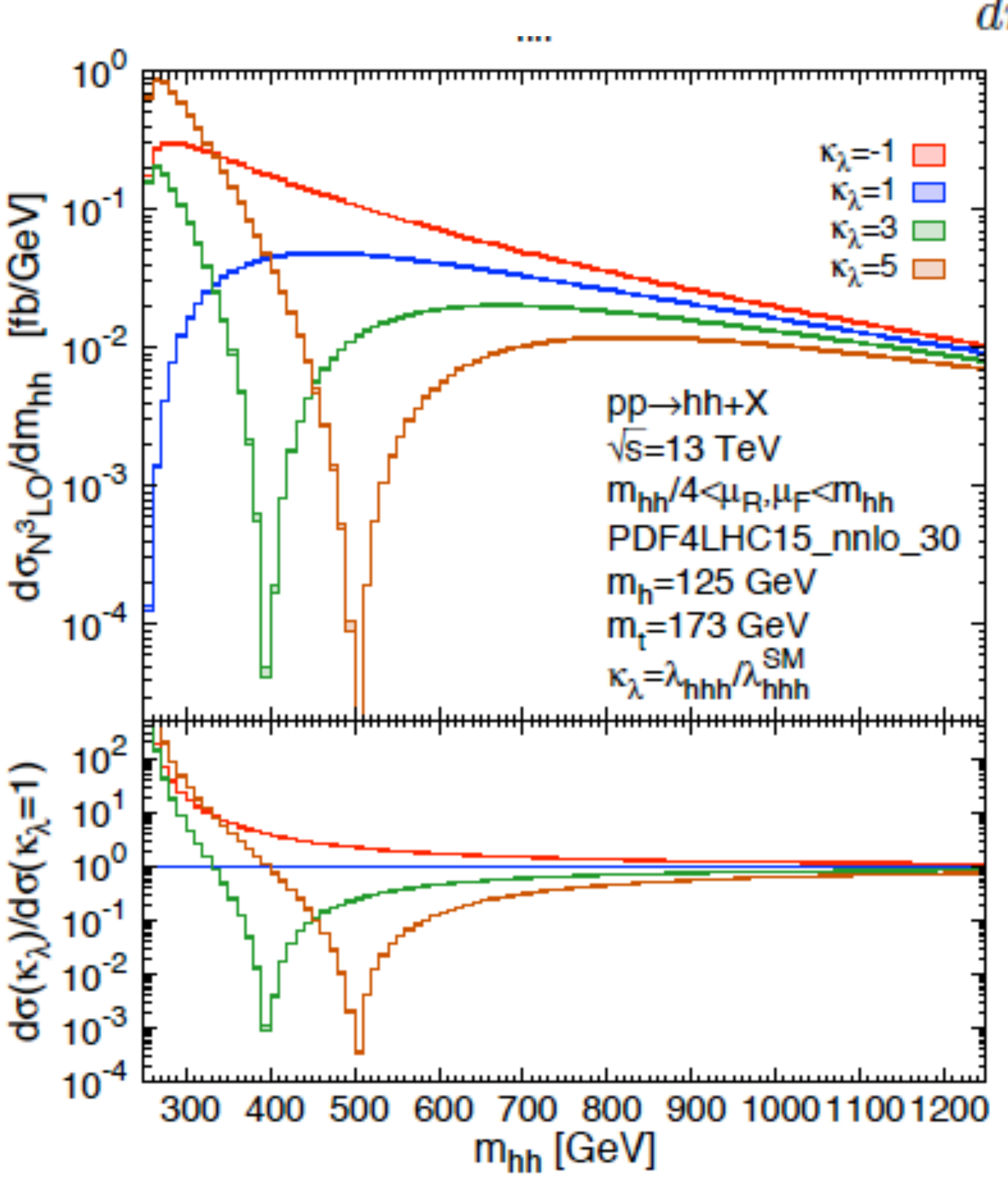
- **Infinite top-quark mass limit**
  - A N³LO differential distribution

Chen, Li, HSS, Wang (JHEP'20)

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

$$f_{h\to hh} \propto \sqrt{m^2_{hh}-4m^2_h} \qquad m_{hh} > 2m_h$$

$$\left(\frac{C_{hh}}{C_h} - \frac{6\lambda_{hhh}v^2}{m^2_{hh}-m^2_h}\right)^2 \simeq \left(1-\kappa_\lambda\frac{3m^2_h}{m^2_{hh}-m^2_h}\right)^2$$



$\kappa_\lambda < 0$ ↘ w m_{hh} ↑

$0 < \kappa_\lambda \le 1$ ↗ w m_{hh} ↑

$\kappa_\lambda > 1$ zero when $m_{hh} = \sqrt{1+3\kappa_\lambda}\, m_h$

- Potential useful in BSM searches

HIGGS PAIR GLUON FUSION PRODUCTION

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- **Infinite top-quark mass limit**
  - Other approximated $\mathrm{N^3LO}$ differential distributions

$$\frac{d\sigma_{hh}^{\mathrm{AN^3LO}}}{dO} = \frac{d\sigma_{hh}^{\mathrm{(a,1),NNLO}}}{dO}\frac{\sigma_{hh}^{\mathrm{(a,1),N^3LO}}}{\sigma_{hh}^{\mathrm{(a,1),NNLO}}} + \frac{d\sigma_{hh}^{\mathrm{(a,2),N^3LO}}}{dO} + \frac{d\sigma_{hh}^{\mathrm{b,NNLO}}}{dO} + \frac{d\sigma_{hh}^{\mathrm{c,NLO}}}{dO}$$

Lacking knowledge of fully-differential $\mathrm{N^3LO}$ ggH

$$\frac{d\sigma_{hh}^{(a,1),\mathrm{N^3LO}}}{dO} \stackrel{?}{\approx} \frac{d\sigma_{hh}^{(a,1),\mathrm{NNLO}}}{dO}\frac{\sigma_{hh}^{(a,1),\mathrm{N^3LO}}}{\sigma_{hh}^{(a,1),\mathrm{NNLO}}}$$

$$d\sigma_{hh}^{a} = d\sigma_{hh}^{(a,1)} + d\sigma_{hh}^{(a,2)},$$

$$d\sigma_{hh}^{(a,1)} \equiv d\sigma_{hh}^{a}\Big|_{C_{hh}\to C_h},$$

$$d\sigma_{hh}^{(a,2)} \equiv d\sigma_{hh}^{a} - d\sigma_{hh}^{(a,1)},$$

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
  - Other approximated N^{3}LO differential distributions

$$\frac{d\sigma_{hh}^{\mathrm{AN^3LO}}}{dO} = \frac{d\sigma_{hh}^{(a,1),\mathrm{NNLO}}}{dO}\frac{\sigma_{hh}^{(a,1),\mathrm{N^3LO}}}{\sigma_{hh}^{(a,1),\mathrm{NNLO}}} + \ldots$$

Lacking knowledge of fully-differential N^3...

$$\frac{d\sigma_{hh}^{(a,1),\mathrm{N^3LO}}}{dO} \overset{?}{\approx} \frac{d\sigma_{hh}^{(a,1),\mathrm{N}\ldots}}{dO}$$

$$d\sigma_{hh}^{a} = d\sigma_{hh}^{(a,1)} + d\sigma_{hh}^{(a,2)},$$
$$d\sigma_{hh}^{(a,1)} \equiv d\sigma_{hh}^{a}\Big|_{C_{hh}\to C_h},$$
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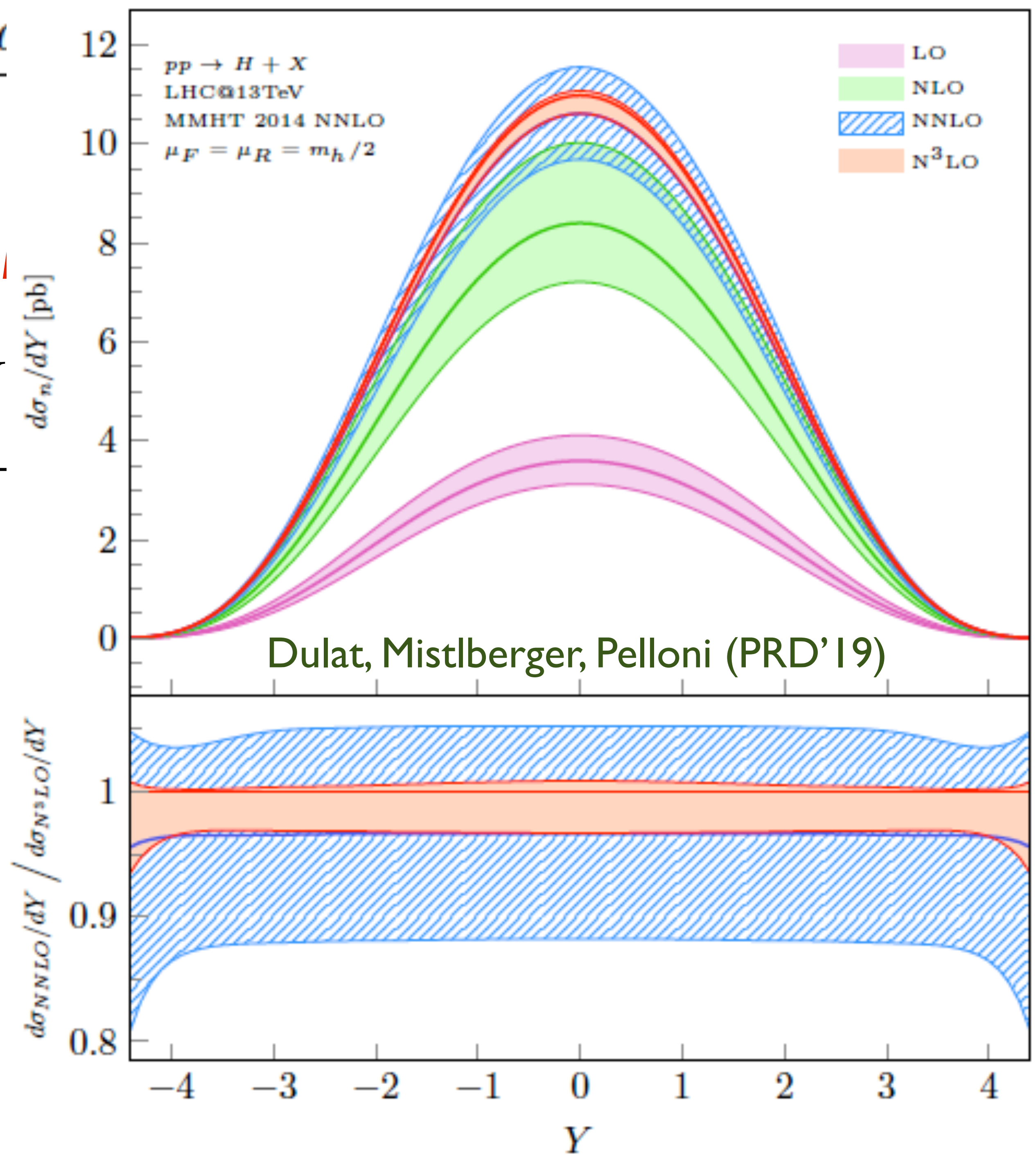

Dulat, Mistlberger, Pelloni (PRD'19)

HIGGS PAIR GLUON FUSION PRODUCTION

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$$\frac{d\sigma_{hh}^{\mathrm{AN^3LO}}}{dO} = \frac{d\sigma_{hh}^{\mathrm{(a,1),NNLO}}}{dO}\frac{\sigma_{hh}^{\mathrm{(a,1),N^3LO}}}{\sigma_{hh}^{\mathrm{(a,1),NNLO}}} + \frac{d\sigma_{hh}^{\mathrm{(a,2),N^3LO}}}{dO} + \frac{d\sigma_{hh}^{\mathrm{b,NNLO}}}{dO} + \frac{d\sigma_{hh}^{\mathrm{c,NLO}}}{dO}$$

Non-trivial scale cancellation emerges
... due to operator mixing Zoller (JHEP'16)

$$d\sigma_{hh}^{a} = d\sigma_{hh}^{(a,1)} + d\sigma_{hh}^{(a,2)},$$

$$d\sigma_{hh}^{(a,1)} \equiv d\sigma_{hh}^{a}\Big|_{C_{hh}\to C_h},$$

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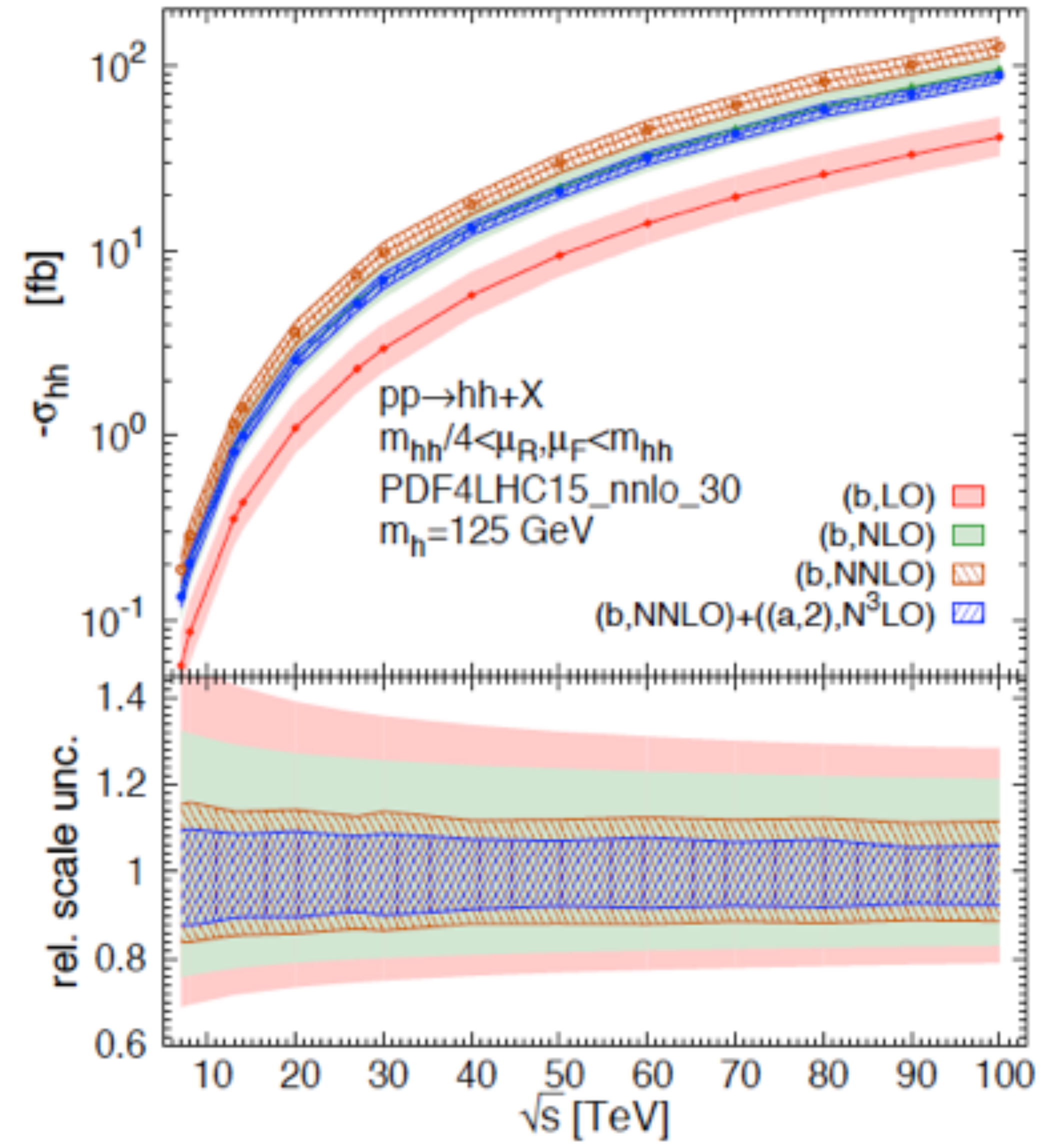
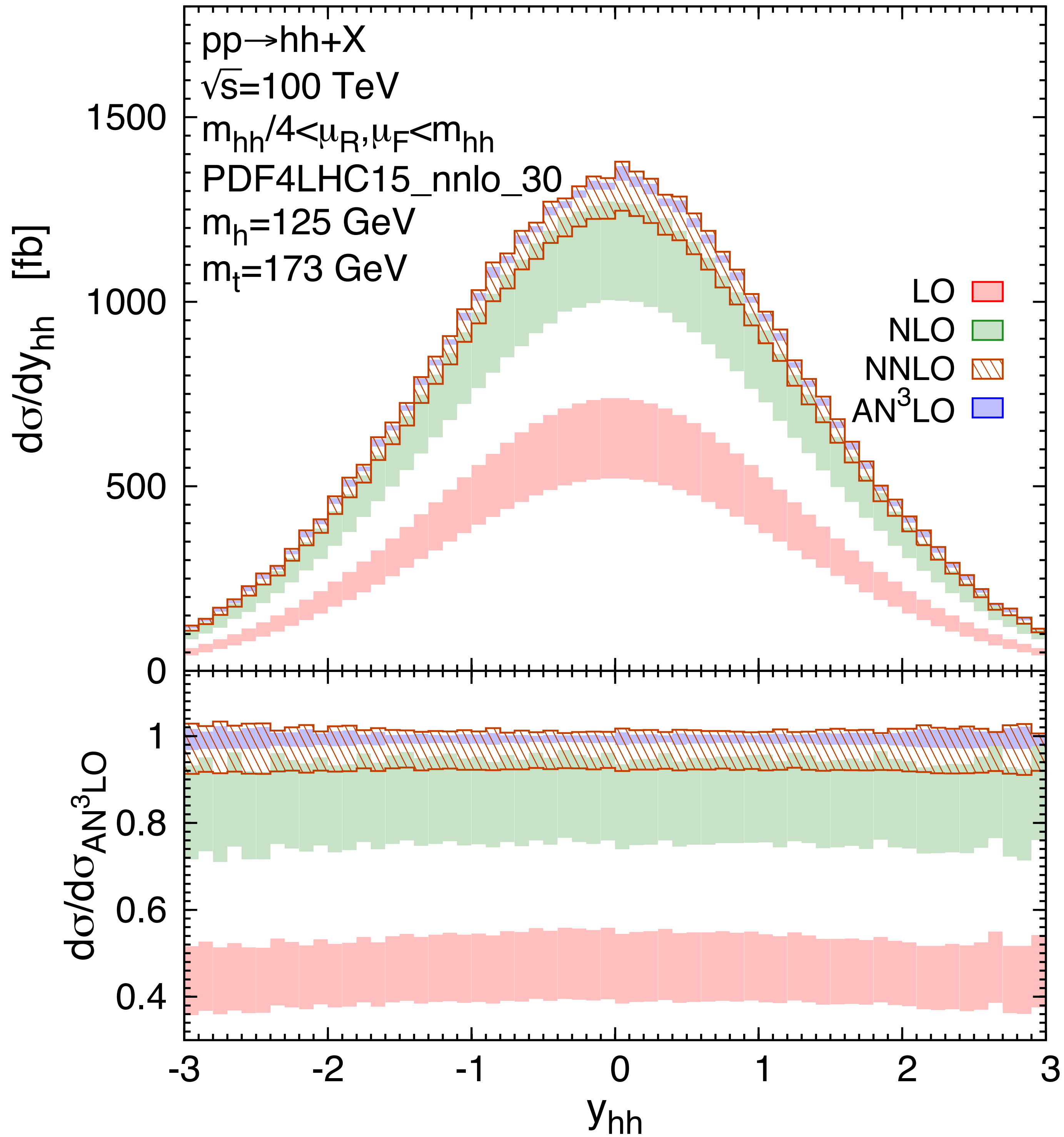
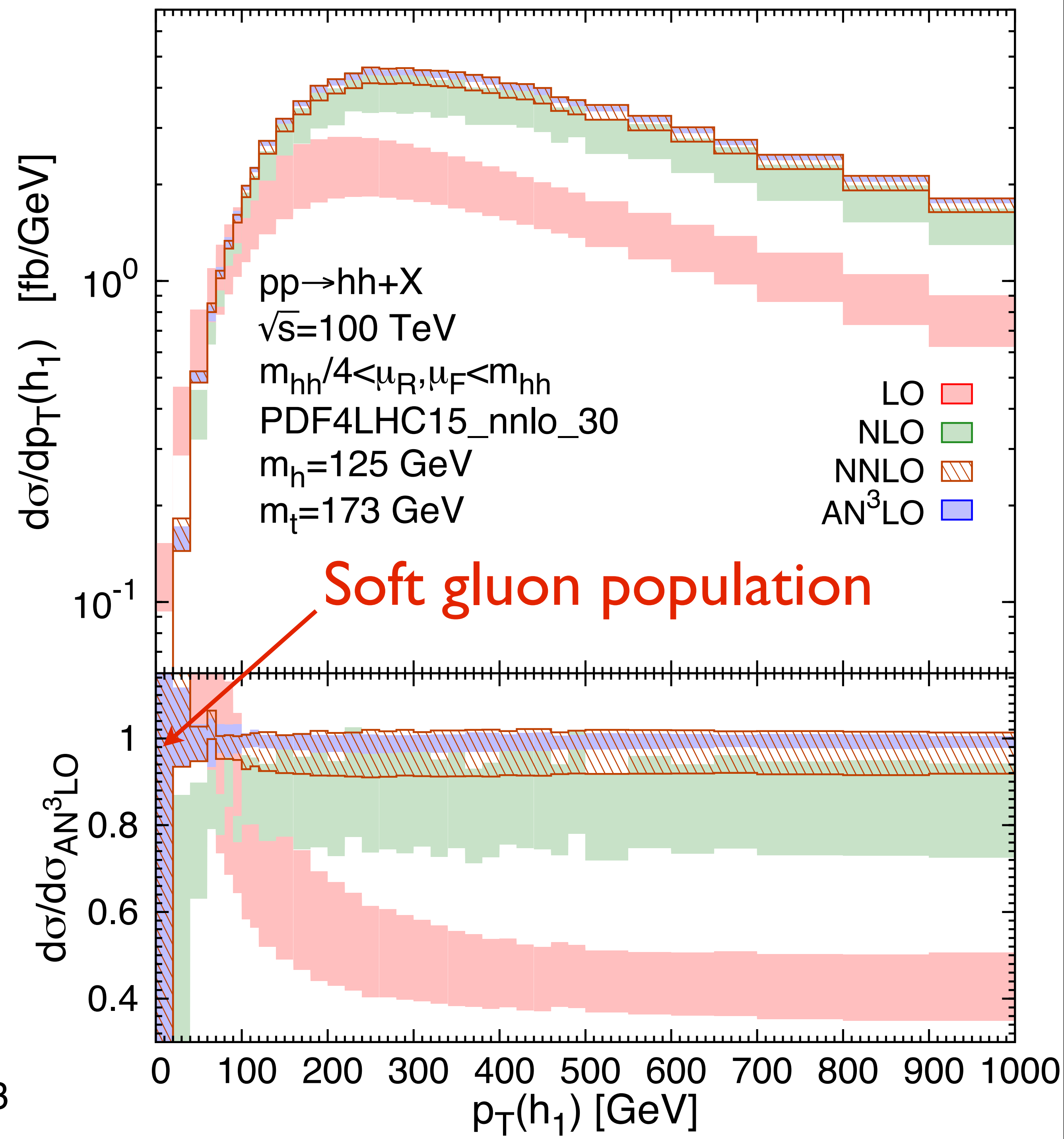


Tuesday, January 19, 21

- **Infinite top-quark mass limit**
  - Two showcases

Chen, Li, HSS, Wang (JHEP'20)





- **Top-quark mass dependent results** NLO_{mt} from Powheg, arXiv:1903.08137
  - AN^3LO distributions: two showcases Chen, Li, HSS, Wang (JHEP'20)