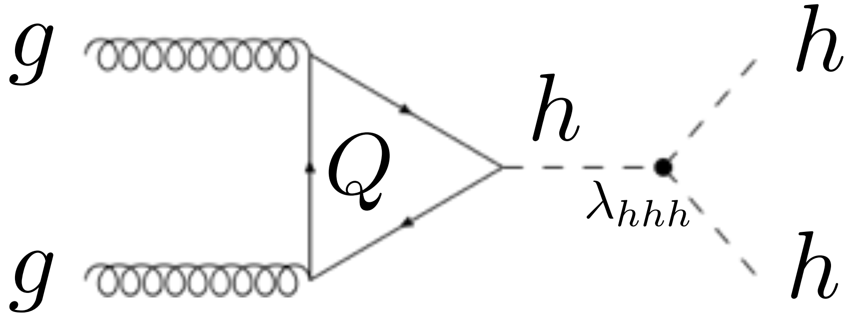
28 July 2020 to 6 August 2020
virtual conference

HIGGS BOSON PAIR PRODUCTION AT N^{3}LO QCD



HUA-SHENG SHAO

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

cnrs dépasser les frontières

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

ICHEP 2020, ONLINE (PRAGUE)
31 JULY 2020

HIGGS SELF COUPLINGS

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  - Unique way to understand the Higgs potential

⟹ *EW symmetry breaking*

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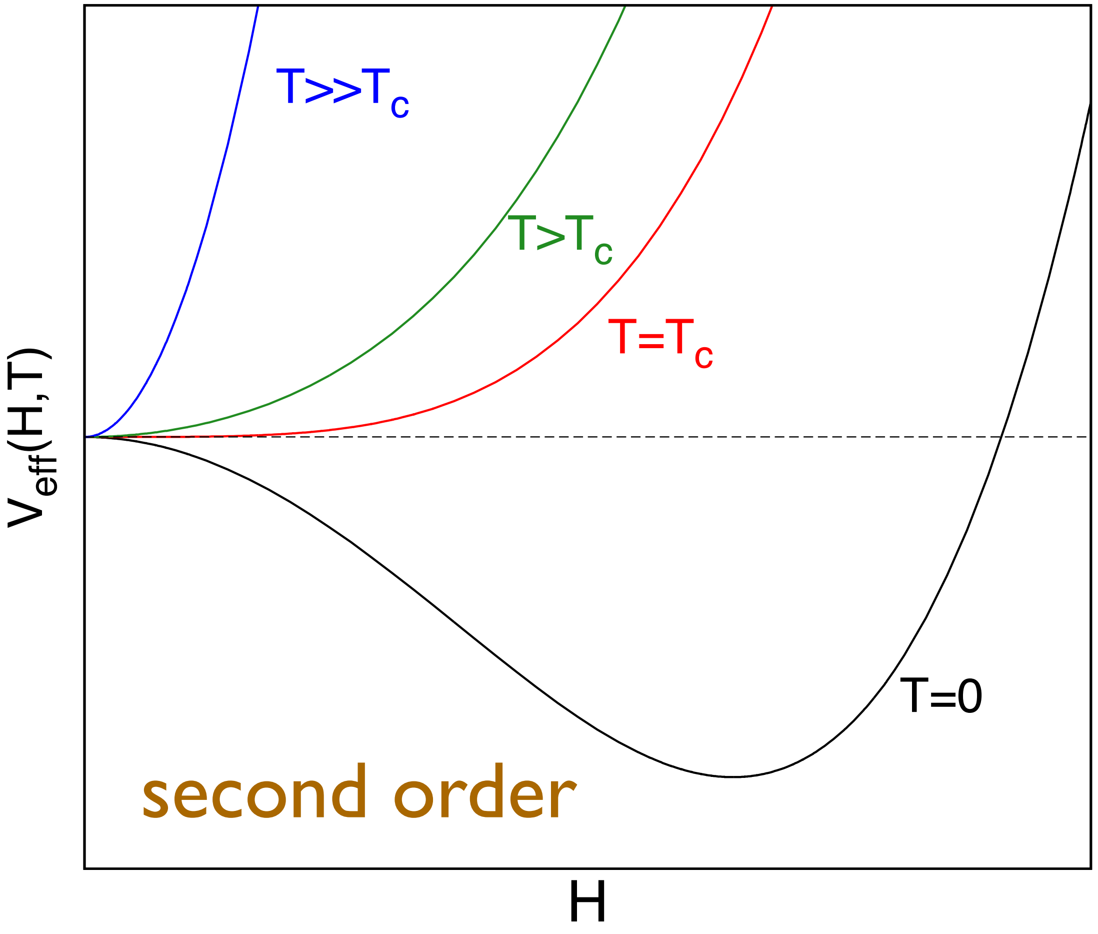

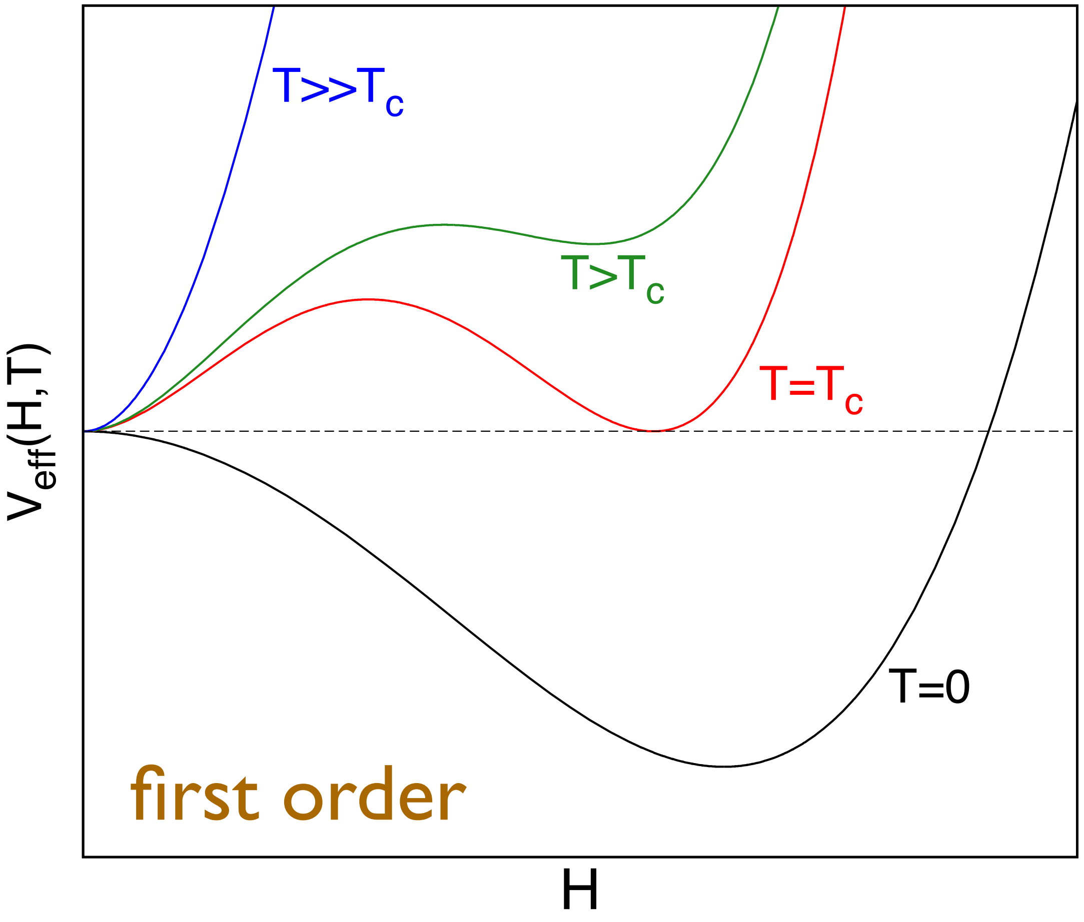

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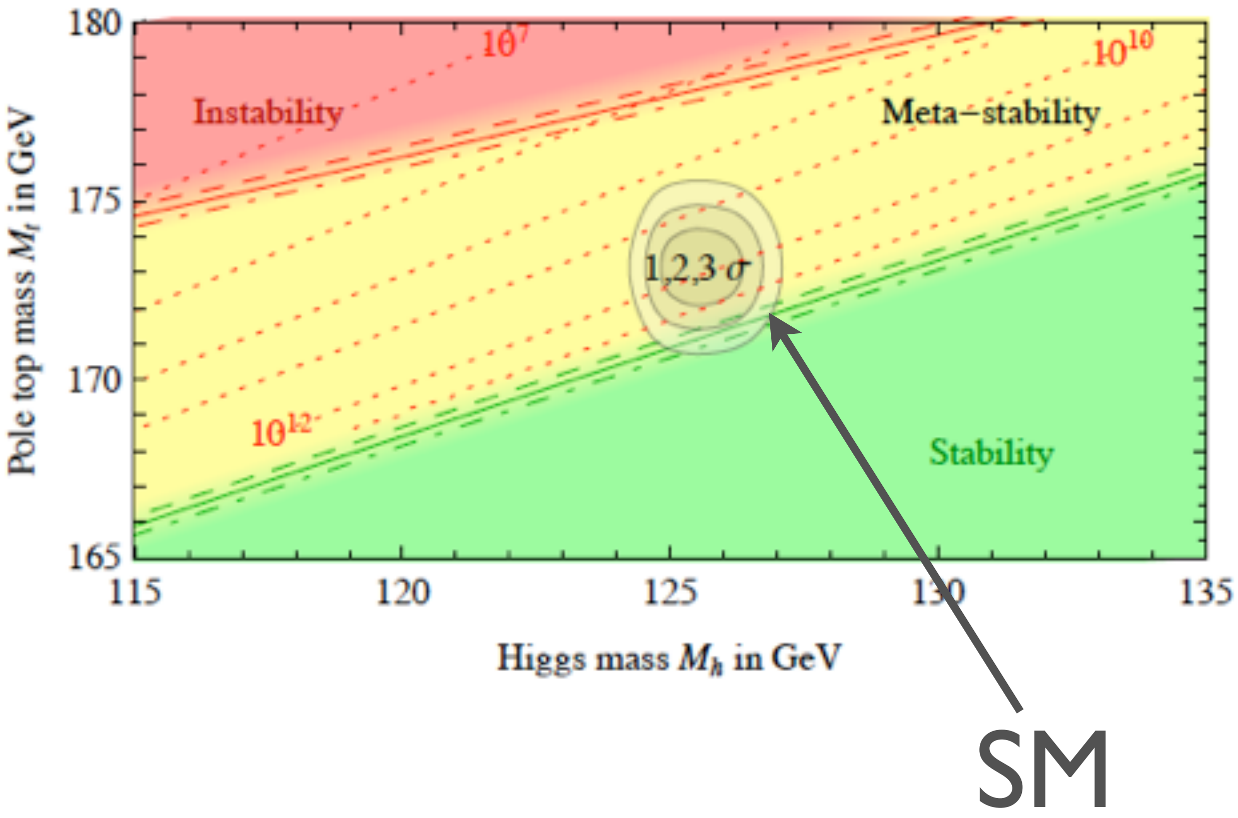
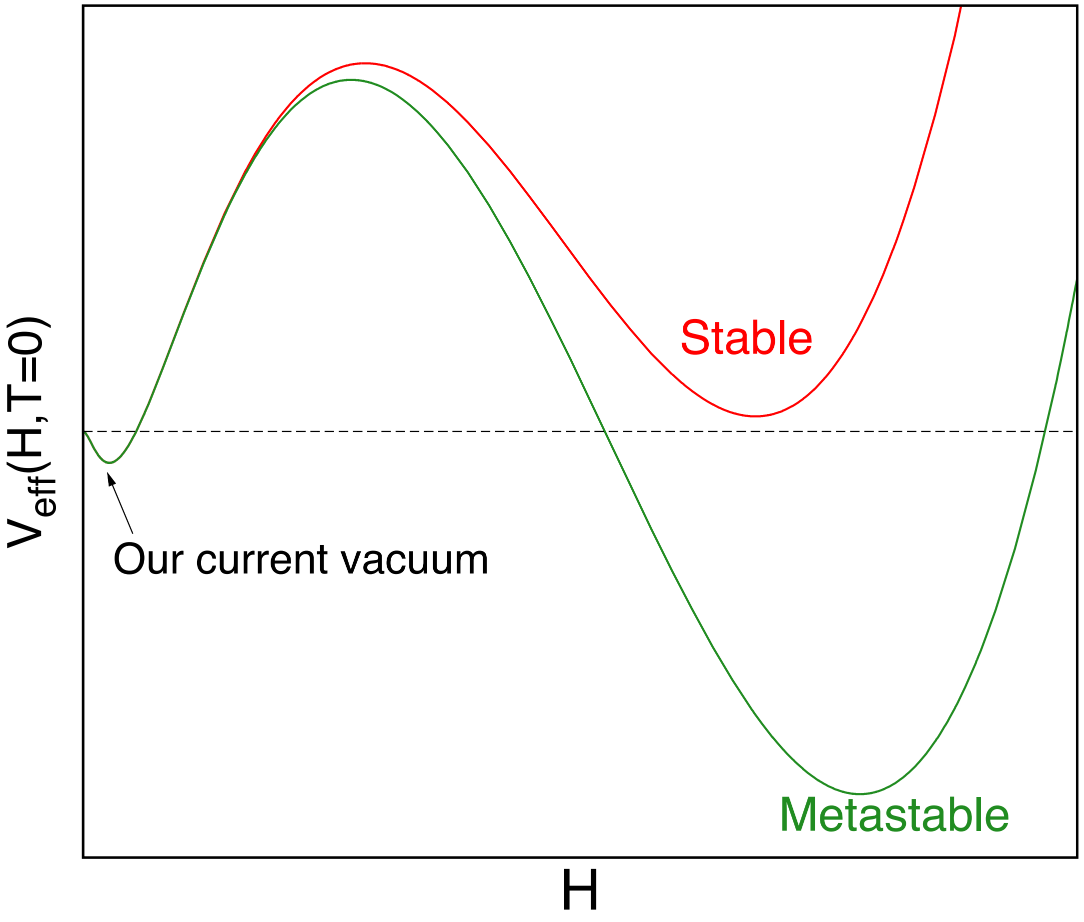


Degrassi et al. (2012)



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

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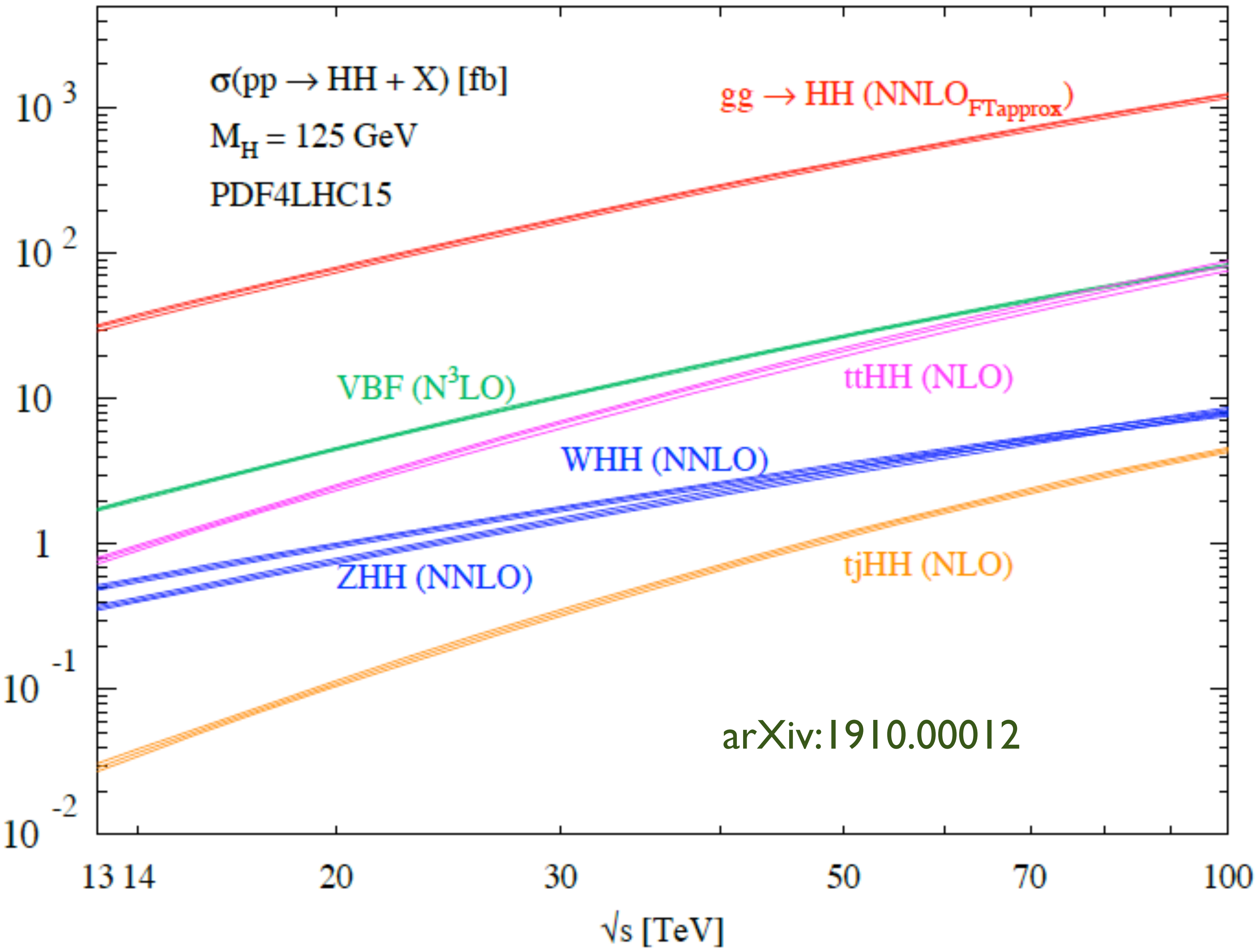

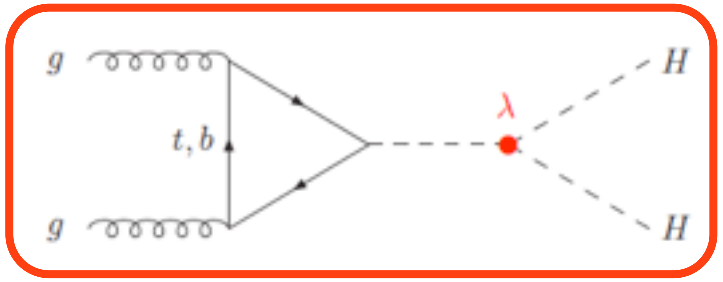

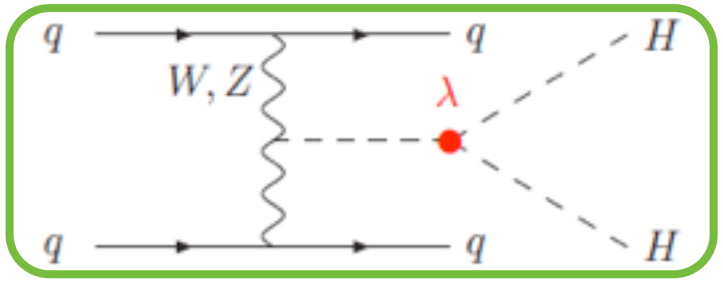

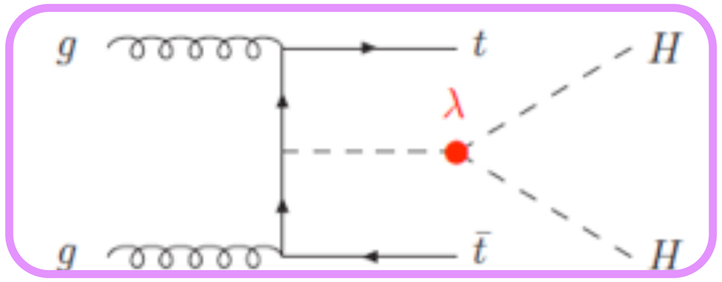

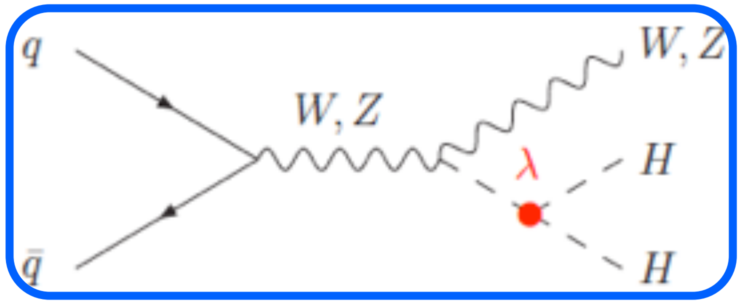

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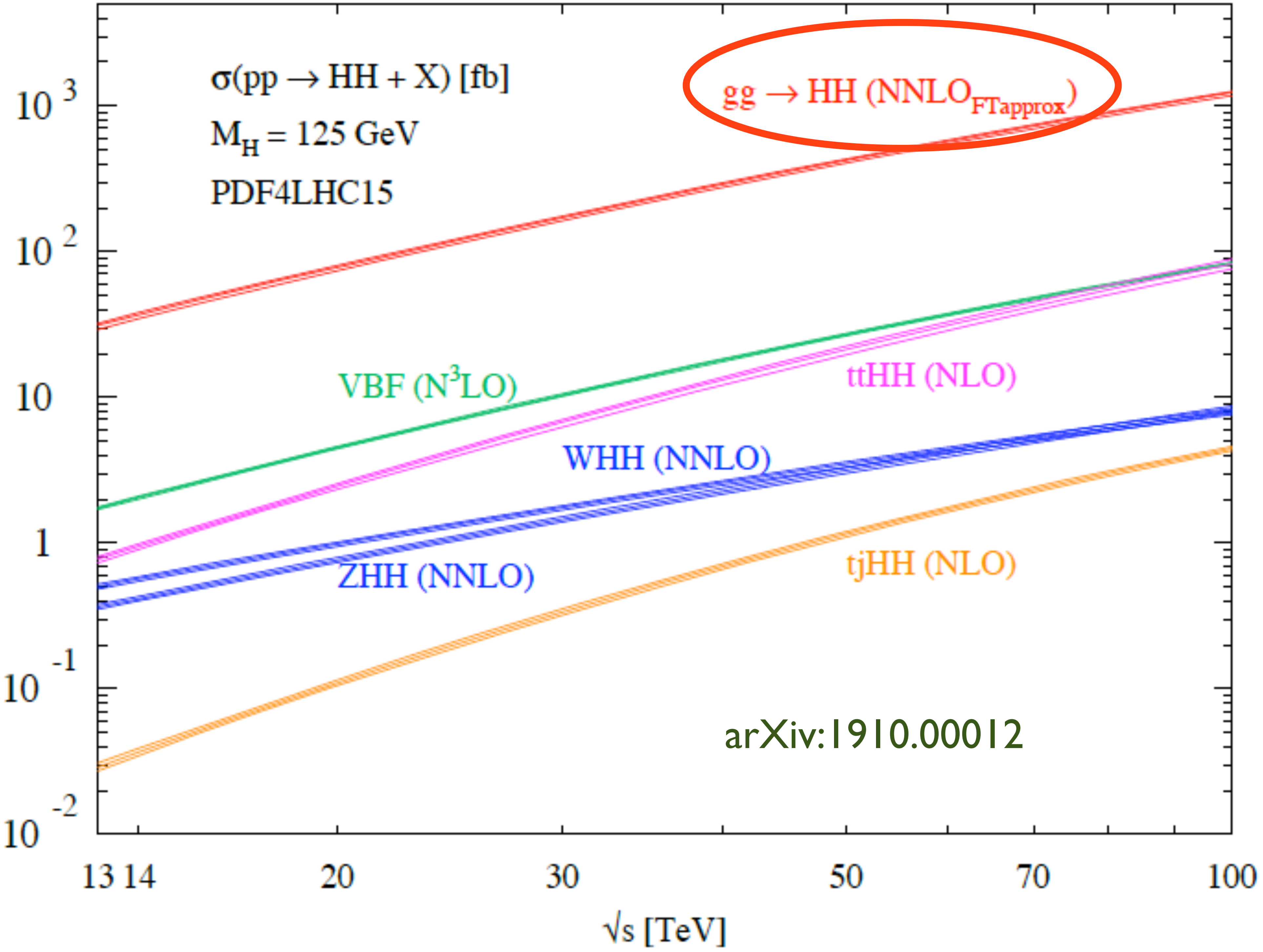
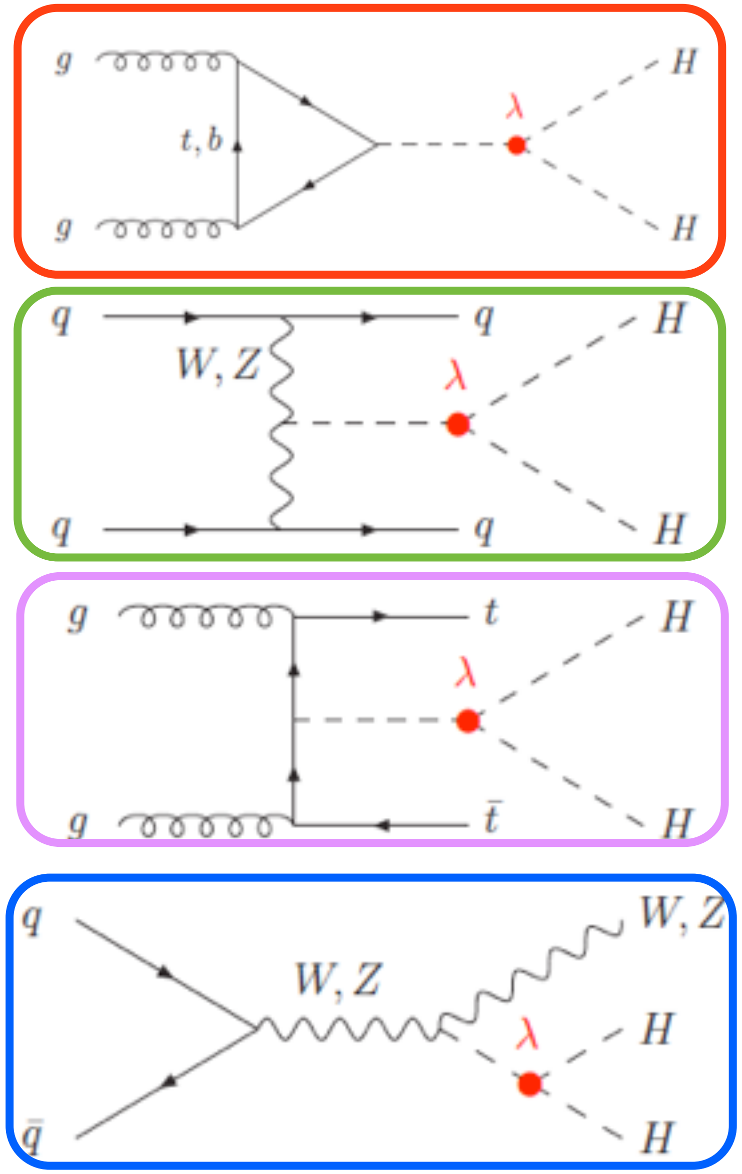
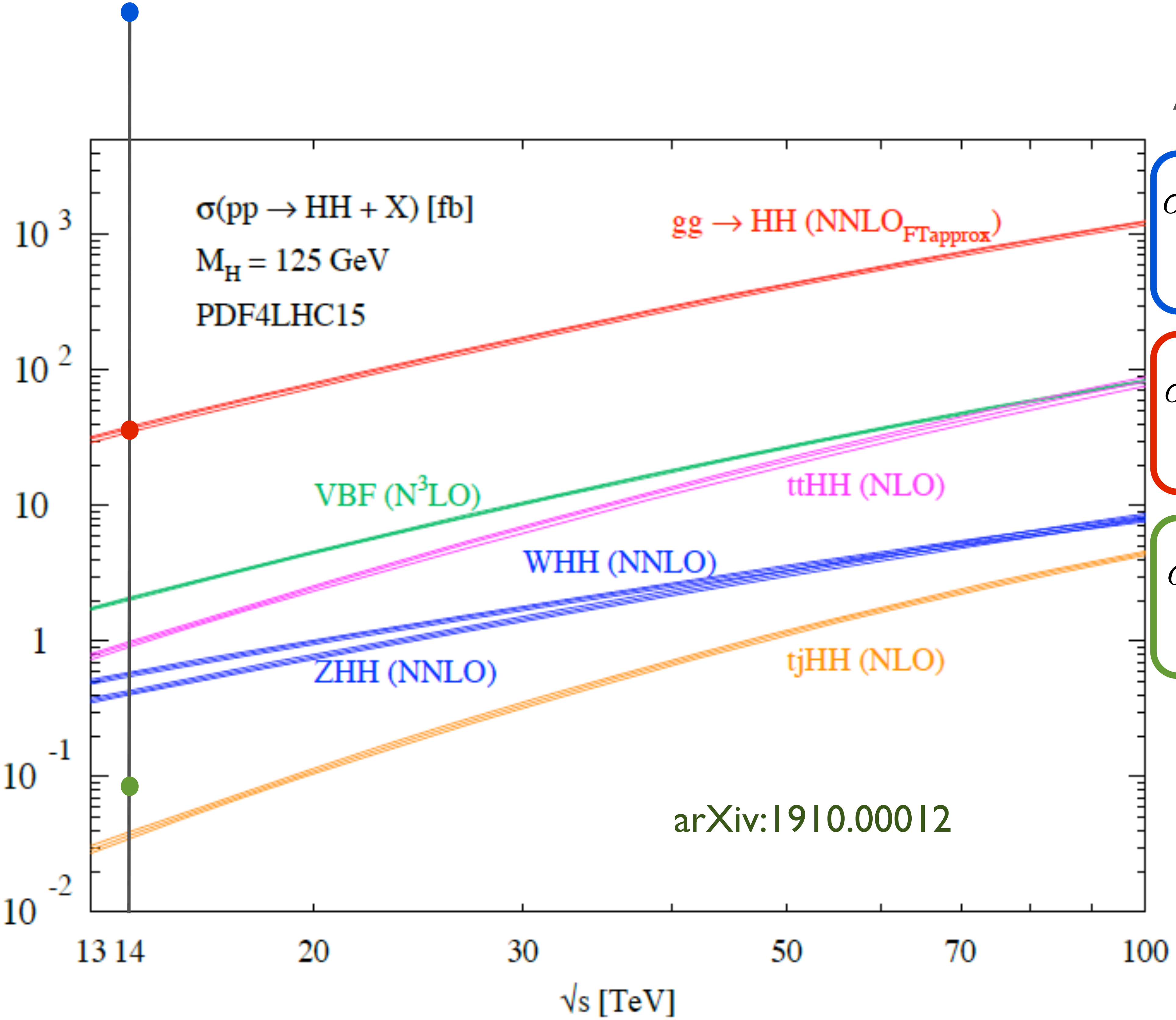


arXiv:1910.00012



GLUON FUSION CROSS SECTIONS



arXiv:1910.00012

At 14 TeV:

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

arXiv:1902.00134

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

arXiv:1910.00012

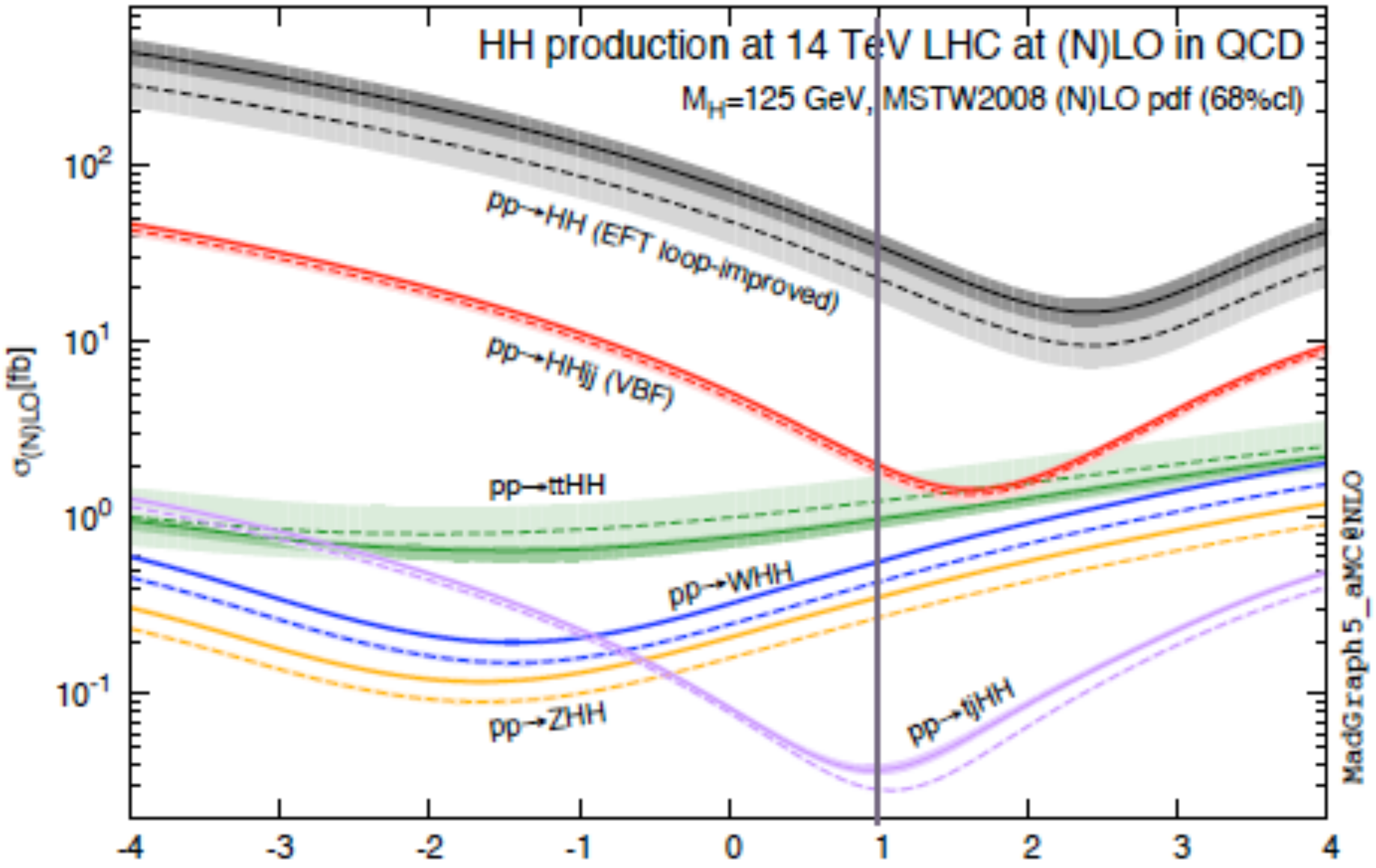
$$\sigma_{hhh}^{\mathrm{NLO_{FTapprox}}} = 89.4\ \mathrm{ab}$$

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.

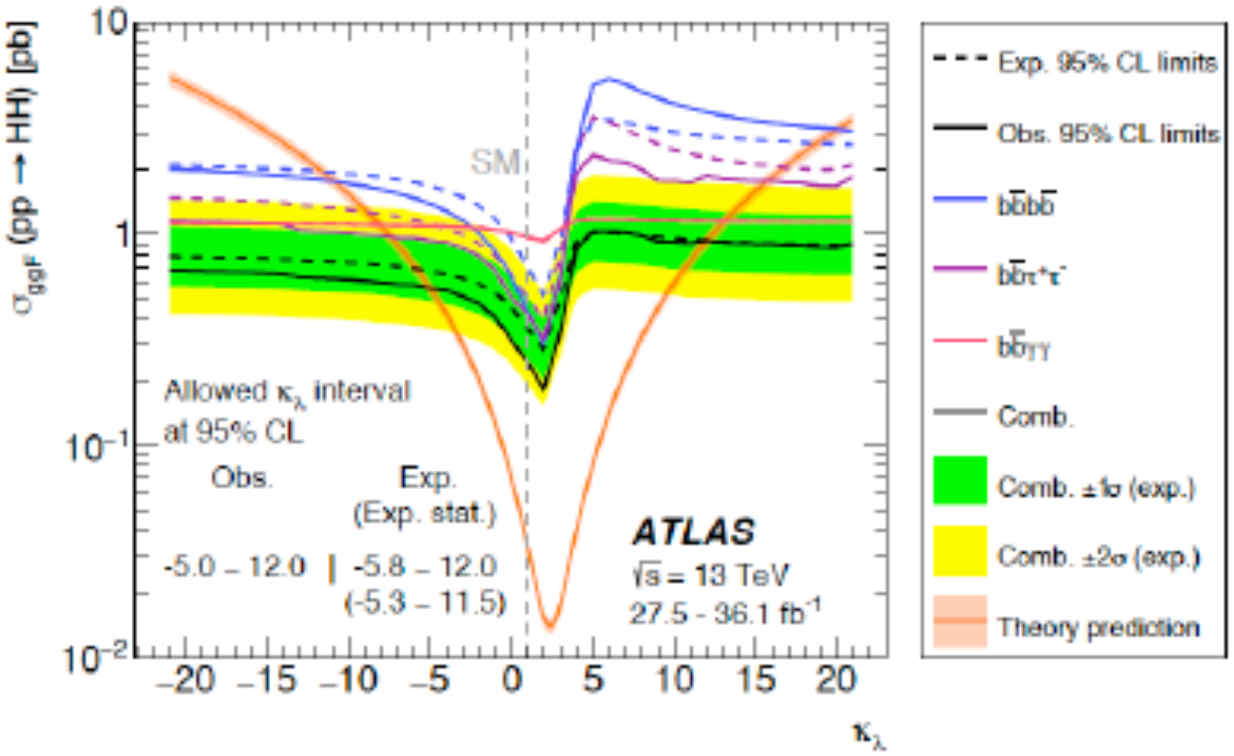
However:

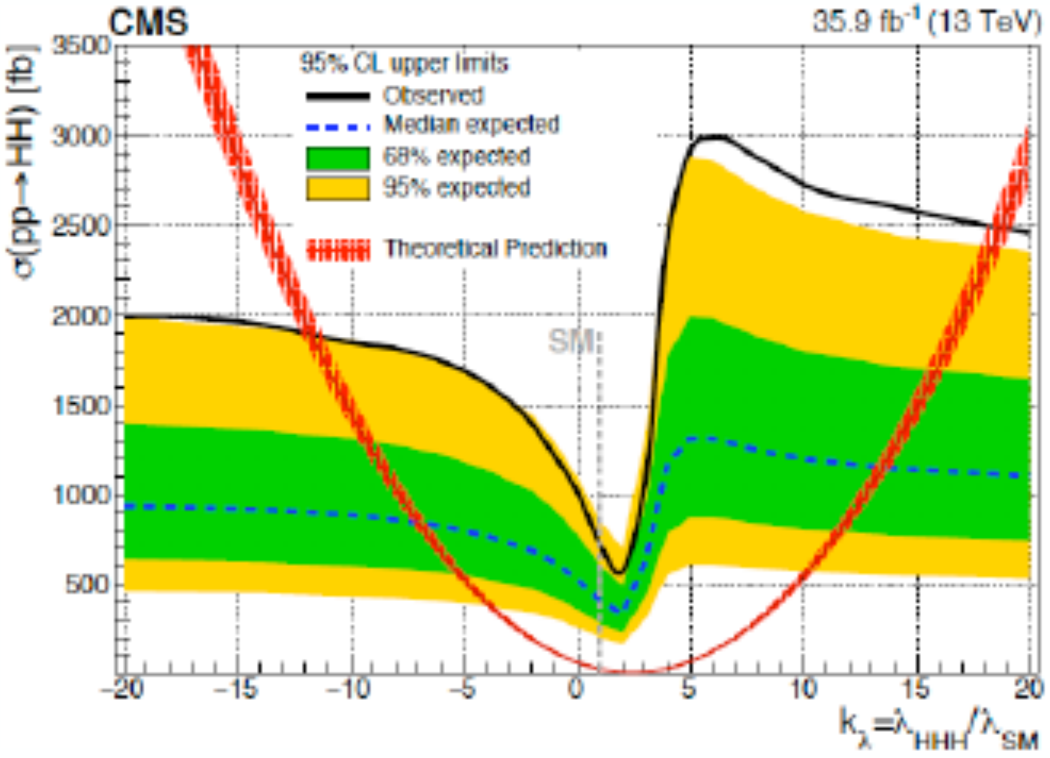
- Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
- The most commonly assumption is only changing the value of λ_{hhh}, which leads to (differential) cross section variations

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

THE MEASUREMENTS

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



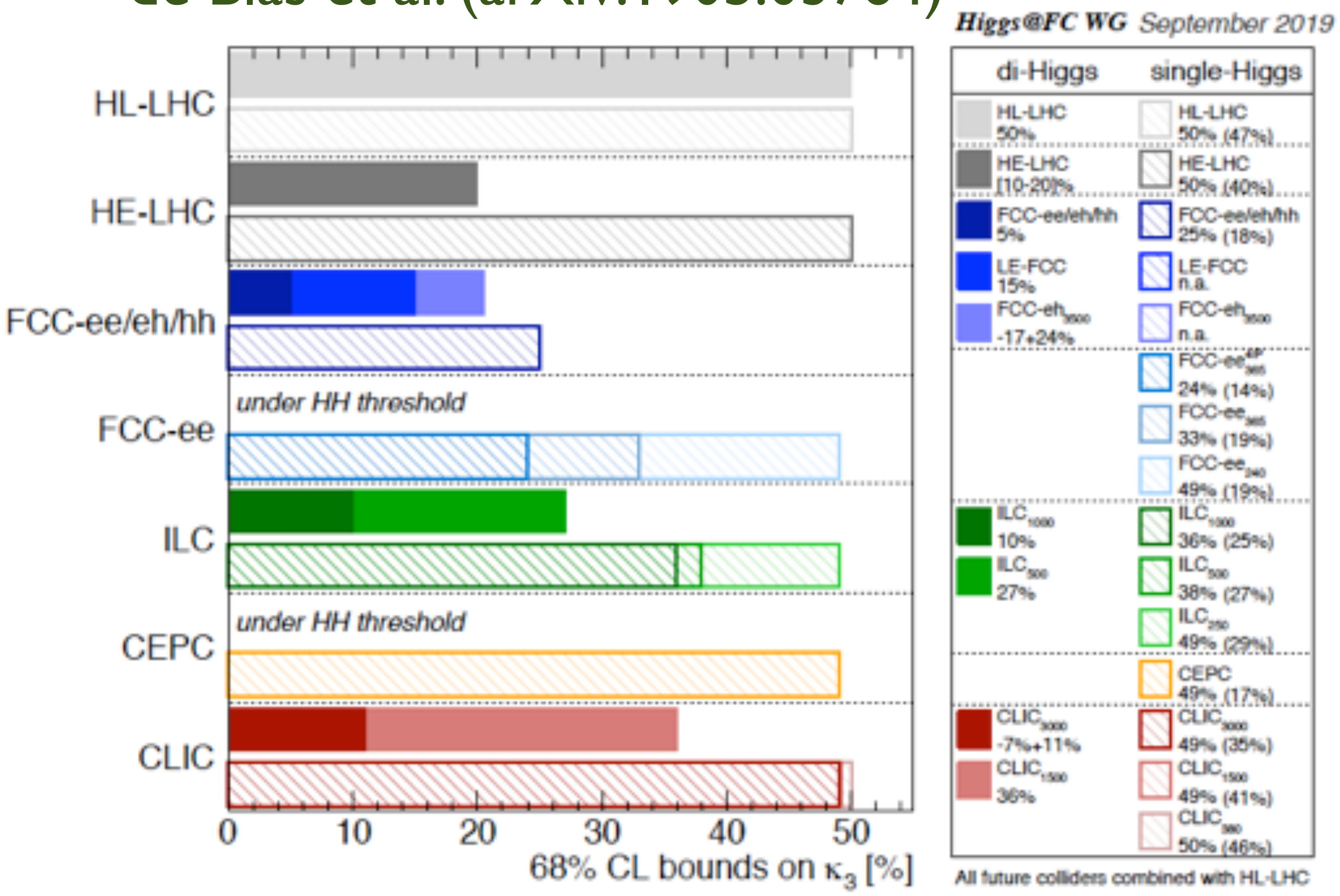


$$-5.0 < \kappa_\lambda < 12 \qquad\qquad -11.8 < \kappa_\lambda < 18.8$$

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

FUTURE PROSPECTS

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

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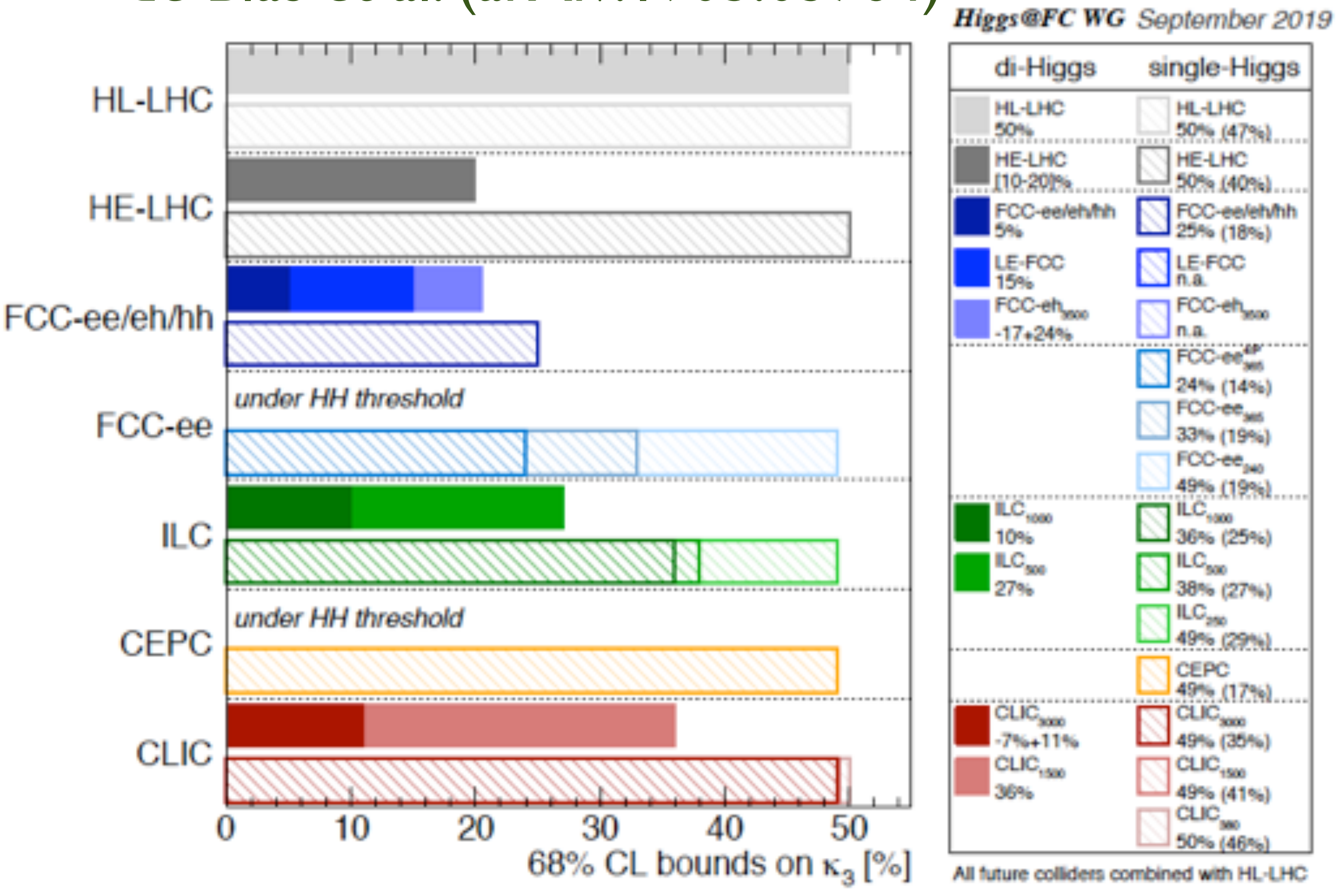

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→ Ultimate precision machine !

Mangano et al. (arXiv:2004.03505)

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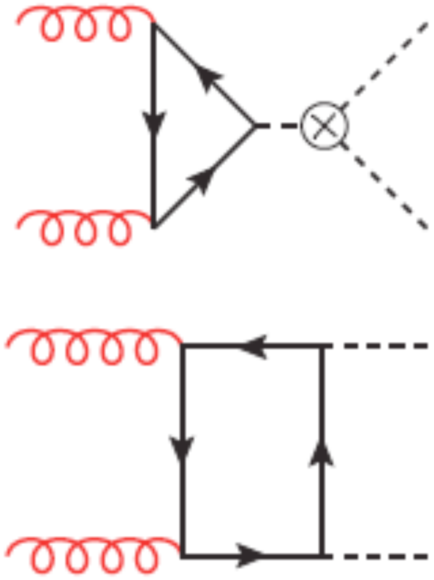
- **Full top-quark mass dependence**
  - Leading order (LO) is a loop-induced process



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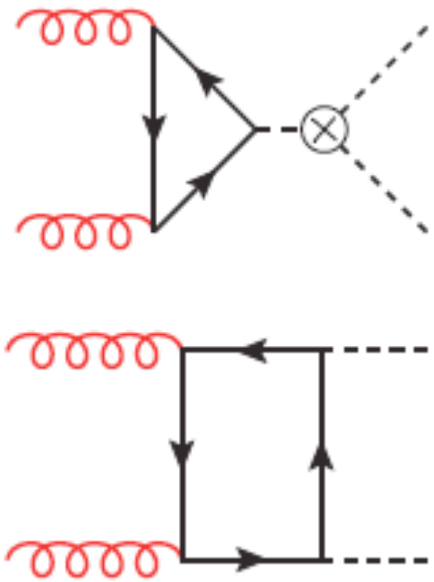

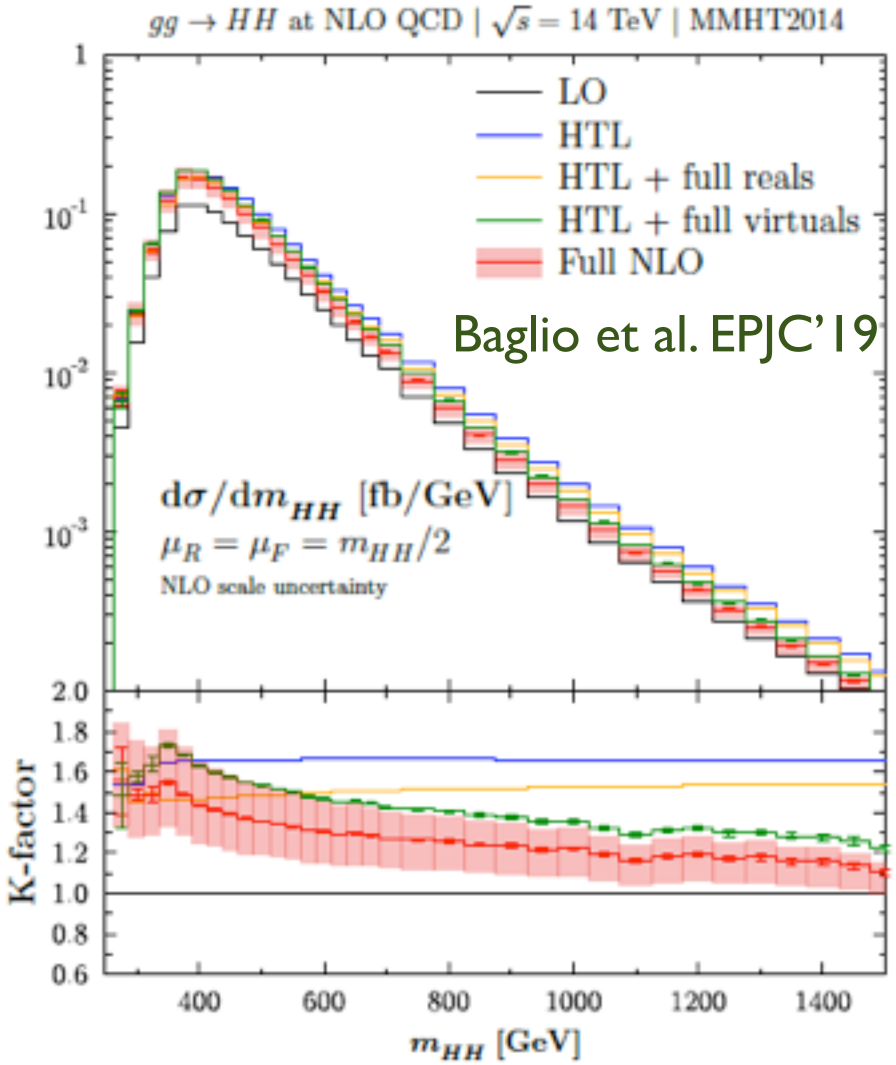

Baglio et al. EPJC'19

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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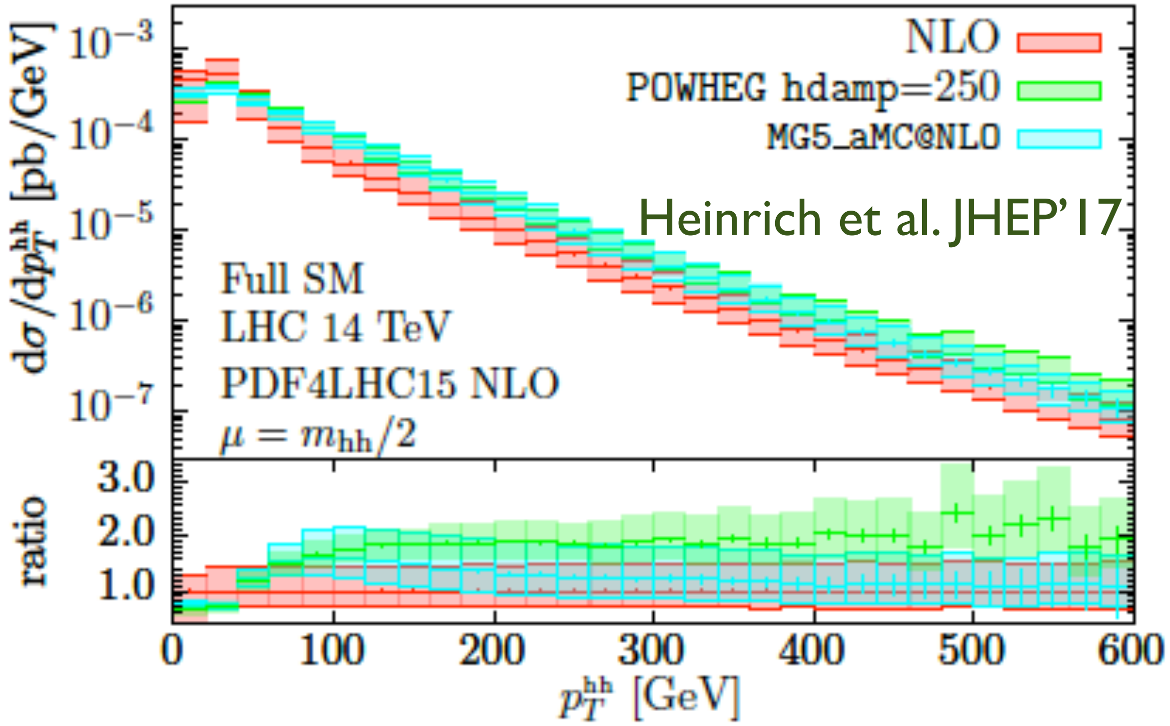
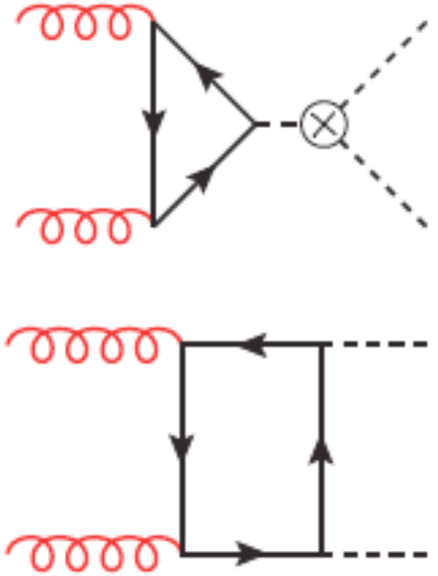


Heinrich et al. JHEP'17



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

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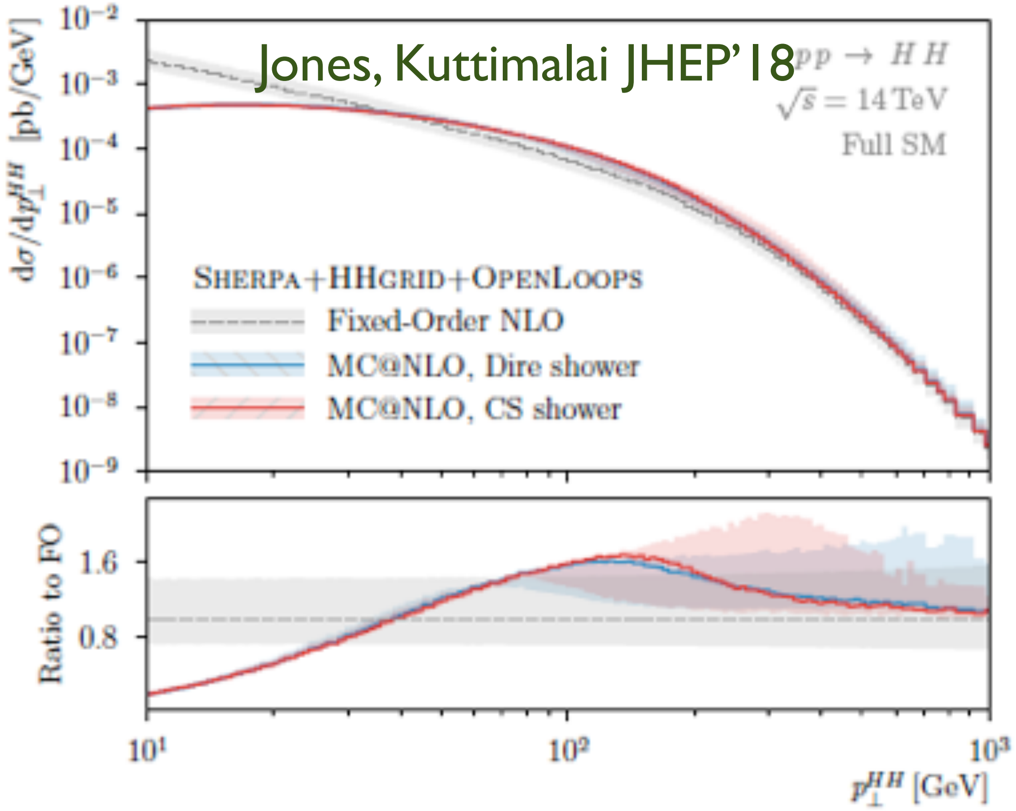
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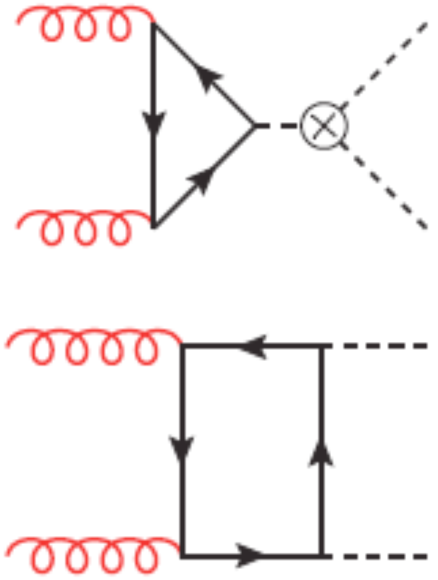

Shower scale uncertainty is also significant at large p_T^{hh}

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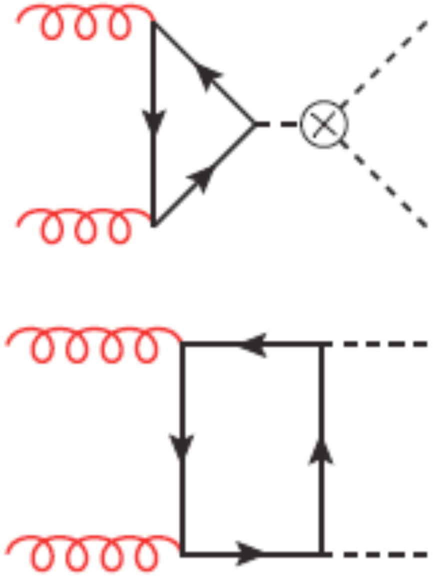
  - Scale unc. (>10%)

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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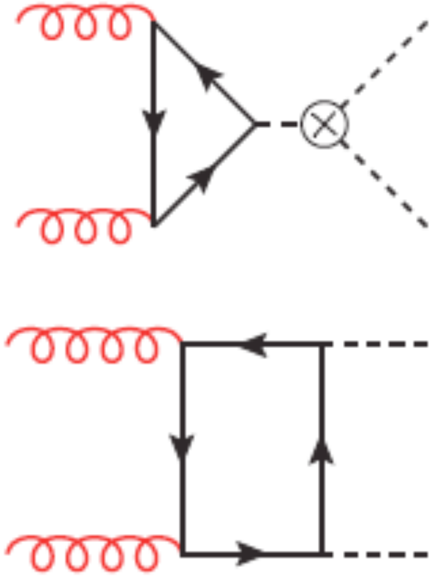

$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=300\text{ GeV}} = 0.02978(7)^{+6\%}_{-34\%}\text{ fb/GeV},$$

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

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

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

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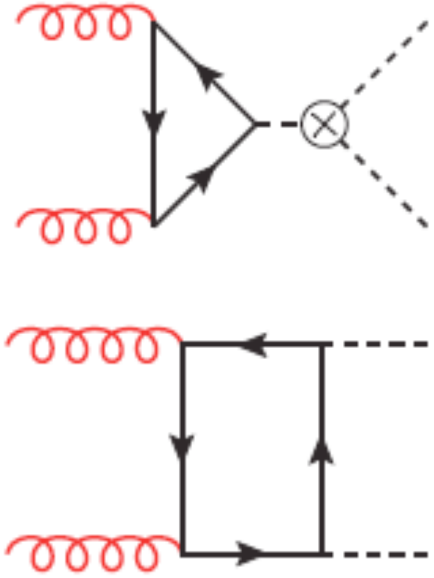
  - Scale unc. (>10%)
  - ... and large top-quark mass scheme dependence
  - A lot of analytical approximations (well-motivated to deepen understanding)

    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)



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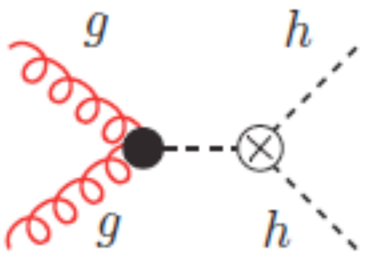
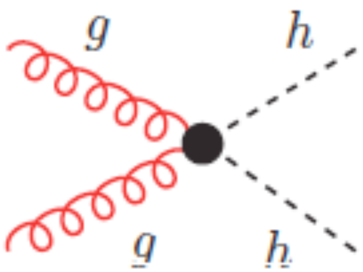
$$\mathcal{L}_{\rm eff} = -\frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu} \left(C_h \frac{h}{v} - C_{hh} \frac{h^2}{2v^2} \right)$$





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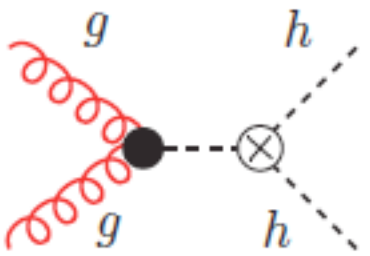
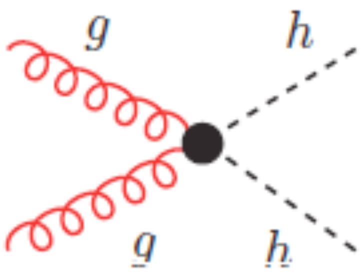
Schroder and Steinhauser JHEP'06;Baikov et al. PRL'17; Spira JHEP'16; Gerlach et al. JHEP'18





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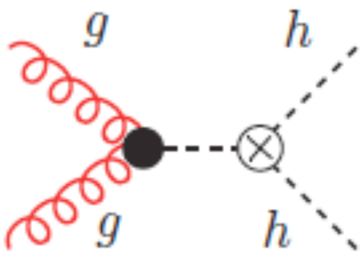
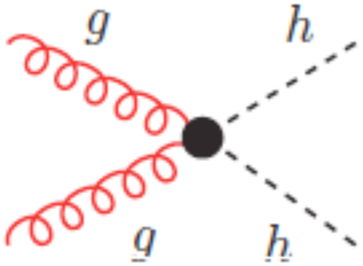
    - NNLO was known as well Florian and Mazzitelli PLB'13,PRL'13; Grigo et al. NPB'14; Florian et al. JHEP'16
    - Threshold resummation Shao et al. JHEP'13; Florian and Mazzitelli JHEP'15, JHEP'18
    - $\mathrm{NLO}_{\rm FTapprox}$: NLO plus full top quark mass in Born and real Frederix et al. PLB'14; Maltoni et al. JHEP'14
    - Combine NNLO with full top-quark mass NLO Grazzini et al. JHEP'18





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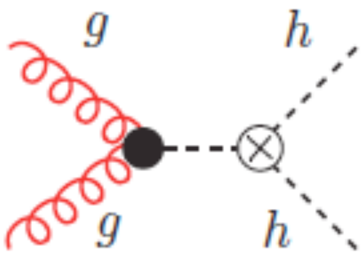
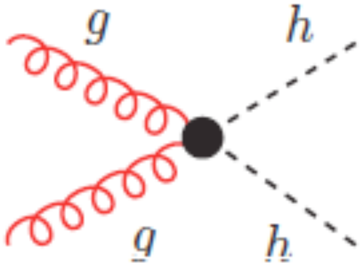


Our aim is to push the calculation to N^{3}LO !



HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**

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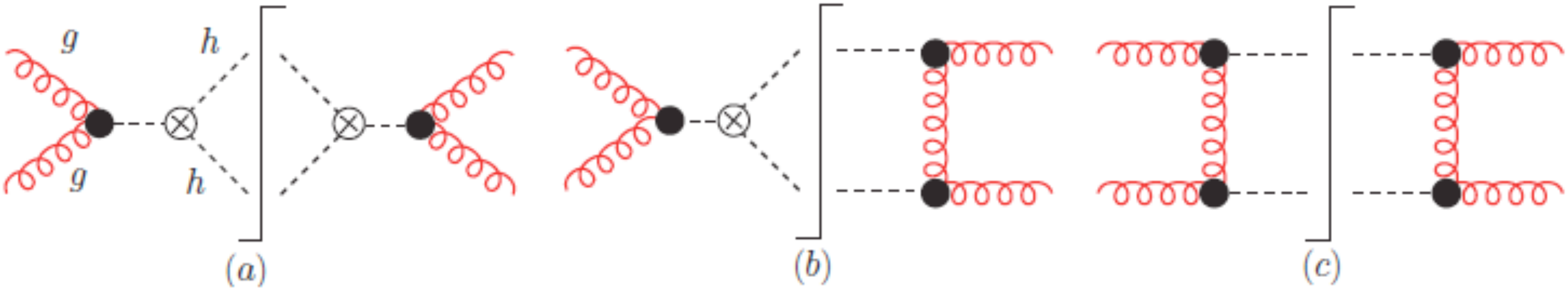

Chen, Li, HSS, Wang (1909.06808)

	LO	NLO	NNLO	N^{3}LO
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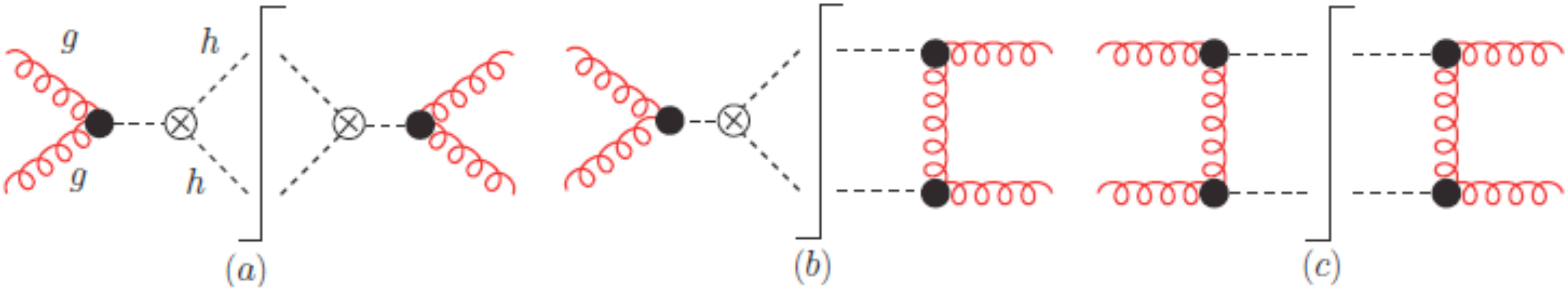

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$$d\sigma_{hh} = d\sigma^a_{hh} + d\sigma^b_{hh} + d\sigma^c_{hh}$$

- class-a: same topology as ggH

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

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

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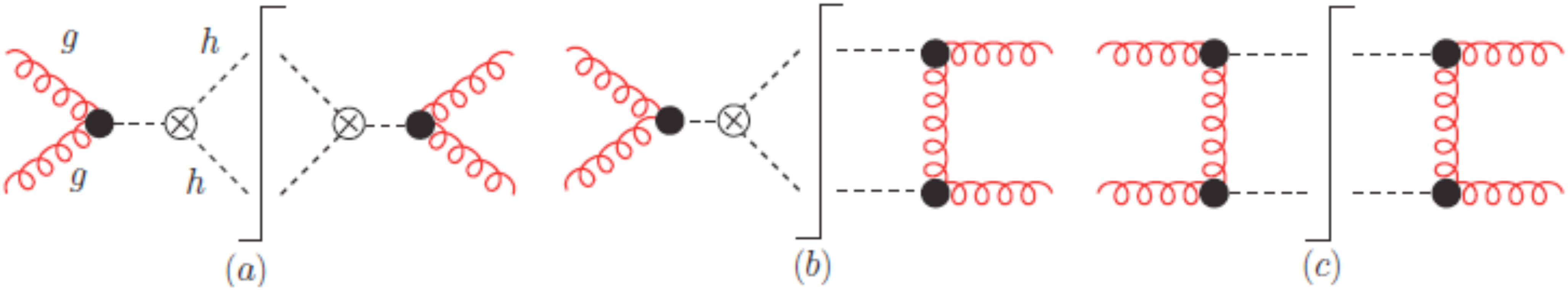

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From iHixs2

Dulat et al. CPC'18

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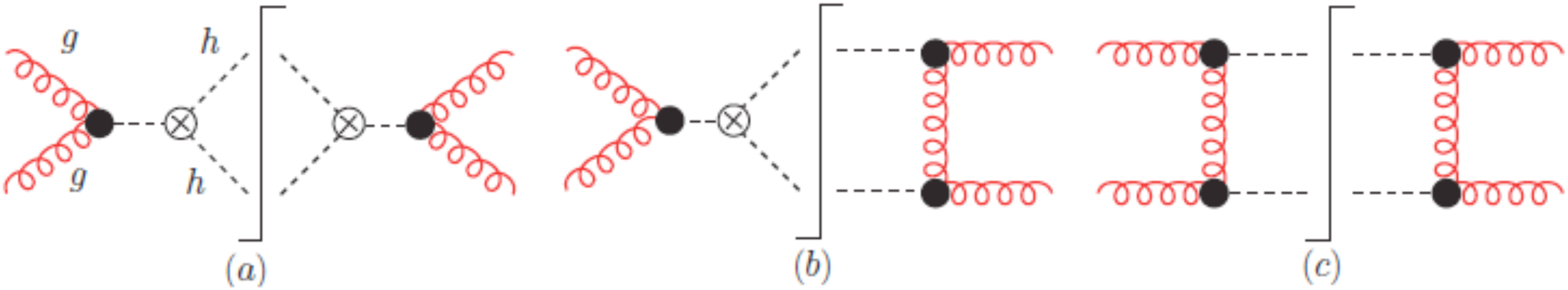

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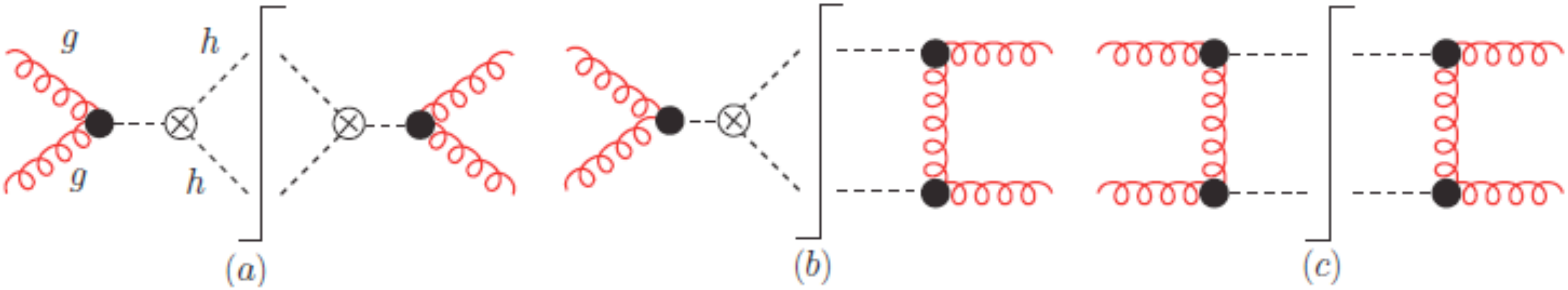

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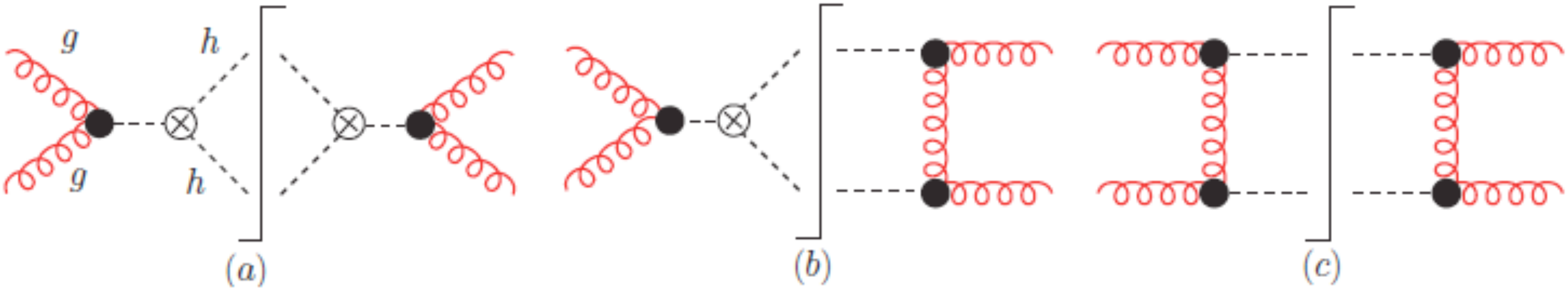

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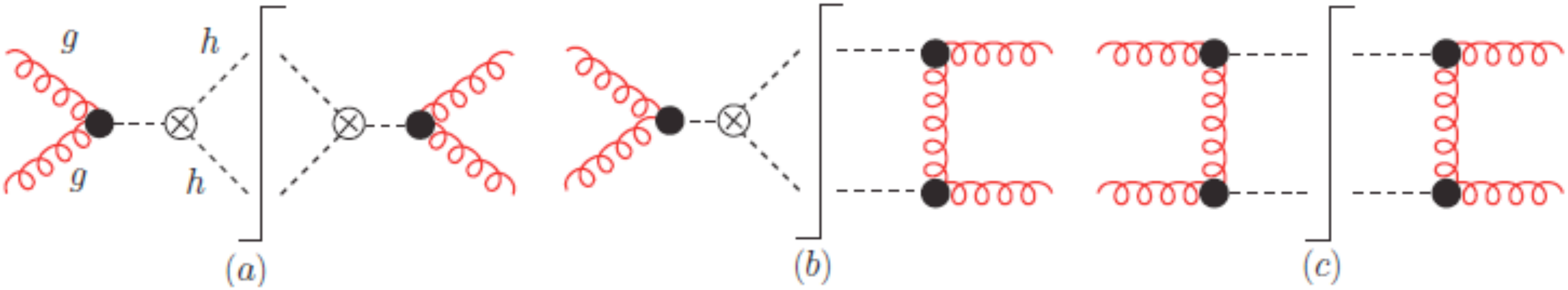

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$\mathcal{H}$ hard function

two-loop amplitude

Banerjee et al., JHEP'18

new one-loop amplitude

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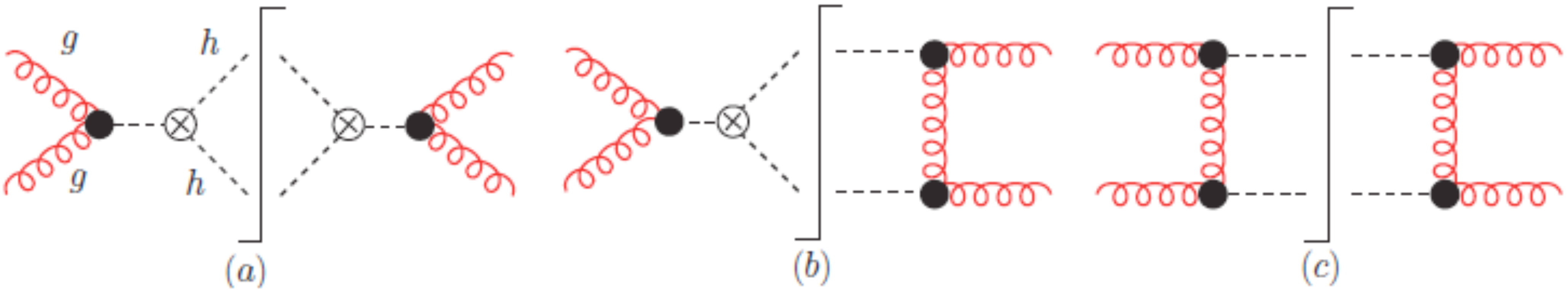

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$\mathcal{B}_i$ TMD beam function

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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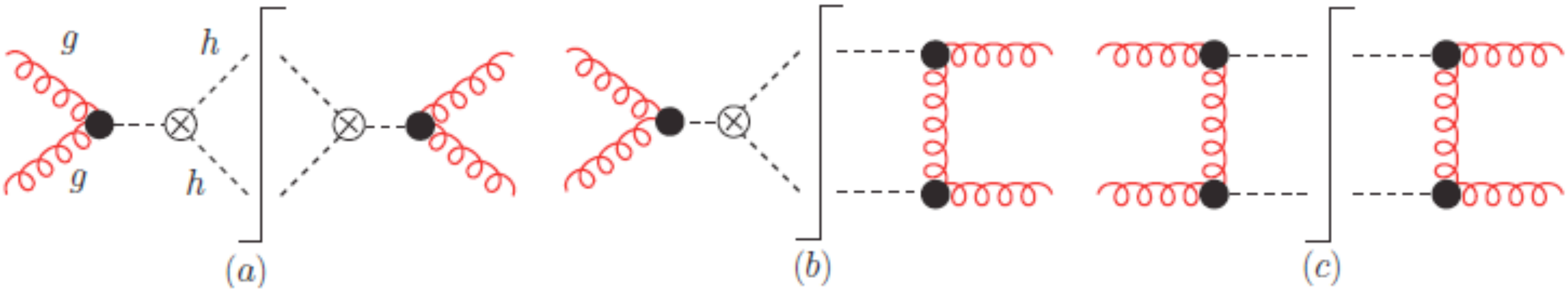

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MG5_aMC: $d\sigma^{b,\rm NNLO}_{hh}\Big|_{p_T^{hh}>p_T^{\rm veto}} = d\sigma^{b,\rm NLO}_{hh+j}$

New and validated NLO model

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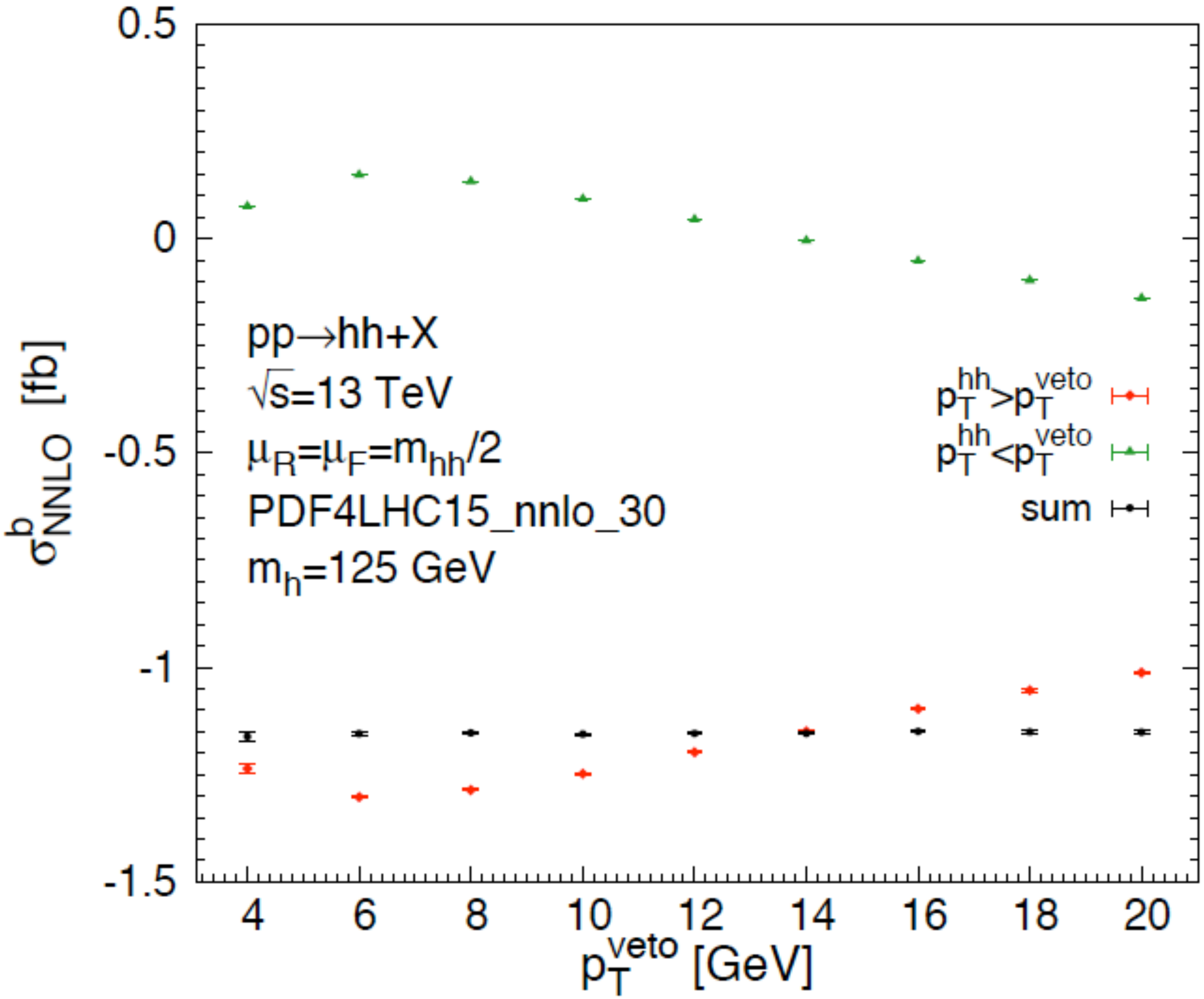

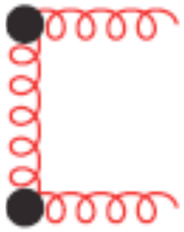

ang (1909.06808)

tot

a

b

c

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

- class-

ani & 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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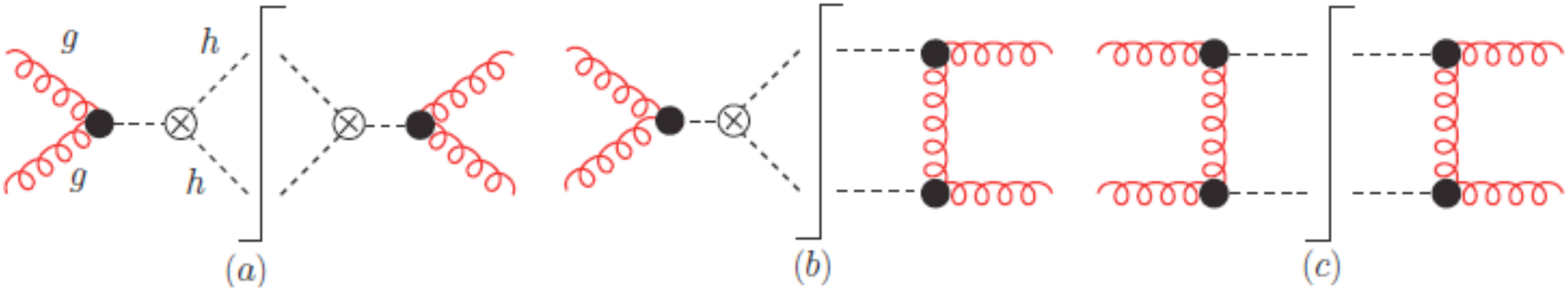

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Chen, Li, HSS, Wang (1909.06808)

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- class-c: need NLO (full fledged)

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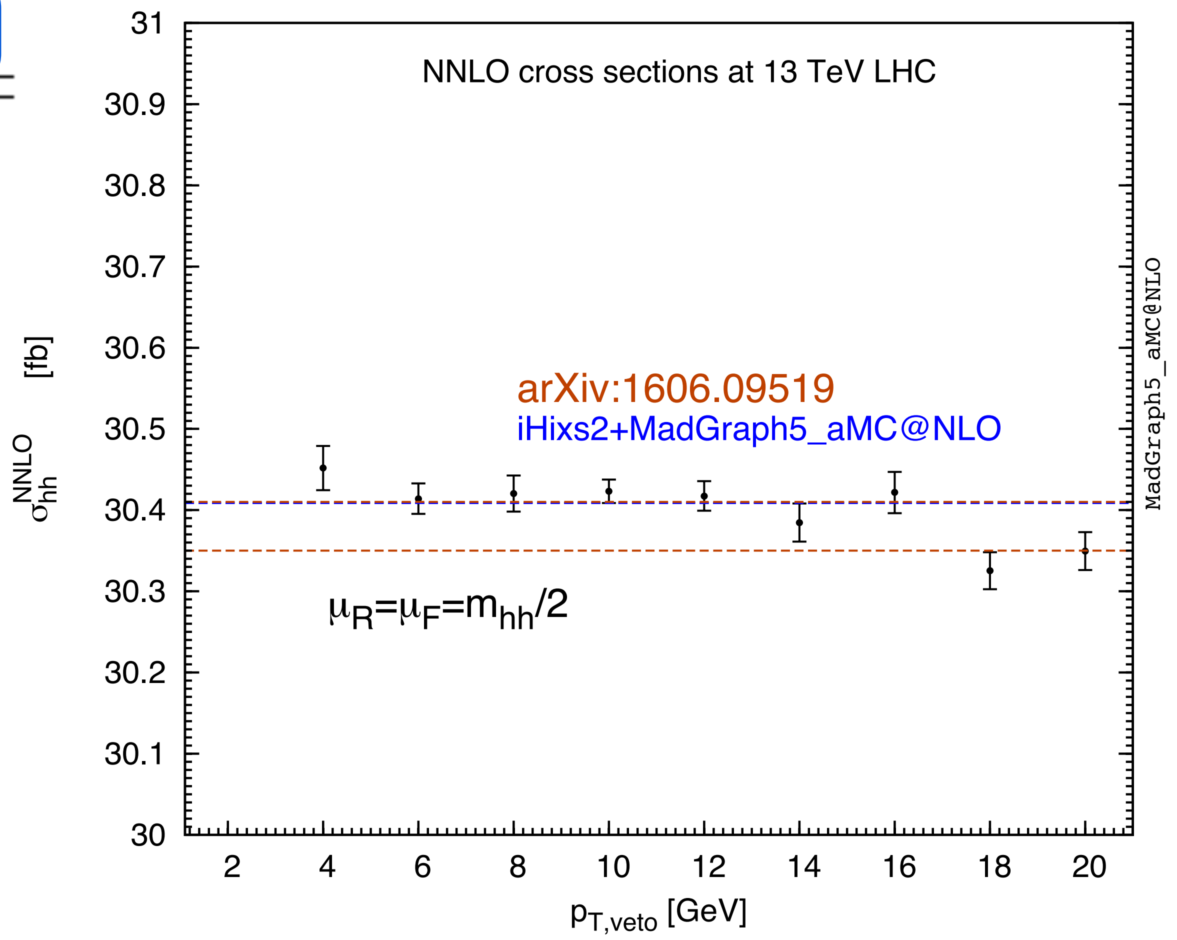
✓ At least two independent calculations



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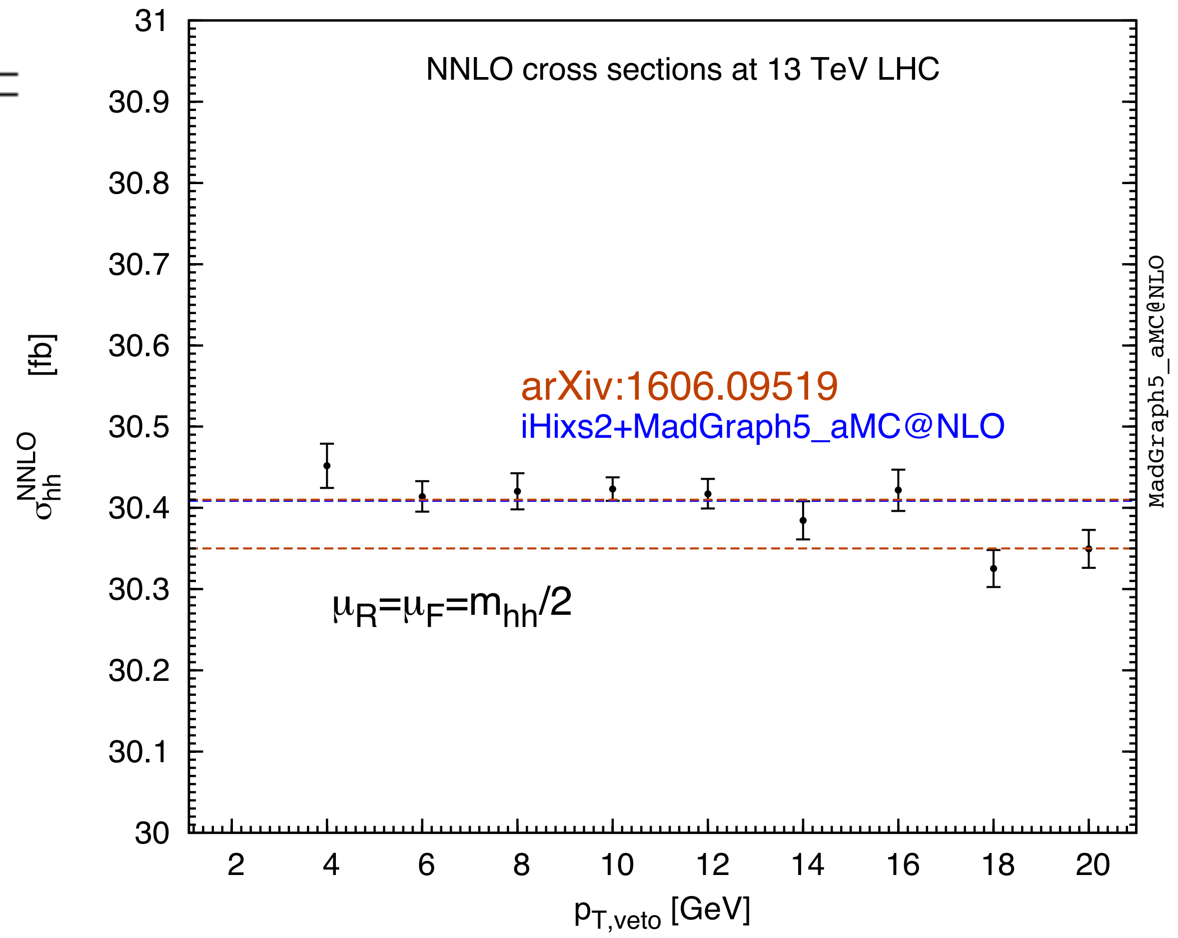

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√ At least two independent calculations

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√ Check piece-by-piece

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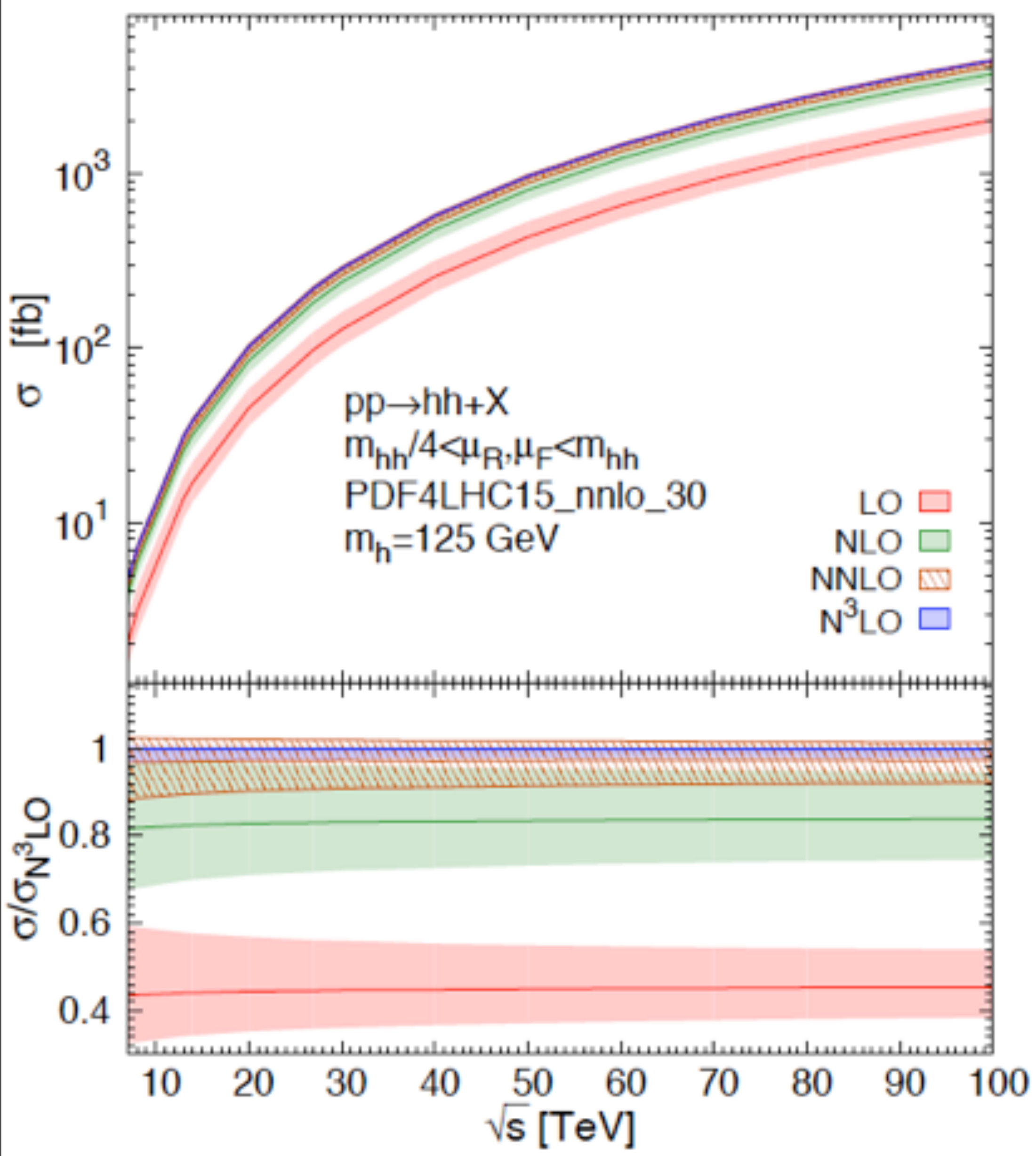
- **Infinite top-quark mass limit**
  - N^{3}LO cross sections



in unit of fb

Chen, Li, HSS, Wang (1909.06808)

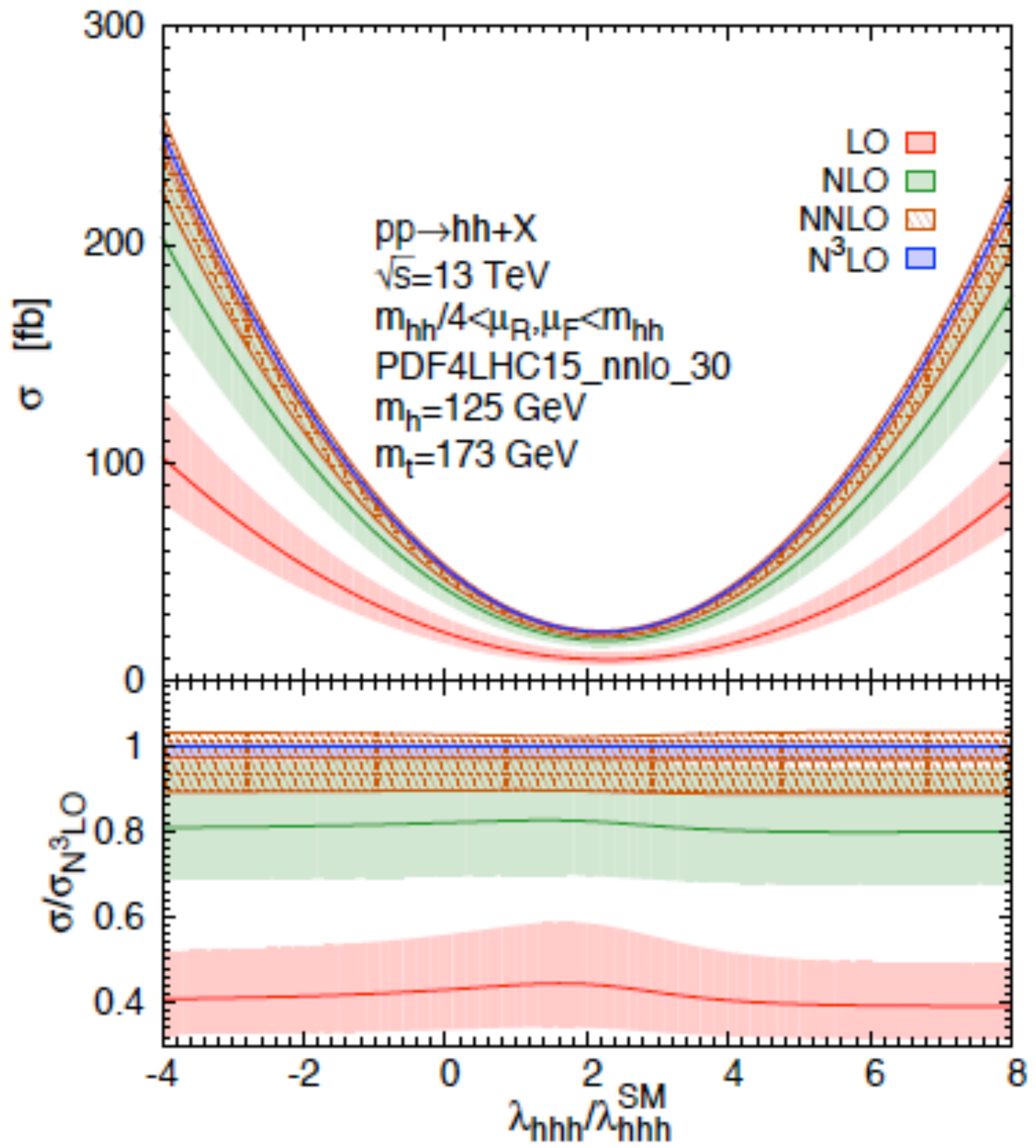
order \ $\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$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

- Scale unc. is significantly reduced !
- PDF unc. > Scale unc. now !
- Very good perturbative convergence !

HIGGS PAIR GLUON FUSION PRODUCTION

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

Chen, Li, HSS, Wang (1912.13001)



- Shapes change from LO to NLO and from NLO to NNLO

- The shape variation from NNLO to N^3LO is quite invisible

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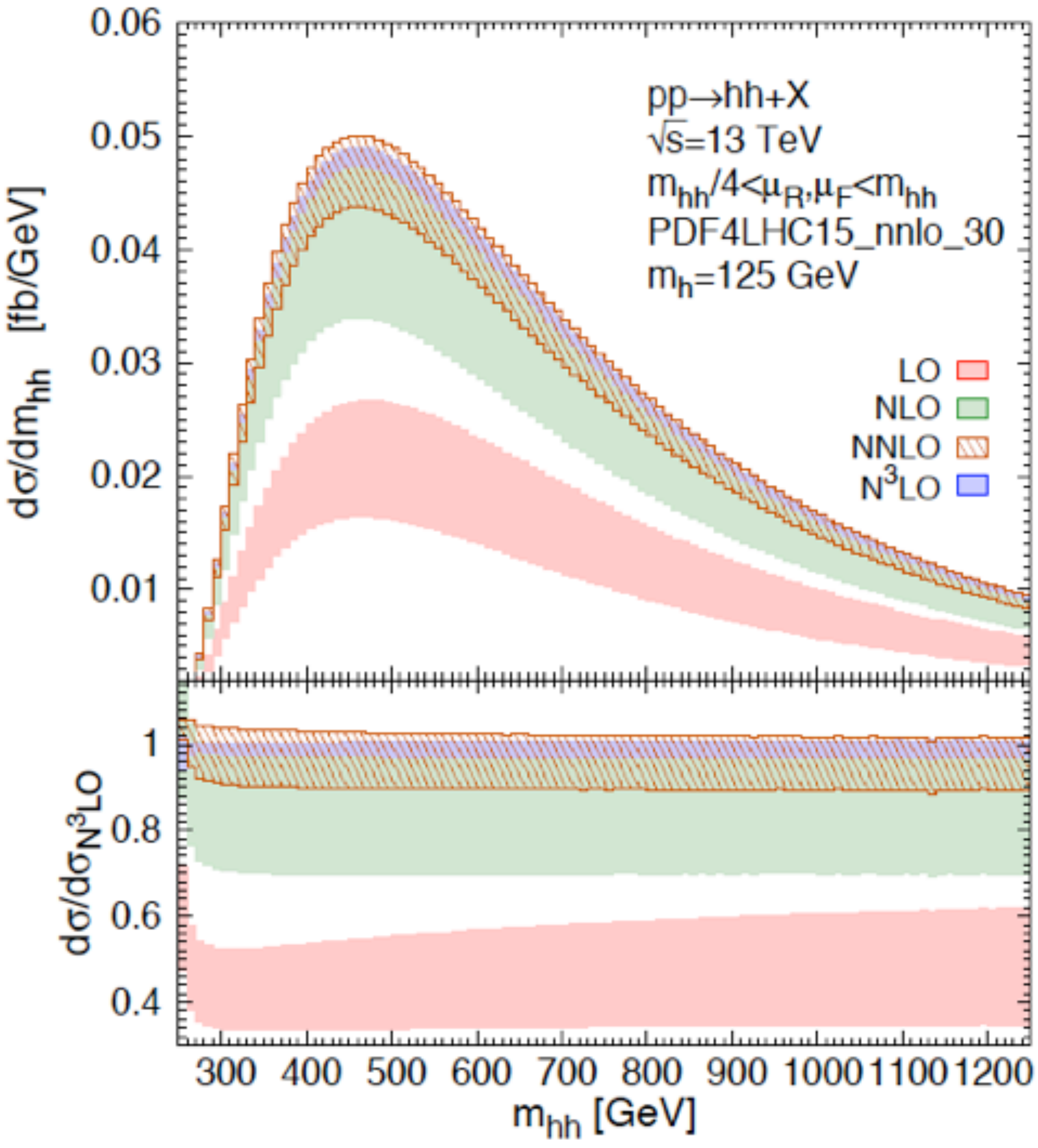
Chen, Li, HSS, Wang (1909.06808)



- Scale unc. is significantly reduced !
- Very good perturbative convergence !
- N^{3}LO/NNLO is quite flat

TOP QUARK MASS APPROXIMATIONS

Chen, Li, HSS, Wang (1912.13001)

- **Several approximations:**

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

- $\mathbf{N^kLO{\oplus}N^lLO}_{m_t}$

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

missing top mass in correction

- $\mathbf{N^kLO{\otimes}N^lLO}_{m_t}$

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Same K factor for mass correction

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

Born mass improved for correction

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missing top mass in correction

The best !

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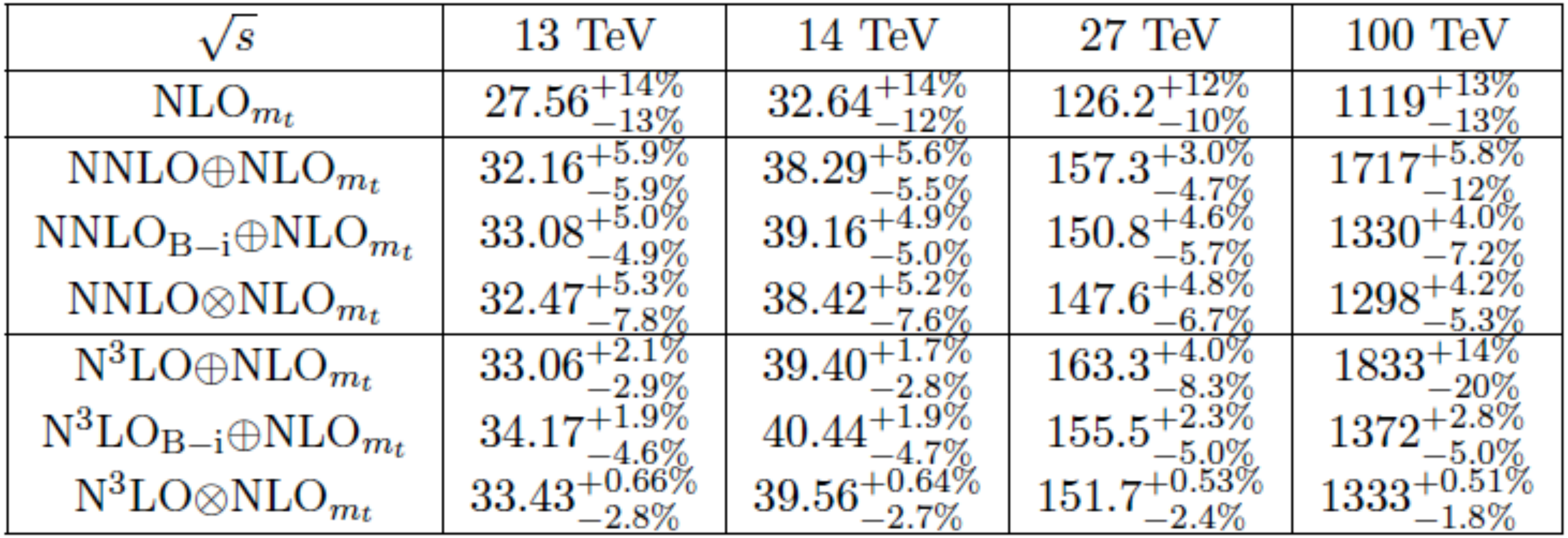
Born mass improved for correction

TOP QUARK MASS RESULTS

- **Top-quark mass dependent results** NLO$_{\mathrm{mt}}$ from Powheg, arXiv:1903.08137
  - N^{3}LO cross sections

Chen, Li, HSS, Wang (1912.13001)

in unit of fb



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

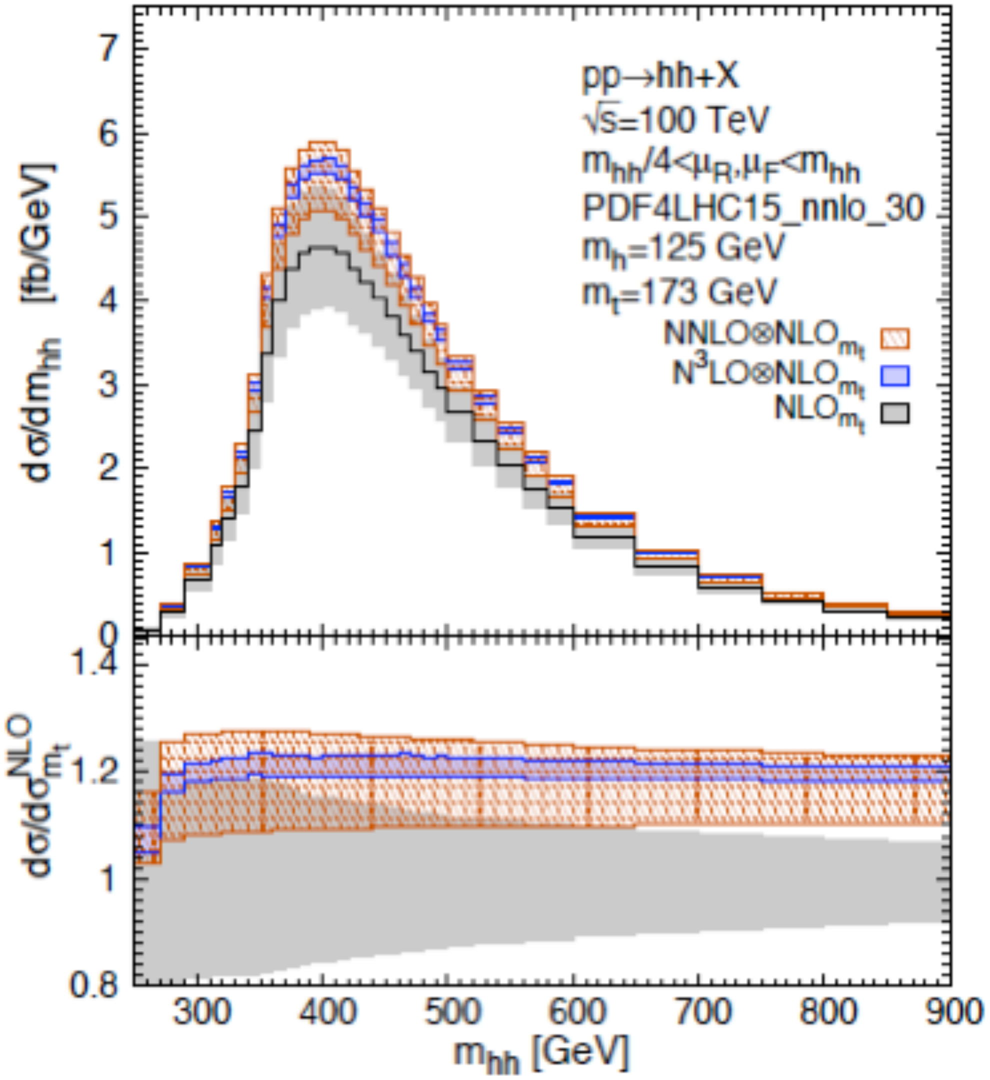
- N^{3}LO enhances NNLO by 3% but enhances NLO by 20%
- N^{3}LO reduces scale unc. to 3%
- The missing top quark mass uncer. at N^{3}LO is around 5%
- The top mass scheme uncer. is unknown (not expected to be improved)

TOP QUARK MASS RESULTS

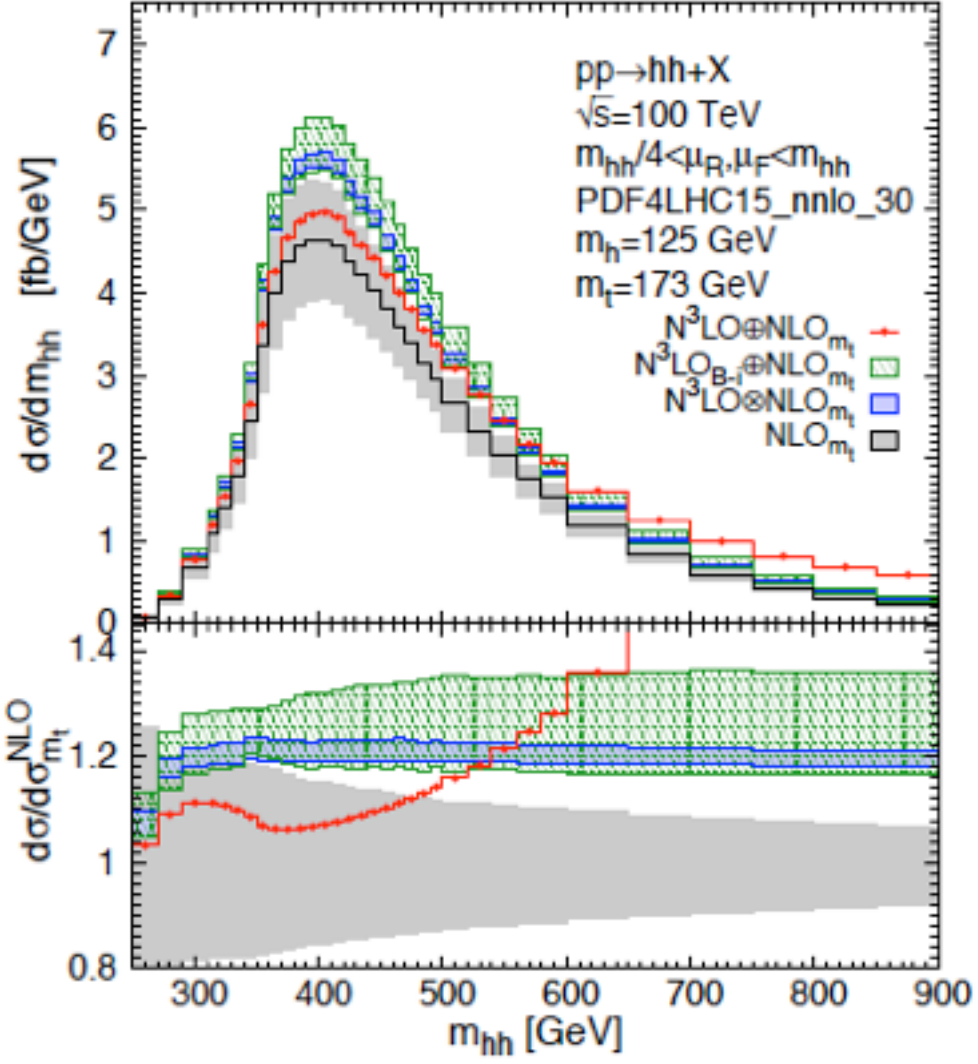
- **Top-quark mass dependent results** NLO$_{mt}$ from Powheg, arXiv:1903.08137
  - N^{3}LO distributions

Chen, Li, HSS, Wang (1912.13001)

NNLO vs N^{3}LO



3 top mass approx.



- Scale is again significantly reduced from NNLO to N^{3}LO
- Missing top-quark mass effect at large mhh 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 3% (2%) at 13 (100) TeV. PDF uncertainty is bigger than scale uncertainty.
- The 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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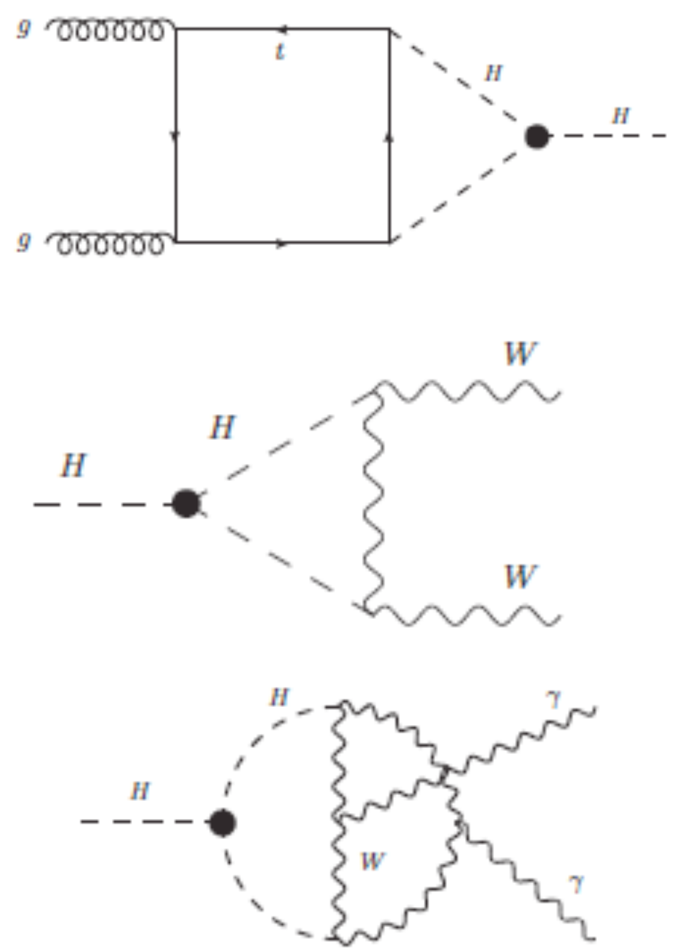
Thank you for your attention !

BACKUP

THE INDIRECT PROBE

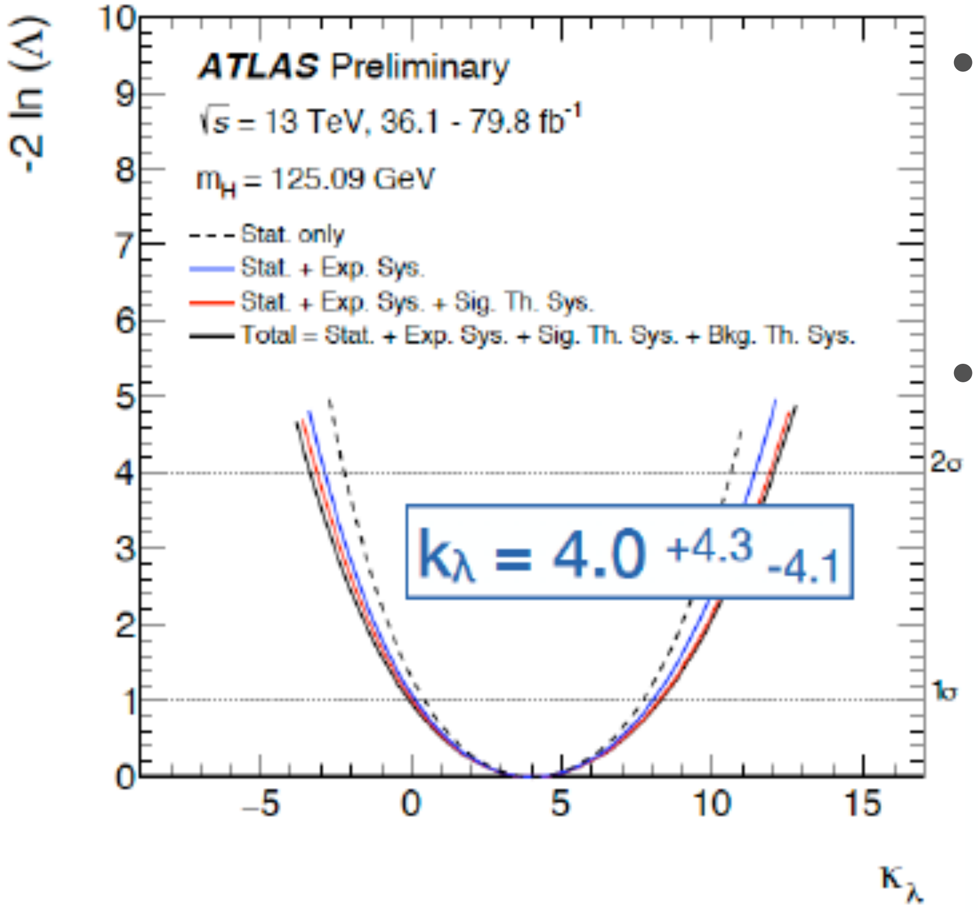
arXiv:1709.08649



- Exploit the dependence of single-Higgs production and decay rates on λ_{hhh} entering via loops

- One can perform a one-parameter fit assuming other couplings being SM like.

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{Br}^f}{\sigma_{\mathrm{SM},i} \cdot \mathrm{Br}^f_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$
$$\mu_i = 1 + \delta\sigma_i(\lambda_{hhh})$$
$$\mu^f = 1 + \delta\mathrm{Br}^f(\lambda_{hhh})$$



- Similar constraints than from hh measurements.

- However, it is limited by systematics. Then, less room to be improved at HL-LHC than hh.

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
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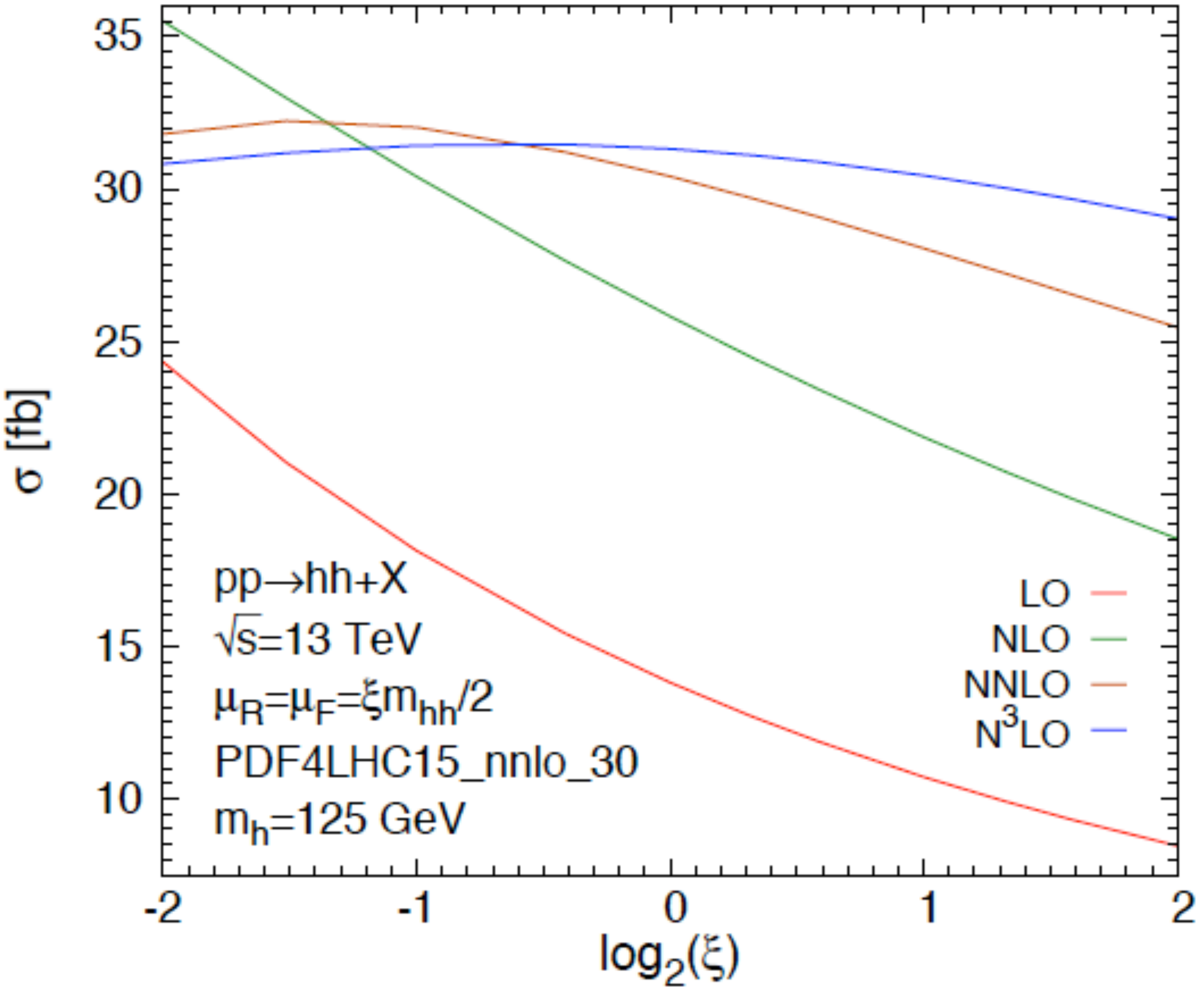
Chen, Li, HSS, Wang (1909.06808)



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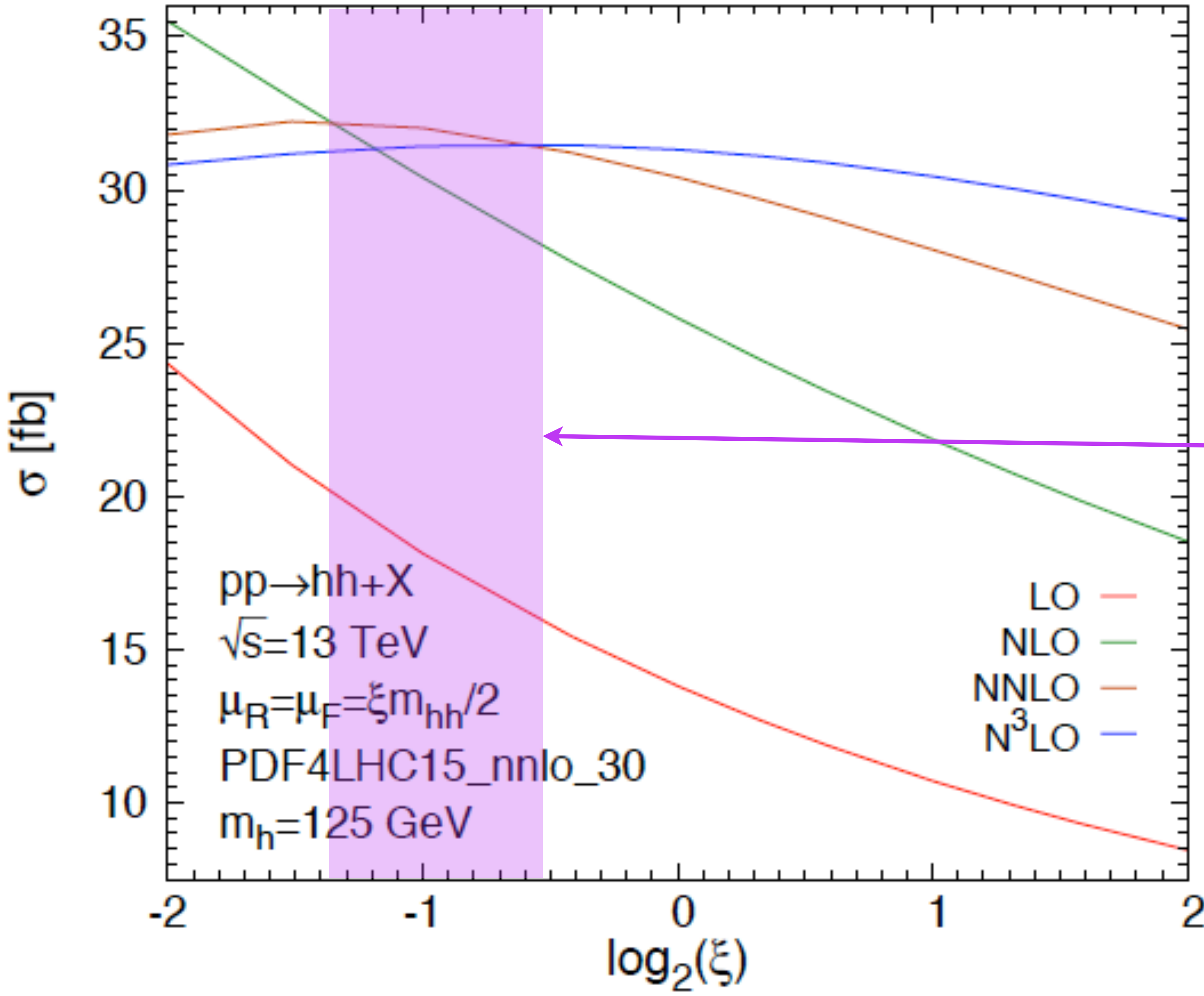


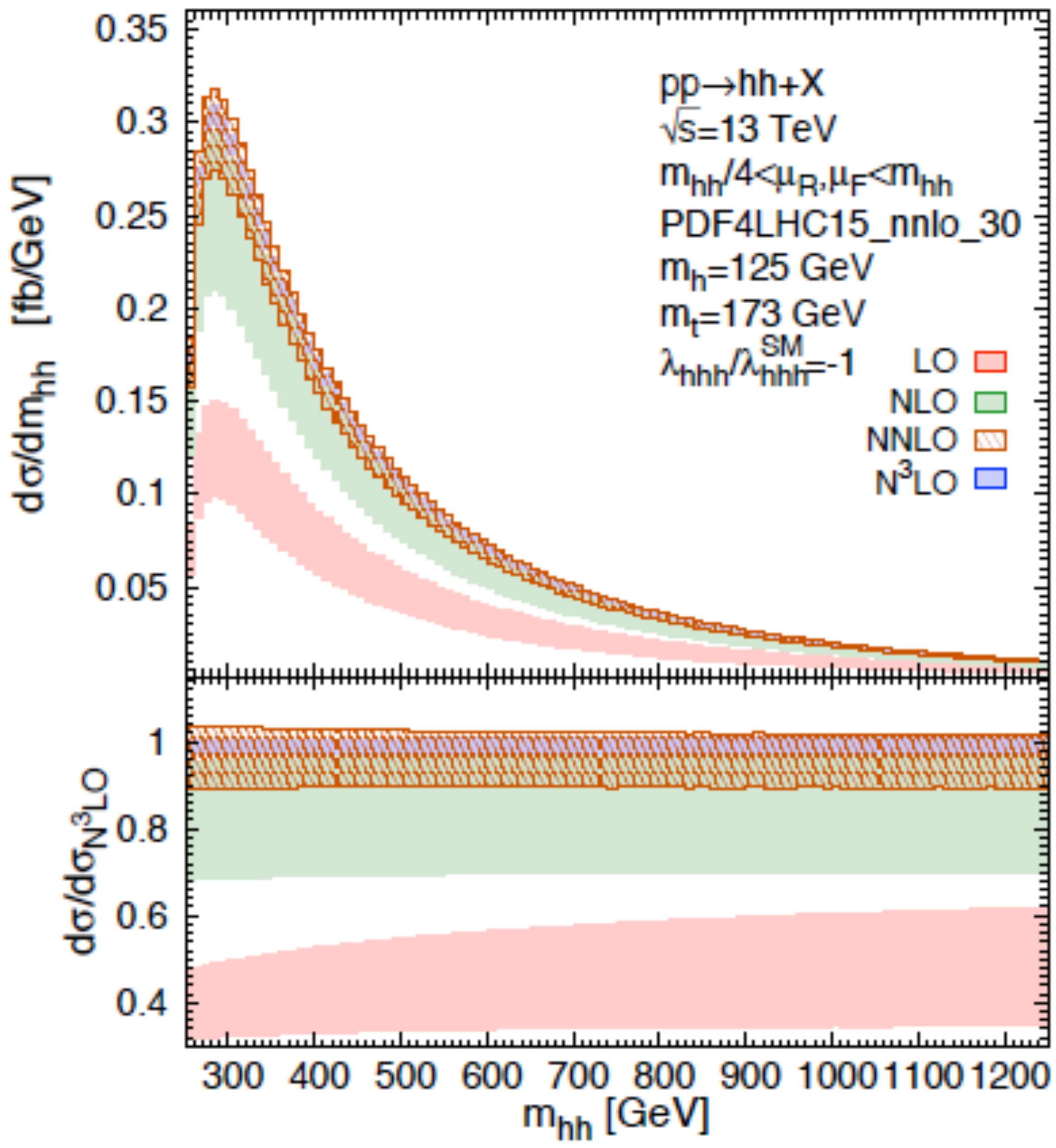
The optimal scale choices

HIGGS PAIR GLUON FUSION PRODUCTION

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

Chen, Li, HSS, Wang (1912.13001)

$$\kappa_\lambda = -1$$



HIGGS PAIR GLUON FUSION PRODUCTION

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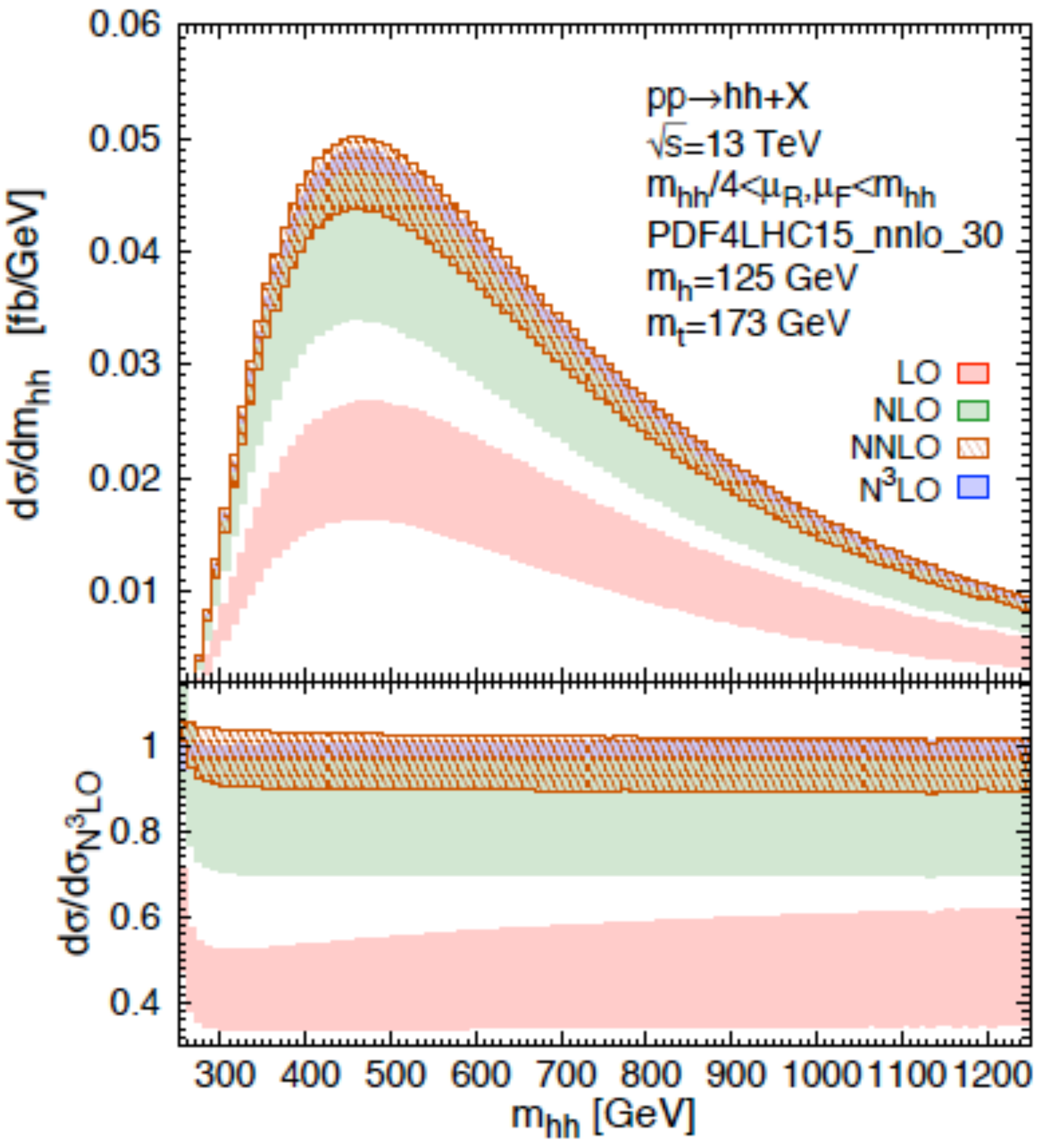
Chen, Li, HSS, Wang (1912.13001)

$$\kappa_\lambda = 1$$



HIGGS PAIR GLUON FUSION PRODUCTION

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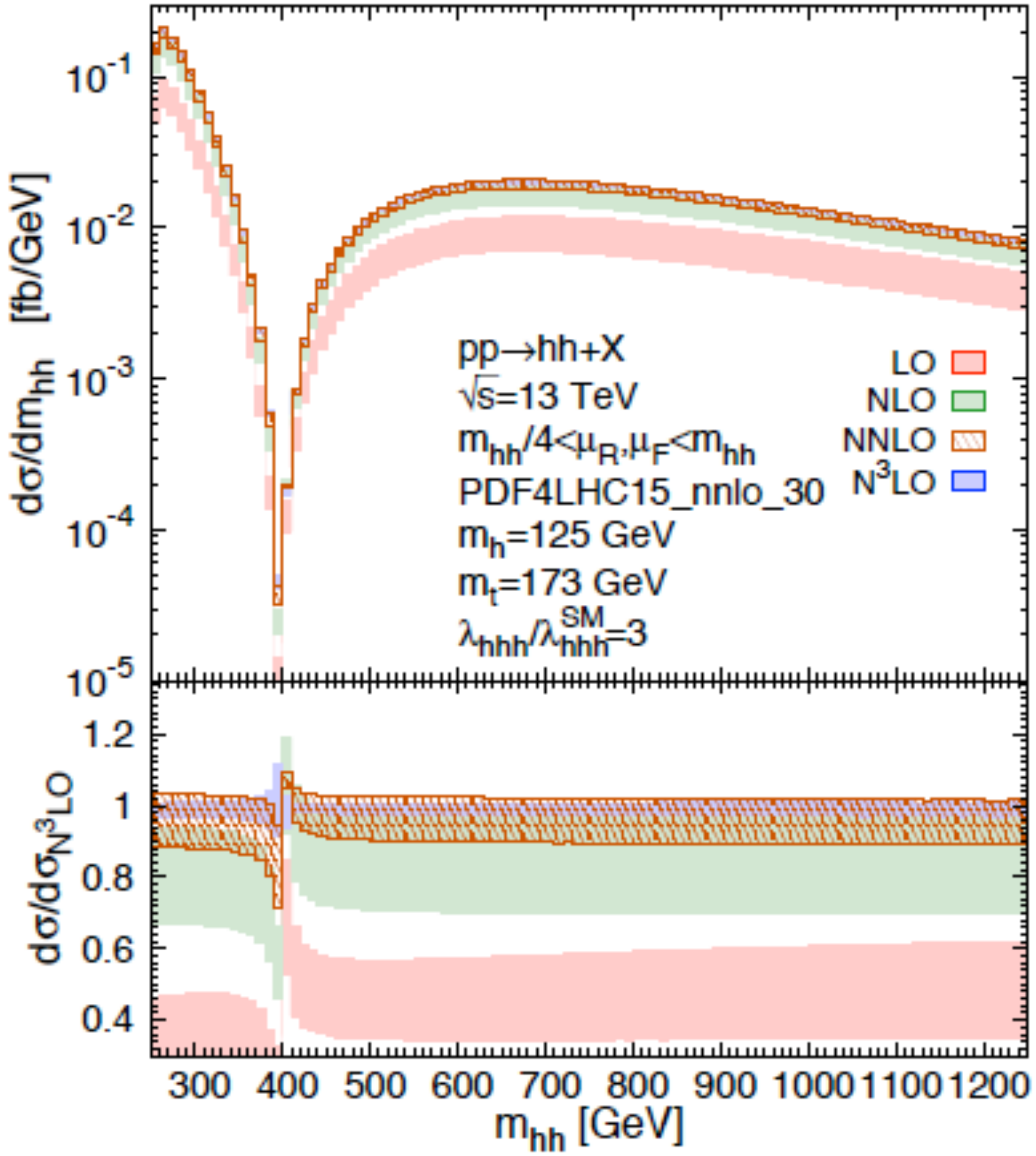
Chen, Li, HSS, Wang (1912.13001)

$$\kappa_\lambda = 3$$



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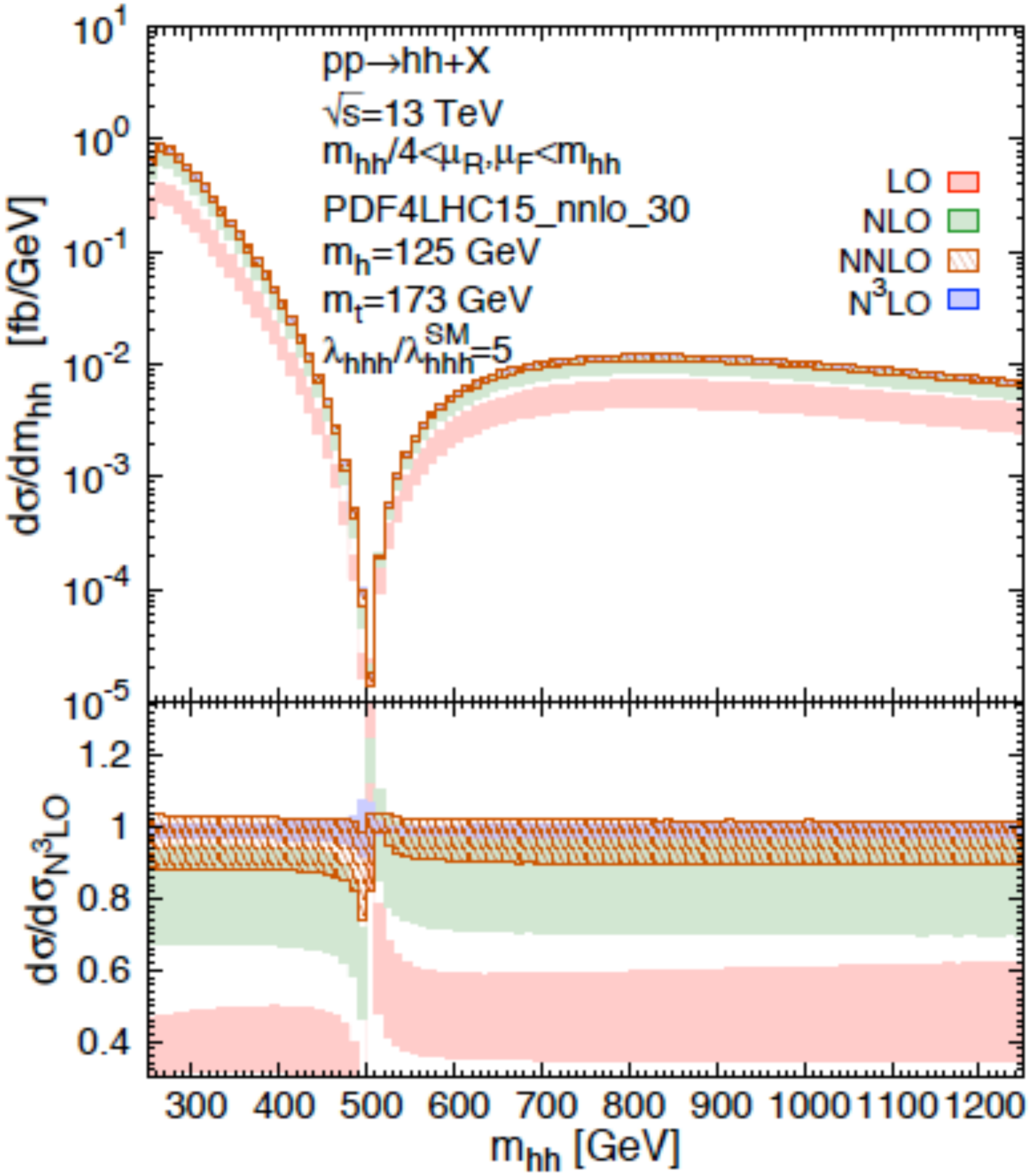
Chen, Li, HSS, Wang (1912.13001)

$$\kappa_\lambda = 5$$



HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
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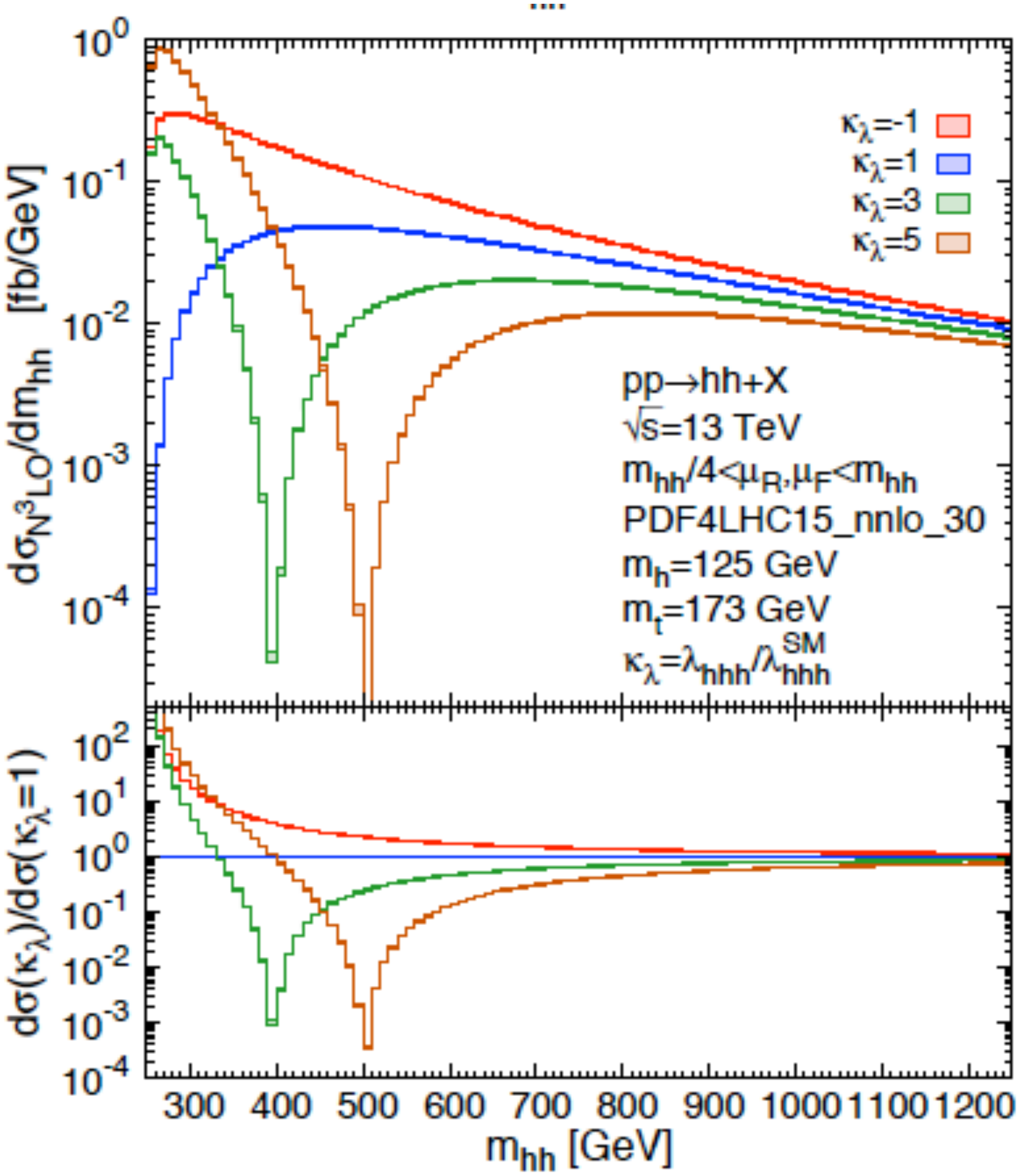
Chen, Li, HSS, Wang (1912.13001)

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

....



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

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

$$\begin{cases} \kappa_\lambda<0 & \searrow \quad \text{w} \quad m_{hh}\uparrow \\ 0<\kappa_\lambda\le 1 & \nearrow \quad \text{w} \quad m_{hh}\uparrow \\ \kappa_\lambda>1 & \text{zero when } m_{hh}=\sqrt{1+3\kappa_\lambda}\,m_h \end{cases}$$

- Potential useful in BSM searches

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
  - N^3LO other differential distribution Chen, Li, HSS, Wang (1912.13001)

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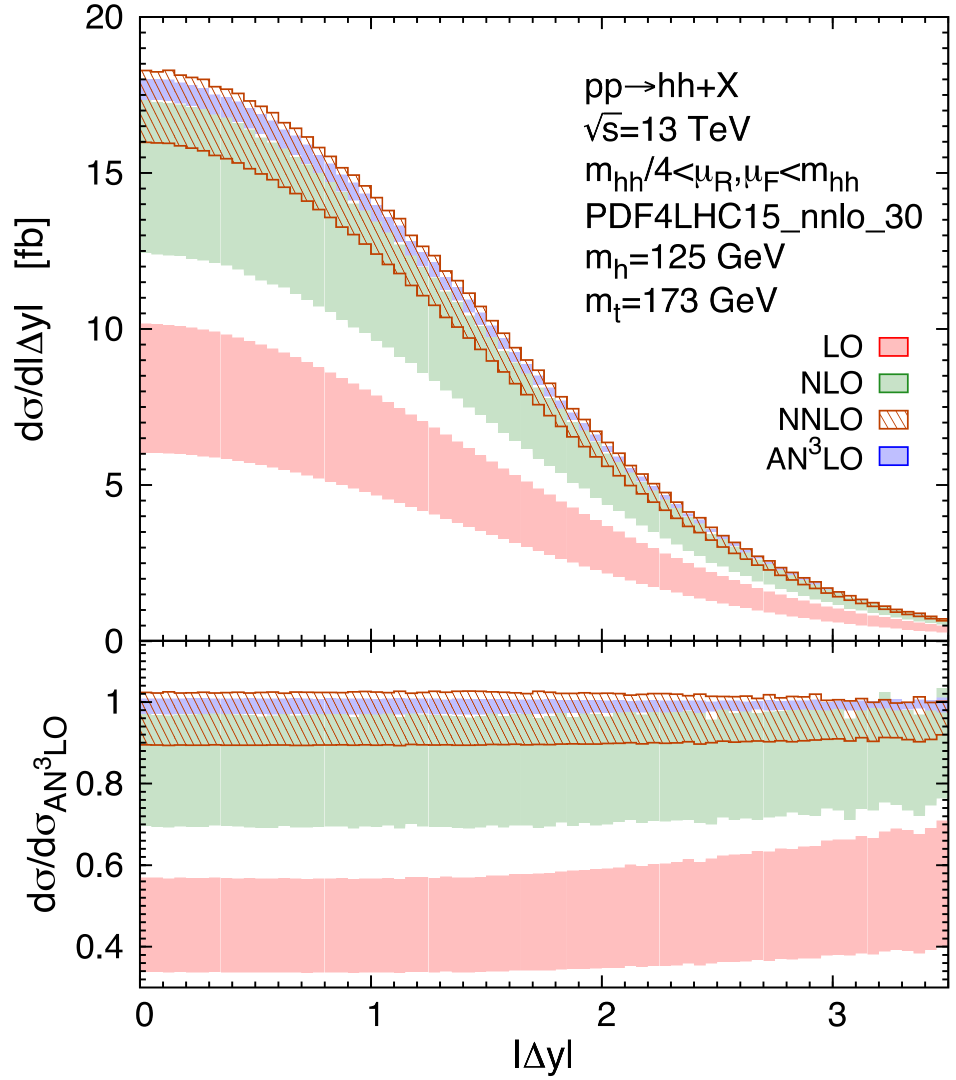
    - Impossible as we are even lacking of fully-differential ggH

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
  - N^3LO other differential distribution — Chen, Li, HSS, Wang (1912.13001)
    - Impossible as we are even lacking of fully-differential ggH
    - but ... possible with some approximations

e.g. rapidity difference

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



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

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