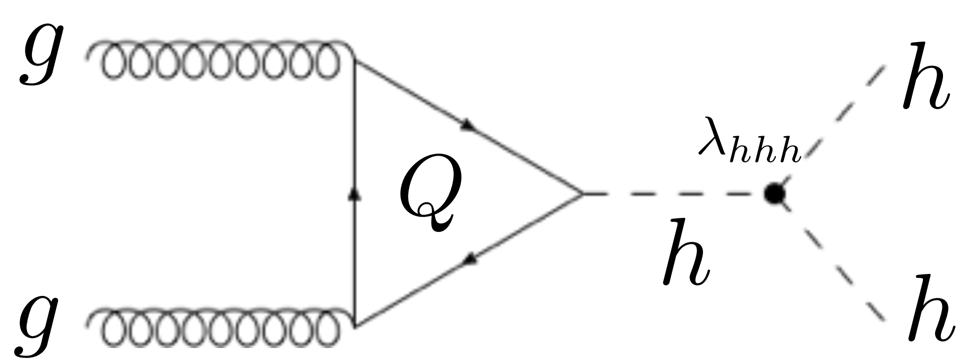
Higgs Boson Pair Production Via Gluon Fusion at N^{3}LO in QCD



Hua-Sheng Shao

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

IHEP, Beijing

14 October 2019

Wednesday, October 9, 19

THE BIG QUESTIONS IN FUNDAMENTAL PHYSICS

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

M. Mangano's talk at Higgs Hunting 2019 in Paris

- **Data driven**
  - Dark matter
  - Neutrino masses
  - Matter vs anti-matter asymmetry
  - Dark energy
  - ...
- **Theory driven**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - ...

The path to answer these questions is ambiguous.

One question stemming from the LHC appears to single out a unique defined direction ...

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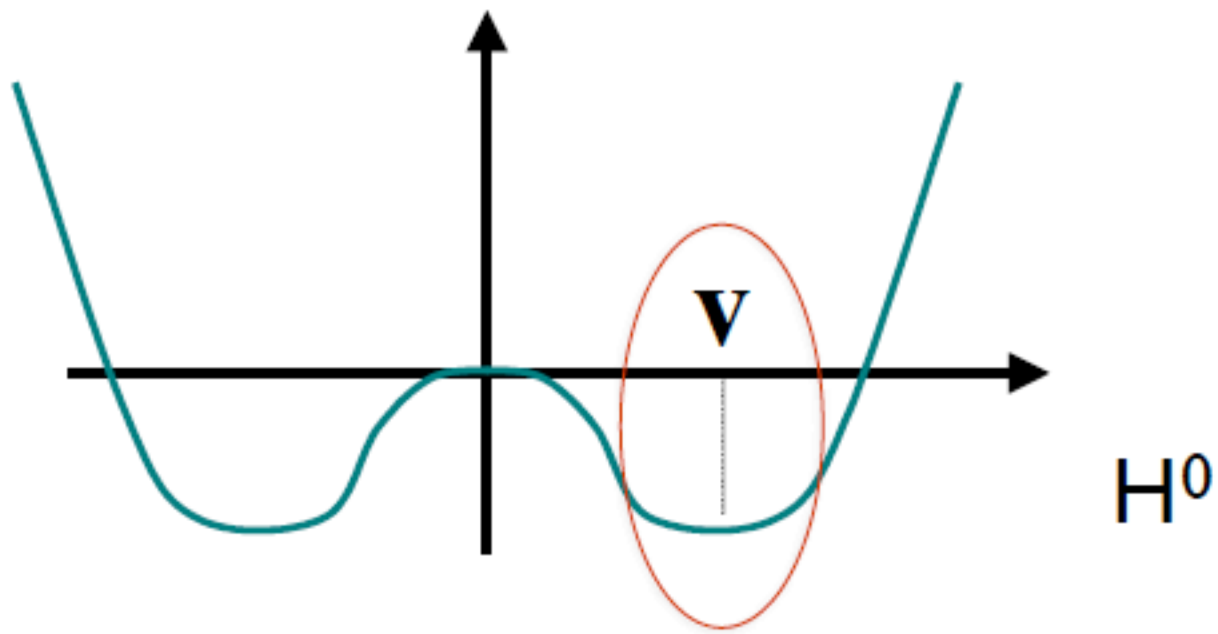

$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

- Th

ttern)

We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

One ... ection ...

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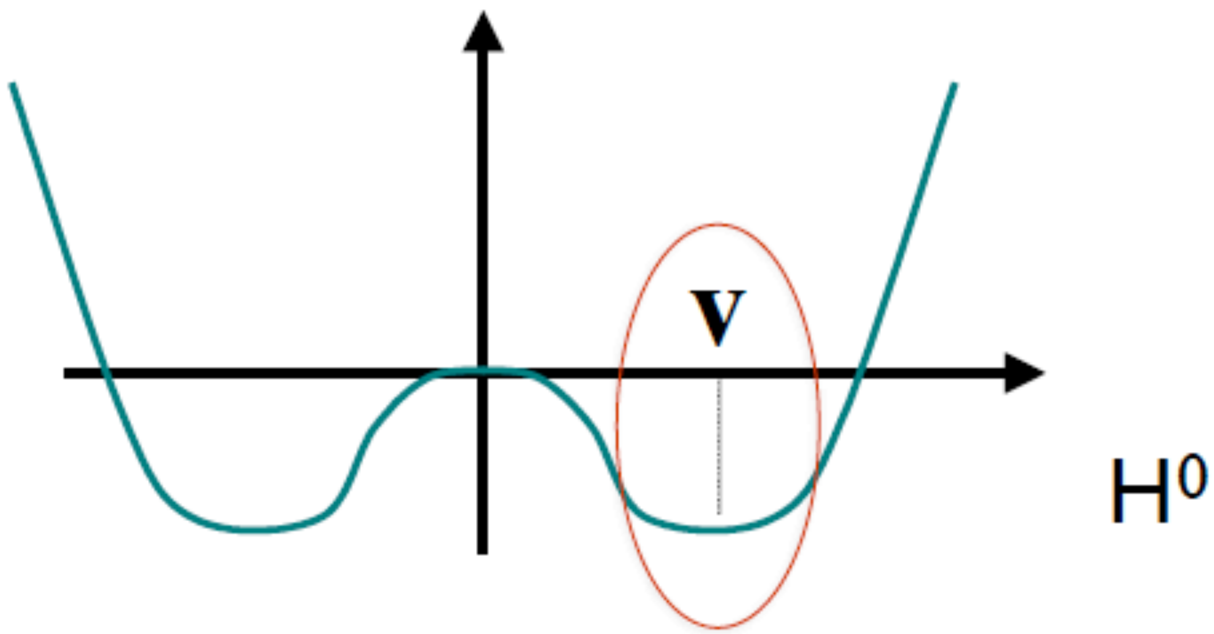

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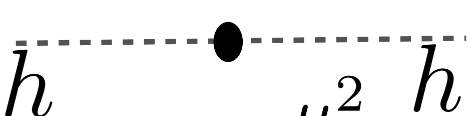

$$m_h^2 = \frac{\mu^2}{2}$$

Who ordered that ?

$$m_h = 125.18 \pm 0.16 \text{ GeV}$$

PDG2018

We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

One (… ection ...

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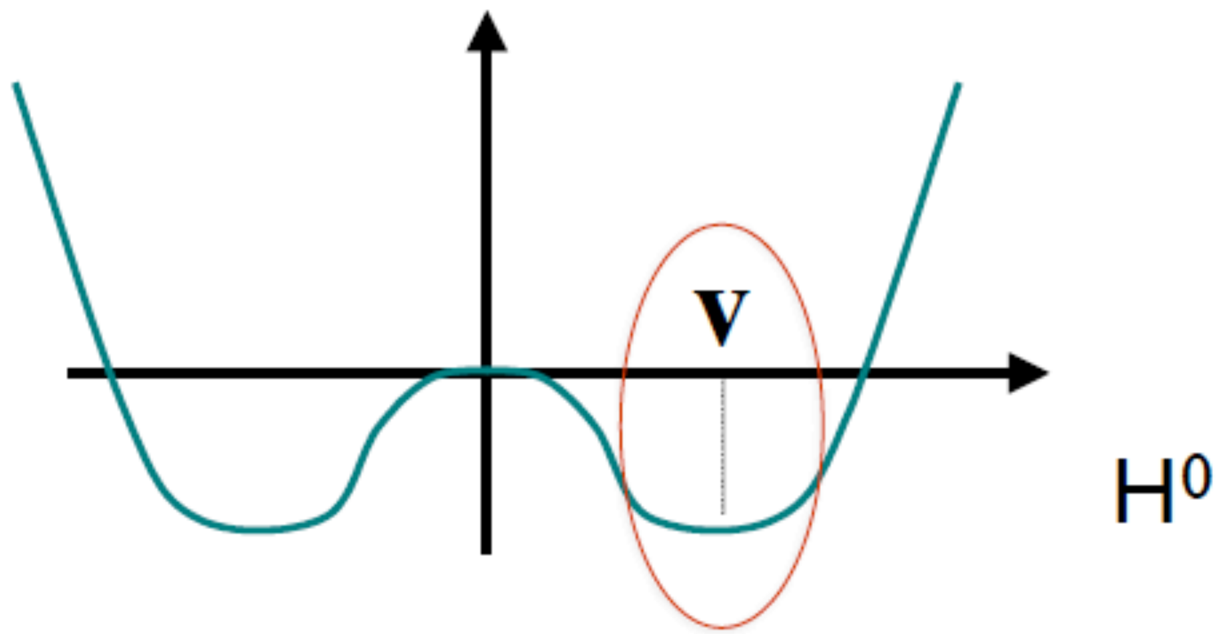


- **Th**

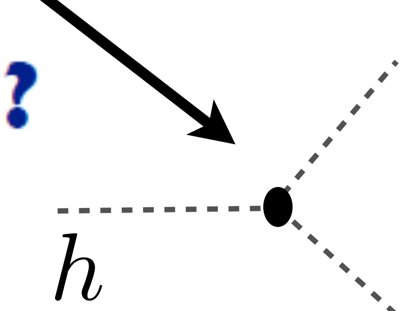
ttern)

$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

$$-5.0 < \frac{\lambda_{hhh}}{\lambda_{hhh,\mathrm{SM}}} < 12.1$$

ATLAS (1906.02025)



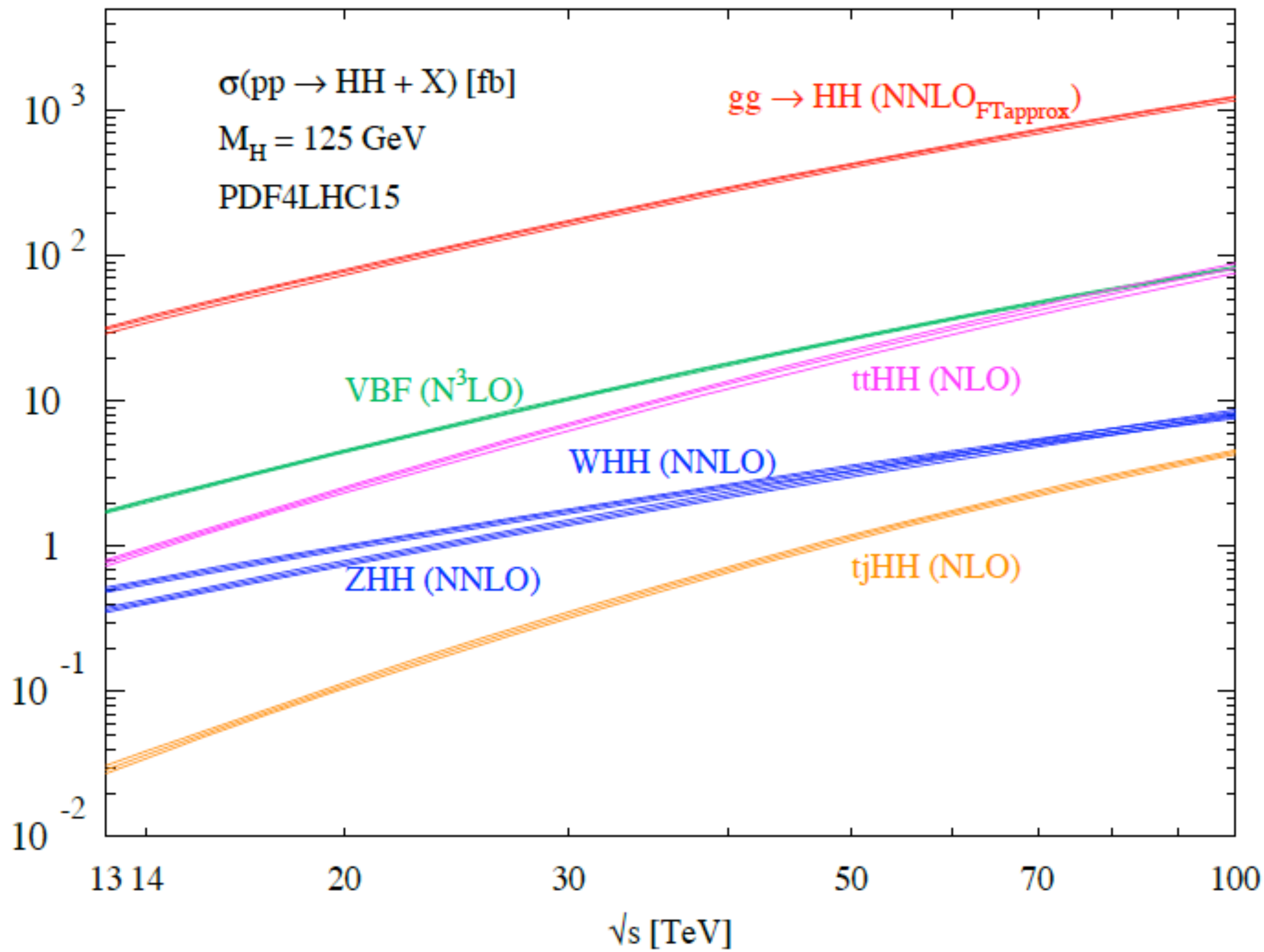
$$\lambda_{hhh} = \sqrt{\frac{\lambda}{2}}\frac{m_h}{2}$$

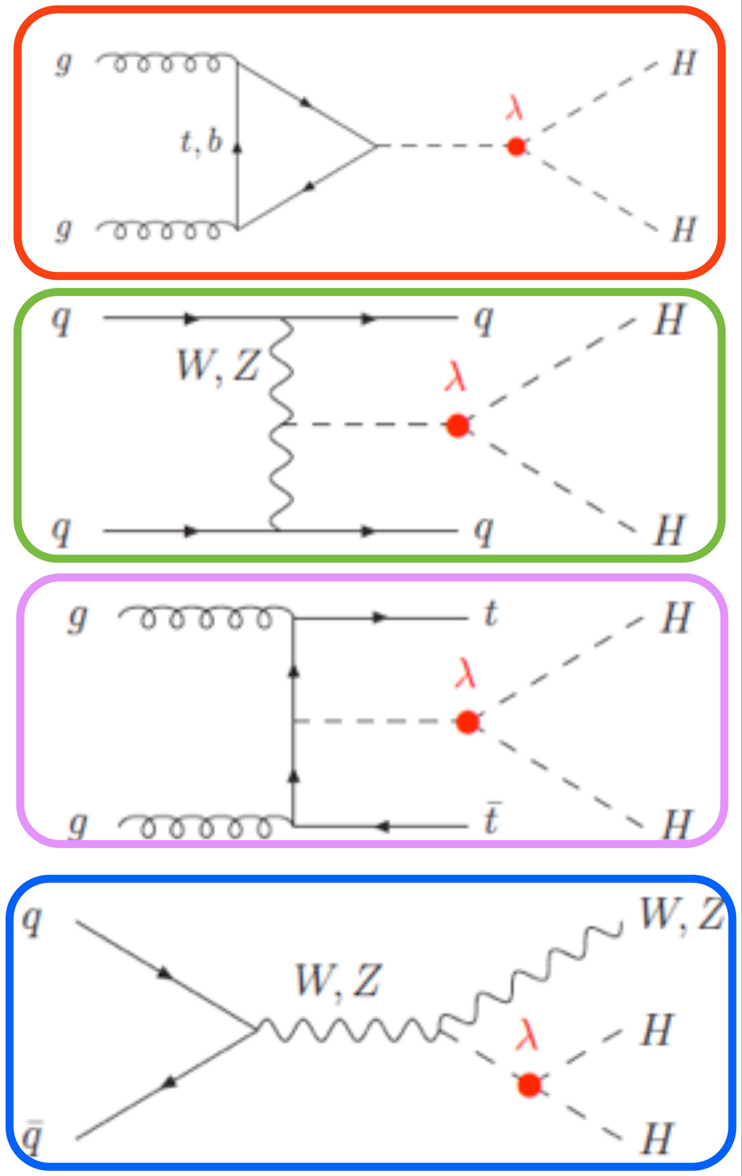
We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

One ... *ection ...*

HIGGS BOSON PAIR PRODUCTION

arXiv:1910.00012





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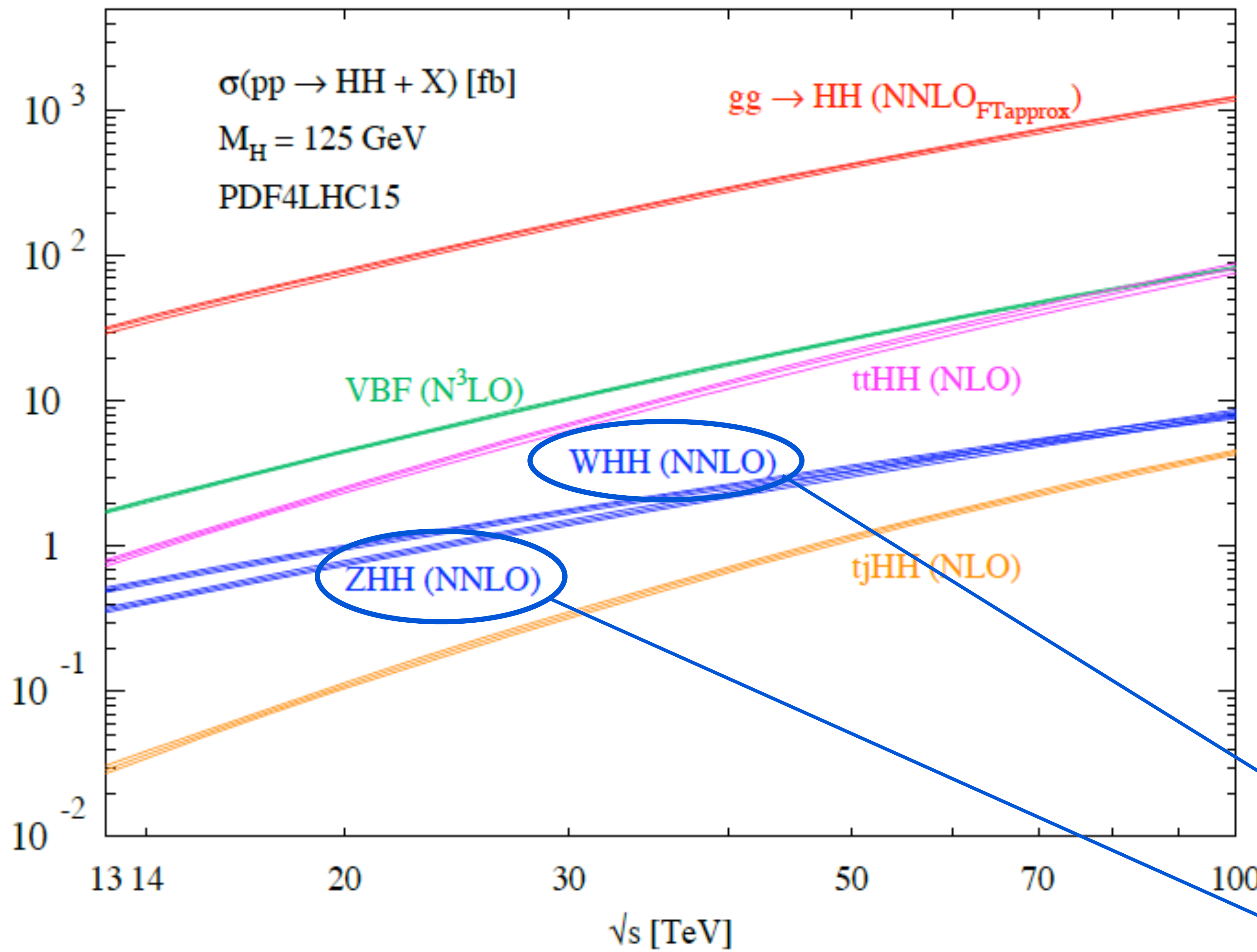

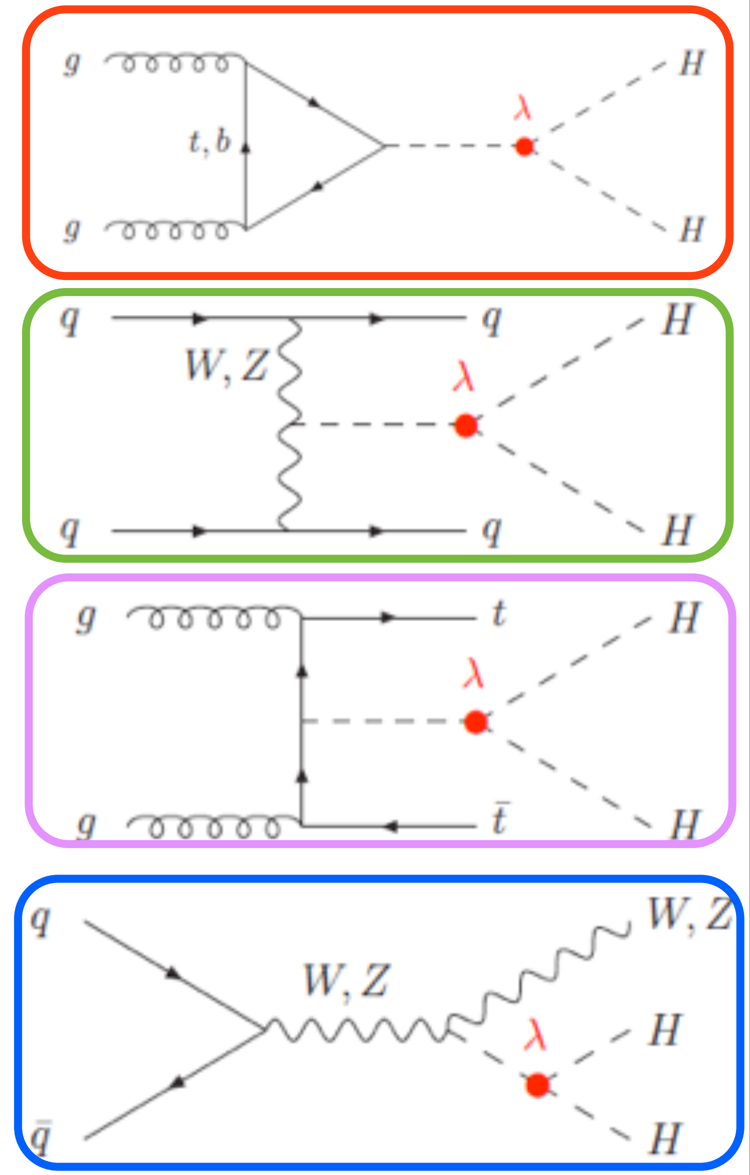

Li & Wang PLB'17

Li & Li & Wang PRD'18

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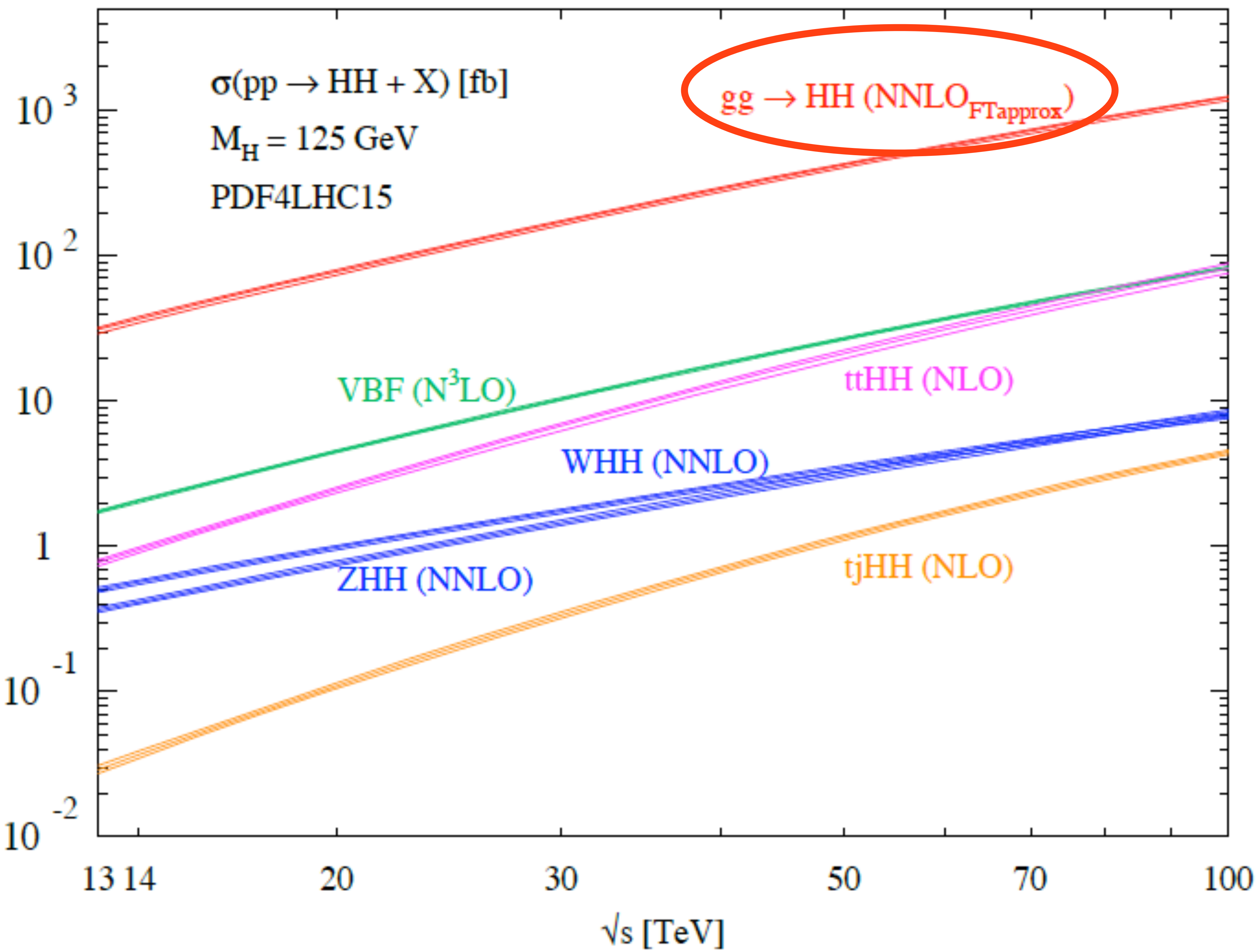
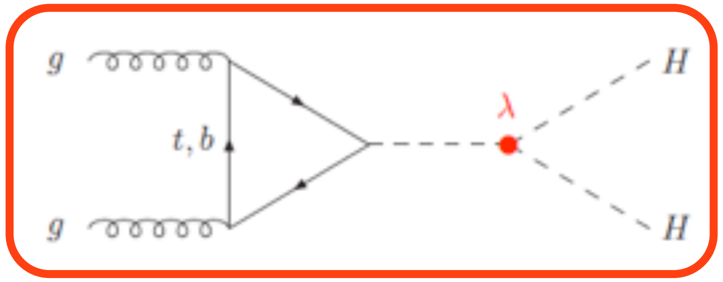
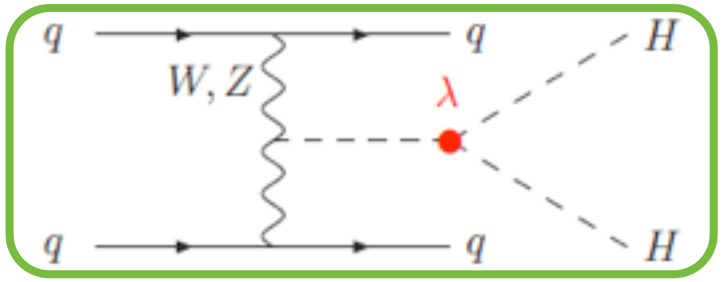
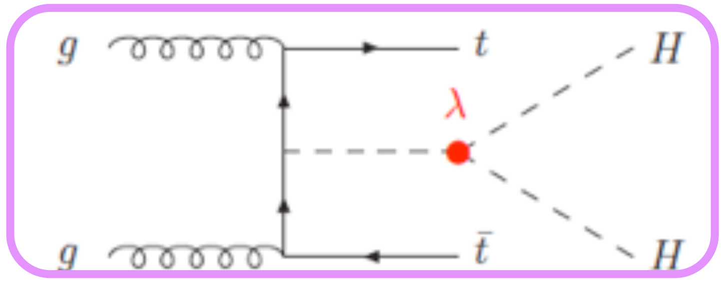
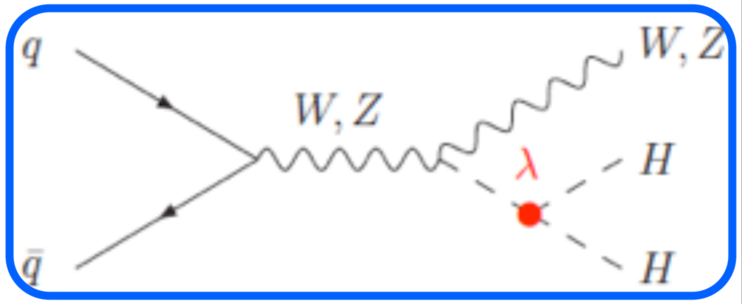


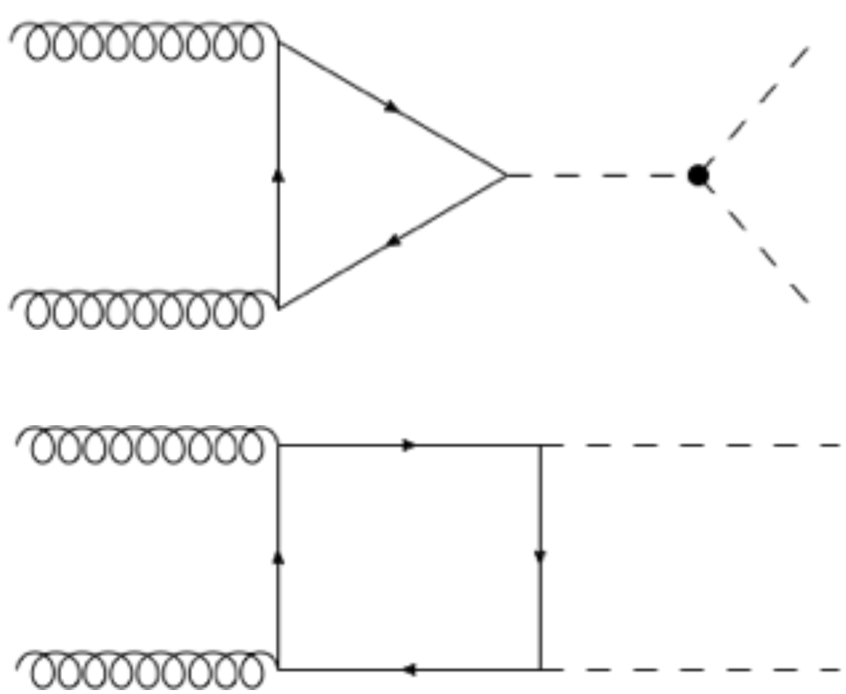








- **Full top-quark mass dependence**
  - Leading order (LO) is a loop-induced process



HIGGS PAIR GLUON FUSION PRODUCTION

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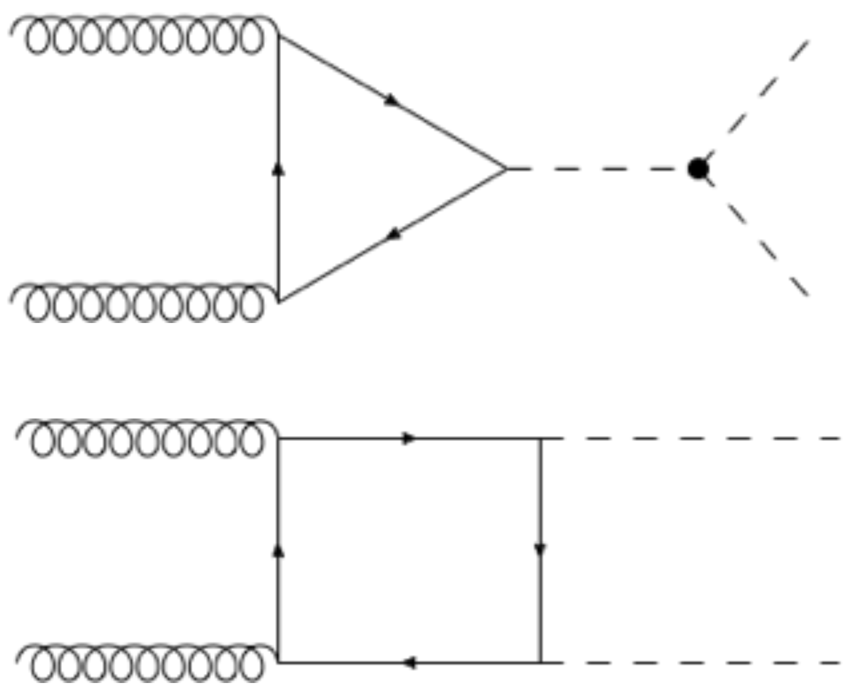
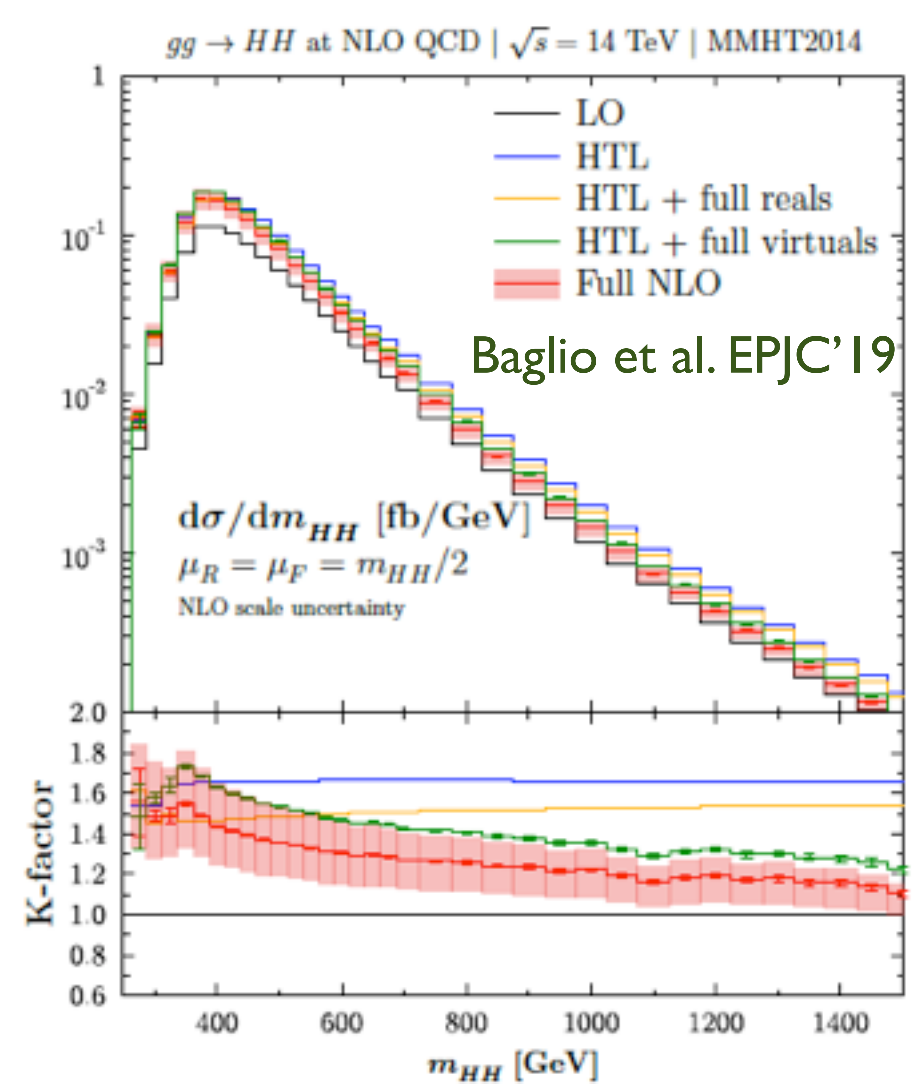
Borowka et al. PRL'16, JHEP'16; Baglio et al. EPJC'19





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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  - ... even after matching to parton showers (i.e. NLO+PS)

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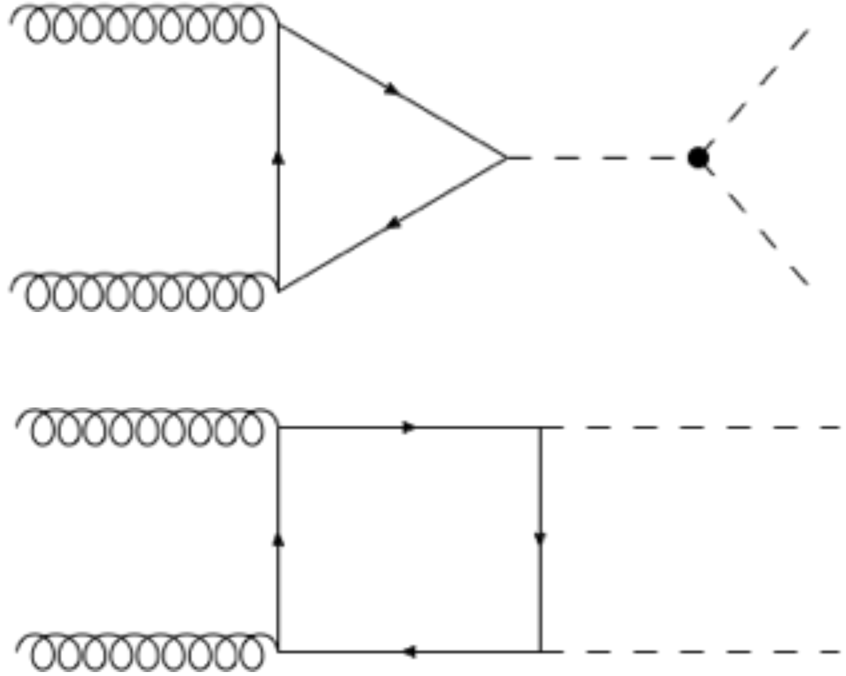

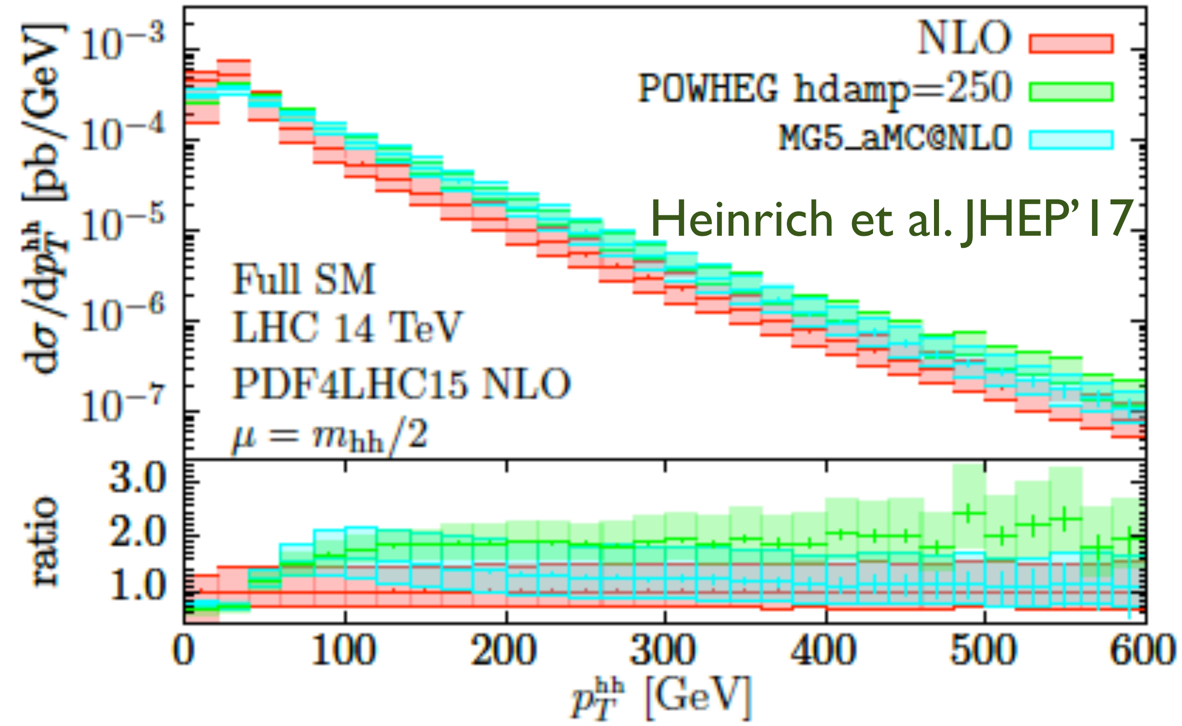

Matching scheme dependence starts to be significant at large p_T^{hh}

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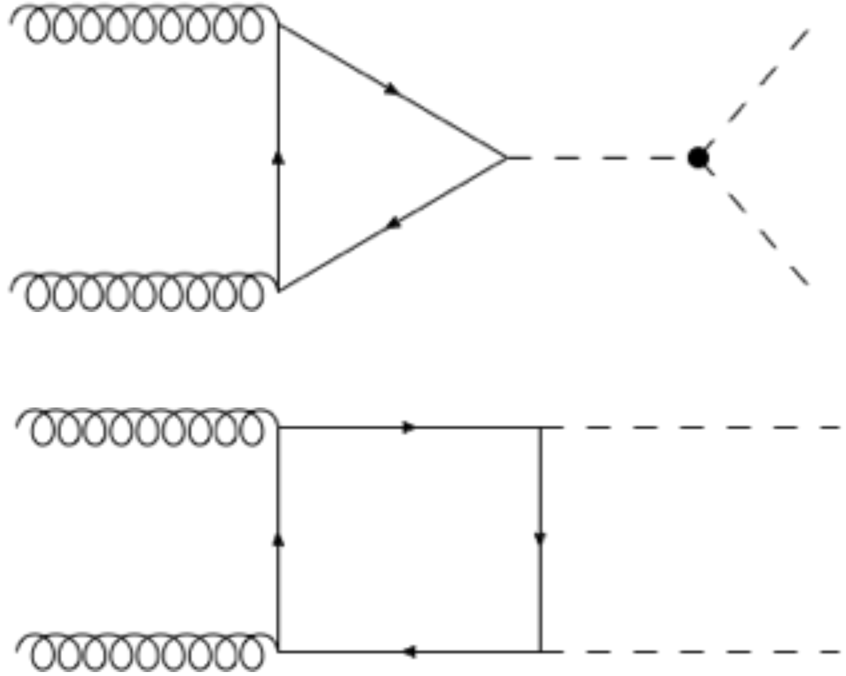

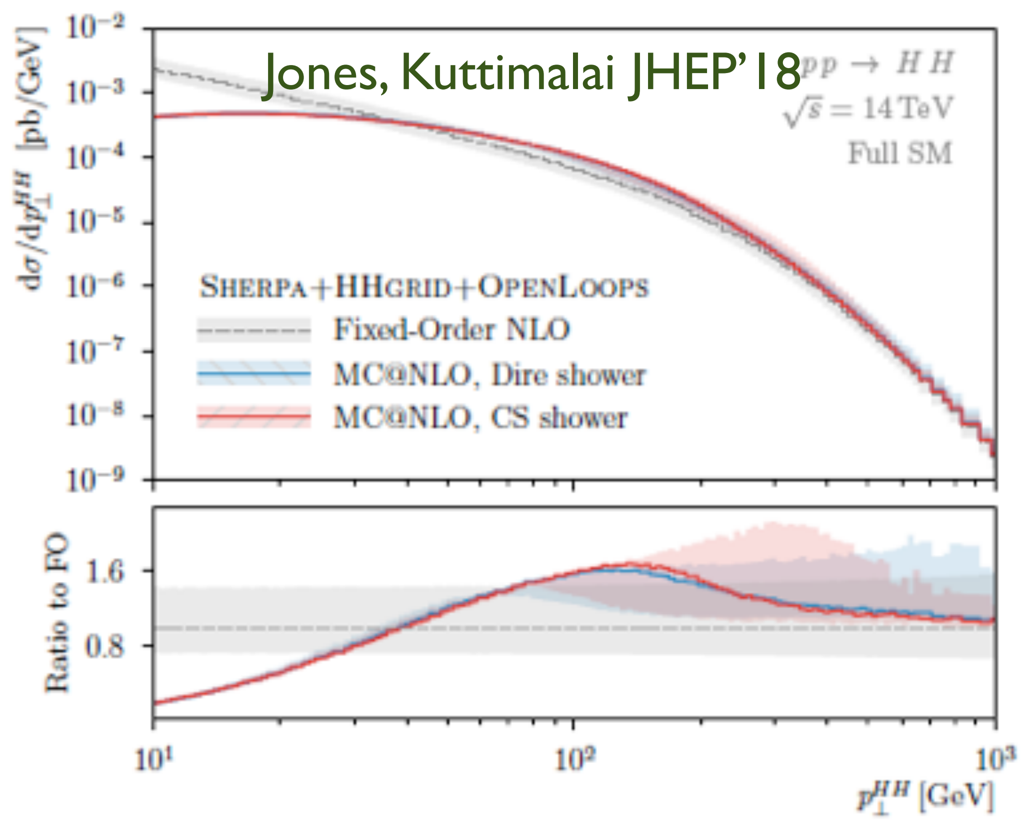

Shower scale uncertainty is also significant at large p_T^{hh}

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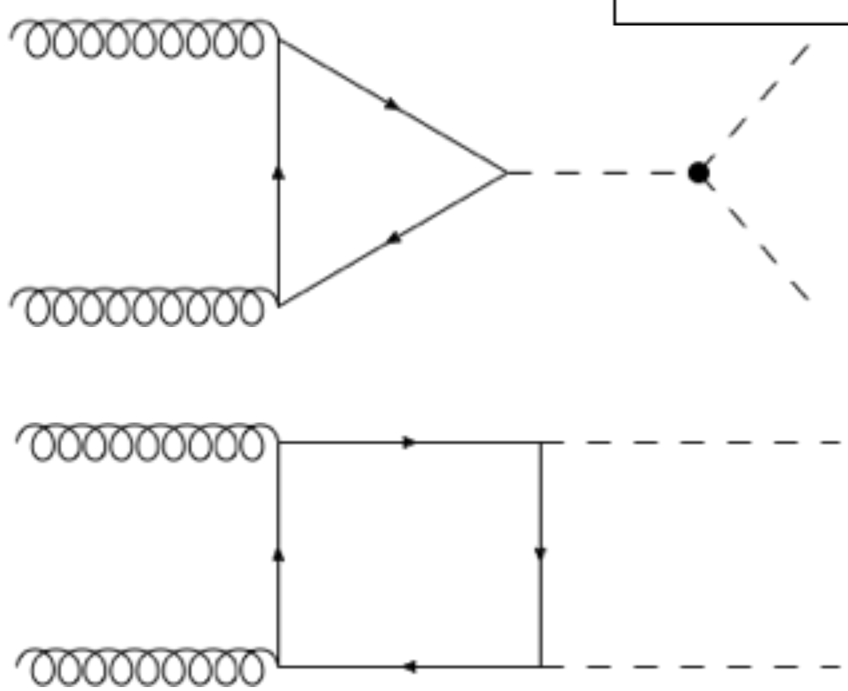
  - Scale unc. (>10%)

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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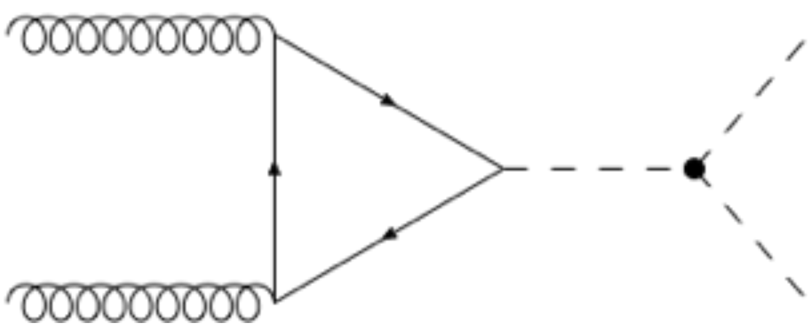

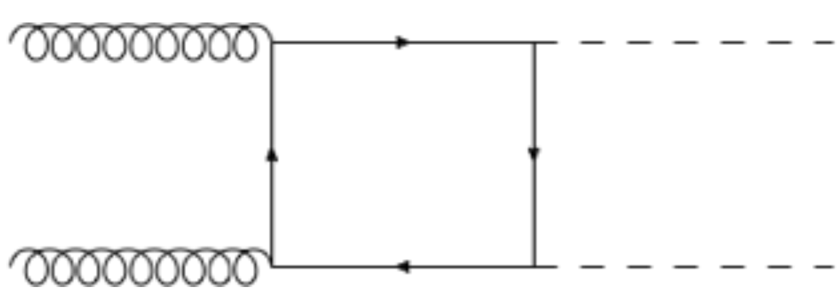

$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=300\text{ GeV}} = 0.02978(7)^{+6\%}_{-34\%}\text{ fb/GeV},$$
$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=400\text{ GeV}} = 0.1609(4)^{+0\%}_{-13\%}\text{ fb/GeV},$$
$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=600\text{ GeV}} = 0.03204(9)^{+0\%}_{-30\%}\text{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

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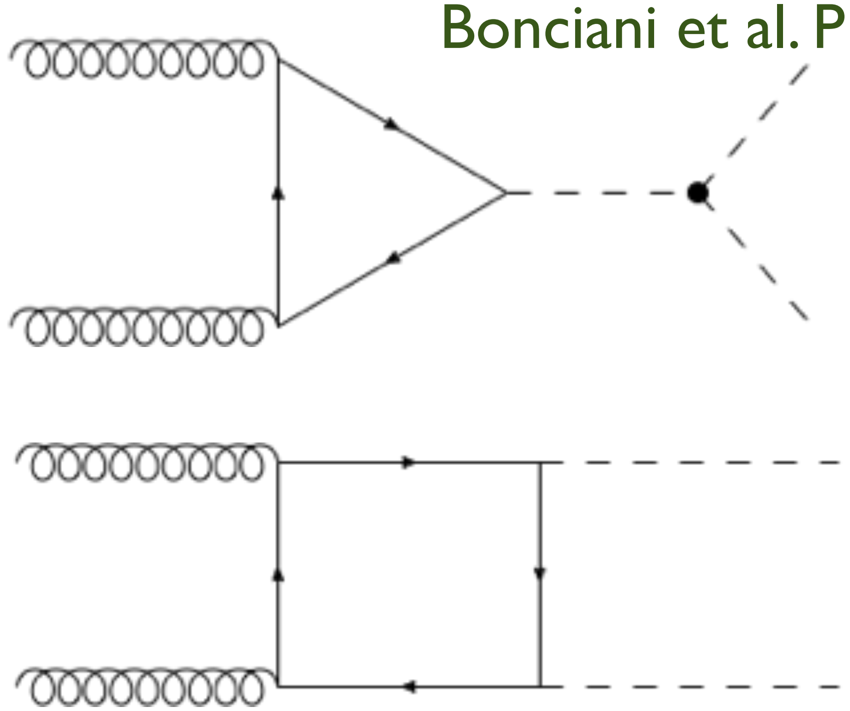
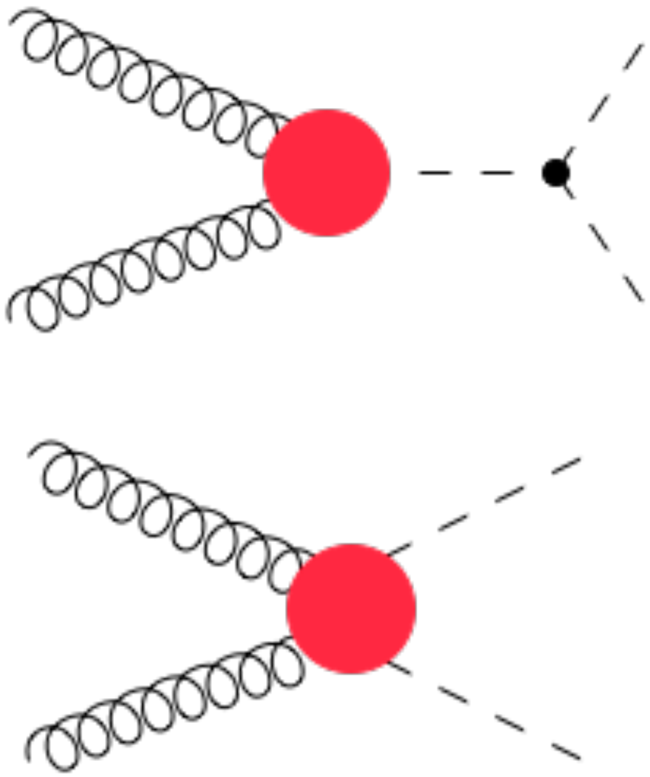
  - Scale unc. (>10%)
  - ... and large top-quark mass scheme dependence
  - A lot of analytical approximations (well-motivated to deepen understanding)

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



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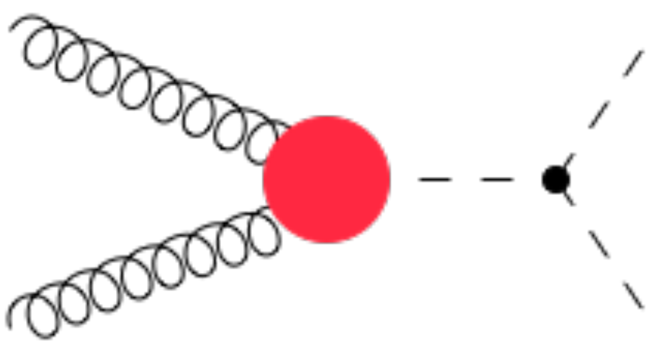
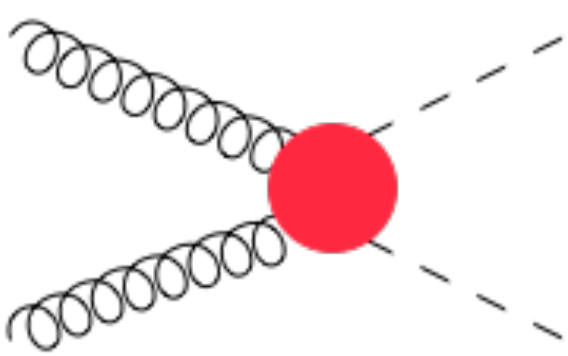
  - The Wilson coefficients C_h and C_{hh} are known up to 4 loops

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





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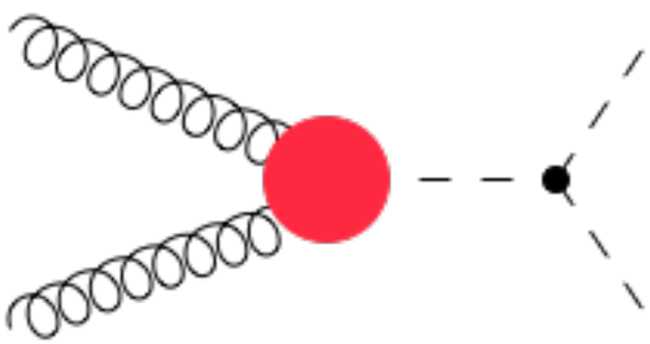
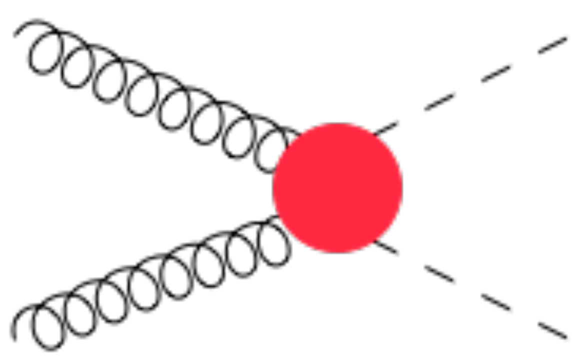
    Schroder and Steinhauser JHEP'06;Baikov et al. PRL'17; Spira JHEP'16; Gerlach et al. JHEP'18
  - Technically, it is much easier to achieve high precision
    - NLO was 20 years old Dawson PRD'98
    - NNLO was known as well Florian and Mazzitelli PLB'13,PRL'13; Grigo et al. NPB'14; Florian et al. JHEP'16
    - Threshold resummation Shao et al. JHEP'13; Florian and Mazzitelli JHEP'15, JHEP'18
    - $\text{NLO}_{\text{FTapprox}}$: 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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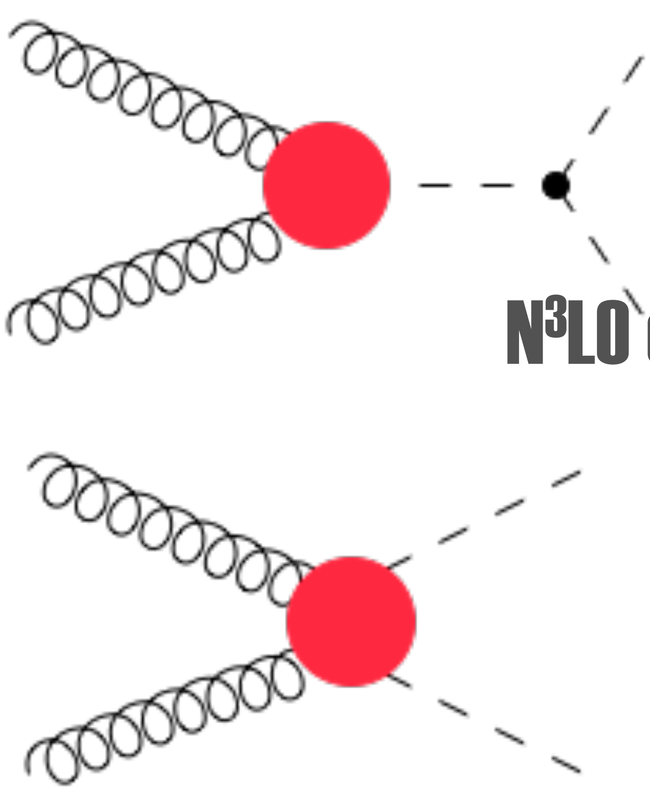
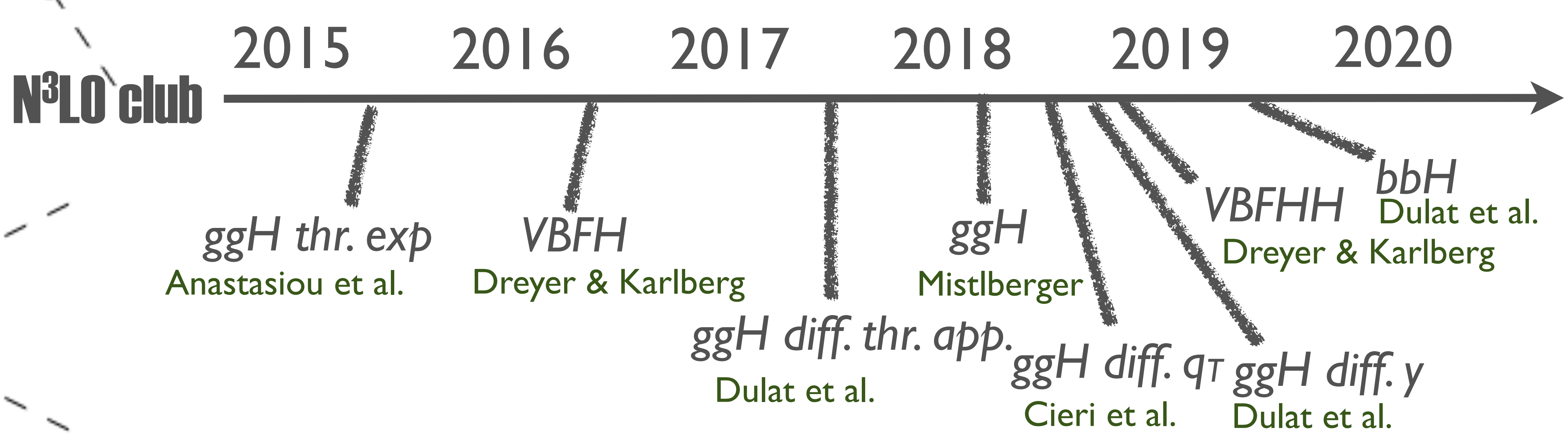


Our aim is to push the calculation to N^3LO !



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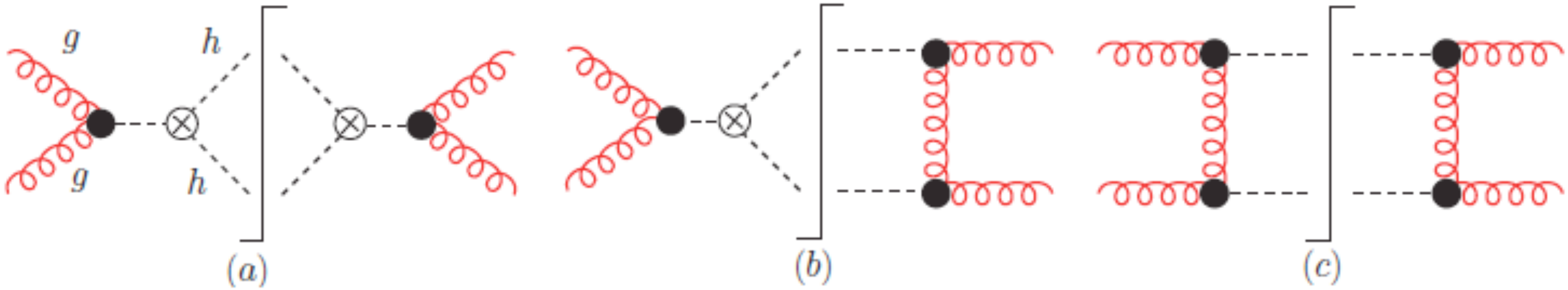

	LO	NLO	NNLO	N^3LO
total	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
a	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
b	0	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
c	0	0	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$

Chen, Li, HSS, Wang (1909.06808)

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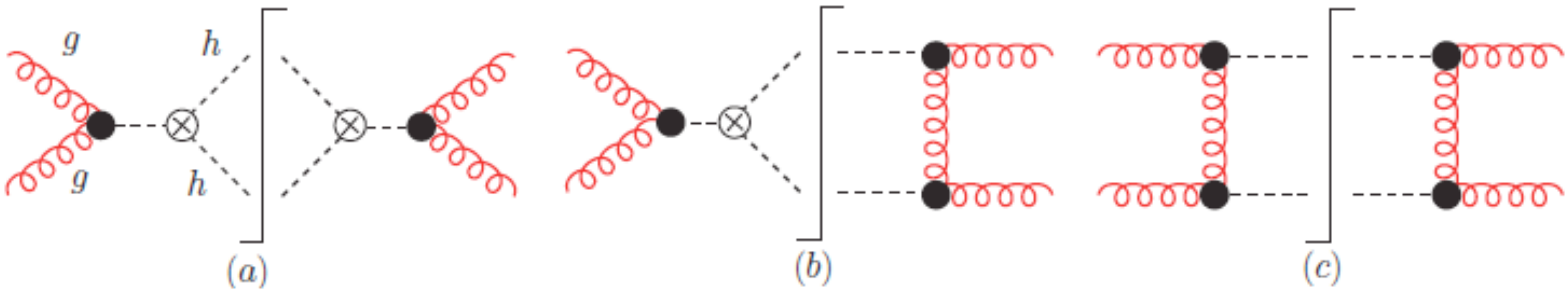

Chen, Li, HSS, Wang (1909.06808)

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b	0	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
c	0	0	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$

- 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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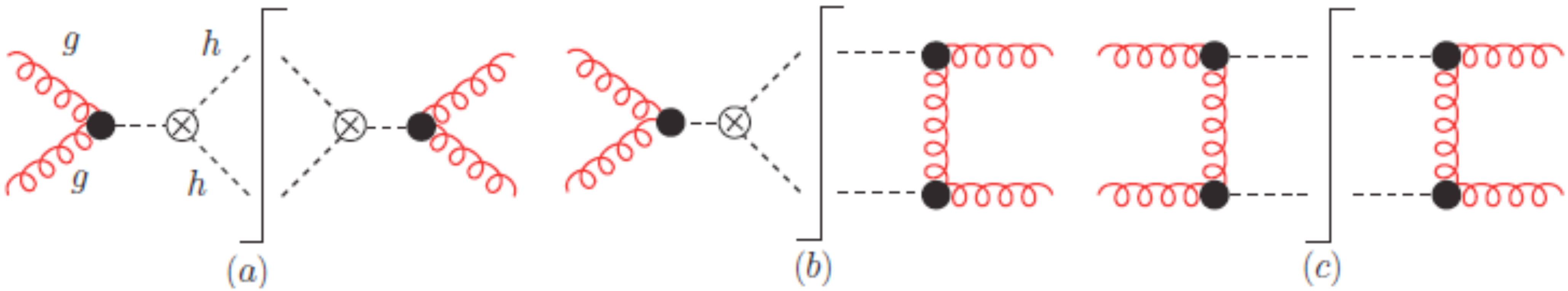

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From iHixs2

Dulat et al. CPC'18

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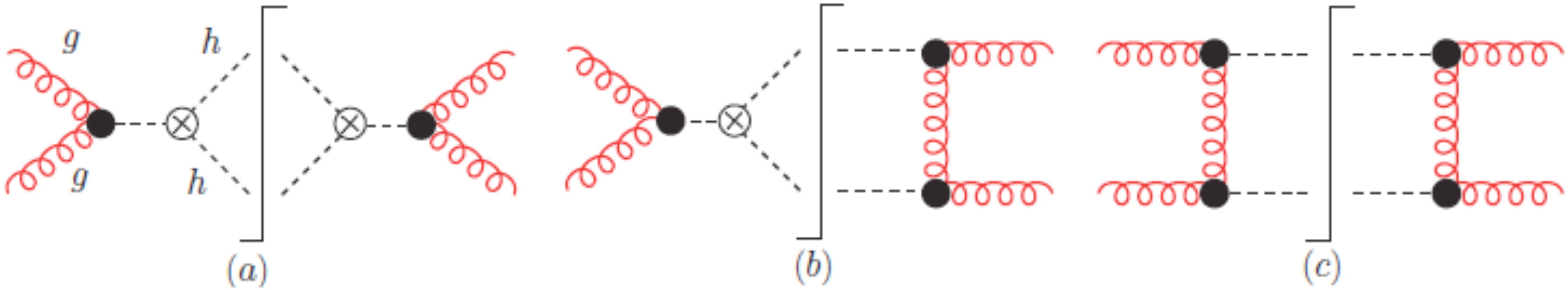

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Chen, Li, HSS, Wang (1909.06808)

HIGGS PAIR GLUON FUSION PRODUCTION

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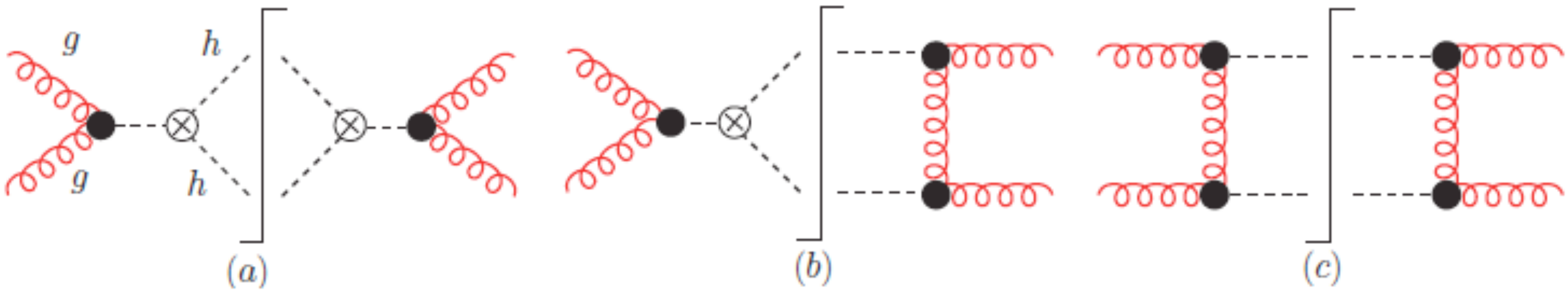

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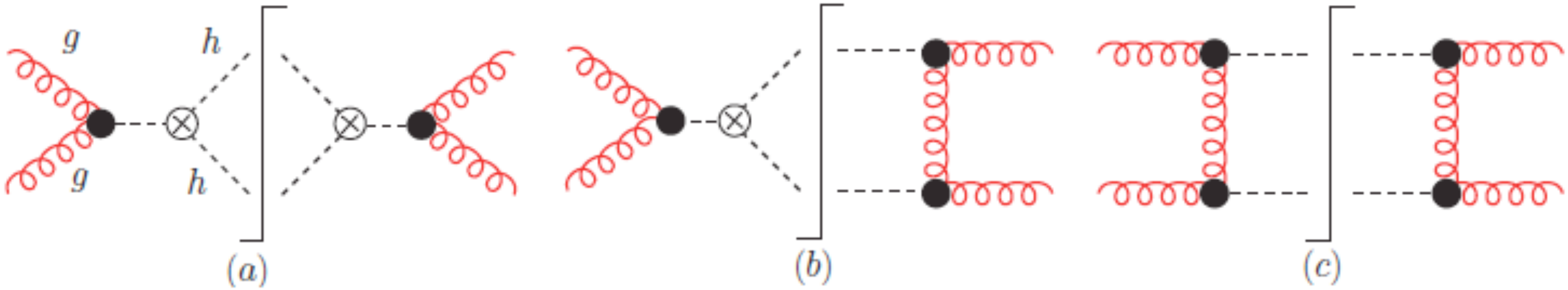

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HIGGS PAIR GLUON FUSION PRODUCTION

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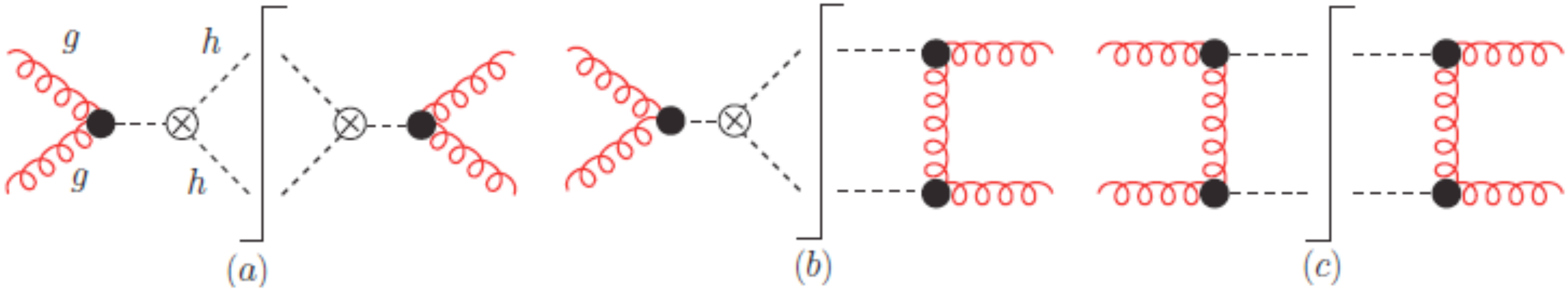

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$\mathcal{H}$ hard function

two-loop amplitude

Banerjee et al., JHEP'18

new one-loop amplitude

Wednesday, October 9, 19

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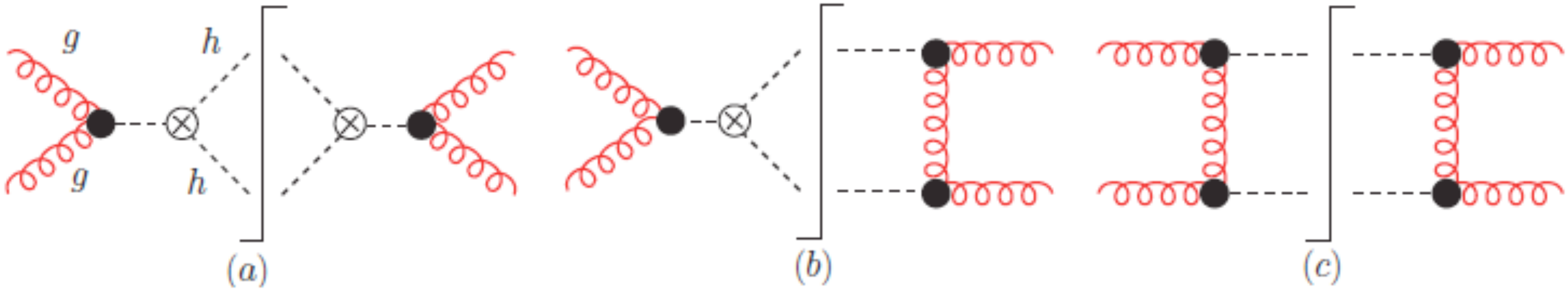

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$\mathcal{B}_i$ TMD beam function

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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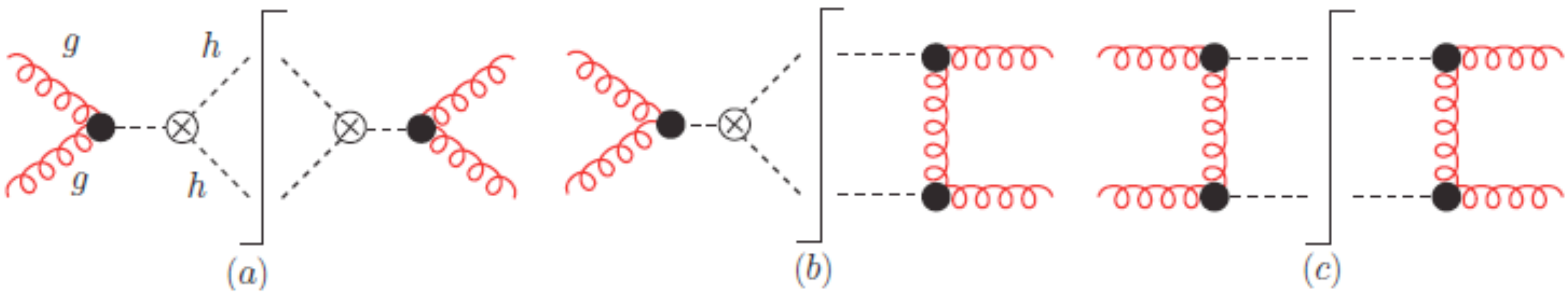

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MG5_aMC: $d\sigma^{b,{\rm NNLO}}_{hh}\Big|_{p_T^{hh}>p_T^{\rm veto}} = d\sigma^{b,{\rm NLO}}_{hh+j}$

New and validated NLO model

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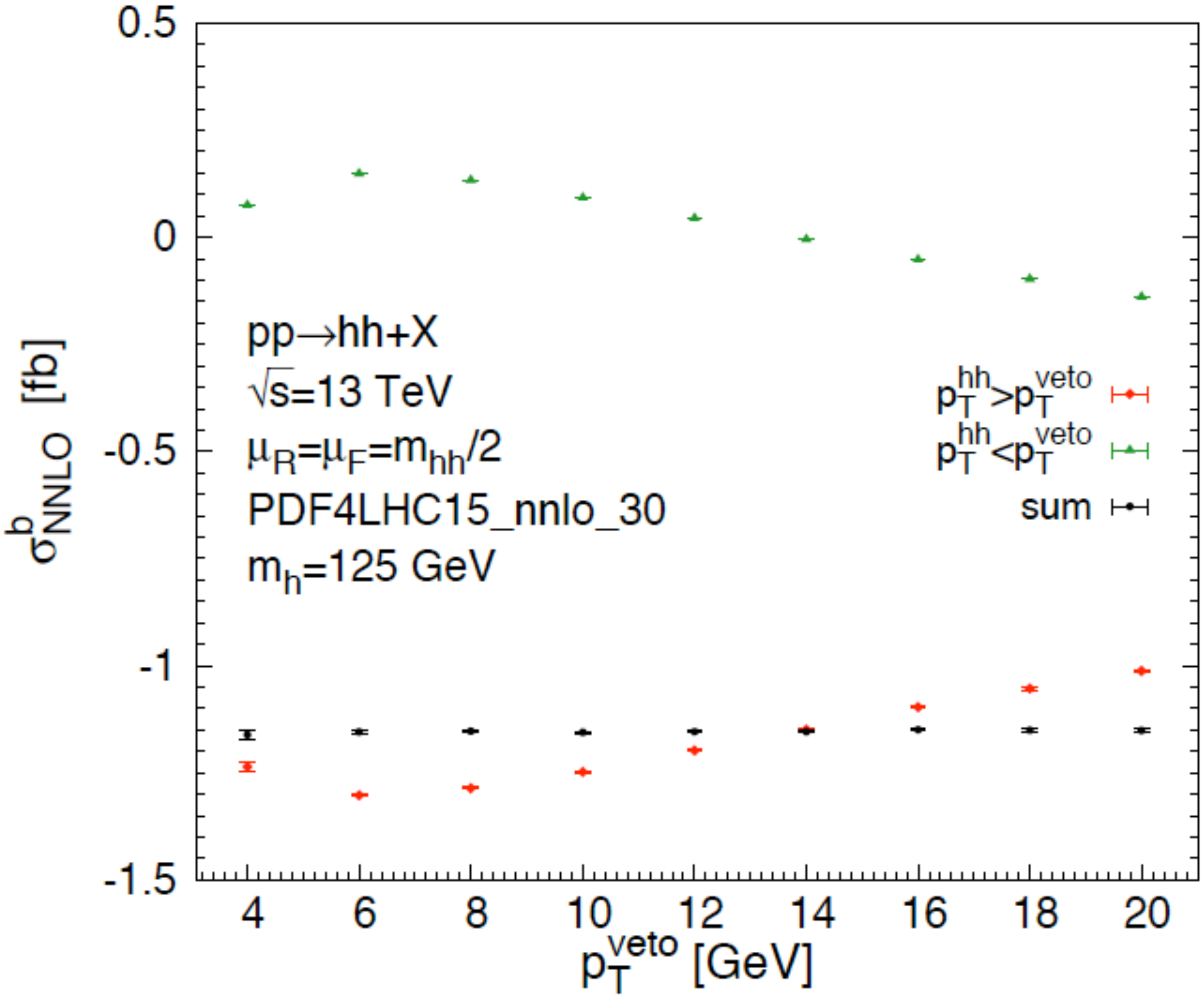

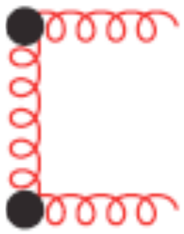

tot

a

b

c

ang (1909.06808)

- class-

ni & Grazzini PRL'07)

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

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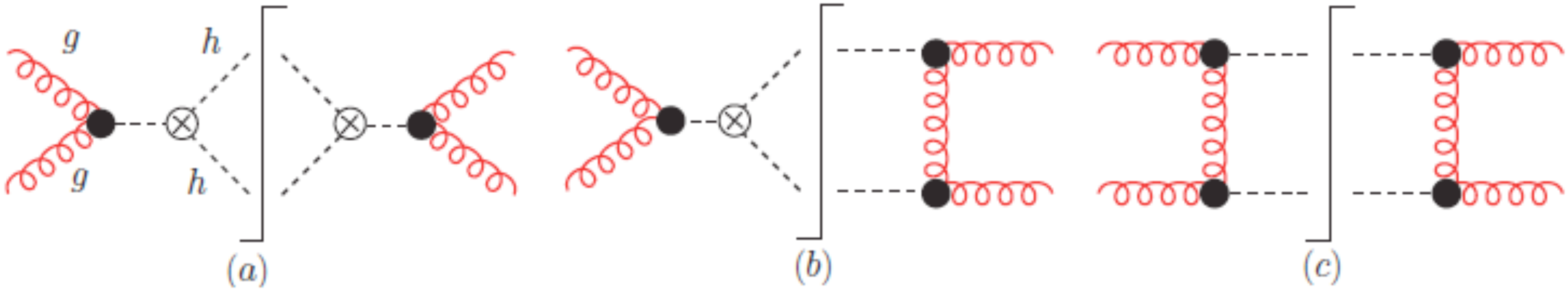

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Chen, Li, HSS, Wang (1909.06808)

- class-c: need NLO (full fledged)

HIGGS PAIR GLUON FUSION PRODUCTION

- **Infinite top-quark mass limit**
  - A lot of cross checks

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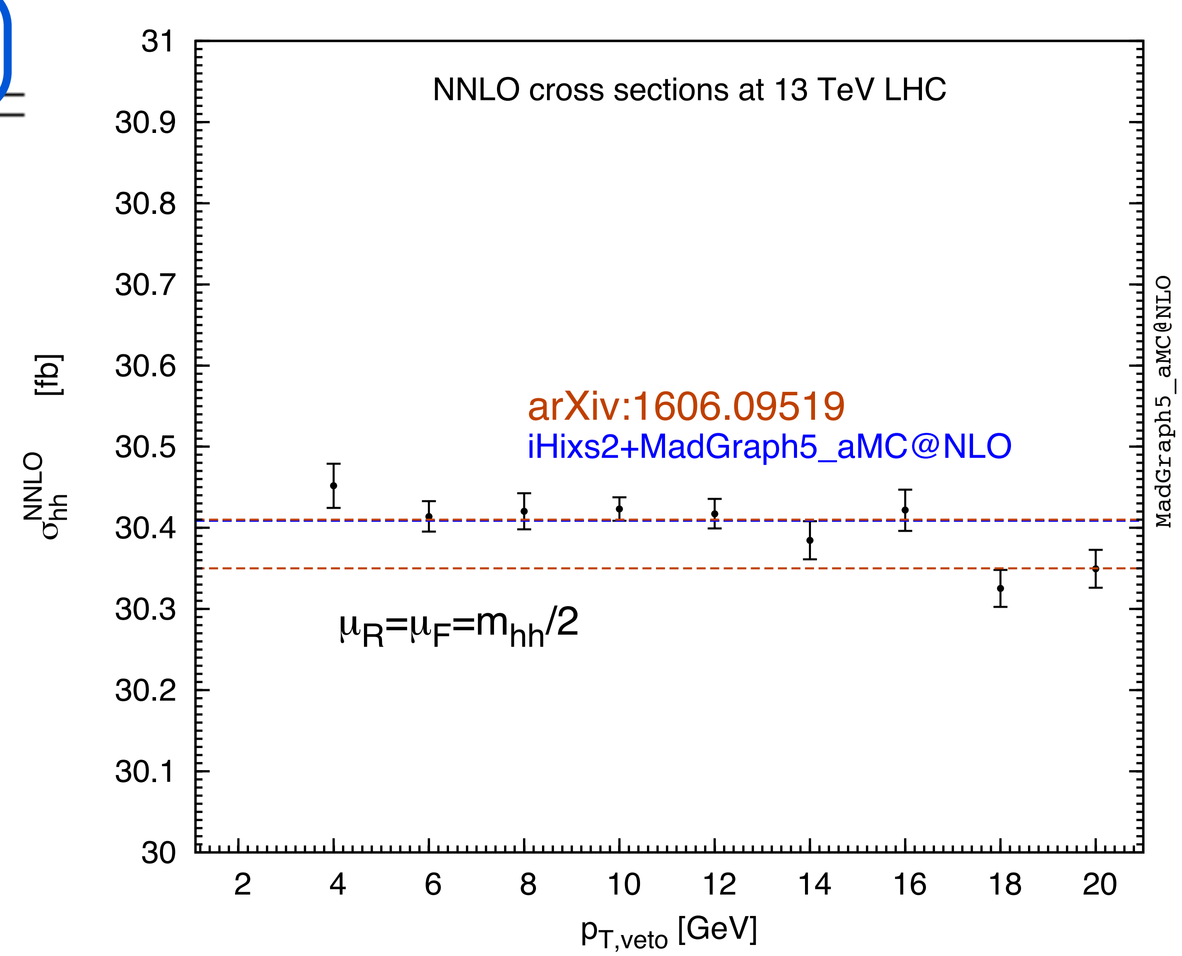
√ At least two independent calculations



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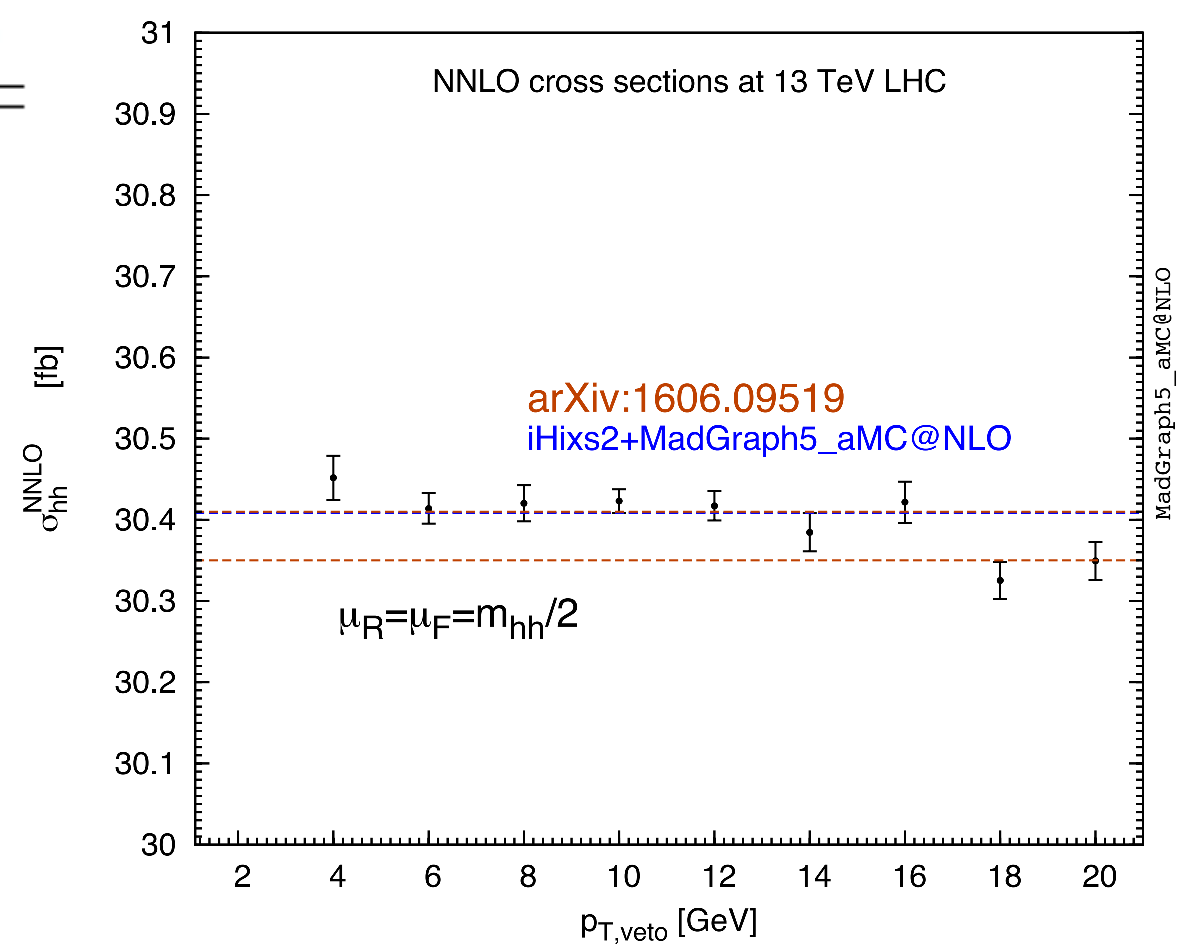

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√ Check piece-by-piece

HIGGS PAIR GLUON FUSION PRODUCTION

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

in unit of fb

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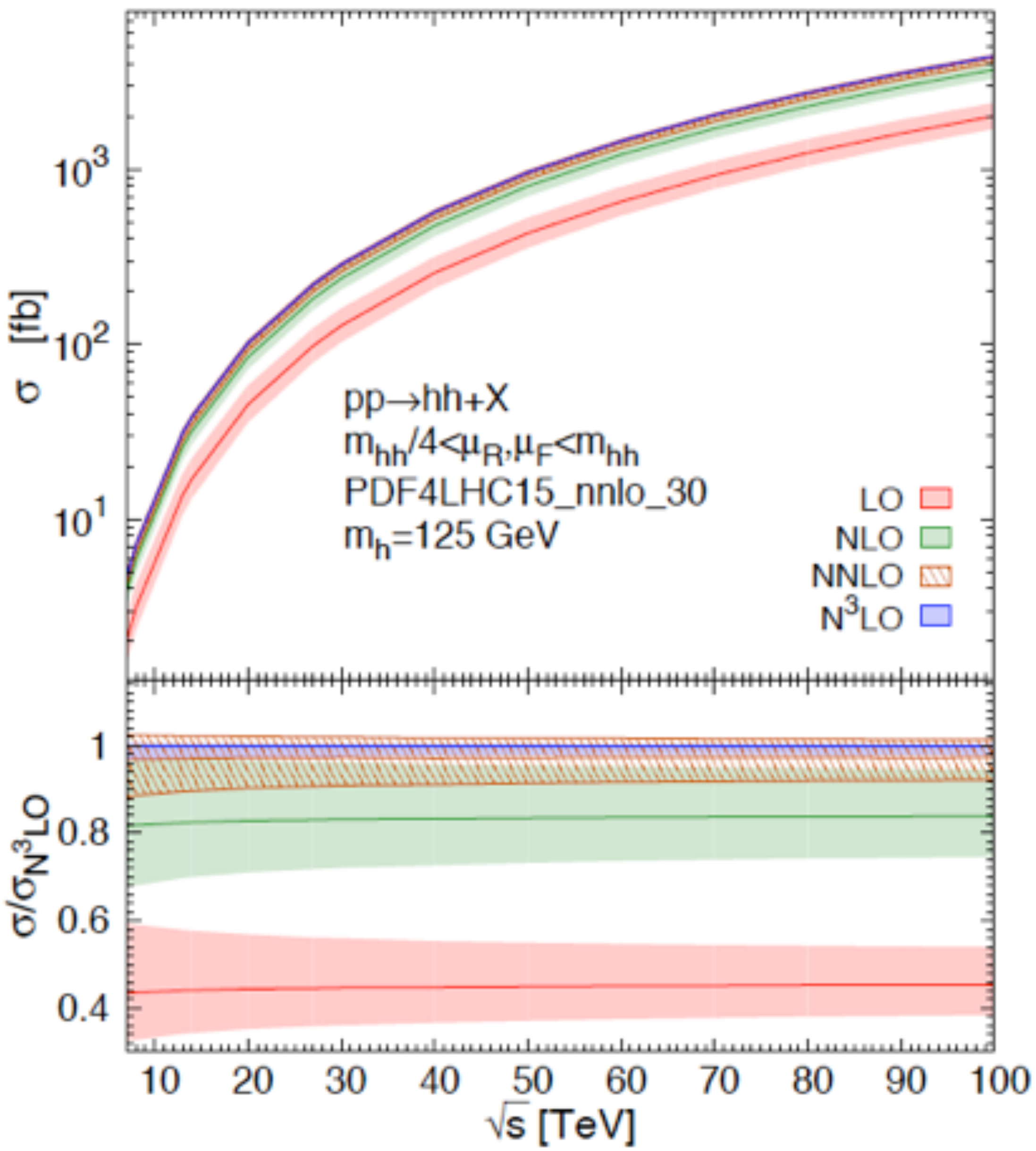
order \ $\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
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 !
- Very good perturbative convergence !

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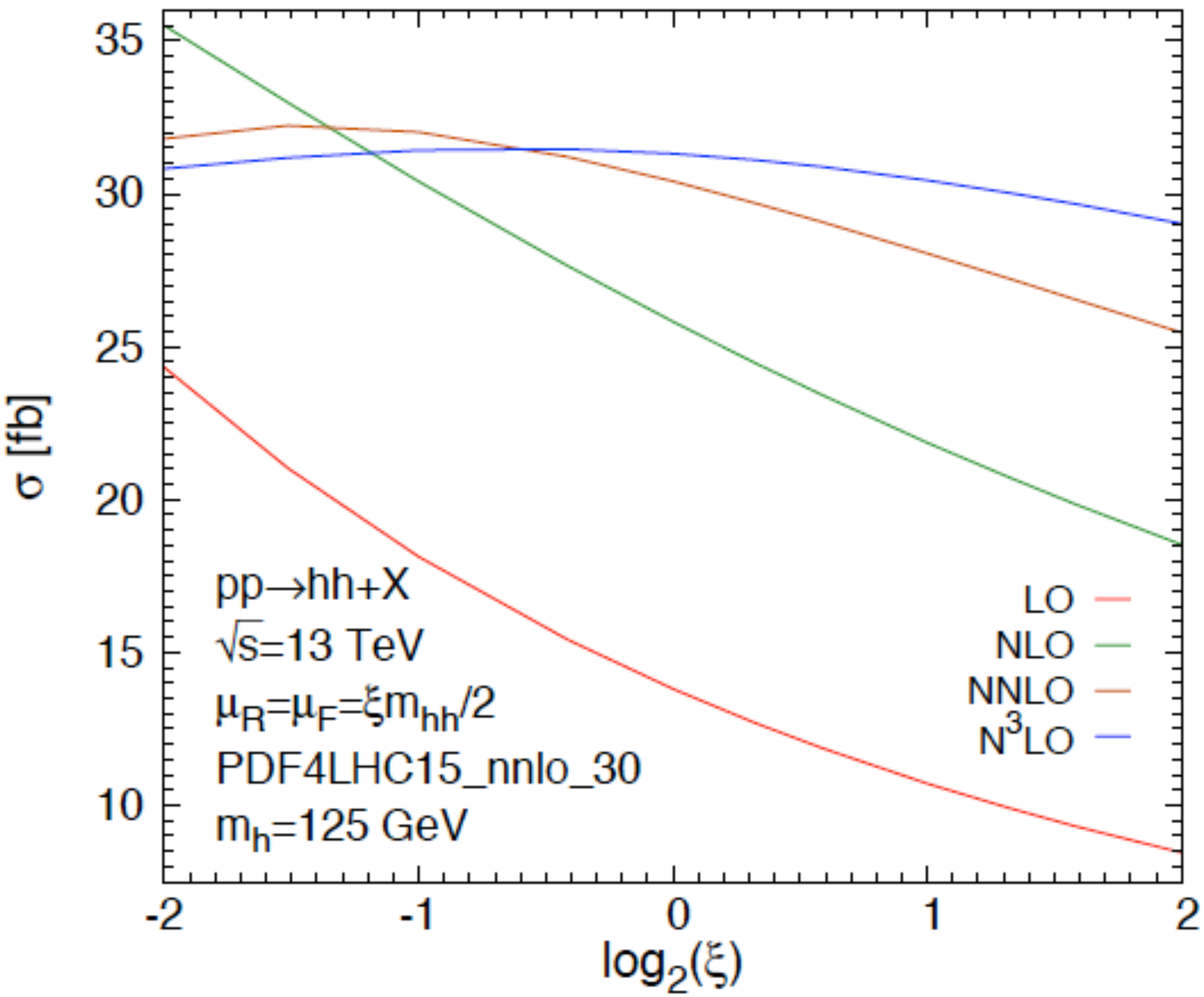

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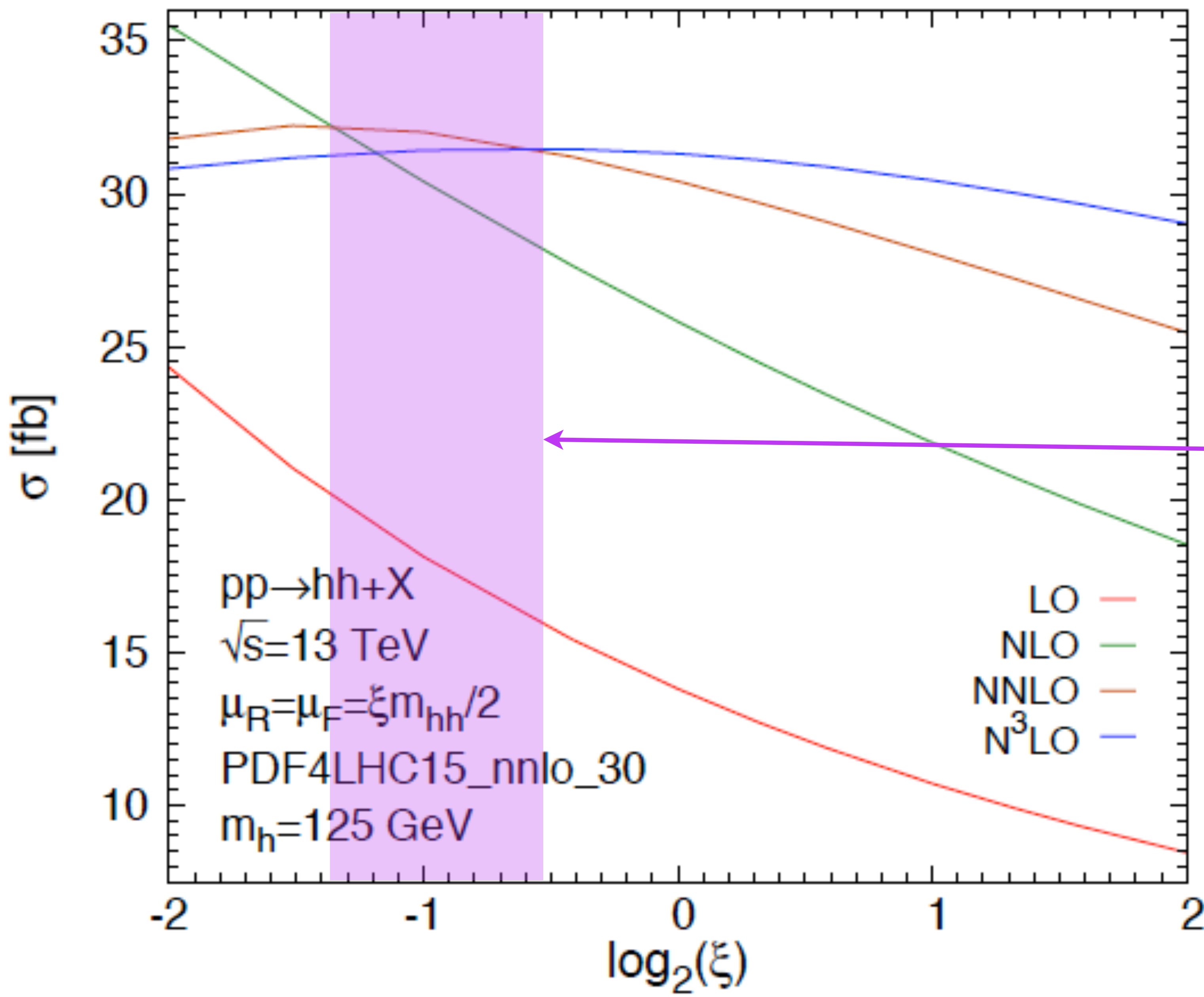

The optimal scale choices

HIGGS PAIR GLUON FUSION PRODUCTION

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

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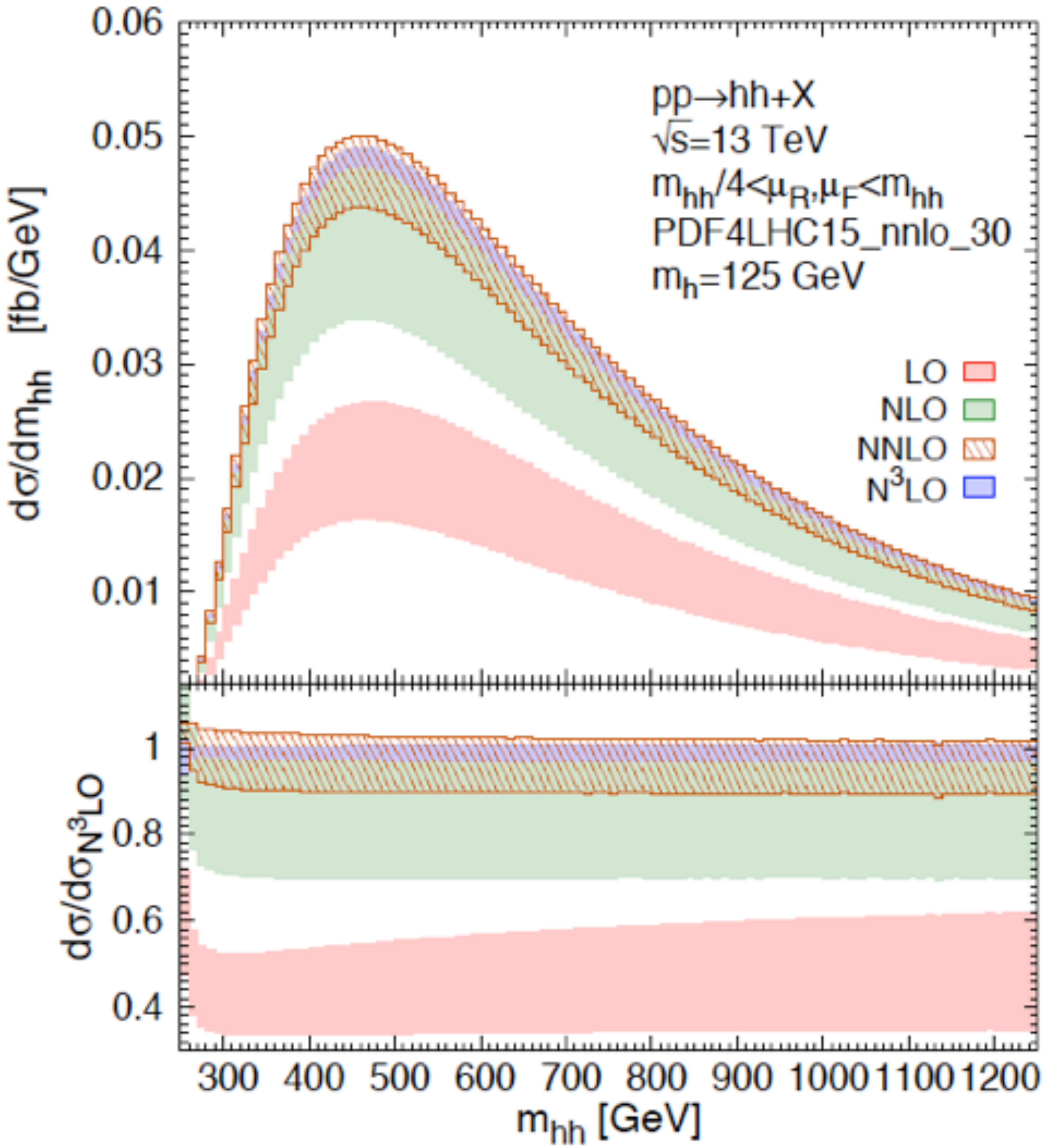

- Scale unc. is significantly reduced !
- Very good perturbative convergence !
- $N^3LO/NNLO$ is quite flat

CONCLUSIONS & OUTLOOKS

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- 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.
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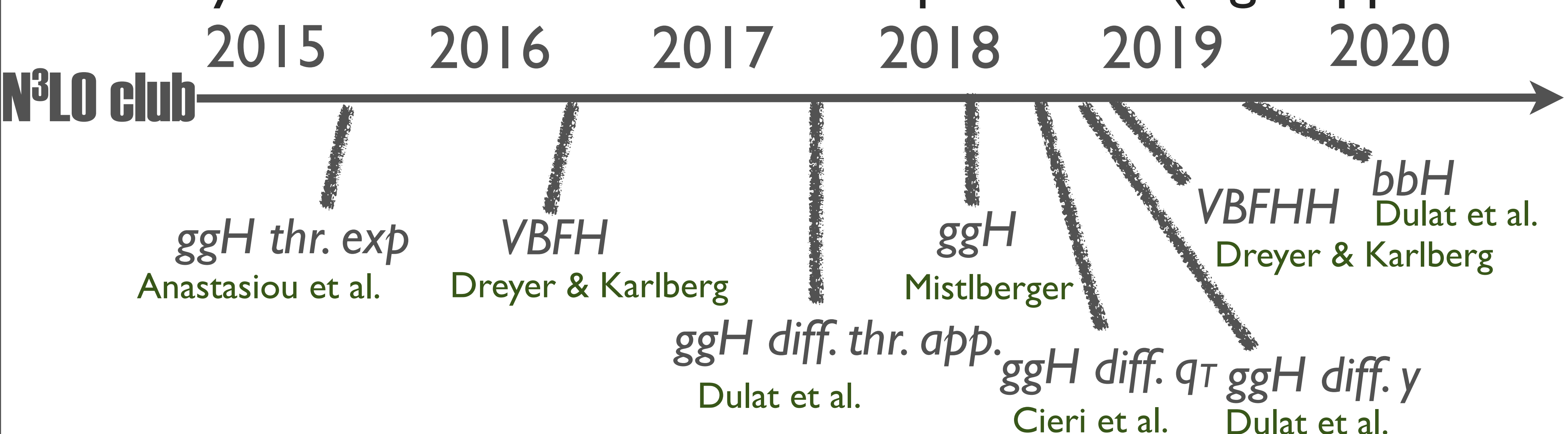

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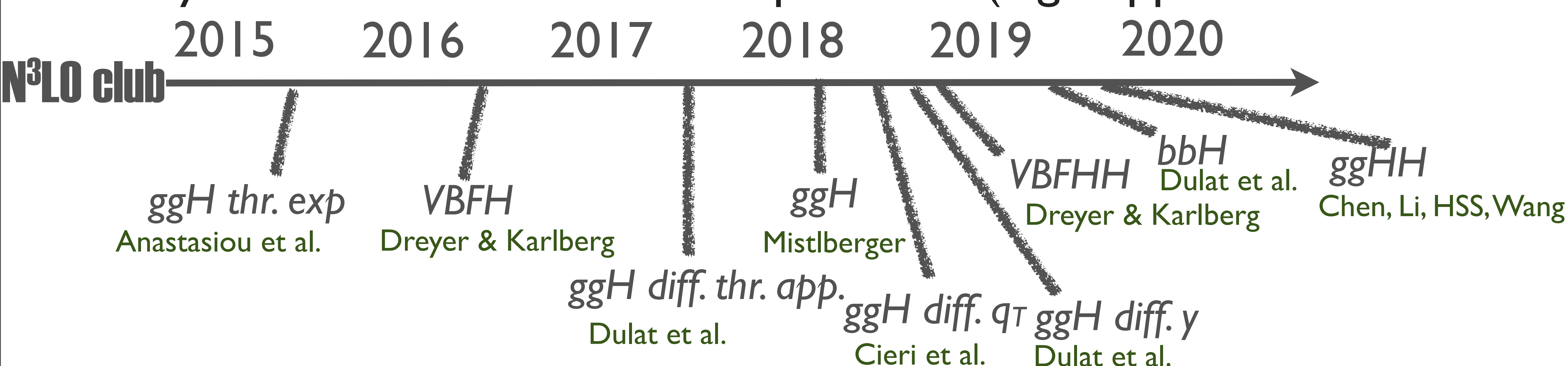

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