Higgs boson pair production

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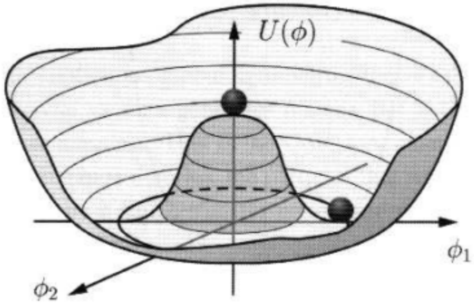
Rencontres de Blois, June 2018

Outline

- **Introduction:**
  - Motivation, main production and decay modes
  - Status and prospects for the LHC
- **QCD corrections for HH production:**
  - NLO with full M_t dependence
  - NNLO including finite M_t effects
  - Resummation
  - BSM EFT dimension 6 operators
- **Conclusions**

Multi-Higgs production → Direct access to Higgs self-couplings



Self-couplings determined by the Higgs potential

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$$

In the SM: $\lambda = \lambda' = M_H^2/(2v^2)$

Produce an off-shell
Higgs boson that decays into:

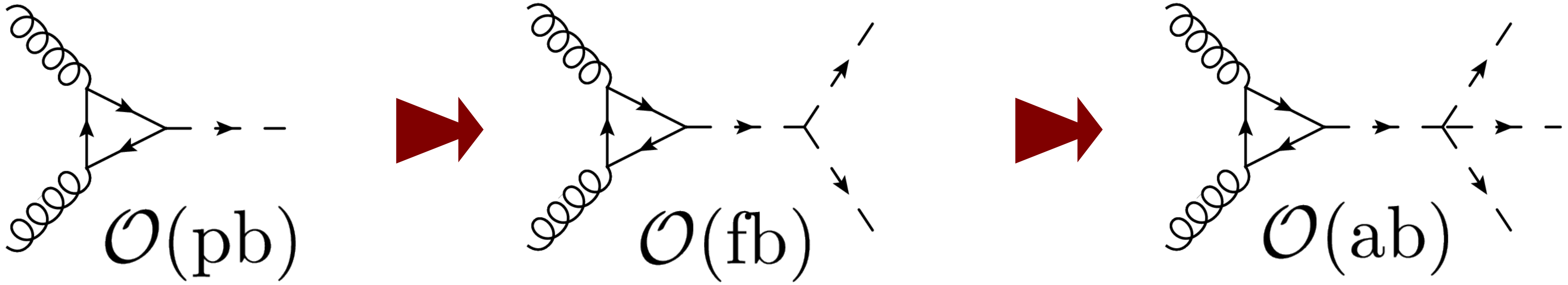
Trilinear coupling

$$H^* \to HH$$

Quartic coupling

$$H^* \to HHH$$

Experimentally very challenging!

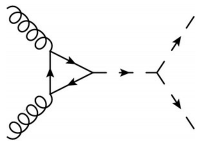


At the LHC:

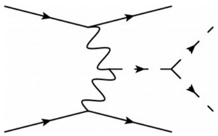
Double Higgs production:
challenging

Triple Higgs production:
impossible

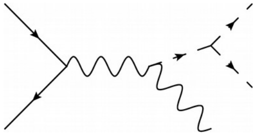
Production modes



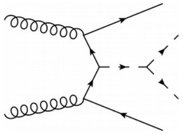
Gluon fusion



Vector boson fusion
NLO [1,2] NNLO [3]

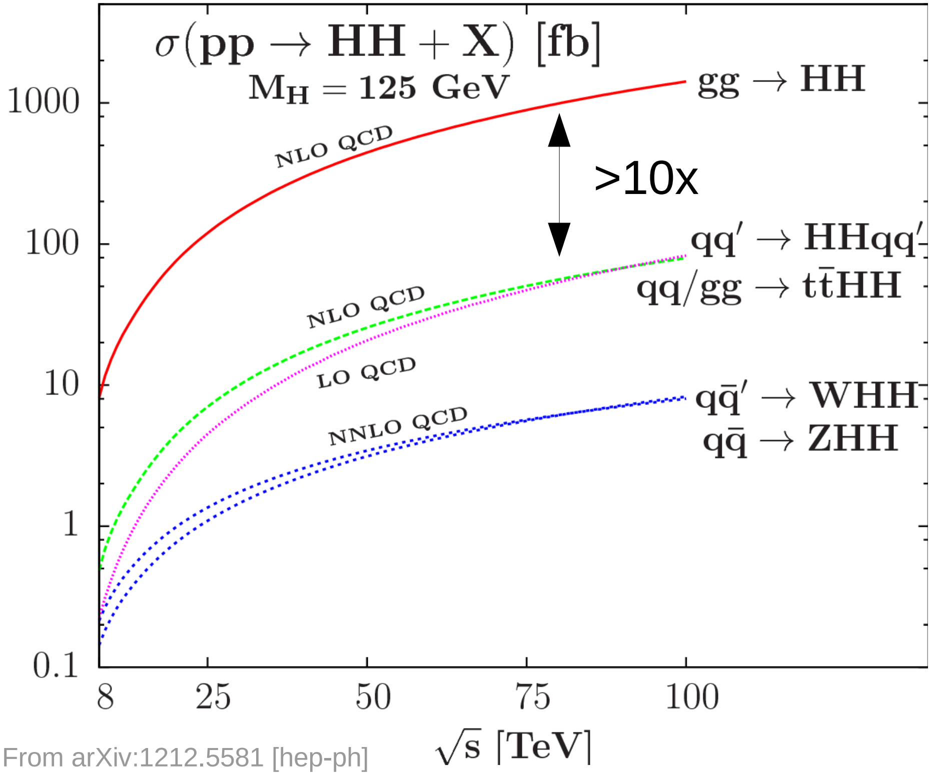


Higgs–strahlung
NLO [1,2] NNLO [1,4,5]



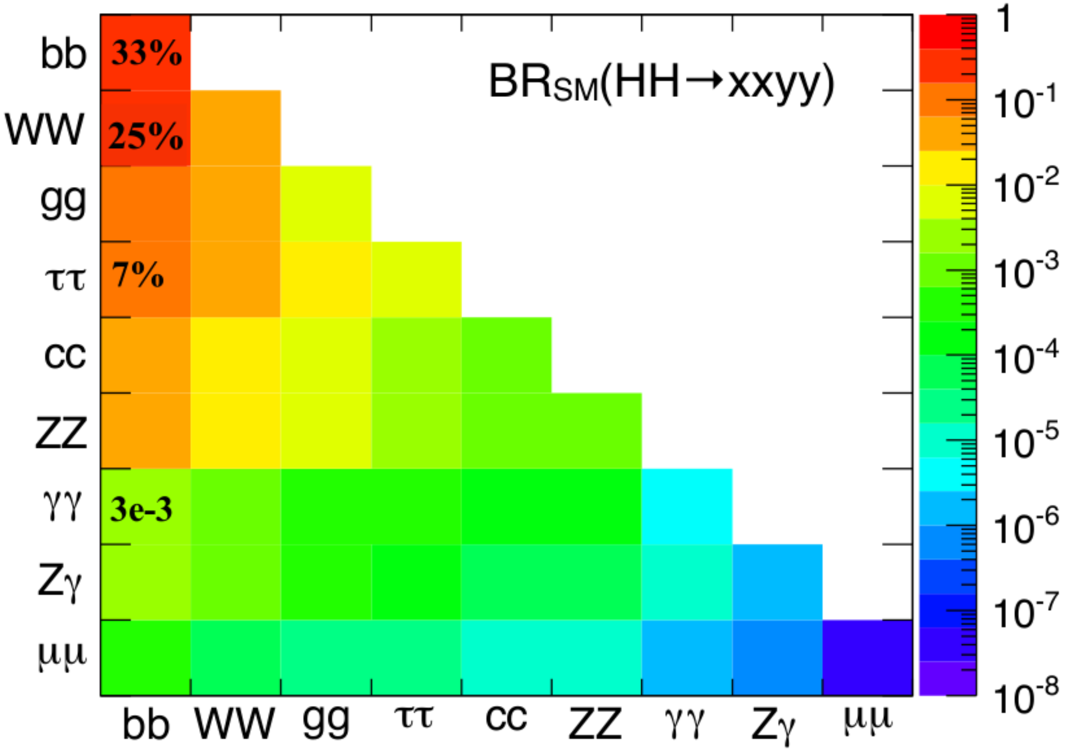
ttHH
NLO [2]

[1] Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira 12;
[2] Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro 14;
[3] Ling, Zhang, Ma, Guo, Li, Li 14; [4] Li, Wang 16; [5] Li, Li, Wang 17;



From arXiv:1212.5581 [hep-ph]

Decay channels



Relevant channels:
in general at least one H → bb to have large BR

bbbb:	highest BR, high QCD and tt contamination
bbWW:	high BG, large irreducible tt background
bbττ:	relatively low background and low BR
bbγγ:	high purity, very low BR

LHC results

BSM scenarios can substantially enhance the HH cross section or produce a resonance

↓

Both **resonant** and **non-resonant** searches have been performed at ATLAS and CMS

$\sigma/\sigma_{\mathrm{SM}}$ 95% C.L. (exp)

	ATLAS	CMS
bbbb	<13 (21)	
bbWW		<79 (89)
bbττ		<30 (25)
bbγγ	<22 (28)	<24 (19)
WWγγ	<230 (160)	

Thomas Strebler, Blois 2018

$\mathcal{O}(10)$ x SM sensitivity with 36fb^{-1} of data

...and prospects

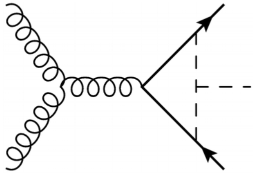
- Assuming a SM rate, HH production should be **observed** at the **HL-LHC**
- Expected uncertainty on the signal yield: O(50%) using bbγγ and bbττ
- Combination with other decay channels (specially 4b) will reduce this uncertainty

[ATL-PHYS-PUB-2014-019, ATL-PHYS-PUB-2015-046, CMS PAS FTR-15-002]

Higgs pair production should be observed at the HL-LHC... but we also want to measure λ

Assuming a SM-like scenario

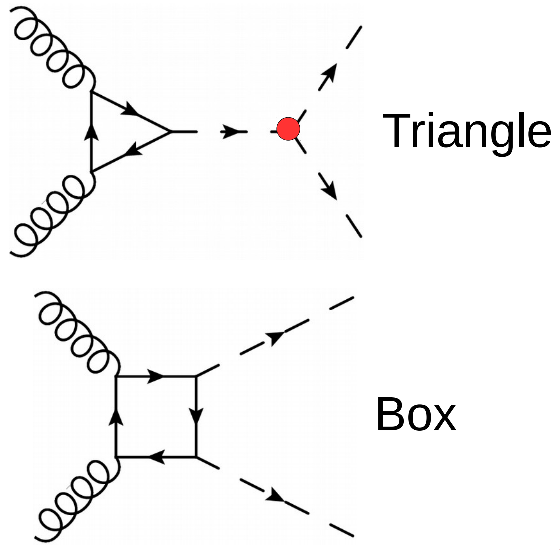
- Determination of λ will require full HL-LHC integrated luminosity and the combination of the different decay channels
- Even then, **uncertainties on λ** will be $\mathcal{O}(1)$
- Complementary information from **loop effects** in single Higgs and EW precision observables

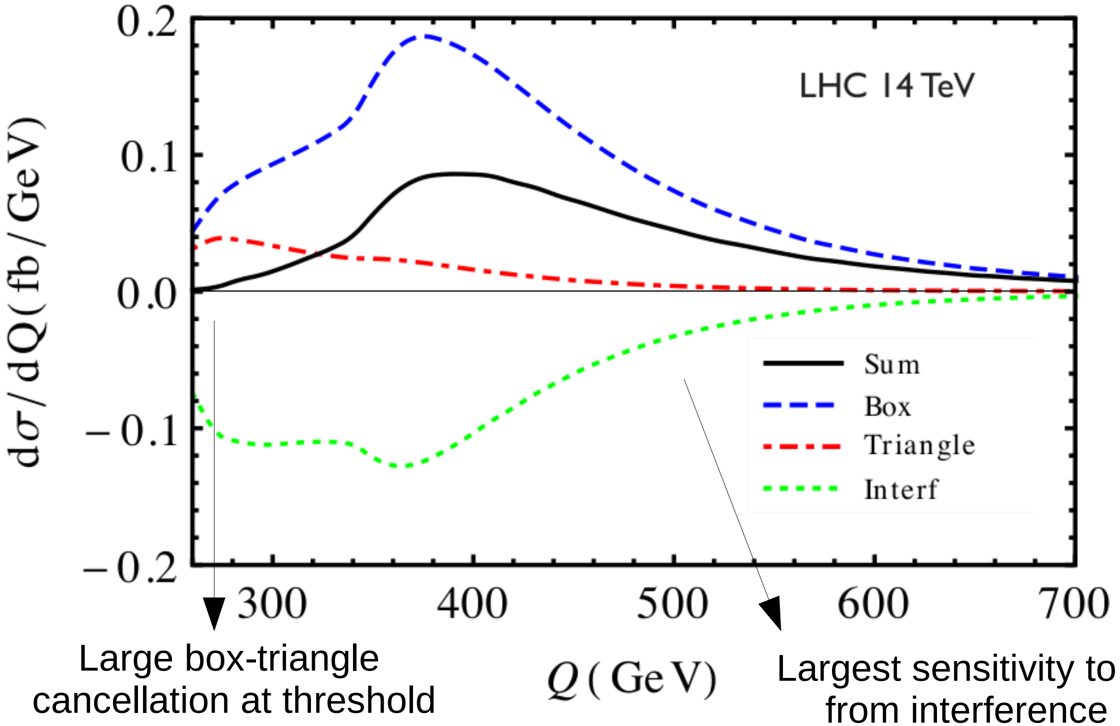


- Precision determination: **future colliders** HE-LHC ~ 30%, FCC-100 ~ 5%

HH production via gluon fusion

Loop induced process. At LO:





Large box-triangle cancellation at threshold

Largest sensitivity to λ from interference

- Lot of recent progress for the QCD predictions

NLO full top mass [1]

Approximate NNLO [2]

Threshold resummation at NNLL ($M_t \to \infty$) [5,6]

qt-resummation at NLL [7]

NLO+PS [3,4]

$M_t \to \infty$ NNLO including dim 6 operators [8]

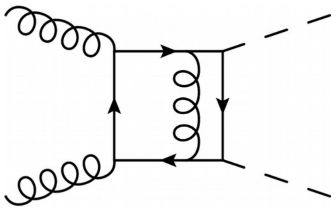
[1] Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 16; [2] Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, JM 18; [3] Heinrich, Jones, Kerner, Luisoni, Vryonidou 17; [4] Jones, Kuttimalai 17; [5] Shao, Li, Li, Wang 13; [6] de Florian, JM 15; [7] Ferrera, Pires 16; [8] de Florian, Fabre, JM 17;

NLO with full top mass dependence

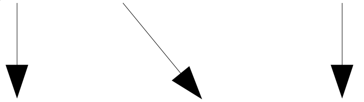
- Calculation of QCD corrections is really difficult: exact NLO only became available in 2016

Borowka et al. arXiv:1604.06447

- Two-loop virtual corrections computed numerically using sector decomposition
- Grid available for fast numerical evaluation



- NLO matched to parton shower using MC@NLO and POWHEG frameworks



Sherpa Pythia

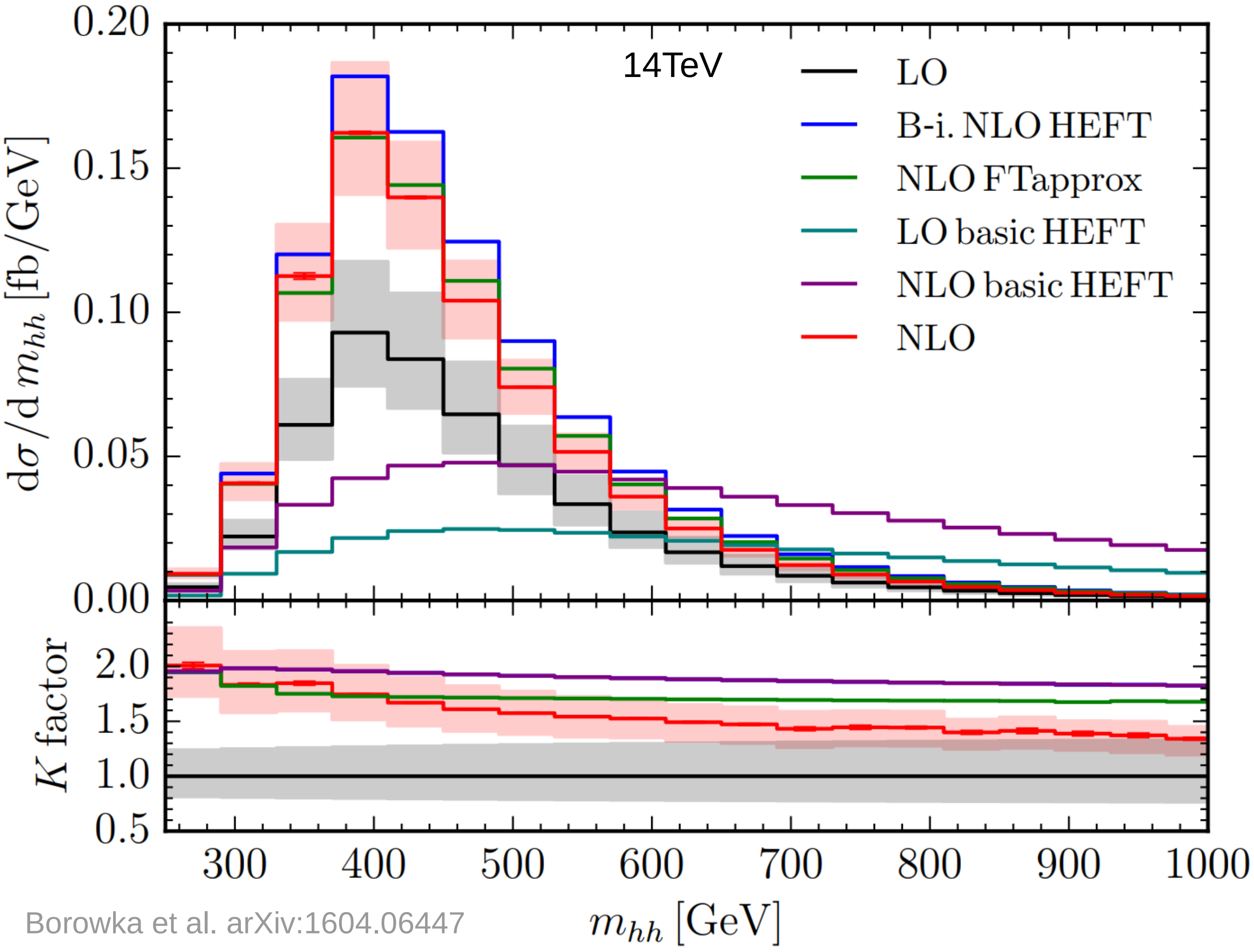
Jones, Kuttimalai arXiv:1711.03319 Heinrich et al. arXiv:1703.09252

- NLO corrections are very large (~66% for total cross section at 14TeV)
- Beyond that: heavy top quark mass limit (HTL, also called HEFT)

- Typically, corrections computed in the HEFT and normalized by exact LO differentially in M_{hh}

HTL vs full theory

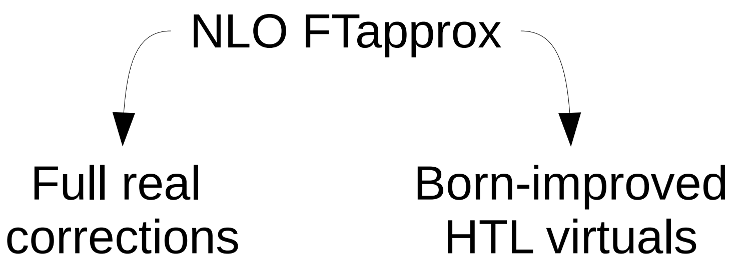
- Heavy M_t limit → Worse than for single Higgs (larger invariant mass)
  Dominant contribution to total XS is above $2M_t$ threshold
- Born improved overestimates the NLO total XS by a 15% (~42% the pure NLO piece)
- Poor description of the tail of some distributions



Borowka et al. arXiv:1604.06447

We can do better, for instance:

Maltoni, Vryonidou and Zaro, arXiv:1408.6542



NLO FTapprox

Full real corrections

Born-improved HTL virtuals

- Overestimates NLO total XS by only 4% (~11% the NLO piece)
- Better description of distributions

HH at NNLO with M_t effects

Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, JM [arXiv:1803.02463]

- **Goal:** combine **full NLO** with **heavy-M_t NNLO**, and improve NNLO piece to account for **finite-M_t effects**

- **Double real** corrections can be computed in the **full theory** (one-loop amplitudes)

- Idea: construct an approximation in which they are treated in an exact way

We perform a **subprocess-wise reweighting**: for each n-loop squared amplitude

$$\mathcal{A}^{(n)}_{\mathrm{HEFT}}(ij \to HH + X)$$

we apply the reweighting

$$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\mathrm{Born}}_{\mathrm{Full}}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\mathrm{HEFT}}(ij \to HH + X)}$$

- Amplitudes that are tree-level in the HTL are treated exactly

- At NLO this procedure agrees with the FTapprox

- **Fully differential** results, based on public code MATRIX [Kallweit, Grazzini, Wiesemann 17]

- Most advanced parton level prediction for this process

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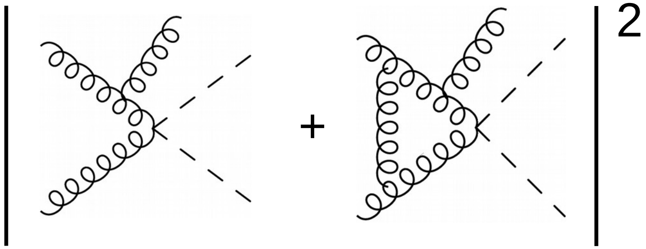
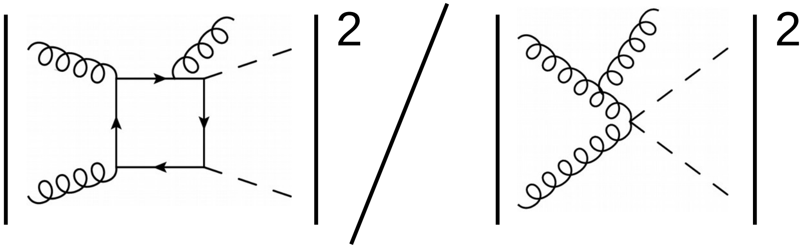
E.g. the squared amplitude:



is reweighted by:



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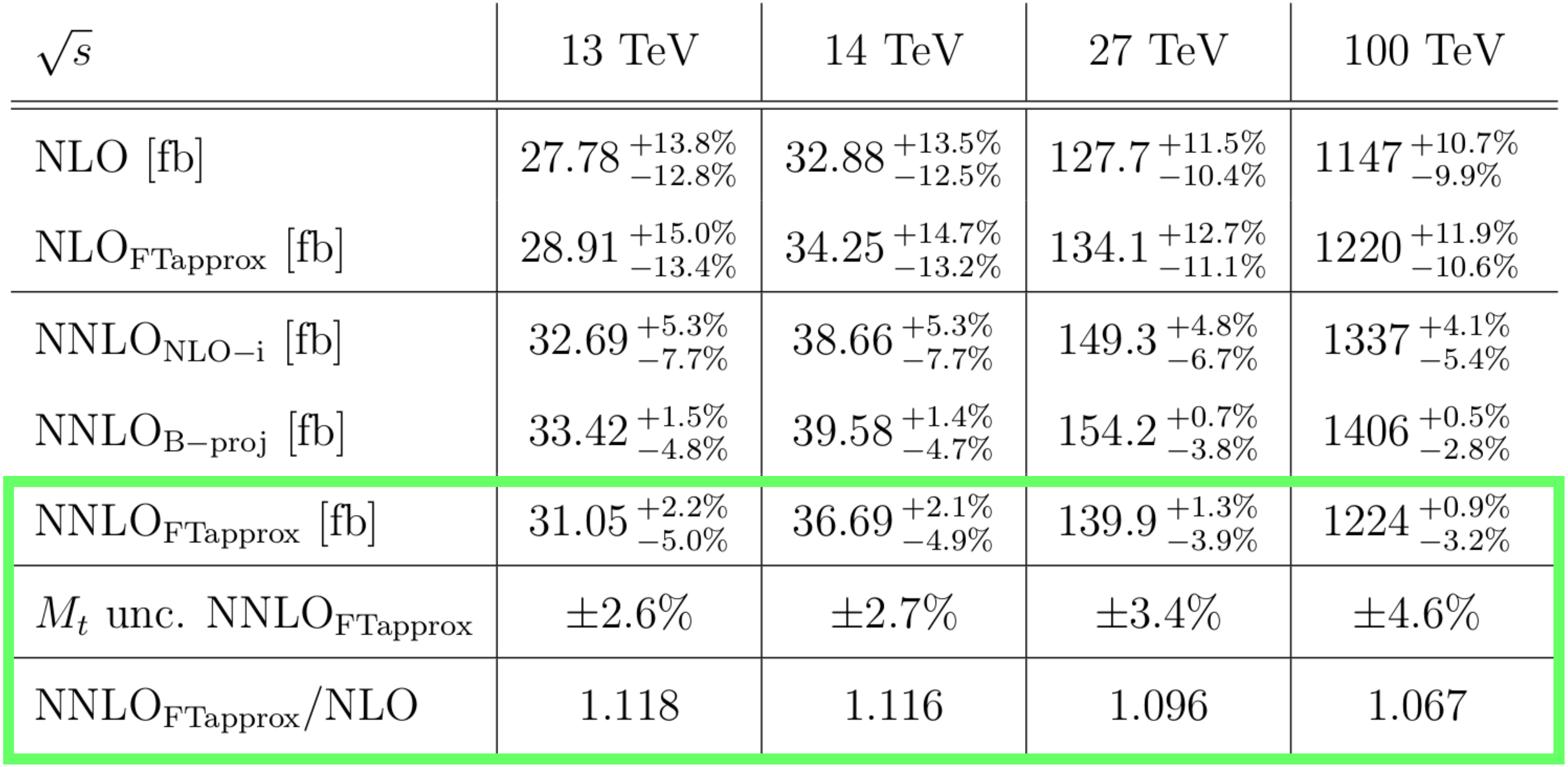
NNLO total cross sections



$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
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M_t unc. $\text{NNLO}_{\text{FTapprox}}$	±2.6%	±2.7%	±3.4%	±4.6%
$\text{NNLO}_{\text{FTapprox}}/\text{NLO}$	1.118	1.116	1.096	1.067

- **Increase** w.r.t. previous order of about **12% for LHC**, size decreasing with the energy

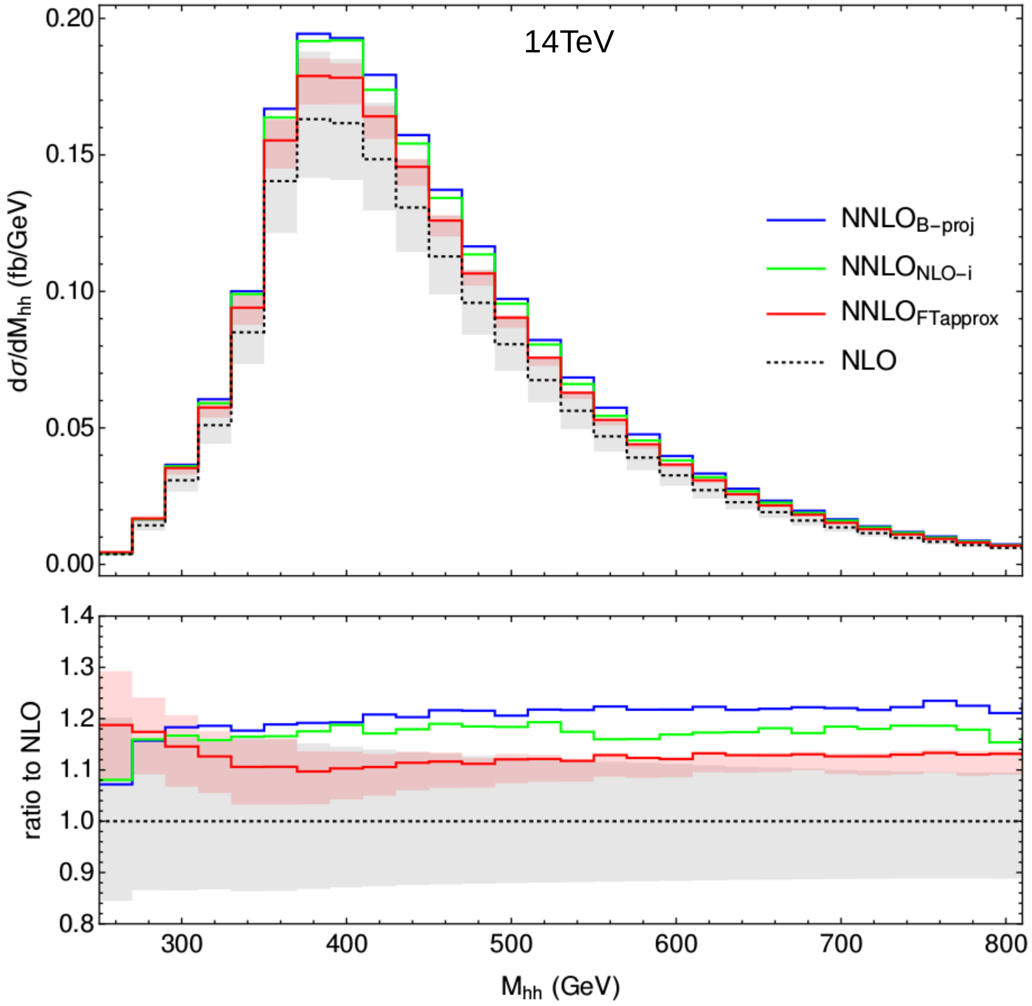
- Smaller cross sections compared to previous approximations (larger difference for higher energies)

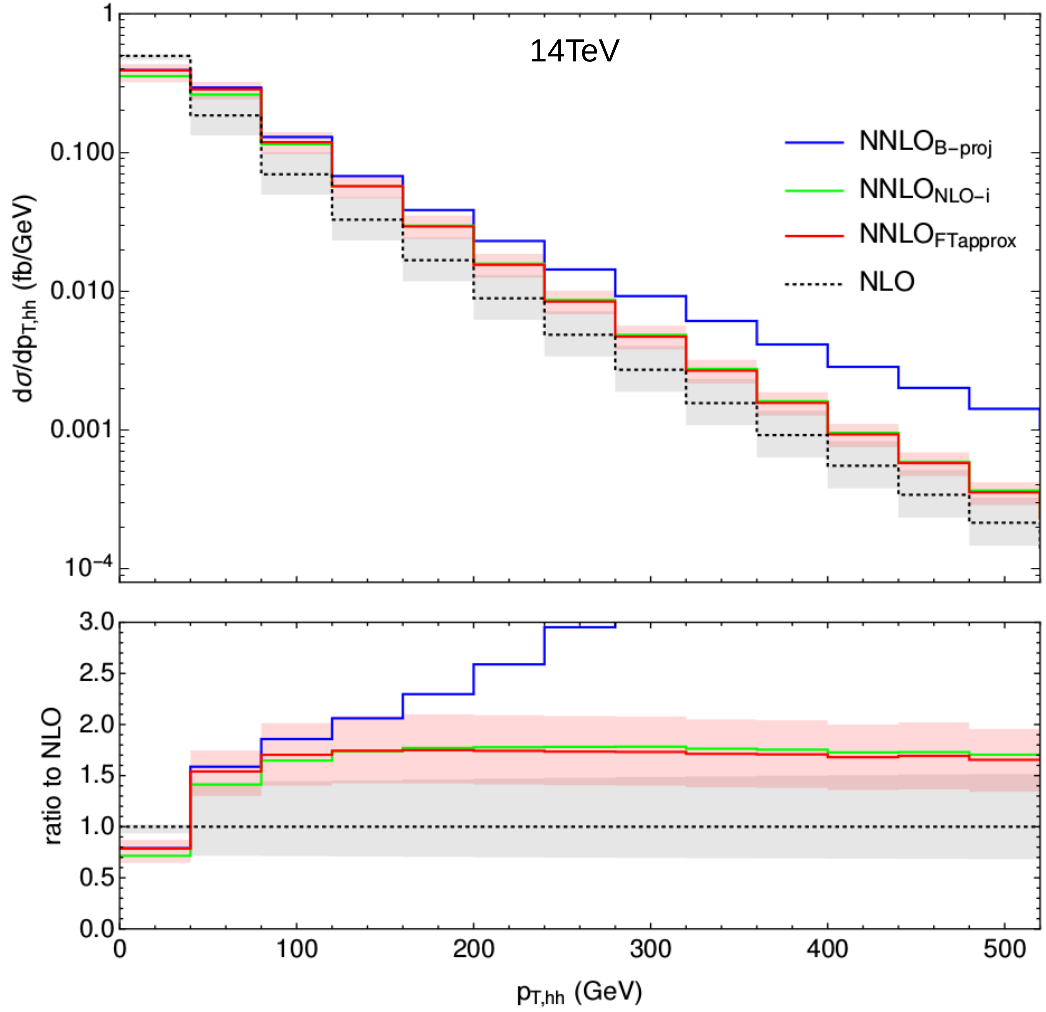
- Strong **reduction** of the **scale uncertainties**

- Size of **missing M_t effects** estimated at the **few percent level**
  Based on performance at previous order and on comparison between different approximations

- Results computed in the on-shell scheme, no estimation of M_t renormalization scheme uncertainties

NNLO differential distributions





- FTapprox presents larger corrections at threshold, minimum corrections at M_{hh} ~ 400GeV, slow increase towards the tail

- Scale uncertainties are substantially reduced

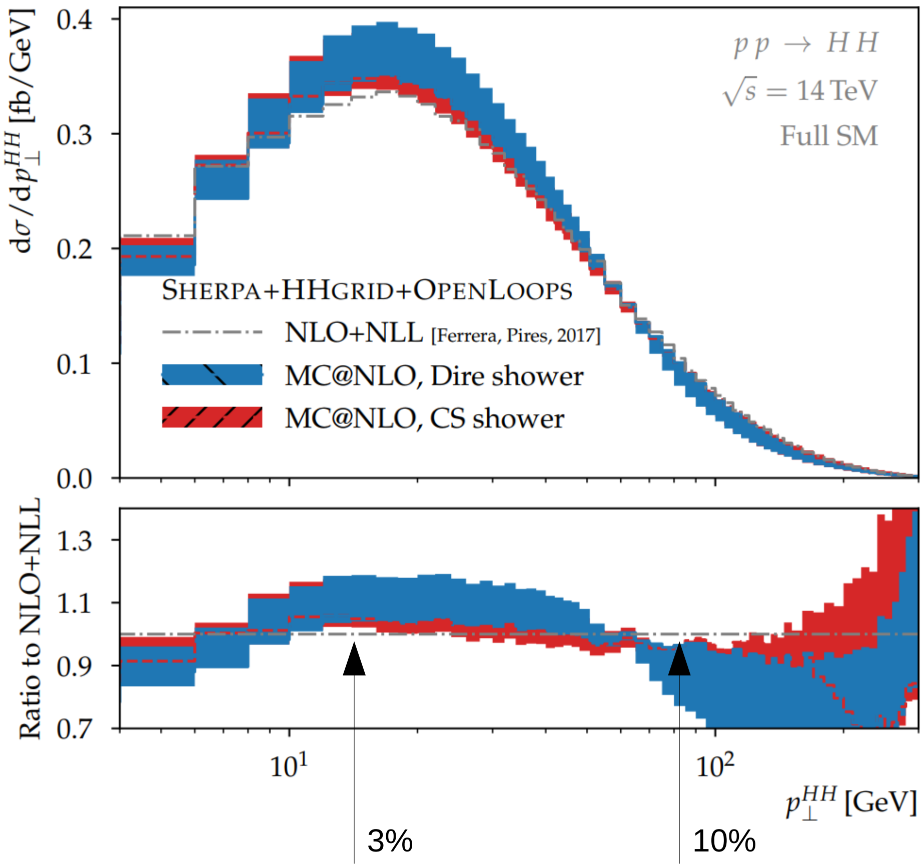
- Overlap with the NLO band

- Born-improved HTL (blue) has wrong scaling in the tail. No information about lowest order for $p_{T,hh}$

- Distribution trivial at LO: NNLO is effectively NLO Large corrections and sizeable scale uncertainties

Resummation

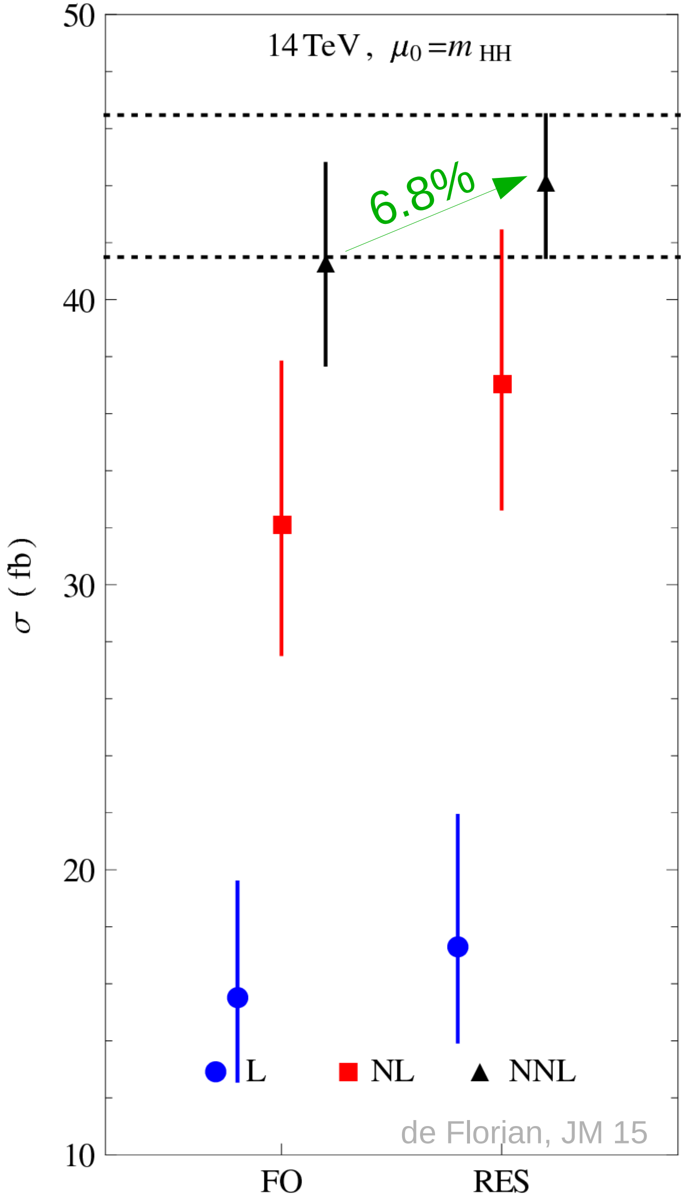
- **q_T-resummation** computed at NLL with full M_t dependence
  Ferrera, Pires 16
- Allows to perform predictions for low $p_{T,HH}$
- Satisfactory agreement with NLO+PS
  Jones, Kuttimalai 17



3%

10%

Analytic resummation uncertainties not included in the plot



6.8%

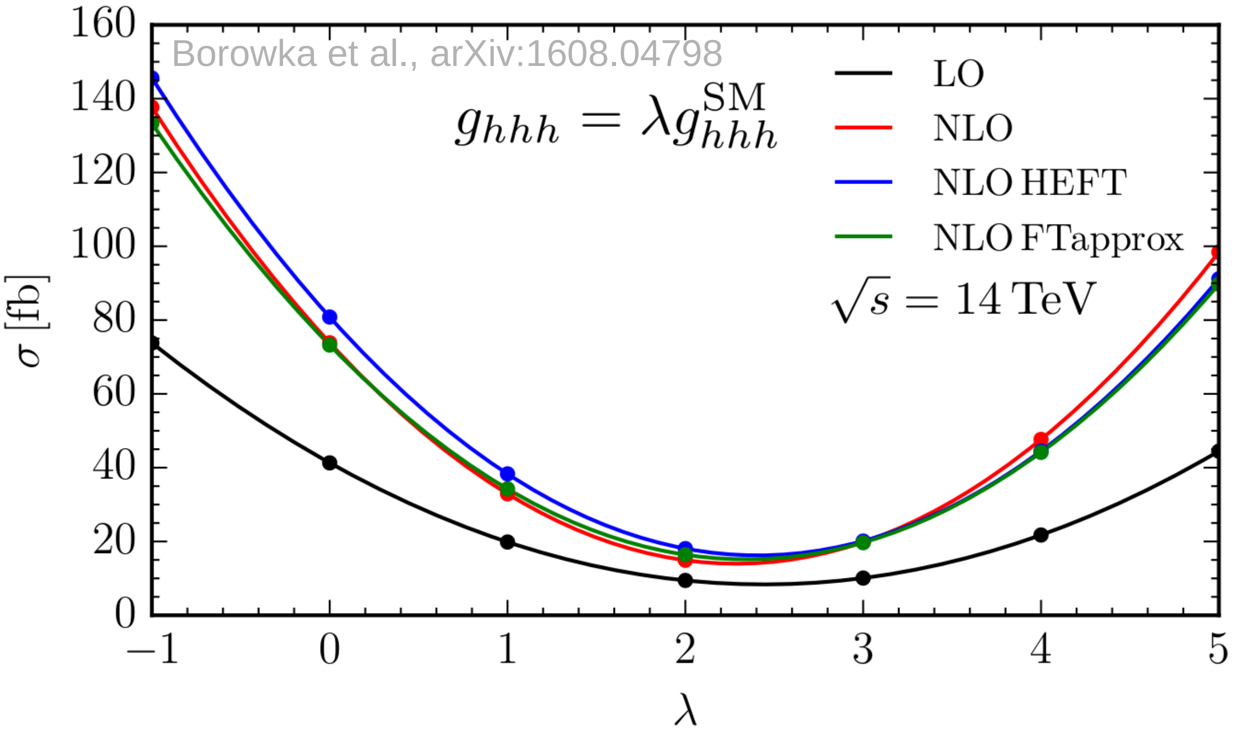
Further scale unc. reduction at NNLL

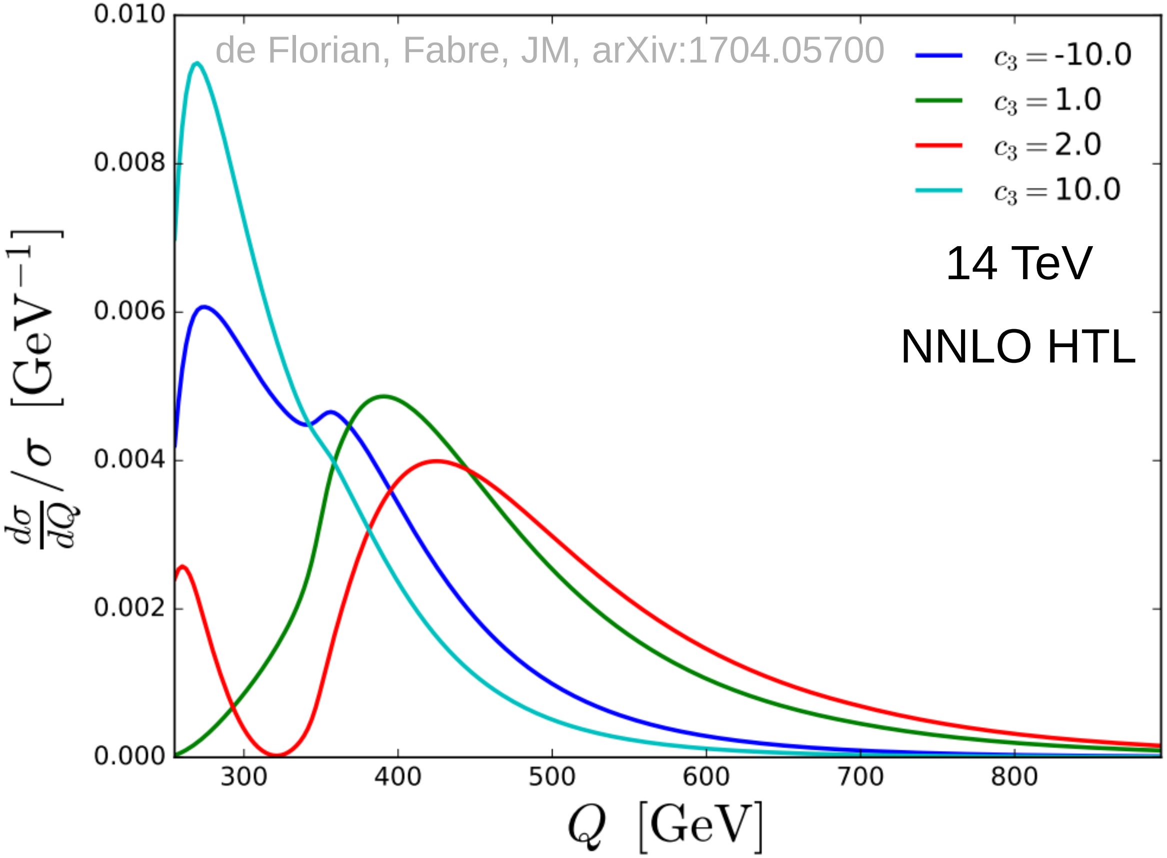
de Florian, JM 15

- **Threshold resummation** computed at NNLL in the HTL
  Shao, Li, Li, Wang 13; de Florian, JM 15
- About 7% effect at 14TeV and μ = M_{hh}, but smaller (~0.7%) for μ = $M_{hh}/2$

Sensitivity to λ_{hhh}

- λ variation computed at NLO and HTL NNLO
- Minimum around λ=2
- Larger XS for negative λ due to absence of destructive interference

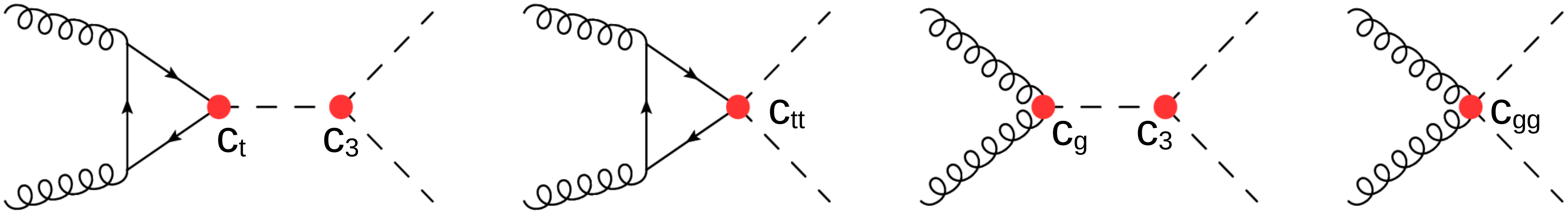




- λ=1 (SM) leads to big cancellation at threshold
- M_{hh} distribution can increase the sensitivity to λ

BSM EFT

Just varying λ is not enough! In general we have to consider all relevant EFT operators



Several studies using EFT approach

HL-LHC sensitivity to λ [1,2,3,4]

- bbγγ most sensitive channel for λ determination
- [-0.1, 6.4] 95% C.L. for λ at HL-LHC [4]

Cluster analysis [5,6]

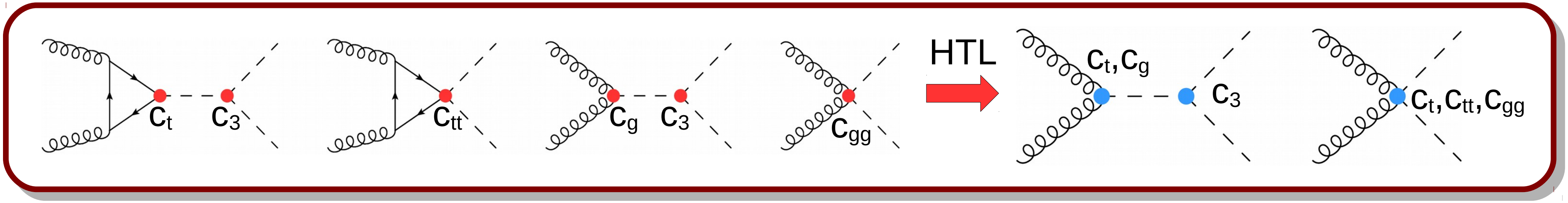
- Shape classification of the parameter space
- 12 clusters with points that lead to similar phenomenology + 12 benchmark points
- Simplification of the analysis

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

[1] Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer 12; [2] Goertz, Papaefstathiou, Yang, Zurita 14; [3] Azatov, Contino, Panico, Son 15
[4] Kim, Sakaki, Son 18; [5] Carvalho, Dall'Osso, Dorigo, Goertz, Gottardo, Tosi 15;
[6] Carvalho, Dall'Osso, Manzano, Dorigo, Goertz, Gouzevich, Tosi 16

BSM EFT – QCD corrections

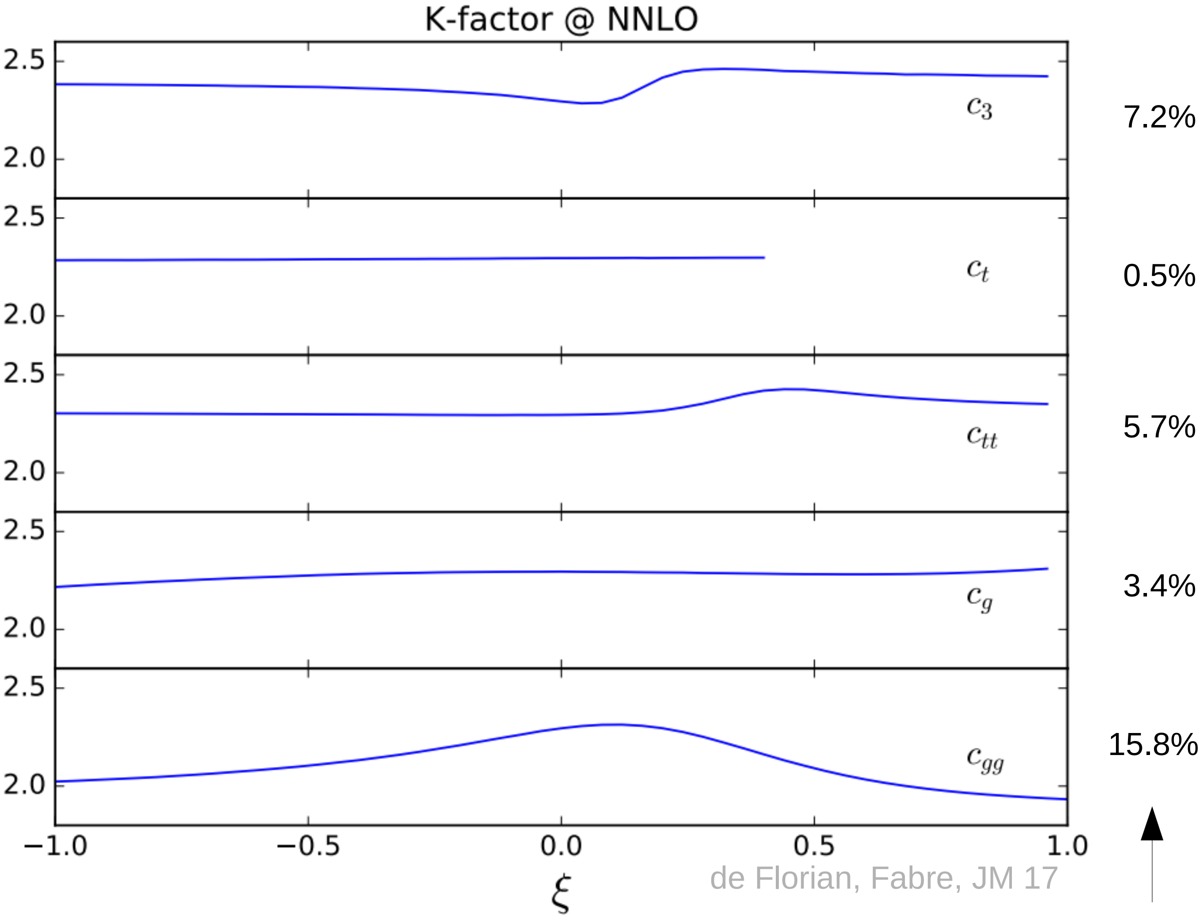
- NLO [1] and NNLO [2] QCD corrections computed in the HTL



- Large corrections, in general mild dependence on the couplings

$$\begin{aligned} c_3 &= 1 + 10\,\xi\,, \\ c_t &= 1 + 0.35\,\xi\,, \\ c_{tt} &= 1.5\,\xi\,, \\ c_g &= 0.15\,\xi\,, \\ c_{gg} &= 0.15\,\xi\,. \end{aligned}$$

- Larger dependence when varying various couplings simultaneously



de Florian, Fabre, JM 17

Max NNLO K-fac variation w.r.t. SM

- NLO analysis with full M_t dependence in preparation [3]

[1] Gröber, Mühlleitner, Spira, Streicher 15; [2] de Florian, Fabre, JM 17; [3] Buchalla, Capozi, Celis, Heinrich, Scyboz (To appear)

Conclusions

- **HH production** is an important measurement to probe the Higgs **self-coupling**

- Current limit: $\mathcal{O}(10)$ x SM cross section

- Should be **observed** in the **HL-LHC**

Lot of recent progress in the **theoretical predictions**:

- **NLO** with **full M_t dependence**, very large corrections

- **NLO + PS** available

- Beyond that: **$\mathrm{NNLO}_{\mathrm{FTapprox}}$**, which includes finite M_t effects at NNLO
  Current HXSWG recommendation for the total XS

- Large reduction of theoretical uncertainties w.r.t. previous order and to other approximations

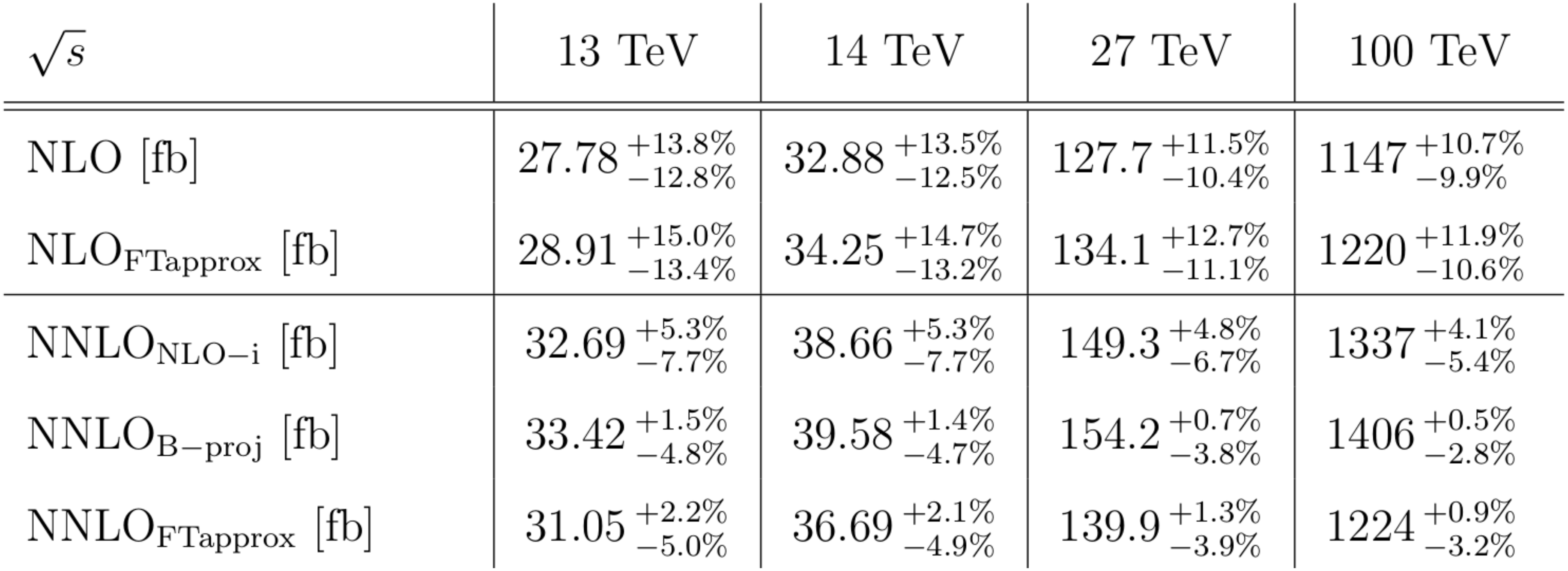
- QCD corrections for BSM EFT studied in the $M_t \to \infty$ limit

- **Outlook:** $\mathrm{NNLO}_{\mathrm{FTapprox}}$ for non-SM self-couplings, inclusion of Higgs decays, estimation of M_t renormalization scheme uncertainties, BSM EFT at NLO with full M_t dependence

Thanks!

Backup slides

Top quark mass uncertainties



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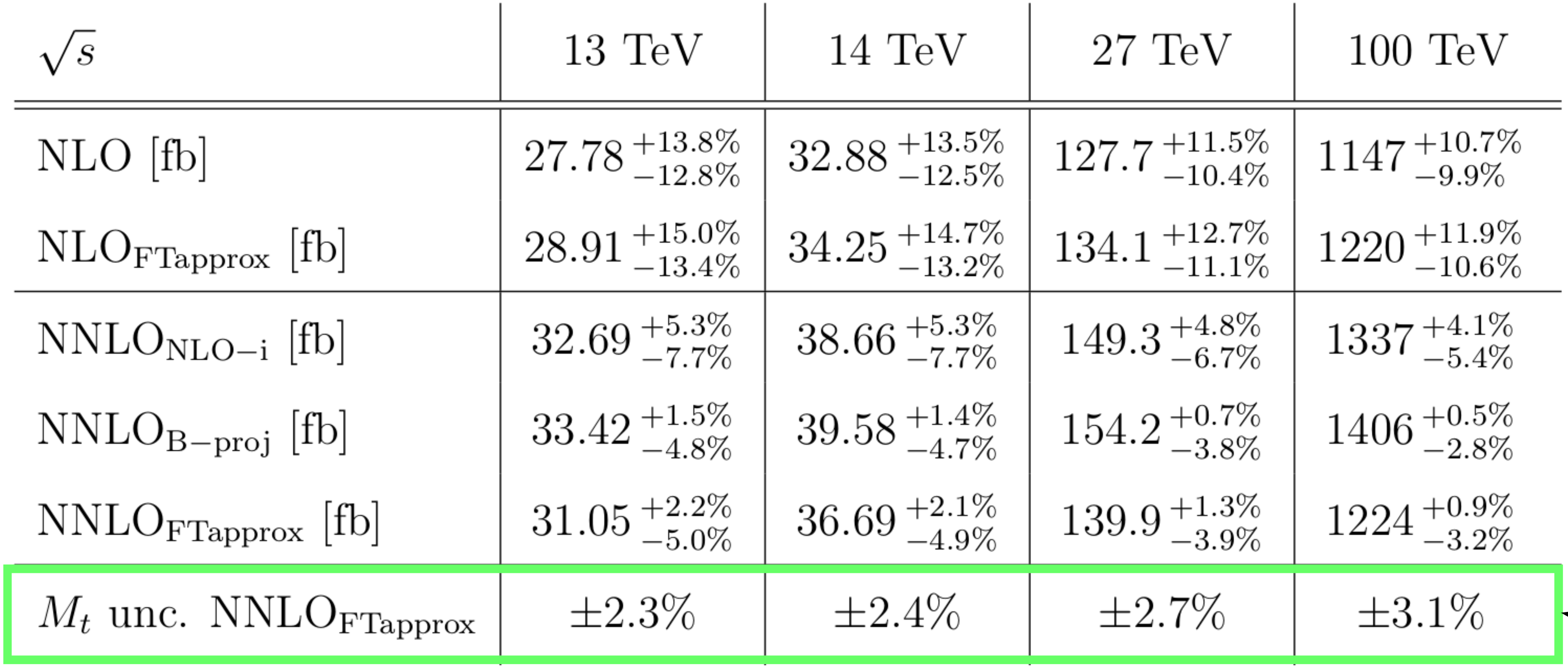
- At NLO the FTapprox overestimates full NLO by 4% → 11% for the pure NLO contribution
- Assuming a ±11% uncertainty for the pure NNLO piece → ±1.2% uncertainty at NNLO
- Multiply by a factor of 2 to be more conservative (14TeV)

Top quark mass uncertainties



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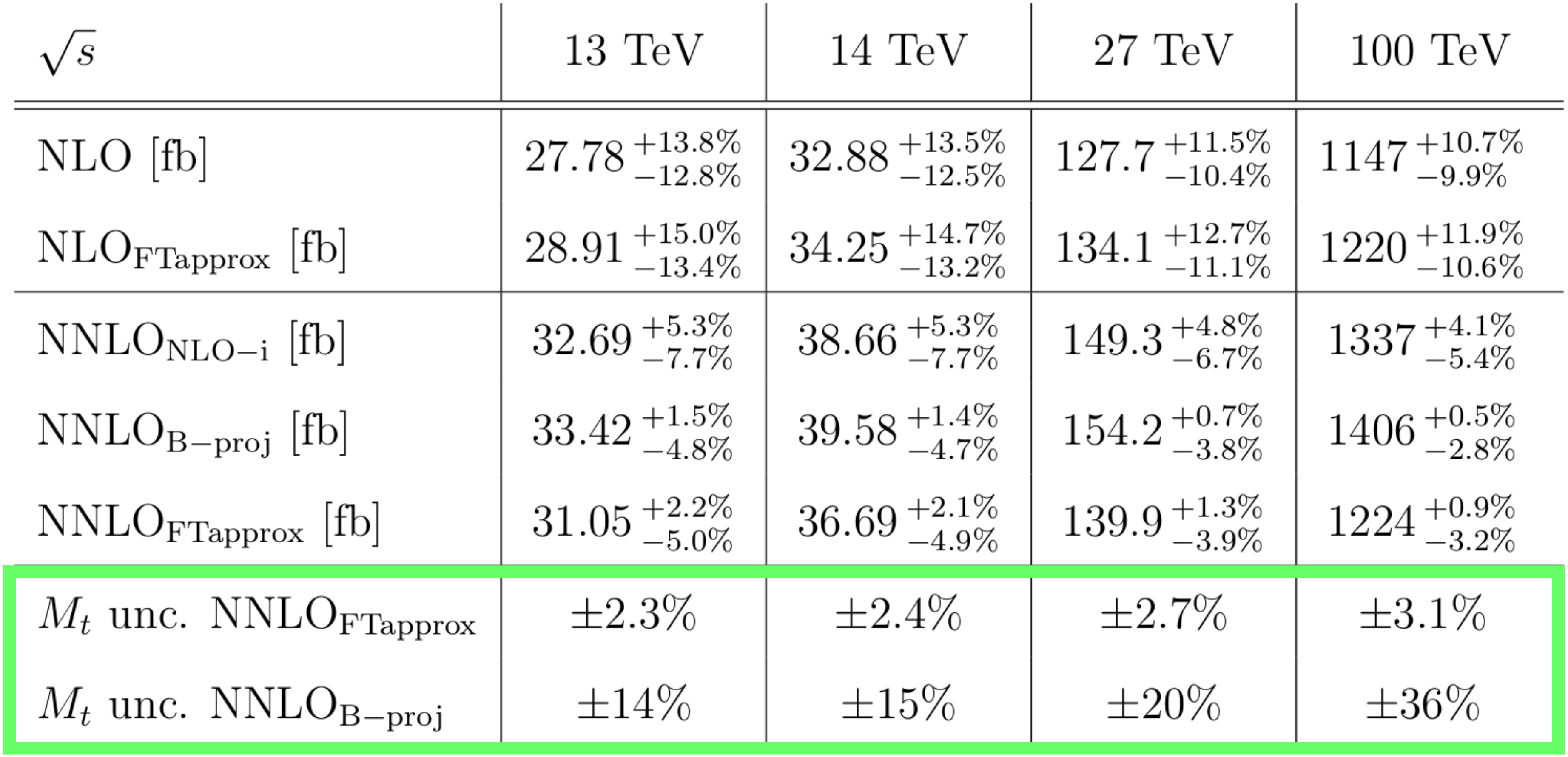
$\mathrm{NNLO}_{\mathrm{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	±2.3%	±2.4%	±2.7%	±3.1%

- At NLO the FTapprox overestimates full NLO by 4% → 11% for the pure NLO contribution
- Assuming a ±11% uncertainty for the pure NNLO piece → ±1.2% uncertainty at NNLO
- Multiply by a factor of 2 to be more conservative (14TeV)

Top quark mass uncertainties



$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO}_{\mathrm{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
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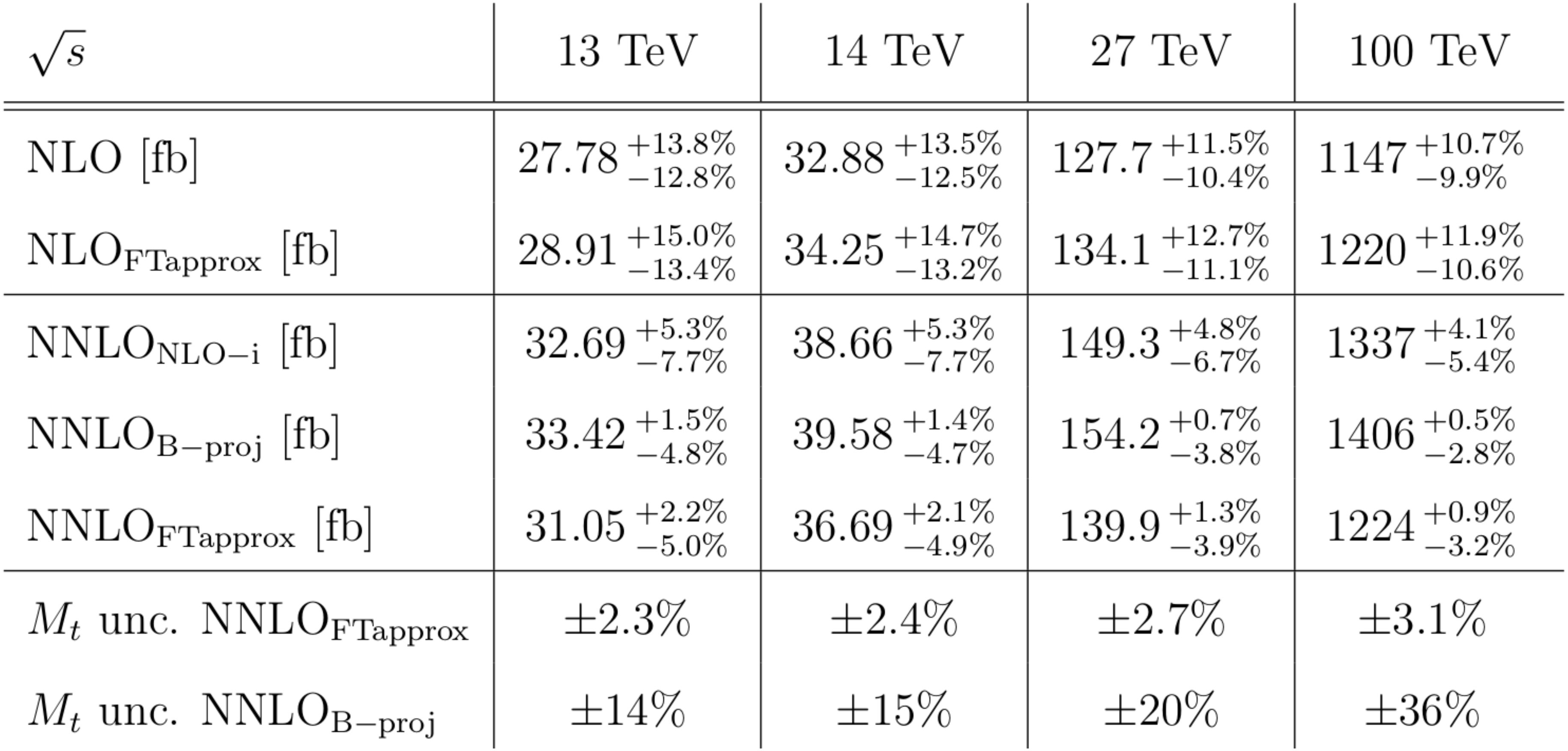
M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	$\pm 2.3\%$	$\pm 2.4\%$	$\pm 2.7\%$	$\pm 3.1\%$
M_t unc. $\mathrm{NNLO}_{\mathrm{B-proj}}$	$\pm 14\%$	$\pm 15\%$	$\pm 20\%$	$\pm 36\%$

- At NLO the FTapprox overestimates full NLO by 4% → 11% for the pure NLO contribution
- Assuming a ±11% uncertainty for the pure NNLO piece → ±1.2% uncertainty at NNLO
- Multiply by a factor of 2 to be more conservative (14TeV)

We can repeat the procedure for the Born-projected approximation

→ Compatible results even without the factor of 2

Top quark mass uncertainties



$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
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M_t unc. $\text{NNLO}_{\text{FTapprox}}$	±2.3%	±2.4%	±2.7%	±3.1%
M_t unc. $\text{NNLO}_{\text{B-proj}}$	±14%	±15%	±20%	±36%

- But the difference between FTapprox and NLO-i increases with the collider energy faster than this uncertainty estimate
- To be more conservative, take half the difference between FTapprox and NLO-i

Top quark mass uncertainties

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
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M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	±2.3%	±2.4%	±2.7%	±3.1%
M_t unc. $\mathrm{NNLO}_{\mathrm{B-proj}}$	±14%	±15%	±20%	±36%
M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	±2.6%	±2.7%	±3.4%	±4.6%

- But the difference between FTapprox and NLO-i increases with the collider energy faster than this uncertainty estimate

- To be more conservative, take half the difference between FTapprox and NLO-i

Small difference for LHC, more conservative for larger energies

NLO-improved approximation – $\mathrm{NNLO}_{\text{NLO-i}}$

Done originally in Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk and Zirke, arXiv:1608.04798 [hep-ph]

Simplest approach: for **each bin** of each histogram we do

$$\mathrm{NNLO}_{\text{NLO-i}} = \mathrm{NLO} \times \left(\frac{\mathrm{NNLO}}{\mathrm{NLO}}\right)_{\text{HEFT}}$$

- Observable level reweighting, technically simple
- Finite Mt effects in the NNLO piece enter via the full NLO
- Has to be repeated for each observable and binning (bin size dependent!)
- We compute the total cross section based on the M_{hh} distribution

Born-projected approximation – NNLO$_{\text{B-proj}}$

Reweight each NNLO event by the ratio of
the full and HEFT Born squared amplitudes

Different multiplicities (double real and real-virtual corrections)

↓

Projection to Born kinematics needed

We make use of the qT-recoil procedure:

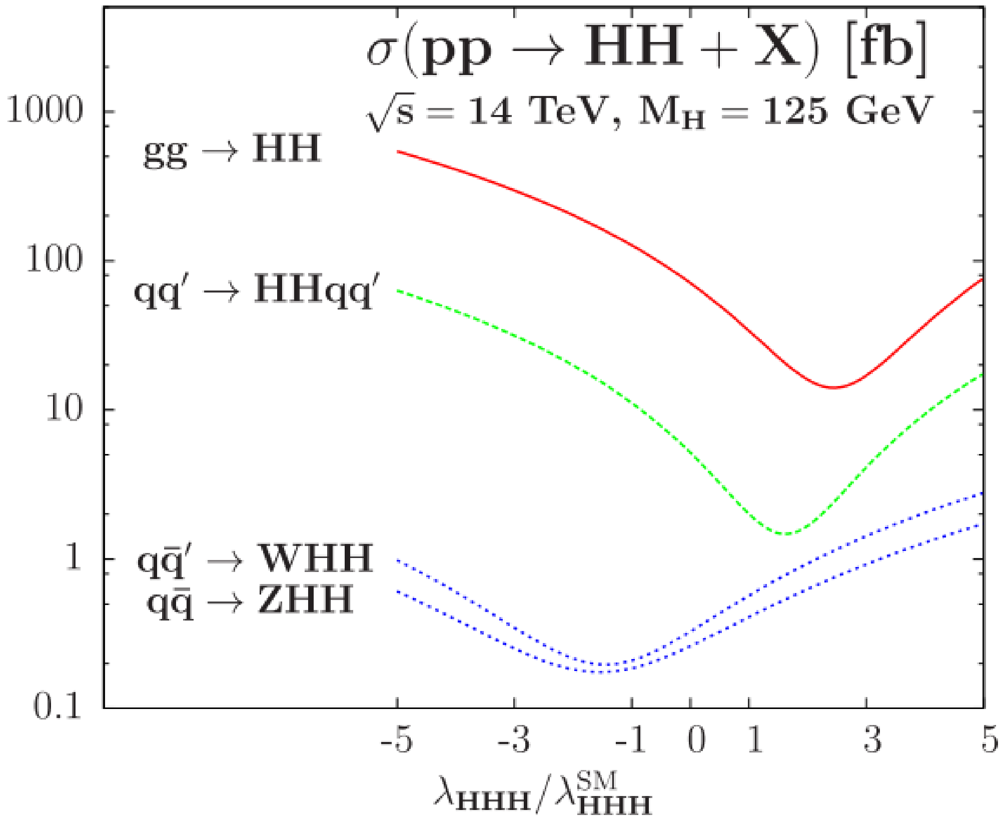
Catani, de Florian, Ferrera and Grazzini, arXiv:1507.06937 [hep-ph]

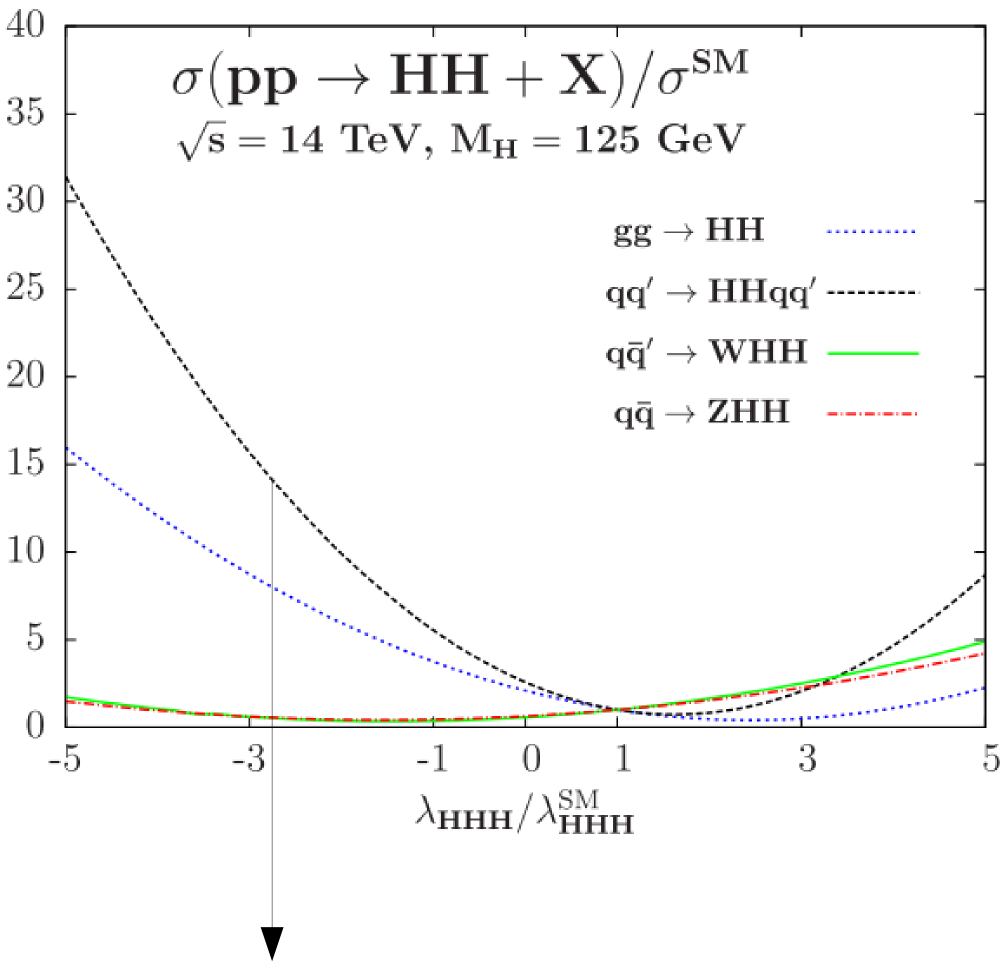
- Momenta of the Higgs bosons remain unchanged
- The new initial state partons momenta absorb the qT due to the additional radiation
- Initial state momenta remain massless, and their transverse component goes to zero when qT goes to zero (and then qT-cancellation is not spoiled)

Finite Mt effects entering only via the Born amplitude: no information about real radiation

λ variation

Sensitivity to Higgs self-coupling for the different HH production mechanisms



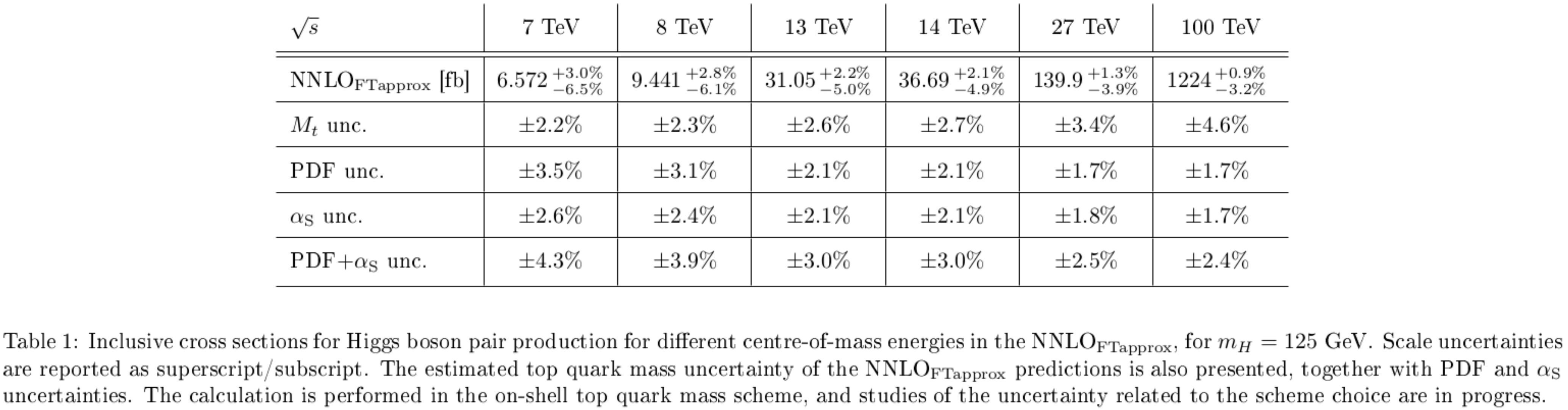


Larger sensitivity in the VBF production mode,
but much smaller cross section

From arXiv:1212.5581 [hep-ph]

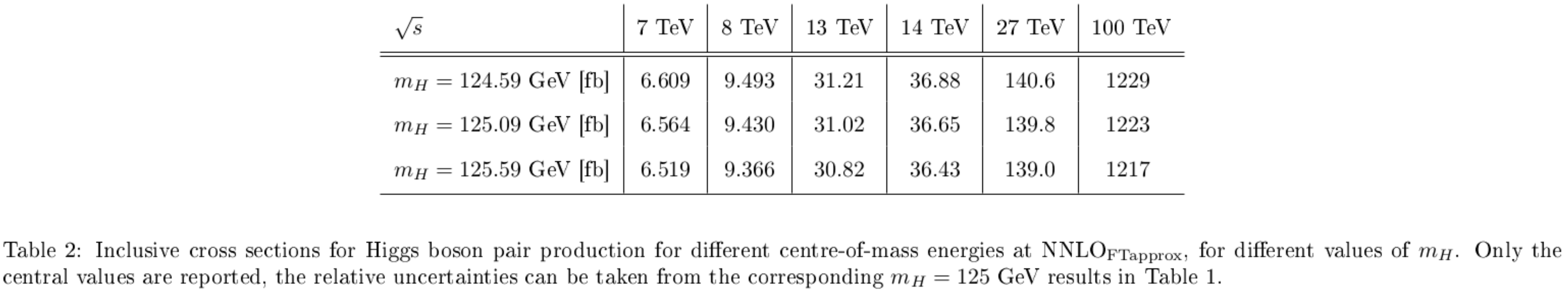
NNLO$_{\text{FTapprox}}$ total cross sections

Current recommendations from HXSWG



$\sqrt{s}$	7 TeV	8 TeV	13 TeV	14 TeV	27 TeV	100 TeV
NNLO$_{\text{FTapprox}}$ [fb]	$6.572\,^{+3.0\%}_{-6.5\%}$	$9.441\,^{+2.8\%}_{-6.1\%}$	$31.05\,^{+2.2\%}_{-5.0\%}$	$36.69\,^{+2.1\%}_{-4.9\%}$	$139.9\,^{+1.3\%}_{-3.9\%}$	$1224\,^{+0.9\%}_{-3.2\%}$
M_t unc.	±2.2%	±2.3%	±2.6%	±2.7%	±3.4%	±4.6%
PDF unc.	±3.5%	±3.1%	±2.1%	±2.1%	±1.7%	±1.7%
α_S unc.	±2.6%	±2.4%	±2.1%	±2.1%	±1.8%	±1.7%
PDF+α_S unc.	±4.3%	±3.9%	±3.0%	±3.0%	±2.5%	±2.4%

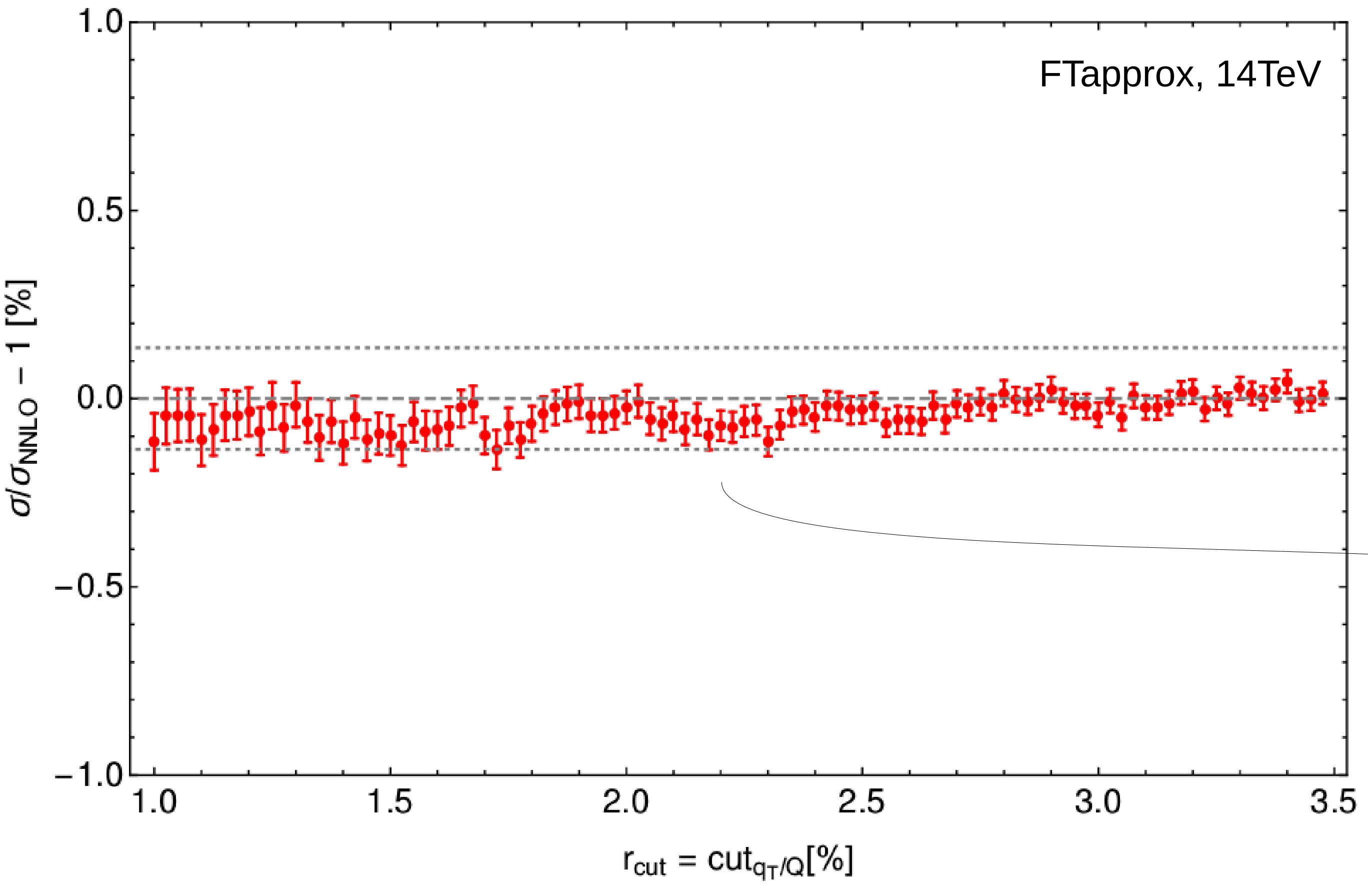
Table 1: Inclusive cross sections for Higgs boson pair production for different centre-of-mass energies in the NNLO$_{\text{FTapprox}}$, for $m_H = 125$ GeV. Scale uncertainties are reported as superscript/subscript. The estimated top quark mass uncertainty of the NNLO$_{\text{FTapprox}}$ predictions is also presented, together with PDF and α_S uncertainties. The calculation is performed in the on-shell top quark mass scheme, and studies of the uncertainty related to the scheme choice are in progress.



$\sqrt{s}$	7 TeV	8 TeV	13 TeV	14 TeV	27 TeV	100 TeV
$m_H = 124.59$ GeV [fb]	6.609	9.493	31.21	36.88	140.6	1229
$m_H = 125.09$ GeV [fb]	6.564	9.430	31.02	36.65	139.8	1223
$m_H = 125.59$ GeV [fb]	6.519	9.366	30.82	36.43	139.0	1217

Table 2: Inclusive cross sections for Higgs boson pair production for different centre-of-mass energies at NNLO$_{\text{FTapprox}}$, for different values of m_H. Only the central values are reported, the relative uncertainties can be taken from the corresponding $m_H = 125$ GeV results in Table 1.

Numerical stability



Extrapolation uncertainty
of ±0.14%

Variations below 0.2%

- Extrapolation to $r_{\mathrm{cut}} \to 0$ via linear least χ^2 fit (vs quadratic in default MATRIX)
- Upper bound of the interval varied to get the best fit and uncertainty estimation