HH production at NNLO including M_t effects

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In collaboration with M. Grazzini, G. Heinrich, S. Jones, S. Kallweit, M. Kerner, J. Lindert

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HXSWG general meeting
26 March 2018

HH production via gluon fusion

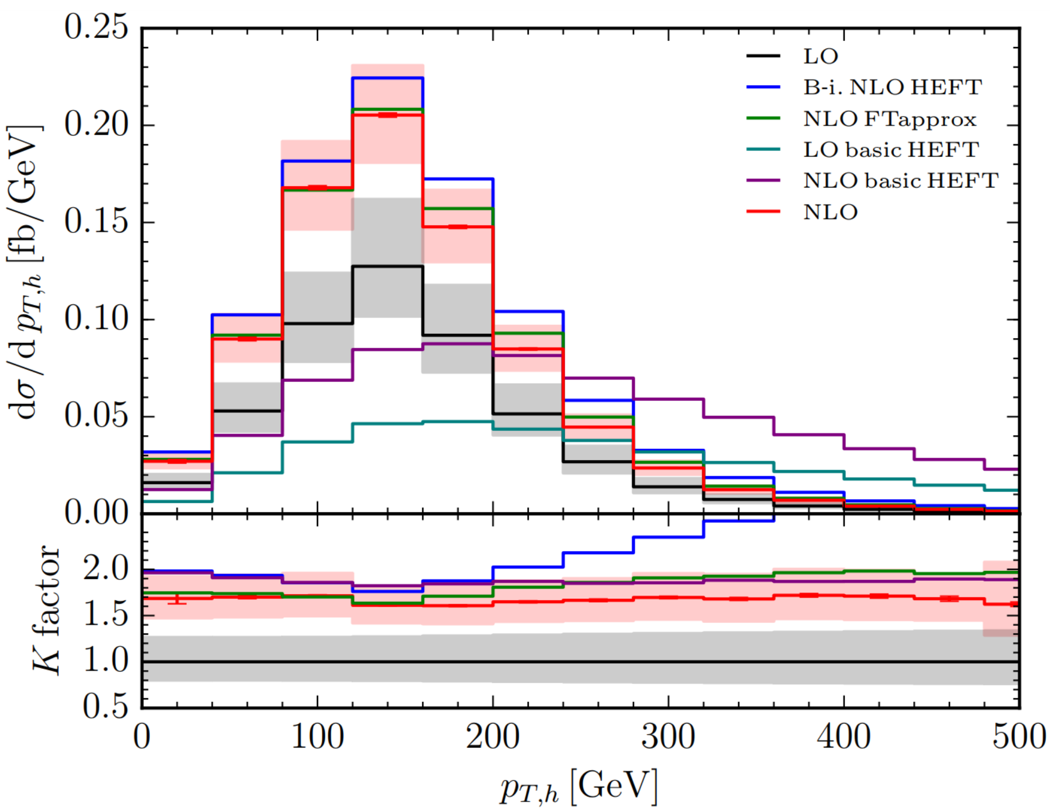
- **NLO** corrections are **large** (~66% at 14TeV), and with still **sizeable uncertainties** (~±13%)

[S. Borowka et al. arXiv:1604.06447]

- **Beyond that:** Higgs Effective Field Theory (**HEFT**)

Top quark integrated out → Effective tree-level gluons-Higgs coupling

- Corrections computed in the HEFT and typically normalized by exact LO differentially in M_{hh}



- HEFT: large M_t limit → Worse than for single Higgs (larger invariant mass)
- Born improved overestimates the NLO total XS by a 15%
- Poor description of the tail of some distributions

- To obtain accurate NNLO results, we need to **combine the HEFT NNLO with the full NLO**
- Moreover, we need to include **finite M_t effects** in the NNLO corrections

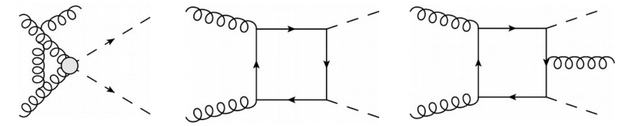
HH at NNLO with M_t effects

Higgs boson pair production at NNLO with top quark mass effects

M. Grazzini, G. Heinrich, S. Jones, S. Kallweit, M. Kerner, J. Lindert, JM [arXiv:1803.02463]

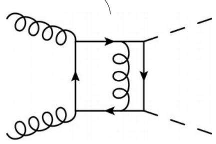
- Fully differential parton-level predictions for Higgs boson pair production via gluon fusion
- Combination of full NLO with large-M_t NNLO
- NNLO piece improved with different reweighting techniques to account for finite-M_t effects
- Estimation of remaining M_t uncertainty at NNLO
- Most advanced perturbative prediction available to date

Technical ingredients

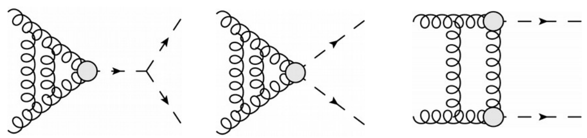


Tree-level and one-loop amplitudes (HEFT and full-M_t) → OpenLoops
[Cascioli, Lindert, Maierhofer, Pozzorini]

Full NLO (two-loop) virtual corrections → two dimensional grid + interpolation
[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke, '16]



Analytical results for NNLO two-loop corrections in the HEFT
[de Florian, JM, '13]



NNLO subtraction formalism: q_T-subtraction
[Catani, Grazzini, '07]

Implementation based on public code MATRIX
[Kallweit, Grazzini, Wiesemann, '17]

We worked with three different **approximations** for the **pure NNLO piece:**

- NLO-improved approximation – $NNLO_{NLO\text{-}i}$
- Born-projected approximation – $NNLO_{B\text{-}proj}$
- Full-theory approximation – $NNLO_{FTapprox}$

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

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

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

- Observable level reweighting, technically simple
- Finite M_t 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 – $NNLO_{B\text{-}proj}$

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 q_T-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 q_T due to the additional radiation
- Initial state momenta remain massless, and their transverse component goes to zero when q_T goes to zero (and then q_T-cancellation is not spoiled)

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

Full-theory approximation – $\text{NNLO}_{\text{FTapprox}}$

- 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

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

we apply the reweighting

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

- Same partonic subprocess used for reweighting: no need for a projection
- Amplitudes that are tree-level in the HEFT are treated exactly
- At NLO this agrees with the FTapprox in Maltoni, Vryonidou and Zaro, arXiv:1408.6542 [hep-ph]
- Great performance at NLO (4% difference with full NLO) + full M_t dependence in double reals

Our best NNLO prediction

Full-theory approximation – $\text{NNLO}_{\text{FTapprox}}$

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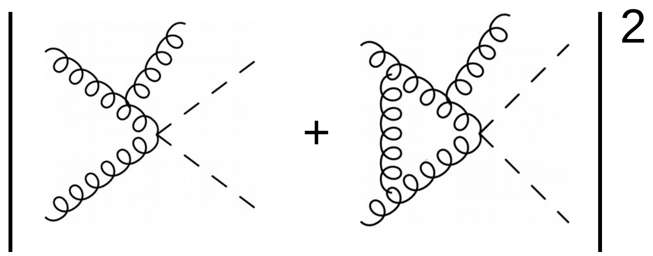
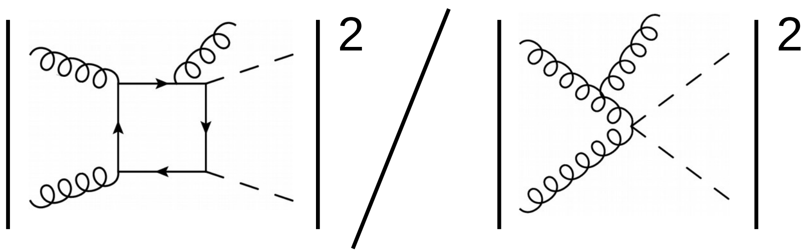
E.g. the squared amplitude:



is reweighted by:



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Numerical results

Setup of the calculation:

- M_h = 125GeV M_t = 173GeV
- PDF4LHC15 sets at each corresponding order
- Central scale value $\mu_0 = M_{hh}/2$ (smaller resummation effects)
- Scale uncertainties: 7-point variation
- Results for 13, 14, 27 and 100TeV
- No bottom quark contributions (effect below 1% at LO)
- No top quark width effects (2% at LO for the total cross section)

Total cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO_{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\mathrm{NNLO_{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\mathrm{NNLO_{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\mathrm{NNLO_{FTapprox}}$ [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. $\mathrm{NNLO_{FTapprox}}$	±2.6%	±2.7%	±3.4%	±4.6%
$\mathrm{NNLO_{FTapprox}}$/NLO	1.118	1.116	1.096	1.067

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$\text{NNLO}_{\text{FTapprox}}/\text{NLO}$	1.118	1.116	[illegible]	[illegible]

B-proj > NLO-i > FTapprox

Increase with respect to NLO at 14TeV:

B-proj:	20%
NLO-i:	18%
FTapprox:	**12%**

$$\sigma_{\text{YR4}} = \sigma^{\text{HEFT}}_{\text{NNLL}} + \delta_t\, \sigma^{\text{HEFT}}_{\text{NLO}}$$

$$\sigma^{\text{exact}}_{\text{NLO}} = \sigma^{\text{HEFT}}_{\text{NLO}}(1 + \delta_t)$$

About 8% smaller than the current recommendation (YR4)

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- Size of perturbative corrections decreases with the energy for the FTapprox
- This doesn't happen for the other two approximations
- Not fully surprising: similar behavior for NLO K-factor

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- Strong reduction of the scale uncertainties at NNLO
- About a factor of 3 for the FTapprox at 14TeV

Even stronger reduction at 100TeV

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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)

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We can repeat the procedure for the Born-projected approximation

→ Compatible results even without the factor of 2

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- 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

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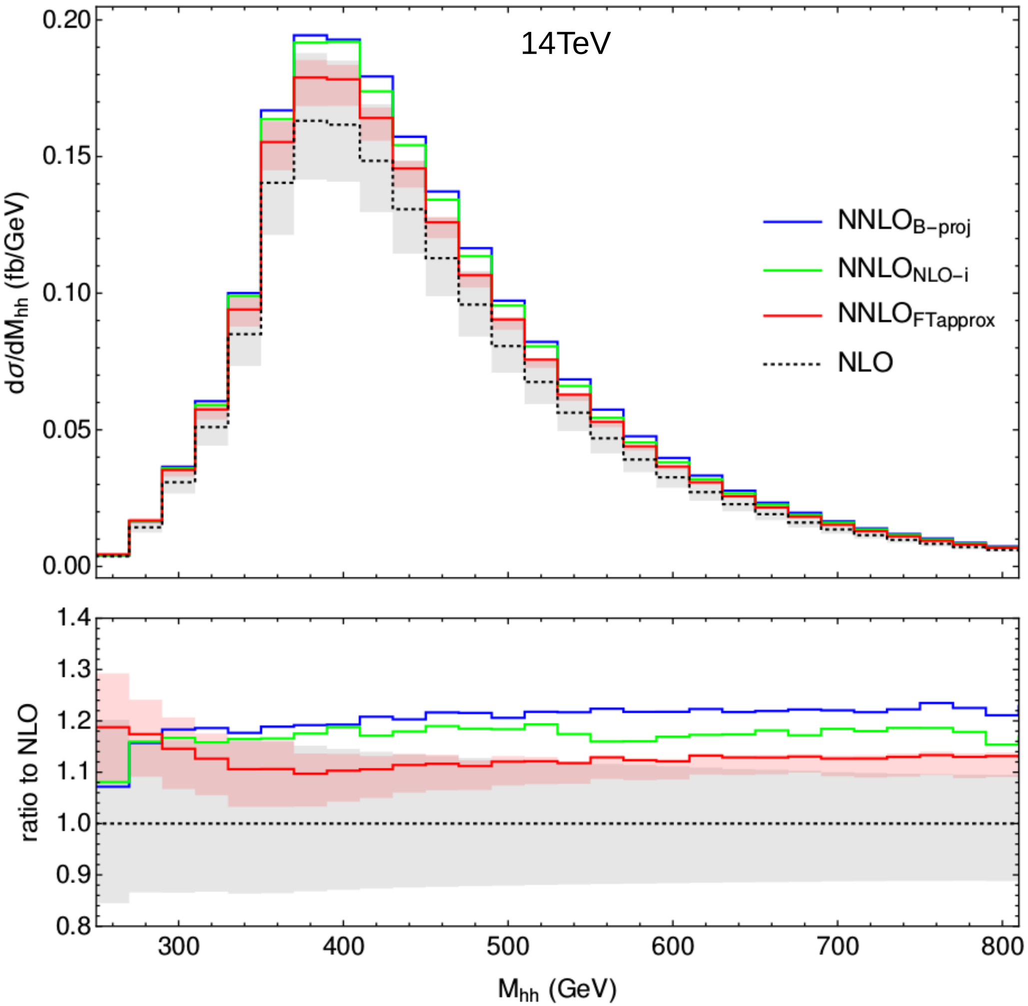
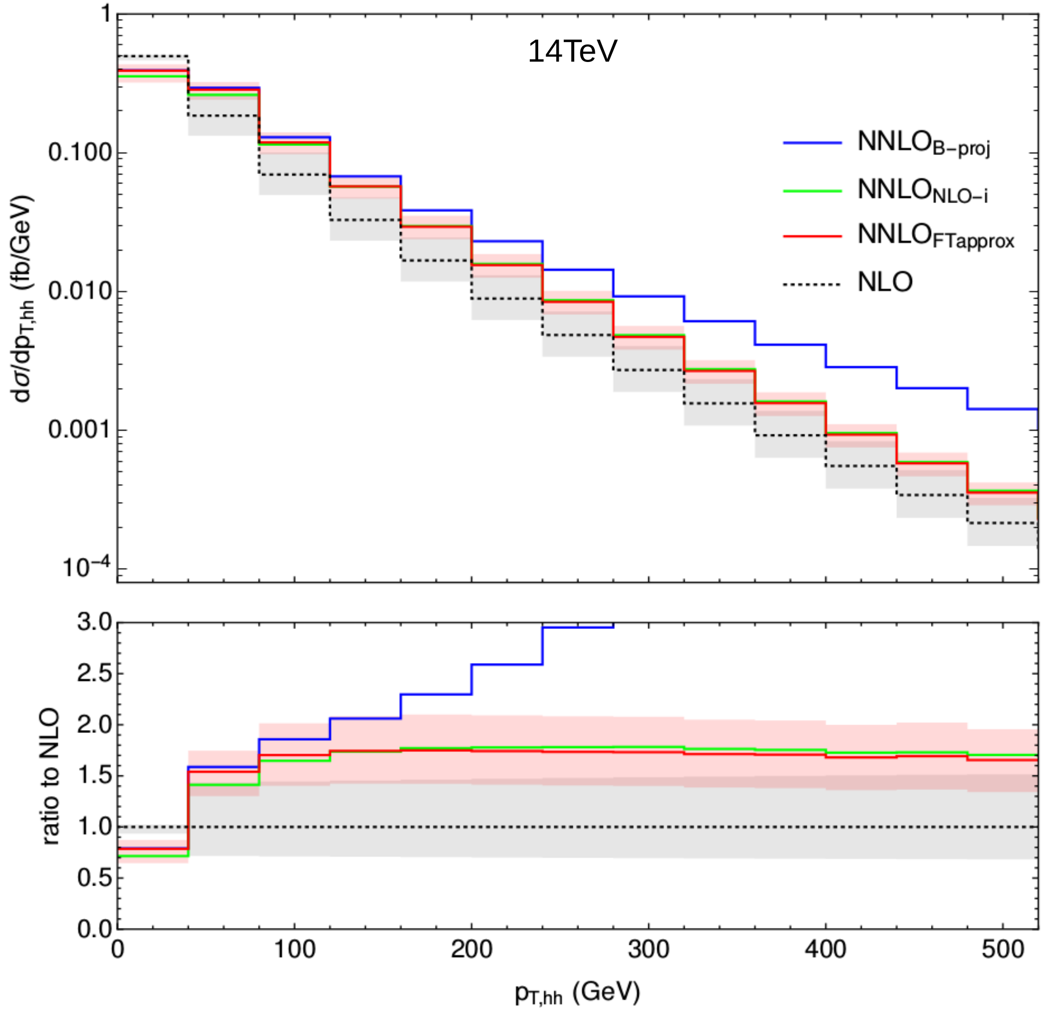
Small difference for LHC, more conservative for larger energies

Differential distributions

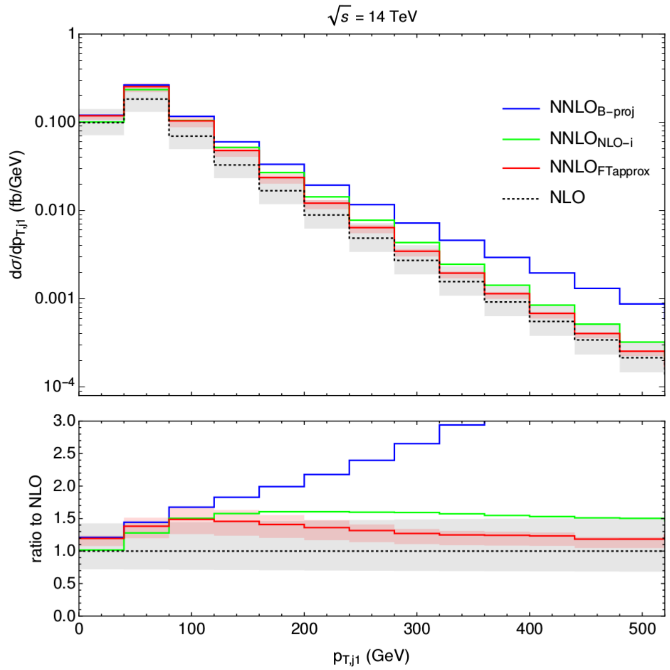


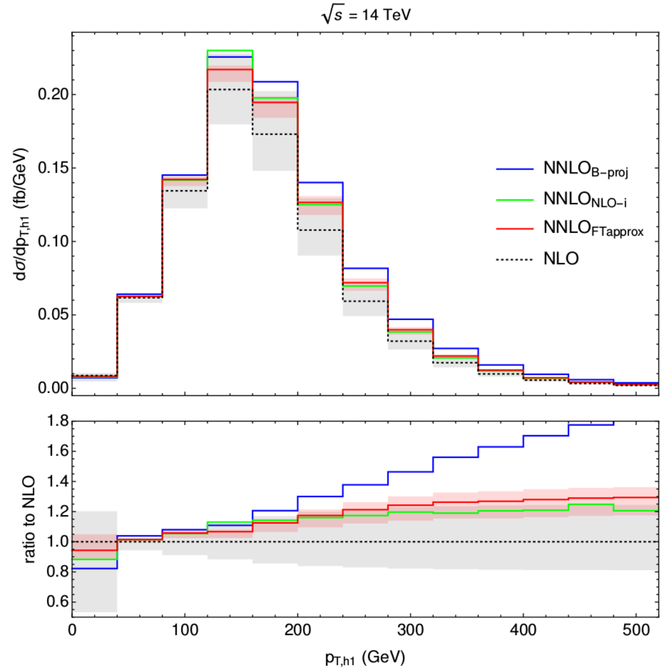


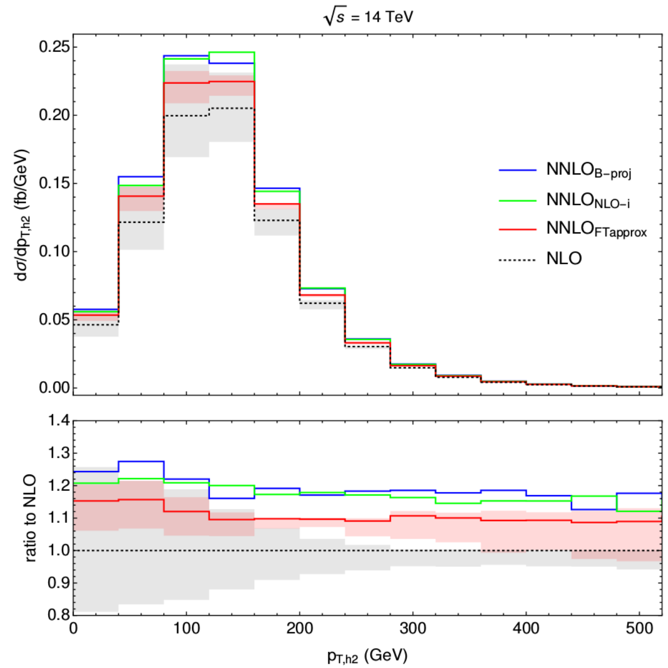
- B-proj and NLO-i have similar behaviors
- FTapprox presents larger corrections at threshold, minimum corrections at M_{hh} ~ 400GeV, slow increase towards the tail
- Scale uncertainties are substantially reduced
- Overlap with the NLO band

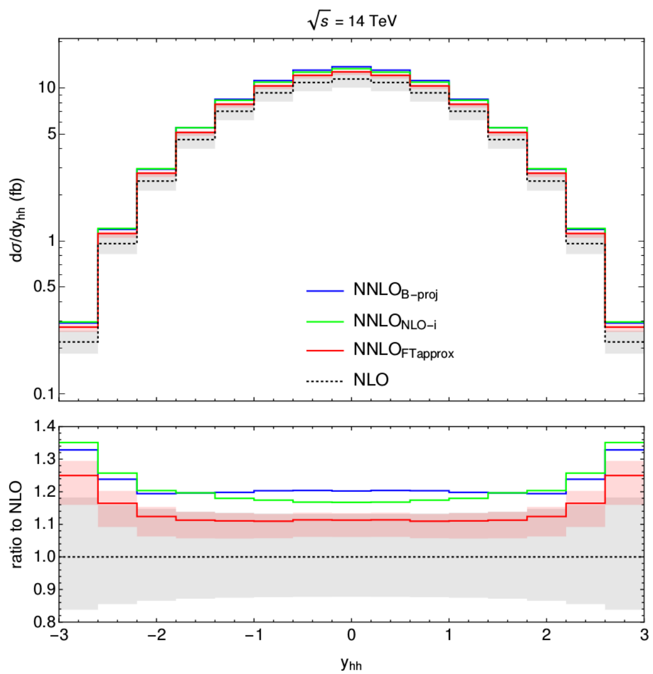
- NNLO$_{B-proj}$ has wrong scaling in the tail
  No information about lowest order for $p_{T,hh}$
- NNLO$_{FTapprox}$ agrees with NNLO$_{B-proj}$ for low $p_{T,hh}$, and with NNLO$_{NLO-i}$ in the tail
- Distribution trivial at LO: NNLO is effectively NLO
  Large corrections and sizeable scale uncertainties

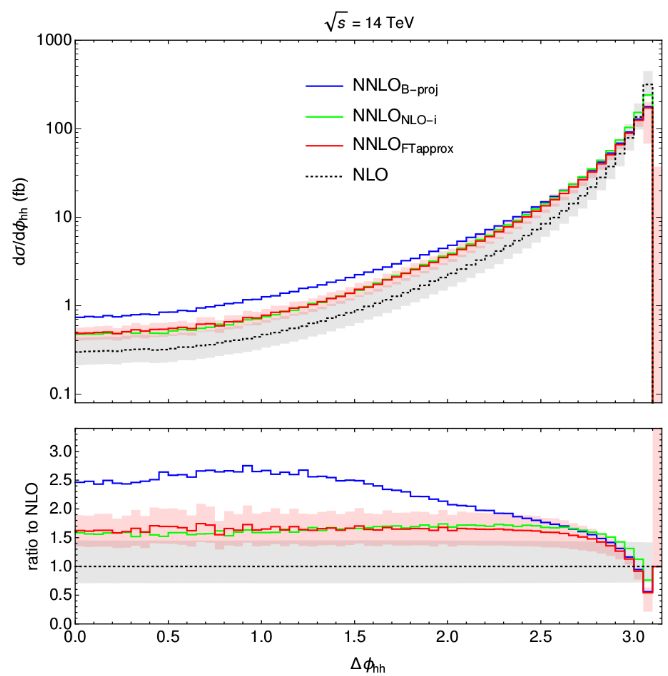
Differential distributions











Discussed in backup slides

Conclusions

- We **combined** the full NLO with the NNLO corrections computed in the HEFT
- **Fully differential** results, using q_T-subtraction
- NNLO piece improved via different **reweightings** to account for **finite M_t effects**
- Our best prediction includes the **full double-real loop-induced** amplitudes
- Increase with respect to NLO from 12% at 13TeV to 7% at 100TeV
- Remaining **M_t uncertainty: few percent** level
- **Most advanced** perturbative prediction for HH available to date

- Our proposal is to **update** the current **total XS** and **M_t uncertainties** recommendation (YR4) to the **$NNLO_{FTapprox}$** presented here
- For the moment, for distributions **rescale NLO+PS by $NNLO_{FTapprox}$ total XS**
- Comments and suggestions are very welcome!

Thanks!

Backup slides

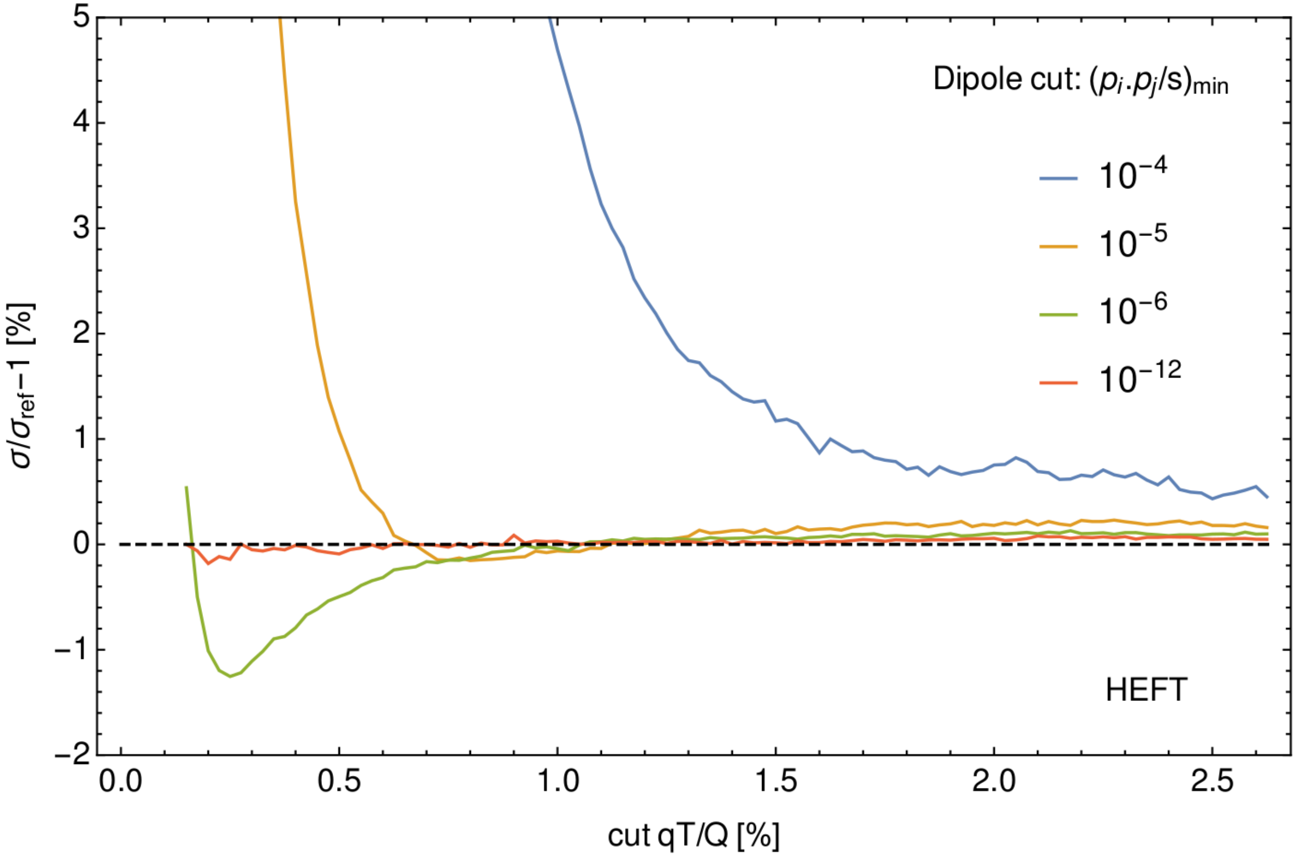
Numerical stability

- Loop-induced double real amplitudes can became unstable close to *dipole singularities*

Small $\alpha = \dfrac{p_i \cdot p_j}{\hat{s}}$, i and j emitters

- Quadruple precision rescue non viable (~10 minutes per PS point for gg→HHgg)

- Using a too large cut on α spoils the qT-cancellation



Numerical stability

Solution: we introduced a new parameter, $\alpha_{\text{L-i,cut}}$, below which we approximate the loop-induced amplitudes by the Born reweighted HEFT

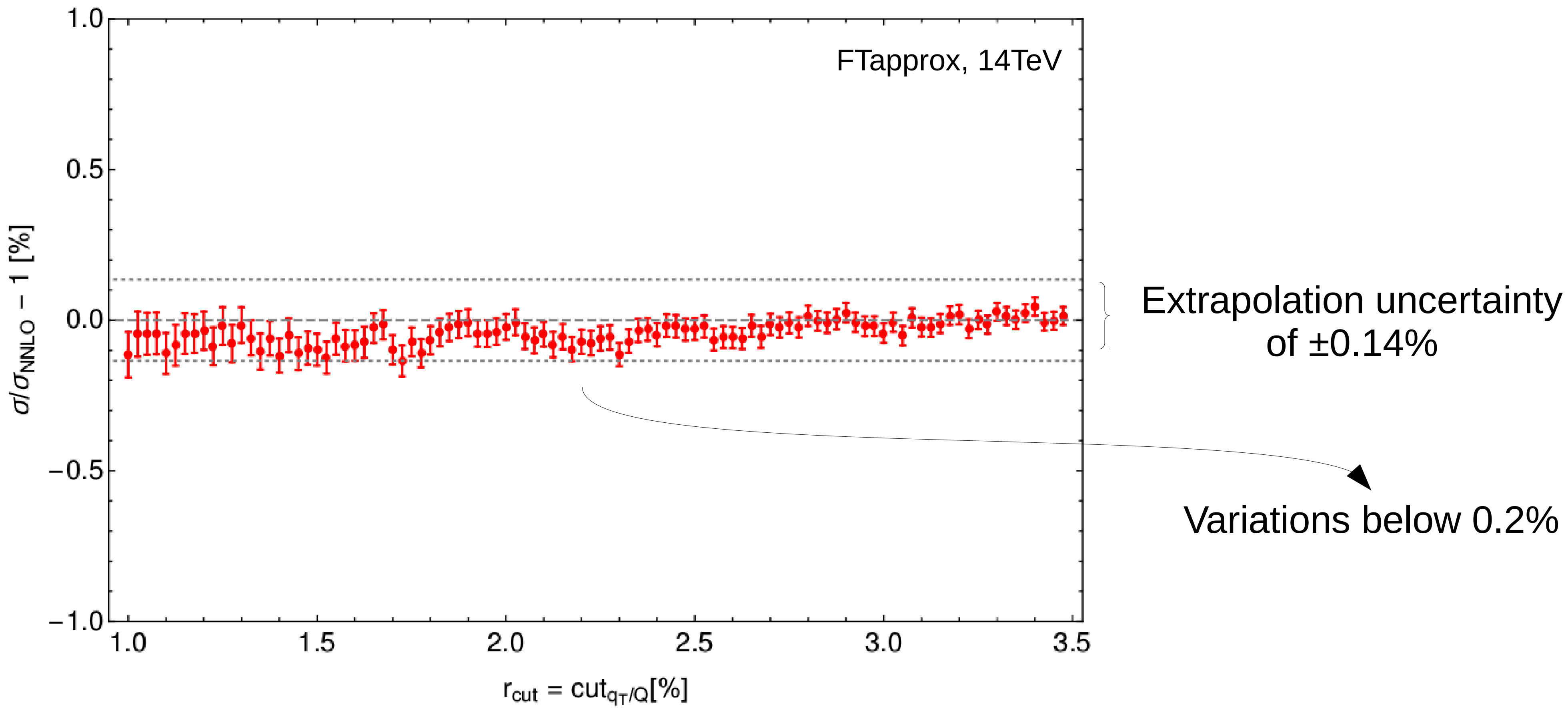
- We avoid evaluating the double real loop induced amplitudes in the unstable regions
- We can use a lower overall dipole cut ⟶ we don't spoil the qT-cancellation

$$\alpha_{\text{L-i,cut}} = \underbrace{10^{-3} \text{ to } 10^{-5}}$$

Results independent in this range

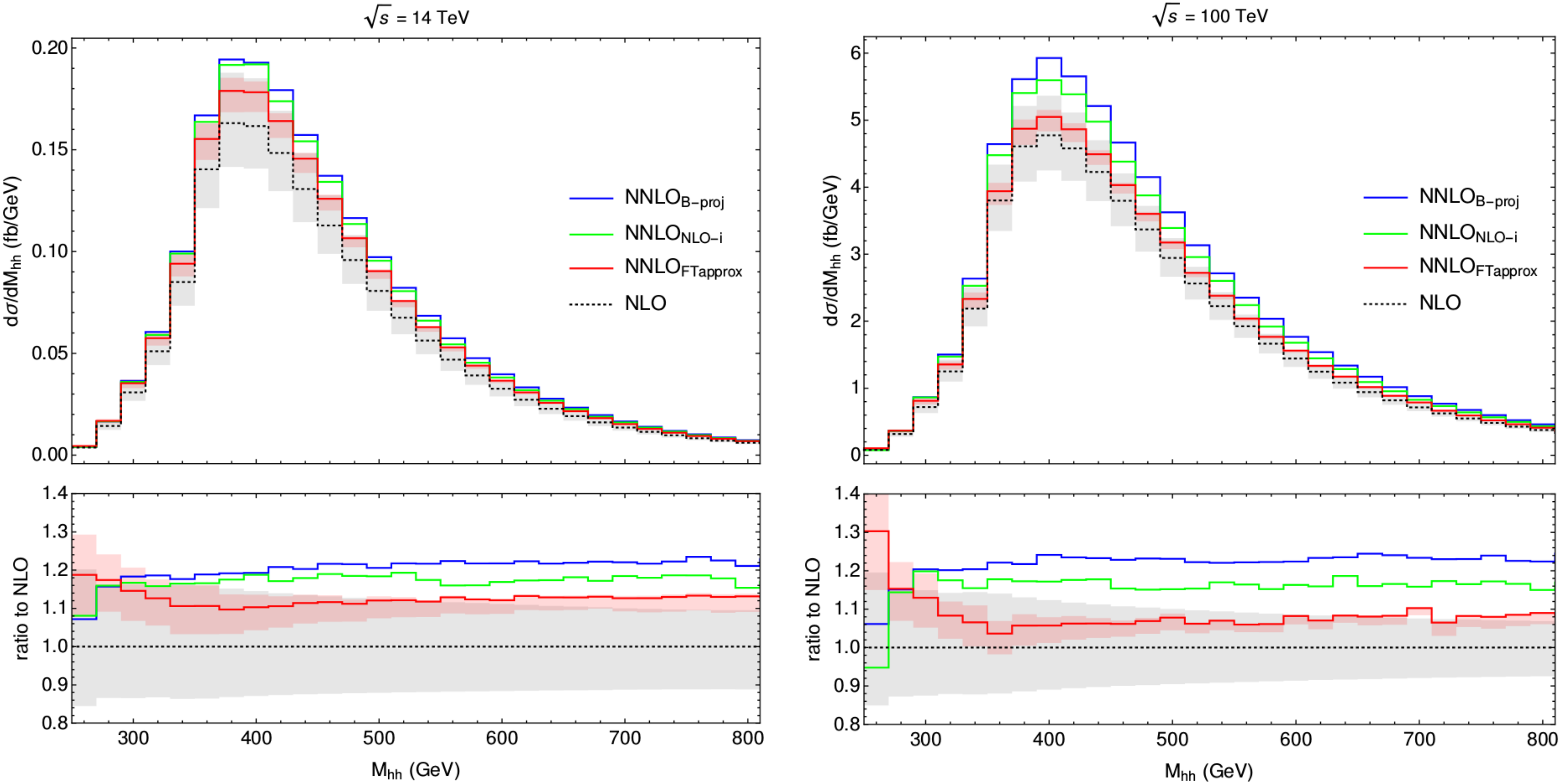
$$\alpha_{\text{cut}} = 10^{-10}$$

Numerical stability



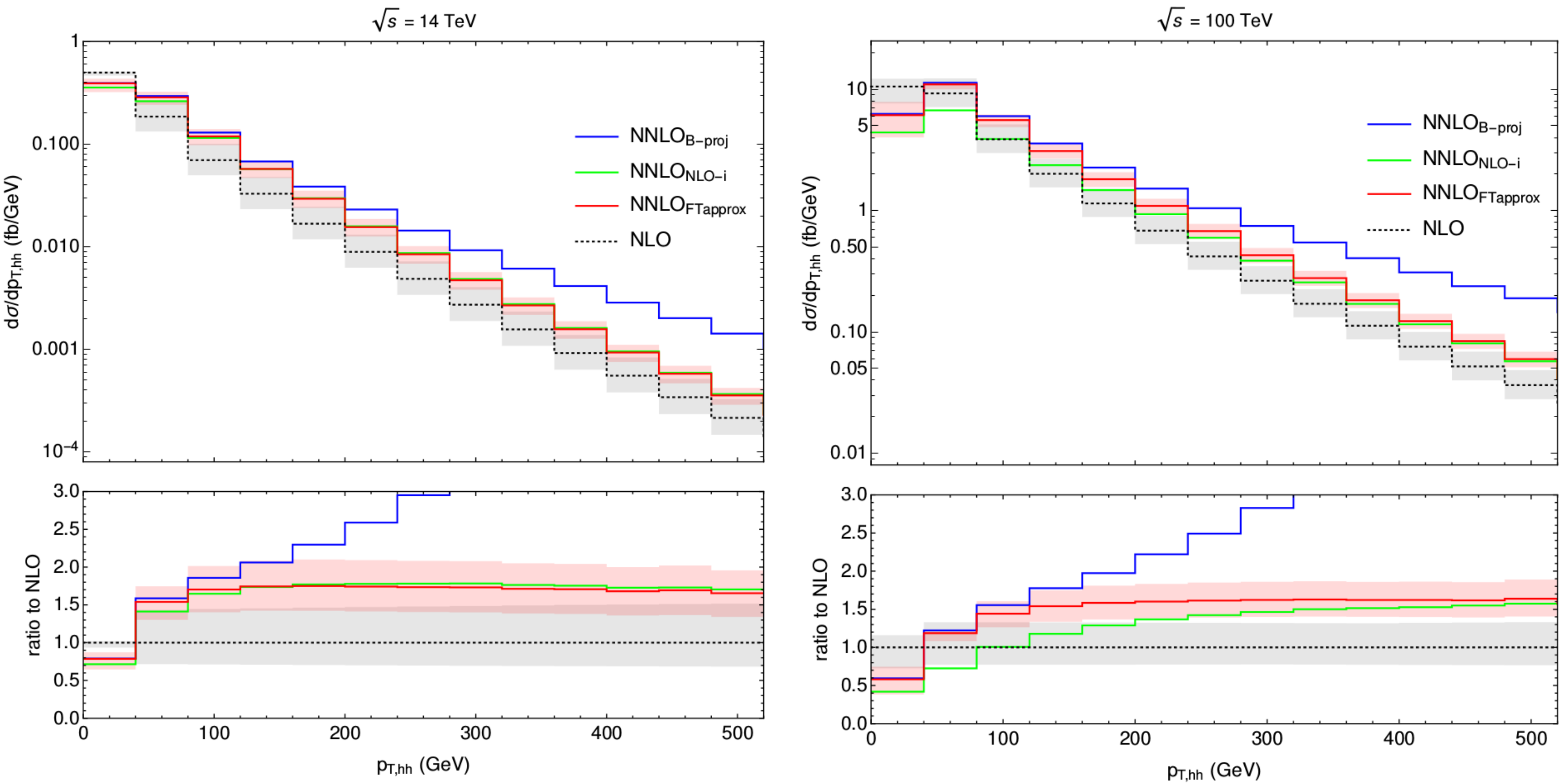
- Extrapolation to $r_{cut} \to 0$ via linear least χ^2 fit (vs quadratic in default MATRIX)
- Upper bound of the interval varied to get the best fit and uncertainty estimation

Differential distributions – M_{hh}



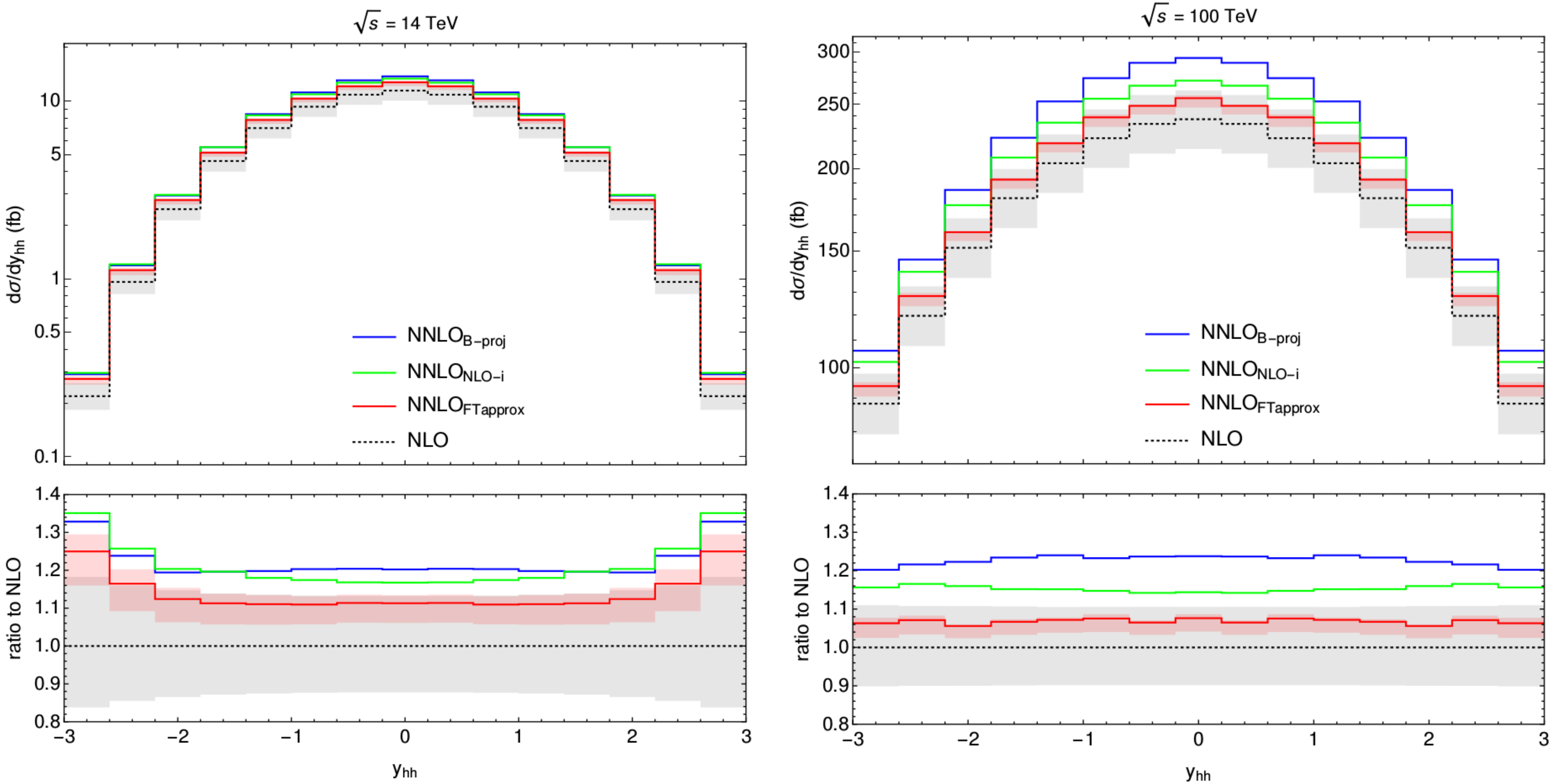
- Previous features enhanced at 100TeV
- Slower decrease in the tail of the distribution
- Larger separation between the different NNLO predicitons, smaller corrections for the FTapprox
- FTapprox different behavior at threshold even stronger: due to contributions from events with hard radiation

Differential distributions – $p_{T,hh}$



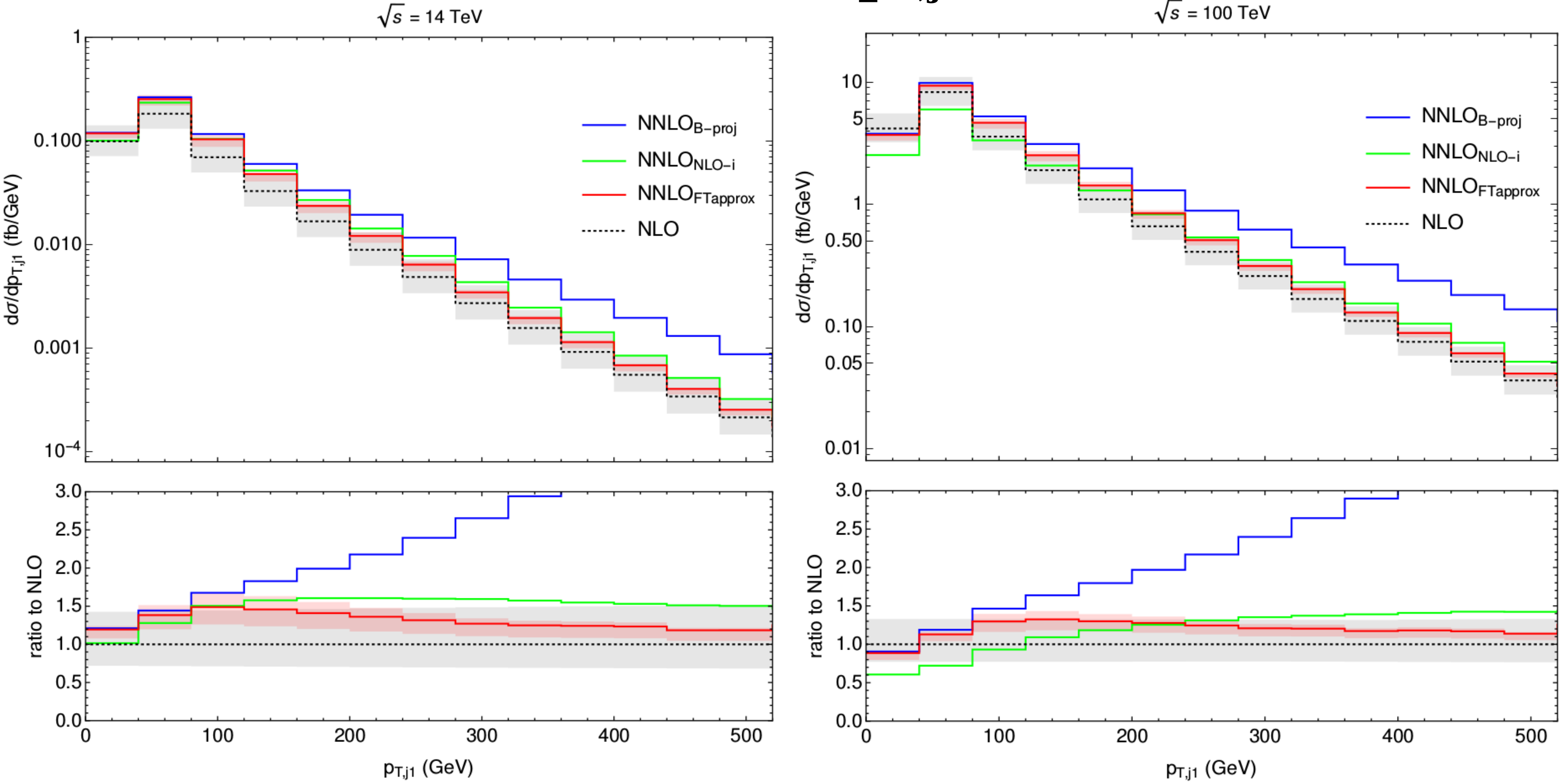
- Different behaviors are more pronounced at 100TeV
- Larger separation between FTapprox and NLO-i (almost full agreement in the tail)
- FTapprox agrees with B-proj for low $p_{T,hh}$

Differential distributions – y_{hh}



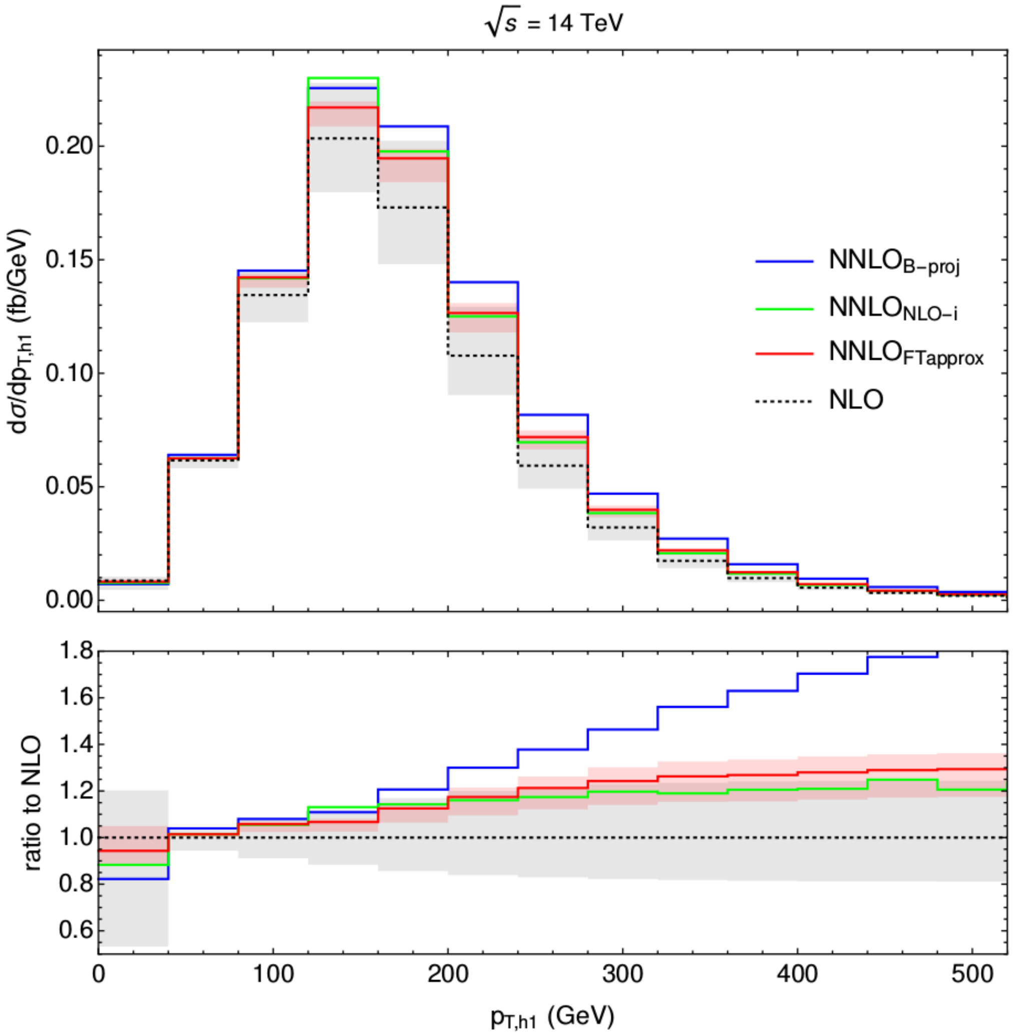
- Not very different behaviors between the different approximations (besides normalization)
- Largest shape difference in the central region for NLO-i

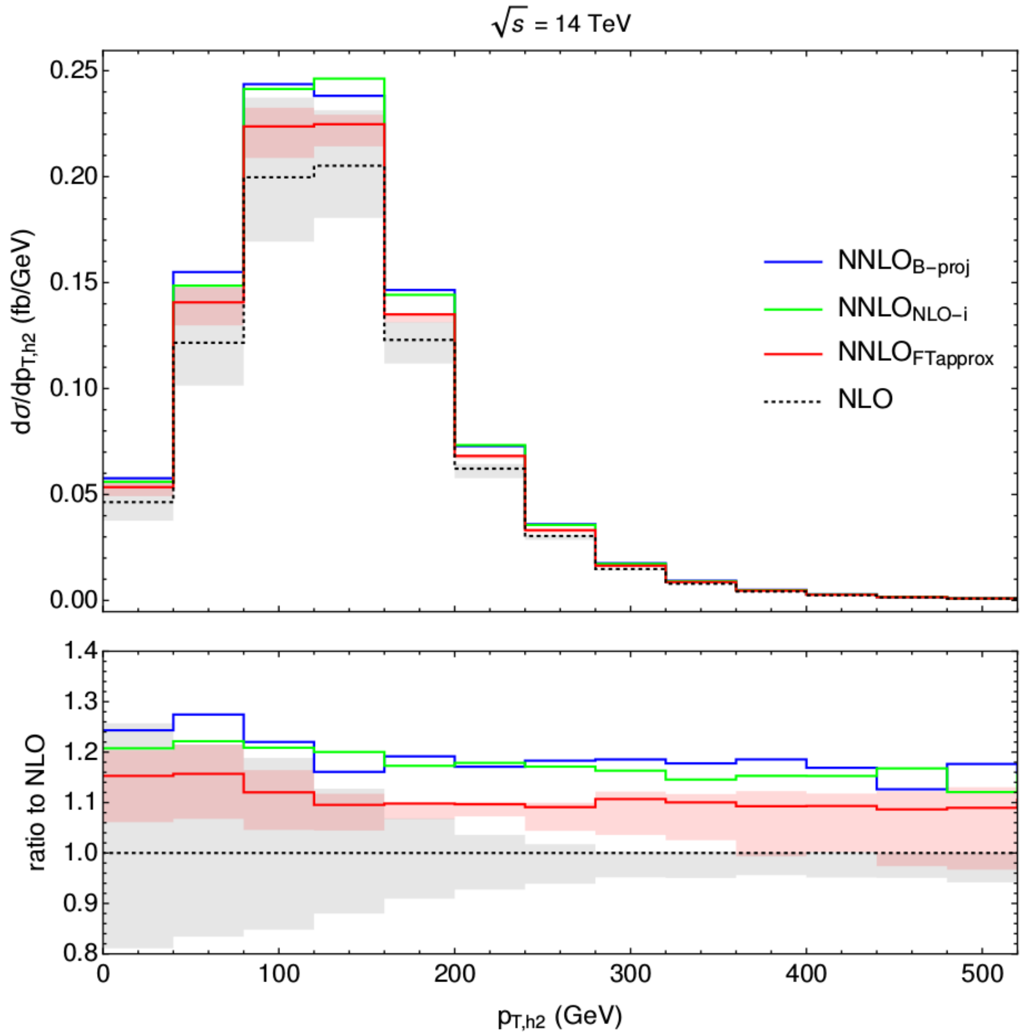
Differential distributions – $p_{T,j1}$



- Huge unphysical corrections in the tail for the B-proj approximation
- More pronounced differences between FTapprox and NLO-i compared to $p_{T,hh}$
- FTapprox predicts a softer spectrum, corrections contained in the NLO uncertainty band

Differential distributions – $p_{T,h1}$ and $p_{T,h2}$

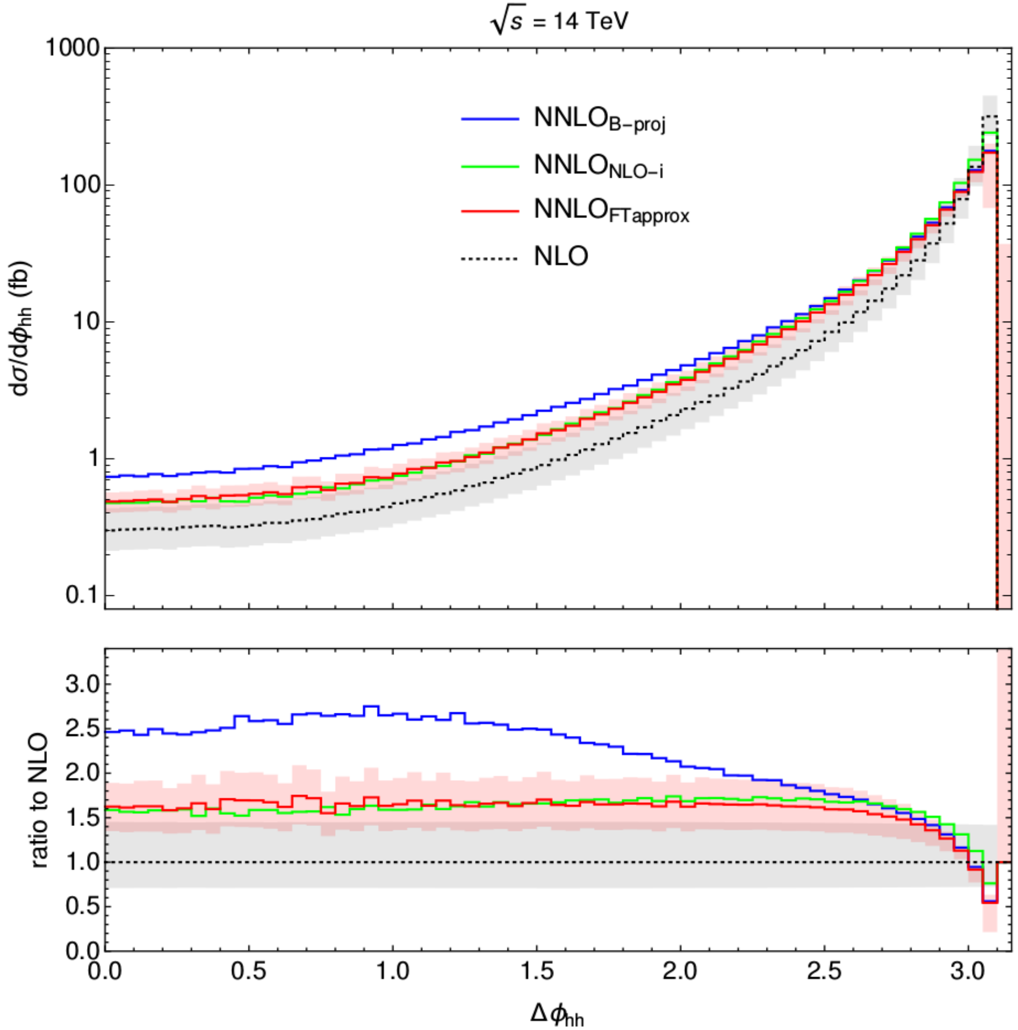


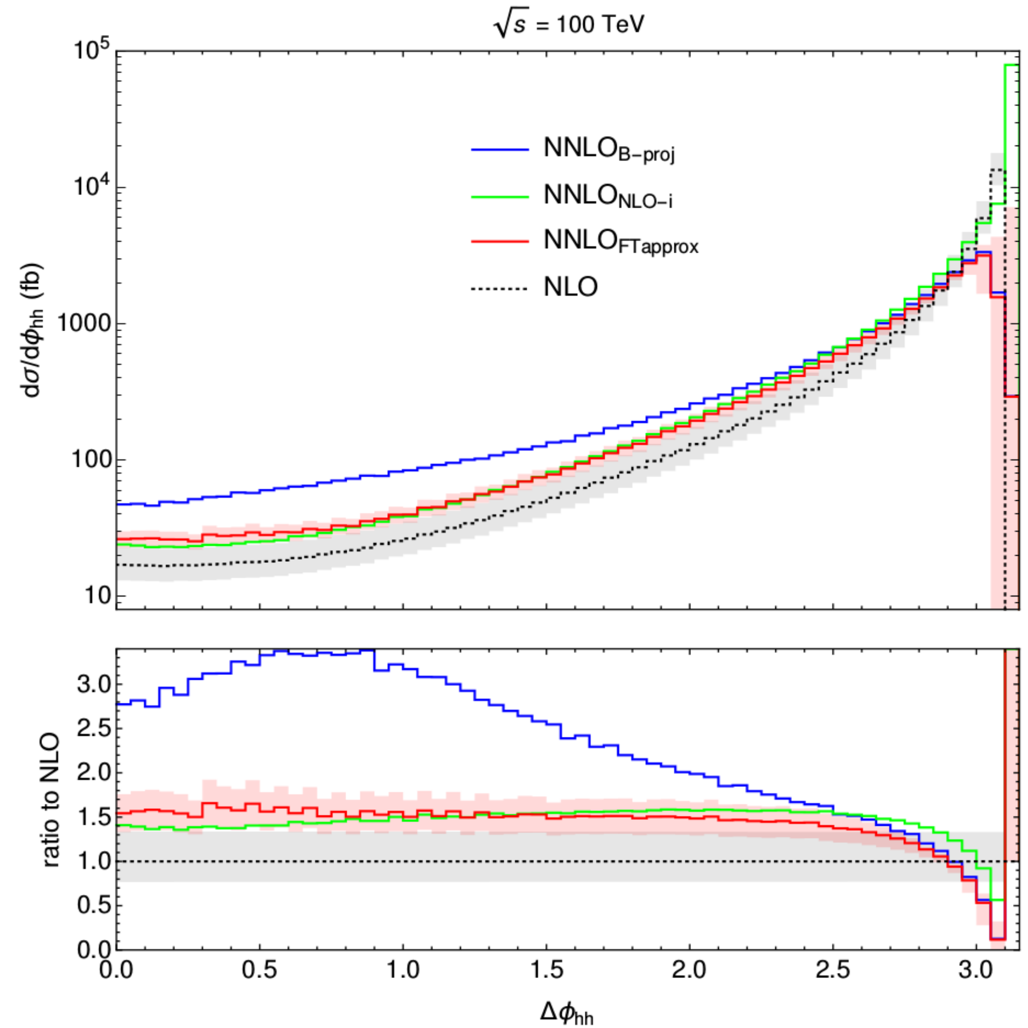


- Hardest Higgs pT spectrum:
  Large corrections in the tail of the B-proj approximation
  Good agreement between FTapprox and NLO-i

- Softer Higgs pT spectrum:
  Similar shape for all approximations
  Larger NNLO scale uncertainties in the tail

Differential distributions – $\Delta\phi_{hh}$





- Trivial at LO: back-to-back. NNLO effectively NLO
- Large corrections above 50%, sizable scale uncertainties
- B-proj approximations predicts larger corrections in the region dominated by hard radiation
- Good general agreement between FTapprox and NLO-i, larger differences close to π