Precise QCD predictions for Higgs boson pair production

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Outline

- **Introduction:**

  Motivation, main production and decay modes

  Status and prospects for the LHC

- **QCD corrections in the large M_t limit:**

  NNLO cross section

  Threshold resummation at NNLL

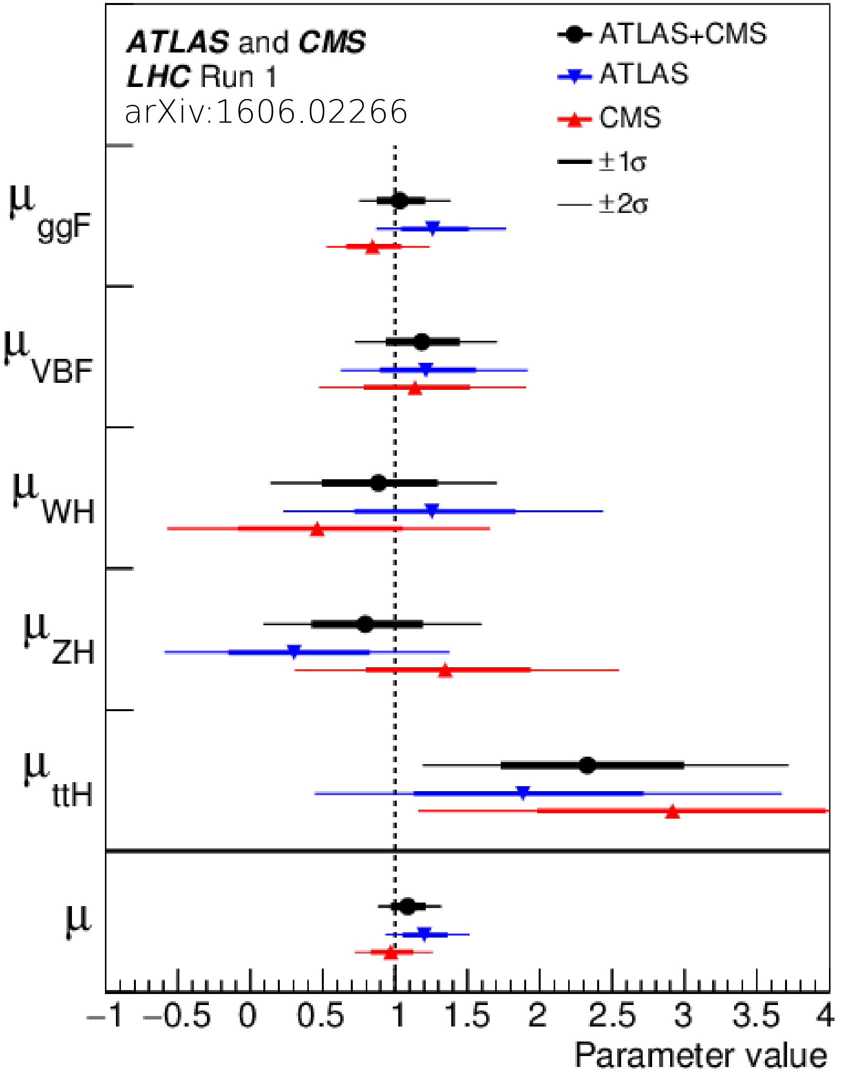
- **NNLO predicitons with finite M_t effects:**

  Technical ingredients, NNLO approximations

  Total cross sections and differential distributions

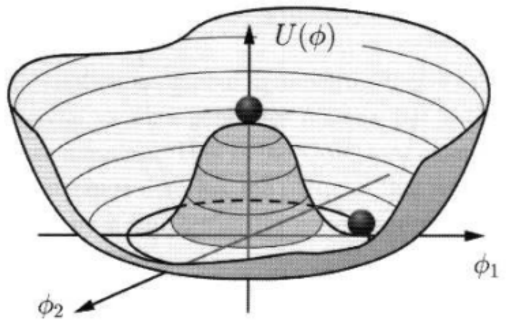
- **Conclusions**

Multi-Higgs production



- Higgs couplings to fermions and gauge bosons so far compatible with SM

- What happens for the Higgs self-couplings?
  Are they relevant?
  How can we measure them?



- **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: $\lambda = \lambda' = M_H^2/(2v^2)$

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

Produce an **off-shell**
Higgs boson that decays into:

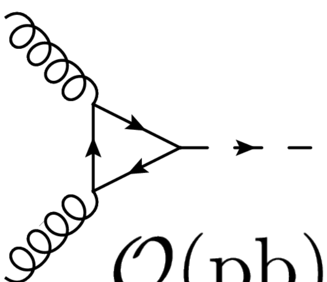
Trilinear coupling

$$H^* \to HH$$

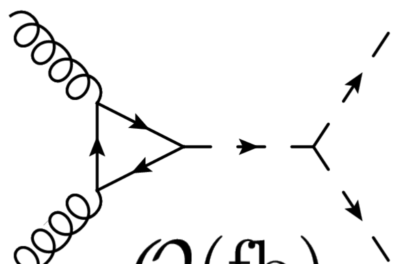
Quartic coupling

$$H^* \to HHH$$

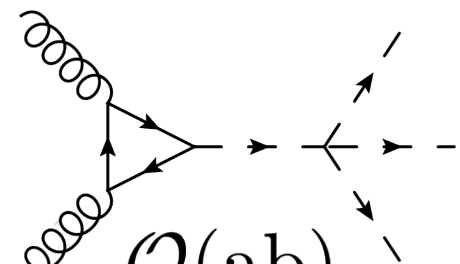
Experimentally very challenging!



$\mathcal{O}(\mathrm{pb})$



$\mathcal{O}(\mathrm{fb})$



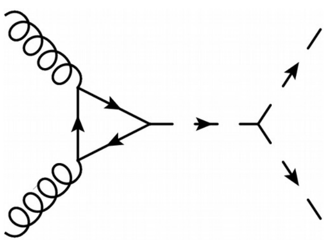
$\mathcal{O}(\mathrm{ab})$

At the LHC:

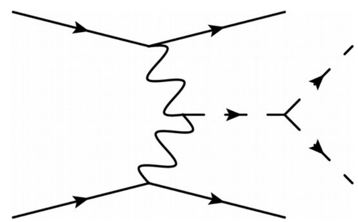
Double Higgs production:
challenging

Triple Higgs production:
impossible

Double Higgs production mechanisms

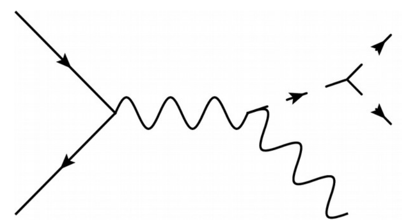


Gluon fusion



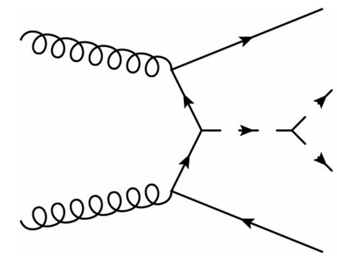
Vector boson fusion

NLO [1,2] NNLO [3]



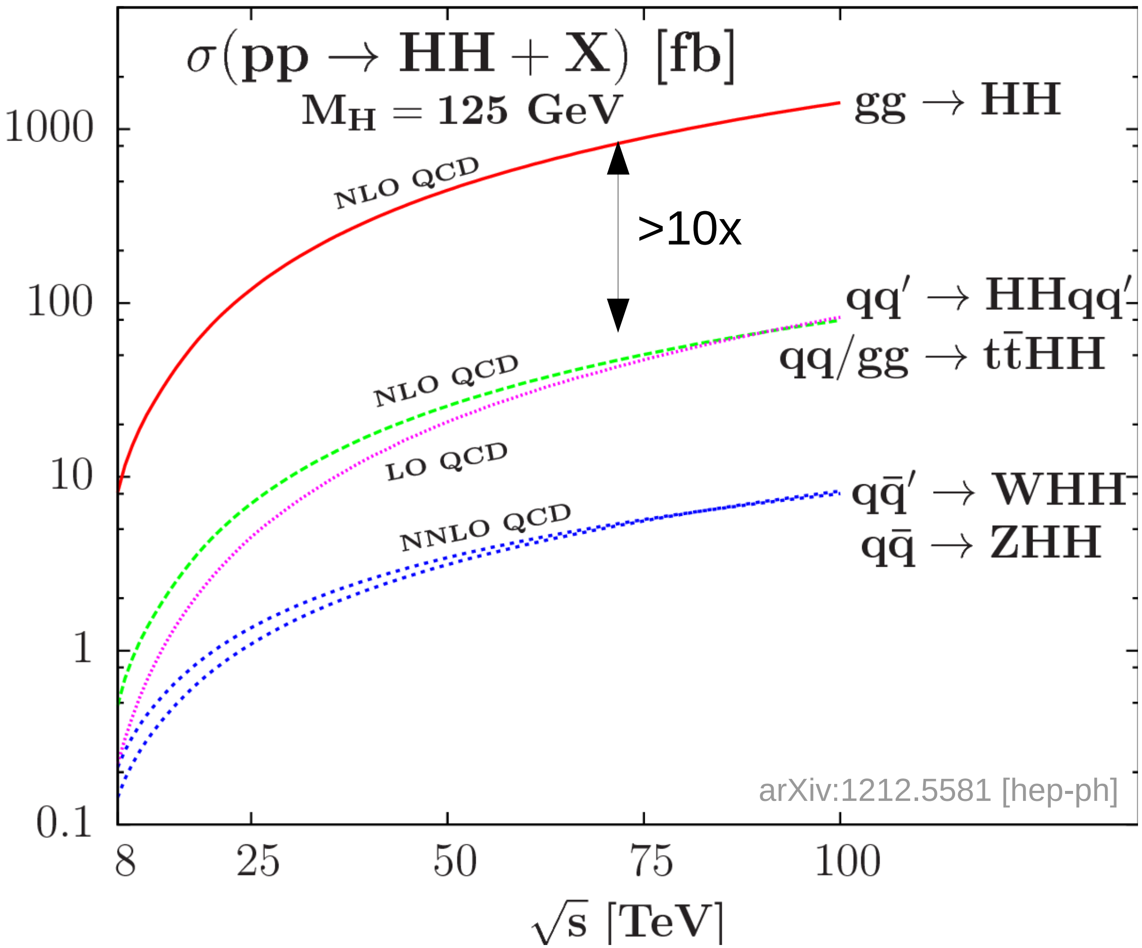
Higgs–strahlung

NLO [1,2] NNLO [1,4,5]



ttHH

NLO [2]



Gluon fusion

⬇

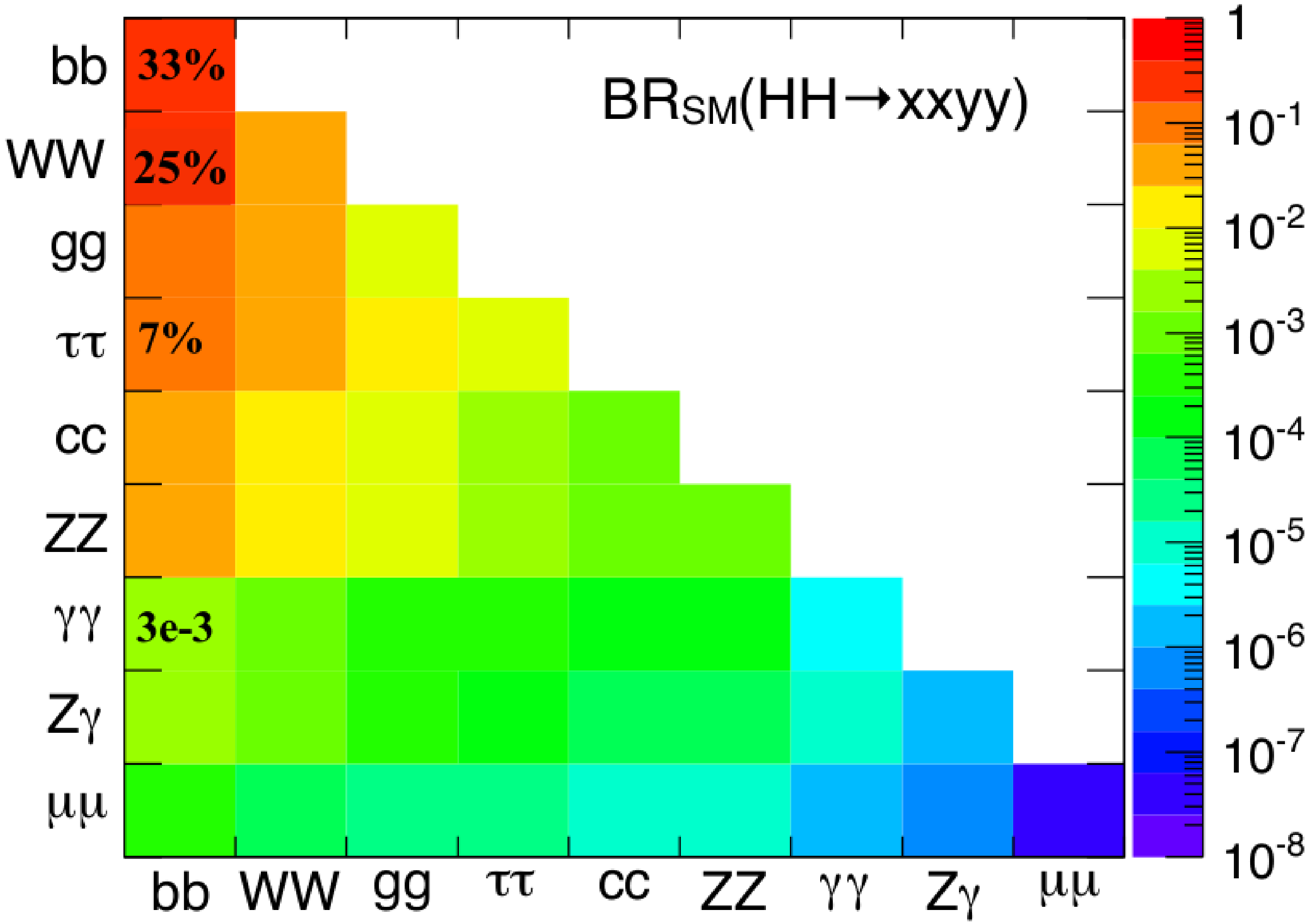
Main production channel

~1000 times smaller than single Higgs XS

Measurement of subleading channels is very difficult

[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;

Di-Higgs 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

Results from non-resonant searches, upper limits:

- Run-I

  ATLAS combined: 70 x SM
  CMS bbγγ: 74 x SM

- Run-II

  Reaching O(10) xSM sensitivity

- SM sensitivity: full HL-LHC statistics

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

	ATLAS	CMS
bbbb	<29 (38)	<342 (308)
bbWW		<79 (89)
bbττ		<28 (25)
bbγγ	<117 (161)	<19 (17)
WWγγ	<747 (386)	

P. Meridiani, EPS17

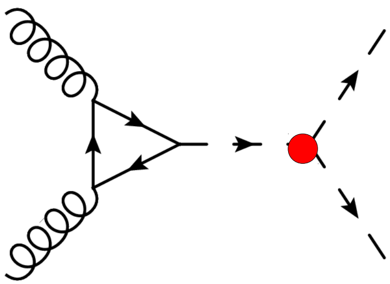
3 fb^{-1}	13 fb^{-1}	36 fb^{-1}

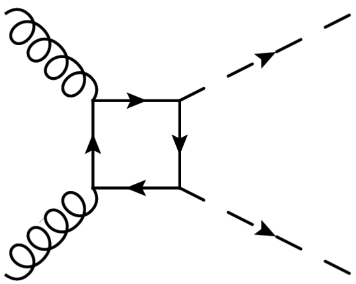
Prospects for the LHC and beyond

- Assuming a SM rate, HH production should be observed at the HL-LHC
- Expected uncertainty on the signal yield: O(50%) using $bb\gamma\gamma$ and $bb\tau\tau$
- 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





Not all the contributions are sensitive!

Assuming a SM-like scenario

- Determination of λ will require full HL-LHC integrated luminosity and the combination of the different channels
- Even then, uncertainties on λ will be large
- Complementary information from loop effects in single Higgs and EW precision observables
- Precision determination of λ: one motivation for a future collider

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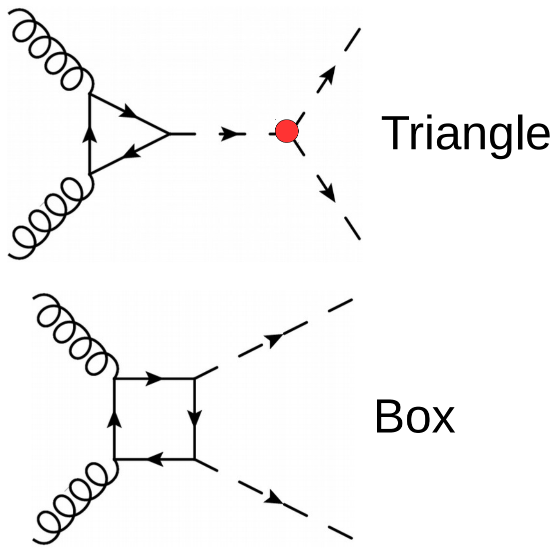
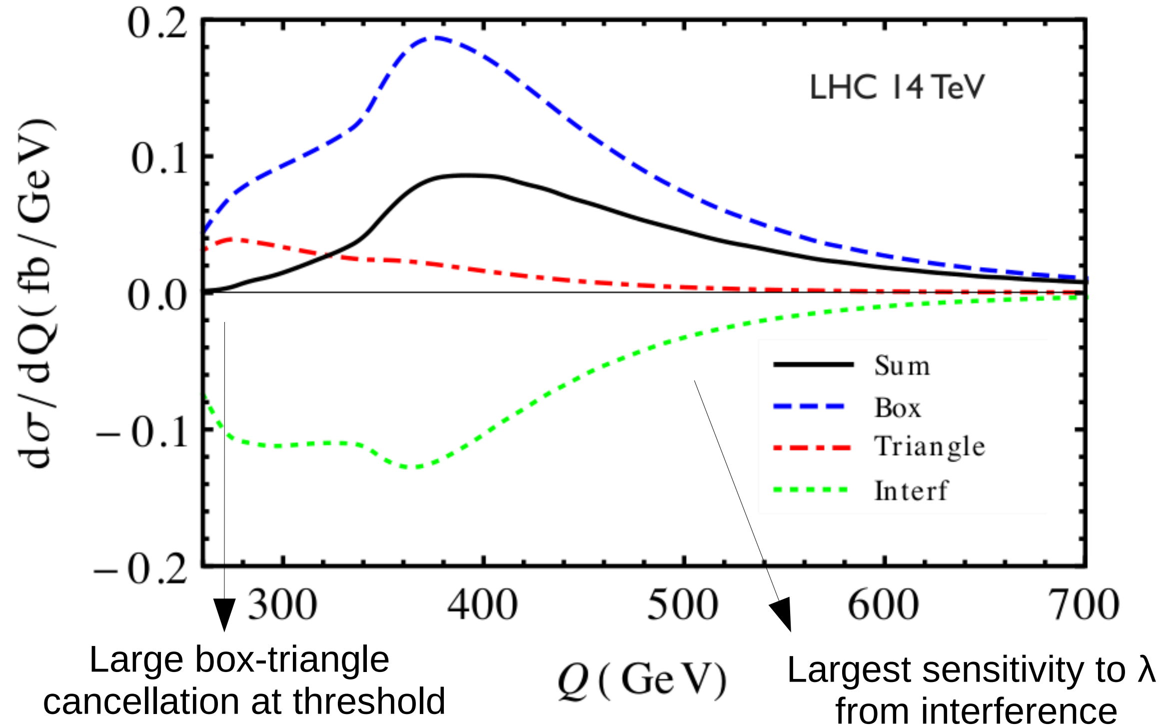
HH production via gluon fusion





- 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]

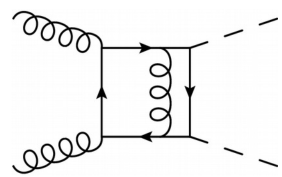
[1] Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 16; [2] Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, JM 18; [3] Heinrich, Jones, Kerner, Luisoni, Vryonidou 17; [4] Jones, Kuttimalai 17; [5] Shao, Li, Li, Wang 13; [6] de Florian, JM 15; [7] Ferrera, Pires 16; [8] de Florian,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



- 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}

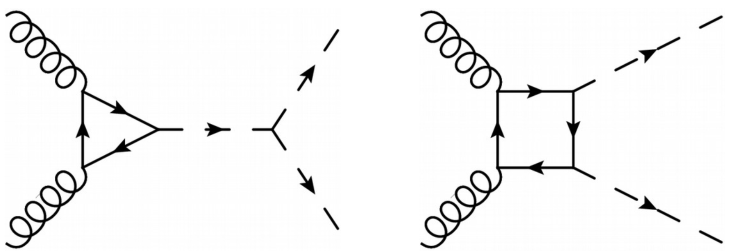
(16% overestimation at NLO – further improvements also possible, but more about this later)

QCD corrections in the HEFT

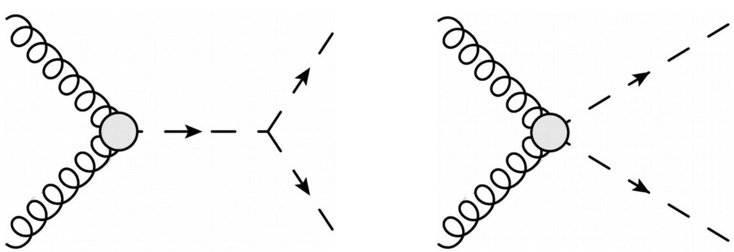
D. de Florian and JM, 1309.6594
Grigo et al., 1408.2422

E.g.: virtual corrections

Leading Order (1-loop)



Full theory



Eff. theory

- The effective vertices have the same structure!

$$\mathcal{L}_{ggH} \propto G_{\mu\nu} G^{\mu\nu} H/v$$

$$\mathcal{L}_{ggHH} \propto G_{\mu\nu} G^{\mu\nu} (H/v)^2$$

- Profit from the single Higgs production results!

QCD corrections in the HEFT

D. de Florian and JM, 1309.6594
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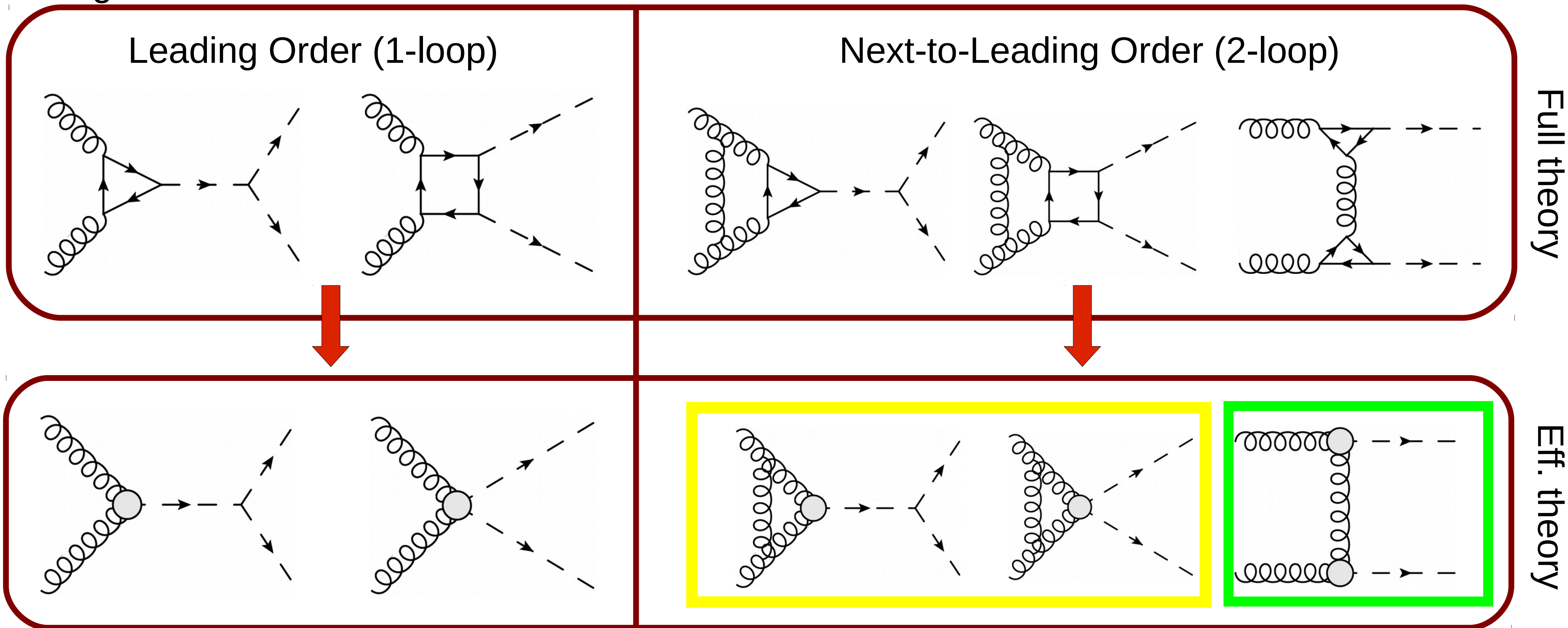

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- Profit from the single Higgs production results!

- We can split the calculation

$$Q^2\frac{d\hat{\sigma}}{dQ^2} = \hat{\sigma}^a + \hat{\sigma}^b$$

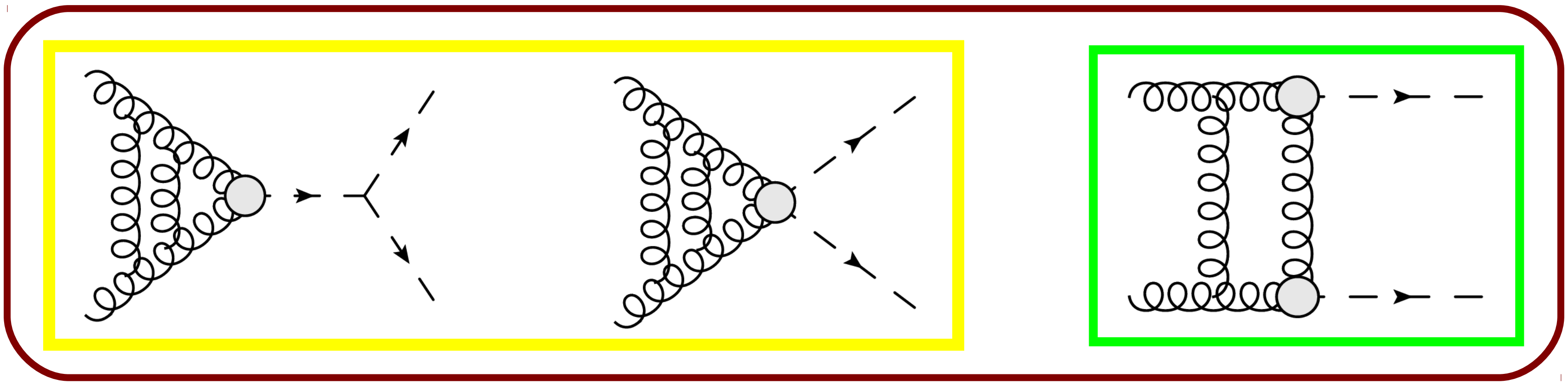
Single-Higgs like

Starts at NLO

New topologies with two effective vertices

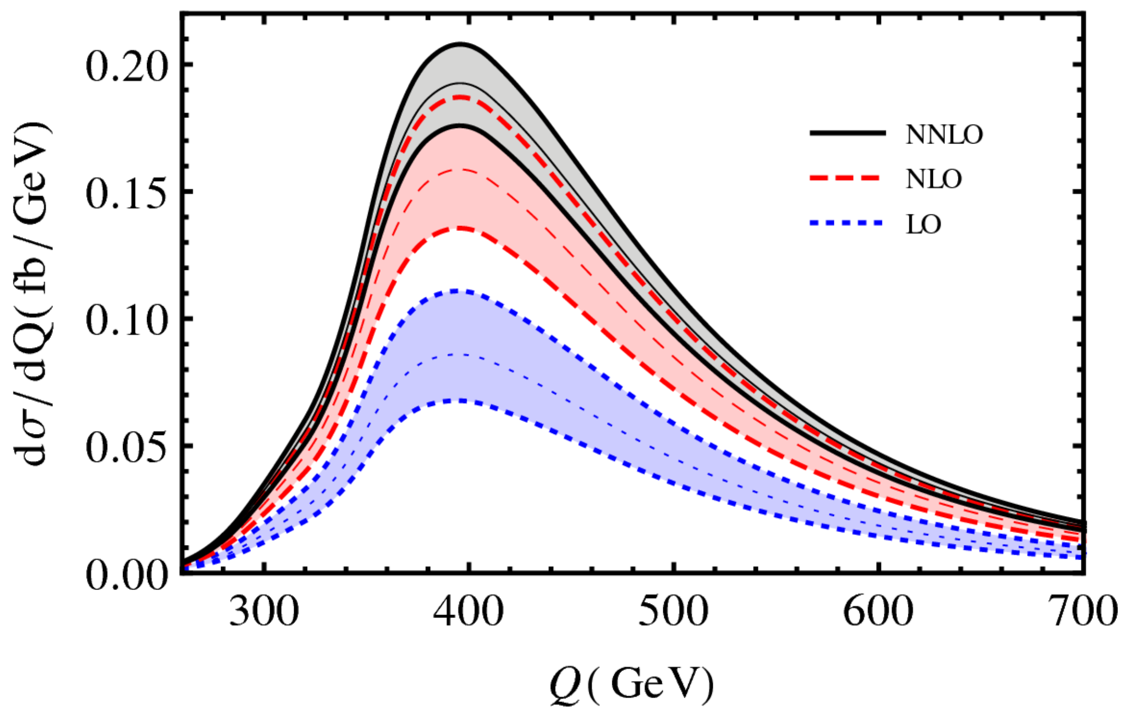
QCD corrections in the HEFT

- At NNLO we have



- Similar idea for real-virtual and double-real corrections

We obtained analytical results for the NNLO total cross section, differential only in the HH invariant mass



- Extended to include BSM effects via EFT dimension 6 operators (backup slides)

D. de Florian, I. Fabre and JM
[arXiv:1704.05700]

Threshold Resummation

D. de Florian and JM, 1505.07122
Shao et al., 1301.1245

- **All-order** summation of **threshold enhanced** contributions

Higgs pair invariant mass

$$z = \frac{Q^2}{\hat{s}}$$

(Resummation performed in Mellin space)

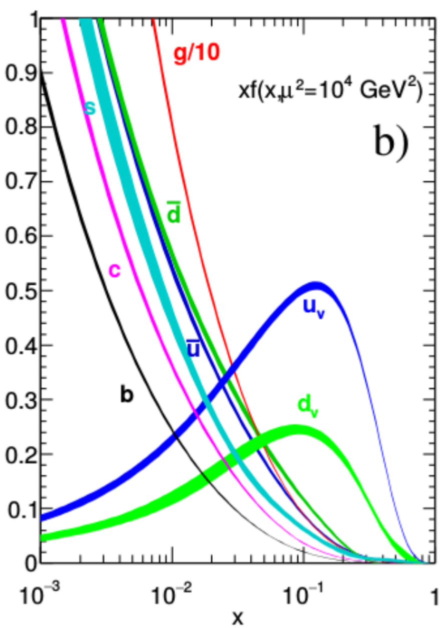
Threshold:

$$z \to 1 \iff N \to \infty$$

- Originated by **soft gluon** emissions
- Threshold enhanced contributions: $(\ln N)^k$

Leading Log $\longrightarrow$ $\alpha_S^n \ln^{n+1} N$
Next-to-Leading Log $\longrightarrow$ $\alpha_S^n \ln^n N$
Next-to-Next-to-Leading Log $\longrightarrow$ $\alpha_S^n \ln^{n-1} N$

- Resummed contributions should **account** for a large part of the uncalculated **missing higher orders**



- Parton distributions prefer lower partonic center of mass energies
- Relatively large invariant mass $\longrightarrow$ Corrections dominated by threshold contributions
- Explicitly checked for HH up to NNLO via soft-virtual approximation

Threshold Resummation

$$G^{(\mathrm{res})}_{gg,N} = \Delta_N \times C_{gg} + \mathcal{O}(1/N)$$

Partonic cross section
(in Mellin space)

Sudakov factor
Exponentiates the
large log corrections

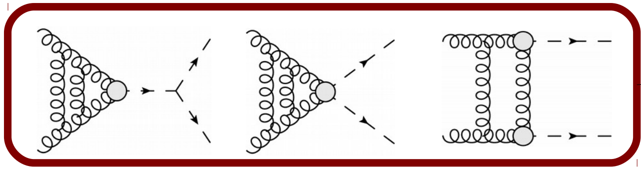
Constant contributions
Virtual and non-logarithmic
soft terms

- **Constant contributions:**

Virtual and non-logarithmic
soft contributions

$$C_{gg} = 1 + \sum_{n=1} \left(\frac{\alpha_S}{2\pi}\right)^n C^{(n)}_{gg}$$

$$\mathrm{N}^i\mathrm{LL} \xleftarrow{\text{Needed for}} C^{(i)}_{gg} \xrightarrow{\text{Obtained from}} \mathrm{N}^i\mathrm{LO}$$



Universal structure: only process dependence encoded in FO virtual corrections

D. de Florian, JM, arXiv:1209.0673

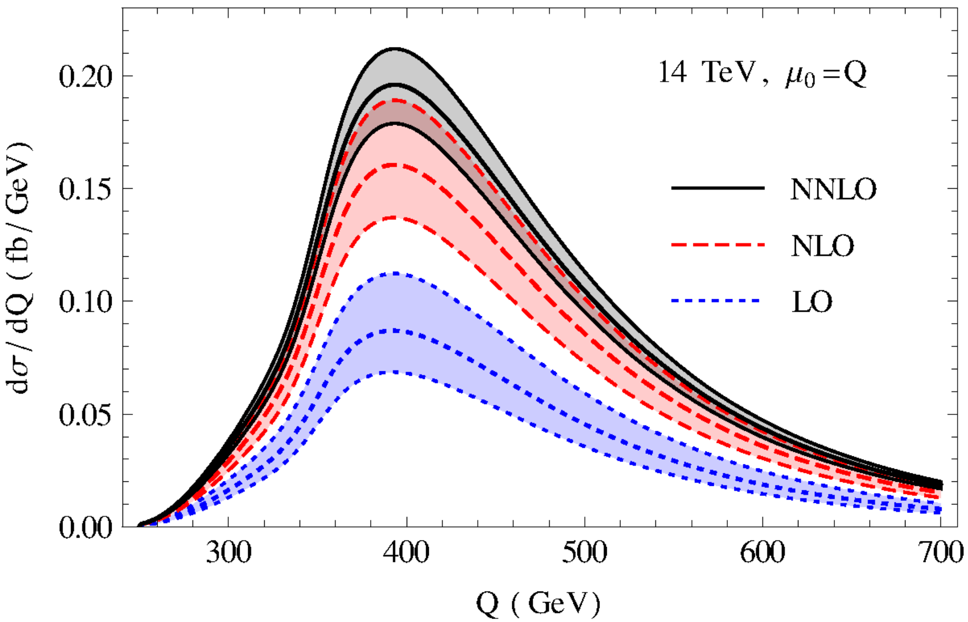
- **Resummed contribution is matched to the fixed order result**

$$\sigma^{NNLL} = \sigma^{res} - \sigma^{res}\big|_{\mathcal{O}(\alpha_S^4)} + \sigma^{NNLO}$$

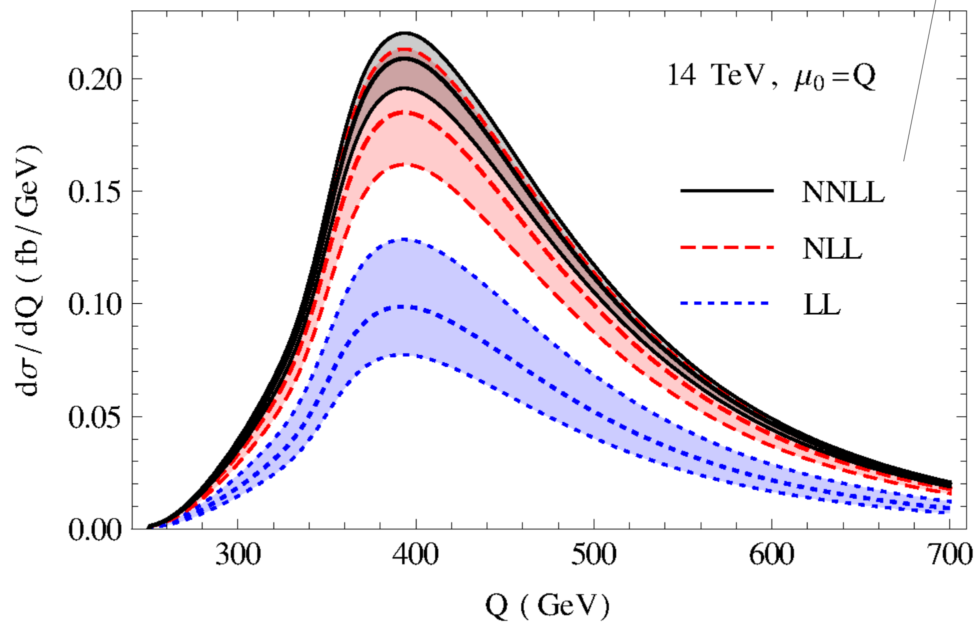
NNLO+NNLL numerical results

Here NNLL means
NNLL+NNLO, etc

Fixed order

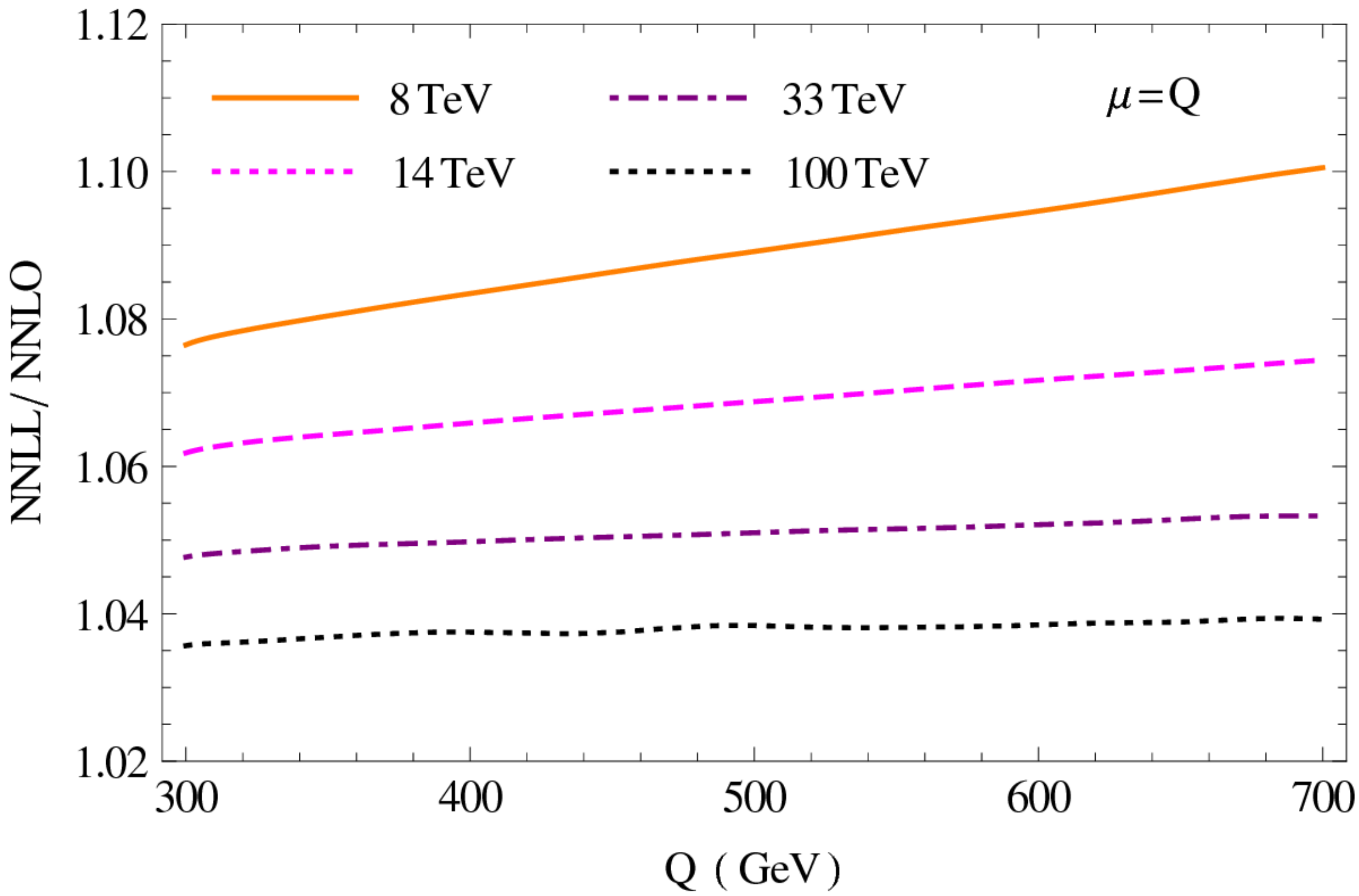


Resummed



- Shape: small differences between FO and resummed distributions
- Uncertainty reduction from NNLO to NNLL
- Resummed contributions $\longrightarrow$ increase of the cross section

- **NNLL/NNLO ratio vs. HH invariant mass**



Increase in total XS:

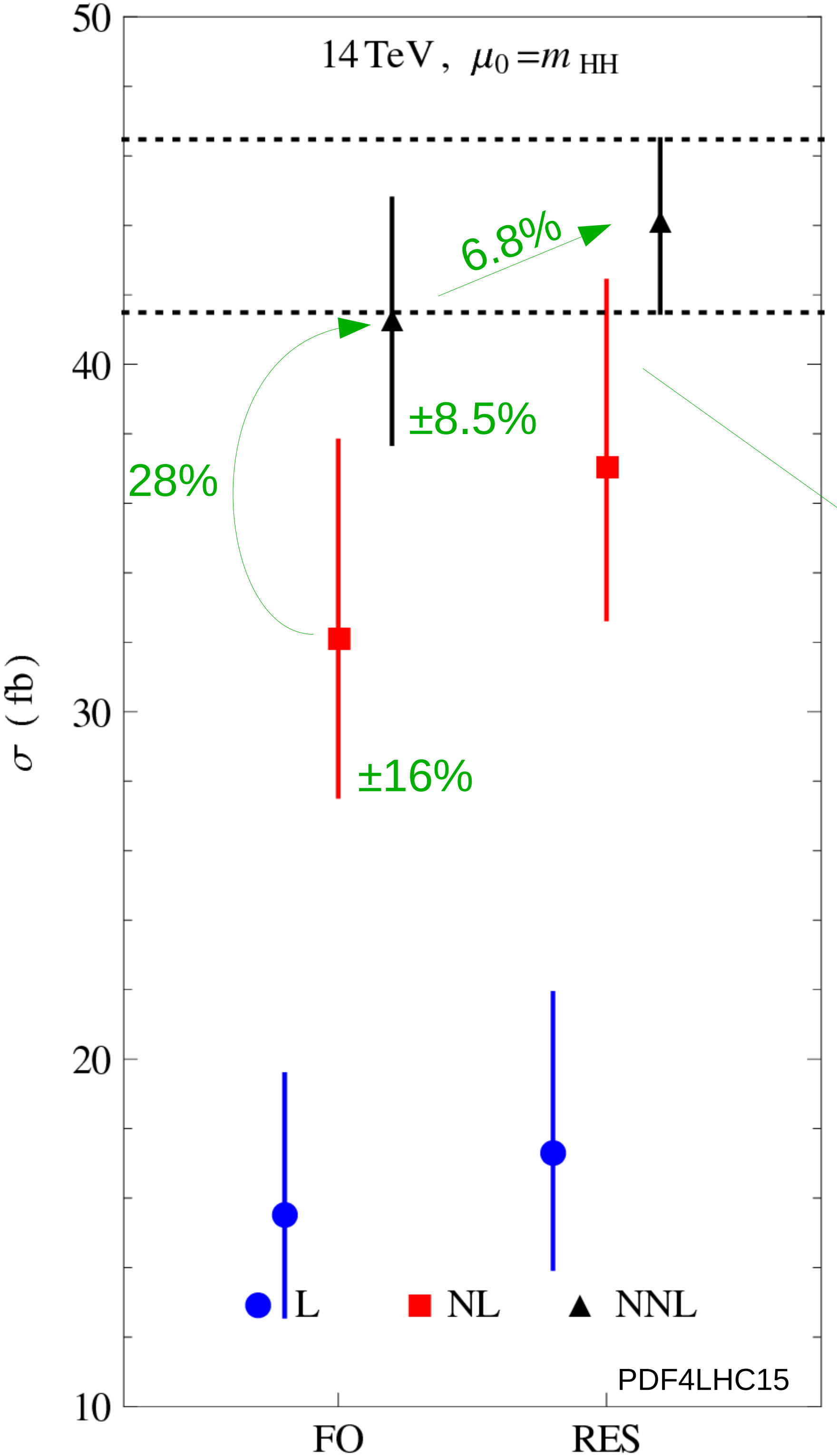
→ 8.9% at 8TeV

→ 6.8% at 14TeV

→ 3.8% at 100TeV

- NNLL always larger than NNLO, ratio is almost linear in Q
- Ratio increases for larger invariant masses → Closer to partonic threshold
- Larger collider energies → Smaller resummation effects (further from threshold)

- **Total cross section**

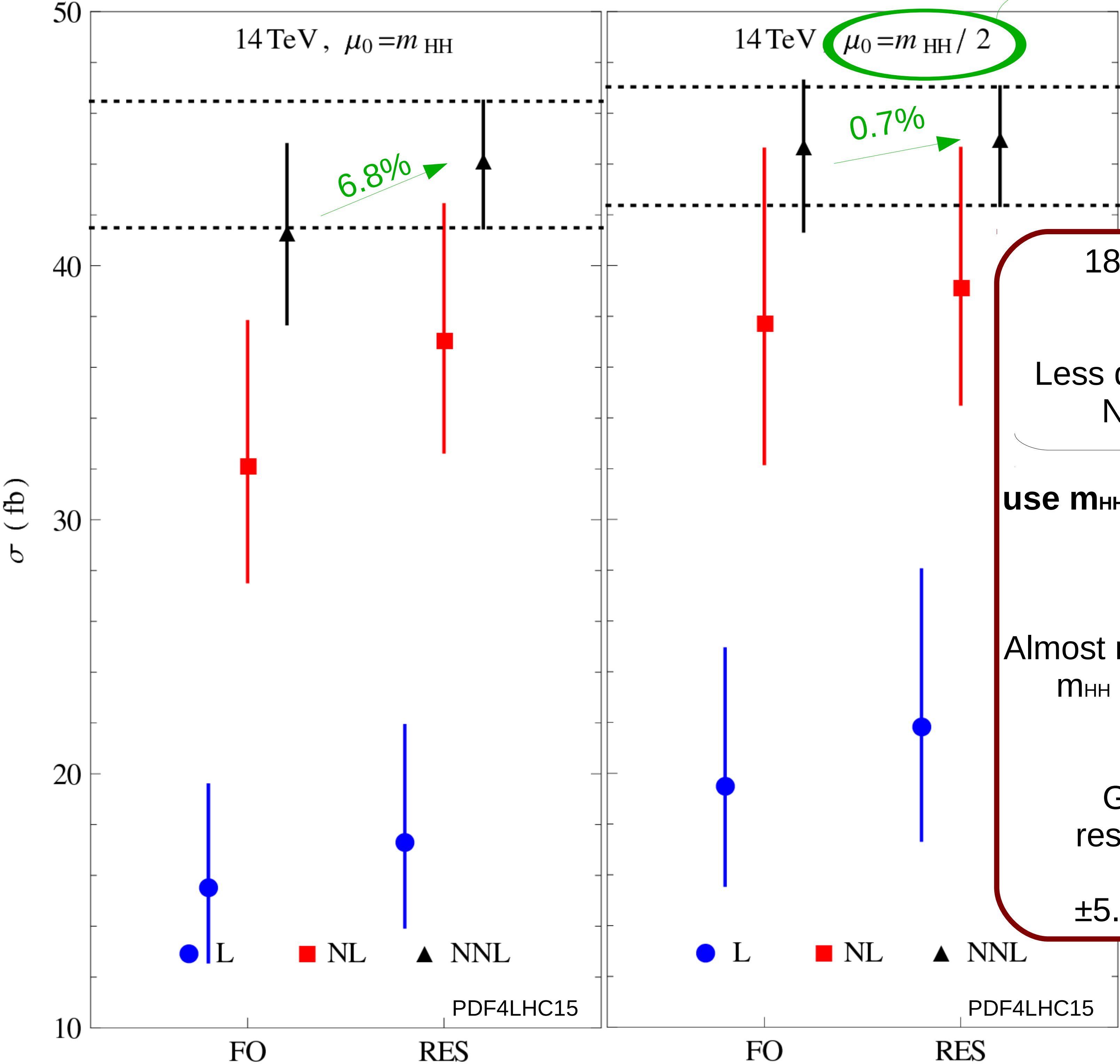


Further scale unc. reduction at NNLL

(From ±8.5% to ±5.5%)

Larger overlap between NLL and NNLL

- **Total cross section**



Same features, but more moderate corrections

18% increase from NLO to NNLO

Less differences between NNLO and NNLL

use $m_{HH}/2$ for FO predictions

Almost no difference between m_{HH} and $m_{HH}/2$ at NNLL

Great stability of resummed NNLL XS

±5.2% unc. for $m_{HH}/2$

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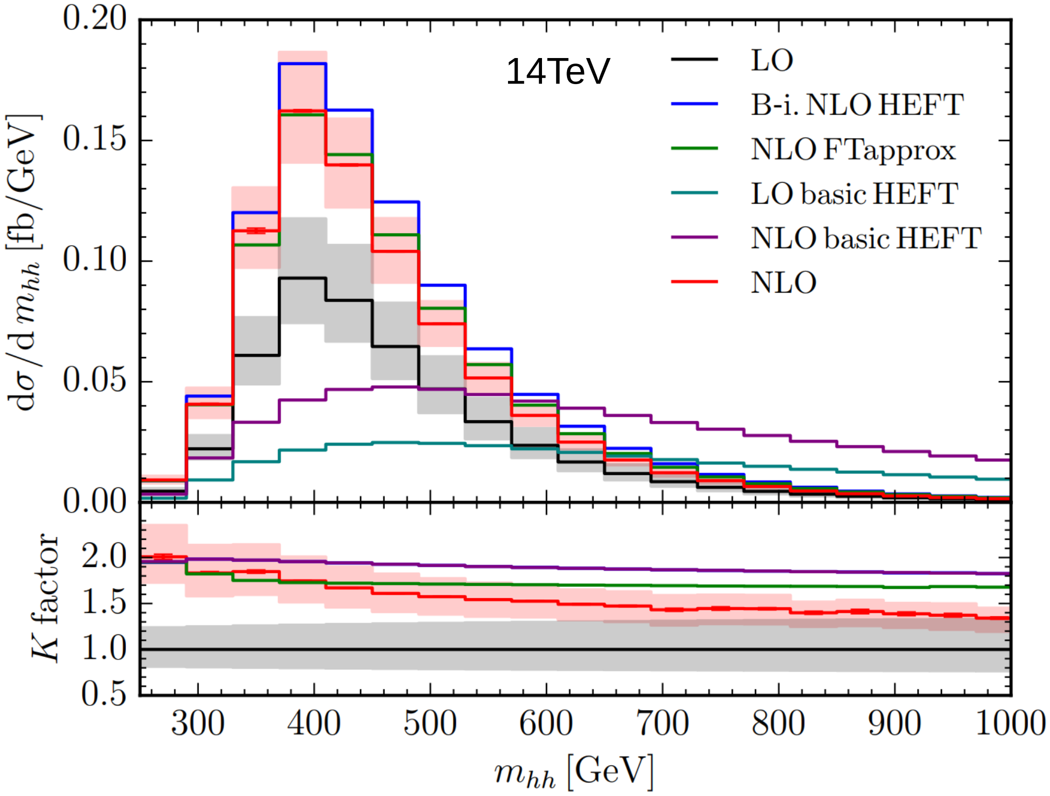
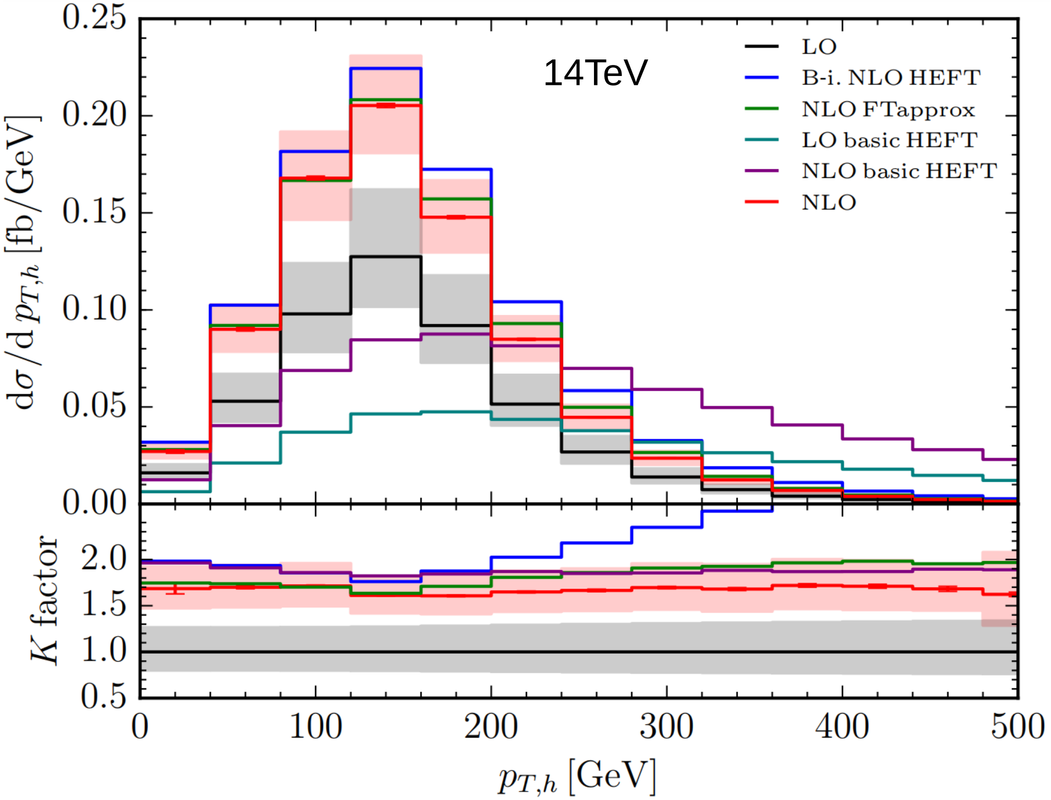
HEFT vs full theory

- 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 (associated with hard radiation)

NLO distributions [S. Borowka et al., arXiv:1608.04798]





- 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

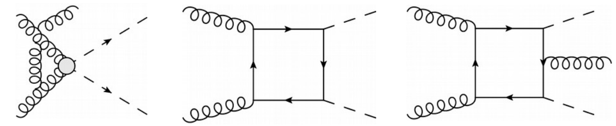
HH at NNLO with M_t effects

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]

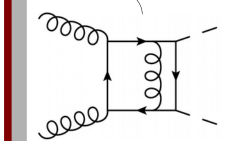
- Fully differential predictions for Higgs boson pair production via gluon fusion
- Combination of full NLO with large-M_t NNLO
- NNLO piece improved with different reweighting techniques to account for finite-M_t effects
- Estimation of remaining M_t uncertainty at NNLO
- Most advanced perturbative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

Technical ingredients

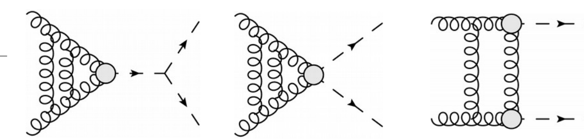


Tree-level and one-loop amplitudes (HEFT and full-M_t) → OpenLoops
[Cascioli, Lindert, Maierhofer, Pozzorini]

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

qT subtraction

[Catani, Grazzini, '12]
[Catani, Cieri, de Florian, Ferrera, Grazzini, '14]

real-real and real-virtual
of inclusive HH@NNLO

$$d\sigma^{HH}_{\mathrm{NNLO}}\Big|_{q_T\neq 0} = d\sigma^{HH+\mathrm{jet}}_{\mathrm{NLO}}$$

Computed with any
NLO subtraction formalism

- Only qT → 0 infrared divergencies remain
- But small qT behavior known from qT resummation!

Process indep.
counterterm

$$d\sigma^{HH}_{\mathrm{NNLO}} = \mathcal{H}^{HH}_{\mathrm{NNLO}} \otimes d\sigma^{HH}_{\mathrm{LO}} + \underbrace{\left[d\sigma^{HH+\mathrm{jet}}_{\mathrm{NLO}} - d\sigma^{\mathrm{CT}}_{\mathrm{NNLO}}\right]}_{\text{Finite for qT} \to 0}$$

Hard coefficient that
includes the two-loop corrections

Our implementation is based on the public code MATRIX [Kallweit, Grazzini, Wiesemann]

qT subtraction

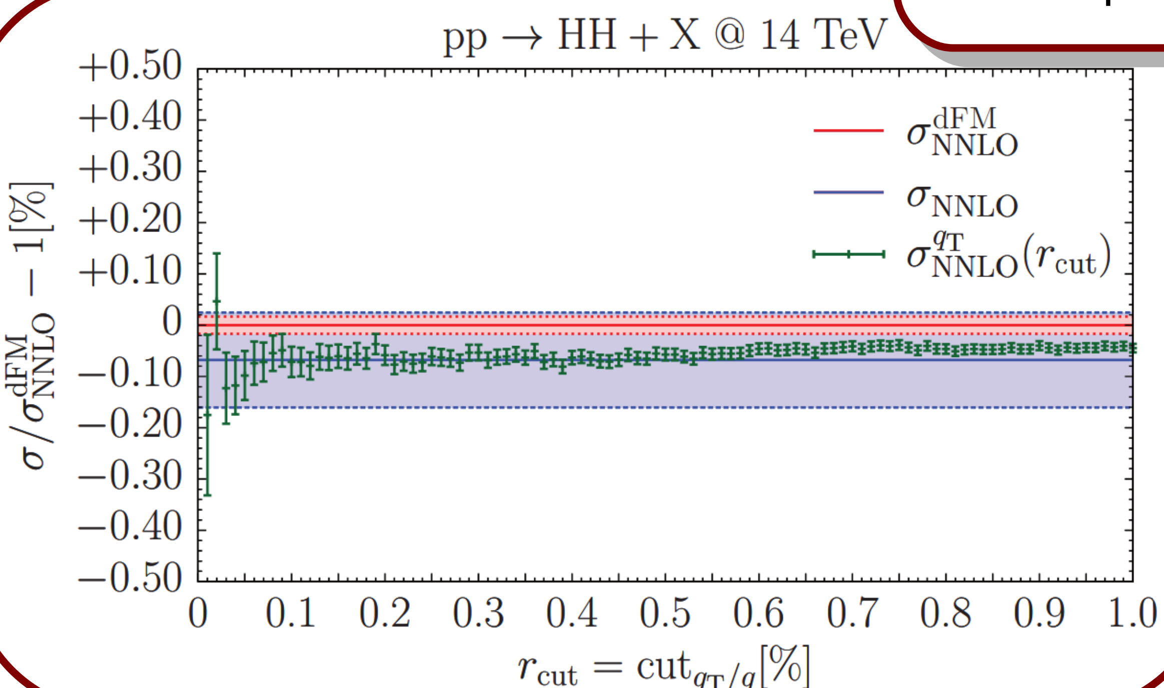
[Catani, Grazzini, '12]
[Catani, Cieri, de Florian, Ferrera, Grazzini, '14]

$$d\sigma^{HH}_{\rm NNLO} = \mathcal{H}^{HH}_{\rm NNLO} \otimes d\sigma^{HH}_{\rm LO} + \underbrace{\left[d\sigma^{HH+\rm jet}_{\rm NLO} - d\sigma^{\rm CT}_{\rm NNLO} \right]}_{\text{Finite for qT} \to 0}$$

We need to introduce a cutoff ← Individually divergent when qT → 0

$$r = q_T/Q$$

- Introduce an r_{cut}
- Check that results are independent of r_{cut}
- Extrapolate $r_{cut} \to 0$ result



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 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)

$\Downarrow$

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

Full-theory approximation – 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

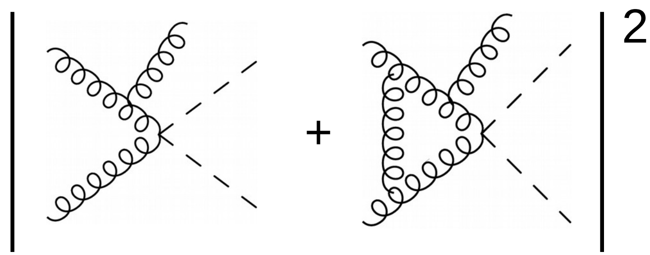
[Discussion numerical stability in backup slides]

Our best NNLO prediction

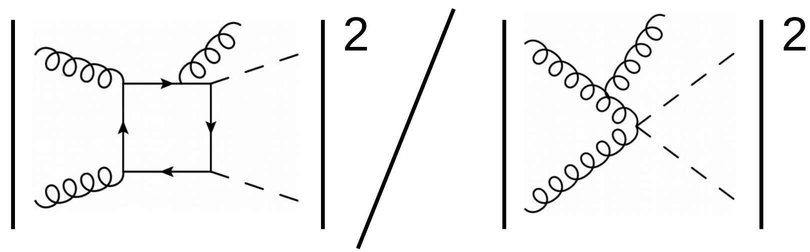
Full-theory approximation – $\mathrm{NNLO}_{\mathrm{FTapprox}}$

- 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

E.g. the squared amplitude:



is reweighted by:



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Our best NNLO prediction

[Discussion numerical stability in backup slides]

Numerical results

Setup of the calculation:

- M_h = 125GeV M_t = 173GeV
- PDF4LHC15 sets at each corresponding order
- Central scale value $\mu_0 = M_{hh}/2$
- 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)
- On-shell scheme for M_t, no estimation of scheme uncertainties

Total cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO}_{\mathrm{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\mathrm{NNLO}_{\mathrm{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
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M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	$\pm 2.6\%$	$\pm 2.7\%$	$\pm 3.4\%$	$\pm 4.6\%$
$\mathrm{NNLO}_{\mathrm{FTapprox}}/\mathrm{NLO}$	1.118	1.116	1.096	1.067

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B-proj > NLO-i > FTapprox

Increase with respect to NLO at 14TeV:

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

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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% $\Rightarrow$ 11% for the pure NLO contribution
- Assuming a ±11% uncertainty for the pure NNLO piece $\Rightarrow$ ±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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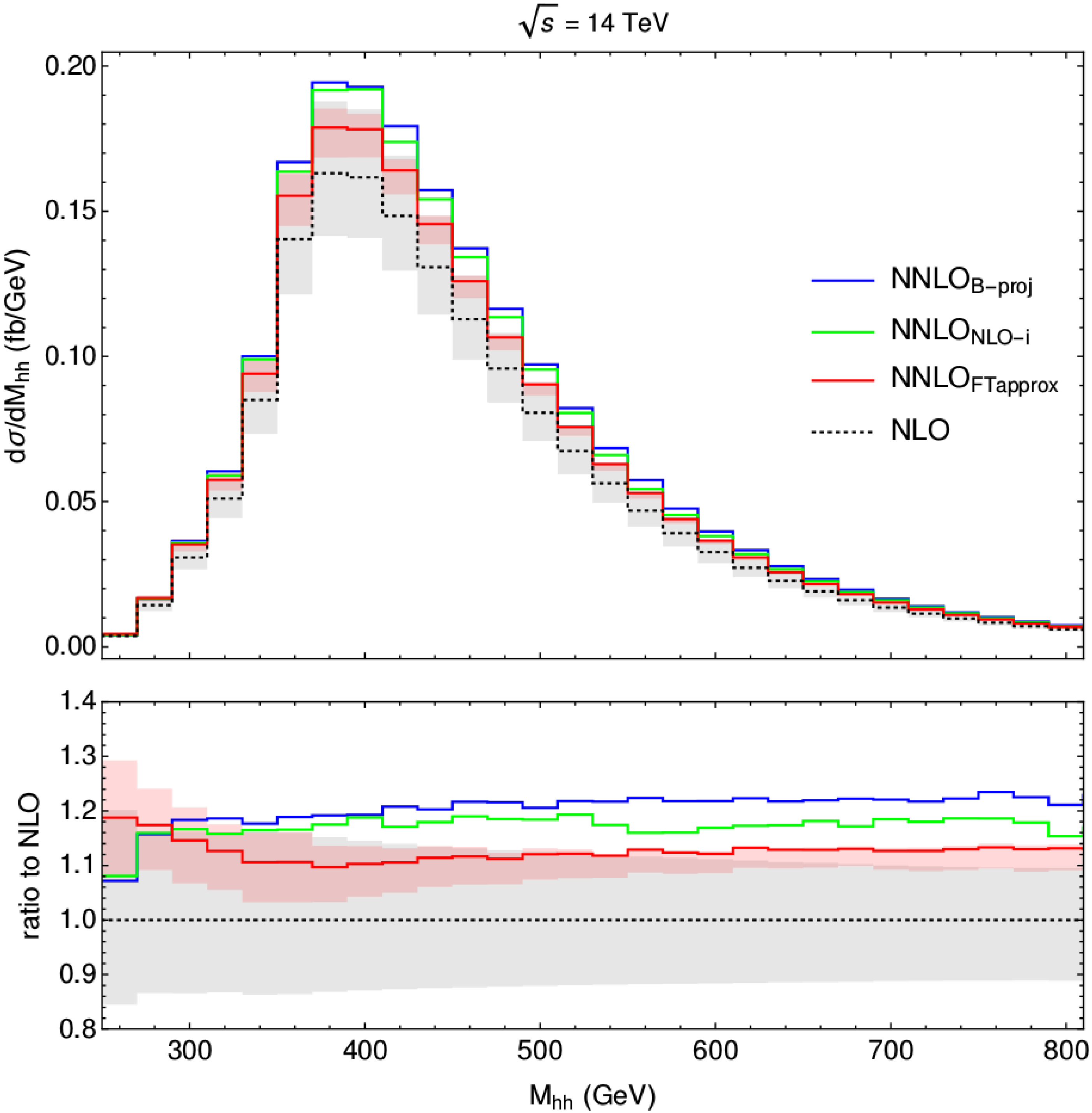
- But the difference between FTapprox and NLO-i increases with the collider energy faster than this uncertainty estimate
- To be more conservative, take half the difference between FTapprox and NLO-i

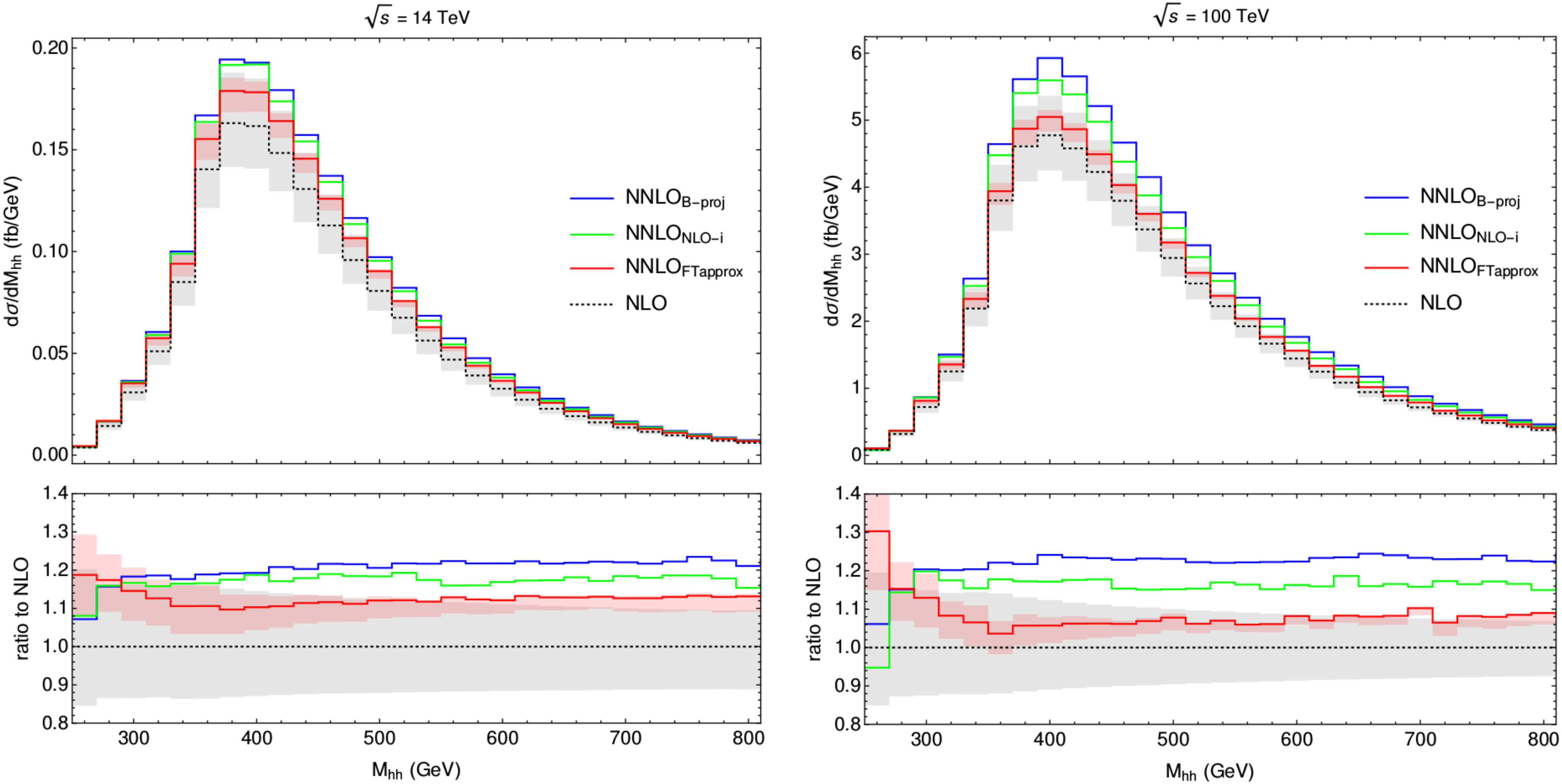
Small difference for LHC, more conservative for larger energies

Differential distributions – M_{hh}



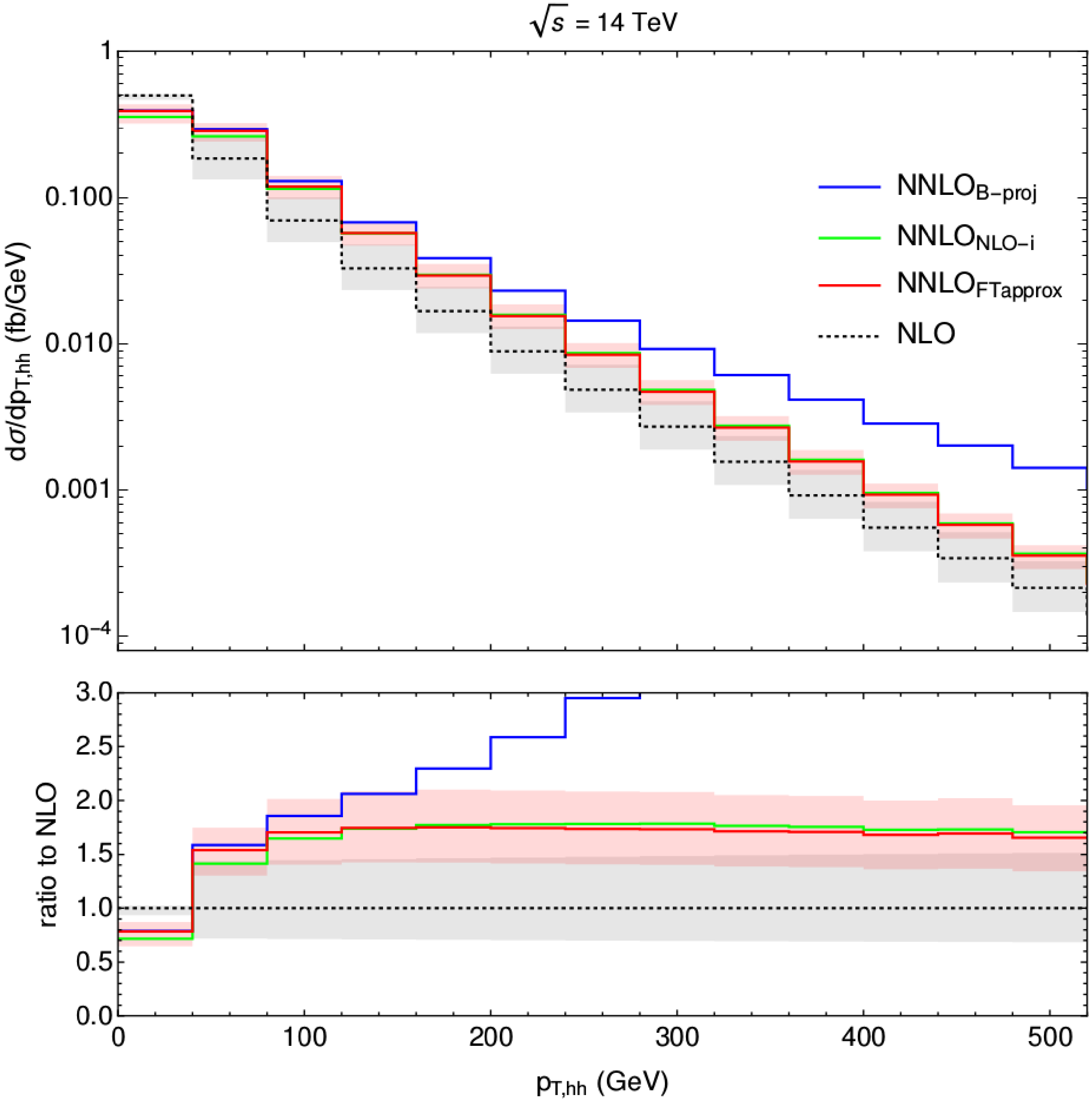
- B-proj and NLO-i have similar behaviors
- FTapprox presents larger corrections at threshold, minimum corrections at Mhh ~ 400GeV, slow increase towards the tail
- Scale uncertainties are substantially reduced in the whole range
- Overlap with the NLO band

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 – $p_{T,hh}$



- B-proj corrections huge in the tail

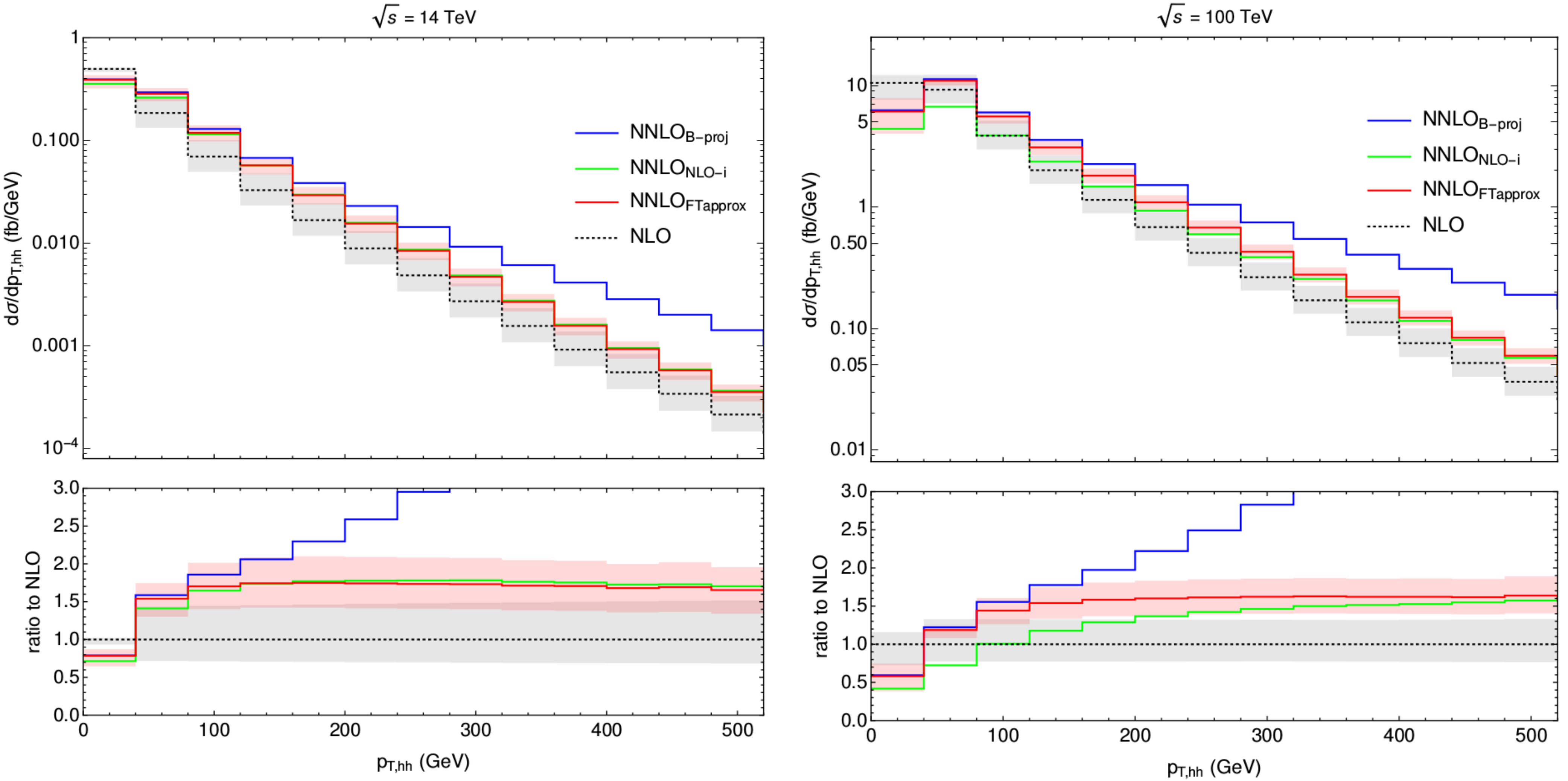
No surprise: no information about the lowest-order prediction for this observable

- Other two predictions in very good agreement
- Distribution trivial at LO: NNLO is effectively NLO

Very large corrections

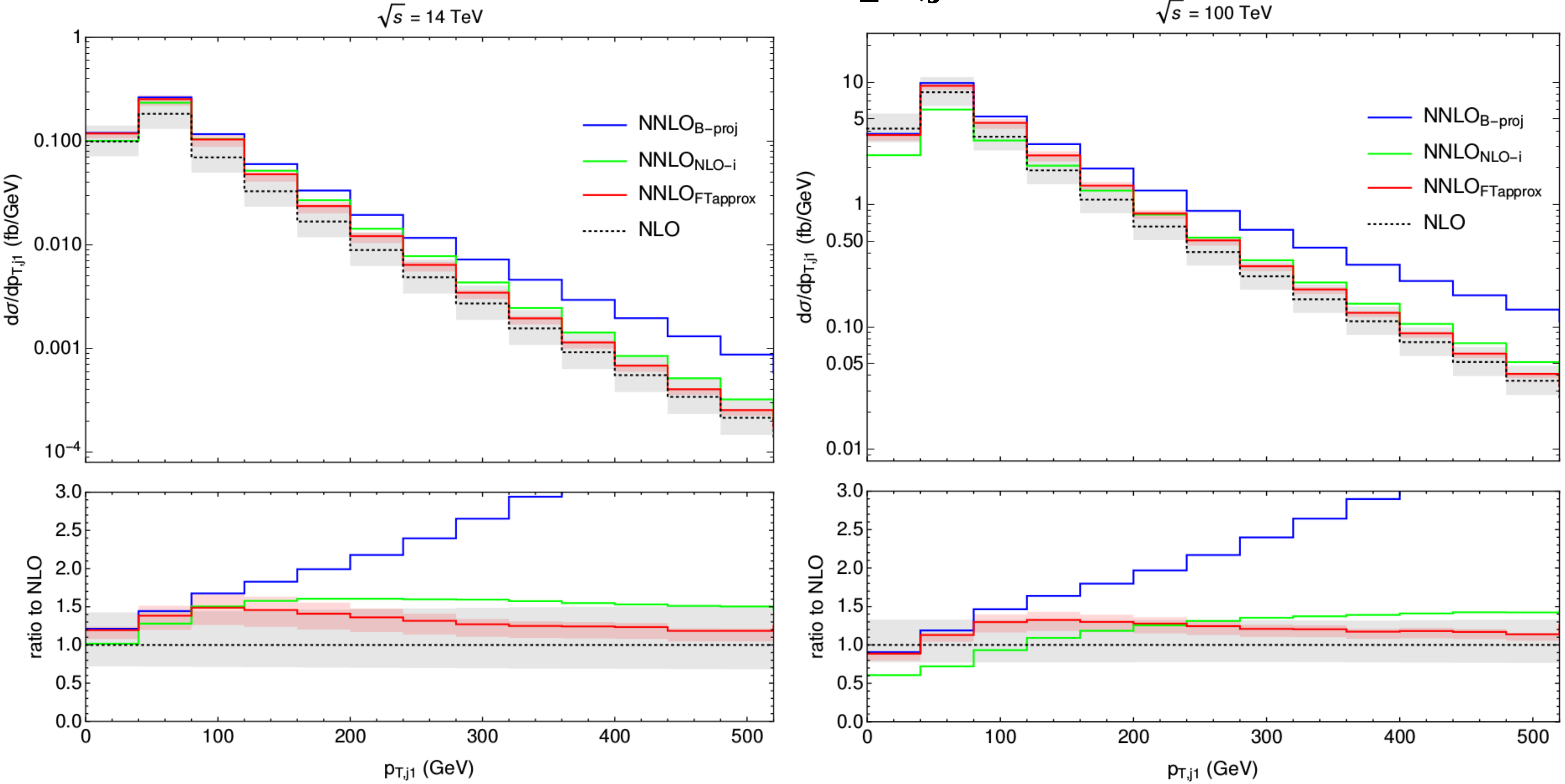
Sizeable scale uncertainties

Differential distributions – $p_{T,hh}$



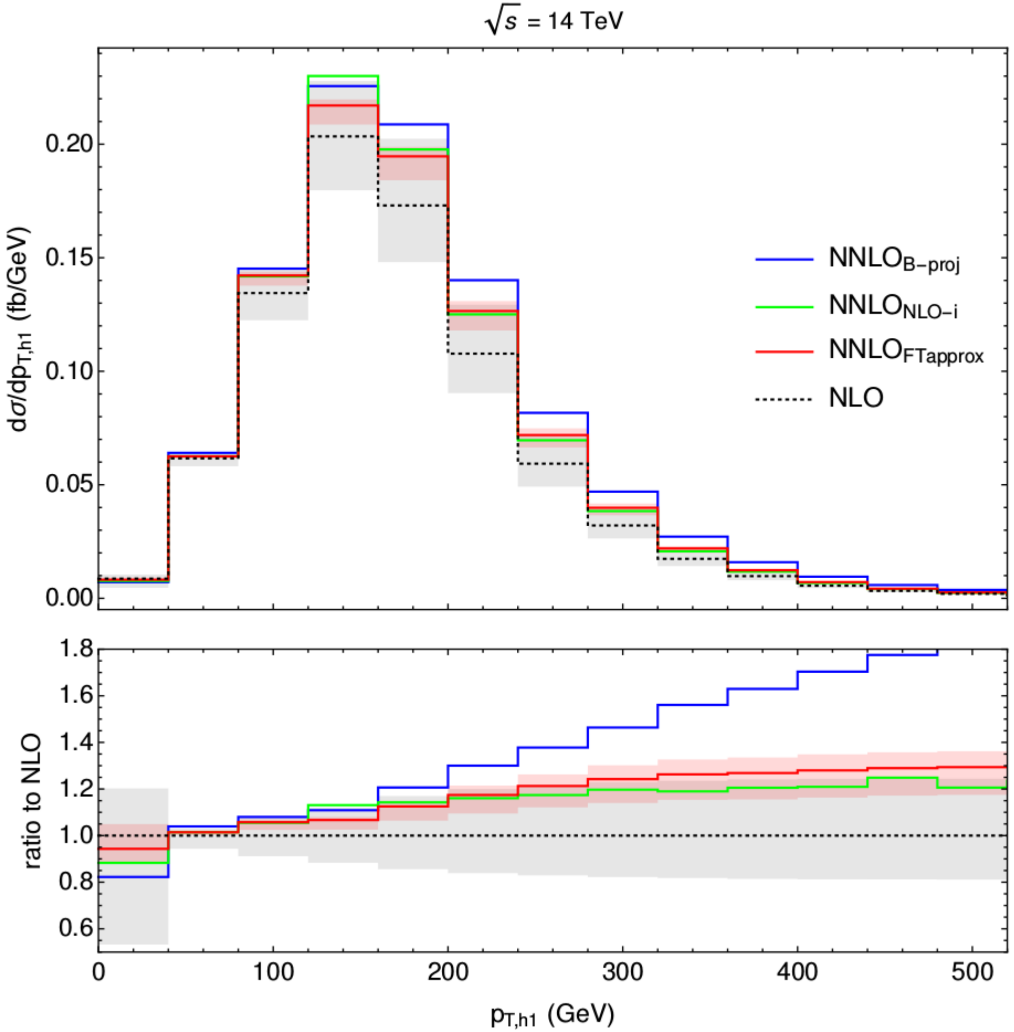
- Different behaviors are more pronounced at 100TeV
- Larger separation between FTapprox and NLO-i (almost full agreement in the tail)
- FTapprox agrees with B-proj for low $p_{T,hh}$

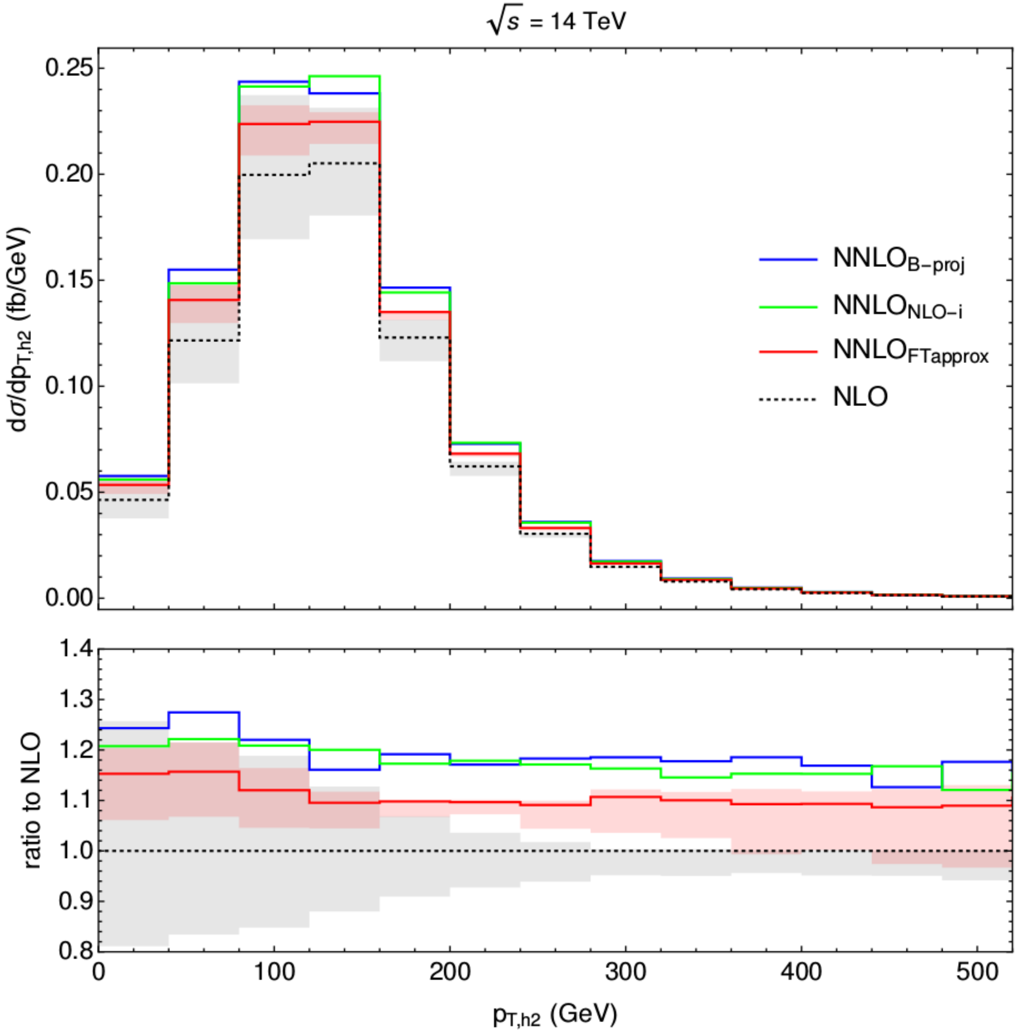
Differential distributions – $p_{T,j1}$



- 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 $p_{T,h2}$



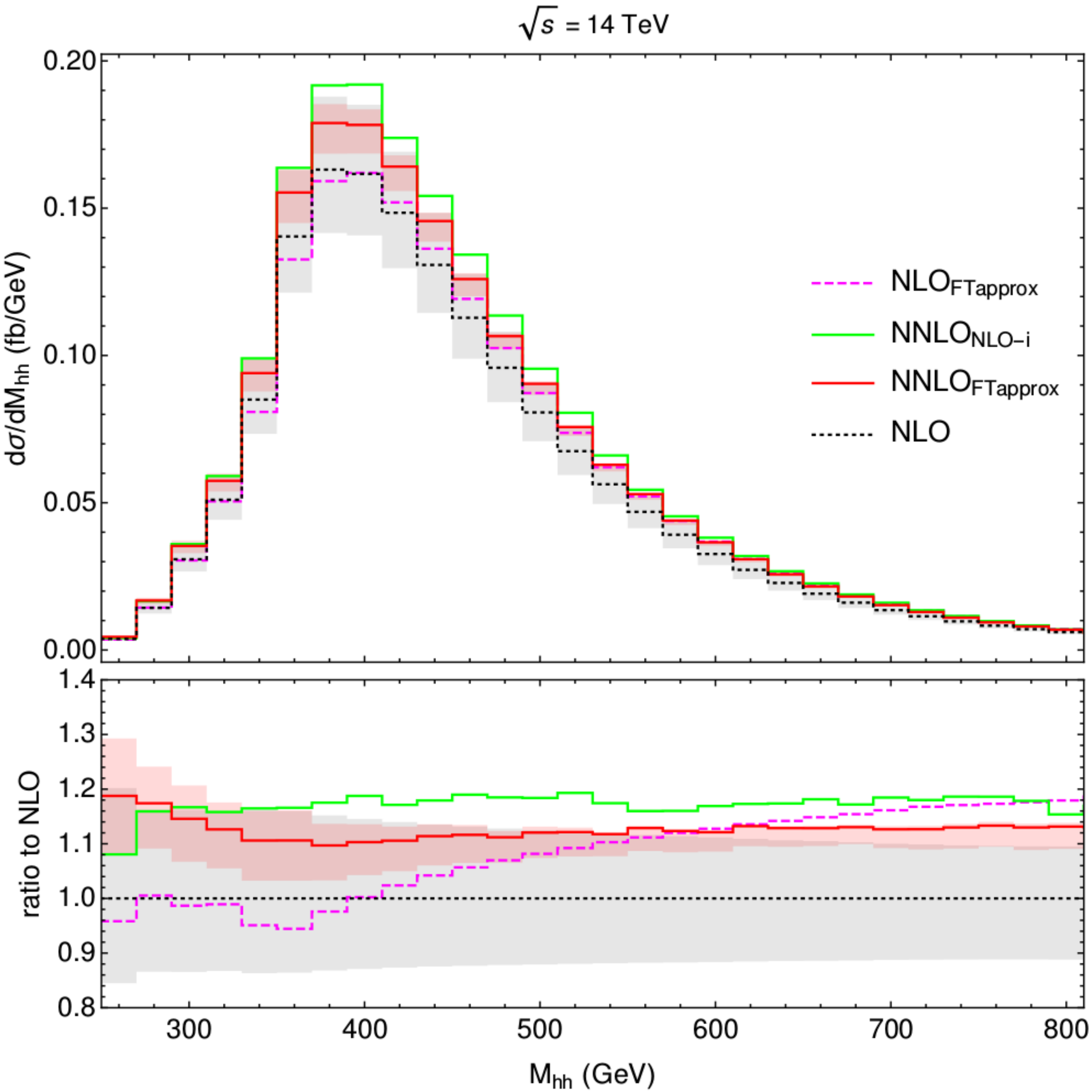


- Hardest Higgs pT spectrum:
  Large corrections in the tail of the B-proj approximation
  Good agreement between FTapprox and NLO-i

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

M_t uncertainties for distributions

Based on the performance of the FTapprox at NLO and on the separation between the NNLO approximations, we can roughly estimate the size of the Mt uncertainties for distributions



For the Higgs pair invariant mass we can look at the previous order:

- Below M_{hh} ~ 500GeV good accuracy at NLO, similar to inclusive cross section

~±3% uncertainty at NNLO

- Quality decreases in the tail

O(±10%) uncertainty at NNLO

Something similar can be done for y_{hh}, $p_{T,h1}$ and $p_{T,h2}$

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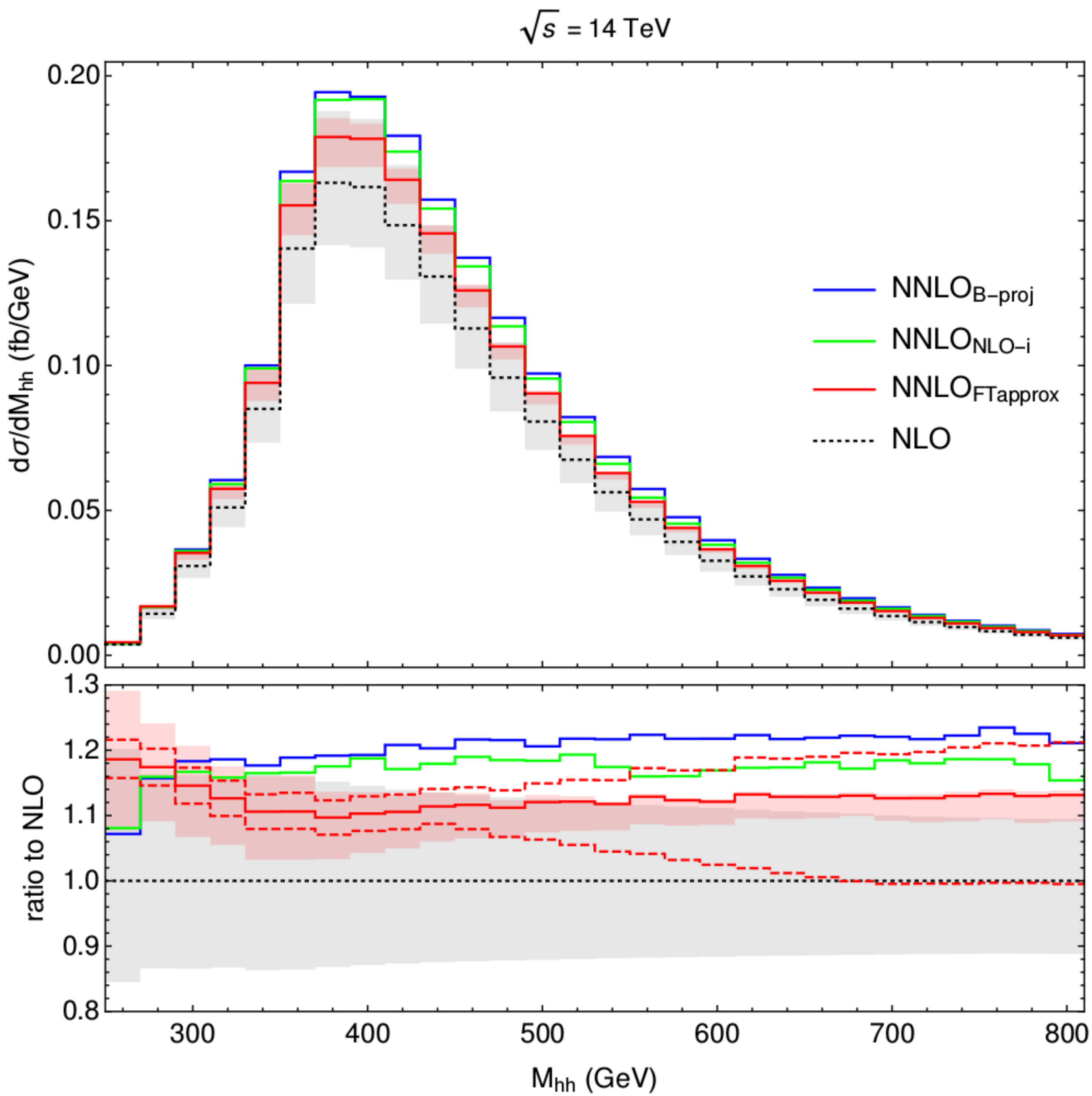

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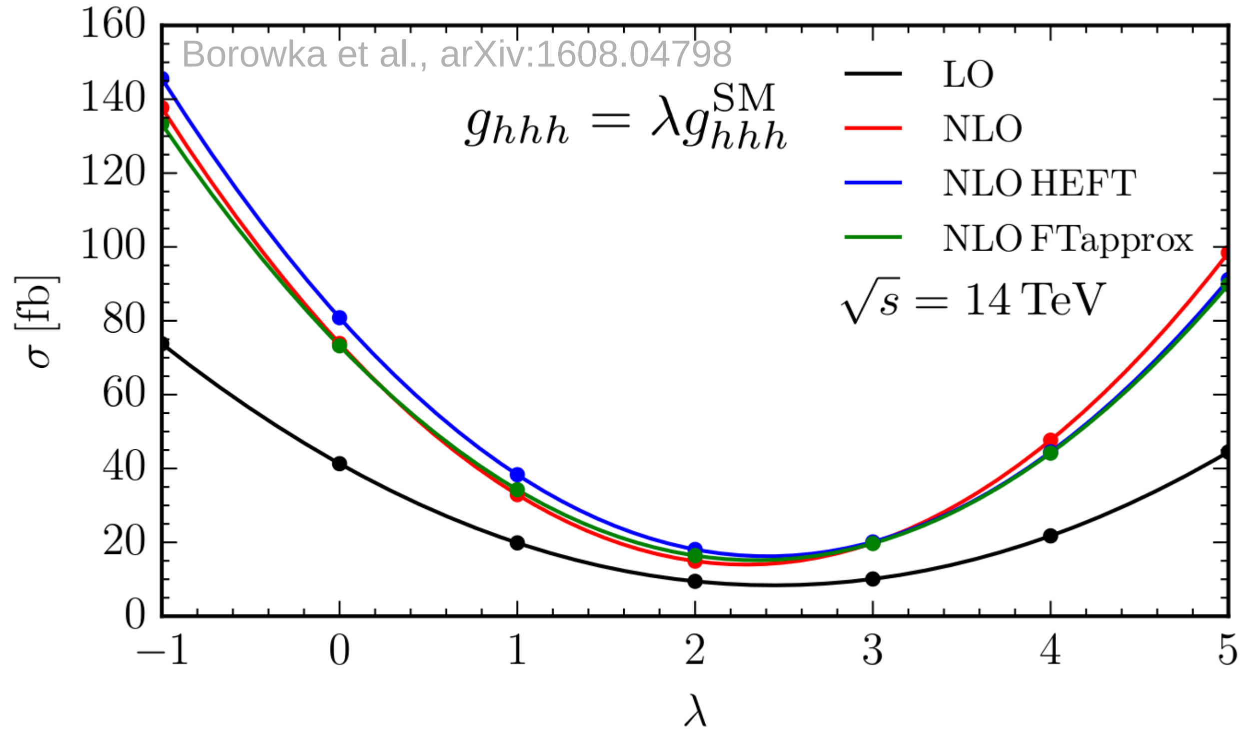
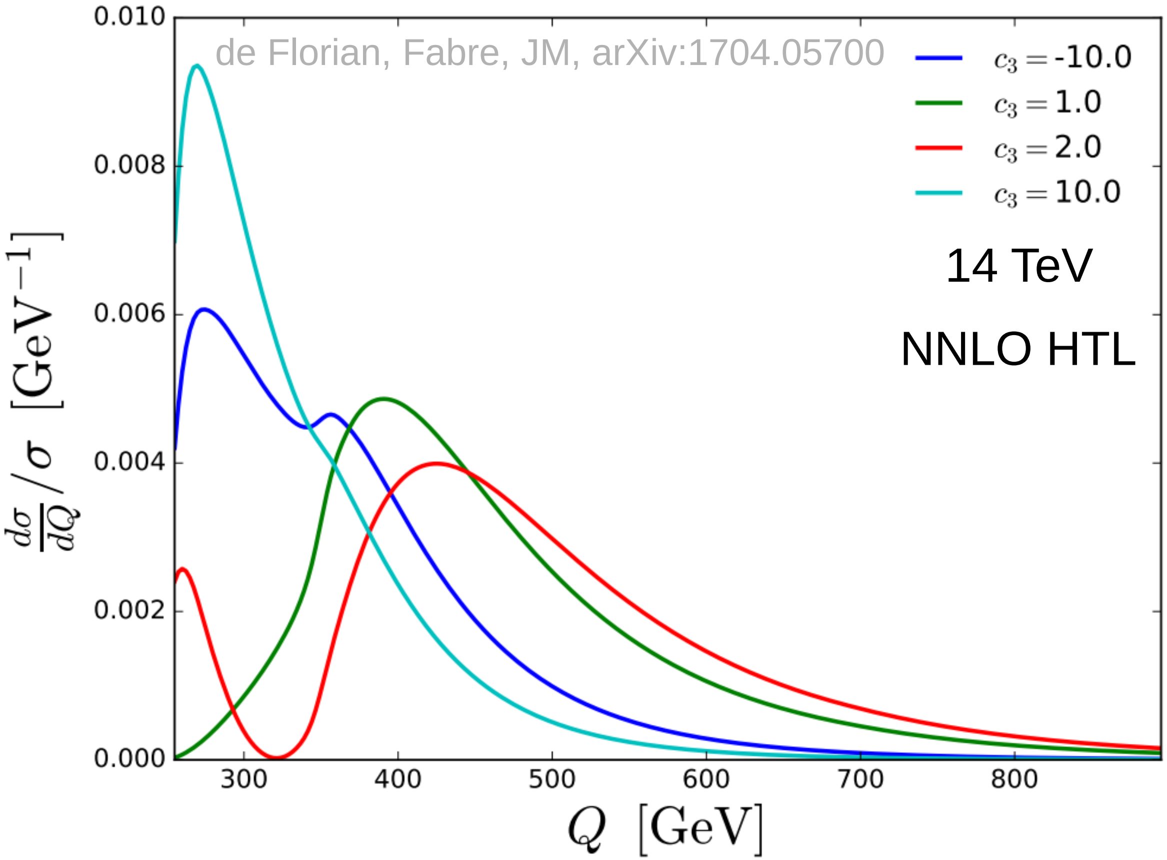
Something similar can be done for y_{hh}, $p_{T,h1}$ and $p_{T,h2}$

Sensitivity to λ_{hhh}

[NLO and HEFT NNLO]

- Minimum around λ=2
- Larger XS for negative λ due to absence of destructive interference

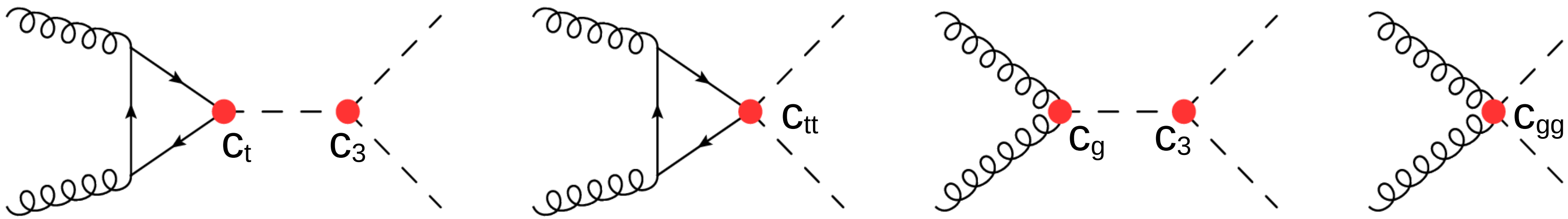




- λ=1 (SM) leads to big cancellation at threshold
- M_{hh} distribution can increase the sensitivity to λ

BSM EFT

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



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

- Large corrections, in general small dependence on the couplings

$$
\begin{aligned}
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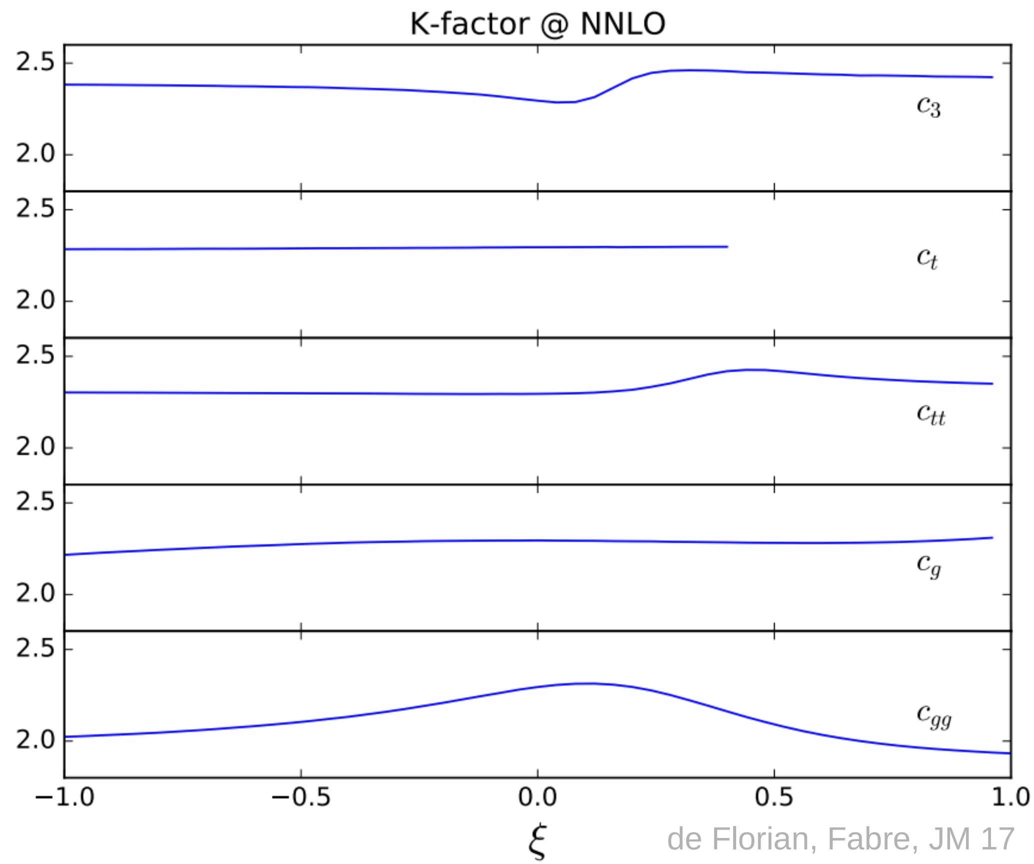
\end{aligned}
$$



de Florian, Fabre, JM 17

- 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 the main way of measuring Higgs **self-coupling**
- Current limit: ~O(10) x SM cross section
- Should be **observed** in the **HL-LHC**
- Precision measurement of $\lambda \rightarrow$ future collider
- Lot of recent progress in the **theoretical predictions**:

  NLO: full M_t dependence

  Beyond: Large-M_t limit

- **NNLO** in the large-M_t limit
- Threshold resummation at **NNLL**

  Further reduction of scale uncertainties

  Suggests to use $\boldsymbol{\mu_0=M_{hh}/2}$ for fixed order predictions

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

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

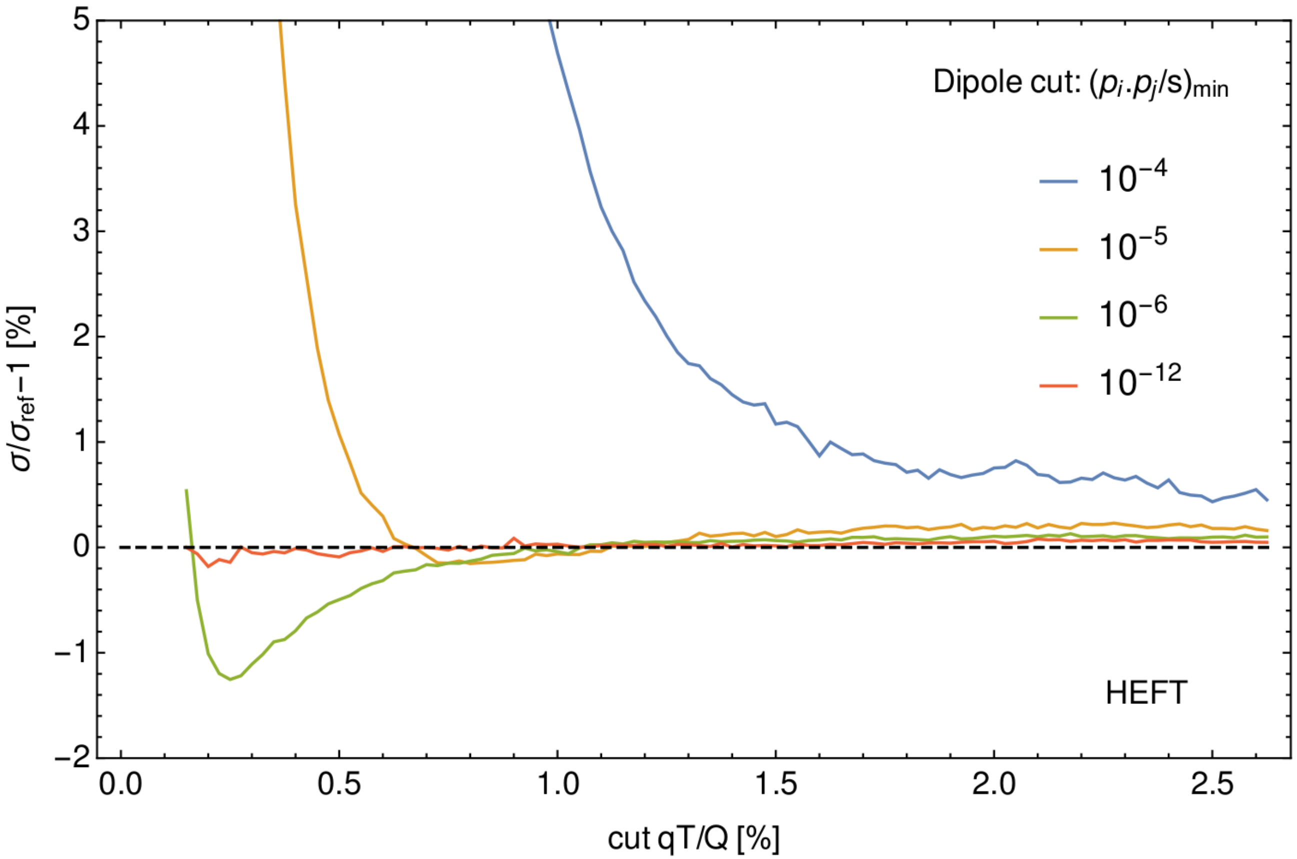
Numerical stability

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

$$\text{Small} \quad \boxed{\alpha = \frac{p_i \cdot p_j}{\hat{s}}} \text{, i and j emitters}$$

- 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

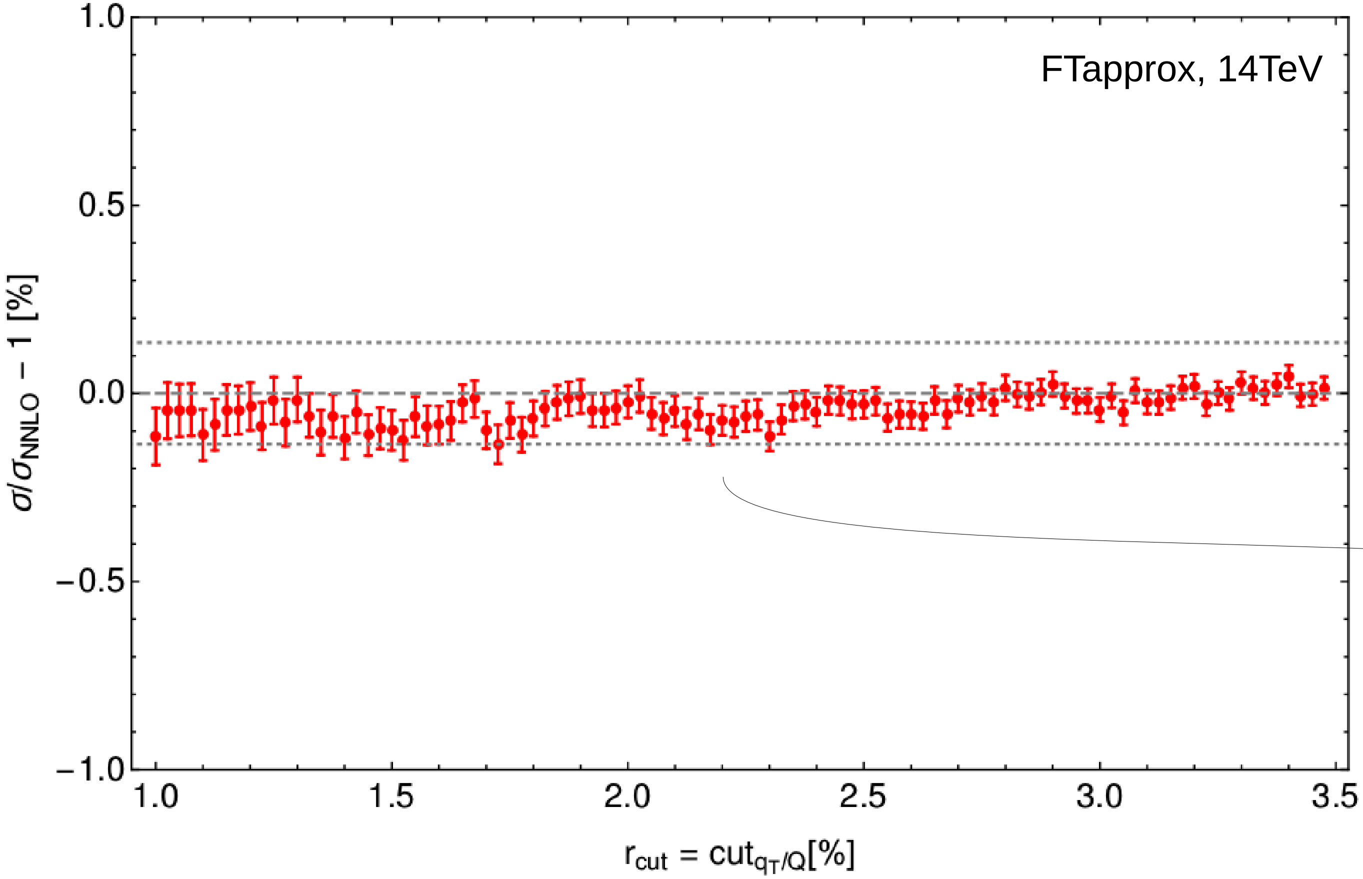
- We avoid evaluating the double real loop induced amplitudes in the unstable regions
- We can use a lower overall dipole cut $\longrightarrow$ we don't spoil the qT-cancellation

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

Results independent in this range

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

Numerical stability



Extrapolation uncertainty of ±0.14%

Variations below 0.2%

- 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

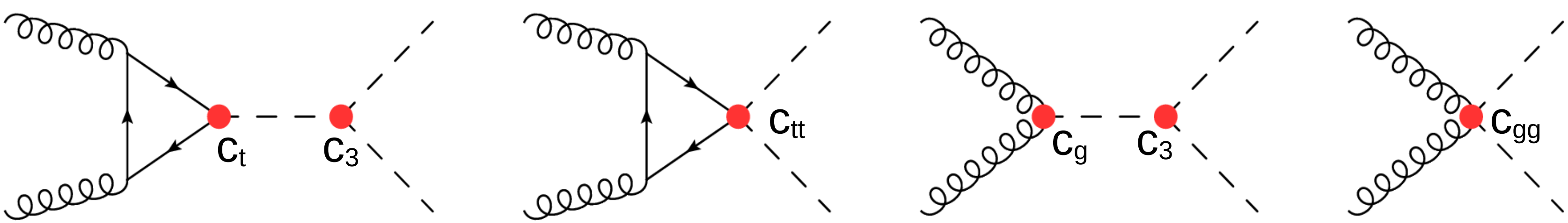
NNLO including dim 6 operators

D. de Florian, I. Fabre and JM
[arXiv:1704.05700]

We extended the computation to include BSM effects via EFT dimension 6 operators

$$\mathcal{L}_{\text{eff}} = -M_t\,\bar{t}t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - c_3\frac{1}{6}\left(\frac{3M_h^3}{v}\right)h^3 + \frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v} + c_{gg}\frac{h^2}{2v^2}\right)$$

- All relevant dimension 6 operators that vanish when h=0
- The SM corresponds to $c_t=c_3=1$ and $c_{tt}=c_g=c_{gg}=0$



NNLO including dim 6 operators

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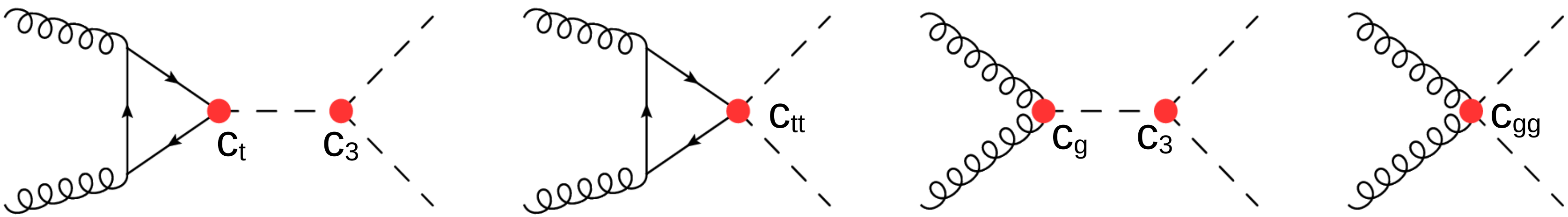
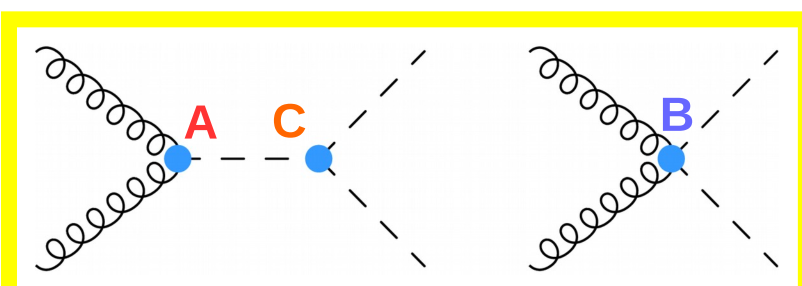


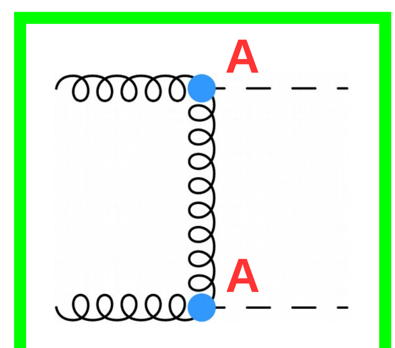
Large top quark mass limit

$$\mathcal{L}_{\rm eff}^{\rm HTL} = \frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left\{\frac{h}{v}\left[\underbrace{\frac{c_t}{12}C_H + c_g}_{\textbf{A}}\right] + \frac{h^2}{2v^2}\left[\underbrace{-\frac{c_t^2}{12}C_{HH} + \frac{c_{tt}}{12}C_H + c_{gg}}_{\textbf{B}}\right]\right\} - \underbrace{c_3\frac{1}{6}\left(\frac{3M_h^3}{v}\right)}_{\textbf{C}}h^3$$

- Same couplings we have already in the SM HTL → easy to obtain the NNLO corrections
- Non trivial interplay between the different couplings:



LO



NLO

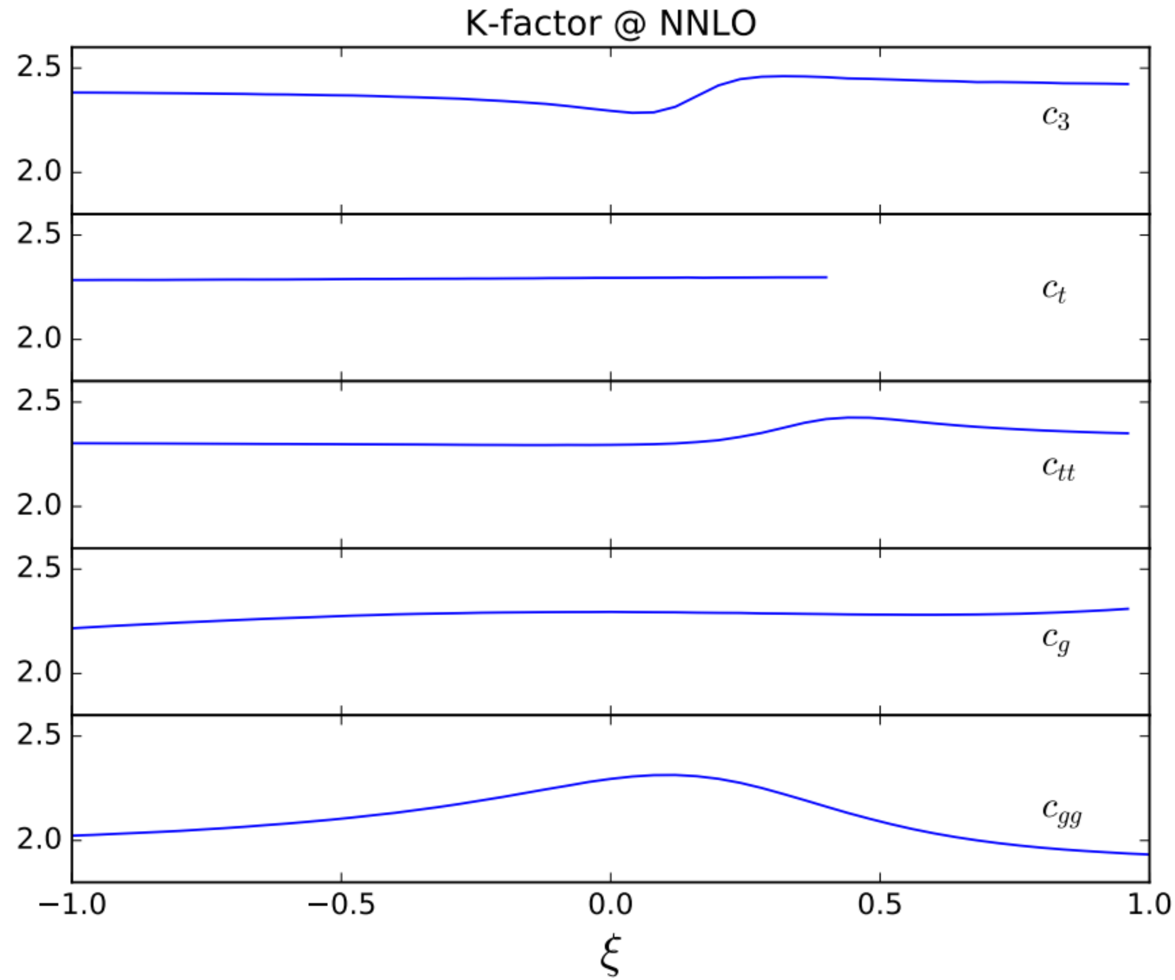
NNLO including dim 6 operators

Does the size of the corrections change when we move away from the SM?

- We vary one coupling at a time:

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

- Large corrections, but small dependence on the couplings



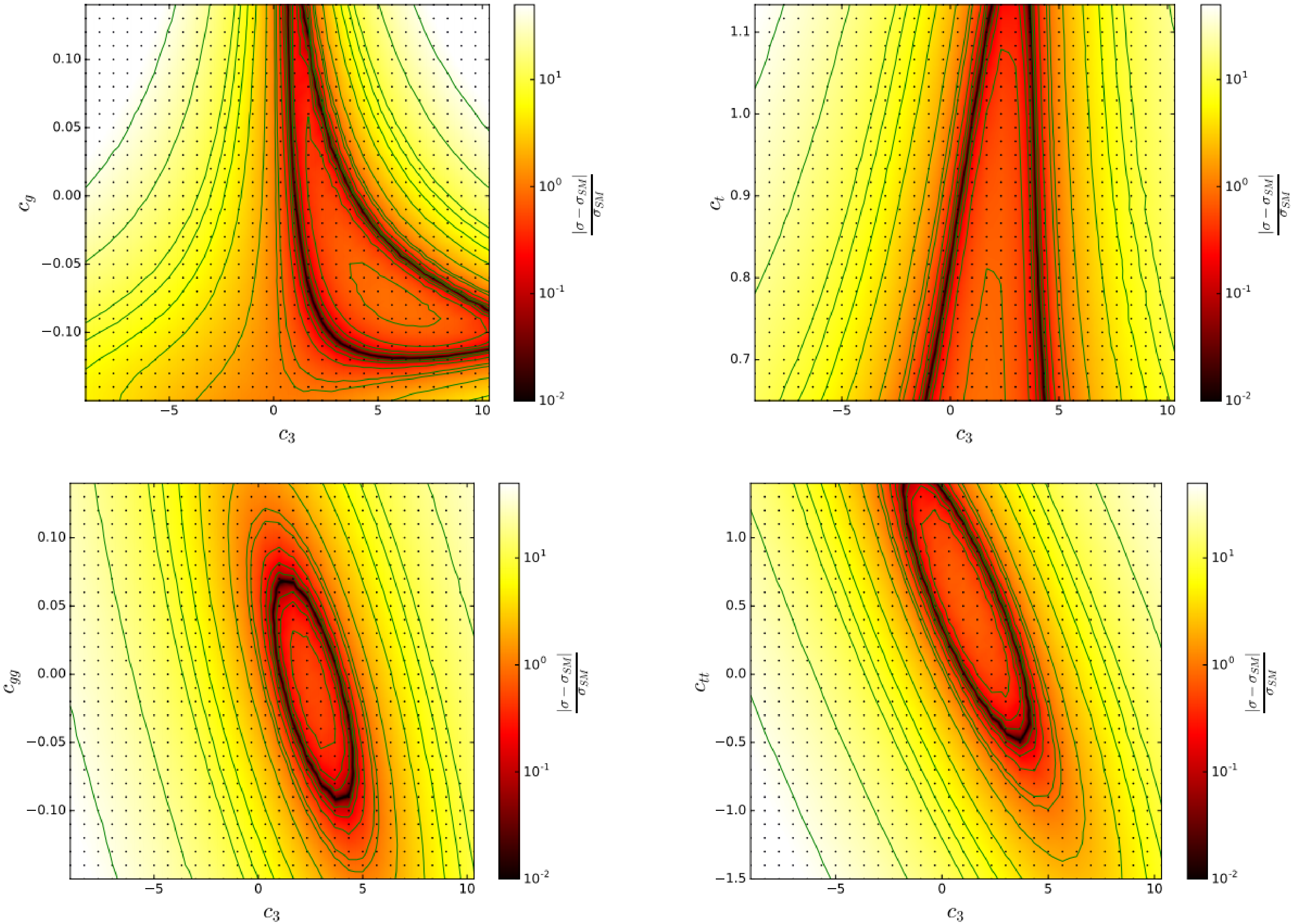
$$\Delta K^{c_{gg}} = \frac{\max|K(c_{gg}) - K_{SM}|}{K_{SM}} \approx 15.8\% \qquad \text{at } c_{gg} = 0.15\,.$$

$$\begin{aligned} \Delta K^{c_3} &\approx 7.2\% && \text{at } c_3 = 4.20\,, \\ \Delta K^{c_{tt}} &\approx 5.7\% && \text{at } c_{tt} = 0.66\,, \\ \Delta K^{c_g} &\approx 3.4\% && \text{at } c_g = -0.15\,, \\ \Delta K^{c_t} &\approx 0.5\% && \text{at } c_t = 0.65\,. \end{aligned}$$

Larger deviations when doing simultaneous variations, but mainly in regions where the cross section is small

Degeneracy and M_{hh} distribution

Different combinations of couplings can give a total XS similar to SM

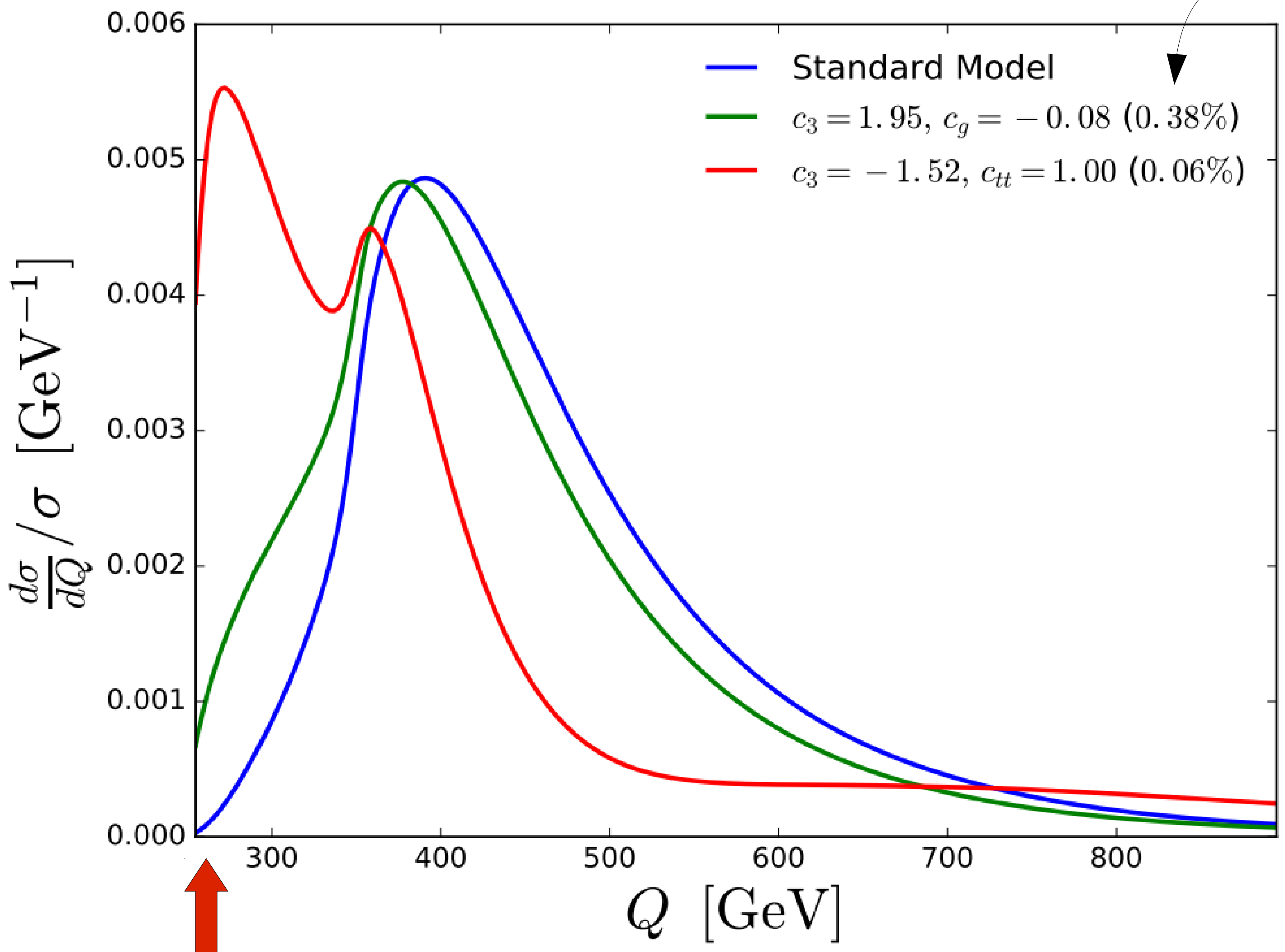


Degeneracy and M_{hh} distribution

The invariant mass distribution can help disentangling the degeneracy

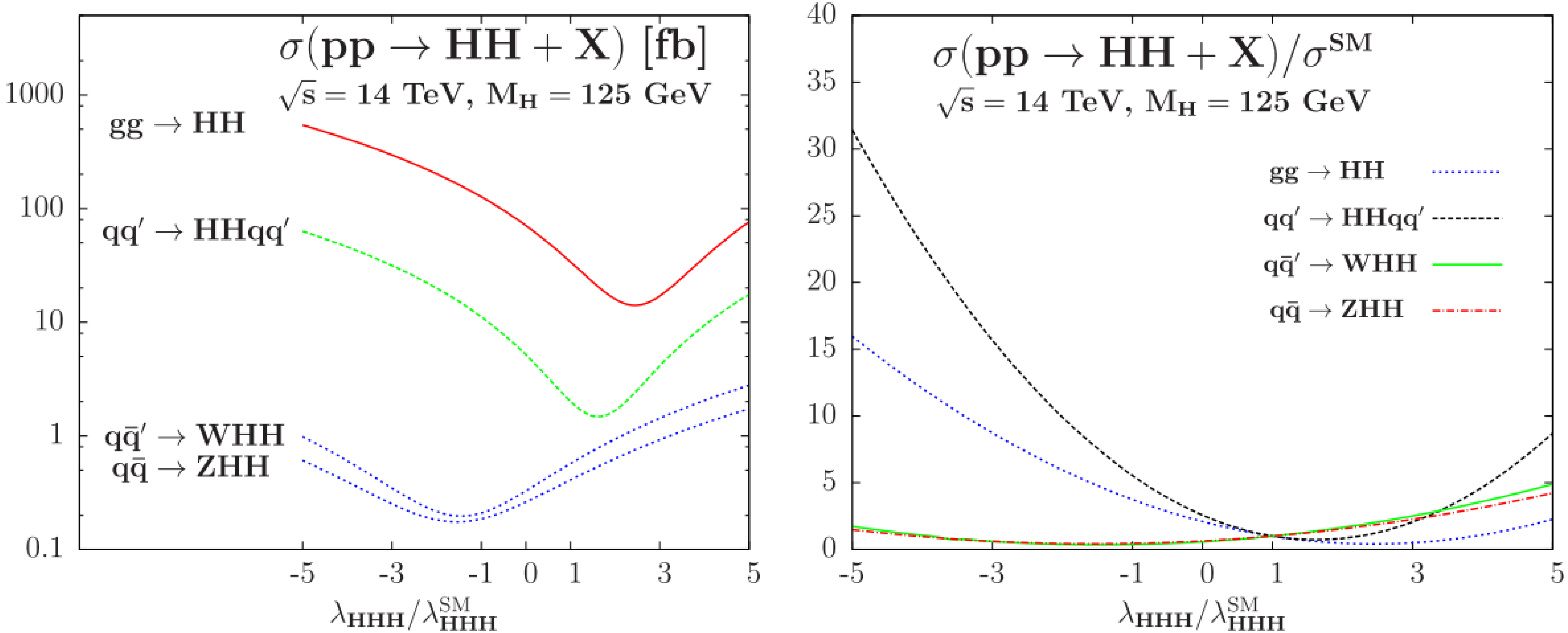
S. Borowka et al. [arXiv:1608.04798]
de Florian, Fabre, JM [arXiv:1704.05700]

Deviation w.r.t. SM XS



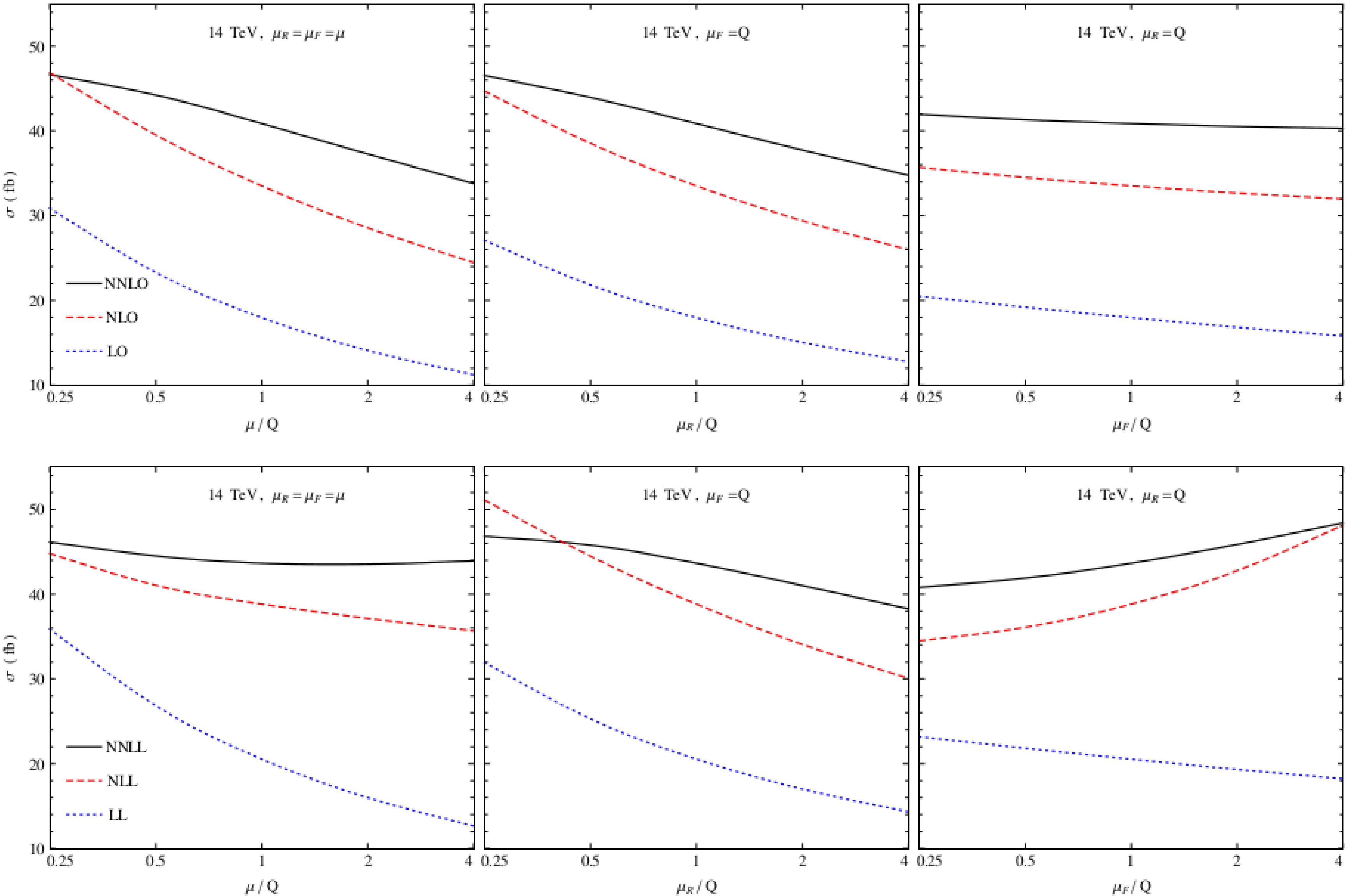
Threshold is particularly sensitive due to triangle-box cancellations in the SM

Sensibility to self-coupling for the different production mechanisms

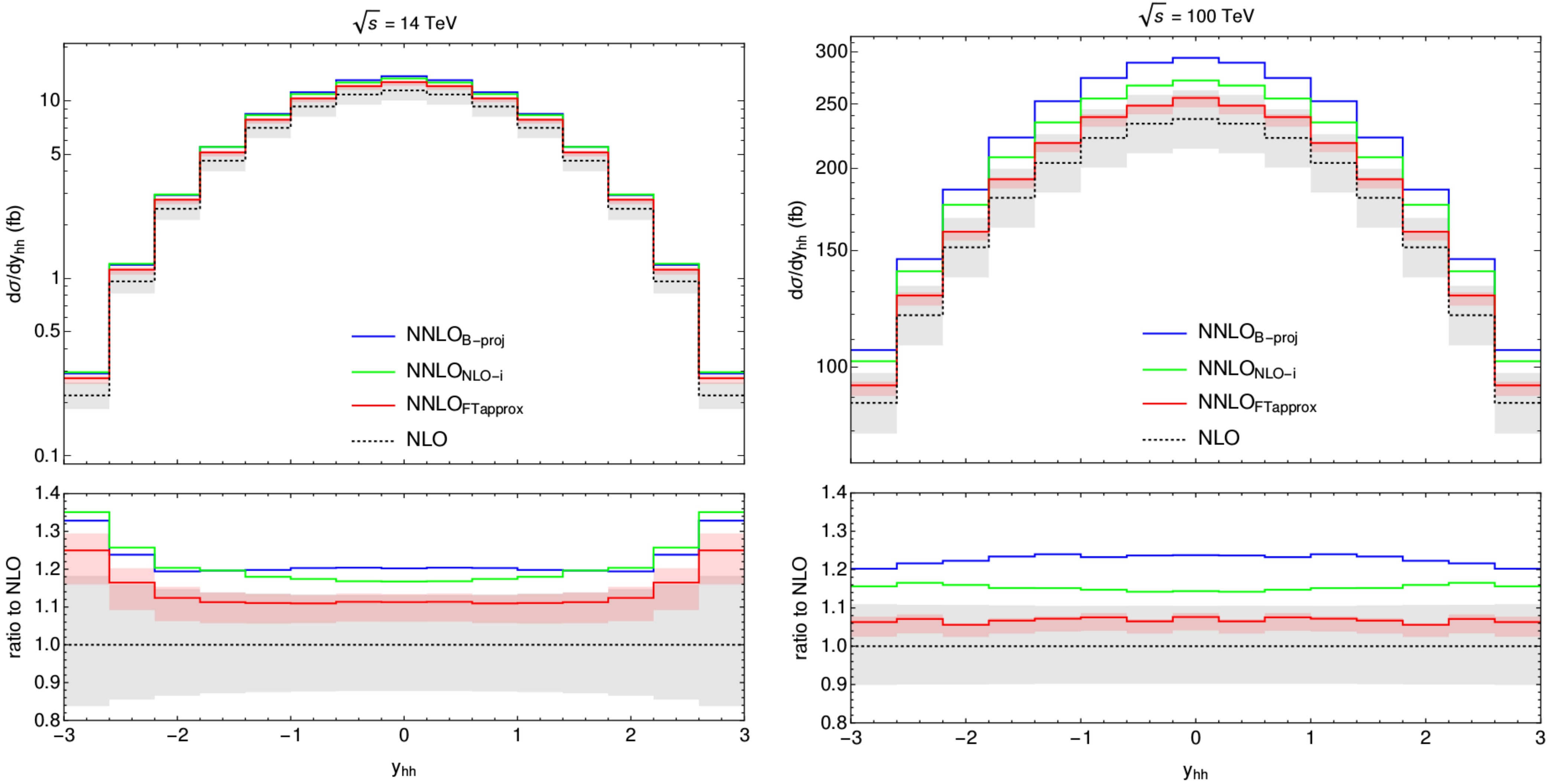


From arXiv:1212.5581 [hep-ph]

Scale variation for fixed order and resummed total XS

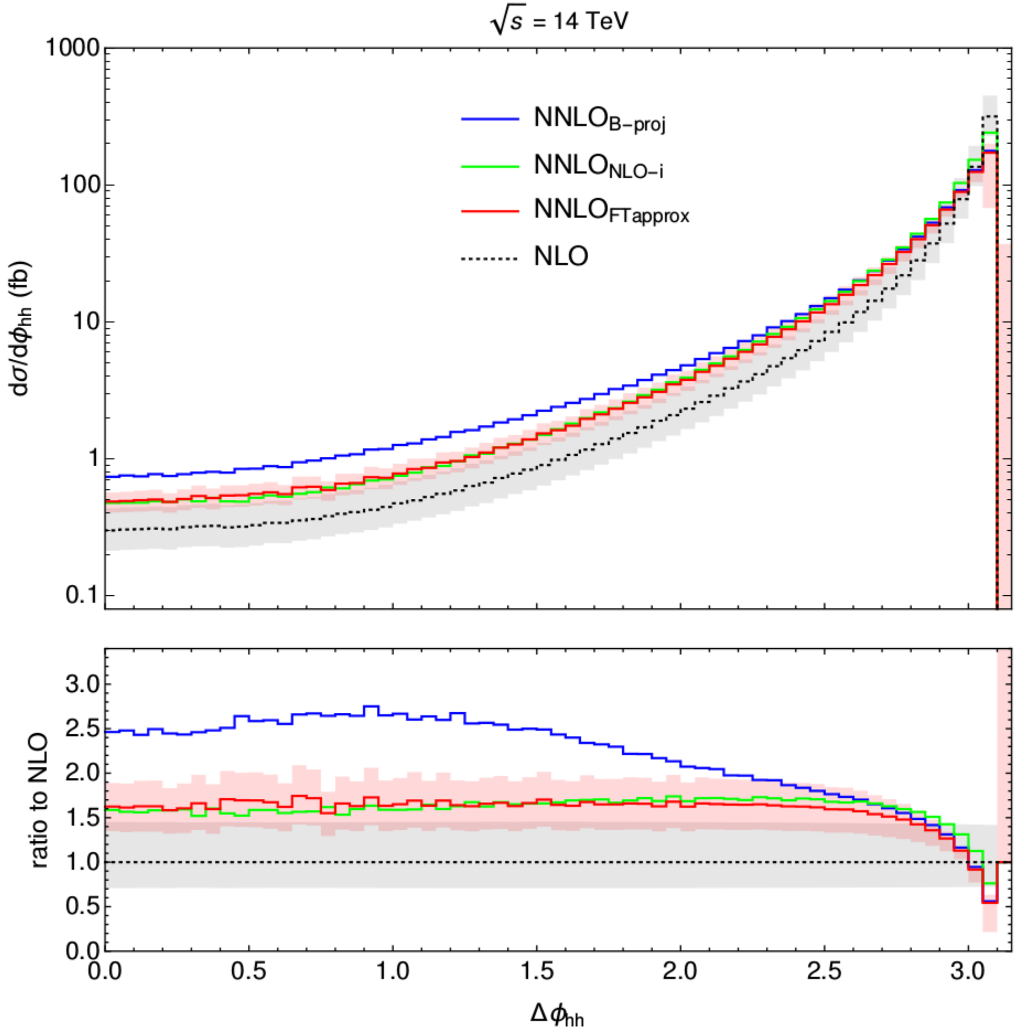


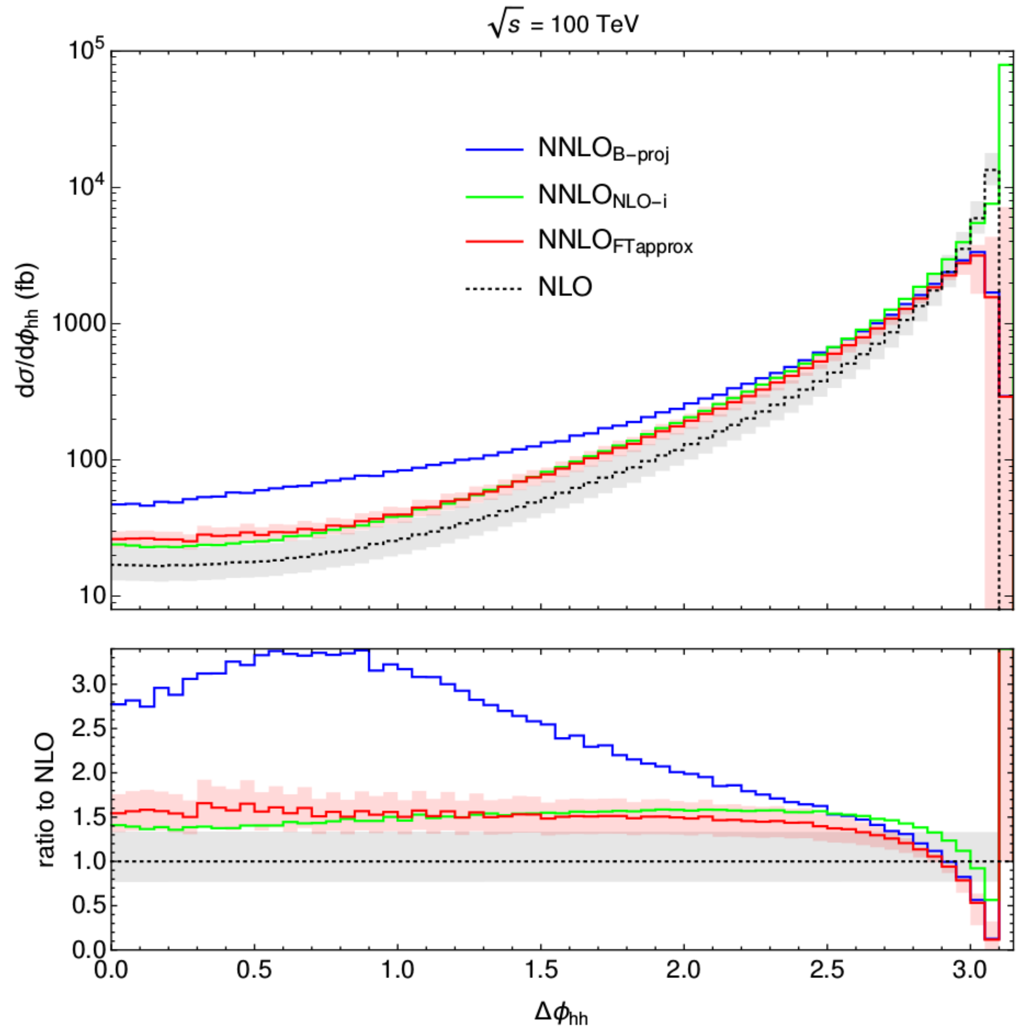
Differential distributions – y_{hh}



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

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

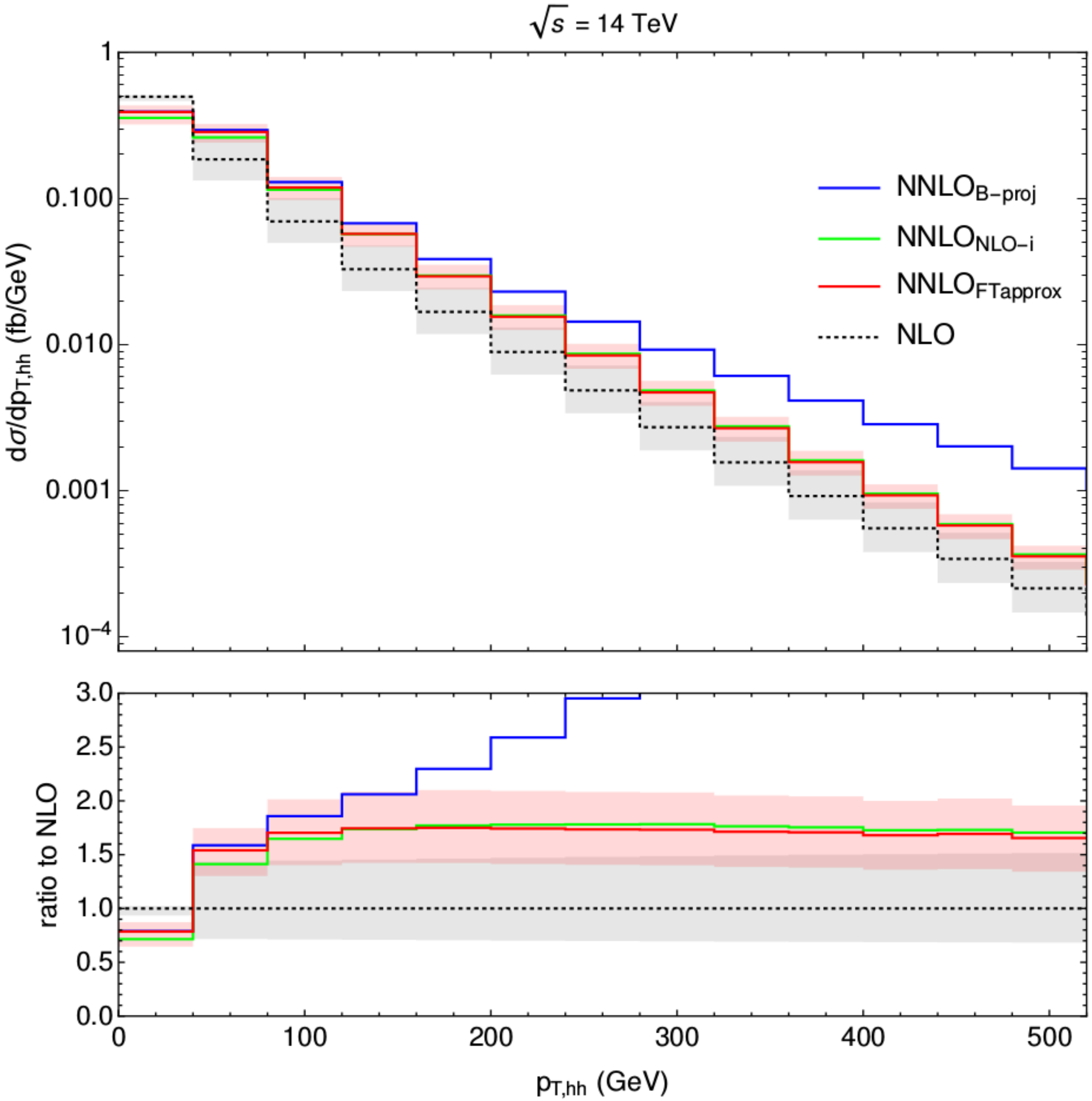




- Trivial at LO: back-to-back. NNLO effectively NLO
- Large corrections above 50%, sizable scale uncertainties
- B-proj approximations predicts larger corrections in the region dominated by hard radiation
- Good general agreement between FTapprox and NLO-i, larger differences close to π

M_t uncertainties for distributions

Based on the performance of the FTapprox at NLO and on the separation between the NNLO approximations, we can roughly estimate the size of the Mt uncertainties for distributions



- Distributions not defined/trivial at LO are exactly reproduced by FTapprox at NLO → more difficult to estimate uncertainties!

We can use the difference between FTapprox and NLO-i as an estimate

- Relatively low uncertainties for hh transverse momentum and azimuthal separation, larger for leading jet pT

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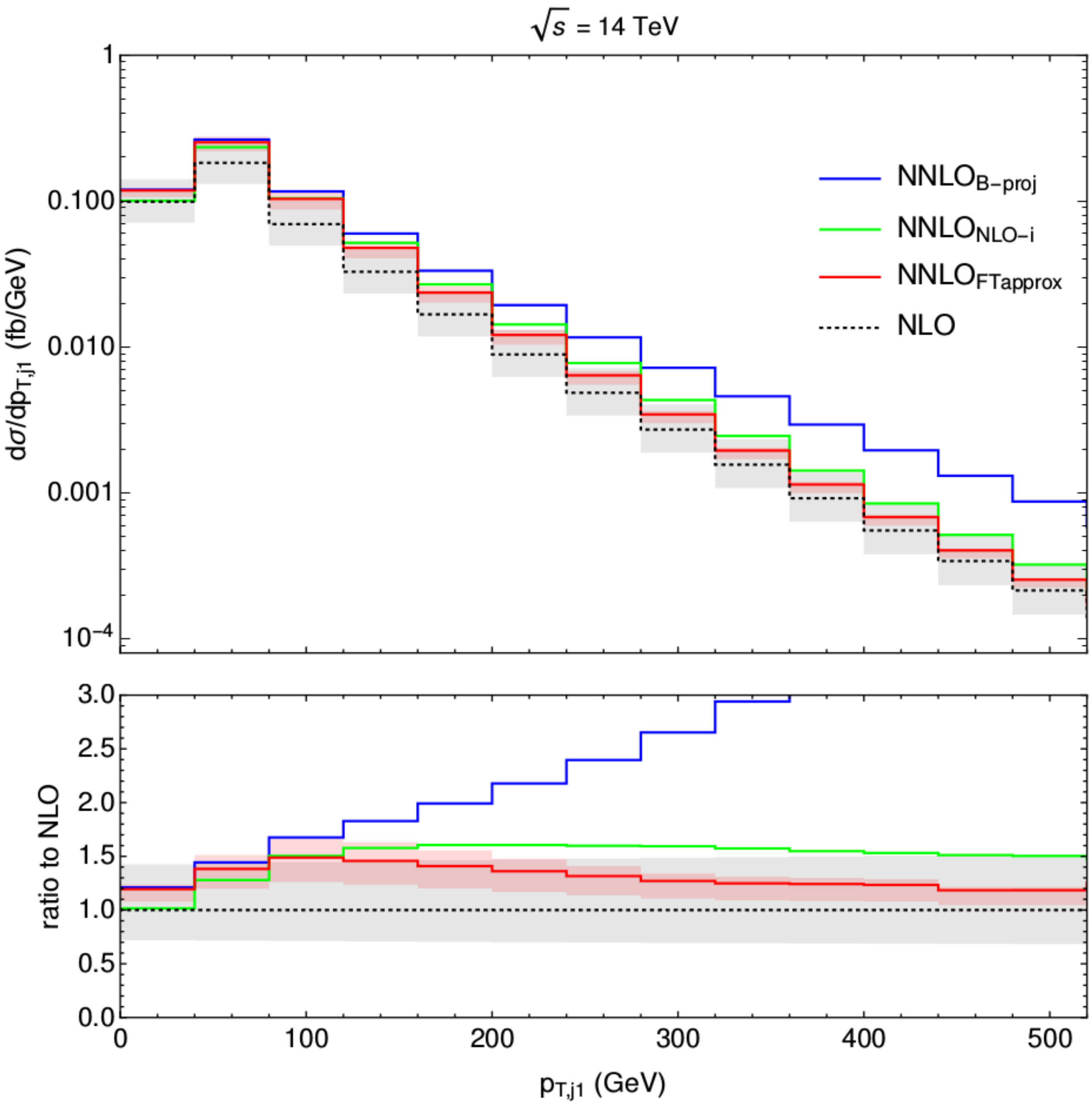

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