Quark-mass effects in Higgs production

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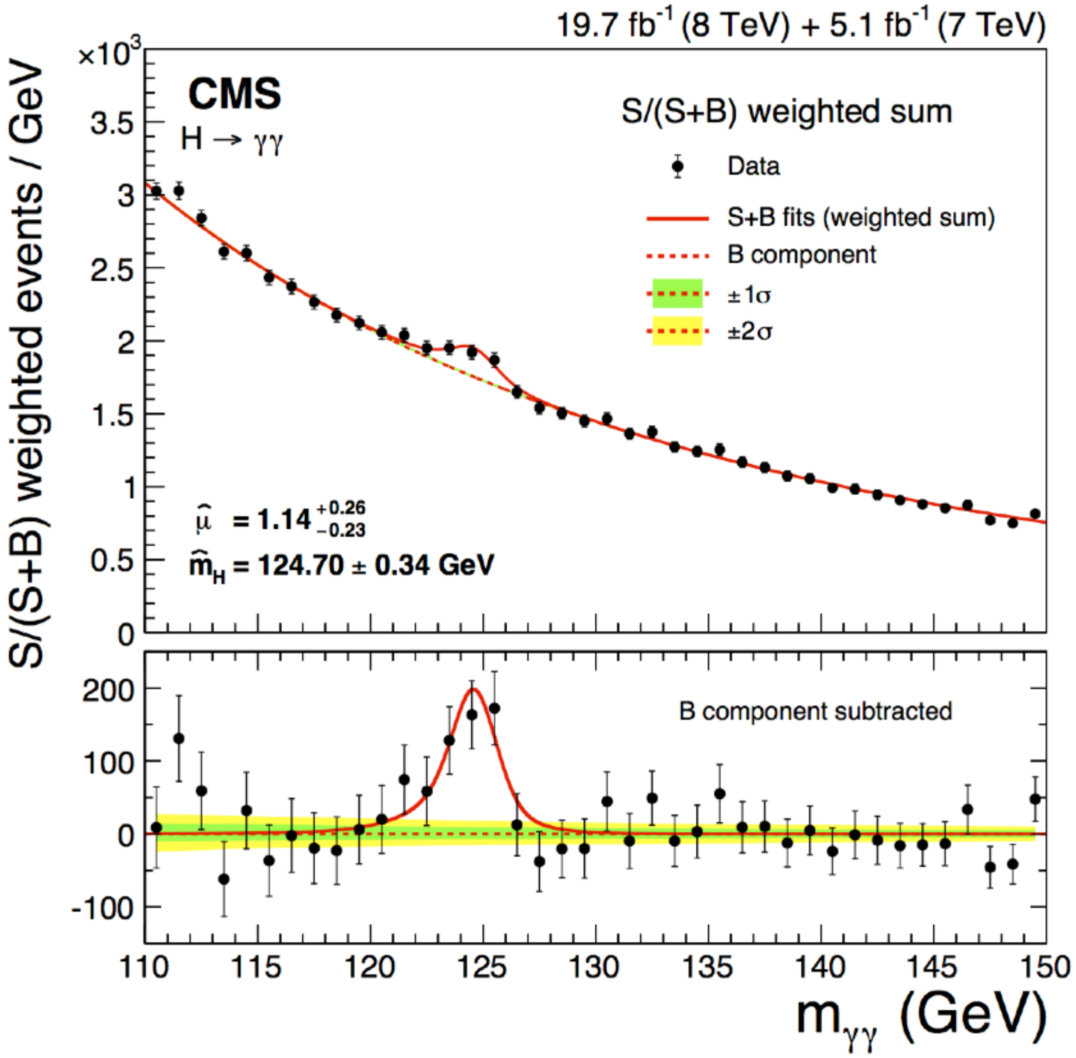
IRN Terascale
Higgs-session
IPPP, Durham, 6. August 2018

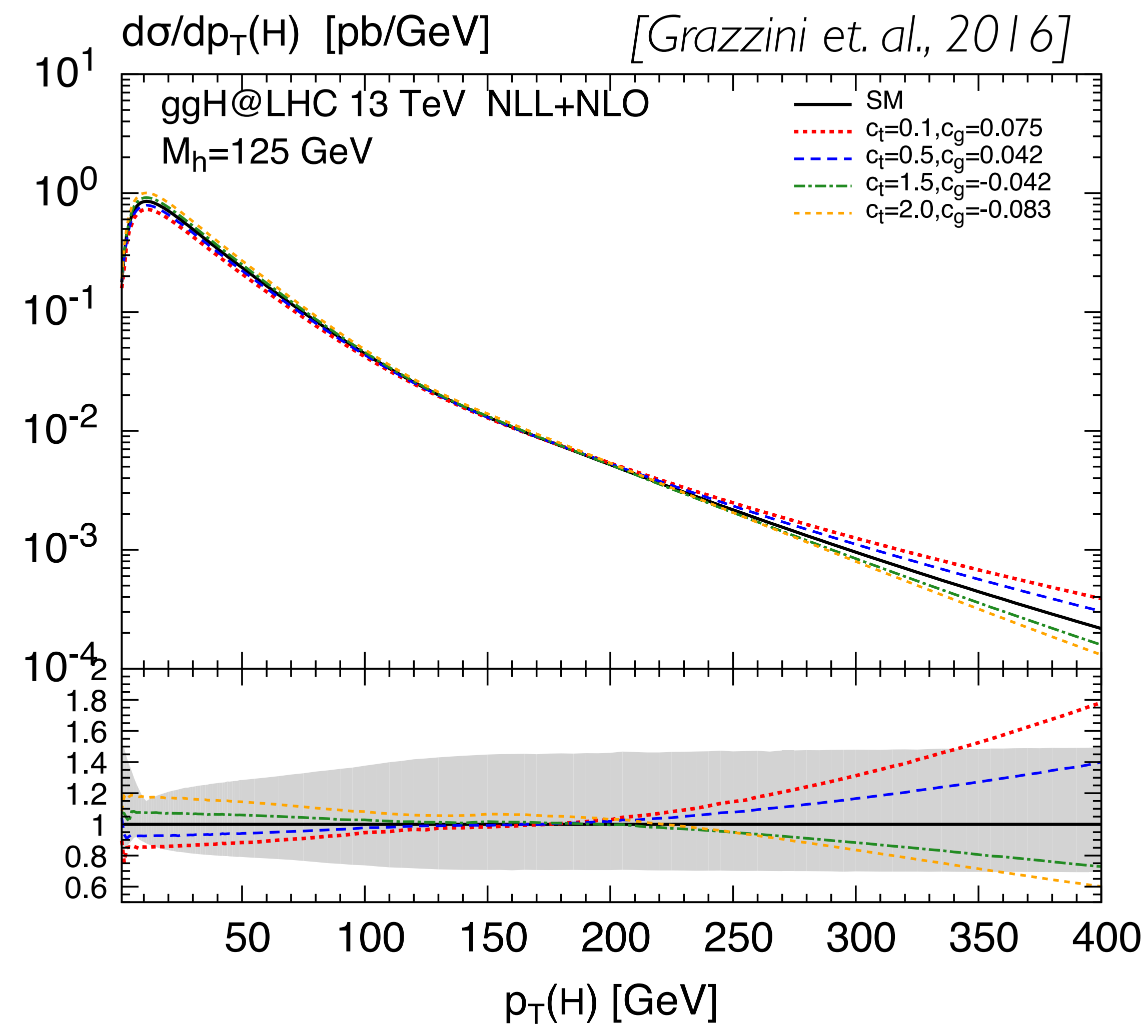
Finding the Higgs was "easy"…

[CMS diphoton Higgs search, arXiv:1407.0558]



Bump hunting: little to no theoretical input needed.

…finding new physics might be very tough.

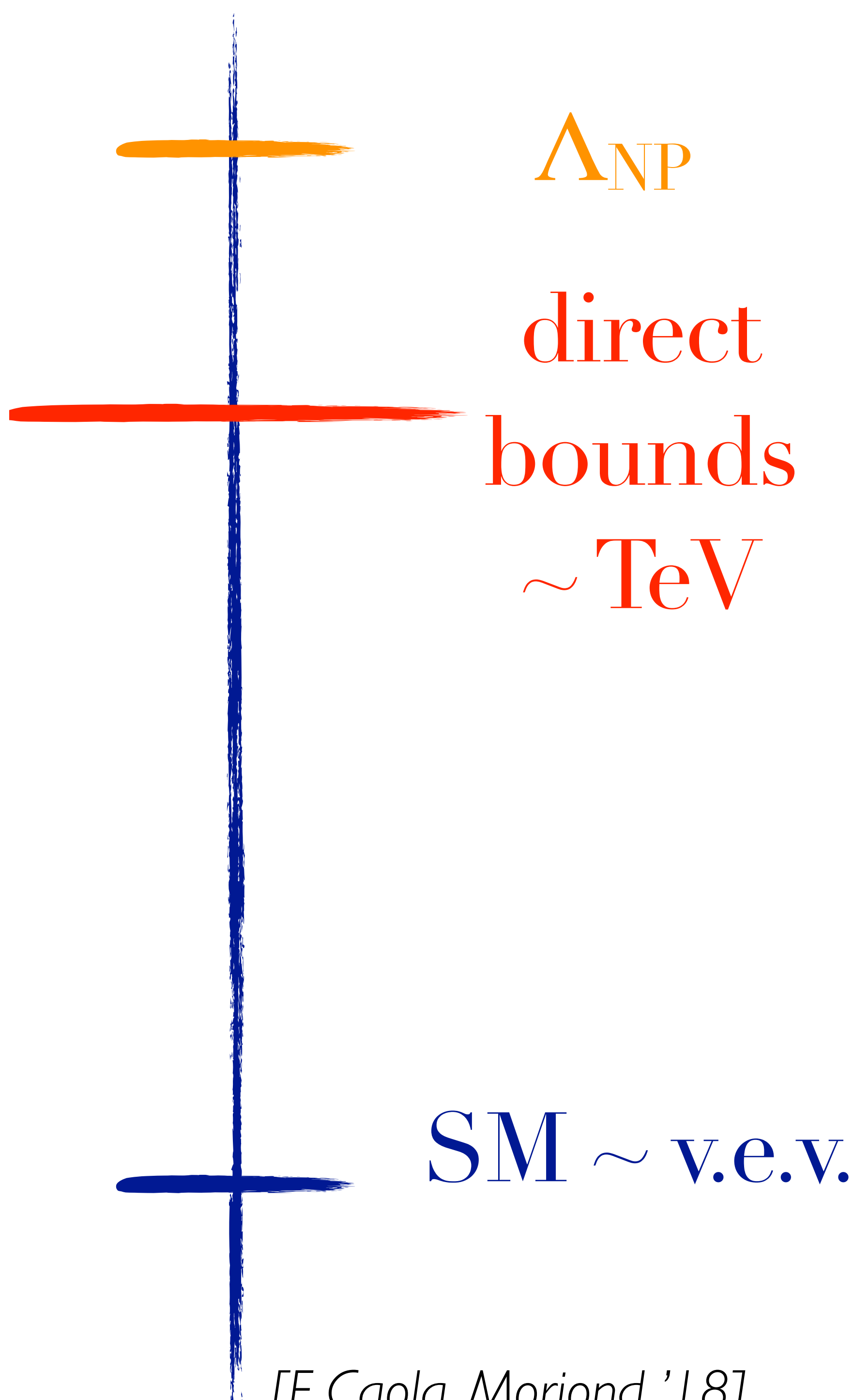


Look for BSM effects in small deviations from SM predictions:

→ **Higgs processes natural place to look at**

→ **good control on theory necessary!**

“good control” ?



[F. Caola, Moriond '18]

Imagine to have new physics at a (heavish) scale Λ_{NP}

Typical modification to observable w.r.t. standard model prediction:

$$\delta O \sim Q^2 / \Lambda_{NP}{}^2$$

To gain over direct bounds:

IN THE BULK:

$Q \sim M_H \rightarrow$ few percent

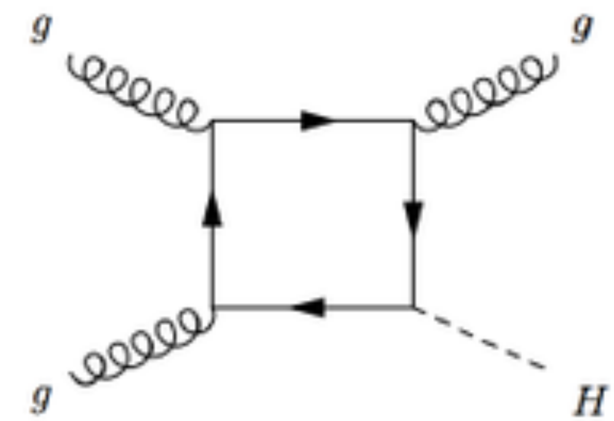
IN THE TAIL:

$Q \gtrsim 500$ GEV $\rightarrow$

~10-20%

Outline

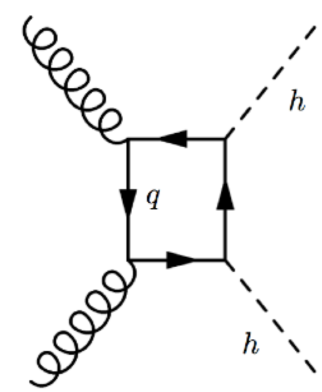
Higgs-pT

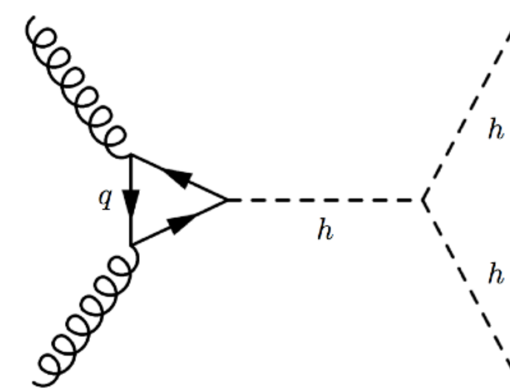


LO: Ellis et. al. '88; U. Baur et. al., '90

- ~40% remaining scale uncertainty
- $K^{HEFT} \sim 1.8$

Di-Higgs



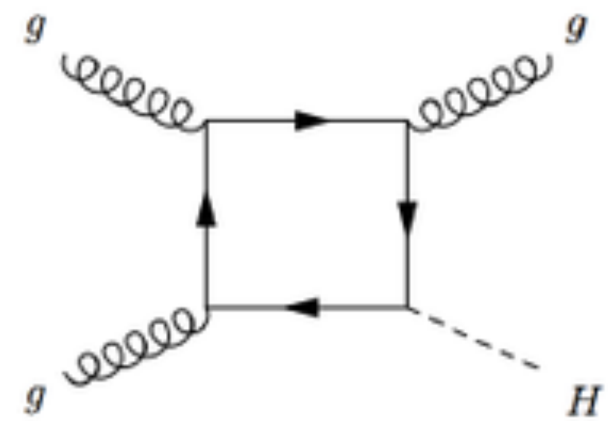


LO: Eboli et. al. '87; Glover, van der Bij '88

- ~25% remaining scale uncertainty
- $K^{HEFT} \sim 1.85$

Outline

Higgs-pT



Di-Higgs

Higgs-pT: two regimes

$p_\perp \ll m_t$ ↙ ↘ $p_\perp > m_t$

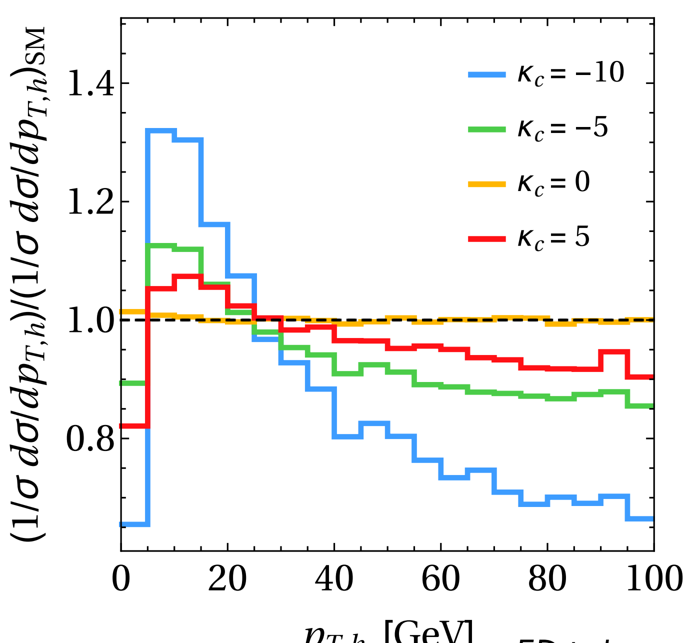
Possibility to constrain the charm-Yukawa coupling

$$\mathrm{d}\sigma/\mathrm{d}p_\perp \propto y_t^2 + y_t y_b + y_b^2 + y_t y_c + \ldots$$

for $p_\mathrm{T} \ll m_H$ ~10% ~1% <<1%

$$A^Q_{gg\to Hg} \sim m_Q^2/m_H^2 \log^2\left(p_\perp^2/m_Q^2\right)$$

➡ Sudakov-like logarithmic enhancement of light-quark contribution at small pT



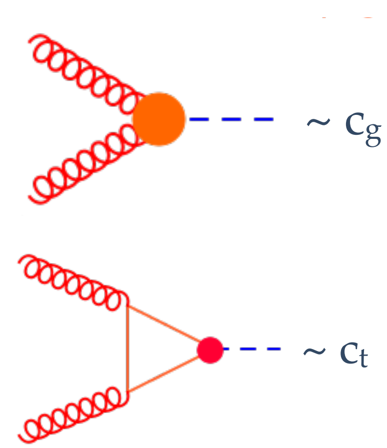
[Bishara, Haisch, Monni, Re; '16]

Sensitive probe of New Physics

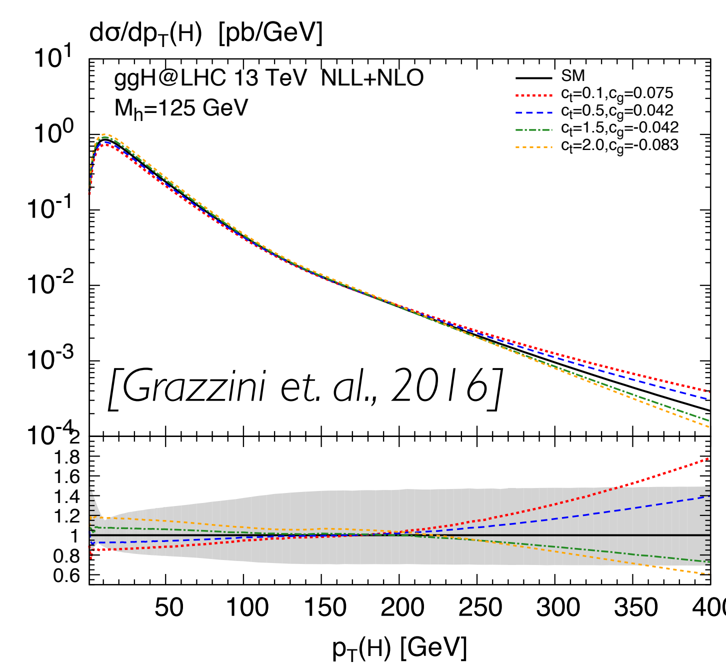
➜ In particular: disentangle c_g vs. c_t,:

$$\frac{\mathrm{d}\sigma_H}{\mathrm{d}p_\perp^2} \sim \frac{\sigma_0}{p_\perp^2}\begin{cases}(c_g + c_t)^2, & p_\perp^2 < 4m_t^2,\\ \left(c_g + c_t\frac{4m_t^2}{p_\perp^2}\right)^2, & p_\perp^2 > 4m_t^2.\end{cases}$$

Note: inclusive measurements only allow to constrain $(c_g + c_t)^2$

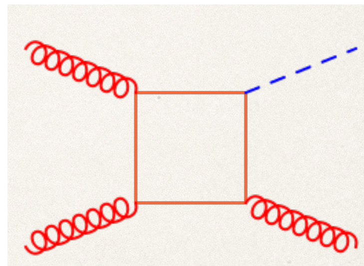


SM: c_g=0, c_t=1



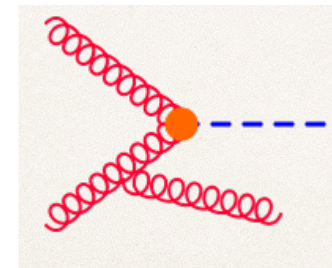
Higgs-pT: higher-order corrections

full theory: loop-induced



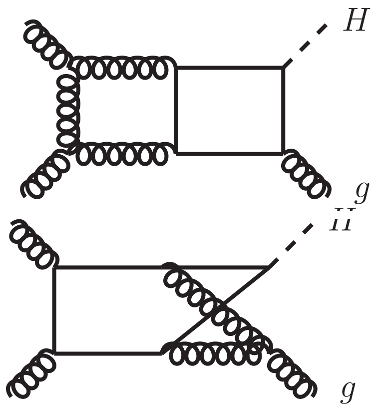
integrate-out

heavy quarks



HEFT: tree-level at LO

Bottleneck:
massive two-loop amplitudes

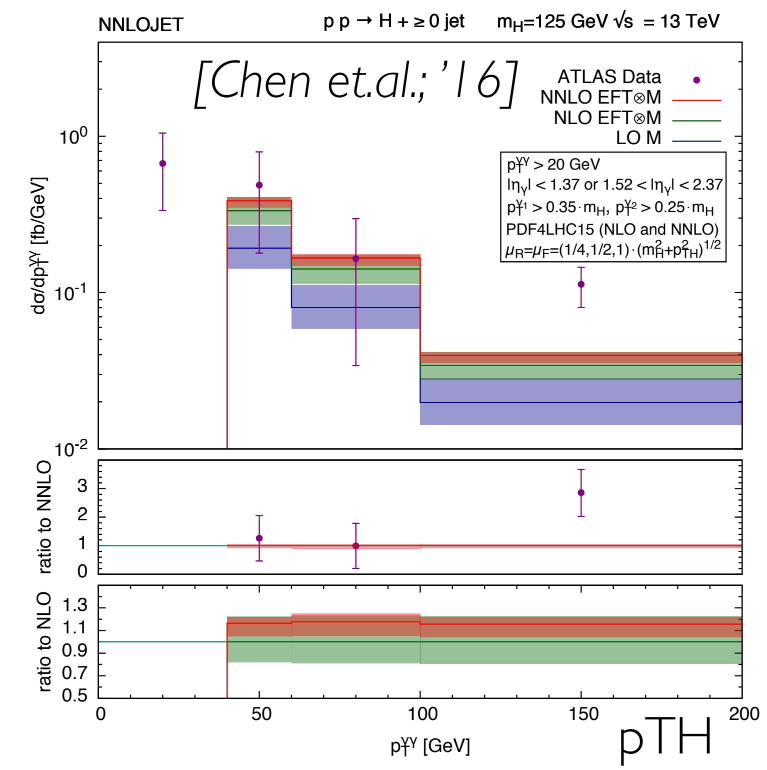


NLO

NNLO

[Chen et.al.; '14+'16
Boughezal et. al.; '15,
Caola et.al.; '15]

Bottleneck: IR subtraction



Ansätze:

- analytical: very hard, planar MI known [Bonciani et. al., '16]
- numerical: very ~~CPU/~~GPU intensive [Jones et. al., '18]
- expansions: has to be performed carefully, very versatile

[Melnikov et. al., '16+'17]

perturb. uncertainties in HEFT under very good control:

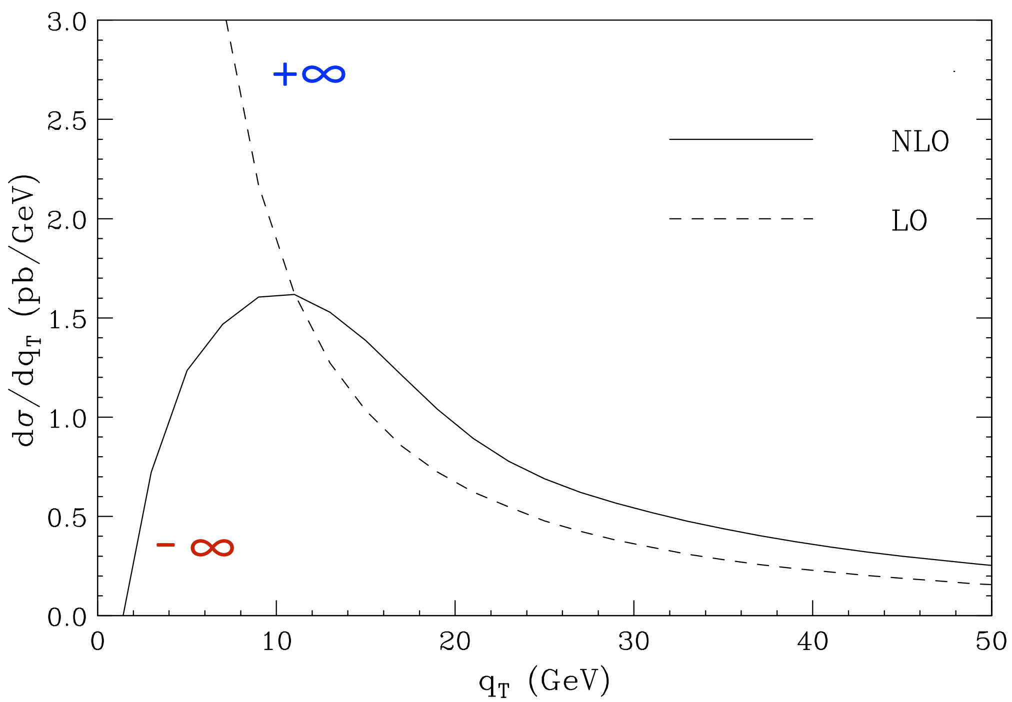
- ~10% scale variation
- stable shapes

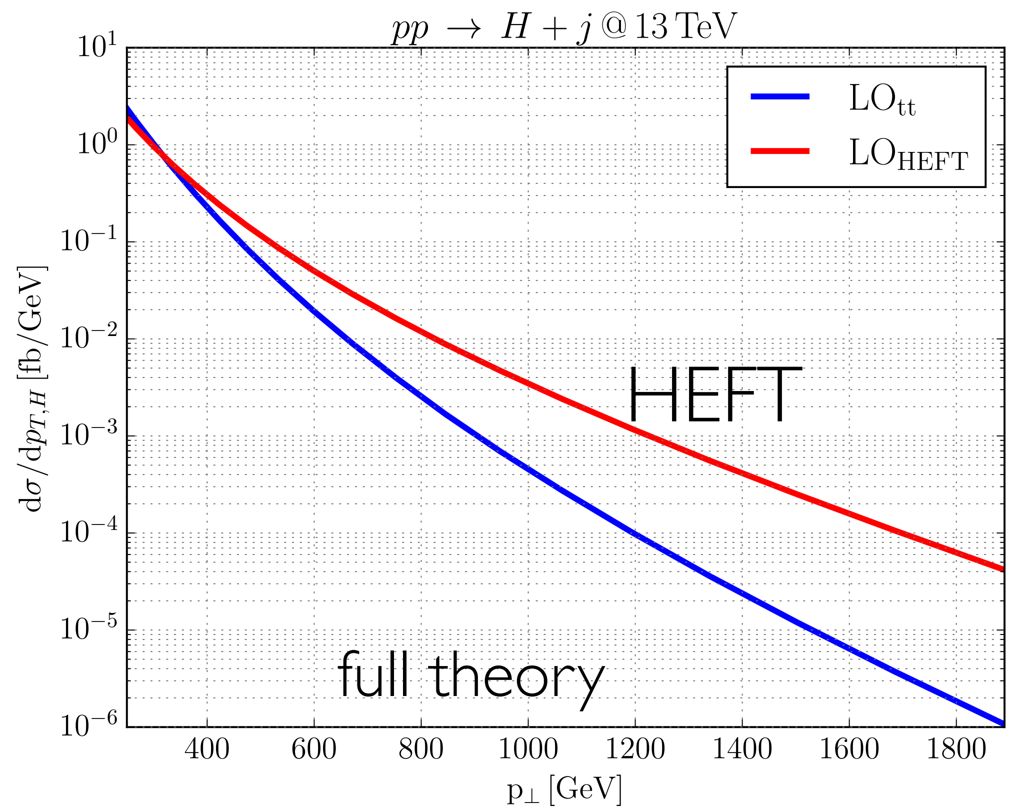
Idea: QCD corrections factorize
➜ apply K-factors from HEFT to lower order predictions in full theory ➜ check!!

NNLO+NXLL

Higgs-pT: two regimes

$p_\perp \ll m_t$ $\quad$ $p_\perp > m_t$





$\sim p_T^{-2}$

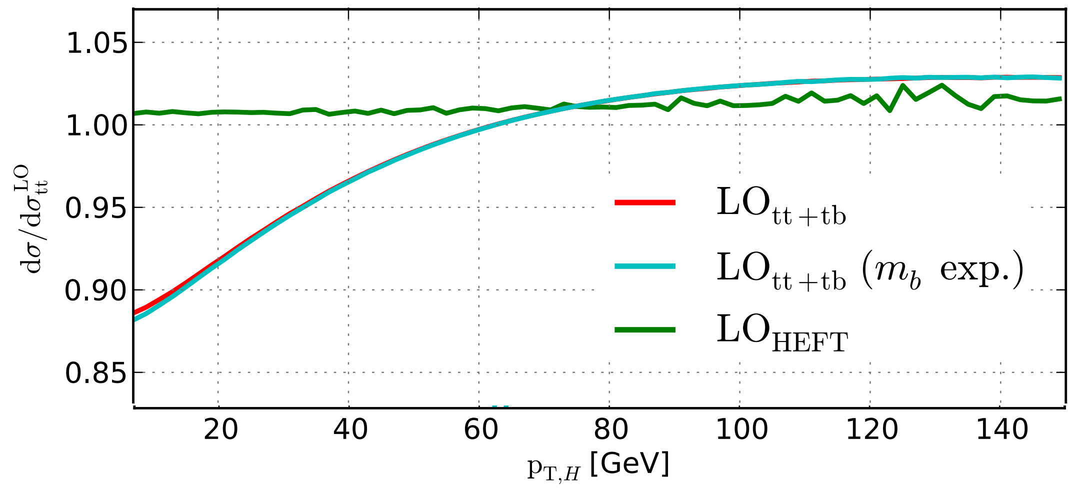
$\sim p_T^{-4}$

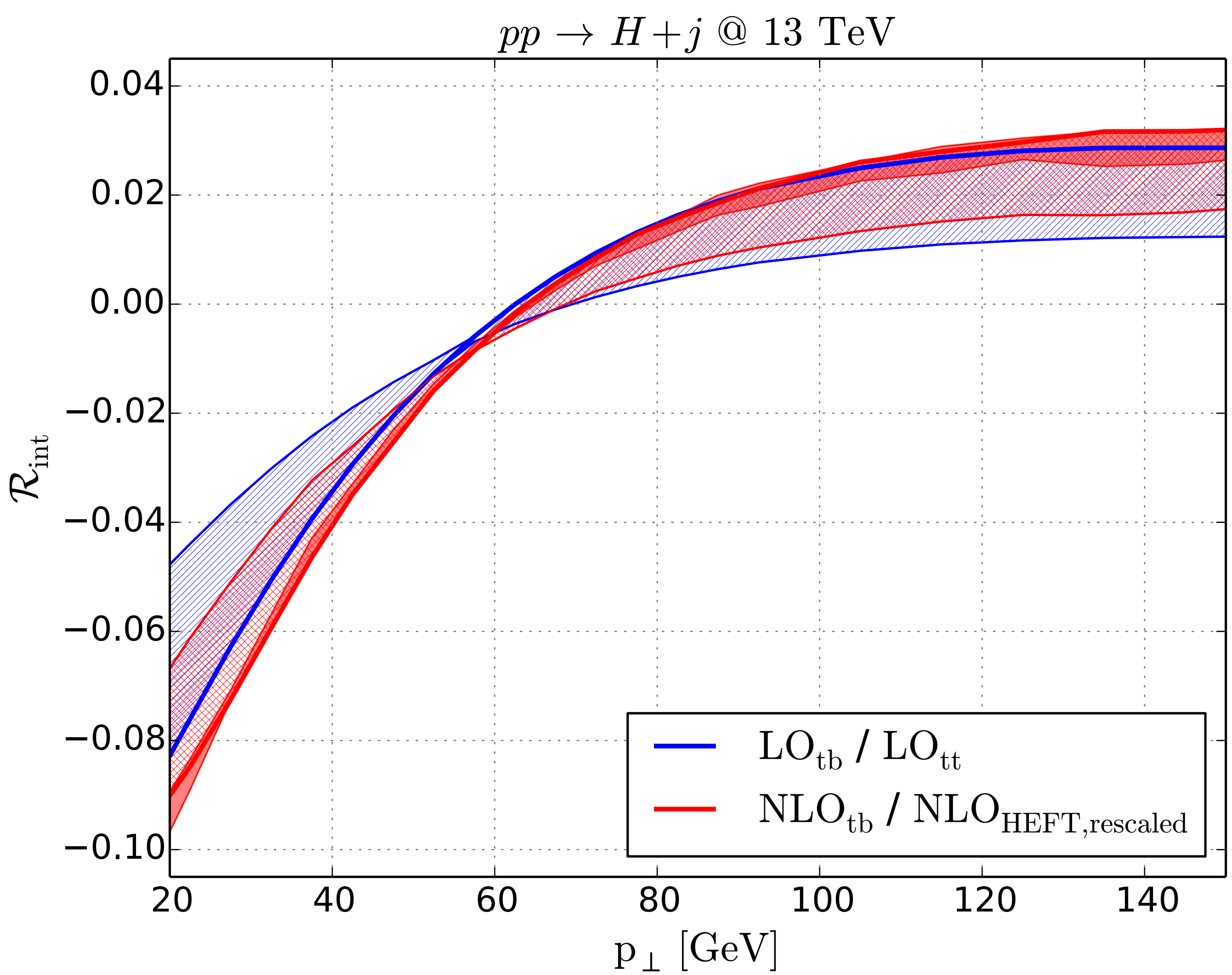
- Fixed-order breaks down at low pT
- point-like ggH (HEFT) and full theory have very different high energy behaviour.

$p_T^H \ll m_H$: bottom mass effects at NLO

[JML, Melnikov, Tancredi, Wever '17]

- expansion of the two-loop integrals in (m_b^2/p_T^2)
  [Melnikov, Tancredi, Wever; '16+'17]
- valid at %-level down to pT~10 GeV
- real radiation treated exact with **`OpenLoops`**

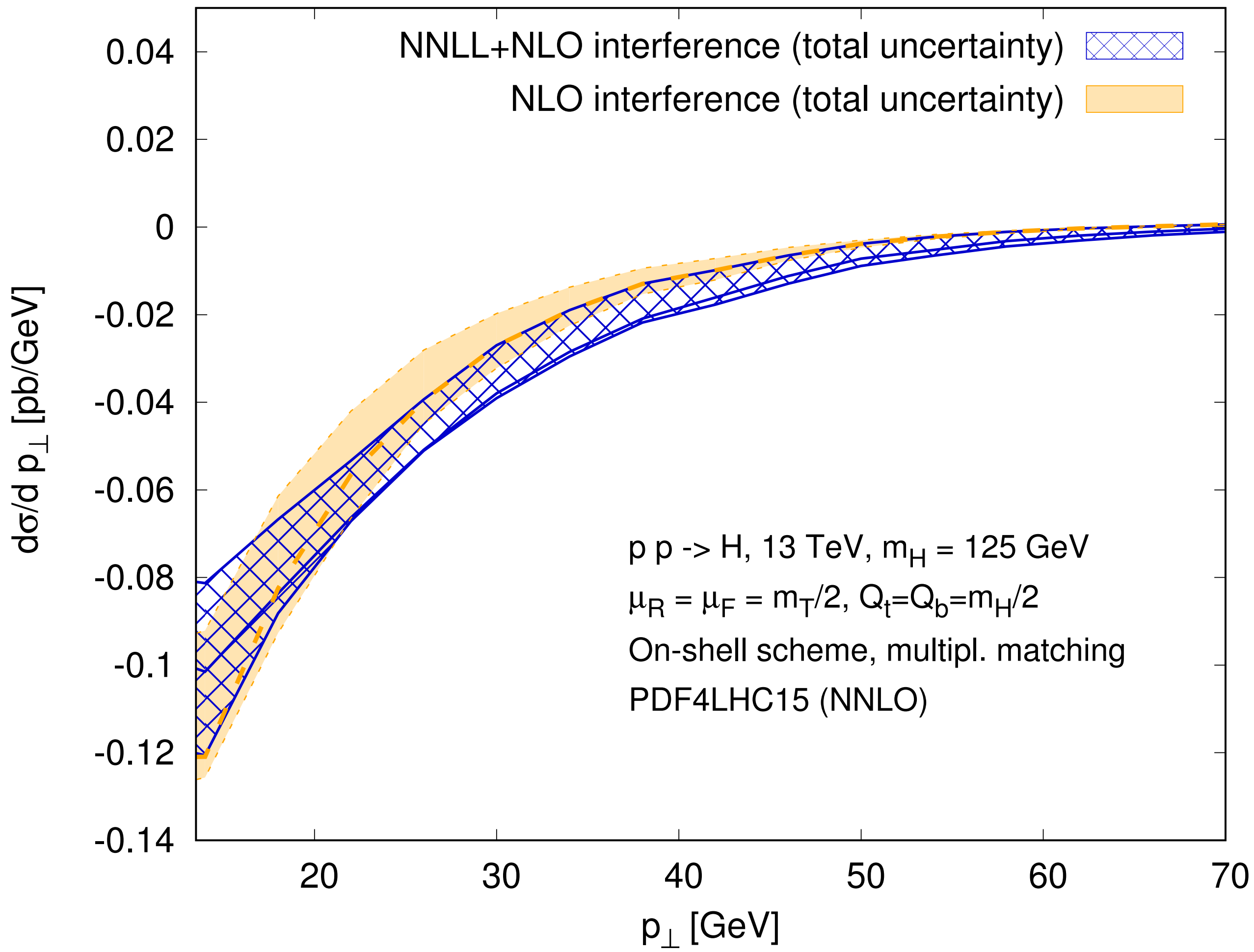


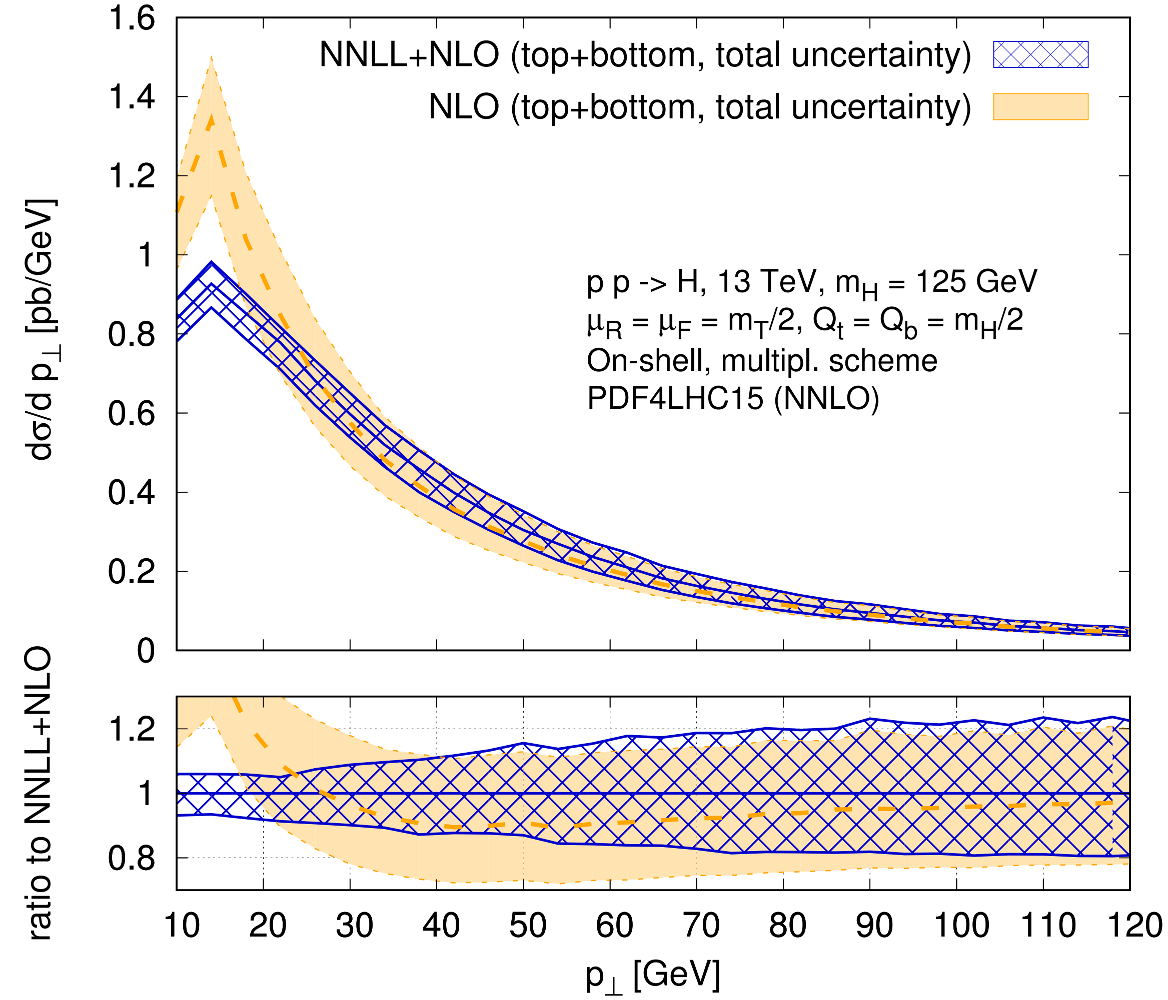


- -(5-10)% for pT=20-40 GeV at LO and NLO
- Despite (large) corrections, the interference shape stable under QCD corrections
  → solid observable
- large mb-renormalisation scheme dependence tamed at NLO

$p_\perp \ll m_t$: bottom mass effects at NLO+NNLL

[Caola, JML, Melnikov, Monni, Tancredi, Wever '17]



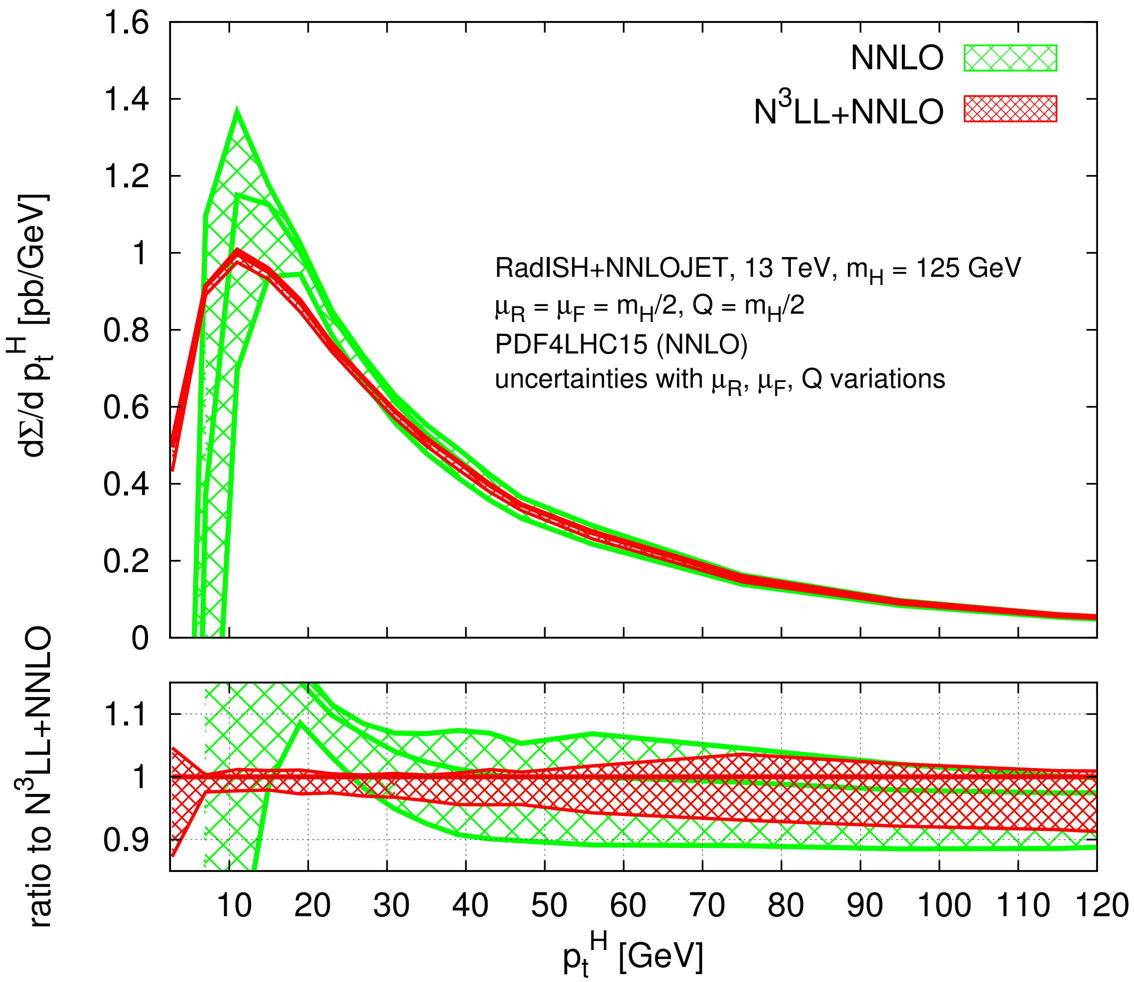


- remaining uncertainty of 20% on interference
- dominated by scheme ambiguity
- subleading uncertainties:
  - μ_R/μ_F ~ 15%
  - $Q_b = m_H/2$ vs. $Q_b = 2m_b$ ~ 15%
- translates into ~1-2% error on total spectrum

- uncertainties at the level of 5-20%
- Resummation effects relevant for pT ≲ 40 GeV
- further improvement when combined with NNLO for yt^2

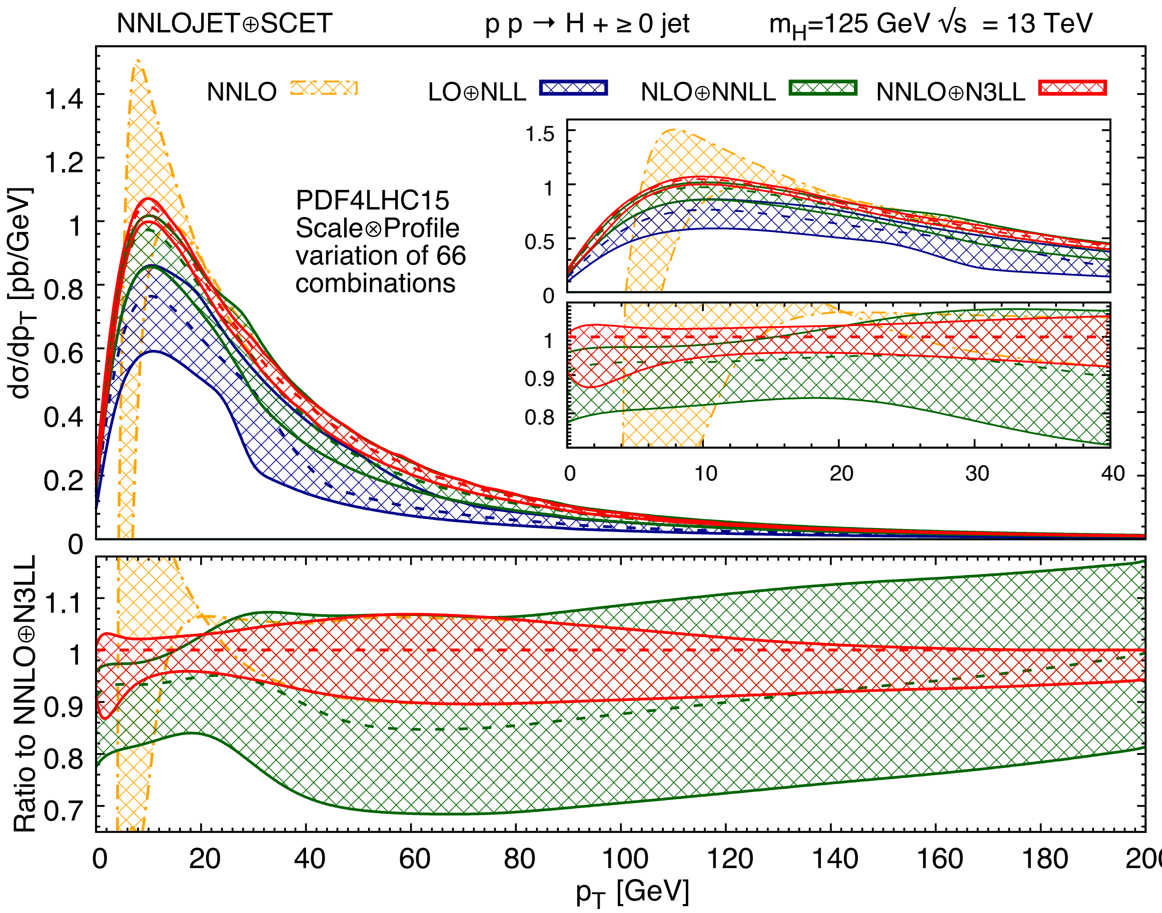
$p_\perp \ll m_t$: NNLO+N3LL in HEFT

[Bizon, Monni,Re,Rottoli,Torrielli+NNLOJET '17,'18]



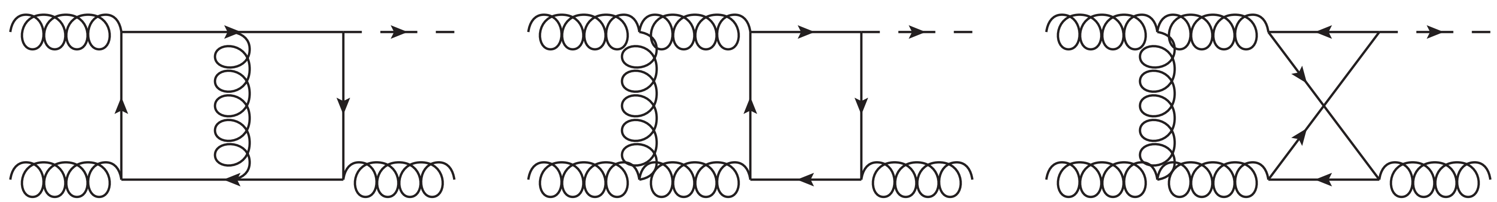
- Resummation performed in momentum space
- Multiplicative matching
- Results for fiducial phase-space available

[Li, Neill, Schulze, Stewart, Zhu+NNLOJET '18]



- Resummation performed in b-space within SCET
- Additive matching

$p_{\mathrm{T}}^{H} \geq m_H$: virtual two-loop amplitudes

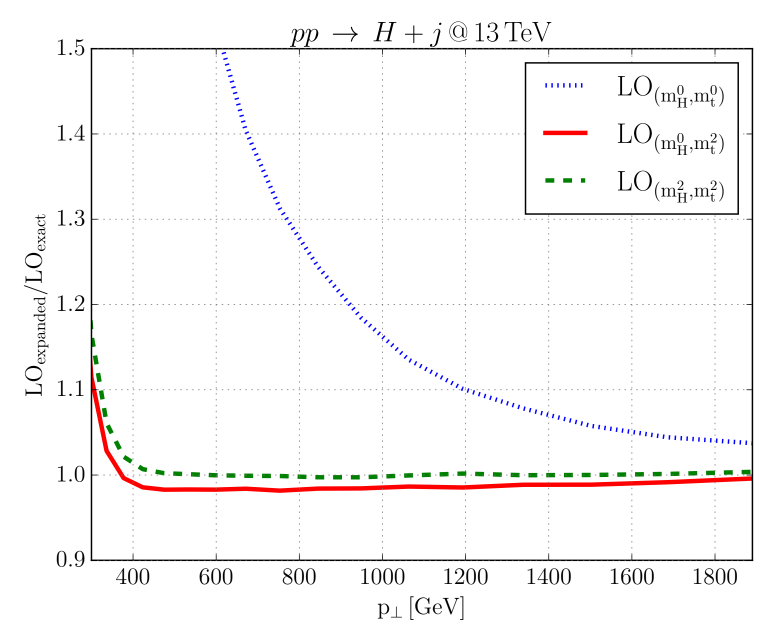


- A four-scale problem: three external (s,pT,mh) and one internal (mt)
- 264 Feynman integrals, complicated reduction
- Only partial (planar topologies) analytic result with the full top mass dependence available (R. Bonciani, et al., 2016)
- Two recent approaches:

Numerical integration with SecDec
[S. P. Jones, et al., 2018]

- Sector decompose integrals with SecDec
- Numerically integrate sectors with Quasi-Monte-Carlo integration
- Accelerate with OpenCL on GPUs
- valid in all of the phase-space

Expansion in $\eta = -\frac{m_H^2}{4m_T^2}, \quad \kappa = -\frac{m_T^2}{s}$
at the level of differential equations
[Kudashkin, Melnikov, Wever; '17]



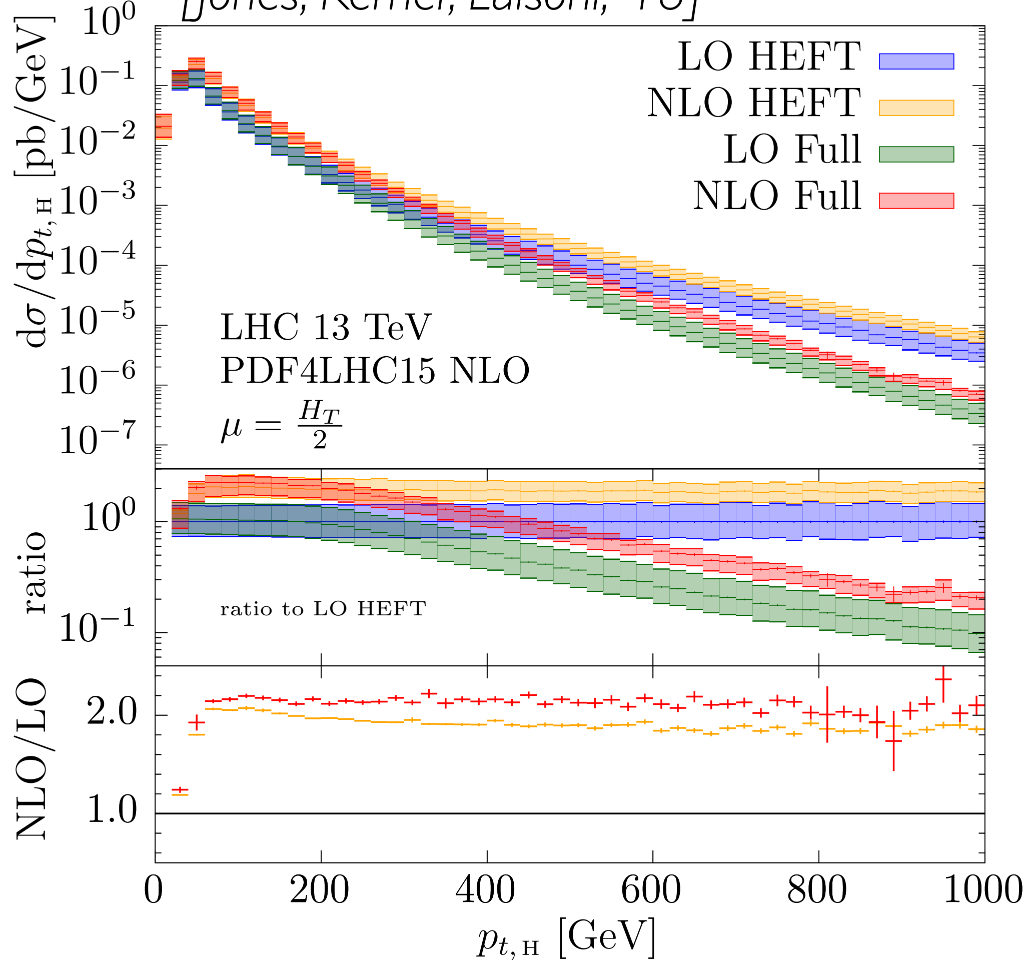
- valid at %-level for large pT

$p_T^H \geq m_H$: top mass effects at NLO

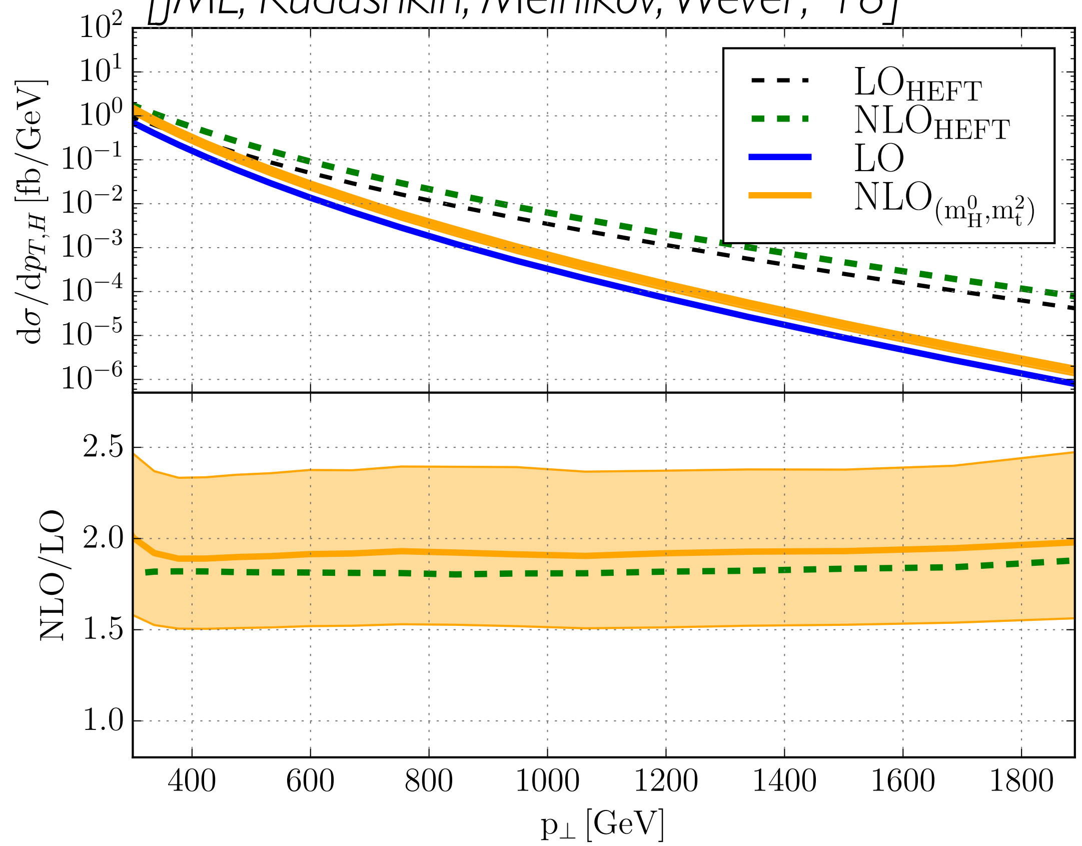
- numerical integration of two-loop integrals based on **SecDec** *[Borowka et.al.]*
- valid in all of the phase-space

- expansion of the two-loop integrals up to $(m_t^2/p_T^2)^1$, $(m_H^2/p_T^2)^0$ at the level of the DE *[Kudashkin, Melnikov, Wever; '17]*

[Jones, Kerner, Luisoni; '18]



[JML, Kudashkin, Melnikov, Wever; '18]



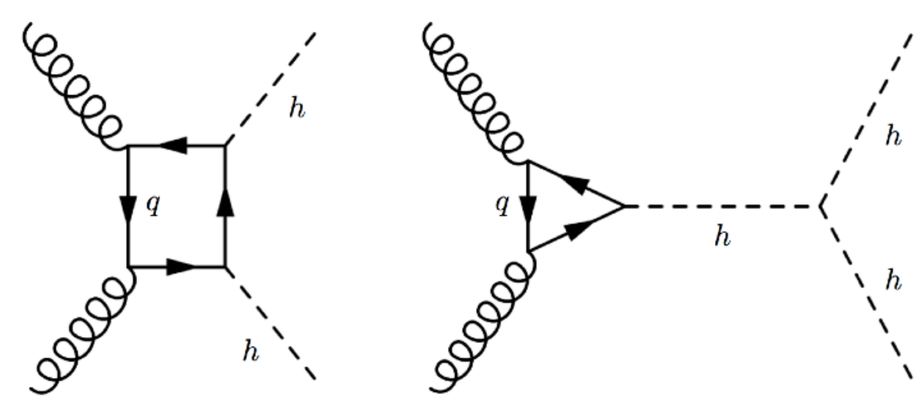
- NLO corrections very similar as in HEFT: K~2 with remaining scale uncertainties: **~20-25%**
- hardly any shape dependence
- Outlook: combine with NNLO in HEFT

Control of the high-H-pT tail at NLO opens the door for new physics searches in this regime!

Outline

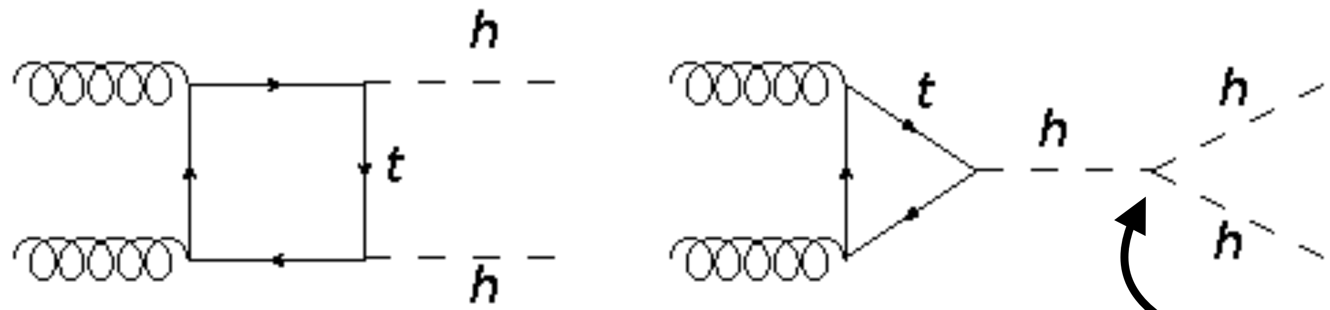
Higgs-pT

Di-Higgs

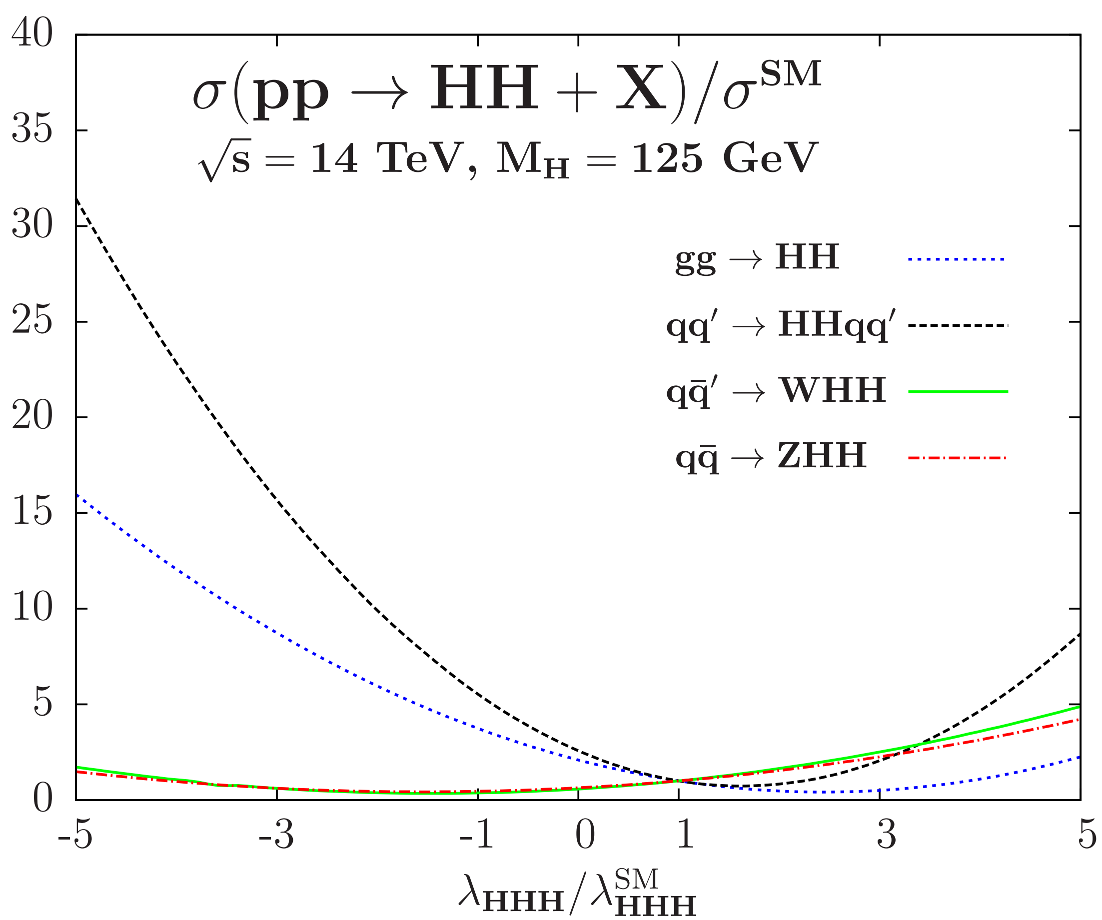


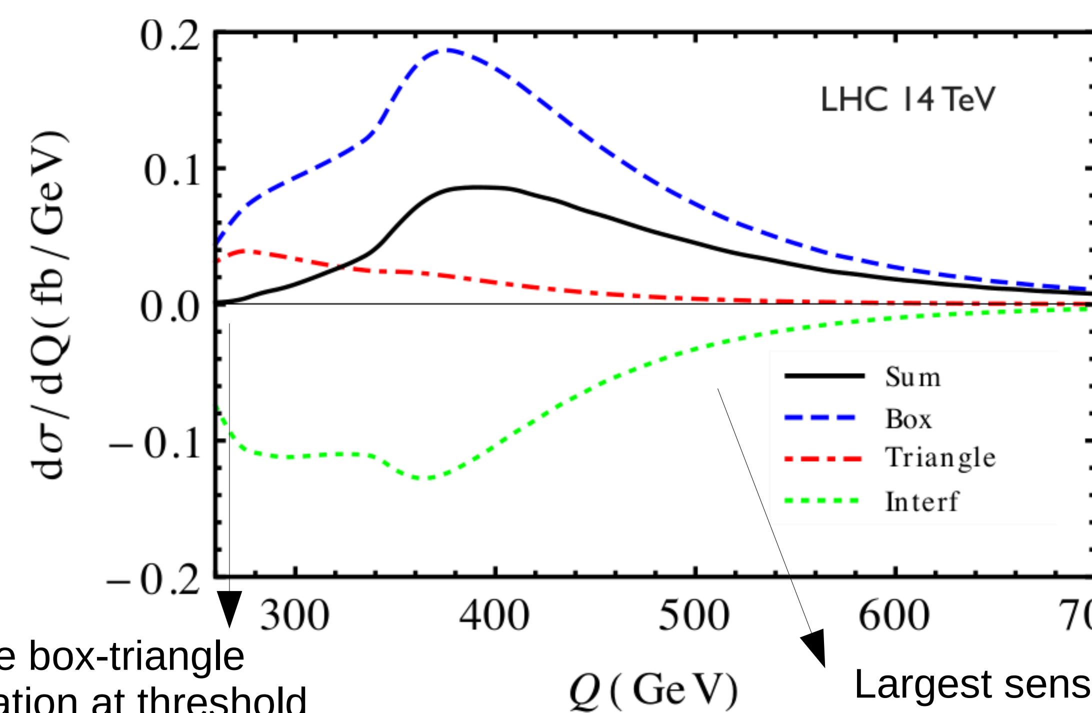
Di-Higgs

- pp→HH offers direct access to the trilinear Higgs coupling



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



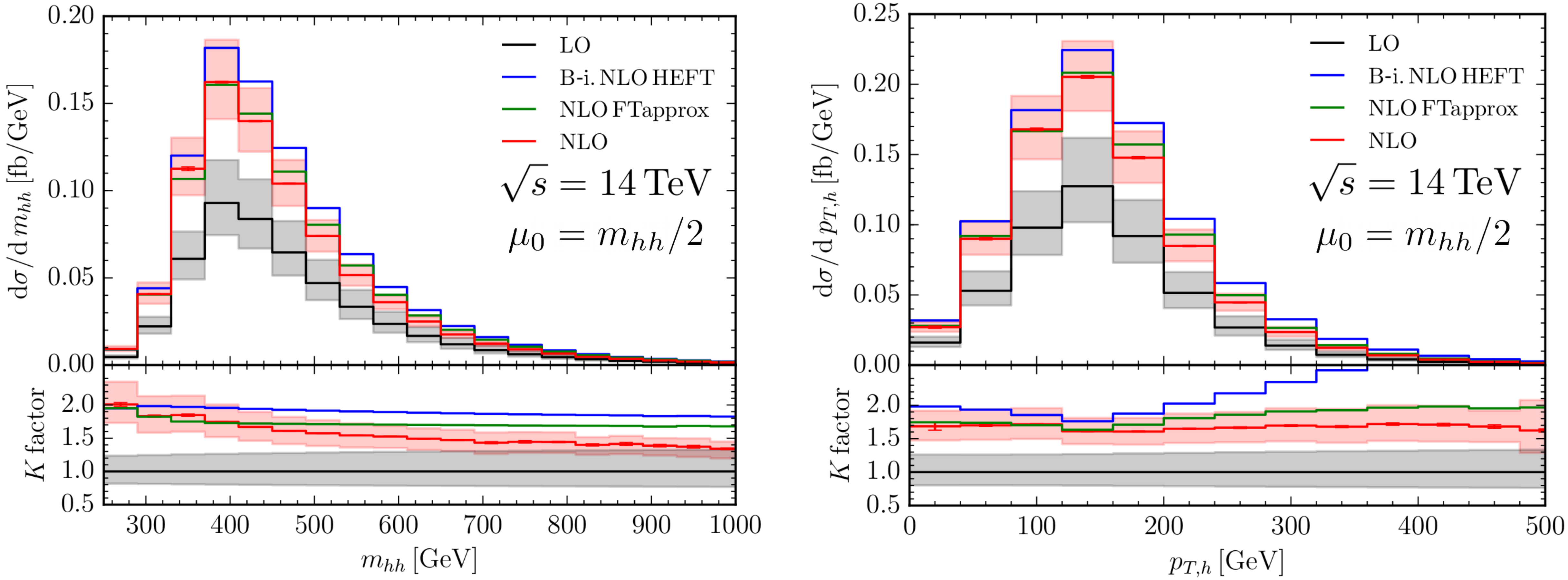


Large box-triangle cancellation at threshold

Largest sensitivity to λ from interference

Di-Higgs @ NLO

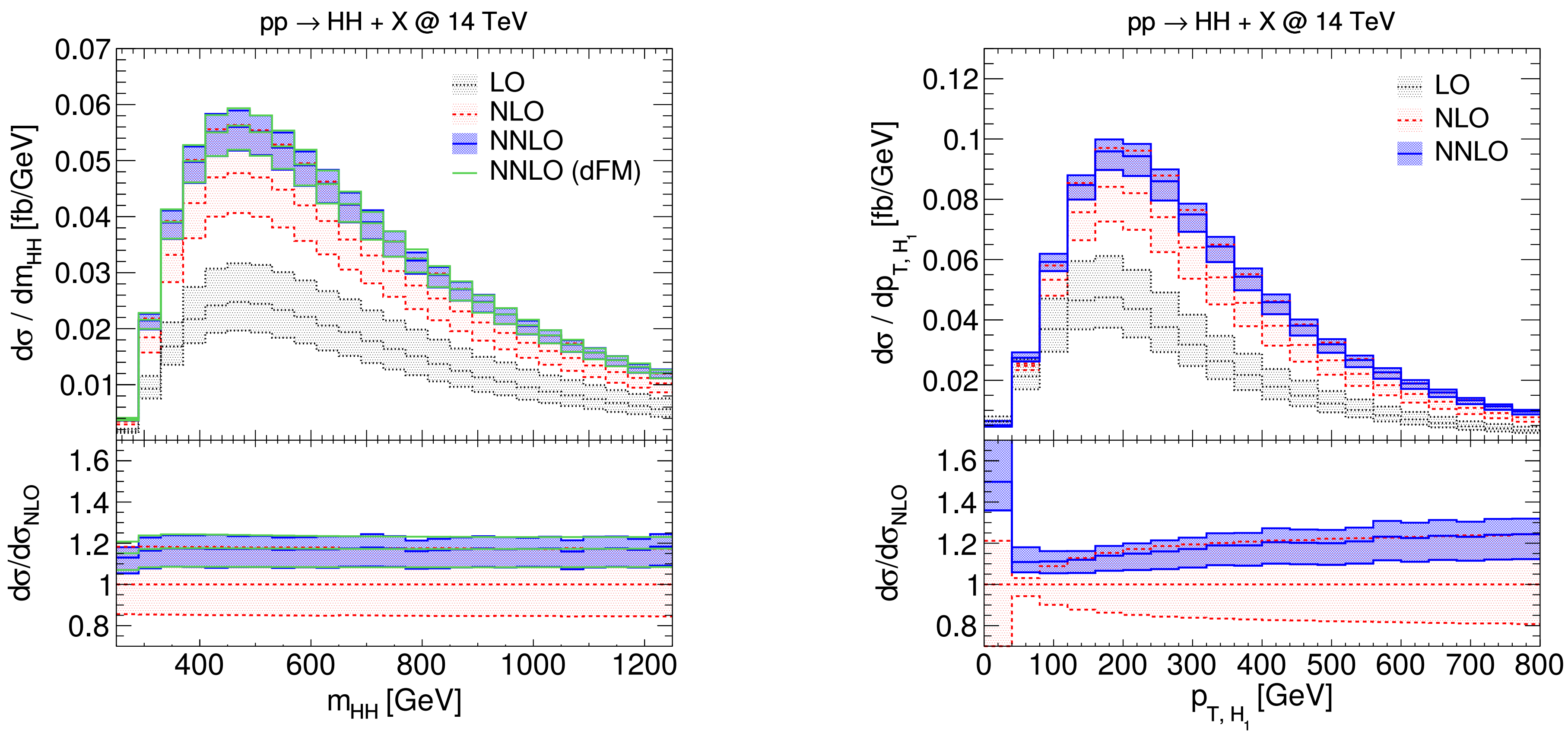
Again: Numerical integration with SecDec
[Borowka, et al., '16]



- Very large corrections NLO corrections: +66% for total XS
- Exact top-masses yield 16% smaller corrections than NLO Born-improved HEFT, and 4% smaller than NLO FTapprox (reals with exact dependence)
- In general non-trivial shape dependence of the corrections on the kinematics
- Remaining scale uncertainties: ~13% but no overlap with LO → try to go beyond NLO

Di-Higgs @ NNLO in HEFT

[de Florian, JML, et.al. '16]



- NNLO corrections:
  - almost flat in m_{HH}, small shape in pTH1
  - at the level of ~20%
  - remaining scale uncertainties at the level of 10%
  - overlap with NLO uncertainty band
- How to combine with exact NLO?

Di-Higgs @ NNLO with top mass effects

Born-projected approximation:

- Reweight by LO ratio full/HEFT at the level of squared amplitudes
- Projection to Born kinematics needed for reweighting: non-unique

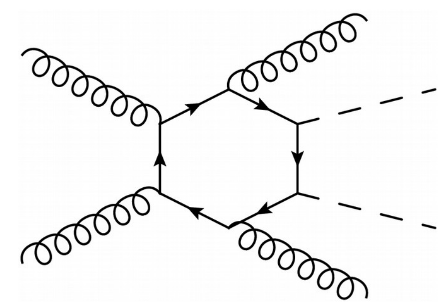
NLO-improved approximation:

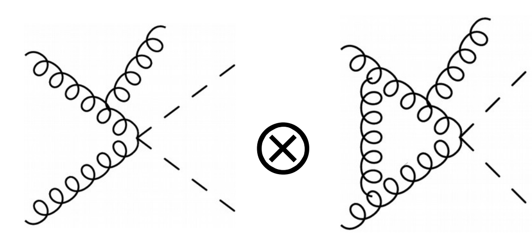
- Observable level reweighting
- For each bin of each histogram do

$$d\sigma_{\rm NLO} \times \left(\frac{d\sigma_{\rm NNLO}}{d\sigma_{\rm NLO}}\right)_{\rm HEFT}$$

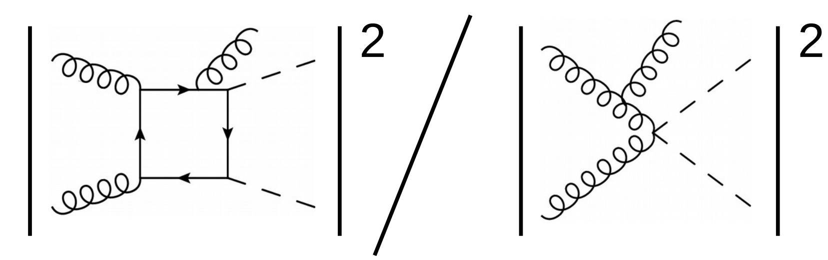
NNLO$_{\rm FTapprox}$

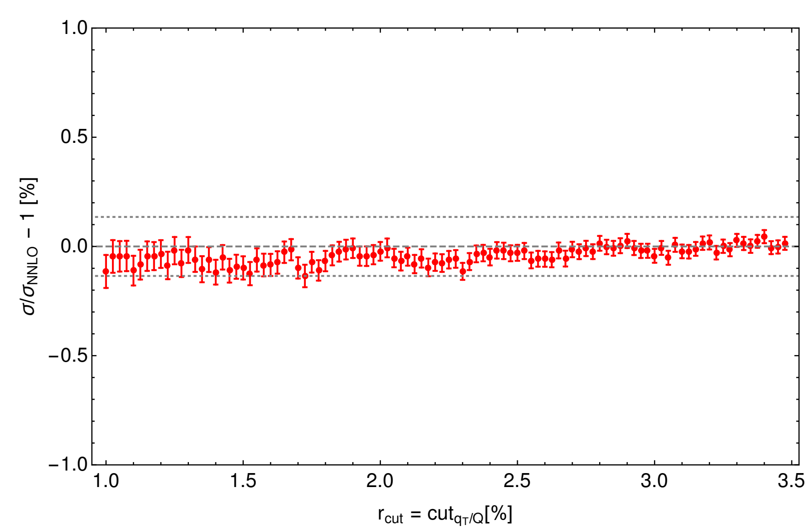
- only approximate NNLO coefficient
- keep full top mass dependence in double-real
- reweight double-virtual and real-virtual amplitudes in HEFT with corresponding tree amplitudes (no projection needed)
- make sure IR subtraction in qT slicing method is unspoiled





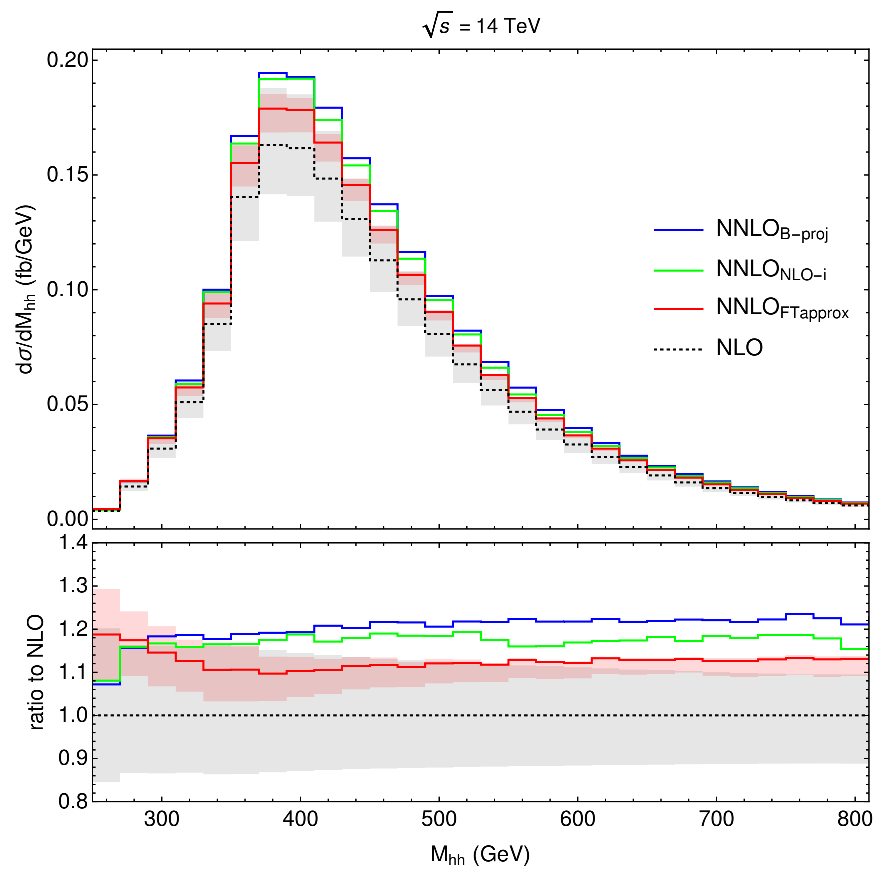
reweight by

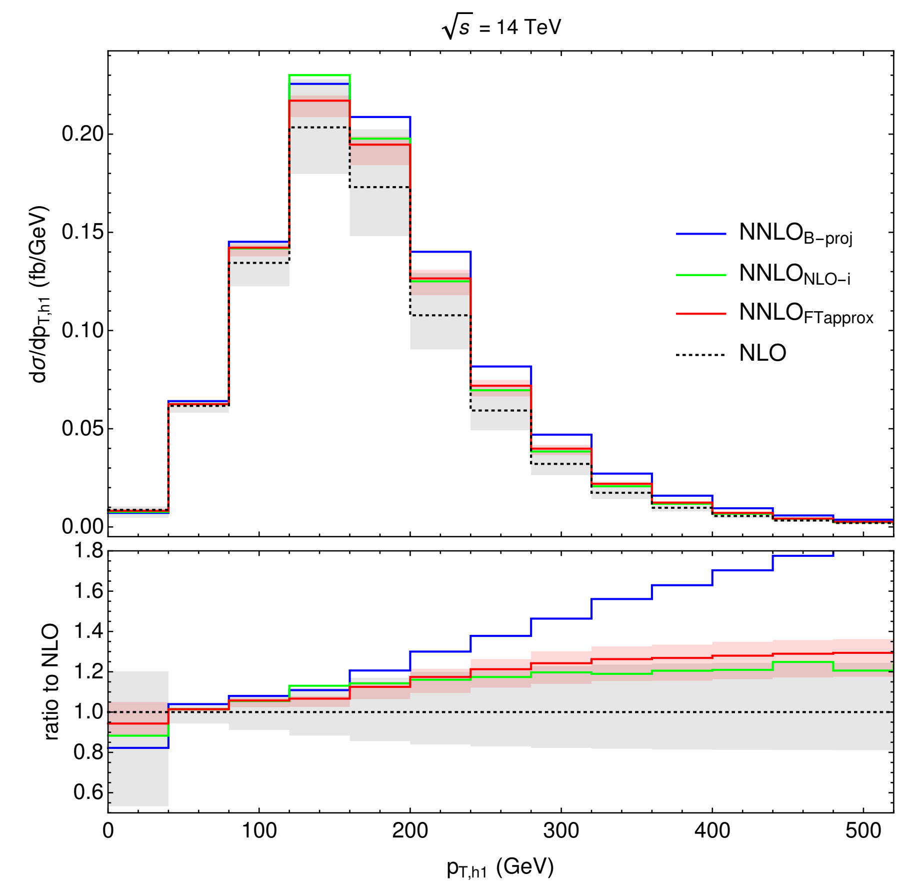




Numerical complexity in the loop-induced double-real similar to requirements for real-virtual in tree-induced 2→3 NNLO!

Di-Higgs @ NNLO with top mass effects





- FTapprox presents larger corrections at threshold, minimum corrections at M_{hh} ~ 400GeV, slow increase towards the tail
- Scale uncertainties in FTapprox are substantially reduced
- Overlap with the NLO band
- up to ~10% smaller corrections in FTapprox compared to the other approximations

- wrong scaling at large energies for $\mathrm{NNLO}_{\text{B-proj}}$
- overlap of NLO and $\mathrm{NNLO}_{\text{FTapprox}}$ bands
- $\mathrm{NNLO}_{\text{FTapprox}}$ ~$\mathrm{NNLO}_{\text{NLO-i}}$

$\sqrt{s}$	14 TeV
NLO [fb]	$32.88^{+13.5\%}_{-12.5\%}$
$\mathrm{NLO}_{\mathrm{FTapprox}}$ [fb]	$34.25^{+14.7\%}_{-13.2\%}$
$\mathrm{NNLO}_{\mathrm{NLO-i}}$ [fb]	$38.66^{+5.3\%}_{-7.7\%}$
$\mathrm{NNLO}_{\mathrm{B-proj}}$ [fb]	$39.58^{+1.4\%}_{-4.7\%}$
$\mathrm{NNLO}_{\mathrm{FTapprox}}$ [fb]	$36.69^{+2.1\%}_{-4.9\%}$
M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	$\pm 2.7\%$
$\mathrm{NNLO}_{\mathrm{FTapprox}}$/NLO	1.116

➡uncertainties on total XS largely reduced!

Conclusions

- Without a clear sign of new-physics it is crucial to perform detailed theory vs. experiment comparisons, to look for possible deviations.
  - ➡ Higgs is an obvious place to look at!

- H-pT @ NLO:
  - remaining uncertainties: ~20% (NNLO in HEFT: 10%)
  - corrections very similar as in HEFT
  - Outlook: NNLO with mass effects

- Di-Higgs @ $\text{NNLO}_{\text{FTapprox}}$
  - remaining uncertainties for inclusive cross section: ~3.5%
  - somewhat larger in distributions due to mass effects
  - at this level: top-mass scheme ambiguity relevant