Fixed Order Predictions for Higgs Boson Production at Large Transverse Momentum

Jonas M. Lindert

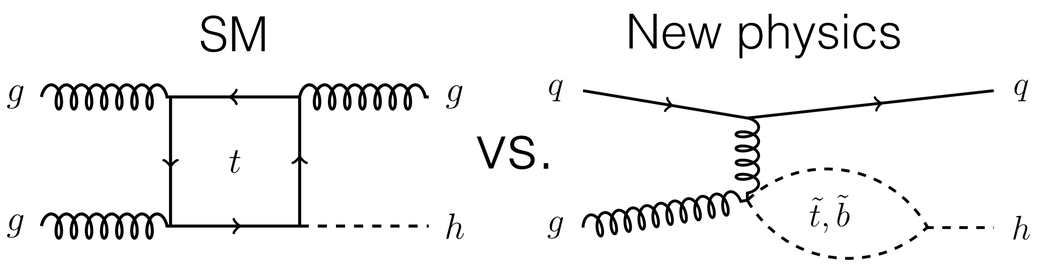
University of Sussex

Science & Technology Facilities Council

UK Research and Innovation

Higgs 2020
Online, 27. November 2020

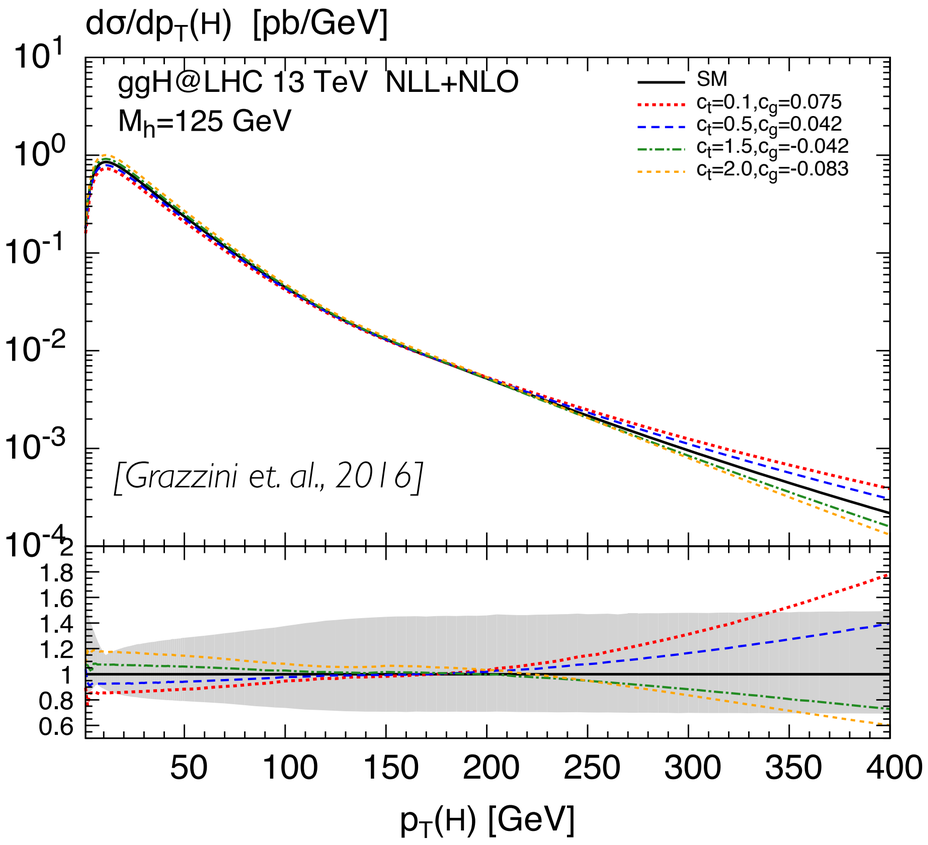
Higgs-pT: a gateway to new physics?



Look for BSM effects in small deviations from SM predictions:

→ Higgs processes natural place to look at

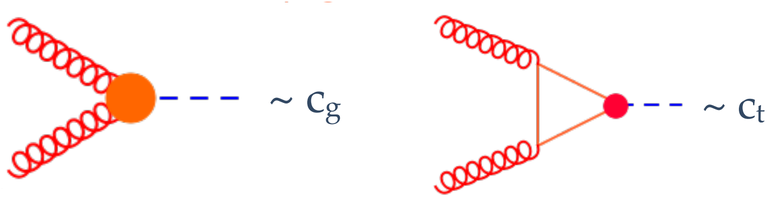
→ **very good control on theory necessary!**



➜ Higgs-pT allows disentangle c_g vs. c_t,:

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

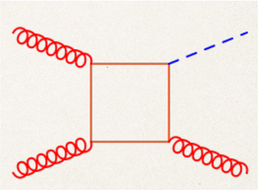
Note: inclusive measurements only allow to constrain $(c_g + c_t)^2$



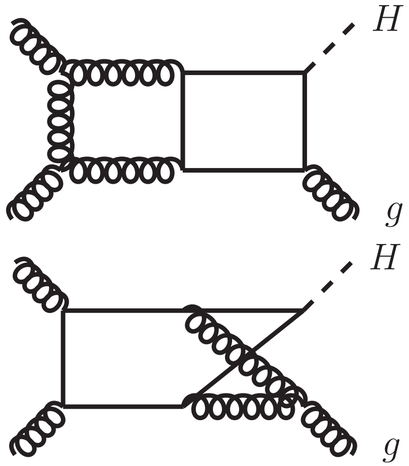
SM: c_g=0, c_t=1

Higgs-pT: higher-order corrections

full theory: loop-induced



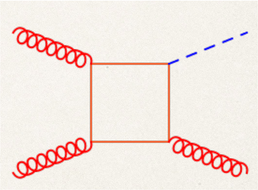
Bottleneck:
massive two-loop amplitudes



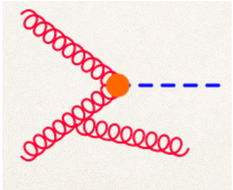
NLO?

Higgs-pT: higher-order corrections

full theory: loop-induced

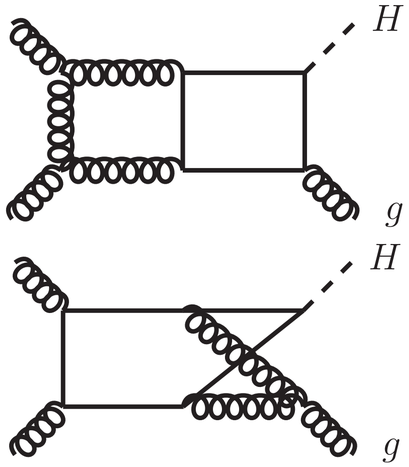


integrate-out heavy quarks



HEFT: tree-level at LO

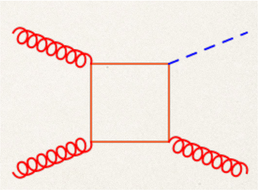
Bottleneck:
massive two-loop amplitudes



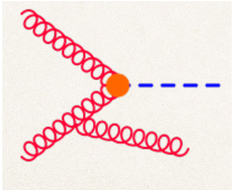
NLO?

Higgs-pT: higher-order corrections

full theory: loop-induced

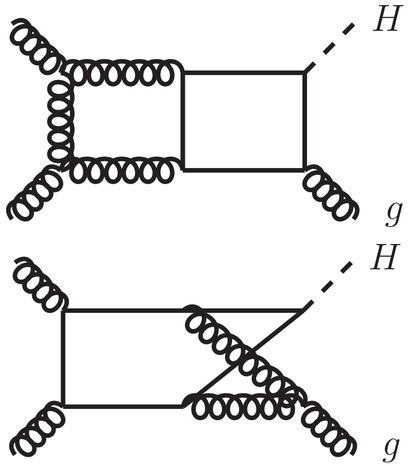


integrate-out heavy quarks



HEFT: tree-level at LO

Bottleneck:
massive two-loop amplitudes

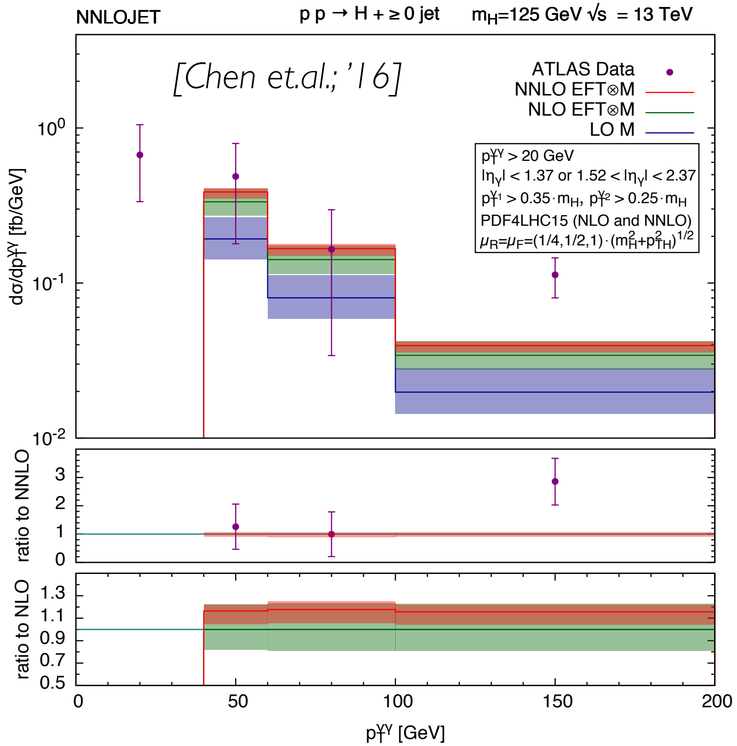


NLO?

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

NNLO

Bottleneck: IR subtraction

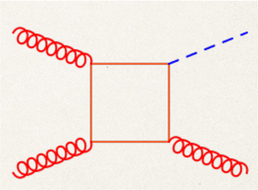


perturb. uncertainties in HEFT under very good control:

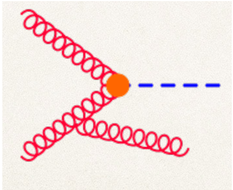
- **~10% scale variation**
- **stable shapes**

Higgs-pT: higher-order corrections

full theory: loop-induced

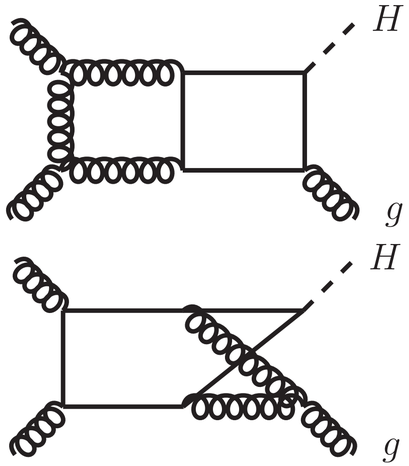


integrate-out heavy quarks →



HEFT: tree-level at LO

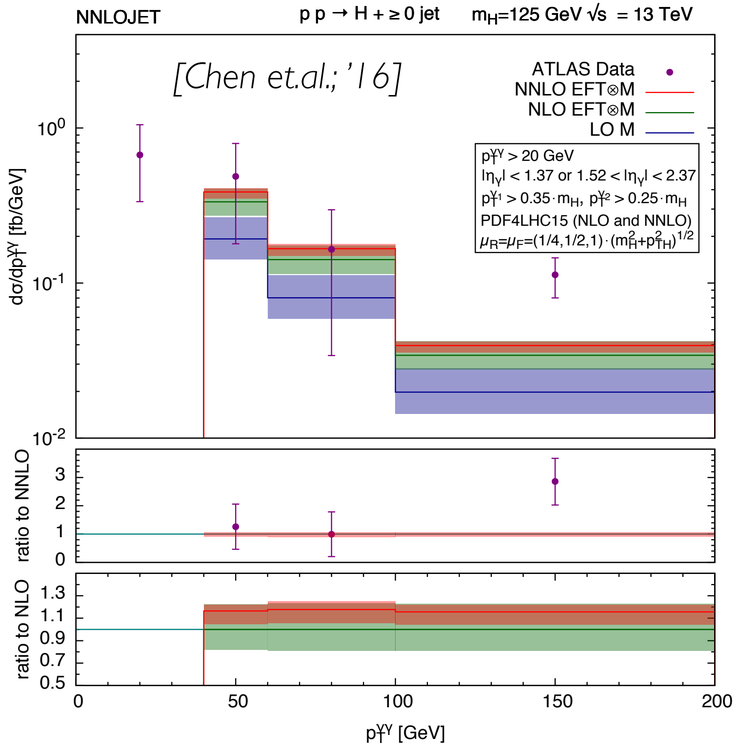
Bottleneck:
massive two-loop amplitudes



NLO?

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

Bottleneck: IR subtraction



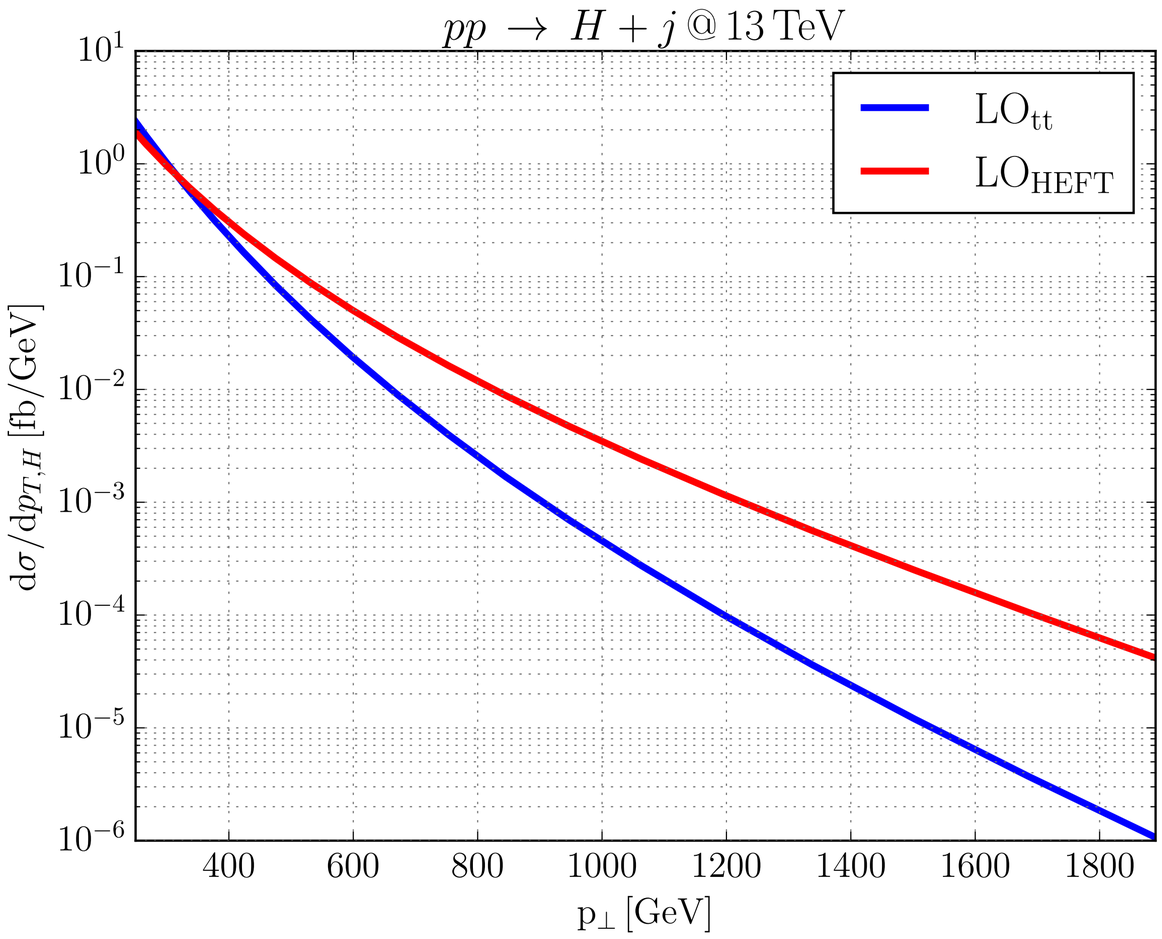
NNLO

perturb. uncertainties in HEFT under very good control:

- **~10% scale variation**
- **stable shapes**

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

Higgs-pT: scaling



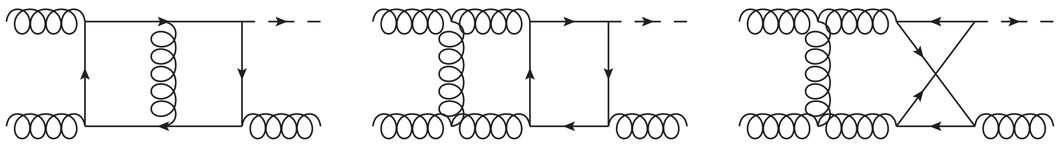
$$\frac{\mathrm{d}\sigma_H}{\mathrm{d}p_\perp^2} \sim \frac{\sigma_0}{p_\perp^2} \begin{cases} (c_g + c_t)^2, & p_\perp^2 < 4m_t^2, \\ \left(c_g + c_t \frac{4m_t^2}{p_\perp^2}\right)^2, & p_\perp^2 > 4m_t^2. \end{cases}$$

HEFT $\sim p_{\mathrm{T}}^{-2}$

full theory $\sim p_{\mathrm{T}}^{-4}$

- point-like ggH (HEFT) and full theory have very different high energy behaviour.

H+j: virtual two-loop amplitudes



- A **four-scale problem**: three external (s,pT,mh) and one internal (mt)
- 264 Feynman integrals, complicated reduction
- Three approaches:

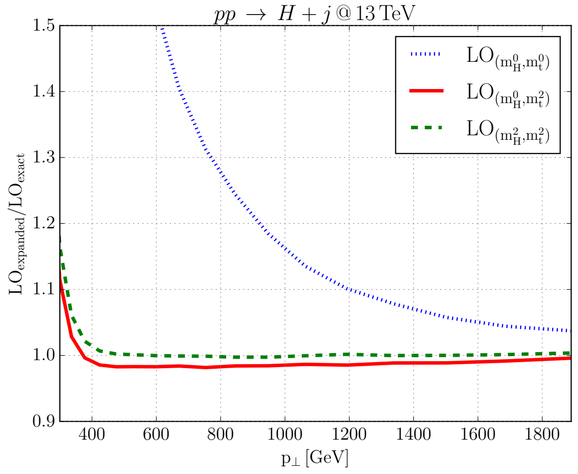
Analytic reduction and integration
[R. Bonciani, et al., 2016+2019, H. Frellesvig, et al., 2018+2020]

- very complicated (elliptic integrals)
- MI's for all planar and non-planar topologies available!
- No pheno yet

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 at the level of differential equations
[Melnikov, Tancredi, Wever; ; '16+'17]
[Kudashkin, Melnikov, Wever; '17]

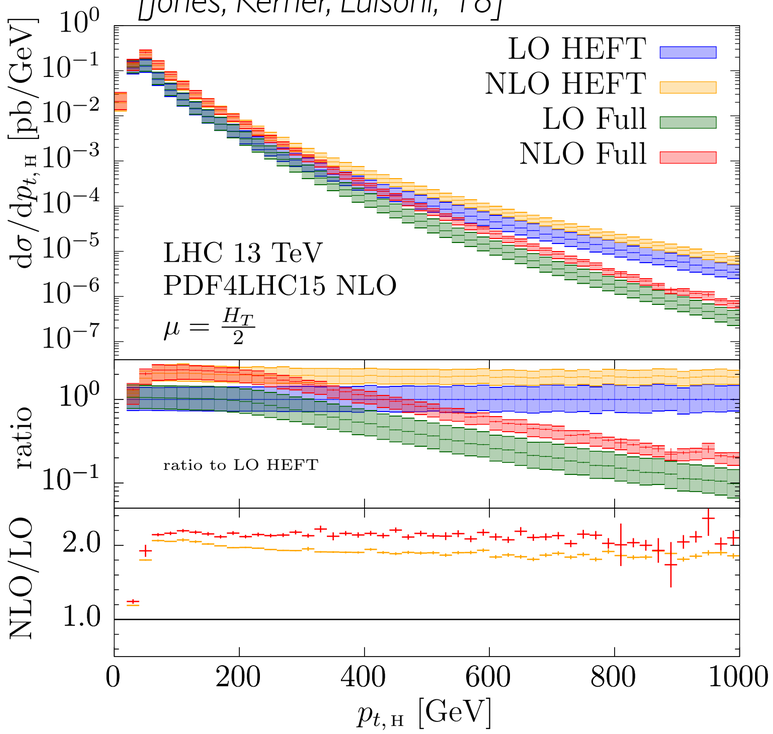


- valid at %-level for large pT

Full theory at NLO

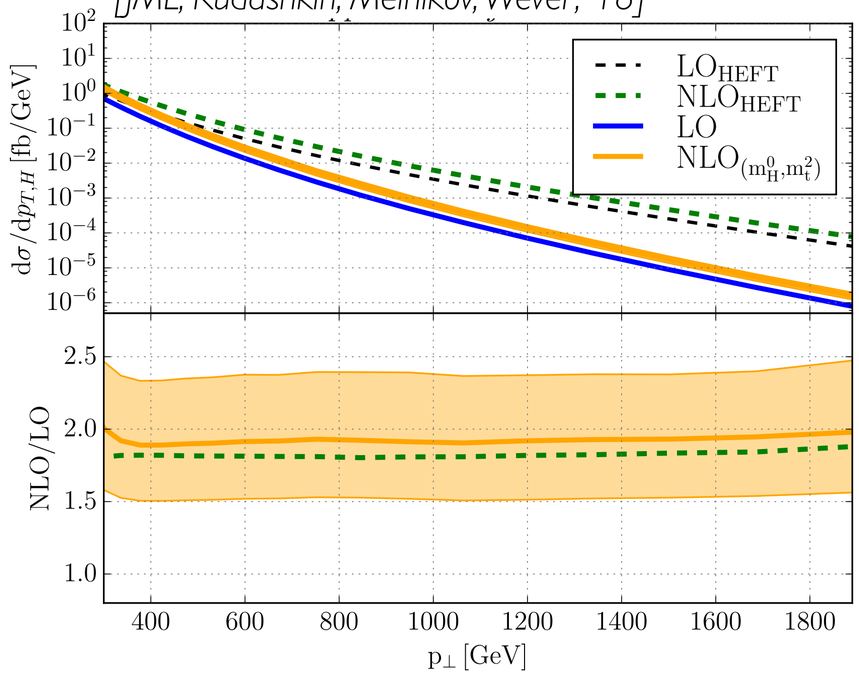
- numerical integration of two-loop integrals based on **SecDec** *[Borowka et.al.]*
- valid in all of the phase-space

[Jones, Kerner, Luisoni; '18]



- 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]*
- valid at %-level for large pT

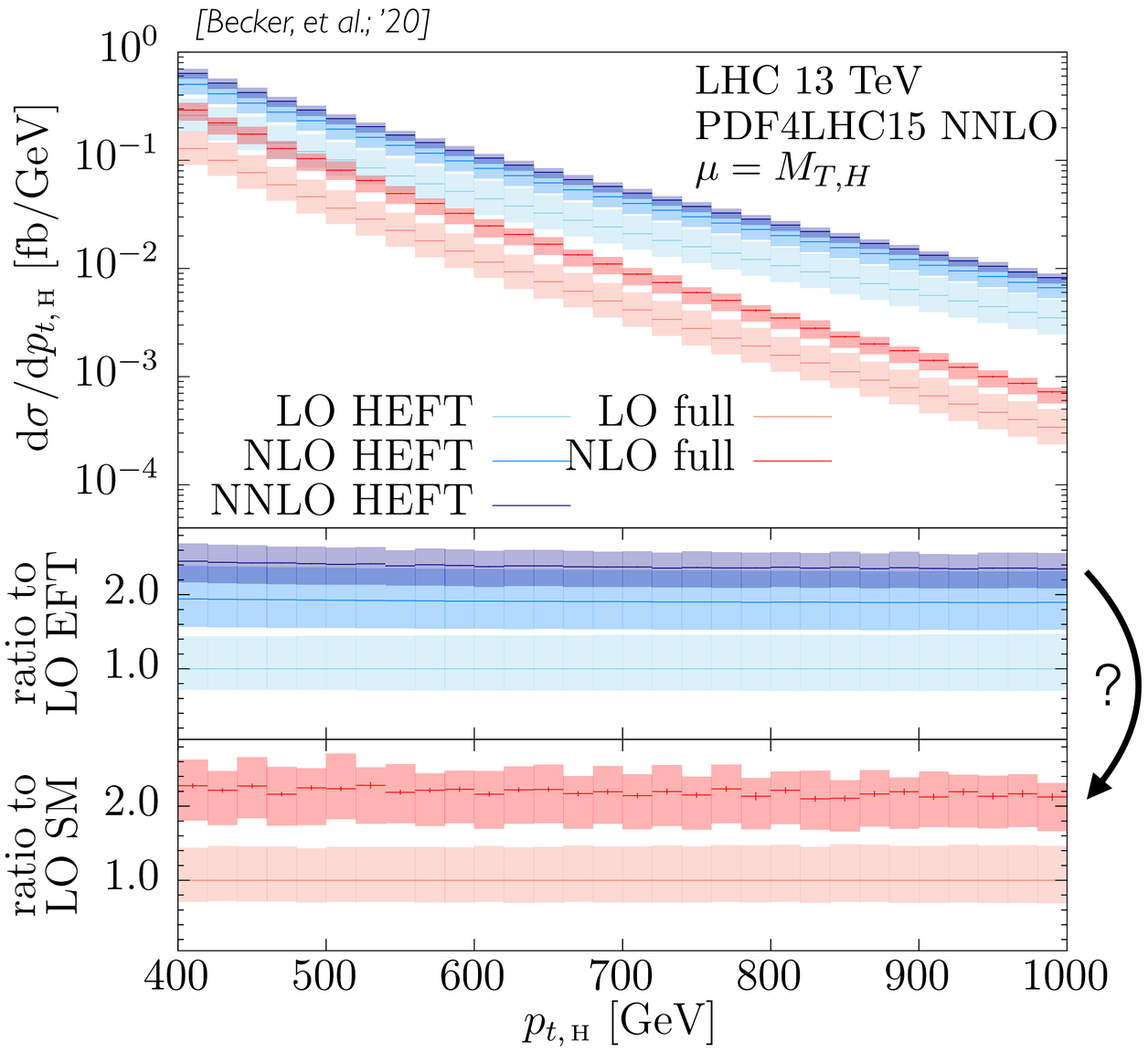
[JML, Kudashkin, Melnikov, Wever; '18]



- NLO corrections very similar as in HEFT: K~2 with remaining scale uncertainties ~20-25%
- hardly any shape dependence
- NLO(full) / NLO(HEFT) ~ 10%

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

Approximating mass effects at NNLO

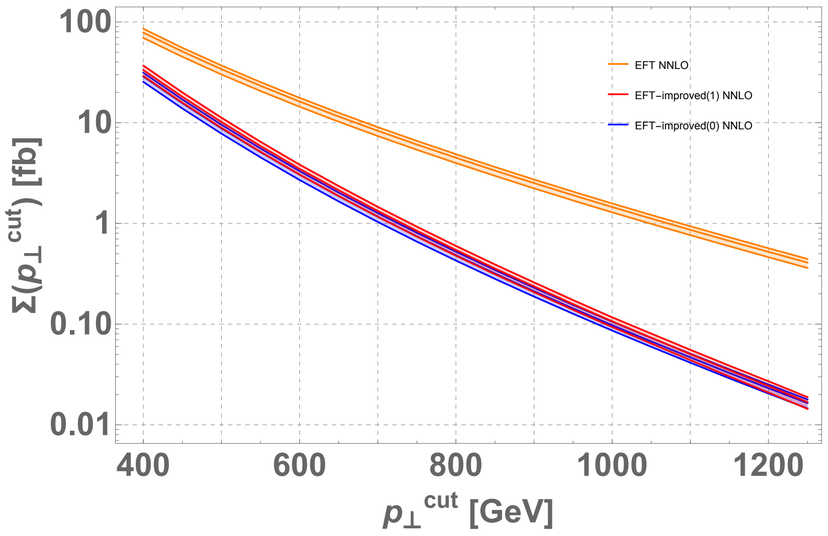


?

$$\Sigma^{\text{EFT-improved (1), NNLO}}(p_\perp^{\text{cut}}) \equiv \frac{\Sigma^{\text{SM, NLO}}(p_\perp^{\text{cut}})}{\Sigma^{\text{EFT, NLO}}(p_\perp^{\text{cut}})}\,\Sigma^{\text{EFT, NNLO}}(p_\perp^{\text{cut}})$$

Approximating mass effects at NNLO

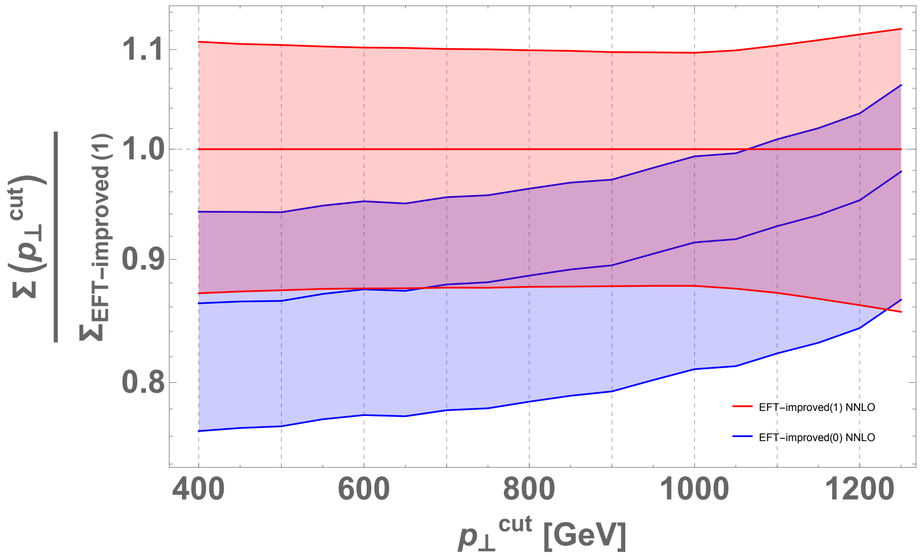
[Becker, et al.; '20]



$$\Sigma^{\text{EFT-improved (0), NNLO}}(p_\perp^{\text{cut}}) \equiv \frac{\Sigma^{\text{SM, LO}}(p_\perp^{\text{cut}})}{\Sigma^{\text{EFT, LO}}(p_\perp^{\text{cut}})}\,\Sigma^{\text{EFT, NNLO}}(p_\perp^{\text{cut}})$$

$$\Sigma^{\text{EFT-improved (1), NNLO}}(p_\perp^{\text{cut}}) \equiv \frac{\Sigma^{\text{SM, NLO}}(p_\perp^{\text{cut}})}{\Sigma^{\text{EFT, NLO}}(p_\perp^{\text{cut}})}\,\Sigma^{\text{EFT, NNLO}}(p_\perp^{\text{cut}})$$

(i) (ii)



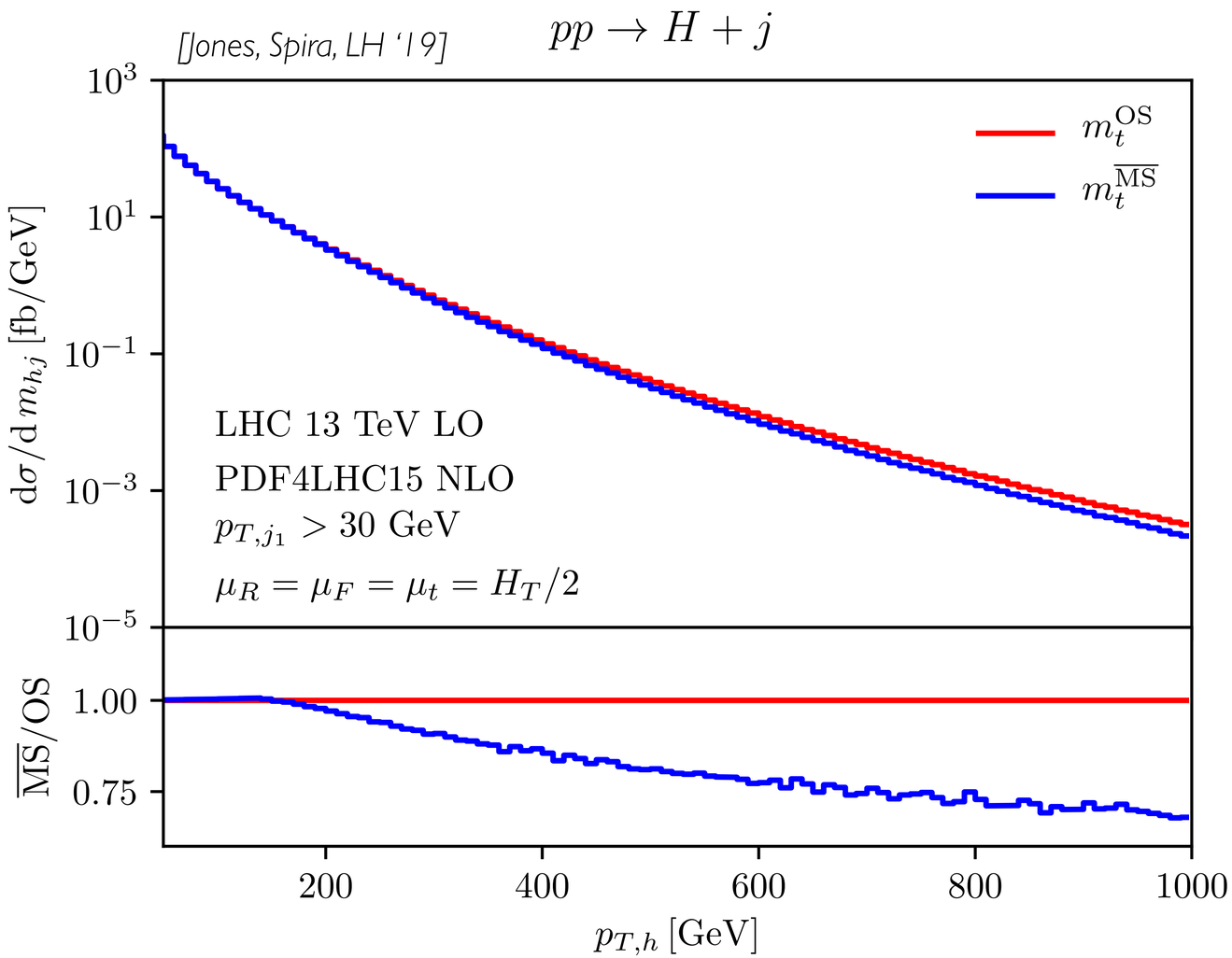
Uncertainty at EFT-improved (1)-NNLO: ~**13%**

- 7-pt scale variations in (i) and (ii) independently
- mass uncertainty:

$$\delta_{\text{NNLO}, m_t} \equiv \frac{\delta\Sigma^{\text{SM, NLO}} - \delta\Sigma^{\text{improved(0), NLO}}}{\delta\Sigma^{\text{EFT, NLO}}} \times \delta\Sigma^{\text{EFT, NNLO}}$$

$$= \frac{\delta\Sigma^{\text{SM, NLO}} - \delta\Sigma^{\text{improved(0), NLO}}}{\delta\Sigma^{\text{improved(0), NLO}}} \times \delta\Sigma^{\text{improved(0), NNLO}}$$

Top-quark mass scheme uncertainty

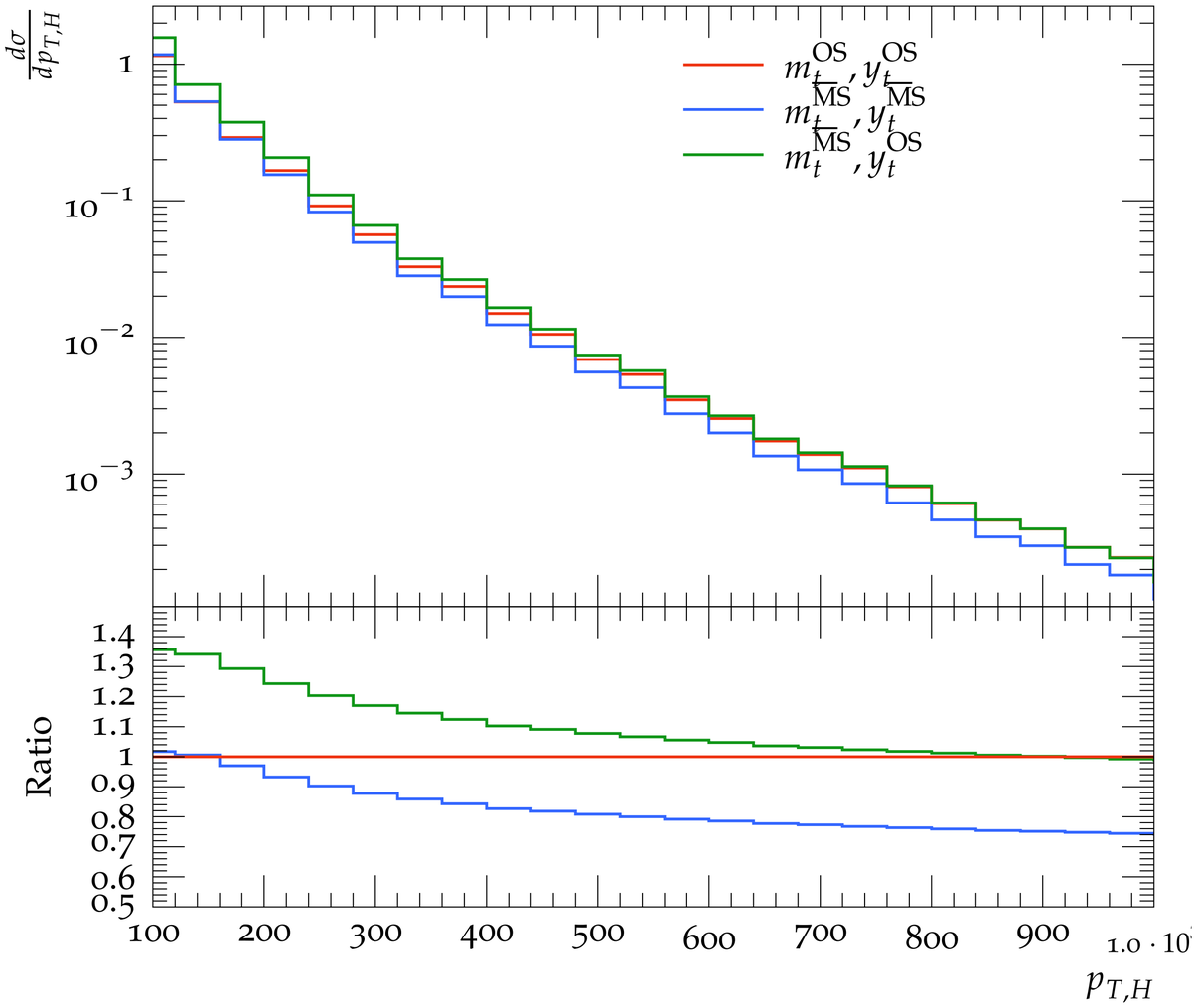


$$m_t^{\overline{\rm MS}} = \overline{m}(\mu_t)$$

$$\mu_t = H_T/2 = 1/2\left(\sqrt{m_h^2 + p_{t,h}^2} + \sum_i |p_{t,i}|\right)$$

- Sizeable effects at large H-pT, up to ~25%

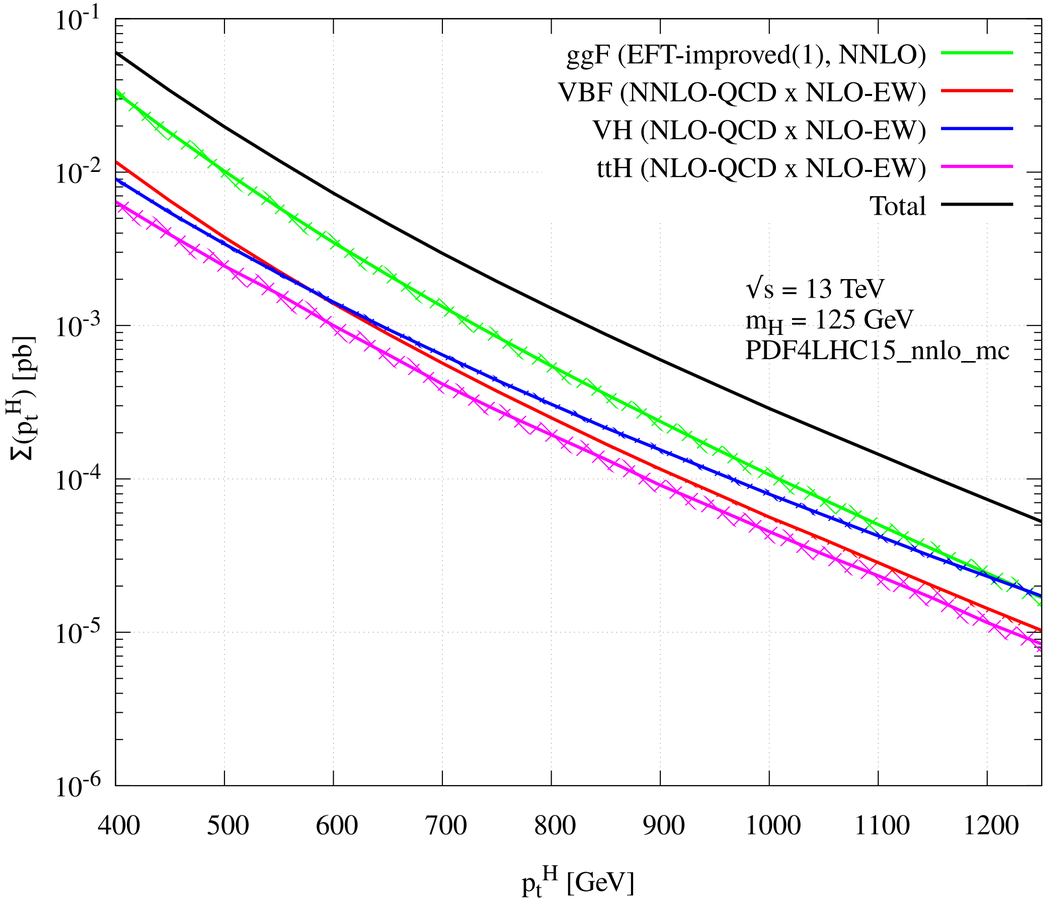
Top-quark mass scheme uncertainty



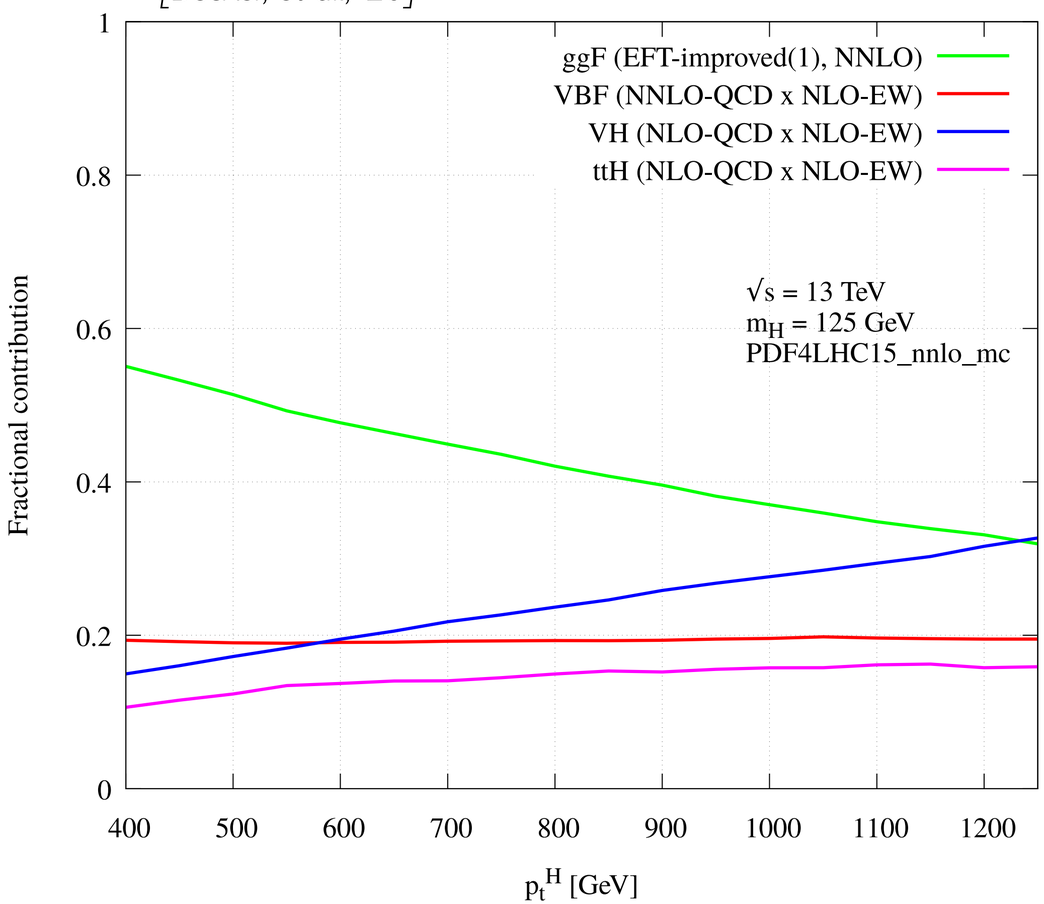
$$"m_t^{\overline{\mathrm{MS}}}" = 150 \text{ GeV}$$

- Small effects at large H-pT when Yukawa coupling kept in on-shell scheme.
- Careful analysis (possibly at NLO) needed to investigate this uncertainty.

Higgs at very high-pT: production modes beyond ggH



[Becker, et al.; '20]

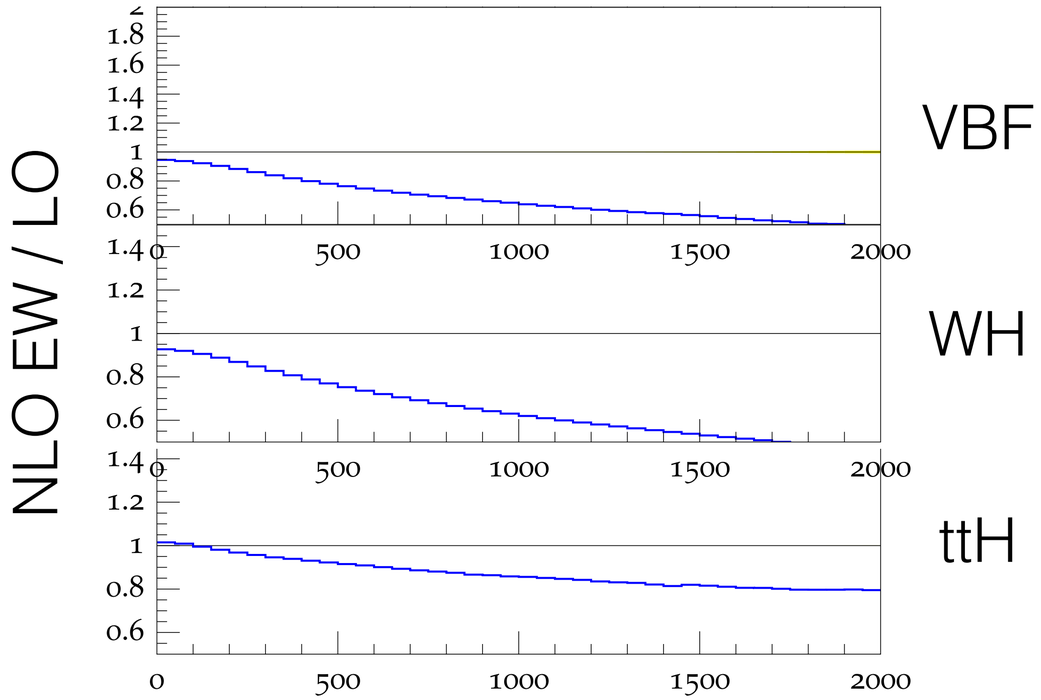


→ At very high pT all channels contribute significantly!

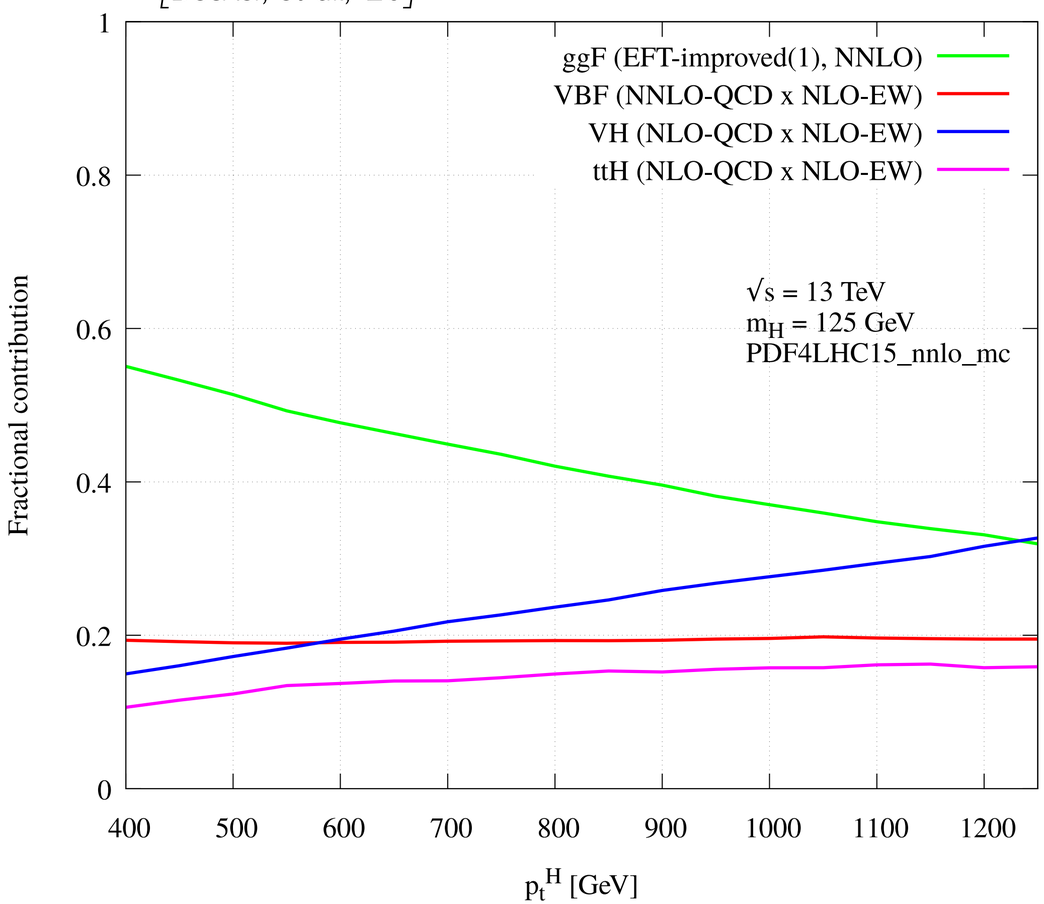
→ Reason: s-channel vs. t-channel and gluon- vs. quark-induced

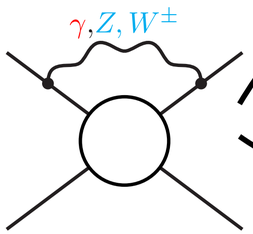
→ Also: very different impact of QCD and EW higher-order corrections

Higgs at very high-pT: production modes beyond ggH



[Becker, et al.; '20]





→ large negative virtual EW Sudakov corrections (process dependent)

→ at high-pT: crucial to consider NLO EW corrections!

Conclusions

- Higgs-pT is an obvious place to look for new physics
- NLO corrections for Higgs-pT in full theory very close to results in HEFT.
- Current best prediction: NNLO(HEFT) X NLO(full)/NLO(HEFT).
- Largest remaining uncertainty due to top-quark mass scheme ambiguity
- At large Higgs-pT all production modes contribute (QCD and EW higher-orders mandatory)

Breakout room (after the session):
https://universityofsussex.zoom.us/j/6873823319

BACKUP

Higgs-pT: two regimes

$p_\perp \ll m_t$ $\qquad$ $p_\perp > m_t$

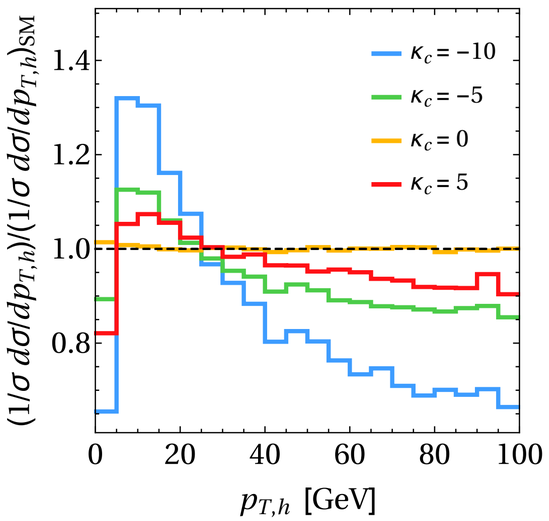
Possibility to constrain the charm-Yukawa coupling

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

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

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

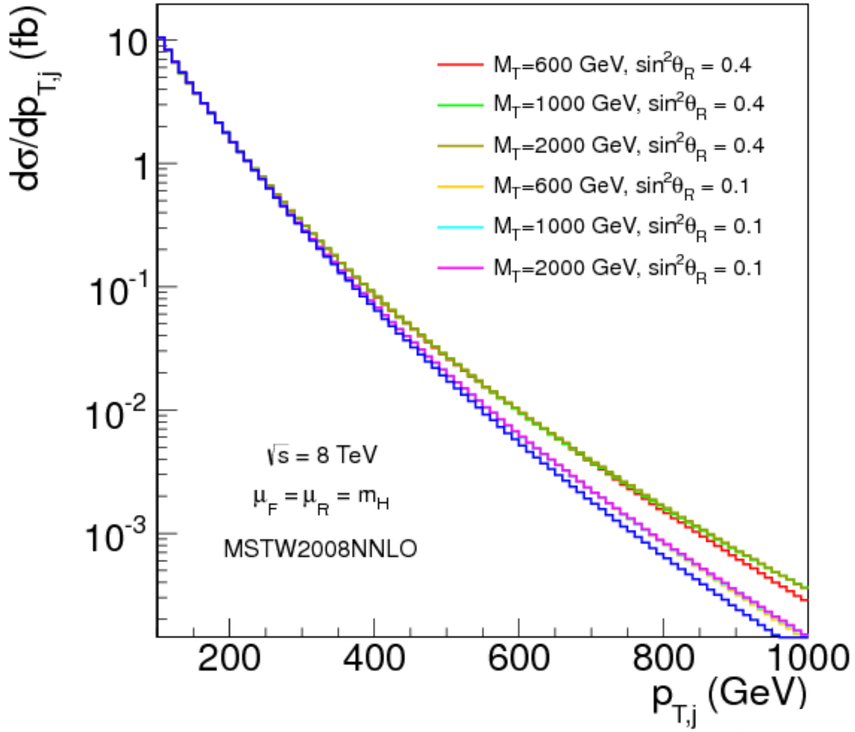
➡ Sudakov-like logarithmic enhancement of light-quark contribution at small pT



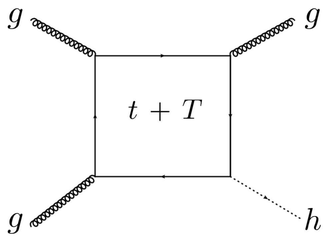
[Bishara, Haisch, Monni, Re; '16]

Sensitive probe of New Physics

[Banfi, Martin, Sanz '13]

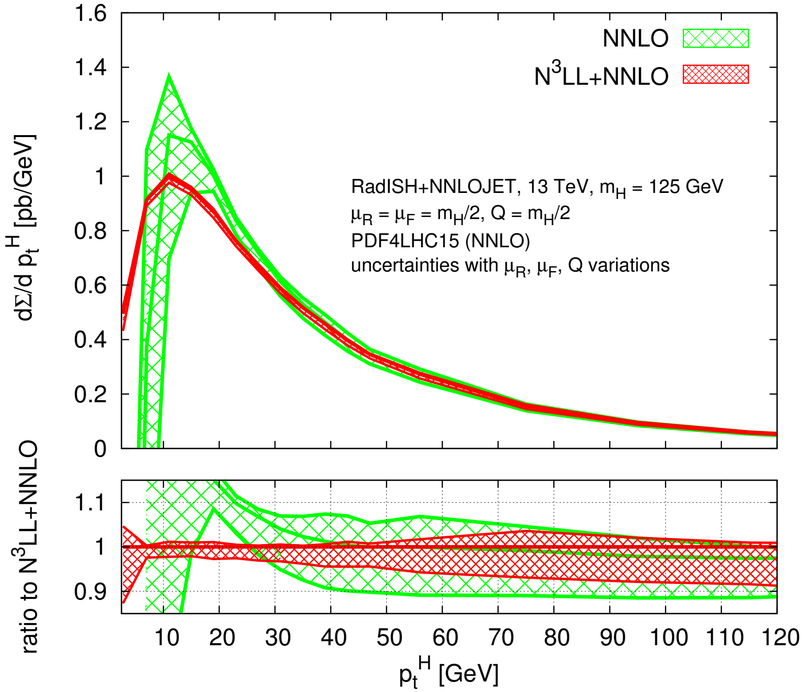


fermonic top partners,
e.g. in Composite Higgs models

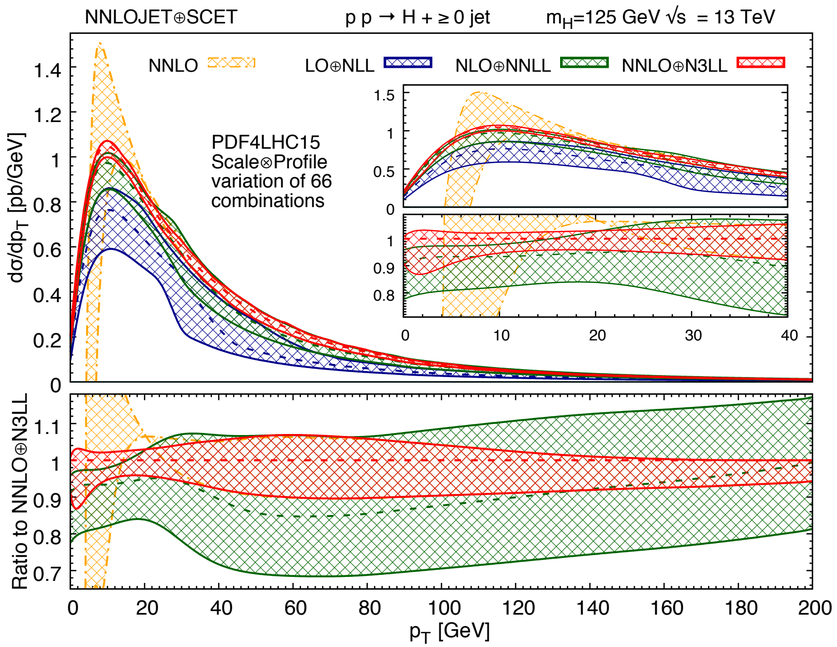


$p_\perp \ll m_t$: NNLO+N3LL in HEFT

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



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



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

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