Heavy quark effects in resummed predictions for Higgs boson production

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Introduction

- Perturbative predictions for Higgs boson production obtained in the large top mass limit

- Perturbative corrections are sizeable. Fixed-order and resummed predictions are available for different observables and perturbative uncertainties are under control

- One should wonder if corrections to the heavy-top approximation are of the order of such uncertainties

- A precise assessment is necessary when experimental uncertainties become as small as $\sim 10\%$

State of the art

- Exact treatment of quark masses in Higgs production cross section (distributions) is available up to NLO (LO)

  HIGLU, MCFM, HPRO, SusHi, ...

- Some terms of the $1/m_t^n$ expansion calculated for NLO distributions

  Harlander, Neumann, Ozeren, Wiesemann

- Mass effects have been implemented to LO accuracy for distributions in Monte Carlo event generators (Herwig, POWHEG, MC@NLO, ...)

  Corcella et al.; Bagnaschi et al.; Frixione et al.

- ... and included in resummed predictions for
  - Higgs transverse momentum $p_{\mathrm{t,H}}$ spectrum

    Mantler, Wiesemann; Grazzini, Sargsyan

  - leading jet $p_{\mathrm{t,jet}}$ spectrum

    Banfi, Zanderighi, PFM

- The present talk analyses the impact of top and bottom quarks on leading-jet and Higgs-boson transverse momentum spectrum

Overview of Sudakov resummation (heavy-top case)

- Momentum-space resummation of $\ln(m_H/p_t)$ can be carried out in the CAESAR framework

- The resummation of large logarithms leads to different logarithmic structures for $p_{t,H}$ and $p_{t,jet}$

$$\Sigma(p_t) \sim e^{-R(p_t)}\mathcal{F}(R') \qquad R' = dR(p_t)/d\ln(Q/p_t)$$

Sudakov Radiator

Multiple-emissions effects

- for $p_{t,H}$

$$\mathcal{F}(R') = e^{-R'\gamma_E}\frac{\Gamma(1-R'/2)}{\Gamma(1+R'/2)} + \mathcal{O}(\text{NNLL})$$

- for $p_{t,jet}$

$$\mathcal{F}(R') = 1 + \mathcal{O}(\text{NNLL})$$

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Sudakov Radiator → $e^{-R(p_{\rm t})}$

Multiple-emissions effects → $\mathcal{F}(R')$

- for $p_{\rm t,H}$

$$\mathcal{F}(R') = e^{-R'\gamma_E}\frac{\Gamma(1-R'/2)}{\Gamma(1+R'/2)} + \mathcal{O}(\rm NNLL)$$

Singularity at $R' = 2$!!!

It appears when cancellations between emissions $p_{\rm t}$ dominate over the Sudakov suppression in generating a small $p_{\rm t,H}$

It can be avoided by performing a Fourier-space resummation

Collins et al. ; Bozzi et al.

- for $p_{\rm t,jet}$

$$\mathcal{F}(R') = 1 + \mathcal{O}(\rm NNLL)$$

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It corresponds to $p_{t,H} \simeq 4.8$ GeV, for $Q = m_H/2$

Pushed to lower values both by lowering Q and by higher-order resummation (known up to NNLL)

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No clustering at NLL !

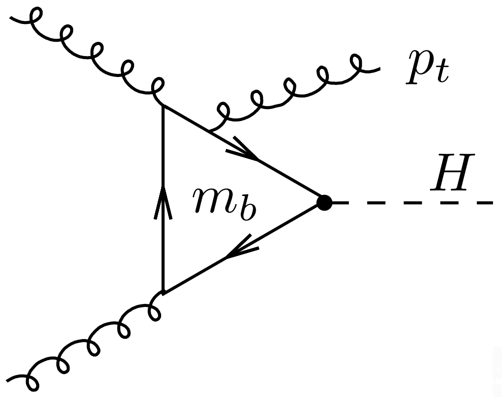
Banfi, Salam, Zanderighi

Dependence on jet-radius enters at NNLL

No divergence in momentum-space resummation

Exact treatment of quark masses

- When quark masses m_b, m_t are taken into account, new non-factorizing logarithmic terms pop up in the regime $m_b^2 << p_{\rm t}^2 << m_H^2$



e.g. including top and bottom quarks at relative order $\mathcal{O}(\alpha_s)$

- soft limit (squared amplitude)

$$\sim (m_b/m_H)^4 \ln^4(m_b^2/p_{\rm t}^2)$$

non-factorizing terms completely cancel in the top-bottom interference

- collinear limit (squared amplitude)

$$\sim (m_b m_t)^2/m_H^4 \ln^2(m_b^2/p_{\rm t}^2) \ln^2(m_t^2/p_{\rm t}^2)$$

interference terms survive and give a dominant contribution

- These new terms vanish for $p_{\rm t} \leq m_b$, so that the standard factorization of soft and collinear singularities is preserved as $p_{\rm t} \to 0$

Implementation of mass effects

- In the region $p_t \sim 25 - 30$ GeV the logarithms $\ln(p_{\rm t}/m_b)$ should be resummed. All-order structure so far unknown. Phase-space suppression kills them at high $p_{\rm t}$
- They can be formally treated as a finite remainder that vanishes when $p_{\rm t} \to 0$
- As any remainder, the non-factorizing terms are thus computed at fixed-order and matched to the resummed calculation

$$\Sigma(p_{\rm t}) \sim C(\alpha_s, \mu_R, \mu_F, Q, m_H, m_b, m_t) e^{-R(p_{\rm t})} \mathcal{F}(R') + \text{remainder}$$

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Prefactor contains coefficient functions as in the heavy-top limit and full virtual corrections with both top and bottom quarks running in the loop.
It contains large logarithms $\ln(m_H/m_b)$

Spira et al.; Harlander et al.; Bonciani et al.

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Resummation of logarithms $\ln(m_H/p_{\rm t})$ as in the large-m_t limit

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It contains power suppressed terms and non-factorizing logs $\ln(p_{\rm t}/m_b)$

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Matching to fixed order

- Resummation and matching up to NNLL+NNLO for $p_{\rm t,jet}$, $p_{\rm t,H}$ have been implemented in the programme JetVHeto, including mass effects

- We use approximate relative $\mathcal{O}(\alpha_s^2)$ corrections obtained as

hnnlo-v2.0 - Grazzini, Sargsyan

$$\Sigma^{(2)}_{\rm approx}(p_{\rm t}) = \frac{\sigma_0^{m_t-\rm only}}{\sigma_0^{m_t\to\infty}} \Sigma^{(2)}_{m_t\to\infty}(p_{\rm t})$$

- When matching to the NNLL resummed result, one is to replace the expansion of the resummation formula at $\mathcal{O}(\alpha_s^2)$ with the modified one

$$\Sigma_{\rm matched}(p_{\rm t}) = \Sigma_{\rm res}(p_{\rm t})/\sigma_0$$
$$\times\left(1+\Sigma^{(1)}_{\rm fo}(p_{\rm t}) - \Sigma^{(1)}_{\rm res}(p_{\rm t}) + \Sigma^{(2)}_{\rm fo,approx}(p_{\rm t}) - \boxed{\Sigma^{(2)}_{\rm res}(p_{\rm t})} - \Sigma^{(1)}_{\rm res}(p_{\rm t})/\sigma_0\left(\Sigma^{(1)}_{\rm fo}(p_{\rm t}) - \Sigma^{(1)}_{\rm res}(p_{\rm t})\right)\right)$$

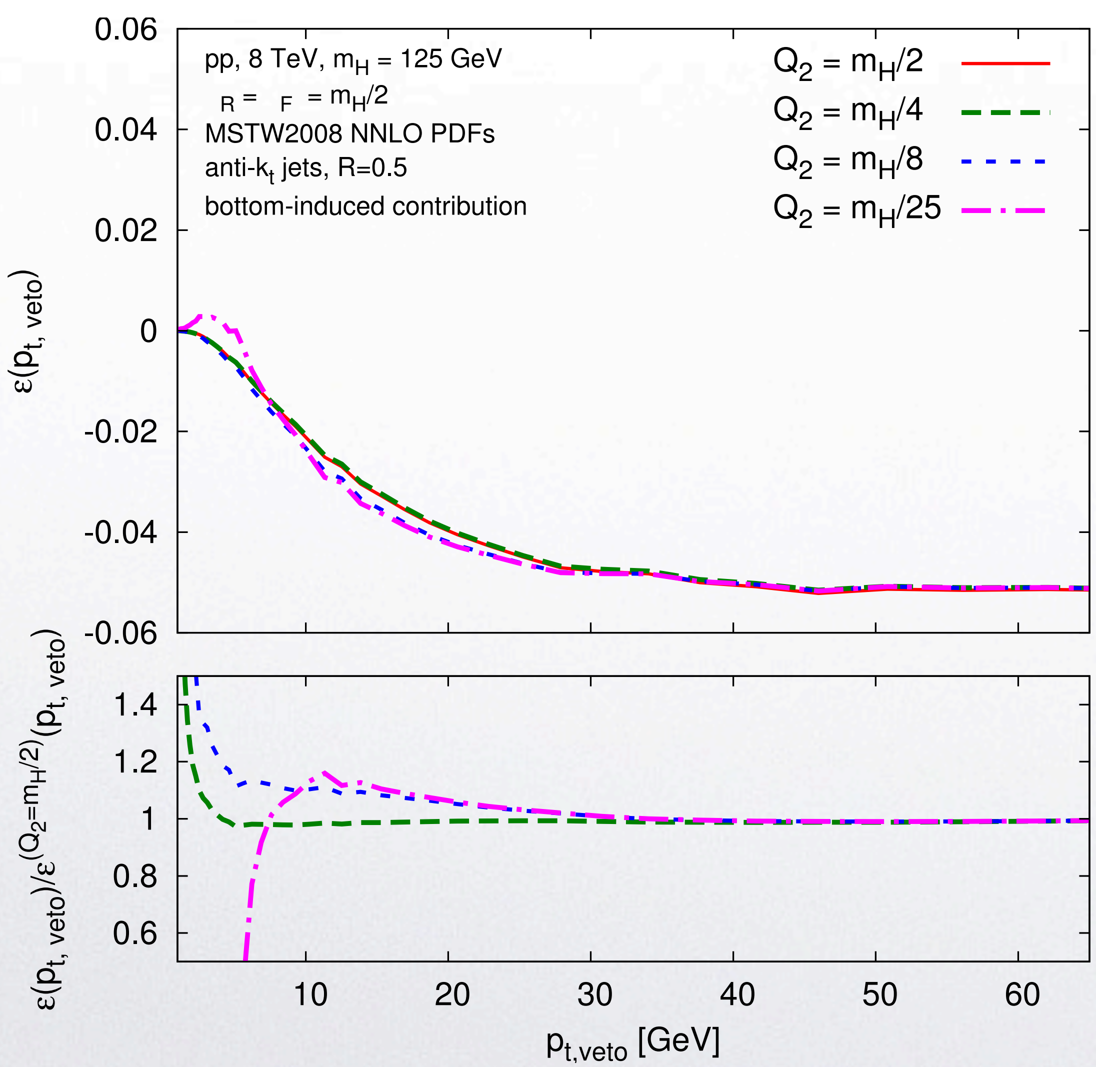
$$\Sigma^{(2)}_{\rm res}(p_{\rm t}) = \frac{\sigma_0^{m_t-\rm only}}{\sigma_0^{m_t\to\infty}} \Sigma^{(2)}_{\rm res, m_t\to\infty}(p_{\rm t})$$

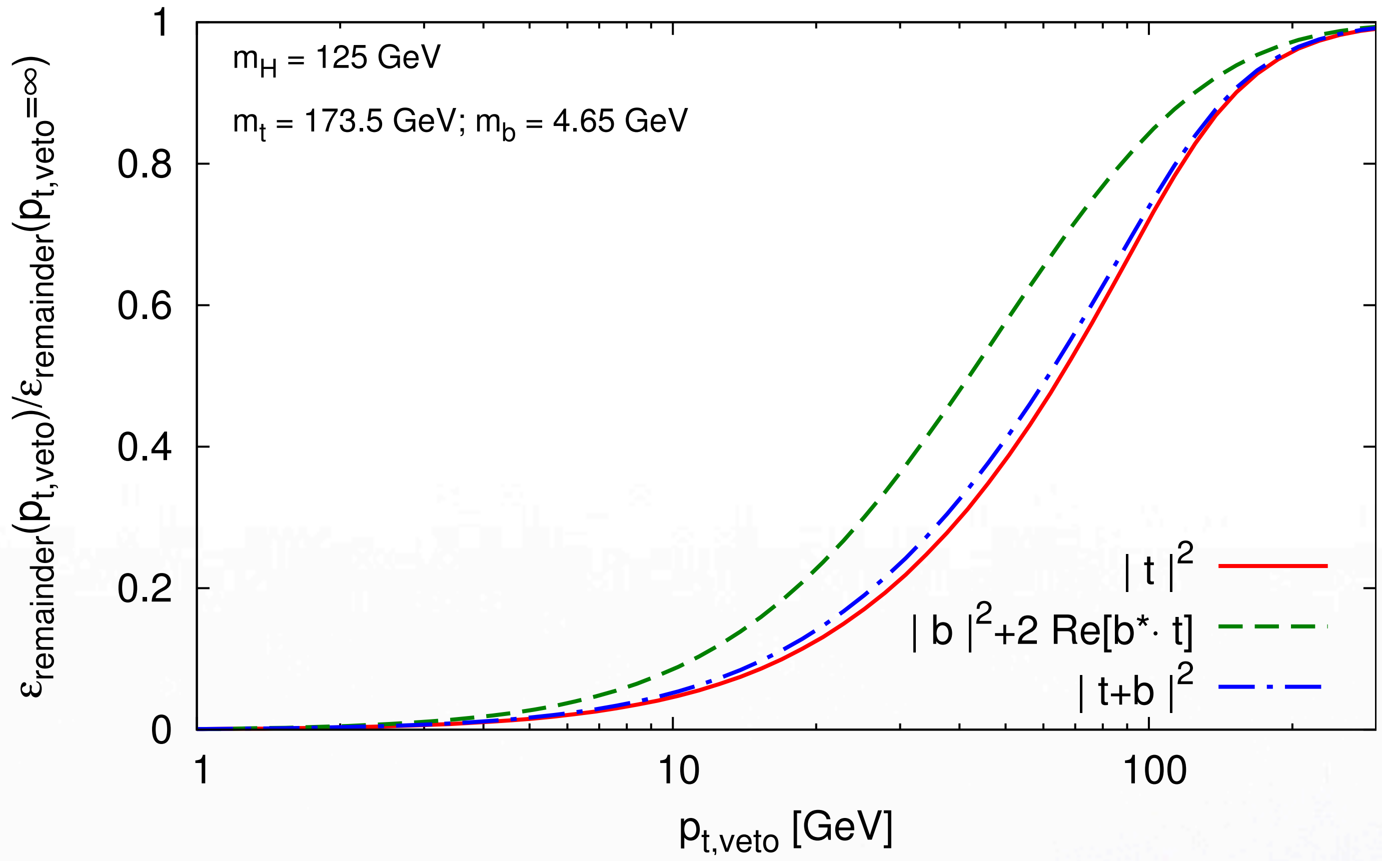
- This ensures NNLL accuracy in the Sudakov region. However, the difference between the matched and fixed-order result will be of $\mathcal{O}(\alpha_s^2)$ rather than $\mathcal{O}(\alpha_s^3)$!!

Results for jet-veto efficiency

The remainder is larger for the bottom-induced contribution (squared bottom amplitude plus top-bottom interference) and suggests to choose the corresponding resummation scale to be smaller than the one associated to the top-quark contribution
i.e.

$$Q_1 \simeq m_H/2,\; Q_2 \simeq m_H/4$$





The dependence of the matched NNLL+NNLO bottom-induced contribution on the associated resummation scale is negligible beyond ~ 40 GeV.

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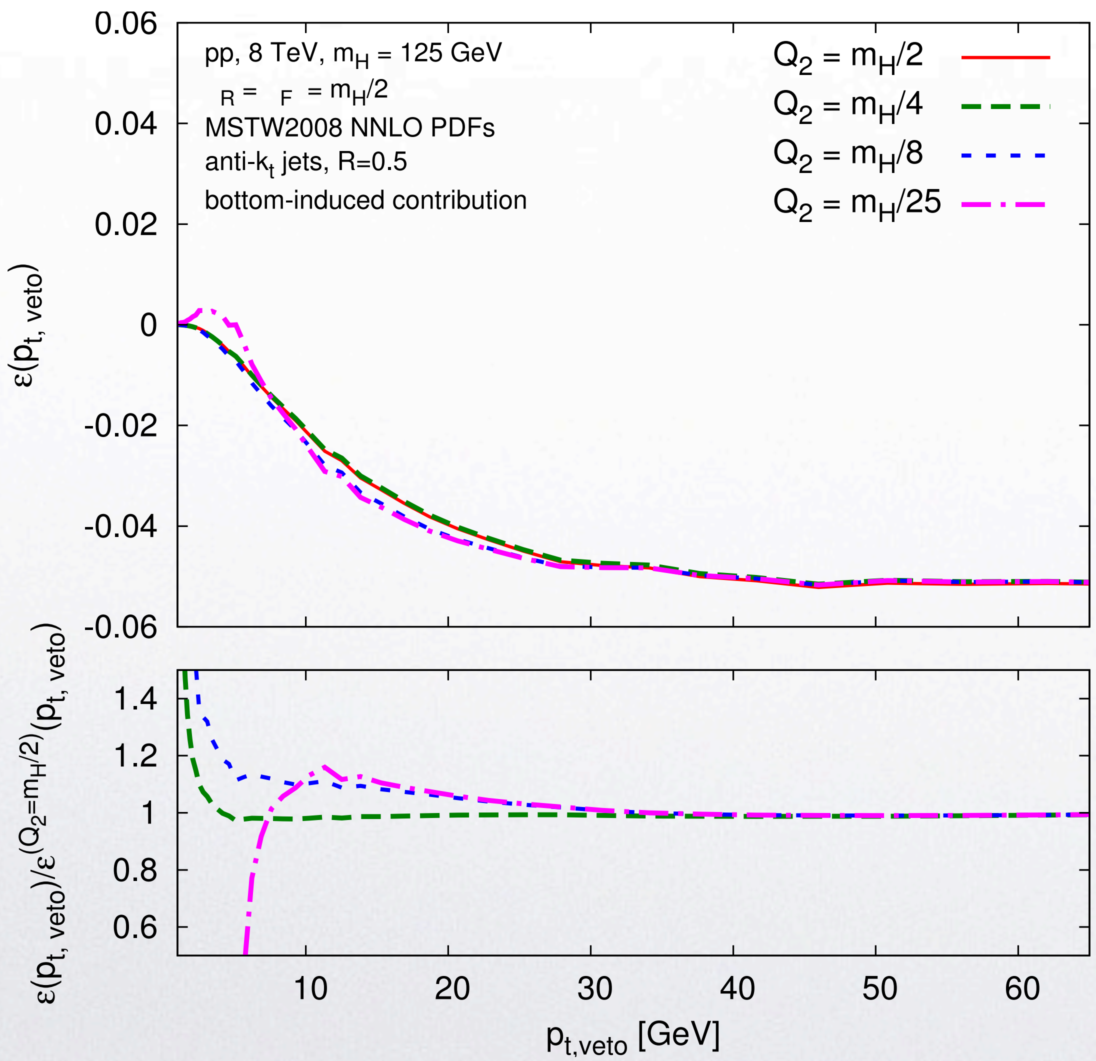

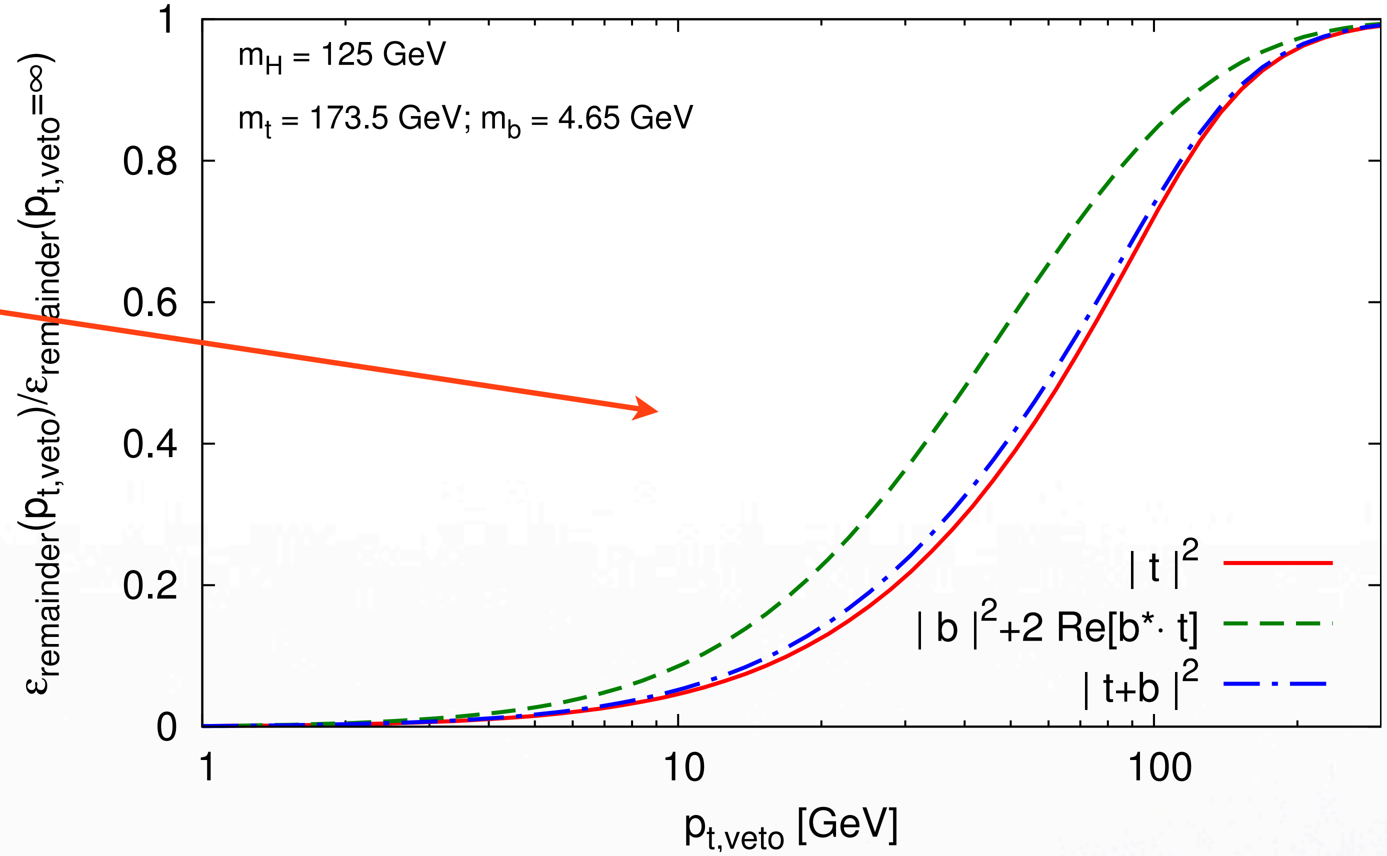

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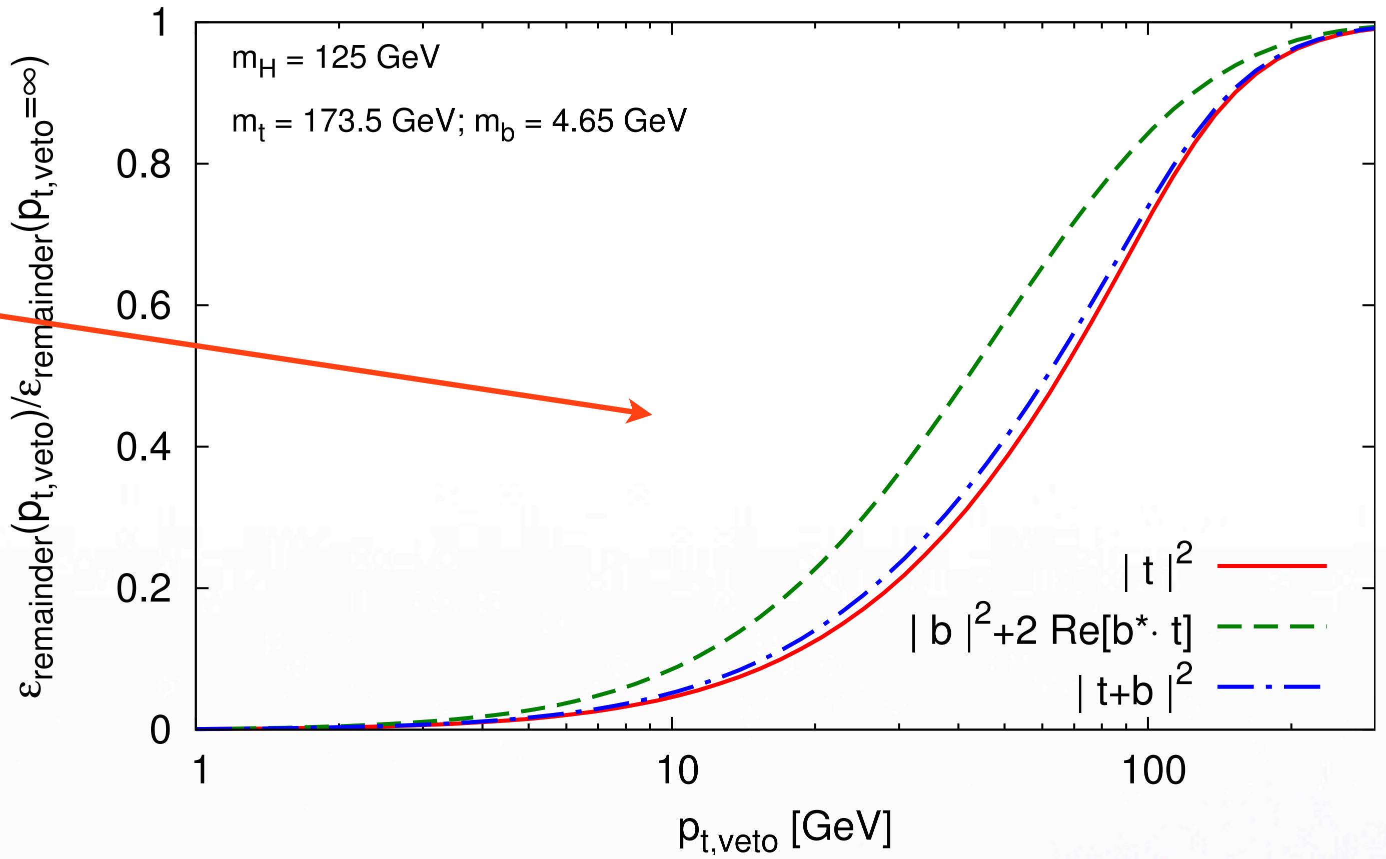

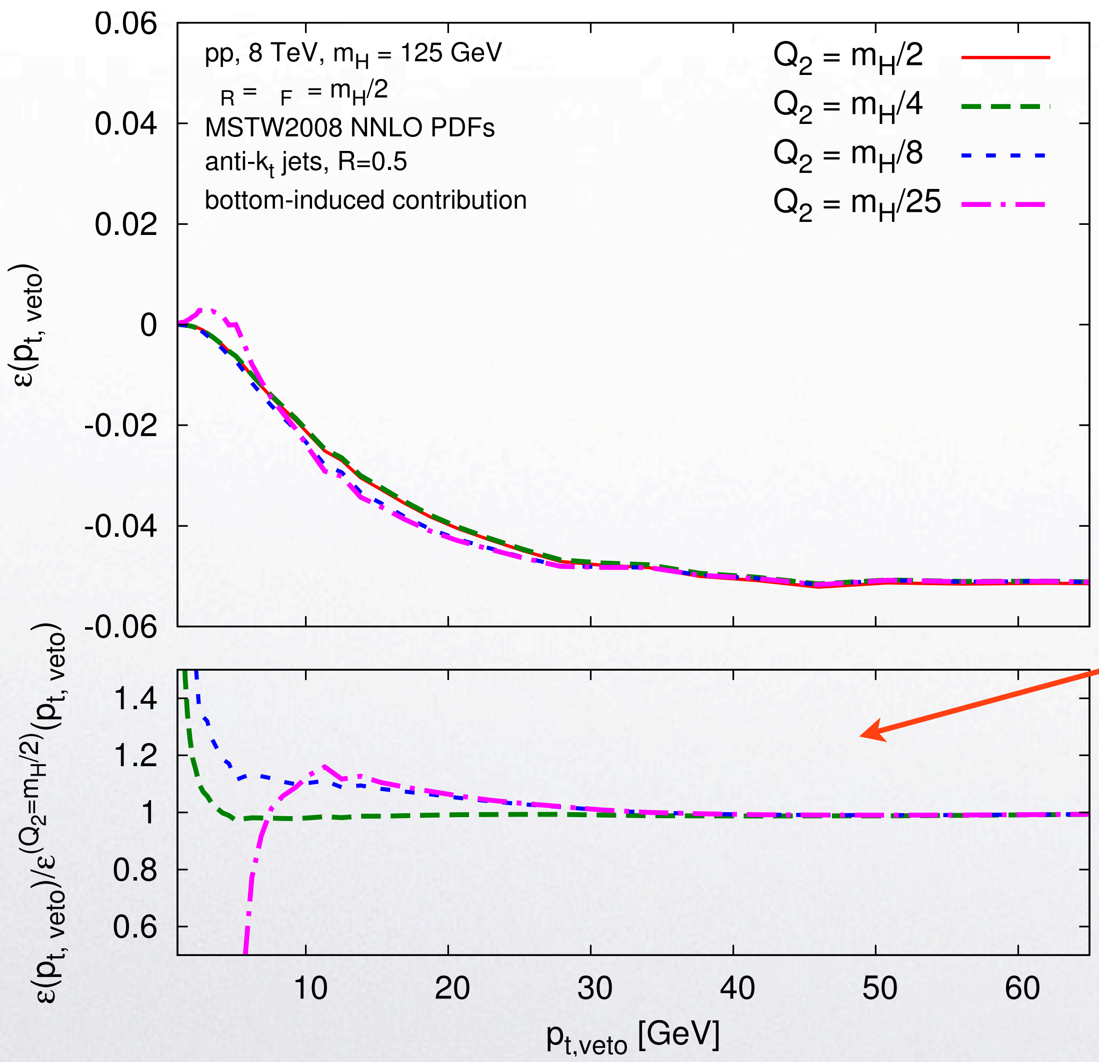

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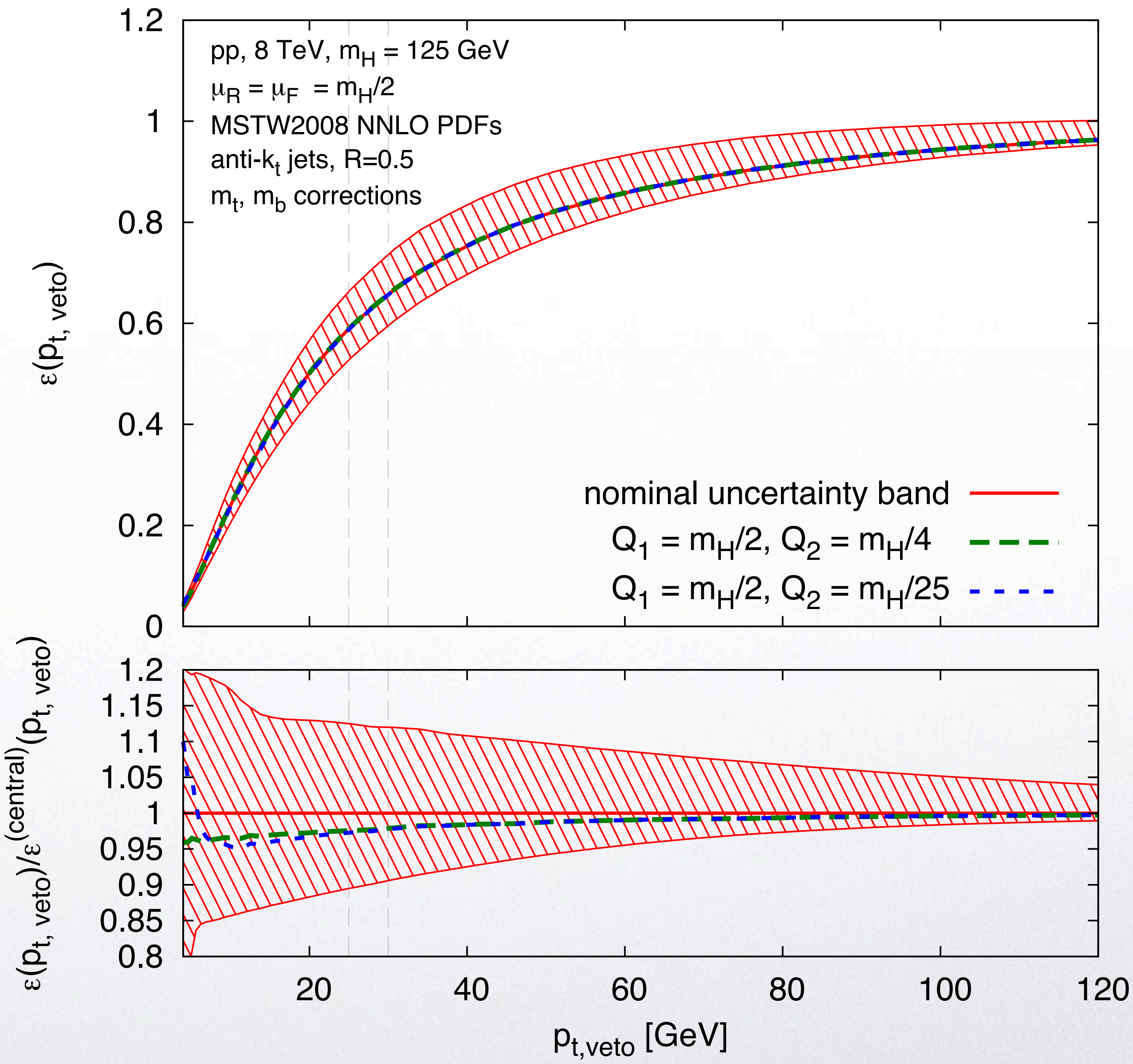
Results for jet-veto efficiency

The bottom-induced renormalization scale Q_2 variation has a moderate impact on the total (top+bottom) jet-veto efficiency. Therefore we decide to set $Q_2 = Q_1 = m_H/2$ as our default central value

Uncertainty band is the envelope of renormalization, factorization and resummation scale variations + spread between three matching schemes

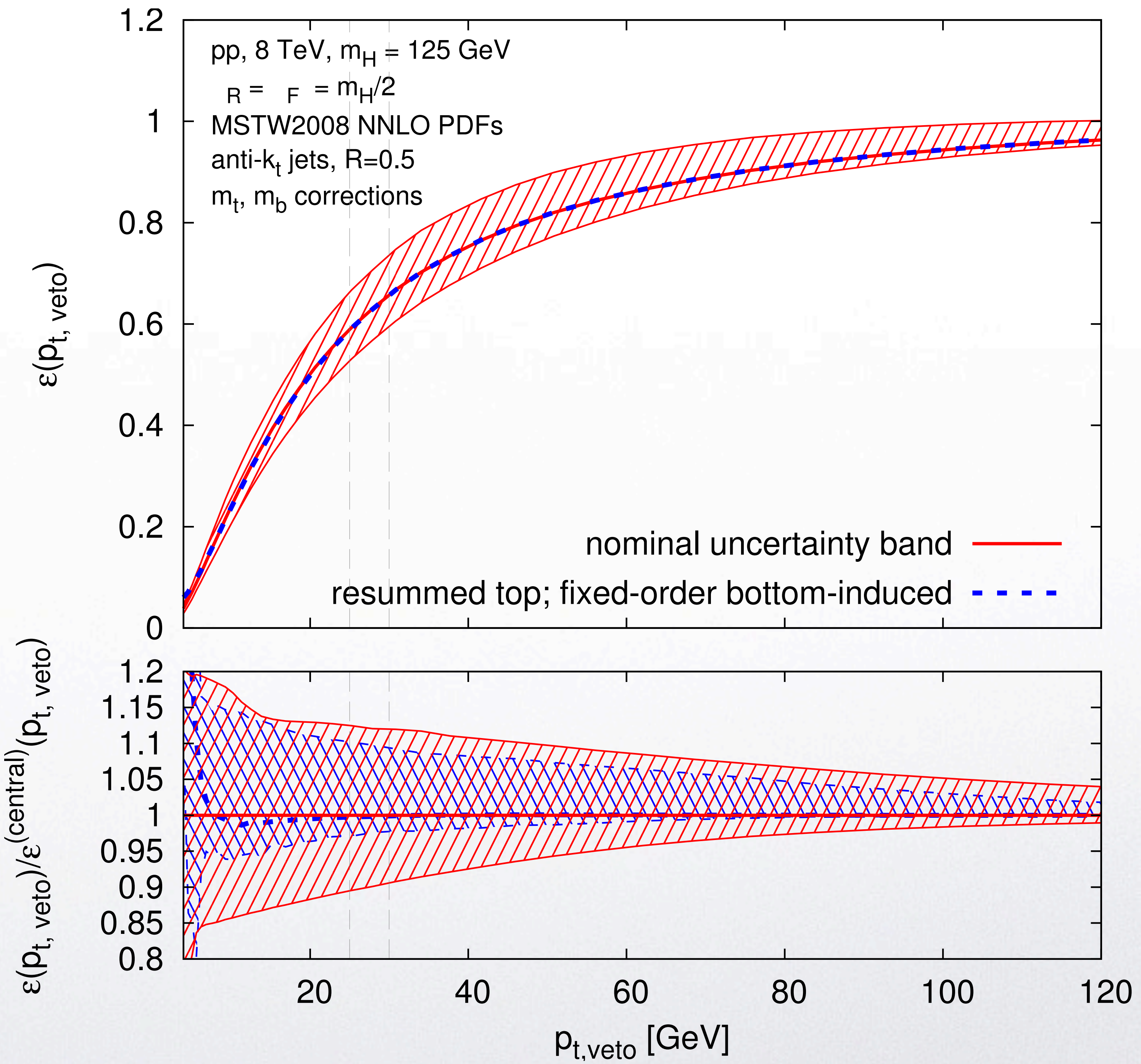


Results for jet-veto efficiency

To assess the uncertainty associated with the unknown higher-order mass effects, we design different matching schemes in which the non-factorizing terms are treated (enhanced) differently

1) treat bottom-induced terms at fixed-order

The blue uncertainty band is the envelope of renormalization and factorization scales for the fixed-order bottom-induced part and of renormalization, factorization and resummation scales for the resummed top contribution



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2) exponentiate the bottom-induced contribution

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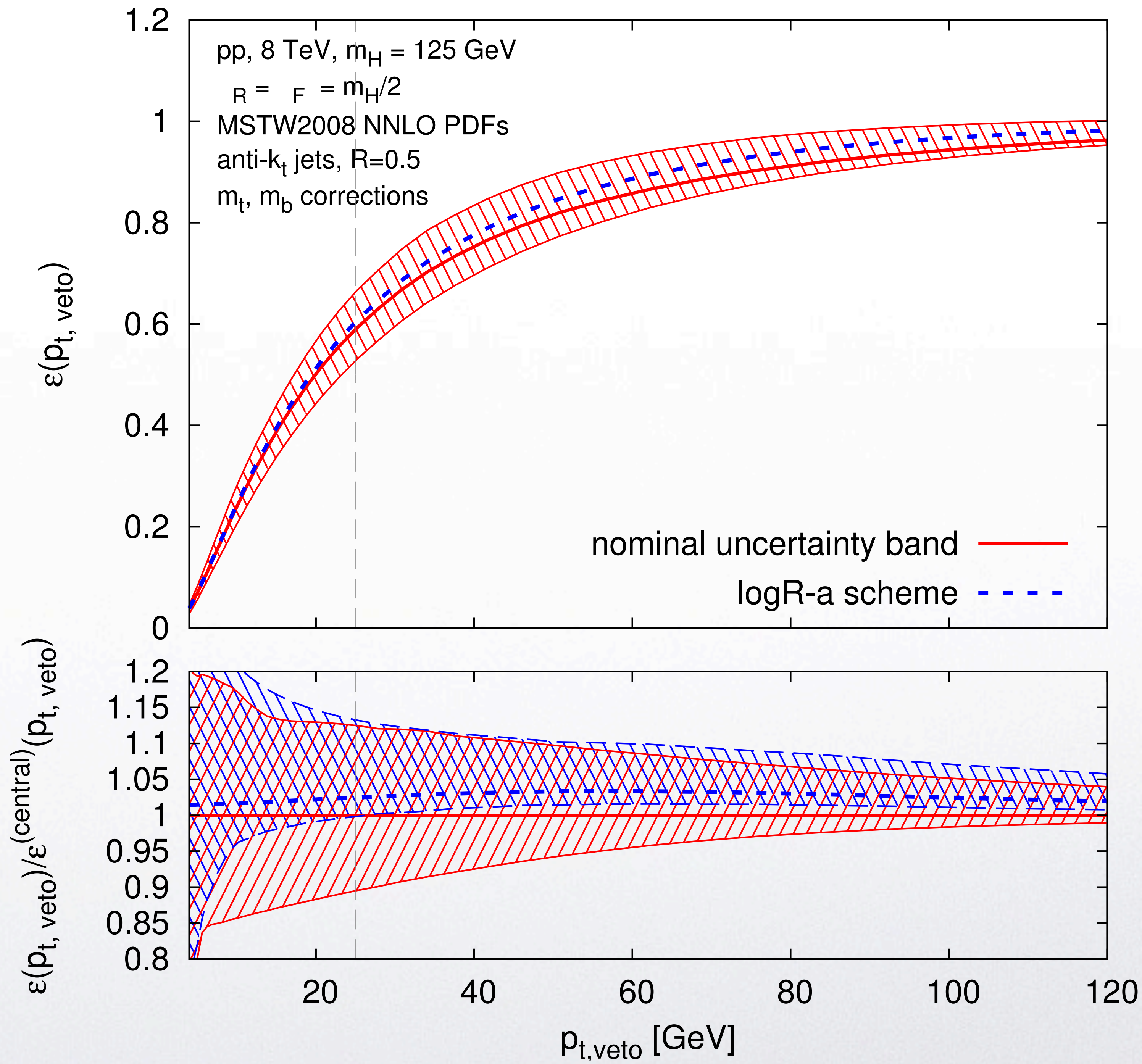

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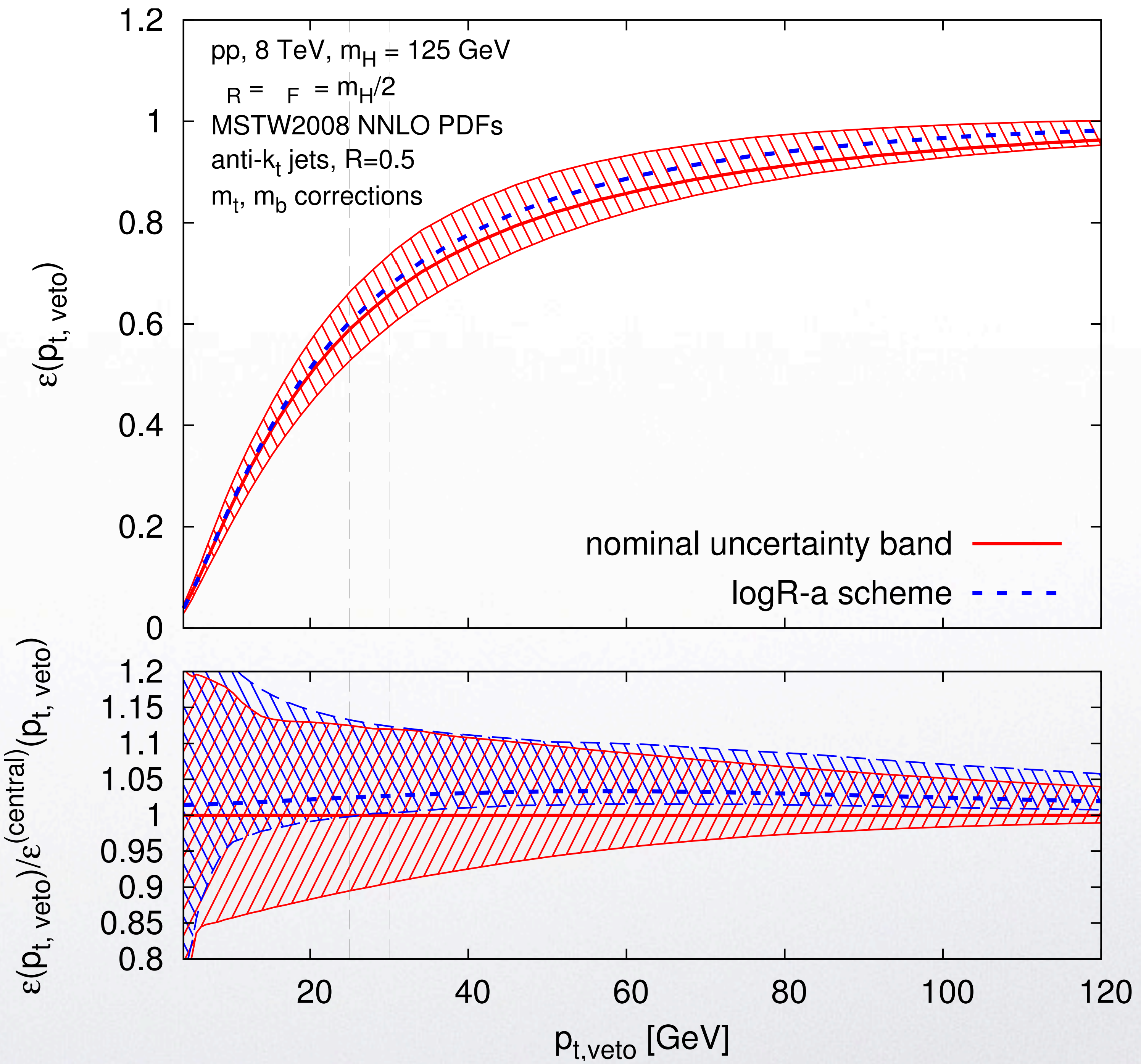


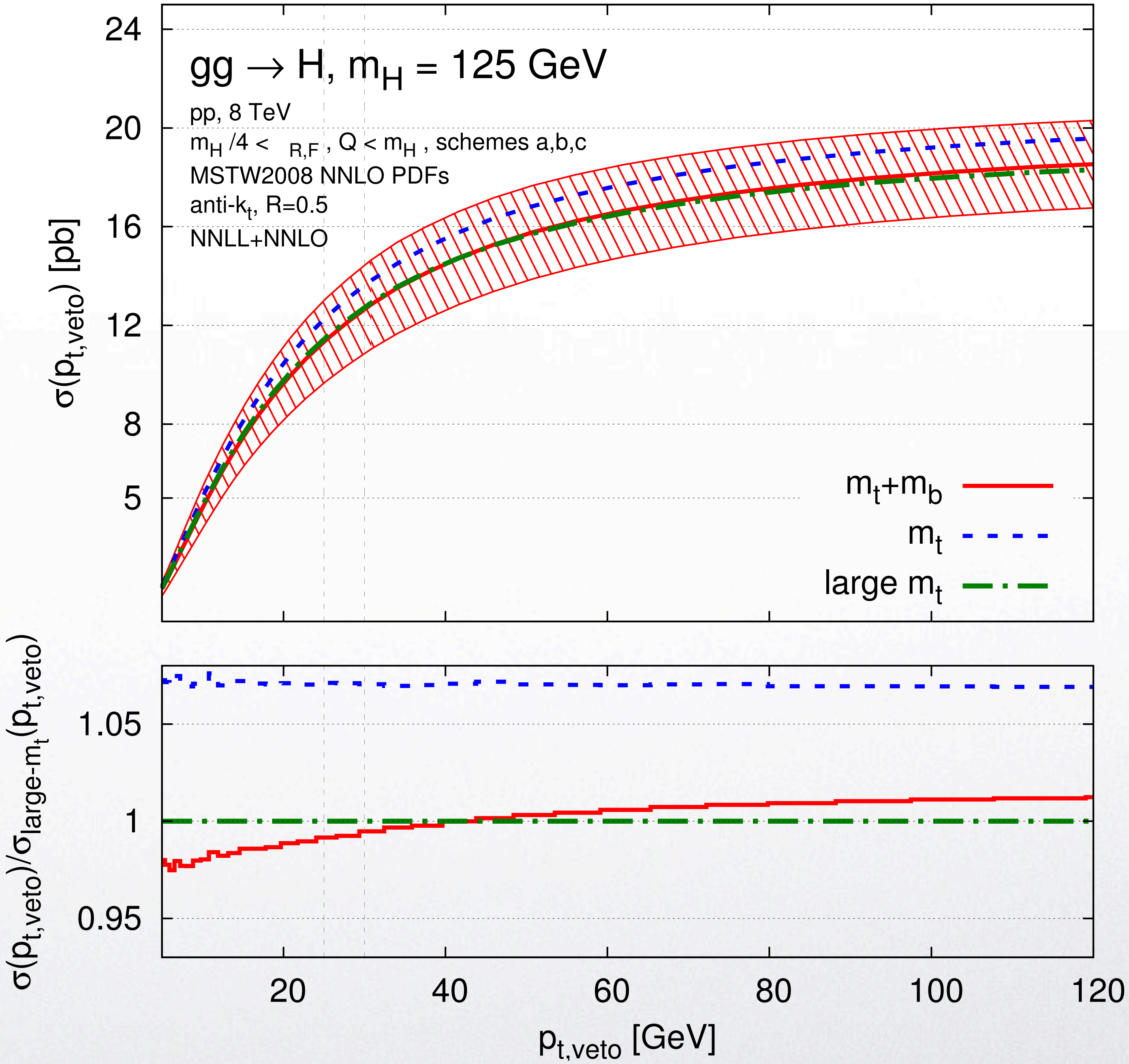
The blue uncertainty band is the envelope of renormalization, factorization and resummation scales

In both cases we observe that the central values are within our nominal uncertainty band - conservative estimate

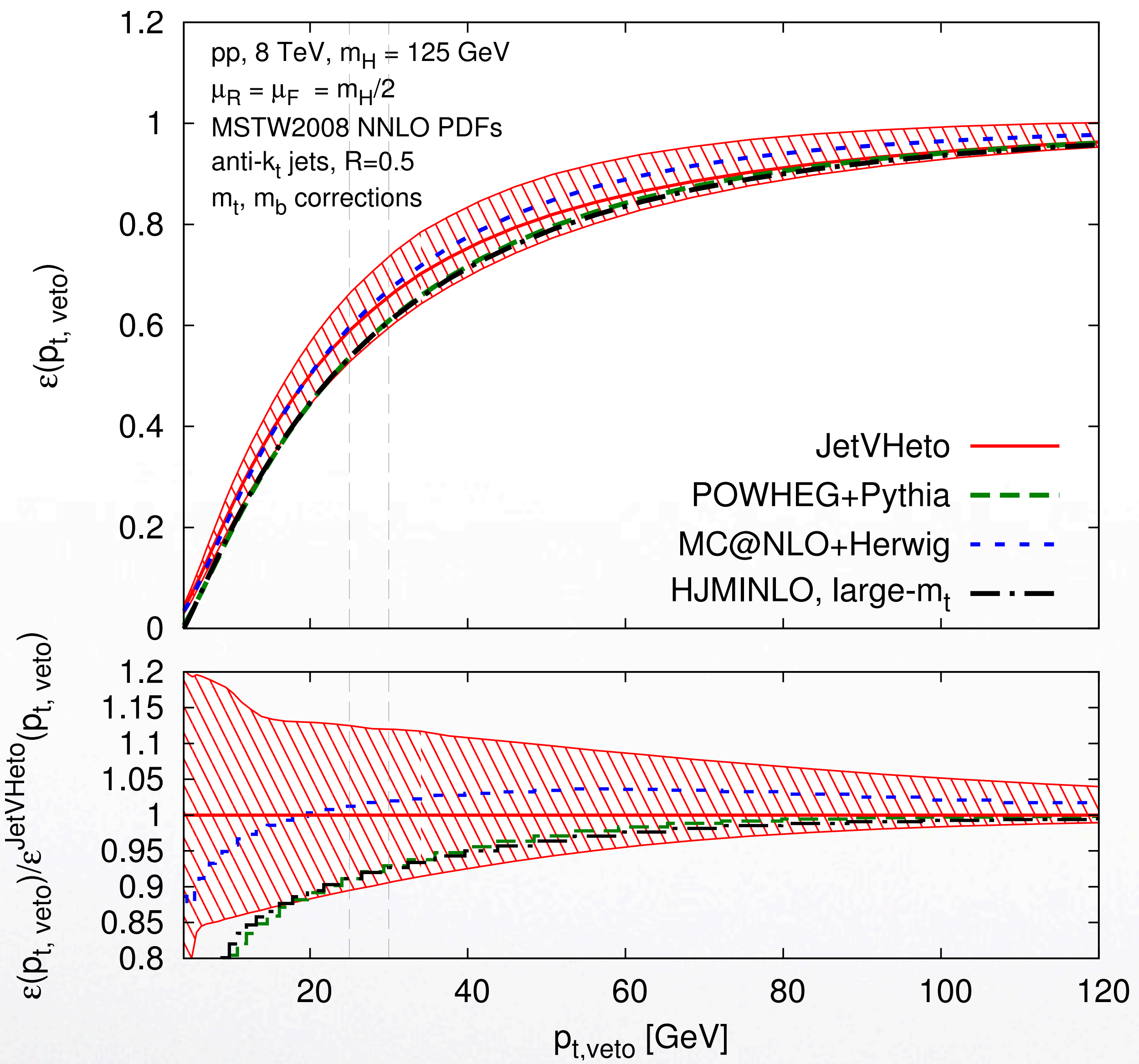
The effect of top-quark amounts to an over-all rescaling whilst the bottom quark distorts the shape of the spectrum.

The total effect is small: $\sim 3\%$ at small transverse momentum and $\leq 2\%$ in the high-$p_{t,\mathrm{veto}}$ region

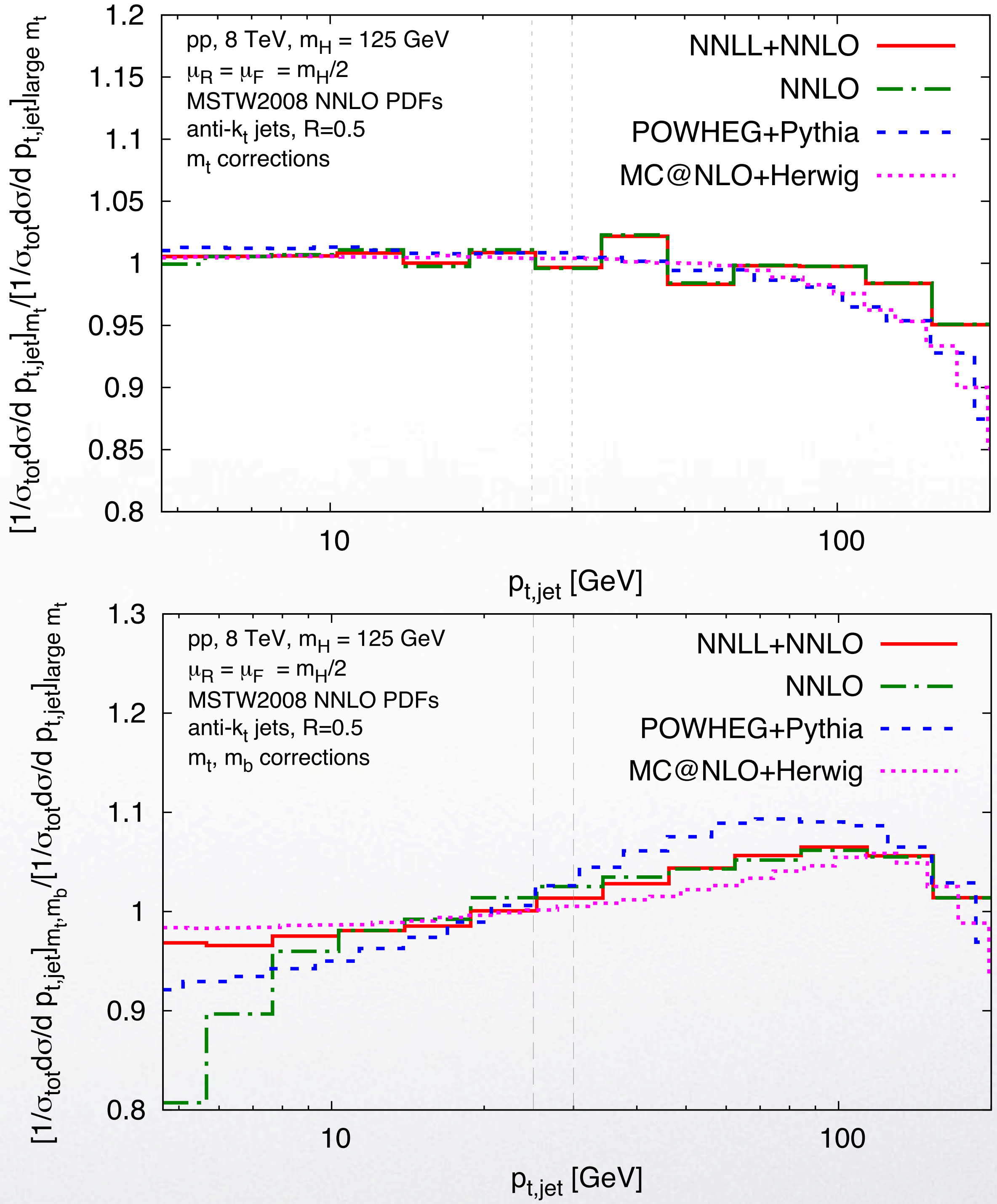
Uncertainty band obtained with the efficiency method, i.e. errors on jet-veto efficiency and total cross section treated as totally uncorrelated



Comparison to Monte Carlo for jet-veto efficiency



Good agrement with MC generators.
MC@NLO agrees better with the NNLL+NNLO prediction

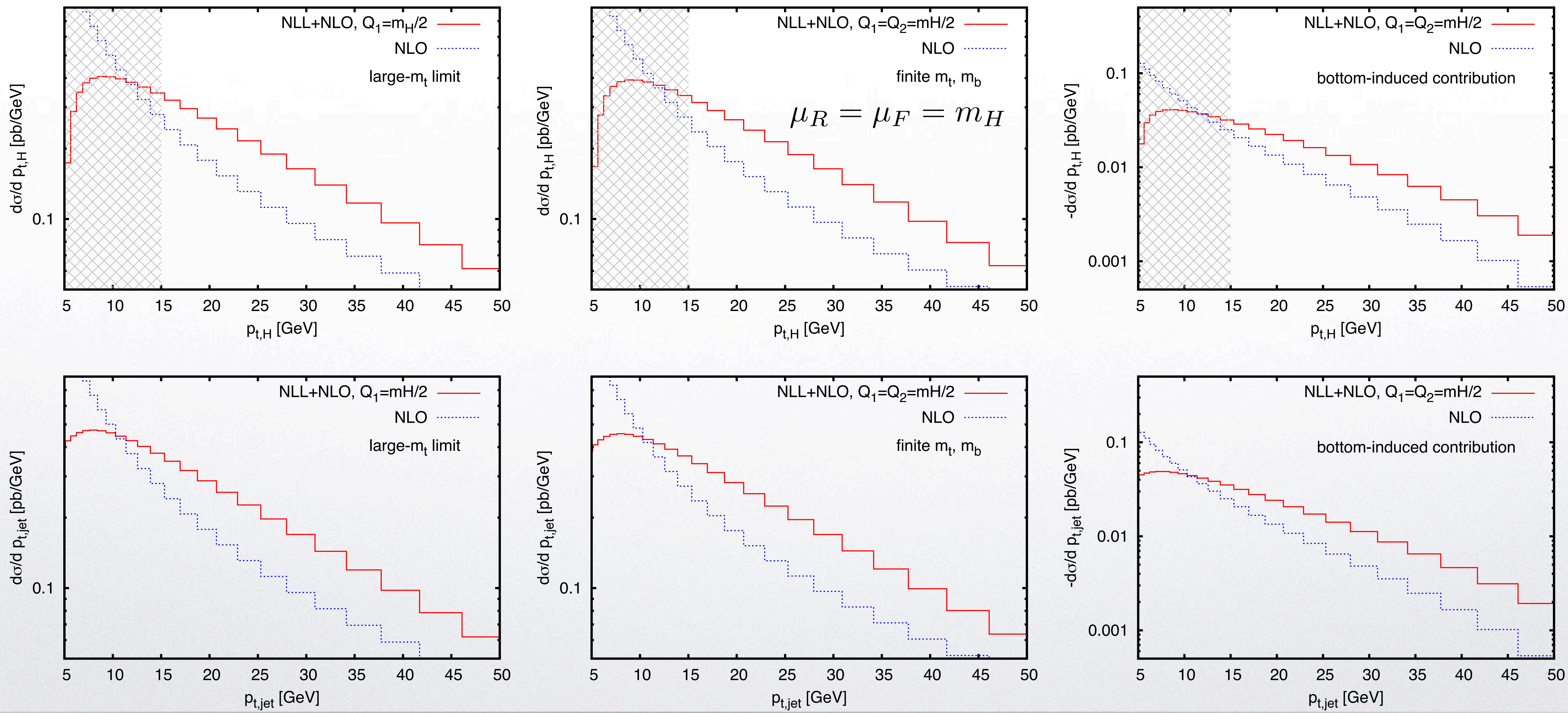


NNLO distributions obtained with hnnlo-v2.0

Comparison between leading-jet and Higgs p_t

NLL+NLO matching significantly differs from fixed-order result in the intermediate p_t region

Reason: large logarithmic left-over at $\mathcal{O}(\alpha_s^2)$ in the resummation



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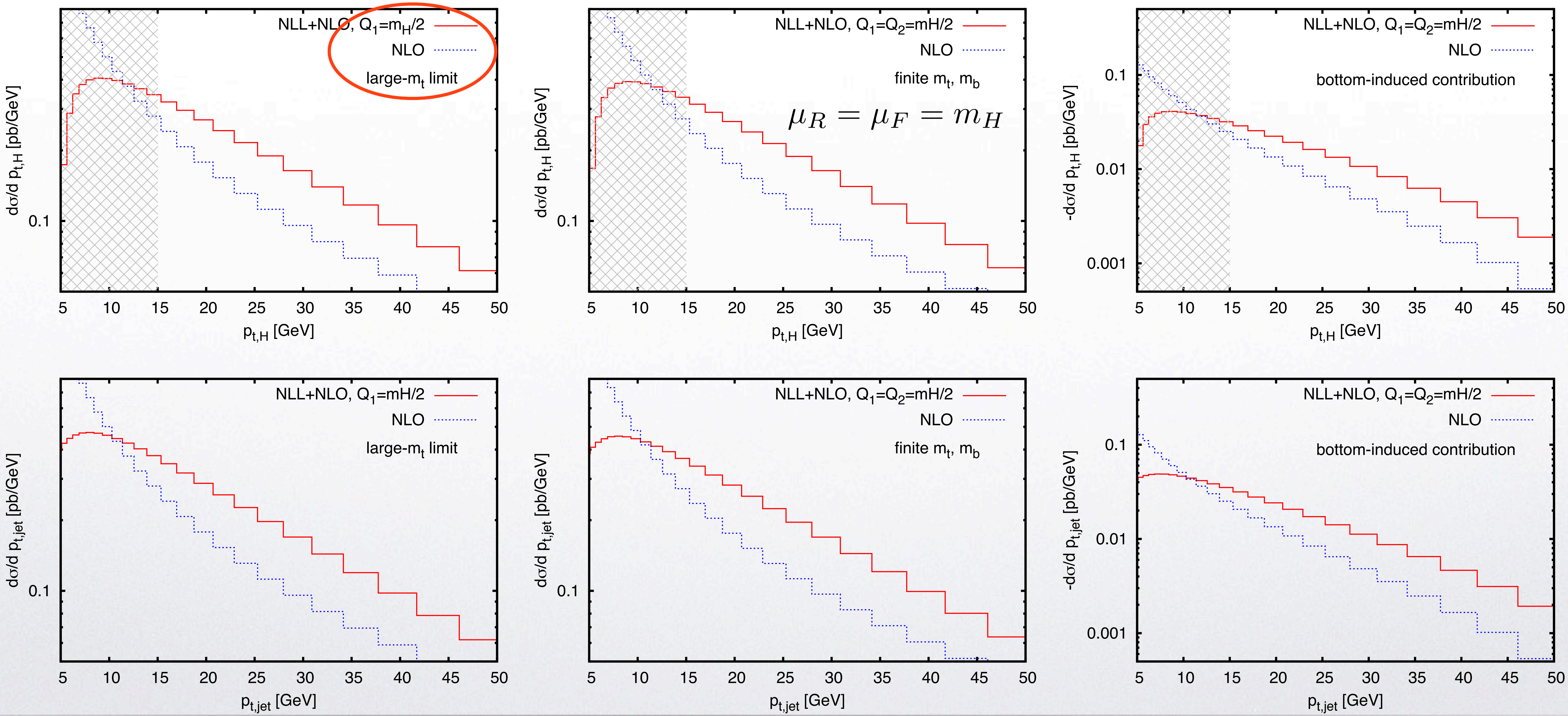

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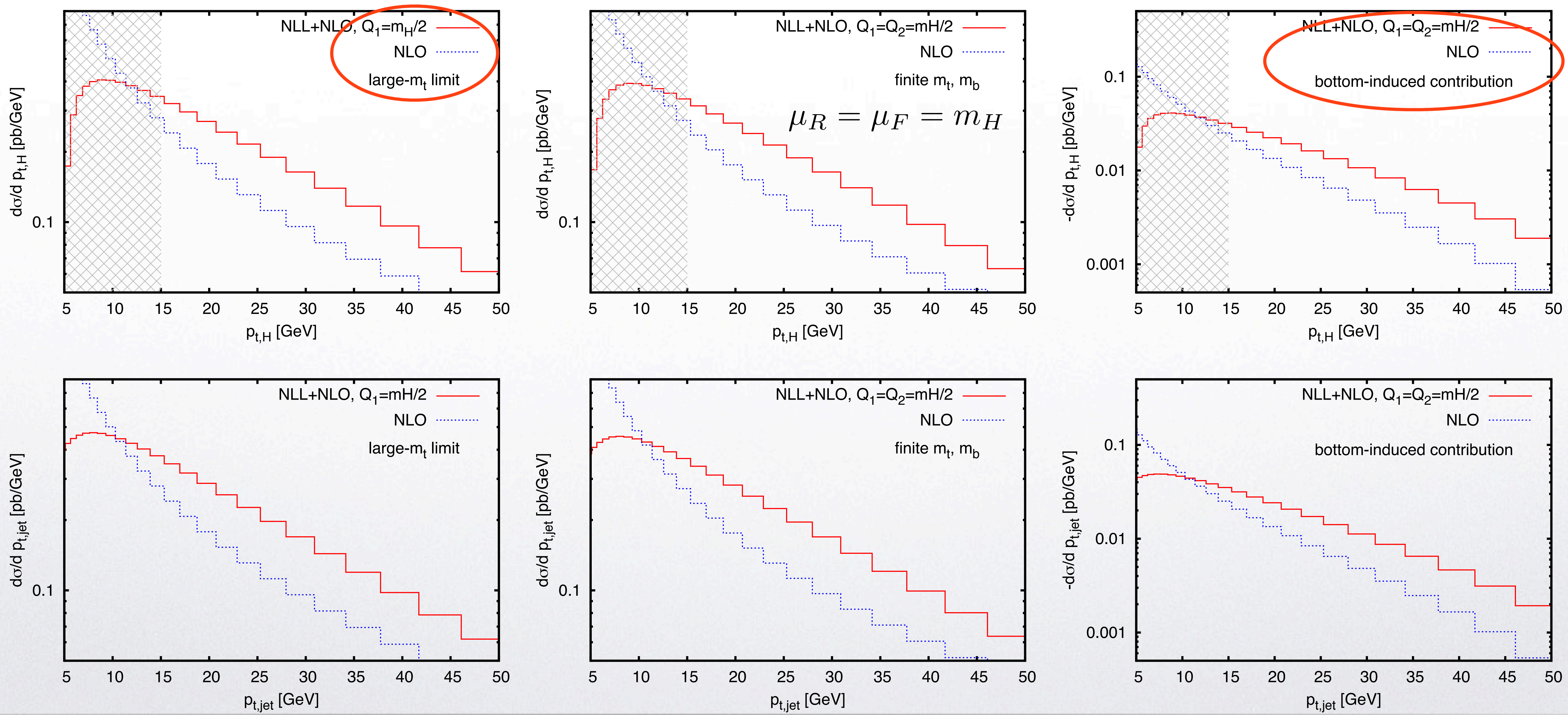
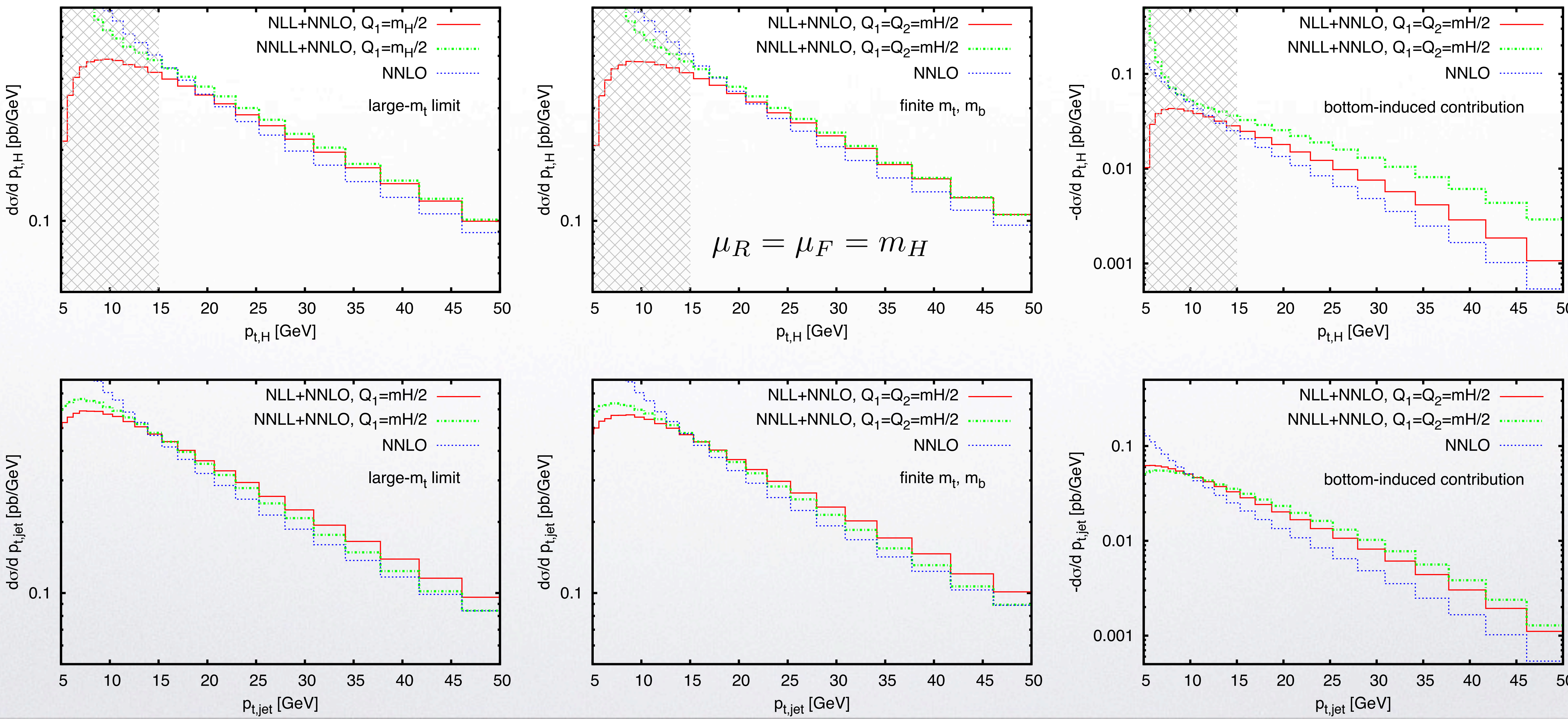


Comparison between leading-jet and Higgs p_t

Higher-order matching (i.e. NLL+NNLO, NNLL+NNLO) technically solves the problem.

True in the heavy-top limit for which the exact NNLO is known : $\mathcal{O}(\alpha_s^3)$ mismatch

When mass effects are included, an approximate NNLO is used : still has an $\mathcal{O}(\alpha_s^2)$ mismatch



Comparison between leading-jet and Higgs p_t

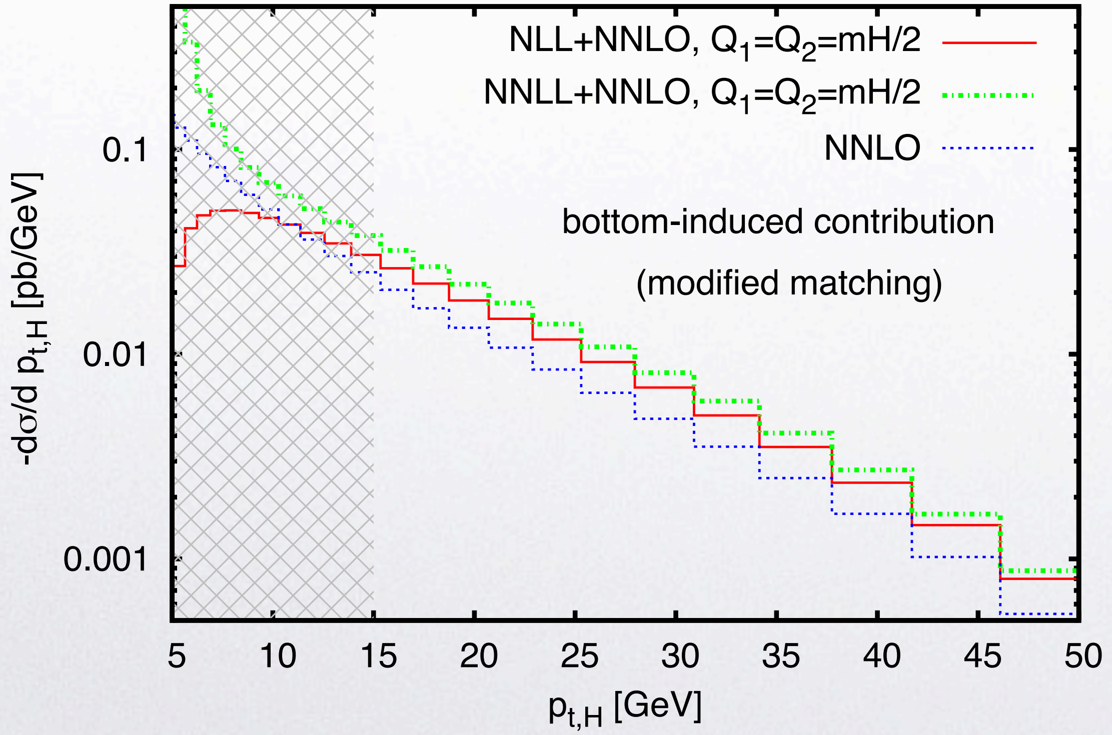
To investigate this effect, one can use the correct $\mathcal{O}(\alpha_s^2)$ expansion of the resummation formula in the matching schemes. This leads to a $\mathcal{O}(\alpha_s^3)$ difference between the matched and the fixed-order distributions.

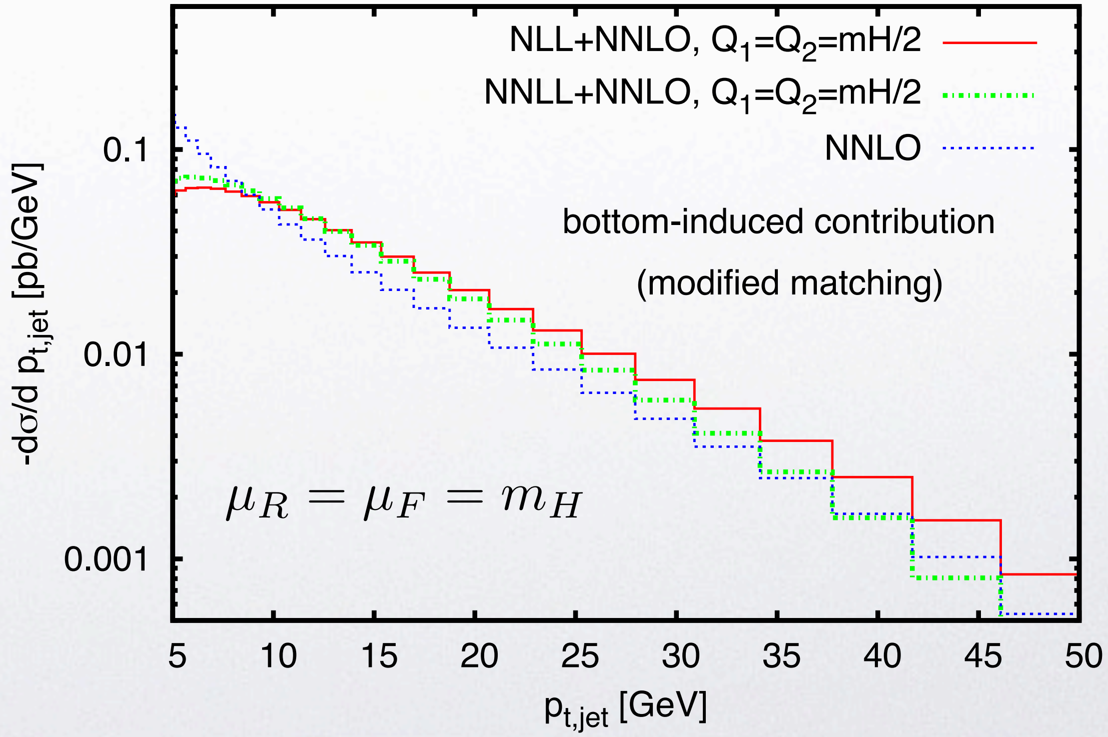
$$\Sigma_{\text{matched}}(p_t) = \Sigma_{\text{res}}(p_t)/\sigma_0$$
$$\times\left(1 + \Sigma_{\text{fo}}^{(1)}(p_t) - \Sigma_{\text{res}}^{(1)}(p_t) + \Sigma_{\text{fo,approx}}^{(2)}(p_t) - \boxed{\Sigma_{\text{res}}^{(2)}(p_t)} - \Sigma_{\text{res}}^{(1)}(p_t)/\sigma_0\left(\Sigma_{\text{fo}}^{(1)}(p_t) - \Sigma_{\text{res}}^{(1)}(p_t)\right)\right)$$

Correct expansion of the resummation formula

However, this solution spoils the logarithmic accuracy in the Sudakov region

Resulting distributions as in the heavy-top case, i.e. no effect due to non-factorizing terms





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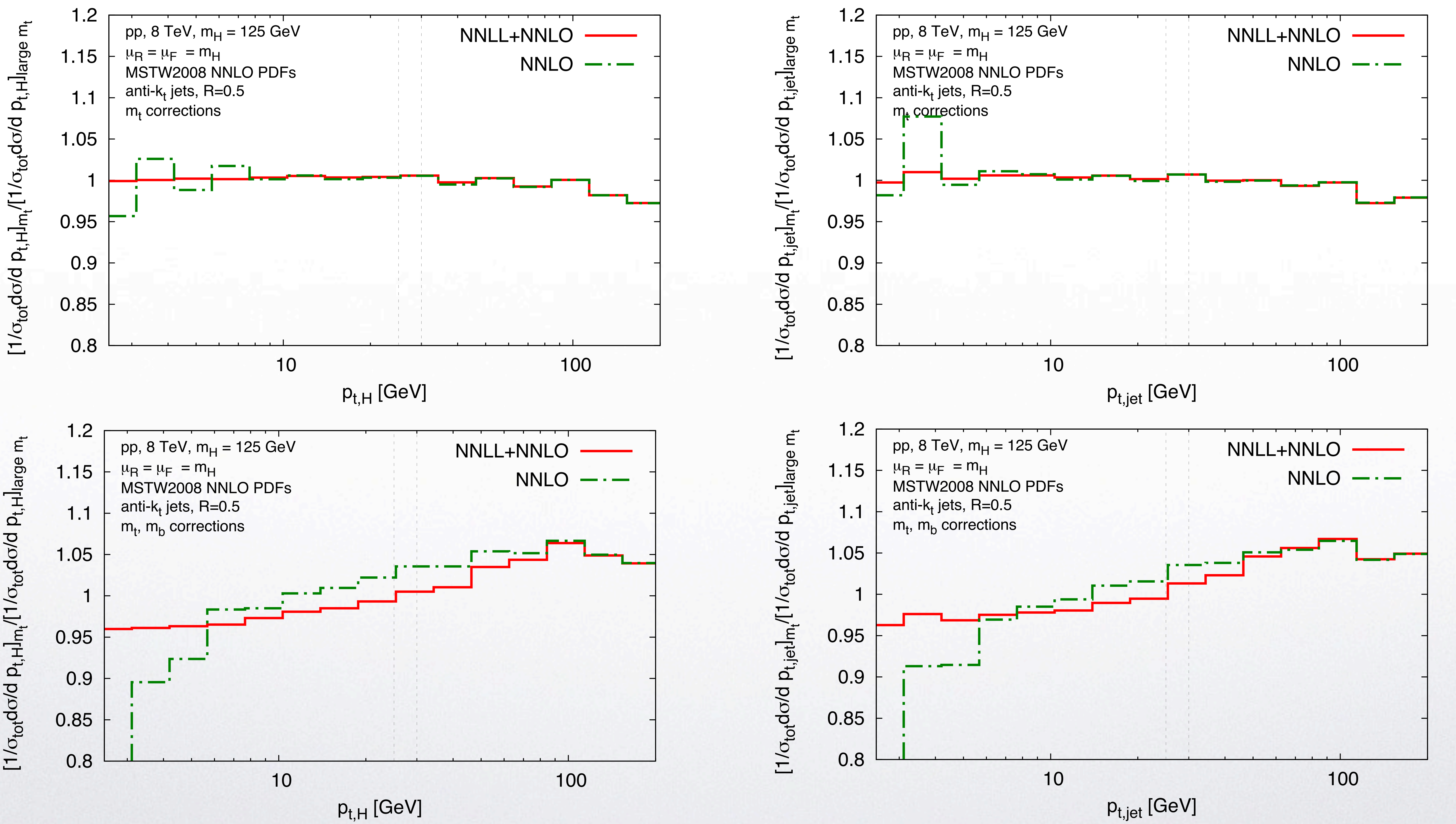

Conclusions

- Exact mass effects now implemented in resummed predictions for both the leading-jet and the Higgs-boson transverse momentum

- Their impact is found to be small (ratio to large-m_t distributions in the range $\sim [-4\%, +6\%]$ with approximate NNLO). Numerically similar impact on $p_{\rm t,jet}$ and $p_{\rm t,H}$

- Assessment of theory uncertainties in the vetoed cross section robust against uncertaintites associated with higher-order non-factorizing terms

- Either full NNLO calculation with exact treatment of quark masses or resummation of the new logarithms desirable to assess such effects more precisely