Jet-vetoed Higgs cross section in gluon fusion at N3LO+NNLL+LL_R

P. F. Monni
CERN

Work in collaboration with A. Banfi, F. Caola, F. Dreyer, F. Dulat, G. Salam and G. Zanderighi

[1511.02886]

WG1 ggF subgroup meeting - CERN 15 November 2016

Outline: the 0-jet cross section

[Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056]
[Anastasiou et al. 1602.00695]

total cross section @ N3LO

~3% increase at 13 TeV for $\mu_R = \mu_F = m_H/2$

[Boughezal, Caola, Melnikov, Petriello, Schulze 1504.07922]
[Boughezal, Focke, Giele, Liu, Petriello 1505.03893]
[Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier 1607.08817]

H+1jet @ NNLO

~5% increase at veto scales for $\mu_R = \mu_F = m_H/2$

NNLL resummation

[Banfi, PM, Salam, Zanderighi 1206.4998]
[Becher, Neubert, Rothen 1307.0025]
[Stewart, Tackmann, Walsh, Zuberi 1307.1808]

Quark-mass effects

[Banfi, PM, Zanderighi 1308.4634]
[Mantler, Wiesemann 1210.8263]
[Grazzini, Sargsyan 1306.4581]

LL small-R resummation

[Dasgupta, Dreyer, Salam, Soyez 1411.5182]

Uncertainties with the JVE method

- Matched predictions for the 0-jet cross section have a more reliable error estimate. Different sources of uncertainty can be probed independently through variations of the appropriate scales (i.e. renorm./factor. scales vs. resummation scale Q)

- However, one would like a method for the determination of the uncertainties of exclusive cross sections which is:
    - robust against the inclusion of sizeable unknown effects, for instance exact quark-mass effects
    - reliable (i.e. resilient to accidental cancellations) even when the resummation is not available (e.g. combination of different jet multiplicities)
    - Not overly conservative in any kinematic regime

Uncertainties with the JVE method

- Jet Veto Efficiency (JVE) method's synopsis:

[Banfi, Salam, Zanderighi 1203.5773]

  - JVE is a ratio of perturbative quantities - i.e. it admits a number of possible definitions at each perturbative order

$$\sigma_{\rm tot,n} = \sum_{i=0}^{n} \sigma^{(i)}\,, \qquad \Sigma(p_{\rm t,veto}) = \sigma^{(0)} + \sum_{i=1}^{n} \Sigma^{(i)}(p_{\rm t,veto})$$

$$\Sigma^{(i)}(p_{\rm t,veto}) = \sigma^{(i)} + \bar{\Sigma}^{(i)}(p_{\rm t,veto}) \qquad \bar{\Sigma}^{(i)}(p_{\rm t,veto}) = -\int_{p_{\rm t,veto}}^{\infty} dp_{\rm t} \frac{d\Sigma^{(i)}(p_{\rm t})}{dp_{\rm t}}$$

  - In the large-logarithms region, JVE's uncertainty is dominated by Sudakov effects - i.e. uncertainties uncorrelated with the error in the total cross section

$$\Sigma(p_{\rm t,veto}) = \epsilon(p_{\rm t,veto})\sigma_{\rm tot} \qquad \delta\Sigma(p_{\rm t,veto}) = \sqrt{\epsilon^2\delta^2\sigma_{\rm tot} + \delta^2\epsilon\sigma_{\rm tot}^2}$$

Uncertainties with the JVE method

- e.g. at NNLO, three different efficiency schemes are available

$$\epsilon^{(a)}_{\rm NNLO}(p_{\rm t,veto}) = 1 + \frac{1}{\sigma_{\rm tot,2}} \sum_{i=1}^{2} \bar{\Sigma}^{(i)}(p_{\rm t,veto}) \,,$$

$$\epsilon^{(b)}_{\rm NNLO}(p_{\rm t,veto}) = 1 + \frac{1}{\sigma_{\rm tot,1}} \sum_{i=1}^{2} \bar{\Sigma}^{(i)}(p_{\rm t,veto}) \,,$$

$$\epsilon^{(c)}_{\rm NNLO}(p_{\rm t,veto}) = 1 + \frac{1}{\sigma_{\rm tot,0}} \left[\sum_{i=1}^{2} \bar{\Sigma}^{(i)}(p_{\rm t,veto}) - \frac{\sigma^{(1)}}{\sigma_{\rm tot,0}} \bar{\Sigma}^{(1)}(p_{\rm t,veto}) \right]$$

Spread between schemes sensitive to the convergence of *all* previous orders

- Resummation fits in naturally (each efficiency scheme corresponds to a different matching scheme), providing a better control of Sudakov effects, i.e. reducing the spread between different efficiency schemes (separation of uncertainty sources)

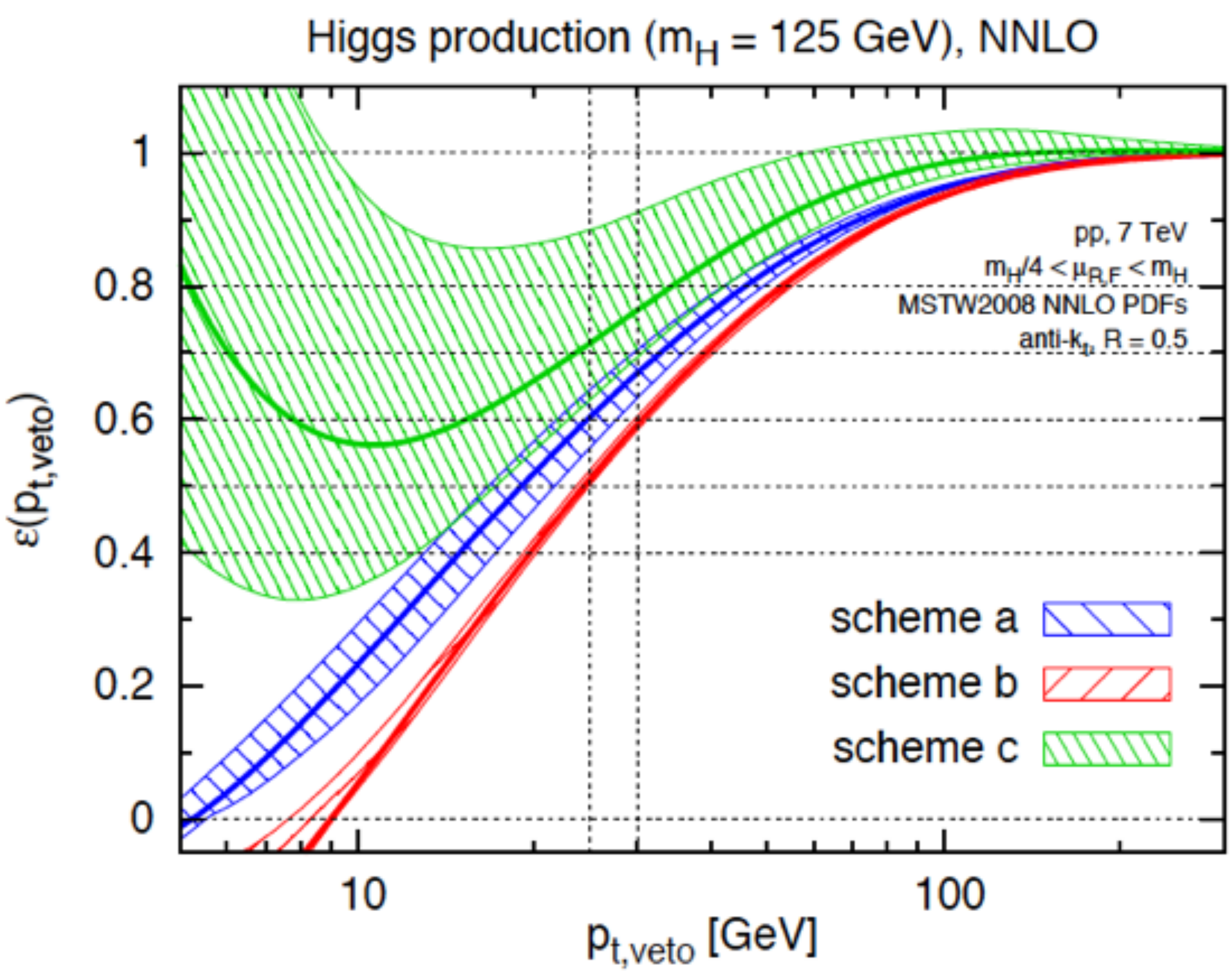
U… …thod

- e.g. a … available

$\epsilon^{(a)}_{\rm NNLO}(p_{\rm t,veto})$

$\epsilon^{(b)}_{\rm NNLO}(p_{\rm t,veto})$

$\epsilon^{(c)}_{\rm NNLO}(p_{\rm t,veto})$

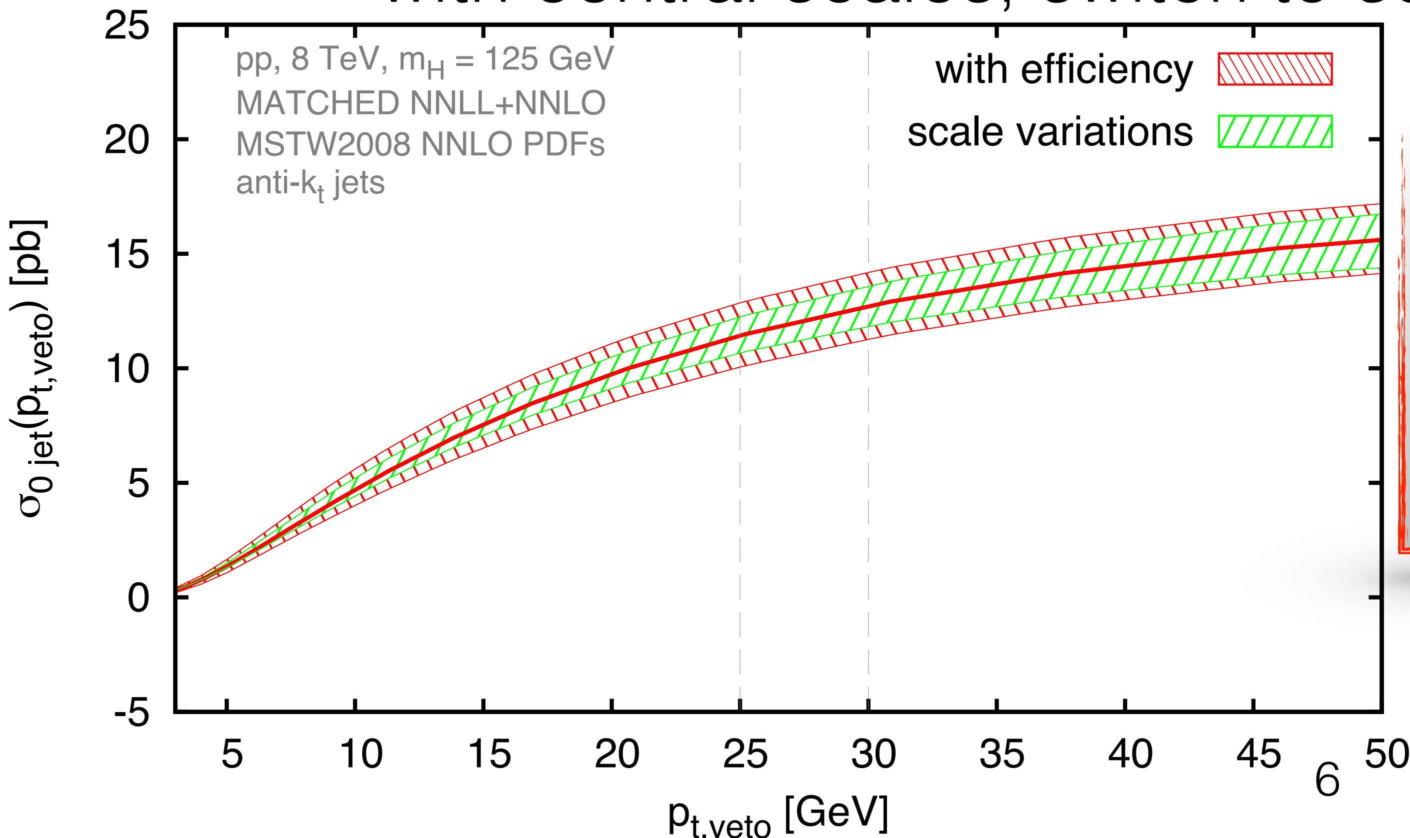


…hemes sensitive to the … *all* previous orders

- Resummation fits in naturally (each efficiency scheme corresponds to a different matching scheme), providing a better control of Sudakov effects, i.e. reducing the spread between different efficiency schemes (separation of uncertainty sources)

OLD JVE prescription

- Prescription at NNLO+NNLL (a.k.a. old JVE method): uncertainty for JVE as the envelope of the following variations
  - with scheme (a), vary scales μ_R/μ_F by a factor of 2 in either direction while keeping $1/2 \leq \mu_R/\mu_F \leq 2$
  - with central μ_R/μ_F , vary the resummation scale Q by a factor of 2
  - with central scales, switch to schemes (b), (c)



Final uncertainty in the 0-jet cross section slightly larger (but not overly conservative) than the Q, renorm./fact. scales variations. Slightly conservative estimate reasonable considering the large corrections at NNLO

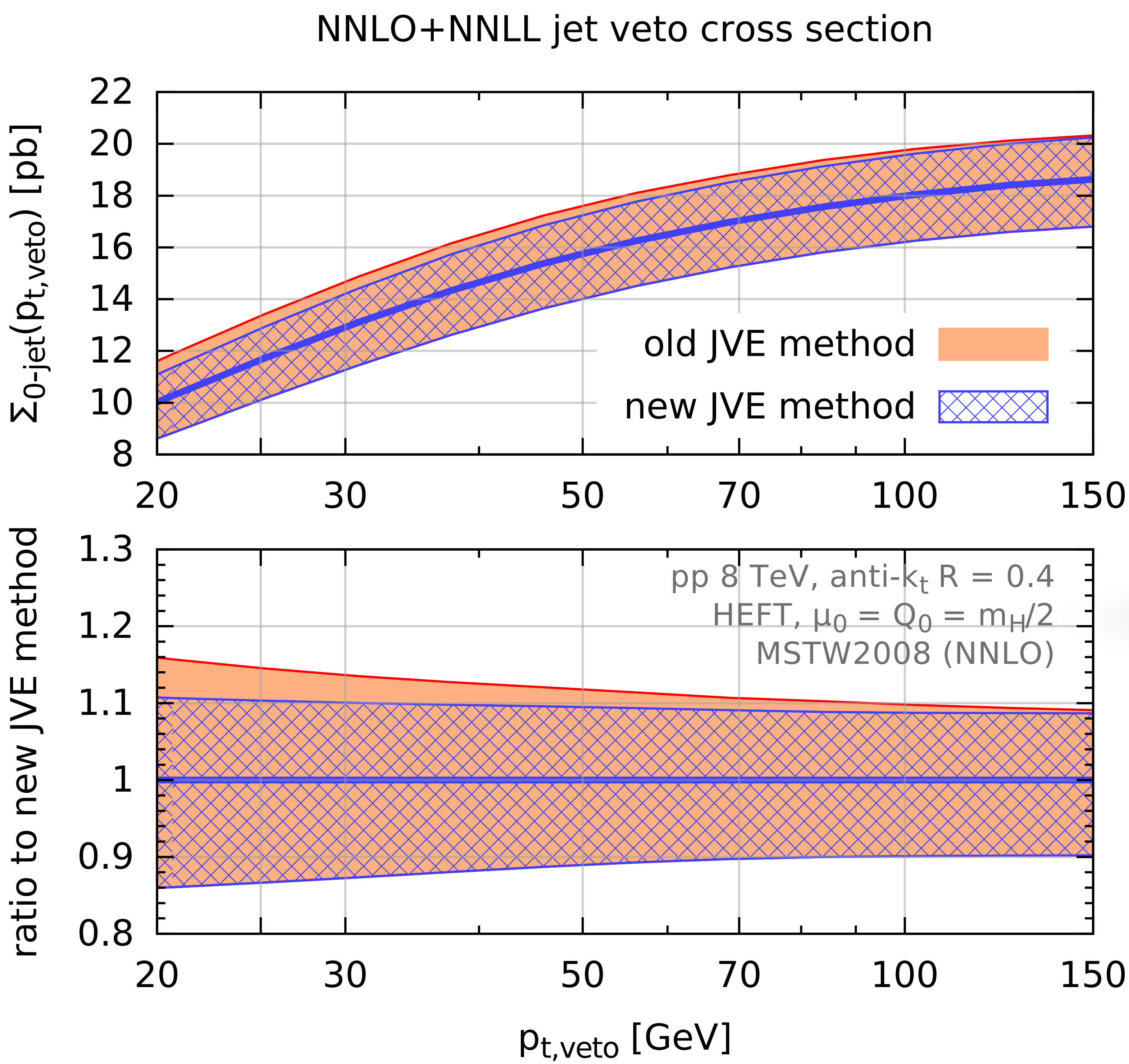
Updated JVE prescription for 0-jet bin

What's new

- Updated uncertainty prescription for the JVE:
  - with scheme (a), vary scales μ_R/μ_F by a factor of 2 in either direction while keeping $1/2 \leq \mu_R/\mu_F \leq 2$ (7 points)
  - keeping renormalisation and factorisation scales to their respective central values, vary the resummation scale ($Q_b = Q$) in the range $2/3 \leq Q/Q_0 \leq 3/2$
  - keeping central scales, switch to matching scheme (b)
  - with scheme (a) and keeping central scales, vary R_0 by a factor of 2
  - final uncertainty defined as the envelope of the above variations
- Uncertainty in the 0-jet cross section obtained by combining in quadrature with the error in the total cross section

$$\Sigma(p_{\mathrm{t,veto}}) = \epsilon(p_{\mathrm{t,veto}})\sigma_{\mathrm{tot}} \qquad \delta\Sigma(p_{\mathrm{t,veto}}) = \sqrt{\epsilon^2\delta^2\sigma_{\mathrm{tot}} + \delta^2\epsilon\sigma_{\mathrm{tot}}^2}$$

Updated NNLO+NNLL results at 8 TeV

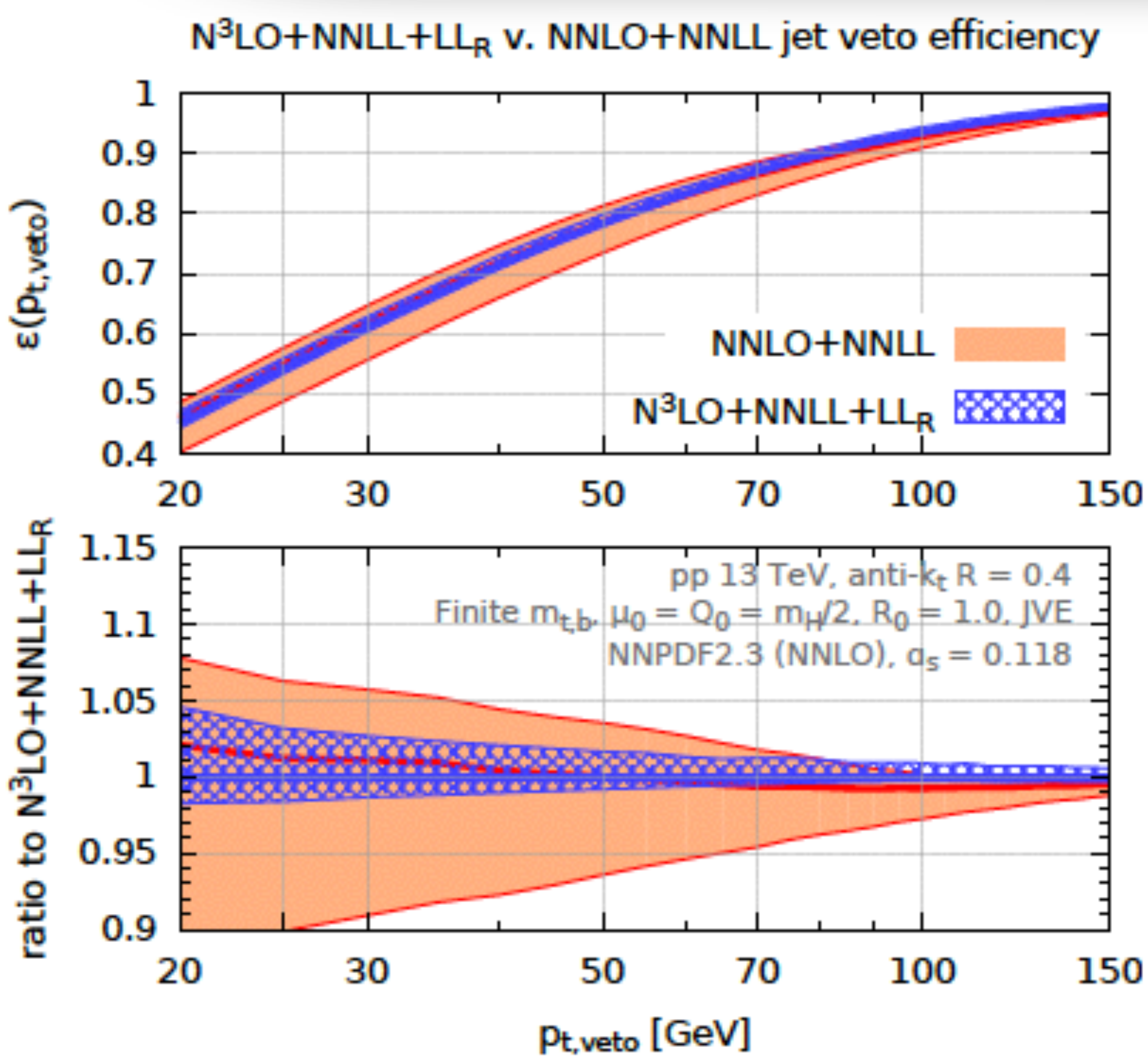


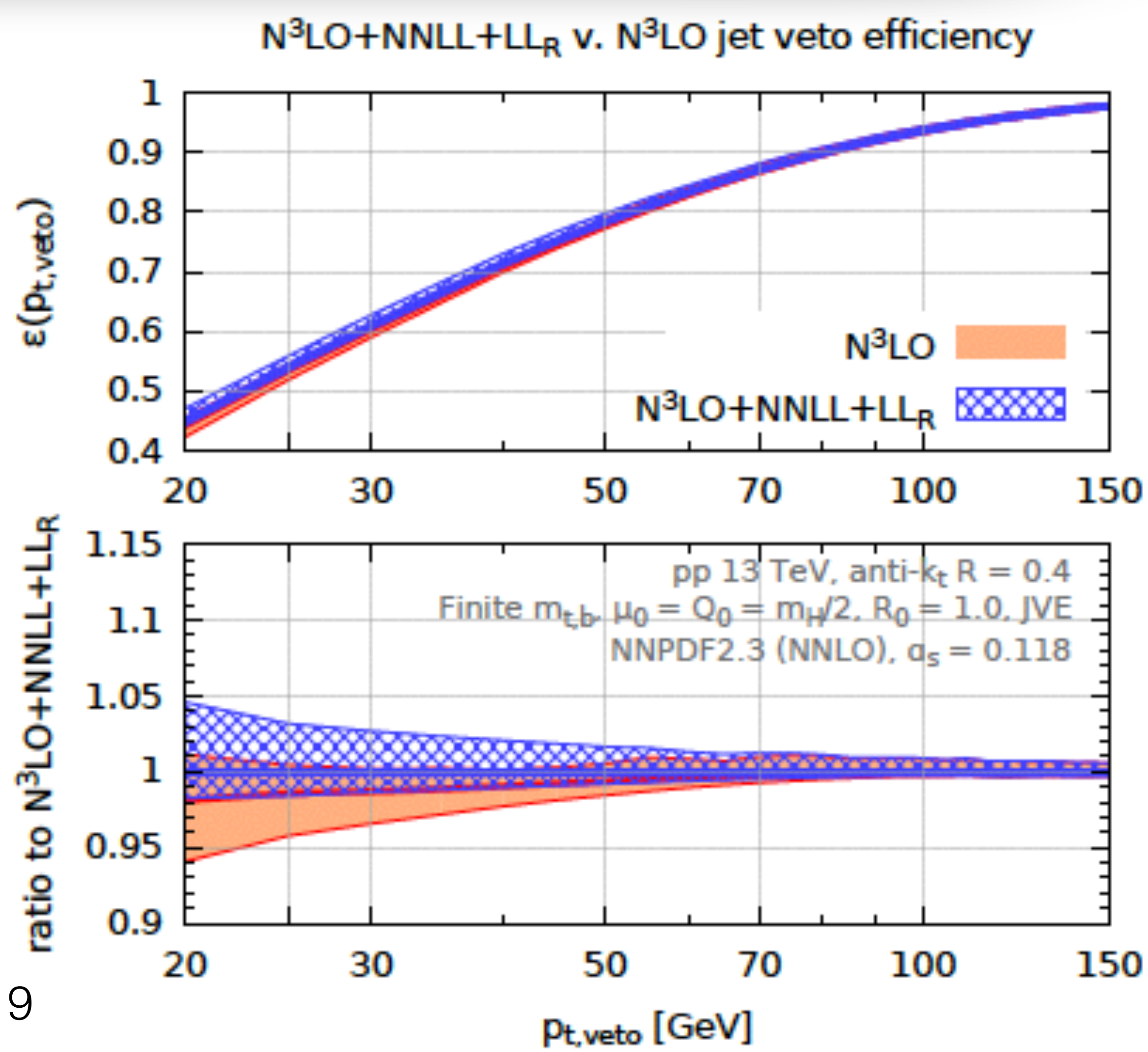
- Uncertainty reduction due to smaller range of Q variation at small pt, and absence of scheme (c) at high pt

Predictions at LHC13

- Jet-veto efficiency with $\mu_R = \mu_F = m_H/2$ (see backup for mH)

> - Moderate corrections w.r.t. NNLO+NNLL (~1-2%) - consistently, theory uncertainty reduced by more than a factor of two (~8% —> ~3%)
> - Impact of resummation w.r.t. N3LO at the 2% level - similar uncertainties (this is peculiar of this scale, doesn't occur at e.g. mH)

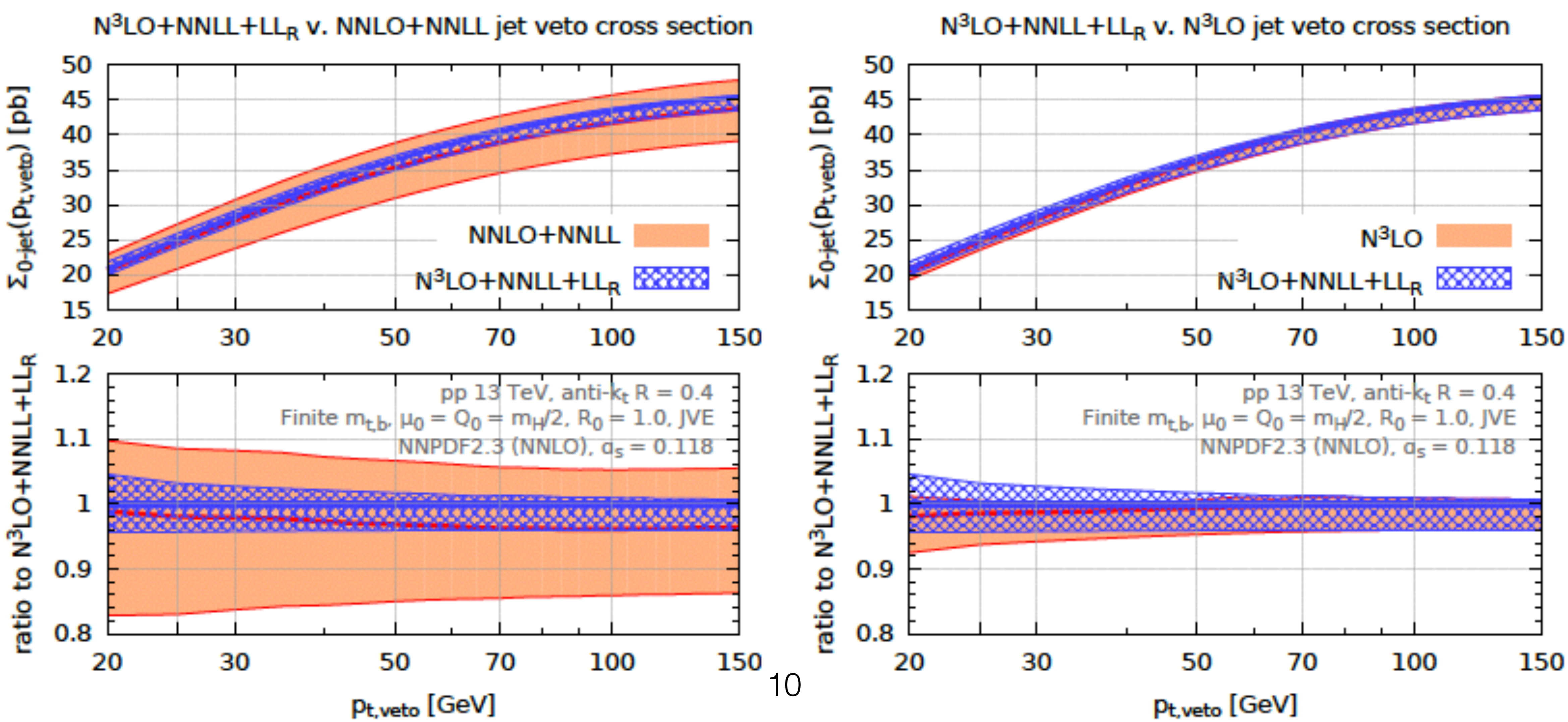




Predictions at LHC13

- 0-jet cross section with $\mu_R = \mu_F = m_H/2$

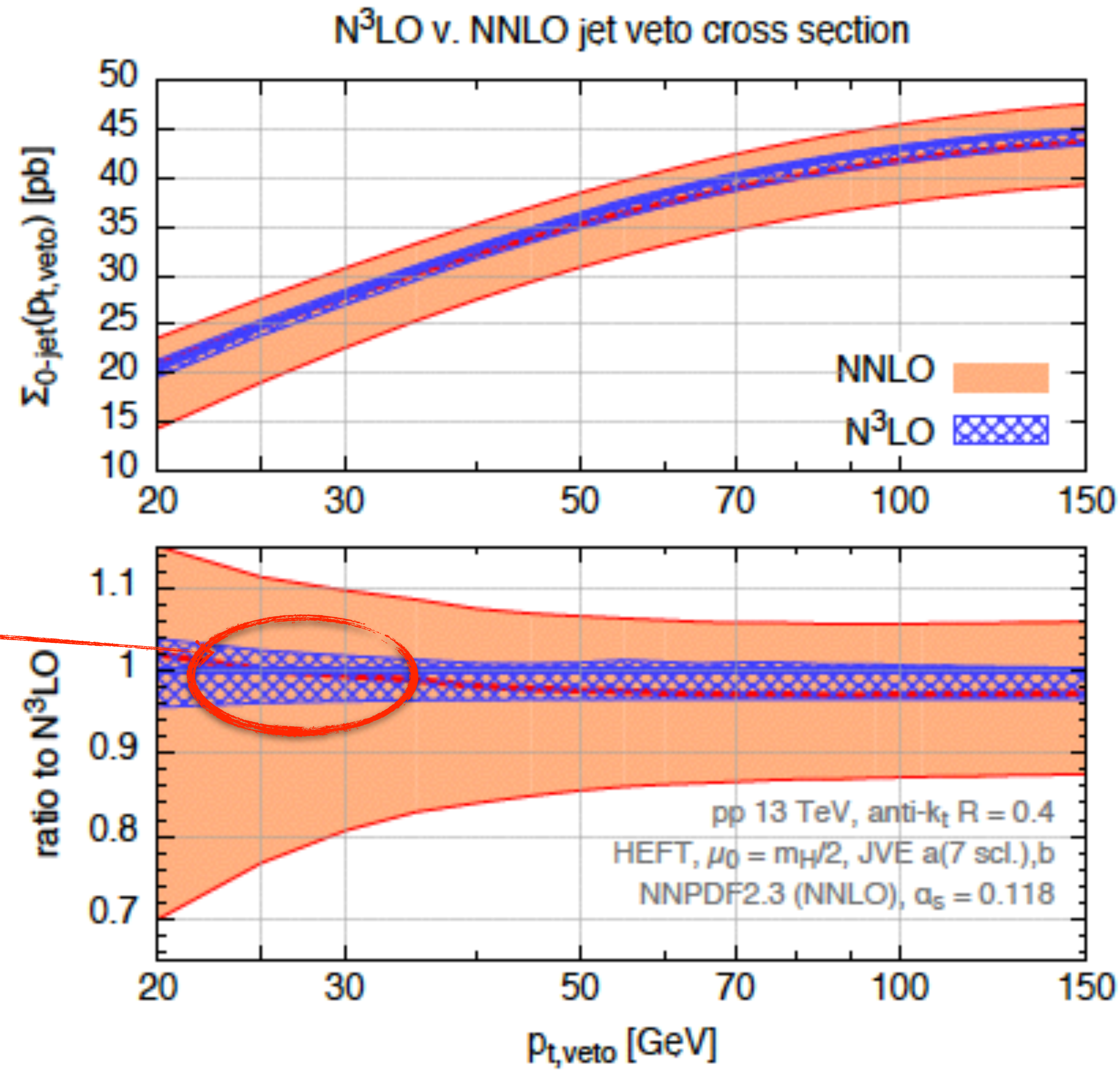
- Moderate increase in the 0-jet cross section (~2%) w.r.t. NNLO+NNLL - significant reduction of the theory uncertainty



Impact of NNLL resummation

- Important to understand (a priori) where exactly resummation and fixed-order are reliable (and estimate the matching uncertainty)

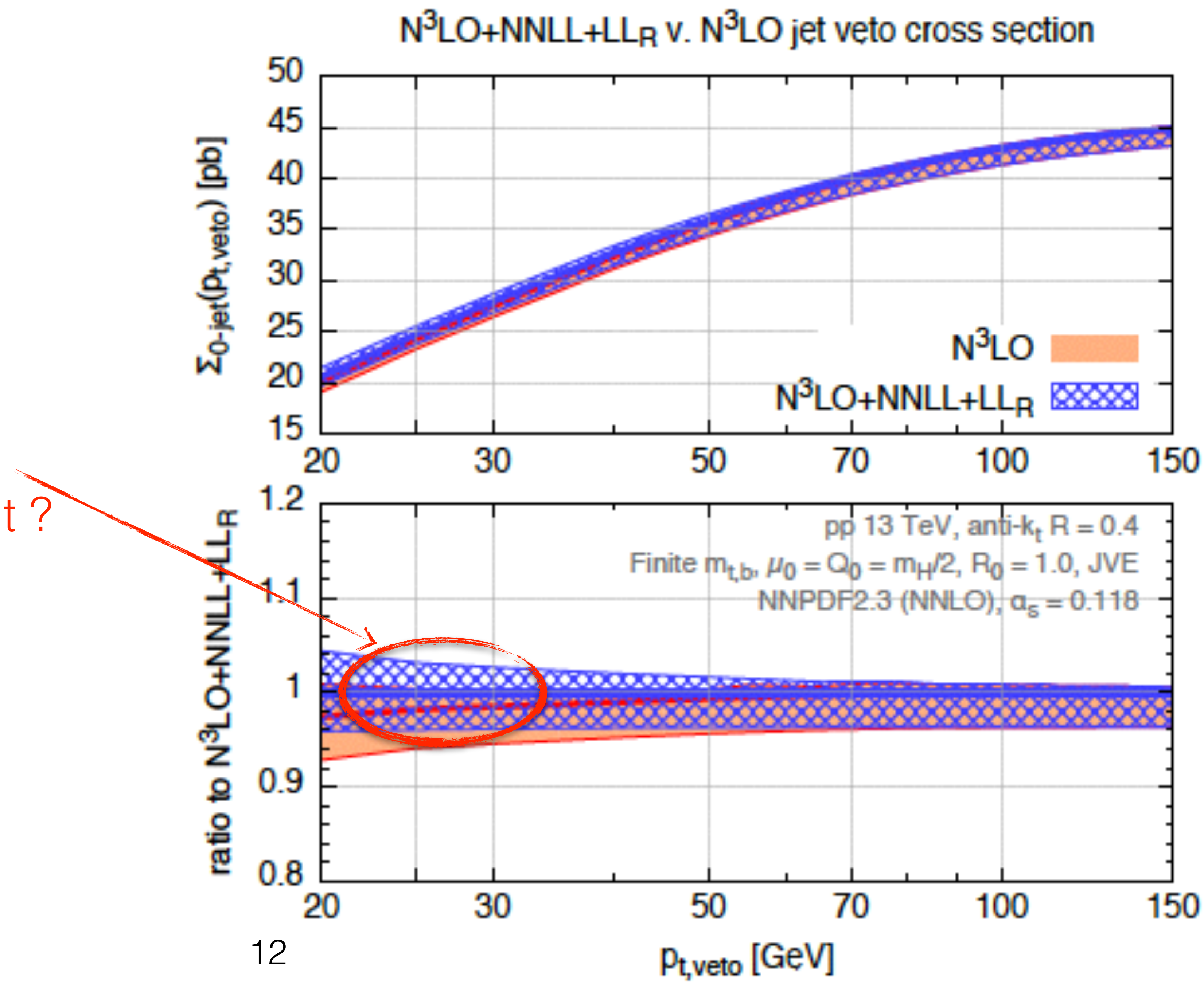
at pt ~25-30 GeV
N3LO (pure fixed order) corrections
have a 1-2% impact
(this varies with central scales)



Impact of NNLL resummation

- Important to understand (a priori) where exactly resummation and fixed-order are reliable (and estimate the matching uncertainty)

Impact of the resummation
is of the same order (~2%).
How accurate is this statement ?



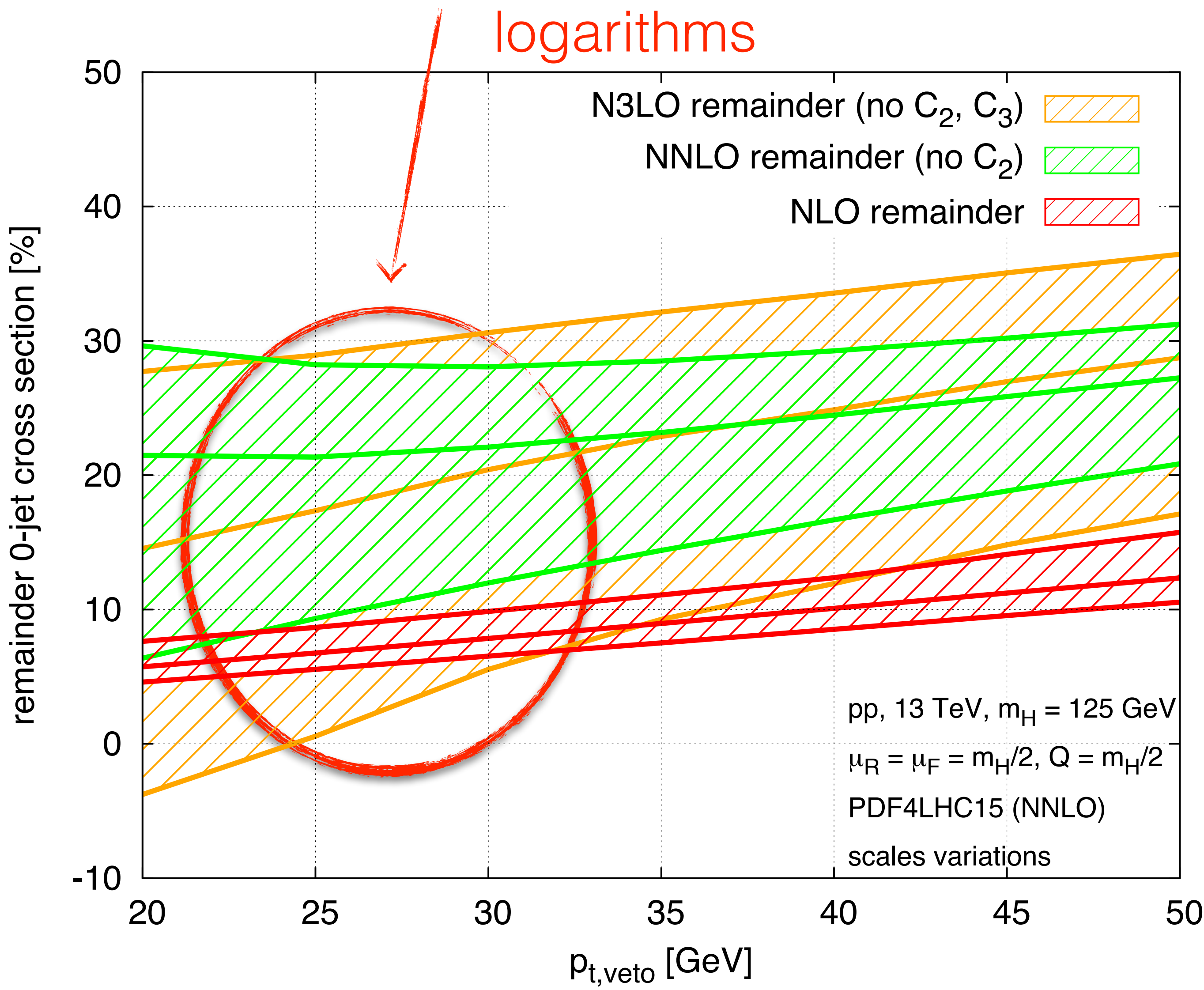
Impact of NNLL resummation

- Important to understand (a priori) where exactly resummation and fixed-order are reliable (and estimate the matching uncertainty)

pt ~ 25-30 GeV is a transition region where logarithms are the dominant part of the perturbative expansion, although fixed-order still works fine (i.e. the coupling suppression is still effective) Resummation effects seem physical.

Some care is required with the uncertainties (impact of matching scheme and modified logarithms)

~ 70-80% of the perturbative expansion is made of logarithms

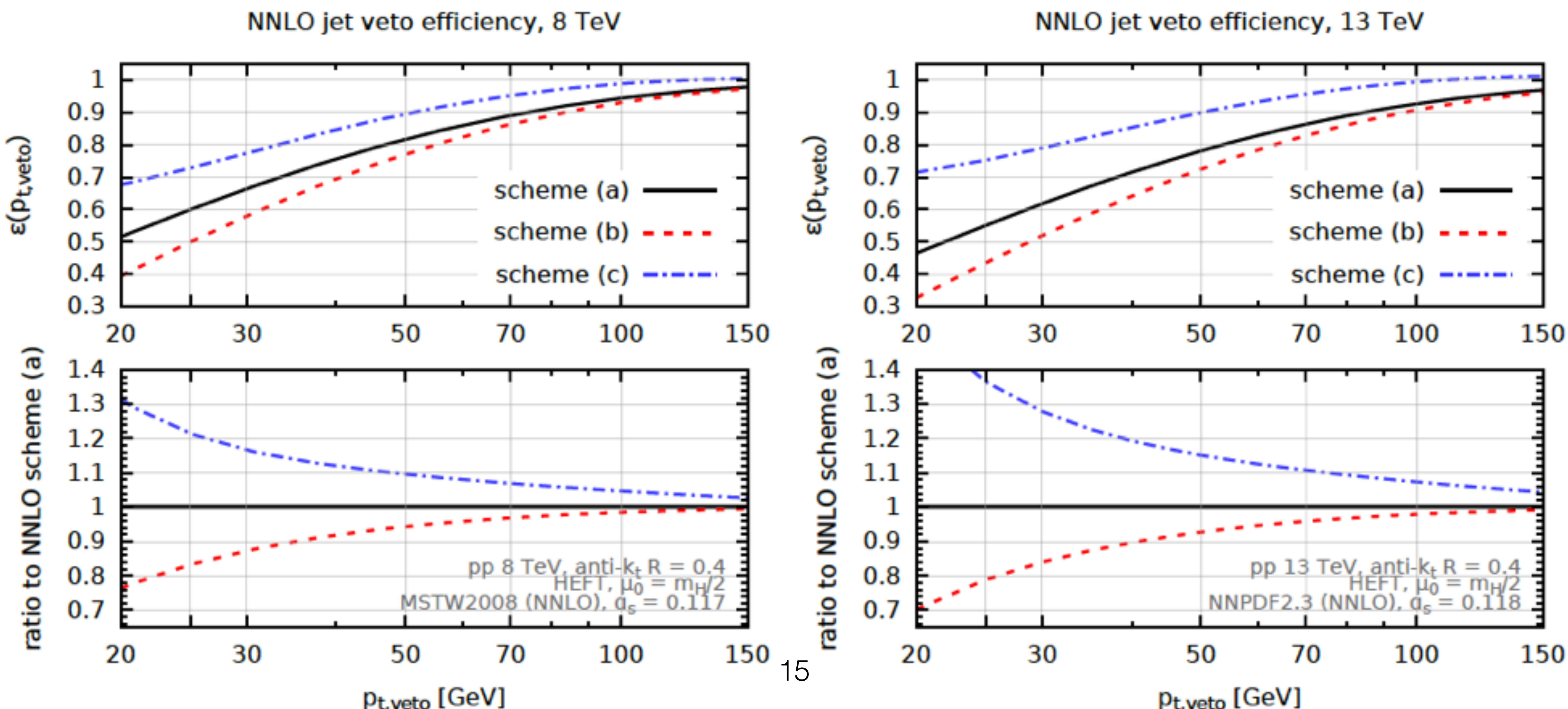


Differences with the OLD JVE prescription

Potential issues with efficiency schemes

- Possible issues can appear when the perturbative series for the total cross section features a very poor convergence, and the geometric expansion which defines the efficiency schemes can be badly defined

- This feature shows up already at NNLO for scheme (c) at larger c.o.m. energies —> NLO K factor grows from ~2.2 (8 TeV) to ~2.3 (13 TeV)

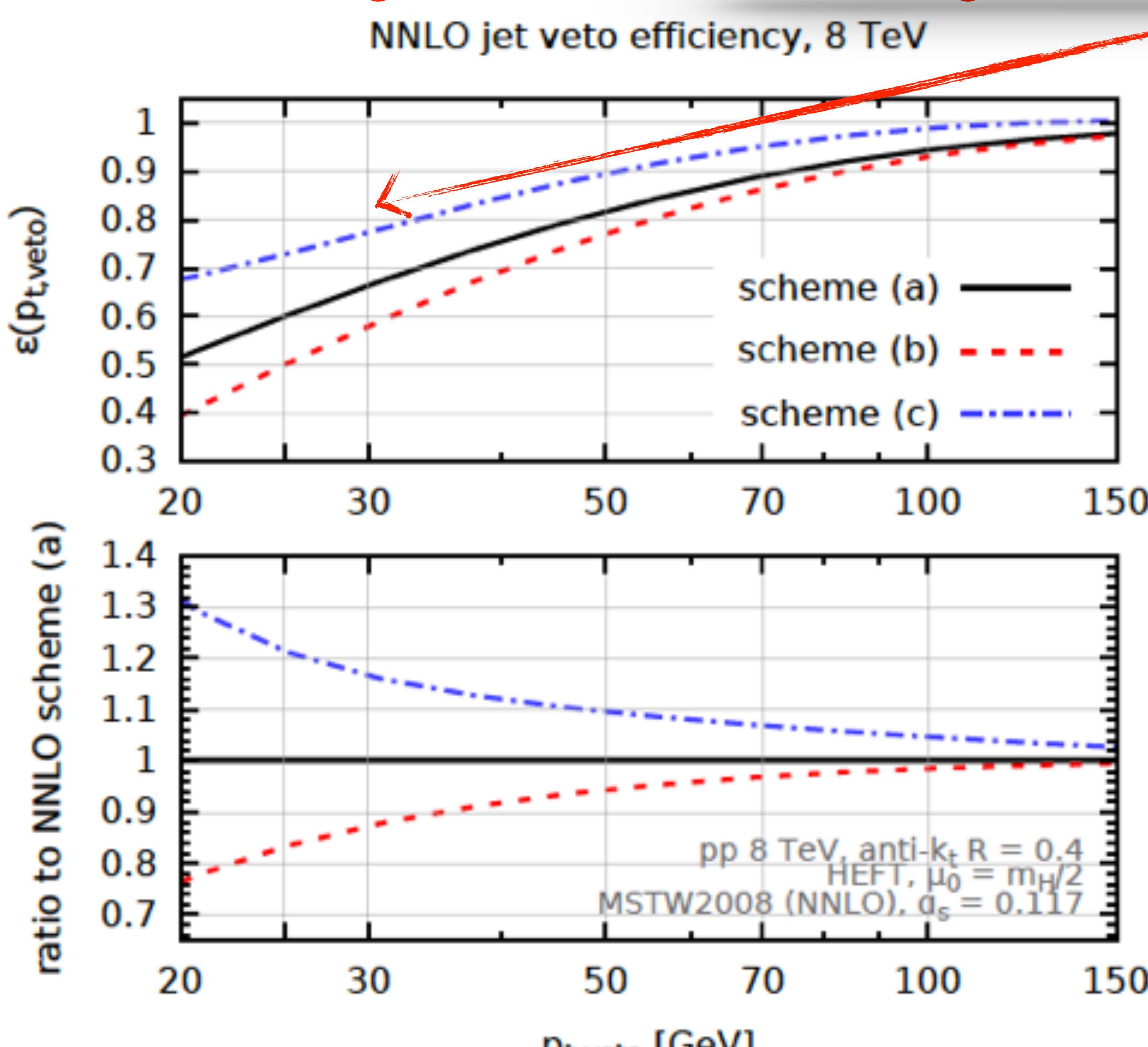


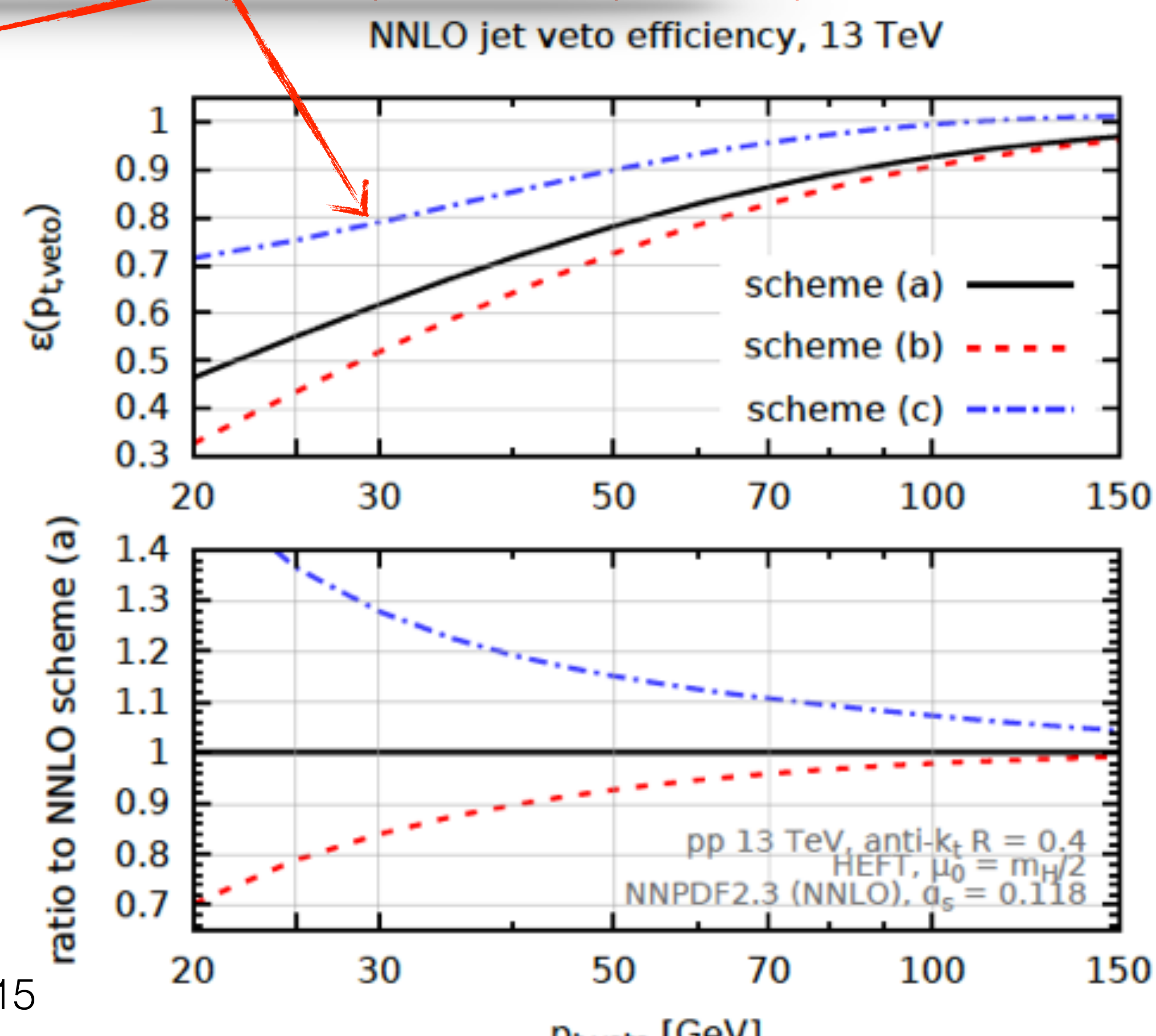
Potential issues with efficiency schemes

- Possible issues can appear when the perturbative series for the total cross section features a very poor convergence, and the geometric expansion which defines the efficiency schemes can be badly defined

- This feature shows … ger c.o.m. energies —> NLO … TeV)

Scheme (c)'s efficiency increases with the energy (unphysical)

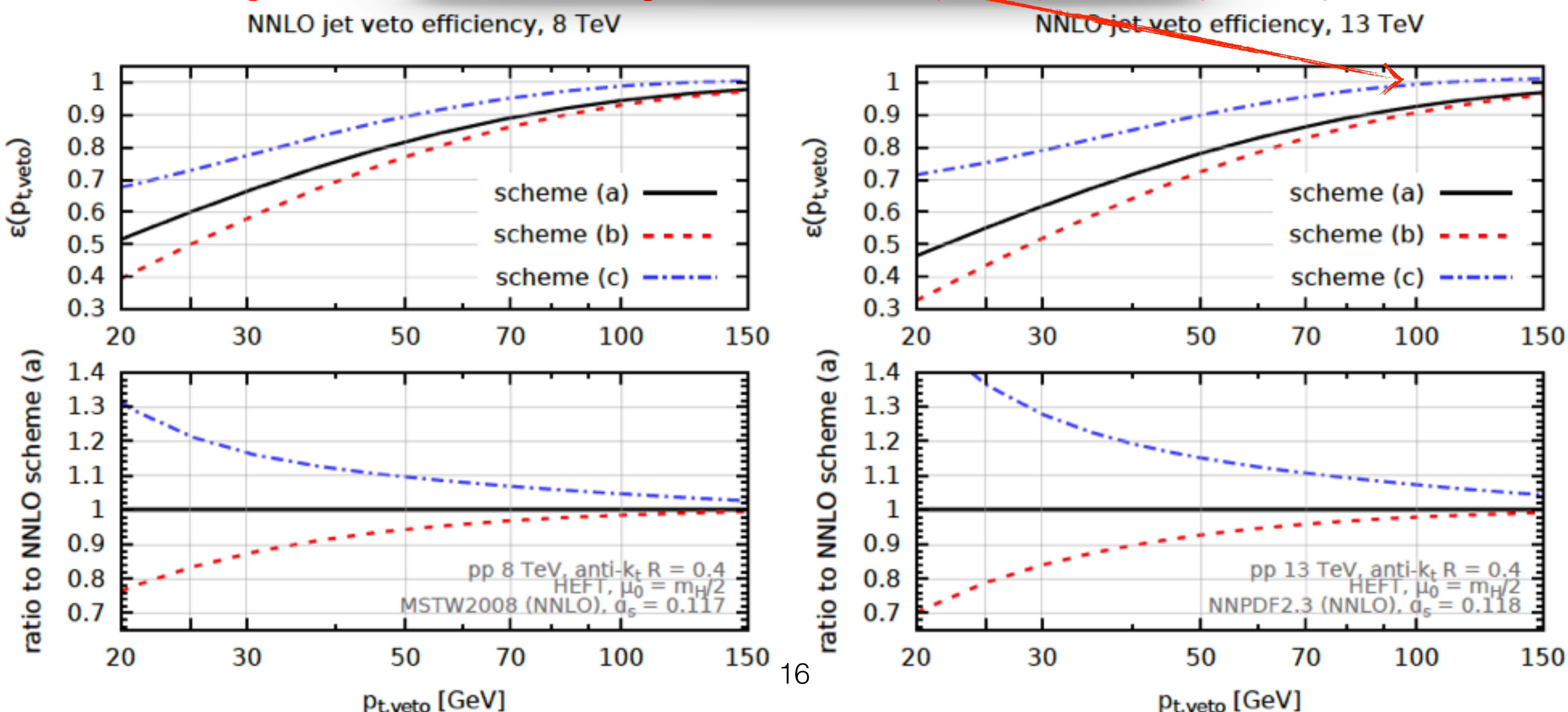




Potential issues with efficiency schemes

- Possible issues can appear when the perturbative series for the total cross section … the geometric expansion whic… …dly defined
- This feature sh… …t larger c.o.m. energies —> … (13 TeV)

Scheme (c)'s efficiency becomes larger than one at high scales. Overly large uncertainty also in the tail of the leading jet's pt spectrum compared to NNLO



Efficiency schemes at N3LO

- 5 schemes for the jet-veto efficiency available at this order for H

$\sigma^{(3)} \rightarrow$ [Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056]

$\bar{\Sigma}^{(3)}(p_{t,\mathrm{veto}}) \rightarrow$ [Boughezal, Caola, Melnikov, Petriello, Schulze 1504.07922]

$$\epsilon^{(a)}(p_{t,\mathrm{veto}}) = 1 + \frac{1}{\sigma_{\mathrm{tot},3}} \sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\mathrm{veto}})$$

$$\epsilon^{(b)}(p_{t,\mathrm{veto}}) = 1 + \frac{1}{\sigma_{\mathrm{tot},2}} \sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\mathrm{veto}}) \,,$$

$$\epsilon^{(c)}(p_{t,\mathrm{veto}}) = 1 + \frac{1}{\sigma_{\mathrm{tot},1}} \left[\sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\mathrm{veto}}) - \frac{\sigma^{(2)}}{\sigma_{\mathrm{tot},0}} \bar{\Sigma}^{(1)}(p_{t,\mathrm{veto}})\right],$$

$$\epsilon^{(c')}(p_{t,\mathrm{veto}}) = 1 + \frac{1}{\sigma_{\mathrm{tot},1}} \left[\sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\mathrm{veto}}) - \frac{\sigma^{(2)}}{\sigma_{\mathrm{tot},1}} \bar{\Sigma}^{(1)}(p_{t,\mathrm{veto}})\right],$$

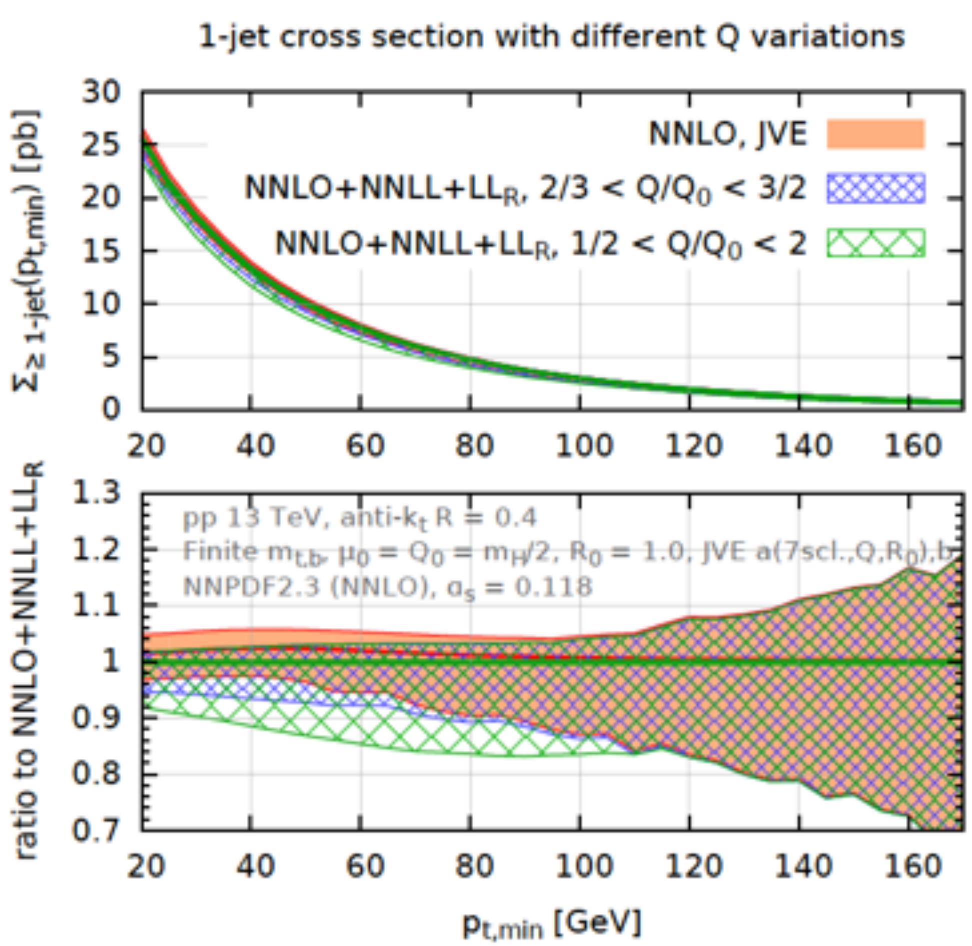
$$\rightarrow \sigma_{\mathrm{tot},1} = \sigma^{(0)} + \sigma^{(1)}$$

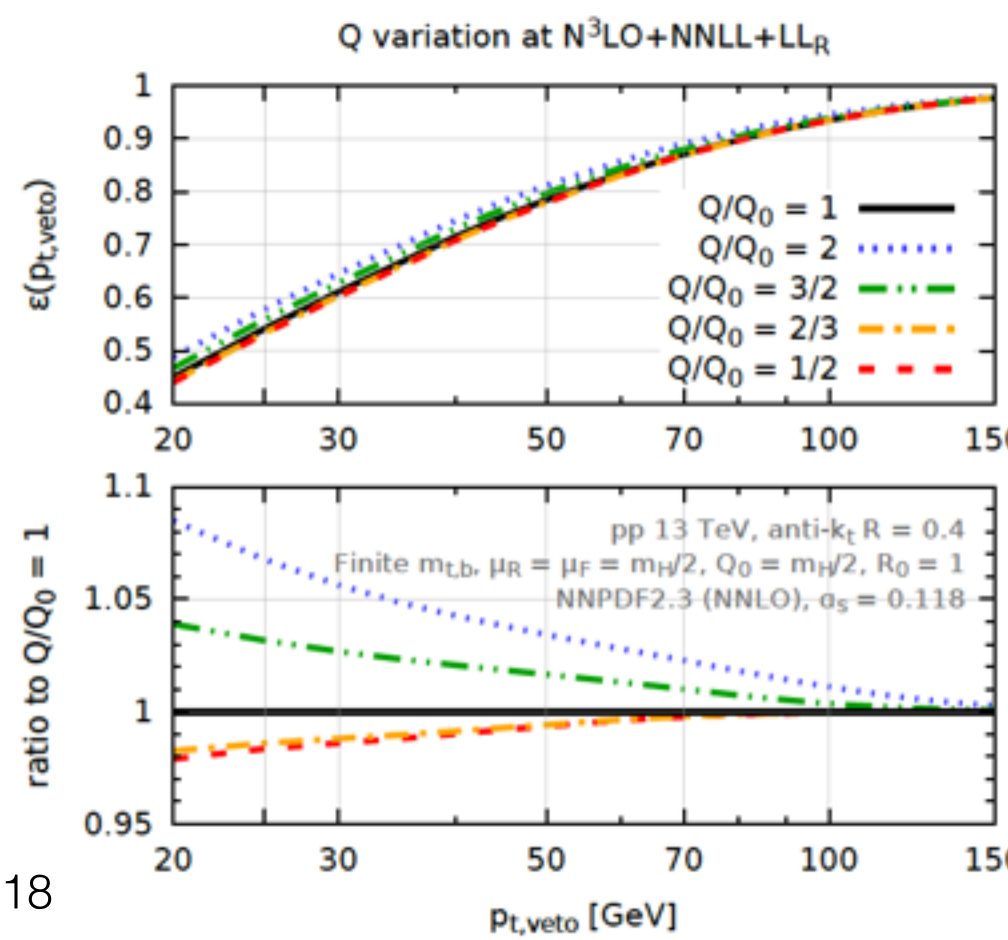
$$\epsilon^{(d)}(p_{t,\mathrm{veto}}) = 1 + \frac{1}{\sigma_{\mathrm{tot},0}} \left[\sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\mathrm{veto}}) - \frac{\sigma^{(1)}}{\sigma_{\mathrm{tot},0}} (\bar{\Sigma}^{(1)}(p_{t,\mathrm{veto}}) + \bar{\Sigma}^{(2)}(p_{t,\mathrm{veto}})) + \frac{\sigma^{(1)}\sigma^{(1)} - \sigma^{(0)}\sigma^{(2)}}{(\sigma_{\mathrm{tot},0})^2} \bar{\Sigma}^{(1)}(p_{t,\mathrm{veto}})\right].$$

Schemes (c) and (d) are sensible only if the NLO K factor is small, therefore show the same issues as scheme (c) at NNLO

Resummation uncertainties

- Matching to NNLL resummation of jet-veto logarithms is performed by means of two multiplicative matching schemes which correspond to the two efficiency schemes (a) and (b) respectively
- In addition to μ_R/μ_F scales (x 2) and schemes (a,b) variations, the size of subleading logarithmic terms is estimated by varying the resummation scale Q around its central value $Q_0 = m_H/2$:
$$\ln \frac{M}{p_{\mathrm{t,veto}}} \to \ln \frac{Q}{p_{\mathrm{t,veto}}} + \ln \frac{M}{Q}$$
    - The old variation range $1/2 \leq Q/Q_0 \leq 2$ is conservative and allows for resummation effects up to $\sim m_H$ (larger uncertainty band in tail of jet pt spectrum)





Resummation uncertainties

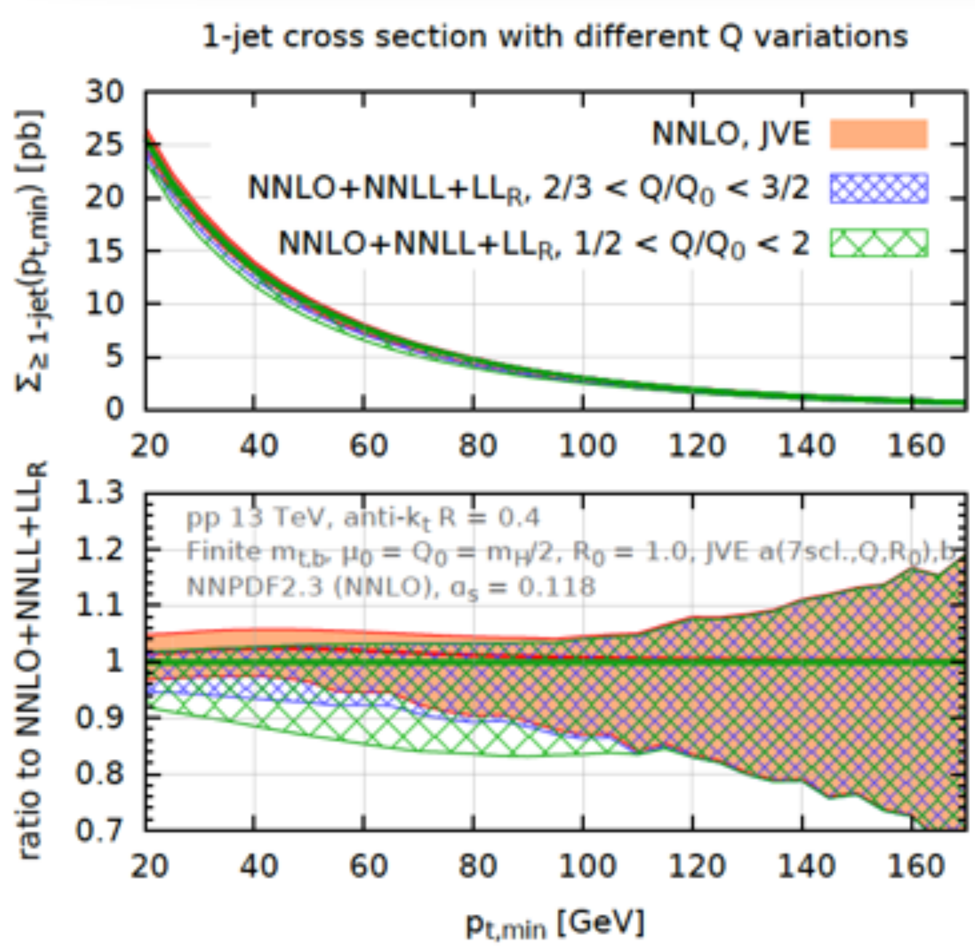
- Matching to NNLL resummation of jet-veto logarithms is performed by means of two multiplicative matching schemes which correspond to the two efficiency schemes (a) and (b) respectively

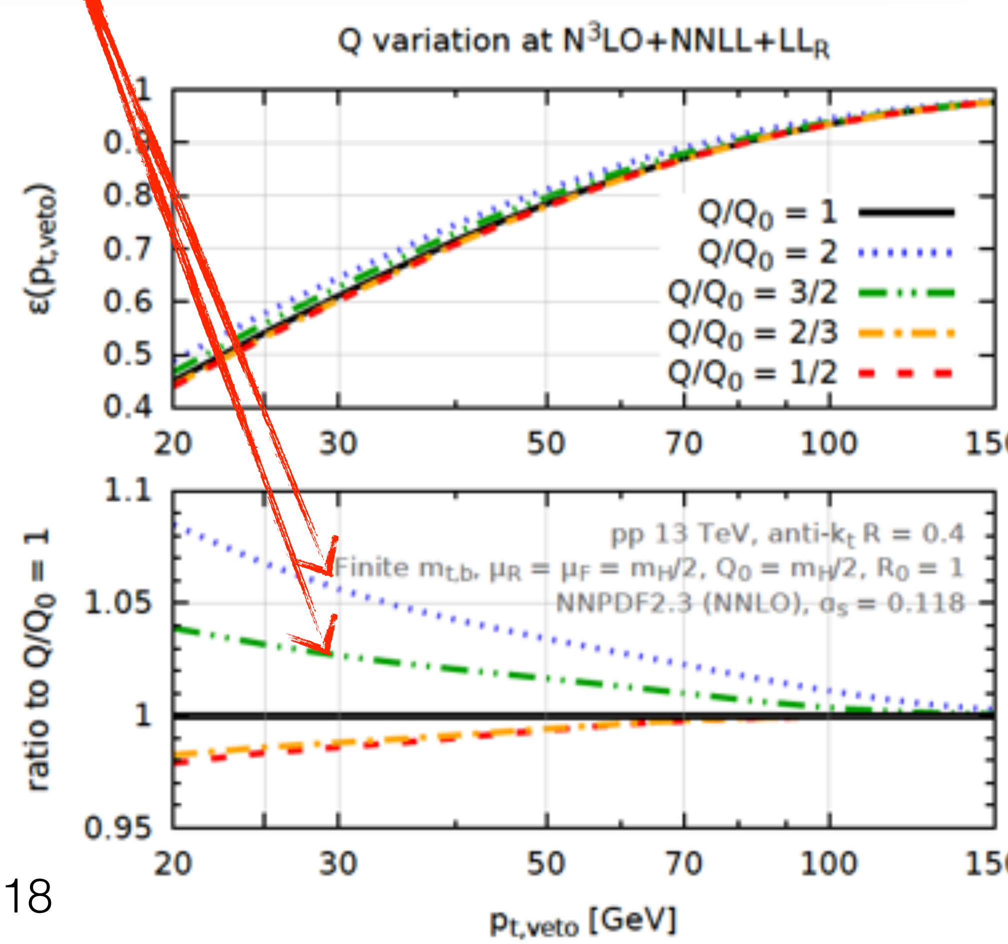
- In ... ding log ... ntral val ...

    - ... ation effects up to $\sim m_H$ (larger uncertainty band in tail of jet pt spectrum)

- Given the good convergence observed with the inclusion of N3LO corrections, we use the variation range $2/3 \leq Q/Q_0 \leq 3/2$ which gives a less conservative uncertainty at large pt

- The Q dependence is reduced everywhere along the spectrum



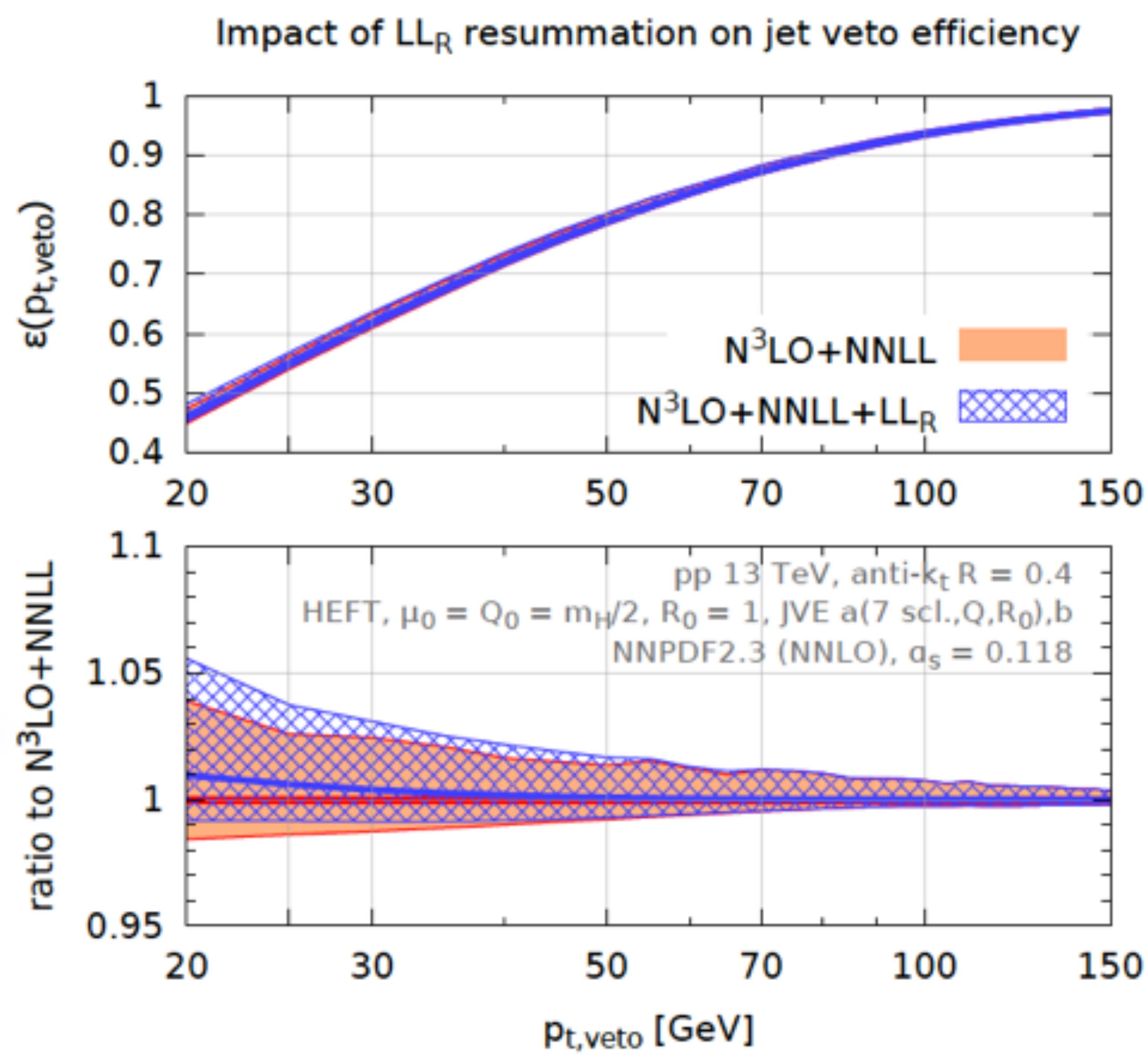


Jet radius logarithms

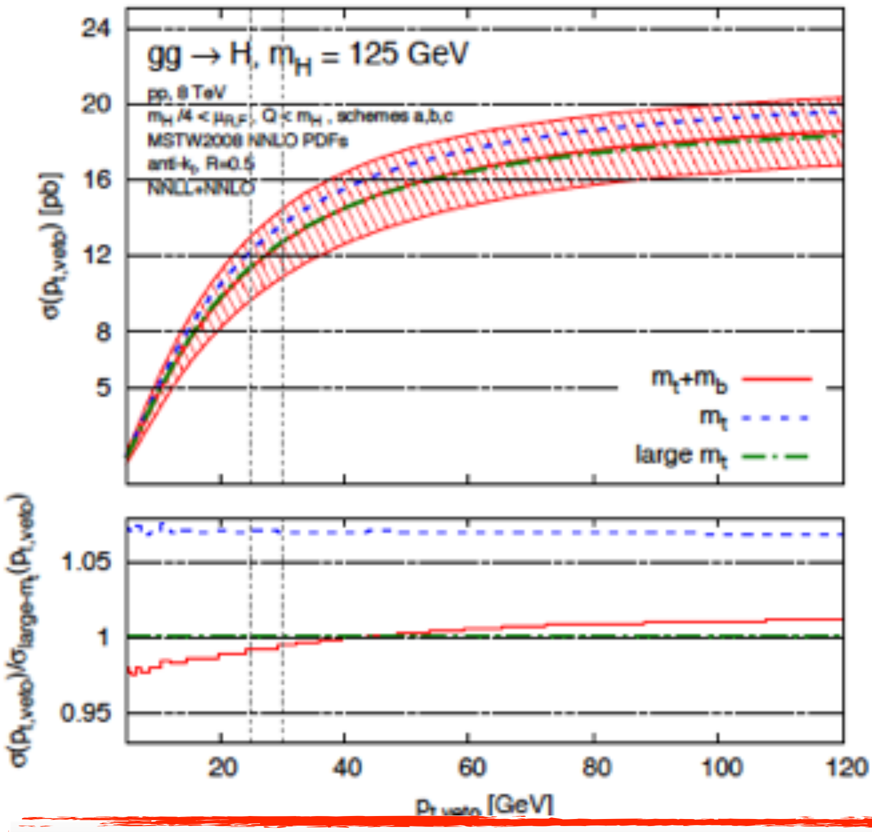
[Dasgupta, Dreyer, Salam, Soyez 1411.5182]

- In addition to the other theoretical uncertainties previously considered, the error associated with small-R resummation is estimated by varying $1/2 \leq R_0 \leq 2$

- Small impact (~1%) with R=0.4
- Slight increase in uncertainty band due to larger Q dependence of the all-order correlated contribution (gluon splitting)
- R_0 dependence moderate (backup)

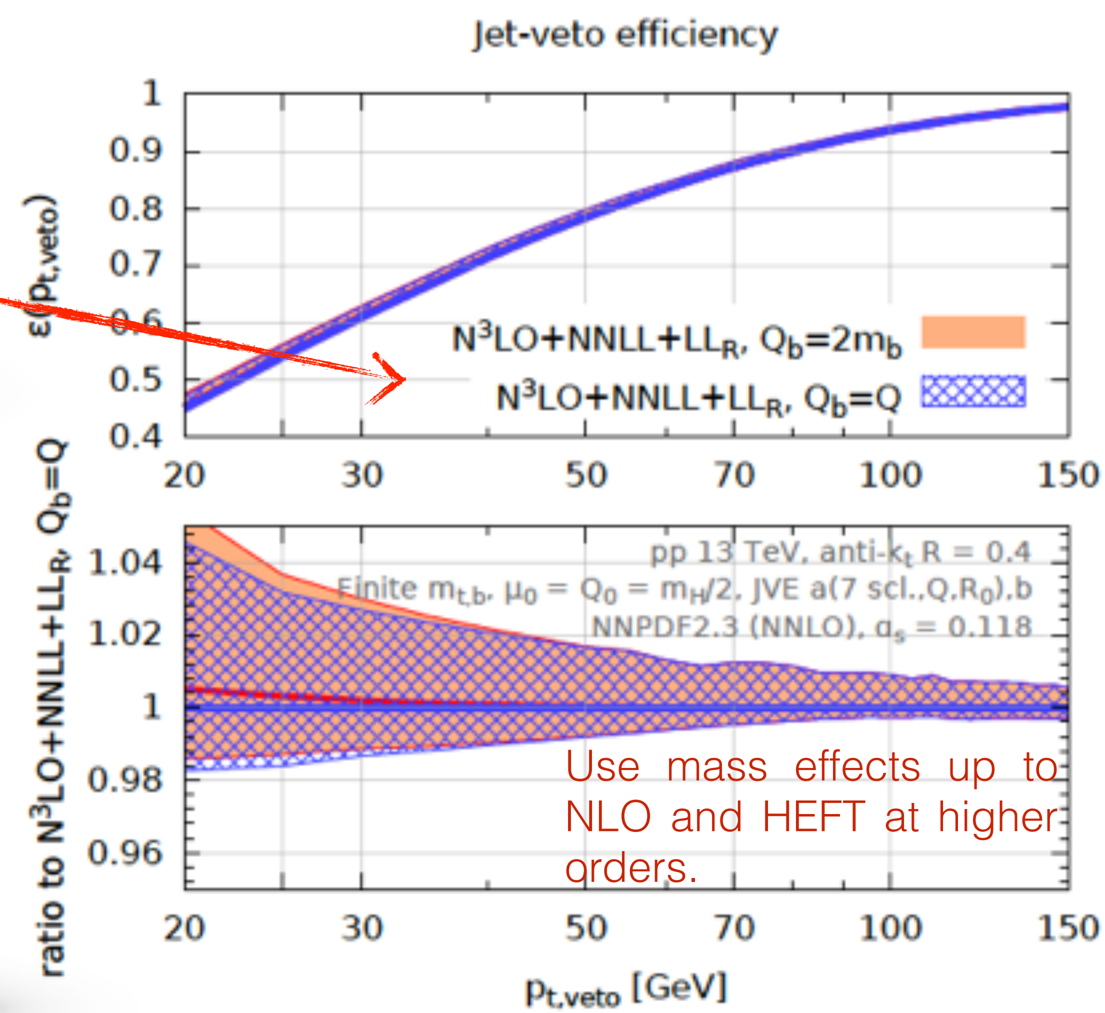


Quark-mass effects



- Treat "bottom" logs on the same footing as other regular terms which vanish when $p_t \to 0$
  [Banfi, PM, Zanderighi 1308.4634]
  [Mantler, Wiesemann 1210.8263]
- Switch off resummation around mb for the bottom contribution (i.e. set $Q_b \sim m_b$)
  [Grazzini, Sargsyan 1306.4581]

Here Q_b is varied by a factor of 2 in the $Q_b = 2m_b$ case, while for the second case with $Q_b = Q$ we stick to the nominal variation by a factor of 3/2



- Difference between the two prescriptions is negligible above 20 GeV therefore we choose to set $Q_b = Q = m_H/2$
- resummation of mass logs moderate at DL (abelian lim)
  [Melnikov, Penin 1602.09020]
- NNLO calculation desirable - will also help establish which prescription is more appropriate
  [gg->hg in Melnikov, Tancredi, Wever 1610.03747]

Including a one-jet bin

The case with 3 jet bins

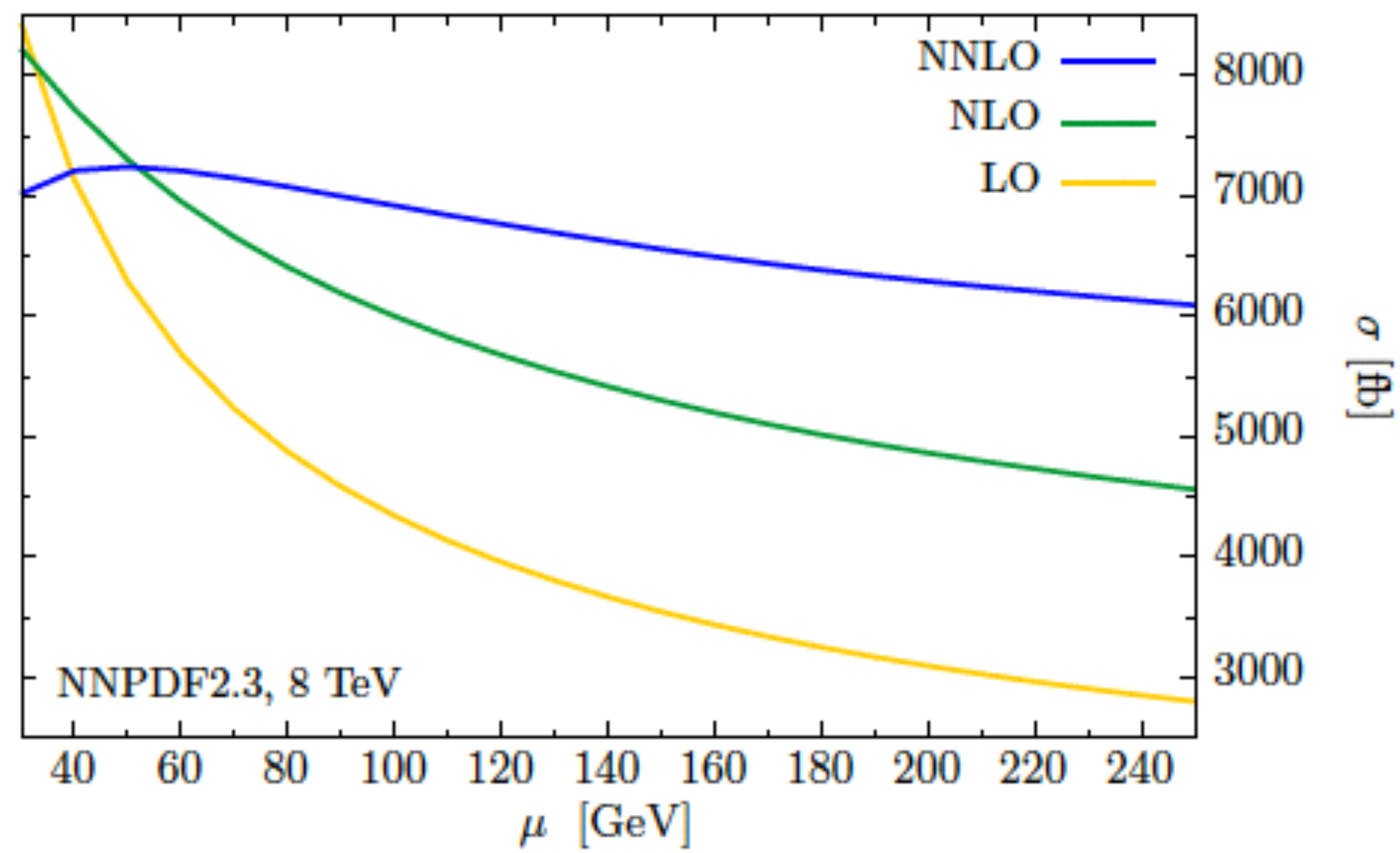
The (exclusive) 1-jet bin can be added - 3 schemes available at NNLO

$$\epsilon_1^{(a)} = 1 - \frac{\sigma_{\geq 2-\mathrm{jet}}^{\mathrm{NLO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{NNLO}}},$$

$$\epsilon_1^{(b)} = 1 - \frac{\sigma_{\geq 2-\mathrm{jet}}^{\mathrm{NLO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{NLO}}},$$

$$\epsilon_1^{(c)} = 1 - \frac{\sigma_{\geq 2-\mathrm{jet}}^{\mathrm{NLO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{LO}}} + \left(\frac{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{NLO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{LO}}} - 1\right) \frac{\sigma_{\geq 2-\mathrm{jet}}^{\mathrm{LO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{LO}}}.$$

NLO K factor for the inclusive XS within the radius of convergence. Scheme (c) is sensible in this case



The case with 3 jet bins

The (exclusive) 1-jet bin can be added - 3 schemes available at NNLO

[PM Les Houches proceedings 2013]

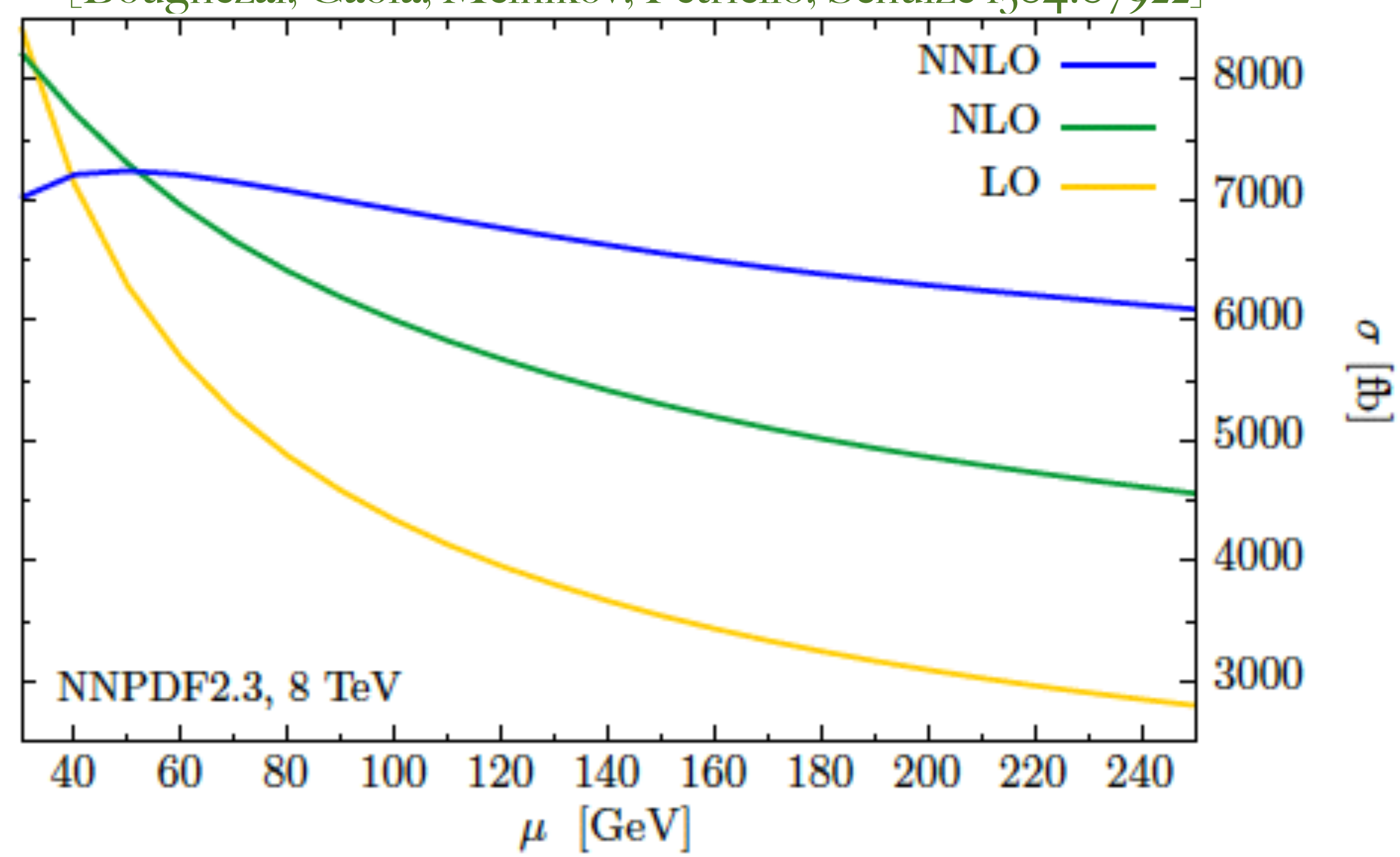
$$\epsilon_1^{(a)} = 1 - \frac{\sigma_{\geq 2-\mathrm{jet}}^{\mathrm{NLO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{NNLO}}},$$

$$\epsilon_1^{(b)} = 1 - \frac{\sigma_{\geq 2-\mathrm{jet}}^{\mathrm{NLO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{NLO}}},$$

$$\epsilon_1^{(c)} = 1 - \frac{\sigma_{\geq 2-\mathrm{jet}}^{\mathrm{NLO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{LO}}} + \left(\frac{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{NLO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{LO}}} - 1\right)\frac{\sigma_{\geq 2-\mathrm{jet}}^{\mathrm{LO}}}{\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{LO}}}.$$

NLO K factor for the inclusive XS within the radius of convergence. Scheme (c) is sensible in this case

[Boughezal, Caola, Melnikov, Petriello, Schulze 1504.07922]



The case with 3 jet bins: covariance matrix

The (exclusive) 1-jet bin can be added - 3 schemes available at NNLO

$$\mathrm{Cov}[\sigma_{0-\mathrm{jet}}, \sigma_{1-\mathrm{jet}}, \sigma_{\geq 2-\mathrm{jet}}] = \begin{pmatrix} \Delta\sigma_{0-\mathrm{jet}} \cdot \Delta\sigma_{0-\mathrm{jet}} & \Delta\sigma_{0-\mathrm{jet}} \cdot \Delta\sigma_{1-\mathrm{jet}} & \Delta\sigma_{0-\mathrm{jet}} \cdot \Delta\sigma_{\geq 2-\mathrm{jet}} \\ & \Delta\sigma_{1-\mathrm{jet}} \cdot \Delta\sigma_{1-\mathrm{jet}} & \Delta\sigma_{1-\mathrm{jet}} \cdot \Delta\sigma_{\geq 2-\mathrm{jet}} \\ & & \Delta\sigma_{\geq 2-\mathrm{jet}} \cdot \Delta\sigma_{\geq 2-\mathrm{jet}} \end{pmatrix}$$

$$\begin{aligned} \Delta\sigma_{0-\mathrm{jet}} &= (0\,,\ \sigma_{\mathrm{tot}}\delta\epsilon_0\,,\ \epsilon_0\delta\sigma_{\mathrm{tot}})\,, \\ \Delta\sigma_{1-\mathrm{jet}} &= ((1-\epsilon_0)\sigma_{\mathrm{tot}}\delta\epsilon_1\,,\ -\epsilon_1\sigma_{\mathrm{tot}}\delta\epsilon_0\,,\ \epsilon_1(1-\epsilon_0)\delta\sigma_{\mathrm{tot}})\,, \\ \Delta\sigma_{\geq 2-\mathrm{jet}} &= (-(1-\epsilon_0)\sigma_{\mathrm{tot}}\delta\epsilon_1\,,\ -(1-\epsilon_1)\sigma_{\mathrm{tot}}\delta\epsilon_0\,,\ (1-\epsilon_1)(1-\epsilon_0)\delta\sigma_{\mathrm{tot}}). \end{aligned}$$

The case with 3 jet bins: covariance matrix

The (exclusive) 1-jet bin can be added - 3 schemes available at NNLO

[PM Les Houches proceedings 2013]

$$\mathrm{Cov}[\sigma_{0-\mathrm{jet}}, \sigma_{1-\mathrm{jet}}, \sigma_{\geq 2-\mathrm{jet}}] = \begin{pmatrix} \Delta\sigma_{0-\mathrm{jet}} \cdot \Delta\sigma_{0-\mathrm{jet}} & \Delta\sigma_{0-\mathrm{jet}} \cdot \Delta\sigma_{1-\mathrm{jet}} & \Delta\sigma_{0-\mathrm{jet}} \cdot \Delta\sigma_{\geq 2-\mathrm{jet}} \\ & \Delta\sigma_{1-\mathrm{jet}} \cdot \Delta\sigma_{1-\mathrm{jet}} & \Delta\sigma_{1-\mathrm{jet}} \cdot \Delta\sigma_{\geq 2-\mathrm{jet}} \\ & & \Delta\sigma_{\geq 2-\mathrm{jet}} \cdot \Delta\sigma_{\geq 2-\mathrm{jet}} \end{pmatrix}$$

$$\begin{aligned} \Delta\sigma_{0-\mathrm{jet}} &= (0\,,\ \sigma_{\mathrm{tot}}\delta\epsilon_0\,,\ \epsilon_0\delta\sigma_{\mathrm{tot}})\,, \\ \Delta\sigma_{1-\mathrm{jet}} &= ((1-\epsilon_0)\sigma_{\mathrm{tot}}\delta\epsilon_1\,,\ -\epsilon_1\sigma_{\mathrm{tot}}\delta\epsilon_0\,,\ \epsilon_1(1-\epsilon_0)\delta\sigma_{\mathrm{tot}})\,, \\ \Delta\sigma_{\geq 2-\mathrm{jet}} &= (-(1-\epsilon_0)\sigma_{\mathrm{tot}}\delta\epsilon_1\,,\ -(1-\epsilon_1)\sigma_{\mathrm{tot}}\delta\epsilon_0\,,\ (1-\epsilon_1)(1-\epsilon_0)\delta\sigma_{\mathrm{tot}}). \end{aligned}$$

Conclusions

- State-of-the-art predictions for the jet-veto efficiency and 0-jet cross section in H production includes:
  - N3LO corrections to the total cross section
  - NNLO corrections to the inclusive 1-jet cross section
  - NNLL resummation for jet-veto logarithms
  - small-R resummation effects at LL accuracy
  - heavy-quark mass effects

[Code JetVHeto-v3.0 available at https://jetvheto.hepforge.org/]

- JVE method has been revisited to ameliorate some features that show up at higher energies and taking into account the good convergence of the perturbative series

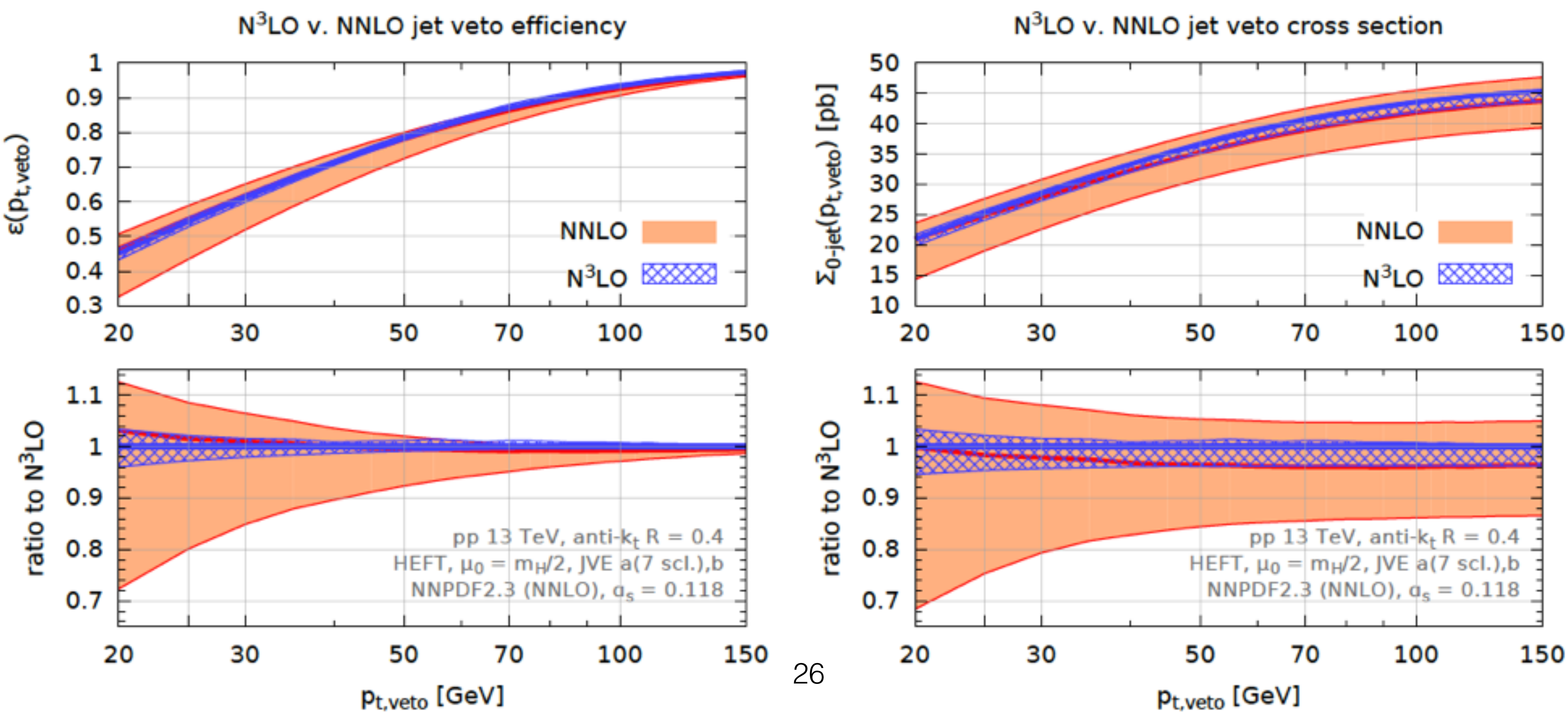
- Corrections w.r.t. to the previous NNLO+NNLL predictions are at the few-percent level - theoretical uncertainties are reduced to ~3% (efficiency)/ ~4% (0-jet cross section)

- At this level of precision other effects become as important (quark masses at NNLO, EW, non-perturbative corrections) - PDF and strong coupling uncertainties also of the same order

Additional material

Updated JVE prescription @ N3LO

- The same issue can show up in other processes with large NLO K factors - in these cases it is not safe to expand around K -> 0
- Updated scheme prescription: we limit ourselves to schemes (a) and (b) (i.e. expand out the last perturbative order for the total cross section)
    - This provides useful information and it's not overly conservative at both small and large pt.



Numerics at the 13 TeV LHC ($\mu_0 = m_H/2$)

LHC 13 TeV [pb]	$\sigma_{\mathrm{tot},2}$	$\sigma_{\mathrm{tot},3}$	$\sigma^{\mathrm{NLO}}_{1j\geq 25\mathrm{GeV}}$	$\sigma^{\mathrm{NNLO}}_{1j\geq 25\mathrm{GeV}}$	$\sigma^{\mathrm{NLO}}_{1j\geq 30\mathrm{GeV}}$	$\sigma^{\mathrm{NNLO}}_{1j\geq 30\mathrm{GeV}}$
EFT	$45.2^{+4.0}_{-4.6}$	$46.6^{+0.0}_{-1.7}$	$20.3^{+3.6}_{-3.4}$	$21.3^{+0.3}_{-1.3}$	$17.3^{+3.0}_{-2.9}$	$18.1^{+0.2}_{-1.1}$
t-only	$47.1^{+4.3}_{-4.9}$	$48.6^{+0.2}_{-2.0}$	$20.7^{+3.8}_{-3.5}$	$21.8^{+0.4}_{-1.4}$	$17.6^{+3.2}_{-3.0}$	$18.4^{+0.2}_{-1.2}$
t, b	$44.9^{+4.2}_{-4.7}$	$46.4^{+0.2}_{-1.9}$	$20.6^{+3.7}_{-3.5}$	$21.6^{+0.4}_{-1.4}$	$17.6^{+3.2}_{-3.0}$	$18.4^{+0.2}_{-1.2}$

Scale variation. N3LO total cross section updated after latest "bug"-fix

Full NLO and HEFT for NNLO
N3LO corrections

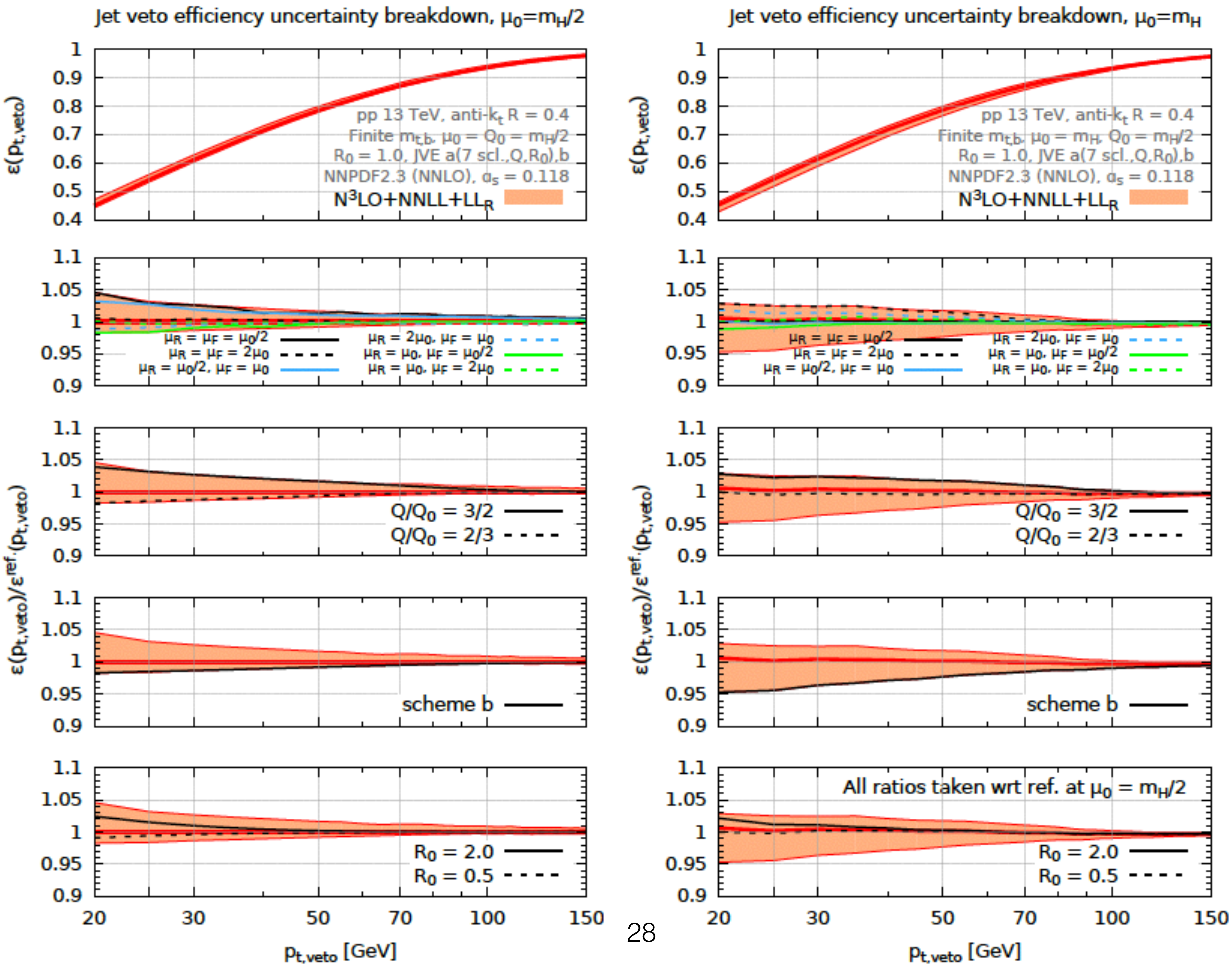
LHC 13 TeV	$\epsilon^{\mathrm{N^3LO+NNLL+LL_R}}$	$\Sigma^{\mathrm{N^3LO+NNLL+LL_R}}_{0\text{-jet}}$ [pb]	$\Sigma^{\mathrm{N^3LO}}_{0\text{-jet}}$	$\Sigma^{\mathrm{NNLO+NNLL}}_{0\text{-jet}}$
$p_{t,\mathrm{veto}} = 25$ GeV	$0.541^{+0.017}_{-0.009}$	$25.1^{+0.8}_{-1.1}$	$24.7^{+0.5}_{-1.2}$	$24.6^{+2.6}_{-3.8}$
$p_{t,\mathrm{veto}} = 30$ GeV	$0.611^{+0.016}_{-0.008}$	$28.3^{+0.8}_{-1.2}$	$28.0^{+0.4}_{-1.3}$	$27.8^{+2.9}_{-4.0}$

JVE

LHC 13 TeV	$\Sigma^{\mathrm{NNLO+NNLL+LL_R}}_{\geq 1\text{-jet}}$ [pb]	$\Sigma^{\mathrm{NNLO}}_{\geq 1\text{-jet}}$ [pb]
$p_{t,\mathrm{min}} = 25$ GeV	$21.3^{+0.4}_{-1.2}$	$21.6^{+0.7}_{-1.0}$
$p_{t,\mathrm{min}} = 30$ GeV	$18.0^{+0.4}_{-1.0}$	$18.4^{+0.6}_{-0.9}$

JVE

Breakdown of uncertainties



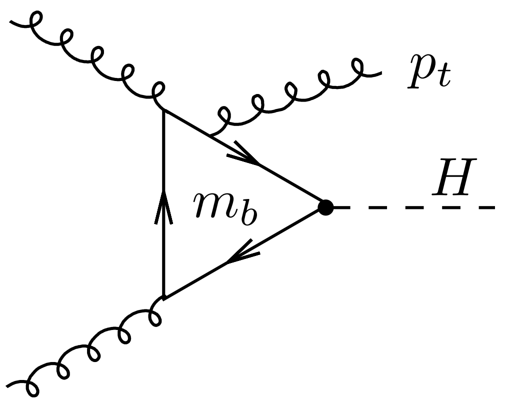
Quark-mass effects

- When exact mass loops are considered, the bottom-quark amplitude is enhanced by logarithms of the ratio p_t/m_b in the regime $m_b^2 << p_\mathrm{t}^2 << m_H^2$
  - e.g. at NLO (currently the state-of-the-art prediction for the full process), the 0-jet cross section features terms of the type

[Banfi, PM, Zanderighi 1308.4634]
[Grazzini, Sargsyan 1306.4581]

$$\alpha_s \frac{m_b^2 m_t^2}{m_H^4} \ln^2 \frac{p_{\mathrm{t,veto}}}{m_b} \ln \frac{p_{\mathrm{t,veto}}}{m_H} \qquad \text{(interference)}$$

$$\alpha_s \frac{m_b^4}{m_H^4} \ln^4 \frac{p_{\mathrm{t,veto}}}{m_b} \ln^2 \frac{p_{\mathrm{t,veto}}}{m_H} \qquad \text{(bottom squared)}$$



- These logarithms do not exist for $p_\mathrm{t} \leq m_b$ (HQEFT picture) , therefore QCD factorisation is preserved in the limit $p_t \to 0$ (i.e. the new logarithms are never divergent and come with a bunch of other regular terms $\sim \mathcal{O}(p_t^2)$)

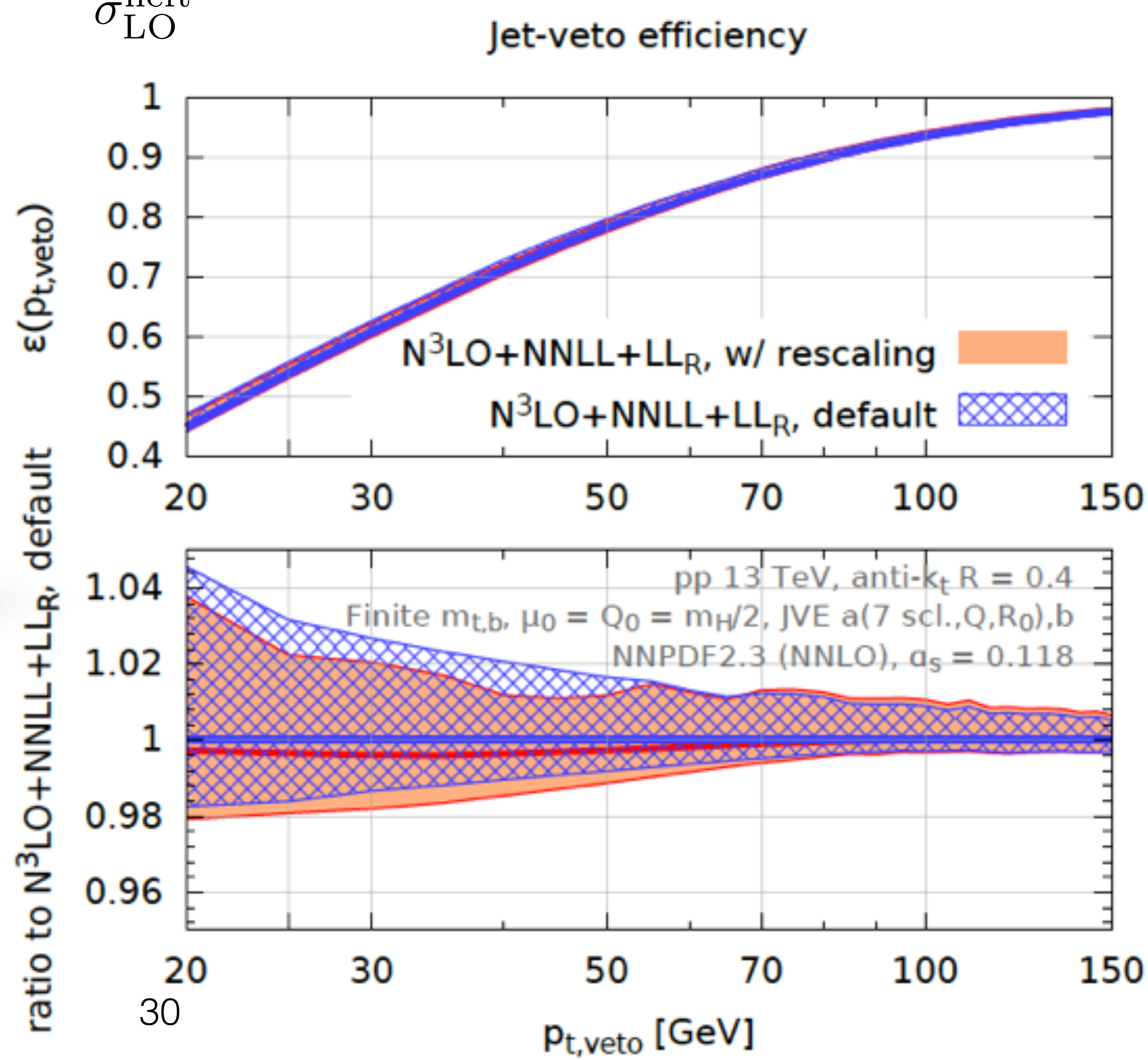
$$|\mathcal{M}(\{\tilde{p}\}, k_1, ..., k_n)|^2 = |M_{\mathrm{Born}}(\{\tilde{p}\})|^2 |M_{\mathrm{div}}(k_1, ..., k_n)|^2 + \text{regular terms}$$

- At normal jet-veto scales their contribution is potentially large, and an all-order treatment is preferable

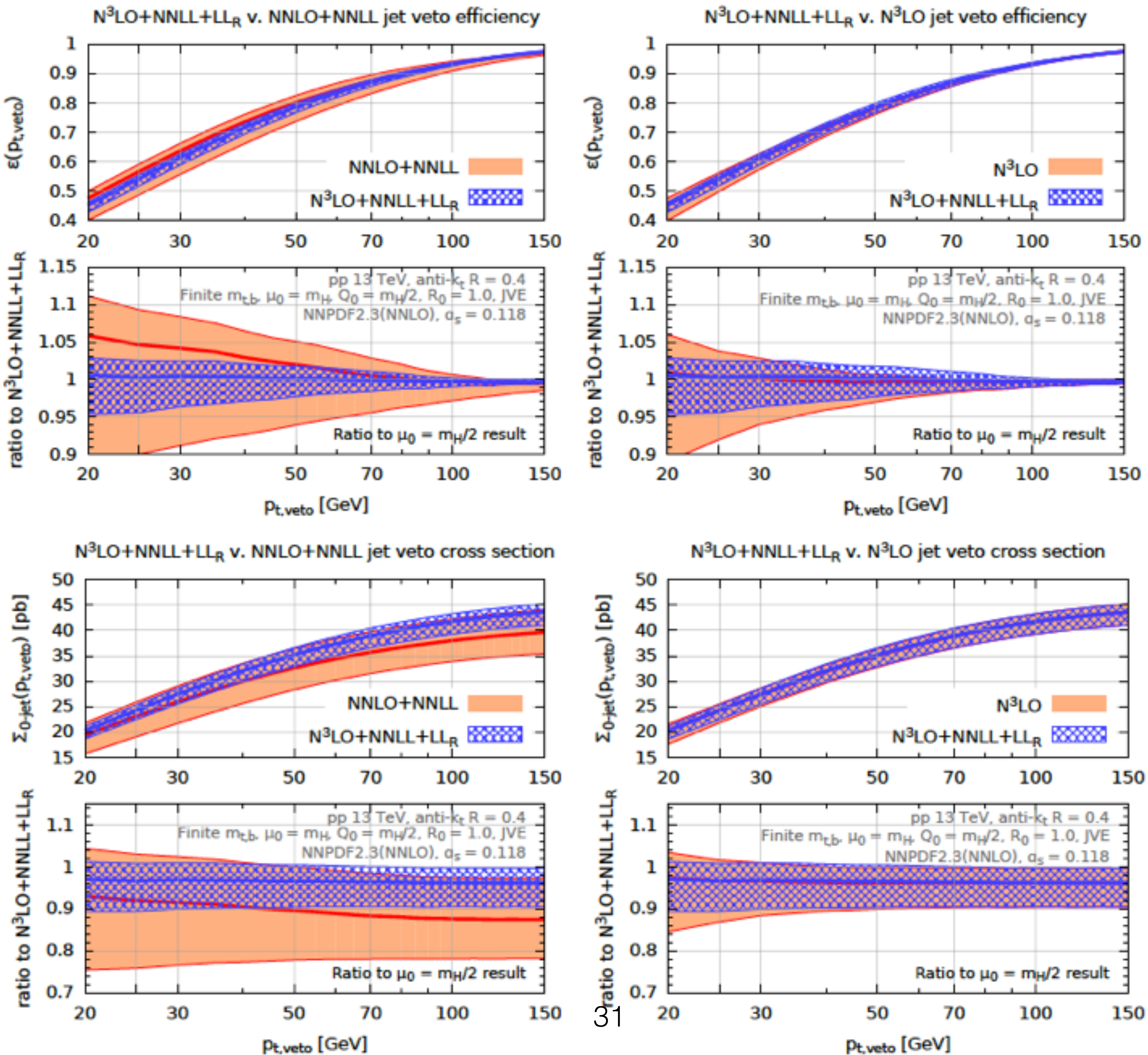
Quark-mass effects

- Robustness against possible sizeable quark-mass effects beyond NLO is tested by rescaling the NNLO and N3LO 0-jet cross sections by the factor $\frac{\sigma_{\rm LO}^{\rm t}}{\sigma_{\rm LO}^{\rm heft}}$

- Impact on the central value moderate
- Slight reduction of uncertainty at small pt

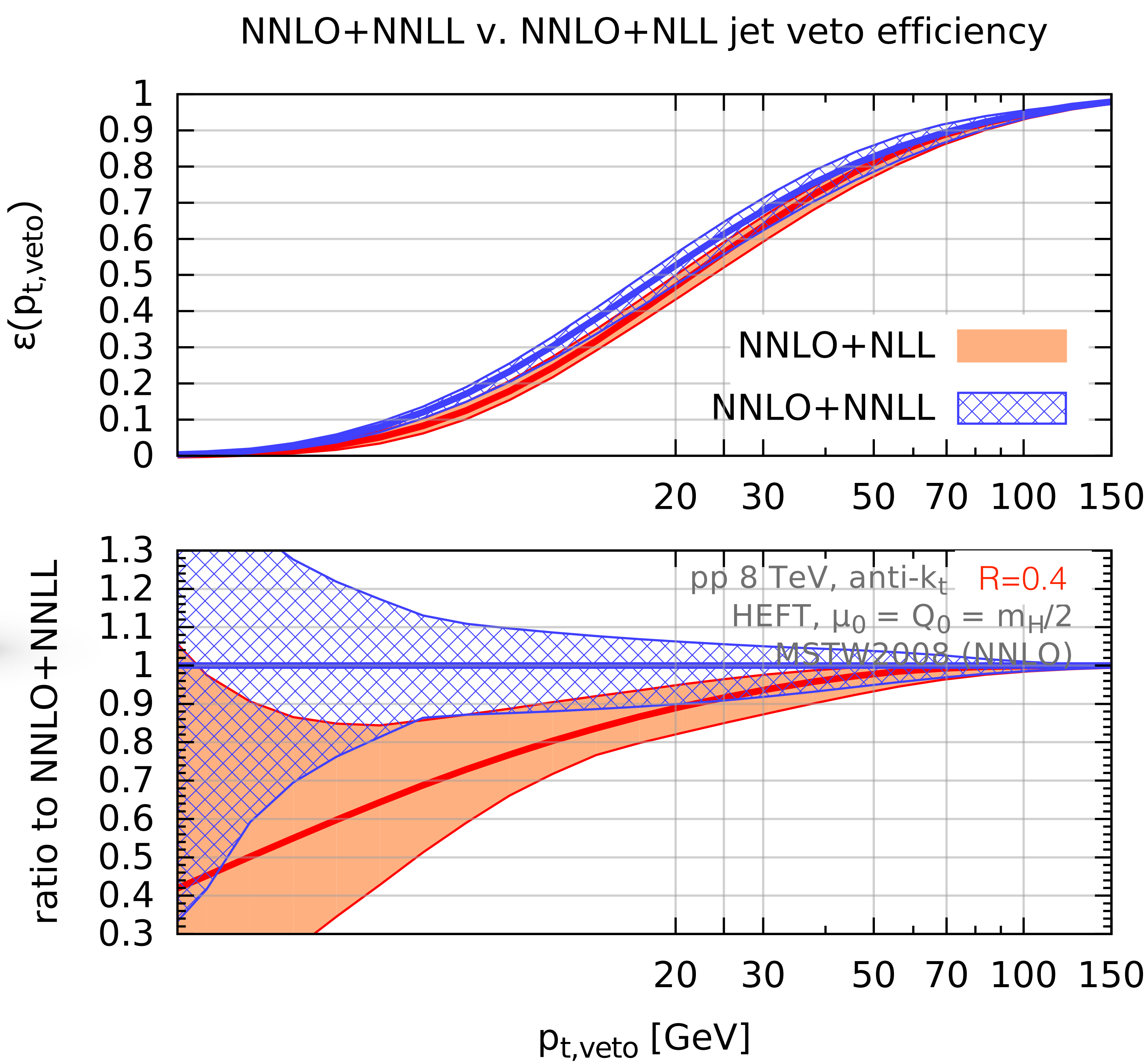


Results at the 13 TeV LHC $(\mu_0 = m_H)$

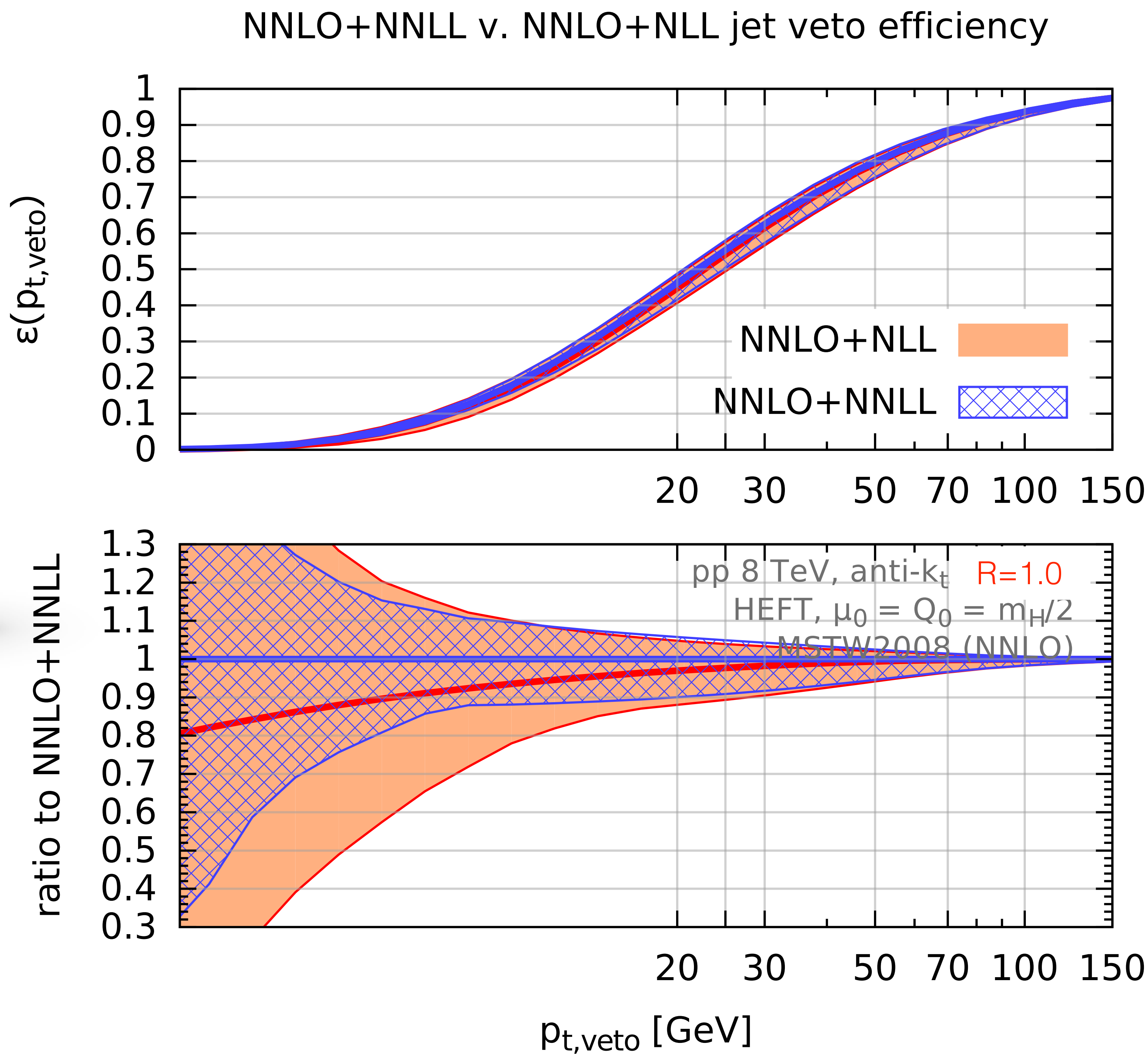


NNLL+NNLO v. NLL+NNLO

Moderate uncertainty reduction with R=0.4 due to the large NNLL corrections associated with the soft gluon splitting



NNLL+NNLO v. NLL+NNLO



Gluon splitting significantly reduced for R=1.0, NNLL corrections smaller.