Inclusive jet spectrum for small-radius jets

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Outline

1. Precision & jets

2. Resummation & Matching
   - Small-R formalism and validity
   - Matching LL_R to fixed order

3. NP effects & comparison to data
   - Hadronisation & UE corrections
   - Comparison to ATLAS and ALICE data

4. Conclusion

PRECISION & JETS

Jets in the era of precision phenomenology

High precision will be a key element in the future of particle physics

- Higgs physics
- EW physics
- PDF extractions
- BSM searches

Many processes involve jets (used in about $2/3$ of recent ATLAS and CMS papers)

- What are the limits on precision in such processes?
- How far can they be pushed?

Case study: the inclusive jet spectrum

Plays a central role in collider physics

- Important for PDFs, α_s extractions, new physics at high p_t, ...
- Challenging experimentally (JES errors) and theoretically (sensitive to perturbative & non-perturbative effects).
- Provides a simple context to study problems appearing also in more complicated processes.

Degree of consistency between experimental and theory comparisons at different R values provides powerful check of accuracy.

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We aim to investigate the R-dependence of jet spectra, with particular focus on the small radius limit.

Our tools

Fixed order calculations

- NLO from NLOJet++ dijet process.
- NNLO is still work in progress, but full NNLO R-dependent terms can be obtained from NLOJet++ 3-jet process.

Small-R resummation

- Generating functional approach to resum Leading Logs of jet radius in the small-R limit

$$\alpha_s^n \ln^n \frac{1}{R^2}\,.$$

- Matched to fixed order calculations using appropriate scheme.

Non-perturbative effects

- We will adopt correction factors derived from Monte Carlo generators.

RESUMMATION & MATCHING

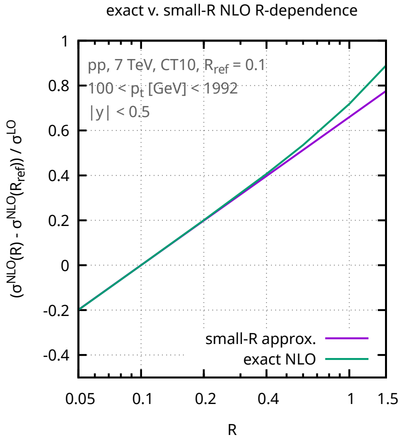
Small-R resummation for the inclusive jet spectrum

Small-R inclusive "microjet" spectrum obtained from convolution of the inclusive microjet fragmentation function with the LO inclusive spectrum

$$\sigma^{\mathrm{LL}_R}(p_t, R) \equiv \sum_k \int_{p_t} \frac{dp'_t}{p'_t} f^{\mathrm{incl}}_{\mathrm{jet}/k}\left(\frac{p_t}{p'_t}, t(R, R_0, \mu_R)\right) \frac{d\sigma^{(k)}}{dp'_t}$$

Validity of small-R approx. can be checked by looking at differences between R values.

Overlap of the curves indicates that the small-R approximation is good.



Matching NLO and LL$_R$

Precise resummed predictions require matching to NLO.

We adopt multiplicative matching

$$\sigma^{\text{NLO+LL}_R} = \underbrace{(\sigma_0 + \sigma_1(R_0))}_{\text{large } R_0 \text{ jet prod.}} \times \underbrace{\left[\frac{\sigma^{\text{LL}_R}(R)}{\sigma_0} \times \left(1 + \frac{\sigma_1(R) - \sigma_1(R_0) - \sigma_1^{\text{LL}_R}(R)}{\sigma_0}\right)\right]}_{\text{small } R \text{ fragmentation factor}}$$

Physical interpretation of different terms suggests alternative expression for the NLO cross section

$$\sigma^{\text{NLO,mult.}} = (\sigma_0 + \sigma_1(R_0)) \times \left(1 + \frac{\sigma_1(R) - \sigma_1(R_0)}{\sigma_0}\right)$$

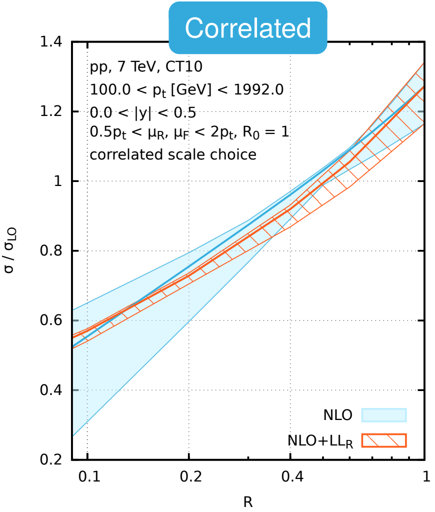
Correlated vs. uncorrelated scale variation

Uncorrelated scale variation gets rid of unphysical cancellations in uncertainty bands

Different terms in matched predictions lead to cancellations due to K-factors going in opposite directions

Correlated scale variation:

Keep the same scale in both factors.



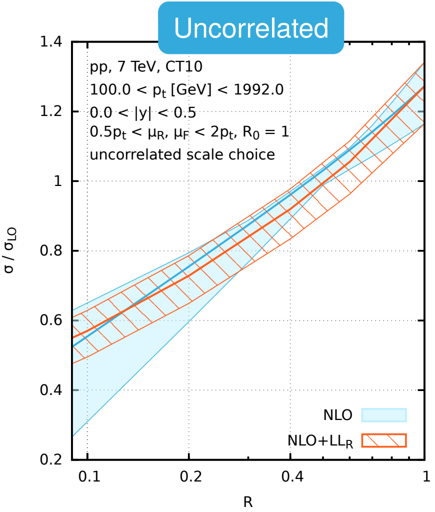
Correlated vs. uncorrelated scale variation

Uncorrelated scale variation gets rid of unphysical cancellations in uncertainty bands

Different terms in matched predictions lead to cancellations due to K-factors going in opposite directions

Uncorrelated scale variation:

Vary scale independently in each factor, and add resulting uncertainties in quadrature.



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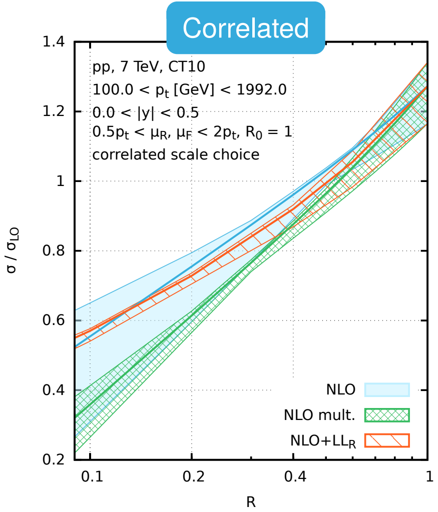

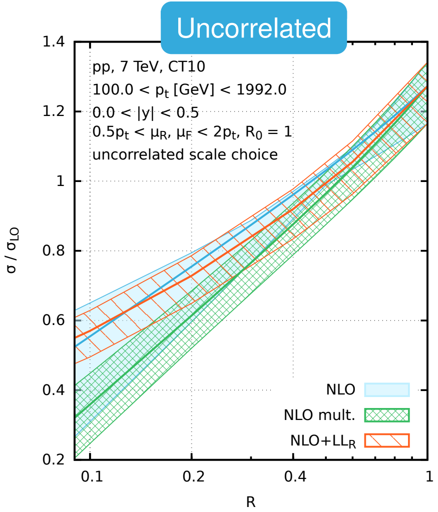

Small-R approximation beyond NLO

How important are subleading effects at higher orders?

Compute difference between R values at NNLO

$$\sigma^{\text{NNLO}}(R) - \sigma^{\text{NNLO}}(R_{\text{ref}})$$
$$= \sigma^{\text{NLO}_{3j}}(R) - \sigma^{\text{NLO}_{3j}}(R_{\text{ref}})$$

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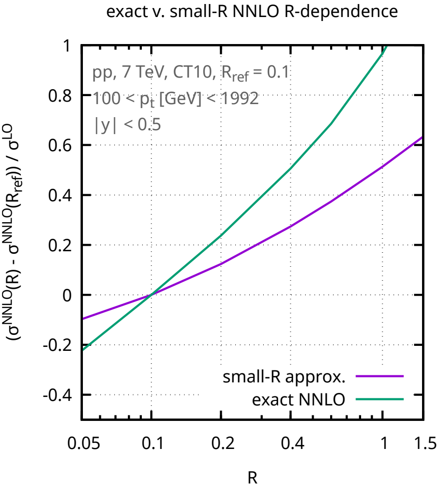
Substantial subleading $\alpha_s^n \ln^{n-1} R$ contribution!

Ideally, one would like a full NLL$_R$ resummation.



Including subleading terms

It is clear that formally subleading $\alpha_s^n \ln^{n-1} R$ terms can be sizeable.

A full NLL_R resummation is not possible at the moment, and would require substantial further work . . .

. . . but we can at least include $\alpha_s^2 \ln R$ terms by matching to NNLO.

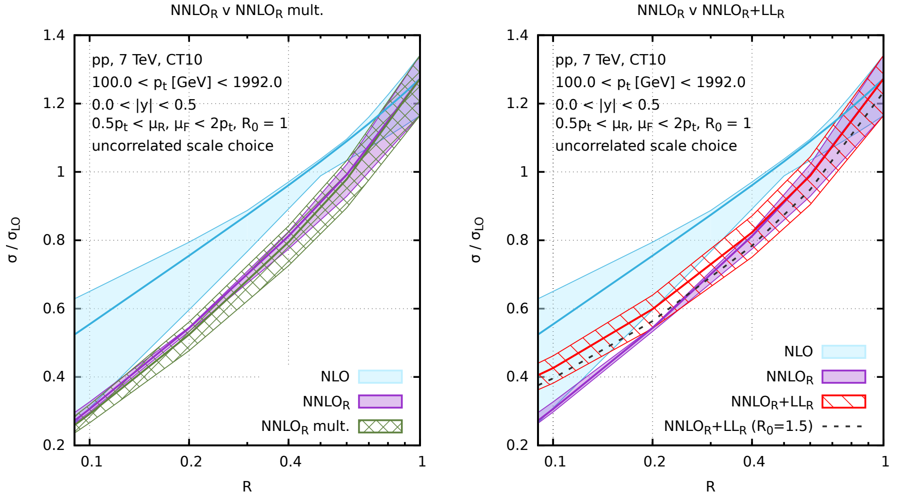
Since full calculation is not yet available, construct a stand-in for NNLO

$$\sigma^{\text{NNLO}_R}(R, R_m) \equiv \sigma_0 + \sigma_1(R) + \underbrace{\left[\sigma_2(R) - \sigma_2(R_m)\right]}_{\text{from NLO 3-jet}}$$

Which has NNLO accurate R-dependence. R_m is an arbitrary angular scale, taken to be $R_m = 1$.

Results at NNLO_R and NNLO_R+LL_R

NNLO_R brings large corrections at small radii, and steeper R dependence.



NON-PERTURBATIVE EFFECTS AND COMPARISON TO DATA

Non-perturbative effects

There are two main non-perturbative effects

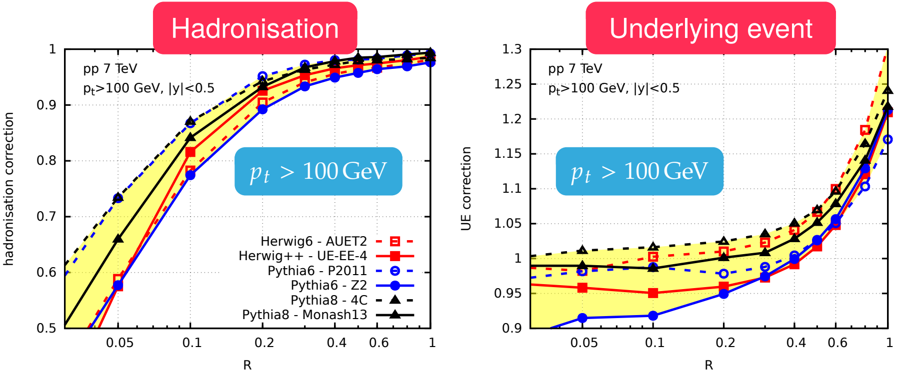
- Hadronisation : the transition from parton-level to hadron-level
- Underlying event : multiple interactions between partons in the colliding protons

They are separate effects, and so it is important to examine them separately.

- Hadronisation shifts jet p_t by $\sim 1/R$, so it matters a lot at small R.
- UE shifts the jet p_t by $\sim R^2$, so it matters at large R.

Hadronisation and UE corrections

We will include non-perturbative effects by rescaling spectra with factors derived from Monte Carlo simulations.



Surprising behaviour of UE corrections at small radii: some factors smaller than one (ie. removing energy), and not suppressed at high p_t.

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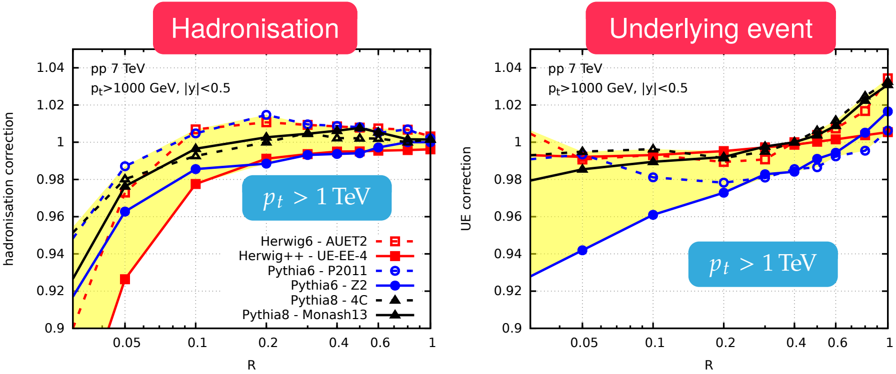
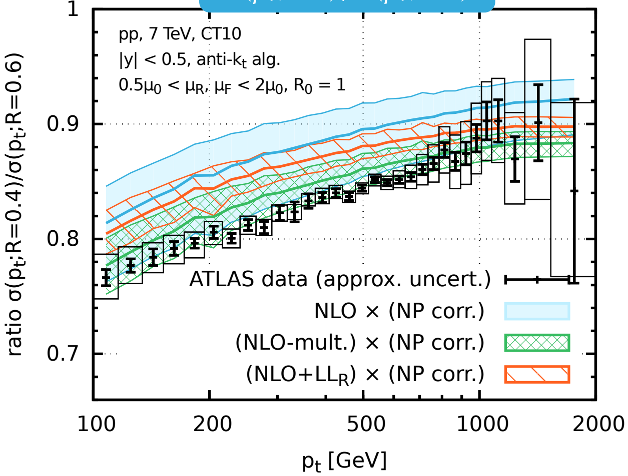


Surprising behaviour of UE corrections at small radii: some factors smaller than one (ie. removing energy), and not suppressed at high p_t.

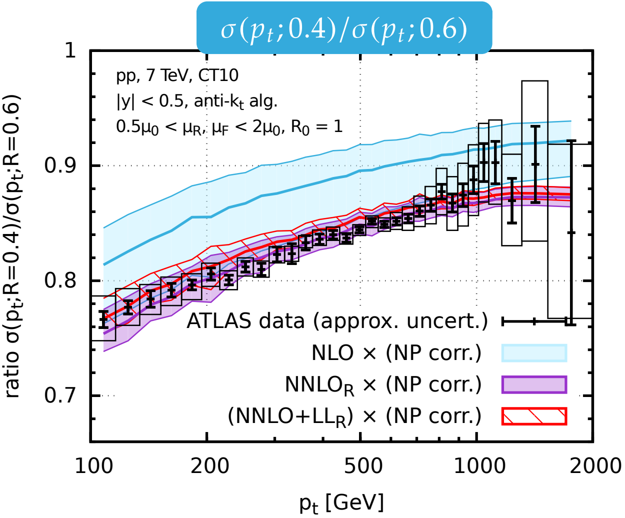
Take ratio of $R = 0.4$ and $R = 0.6$ spectra. Allows us to study directly the R-dependence

$\sigma(p_t; 0.4)/\sigma(p_t; 0.6)$



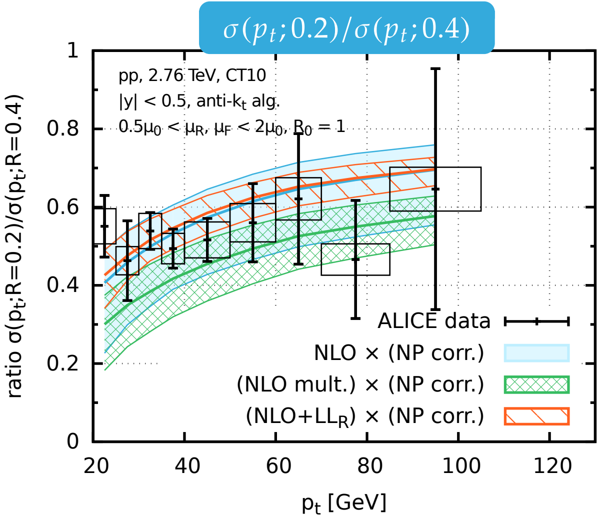
Comparison to ATLAS data: ratio of jet spectra

NLO not enough to get the ratio right! NNLO$_R$ and LL$_R$ corrections are essential to have accurate predictions.



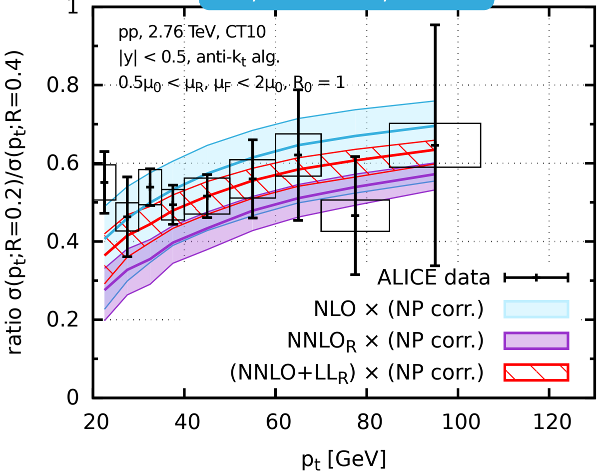
Comparison to ALICE data: ratio of jet spectra

Take ratio of $R = 0.2$ and $R = 0.4$ spectra. Allows us to study directly the R-dependence



For the ratio again, NNLO_R+LL_R provides best match for the data.

$\sigma(p_t;0.2)/\sigma(p_t;0.4)$



CONCLUSION

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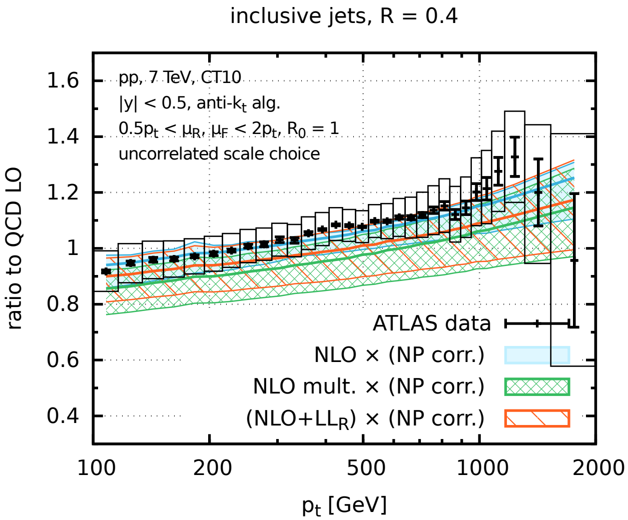
- NLO-mult predictions and uncorrelated scale variations are important tools for reliably estimating missing higher-order uncertainties.
- Need perturbative control over full R range. We gain insight into what happens using NNLO$_R$ and LL$_R$ predictions.
  - R-dependence is strongly modified compared to NLO.
  - LL$_R$ resummation can be important for $R < 0.4$.
- Using multiple R values can give a powerful probe of systematics. Suggestion:
  - $R = 0.2$ or 0.3 (enhances hadronisation, suppresses UE)
  - $R = 0.4$ (mixes all effects)
  - $R = 0.6$ or 0.7 (enhances UE, suppresses hadronisation)

Code and plots will be published on microjets.hepforge.org.

BACKUP SLIDES

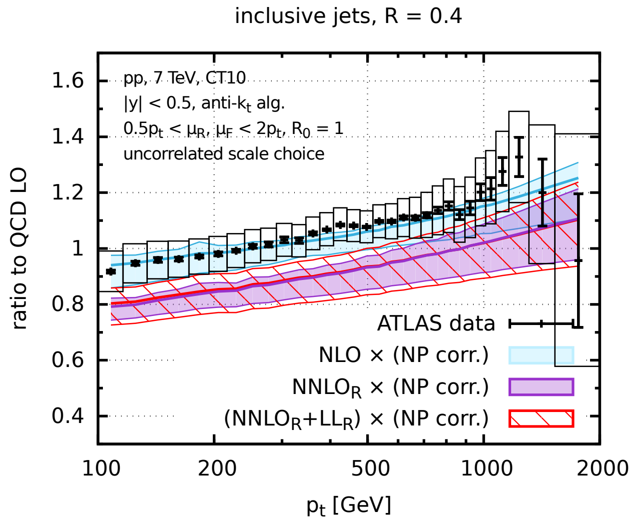
Comparison to data: ATLAS with $R = 0.4$

Small-R resummation shifts the spectrum by $5 - 10\%$, and increases the scale dependence of the NLO prediction.



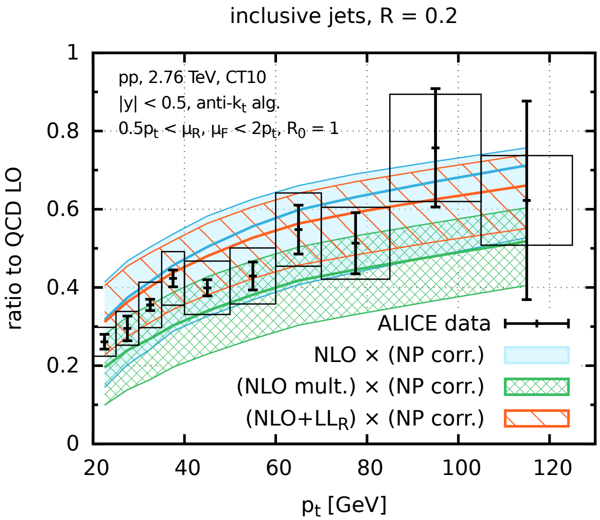
Comparison to data: ATLAS with $R = 0.4$

Partial NNLO$_R$ results shift the predictions further away from data.

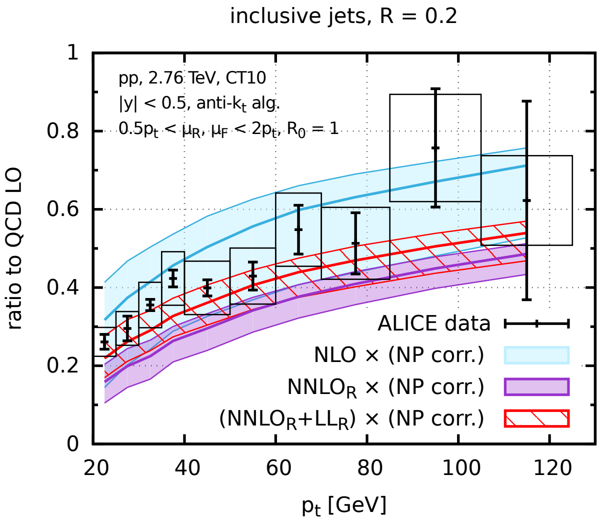


Comparison to data: ALICE with $R = 0.2$

Small-R resummation somewhat improves agreement with ALICE data, and reduces the scale dependence of the NLO prediction.



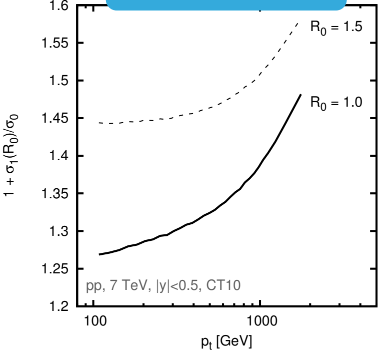
NNLO_R+LL_R deviates from NNLO_R by up to 30% at low p_t, and provides best match for the data.



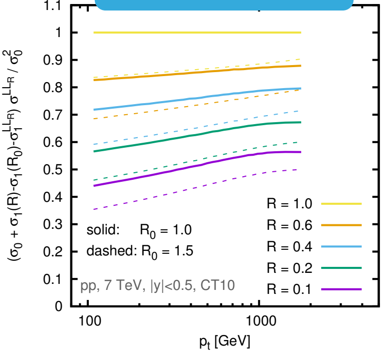
Unphysical cancellations in scale dependence

Different terms in matched predictions lead to K-factors going in opposite directions

large R_0 jet prod.



small-R frag. factor



Partial cancellation in higher order effects can be dangerous when estimating scale uncertainties.

Evaluate independently and add in quadrature.

Jet radius value

Jet radius values for different experiments, excluding substructure R choices

	ATLAS	CMS	ALICE	LHCb
R	$0.2^{*}, 0.4 - 0.6$	$0.3^{*}, 0.5, 0.7$	$0.2 - 0.4$	$0.5, 0.7$

* for PbPb only

Definitions

Define quantity $\Delta_1(p_t, R, R_{\text{ref}})$, where

$$\Delta_i(p_t, R, R_{\text{ref}}) \equiv \frac{\sigma_i(p_t, R) - \sigma_i(p_t, R_{\text{ref}})}{\sigma_0(p_t)}$$

Here $\sigma_i(p_t)$ corresponds to the order α_s^{2+i} contribution to the inclusive jet cross section in a given bin of p_t.

At NNLO, we also define

$$\Delta_{1+2}(p_t, R, R_{\text{ref}}) \equiv \Delta_1(p_t, R, R_{\text{ref}}) + \Delta_2(p_t, R, R_{\text{ref}})$$

Matching NNLO and LL$_R$

Extend the multiplicative matching to NNLO

$$\sigma^{\text{NNLO+LL}_R} = (\sigma_0 + \sigma_1(R_0) + \sigma_2(R_0)) \times \\ \times \left[\frac{\sigma^{\text{LL}_R}(R)}{\sigma_0} \times \left(1 + \Delta_{1+2}(R, R_0) - \frac{\sigma_1^{\text{LL}_R}(R) + \sigma_2^{\text{LL}_R}(R)}{\sigma_0} \right.\right. \\ \left.\left. - \frac{\sigma_1^{\text{LL}_R}(R) \left(\sigma_1(R) - \sigma_1^{\text{LL}_R}(R) \right)}{\sigma_0^2} - \frac{\sigma_1(R_0)}{\sigma_0} \left(\Delta_1(R, R_0) - \frac{\sigma_1^{\text{LL}_R}(R)}{\sigma_0} \right) \right) \right]$$

and define "NNLO mult.", which factorises the production of large-R_0 jets from the fragmentation to small-R jets

$$\sigma^{\text{NNLO,mult.}} = (\sigma_0 + \sigma_1(R_0) + \sigma_2(R_0)) \times \\ \times \left(1 + \Delta_{1+2}(R, R_0) - \frac{\sigma_1(R_0)}{\sigma_0} \Delta_1(R, R_0) \right)$$

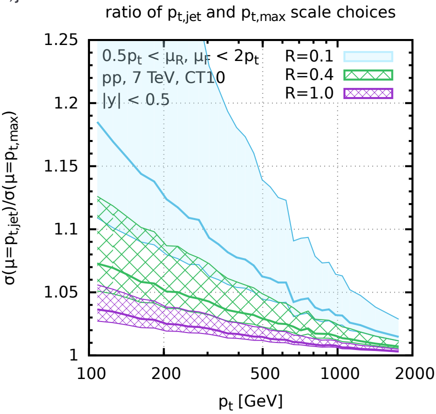
Choice of scale μ_0 beyond LO

Two prescriptions for central renormalisation and factorisation scale

- Single scale for whole event, set by p_t of hardest jet in the event, $\mu_0 = p_{t,\max}$.
- Different scale for each jet, $\mu_0 = p_{t,\text{jet}}$.

Prescriptions are identical at LO but can differ substantially starting from NLO.

Strong dependence on jet radius: For $R = 0.1$, $\mu_0 = p_{t,\text{jet}}$ scale increases σ by 20% at low p_t.

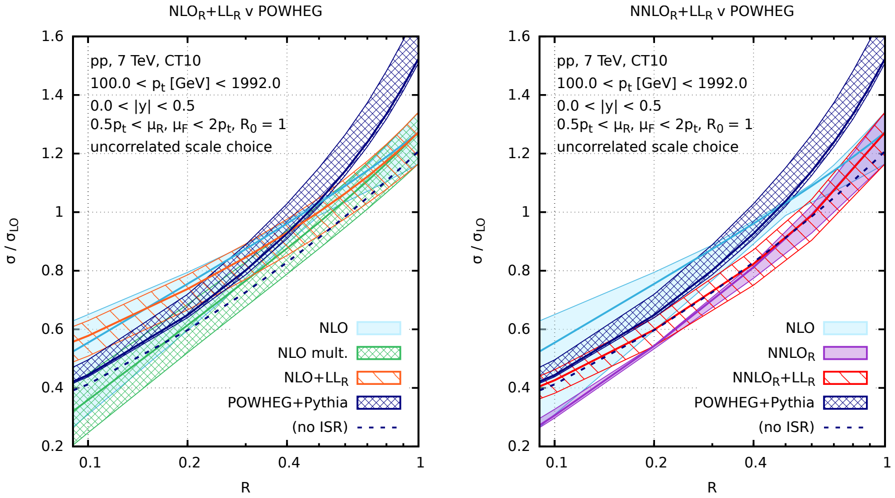


Choice of scale μ_0 beyond LO

We will use a single scale, taken to be the hardest jet in the event, as clustered with $R = 1$: $\mu_0 = p_{t,\max}^{R=1}$.

- At small R, NNLO correction suppress the cross section, so $\mu_0 = p_{t,\text{jet}}$ prescription goes in the wrong direction.
- Main difference between prescriptions comes from when softest parton falls outside leading two jets. One jet then has reduced p_t and the choice $\mu_0 = p_{t,\text{jet}}$ gives a smaller scale. This occurs with a probability that is enhanced by $\ln 1/R$.
- $\mu = p_{t,\text{jet}}$ scale choice introduces correction that goes in wrong direction because it leads to smaller scale (and larger α_s) for real part, but without corresponding modification of virtual part. Thus it breaks the symmetry between real and virtual corrections.

Compare with POWHEG's dijet process, showered with Pythia v8.186.



Impact of finite two-loop corrections

The NNLO$_R$ predictions have all elements of full NNLO correction except those associated with 2-loop and squared 1-loop diagrams.

To examine missing contributions, introduce factor K corresponding to NNLO/NLO ratio for a jet radius of R_m

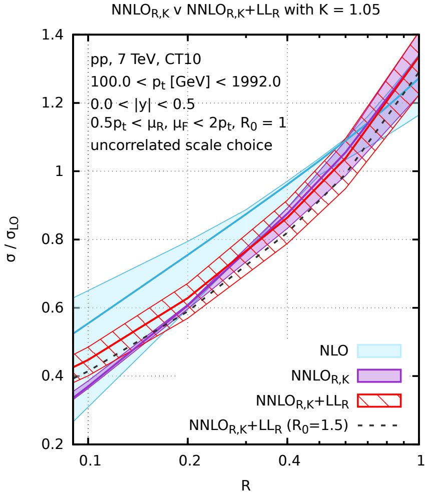
$$\sigma^{\text{NNLO}_{R,K}}(R_m) = K \times \sigma^{\text{NLO}}(R_m)$$

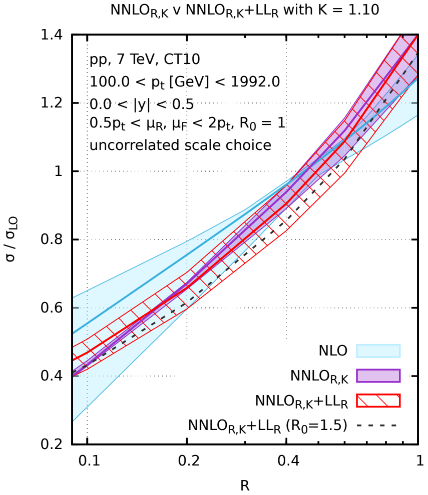
For other values of the jet radius, we have

$$\sigma^{\text{NNLO}_{R,K}}(R) = \sigma_0 \left[1 + \frac{\sigma_1(R)}{\sigma_0} + \Delta_2(R, R_m) + (K-1) \times \left(1 + \frac{\sigma_1(R_m)}{\sigma_0}\right)\right]$$

$\text{NNLO}_{R,K}$ and $\text{NNLO}_{R,K}$+LL_R results with K-factor

Taking $K > 1$ increases overlap between $\text{NNLO}_{R,K}$ and $\text{NNLO}_{R,K}$+LL_R.





Comparison to data with a K-factor

We can compare predictions with a factor $K = 1.10$ to data from ATLAS and ALICE.