Inclusive jet spectrum at small radii

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based on arXiv:1411.5182 and work in preparation

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Outline

1. Precision & jets
2. Resumming & Matching
   - Small-R formalism and validity
   - Matching LL_R to fixed order
   - Scale choice beyond LO
3. Non-perturbative effects
4. Comparisons to data
5. 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
- PDF extractions
- EW physics
- BSM searches

Many processes use jets

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

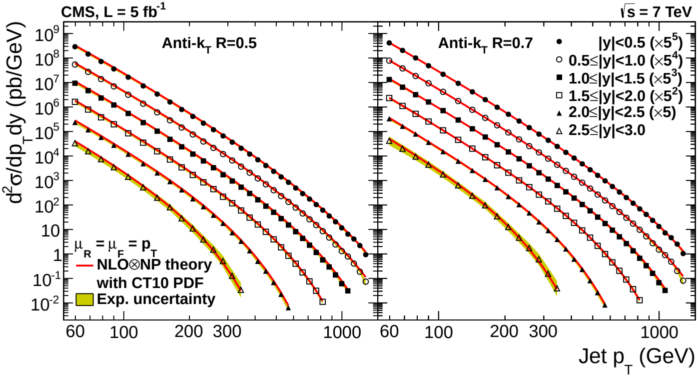
A case study with the inclusive jet spectrum

The inclusive jet spectrum plays a central role

- Important for PDFs, α_s extractions, new physics at high p_t, and in heavy-ion collisions.
- Experimentally challenging (e.g. Jet energy scale errors).
- Theoretically challenging (sensitive to perturbative effects, hadronisation and underlying event).
- Provides a simple context to study problems that appear also in more complicated processes.

R dependence as a handle for validation

ATLAS, CMS, and ALICE have results for two separate R values.



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

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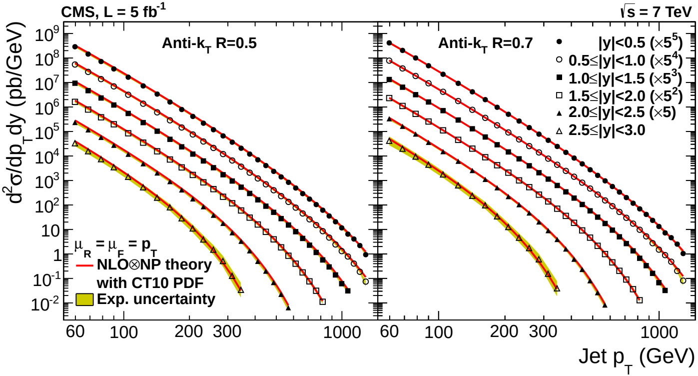

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We aim to investigate the R-dependence of jet spectra, with particular focus on the small radius limit.

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

- Start by examining analytical estimates.
- We will adopt correction factors derived from Monte Carlo generators.

RESUMMATION & MATCHING

Small-R resummation for the inclusive jet spectrum

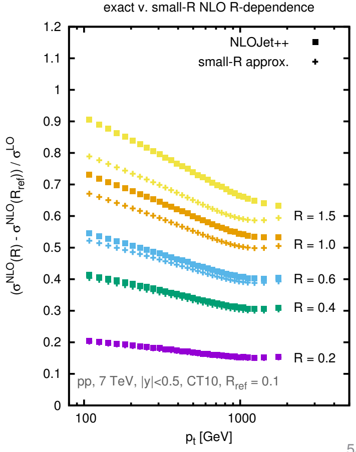
Small-R inclusive "microjet" spectrum obtained from convolution of the inclusive microjet fragmentation function with the LO inclusive spectrum

$$\sigma^{\mathrm{LL}_R}(p_t, R) \equiv \frac{d\sigma_{\mathrm{jet}}^{\mathrm{LL}_R}}{dp_t} = \sum_k \int_{p_t} \frac{dp_t'}{p_t'} f_{\mathrm{jet}/k}^{\mathrm{incl}}\left(\frac{p_t}{p_t'}, t(R, R_0, \mu_R)\right) \frac{d\sigma^{(k)}}{dp_t'}$$

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

Compare inclusive spectrum from NLOJet++ with small-R approximation

Agreement of squares and crosses indicates that the small-R approximation is good.



Matching NLO and LL$_R$

Precise resummed predictions require matching to NLO.

Necessary condition that matching must satisfy

$$\frac{d\sigma^{\mathrm{LL}_R+\mathrm{NLO}}}{d\sigma^{\mathrm{LO}}} \to 0 \qquad \text{for } R \to 0\,.$$

For this reason, we adopt multiplicative matching,

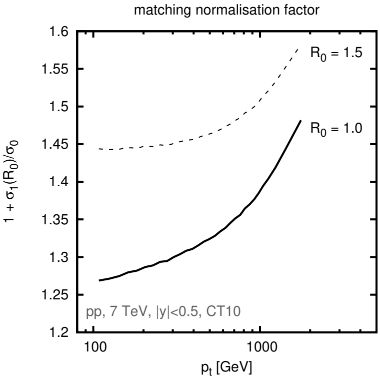
$$\sigma^{\mathrm{NLO+LL}_R} = \underbrace{(\sigma_0 + \sigma_1(R_0))}_{\text{large } R_0 \text{ jet prod.}} \times \underbrace{\left[\frac{\sigma^{\mathrm{LL}_R}(R)}{\sigma_0} \times \left(1 + \frac{\sigma_1(R) - \sigma_1(R_0) - \sigma_1^{\mathrm{LL}_R}(R)}{\sigma_0}\right)\right]}_{\text{small } R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

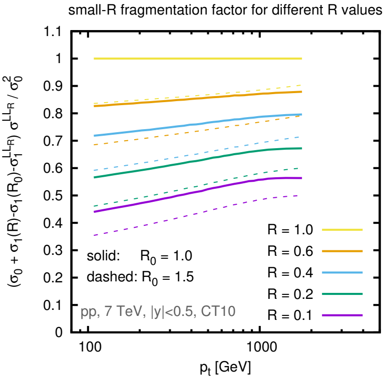
Physical interpretation of different terms suggests alternative expression for the NLO cross section

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

Unphysical cancellations in scale dependence

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



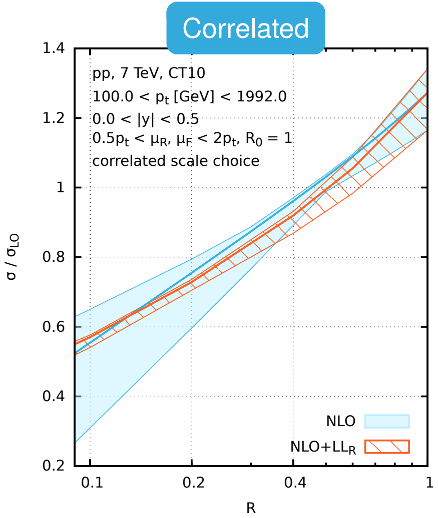


Partial cancellation in higher order effects can be dangerous when estimating scale uncertainties.

Evaluate independently and add in quadrature.

Correlated vs. uncorrelated scale variation

Uncorrelated scale variation gets rid of unphysical cancellations in uncertainty bands



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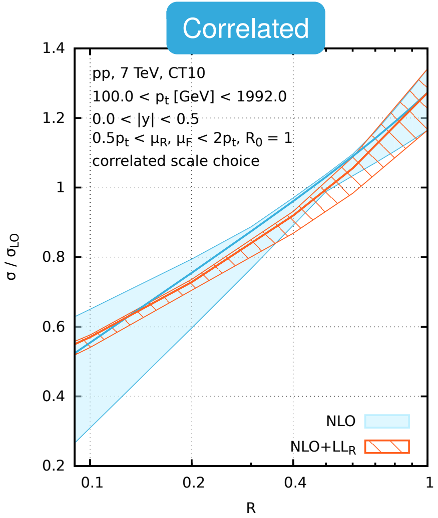

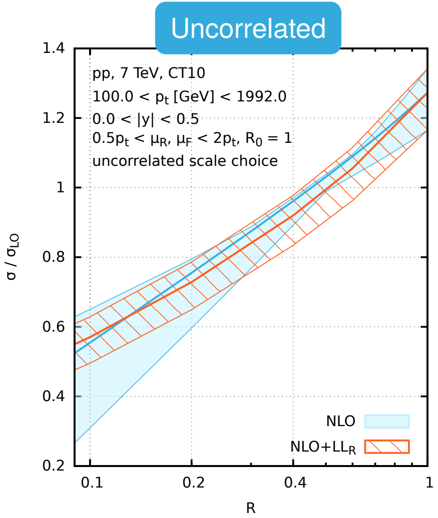

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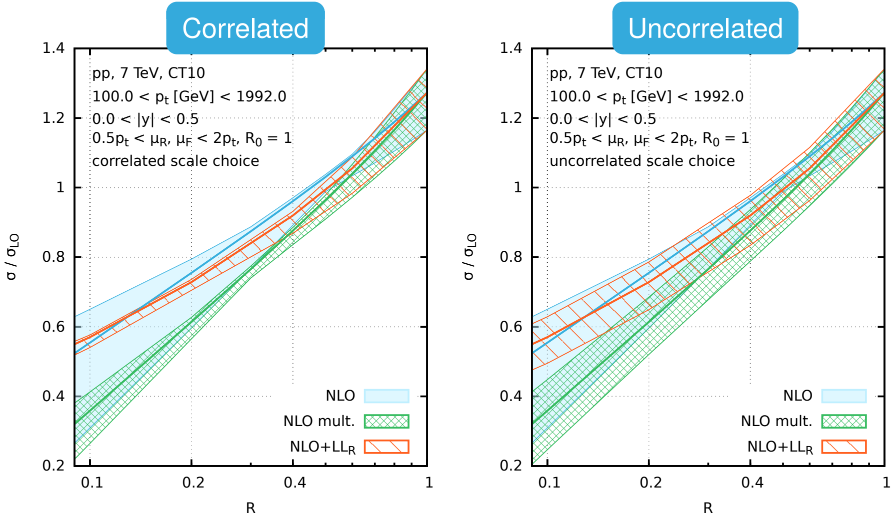

Small-R approximation beyond NLO

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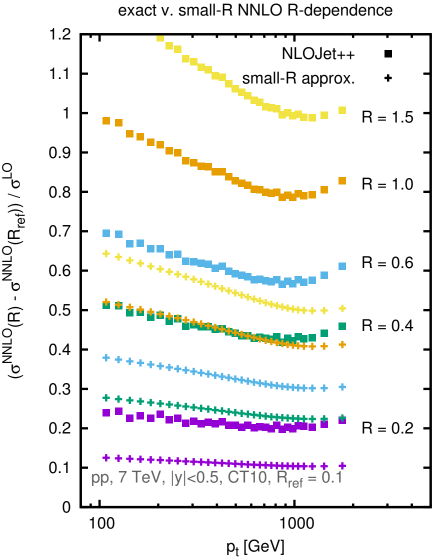
Substantial subleading $\alpha_s^n \ln^{n-1} R$ contribution!

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 . . .

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

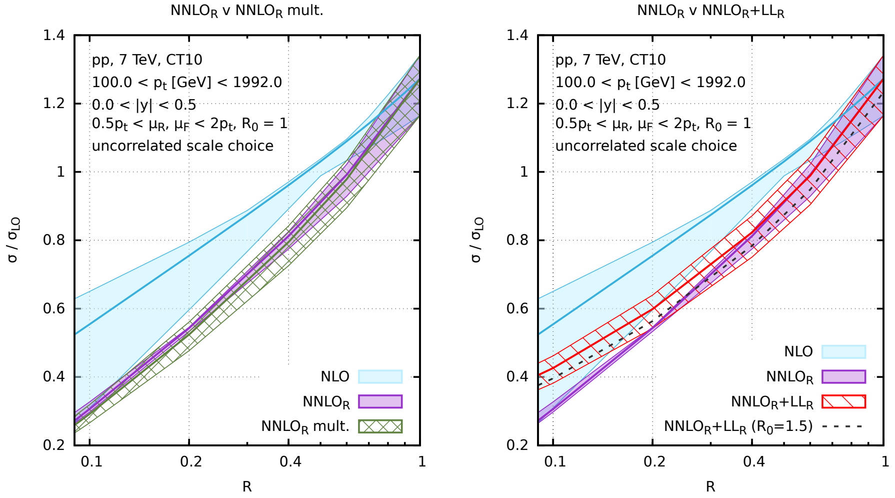
Since full calculation is not yet available, construct a stand-in for NNLO

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

Which has NNLO accurate R-dependence. R_m is an arbitrary 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.



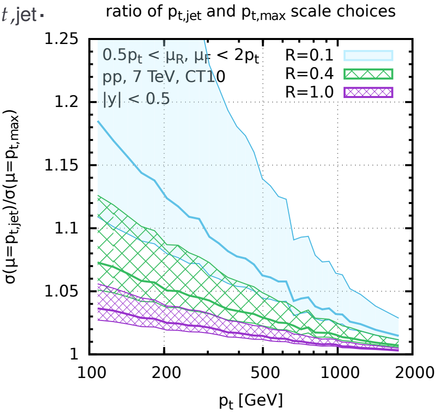
Choice of scale μ_0 beyond LO

Two prescriptions for central renormalisation and factorisation scale

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

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

We favour the $p_{t,\text{max}}$ scale choice.



NON-PERTURBATIVE EFFECTS

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.

Analytical hadronisation model

From event-shape measurements in DIS and e^+e^- collisions, it has been argued that the average hadronisation p_t shift should be roughly

$$\langle \Delta p_t \rangle \simeq -\frac{C}{C_F}\left(\frac{1}{R} + \mathcal{O}(1)\right) \times 0.5\,\text{GeV}$$

where C is the colour factor of the initiating parton, $C_F = \frac{4}{3}$ (quark) or $C_A = 3$ (gluon).

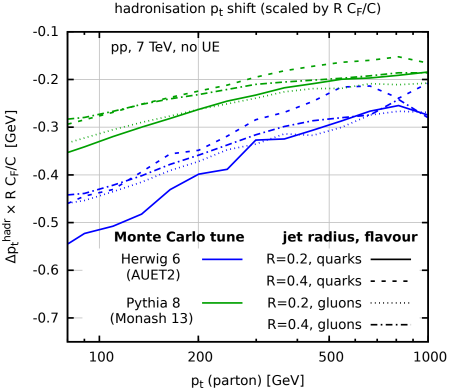
[Dasgupta, Magnea, Salam JHEP 0802 (2008) 055]

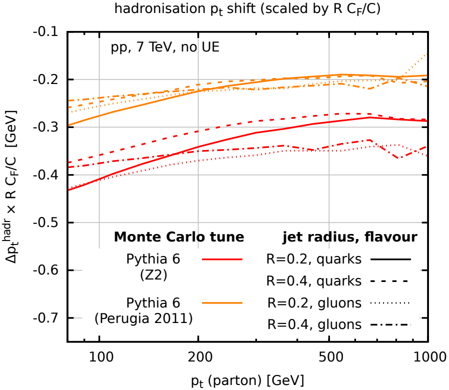
Predictions: the shift in jet p_t rescaled by RC_F/C

- should be identical for quarks and gluons and for different R values,
- should be p_t independent and cluster around $0.5\,\text{GeV}$.

Hadronisation for different Monte Carlo tunes

Shift in jet p_t induced by hadronisation, rescaled by a factor RC_F/C.

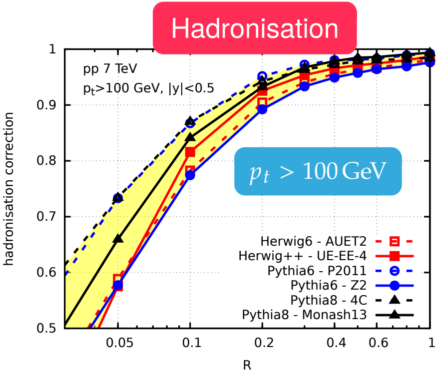


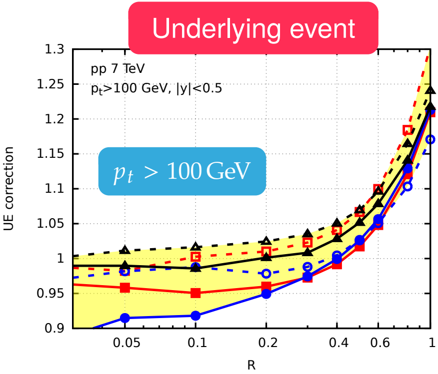


Reasonable agreement with analytical model for colour and R scaling, but strong p_t dependence and large differences between tunes.

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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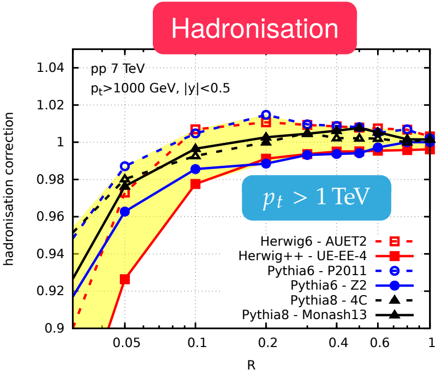
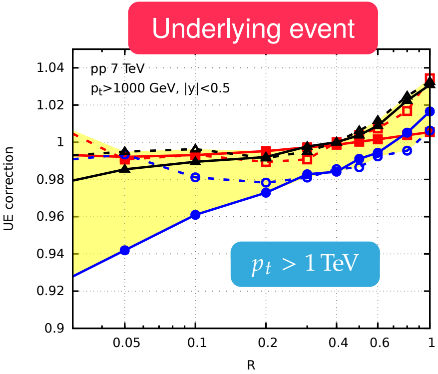




Surprising behaviour of UE corrections at small radii: some factors smaller than one (ie. removing energy), and not suppressed at high p_t.

COMPARISONS TO DATA

What data? What settings?

Most of our new information is for smaller values of R

Therefore, we concentrate here on data with smallest R values

- ALICE data at $\sqrt{s} = 2.76\,\mathrm{TeV}$, for $R = 0.2$ and $R = 0.4$.
- ATLAS data at $\sqrt{s} = 7\,\mathrm{TeV}$, for $R = 0.4$ and $R = 0.6$.
- Sorry…

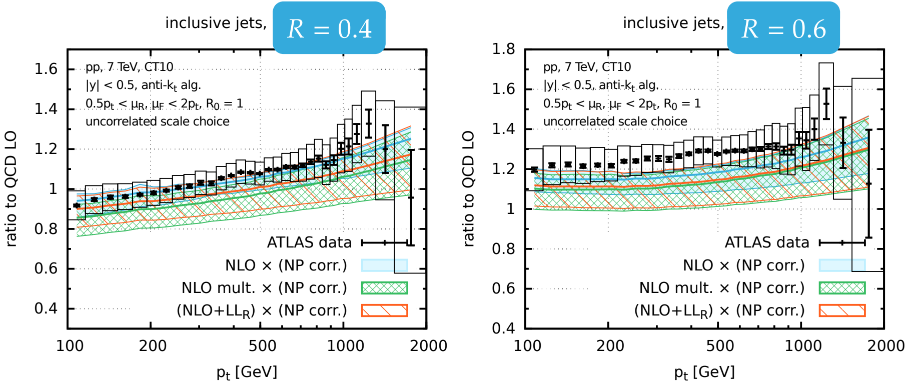
Settings

- Scale is set to hardest jet in the event, as clustered with $R = 1$

$$\mu_0 = p_{t,\max}^{R=1}, \quad \mu_0/2 < \mu_F, \mu_R < 2\mu_0 \text{ (uncorrelated variation)}.$$

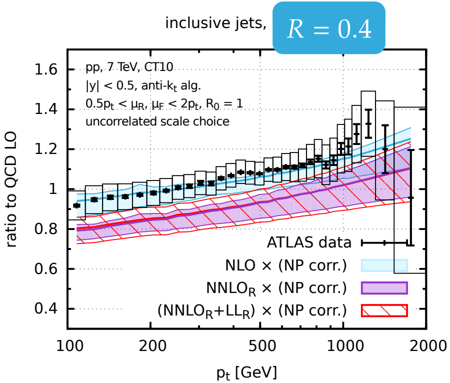
- PDF used is CT10 NLO set.

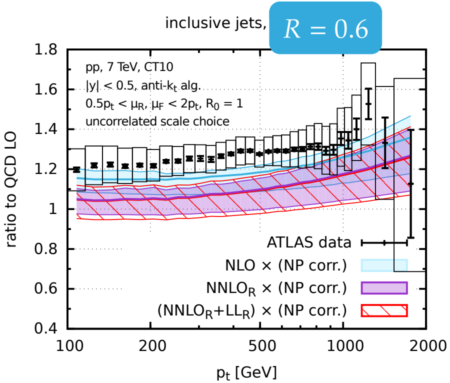
Small-R resummation shifts the spectrum by $5 - 10\%$, and increases the scale dependence of the NLO prediction.



Comparison to data: ATLAS with $R = 0.4, 0.6$

NNLO_R, $\text{NNLO}_R\text{+LL}_R$ results shift the predictions further away from data.

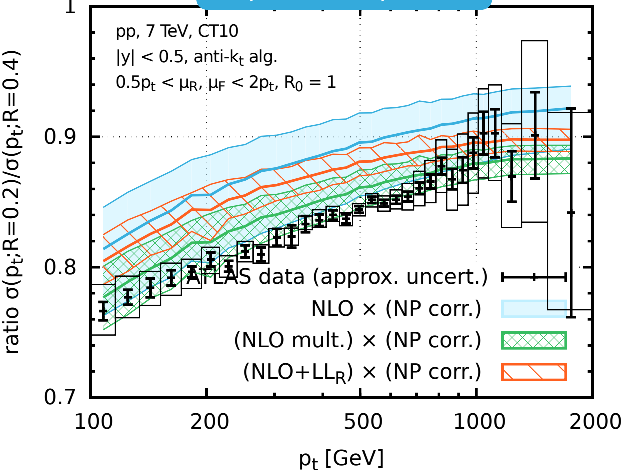




Comparison to ATLAS data: ratio of jet spectra

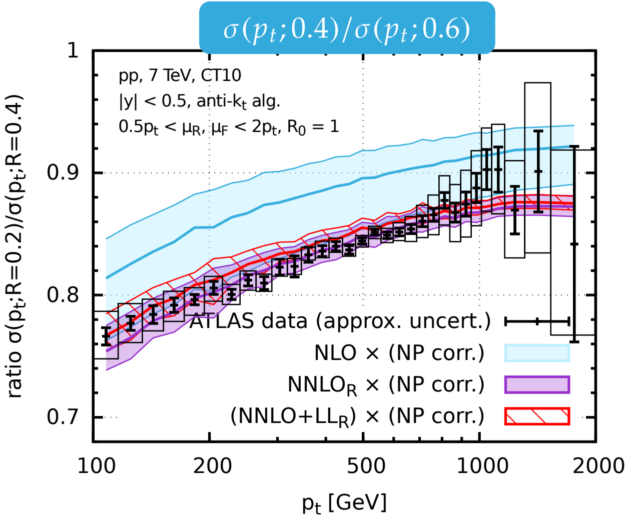
Take ratio of $R = 0.4$ and $R = 0.6$ spectra. Allows us to study directly the R-dependence

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



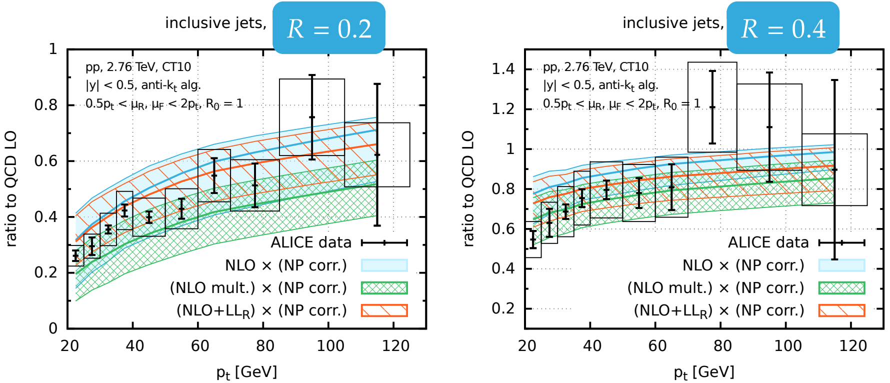
Comparison to ATLAS data: ratio of jet spectra

NLO not enough to get the ratio right! NNLO_R and LL_R corrections are essential to have accurate predictions.



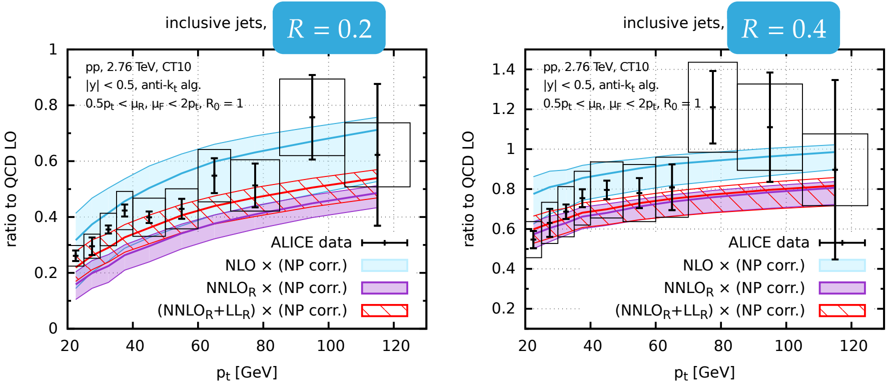
Comparison to data: ALICE with $R = 0.2, 0.4$

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



Comparison to data: ALICE with $R = 0.2, 0.4$

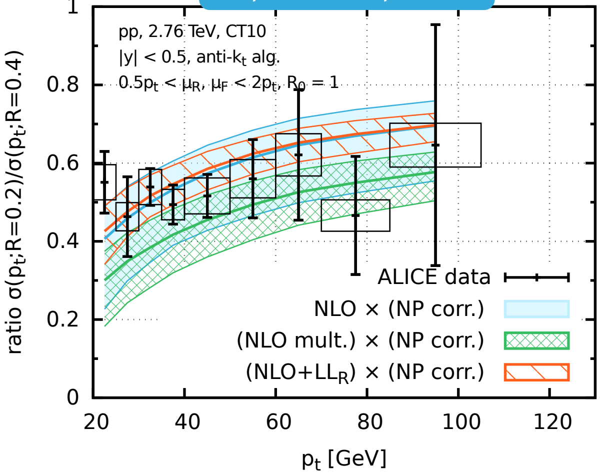
NNLO_R+LL_R deviates from NNLO_R by up to 30% at low p_t, and provides best match for the data.



Comparison to ALICE data: ratio of jet spectra

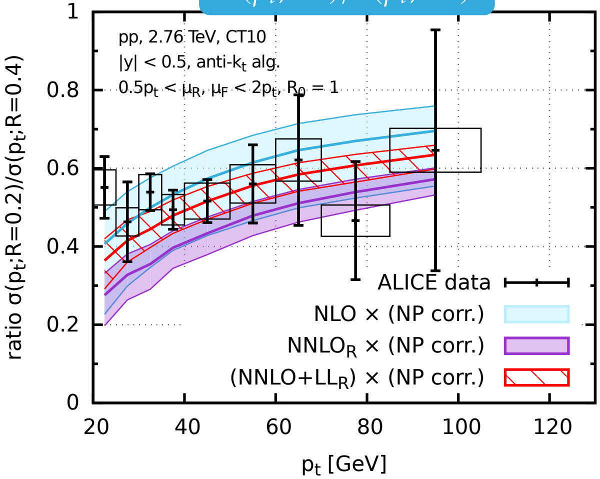
Take ratio of $R = 0.2$ and $R = 0.4$ spectra. Allows us to study directly the R-dependence

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



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

Conclusion

- Using multiple R values can give a powerful probe of systematics. Suggestions
  - $R = 0.2$ or 0.3 (enhances hadronisation, suppresses UE)
  - $R = 0.4$ (mixes all effects)
  - $R = 0.6$ or 0.7 (enhances UE, suppresses hadronisation)

- 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 $R < 0.4$.

- Comparison to data ATLAS and ALICE data: R-dependence works well, but an absolute comparison will require full NNLO calculation.

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

BACKUP SLIDES

Definitions

We consider emissions at successively smaller angular scales from an initial parton. Use an evolution variable t defined by

$$t(R, R_0, p_t) = \int_{R^2}^{R_0^2} \frac{d\theta^2}{\theta^2} \frac{\alpha_s(p_t\theta)}{2\pi} \sim \frac{\alpha_s}{2\pi} \ln \frac{R_0^2}{R^2}, \quad R_0 \sim 1$$

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

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

Generalised k_t algorithm with incoming hadrons

Basic idea is to invert QCD branching process, clustering pairs which are closest in metric defined by the divergence structure of the theory.

Definition

1. For any pair of particles i, j find the minimum of

$$d_{ij} = \min\{k_{ti}^{2p}, k_{tj}^{2p}\}\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = k_{ti}^{2p}, \quad d_{jB} = k_{tj}^{2p}$$

   where $\Delta R_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$.
2. If the minimum distance is d_{iB} or d_{jB}, then the corresponding particle is removed from the list and defined as a jet, otherwise i and j are merged.
3. Repeat until no particles are left.

The index p defines the specific algorithm, with $p = \pm 1, 0$.

Jet radius values

Jet radius values for different experiments, excluding substructure R choices

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

* for PbPb only

Disadvantages of $p_{t,\text{jet}}$ scale choice

We use a single scale, taken as hardest jet in the event, 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 softest parton falling outside leading two jets. One jet then has reduced p_t and the choice $\mu_0 = p_{t,\text{jet}}$ gives a smaller scale. Occurs with probability enhanced by $\ln 1/R$.
- 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.

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

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

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

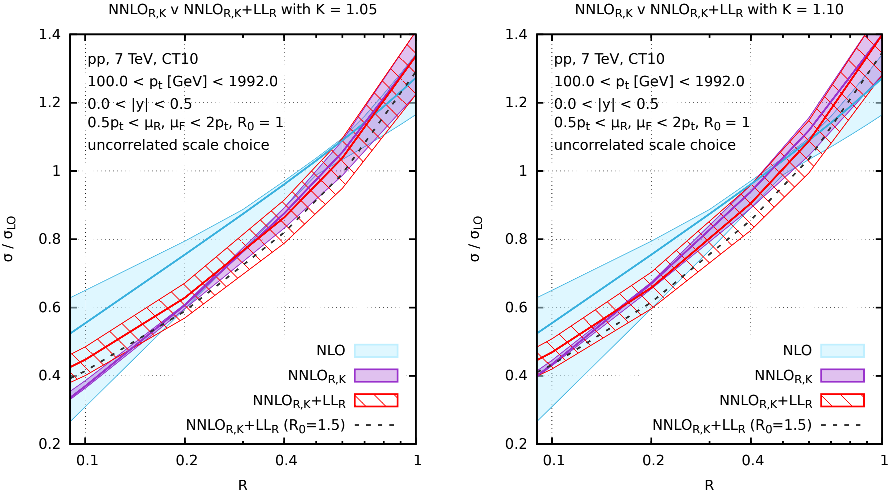
$$\sigma^{\text{NNLO}_{R,K}}(R_m) = K \times \sigma^{\text{NLO}}(R_m)$$

For other values of the jet radius, we have

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

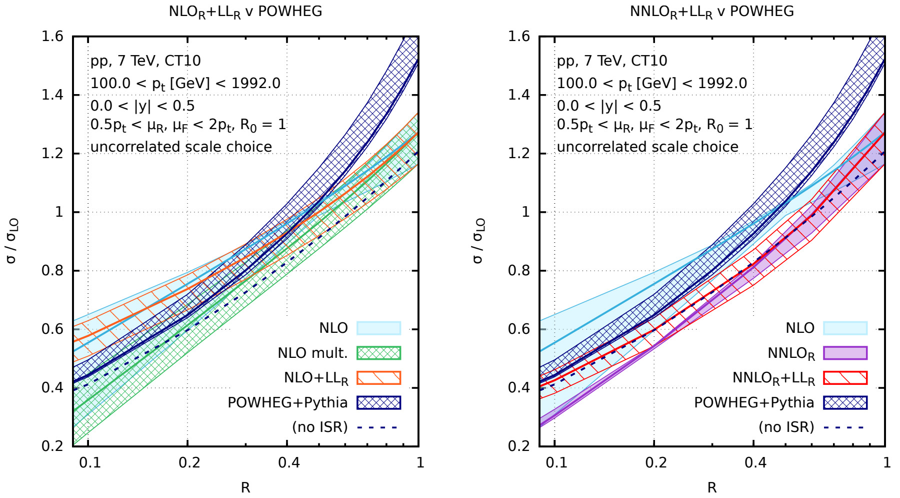
NNLO$_{R,K}$ and NNLO$_{R,K}$+LL$_R$ results with K-factor

Taking $K > 1$ increases overlap between NNLO$_{R,K}$ and NNLO$_{R,K}$+LL$_R$.



Comparison to POWHEG

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



Comparison to POWHEG with K-factor

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