Phenomenology of small-radius jets at the LHC

Rencontre de Physique des Particules, Annecy, 26 January 2016

Frédéric Dreyer

Laboratoire de Physique Théorique et Hautes Énergies & CERN

based on arXiv:1411.5182 and work in preparation

in collaboration with Gavin Salam, Matteo Cacciari, Mrinal Dasgupta & Gregory Soyez

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 use jets

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

Case study: the inclusive jet spectrum, which plays a central role

- 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.

Jet algorithms and choice of jet radius

A jet algorithm maps final state particle momenta to jet momenta.

$$\underbrace{\{p_i\}}_{\text{particles}} \Longrightarrow \underbrace{\{j_k\}}_{\text{jets}}$$

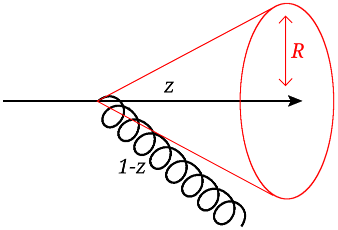
This requires an external parameter, the jet radius R, specifying up to which point separate partons are recombined into a single jet.

What are usual values for the jet radius R ?

- Most common choice is $R = 0.4 - 0.5$.
- In some environments (eg. heavy ions), values down to $R = 0.2$ are used to mitigate high pileup and underlying event contamination.
- Many modern jet tools (eg. trimming and filtering) resolve small subjets (typically with $R_{\text{sub}} = 0.2 - 0.3$) within moderate & large R jets.

Perturbative properties of jets

Jet properties will be affected by gluon radiation and $g \to q\bar{q}$ splitting.



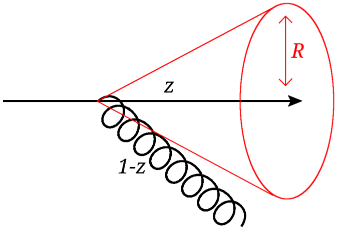
Emissions outside of the jet reduce the jet energy.

Average energy difference between hardest final state jet and initial quark, considering emissions beyond the reach of the jet

$$\left\langle \frac{\text{quark } E - \text{jet } E}{\text{quark } E} \right\rangle = \frac{C_F}{\pi}\left(2\ln 2 - \frac{3}{8}\right) \alpha_s \ln R + \ldots$$

Perturbative properties of jets

Jet properties will be affected by gluon radiation and $g \to q\bar{q}$ splitting.



Emissions outside of the jet reduce the jet energy.

Average energy difference between hardest final state jet and initial quark, considering emissions beyond the reach of the jet

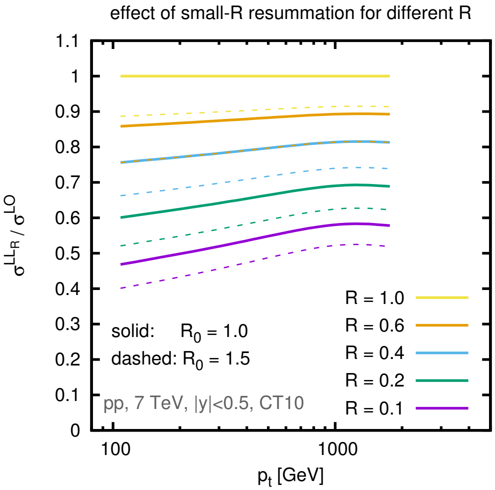
$$\left\langle \frac{\text{quark } E - \text{jet } E}{\text{quark } E} \right\rangle = \frac{C_F}{\pi}\left(2\ln 2 - \frac{3}{8}\right)\alpha_s \ln R + \ldots$$

$\alpha_s \ln R$ implies large corrections for small R.

How relevant are small-R effects?

Energy loss has big effect on jet spectrum.

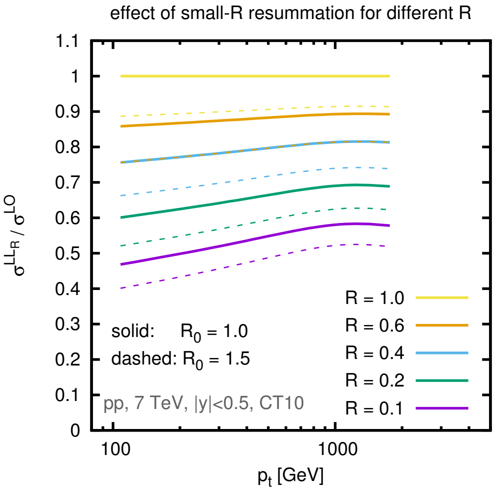
R	corr. to jet spect.
0.4	$\mathcal{O}(-25\%)$
0.2	$\mathcal{O}(-40\%)$



How relevant are small-R effects?

Energy loss has big effect on jet spectrum.

R	corr. to jet spect.
0.4	$\mathcal{O}(-25\%)$
0.2	$\mathcal{O}(-40\%)$



We aim to resum leading logarithmic $(\alpha_s \ln R)^n$ terms and study the R-dependence of jet spectra.

RESUMMATION & MATCHING

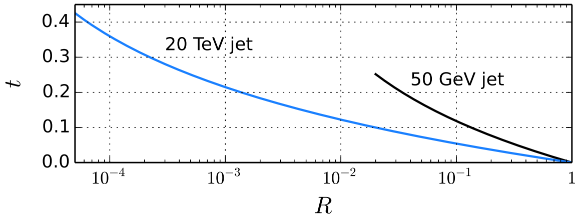
Small-R resummation for the inclusive jet spectrum

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

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

where t is an evolution variable defined by

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



Matching NLO and LL$_R$

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,

$$\sigma^{\mathrm{NLO+LL}_R} = (\sigma_0 + \sigma_1(R_0)) \times \left[\frac{\sigma^{\mathrm{LL}_R}(R)}{\sigma_0} \times \left(1 + \frac{\sigma_1(R) - \sigma_1(R_0) - \sigma_1^{\mathrm{LL}_R}(R)}{\sigma_0} \right) \right]$$

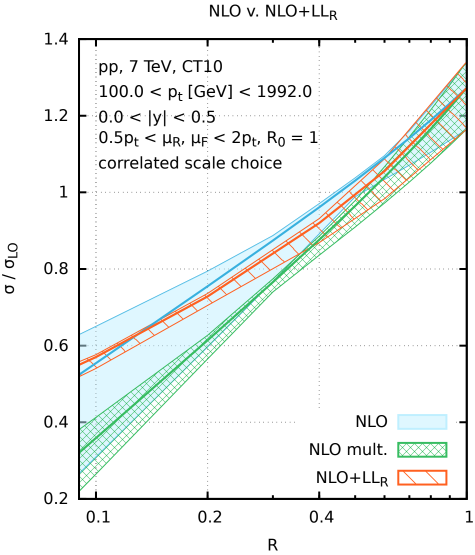
Physical interpretation of different terms suggests alternative expression for the NLO cross section

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

Matched NLO+LL$_R$ results

Small-R resummation changes the scale dependence.

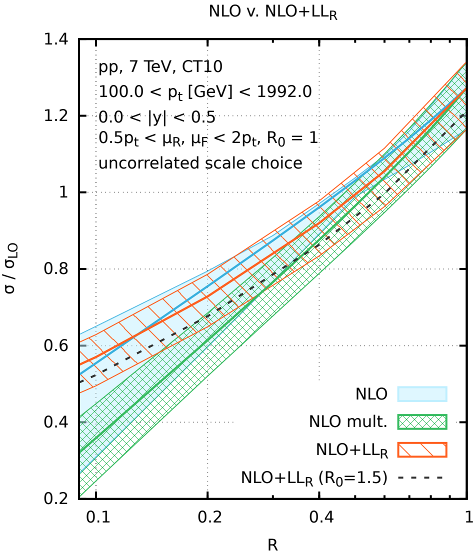
Large cancellations between scale dependence of partonic scattering & small-R fragmentation contributions.



Matched NLO+LL$_R$ results

Small-R resummation changes the scale dependence.

$\Rightarrow$ so add scale variation from those two components in quadrature.



Small-R approximation beyond NLO

How important are subleading effects at higher orders?

Compute difference between R values at NNLO

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

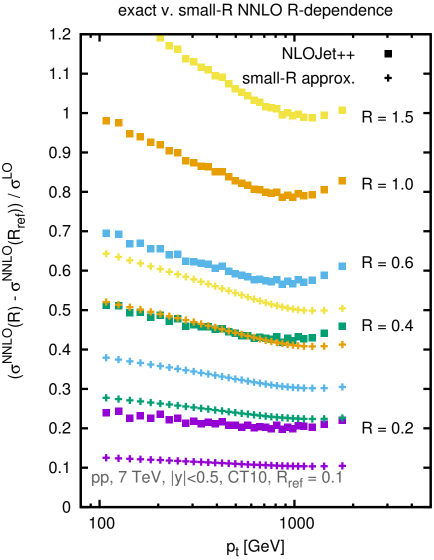
How important are subleading effects at higher orders?

Compute difference between R values at NNLO

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

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.

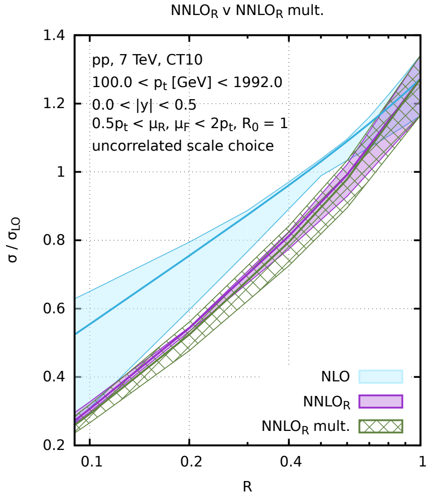
Since full calculation is not yet available, construct a stand-in for NNLO

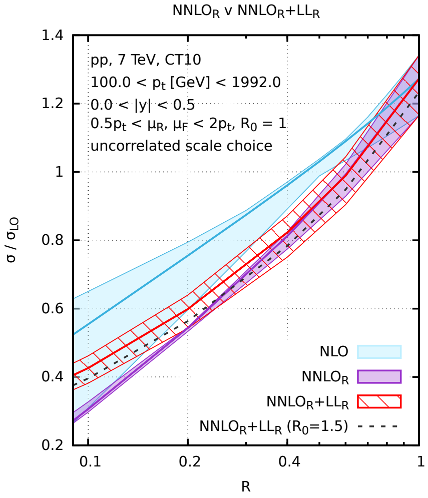
$$\sigma^{\text{NNLO}_R}(R, R_m) \equiv \sigma_0 + \sigma_1(R) + \sigma_2(R) - \sigma_2(R_m)$$

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.





NON-PERTURBATIVE EFFECTS AND COMPARISON TO DATA

Non-perturbative effects

There are two main non-perturbative effects

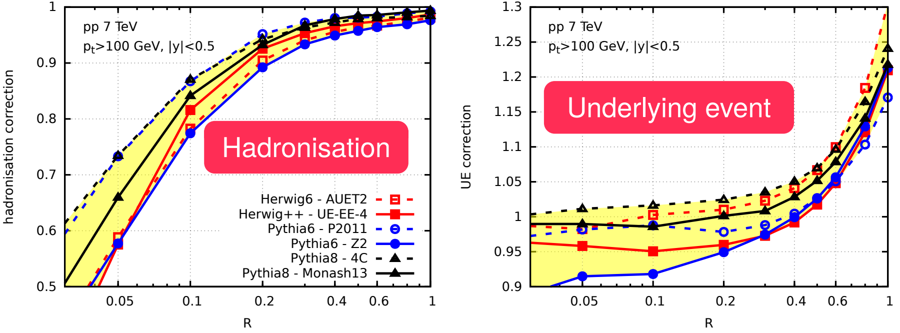
- Hadronisation : the transition from parton-level to hadron-level
- Underlying event : multiple interactions between partons in the colliding protons

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.

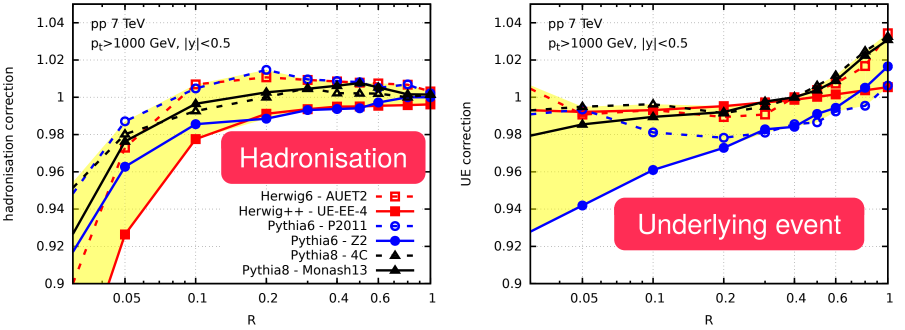
Hadronisation and UE corrections

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.

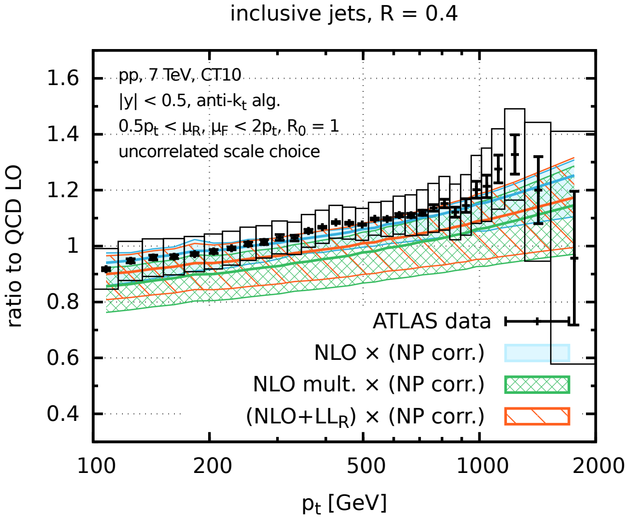
We will include non-perturbative effects by rescaling spectra with factors derived from Monte Carlo simulations.



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

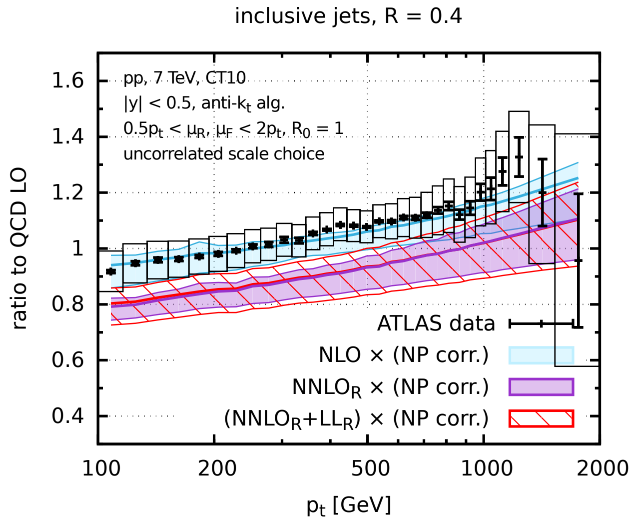
Comparison to data: ATLAS with $R = 0.4$

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



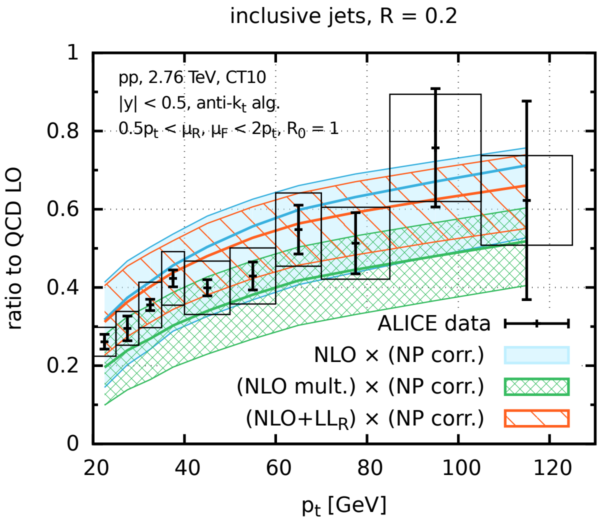
Comparison to data: ATLAS with $R = 0.4$

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



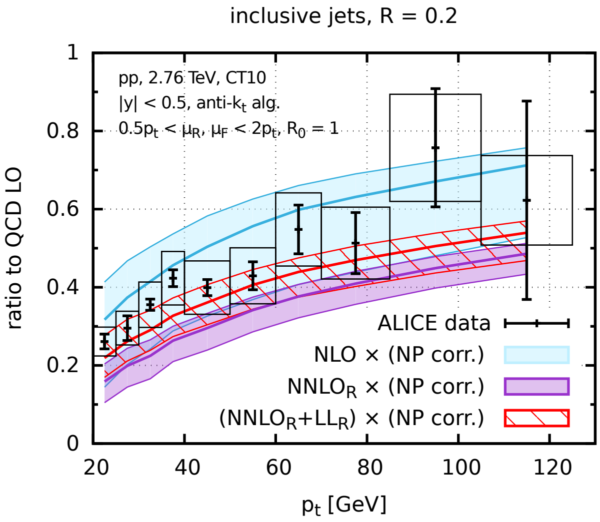
Comparison to data: ALICE with $R = 0.2$

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



Comparison to data: ALICE with $R = 0.2$

NNLO$_R$+LL$_R$ deviates from NNLO$_R$ by up to 30% at low p_t, and provides best match for the data.



CONCLUSION

Conclusion

- Discussed small-R effects in jet calculations and R-dependence of inclusive jet spectra. Showed that small-R effects can be substantial, reducing the inclusive jet spectrum by $25 - 40\%$ for $R = 0.4 - 0.2$.

- 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

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

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

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 value

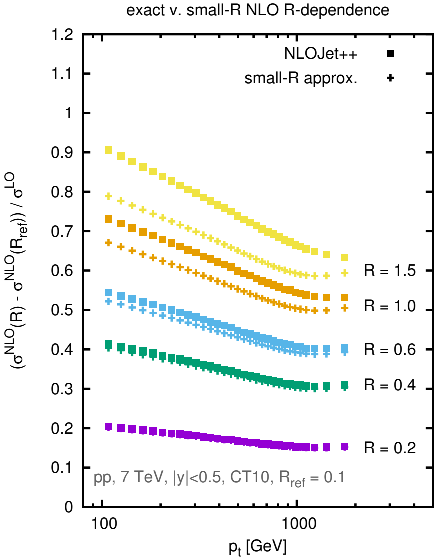
Jet radius values for different experiments, excluding substructure R choices

	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

Validity of small-R approximation

Small-R is a valid for $R \leq 1$, but starts to break down around $R \sim 1$.



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

We look at differences between R values.

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

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

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

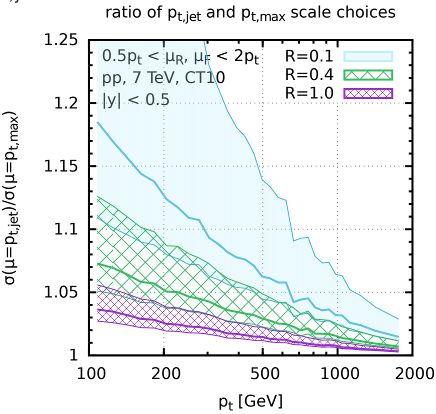
Choice of scale μ_0 beyond LO

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.

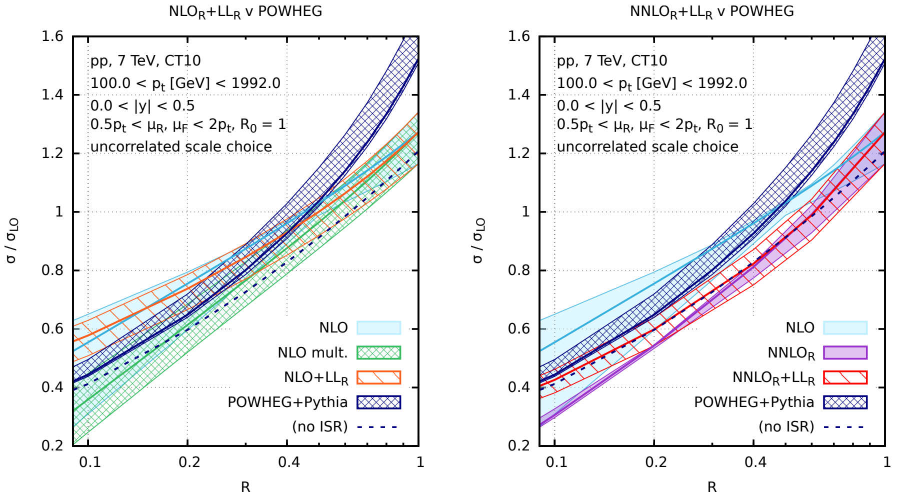


Choice of scale μ_0 beyond LO

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

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

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$_R$.