Inclusive jet spectrum for small-radius jets

Parton Shower & Resummation, Paris, 4 July 2016

Frédéric Dreyer

Laboratoire de Physique Théorique et Hautes Énergies & CERN

based on JHEP 1504 (2015) 039 and JHEP 1606 (2016) 057

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

Outline

PRECISION & JETS

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

- ▶ Higgs physics
- ▶ PDF extractions
- ▶ EW physics
- ▶ 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.

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.

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

R dependence as a handle for validation

ATLAS, CMS, and ALICE have results for two separate R values.
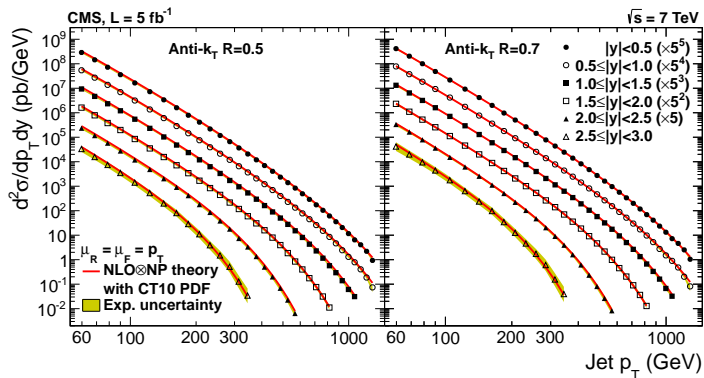
Degree of consistency between experimental and theory comparisons at different R values provides powerful check of accuracy.

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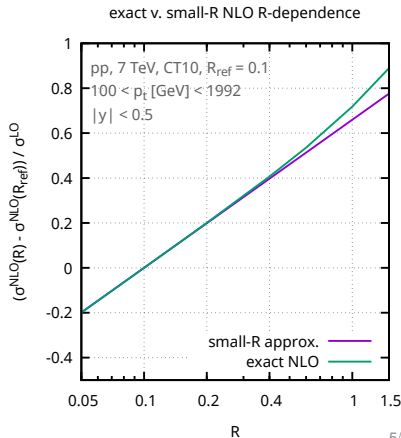
$$\sigma^{LL_R}(p_t, R) \equiv \sum_k \int_{p_t} \frac{dp'_t}{p'_t} f^{incl}_{jet/k}\left(\frac{p_t}{p'_t}, t(R, R_0, \mu_R)\right) \frac{d\sigma^{(k)}}{dp'_t}$$

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

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

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

[Nagy Phys.Rev. D68 (2003) 094002]

exact v. small-R NLO R-dependence

pp, 7 TeV, CT10, R_{ref} = 0.1
$100 < p_t$ [GeV] < 1992
$|y| < 0.5$

y-axis: $(\sigma^{NLO}(R) - \sigma^{NLO}(R_{ref})) / \sigma^{LO}$
x-axis: R

small-R approx.
exact NLO

Precise resummed predictions require matching to NLO.

We adopt multiplicative matching

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

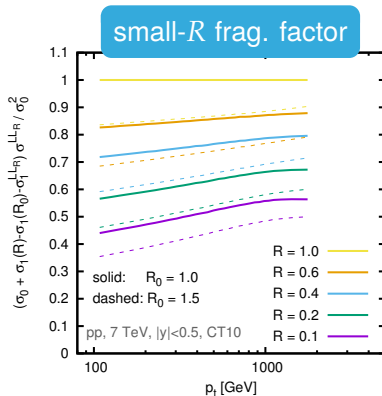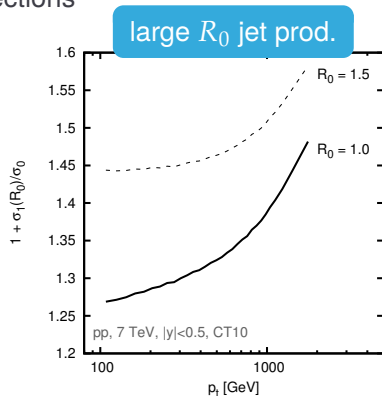$\underbrace{\qquad\qquad}_{\text{large } R_0 \text{ jet prod.}}$ $\underbrace{\qquad\qquad\qquad}_{\text{small } R \text{ fragmentation factor}}$

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

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

Unphysical cancellations in scale dependence

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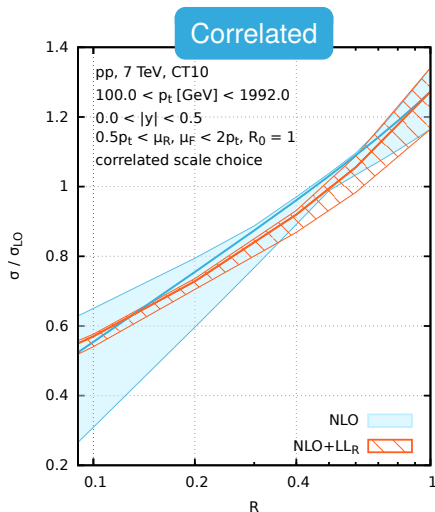

Partial cancellation in higher order effects can be dangerous when estimating scale uncertainties.

Evaluate independently and add in quadrature.

Correlated vs. uncorrelated scale variation

Uncorrelated scale variation gets rid of unphysical cancellations in uncertainty bands

Correlated scale variation:
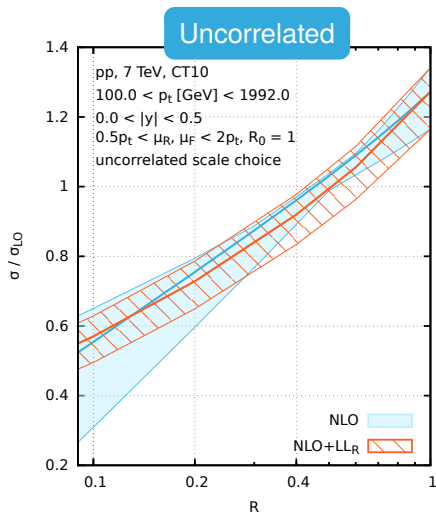Keep the same scale in both factors.

Correlated vs. uncorrelated scale variation

Uncorrelated scale variation gets rid of unphysical cancellations in uncertainty bands
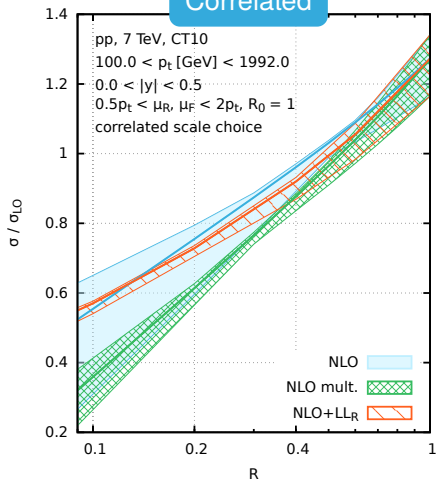
Uncorrelated scale variation:
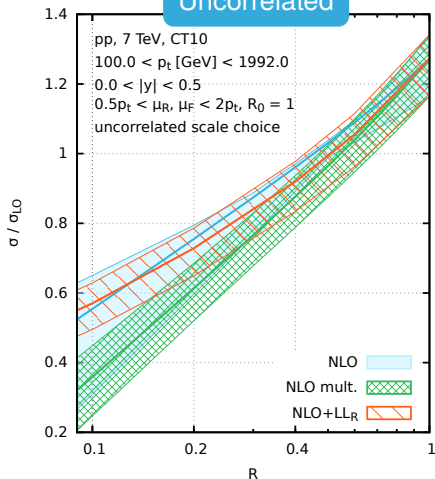Vary scale independently in each factor, and add resulting uncertainties in quadrature.

Correlated vs. uncorrelated scale variation

Uncorrelated scale variation gets rid of unphysical cancellations in uncertainty bands

Small-R approximation beyond NLO

How important are subleading effects at higher orders?

Compute difference between R
values at NNLO

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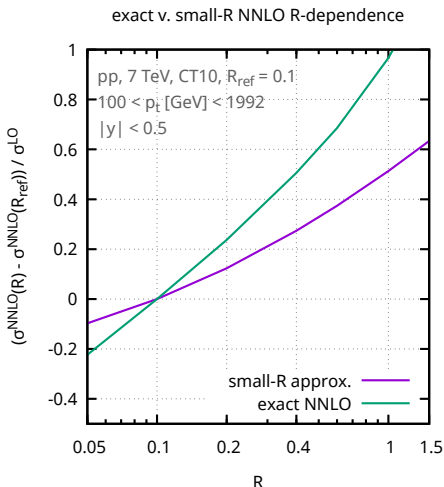
Small-R approximation beyond NLO

How important are subleading effects at higher orders?

Compute difference between R values at NNLO

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

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

Ideally, one would like a full NLL_R resummation.

exact v. small-R NNLO R-dependence

Legend:
small-R approx.
exact NNLO

pp, 7 TeV, CT10, $R_{\text{ref}} = 0.1$
$100 < p_t$ [GeV] < 1992
$|y| < 0.5$

x-axis: R
y-axis: $(\sigma^{\text{NNLO}}(R) - \sigma^{\text{NNLO}}(R_{\text{ref}})) / \sigma^{\text{LO}}$

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 ...

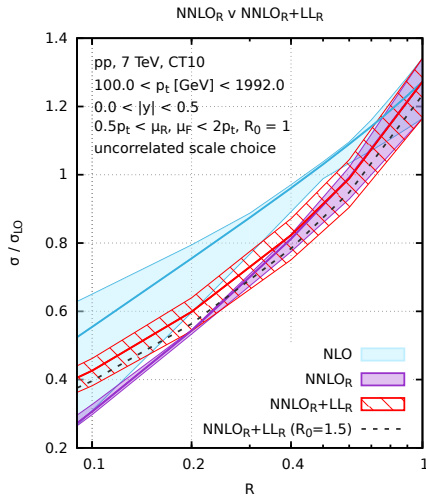... but we can at least include $\alpha_s^2 \ln R$ terms by matching to NNLO.
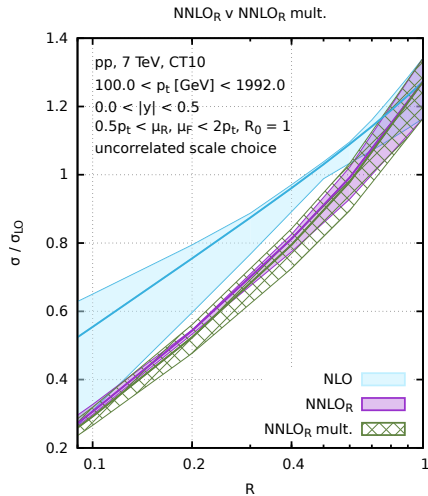
Since full calculation is not yet available, construct a stand-in for NNLO

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

$$\underbrace{\hphantom{\sigma_2(R) - \sigma_2(R_m)}}_{\text{from NLO 3-jet}}$$

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

NNLO$_R$ brings large corrections at small radii, and steeper R dependence.

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
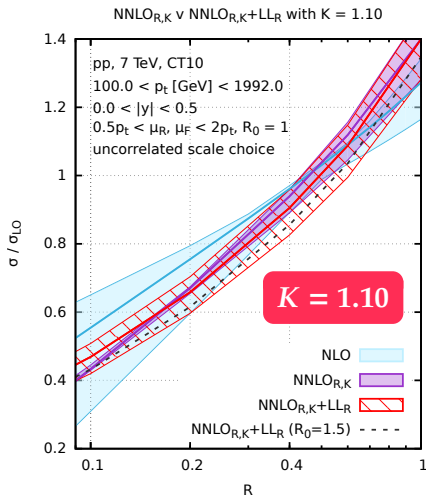
$$\sigma^{NNLO_{R,K}}(R_m) = K \times \sigma^{NLO}(R_m)$$

For other values of the jet radius, we have

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

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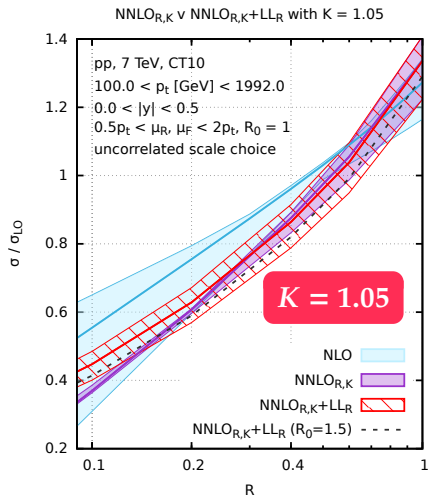
Comparison to POWHEG

Compare with `POWHEG`'s dijet process, showered with `Pythia` 8.186 and `Herwig` 6.521.
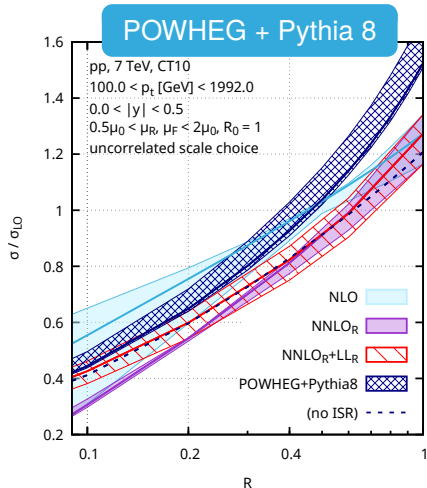
NON-PERTURBATIVE EFFECTS AND COMPARISON TO DATA

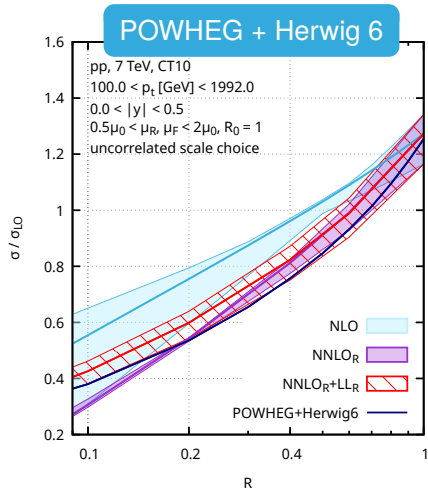There are two main non-perturbative effects

- ▶ 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

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

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 $0.5\,\mathrm{GeV}$.

Shift in jet p_t induced by hadronisation, rescaled by a factor RC_F/C.
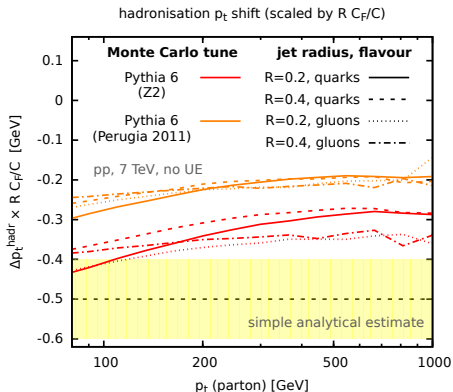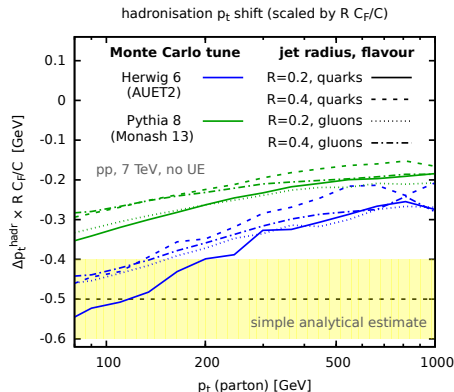
Reasonable agreement with analytical model for colour and R scaling, but strong p_t dependence and large differences between tunes.

Hadronisation and UE corrections

We will include non-perturbative effects by rescaling spectra with factors derived from Monte Carlo simulations.
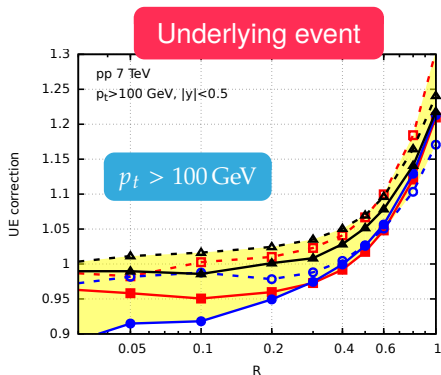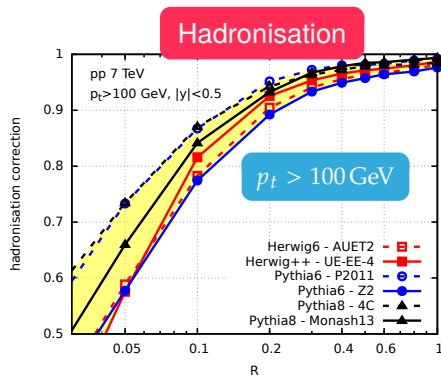
Surprising behaviour of UE corrections at small radii: some factors smaller than one (ie. removing energy), and not suppressed at high p_t.

Hadronisation and UE corrections

We will include non-perturbative effects by rescaling spectra with factors derived from Monte Carlo simulations.
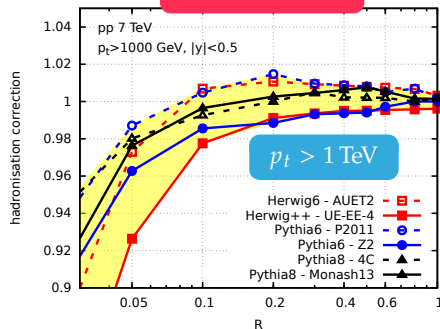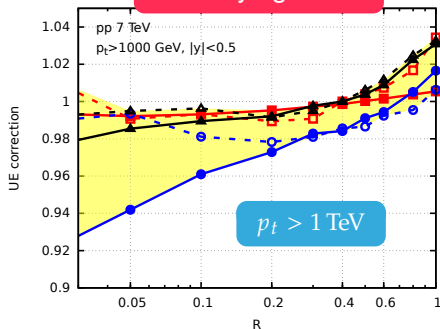
Surprising behaviour of UE corrections at small radii: some factors smaller than one (ie. removing energy), and not suppressed at high p_t.

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 $R = 0.6$.

Settings

- Scale is set to hardest jet in the event, as clustered with $R = 1$
  $$\mu_0 = p_{t,\mathrm{max}}^{R=1}\,, \quad \mu_0/2 < \mu_F, \mu_R < 2\mu_0 \text{ (uncorrelated variation)}.$$
- PDF used is CT10 NLO set.

Partial $NNLO_R$ results shift the predictions further away from data.

inclusive jets, R = 0.4

pp, 7 TeV, CT10
$|y| < 0.5$, anti-k_t alg.
$0.5\mu_0 < \mu_R, \mu_F < 2\mu_0, R_0 = 1$
uncorrelated scale choice

ratio to QCD ($NNLO_R+LL_R$) × (NP)

p_t [GeV]
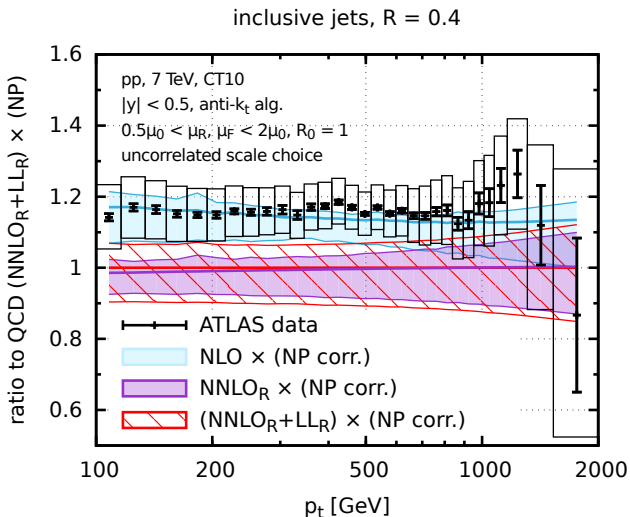
ATLAS data
NLO × (NP corr.)
$NNLO_R$ × (NP corr.)
($NNLO_R+LL_R$) × (NP corr.)

Better agreement with data when taking a constant K-factor modelling impact of two-loop corrections.

inclusive jets, R = 0.4

pp, 7 TeV, CT10
$|y| < 0.5$, anti-k_t alg.
$0.5\mu_0 < \mu_R, \mu_F < 2\mu_0$, $R_0 = 1$
uncorrelated scale choice

$K = 1.10$

ratio to QCD (NNLO$_{R,K}$+LL$_R$) × (NP)

ATLAS data
NLO × (NP corr.)
NNLO$_{R,K}$ × (NP corr.)
(NNLO$_{R,K}$+LL$_R$) × (NP corr.)

p_t [GeV]

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

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

pp, 7 TeV, CT10
$|y| < 0.5$, anti-k_t alg.
$0.5\mu_0 < \mu_R, \mu_F < 2\mu_0$, $R_0 = 1$

ATLAS data (approx. uncert.)
NLO × (NP corr.)
(NLO-mult.) × (NP corr.)
(NLO+LL$_R$) × (NP corr.)

ratio $\sigma(p_t;R=0.4)/\sigma(p_t;R=0.6)$

p_t [GeV]

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

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

inclusive jets, R = 0.2

pp, 2.76 TeV, CT10
$|y| < 0.5$, anti-k_t alg.
$0.5\mu_0 < \mu_R, \mu_F < 2\mu_0, R_0 = 1$
uncorrelated scale choice

ALICE data

NLO × (NP corr.)

NNLO$_R$ × (NP corr.)

(NNLO$_R$+LL$_R$) × (NP corr.)

ratio to QCD (NNLO$_R$+LL$_R$) × (NP)

p_t [GeV]

Adding a K-factor $K = 1.10$ slightly improves agreement with data.

inclusive jets, R = 0.2
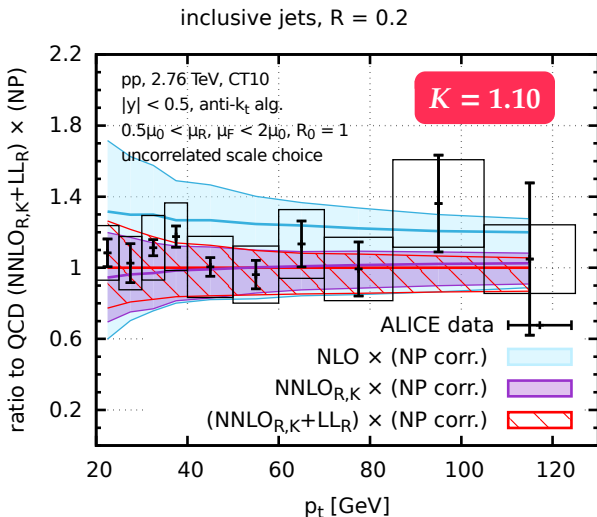
Comparison to ALICE data: ratio of jet spectra

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

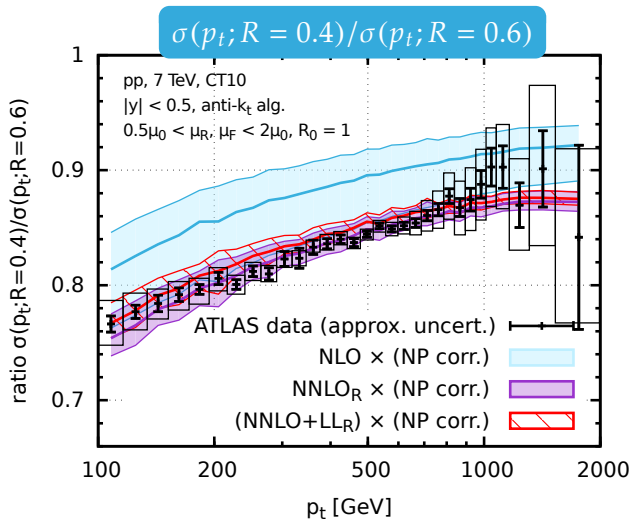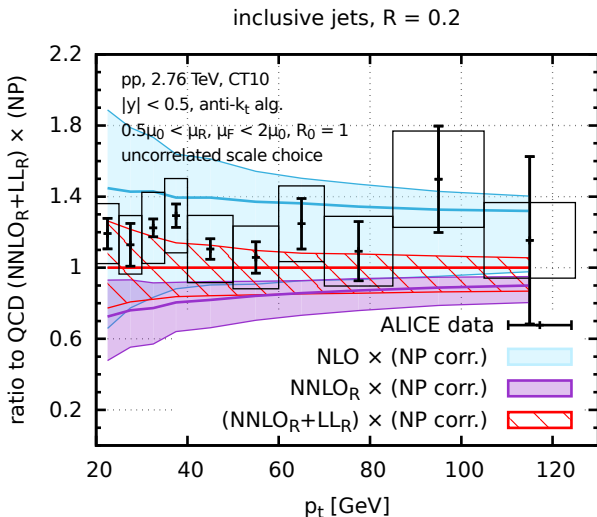In this case, $NNLO_R + LL_R$ provides best match for the data.
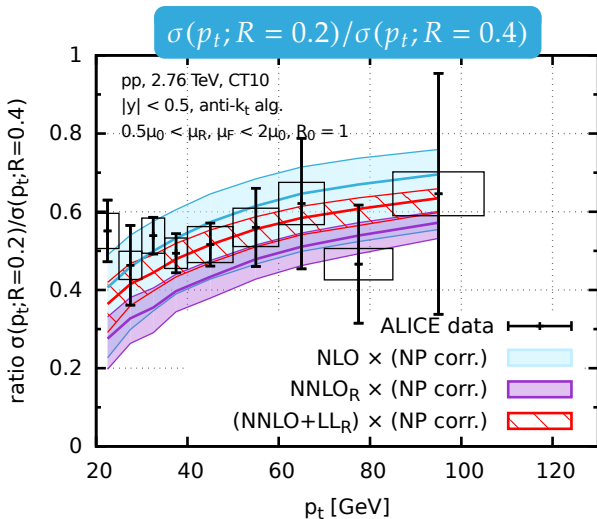
CONCLUSION

- ▶ 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

- ▶ NLO-mult predictions and uncorrelated scale variations are important tools for reliably estimating missing higher-order uncertainties.

> Code and plots available on microjets.hepforge.org.

BACKUP SLIDES

Microjet vetoes

Jet veto resummation for Higgs production has terms

$$\alpha_s^m \ln^{2m} \frac{M_H}{p_{t,\text{veto}}} + \text{subleading}$$

Among the subleading terms there are small-R enhanced terms

$$\alpha_s^{m+n} \ln^m \frac{M_H}{p_{t,\text{veto}}} \ln^n \frac{1}{R^2} + \dots$$

Suspected of having important impact, and calculated by several groups

NNLL jet vetoes	$n = 1$	[Banfi, Monni, Salam, Zanderighi PRL 109 (2012) 202001]
		+ [Becher, Neubert, Rothen JHEP 1301 (2013) 125]
		+ [Stewart, Tackmann, Walsh, Zuberi PRD 89 (2014) 054001]
Alioli & Walsh	$n = 2$ (numerically)	[JHEP 1403 (2014) 119, corr. in arXiv-v3]
Our work	$n = 2$ (analytically)	[JHEP 1504 (2015) 039]
	+ $n \to \infty$ (numerically)	

Jet vetoes

Writing the probability of no gluon emissions above a scale p_t as

$$P(\text{no primary-parton veto}) = \exp\left[- \int_{p_t}^{Q} \frac{dk_t}{k_t} \bar{\alpha}_s(k_t) 2 \ln \frac{Q}{k_t} \right],$$

one can show that including small-R corrections and applying the veto on the hardest microjet, we have

$$\mathcal{U} \equiv P(\text{no microjet veto})/P(\text{no primary-parton veto})$$

$$= \exp\left[- 2\bar{\alpha}_s(p_t) \ln \frac{Q}{p_t} \int_0^1 dz\, f^{\text{hardest}}(z, t(R, p_t)) \ln z \right].$$

The R-dependent correction generates a series of terms

$$\alpha_s^{m+n}(Q) \ln^m(Q/p_t) \ln^n R.$$

Filtering

Definition

Reclustering of a jet on a smaller angular scale $R_{\text{filt}} < R_0$, discarding all but the n_{filt} hardest subjets.

Define $f^{k\text{-hardest}}(z)$ the probability that the k-th hardest subjet carries a momentum fraction z of the initial parton.

We can express the energy loss between the filtered jet and the initial parton as

$$\langle \Delta z \rangle^{\text{filt},n} = \left[\sum_{k=1}^{n} \int dz \, z \, f^{k\text{-hardest}}(z) \right] - 1.$$

Trimming

Definition

- Recluster all particles within a jet into subjets with $R_{\text{trim}} < R_0$.
- Resulting microjets with $p_t \geq f_{\text{cut}} p_t^{\text{parton}}$ are merged and form the trimmed jet, others are discarded.

Energy difference between the trimmed jet and the initial parton of flavour i can then be expressed as a function of f_{cut}

$$\langle \Delta z(f_{\text{cut}}) \rangle_i^{\text{trim}} = \left[\sum_j \int_{f_{\text{cut}}}^{1} dz \, z \, f_{j/i}^{\text{incl}}(z, t) \right] - 1 \,.$$

Caveat: this would need double resummation of $\ln R$ and $\ln f_{\text{cut}}$.

As with filtering, energy loss from trimmed jets with a given R_{trim} is much reduced relative to that from a single microjet with that same radius.

Convergence of the power series is (maybe) better than for filtering.

Resummation of $\ln f_{\text{cut}}$ would be required as well.

Average jet energy loss Δz after trimming with $f_{\text{cut}} = 0.1$.

As with filtering, energy loss from trimmed jets with a given R_{trim} is much reduced relative to that from a single microjet with that same radius.

Convergence of the power series is (maybe) better than for filtering.

Resummation of $\ln f_{\mathbf{cut}}$ would be required as well.

Average jet energy loss Δz after trimming with $f_{\mathbf{cut}} = 0.05$.

Trimming of gluon jets

As with filtering, energy loss from trimmed jets with a given R_{trim} is much reduced relative to that from a single microjet with that same radius.

Convergence of the power series is (maybe) better than for filtering.

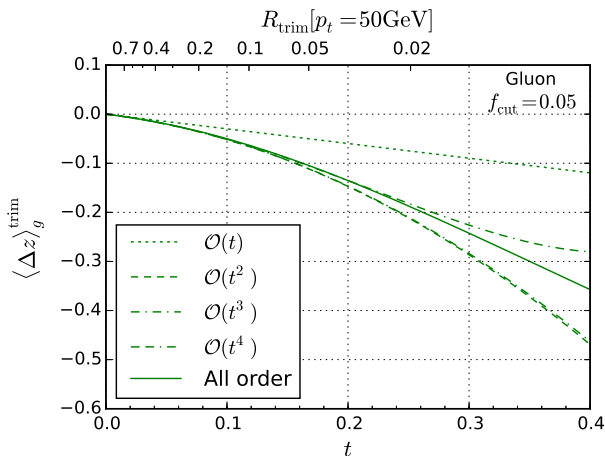Resummation of $\ln f_{\text{cut}}$ would be required as well.
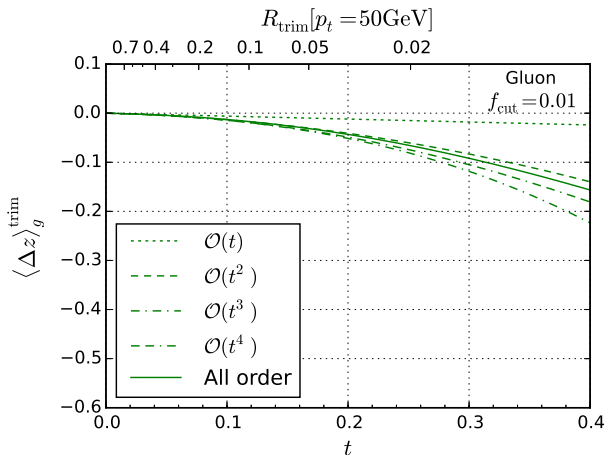
Average jet energy loss Δz after trimming with $f_{\text{cut}} = 0.01$.

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

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

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.

inclusive jets, R = 0.4

pp, 7 TeV, CT10
|y| < 0.5, anti-k_t alg.
$0.5p_t < \mu_R, \mu_F < 2p_t, R_0 = 1$
uncorrelated scale choice

ATLAS data
NLO × (NP corr.)
NLO mult. × (NP corr.)
(NLO+LL$_R$) × (NP corr.)

ratio to QCD LO

p_t [GeV]

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

inclusive jets, R = 0.4

pp, 7 TeV, CT10
|y| < 0.5, anti-k$_t$ alg.
0.5p$_t$ < μ$_R$, μ$_F$ < 2p$_t$, R$_0$ = 1
uncorrelated scale choice

ratio to QCD LO

ATLAS data
NLO × (NP corr.)
NNLO$_R$ × (NP corr.)
(NNLO$_R$+LL$_R$) × (NP corr.)

p$_t$ [GeV]
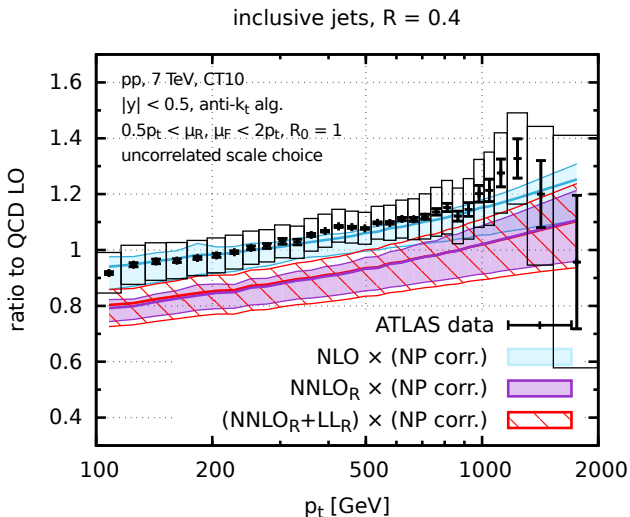
Small-R resummation somewhat improves agreement with ALICE data, and reduces the scale dependence of the NLO prediction.
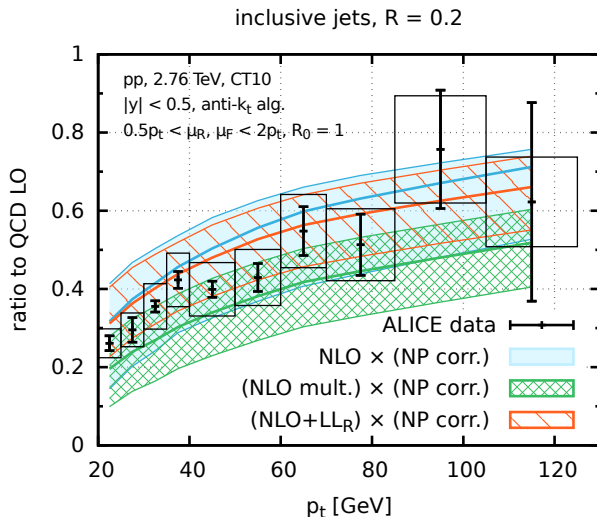
inclusive jets, R = 0.2

Plot axes: x-axis "p_t [GeV]" ranging from 20 to 120; y-axis "ratio to QCD LO" ranging from 0 to 1.

Plot annotations:
pp, 2.76 TeV, CT10
$|y| < 0.5$, anti-k_t alg.
$0.5p_t < \mu_R, \mu_F < 2p_t, R_0 = 1$

Legend:
ALICE data
NLO × (NP corr.)
(NLO mult.) × (NP corr.)
(NLO+LL$_R$) × (NP corr.)

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

inclusive jets, R = 0.2

pp, 2.76 TeV, CT10
|y| < 0.5, anti-k$_t$ alg.
0.5p$_t$ < μ$_R$, μ$_F$ < 2p$_t$, R$_0$ = 1

ratio to QCD LO

ALICE data

NLO × (NP corr.)

NNLO$_R$ × (NP corr.)

(NNLO$_R$+LL$_R$) × (NP corr.)

p$_t$ [GeV]
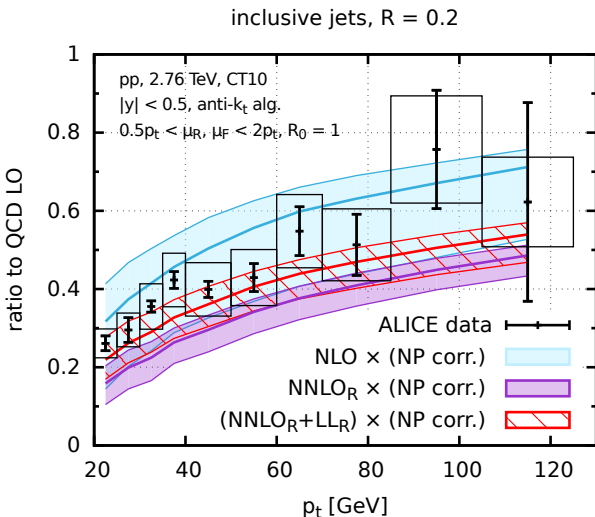
Example of jet algorithm: generalised k_t algorithms

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

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

$$\sigma^{\text{NNLO,mult.}} = (\sigma_0 + \sigma_1(R_0) + \sigma_2(R_0)) \times$$
$$\times \left(1 + \Delta_{1+2}(R, R_0) - \frac{\sigma_1(R_0)}{\sigma_0} \Delta_1(R, R_0) \right)$$
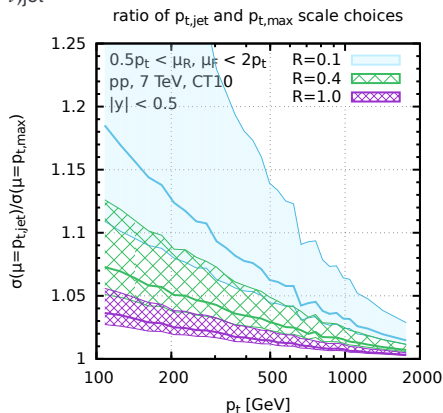
Choice of scale μ_0 beyond LO

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.

ratio of $p_{t,\text{jet}}$ and $p_{t,\max}$ scale choices

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.

NNLO$_{R,K}$+LL$_R$ with K=1.05 v POWHEG

NNLO$_{R,K}$+LL$_R$ with K=1.15 v POWHEG

pp, 7 TeV, CT10
$100.0 < p_t$ [GeV] < 1992.0
$0.0 < |y| < 0.5$
$0.5p_t < \mu_R, \mu_F < 2p_t, R_0 = 1$
uncorrelated scale choice

NLO
NNLO$_{R,K}$
NNLO$_{R,K}$+LL$_R$
POWHEG+Pythia
(no ISR)