Jet shapes in H/V+jet with k_t clustering at hadron colliders

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Motivation

- Jet mass: a typical QCD jet shape that plays an important role in:
  - studying jet's substructure
  - testing QCD
  - identifying new-physics signals
- Jet mass: sensitive to soft & collinear radiation $\rightsquigarrow$ probe:
  - perturbative: ISR, FSR, colour flow, resummation ...
  - non-perturbative: hadronisation, UE, PU ...
- Analytical computations (cf. MC generators) offer:
  - deeper insight into QCD processes
  - better control of theoretical uncertainties
  - precise estimate of missing higher-order contributions

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- Jet mass is an non-global observable. i.e, exclusive observable
  $\rightsquigarrow$ sensitive only to radiation into the jet vicinity.

- NLL resummation requires proper treatment of:
  1. global (Sudakov) logs [primary abelian emissions]
  2. non-global logs (NGLs) [secondary non-abelian emissions]
  3. clustering logs (CLs) [jet algorithms such as k$_t$, C-A]

- Resummation of NGLs/CLs is usually achieved via:
  1. MC program at large-N$_c$ (L-NGLs & NL-NGLs)

     Dagupta & Salam '01, Banfi, Dreyer & Monni '21
  2. Evolution equation (BMS) at large-N$_c$ Banfi, Marchesini & Smye '02
  3. Numerical solution of Weigert equ. at full-N$_c$ Hatta & Ueda '13

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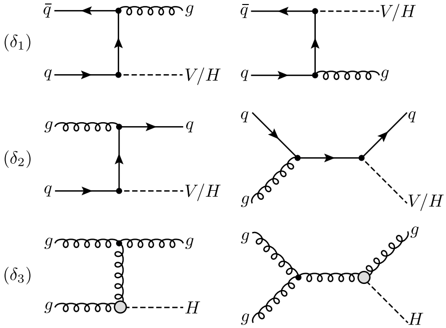
Setup

Processes & kinematics

Production of a Higgs/vector boson $(W^{\pm}/Z/\gamma)$ + high-p_t jet:

Born process: 3 partonic channels



For QCD calculations: all 3 channels are identical:

3 hard coloured QCD partons + 1 colour-neutral boson

$$a + b \to j + X$$

Approx. & jet observable

Eikonal (soft) approx.

$$k_t\,(\text{emission}) \ll p_t\,(\text{jet})$$

Strong-ordering: in gluons' k_t

$$k_{tn} \ll \cdots \ll k_{t2} \ll k_{t1} \ll p_t$$

Jet observable

Normalised (squared) invariant mass of outgoing hardest jet j:

$$\varrho = \frac{1}{p_t^2}\left[p_j + \sum_{i\in\text{jet}} k_i\right] \approx \frac{2}{p_t^2}\sum_{i\in\text{jet}} k_i \cdot p_j = \sum_{i\in\text{jet}} \varrho_i,$$

Note: Jets are defined using a **jet algorithm**

Jet mass distribution

The integrated jet mass distribution:

$$\Sigma(\rho) = \sum_{\delta} \int \mathrm{d}\mathcal{B}_\delta \; \frac{\mathrm{d}\Sigma_\delta(\rho)}{\mathrm{d}\mathcal{B}_\delta} \; \Xi_{\mathcal{B}}$$

- sum over partonic channels
- differential Born configuration
- diffential jet mass distribution for channel δ

$$\frac{\mathrm{d}\Sigma_\delta(\rho)}{\mathrm{d}\mathcal{B}_\delta} = \int_0^\rho \frac{\mathrm{d}^2\sigma_\delta}{\mathrm{d}\mathcal{B}_\delta \mathrm{d}\varrho} \mathrm{d}\varrho$$

- kinemtical cuts on Born configurations

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Jet mass distribution

The differential jet mass distribution in region $\rho \ll 1$:

$$\frac{\mathrm{d}\Sigma_\delta(\rho)}{\mathrm{d}\mathcal{B}_\delta} = \frac{\mathrm{d}\sigma_{0,\delta}}{\mathrm{d}\mathcal{B}_\delta} \; f_{\mathcal{B},\delta}(\rho) \;\; C_{\mathcal{B},\delta}(\rho)$$

- differential partonic Born x-sec
- resums all large logarithms, its form:

$$f_{\mathcal{B},\delta}(\rho) = \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s\, g_3(\alpha_s L) + \cdots\right]$$

  Note: g_1 resums LL, g_2 resums NLL, and so on

- constant (non-log terms) function

$$C_{\mathcal{B},\delta}(\rho) = 1 + \alpha_s C^{(1)}_{\mathcal{B},\delta}(\rho) + \cdots$$

Task: compute g_1, g_2 and determine $C^{(1)}_{\mathcal{B},\delta}$

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Fixed-order calculations

One-gluon emission

Results at 1-loop $\mathcal{O}(\alpha_s)$:

$$f^{(1)}_{\mathcal{B},\delta} = f^{(1)\text{DL}}_{\mathcal{B},\delta} + f^{(1)\text{SL}}_{\mathcal{B},\delta}$$

where

$$f^{(1)\text{DL}}_{\mathcal{B},(ab)} = -\bar{\alpha}_s \frac{L^2}{4} \left(\mathcal{C}_{aj} + \mathcal{C}_{bj}\right), \qquad L \equiv \ln \frac{R^2}{\rho}$$

$$f^{(1)\text{SL}}_{\mathcal{B},(ab)} = -\bar{\alpha}_s L \left[\mathcal{C}_{ab} \frac{R^2}{2} + \left(\mathcal{C}_{aj} + \mathcal{C}_{bj}\right) h(R)\right]$$

with $h(R) = R^2/8 + R^4/576 + \cdots$

Note: This result was first derived by Dasgupta, KK et al '12

Two-gluon emission

Overview

This is the first order at which:

- jet algorithms first differ
- NGLs first appear
- CLs first appear

Jet mass distribution at this order:

$$f^{(2)}_{\mathcal{B},\delta}(\rho) = \; f^{(2)\text{global}}_{\mathcal{B},\delta} \; + \; \mathcal{C}_{2,\delta}(\rho) \; + \; \mathcal{S}_{2,\delta}(\rho)$$

- exponentiation of 1-loop
- CLs coefficient
- NGLs coefficient

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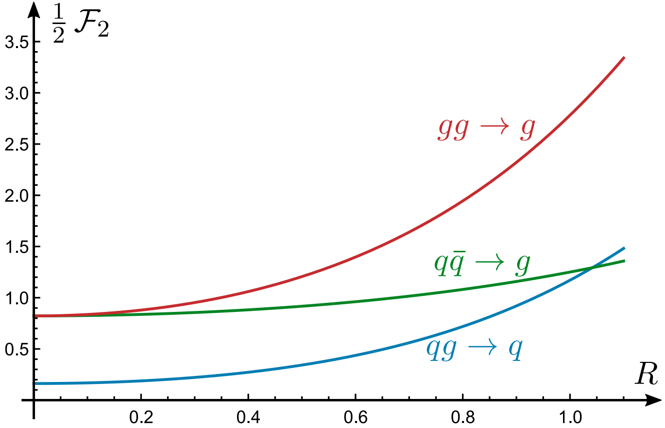
Two-gluon emission

Clustering logs (CLs)

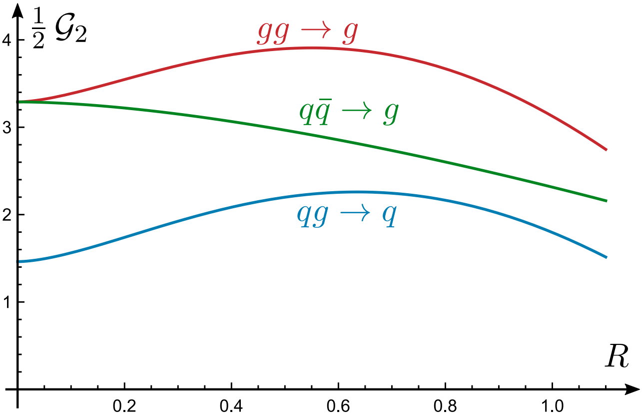
$$C_{2,\delta}(\rho) = \int \mathrm{d}\Phi_{12}\, \mathcal{W}^{\mathrm{R}}_{1,\delta} \mathcal{W}^{\mathrm{R}}_{2,\delta}\, \Theta(\varrho_{1,2} - \rho)\, \Xi^{\mathsf{p}}_{12} = \frac{1}{2!} \bar{\alpha}_s^2 L^2\, \mathcal{F}_2^{\delta}(R)$$



Two-gluon emission

Non-global logs (NGLs)

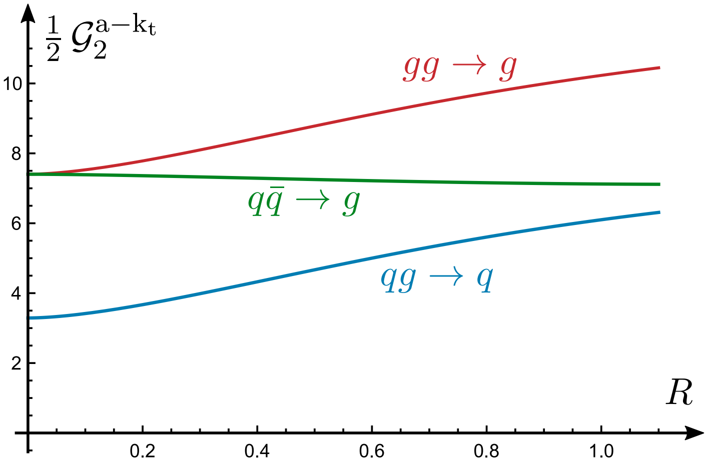
$$\mathcal{S}_{2,\delta}(\rho) = -\int \mathrm{d}\Phi_{12}\, \overline{\mathcal{W}}^{\mathrm{RR}}_{12,\delta}\Theta(\varrho_{1,2} - \rho)\, \Xi^{\mathsf{NG}}_{12} = -\frac{1}{2!}\bar{\alpha}_s^2 L^2\, \mathcal{G}_2^\delta(R)$$



k_t and C-A algorithms

Two-gluon emission

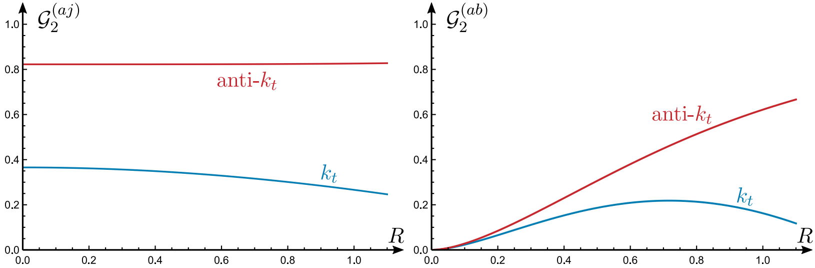
Non-global logs (NGLs)



anti-k_t algorithm

Two-gluon emission

Non-global logs (NGLs)

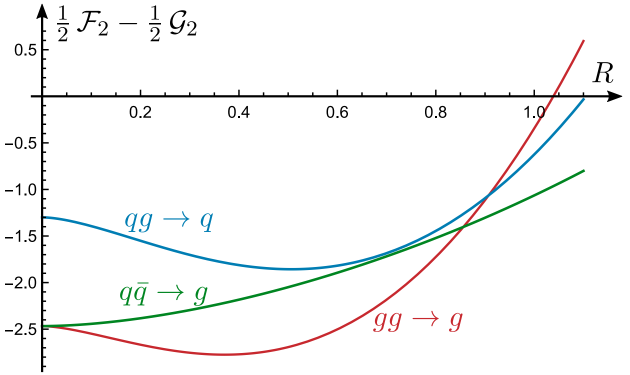


Clustering reduces effect of NGLs via:

- diminishing NGLs coefficients themselves
- CLs coeffs have opposite sign to NGLs coeffs

Two-gluon emission

NGLs + CLs



- For $R \gtrsim 1$ & all channels: NGLs and CLs tend to balance out!
- For small-R: NGLs+CLs have large contribution, especially for g-jets

All-orders & resummation

Resummed formulae

Global form factor

The all-orders NLL-resummed jet mass distribution:

$$\frac{\mathrm{d}\Sigma_\delta(\rho)}{\mathrm{d}\mathcal{B}_\delta} = \frac{\mathrm{d}\sigma_{0,\delta}}{\mathrm{d}\mathcal{B}_\delta}\, f^{\text{global}}_{\mathcal{B},\delta}(\rho)\, \mathcal{S}_\delta(\rho)\, \mathcal{C}_\delta(\rho)\, C_{\mathcal{B},\delta}(\rho)$$

with Sudakov (global) form factor

Dasgupta, KK et al '12

$$f^{\text{global}}_{\mathcal{B},\delta}(\rho) = \frac{1}{\Gamma\left[1+\mathcal{R}'_\delta(\rho)\right]} \exp\left[-\mathcal{R}_\delta(\rho) - \gamma_E \mathcal{R}'_\delta(\rho)\right]$$

$\mathcal{R}$ is the radiator (see ref. above), $\mathcal{R}' = \partial\mathcal{R}/\partial L$

- $f^{\text{global}}_{\mathcal{B},\delta}$: jet algorithm independent
- $f^{\text{global}}_{\mathcal{B},\delta}$: may be deduced from general formula in Banfi et al '03

Resummed formulae

CLs

$\mathcal{C}_\delta(\rho)$: CLs resummed form factor

- jet algorithm dependent (unlike global form factor)
- results from clustering of multiple independent (primary) emissions by jet algorithms
- so far can only be resummed numerically at large-N_c

Dasgupta & Salam '01

- Exponential of 2-loop result approximates all-orders numerical data very well

YD & KK '12

Thus confine ourselves to:

$$\mathcal{C}_\delta(t) \approx \exp\left[\frac{1}{2!}\mathcal{F}_2^\delta(R)\, t^2\right], \quad t = -\frac{1}{2\pi\beta_0}\ln\left(1 - 2\alpha_s\beta_0 L\right)$$

Resummed formulae

NGLs

$\mathcal{S}_\delta(\rho)$: NGLs resummed form factor

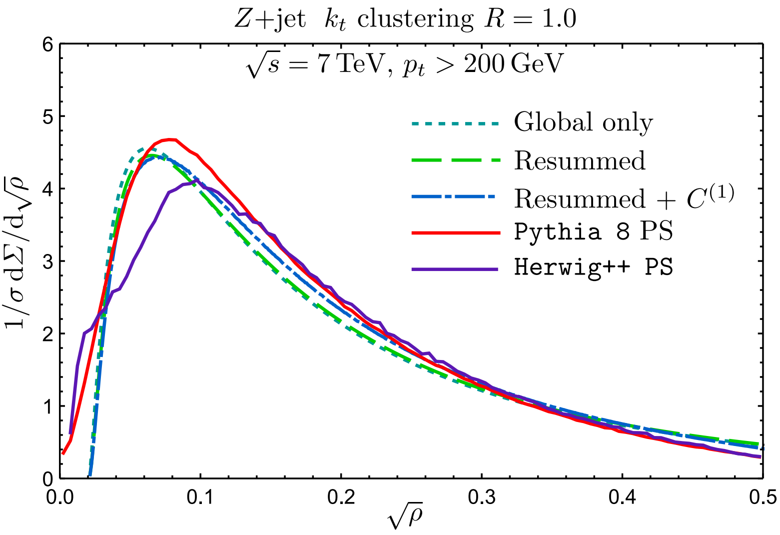
- jet algorithm dependent (unlike global form factor)
- results from an ensemble of correlated gluons emitting one or more soft gluons into the jet region
- so far can only be resummed numerically (see "Motivation")
- Exponential of 2-loop result approximates all-orders numerical data very well for all H/V+jet processes

Thus confine ourselves to:

$$\mathcal{S}_\delta(t) \approx \exp\left[-\frac{1}{2!}\mathcal{G}_2^\delta(R)\, t^2\right]$$

Comparison to MC parton showers

Comparisons to PS



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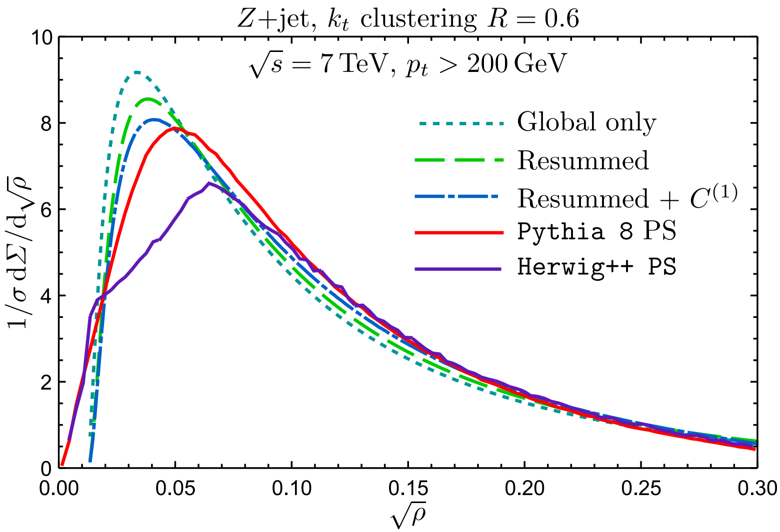

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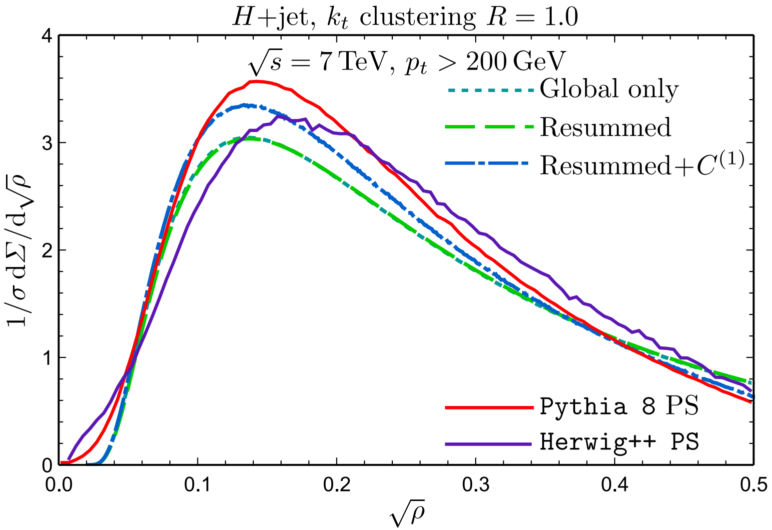

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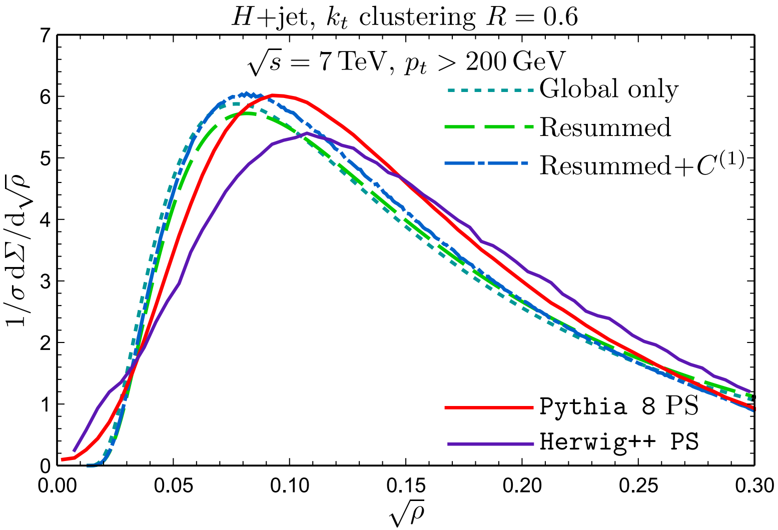

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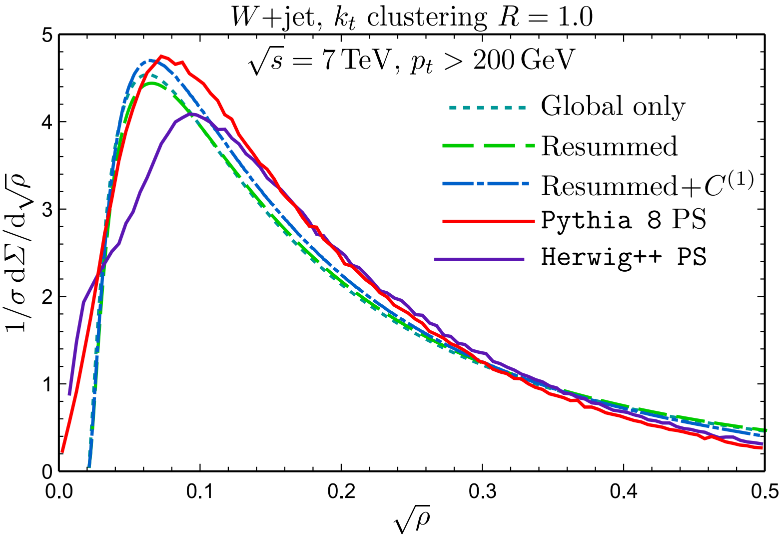
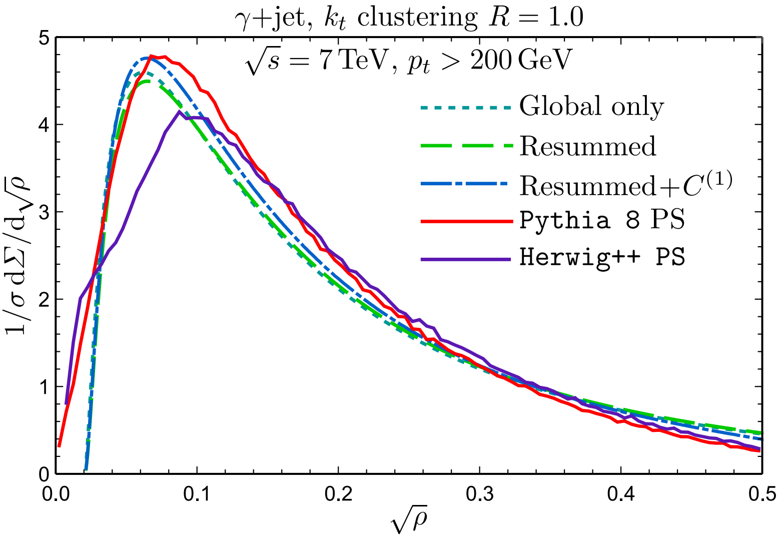
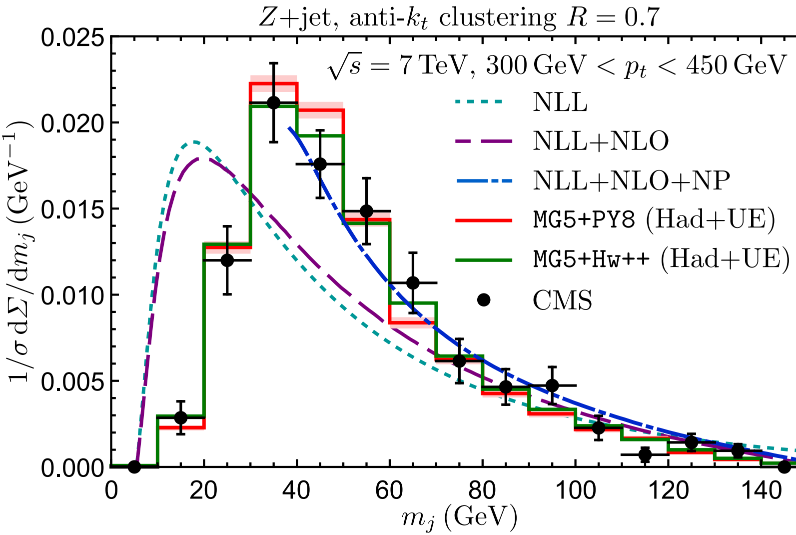




γ+jet, k_t clustering $R = 1.0$
$\sqrt{s} = 7\,\mathrm{TeV}$, $p_t > 200\,\mathrm{GeV}$
Global only
Resummed
Resummed+$C^{(1)}$
Pythia 8 PS
Herwig++ PS
$1/\sigma\, \mathrm{d}\Sigma/\mathrm{d}\sqrt{\rho}$
$\sqrt{\rho}$
0
1
2
3
4
5
0.0
0.1
0.2
0.3
0.4
0.5

Comparison to CMS data

Comparisons to CMS



Conclusion & outlook

Conclusion & outlook

Confirmed previous e^+e^- results:

- NGLs are decreased by jet clustering (other than anti-k_t)
- In small jet-radius limit, NGLs & CLs at hadron colliders concide with those at e^+e^- colliders

New results not present in previous e^+e^- studies:

- Significance of ISR on jet mass distribution
- Role of jet mass as an effective discriminating tool (e.g., gluon and quark jets)

Future projects:

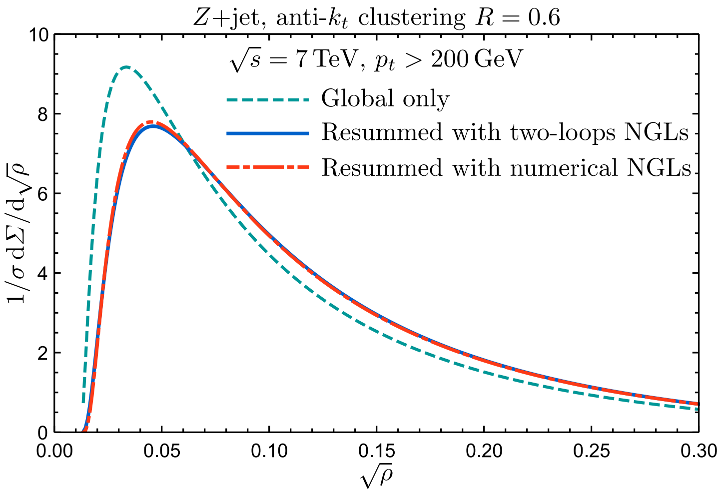
- study distributions of other jet shapes
- investigate other hadronic processes such as dijet production

End

Buck-up

Resummed formulae

NGLs: exp. of 2-loop result



Full analytical NLO jet mass distribution is delicate!

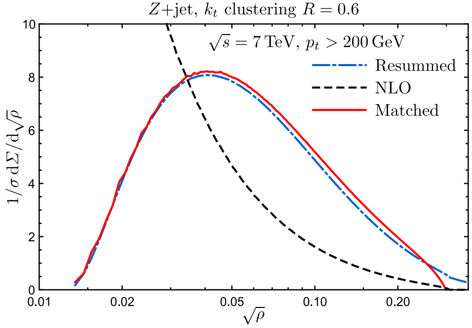
Use MCFM to estimate the Born-averaged NLO factor $C_\delta^{(1)}(\rho)$

Banfi et al '10, Dasgupta, KK et '12

$$\alpha_s C_\delta^{(1)}(\rho) = \frac{1}{\sigma_{0,\delta}}\left[\Sigma_{\mathsf{NLO}}^{(\delta)}(\rho) - \Sigma_{\mathsf{NLL},\alpha_s}^{(\delta)}(\rho)\right]$$

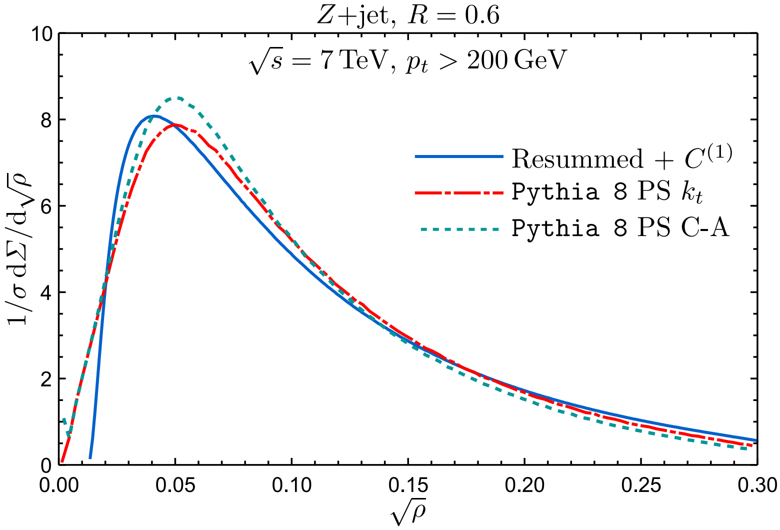
Matching NLL+NLO:

$$\rho_{\max} = \tan^2\frac{R^2}{2}$$



Comparisons to PS

Z+jet with k_t vs C-A



Comparisons to CMS

Estimate of NP effects

NP effects = hadronisation + Underlying Event (UE)

How to quantify NP effects?

- numerically: (MC with NP on)/(MC with NP off)
- analytically: compute the mean value of the change in the jet mass $\langle \delta m_j^2 \rangle$ Dasgupta et al '08

Perform the shift on the mass of the jet on an event-by-event basis

mean value depends on Born channel & kinematics:

$\rightsquigarrow$ make the change $m_j^2 \to m_j^2 - \delta m_j^2$ in Σ_{NLL} then perform convolution

Conclusion

Extended previous work [Dasgupta, KK et al '12] from various aspects:

- presented results for various jet algorithms; k_t and C-A
- computed CLs (absent in anti-k_t)
- investigated jet mass distribution in H/Z/W/γ + jet processes
- computed an estimate of NP effects & compared to experimental data