Soft gluon radiation in LHC jet shapes

Simone Marzani
University of Manchester

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in collaboration with
A. Banfi, M. Dasgupta and K. Khelifa-Kerfa
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Outline

- Jet shapes at hadron colliders
- Soft gluon effects: the first emission
- Independent gluon emissions
  – The role of the jet algorithm
- Correlated gluon emissions: non-global logarithms
- Resummation (for anti-k_t algorithm)
- Conclusions and outlook

High-p_T jet shapes

- Jet shapes enable us to test our understanding of pQCD
- They are also very important for new physics searches

- Much recent activity proposing new jet shapes to distinguish massive boosted particles from QCD background, jet-filtering and jet pruning for accurate reconstruction of mass peaks

see e.g S.D. Ellis et.al 2009,2010,
L. Almeida et.al 2009,
J.Butterworth et.al 2009,
M. Rubin 2010 etc.

- Studies of jet shapes can be divided into two categories:
  - MC simulations
  - Analytical resummations

Jet masses

- Understanding jet mass distributions is crucial for LHC phenomenology
- Jet mass distribution are affected by large logarithms of form

$$\alpha_s \ln^2 \frac{p_T^2}{M^2}$$

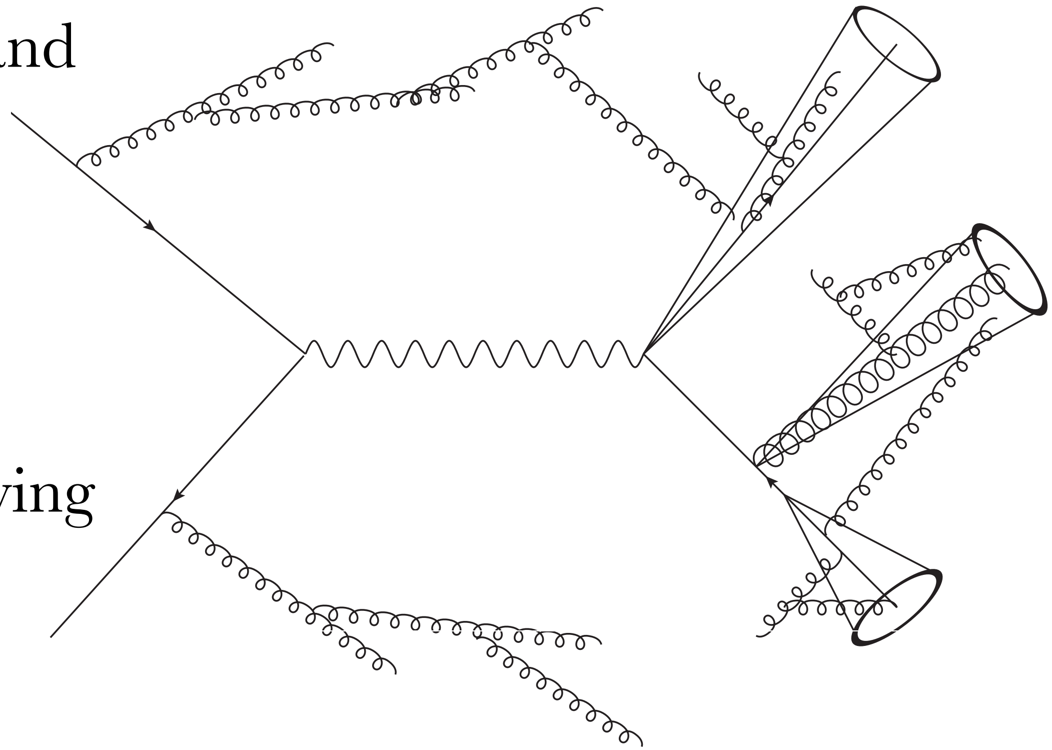
- Reliable calculations in pQCD require resummation
- In e^+e^- resummation exists

CTTW, Burby and Glover

- Can we extend this to hadron colliders ?

The picture at the LHC

- Can we deal with a more complicated environment ?
- Complex colour structure and geometry ?
- Does the choice of the jet algorithm play a role ?
- How do we treat ISR ?
- Can we reduce the underlying event ?



Measuring jet shapes

- A definite method proposed to measure the shape of one or more jets in an event leaving other jets unmeasured

S. Ellis, A. Hornig, C. Lee, C. Vermilion and J.R. Walsh 2009, 2010

$$\Sigma\left(\rho, E_0\right) = \frac{1}{\sigma_0}\int \frac{d\sigma}{d\rho_1' dE_0' d^3\mathbf{P_1} d^3\mathbf{P_2} \dots d^3\mathbf{P_n}} d\rho' dE_0' \Theta(\rho - \rho_1')\Theta(E_0 - E_0')$$

- The hard-jet multiplicity is kept fixed by cut E_0 on hadronic activity outside high-p_T jets

- Simple to define but theoretically challenging

- Multi-scale problem involving disparate scales (hence large logs): p_T, E_0, $\rho\, p_T$ and $R^2\, p_T$ (being R the jet radius)

Logarithmic structure

- At LL level we find double logs

$$\alpha_s^n \ln^{2n} \frac{R^2}{\rho}$$

- At NLL accuracy we have

$$\alpha_s^n \ln^{n} \frac{R^2}{\rho}$$

- but also single logs arising from the E_0 distribution

$$\alpha_s^n \ln^{n} \frac{p_T}{E_0}$$

see talks on jet vetoes

- The resummation of these logs has been first attempted using SCET

SCET resummation

- The resummation has been carried out for e^+e^- collisions and in the limit of narrow jets i.e. small R
- The aim was NLL accuracy (i.e. single logs)

- However
  - in a jet we measure a shape or leave the jet unmeasured
  - outside jets we have a cut E_0

- The observable is sensitive to radiation differently in different regions: non-global logarithms

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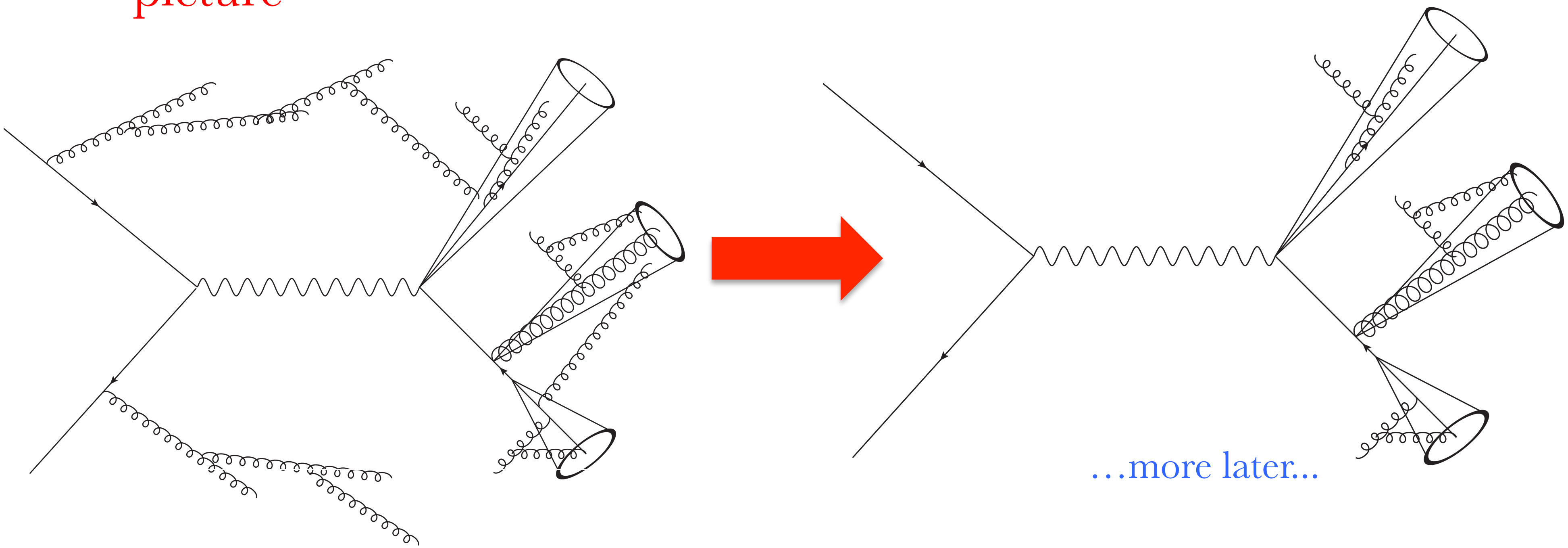
Set up of our study

- We want to address these issues from the point of QCD resummation
- We consider narrow well-separated jets ($R \ll \Delta_{ij}$)
- Not only a convenient limit for the calculation: ISR and UE contributions are reduced
- We shall find that QCD coherence leads to a simpler picture



…more later…

One gluon emission

- As an example of jet-shape we consider the jet-mass in dijets events

$$\rho = \frac{4M_j^2}{p_T^2}$$

- We consider the emission of one soft gluon off a quark-antiquark dipole
- At this level all IRC jet algorithm will give the same answer

$$\begin{aligned}\Sigma_1 = \Sigma_{\rm in} + \Sigma_{\rm out} &= \\ &- \frac{C_F \alpha_s}{2\pi} \ln^2 \frac{R^2}{\rho} \Theta\left(R^2 - \rho\right) - 2C_F \frac{\alpha_s}{\pi} \ln\left(p_T/E_0\right)\left(2\ln\frac{2}{R}\right) \\ &+ \text{hard collinear}\end{aligned}$$

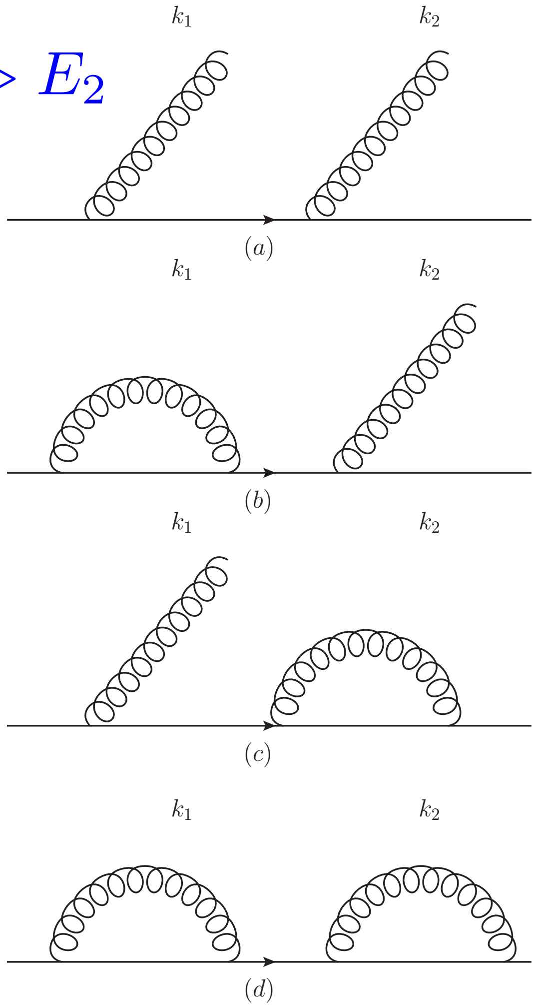
soft gluon inside the measured jet

soft gluon outside either jets, vetoed by E_0

- The naïve expectation is that the resummed result is obtained by exponentiation of the 1-loop contribution

Two independent emissions

$E_1 \gg E_2$



- Consider only the jet mass distribution for simplicity
- Double virtual never contributes
- k_1 in, k_2 out: (a) and (c) cancel; (b) is zero
- k_1 out, k_2 in: (a) and (b) cancel; (c) is zero

- Non vanishing contributions only when both gluons are inside the jet:

$$\Sigma_2 = \frac{1}{2}\left(\frac{C_F \alpha_s}{2\pi}\right)^2 \ln^4\left(\frac{R^2}{\rho}\right),$$

- Consistent with exponentiation
- Is this result the same with any jet algorithm ?

The role of the jet algorithm

- NO ! Because of soft gluon self-clustering
- Two gluons are recombined with each other is their *distance* is smaller than R
- The recombined momentum essentially lies along the harder one
- As a result a hard gluon can pull a softer one out of the jet
- This does not happen if we use anti-k_t algorithm: two soft gluons are always far apart with this measure
- The anti-k_t algorithm in the soft limit works as a perfect cone
- Exponentiation of the independent emission is OK in this case, but what happens with different algorithms ?

C/A and k_t algorithm

- With C/A or kt algorithm two soft gluons can be recombined together
- If k_1 is outside the jet, it can pull k_2 outside (if they are close enough)
- This spoils the cancellation between diagrams (a) and (b) (virtual gluons are unaffected by clustering)
- We have a new single-log contribution wrt to the anti-k_t case:

$$\Sigma_2^{\text{cluster}} = 2C_F^2 \left(\frac{\alpha_s}{2\pi}\right)^2 \ln^2 \frac{1}{\rho} \int \frac{d\phi}{\pi} \ln^2 (2\cos\phi)\, \Theta\left(\cos\phi - \frac{1}{2}\right)$$
$$= 0.364 C_F^2 \left(\frac{\alpha_s}{2\pi}\right)^2 \ln^2 \frac{1}{\rho}.$$

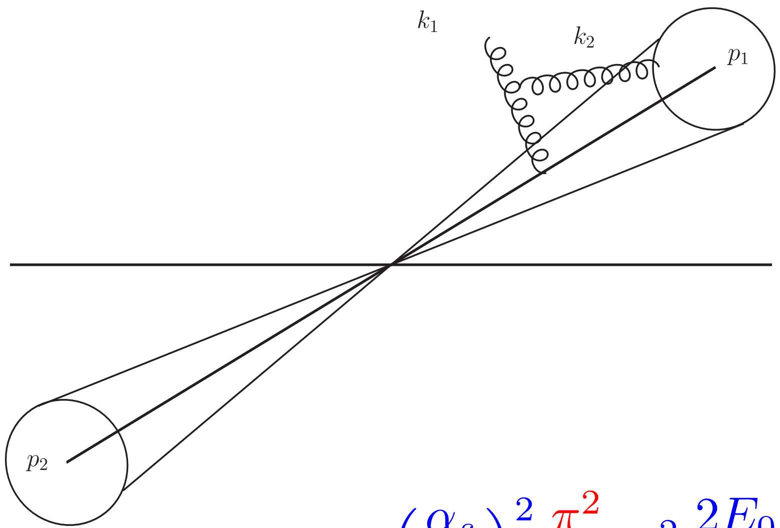
- Coefficient independent of R
- Resummation of clustering logs was shown to be possible for gaps between jets   Delenda, Appleby, Banfi, Dasgupta 2006
- From now on we work with the anti-k_t algorithm

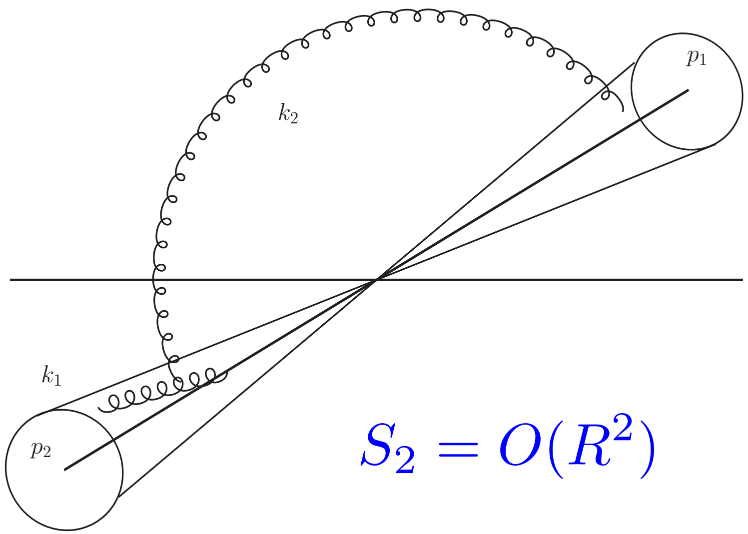
Two correlated emissions

- BUT, even if we use anti-k_t, exponentiation of the independent emission is not the whole story !
- We argued that the observable is non global
- Let's start with the jet mass and compute the contribution coming from two correlated emission
- This is a $C_F C_A$ term
- It is missed by single gluon exponentiation
- If the harder gluon k_1 is in the measured jet and k_2 is outside we have no large logs in small ρ limit
- We are left with the opposite situation k_1 is outside the measured jet and emits k_2 back into the jet

Non-global logarithms

- We have basically two diagrams
- In the $R \ll \Delta_{ij}$ limit we obtain





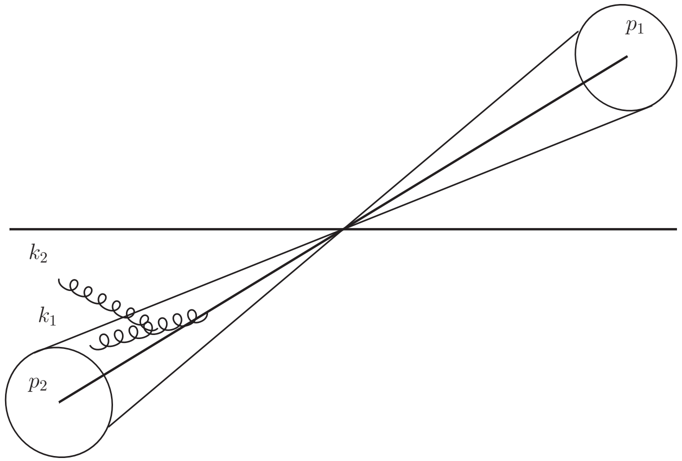
$$S_2 = O(R^2)$$

$$S_2 = -C_F C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{\pi^2}{3} \ln^2 \frac{2E_0 R^2}{\rho p_T} + O(R^2)$$

- The leading contribution is independent of R
- It comes from the region where k_1 and k_2 are collinear
- If the gluon are far away in rapidity the ME falls exponentially

Non-global logarithms (II)

- Let's look at the E_0 distribution
- We also have NG logs when k_1 is in the unobserved jet and k_2 outside both jets
- As before, leading contribution from the collinear region



$$S_2 = -C_F C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{\pi^2}{3} \ln^2 \frac{p_T}{2E_0} + O(R^2)$$

- Same situation originally found in the hemisphere jet mass

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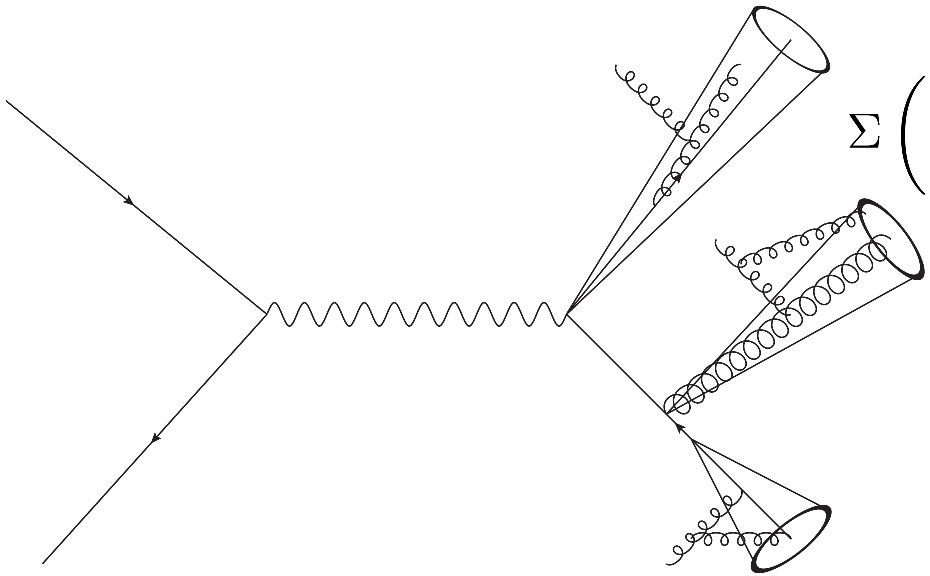
- A simpler picture emerges: NG logs arise independently from the edge of each jet

Resummation



$$\Sigma\left(\frac{R^2}{\rho},\frac{Q}{E_0}\right) \simeq \frac{\exp\left[-\mathcal{R}_\rho-\gamma_E\mathcal{R}'_\rho\right]}{\Gamma\left(1+\mathcal{R}'_\rho\right)}\exp\left[-\mathcal{R}_{E_0}\right]\prod_j S^j\left(\frac{E_0R^2}{p_T\rho},\frac{p_T}{E_0}\right)$$

- The radiator captures independent emission of soft gluons (global-piece) to single log accuracy
- The resummation of correlated emission (NG logs) is performed by the factors S^j (one for each jet)
- The factors S^j are the same as in the hemisphere jet-mass (large N_c)

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Resummation (II)

- In particular we have

$$S^j(t) = \exp\left(-C_F C_A \frac{\pi^2}{3}\left(\frac{1+(at)^2}{1+(bt)^c}\right)t^2\right)$$

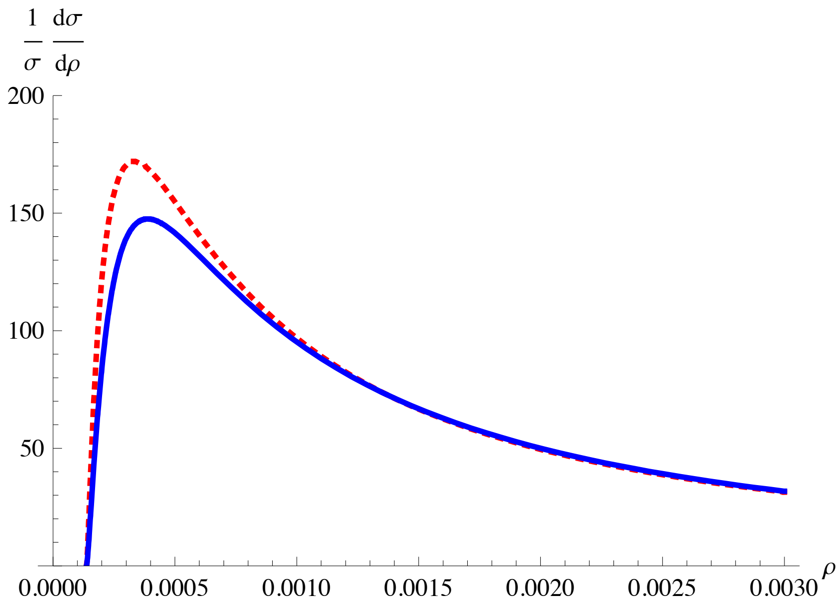
$a = 0.85 C_A,\ b = 0.86 C_A,\ c = 1.33$

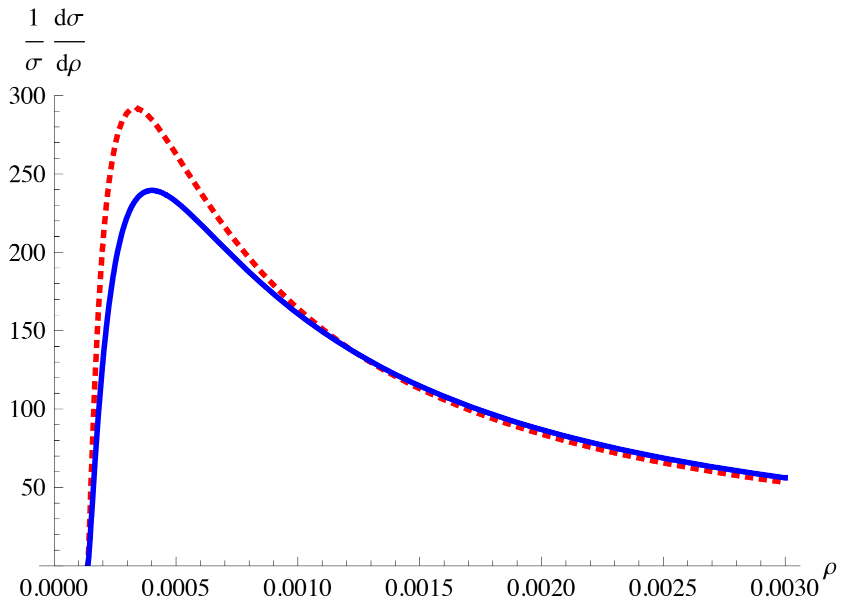
- The evolution variables are different for measured and unmeasured jets

$$t_{\text{measured}} = \frac{1}{2\pi}\int_{\frac{\rho p_T}{2E_0 R^2}}^{1}\frac{dx}{x}\alpha_s(xE_0)$$

$$t_{\text{unmeasured}} = \frac{1}{2\pi}\int_{\frac{2E_0}{p_T}}^{1}\frac{dx}{x}\alpha_s\left(xp_T/2\right)$$

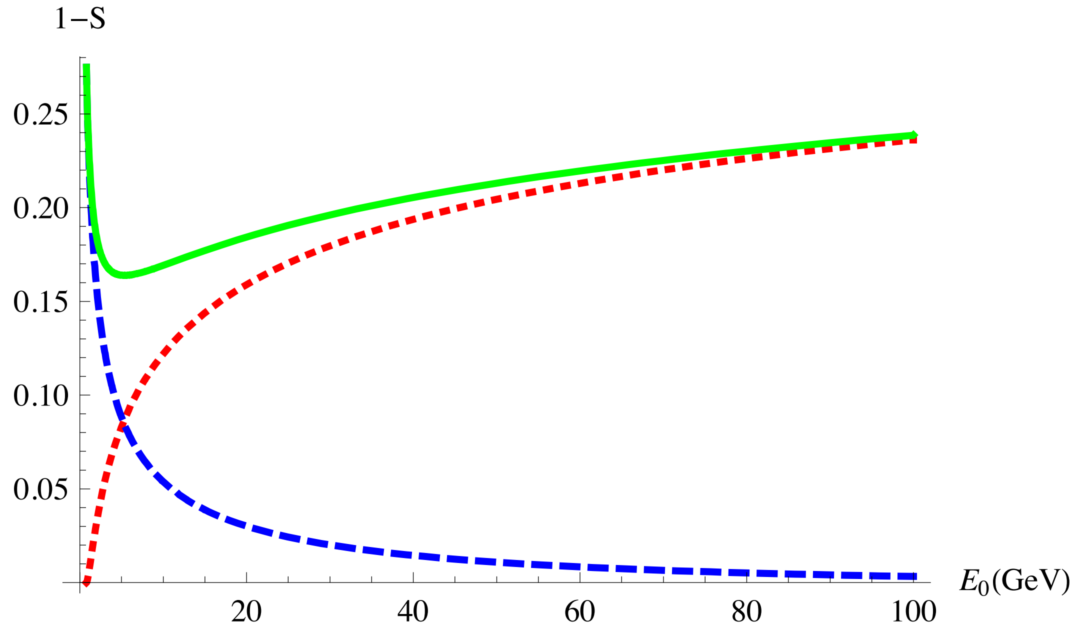
Impact of NG logarithms





- Plot of the jet mass distribution for $E_0 = 15, 60$ GeV (left/right)
- NG logs can have 20 % effect on peak height
- Not very sensitive to E_0
- Neglected terms (R^2/Δ_{ij} as well as $1/N_c^2$) have little impact on phenomenology

E_0-dependence of NG logs



$\rho = 5 \cdot 10^{-4}$

- It was suggested to reduce E_0 to eliminate NG logs
- This does reduce the contribution from the measured jet (red)
- However, choosing $E_0 \sim \rho\, p_T$ gives large contribution from unmeasured jets (blue)
- The overall contribution does not change (green)
- No way to reduce NG logs for the present observable: but we know how to resum them ! (in the large N_c, small R limit)

Conclusions

- Strong interest in examining jet shapes and substructure with several new observables recently proposed
- A lot of MC studies, but analytical approaches can give more insights
- We examined the jet-mass shape of one jet in multi-jet events.
- We discussed a simple ansatz where the standard soft gluon exponentiation is dressed with a product of NG factors (one from each jet)
- We considered the phenomenological impact of the NG logs and argued that they are significant for the peak-height.
- The results apply for the anti-k_t algorithm
- Other algorithms such as kt and C-A lead to complications because of soft gluon self-clustering

Outlook

- Hadron-hadron collisions
- Initial state radiation modifies the resummation
  (but we know what to do)
- Matching to fixed-order QCD
- Comparison to MC analysis
- LHC phenomenology