On QCD jet mass distributions at LHC

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Outline

1. Jet substructure

2. Jet mass in $e^+e^-$
   - Non-global logs
   - Clustering logs

3. Jet mass at hadron colliders
   - Example: Z+1 jet
   - Dijets
Jet substructure

- Substantial recent interest/development in understanding the substructure of jets at LHC.

- Potential tools for separating signal jets (hadronic decays of boosted H \ldots) from QCD background jets.

- Offer a test of pQCD (quark-gluon discrimination \ldots).

- Jet shapes: sensitive to geometrical properties of the energy flow inside a jet.

- Jet grooming techniques: mitigating soft radiation \Rightarrow removing Pile-up/UE \Rightarrow sharper jet properties/enhanced discrimination power.

  e.g. BOOST reviews: Abdesselam et al. ’11, Altheimer et al. ’12
Analytic vs MC

Monte Carlo event generators based on parton-showers

- Provide totally exclusive events on which any number of observables can be measured.
- Can be combined with Fixed-Order programs for accurate description over a wide phase space.
- Include models of NP effects: hadronisation, pile-up and UE, for a realistic description.
- Only leading logarithms are guaranteed to be resummed (although contain many sub-leading terms).
- Work in the large-$N_c$ limit.
Analytic vs MC

Analytical calculations based on QCD and/or SCET

- Often give an inclusive picture of a jet or event, projecting onto single observables.
- Only feasible for a limited set of observables.
- Match fixed-order and resummation (typically NLL and beyond) calculations.
- Have **perturbative precision** that often exceeds MC generators + accuracy can systematically be improved.
- Help further development and validation of MC generators.
Jet mass

- Take the jet mass as a particular jet shape
  1. simplest and most phenomenologically useful.
  2. calculations presented here are generic and thus relevant to other substructure observables.

- Two main regimes in the jet mass distribution:
  1. small mass, \( m_J \ll p_{TJ} \): contains large logs of \( m_J/p_{TJ} \) → requires resummation.
  2. large mass, \( m_J \lesssim m_{TJ} \): requires fixed-order calculation → often obtained via MC programs.

\[
\frac{1}{\sigma} \frac{d\sigma}{dm_J} = (1+\alpha_s C_1+\cdots) \frac{1}{m_J} \left[ \alpha_s A^{(1)} \ln \frac{m_J}{p_{TJ}} + \alpha_s^2 A^{(2)} \ln^3 \frac{m_J}{p_{TJ}} + \cdots \right]
\]

- Focus on small mass region.
Jet mass in $e^+e^-$

- QCD resummation of jet mass in $e^+e^-$ dijet events has long been available.  
  
  Catani et al. ’93, Dasgupta and Salam ’01

- Reliable calculations of jet shape distributions require:
  
  1. Resummation up to NLL.
  2. Fixed-order calculations at NLO.

- Recent attempts for resummation in $e^+e^-$ multi-jet events:
  
  1. angularities
  2. jet mass with jet veto  

  Ellis et al.’09 & ’10  
  Kelley et al.’11
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- Jet mass is a non-global observable: above attempts neglected important contributions at NLL:
  1. non-global logs (NGLs)
  2. clustering logs (CLs) (role of jet algorithms)
  Banfi et al.’10, KKK’11
Jet mass in $e^+e^-$: One gluon

- Study the mass of one or more high-$p_T$ jets in a multi-jet event.
- Jet multiplicity can be kept fixed by imposing a jet veto (neglect for now).
- Follow traditional QCD resummation program (in the eikonal approx.).
- For a soft gluon emitted off a primary $q\bar{q}$ dipole, the emission probability is

$$|\mathcal{M}|^2 = \exp \left[ \frac{\alpha_s}{2\pi} (-2W_{q\bar{q}} t_q \cdot t_{\bar{q}}) \right] |\mathcal{M}_0|^2$$

- All IRC safe jet algorithms produce the same distribution (NLL Sudakov factor)

$$\int \frac{1}{\sigma} \frac{d\sigma}{d\rho} = (1 + \alpha_s C_1) e^{-\mathcal{R}}$$

$$\mathcal{R} = C_F (\alpha_s / 2\pi) \ln^2 (R^2 / \rho), \quad \rho = m_J^2 / p_T^2 J.$$
Jet mass in $e^+e^-$: Two gluons & beyond

NGLs

- Jet mass is a non-global observable (sensitive to only part of phase space).
- Miscancellation of real and virtual correlated emissions give rise to large single-logs, $\alpha_s^2 \ln(R^2/\rho)/\rho$.
- It is a $C_F C_A$ correction missed by naive Sudakov single-gluon exponentation.
- Resummation is currently only feasible numerically and in the large $N_c$ limit.  
  
  Dasgupta and Salam’01, Banfi et al.’02
Jet mass in $e^+e^-$: Two gluons & beyond

CLs and the role of jet algorithms

- Appleby & Seymour suggested using the $k_T$ jet algorithm to reduce NGLs impact.  

  Appleby and Seymour’02
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CLs and the role of jet algorithms

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Appleby and Seymour’02

- BUT! self-gluon clustering of $k_T$ algorithm (also C/A, SISCones ⋯) gave new single-logs (CLs) in independent emission sector.

Banfi and Dasgupta’05, Delenda et al.’06

- Resummation of CLs has generally been achieved through the MC program of Dasgupta and Salam’01.

- Delenda et al.’06 and Delenda and KKK’12 showed exponentiation of CLs and provided an analytical approximation to the all-orders resummation (see Delenda’s talk).
Jet mass in $e^+e^-$: Two gluons & beyond

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- Challenge: $e^+e^-$ understood ⇒ what about hadron-hadron ?
Jet mass in pp collisions
LHC environment

- Complicated messy environment: geometry and colour structure?

- Effect of Initial State radiation (ISR)?

- Role of jet algorithms and related parameters?

- Non-perturbative effects: hadronisation, UE ···
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First attempt: jet function approx. treated collinear branching only, No ISR, No NGLs!!

Li et al.'11 & '12
Jet mass in pp collisions

Emission amplitude

- For simplicity focus on anti-\(k_T\) algorithm \(\sim\) ongoing work on \(k_T\) & C/A

- In the eikonal limit, matrix-element squared of a soft gluon emitted off an ensemble of harder coloured partons in the Born configuration \(\delta\)

\[
|\mathcal{M}_\delta|^2 = \mathcal{M}_{0,\delta}^\dagger \exp \left[ \frac{\alpha_s}{2\pi} \left( -2 \sum_{i<j} W_{ij} \mathbf{t}_i \cdot \mathbf{t}_j \right) \right] \mathcal{M}_{0,\delta}
\]

- \(W_{ij}\) and \(\mathbf{t}_i\) are the antenna function and SU(3) generator (colour matrices) respectively,

\[
W_{ij}(k) = \frac{\mathbf{p}_i \cdot \mathbf{p}_j}{(\mathbf{p}_j \cdot k)(\mathbf{p}_j \cdot k)}
\]

- Dipoles involving the measured jet \(\sim\) double (collinear + soft) logs. Other dipoles \(\sim\) single (soft wide-angle) logs.
Jet mass in pp collisions

Resummation

- For each partonic subprocess $\delta$, the NLL resummed result is

$$\frac{d\sigma_{\delta}}{d\rho} = \text{tr} \left[ H_{\delta} (1 + \alpha_s C_1) e^{-G^\dagger} S e^{-G} \right]$$

- $H_{\delta}$ contains Born contribution and the “colour matrix” $S = 1$ for a particular set of basis.

- The resummed exponent $G$ contains to NLL
  1. collinear (soft+hard) emissions (always diagonal)
  2. wide-angle soft emissions, e.g. ISR $\rightsquigarrow$ full $R$-dependence
  3. non-global logs $\rightsquigarrow$ full $N_c/large\ N_c$ + full $R$-dependence of $\alpha_s^2$ term/$\alpha_s^3$ and beyond

- For phenomenological studies keep $O(R^2) \rightsquigarrow$ better than MC!
Jet mass in pp collisions

Example: Z+1 jet

- Background to $p + p \rightarrow Z + H, H \rightarrow b \bar{b}$. If $H$ is boosted then $b \bar{b}$ end up in a fat jet.

Butterworth et al.’08

- ISR and NGLs have large effects on the peak ($\sim 30\%, \sim 50\%$)
- Previously neglected and attributed instead to NP effects.
Matched distribution (reliable for all values of observable) is obtained through

\[
\frac{1}{\sigma} \frac{d\sigma_{\text{NLL+LO}}}{d\ln \xi} = \frac{1}{\sigma} \left[ \frac{d\sigma_{\text{NLL}}}{d\ln \xi} + \frac{d\sigma_{\text{LO}}}{d\ln \xi} - \frac{d\sigma_{\text{NLL},\alpha_s}}{d\ln \xi} \right], \quad \xi = \sqrt{\rho}
\]
Example: Z+1 jet
Comparison to MC generators

- Compare resummed and matched result NLL+LO to standard MCs (only parton showers “PS”).
- Agreement with Pythia 8 and not so much with Sherpa and Herwig++!
**Example: Z+1 jet**

Hadronisation on

- Estimate hadronisation with a perturbative shift $\xi \rightarrow \xi + \alpha R/p_T$
- Better agreement with/between all MCs.

![Graph showing hadronisation comparison](image-url)
Example 2: dijets

Study the distribution

\[ \frac{d\sigma}{d\xi} = \left( \frac{d\sigma}{d\xi_1} + \frac{d\sigma}{d\xi_2} \right)_{\xi_1=\xi_2=\xi} \]

Effects less severe but sizeable.
Conclusion & Outlook

- Presented jet mass distribution/resummation at hadron colliders.
- Pointed out the necessary contributions for a reliable NLL resummation
  1. ISR
  2. non-global logs
- Applied to Z+1 jet & dijets and showed a reasonable agreement with MC generators (for Z+1 jet)

To be done:
- Determination of $C_1$ and matching to NLO.
- Repeat for other jet substructure observables.
- Repeat for other jet algorithms ($k_T$, C/A, ···)
  - on-going ...
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Extra