Next-to-Leading Order Angularity Distributions with Recoil

Ankita Budhraja (IISERB)

in collaboration with:
Ambar Jain (IISERB) and Massimiliano Procura (CERN)

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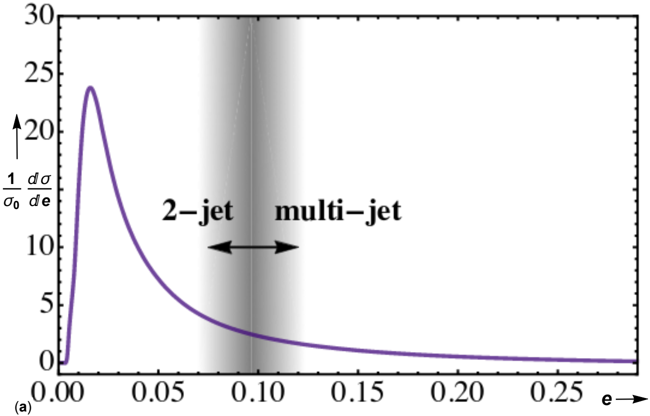
- Event shapes describe the geometrical properties of energy-momentum flow in a QCD event and probe strong interaction at various energy scales.

Bell, et.al. 1808.07867



- **Thrust-** $\tau = \max_{\hat{n}} \frac{1}{Q} \sum_{i \epsilon X} |\vec{p}_i \cdot \hat{n}|$
- **Jet Broadening-** $B = \frac{1}{Q} \sum_{i \epsilon X} |p_{\perp}^{i}|$

Thrust: $$\tau = \frac{1}{Q}\left[\sum_{i\epsilon L}|p_i^+| + \sum_{i\epsilon R}|p_i^-|\right]$$

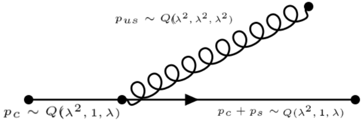
Broadening: $$B = \frac{1}{Q}\left[\sum_{i\epsilon L}\sqrt{p_i^+ p_i^-} + \sum_{i\epsilon R}\sqrt{p_i^- p_i^+}\right]$$

- **Berger, Kucs, Sterman, 03**

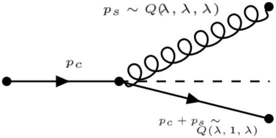
$$\tau_b = \frac{1}{Q}\left[\sum_{i\epsilon L}(p_i^+)^{\frac{1+b}{2}}(p_i^-)^{\frac{1-b}{2}} + \sum_{i\epsilon R}(p_i^+)^{\frac{1-b}{2}}(p_i^-)^{\frac{1+b}{2}}\right] \qquad (1)$$

- For Infrared safety : $-1 < b < \infty$.
- Generalization to *'thrust'* ($b = 1$) and jet *'broadening'* ($b = 0$).
- Varying *'b'* changes the sensitivity of the observable to the substructure of the jet.

- **Thrust:**

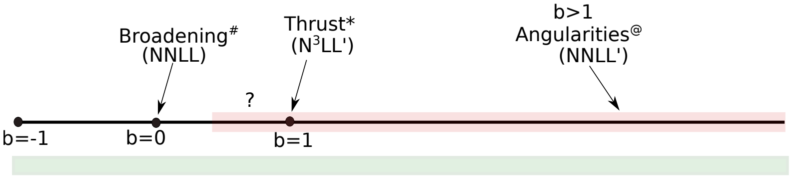


- **Broadening:**



Jet Angularities are novel observables that allow us to transform between recoil-insensitive to recoil-sensitive observables in a continuous manner.

Status of event shapes



*Catani, Trentadue, Turnock, Webber, 93; Florian, Grazzini, 04; Schwartz, 07; Becher, Schwartz, 08; Abbate, Fickinger, Hoang, Mateu, Stewart, 10

#Dokshitzer, Lucenti, Marchesini, Salam, 98; Becher, Bell, Neubert, 11; Chiu, Jain, Neill, Rothstein, 11; Becher and Bell, 12

@Hornig, Lee, Ovanesyan, 09; Bell, Hornig, Lee, Talbert, 18

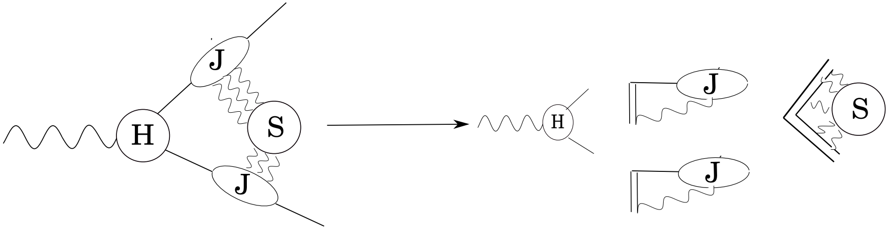


Figure: Factorization of the hard scattering process into individual hard, jet and soft functions.

$$\mathcal{L}_{SCET} = [\mathcal{L}_{\text{n-coll}}]_{\mathcal{J}} + [\mathcal{L}_{\bar{n}\text{-coll}}]_{\mathcal{J}} + [\mathcal{L}_{\text{soft}}]_{\mathcal{S}} + \text{power-correc}^{s}$$
$$d\sigma = Hard \cdot \mathcal{J}_n \otimes \mathcal{J}_{\bar{n}} \otimes \mathcal{S} \quad (2)$$

- Factorization properties of QCD in the soft/collinear limit allows for the separation of the process into hard, jet and soft sectors.
- All factorized sectors depend only on a single dynamical scale and the scale of factorization.

Thrust-like vs Broadening-like factorization

- **Thrust-like**:

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}\tau_L \mathrm{d}\tau_R} = H(Q;\mu)\int \mathrm{d}\tau_n\,\mathrm{d}\tau_{\bar{n}}\,\mathrm{d}\tau_n^s\,\mathrm{d}\tau_{\bar{n}}^s\,\delta(\tau_R - \tau_n - \tau_n^s)\,\delta(\tau_L - \tau_{\bar{n}} - \tau_{\bar{n}}^s)$$
$$\mathcal{J}(\tau_n;\mu)\,\mathcal{J}(\tau_{\bar{n}};\mu)\,\mathcal{S}(\tau_n^s,\tau_{\bar{n}}^s;\mu)$$

- **Broadening-like**:

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}\tau_L \mathrm{d}\tau_R} = H(Q;\mu)\int \mathrm{d}\tau_n\,\mathrm{d}\tau_{\bar{n}}\,\mathrm{d}\tau_n^s\,\mathrm{d}\tau_{\bar{n}}^s\,\delta(\tau_R - \tau_n - \tau_n^s)\,\delta(\tau_L - \tau_{\bar{n}} - \tau_{\bar{n}}^s)$$
$$\int \mathrm{d}\vec{p}_t^{\,2}\,\mathrm{d}\vec{k}_t^{\,2}\,\mathcal{J}(\tau_n,\vec{p}_t^{\,2};\mu,\nu)\,\mathcal{J}(\tau_{\bar{n}},\vec{k}_t^{\,2};\mu,\nu)\,\mathcal{S}(\tau_n^s,\tau_{\bar{n}}^s,\vec{p}_t^{\,2},\vec{k}_t^{\,2};\mu,\nu)$$

Jet Angularity Cross-Section

- $b > 0$

$$\left[\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{d\tau}\right]^{\mathrm{NLO}}_{\mathrm{sing}} = \frac{\alpha_s\,C_F}{\pi}\left\{-\frac{3}{(1+b)}\frac{1}{\tau} - \frac{4}{1+b}\frac{\ln\tau}{\tau} + \frac{4}{b\,(1+b)}\sum_{n=1}^{N=\lceil 1/b\rceil-1}\frac{c_n}{\tau^{1-n\,b}}\right\}$$

with,

$$c_1 = b, \quad c_2 = -\frac{1}{2}b(1+2\,b), \quad c_3 = \frac{1}{6}b(2+9\,b+9\,b^2), \quad \ldots$$

- $b < 0$

$$\left[\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{d\tau}\right]^{\mathrm{NLO}}_{\mathrm{sing}} = \frac{\alpha_s\,C_F}{\pi}\left\{-\frac{3}{(1+b)}\frac{1}{\tau} - \frac{4}{(1+b)^2}\frac{\ln\tau}{\tau} - \frac{4}{b\,(1+b)}\sum_{n=1}^{N=\lceil 1/|b|\rceil-2}\frac{c_n^{'}}{\tau^{1+\frac{n\,b}{1+b}}}\right\}$$

with,

$$c_1^{'} = -\frac{b}{1+b}, \quad c_2^{'} = \frac{b(1-b)}{2(1+b)^2}, \quad c_3^{'} = \frac{b(-2+5\,b-2\,b^2)}{6(1+b)^3}, \quad \ldots$$

where, $\lceil \ldots \rceil$ is the ceiling function, giving the greatest integer strictly less than $1/b$ for $b > 0$ and $1/|b| - 1$ for $b < 0$ case.

b	N = max(n)	% correction for $\tau \sim 0.05$	% correction for $\tau \sim 0.1$
1	0	0	0
0.8	1	4	10
0.5	1	10	20
0.25	3	17	30
0	∞	31	45
-0.2	3	16	27
-0.3	2	8	14
-0.5	0	0	0

Table: Numerical estimation of the size of subleading corrections in the peak region $\sim 0.05 - 0.1$, for different values of b. For a given b value, the maximum value of n up-to which the correction terms are singular is represented by the values given in the second column of the table.

Comparison to numerical data from EVENT2 generator

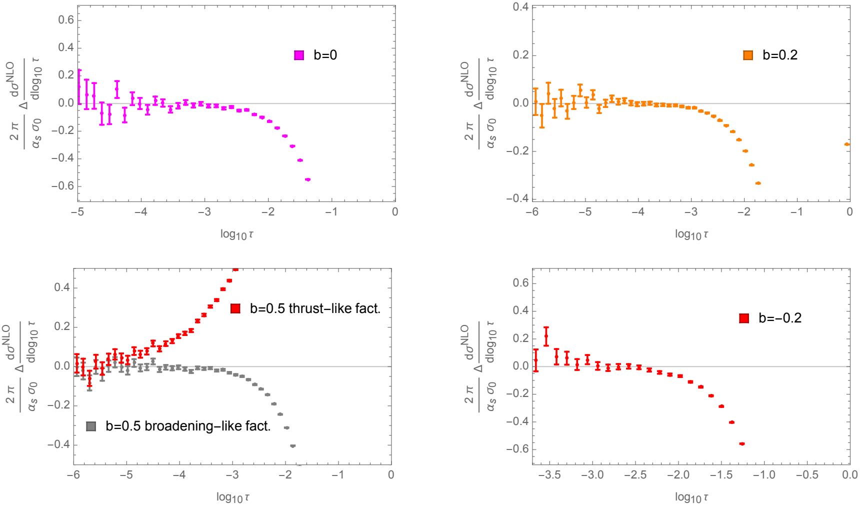


Figure: Differences between EVENT2 and our results from broadening-like factorization at NLO for $\mathrm{d}\sigma/\mathrm{d}\log_{10}\tau$ for different b values.

Summary

- Jet angularities provide a novel way of looking into the substructure which remains unexposed while looking at a single event shape observable.
- A broadening-like factorization for angularities provides the correct distribution for all $b > -1$ angularities while a thrust-like factorization works only in a certain range.
- The fixed order angularity distributions with a broadening-like factorization suggest that the recoil effects are always important for $b < 1$ angularities.
- The recoil contributions, in the form of sub-leading singular terms, for $0 < b < 1$ provide a non-negligible contribution in the peak region. This is expected to effect the resummation of these observables and hence the extraction of the strong coupling.

References

- J. Chiu, A. Jain, D. Neill, and I. Z. Rothstein, *The Rapidity Renormalization Group*, *Phys. Rev. Lett.* **108**.151601, arXiv:1104.0881 [hep-ph].
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- A. Hornig, C. Lee, and G. Ovanesyan, *Effective Predictions of Event Shapes: Factorized, Resummed, and Gapped Angularity Distributions*, *JHEP* **05** (2009) 122, arXiv0901.3780 [hep-ph].


Thank you