Universal Transverse Momentum Dependent Fragmentation in a Jet

Duff Neill, Ignazio Scimemi, Wouter Waalewijn
Topical Group on Hadronic Physics

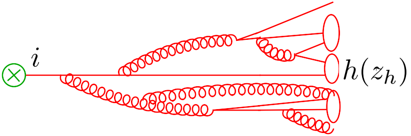
LANL

February 2, 2017

Outline

- Fragmentation in Jets
- Recoil-Free Axes
- Recoil-Free Jet Functions
- Transverse Momentum Dependent Fragmentation in Jets
- First results and out-look

Fragmentation



$e^+e^- \to h(z_h) + X$

$$\frac{d\sigma}{dz_h} = \sum_i \int_{z_h}^1 \frac{d\hat{\sigma}_i}{dz}(z,\mu) D_{i\to h}\left(\frac{z}{z_h},\mu\right)$$

- $d\hat{\sigma}_i$ perturbative cross-section to produce parton i
- $D_{i\to h}$ non-perturbative function for parton i to radiate h
- $D_{i\to h}$ **Universal**.

[Collins, Soper]

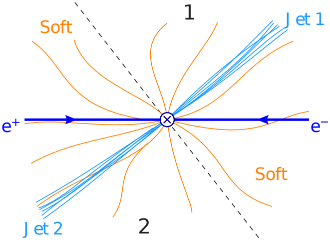
Fragmentation

Awesome! But....

Fragmentation in a Jet is Different

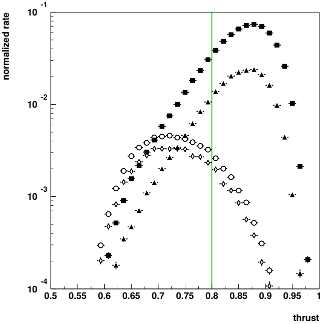
Experimentalist often organize hadronic activity into jets.

- Example: light quark fragmentation at Belle.
- Remove b-quark background by cutting on thrust.
- Shapes event into 2-jet configurations.



(a) $e^+e^- \to$ 2 jets.

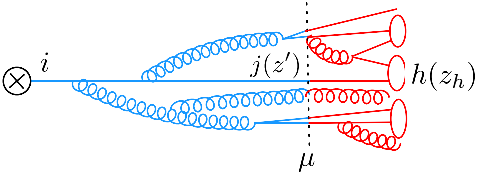
[Belle]



Fragmentation in a Jet is Different But Calculable

$$\frac{d\sigma}{dz_h}(\tau_c) = \int d\tau_n d\tau_{\bar{n}} H_{q\bar{q}}(Q,\mu) J_q(\tau_n,\mu) \mathcal{G}_{\bar{q}\to h}(\tau_{\bar{n}}, z_h, \mu) S(\tau_c - \tau_n - \tau_{\bar{n}}, \mu)$$
$$+ q \leftrightarrow \bar{q} + ...$$

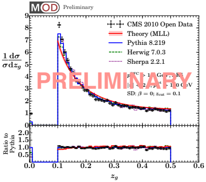
For nice jet definitions, the jet structure is perturbative.



$$\mathcal{G}_{\bar{q}\to h}(\tau, z_h, \mu) = \int_{z_h}^{1} \frac{dz}{z} \mathcal{J}_{ij}(\tau, z, \mu) D_{i\to h}\left(\frac{z}{z_h}, \mu\right) + ...$$

$\mathcal{J}_{ij}$ is perturbatively calculable.
[Procura, Stewart; Jain, et. al.]

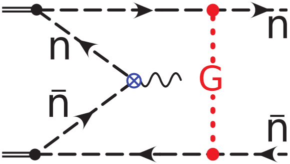
- Hemisphere jets: [Procura, Stewart; Liu; Jain, Procura, Waalewijn; Bauer, Mereghetti; Ritzmann, Waalewijn]
- Exclusive jets: [Procura, Waalewijn; Chien, Kang, Ringer, Vitev, Xing; Baumgart, Leibovich, Mehen, Rothstein; Bain, Dai, Hornig, Leibovich, Makris, Mehen]
- Inclusive jet: [Kaufmann, Mukherjee, Vogelsang; Dai, Kim, Leibovich; Kang, Ringer, Vitev]
- Exotic Fragmentation (soft drop declustering): [Larkoski, Marzani, Thaler; Chien, Vitev]

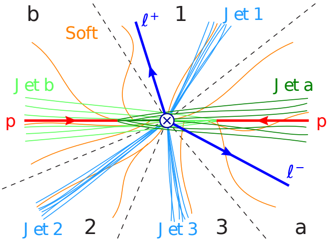


[Larkoski et. al.]

Jets are in the eye of the beholder.

- Global event-shapes (e.g. N-Jettiness): sensitive to Glauber exchanges and factorization violation. [Gaunt; Meng]
- Exclusive Jet Production: Non-global logarithms from restrictions in different phase space regions. [Dasgupta, Salam]
- Inclusive Jet Production: insensitive to soft radition for energy and jet radius effects.

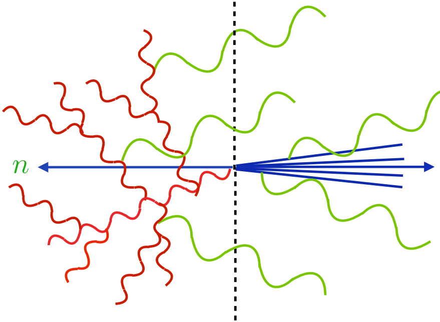




When measuring substructure, being inclusive does not guarantee soft insensitivity

$e^+e^- \to h(z_h, \vec{p}_\perp) + X$

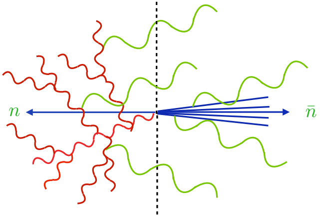
- $\vec{p}_\perp$ measured with respect to thrust axis.
- Total transverse momentum is zero in hemisphere.
- $\vec{p}_\perp = \sum$ everything else.
- **Sensitive to soft recoil.**
- **Number of jets in other hemisphere**



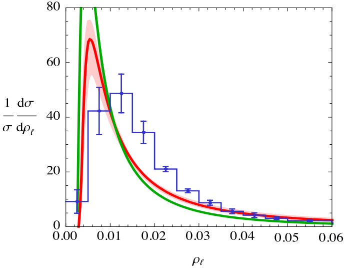
$$\frac{d\sigma}{dz_h d^2\vec{p}_{h\perp}} = \sum_{i,jets} \prod_{jets} J \int \frac{dy}{y} \int d\vec{p}\,'_\perp \mathrm{tr}[\mathbf{H}_i^\dagger(y)\mathbf{S}(\vec{p}\,'_\perp)\mathbf{H}_i(y)] D_{i\to h}\left(\vec{p}_{h\perp} - \vec{p}\,'_\perp, \frac{z_h}{y}\right)$$

Soft Sensitivity and Non-global logs

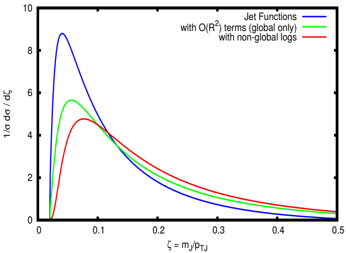
Jet Mass and NGLS, Sudakovs to NLL.



[Becher, et. al.] Compared to ALEPH



[Dasgupta, et. al.]



NGLs, leading log resummations in Large-N_C limit

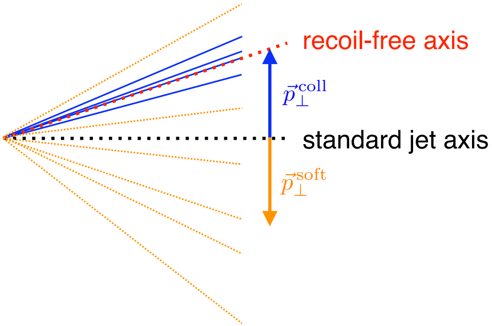
Recoil.

What is issue with $e^+e^- \to h(z_h, \vec{p}_\perp) + X$?

- $\vec{p}_\perp$ measured with respect to thrust axis.
- Total transverse momentum is zero in hemisphere.
- $\vec{p}_\perp = \sum$ everything else.

Thrust axis, just an average axis.

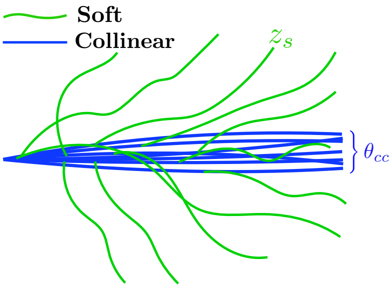
Issue: choosing an axis that is an average:



$$\vec{p}_\perp^{\,\rm coll} + \vec{p}_\perp^{\,\rm soft} = 0$$

Solution: **Recoil free axis capitalizes on Factorization** [Larkoski, DN, Thaler; Bertolini, et. al.; Salam]

The Soft and The Collinear: Factorization

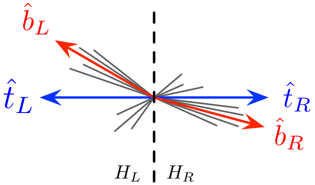


These contributions factorize from each other:

- Collinears sensitive only to *total* momentum contributions from soft radiation.
- Not relative momentum distribuion.

Recoil free axis, a median axis.

- Recoil free axis recoils coherently with the collinear radiation.
- Multi-dimensional **median** of momentum directions.



Example: broadening axis:

$$\hat{b} \text{ minimizes } \tau(\hat{a}) = \frac{1}{E_J} \sum_{i \in J} |\vec{p}_{\hat{a}\perp i}| \,, \text{ i.e., } \tau(\hat{b}) \leq \tau(\hat{a}) \, \forall \hat{a}$$

Recoil free axis: the fast definition

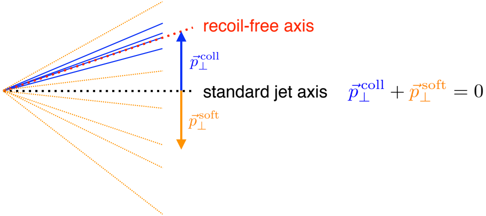
- Jet recombination algorithm (anti-k_t, Cambridge-Aachen)
- Winner-takes ALL:

Recombine particles $1, 2$ into:

$$E_{new} = E_1 + E_2$$

$$\hat{n}_{new} = \begin{cases} \hat{n}_1 \text{ if } E_1 > E_2 \\ \hat{n}_2 \text{ if } E_2 > E_1 \end{cases}$$

Closely approximates broadening axis.



Recoil free Observables

Let $\hat{O}$ be a constraint on the jet, *like* **mass, broadening, thrust**.

- $\hat{O}$ is recoil free if the jet function satisfies:

$$J_N(s,\vec{q}_\perp) = \frac{1}{N}\mathrm{tr}\Big\langle 0\Big|\Phi_n(0)\delta\Big(Q-\bar{n}\cdot\mathbb{P}\Big)\delta^{(2)}\Big(\vec{q}_\perp-\mathbb{P}_\perp\Big)\delta(s-\hat{O})\Phi_n(0)\Big|0\Big\rangle$$
$$= J_N(s,\vec{0}_\perp) + O\Big(\frac{|\vec{q}_\perp|}{Q}\Big)$$

- $\mathbb{P}$ momentum operator
- Φ_n field operator with wilson line.
- Inclusive Jet Function for **thrust** is NOT recoil free:

$$\hat{O} = n\cdot\mathbb{P}$$
$$J_N(s,\vec{q}_\perp;\mu) = F\Big(\frac{Qs-\vec{q}_\perp^{\,2}}{\mu^2}\Big)$$

Recoil Free Fragmentation: Recipe

- Cluster Jets via anti-k_t or C/A with radius R.
- Demand for fragmented hadron.
- Measure Transverse Momentum $\vec{p}_{h\perp}$ with respect to Winner-Takes-All Axis.
- $\frac{|\vec{p}_{h\perp}|}{p_T R} < 1$

$$\frac{d\sigma}{dp_T d\eta dz_h d^2\vec{p}_{h\perp}} = \sum_i \int \frac{dx}{x} d\hat{\sigma}_i\left(\frac{p_T}{x}, \eta, \mu\right) \mathcal{G}_{i\to h}(x, p_T R, \vec{p}_{h\perp}, z_h, \mu)\,, R \ll 1$$

$$\frac{d\sigma}{dp_T d\eta dz_h d^2\vec{p}_{h\perp}} = \sum_i \int \frac{dy}{y} d\hat{\sigma}_i\left(p_T, \eta, R, y, \mu\right) D_{i\to h}(\vec{p}_{h\perp}, \frac{z_h}{y}, \mu) + \ldots, R \sim 1$$

p_T transverse momentum with respect to colliding beam, η-rapidity [Felix's talk yesterday]

- A recoil-free JTMD D is **universal**. Only collinear factorization.

$$\frac{d\sigma}{dz_h d^2\vec{p}_{h\perp}} = \sum_{i,jets}\prod_{jets} J\int\frac{dy}{y}\int d\vec{p}^{\,\prime}_\perp \mathrm{tr}[\mathbf{H}_i^\dagger(y)\mathbf{S}(\vec{p}^{\,\prime}_\perp)\mathbf{H}_i(y)]D_{i\to h}\Big(\vec{p}_{h\perp},\frac{z_h}{y},\vec{p}^{\,\prime}_\perp\Big)$$
$$= \sum_i\int\frac{dy}{y}d\hat{\sigma}_i\Big(y,\mu\Big)D_{i\to h}\Big(\vec{p}_{h\perp},\frac{z_h}{y},\mu\Big)+...$$

Recoil Free Fragmentation: Tower of Factorizations

Boundary Factorizes:

$$\frac{|\vec{p}_{h\perp}|}{p_T R} \ll R \ll 1:$$

$$\mathcal{G}_{i\to h}(x, p_T R, \vec{p}_{h\perp}, z_h, \mu) = \sum_k \int \frac{dy}{y} B_{ik}(x, p_T R, y, \mu) D_{k\to h}\left(\vec{p}_{h\perp}, \frac{z_h}{y}, \mu\right),$$

Non-Perturbative Factorizes:

$$\Lambda_{QCD} \ll |\vec{p}_{h\perp}|:$$

$$D_{i\to h}(\vec{p}_{h\perp}, z_h, \mu) = \sum_k \int \frac{dy}{y} C_{ik}\left(\vec{p}_{h\perp}, \frac{z_h}{y}\right) D_{k\to h}(y, \mu)$$

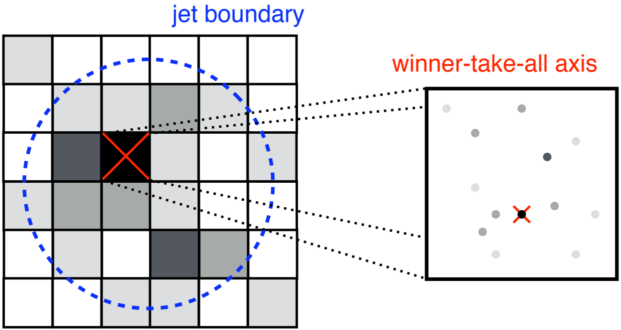
- First factorization true for anti-k_t or C/A, not k_t.
- Second factorization: large invariant mass of collinear splitting.

Factorization of Boundary Effects

$$\frac{|\vec{p}_{h\perp}|}{p_T R} \ll R \ll 1:$$

$$\mathcal{G}_{i\to h}(x, p_T R, \vec{p}_{h\perp}, z_h, \mu) = \sum_k \int \frac{dy}{y} B_{ik}(x, p_T R, y, \mu) D_{k\to h}\left(\vec{p}_{h\perp}, \frac{z_h}{y}, \mu\right),$$

- Define energy "pixels."
- Most energetic pixel wins. Most energetic emissions win.
- anti-k_t and C/A clusters within a pixel first.



Winner-Takes-All and Resummation

- $z_h > \frac{1}{2}$, fragmented particle is axis, $\vec{p}_{h\perp} = 0$
- Calculation identical to fragmentation function to all orders!
- $z_h < \frac{1}{2}$, $\vec{p}_{h\perp}$ cuts off UV-divergence.
- $P_{ij}(x)$ DGLAP kernels.

$$\mu\frac{d}{d\mu}D_{i\to h}(\vec{p}_{h\perp}, z_h, \mu) = \int_{z_h}^{1}\frac{dx}{x}\theta\Big(x-\frac{1}{2}\Big)P_{ij}(x)D_{i\to h}\Big(\vec{p}_{h\perp}, \frac{z_h}{x}, \mu\Big)$$

Applications

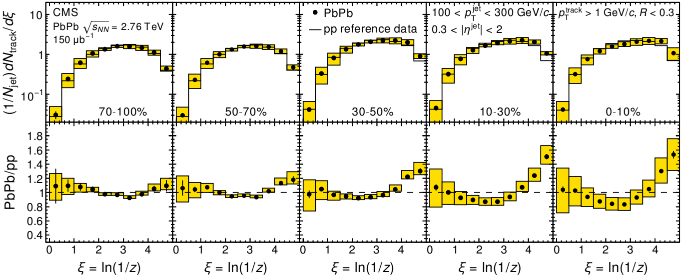
Conclusion:

Recoil Free Fragmentation isolates relative collinear transverse momentum.

- Medium modification to fragmentation.
- Jet substructure.

Medium modification to fragmentation.

- Meaningful comparisons vacuum to medium modifications for jet broadening effects.

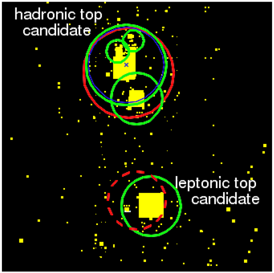


[CMS-HIN-12-013]

Jet Substructure.

Differentiate jet progenitors via the energy and angles of the remnants.

- Robust way to define subjet energy and angular distributions.
- Naturally insensitive to soft background.
- Maximizes how splittings change for hard progenitors.



[ATLAS-CONF-2013-052]