Flavor Flow in Jets and Factorization

Workshop: Jet Physics from RHIC/LHC to EIC

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1. Charge flow at high energy
2. Intrajet charge-order correlations
3. Factorized interjet correlations

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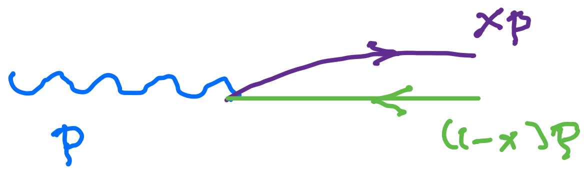
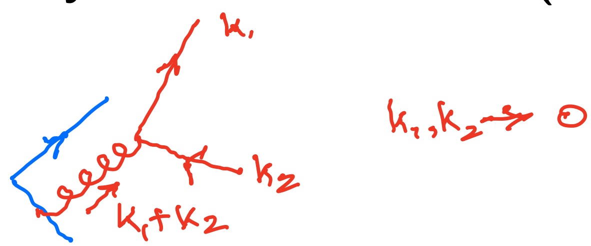
Phys. Rev. D 105, and ongoing.

1.Charge Flow at High Energy

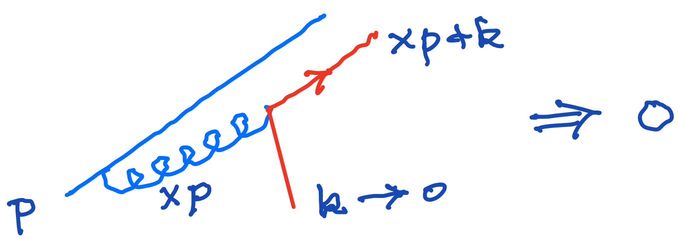
- **Why Charge Flow is Different than Energy Flow**
  - **Both are stable under collinear splittings and recombination, but**



  - **But charge has an instability under soft radiation (starting at α_s^2.)**



- **Nevertheless, soft fermions "stay soft" in perturbation theory up to calculable corrections**



- **It makes sense to use perturbation theory to organize flavor flow – one constituent determines the pion**

- **There have been great advances in the use of energy flow concepts to organize jet evolution and isolate observables that are sensitive to the perturbative-nonperturbative transition.**
  (L. Dixon, I. Moult, H.X. Zhu, 1905.01310, Phys. Rev. D 100 and talk by Ian Moult at this workshop.)

- **It is also possible to construct jet flavor definitions with well-defined evolution.**
  (A. Banfi, G. Salam, G. Zanderighi, EJP (2006) . . . S. Caletti, A. Larkoski, S. Marzani, D. Reichelt, 2205.01117)

- **Here, we will not focus on IR safety, but approach the connection of nonperturbative and perturbative pQCD from a more exclusive direction.**

- **Perhaps contemporary and prospective detectors (as for EIC) have potential to use flavor flow as a probe of hadronization.**

- **If we didn't already know it, could we "discover" a string-based model of hadronization?**
- **To this end, propose an observable that is sensitive to hadronization through charge or flavor correlations, linked to the particles with the highest energies in a jet.**
  - **Consider jets in which the leading particle (L) and next-to-leading (NL) are both pions.** *Comment: This is for convenience only, because it makes the counting simpler.*
  - **If the charges of these pions are random (or if L is fixed and NL is random) then for those events where** *both L and NL pions are charged*,

$$N_{C\overline{C}}^{\text{random}} = N_{CC}^{\text{random}} = \frac{N^{\text{random}}}{2}, \tag{1}$$

where $C\overline{C}$ indicates opposite charges, CC, same charge.

  - **Now consider an "alternating" picture: perturbative shower gives q_L followed by $\bar{q}'_{NL}$, which form pions by sharing a soft pair:**

$$q_L + \bar{q}_{NL} \to q_L + (\bar{q}_s + q_s) + \bar{q}'_{NL} \to \pi(q_L, \bar{q}_s) + \pi(q_s, \bar{q}'_{NL}) \tag{2}$$

Then we get

$$\begin{aligned} N_{C\overline{C}}^{\text{alternating}} &= N^{\text{alternating}}, \\ N_{CC}^{\text{alternating}} &= 0, \end{aligned} \tag{3}$$

and all pairs of L and NL charged pions have opposite charges.

– **Suppose every event results from one of these two processes, with no interference. If a is the percentage of "alternating" events and $1 - a$ of "random" events**

$$r_{\rm asy} \;\equiv\; \frac{N_{CC} \;-\; N_{C\overline{C}}}{N_{CC} \;+\; N_{C\overline{C}}} \;=\; \frac{1-a}{2} - \left(\frac{1-a}{2} + a\right) \;=\; -a\,. \tag{4}$$

In this (classical) picture **a measurement of $r_{\rm asy}$ is a measurement of the fraction of hadronizations that are "string-like", energetic quark and antiquark sharing a soft pair. This is surely too simple, but** this measurement has information.

– **Naively, we expect $a \sim 0.5$, if the shower gives L/NL quarks/antiquarks independently.**

– **Measurements of r can be made differentially in fractions z_L and z_{NL} in a jet, and in terms of a variety of "transverse" kinematic variables: relative transverse momentum, pair invariant mass, pair formation time, etc, including polarization where applicable. These can serve as benchmarks for a future theory of hadronization.**

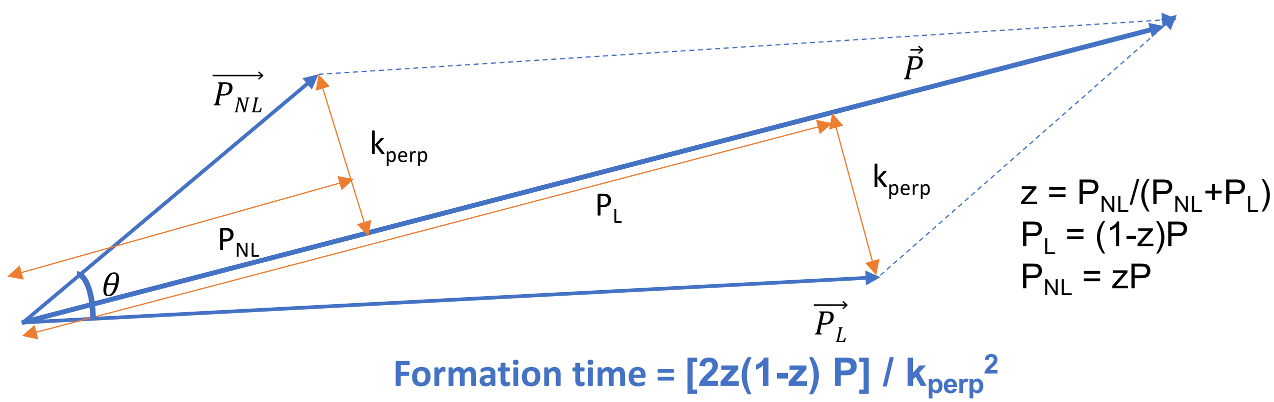
2. Intrajet Leading-Particle Correlations

- **We define an asymmetry:**

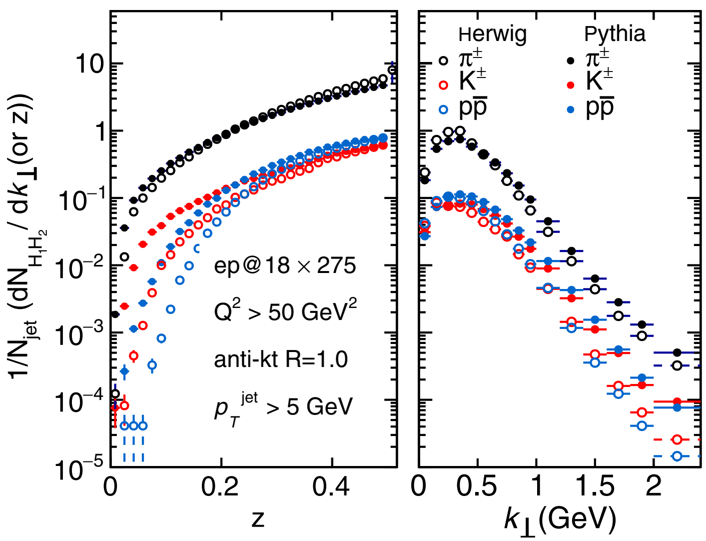
$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1 \overline{h_2}}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1 \overline{h_2}}/\mathrm{d}X}.$$

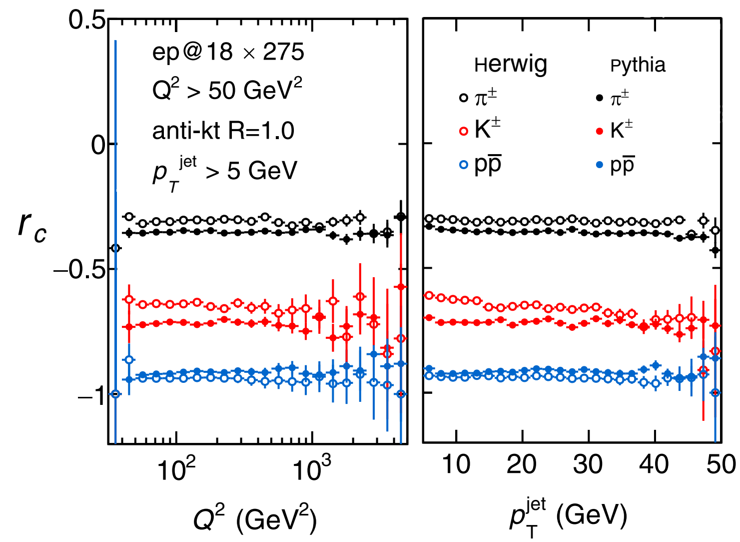
Inclusive or differential various kinematic variables $X = f_{\mathrm{form}}, k_T$.

- **The L-NL kinematics:**



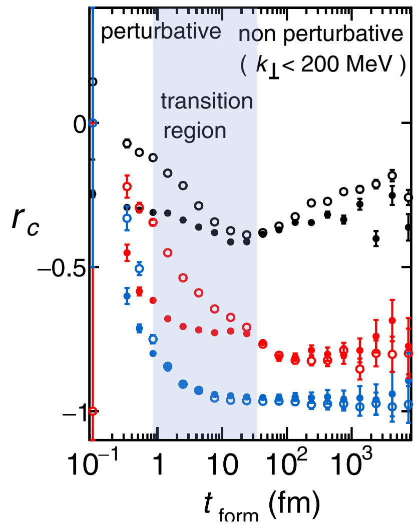
- **Applied to the population of MCEG events:**

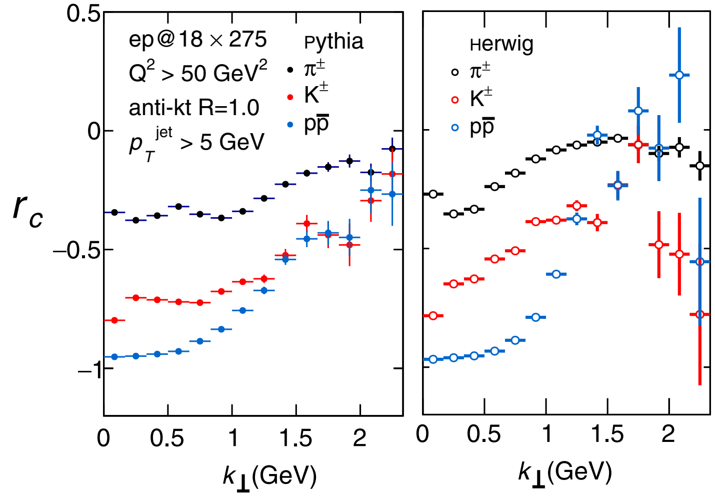




- **For the full set of events,**
  - $z = p_{\rm NL}/(p_L + p_{\rm NL})$ **is peaked near 0.5.**
  - **Relative** $k_\perp$ **peaked at below 0.5 GeV with exponential falloff.**
  - r_c **is nonzero, remarkably independent of** Q **and jet** p_T**.**
  - **Similar, but not identical in Herwig, Phythia.**
- $a \sim -0.5$, **for pions** $\leftrightarrow$ **"alternating" half the time – close to dominant for kaons, protons.**

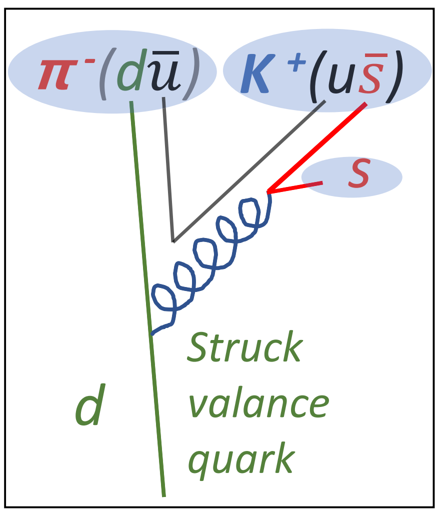
- r_c as a function of formation time and transverse momentum

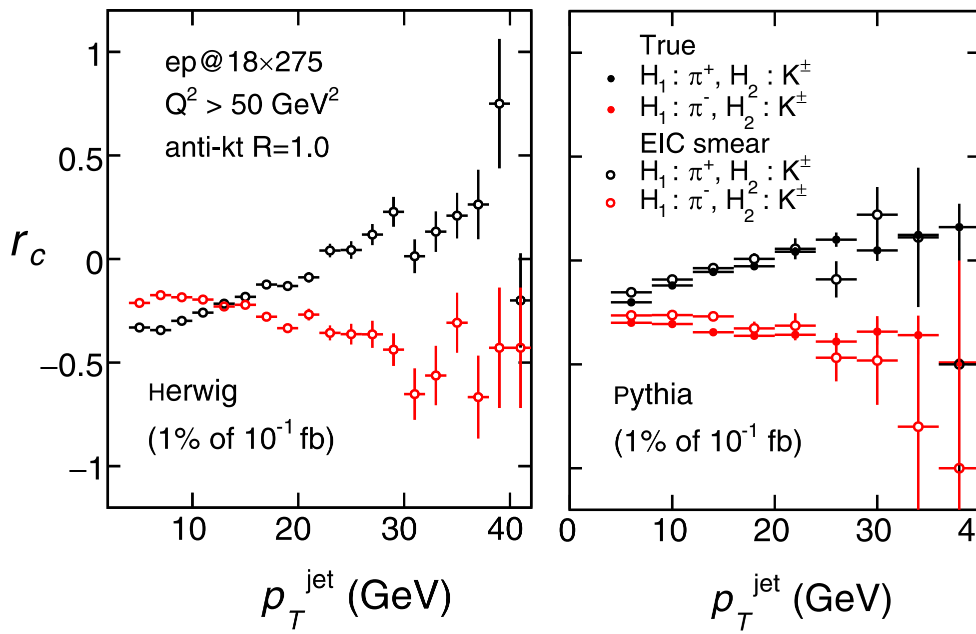




- Signs of three regions.
- Smaller $|r_c|$ for small formation time $\leftrightarrow$ large $k_\perp$.

- **Mixed-flavor combinations have further constraints**
- **Example: Quark content of K-Pi.**
- **in DIS, start with leading u or d quark and start with energetic s or $\bar{s}$ in the partonic shower. Try to hadronize by creating a pair.**
  - $u + s \to \pi^+ + K^- = (u, \bar{d}) + (s, \bar{u})$
  - $u + \bar{s} \to \pi^+ + K^+ = (u, \bar{d}) + (\bar{s}, u)$
  - $d + s \to \pi^- + K^- = (d, \bar{u}) + (s, \bar{u})$
  - $d + \bar{s} \to \pi^- + K^+ = (d, \bar{u}) + (\bar{s}, u) \leftarrow$ **Only here do sea quarks make a pair**





3. Interjet Leading-Particle Correlations

- **Fragmentation and "universality"**

$$E_1 E_2 \frac{\sigma_{I \to h_1, h_2}}{d^3 p_1 d^3 p_2} = E_1 E_2 \sum_{cd} z_c^2 z_d^2 \frac{\hat{\sigma}_{I \to cd}}{d^3 p_1 d^3 p_2} \otimes D_{h_1/c} \otimes D_{h_2/d}$$

$$\equiv \hat{\sigma}_{I \to cd} \otimes D_{h_1/c} \otimes D_{h_2/d}$$

The correlations built into $\hat{\sigma}_{I \to cd}$ are filtered by $D_{h_1/c} \otimes D_{h_2/d}$. To the extent these are known, there is a prediction for nonzero correlations in the factorized cross section

How "universal" are fragmentation functions?

- **Schematically, for $\mathrm{e}^+\mathrm{e}^-$ annihilation, opposite-jet r_c. Denoting $C = \pm$ and $\bar{C} = \mp$:**

$$\boldsymbol{r}_{\mathrm{e}^+\mathrm{e}^-}(\boldsymbol{z}_1, \boldsymbol{z}_2) \;=\; \frac{\sum_{C=\pm} \sum_{F=f,\bar{f}} \left[\hat{\boldsymbol{\sigma}}_{\mathrm{e}^+\mathrm{e}^- \to F\bar{F}} \otimes \boldsymbol{D}_{\pi^C/F} \otimes \boldsymbol{D}_{\pi^C/\bar{F}} \;-\; \hat{\boldsymbol{\sigma}}_{\mathrm{e}^+\mathrm{e}^- \to F\bar{F}} \otimes \boldsymbol{D}_{\pi^{\bar{a}}/F} \otimes \boldsymbol{D}_{\pi^{\bar{C}}/\bar{F}}\right]}{\sum_{a=\pm} \sum_{F=f,\bar{f}} \left[\hat{\boldsymbol{\sigma}}_{\mathrm{e}^+\mathrm{e}^- \to F\bar{F}} \otimes \boldsymbol{D}_{\pi^C/F} \otimes \boldsymbol{D}_{\pi^C/\bar{F}} \;+\; \hat{\boldsymbol{\sigma}}_{\mathrm{e}^+\mathrm{e}^- \to F\bar{F}} \otimes \boldsymbol{D}_{\pi^{\bar{C}}/F} \otimes \boldsymbol{D}_{\pi^{\bar{C}}/\bar{F}}\right]}$$

- **Similarly, for DIS with two jets ($\mathcal{O}(\alpha_s)$)**

$$\boldsymbol{r}_{\mathrm{DIS}}(\boldsymbol{z}_1, \boldsymbol{z}_2) \;=\; \frac{\sum_{C=\pm} \sum_{F=f,\bar{f}} \left[\hat{\boldsymbol{\sigma}}_{\mathrm{e}^- p \to Fg} \otimes \boldsymbol{\mathcal{D}}_{\pi^C/F} \otimes \boldsymbol{\mathcal{D}}_{\pi^C/g} \;-\; \hat{\boldsymbol{\sigma}}_{\mathrm{e}^- p \to Fg} \otimes \boldsymbol{\mathcal{D}}_{\pi^C/F} \otimes \boldsymbol{\mathcal{D}}_{\pi^{\bar{C}}/g}\right]}{\sum_{a=\pm} \sum_{F=f,\bar{f}} \left[\hat{\boldsymbol{\sigma}}_{\mathrm{e}^- p \to Fg} \otimes \boldsymbol{\mathcal{D}}_{\pi^C/F} \otimes \boldsymbol{\mathcal{D}}_{\pi^C/g} \;+\; \hat{\boldsymbol{\sigma}}_{\mathrm{e}^- p \to Fg} \otimes \boldsymbol{\mathcal{D}}_{\pi^C/F} \otimes \boldsymbol{\mathcal{D}}_{\pi^{\bar{C}}/g}\right]}$$

- **The inclusive asymmetry**

$$r_c^{\text{inclusive}} \;=\; \frac{N_{CC} \;-N_{C\bar{C}}}{N_{CC} \;+N_{C\bar{C}}}$$

- **Feature of gluon jets**

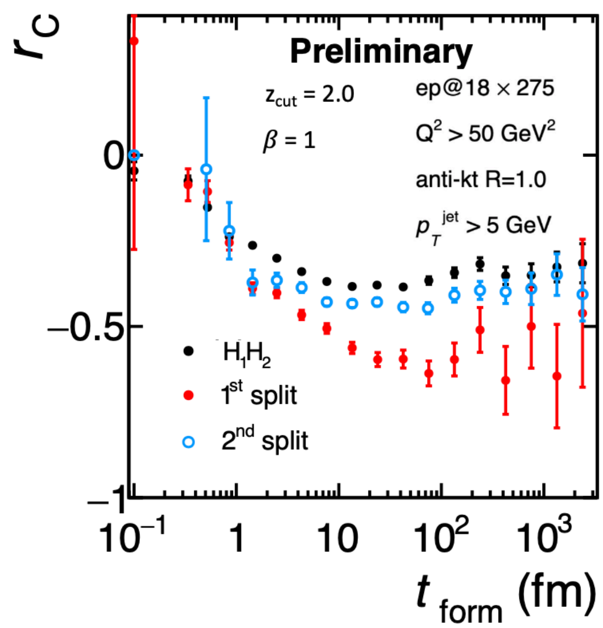
$$\mathcal{D}_{\pi^{\bar{C}}/g} \;=\; \mathcal{D}_{\pi^{C}/g}$$

- **Ensures that**

$$r_{\text{DIS}}(z_1, z_2) \;=\; 0 + \mathcal{O}(\alpha_s^2)$$

- **A feature interited by any gluon jets**

- We should be able to investigate the transition between factorized and coherent flavor flow using jet substructure methods.
- For example, soft drop. Correlations between leading particles in specified “splittings”.
- Can investigate in archived data for inclusive sum over charged particles.



- When an early split contains p_{NL}, the correlation r_c is stronger than for the inclusive data set. An intriguing result, given that the inspiration for the first splitting is wide-angle gluon radiation.

Summary/Ourlook

- Flow of charge in pQCD
- Intrajet correlation r_c
- Interjet/fragmentation correlations
- Conjecture that the transition between these two regimes will shed light on hadronization.
- Some interesting results from event generators, like r_c for pions, kaons, protons, and pi-K correlations.
- The effect is present in preliminary analysis of H1 data involving subjets.
- Experimental results are possible from existing facilities, from Belle to LHC, and for the EIC, with these and other observables.