Probing hadronization with flavor correlation of leading particles in jets

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Outline

- Hadronization: mapping partons to hadrons
  - affects flavor and energy flows of the whole event
- Leading and next-to-leading hadrons within a jet
- Charge correlation $r_c$ and its evolution
- Monte Carlo studies with PYTHIA and Herwig
- Conclusions

See next talk by Mriganka for H1 measurement!
Challenges in hadronization studies

- Hadronization is nonperturbative and requires phenomenological modelings
- High energy collisions involve complicated partons and hadrons distributions
- Initial state radiation, underlying events and target fragmentation in hadron collisions include even larger phase space
- How can we identify microscopic details of hadronization?

Field and Feynman (1978), Andersson et al (1983), Amati and Veneziano (1979), Webber (1984), Winter, Krause and Soff (2004)
Leading and next-to-leading hadrons

- Focus exclusively on
  - collinear regions around dominant energy flows: jets
  - energetic hadrons since soft hadrons are abundant and hard to disentangle their origins

Jet

$H_1$: leading hadron
$H_2$: next-to-leading hadron

$\mathbf{p} = p_{H_1} + p_{H_2}$
$z = p_{H_2}/\mathbf{p}$

Two-particle correlation

Hadronization of most energetic partons
Electron Ion Collider

- A collider covering low and intermediate energy regions is ideal: “how jets emerge”
- We want some perturbative emissions but not too many, or observables not directly affected by these emissions
- We need excellent particle identification for leading particles
- A control over spin and polarization d.o.f. will allow a complete tagging of partonic quantum numbers
- Target hadronization in DIS

Belle II data is also a great opportunity
Charge correlation

\( r_c(X) = \frac{d\sigma_{h_1 h_2}/dX \cdot d\sigma_{h_1 \bar{h}_2}/dX}{d\sigma_{h_1 h_2}/dX + d\sigma_{h_1 \bar{h}_2}/dX} \)

Convention: \( h_1 h_2 \) same sign

\(-1 \leq \gamma_c \leq 1\)

\( \gamma_c \to -1 \) when \( d\sigma_{h_1 \bar{h}_2} \gg d\sigma_{h_1 h_2} \)

\( \gamma_c \to 0 \) when \( H_2 \) not correlated with \( H_1 \)

- Leading dihadron correlation: conditional probability of observing \( H_2 \) in the presence of \( H_1 \)
- Comparing the cross sections of \( h_1 h_2 \) and \( h_1 \bar{h}_2 \) to quantify the flavor constraints
- Evolution of \( r_c \) w.r.t. kinematic phase space \( X \)

We focus on two novelties:

1. Leading dihadrons exclusively
2. Dependence on \( X \): \( z, k_T, T_{\text{form}}, \ldots \)

TASSO (1985), CERN ISR (1979), LEP (1984), NA22 (1989), Bass, Danielewicz and Pratt (2000)
Monte Carlo samples

- 18 GeV electron beam + 275 GeV proton beam
- PYTHIA 6.428 and Herwig 7.1.5
- Impose $Q^2 > 50$ GeV$^2$ so that we have higher $p_T$ jets
- 10 million events
- Jets: $p_T^{\text{particle}} > 0.2$ GeV, $-1.5 < \eta < 3.5$, anti-$k_t R = 1.0$, $p_T^{\text{jet}} > 5$ GeV

Mostly these jets are from struck quarks dominated by valence $u$ and $d$ quarks
Leading dihadron kinematics

- $z$ maximizes at $z = 0.5$, not from perturbative splitting
- Characteristic low $k_\perp$ and cross section falling exponentially

\begin{align*}
\frac{1}{N_{\text{jet}}} \frac{dN_{\text{H}1 \text{H}2}}{dk_{\perp}^2 / d \ln z} &= \text{ep@18} \times 275 \\
Q^2 > 50 \text{ GeV}^2 \\
\text{anti-kT R=1.0} \\
\rho_{T_{\text{jet}}} > 5 \text{ GeV}
\end{align*}
Leading dihadron formation time

![Graphs showing dihadron event count vs. formation time](image)

- Formation time peaks around 1 to 10 fm
- $|r_c|$ maximizes at large formation time
- Significant difference between PYTHIA and Herwig

$t_{\text{form}} = z(1 - z)p/k_{\perp}^{2}$

$\rightarrow \left(\frac{1}{k_{\perp}}\right)^x \left(\frac{p}{k_{\perp}}\right)^y$ Lorentz boost

$\Rightarrow$ proper time

"more "local"
Leading dihadron relative $k_\perp$

- $|r_c|$ maximizes at small $k_\perp$ and decreases as $k_\perp$ increases on the scale of 1-2 GeV
- Suggesting strong nonperturbative correlation at play
Flavor tagging and $\pi K$ correlation

\[ r_c \]

\[ \langle \text{jet} \rangle T \]

\[ \langle \text{jet} \rangle \]

\[ \text{EIC smear} \]

\[ \sigma_{\pi^- K^-} - \sigma_{\pi^- K^+} \]

\[ \sigma_{\pi^- K^-} + \sigma_{\pi^- K^+} \]

\[ r_c \]

\[ \langle \text{jet} \rangle \]

\[ \text{EIC smear} \]

\[ \sigma_{\pi^+ K^+} - \sigma_{\pi^+ K^-} \]

\[ \sigma_{\pi^+ K^+} + \sigma_{\pi^+ K^-} \]

\[ H_1 = \pi^- \quad \text{Red:} \quad r_c = \frac{\sigma_{\pi^- K^-} - \sigma_{\pi^- K^+}}{\sigma_{\pi^- K^-} + \sigma_{\pi^- K^+}} \]

\[ H_1 = \pi^+ \quad \text{Black:} \quad r_c = \frac{\sigma_{\pi^+ K^+} - \sigma_{\pi^+ K^-}}{\sigma_{\pi^+ K^+} + \sigma_{\pi^+ K^-}} \]

\[ \bullet \text{Excellent agreement between EIC smear and true distributions} \]

\[ \bullet \text{measurable at EIC} \]
Flavor constraints

\[ \pi^+ \bar{d} K^+ \]
\[ \pi^+ \bar{d} \bar{u} s \]
\[ \pi^- \bar{d} u s \]
\[ \bar{u} \bar{u} s \]

No simple string configuration

Simple string breaking allowed

Therefore, \( \pi^- K^+ \) is preferred in string hadronization compared to \( \pi^- K^+ \), resulting in large \( |V_{cb}| \). Cluster hadronization shows different flavor constraints.
Correlating leading dihadrons and subjets

* $H_1, H_2$ typically surrounded by perturbative emissions
* Charge correlation maximizes when $H_1, H_2$ appear to be isolated, i.e. resolved at 1st split.
Conclusions

• Leading dihadron correlation is nonperturbative and can illuminate intrinsic features of hadronization
• Besides energy tagging, flavor tagging can be a powerful tool for studying hadronization
• Excellent particle identification and abundant statistics are essential
• Evolution of leading dihadron correlation w.r.t. kinematic variables, as well as hadron-subjet correlation can be used to study perturbative and nonperturbative transition

Opportunities for precision QCD physics in hadronization at Belle II -- a snowmass whitepaper

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