Probing hadronization with flavor correlation of leading particles in jets

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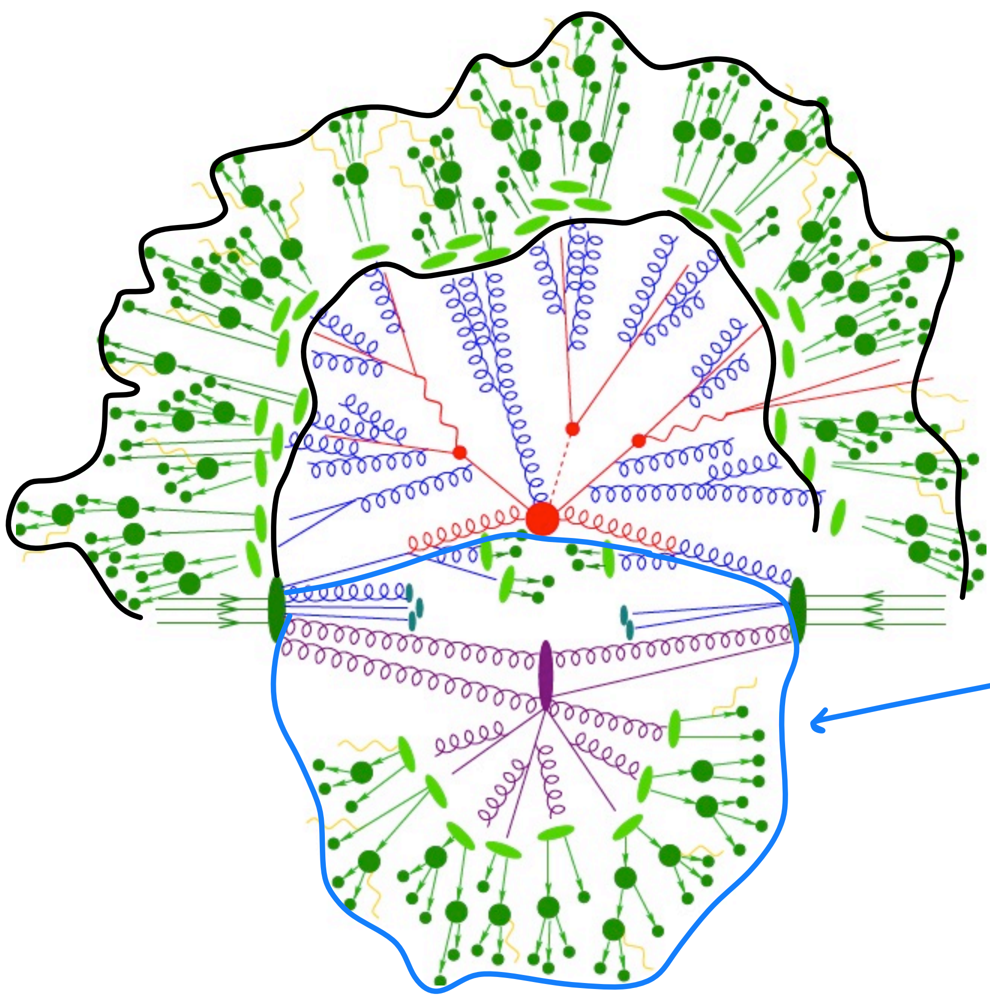
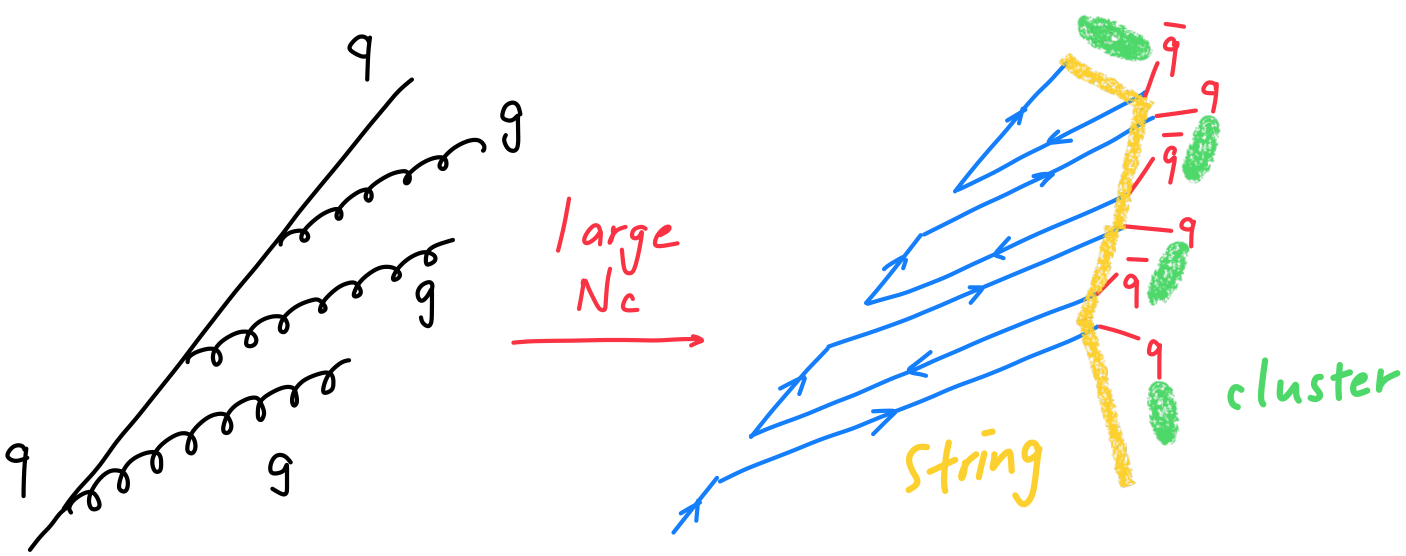
Outline

- 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

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?

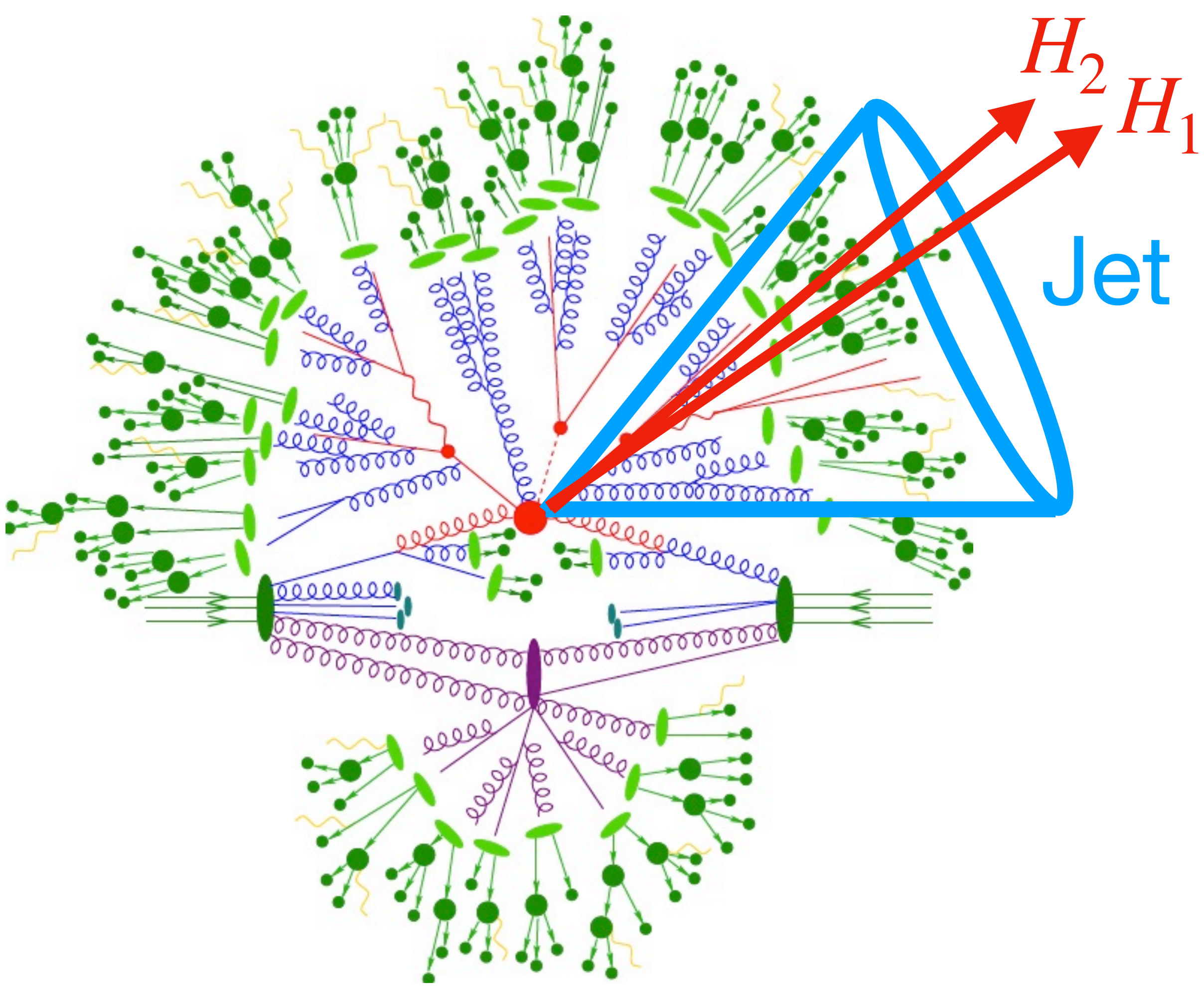


PYTHIA

Field and Feynman (1978), Andersson et al (1983), Amati and Veneziano (1979), Webber (1984), Winter, Krause and Soff (2004)

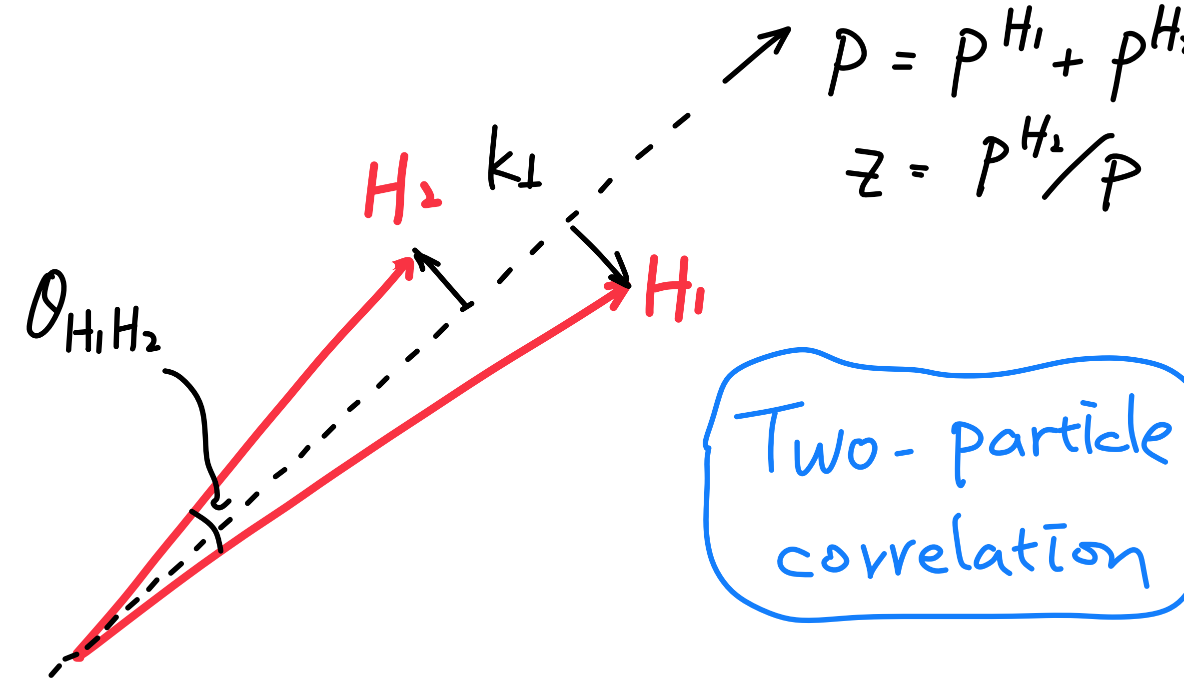
Herwig Sherpa

Leading and next-to-leading hadrons



H_1 : leading hadron

H_2 : next-to-leading hadron

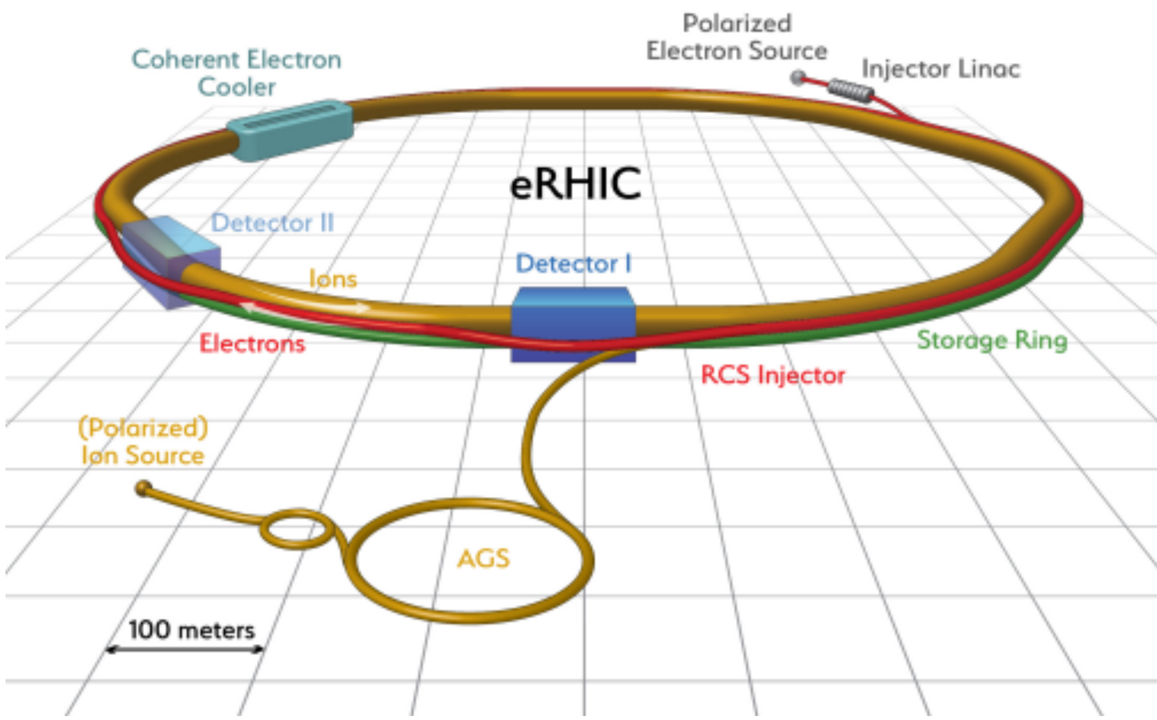


Two-particle correlation

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

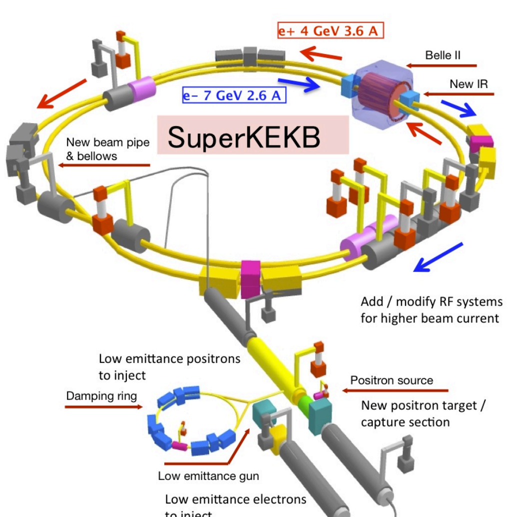
Hadronization of most energetic partons

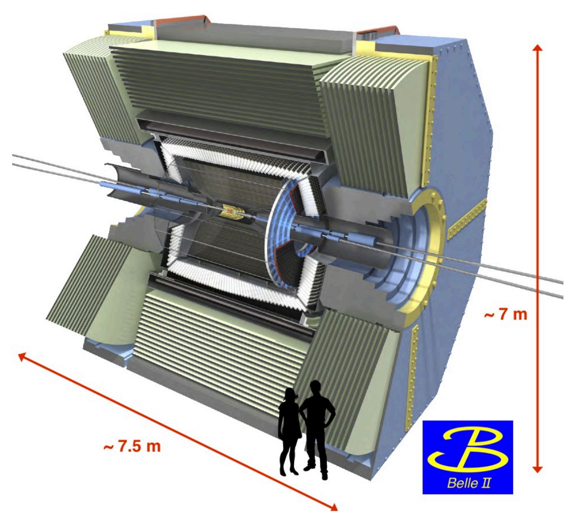
Electron Ion Collider



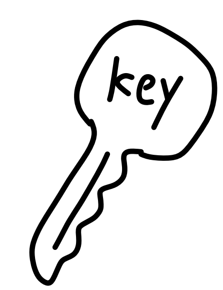
EIC Yellow Report, arXiv: 2103.05419

- 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





Particle ID



High statistics

Belle II data is also a great opportunity

Charge correlation

convention: $h_1 h_2$ same sign

$$r_c(X) = \frac{d\sigma_{h_1h_2}/dX - d\sigma_{h_1\overline{h_2}}/dX}{d\sigma_{h_1h_2}/dX + d\sigma_{h_1\overline{h_2}}/dX}$$

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

↑ "Balane function" as a function of rapidity, inclusive

$-1 \leq r_c \leq 1$

$r_c \to -1$ when $d\sigma_{h_1\overline{h_2}} \gg d\sigma_{h_1h_2}$

$r_c \to 0$ 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_1h_2 and $h_1\overline{h_2}$ to quantify the flavor constraints
- Evolution of r_c w.r.t. kinematic phase space X

We focus on two novelties:

① Leading dihadons exclusively

② Dependence on X: z, $k_\perp$, τ_{form}, ...

Monte Carlo samples

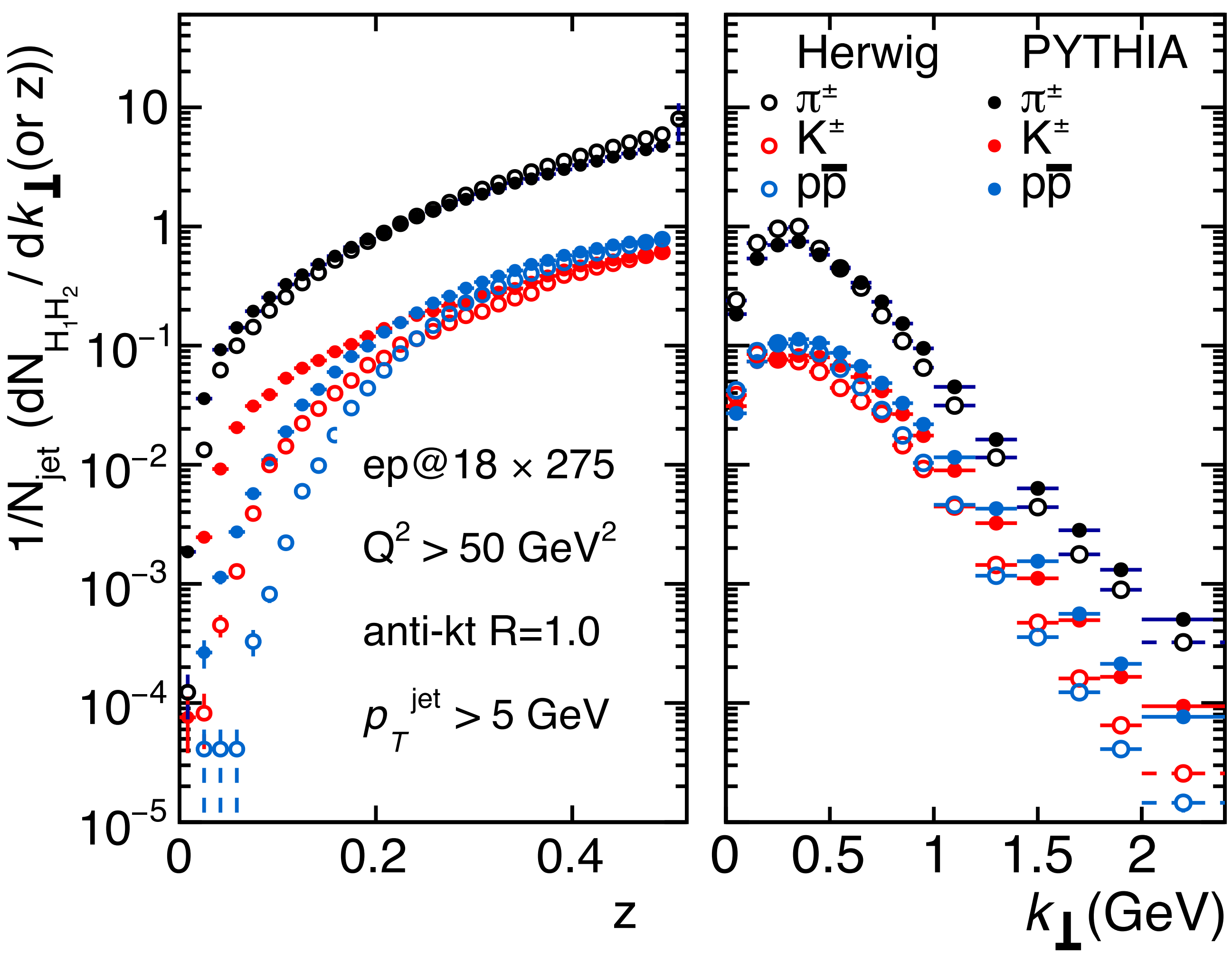
highest design energy

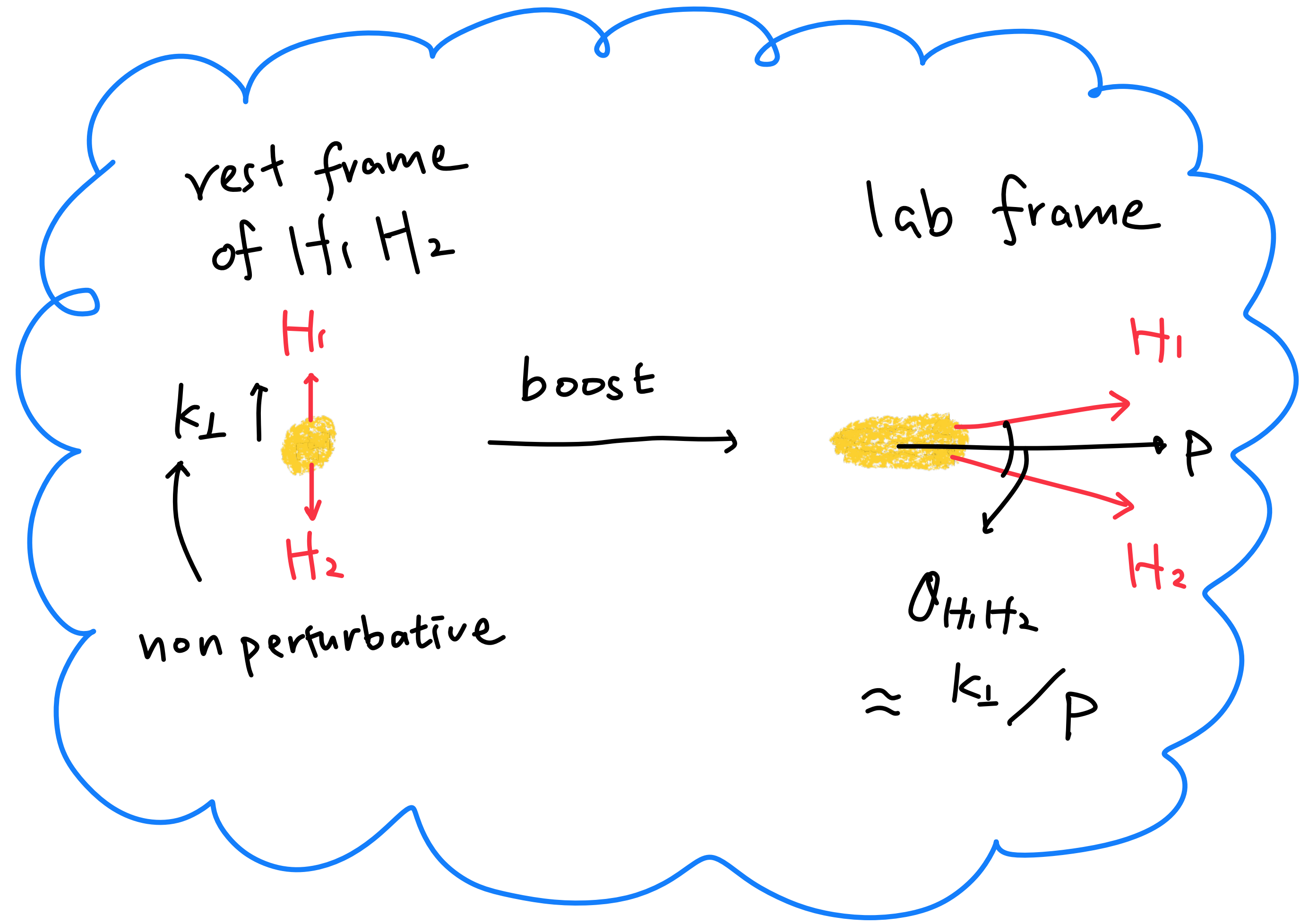
- 18 GeV electron beam + 275 GeV proton beam
- PYTHIA 6.428 and Herwig 7.1.5
- Impose $Q^2 > 50\ \mathrm{GeV}^2$ so that we have higher p_T jets
- 10 million events
- Jets: $p_T^{\mathrm{particle}} > 0.2\ \mathrm{GeV}$, $-1.5 < \eta < 3.5$, anti-k_t $R = 1.0$, $p_T^{\mathrm{jet}} > 5\ \mathrm{GeV}$

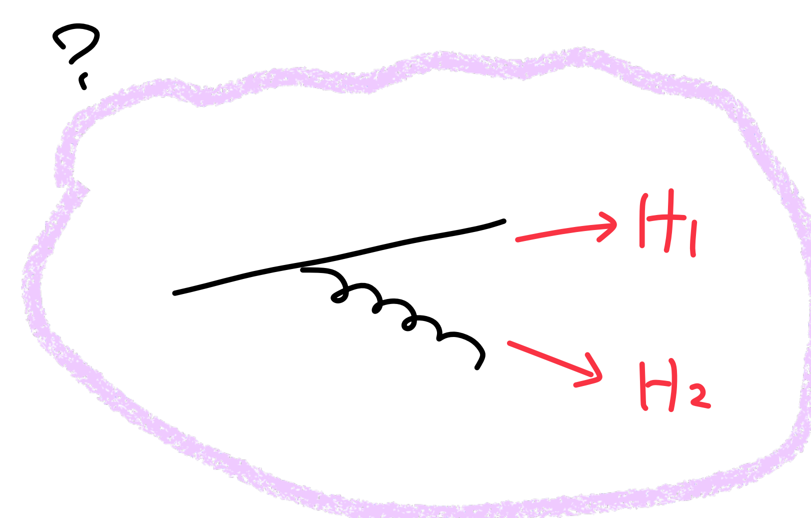
relatively high p_T at EIC energy

Mostly these jets are from struck quarks dominated by valence u and d quarks

Leading dihadron kinematics







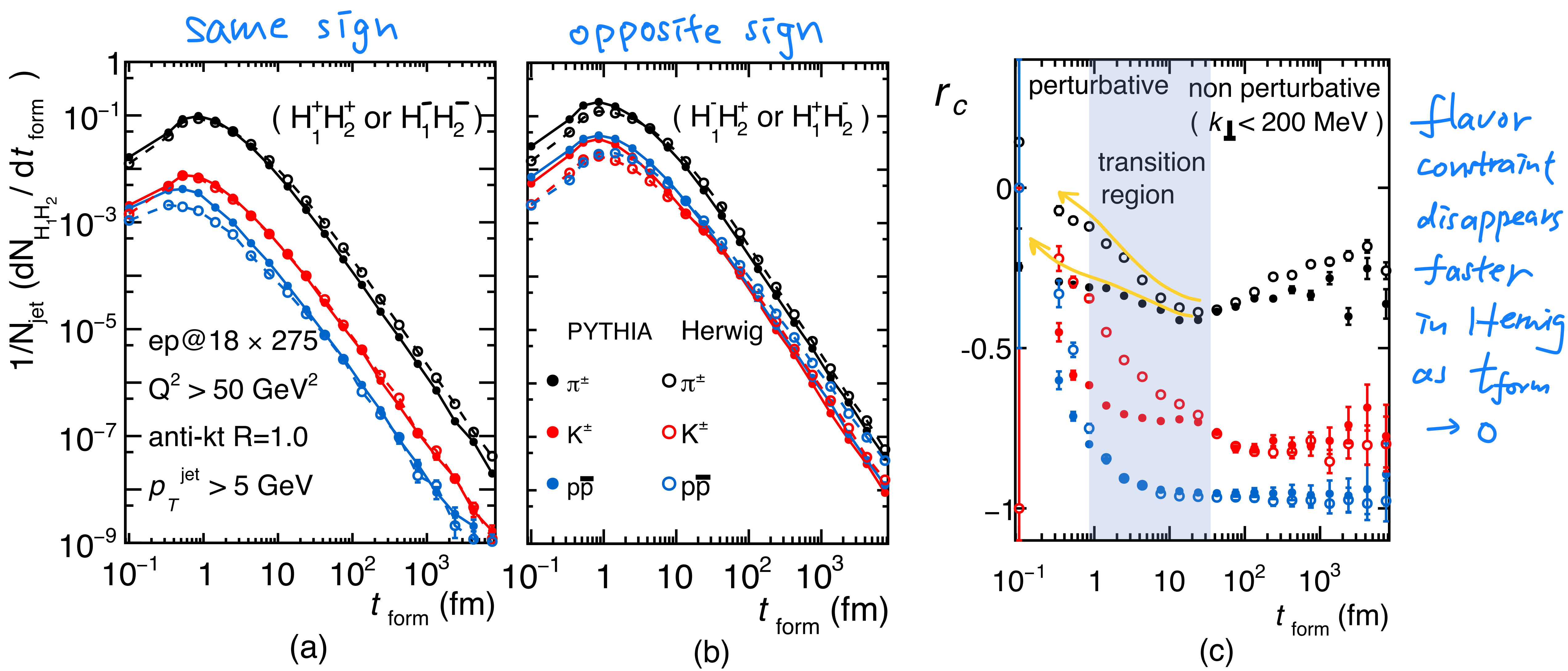
- z maximizes at $z = 0.5$, not from perturbative splitting

Altarelli-Parisi $\propto 1/z$

$\propto 1/k_\perp$

- Characteristic low $k_\perp$ and cross section falling exponentially

Leading dihadron formation time



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

$$\left(\frac{1}{k_\perp}\right) \times \left(\frac{p}{k_\perp}\right)$$

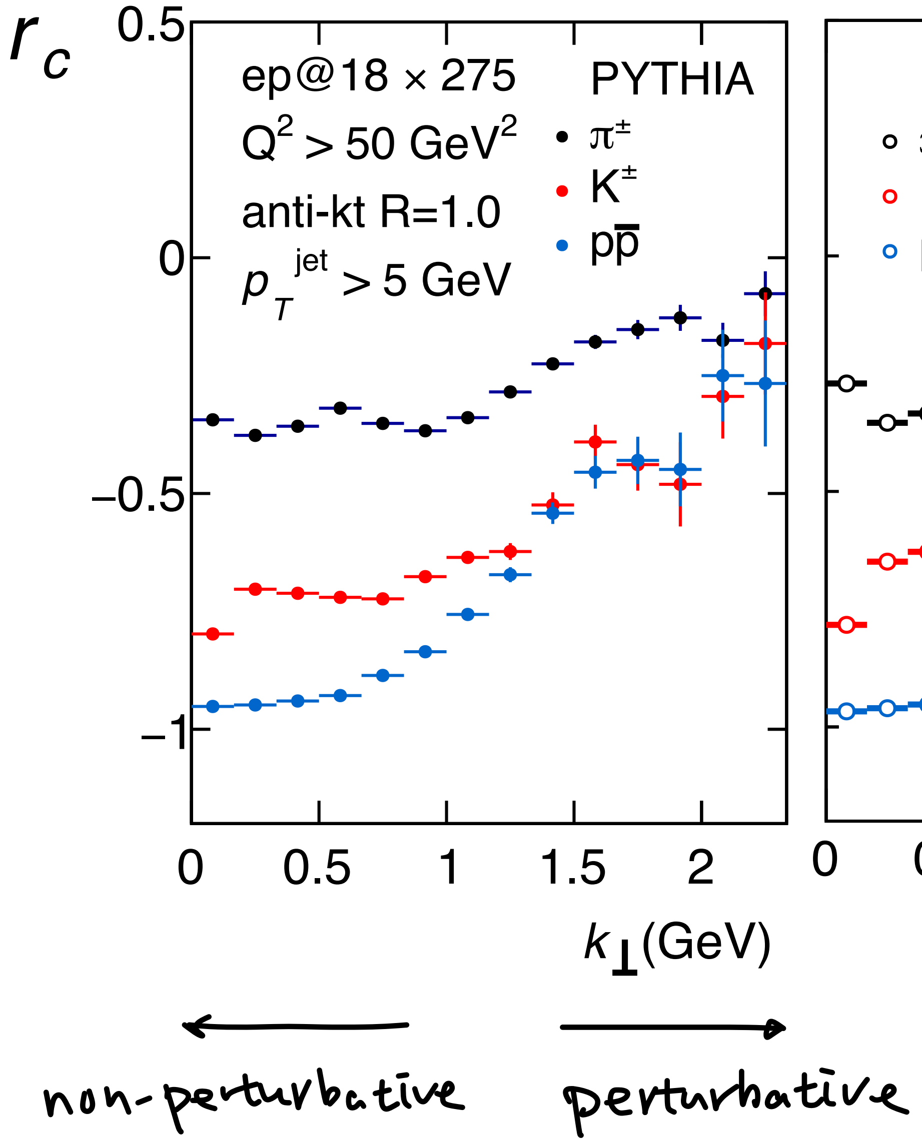
proper time

Lorentz boost

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

more "local"

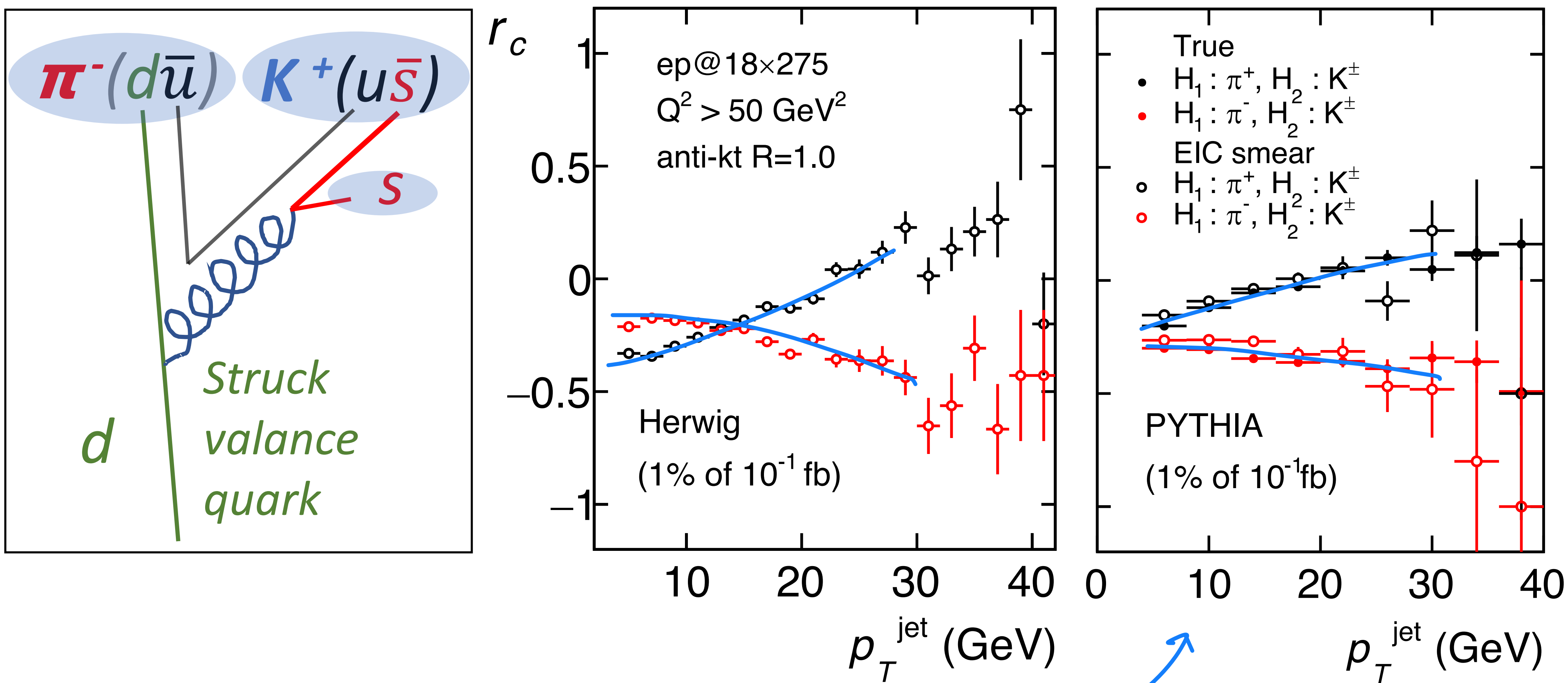
Leading dihadron relative $k_\perp$



- $|r_c|$ 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 πK correlation

* πK separation required.



(a) (b) (c)

significant difference

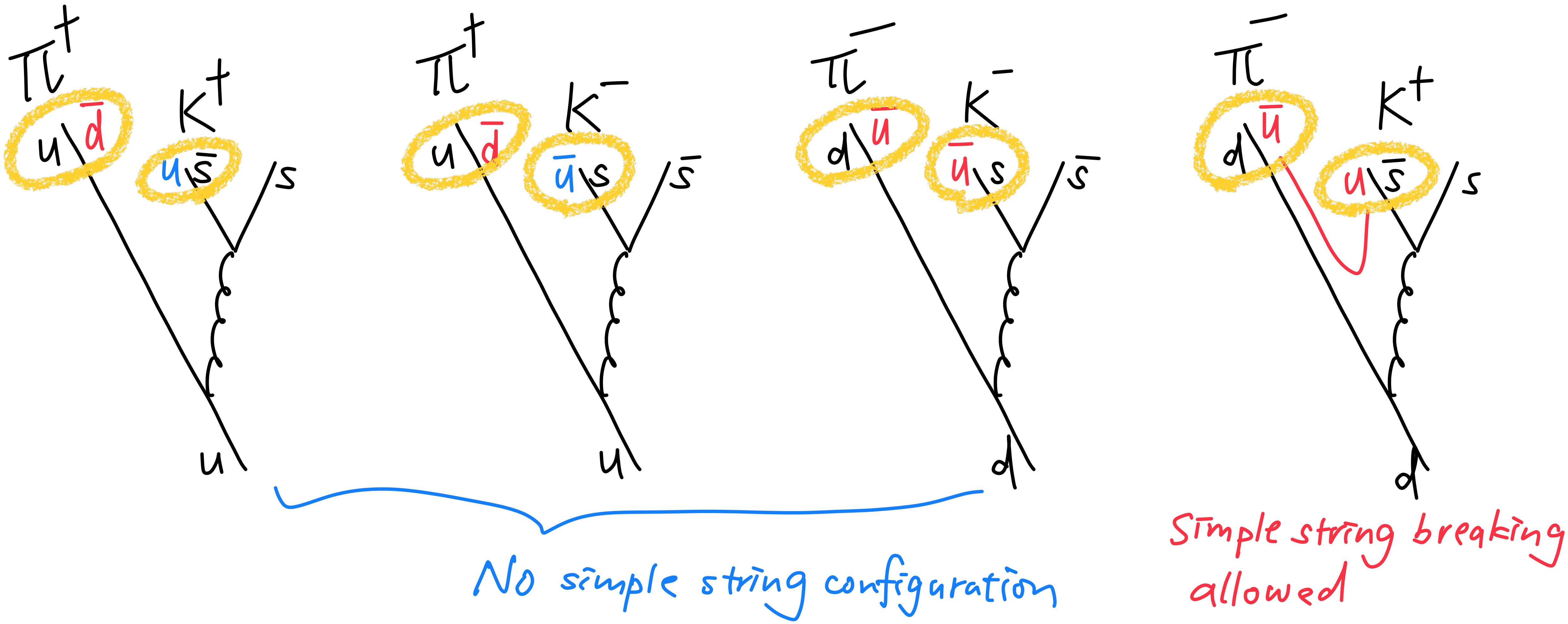
$H_1 = \pi^-$ Red: $r_c = \dfrac{\sigma_{\pi^- K^-} - \sigma_{\pi^- K^+}}{\sigma_{\pi^- K^-} + \sigma_{\pi^- K^+}}$

$H_1 = \pi^+$ Black: $r_c = \dfrac{\sigma_{\pi^+ K^+} - \sigma_{\pi^+ K^-}}{\sigma_{\pi^+ K^+} + \sigma_{\pi^+ K}}$

- Excellent agreement between EIC smear and true distributions

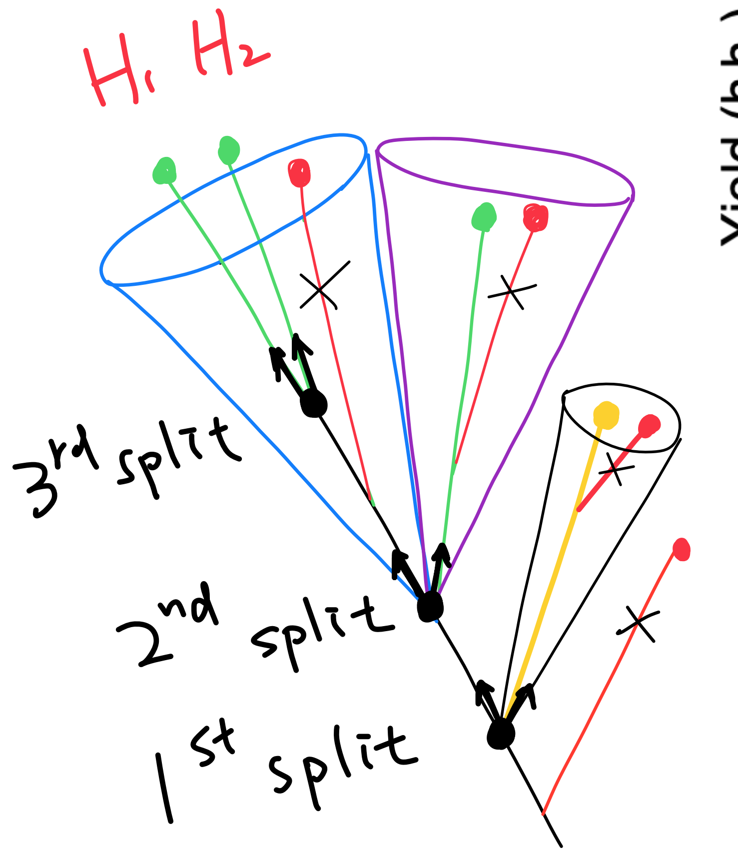
measurable at EIC

Flavor constraints

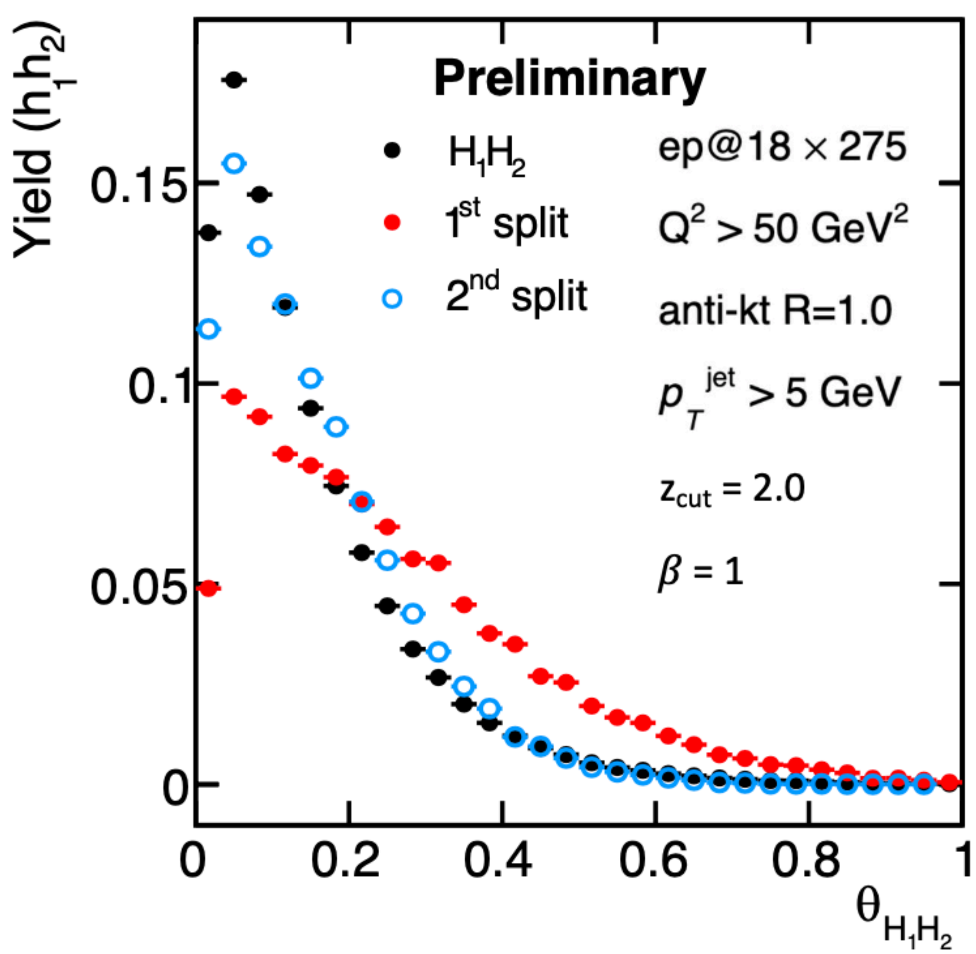


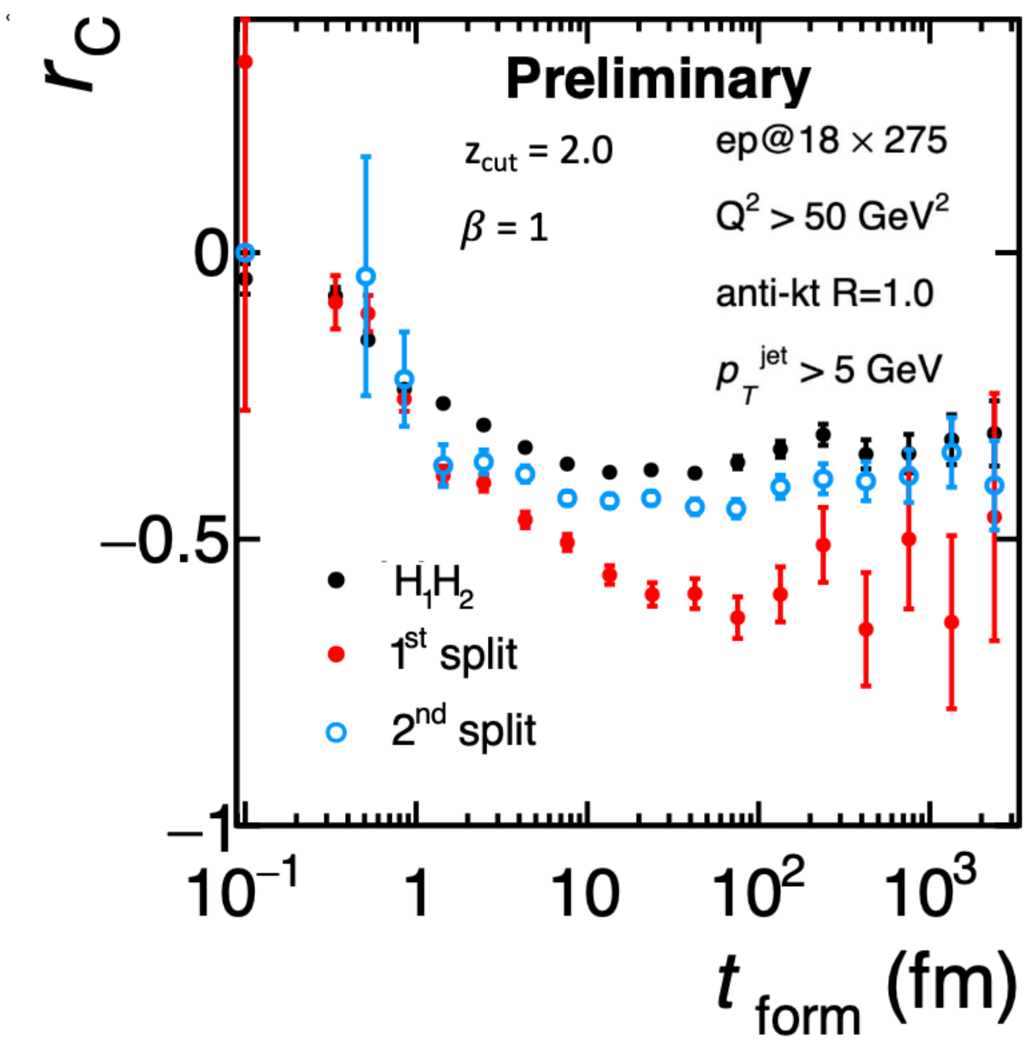
Therefore π^-K^+ is preferred in string hadronization compared to π^-K^+, resulting in large $|r_c|$. Cluster hadronization shows different flavor constraints.

Correlating leading dihadrons and subjets



Angular-ordered declustering and soft-drop to identify subjets as proxy to perturbative emissions





* H_1H_2 typically surrounded by perturbative emissions
* Charge correlation maximizes when H_1H_2 appears 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

A. Accardi, Y. T. Chien, D. d'Enterria, A. Deshpande, C. Dilks, P. A. Gutierrez Garcia, W. W. Jacobs, F. Krauss, S. Leal Gomez, M. Mouli Mondal, K. Parham, F. Ringer, P. Sanchez-Puertas, S. Schneider, G. Schnell, I. Scimemi, R. Seidl, A. Signori, T. Sjöstrand, G. Sterman, A. Vossen