Fragmentation studies using leading particle correlations

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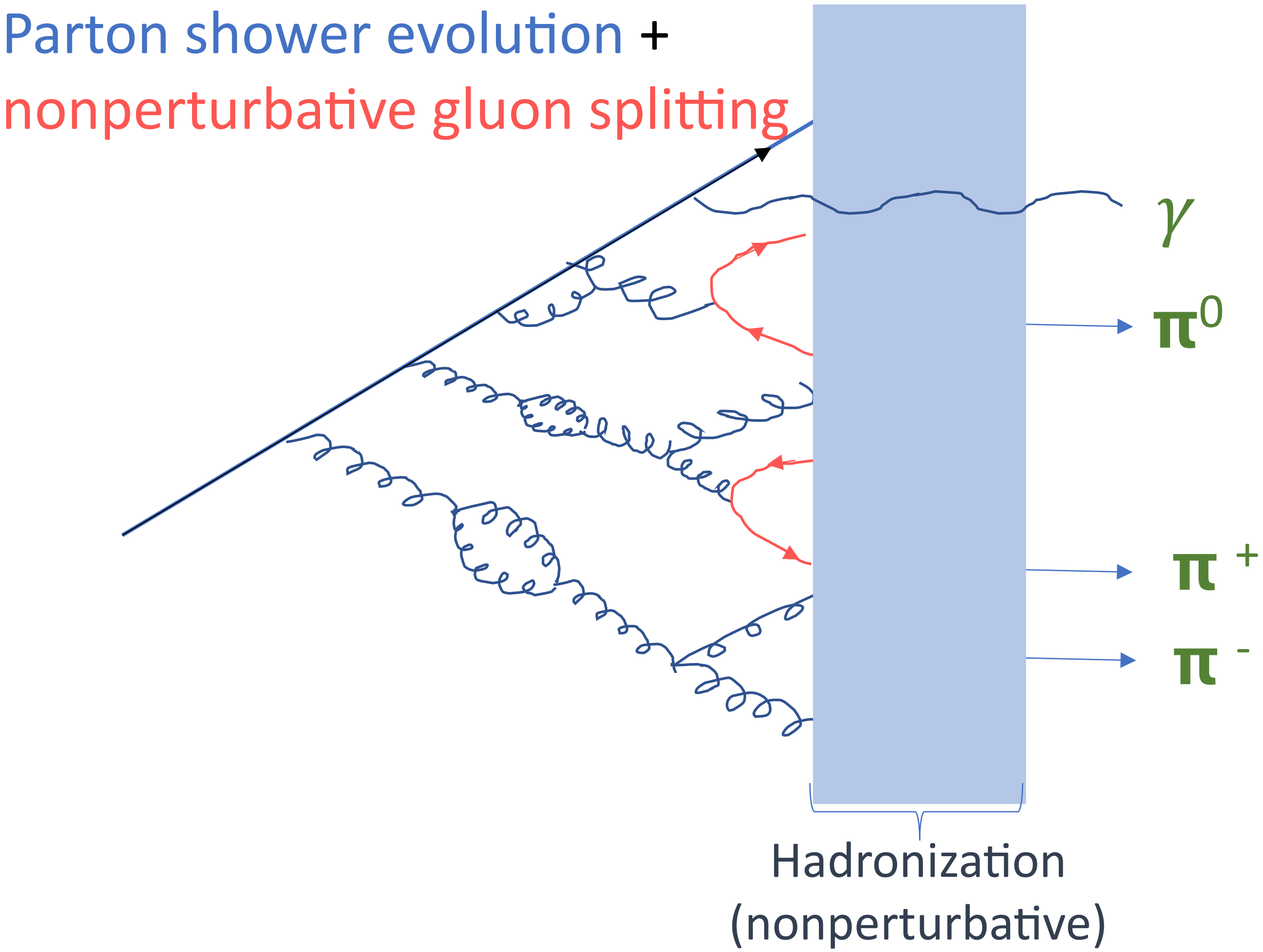
arXiv:2109.15318 : Probing hadronization with flavor correlations of leading particles in jets:

Y.-T.Chien, A. Deshpande, M. M. Mondal, G. Sterman

Outline

- Jets and access to the dynamics of hadronization
- A charge-energy correlation
- Simulation study for electron-proton collisions at the EIC
- Measurements in current experiments hadronization of jets in wide range of collision systems
- Summary

Jets and access to the dynamics of hadronization



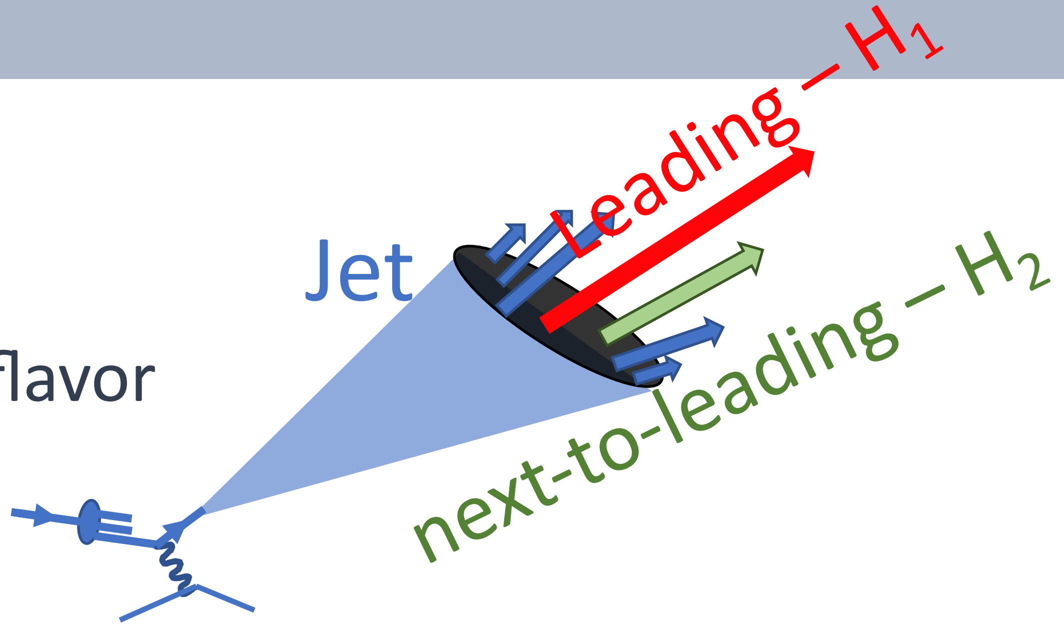
Jets are collimated streams of particles

Dynamics of hadronization can be studied through correlations among particles in a jet

Leading and next-to-leading particles – nonperturbative in origin

New charge-energy correlation

Observable : charge-energy correlation, r_c



- Correlations in momentum, charge and flavor
- **Leading(L)** and **next-to-leading (NL)** momentum particles in a jet

$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$

N_{CC} : # Jets where L and NL particles with same sign charges

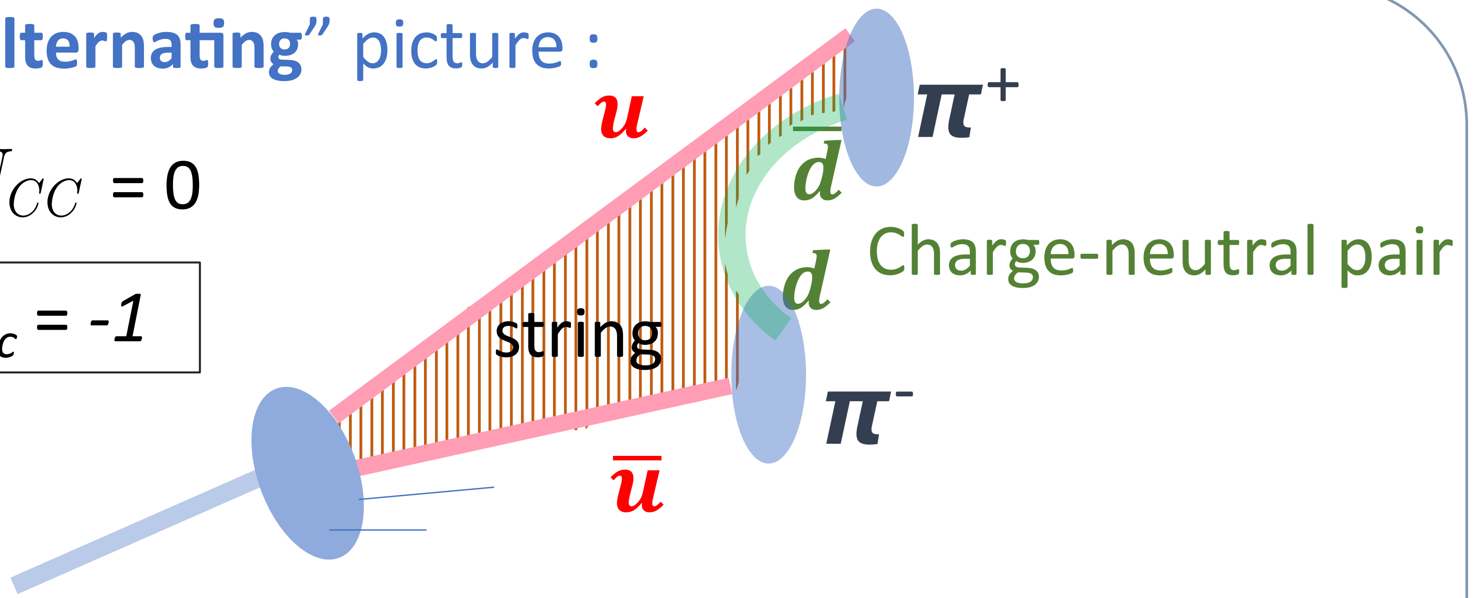
$N_{C\bar{C}}$: # Jets where L and NL particles with opposite sign charges

Significance of $r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$

"**alternating**" picture :

$N_{CC} = 0$

$r_c = -1$



Partonic final state : u and $\bar{u}$

Combine charge-neutral pair : $\bar{d}$ and d

"**random**" picture :

no charge correlation

$N_{CC} = N_{C\bar{C}}$

$r_c = 0$

r_c is a measure of the fraction of "string-like hadronization"

Correlations using PYTHIA and Herwig

Event Generation :

EIC : ep@18x275

PYTHIA 6.428

Herwig 7.1.5

$Q^2 > 50\ GeV^2$

Jets :

anti-k_T R = 1.0

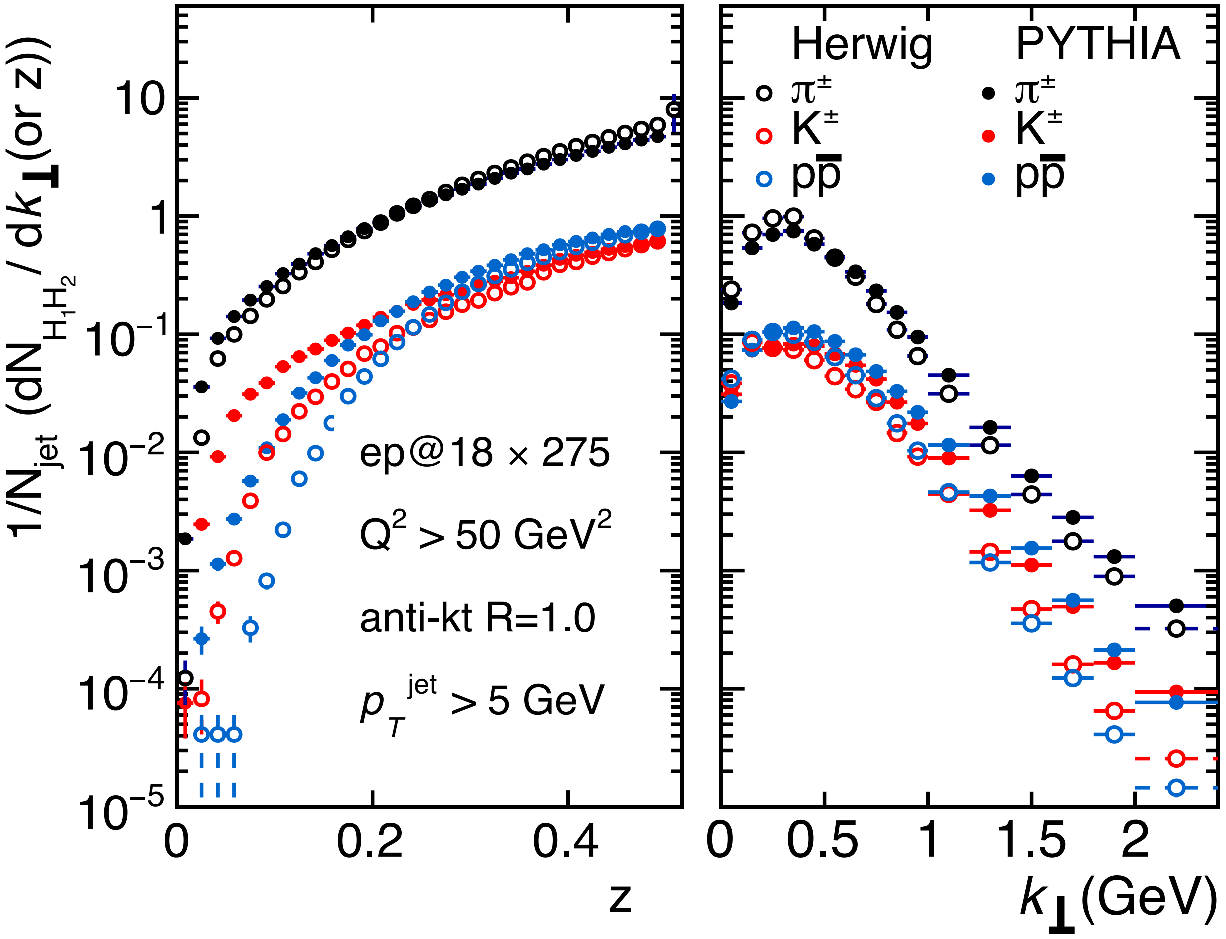
$p_{T,jet} > 5$ GeV/c

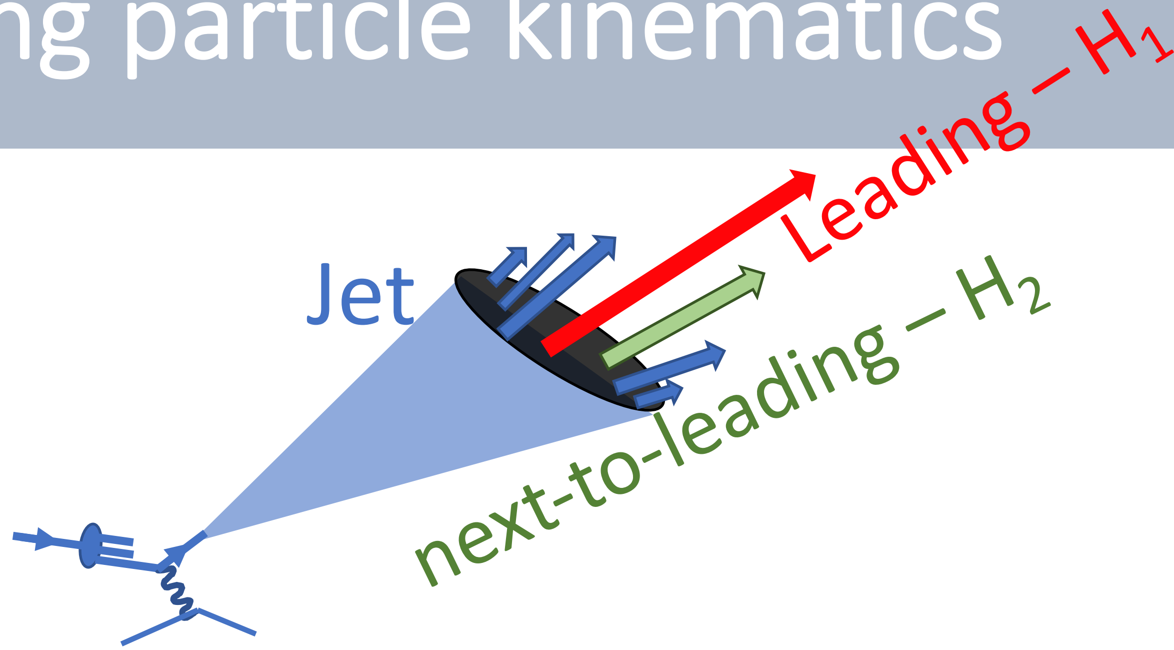
$-2.8 < \eta_{jet} < 2.8$

$p_{T,part} > 0.2$ GeV/c

$-3.5 < \eta_{part} < 3.5$

Leading and Next to leading particle kinematics



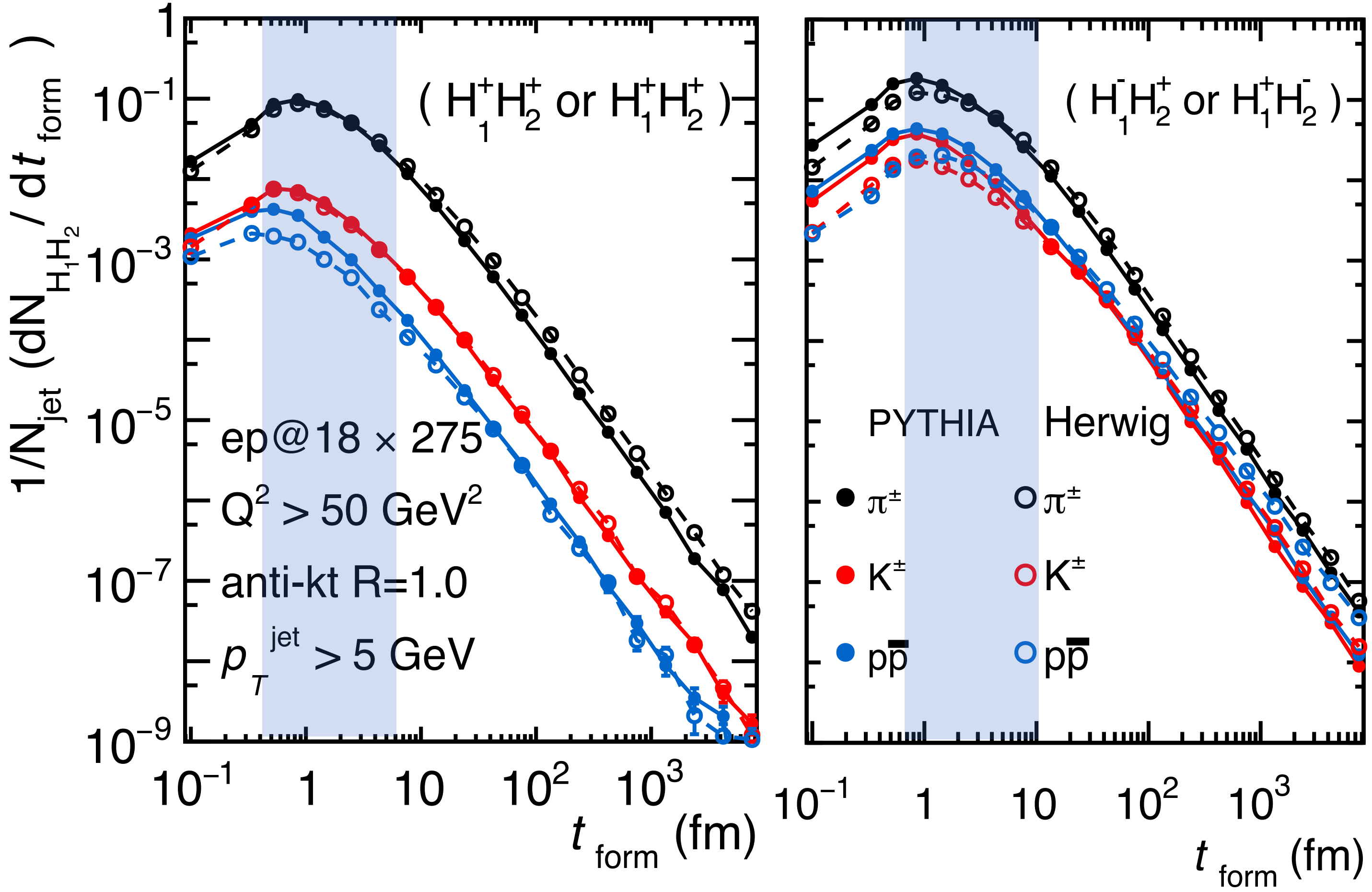


$$p = p^{H_1} + p^{H_2}$$

$$z = p^{H_2}/p$$

$K_{\perp}$ = relative traverse momentum between H_1 and H_2

Formation time



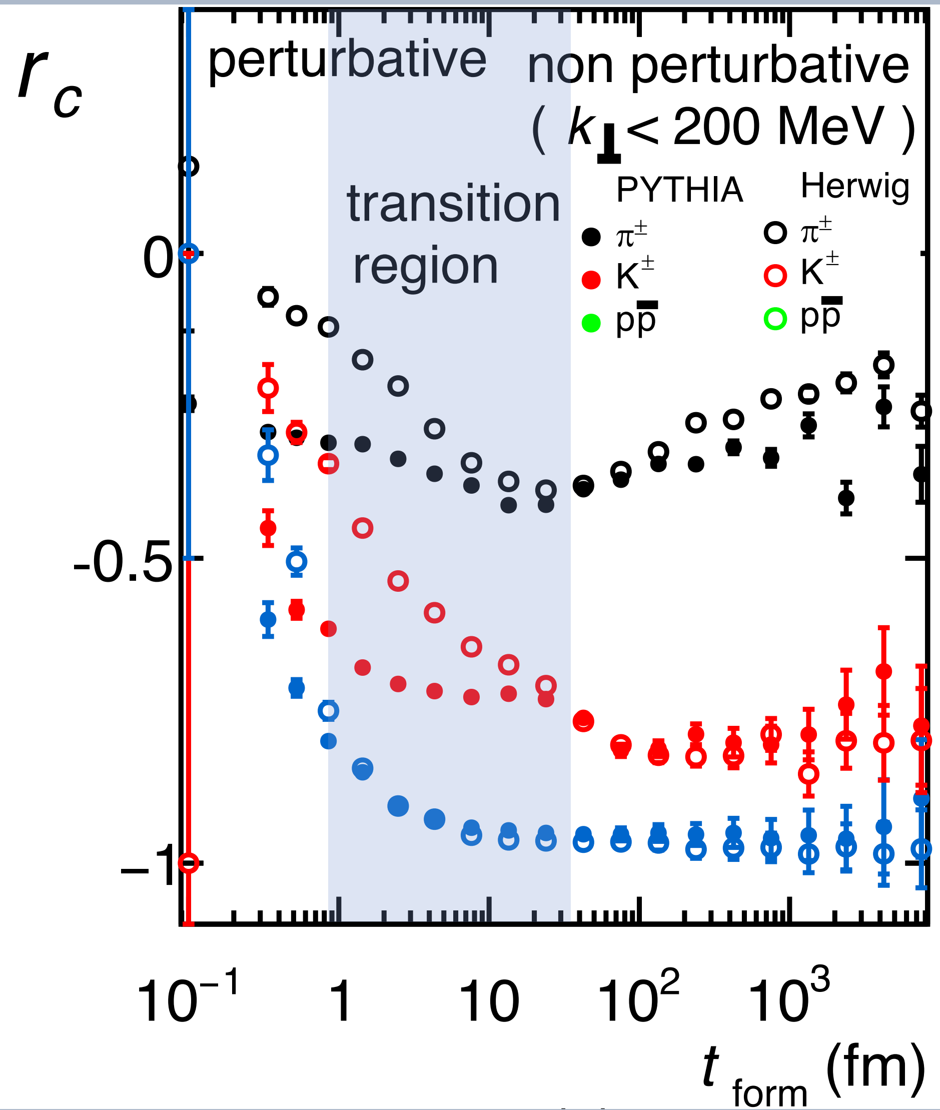
Formation time (t_{form}) :
$[2z(1-z)p] / k_{\perp}^2$

Small formation time :
Small z : perturbative region – soft emission

Large formation time :
z =1/2 : nonperturbative dominated
$k_{\perp}$ < 200 MeV :
intrinsically nonperturbative process

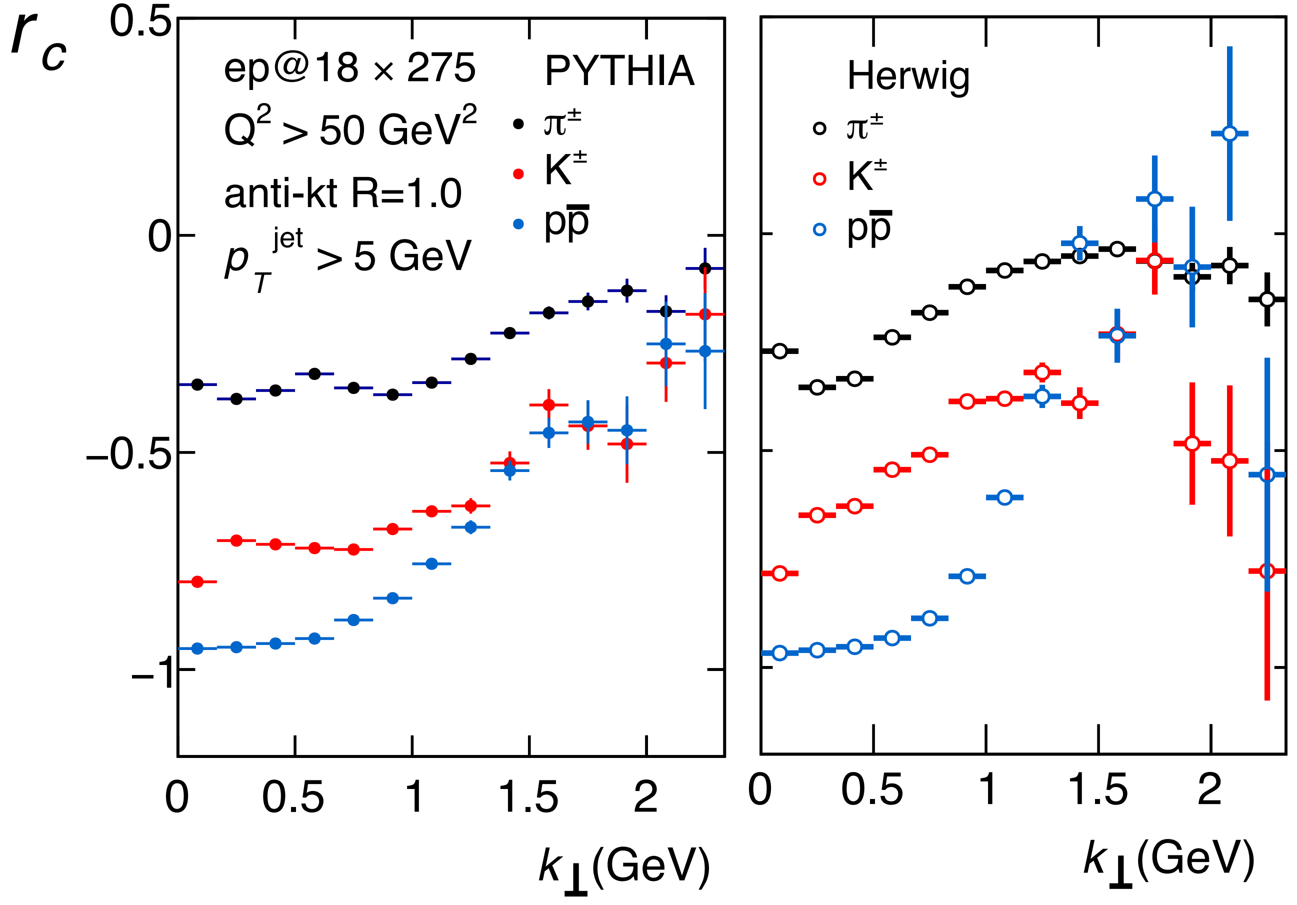
t_{form} is Lorentz dilated and observed in lab frame

Charge-energy correlation with formation time



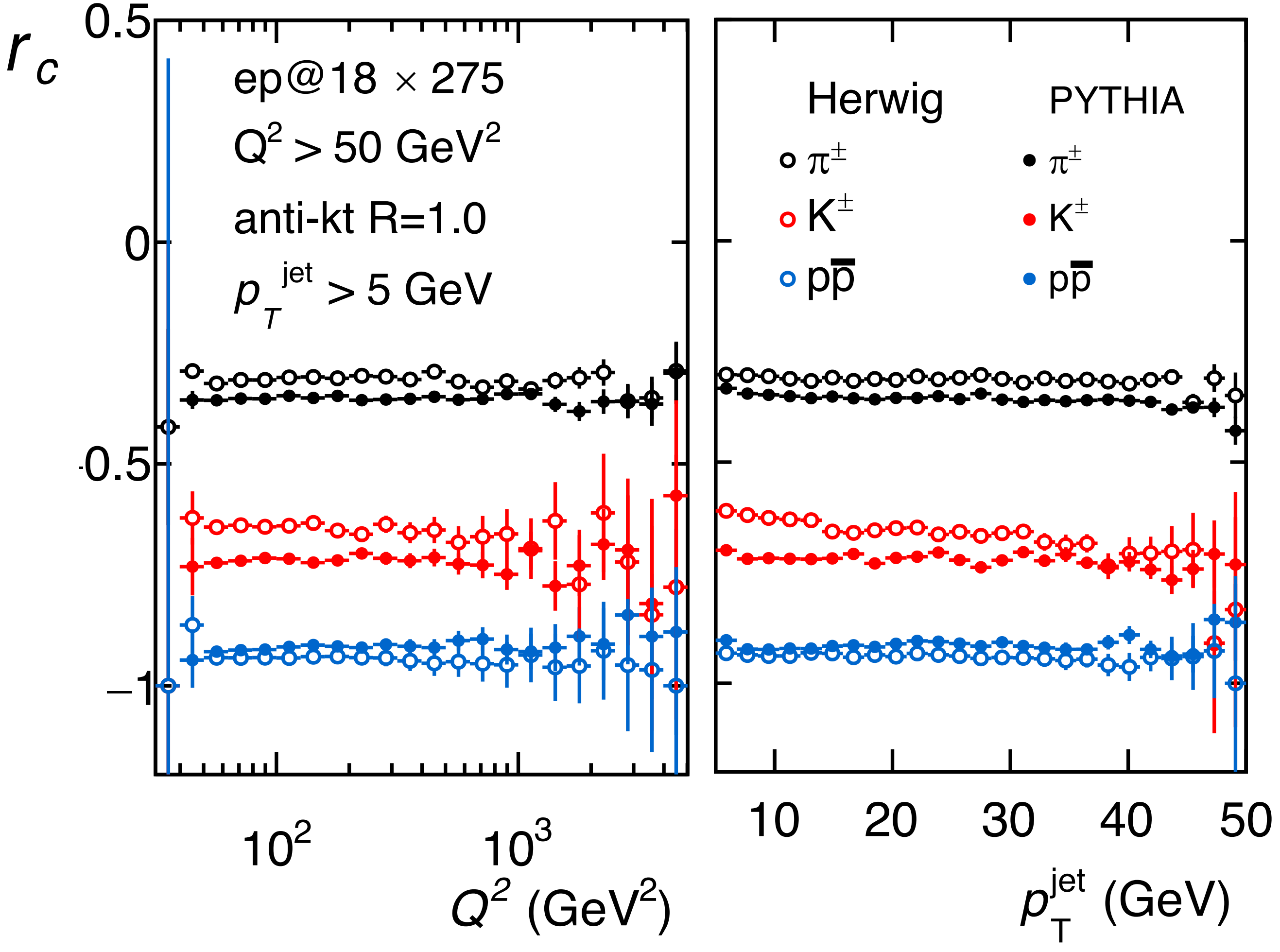
- At early time de-correlations for wide-angle, perturbative emissions.
- There is strong flavor dependence in $\boldsymbol{r_c}$
  - highly unlikely to produce same sign pp or $\bar{p}\bar{p}$ compared to $p\bar{p}$
  - more likely to observe two leading kaons with opposite signs due to strangeness conservation
- Herwig and PYTHIA show distinct features for pions and kaons at t_{form} < 10 fm

Charge-energy correlation with $k_{\perp}$



- The correlation decreases as $K_{\perp}$ increases on the scale of 1-2 GeV.
- The description require both perturbative and nonperturbative inputs.
- Detailed comparison of data and event generator output will help clarify the degrees of freedom necessary to provide a satisfying picture of hadronization

Charge-energy correlation with hard scales



Extraordinary scaling with hard scales of the process, Q^2 and the jet transverse momentum p_T.

Charge-energy correlation with flavor tagging

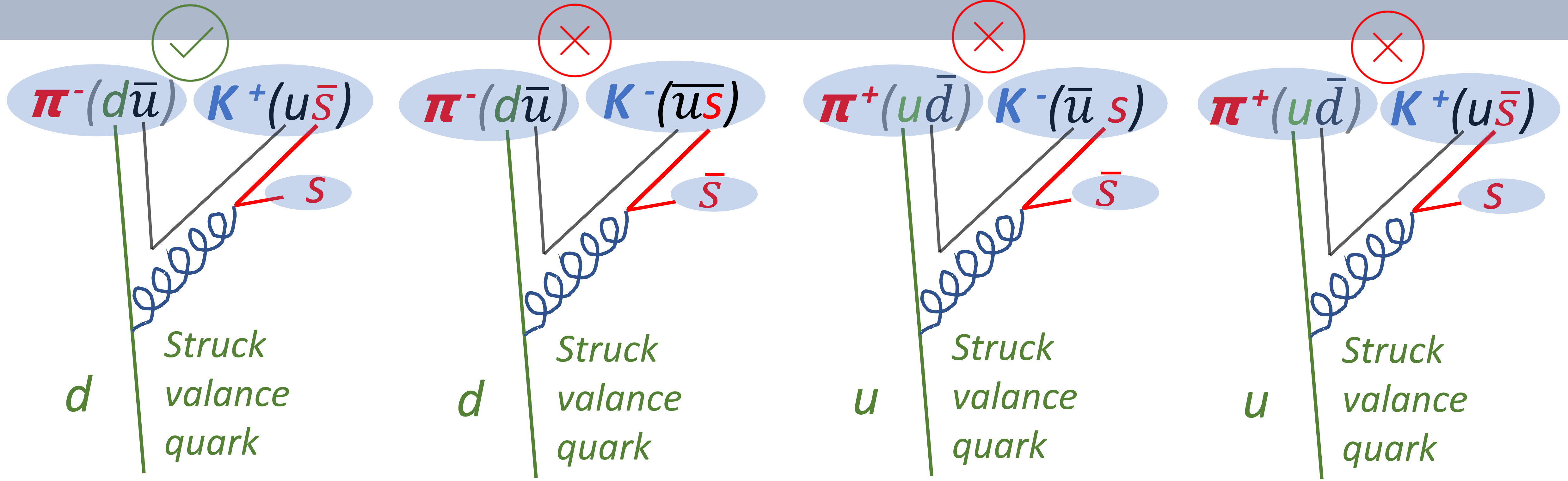
In general, $\boldsymbol{r_c}$ shows strong flavor dependence and we explore further the utility of **strange flavor tagging :**

Case-I (L : π^- NL : $\mathbf{K}^{\pm}$)
Case-II (L : π^+ NL : $\mathbf{K}^{\pm}$)

Strange Jet Tagging
Yuichiro Nakai, David Shih, Scott Thomas
arXiv:2003.09517

Flavor correlations

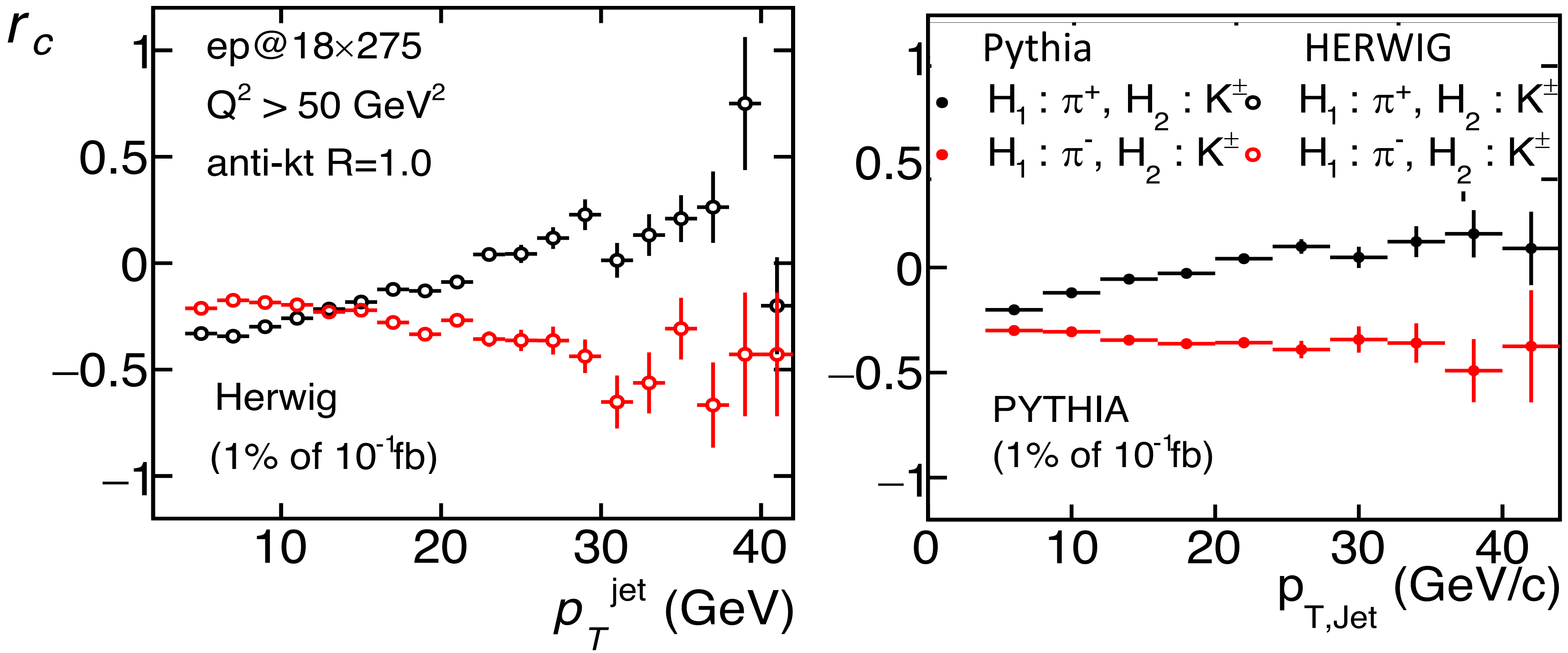
$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$



With struck valance quark, L(π^-) NL(K^+) is preferable for the simplest string breaking between L and NL particles

➢ From this naive picture one expects r_c for π^-K$^\pm$ to be stronger than that of π^+K$^\pm$

Difference in flavor combinations

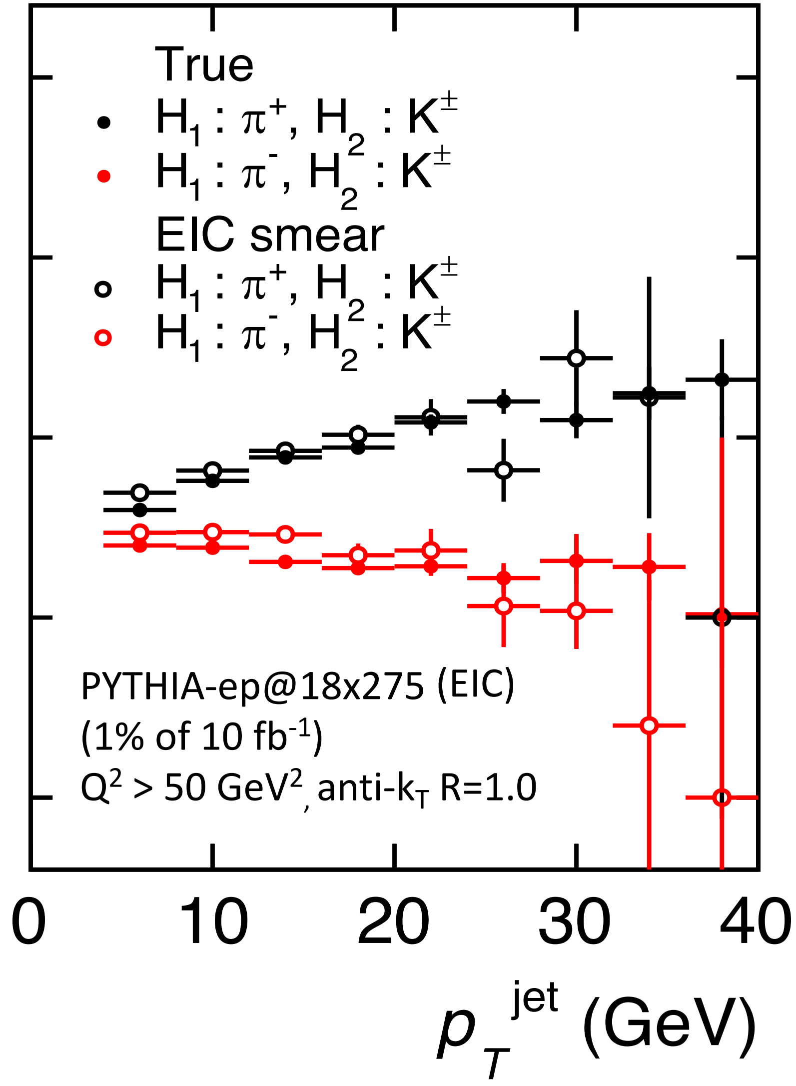


- Correlations are much stronger for $\pi^-K^\pm$ than for $\pi^+K^\pm$ in PYTHIA
- As p_T increases $\pi^+K^\pm$ correlations weakens whereas $\pi^-K^\pm$ strengthens
- Significant difference between PYTHIA and Herwig

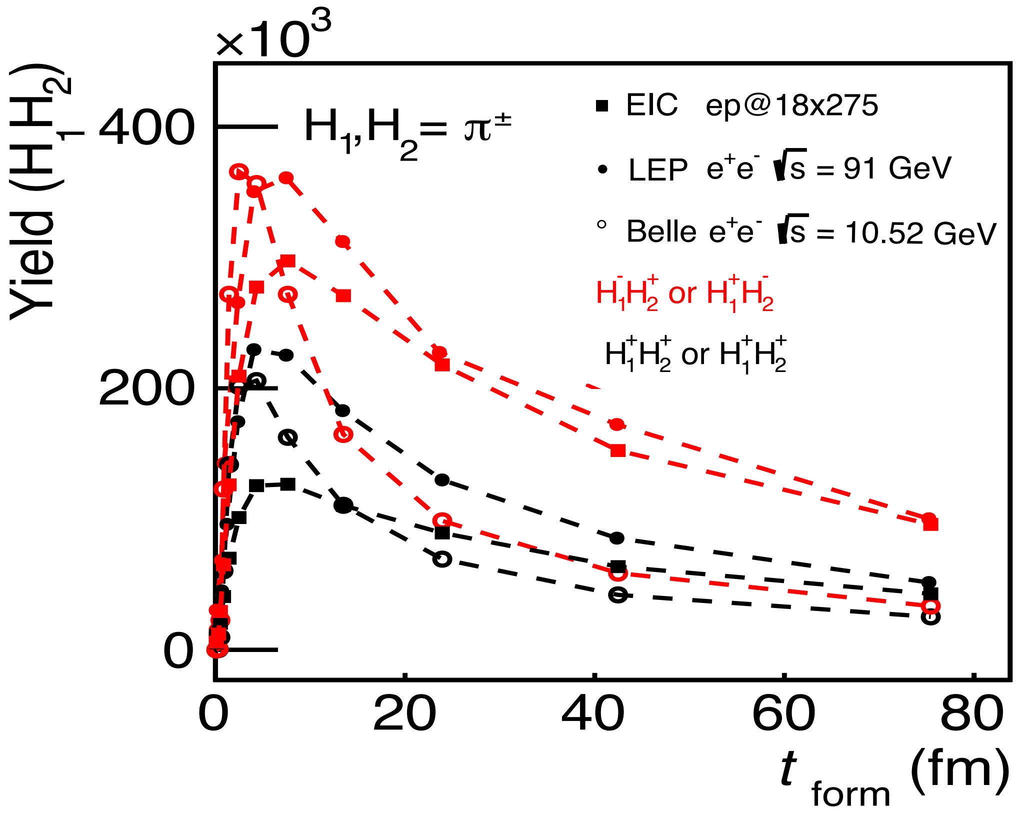
Measurement of r_c

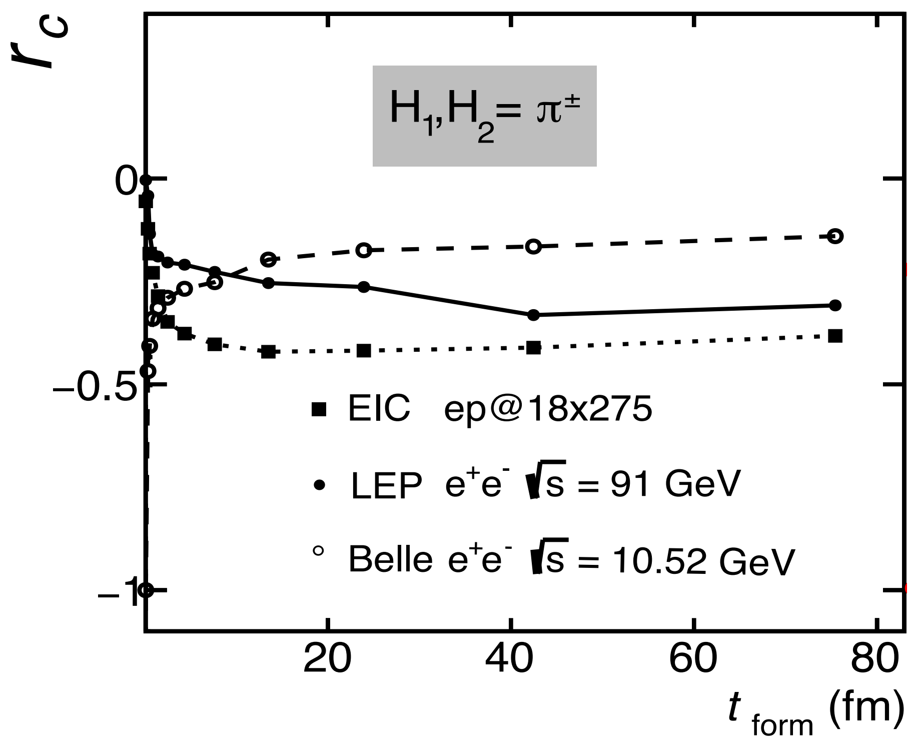
- EIC (flavor) in future, Belle (flavor)
- Charge correlations at LEP, **H1**, RHIC, LHC

- **An *early* impactful measurement at EIC :**
  - ➢ Detector smearing does not affect this observable in a significant way
- **Unique Opportunity at EIC** :
  - ➢ RHIC and HERA has limitations to identify ***π*** and **K** at high momentum
  - ➢ Particle identification requirement (~10 GeV/c for ***π*/K** in central region)



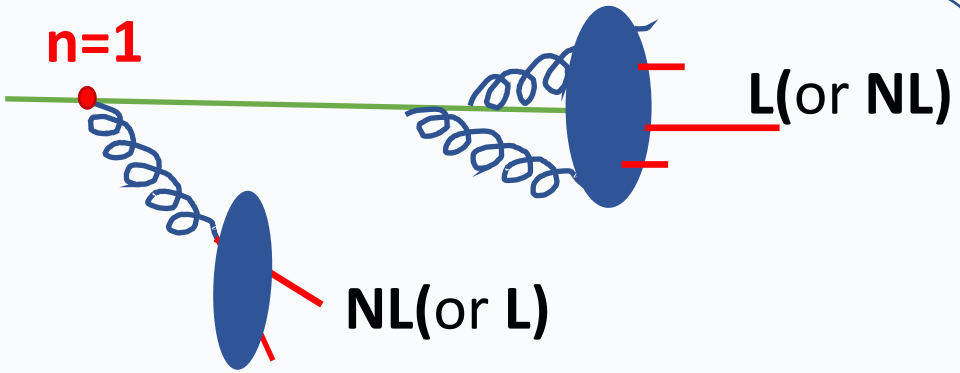
Belle can measure flavor correlations



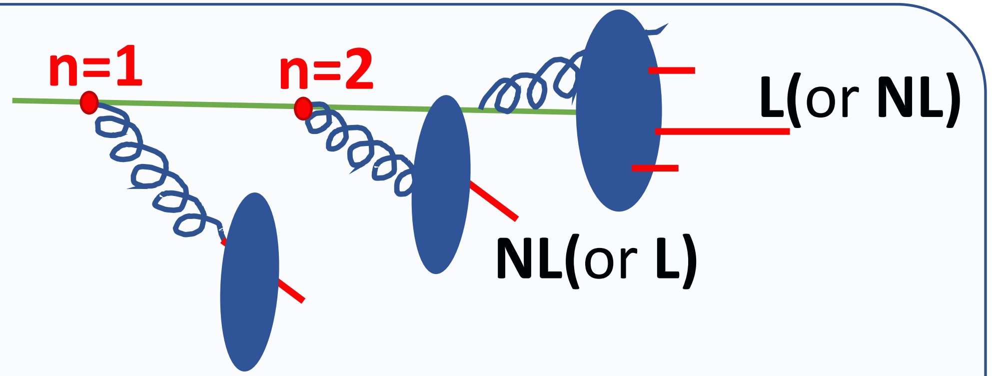


- Belle t_{form} peak appear early
- Belle might be mostly lie in nonperturbative region

Subjet structure



L and NL particle get resolved in first prong (n =1)



L and NL particle get resolved in the second prong (n=2)

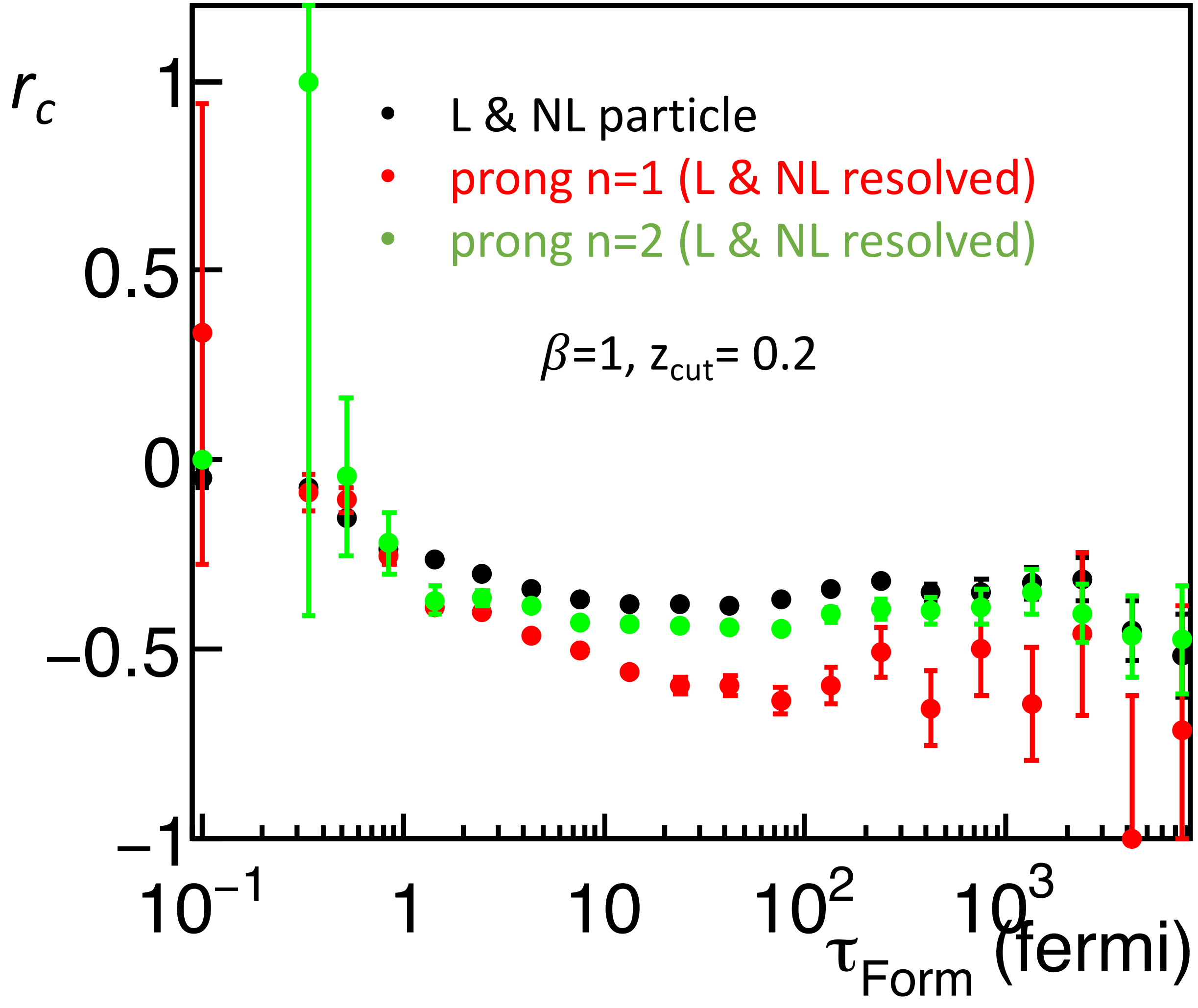
- Confronting the nonperturbative origin of L NL particles with perturbative splittings
- L, NL particles are strongly correlated with the hardest patron in Pythia and Herwig
- Prong structure represent the partonic proxy

Using Recursive soft drop

$$z_{12} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta} , \qquad z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

- Anti-kt R=1.0 and C/A de-clustering tree
- following hardest branch
- dynamic radius

Resolved prong (n_R) and r_C – with τ_F



- The correction can be measured within jet sub-structure framework.
- Possible prediction from perturbative calculation in some kinematic region
- Medium included modifications in hadronization :
  - r_c – eA (cold nuclear matter)
  - r_c – AA (hot nuclear matter)

Summary

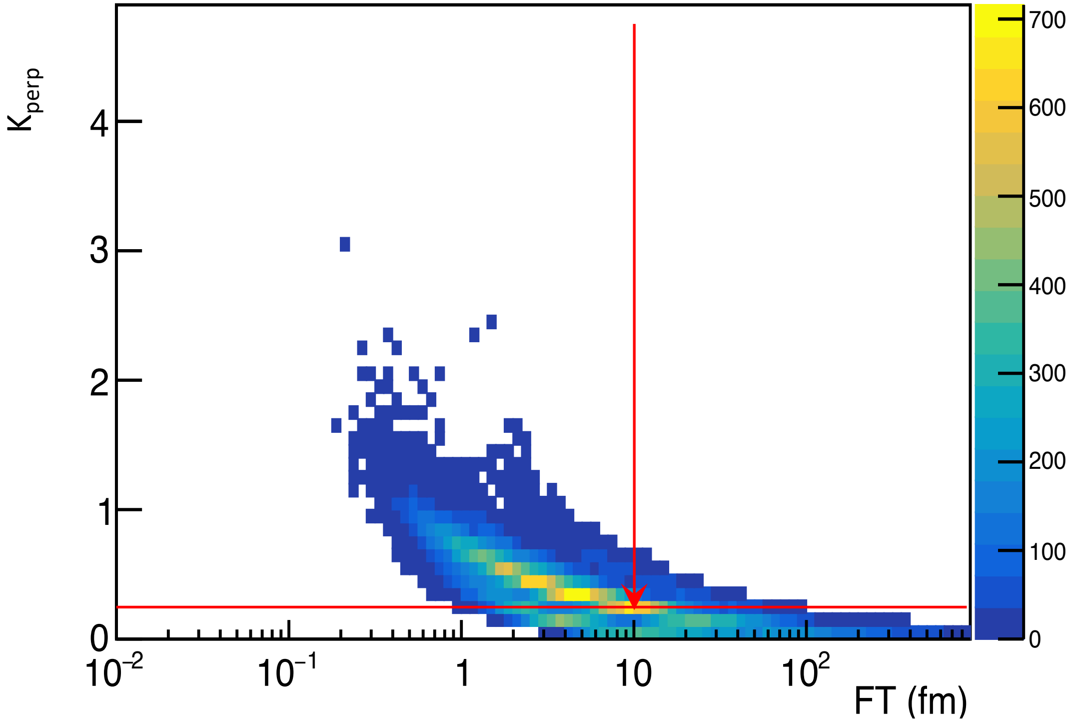
- A charge-energy correlation observable, $\boldsymbol{r_c}$ is introduced to study hadronization using two leading particles in jet
- Significant differences in $\boldsymbol{r_c}$ observed for various flavor combinations
- Flavor-tagged data would have significant impact on the knowledge on string fragmentation inspired models

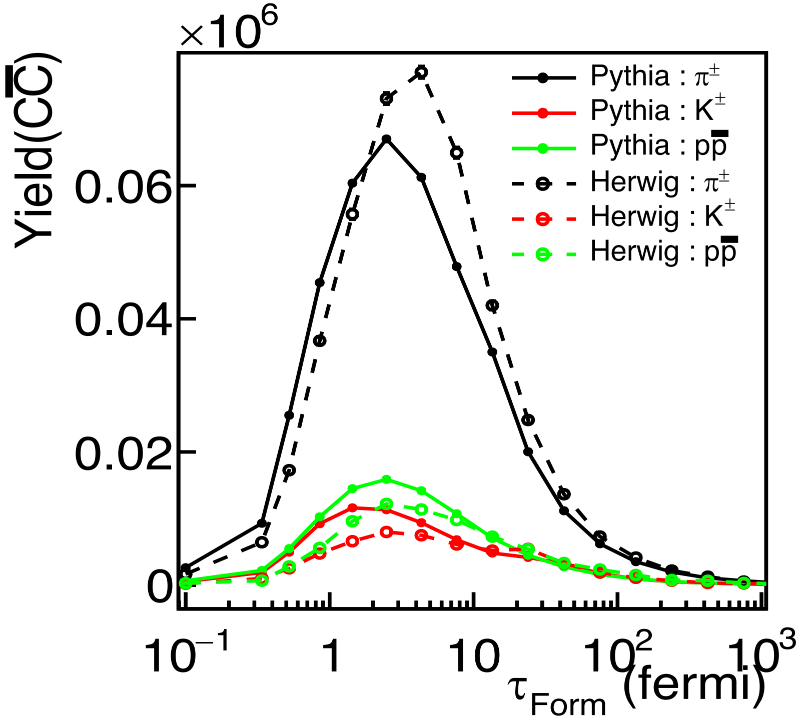
- r_c for different flavors can be measured at EIC very precisely and measurement is being made in some current experiment like H1

- It requires the measurement r_c in different collision systems and environment for better understanding of hadronization dynamics.

Thank you for your attention

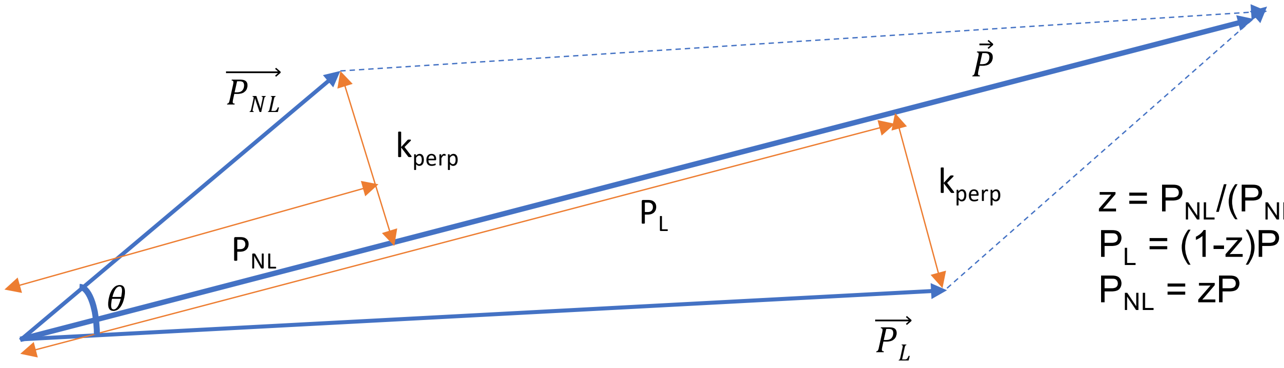
Formation time





τ_{form} **< 1fm** : L and NL particles seem to separate after a very short time, which might decorrelate their hadronization.

τ_{form} **> 10 fm** (K_{perp}< 200 MeV) **:** nonperturbative transverse momenta in the jet, and we don't think that going to longer τ_{form} or smaller k_{perp} leads to new dynamics



$z = P_{NL}/(P_{NL}+P_L)$
$P_L = (1-z)P$
$P_{NL} = zP$

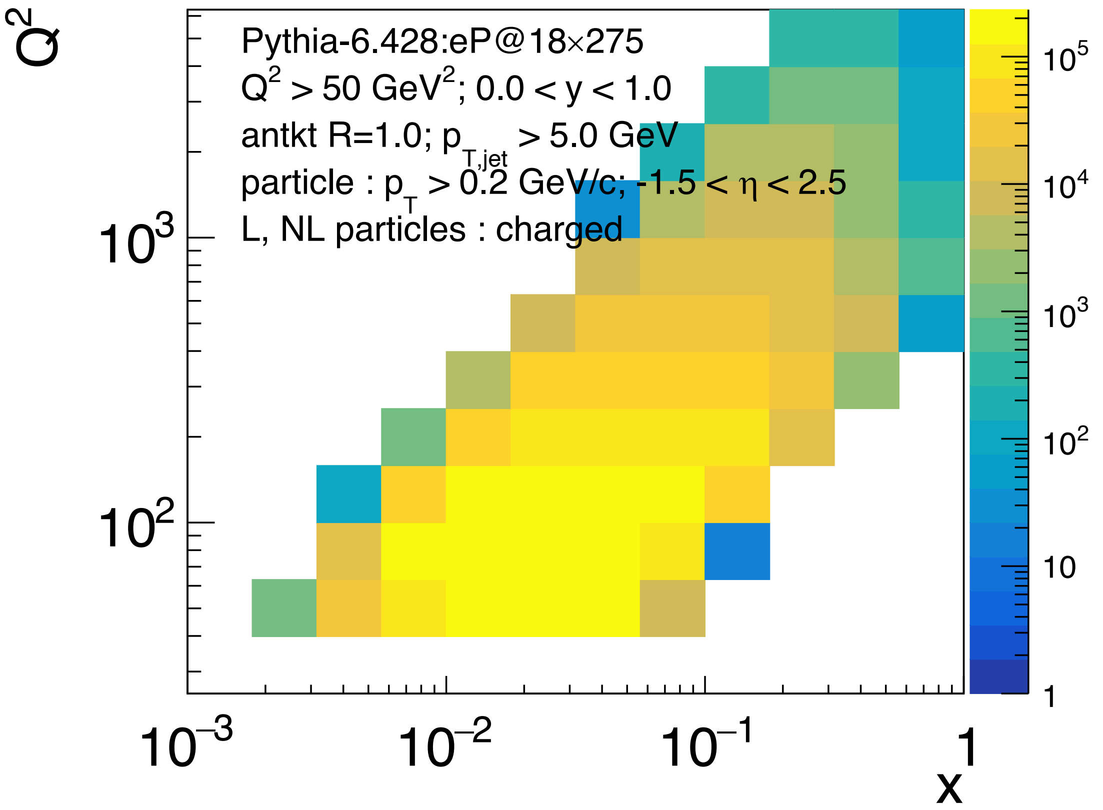
Formation time = [2z(1-z) P] / k_{perp}^2

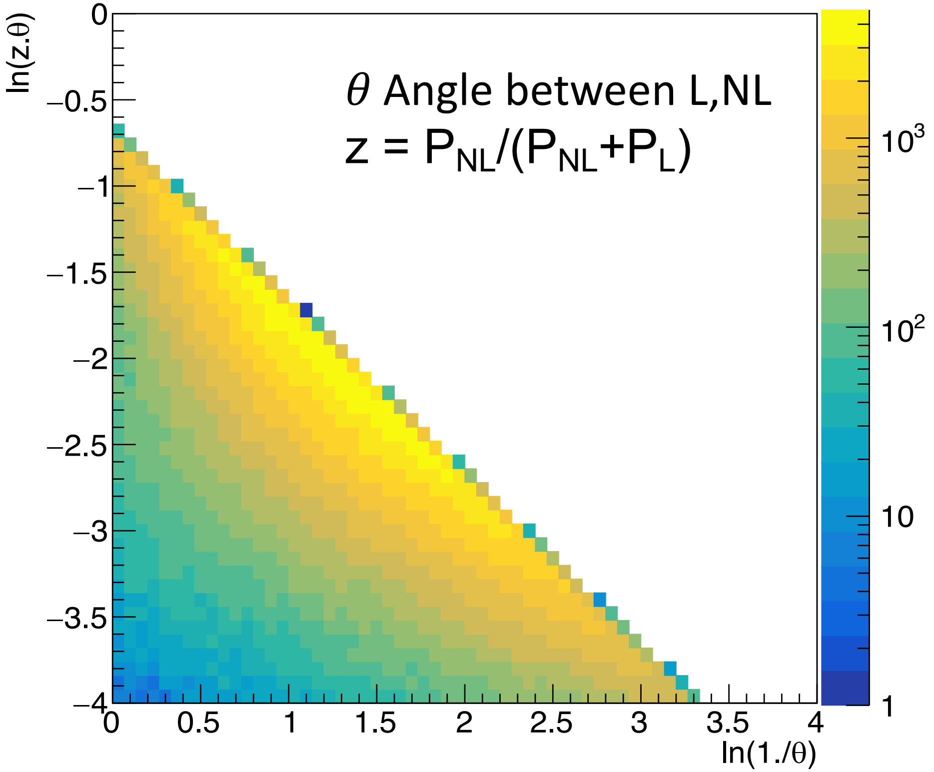
Important region to study in data τ_{form} = "a few fermi" and "a few dozen fermi", k_{perp} = "a few GeV" to "several hundred MeV"

Event acceptance in x-Q^2

Event Generation : Pythia 6.428
Herwig 7.1.5
Q^2 > 50 GeV

Jets : anti-kt R = 1.0
Jet p_T > 5GeV/c
Jet |eta| < 2.8
particle p_T > 0.2GeV/c
particle |eta| < 3.5





Jets at Belle and LEP

Using PYTHIA-8

BELLE initialization at Upsilon mass.

```
pythia.readString("Beams:idA =  11");
pythia.settings.parm("Beams:eA", 7);
pythia.readString("Beams:idB = -11");
pythia.settings.parm("Beams:eB", 4);
double mZ = pythia.particleData.m0(553);
pythia.settings.parm("Beams:eCM", 10.52);
```

LEP initialization at Z0 mass.

```
pythia.readString("Beams:idA =  11");
pythia.settings.parm("Beams:eA", 45);
pythia.readString("Beams:idB = -11");
pythia.settings.parm("Beams:eB", 45);
double mZ = pythia.particleData.m0(23);
pythia.settings.parm("Beams:eCM", 91.0);
```

Particles : $-3 < \eta < 3$ && $p_T > 0.2$GeV/c

R = 0.8

```
fastjet::JetDefinition
jet_def(fastjet::ee_genkt_algorithm, 0.8, -1);
```

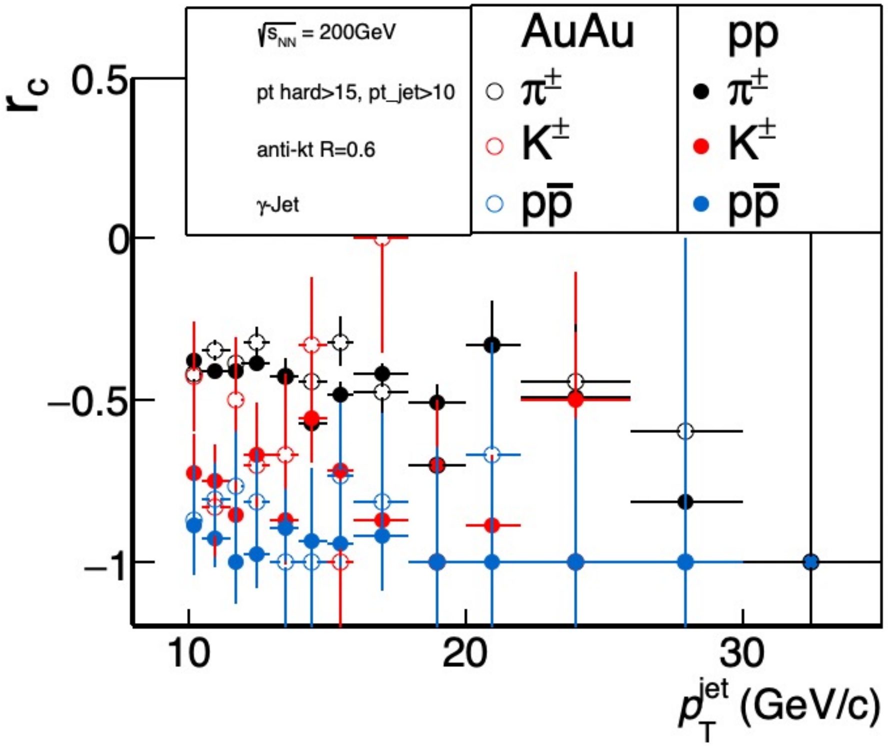
Distance set with angle :

$$d_{ij} = \min\left(E_i^{-2}, E_j^{-2}\right) \frac{1 - \cos\theta_{ij}}{1 - \cos R_0}$$

$$d_{iB} = E_i^{-2},$$

r_c can be studied for fragmentations in other systems

p_T (particles) > 1.2 GeV/c

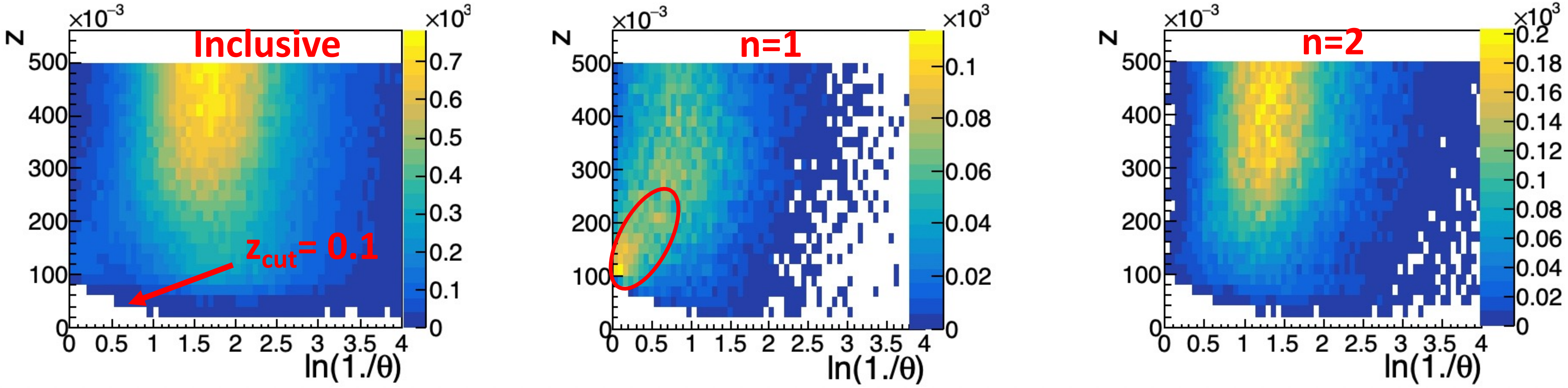


- Modification in cold nuclear matter(eA, pA) and hot nuclear matter (AA) – sPHENIX & STAR
- Measurement at BELLE and LEP

Kinematic region for various resolved prongs

(PYTHIA-6.428) ep@ 18x275, Q^2 > 50 GeV/c, anti-kt R=1.0, $p_{T,Jet}$ > 5 GeV/c

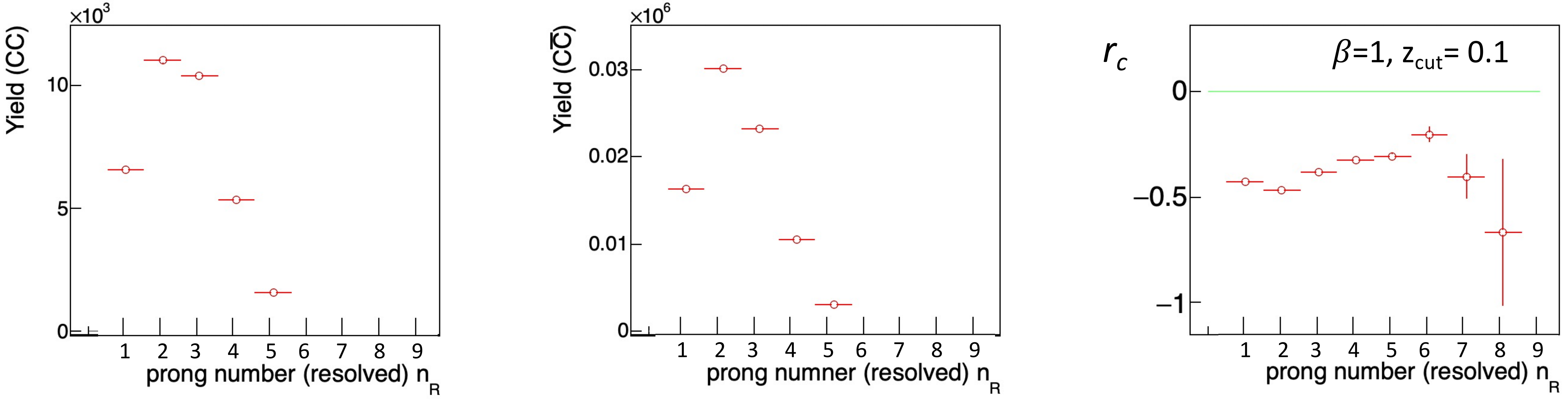
Recursive subjet : β=1, z_{cut}= 0.1



n=1 : wide angle soft radiations

n=2 and higher are relatively harder splitting and narrower in angle

Resolved prong (n_R) and r_C



- For β=1, z_{cut}= 0.1 ~20% of CC and 20% of $C\bar{C}$ pairs get resolved in the first prong
- The average r_c changes changes sightly depending on prong numbers where it get resolved