Probing Jet substructure and hadronization with correlations of leading particles at EIC

Mriganka Mouli Mondal
CFNS, Stony Brook University

(with Y.-T. Chien [CFNS,SBU,GSU], A. Deshpande [CFNS,SBU,YITP], G. Sterman [CFNS,SBU,YITP])

The 2nd Workshop on Jets for 3D Imaging at the EIC

Center for Frontiers in Nuclear Science

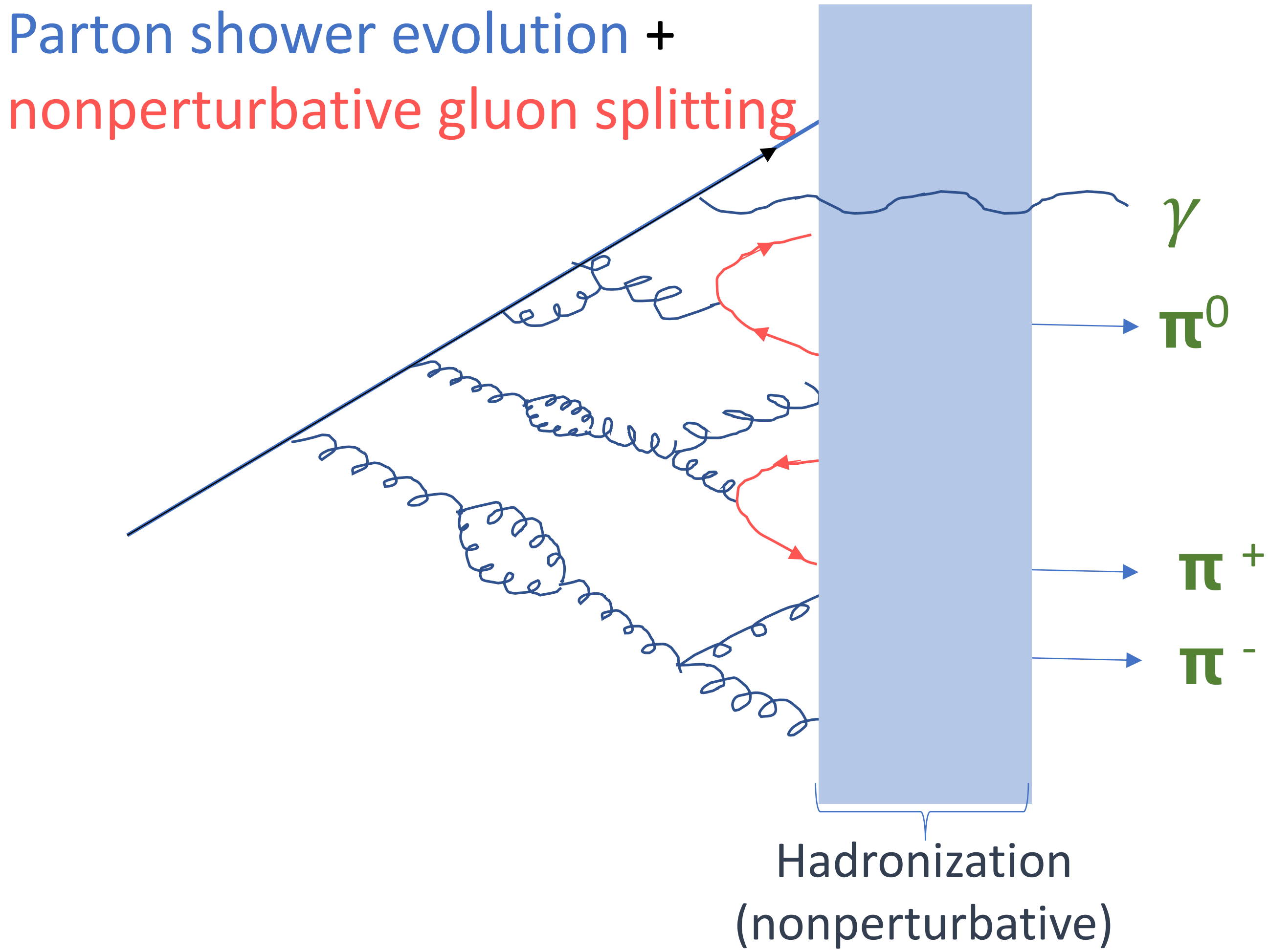
Georgia State University

Stony Brook University

Outline

- Jets : access the dynamics of hadronization
  - ✓Charge-energy correlation for Leading and Next-to-Leading particles
- Correlations for electron-proton collisions at the EIC
  - ✓Flavor correlations
  - ✓Strange flavor tagging
- Charge correlations in recursive soft drop structure
  - ✓Identifying events with simpler fragmentations
- EIC for measuring such correlations
- Summary

Jets and access to the dynamics of hadronization



Dynamics of hadronization are studied through correlations among particles in a jet

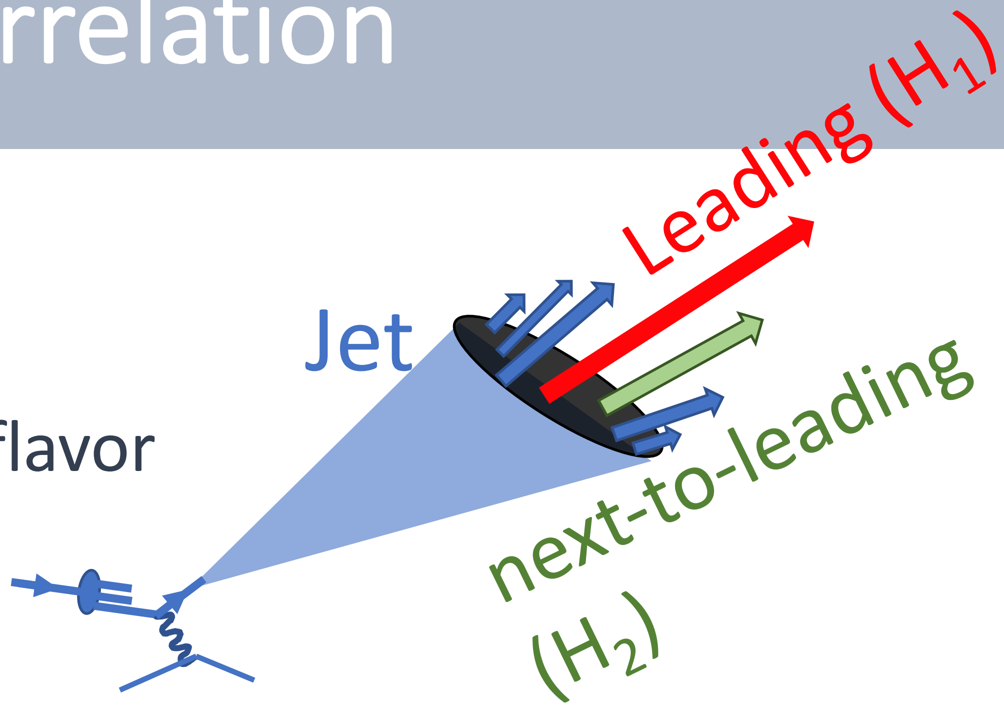
A unique detailed way of study hadronization

- two particles
- L and NL particles - choosing nonperturbative region

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

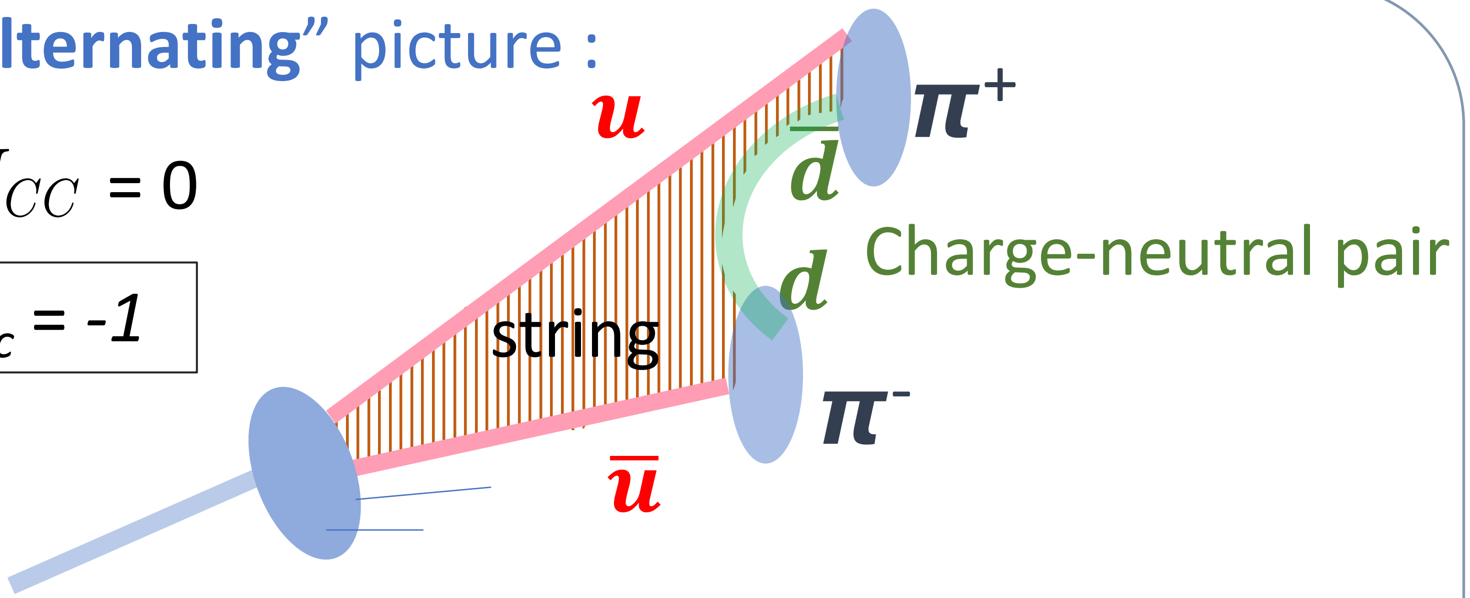
$N_{C\bar{C}}$: # Jets where L and NL particles with opposite sign charges

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"

Results for PYTHIA and Herwig studies

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

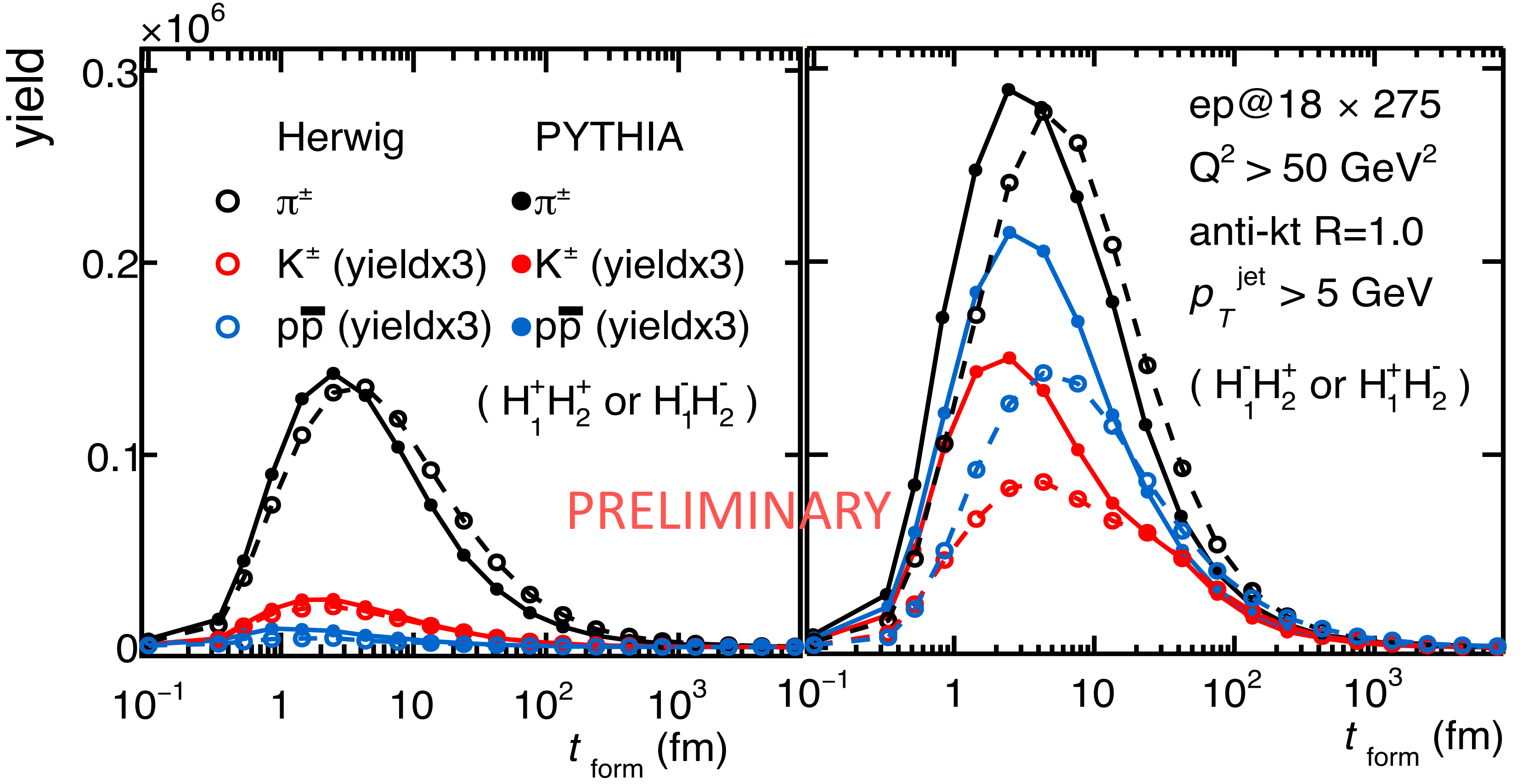
$-2.8 < \eta_{jet} < 2.8$

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

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

String fragmentation vs. cluster hadronization

Formation time



Formation time (t form)

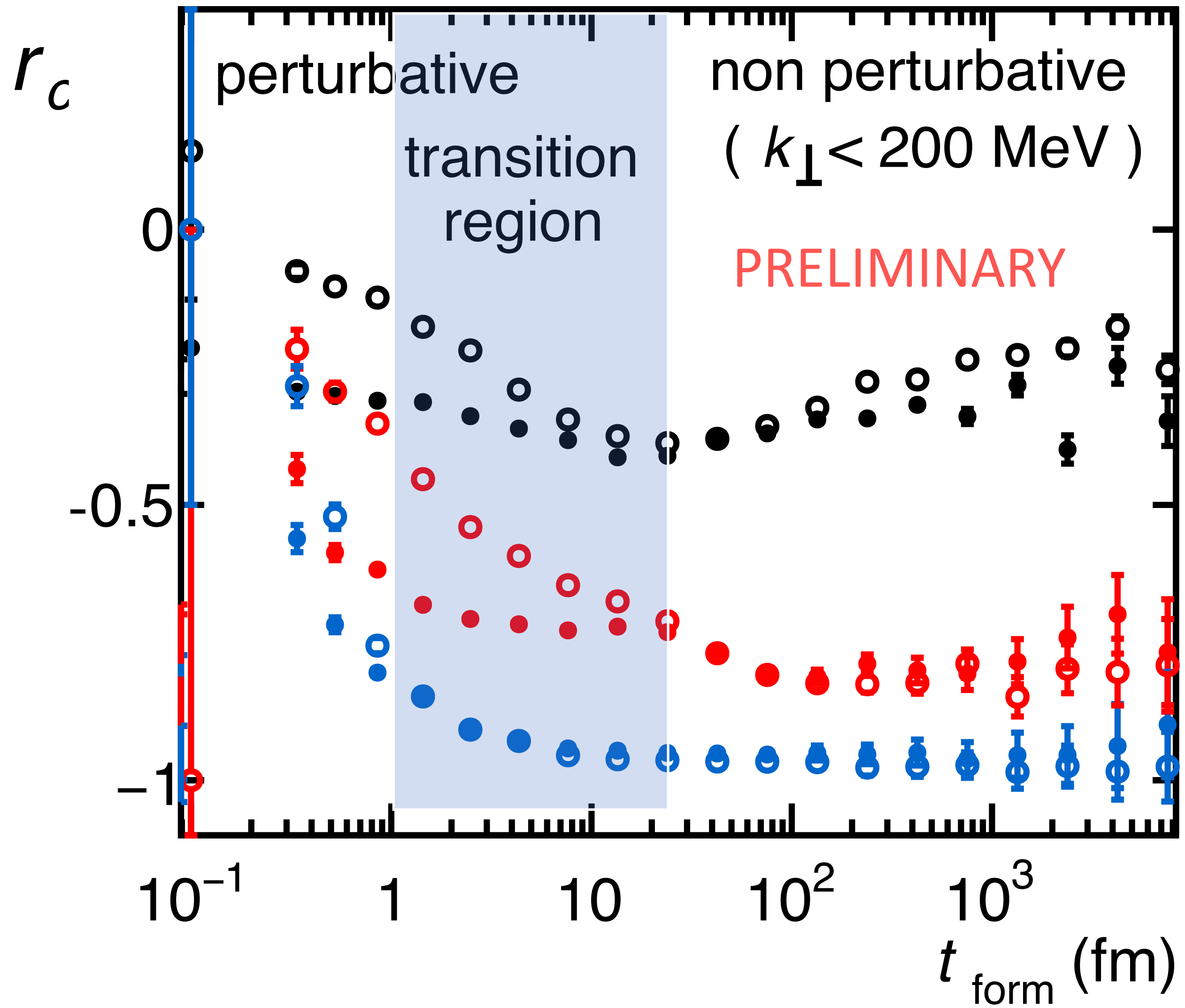
: $[2z(1-z)\ P]/k_{perp}^{2}$

z = momentum fraction of NL particle

$k_{\perp}$ = relative transverse momentum between L & NL

t form is Lorentz dilated and observed in lab frame

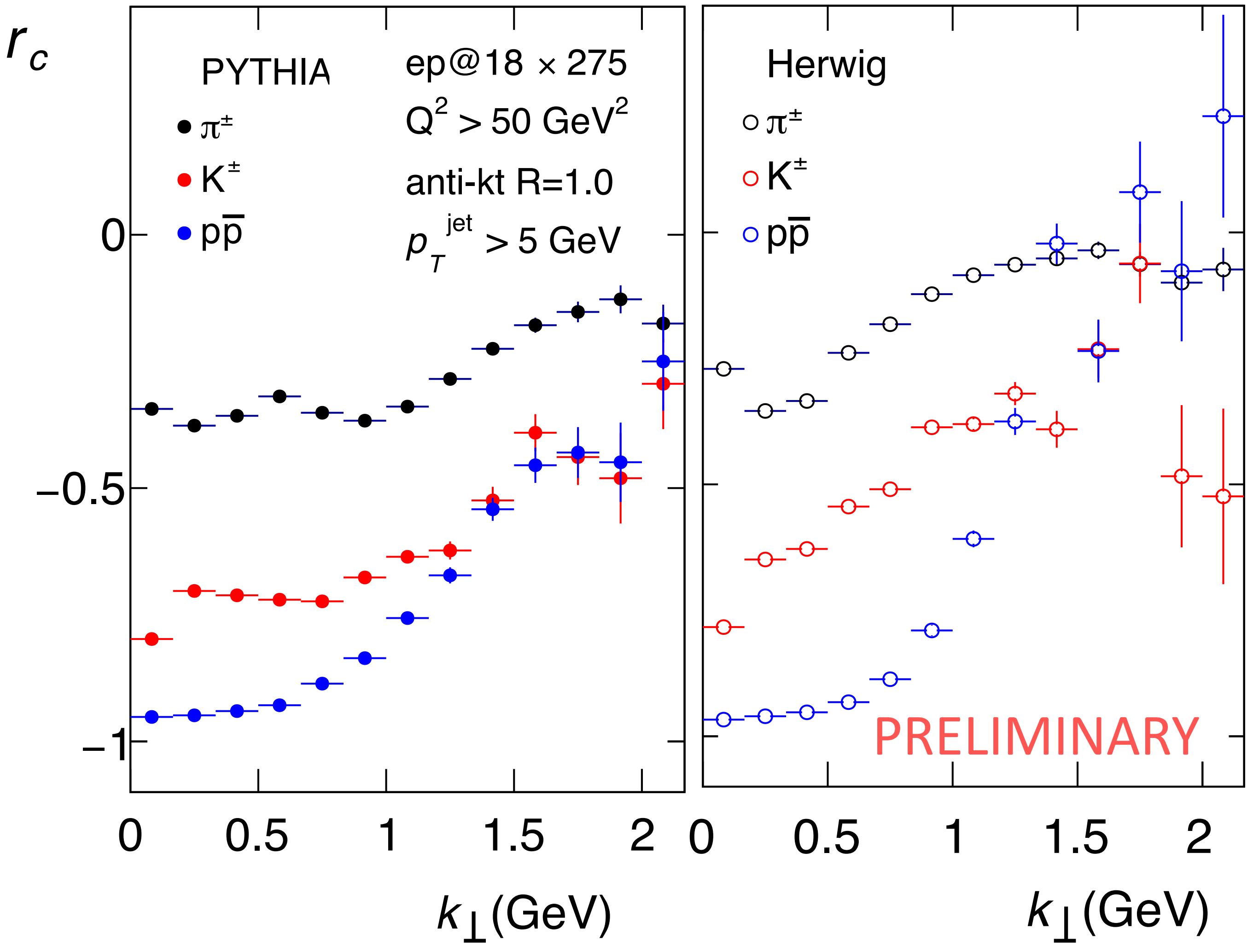
Charge-energy correlation with formation time



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

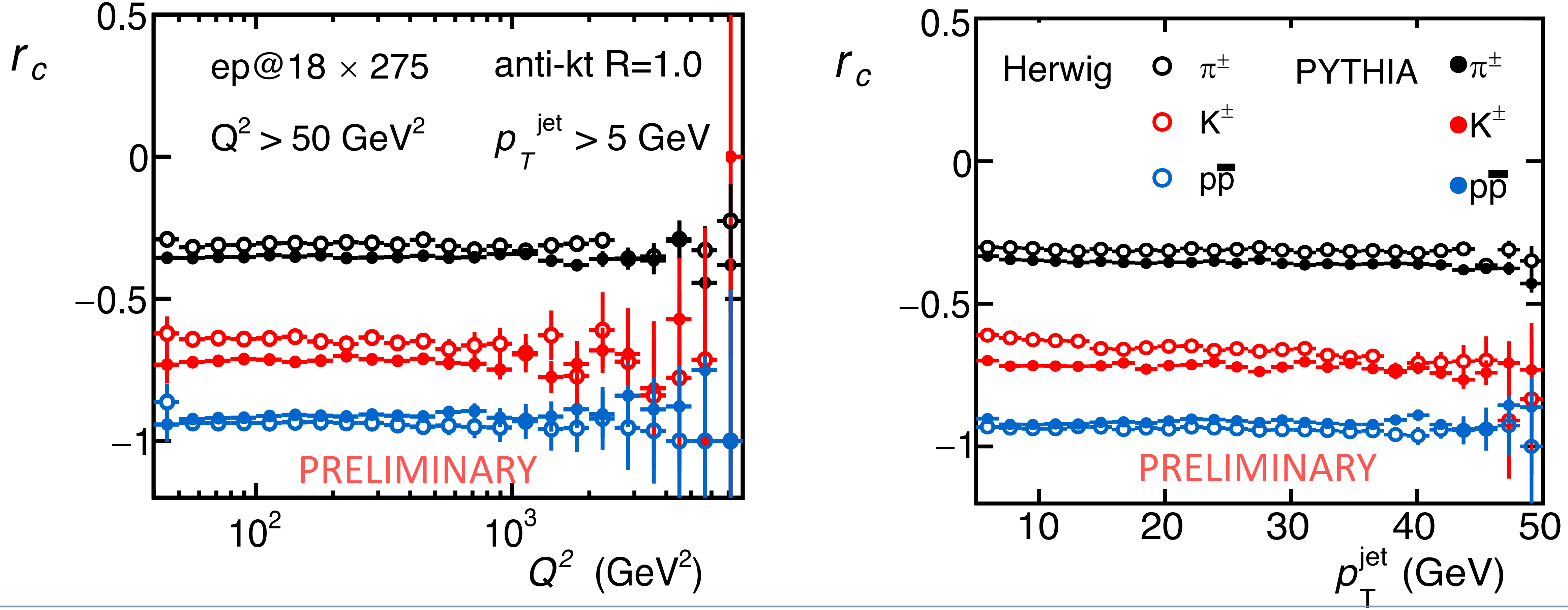
- There is strong flavor dependence in r_c
- In specific kinematic region PYTHIA and Herwig differ significantly

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 scale



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

Charge-energy correlation with flavor tagging

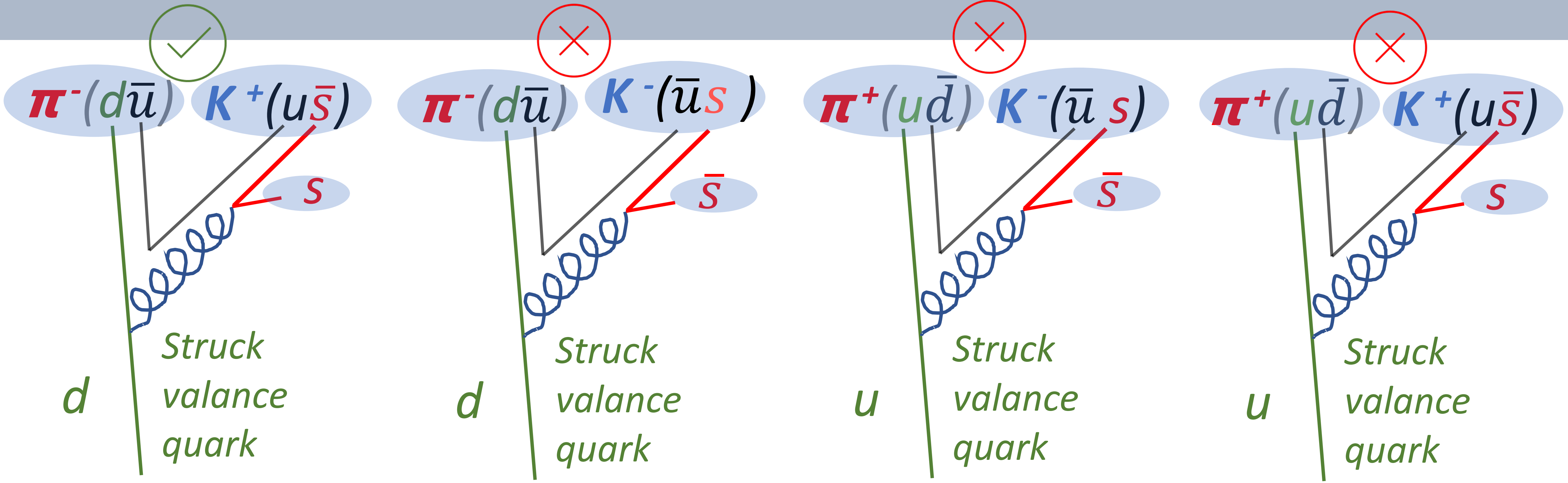
In general, $\boldsymbol{r_c}$ shows strong flavor dependence and we explore further the utility of **strange flavor tagging :**

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

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

Flavor correlations

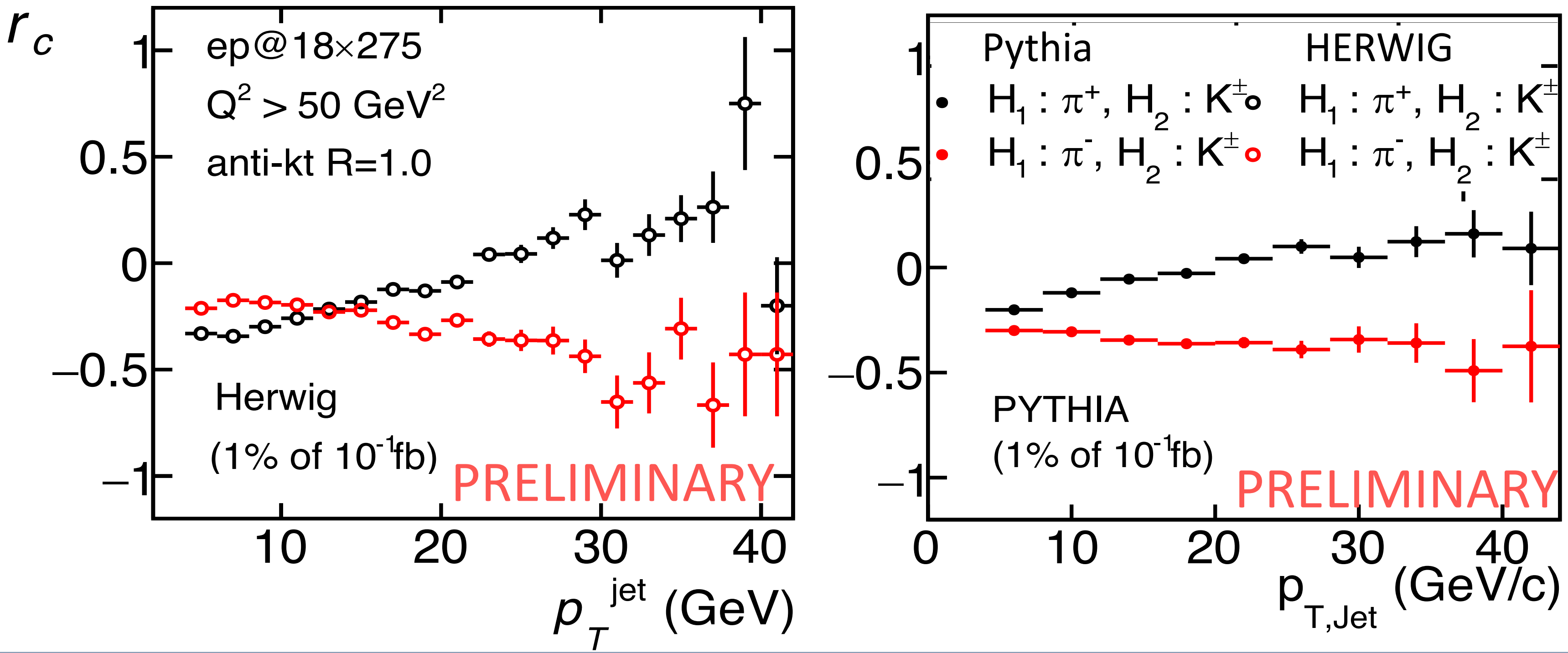
$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$



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 $\pi^- K^\pm$ to be stronger than that of $\pi^+ K^\pm$

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

Subjet structure

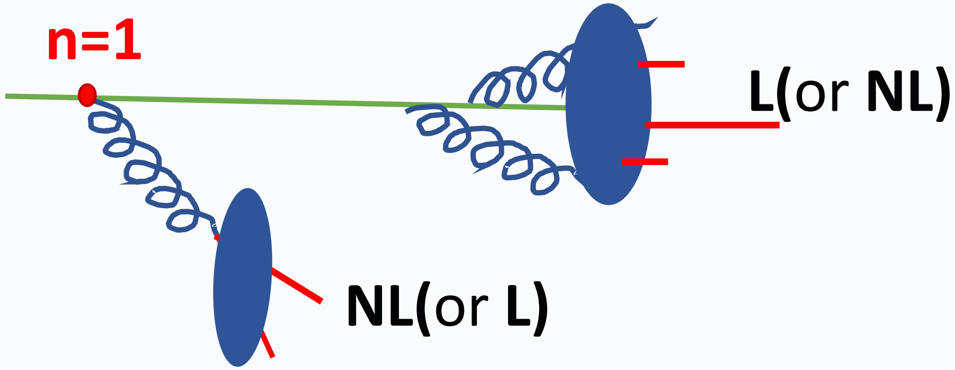
- Significant literature on jet substructure and grooming techniques are available.
- We used some of the available techniques.

Soft Drop
Andrew J. Larkoski, Simone Marzani, Gregory Soyez, Jesse Thaler
JHEP 1405 (2014) 146

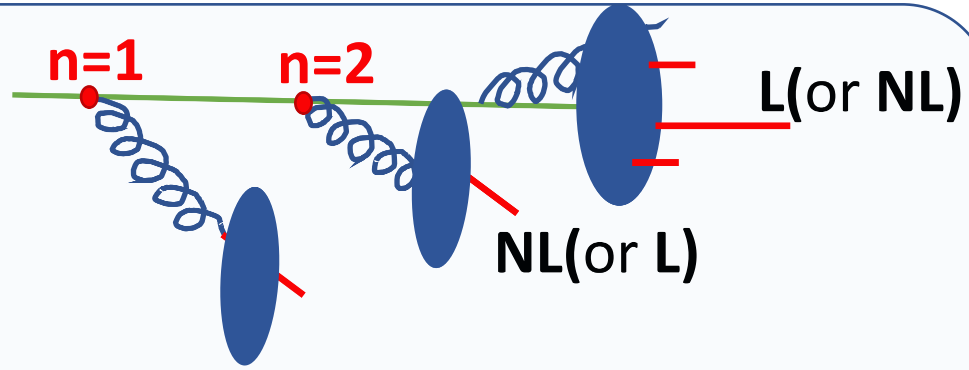
Recursive Soft Drop
Frédéric A. Dreyer, Lina Necib, Gregory Soyez, Jesse Thaler
JHEP06(2018)093

The Lund Jet Plane :
Frederic A. Dreyer, Gavin P. Salam, Gregory Soyez
JHEP06(2018)093

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

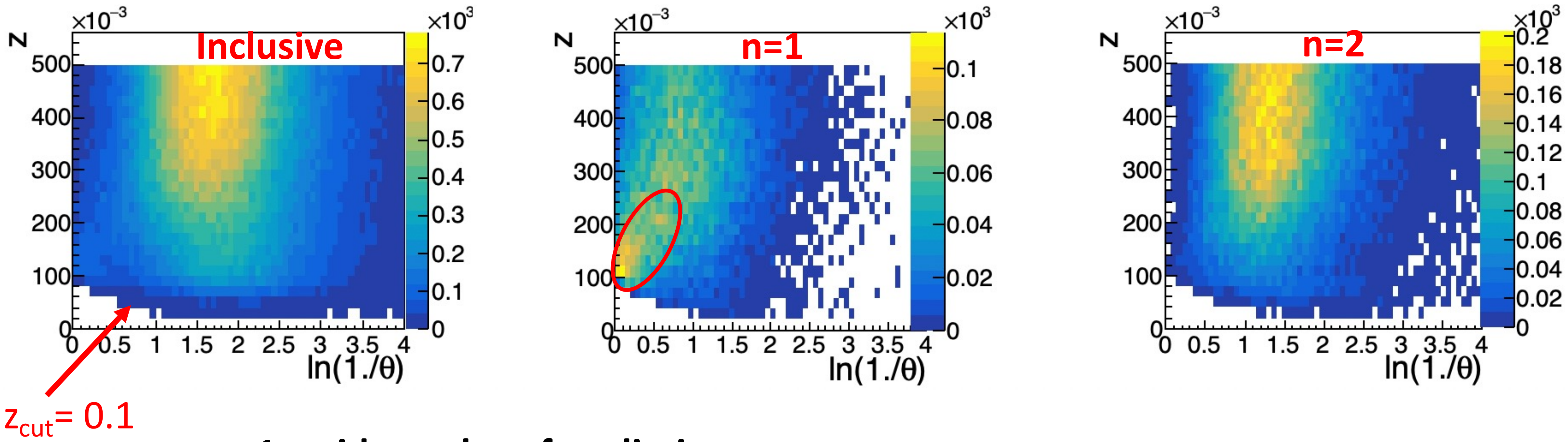
$$z_{12} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}, \qquad z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

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

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

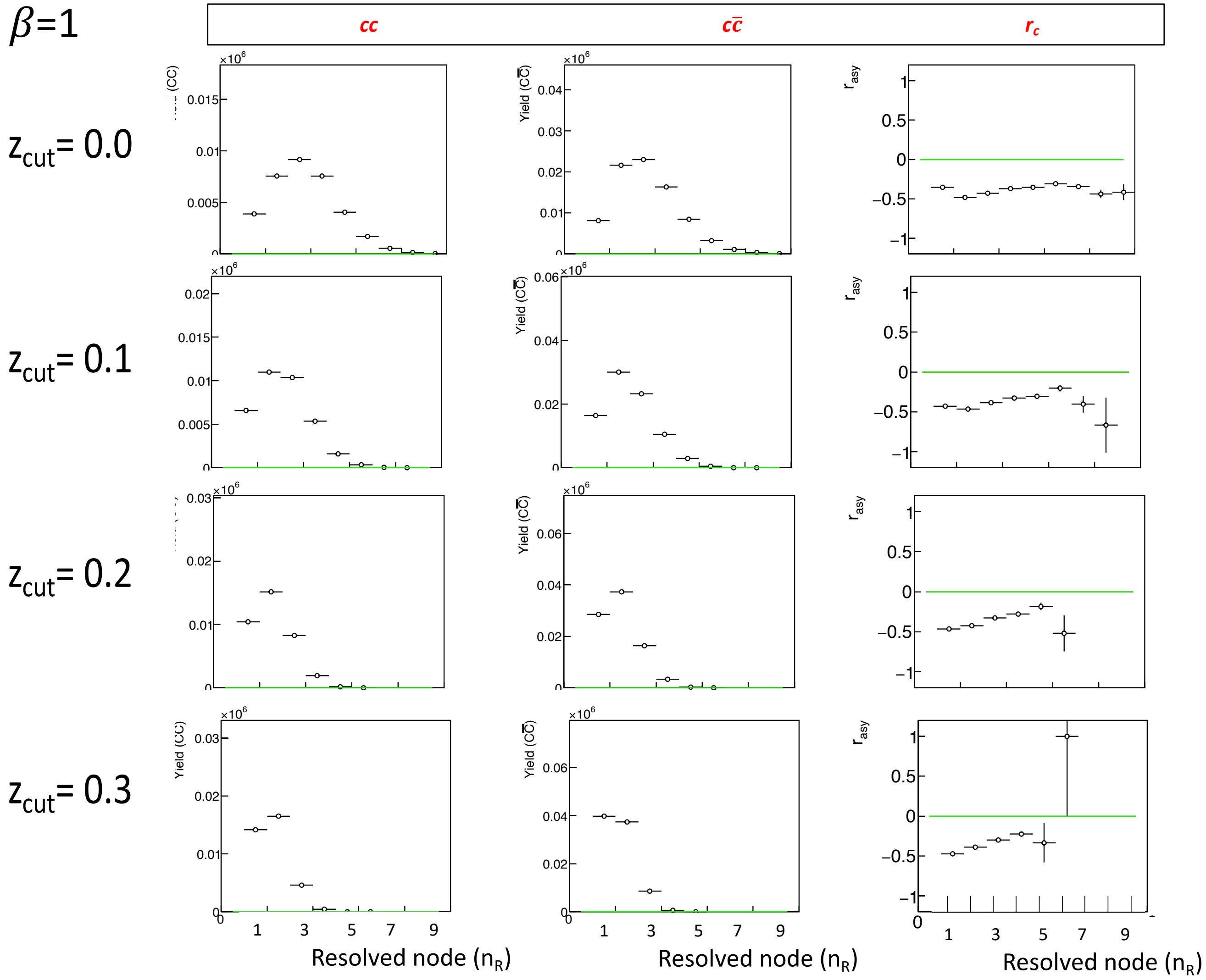
Recursive subjet : β=1, z_{cut}= 0.1



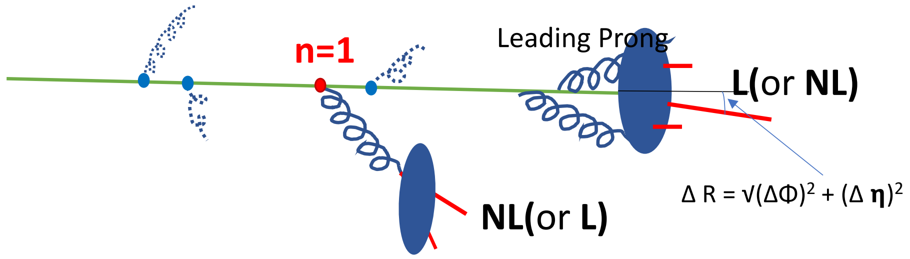
n=1 : wide angle soft radiations

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

Tuning soft drop z_{cut}

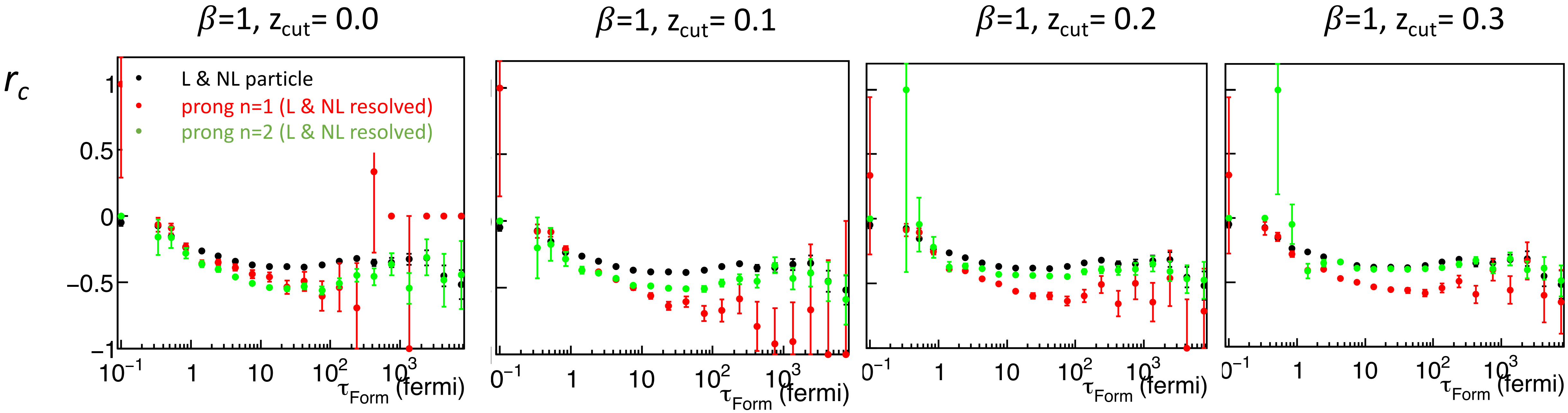


$$z_{12} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}, \qquad z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1}+p_{t,2}}$$



- Different value of z_{cut} rearranging the events in different n_R-class
- Higher z_{cut} in some cases removes some events
- z_{cut}= 0.2 is the place where r_c is monotonic with n_R indicating n_R=1 is correlations is strongest

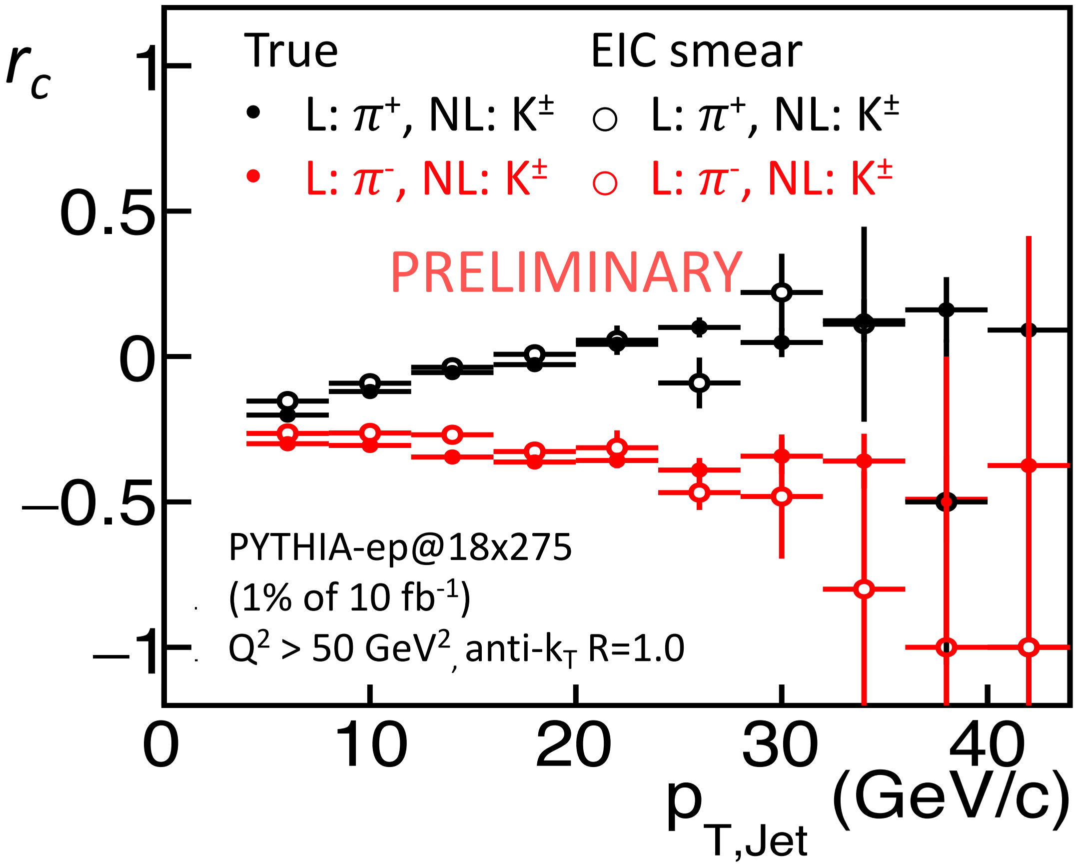
Resolved prong (n_R) and r_C – with τ_{Form}



For z_{cut}= 0.2 the class of events n=1 and n=2 seems to probing two types of strings : one might have evolved with simple (n=1) color connections while the other with relatively complex (n=2) color connections in particular at some region of formation time.

Measurement of flavor tagged r_c

- **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) is already at cutting edge technology
  - Motivate further detector R&D to fulfill the PID requirement



Fragmentation and Jet substructure studies at EIC

- Large dataset with good particle identifications
- Expecting get more insight of string dynamics

H1 and STAR are already making similar measurements

Probing hadronization with flavor correlations of leading particles in jets

Yang-Ting Chien,[1,2,3,*] Abhay Deshpande,[1,2,4,†] Mriganka Mouli Mondal,[1,4,‡] and George Sterman[1,2,4,§]

[1] *Center for Frontiers in Nuclear Science, Stony Brook University, Stony Brook, NY 11794*
[2] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794*
[3] *Physics and Astronomy Department, Georgia State University, Atlanta, GA 30303*
[4] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794*
(Dated: September 29, 2021)

We study nonperturbative flavor correlations between pairs of leading and next-to-leading charged hadrons within jets at the Electron-Ion Collider (EIC). We introduce a new charge correlation ratio observable r_c that distinguishes same- and oppositely-charged pairs. Using Monte Carlo simulations with different event generators, r_c is examined as a function of various kinematic variables for different combinations of hadron species, and the feasibility of such measurements at the EIC is demonstrated. The precision hadronization study we propose will provide new tests of hadronization models and lead to a more quantitative and, perhaps eventually, analytic understanding of nonperturbative QCD dynamics.

appearing arXiv this week

ACKNOWLEDGEMENTS

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Summary

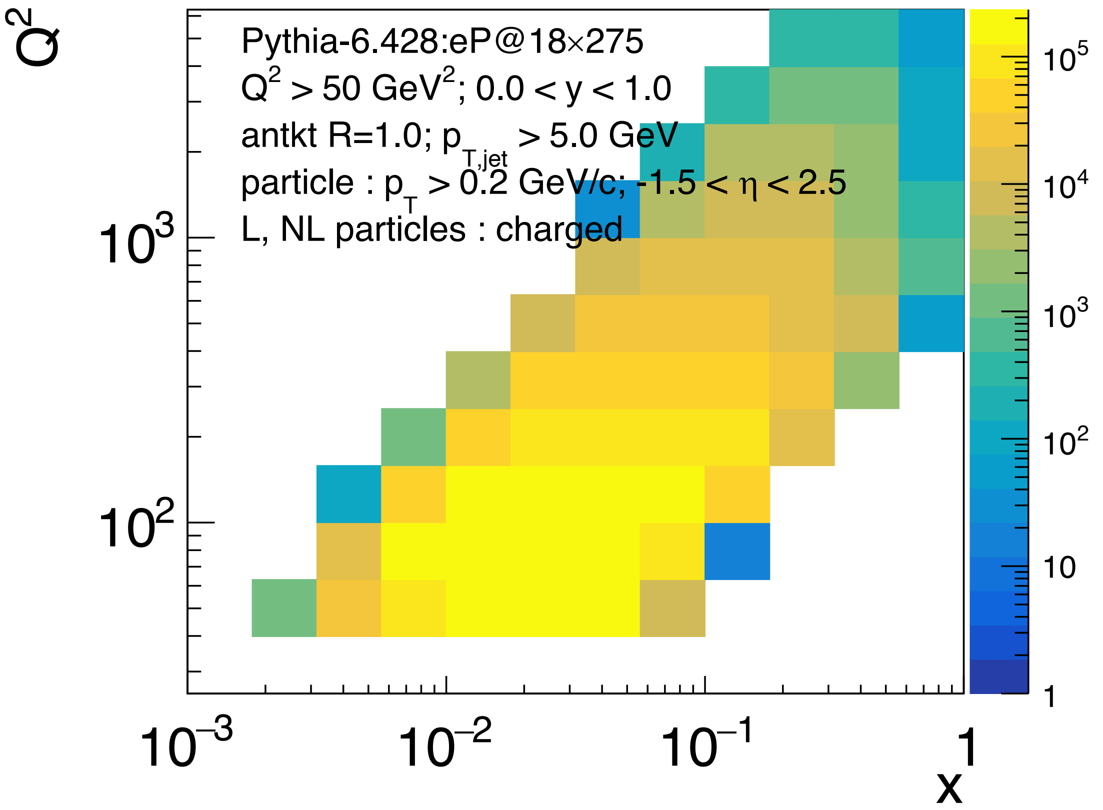
- Hadronization can be studied very precisely at EIC
- A charge-energy correlation observable, $\boldsymbol{r_c}$ is introduced using the leading and next-to-leading particle's charge and kinematic information
- Significant differences in $\boldsymbol{r_c}$ observed for various flavor combinations
- Flavor-tagged data would have significant impact on the knowledge on string fragmentation inspired models
- Understanding $\boldsymbol{r_c}$ with prongs within C/A declustering tree is an alternative way to study hadronization
- Pythia shows distinct features of $\boldsymbol{r_c}$ with formation time for different nodes. These need to be understood and measured from data
- It is essential to have particle identification in wide momentum range at EIC to realize the full potential of flavor-tagged measurements

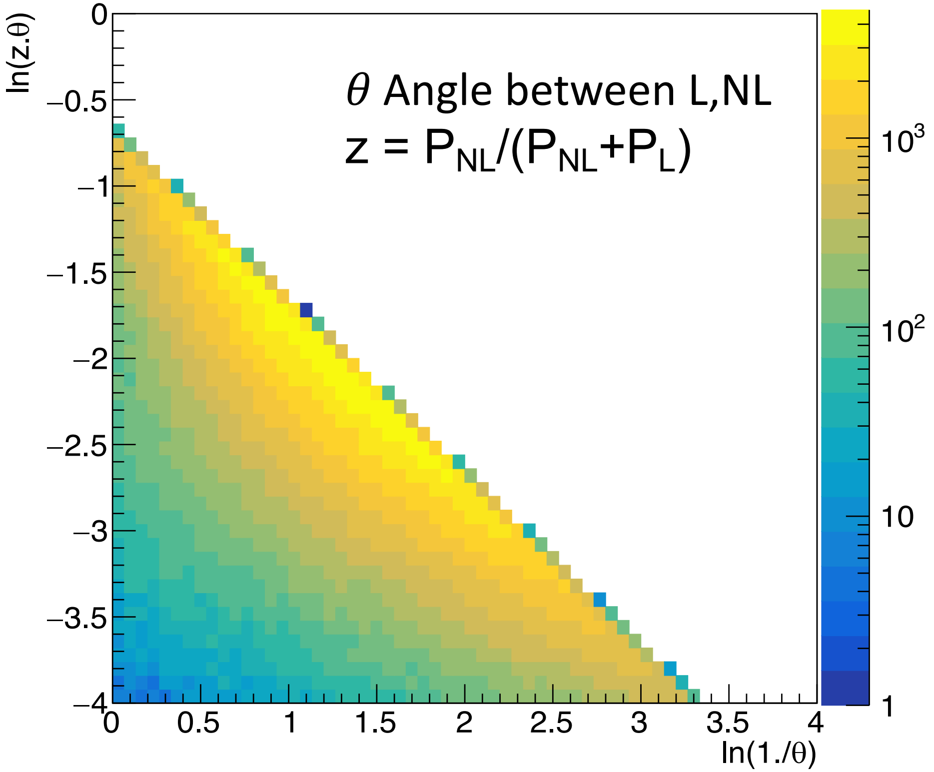
Backup

Event acceptance in x-Q^2

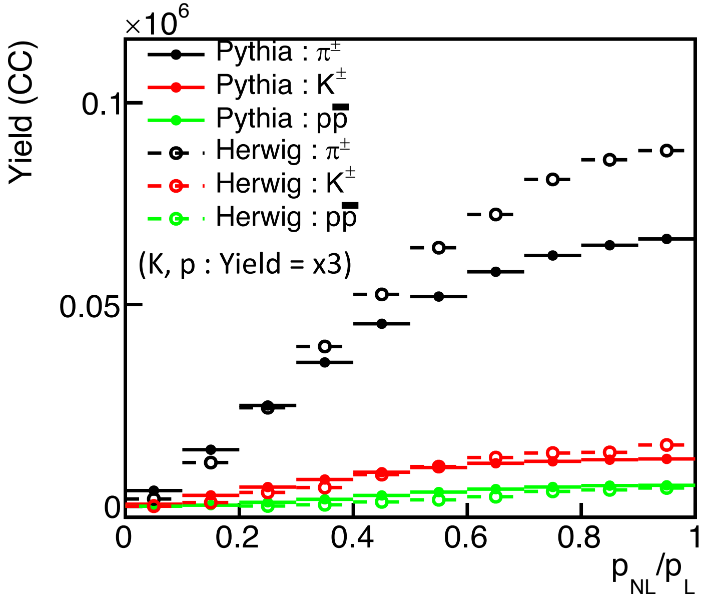
Event Generation : Pythia 6.428
Herwig 7.1.5
$Q^2 > 50$ GeV

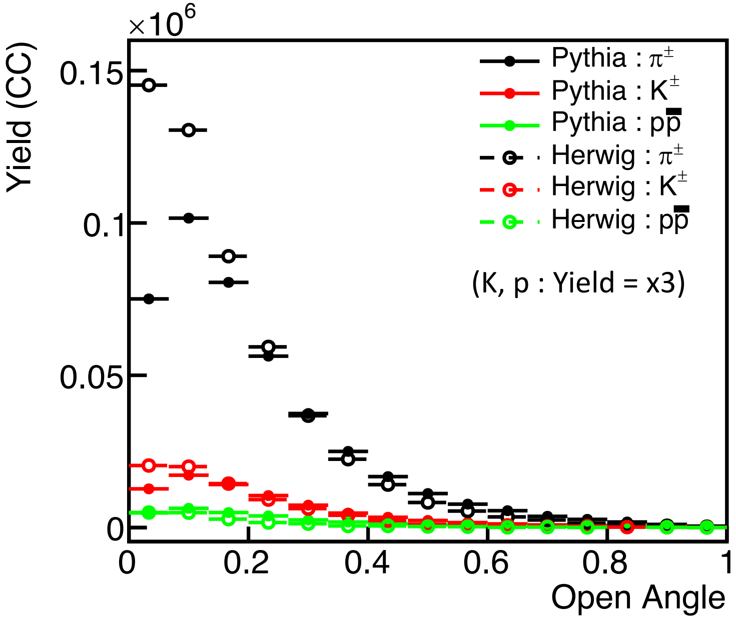
Jets : anti-kt R = 1.0
Jet $p_T > 5$GeV/c
Jet |eta| < 2.8
particle $p_T > 0.2$GeV/c
particle |eta| < 3.5

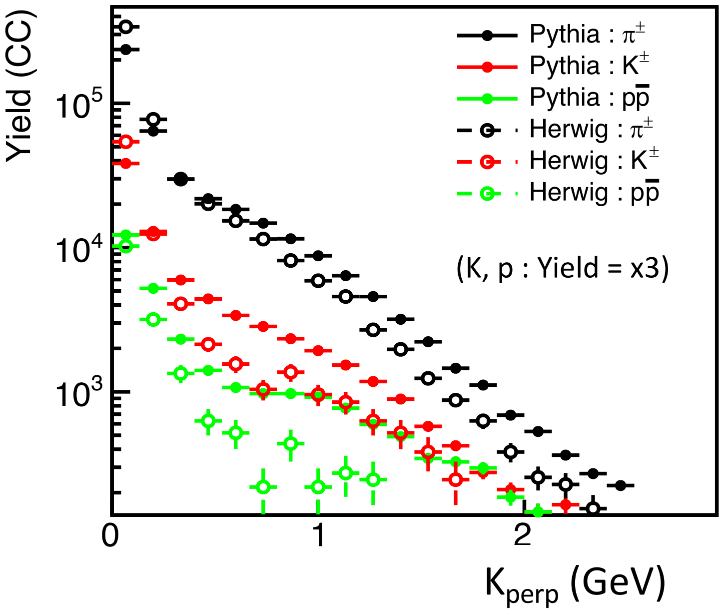




L NL kinematic distribution



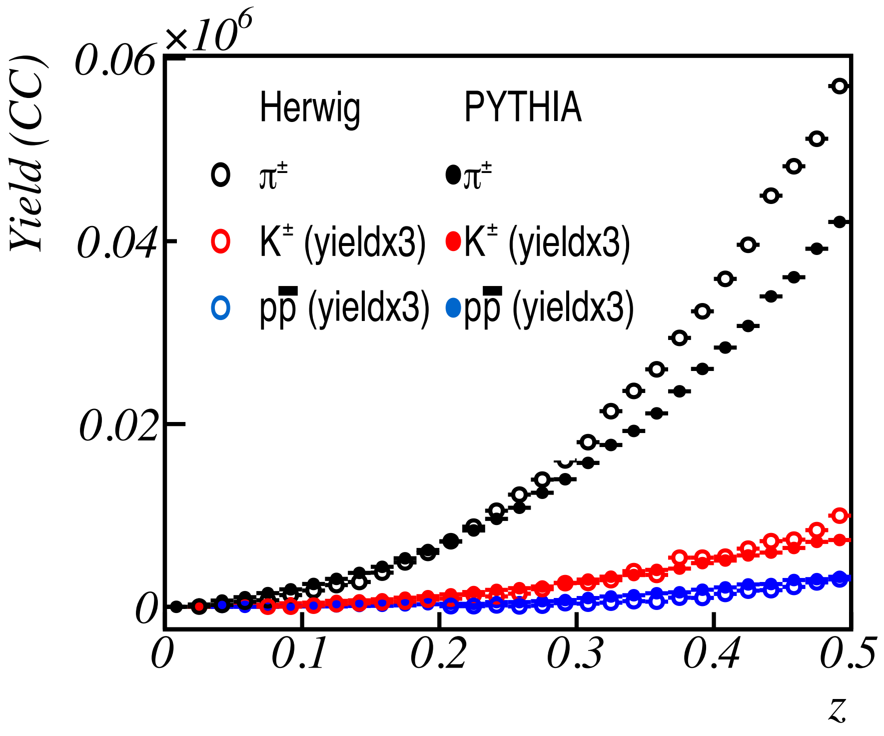


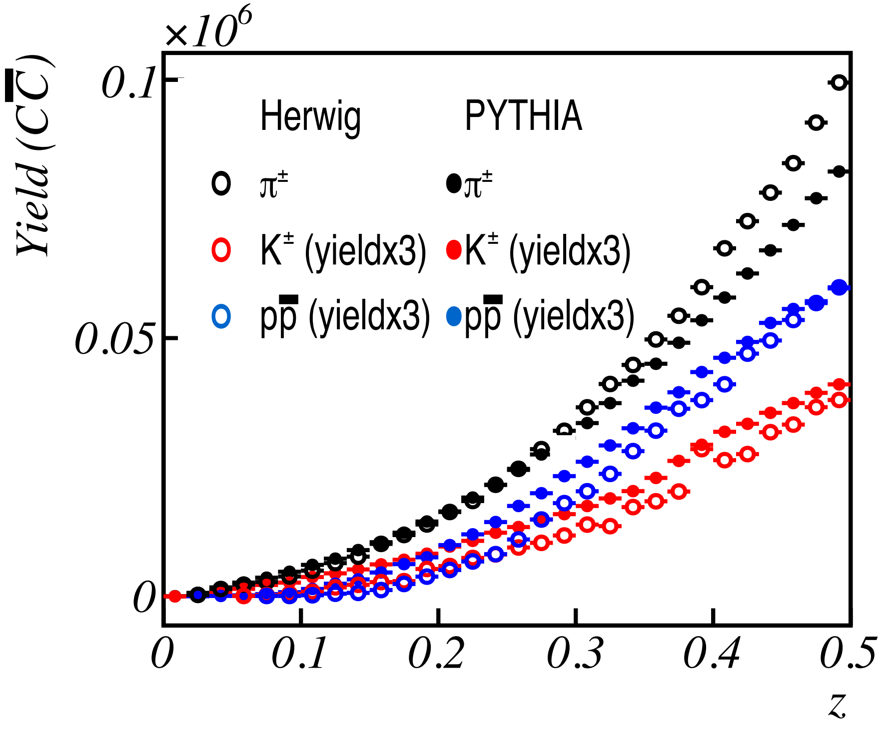


Herwig has more instances when L and NL momentum share nearly equal momentum

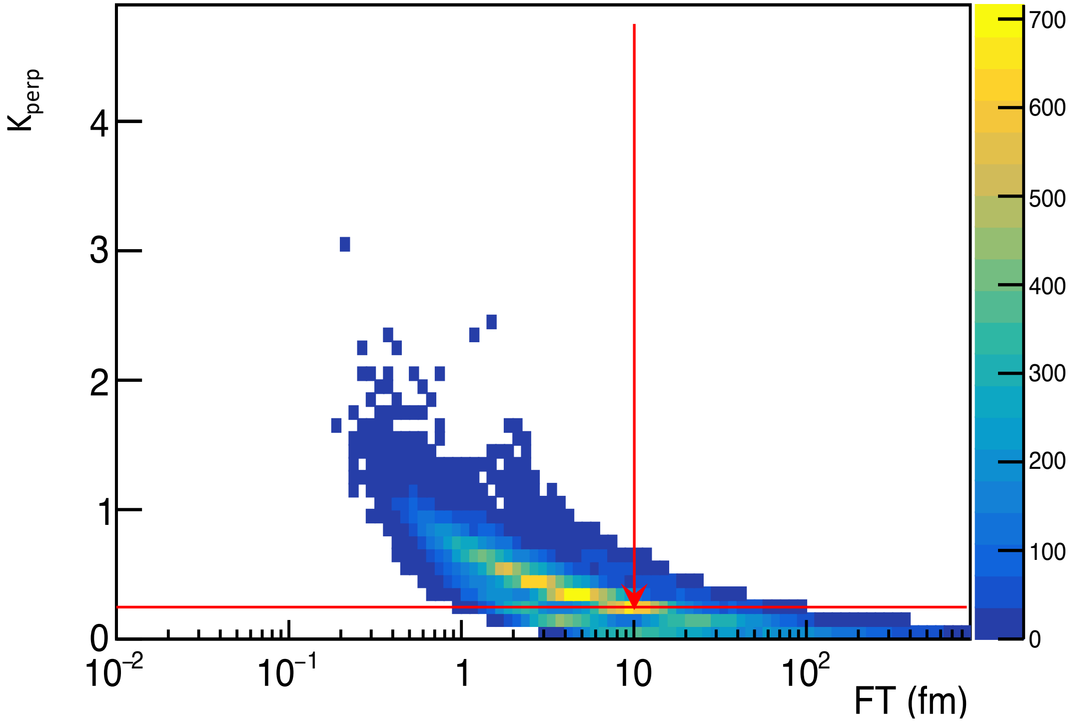
More events in HERWIG has small opening angle between L & NL particles

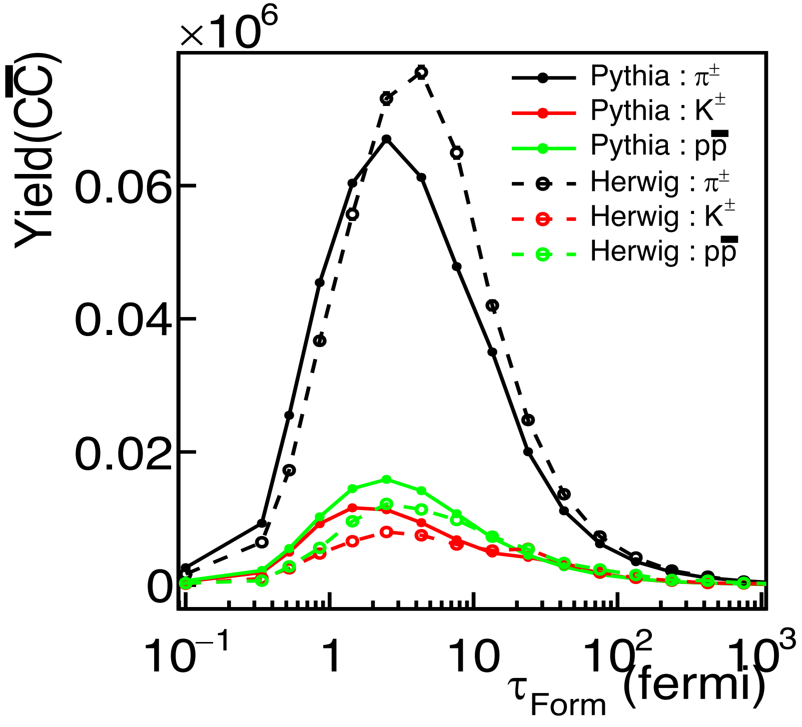
L NL kinematic distribution





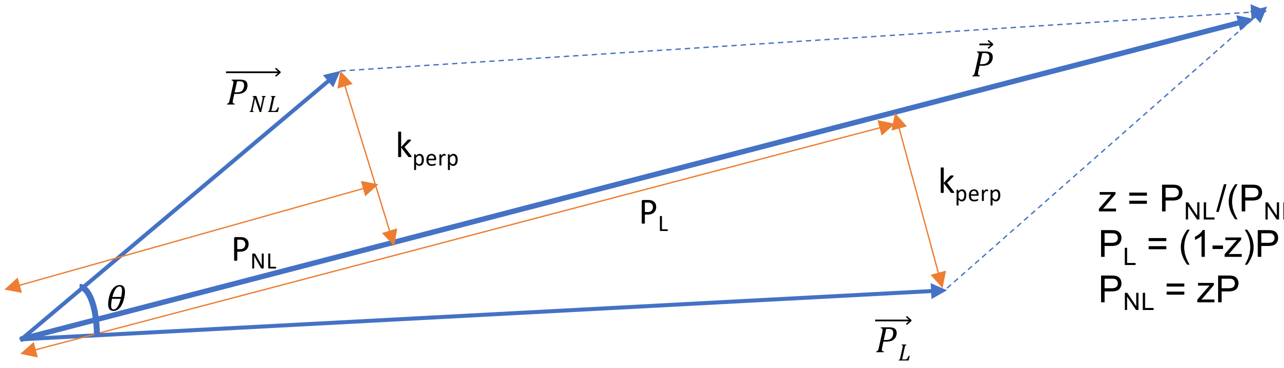
Formation time





$\boldsymbol{\tau_{form}}$ **< 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



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

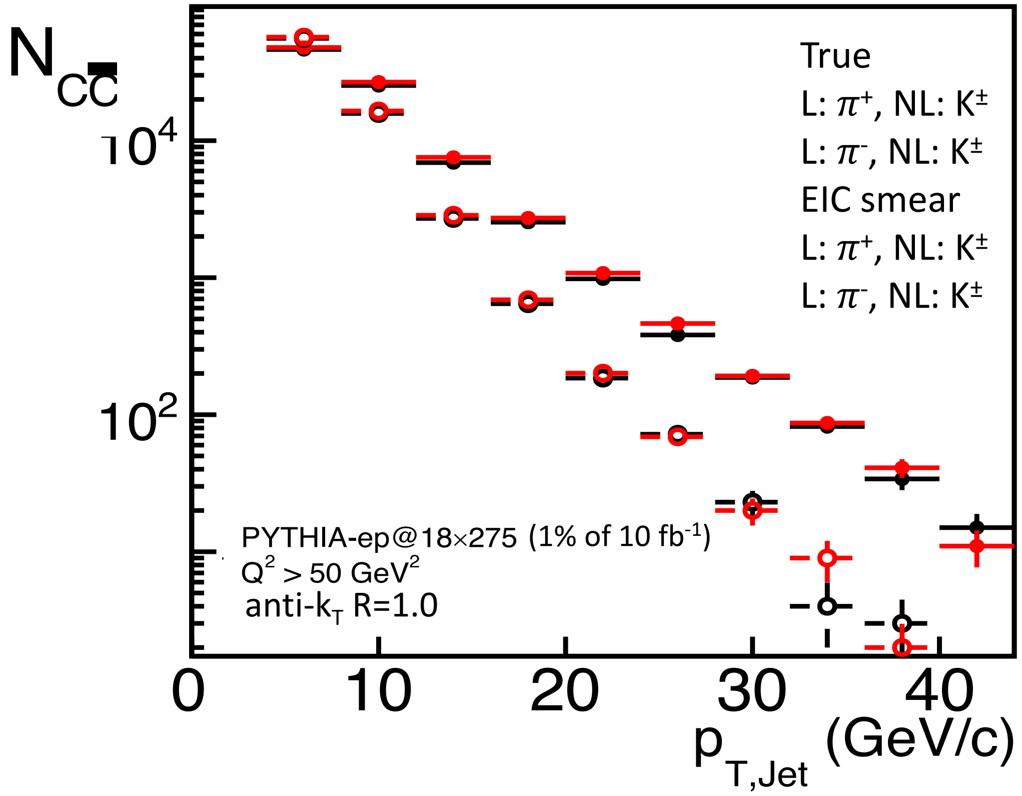
Formation time = [2z(1-z) P] / k_{perp}^2

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"

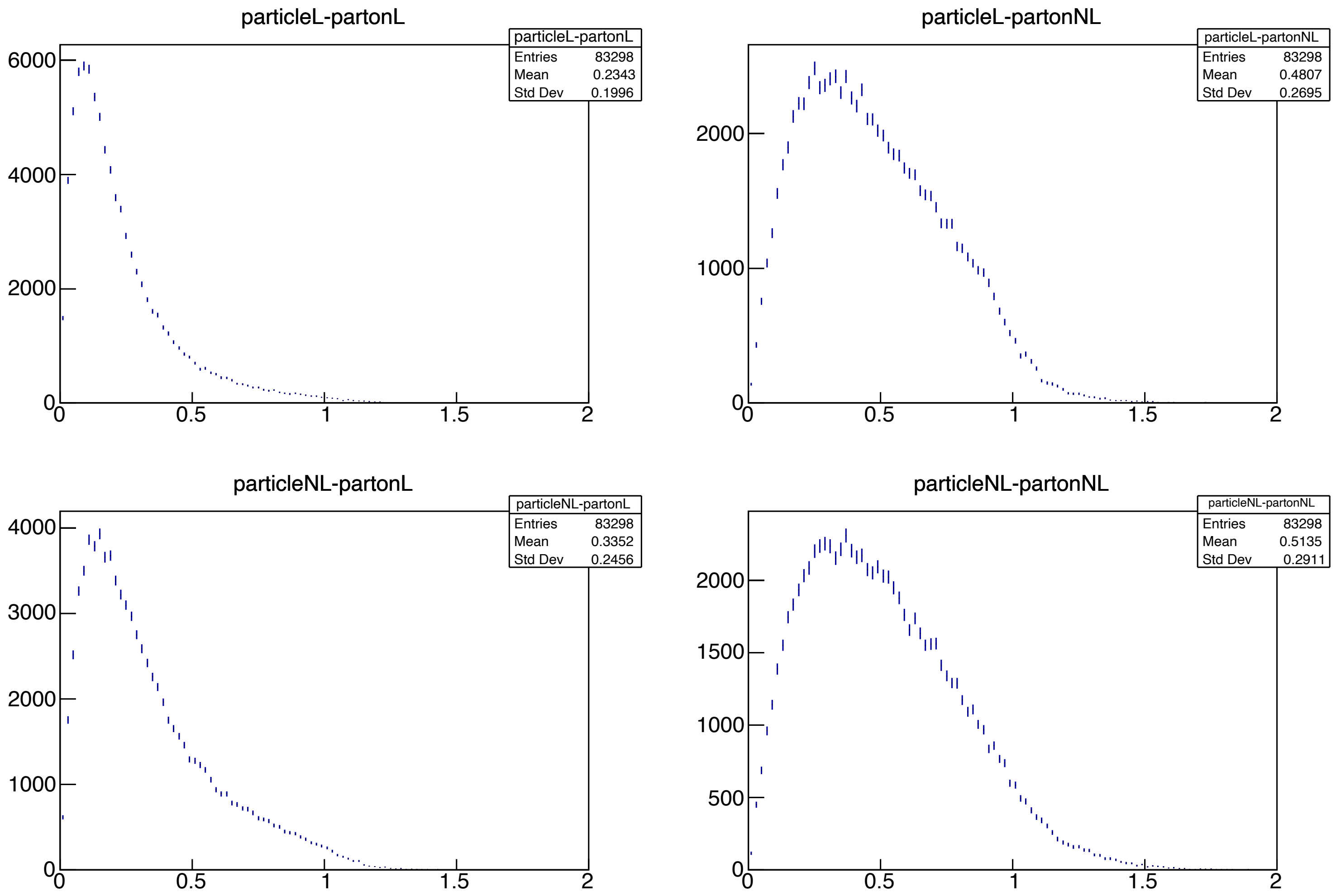
Impact on EIC detector design

arXiv:2103.05419:
EIC Yellow Report

η – range PID limit	Momentum cut (GeV/c²)
-3.5 to -1.0	7
-1.0 to 1.0	10 (Used DIRC parameterization)
1.0 to 2.0	8
2.0 to 3.0	25
3.0 to 3.5	45



L and NL correlations with the first split prongs



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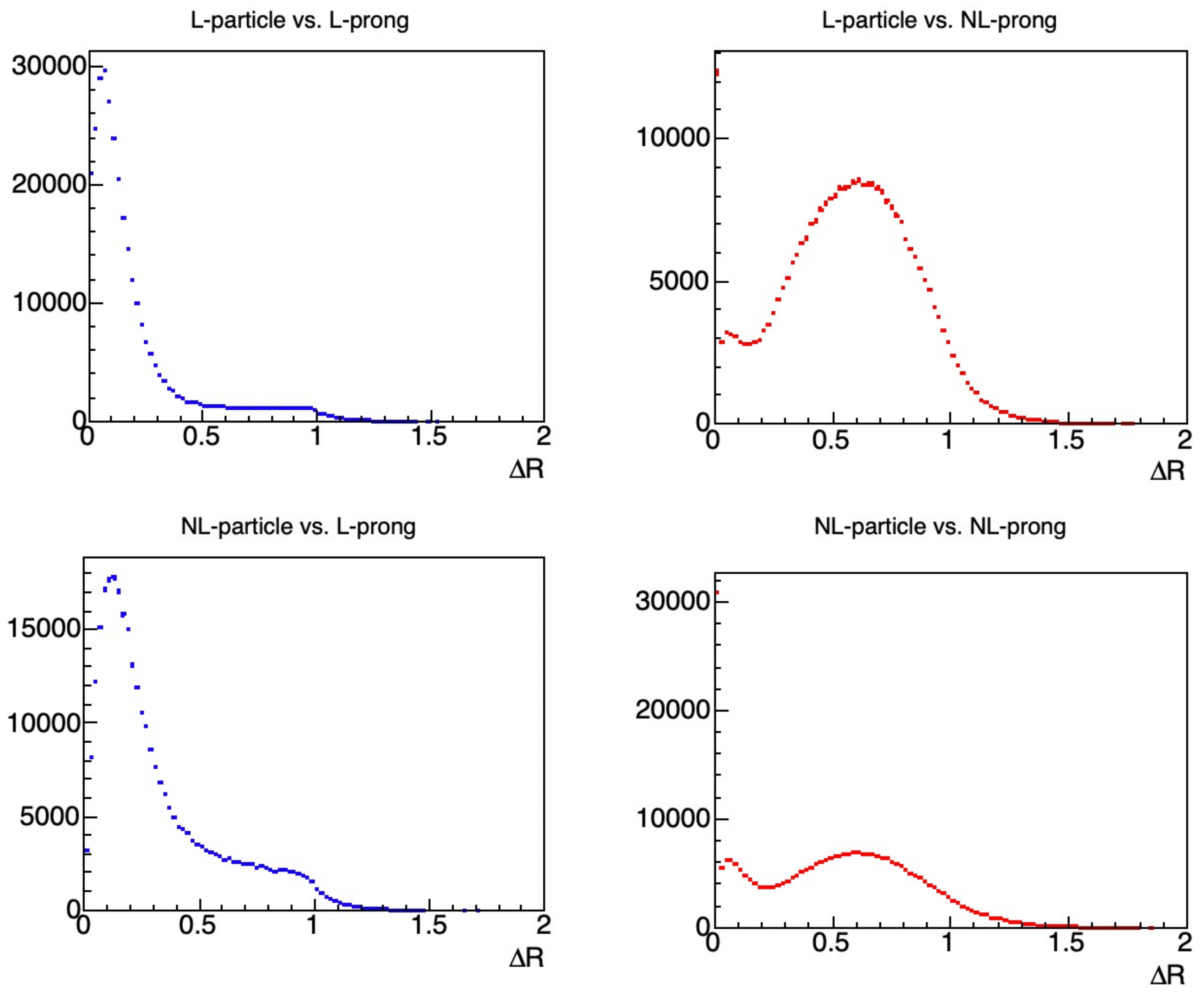
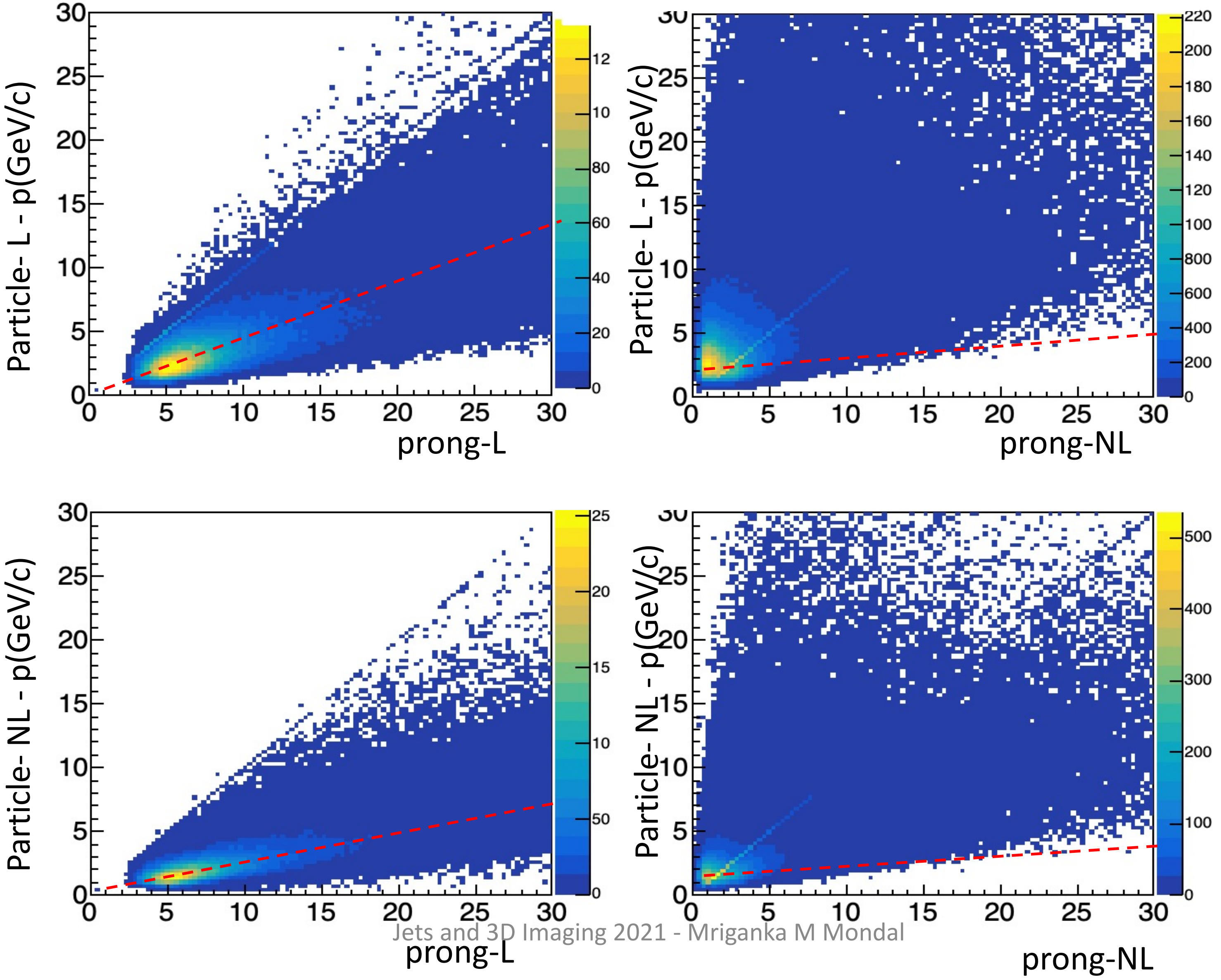
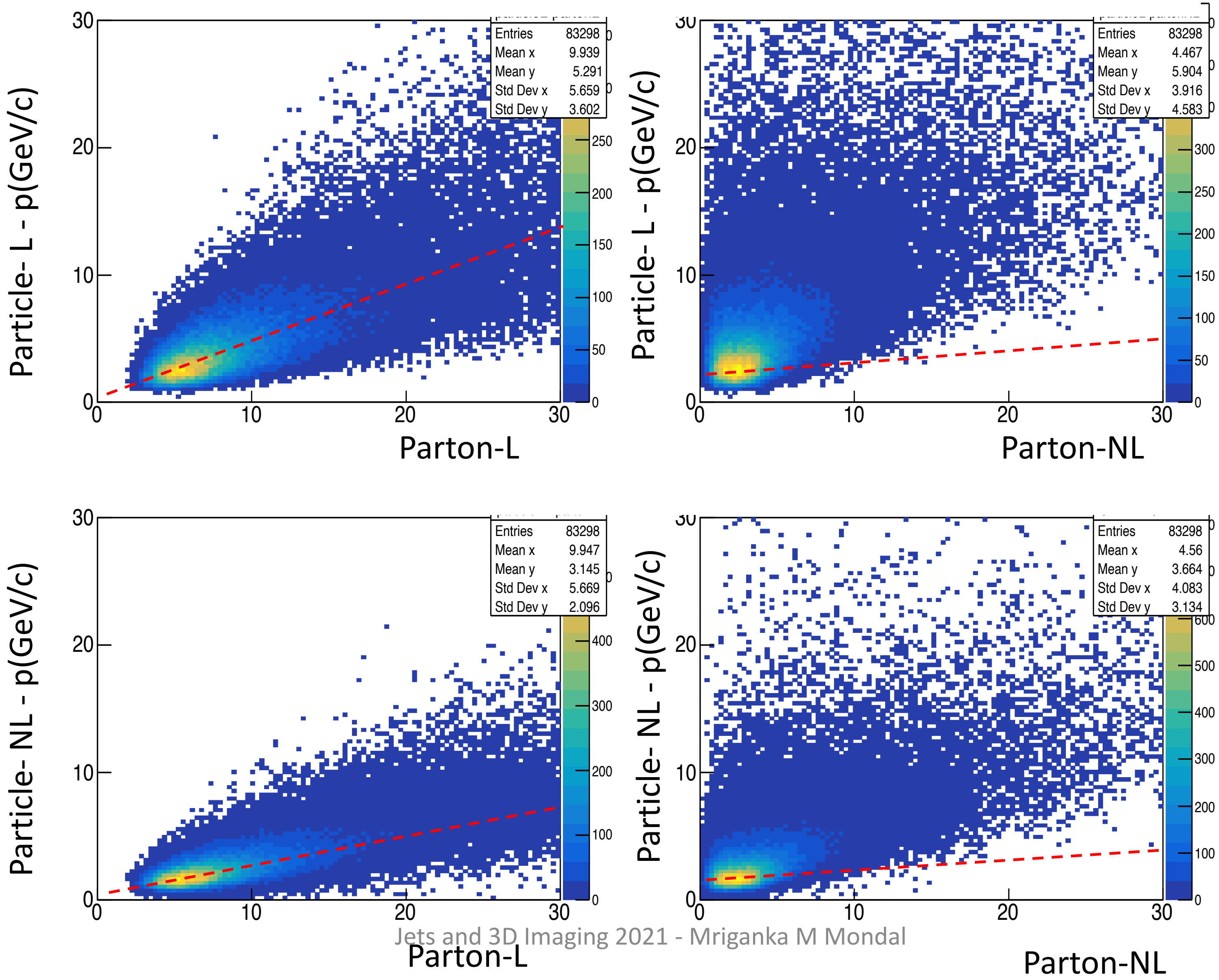
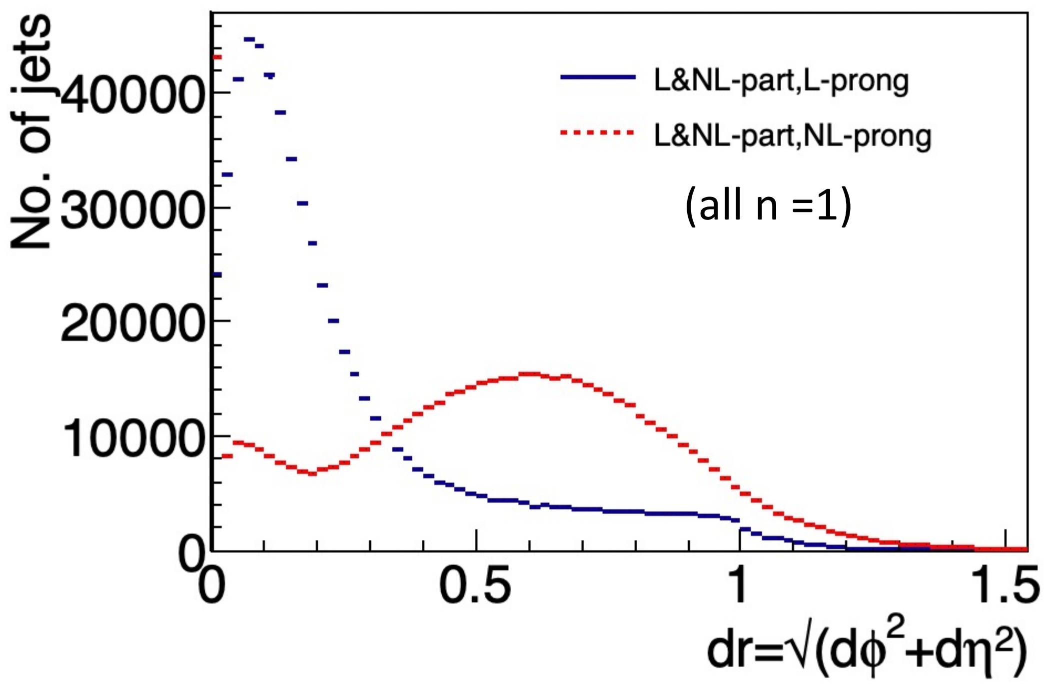
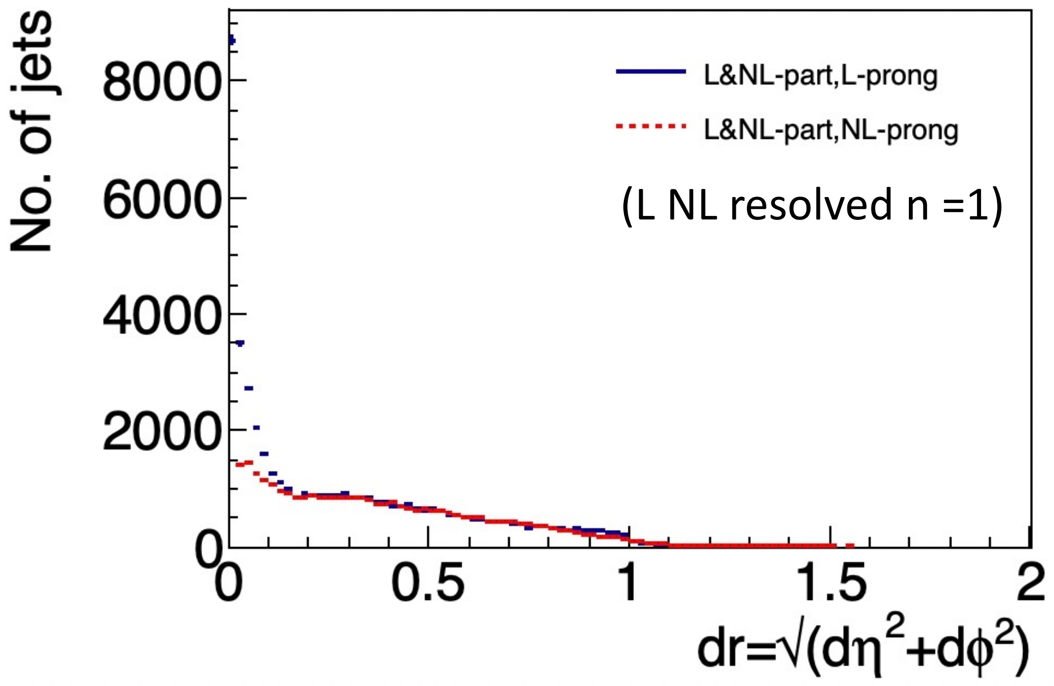



Particle- L - p(GeV/c)
prong-L
Particle- L - p(GeV/c)
prong-NL
Particle- NL - p(GeV/c)
prong-L
Particle- NL - p(GeV/c)
prong-NL


Particle- L - p(GeV/c)
Parton-L
Entries 83298
Mean x 9.939
Mean y 5.291
Std Dev x 5.659
Std Dev y 3.602
Particle- L - p(GeV/c)
Parton-NL
Entries 83298
Mean x 4.467
Mean y 5.904
Std Dev x 3.916
Std Dev y 4.583
Particle- NL - p(GeV/c)
Parton-L
Entries 83298
Mean x 9.947
Mean y 3.145
Std Dev x 5.669
Std Dev y 2.096
Particle- NL - p(GeV/c)
Parton-NL
Entries 83298
Mean x 4.56
Mean y 3.664
Std Dev x 4.083
Std Dev y 3.134

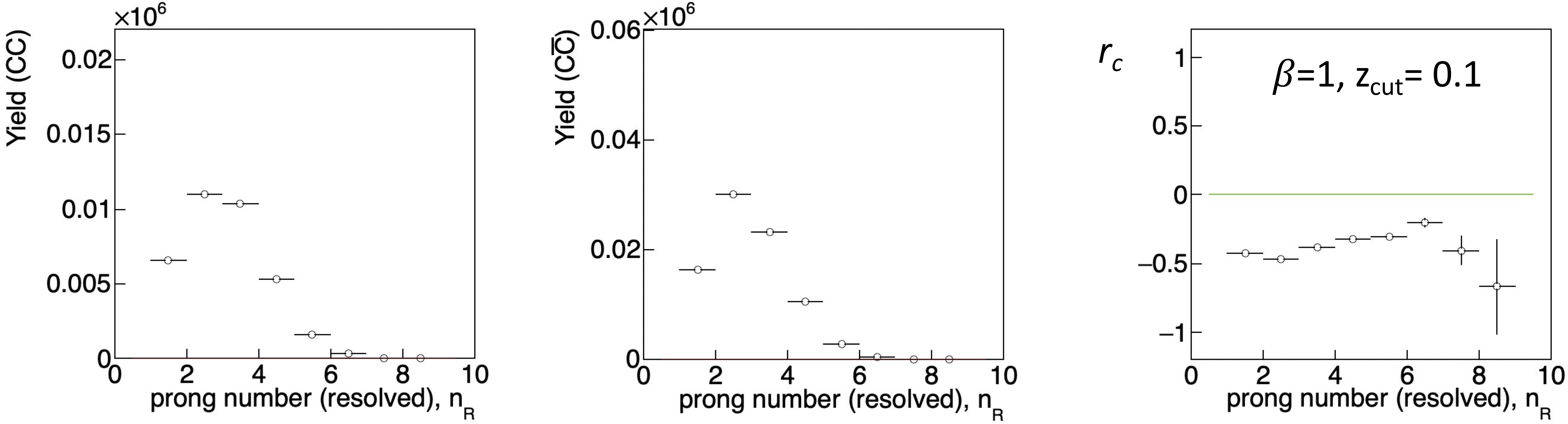
L and NL correlations with the first split prongs





- L, NL particles are strongly correlated with the harder prong in the first split
- However, some “resolved” prongs have strong correlations with a wide tail
- L NL particle are special : originates from the same string or cluster fragmentation which is of nonpertubative in origin

Resolved prong (n_R) and r_C



- For β=1, z_{cut}= 0.1 10% (CC) and 30%($C\bar{C}$) pairs ger resolved in first prong
- The average r_c changes changes sightly depending on prong numbers where it get resolved

z = 1/2 is favored due to Lorentz boost

z = 1/2 is disfavored (soft collinear emissions)