Momentum and charge correlations within jets : a new observable to probe nonperturbative aspects of jet evolution

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

Stony Brook University

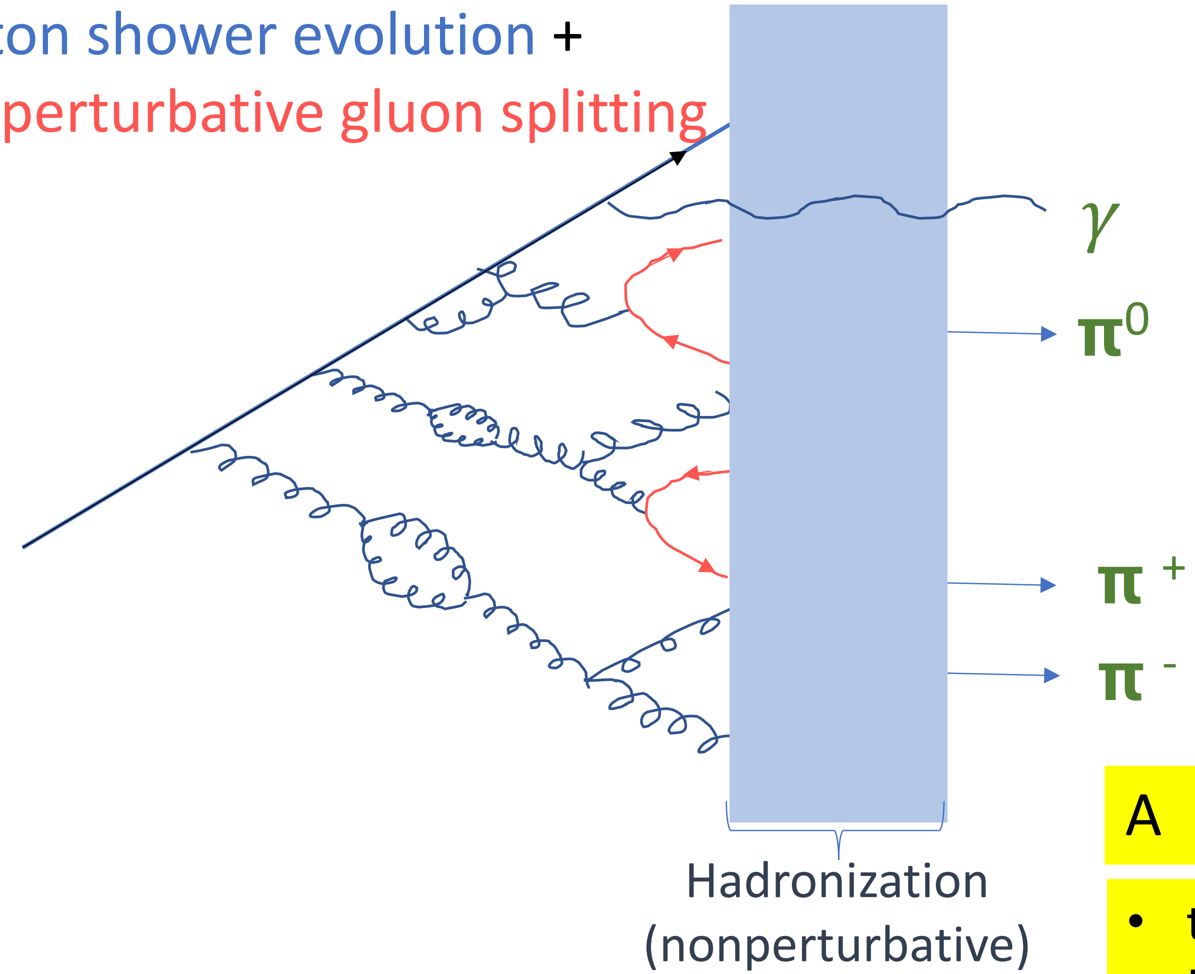
Center for Frontiers in Nuclear Science

Outline

- New charge-energy correlation
- Flavor dependence with simulations for EIC
- Charge correlations in recursive soft drop structure
- Summary

Jets and access to the dynamics of hadronization

Parton shower evolution +
nonperturbative gluon splitting



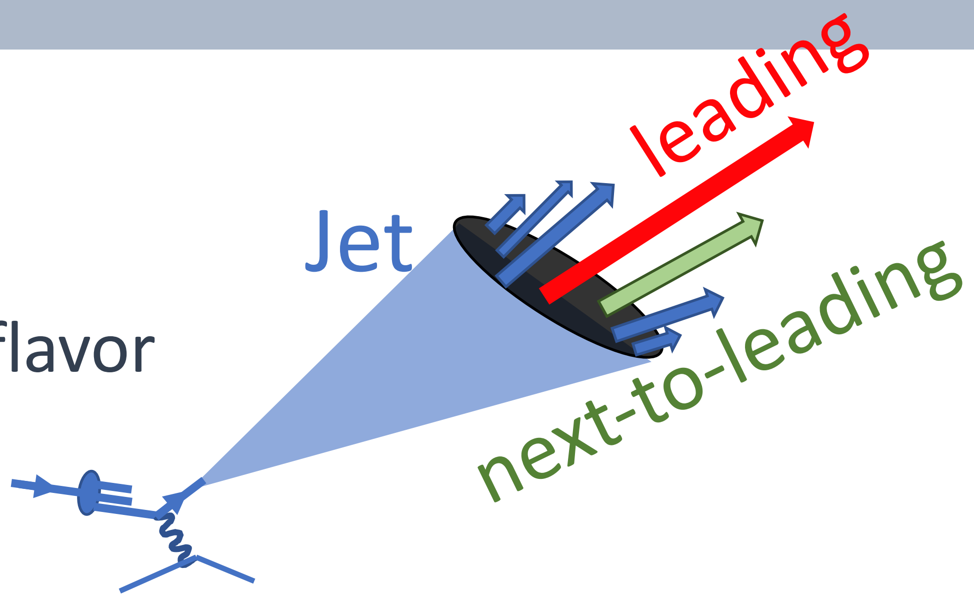
Dynamics of hadronization can be studied through correlations among particles in a jet

A unique detailed way of study hadronization

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

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

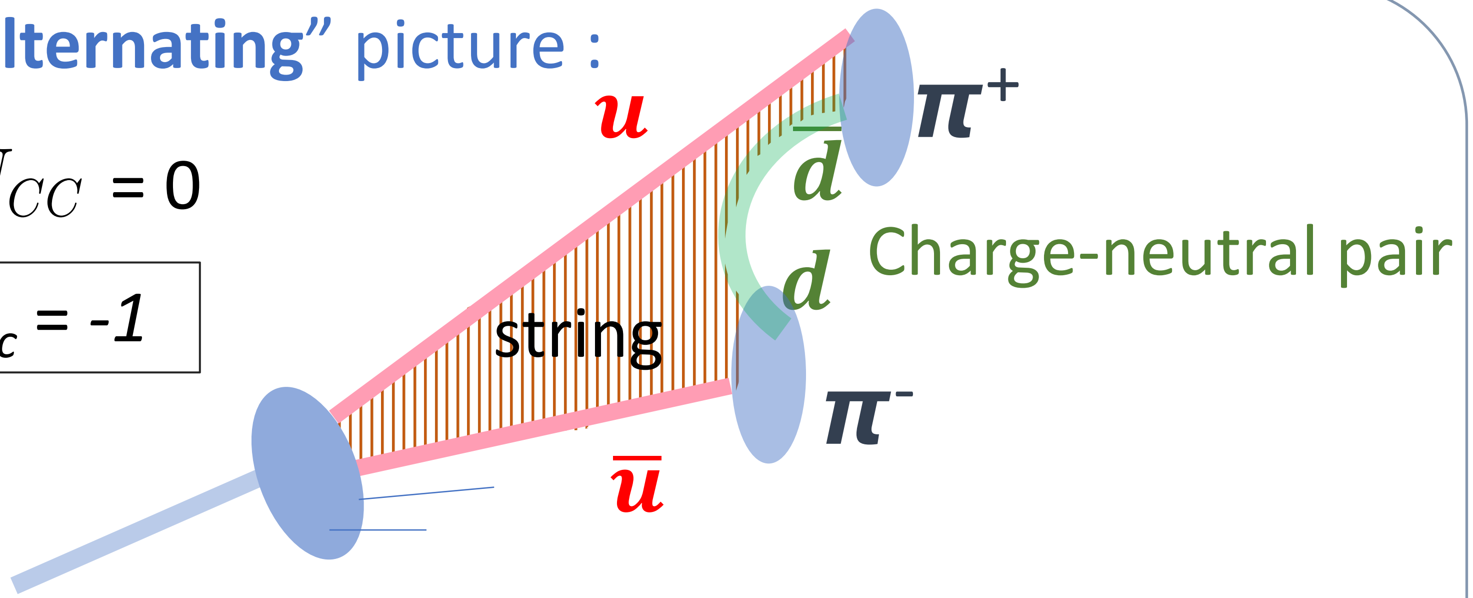
A ***new observable*** with momentum, charge and flavor of leading and next-to-leading particles

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

PYTHIA 6.4 Physics and Manual
Torbjorn Sjostrand, Stephen Mrenna, Peter Skand JHEP 0605:026,2006

Herwig++ Physics and Manual
M. Bhat, *et al.*, Eur.Phys.J.C58:639–707,2008

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

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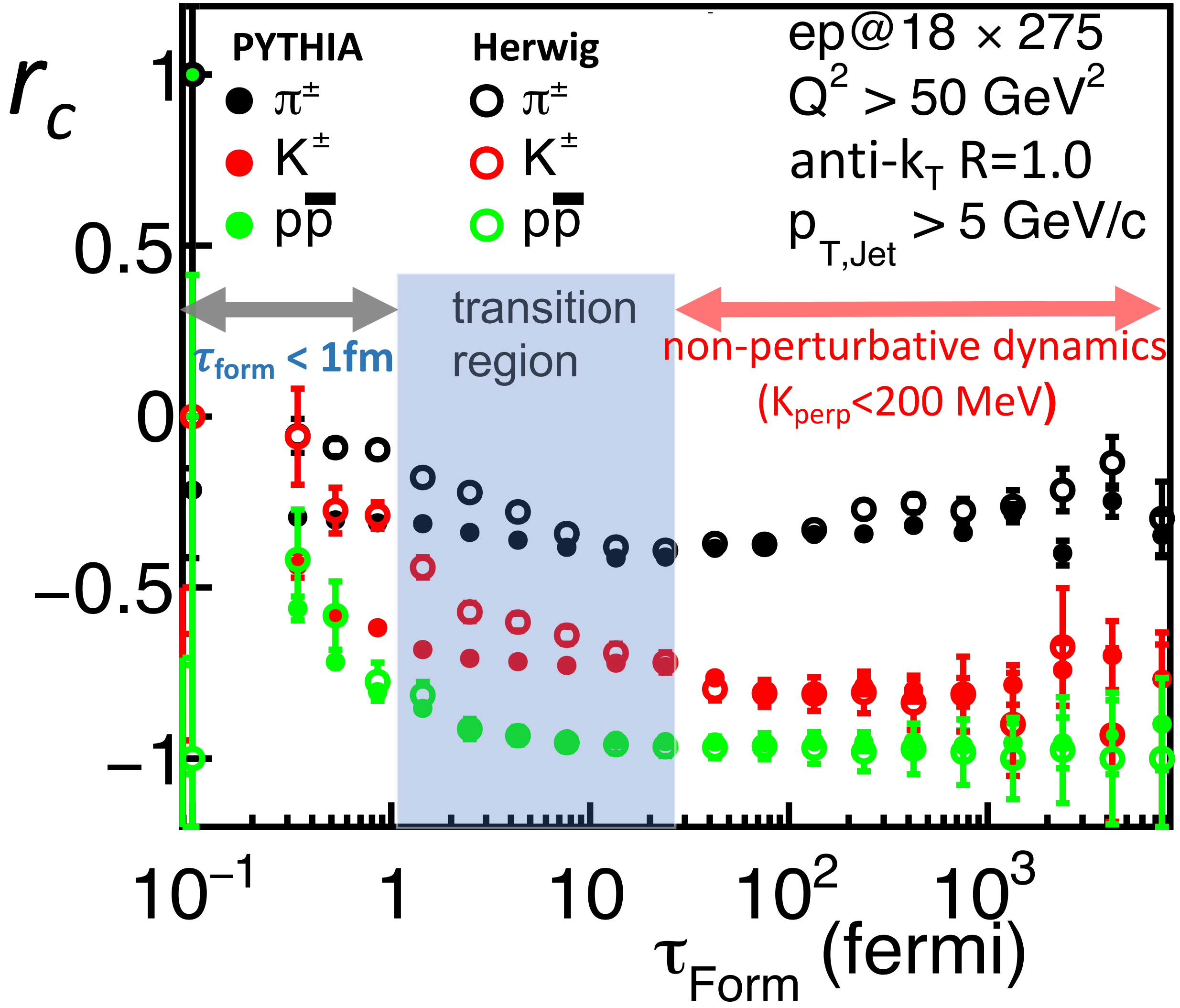
PYTHIA and Herwig has different models of hadronization

Charge-energy correlation with formation time



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

z : momentum fraction of NL particle

k_{perp}: Relative transverse momentum between L & NL

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

The Observable with **"Formation time"**

Charge-energy correlation with flavor tagging

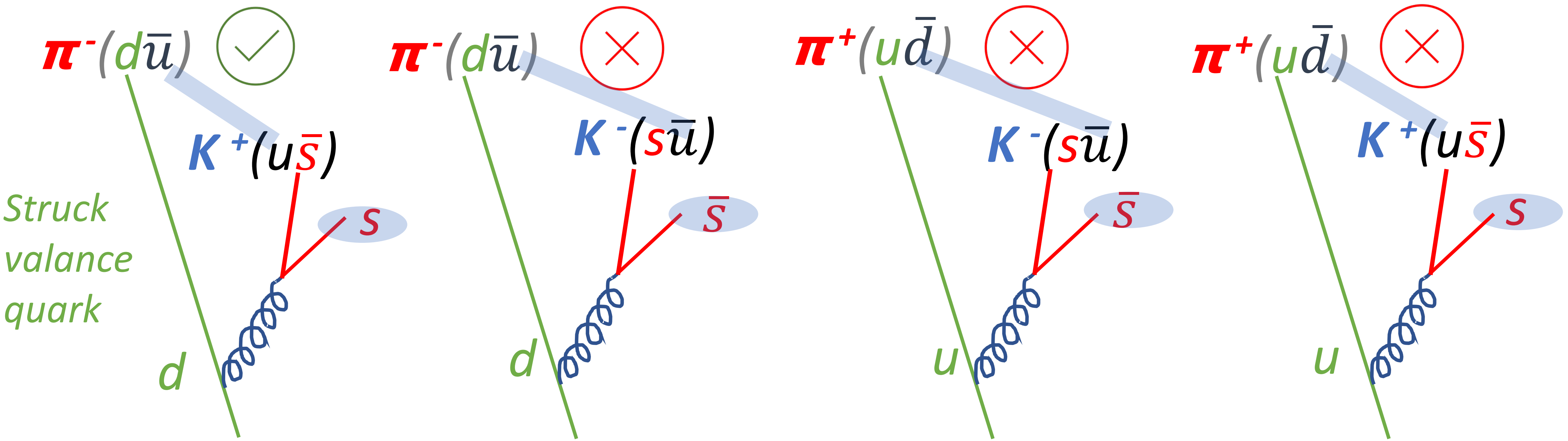
In general, $\boldsymbol{r_c}$ shows strong flavor dependence and we explore further the utility of **strange flavor tagging :**

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

strange flavor tagging

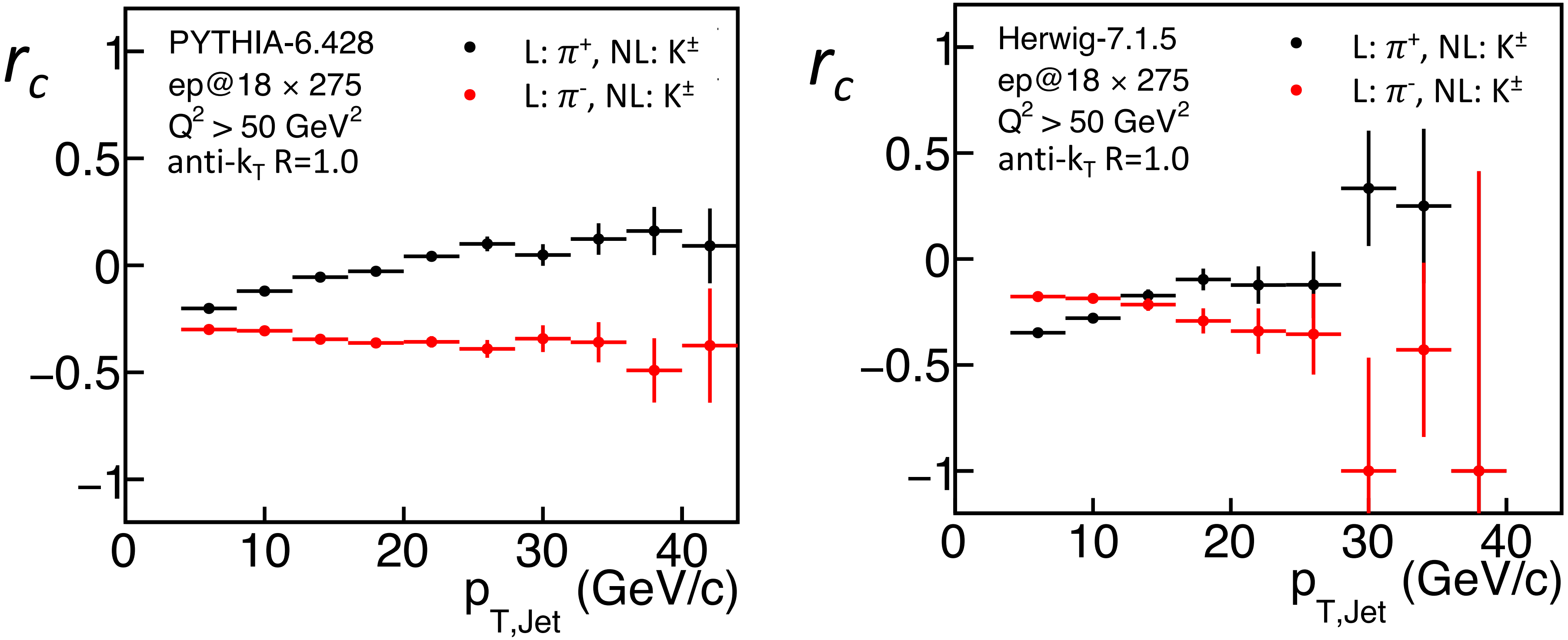
Flavor correlations



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



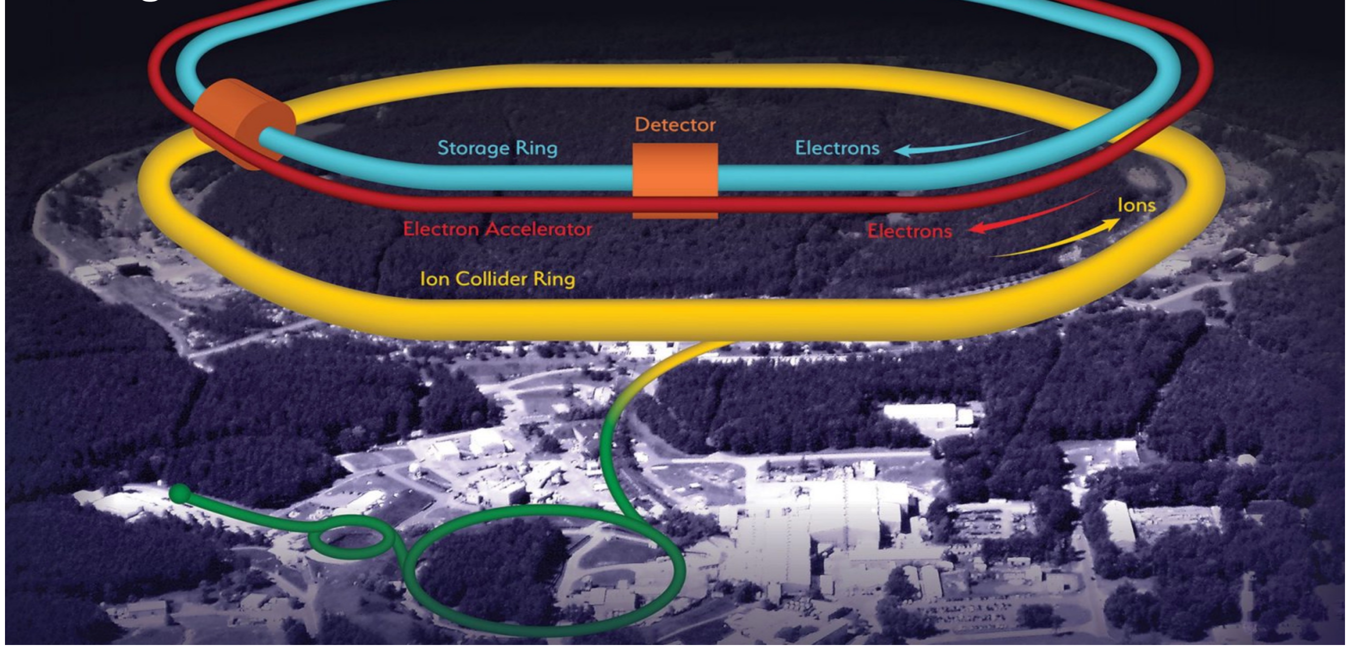
$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$

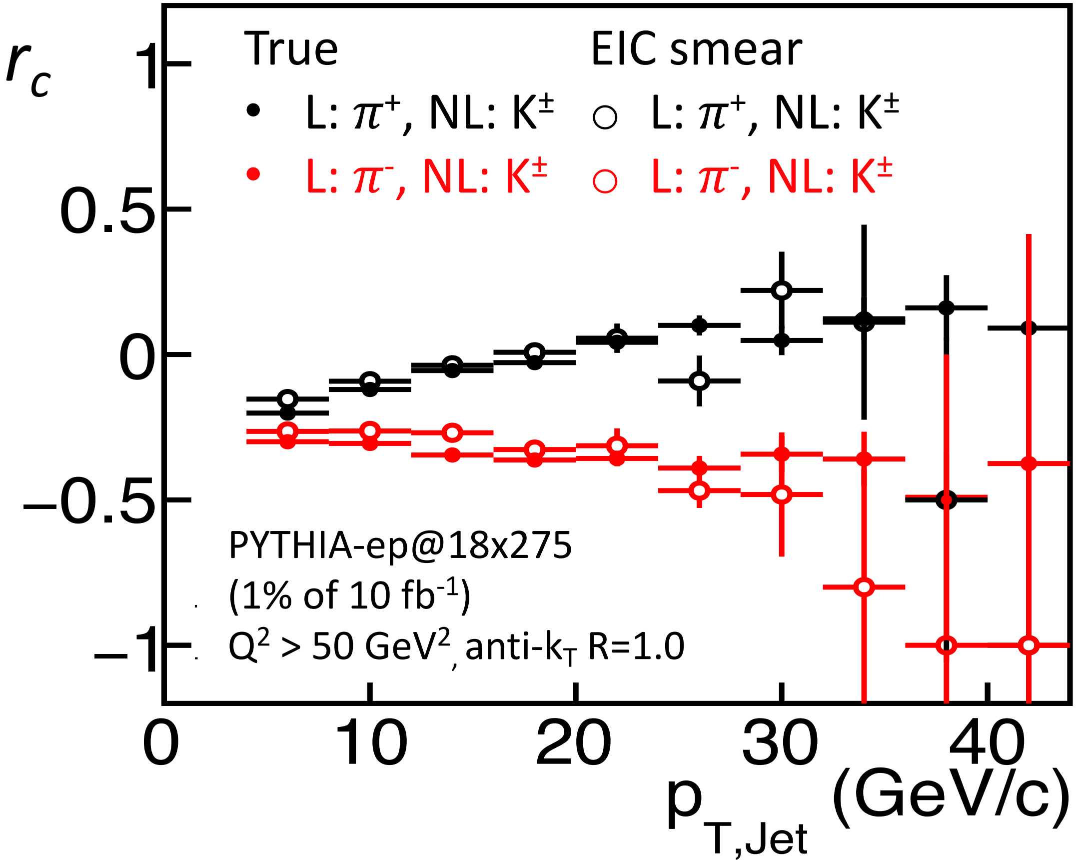
- Correlations are much stronger for $\pi^- K^\pm$ than for $\pi^+ K^\pm$ in PYTHIA
- As p_T increases $\pi^+ K^\pm$ correlations weakens whereas $\pi^- K^\pm$ strengthens
- Significant difference between PYTHIA and Herwig

EIC : Electron Ion Collider

arXiv:2103.05419 EIC Yellow Report

The new machine planned to operate at Brookhaven National Lab during 2032+





LHC, LEP, ILC : can also make such interesting measurements

EIC can perform such measurement precisely and H1 and STAR data are being explored

Subjet structure

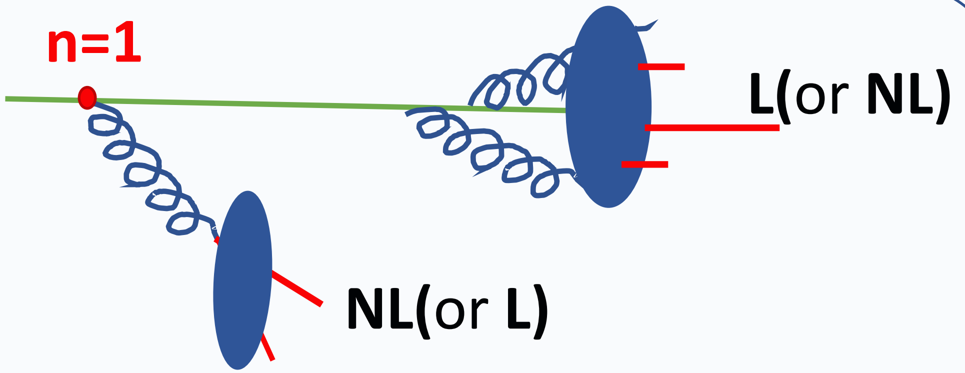
- Significant literature on jet substructure and grooming techniques are available.
- We used some of the available techniques.

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

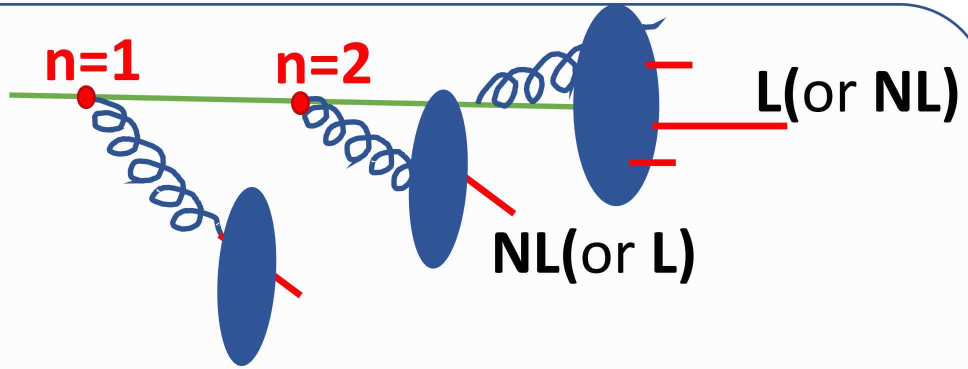
Recursive Soft Drop
Frédéric A. Dreyer, Lina Necib, Gregory Soyez, Jesse Thaler
JHEP06(2018)093

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

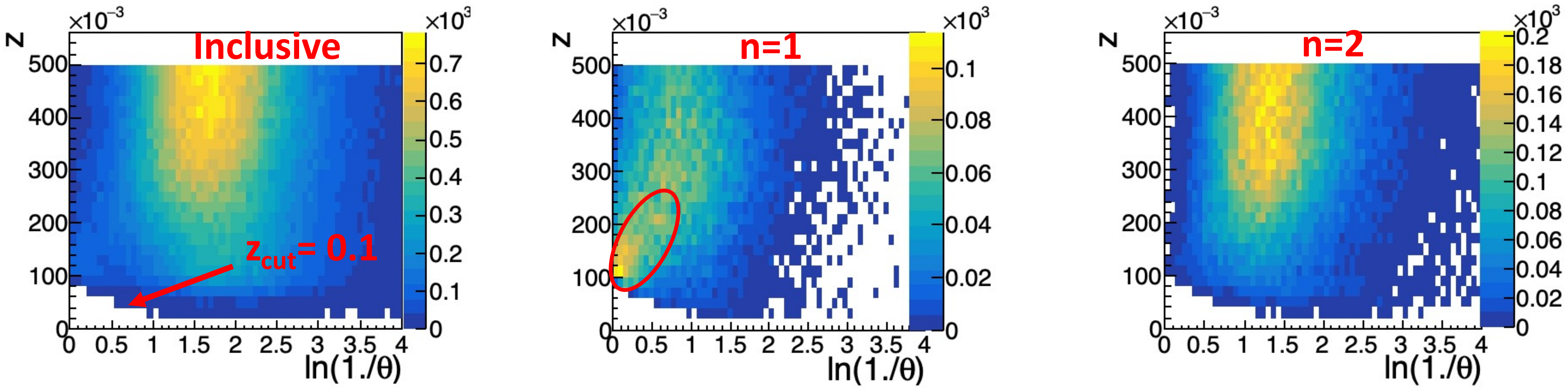
$$z_{12} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta} , \qquad z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

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

Kinematic region for various resolved prongs

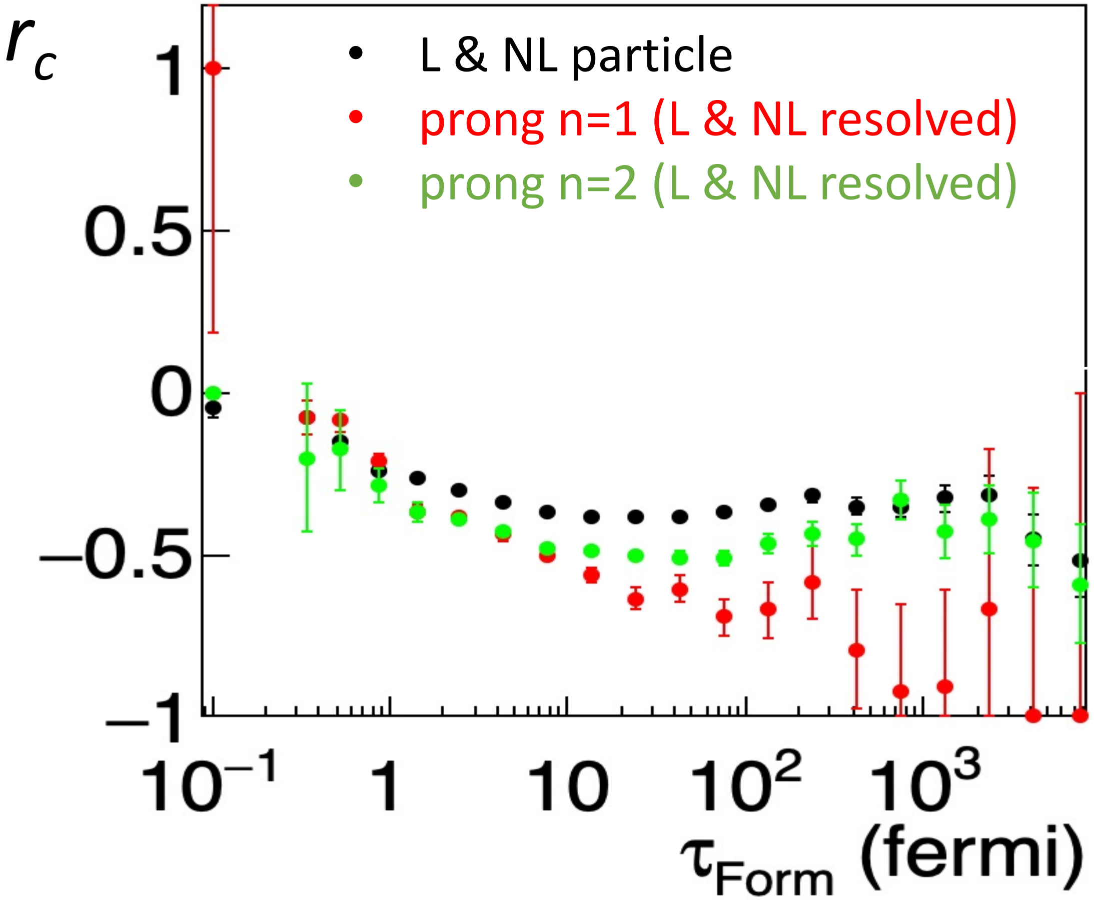
(PYTHIA-6.428) ep@ 18x275, Q^2 > 50 GeV/c, anti-kt R=1.0, $p_{T,Jet}$ > 5 GeV/c

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

L and NL particle and prong correlations



- Pythia shows distinct features of r_c with $\tau_{Form.}$ (data and theoretical input are essential)

Summary

- Hadronization can be studied very precisely at EIC (also LHC, LEP, ILC,…)
- A new 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
- It is essential to have particle identification in wide momentum range at EIC to realize the full potential of flavor-tagged measurements

- 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

Original Slides

Connecting jet substructure to hadronization at the EIC

Mriganka Mouli Mondal
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- Jets and access to the dynamics of hadronization
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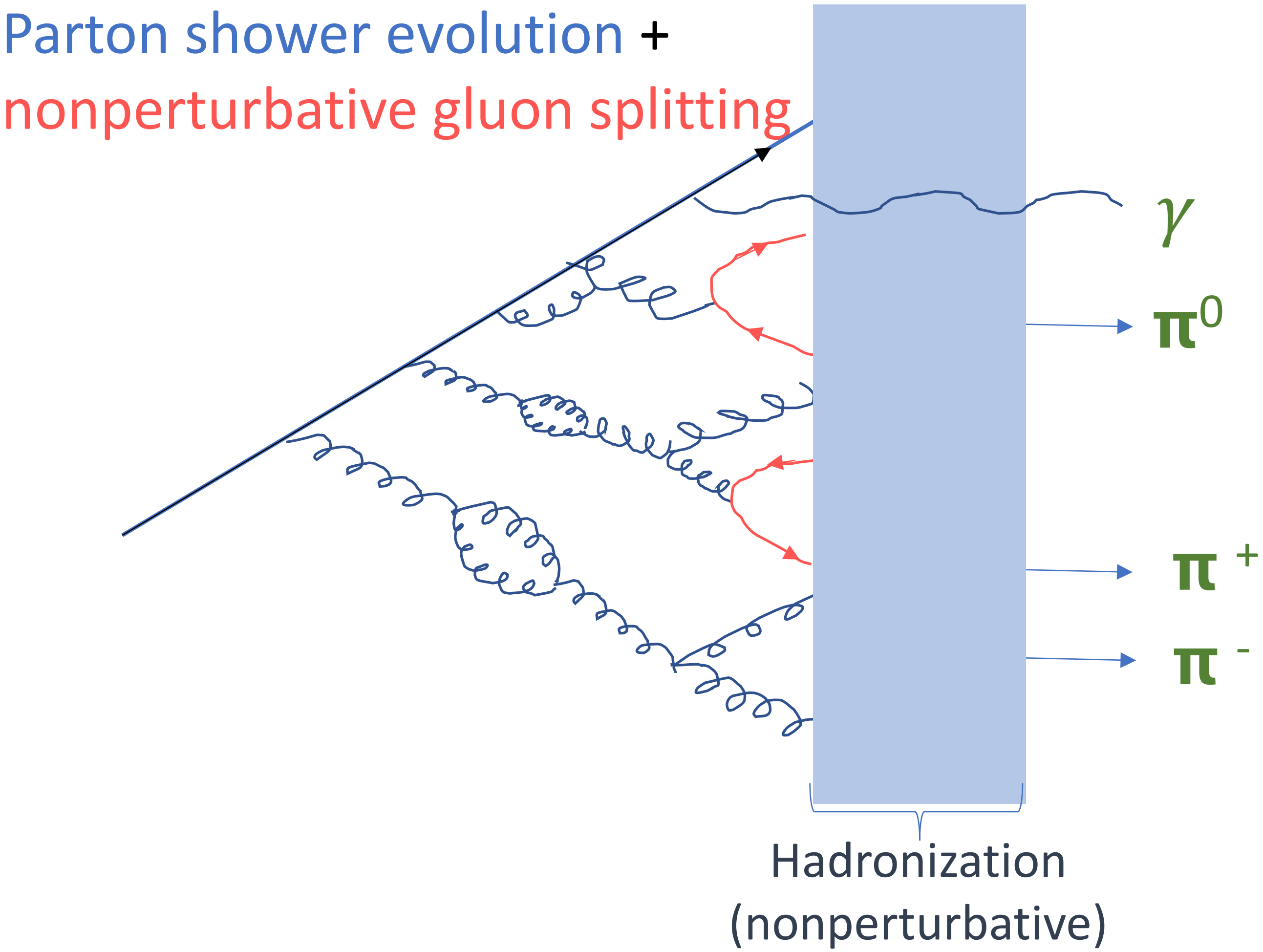

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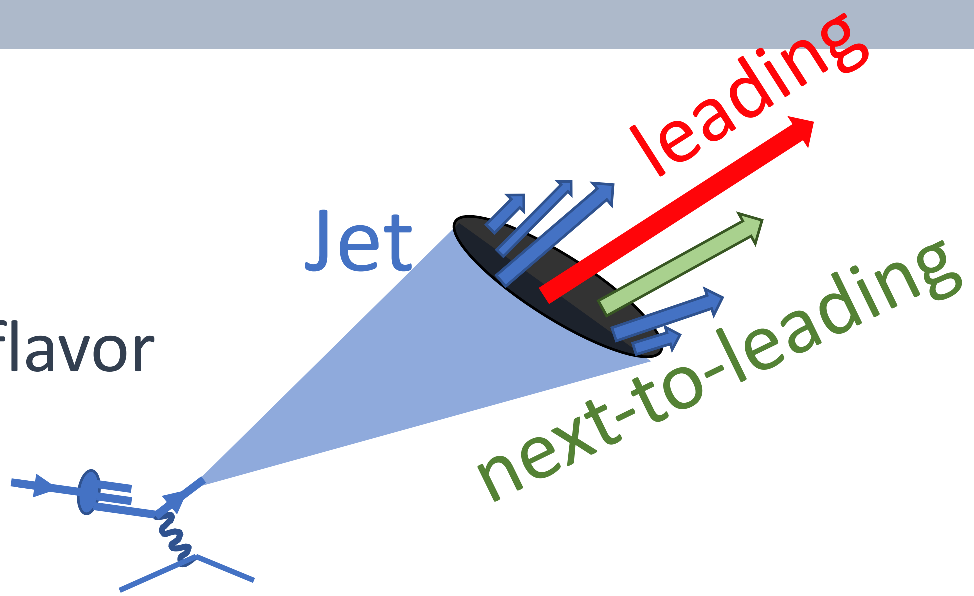

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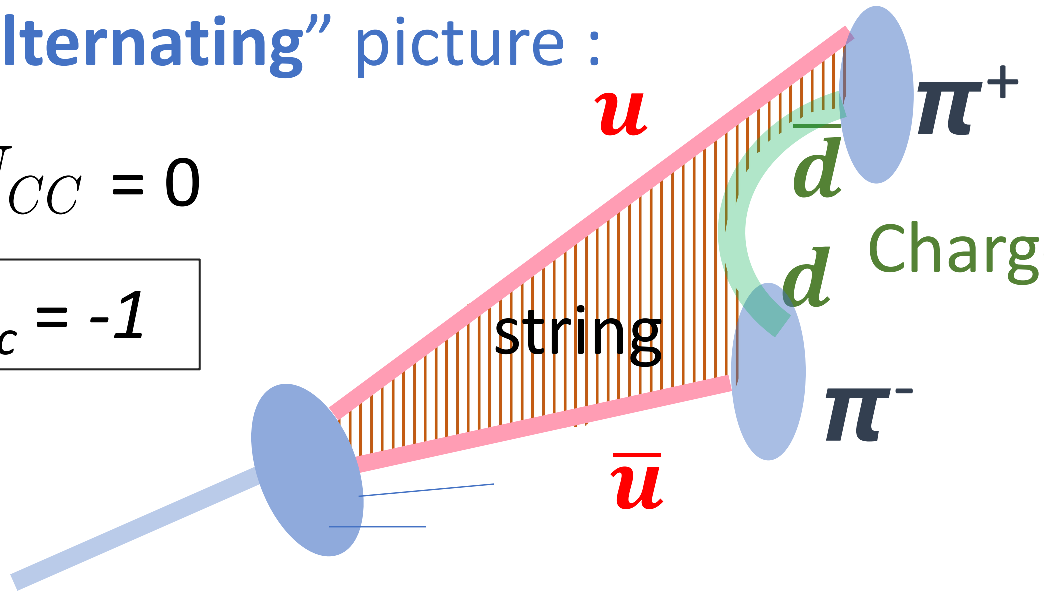

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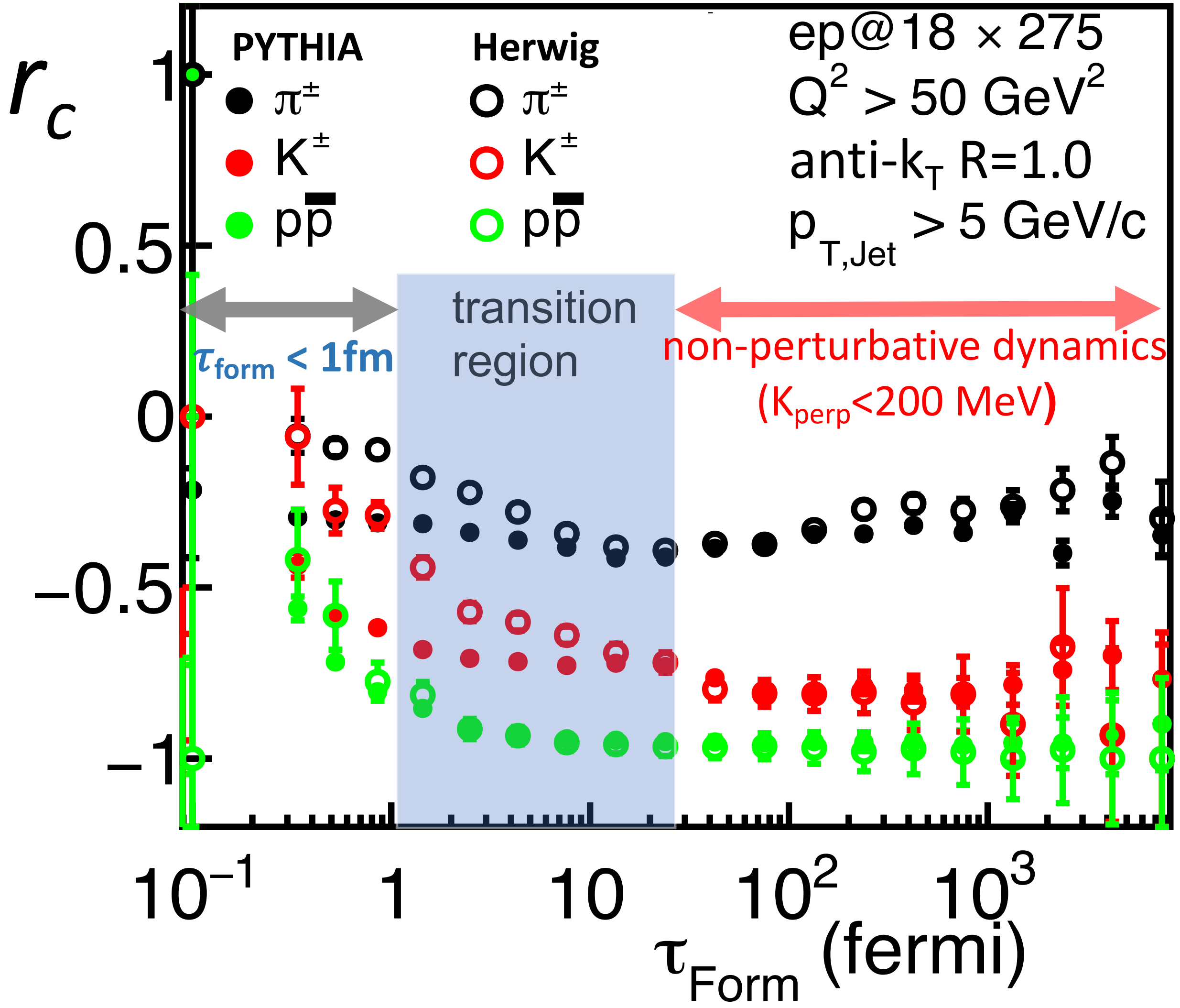

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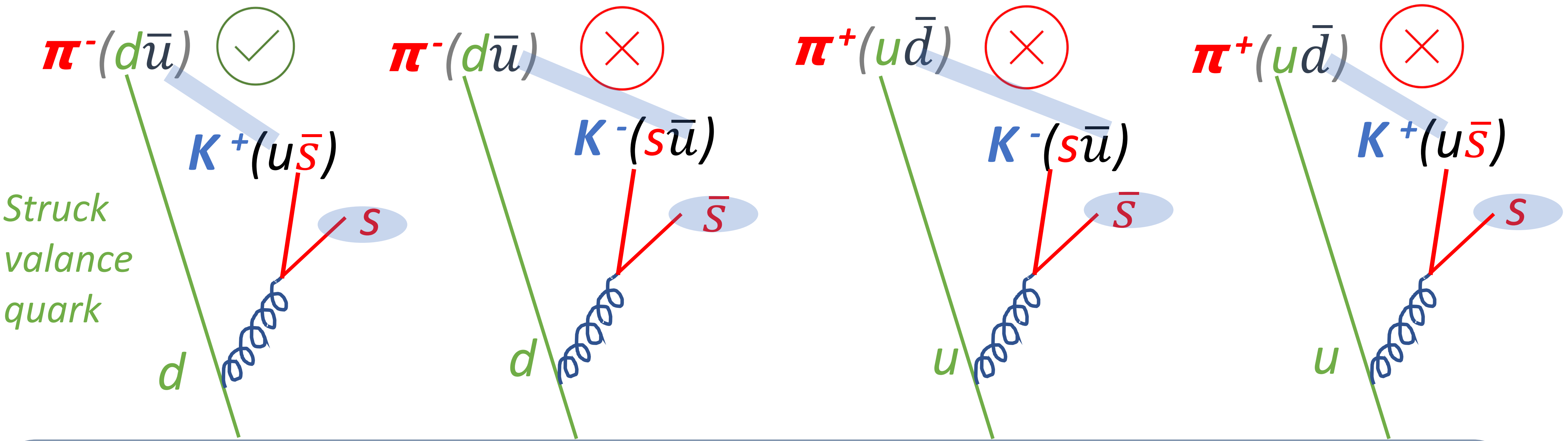

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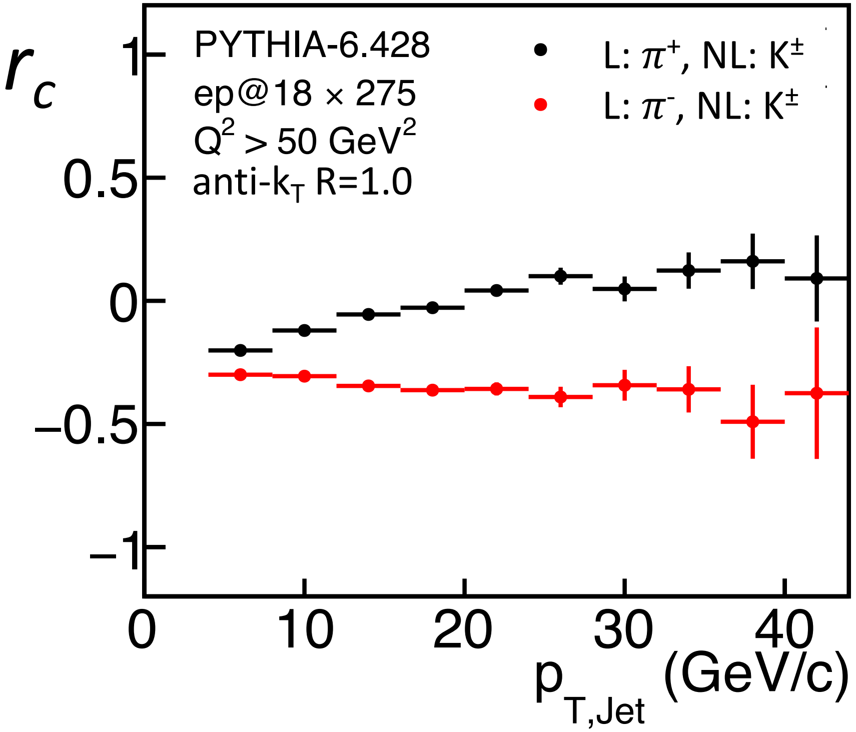

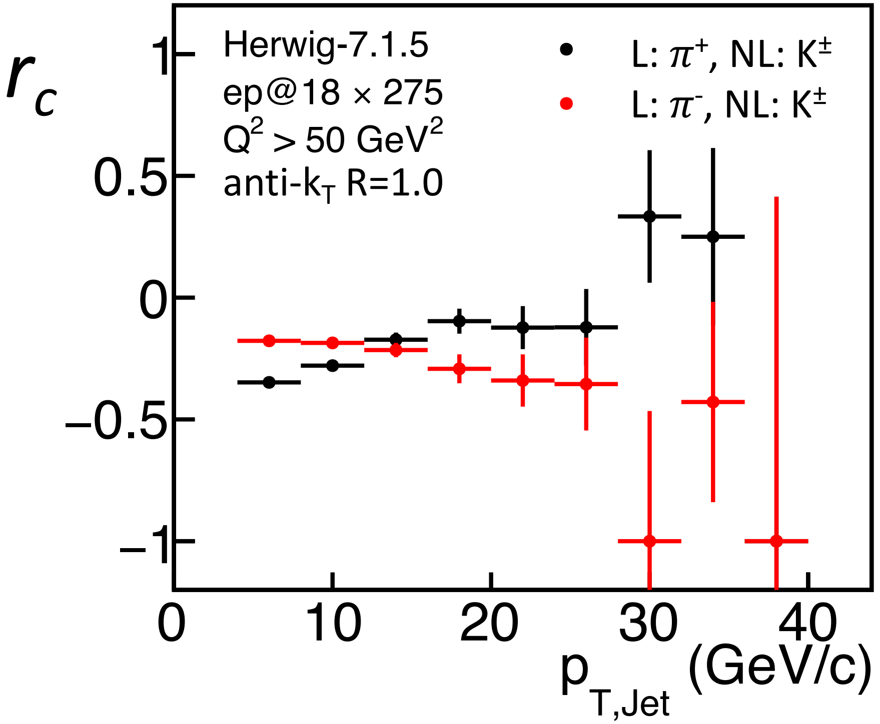

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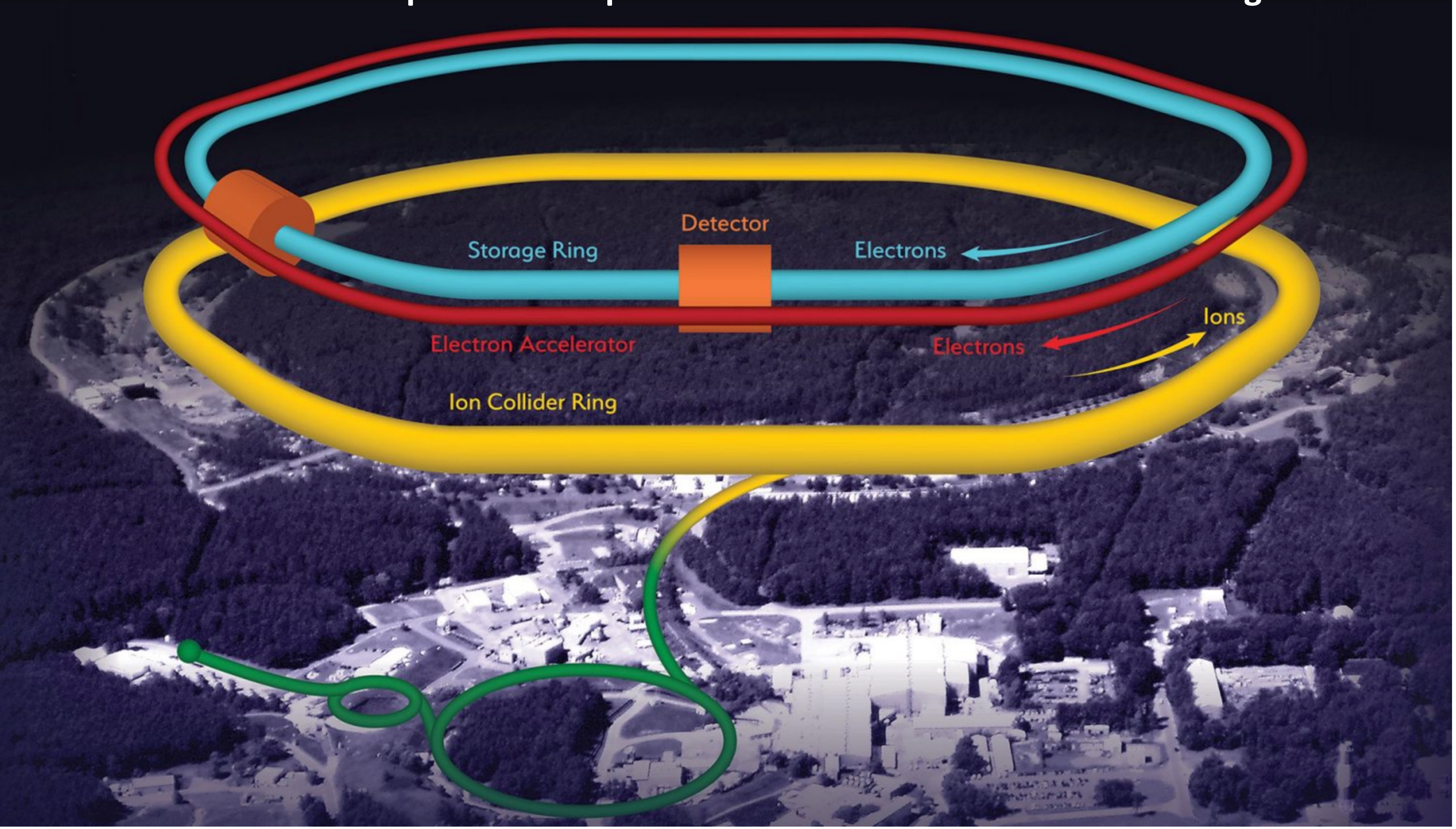
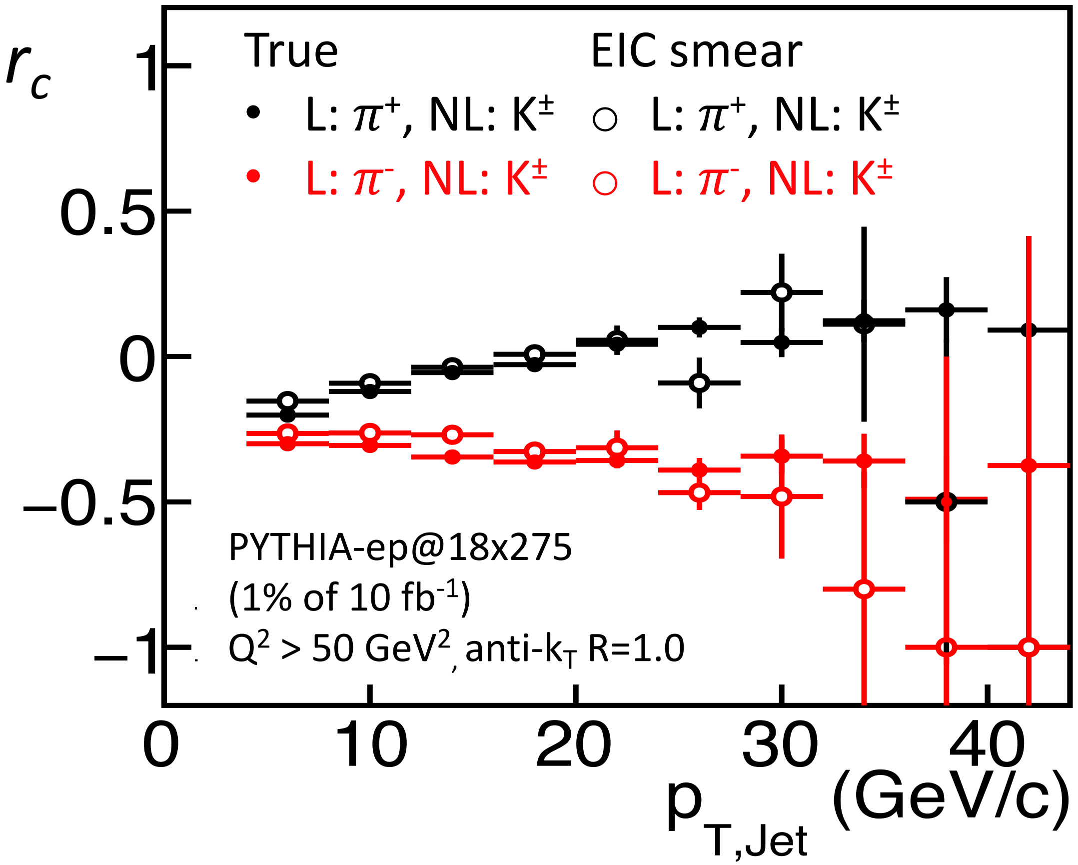


arXiv:2103.05419
EIC Yellow Report

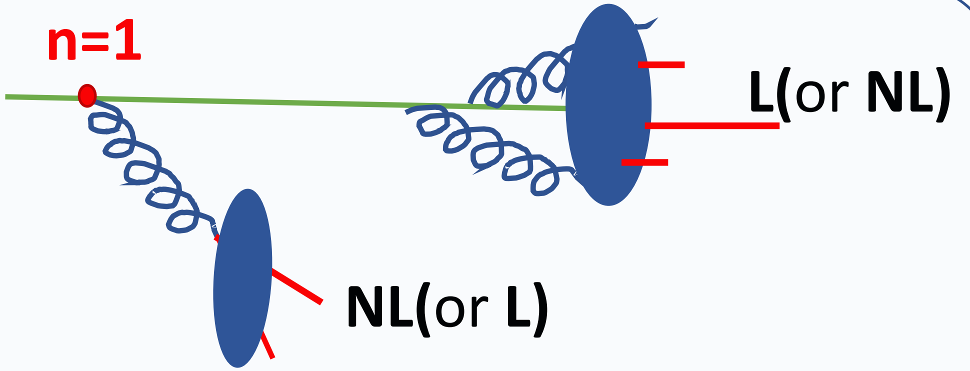
LHC, LEP, ILC :
can also make such
Interesting measurements

Impact on EIC detector design

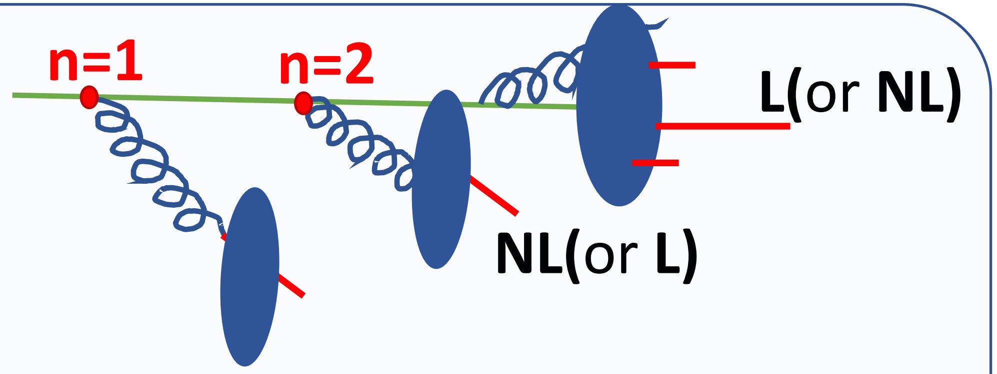
- **An *early* impactful measurement at EIC :**
  - ➢ Detector smearing does not affect this observable in a significant way
- **Unique Opportunity at EIC** :
  - ➢ RHIC and HERA has limitations to identify π and **K** at high momentum
  - ➢ Particle identification requirement (~10 GeV/c for π/**K** in central region) is already at cutting edge technology
  - ➢ Motivate further detector R&D to fulfill the PID requirement



Subjet structure



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



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arXiv:1804.03657v2

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

Kinematic region for various resolved prongs

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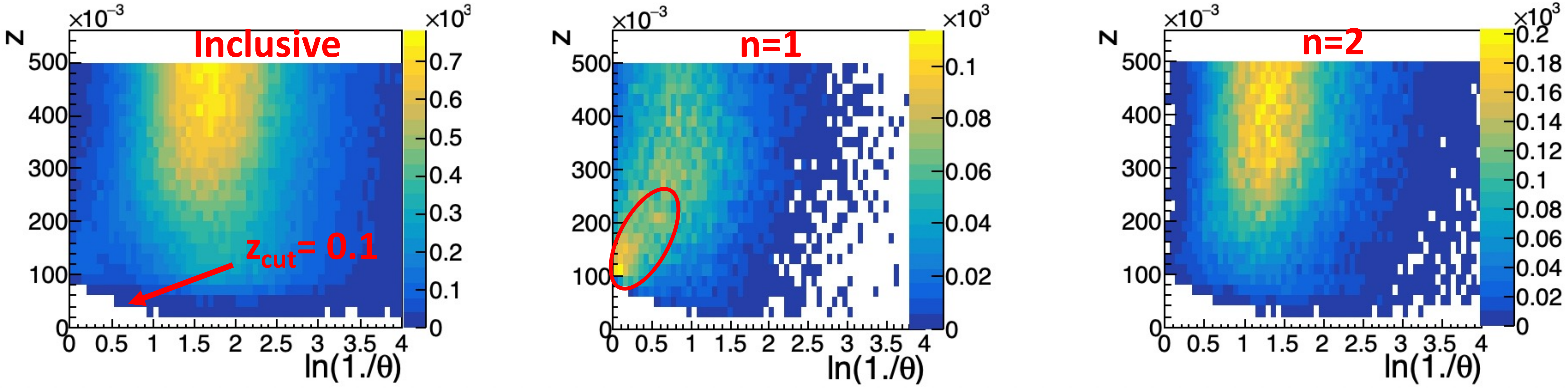

n=1 : wide angle soft radiations

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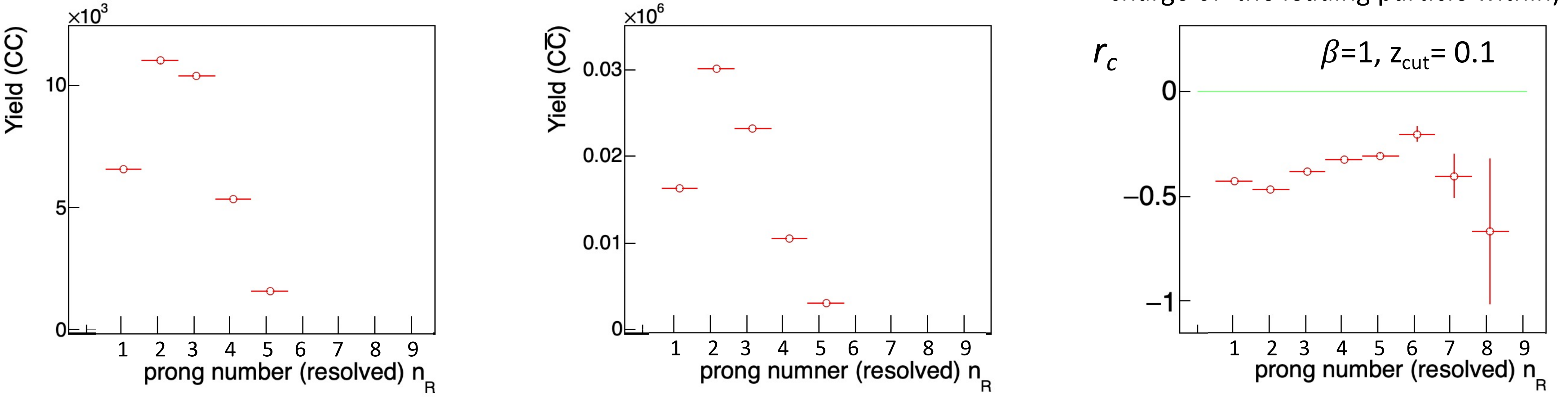
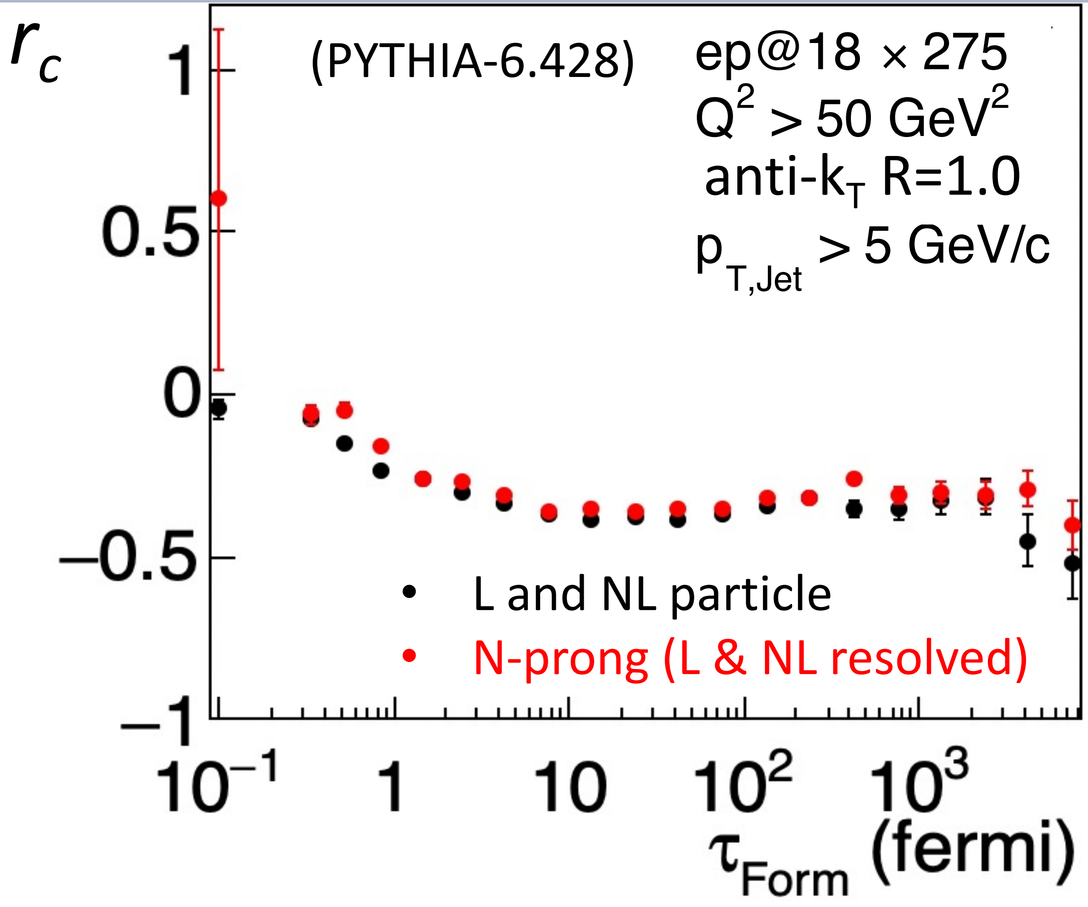
Resolved prong (n_R) and r_C

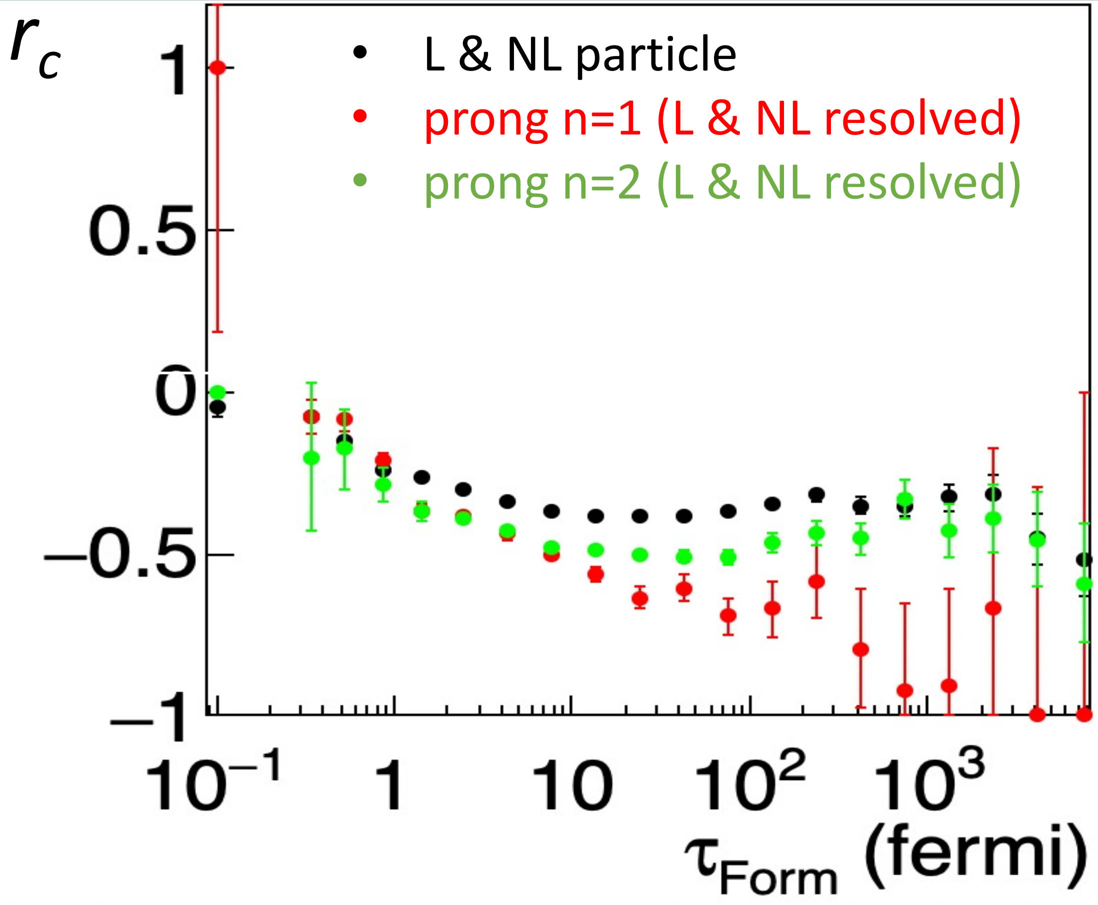
(Charges of prong assigned from the charge of the leading particle within)



- 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 sightly depending on prong numbers where it get resolved

L and NL particle and prong correlations





- r_c converge when when reclusive prong matching allowed to higher depth (n=15)
- Pythia shows distinct features of r_c with $\tau_{Form.}$ (data and theoretical input are very essential)

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- Pythia shows distinct features of r_c with formation time for different nodes. These need to be understood and measured from data

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
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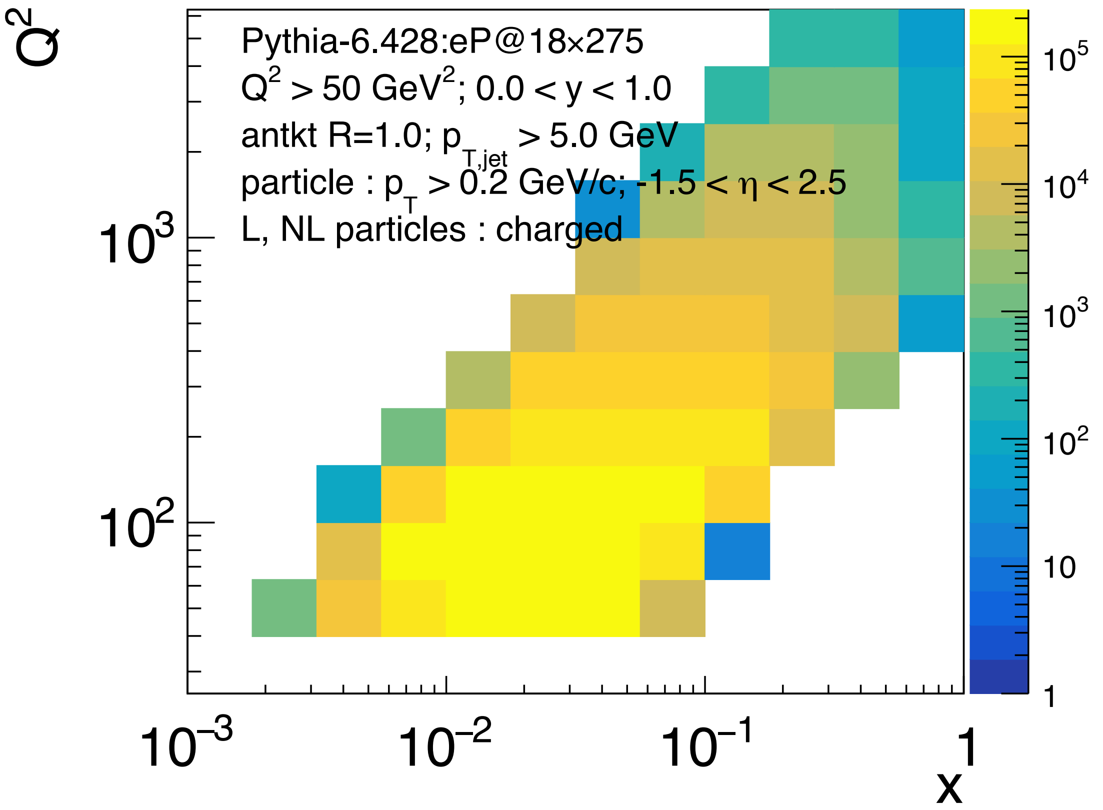
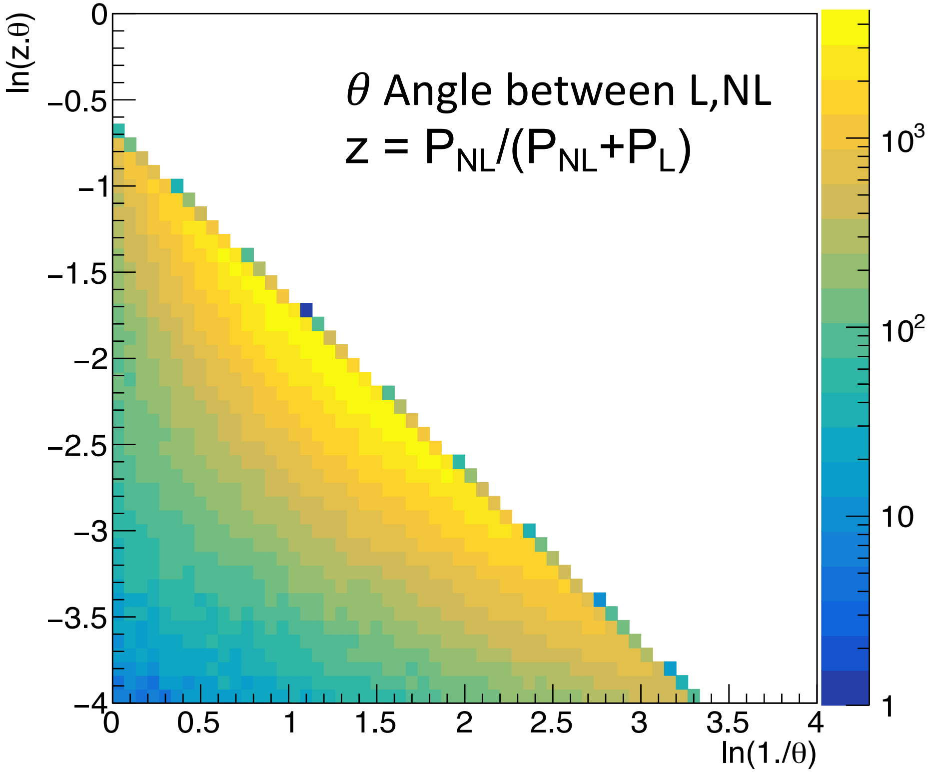
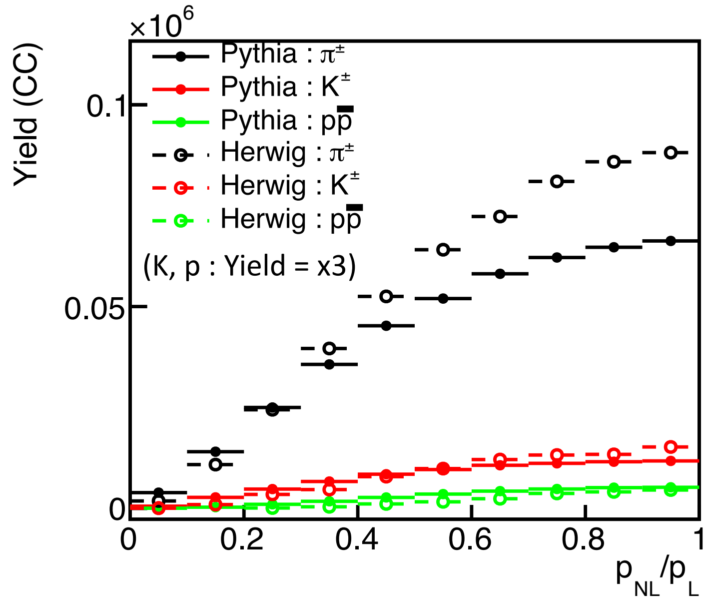
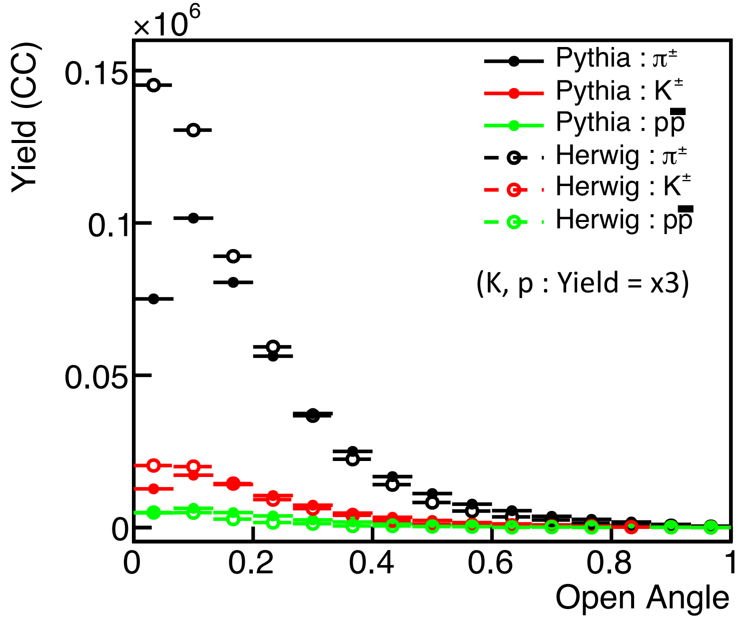
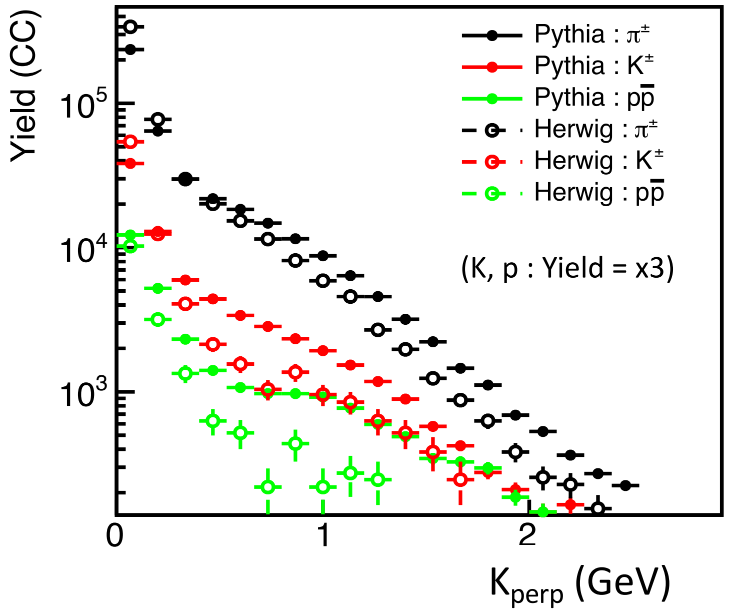




L NL kinematic distribution



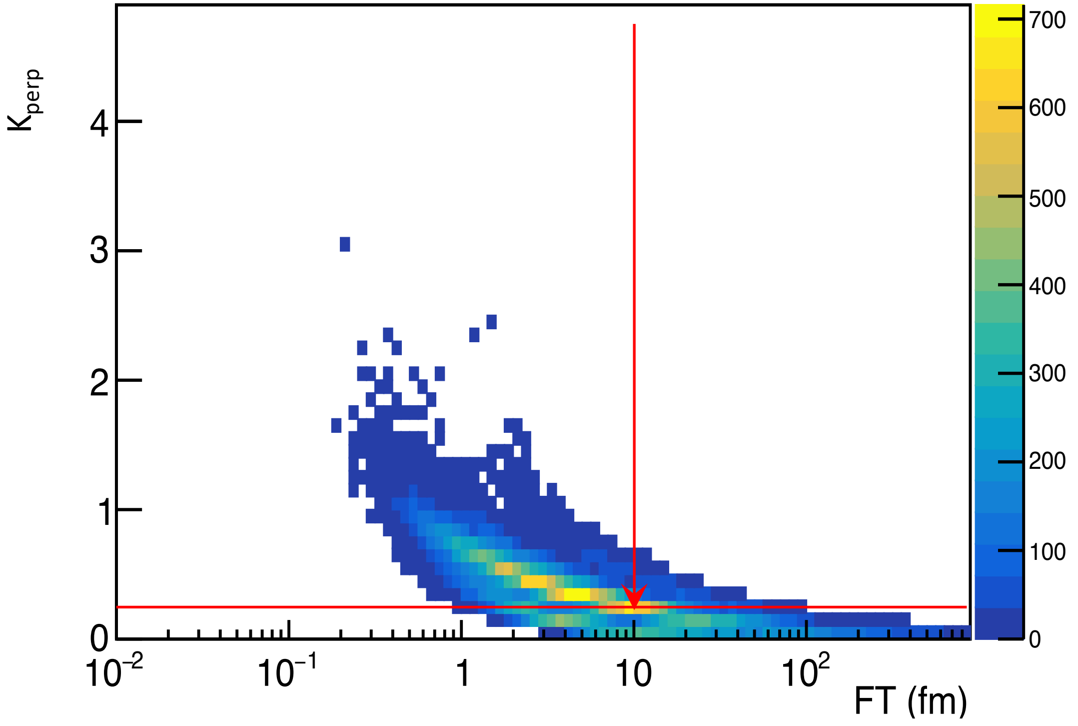


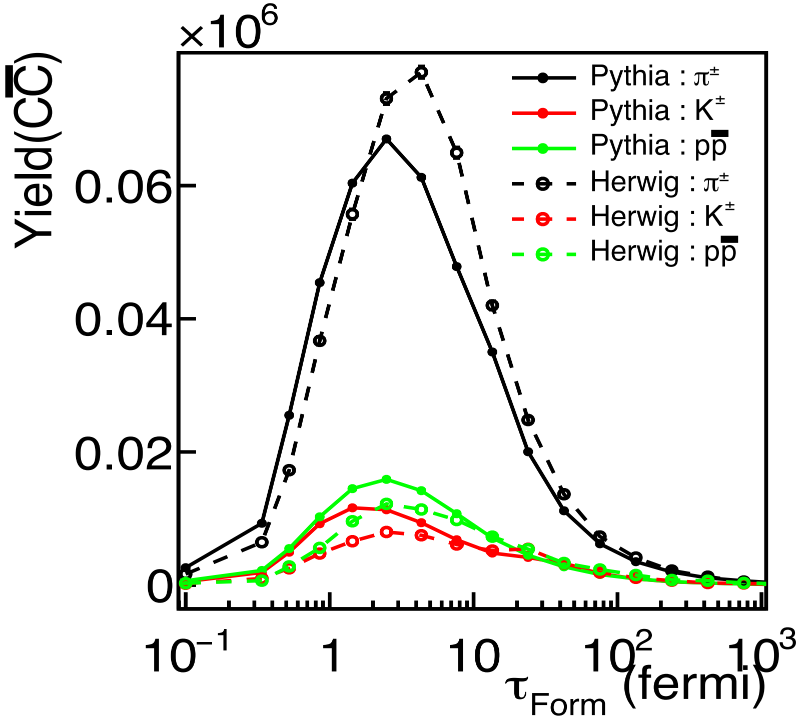


Herwig has more instances when L and NL momentum share nearly equal momentum

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

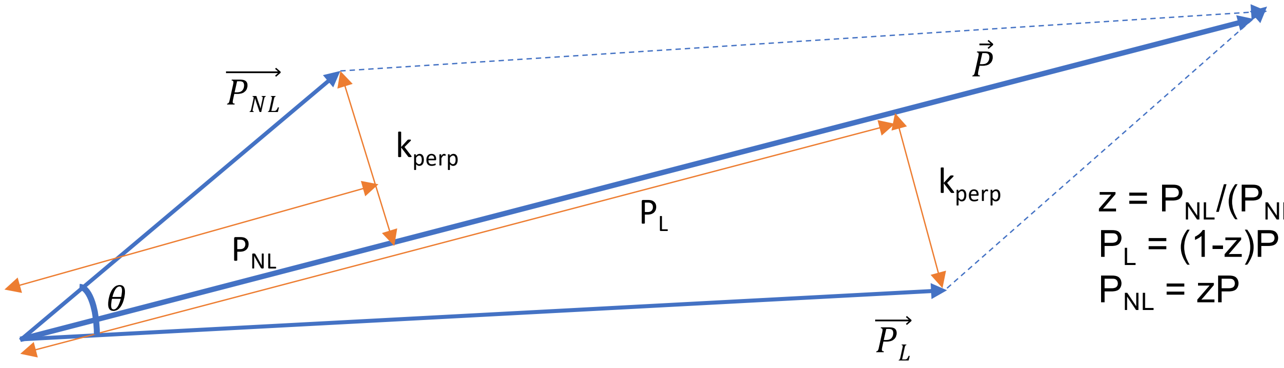
Formation time





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



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

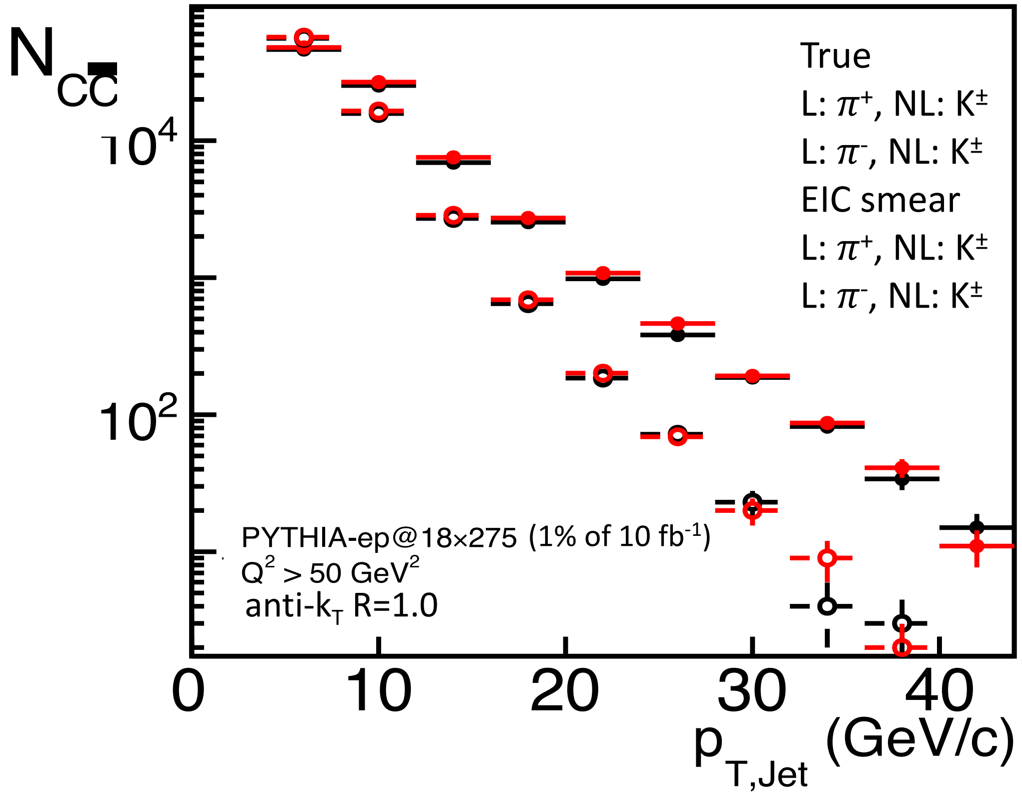
Important region to study in data τ_{form} = "a few fermi" and "a few dozen fermi", k_{perp} = "a few GeV" to "several hundred MeV"

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

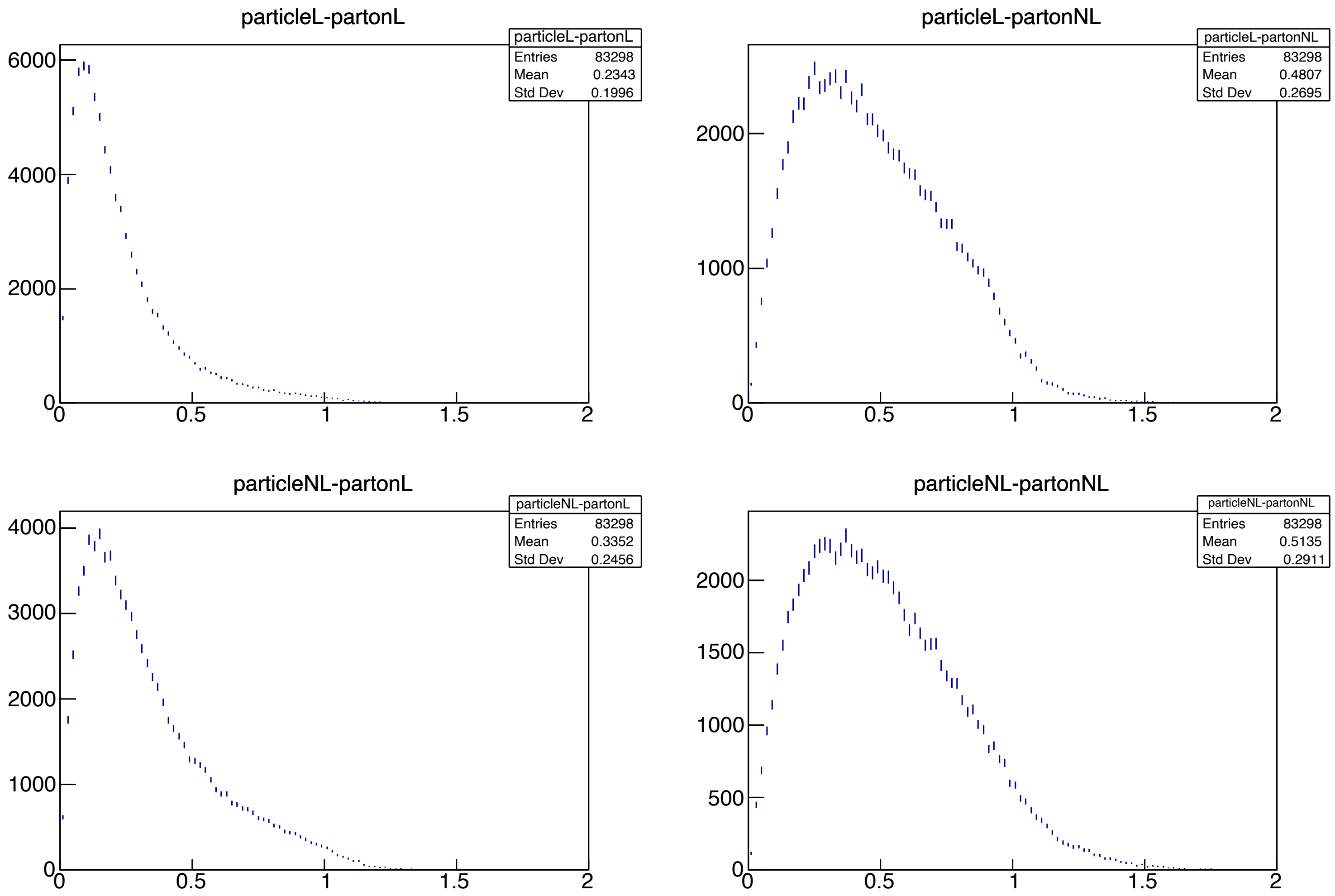
Impact on EIC detector design

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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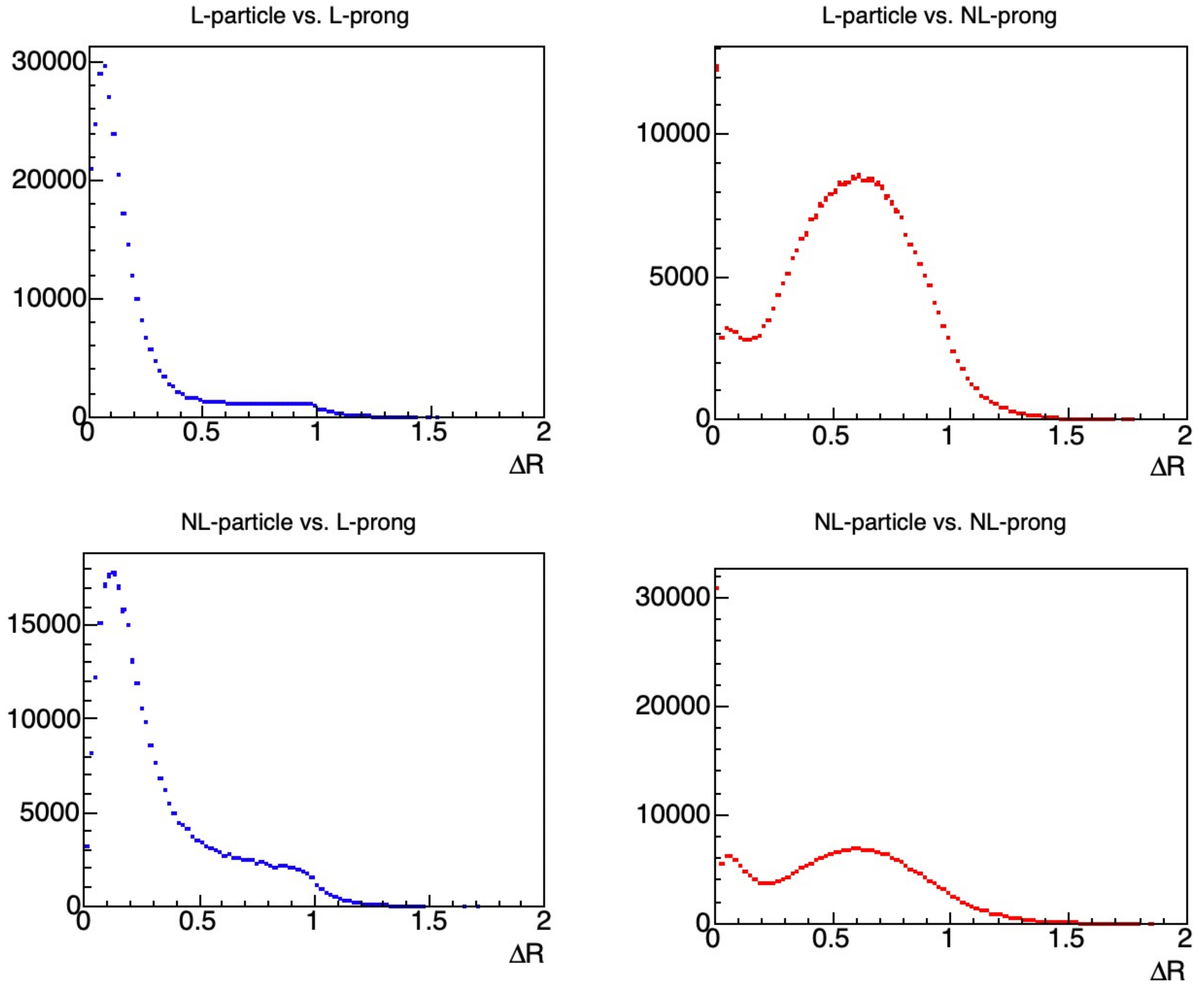
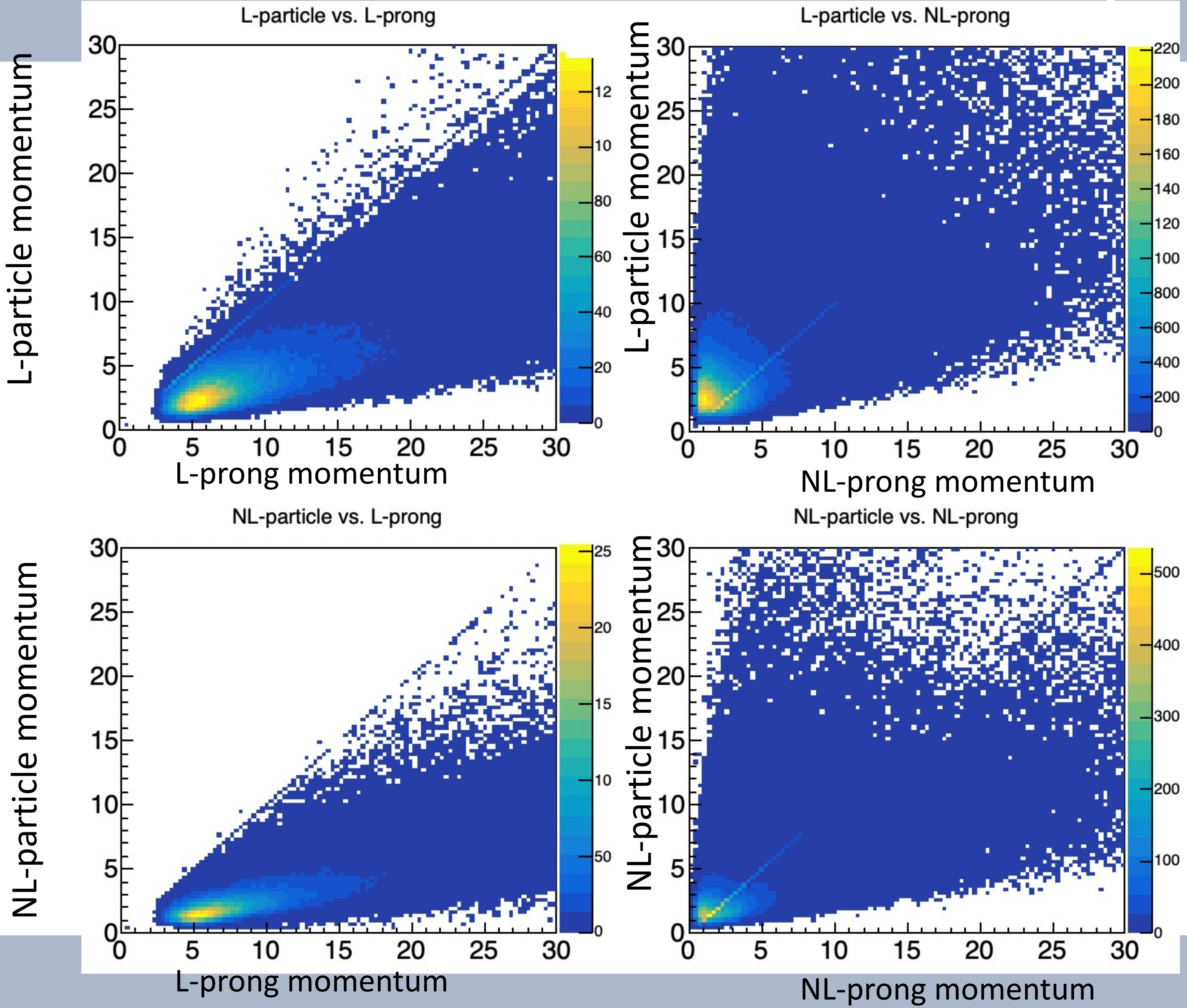
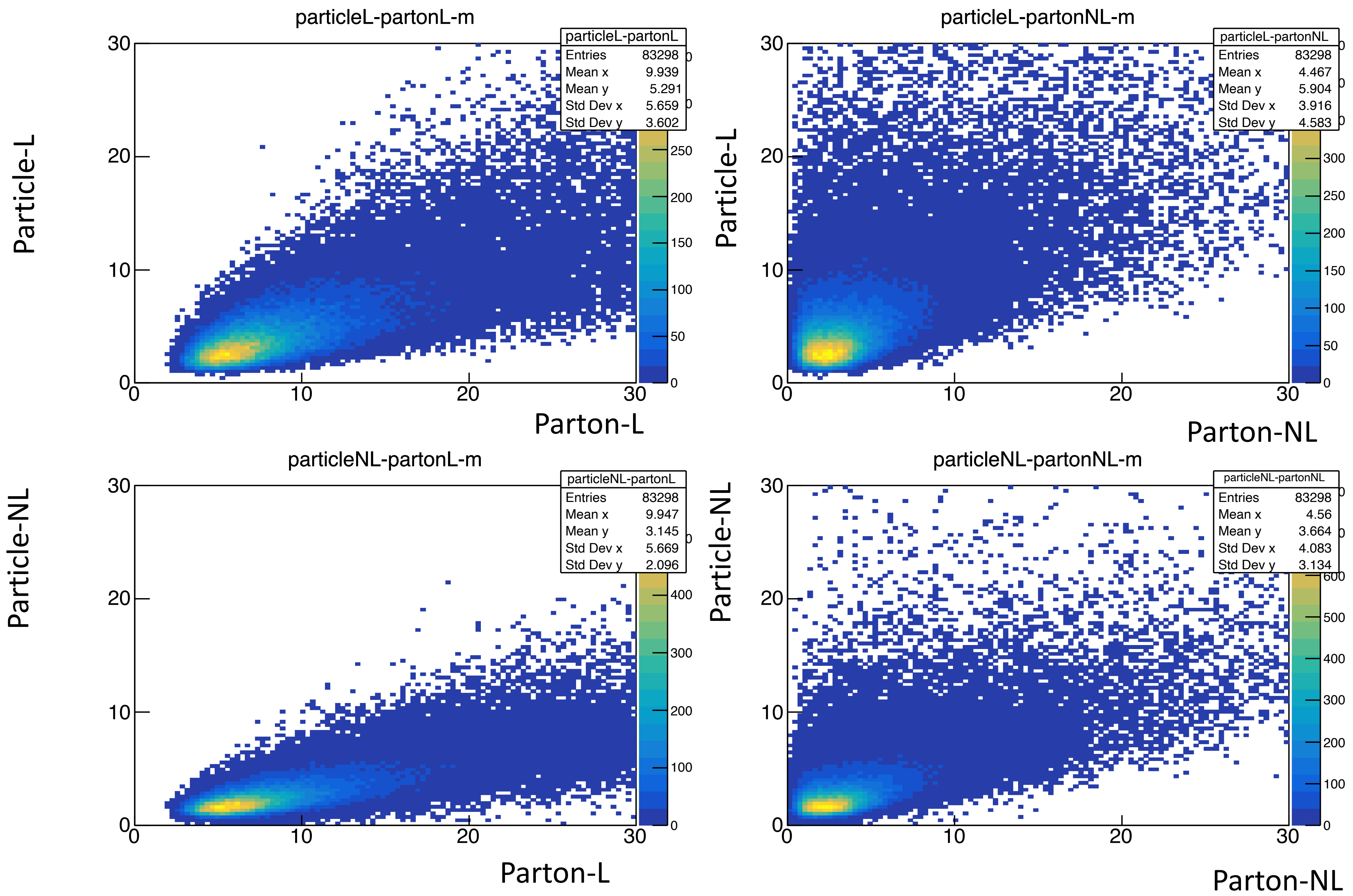


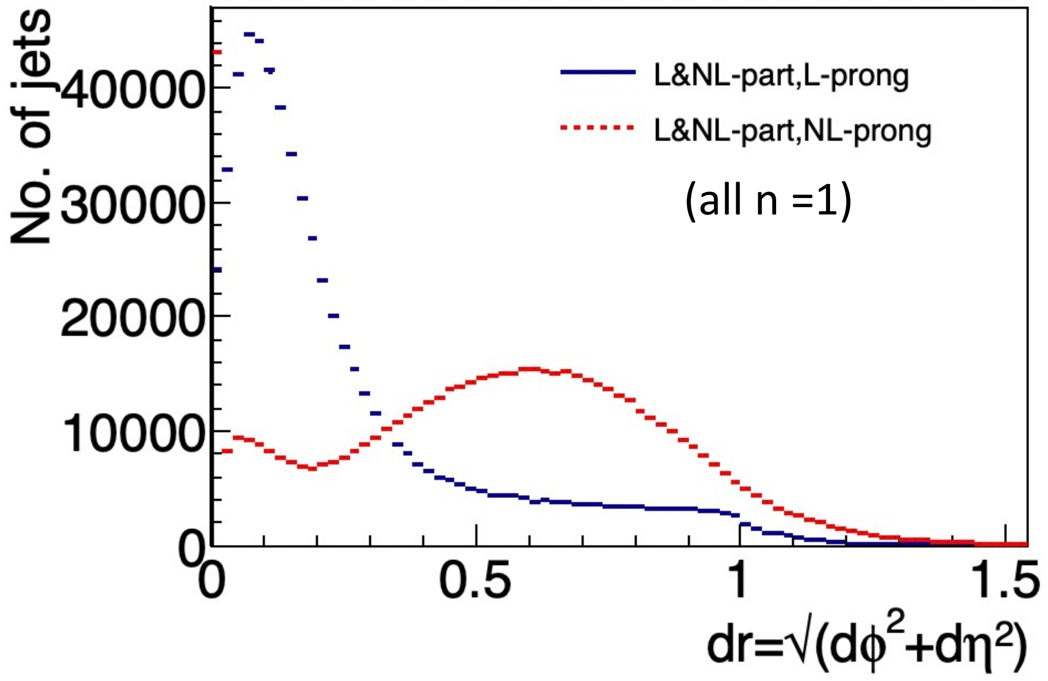
L and NL correlations with the first split prongs

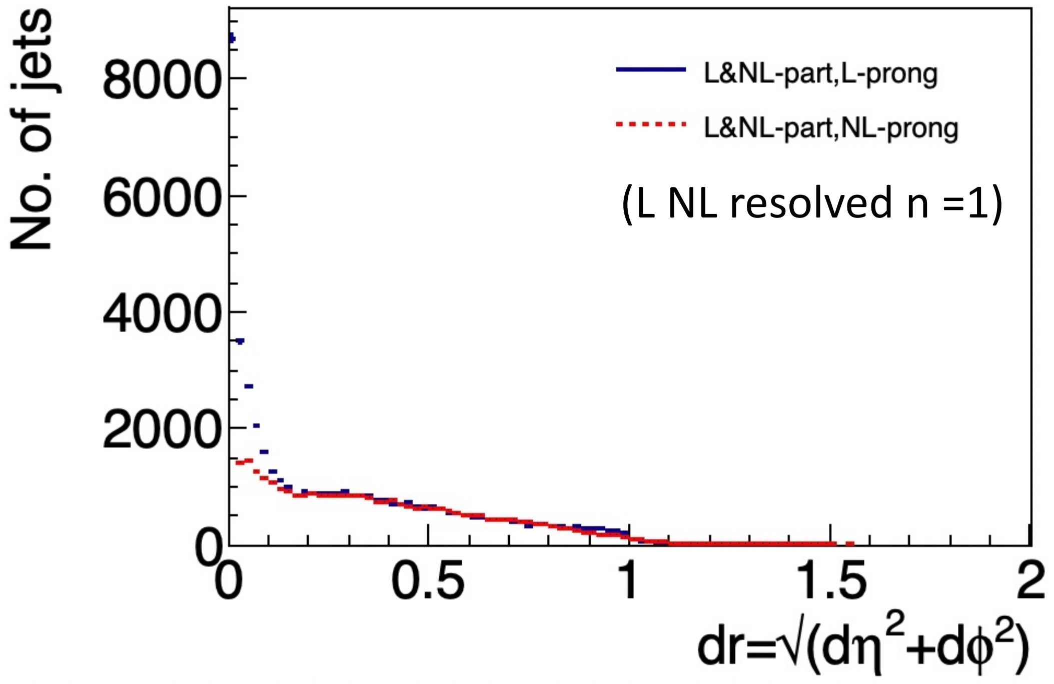




particleL-partonL-m
particleL-partonL
Entries 83298
Mean x 9.939
Mean y 5.291
Std Dev x 5.659
Std Dev y 3.602
Particle-L
Parton-L
particleL-partonNL-m
particleL-partonNL
Entries 83298
Mean x 4.467
Mean y 5.904
Std Dev x 3.916
Std Dev y 4.583
Particle-L
Parton-NL
particleNL-partonL-m
particleNL-partonL
Entries 83298
Mean x 9.947
Mean y 3.145
Std Dev x 5.669
Std Dev y 2.096
Particle-NL
Parton-L
particleNL-partonNL-m
particleNL-partonNL
Entries 83298
Mean x 4.56
Mean y 3.664
Std Dev x 4.083
Std Dev y 3.134
Particle-NL
Parton-NL

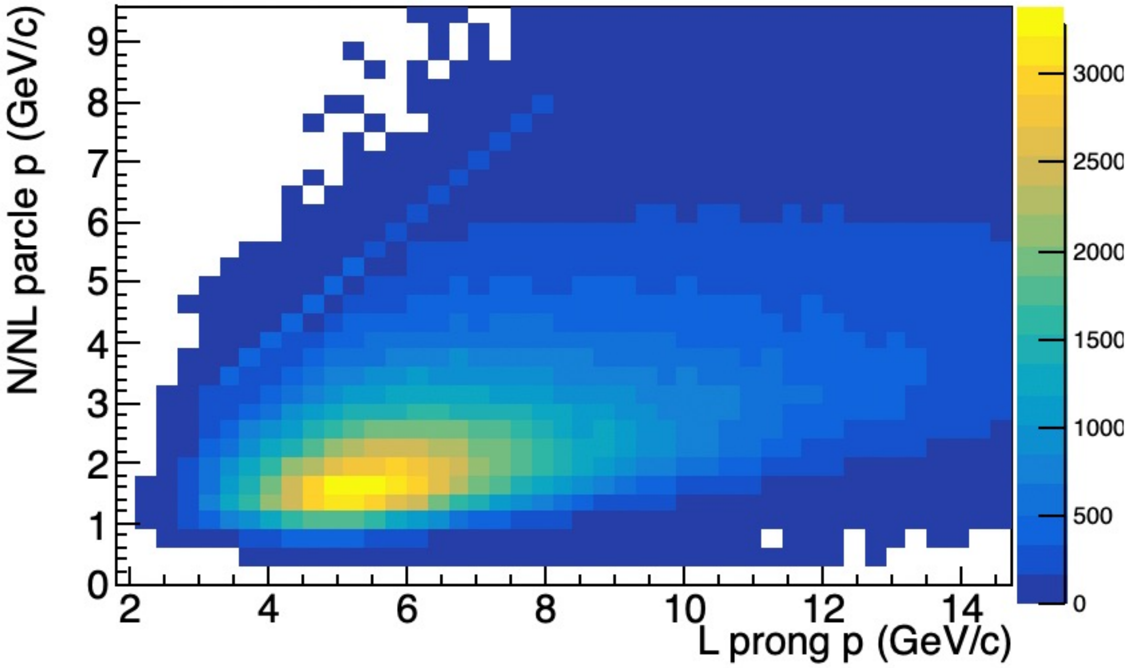
L and NL correlations with the first split prongs

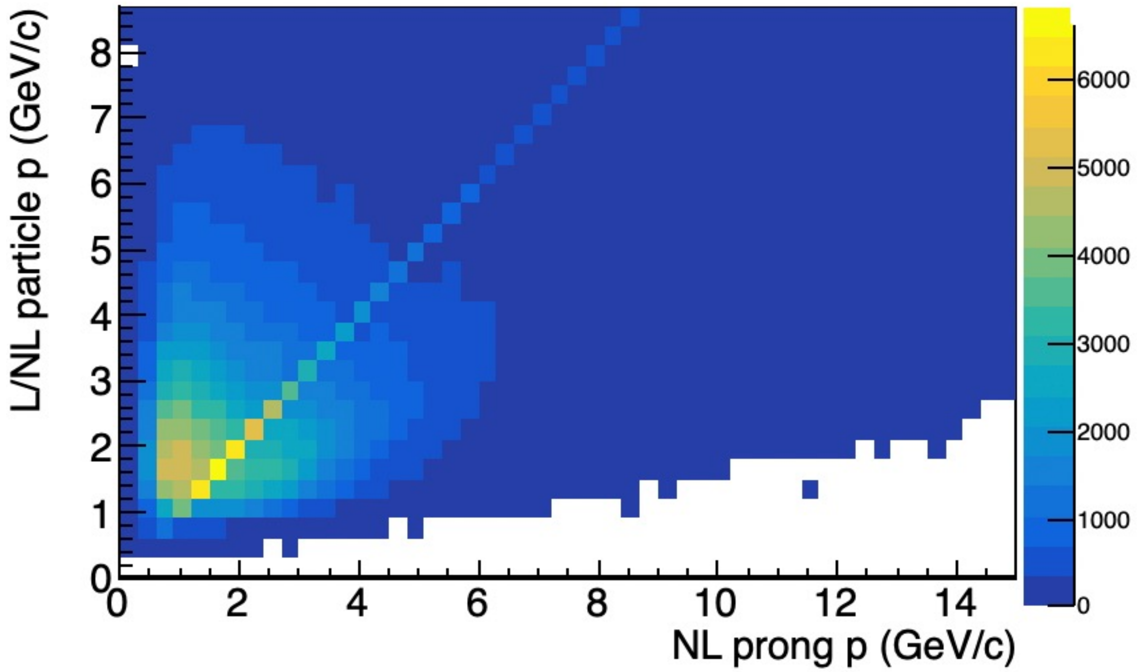




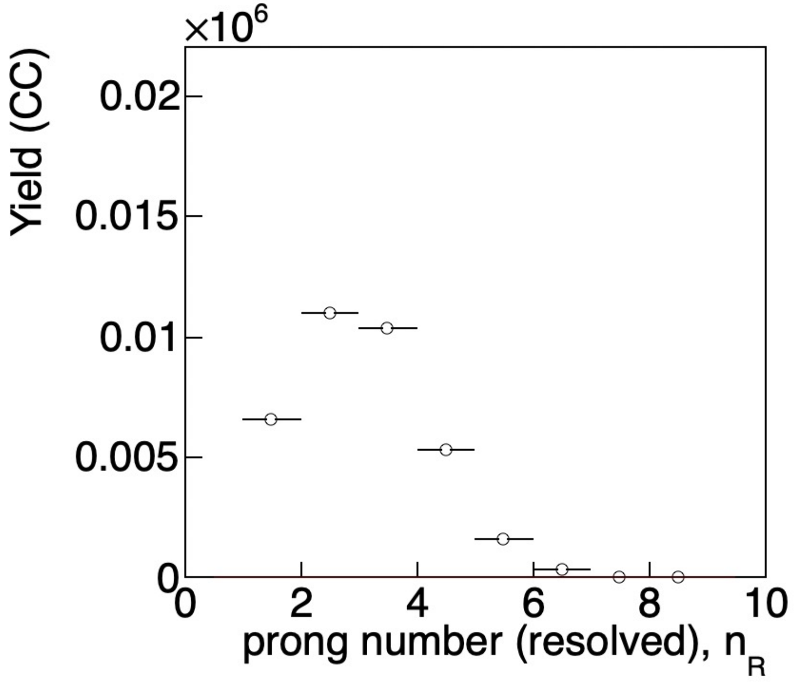
- L, NL particles are strongly correlated with the harder prong in the first split
- However, some "resolved" prongs have strong correlations with a wide tail
- L NL particle are special : originates from the same string or cluster fragmentation which is of nonpertubative in origin

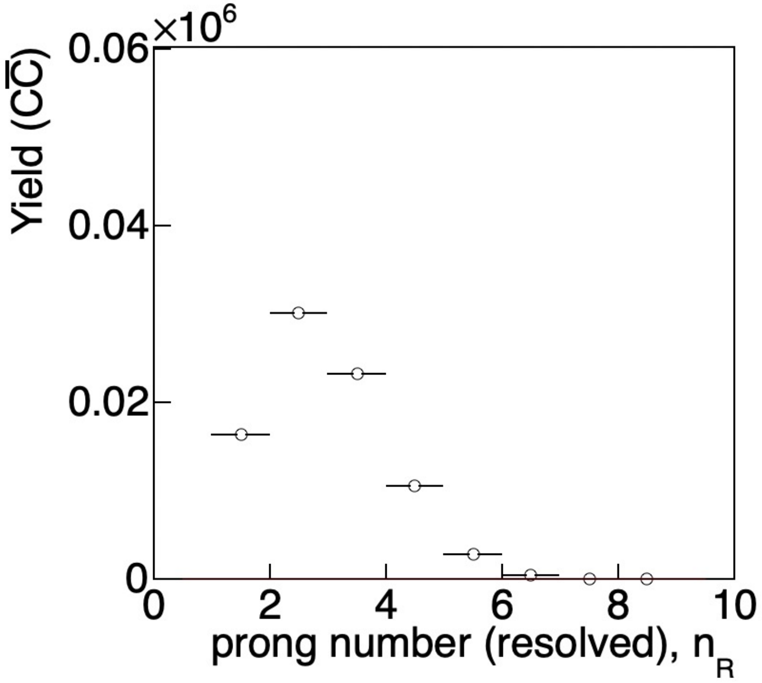
L and NL correlations in momentum

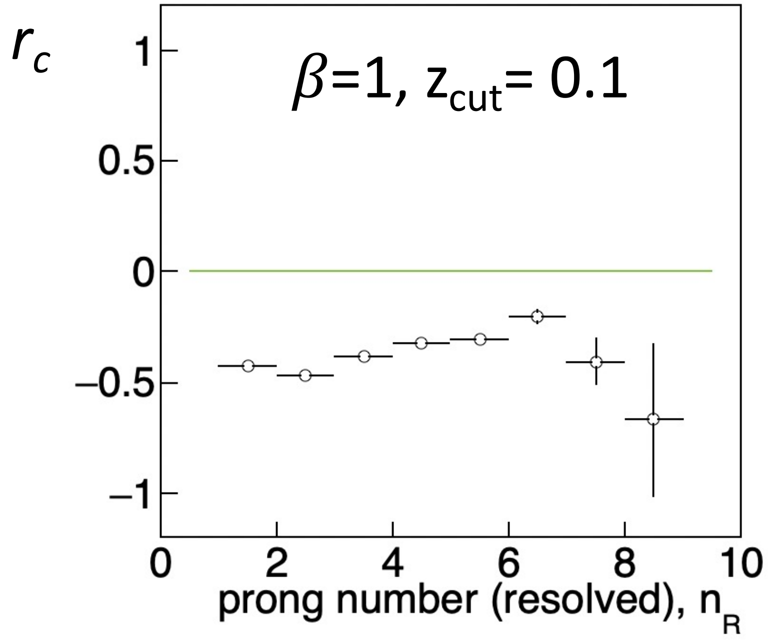




Resolved prong (n_R) and r_C







- 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