Novel Intrajet Leading-Particle Correlations in Formation Time to study Hadronization

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Advancing the Understanding of Non-Perturbative QCD Using Energy Flows, Sep 19 – 22, 2022

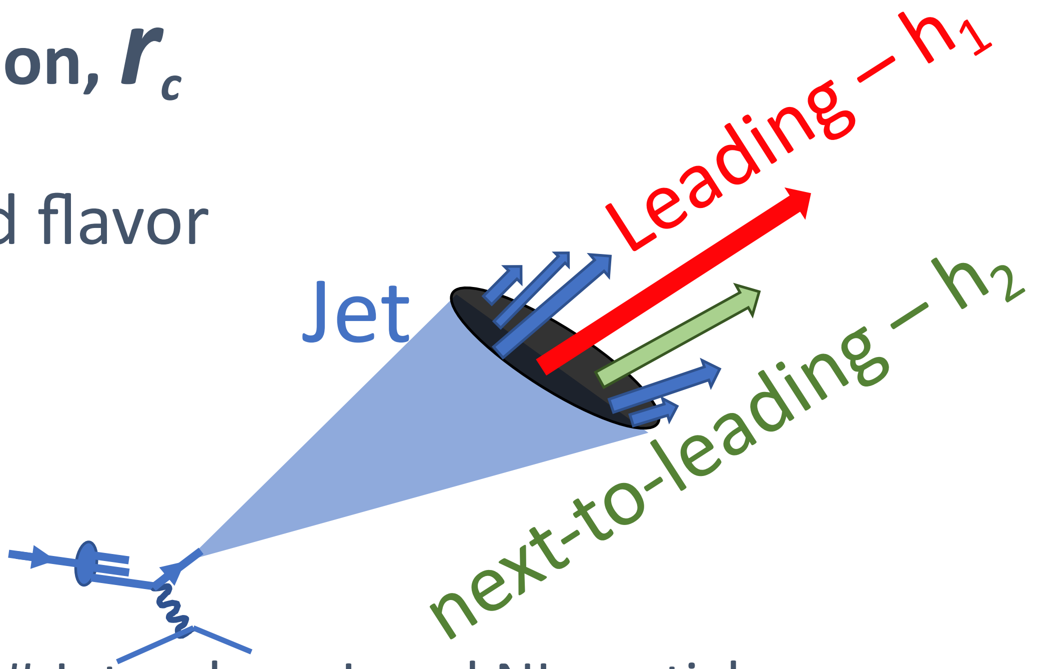
Outline

- **Observable** : charge-momentum correlation (***r*$_c$**) amongst leading hadrons in jets
- **Kinematic variables** : relative transverse momentum between leading particles/prongs (k_T) and formation time (t_{form})
- **Predictions for EIC:** flavor correlations (Phys. Rev. D **105**, L051502)
- **H1 Measurements (**H1prelim-22-032**) :**
  - Subjets as partonic proxies in probing ***r*$_c$** at different splits (prongs)
  - r_c for leading particles & prong kinematics
- **Summary and Outlook**

Charge-energy correlations

Observable : charge-momentum correlation, r_c

- Correlations in momentum, charge and flavor
- **Leading(L)** and **next-to-leading (NL)** momentum particles in a jet
- **h1** and **h2** are charged hadrons only



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

Phys. Rev. D **105**, L051502

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

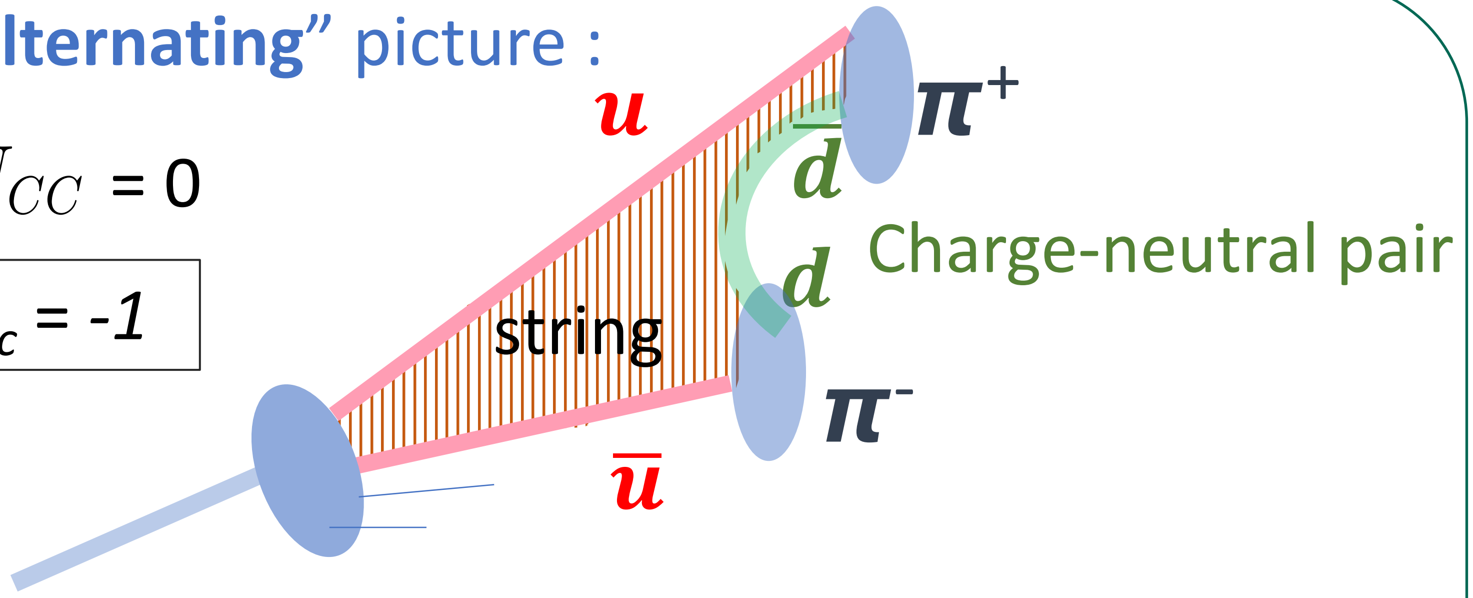
$N_{C\bar{C}}$: # Jets where L and NL particles have opposite sign charges

Significance of r_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 :

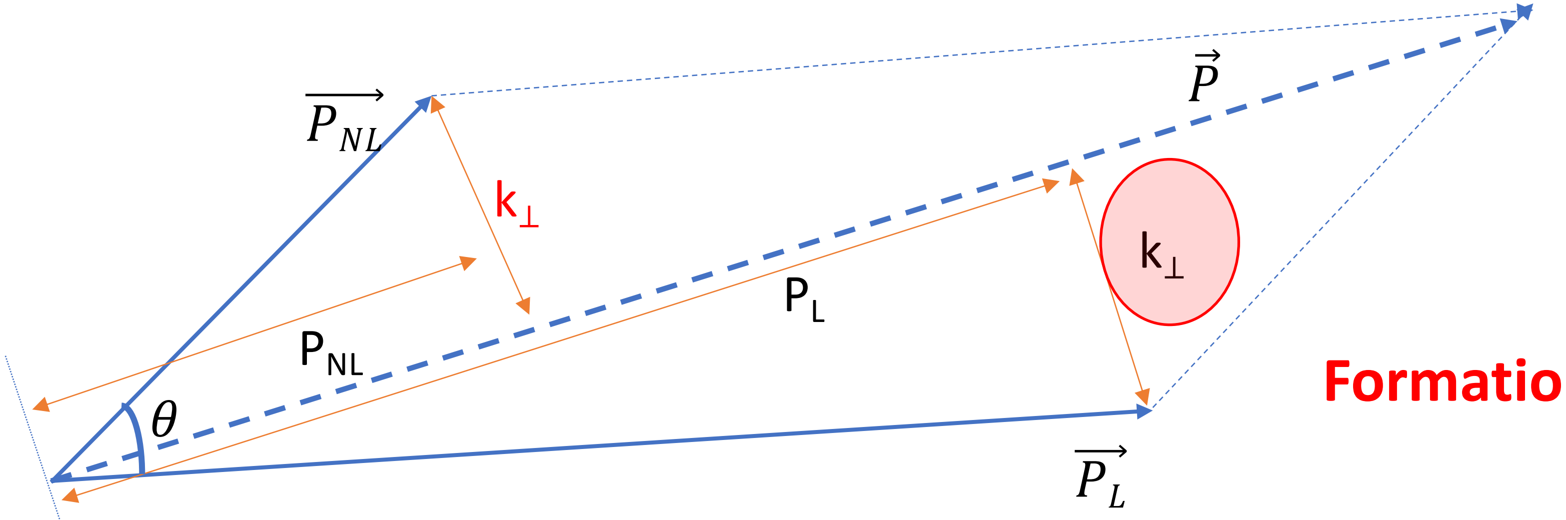
no charge correlation

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

$r_c = 0$

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

Kinematic variables



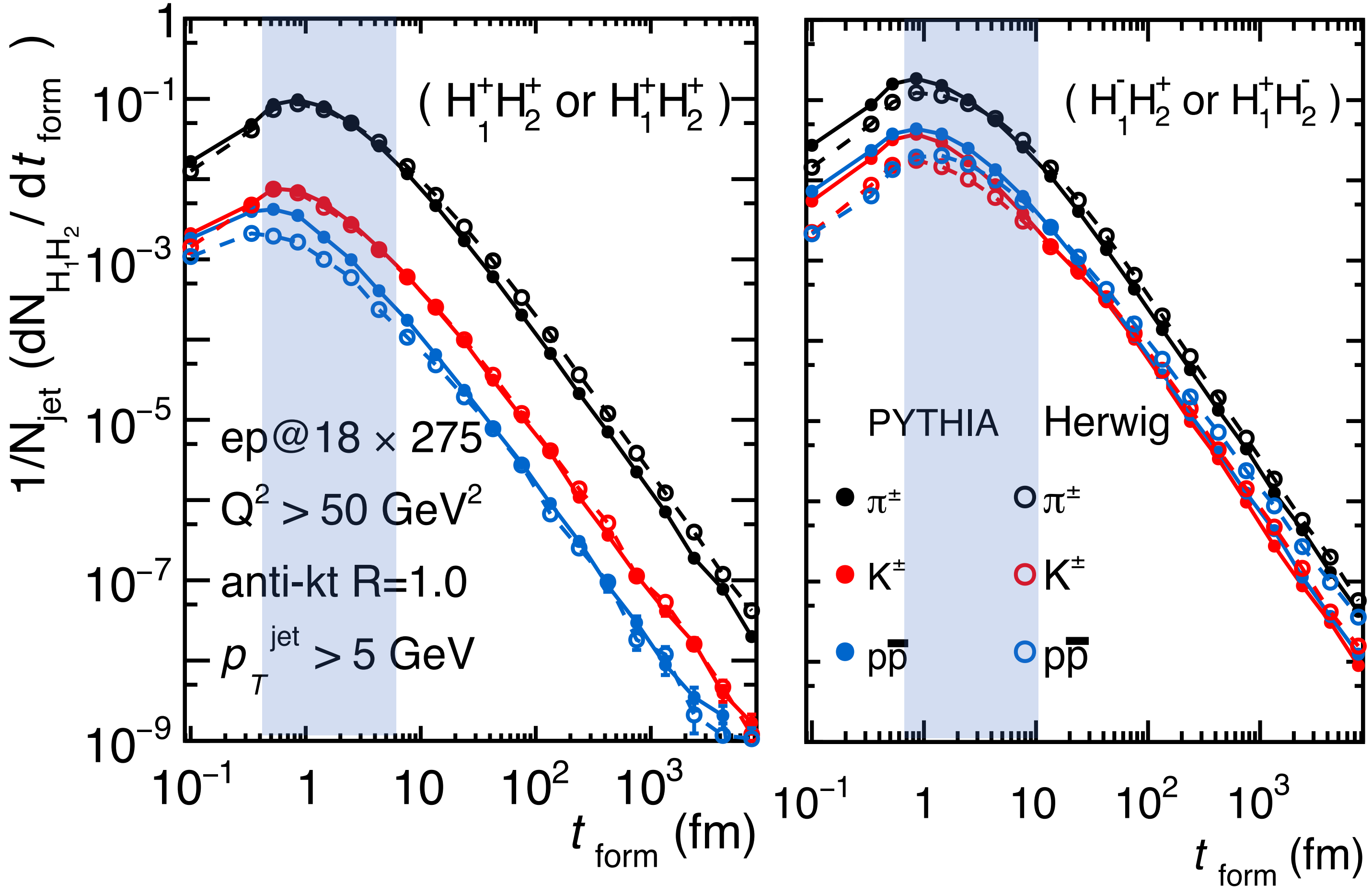
$z = P_{NL}/(P_{NL}+P_L)$
$P_L = (1-z)P$
$P_{NL} = zP$

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

- ✓ **Perturbative (t_{form} < ~1fm)**
  L and NL particles seem to separate after a very short time, which might decorrelate their hadronization
- ✓ **Nonperturbative (t_{form} > ~10 fm)**
  nonperturbative transverse momenta in the jet, $k_\perp$ < 200 MeV. Going to longer t_{form} or smaller $k_\perp$ leads to no new dynamics

- Formation time is time dilated.
- It is sensitive to the perturbative-nonperturbative transition.

Formation time



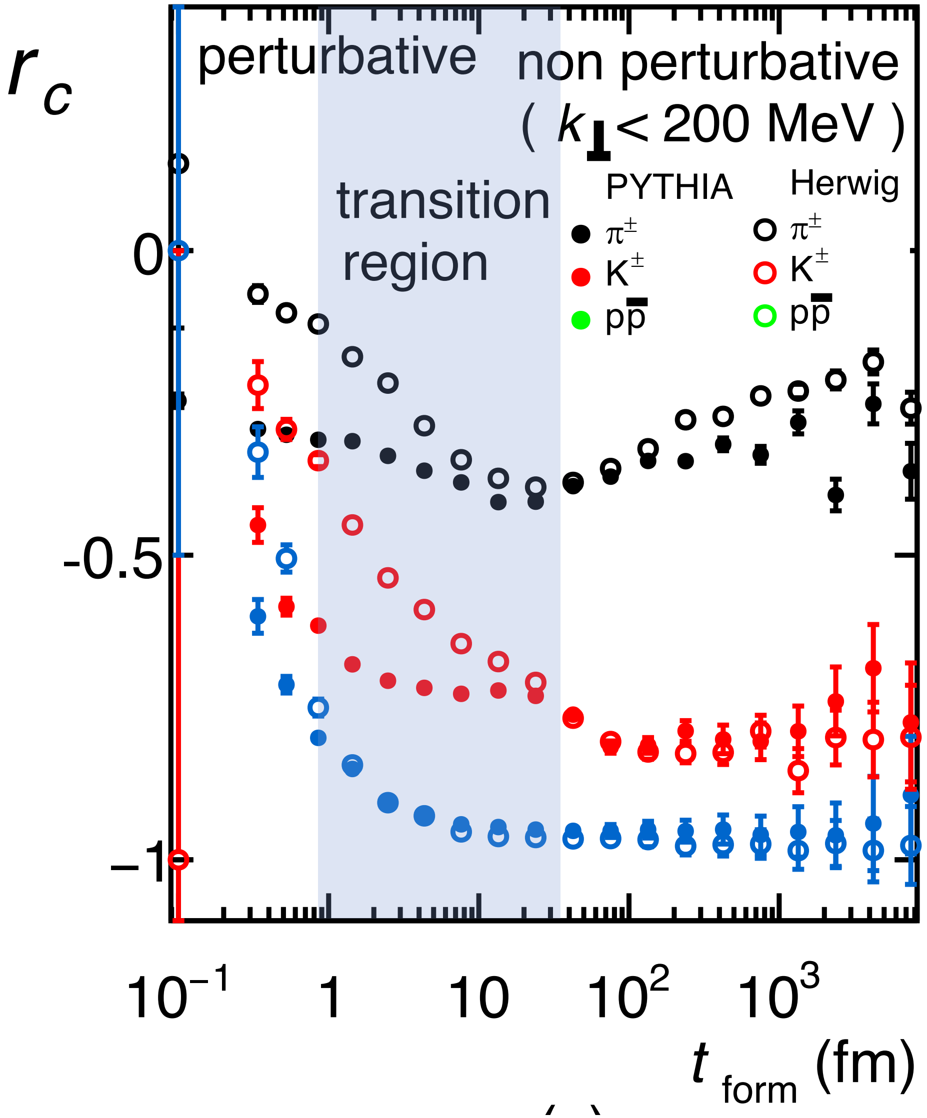
Formation time (t_{form}) :
$[2z(1-z)p] / k_\perp^2$

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

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

Formation tome is sensitive to the perturbative-nonperturbative transition

Charge-charge correlations with formation time



- At early time de-correlations for wide-angle, perturbative emissions.
- There is strong flavor dependence in 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 flavor tagging

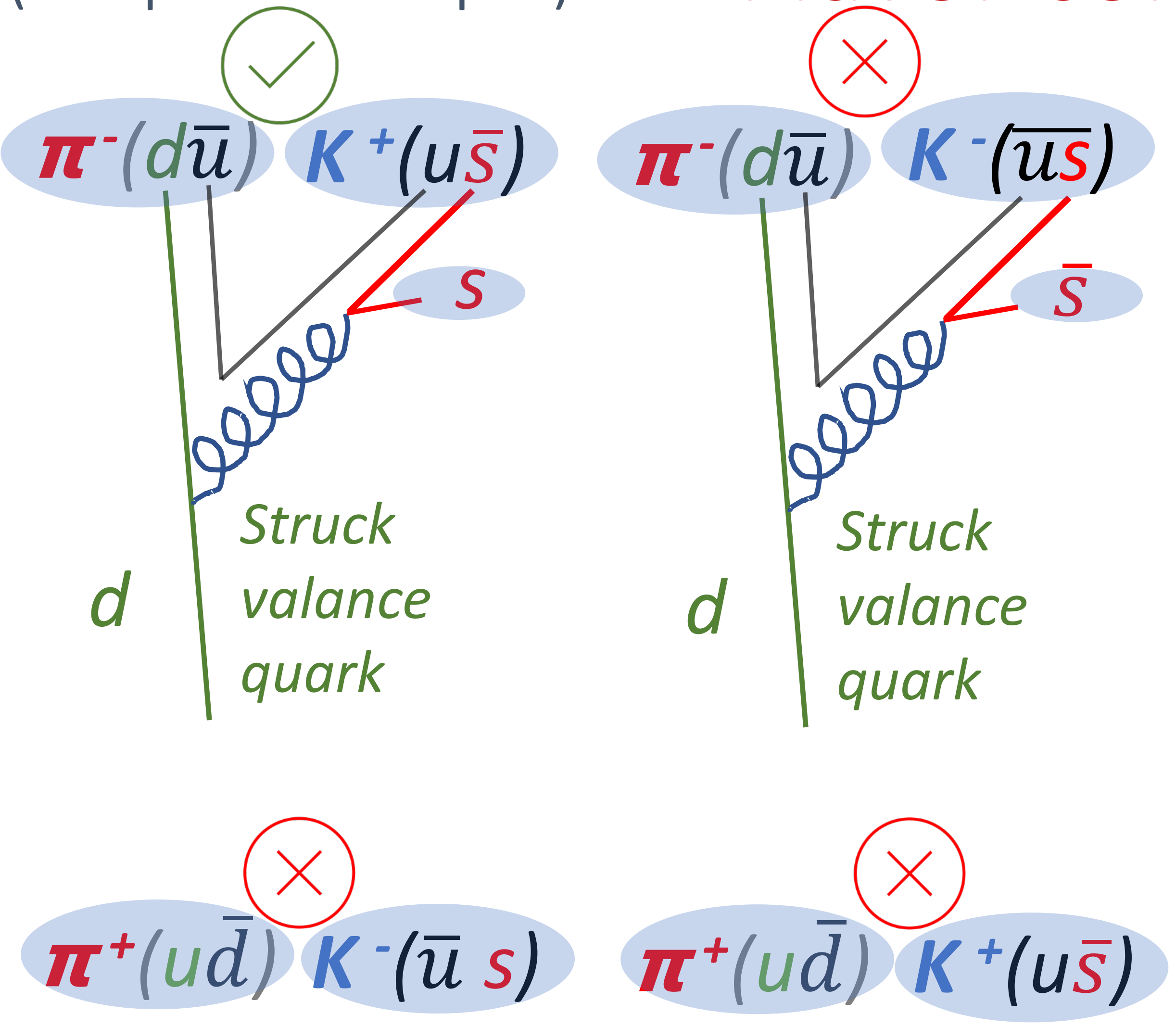
In general, $\boldsymbol{r_c}$ shows strong flavor dependence and we explore further the utility of **strange flavor tagging :**

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

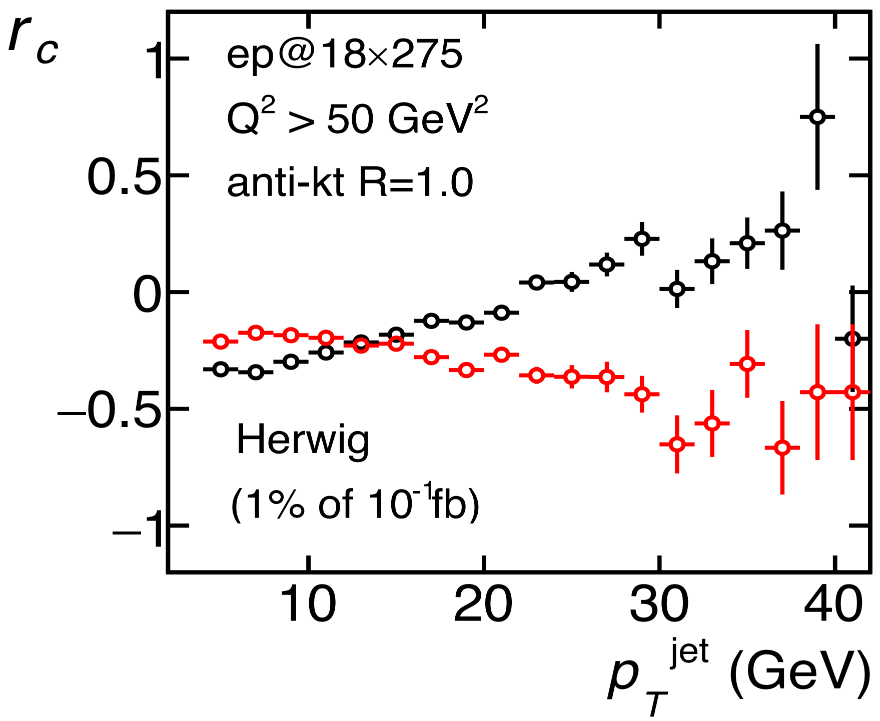
(sea quarks make pair)

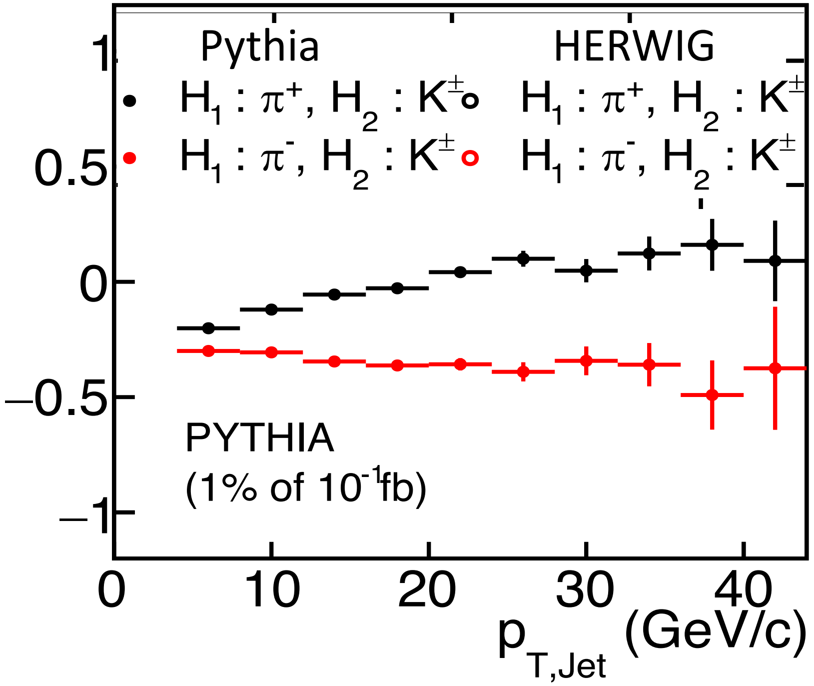


With struck valance quark, $L(\pi^-)$ $NL(K^+)$ is preferable for the simplest string breaking between L and NL particles

- 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





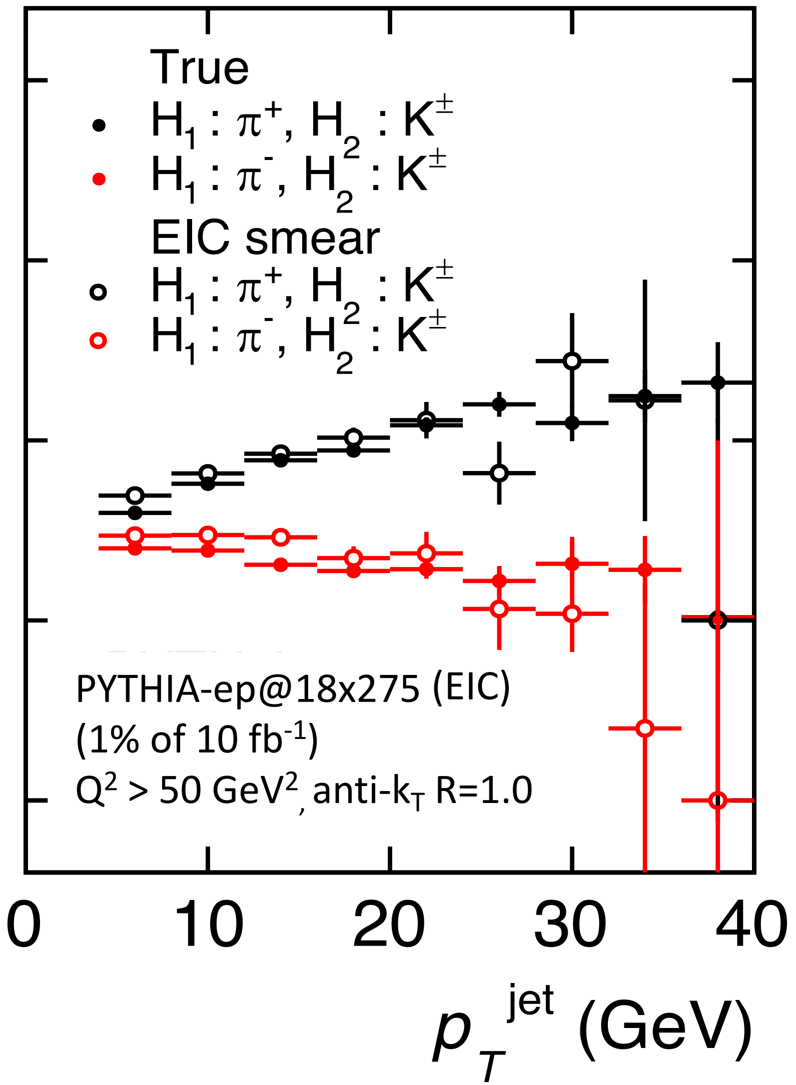
- Correlations are much stronger for $\pi^-K^\pm$ than for $\pi^+K^\pm$ in PYTHIA
- As p_T increases $\pi^+K^\pm$ correlations weakens whereas $\pi^-K^\pm$ strengthens
- Significant difference between PYTHIA and Herwig

Measurements with available data and future experiments

Measurement of r_c

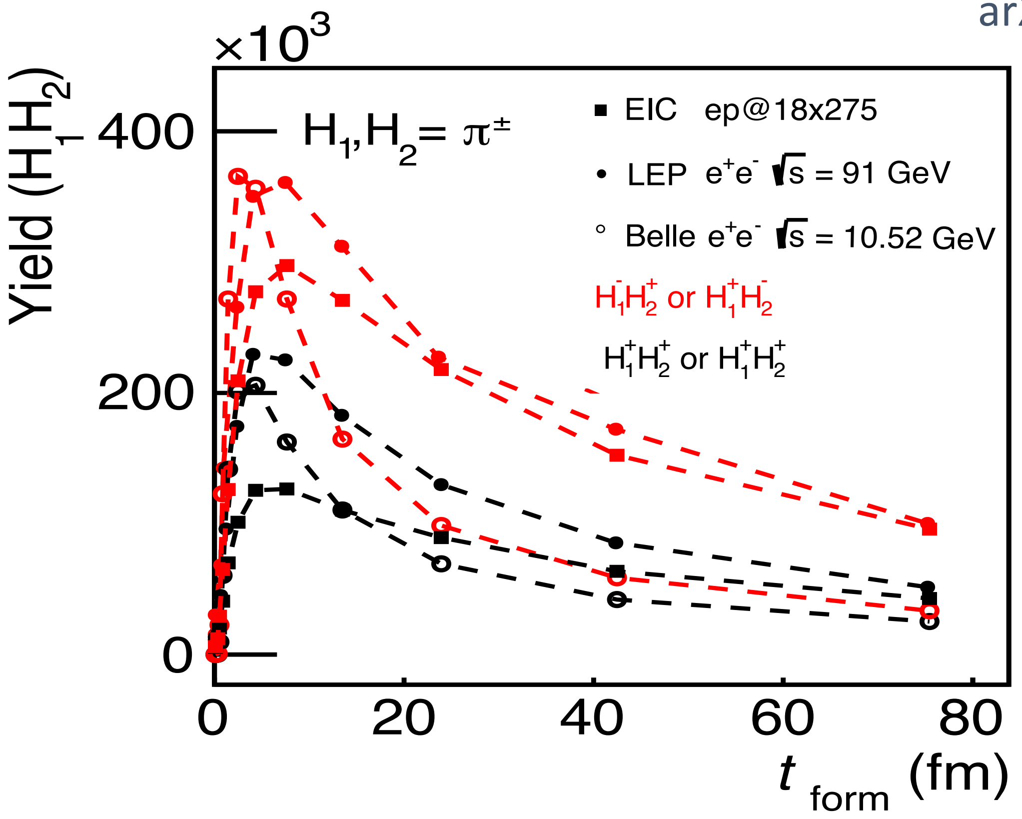
- **EIC (flavor) in future**, Belle (flavor)
- Charge correlations at LEP, H1, RHIC, LHC

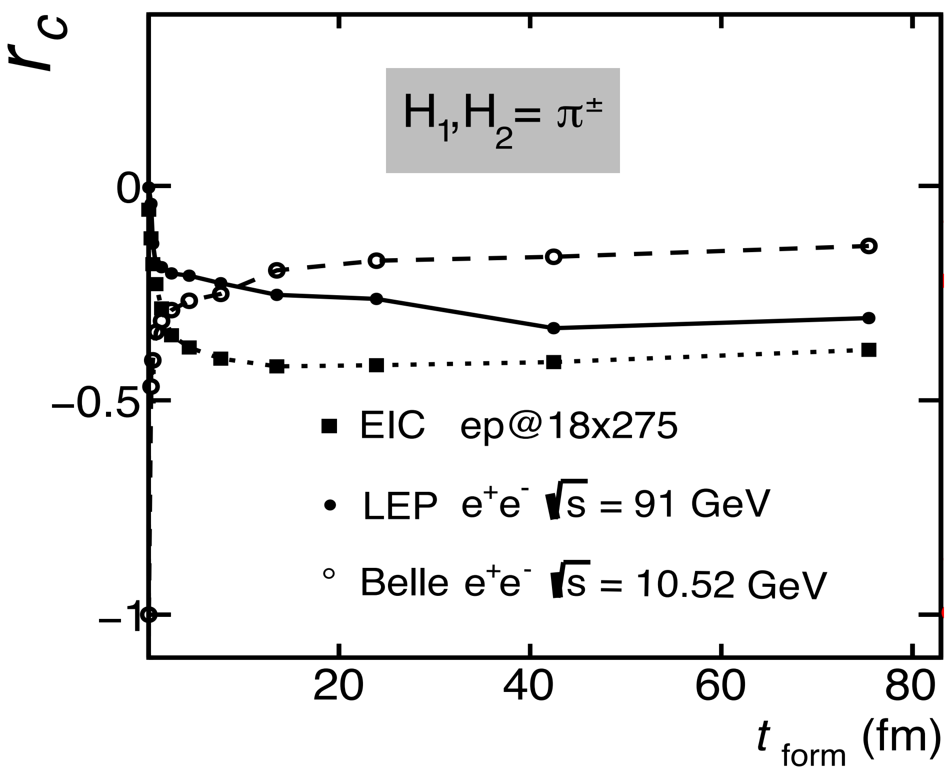
- **An *early* impactful measurement at EIC :**
  - ➢ Detector smearing does not affect this observable in a significant way
- **Unique Opportunity at EIC** :
  - ➢ RHIC and HERA has limitations to identify π and **K** at high momentum
  - ➢ Particle identification requirement (~10 GeV/c for π**/K**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



Belle can measure flavor correlations

arXiv:2204.02280





- Belle t_{form} peak appear early
- Belle might be mostly lie in nonperturbative region
- There is ongoing Belle effort to measure r_c

Measurement at H1

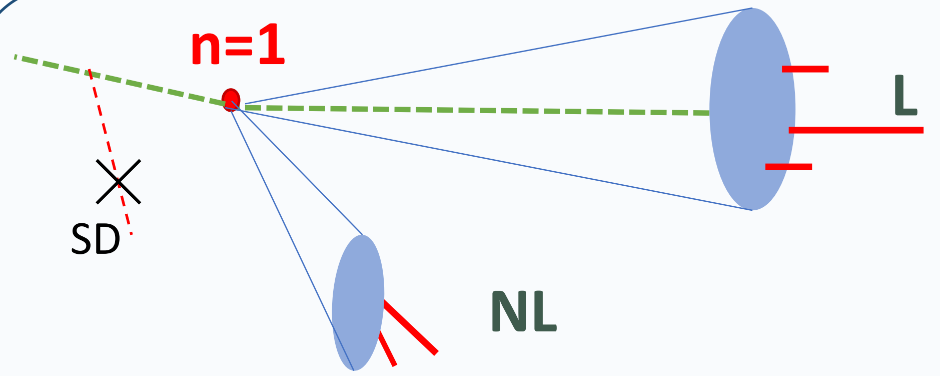
***r_c* is measured for**

✓ L and NL charged particles

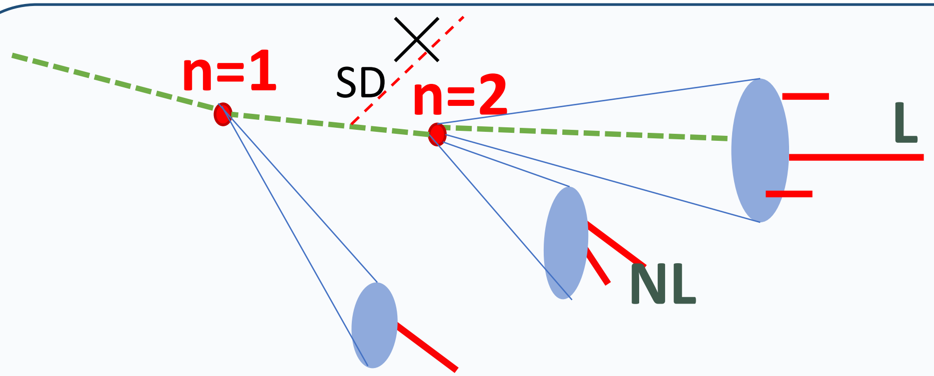
✓ n_R=1. (1st prong)

✓ n_R=2, n_R=3, n_R=4, ……. (2nd+ prong)

r_c for subjets



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



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

- L, NL particles are strongly correlated with the hardest patron
- Prong structure represent the partonic proxy
- **Charge of a subjet** is the charge of its leading particle

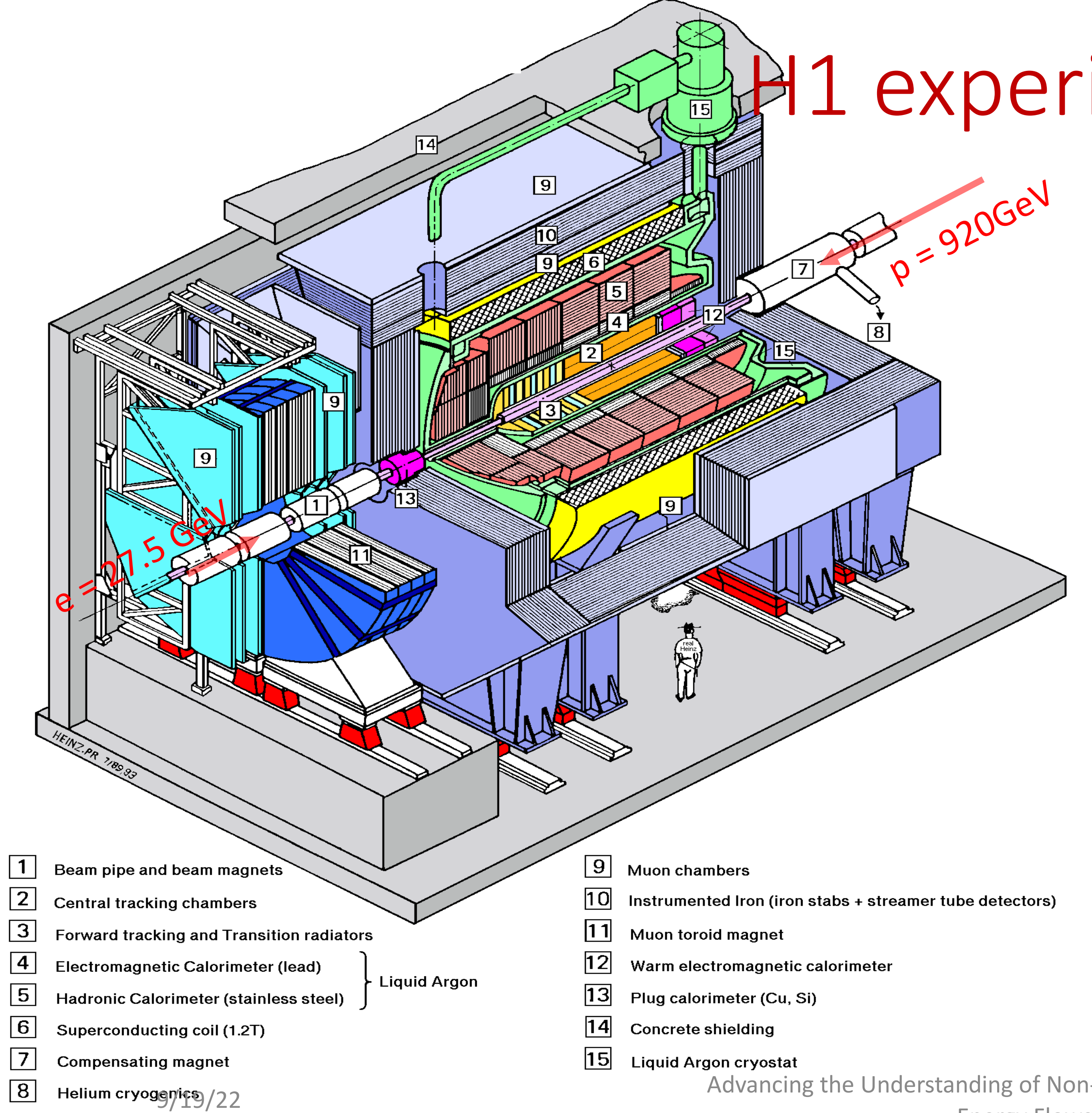
Using Recursive soft drop

- JHEP06(2018)093

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

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

H1 experiment



Liquid Ar Calorimeter

$\sigma/E \approx 11\%/\sqrt{E_{e.}} \oplus 1\%$ (electromagnetic)

$\sigma/E \approx 50\%/\sqrt{E_h} \oplus 3\%$ (hadronic)

CTD

Single Track resolution

$\sigma p_T / p_T = 0.2\%\ p_T/\text{GeV} \oplus 1.5\%$

$\sigma_\theta = 1$ mr

(magnetic field = 1.16 T)

Data : 2004-2007

$\sqrt{s} = 319$ GeV, $\mathcal{L} = 361\ \text{pb}^{-1}$

Event selection and Jet reconstruction

Technical cuts :

-30 cm < zVertex < 30 cm

45 GeV< E-pz < 65 GeV

DIS kinematics :

$Q^2 > 150\ GeV^2$

0.2< y < 0.7

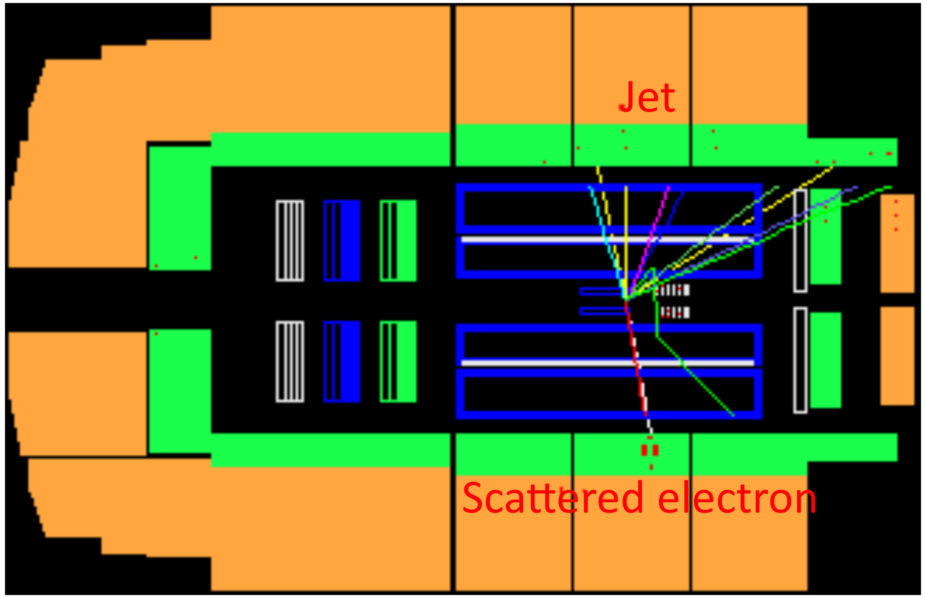
Jet Reconstructions : (Lab frame)

Tracks and clusters : $p_T > 0.2$ GeV/c

anti-kt R = 1.0

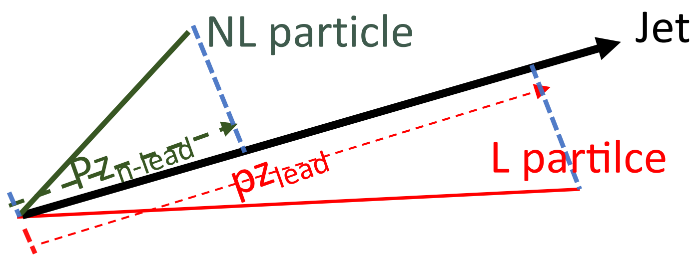
$p_{T,Jet} > 5.0$ GeV/c

$-1.5 < \eta_{T,Jet} < 1.5$

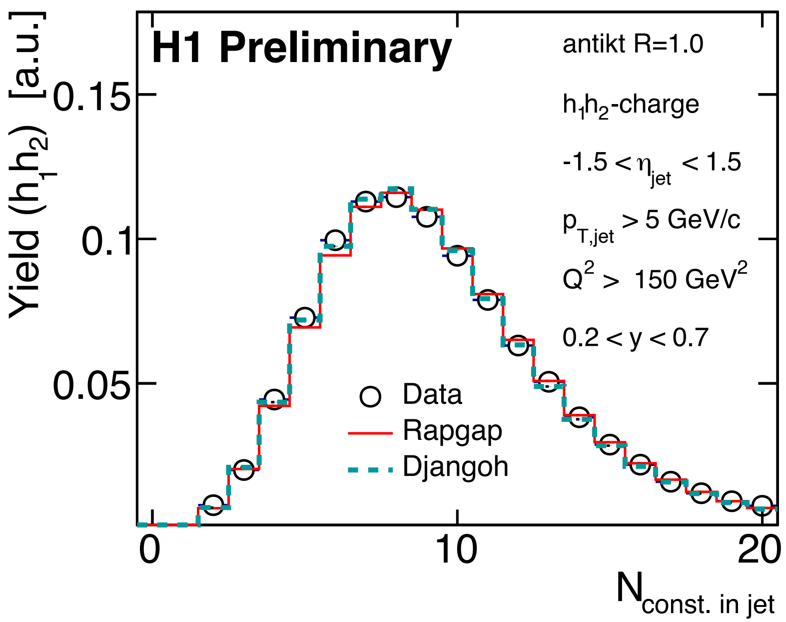


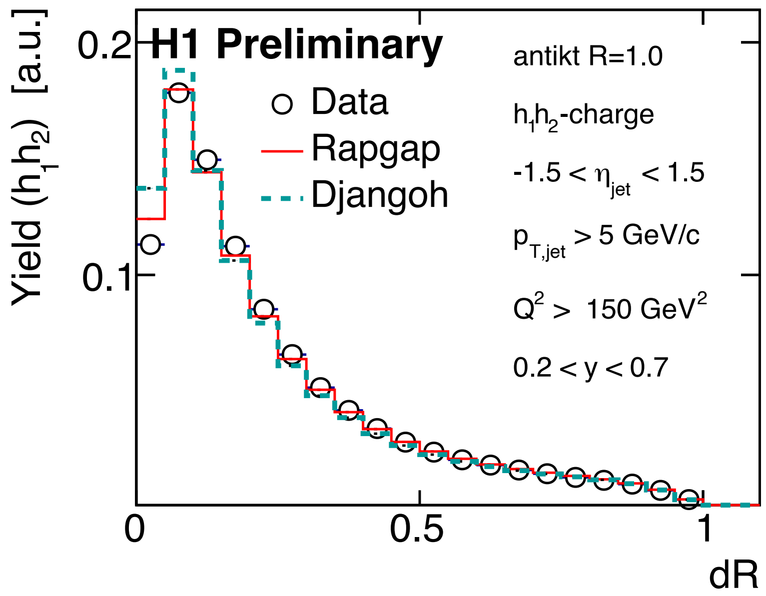
- ✓ The leading and next-to-leading constituents of the jet are selected by their momentum along the jet axis.
- ✓ Both the leading and the next-to-leading constituents are required to be charged (CTD track)

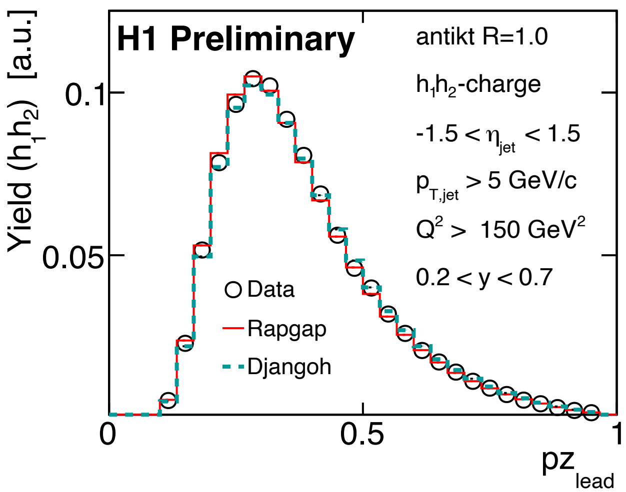
Constituents in Jet

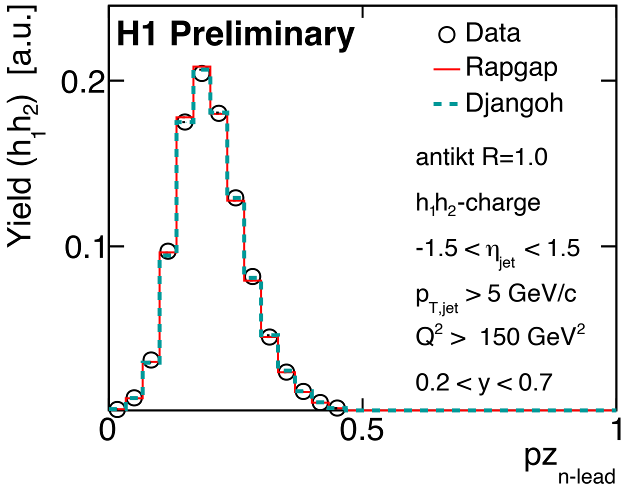


anti-kt R = 1.0 , $p_{T,Jet}$ > 5.0 GeV/c , -1.5 < $\eta_{T,Jet}$ < 1.5 and L,NL charge tracks



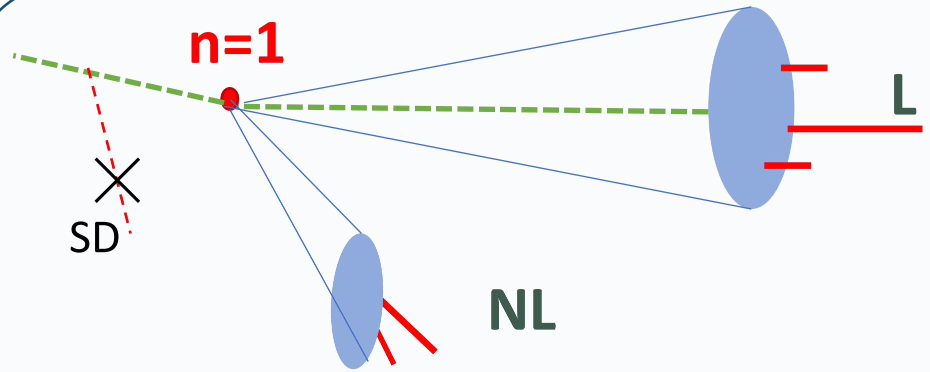




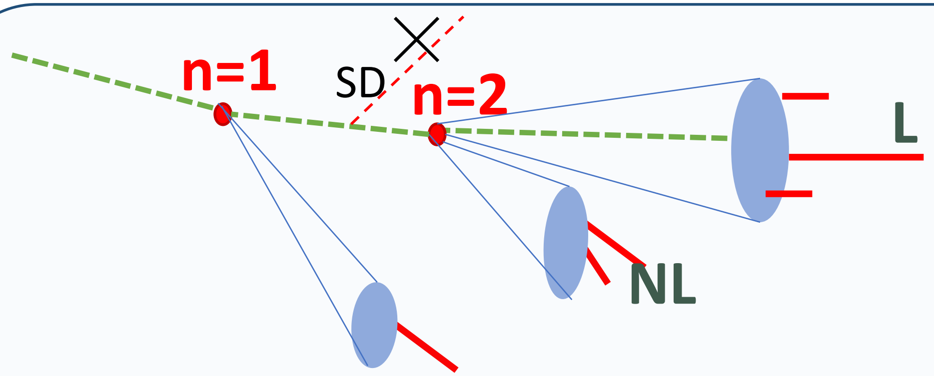


- ✓ Required two leading particles in jets to be charged
- ✓ Djangoh and Rapgap reproduce the DATA distributions well

Measurement of r_c at different prongs



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

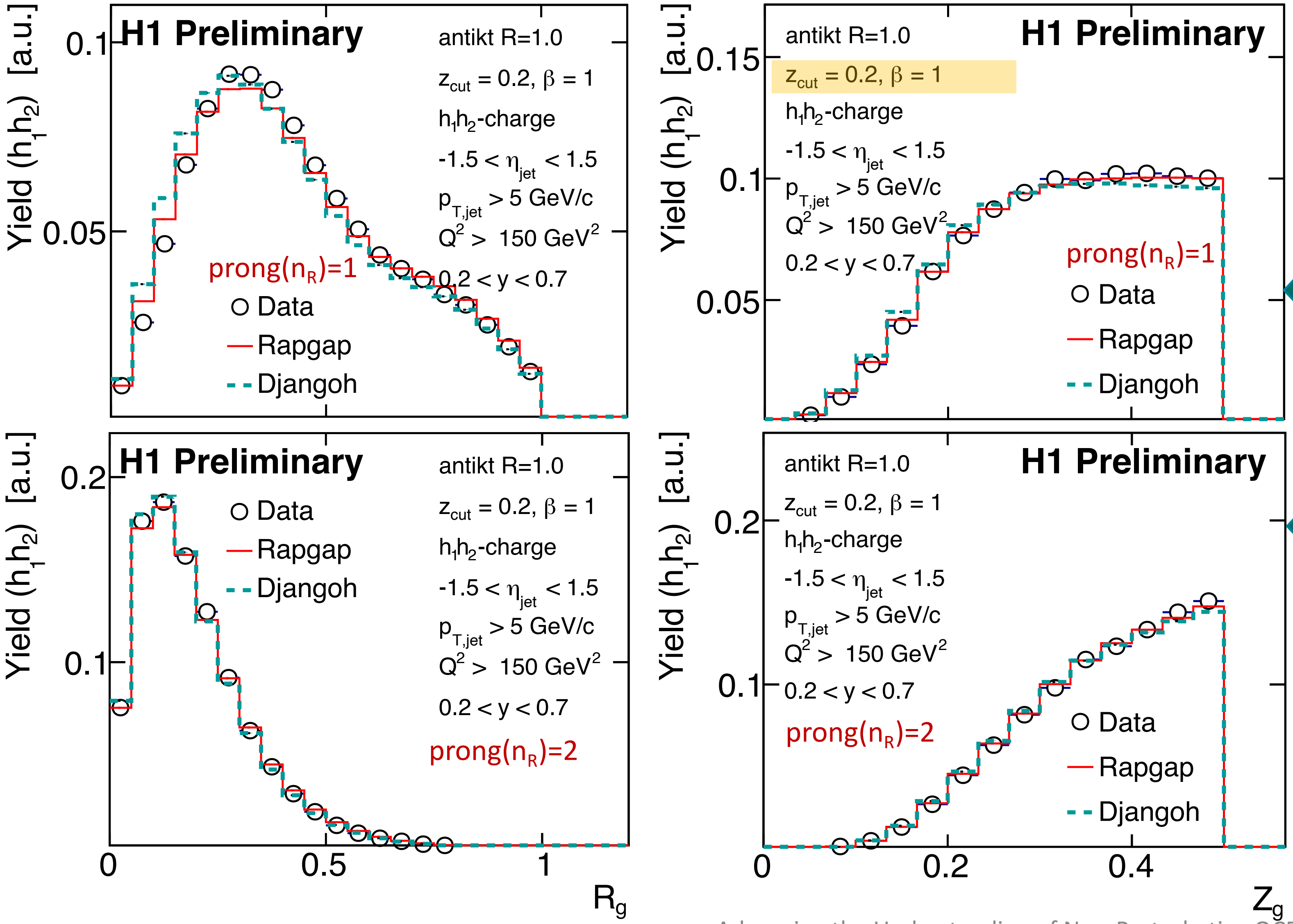


L and NL particle get **resolved in the second prong (n_R = 2)**

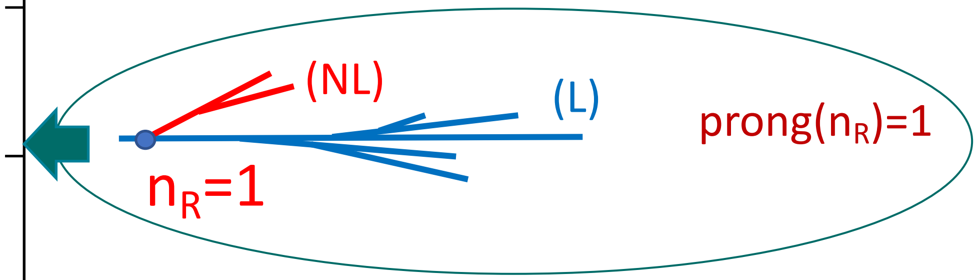
We will measure

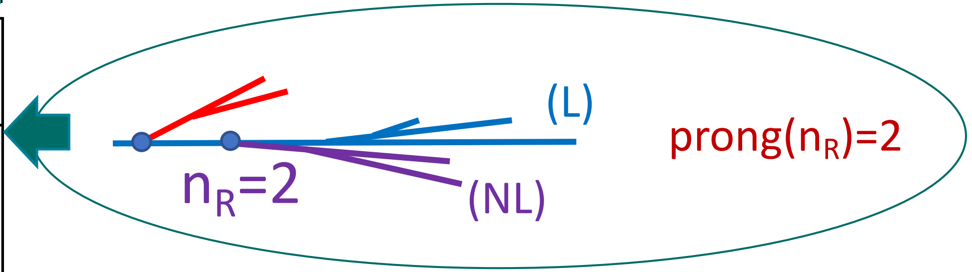
- ✓ r_c for L and NL particles
- ✓ r_c for n_R=1. (1st prong)
- ✓ r_c for n_R=2, n_R=3, n_R=4, ……. (2nd+ prong)

Prong R_g and Z_g distributions



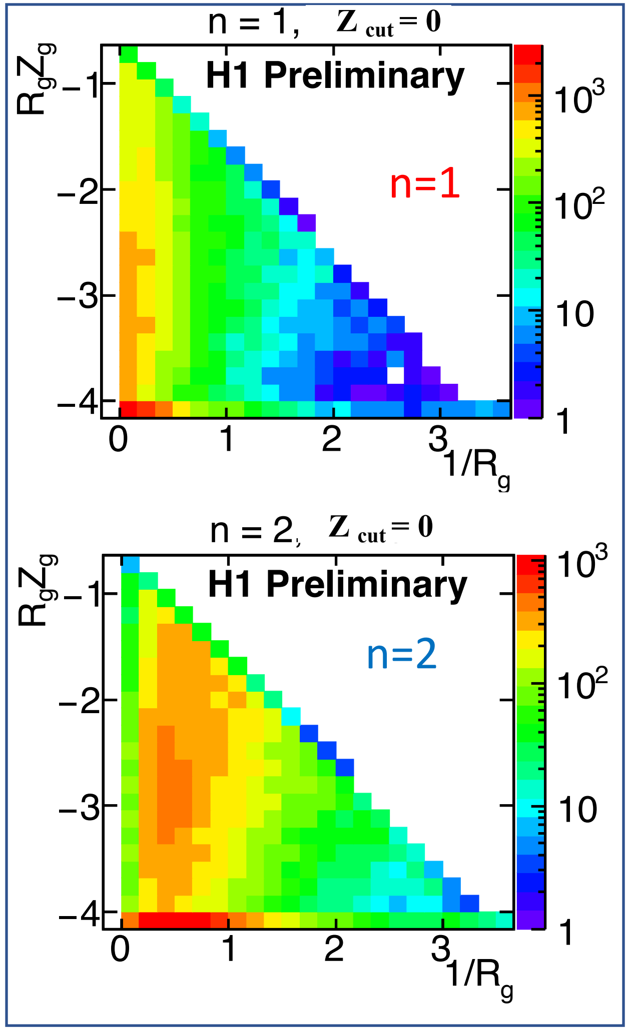
$$z_{12} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}, \qquad z_{12} \equiv \frac{\min(p_{t,1},p_{t,2})}{p_{t,1}+p_{t,2}}$$





✓ R_g of the 1st split is wider and relatively carrying small Z_g compared to the 2nd+ splits

Correlating L&NL particles with prongs



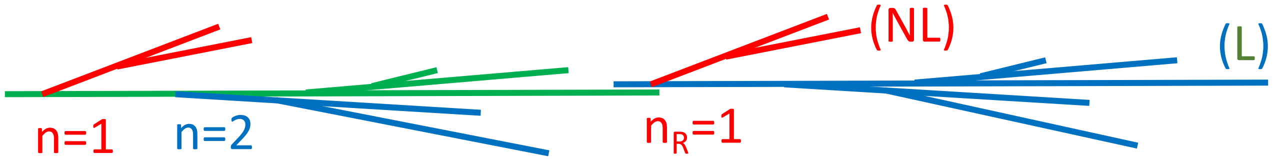
Leading and next-to leading particles are not correlated

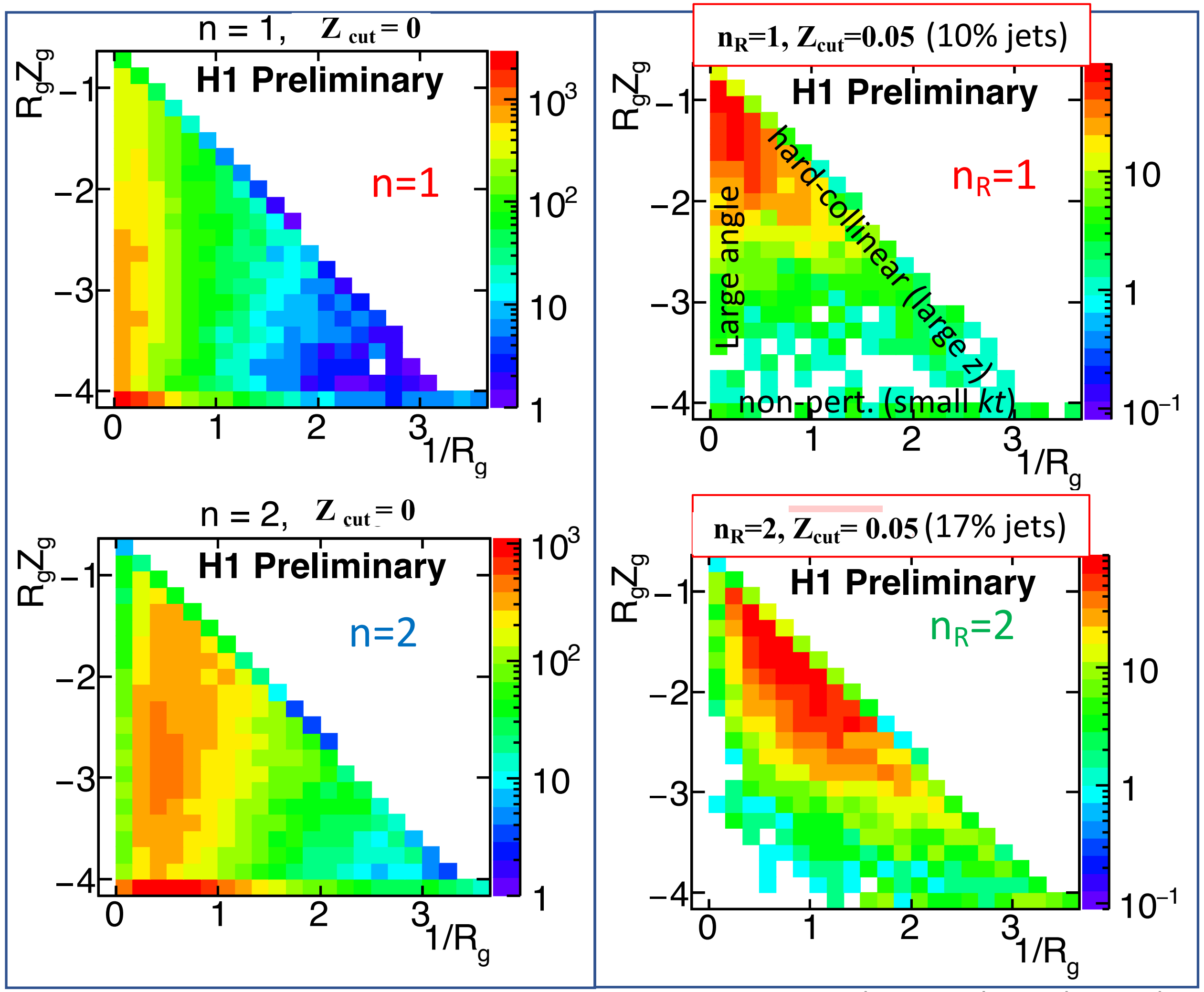
$$z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

$$z_{12} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

First split with small z_{cut} = 0 are large angle soft radiations

Correlating L&NL particles with prongs





Leading and
next-to-leading
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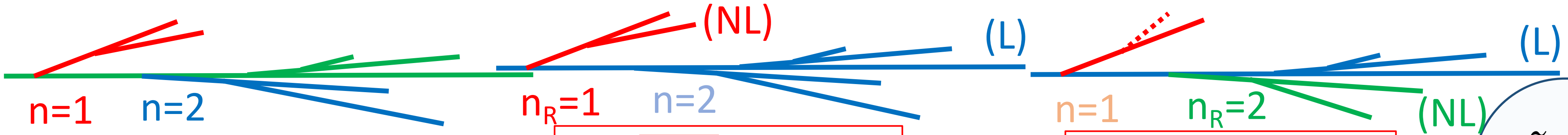
$$z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

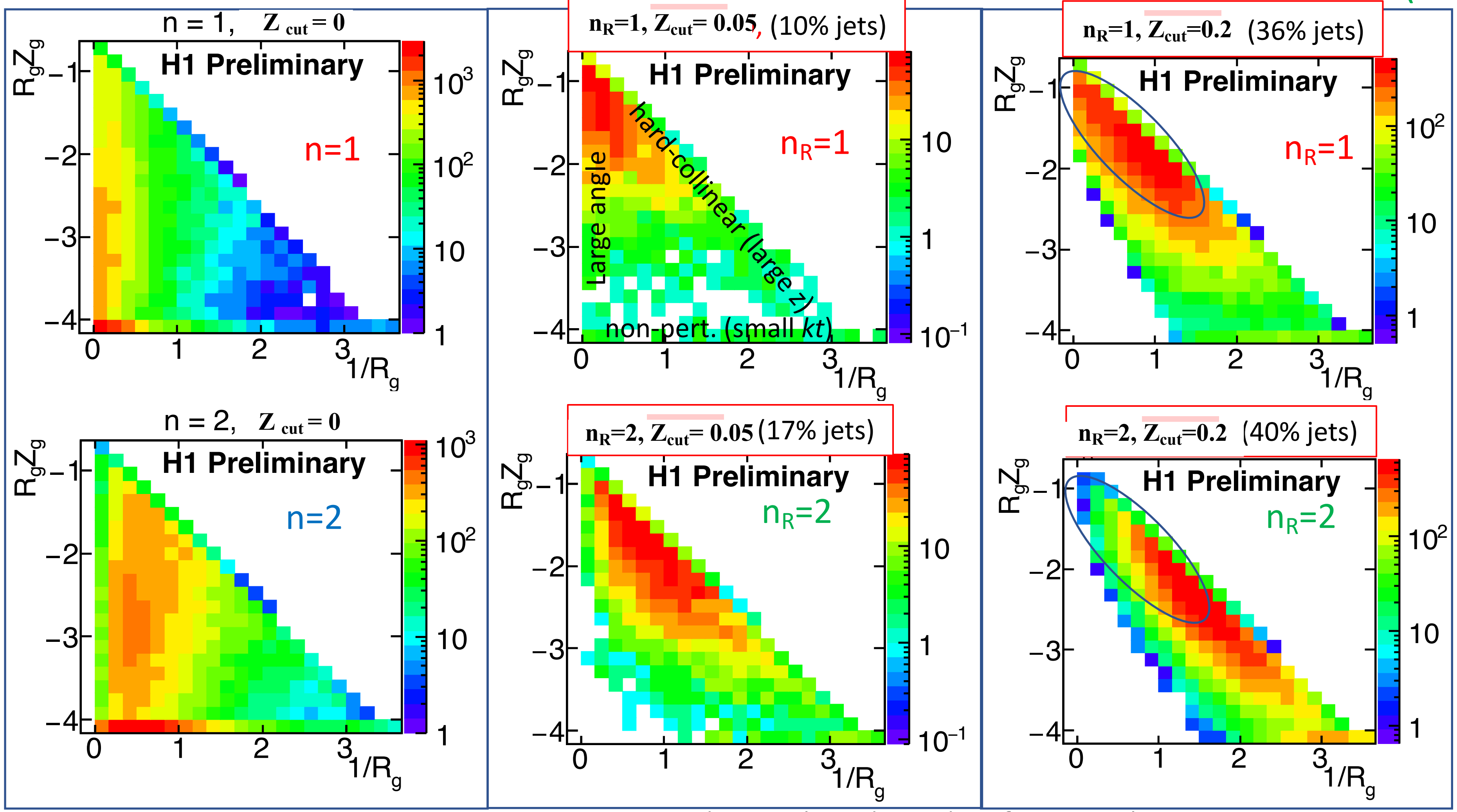
$$z_{12} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

First split with small z_{cut} = 0 are large angle soft radiations

Small fraction of n=1 is in the n_R=1 class

Correlating L&NL particles with prongs





$$z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

$$z_{12} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

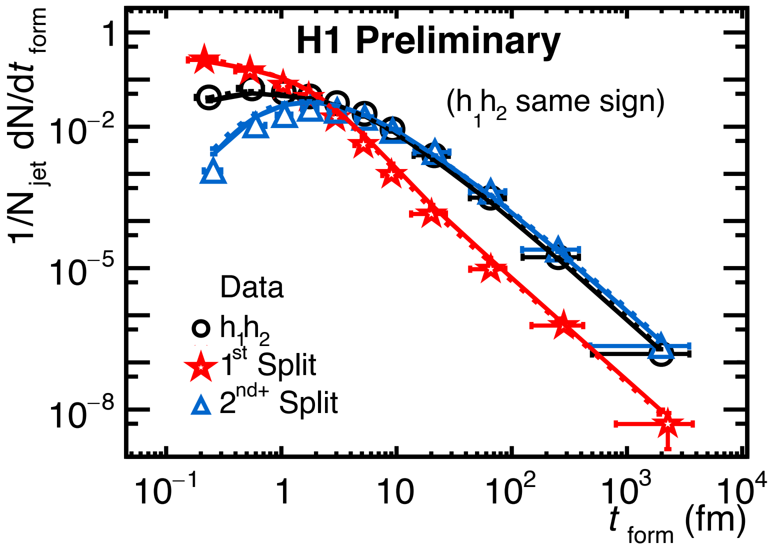
First split with small z_{cut} = 0 are large angle soft radiations

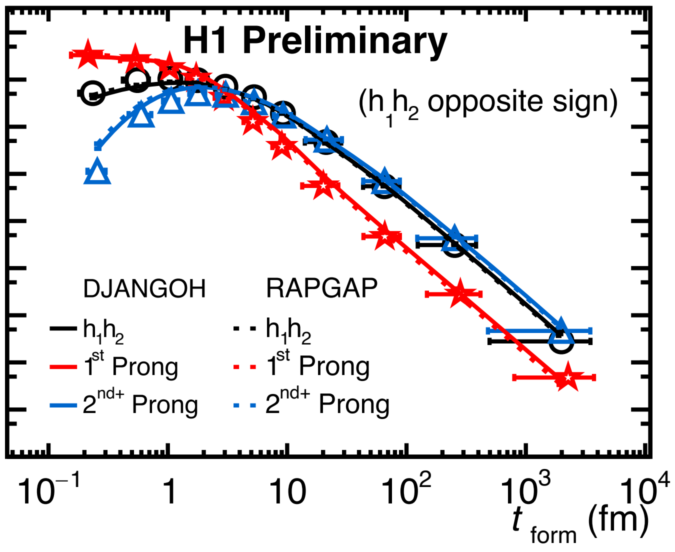
Small fraction of n=1 is in the n_R=1 class

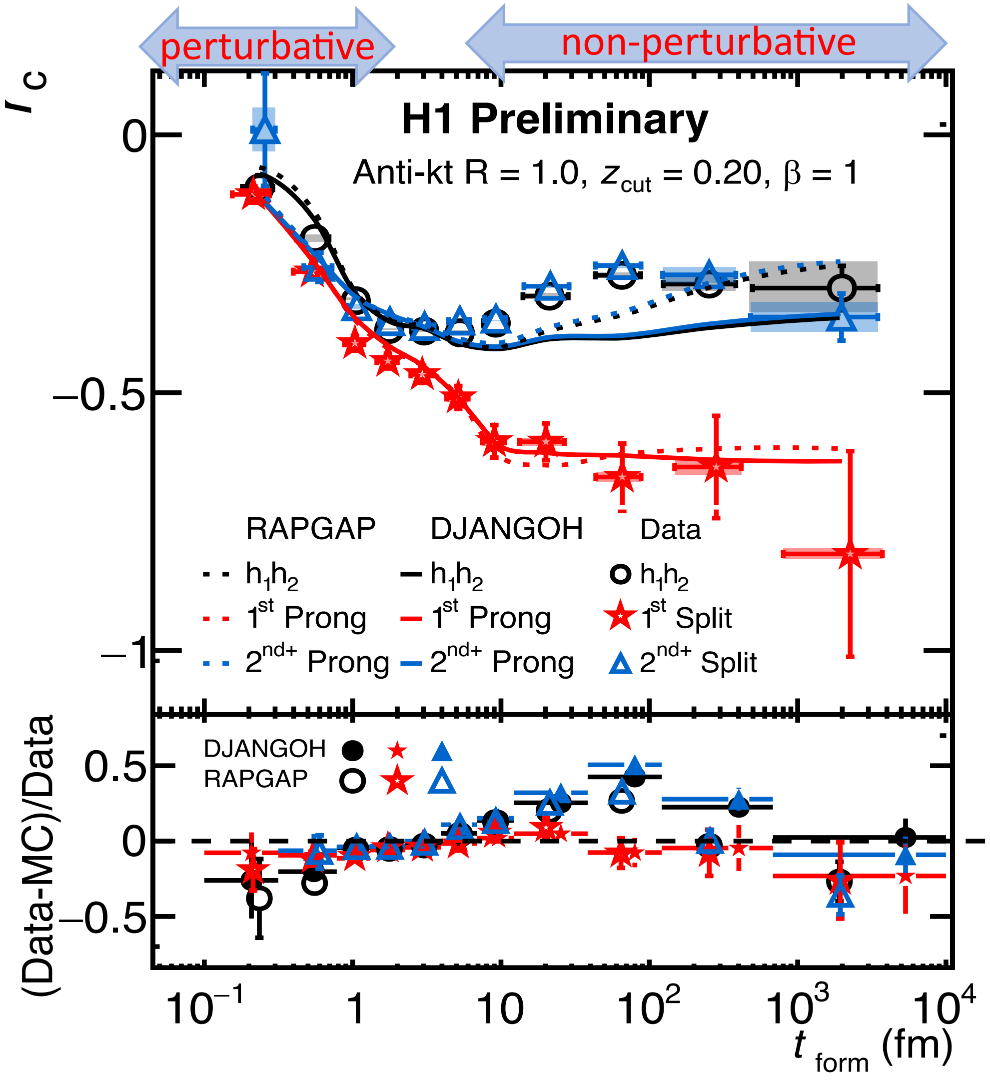
z_{cut} = 0.2 redistribute between n_R=1 class and n_R=2+ classes so that n_R=1 would have sufficient events which are relatively wider angle radiations.

r_c with formation time

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





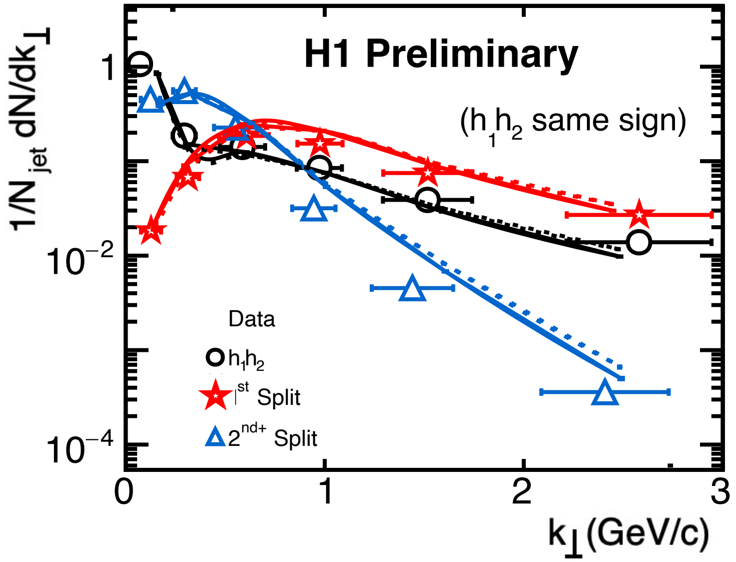


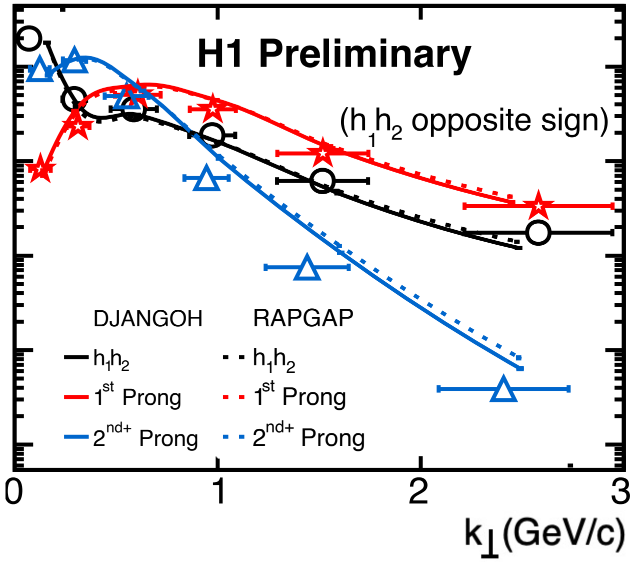
- ✓ Density of leading pairs in small formation time is much large in the 1st split compared to that of later splits.
- ✓ Large decorrelations is seen in r_c at small formation time (< 1 fm)
- ✓ At large formation time r_c is stronger for 2nd+ splits compared to that of 1st split
- ✓ Rapgap and Djangoh values are comparable to data

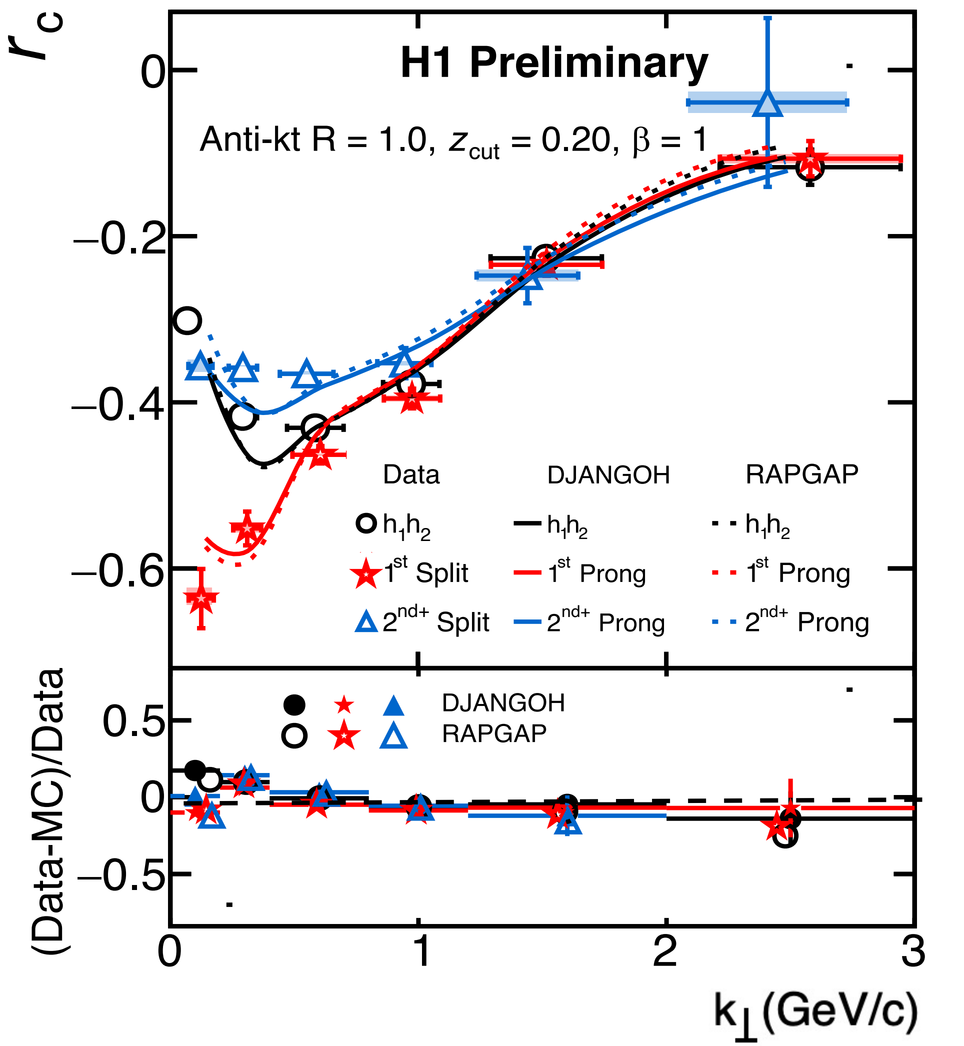
(Error band : bin-by-bin corrections from two different MCs)

r_c with $k_\perp$

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





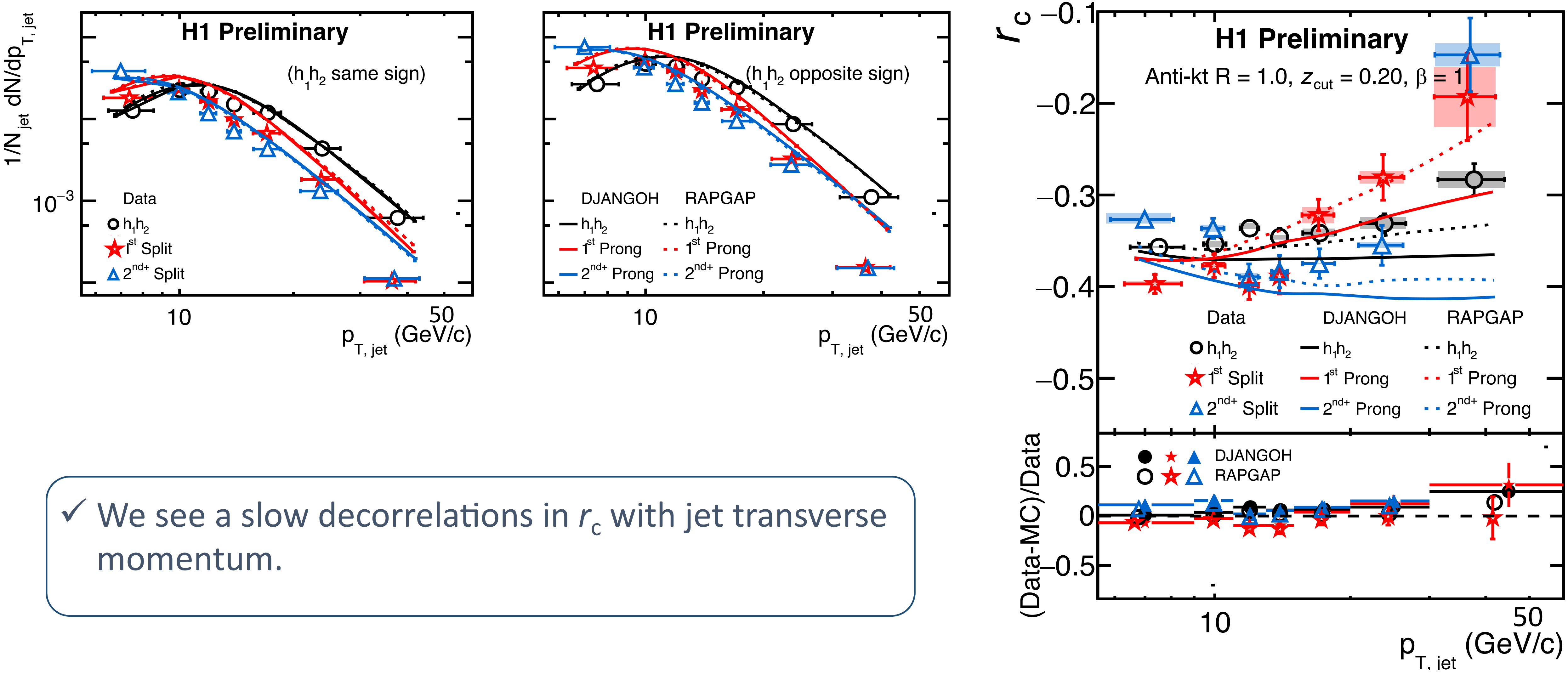


(Error band : bin-by-bin corrections from two different MCs)

- ✓ 1st split mean value is large $k_\perp$ compared to 2nd+ splits
- ✓ Small $k_\perp$ belong mostly in nonperturbative domain and r_c is large. Large $k_\perp$ are related mostly to early gluon splits and r_c is approaching to zero
- ✓ Small $k_\perp$ corresponds to large formation time and stronger correlation observed in the 1st split

r_c with $p_{T,jet}$

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



(Error band : bin-by-bin corrections from two different MCs)

✓ We see a slow decorrelations in r_c with jet transverse momentum.

Summary and Outlook

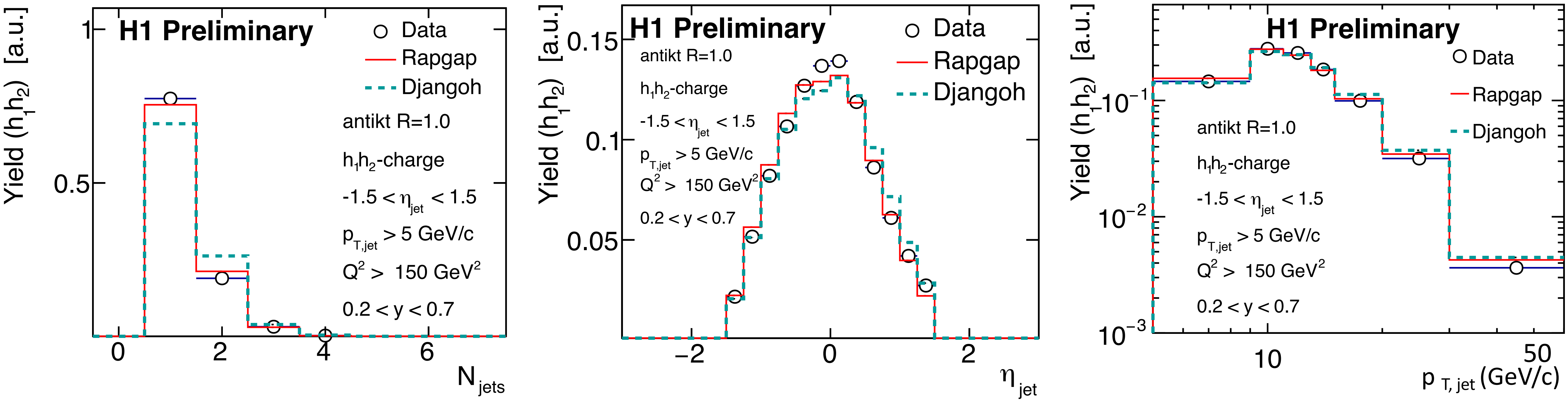
- The observable r_c can probe dynamics of hadronization and the observables like formation time and $k_\perp$ it sensitive to the perturbative-nonperturbative transition.
- Flavor correlations can be studied at EIC in details and tagging strange flavor is sensitive to string picture of hadronization.
- $\boldsymbol{r_c}$ is measured with formation time and $k_\perp$ using leading charged tracks at H1 for the first time. Partonic correlations is made by measuring $\boldsymbol{r_c}$ **for** subjets obtained from recursive soft drop technique.
- r_c for prongs are sensitive to the level of splits. We see r_c is small in the perturbative region and large in nonperturbative region.
- Rapgap and Djangoh follow the trend to the data and correlations are comparable.
- The correlations might be sensitive to fragmentation in medium (nuclear or hot QCD). The observable might be sensitive to medium formed in heavy ion collisions. Measurements are possible for LEP, BELLE, HERA, RHIC and LHC and EIC

Thank you!

backup

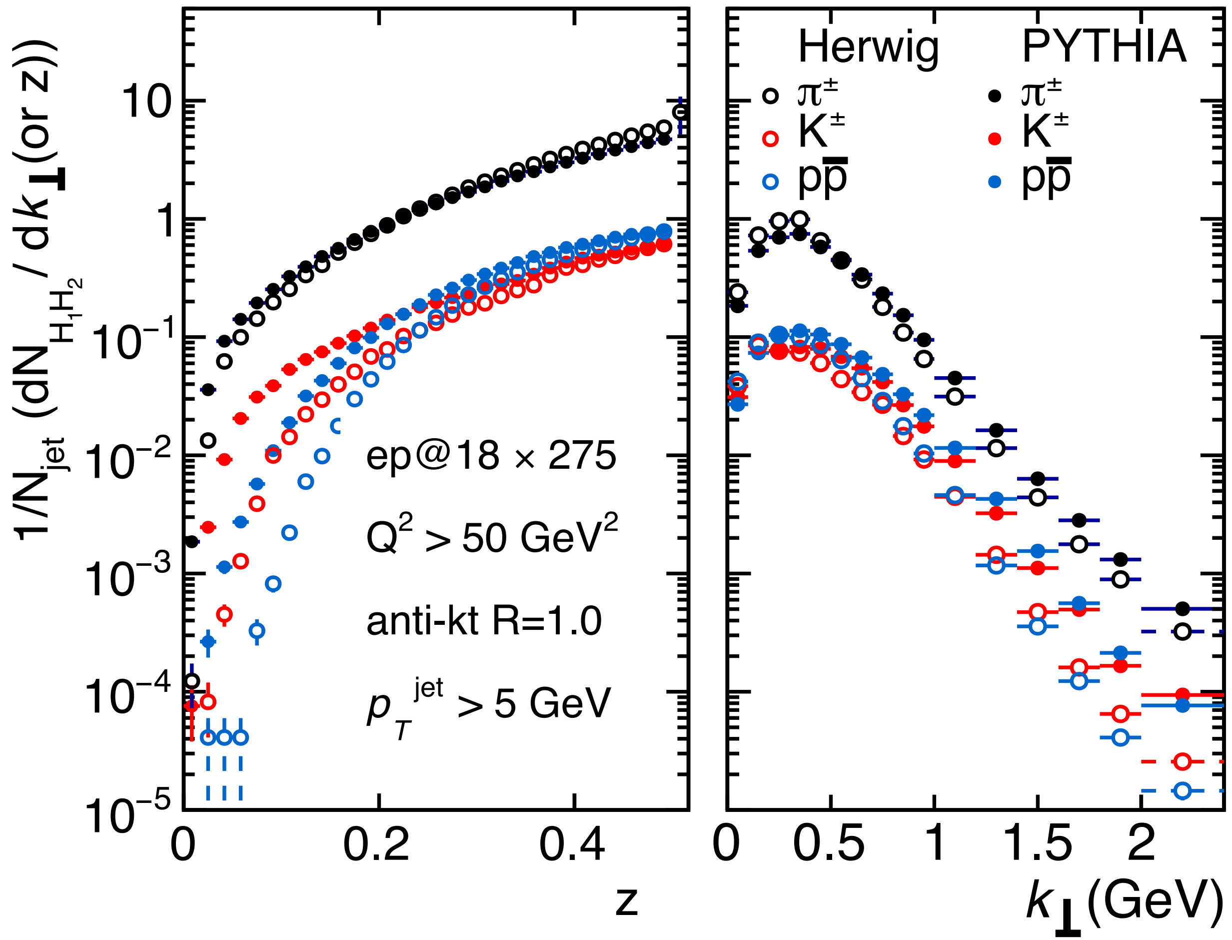
Reconstructed Jets

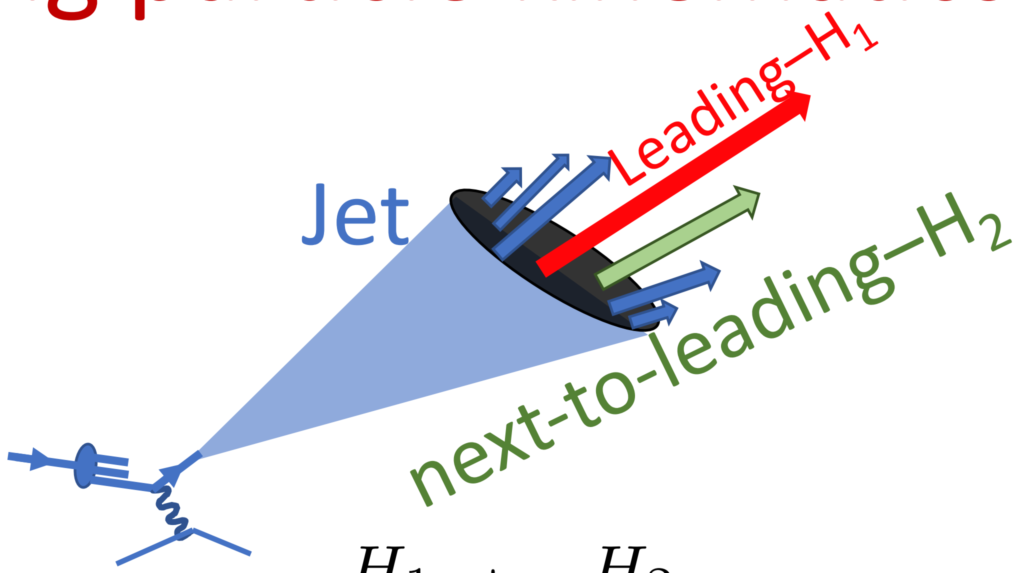
anti-kt R = 1.0 , $p_{T,Jet}$ > 5.0 GeV/c , -1.5 < $\eta_{T,Jet}$ < 1.5 and L,NL charge tracks (Only the leading p_T jet is used for the analysis)



- ✓ Djangoh : Color Dipole Model + Lund string fragmentation and QED radiative corrections
- ✓ Rapgap : QCD matrix elements DGLAP based; with strongly ordered transverse momentum of subsequently emitted partons, + Hadronization : Lund string fragmentation like Pythia and QED radiations
- ✓ Djangoh and Rapgap reproduce the DATA distributions well (reconstruction level)

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

z =1/2 : nonperturbative dominated

$k_\perp$ < 200 MeV : intrinsically nonperturbative process

space–time picture of hadronization

arXiv:1808.04619v2

$$t_{\text{regen}} \sim \frac{\hbar c\, E}{p_\perp^2} = \frac{\hbar c}{p_\perp}\,\frac{E}{p_\perp} \sim \tau_{\text{regen}}\,\gamma$$

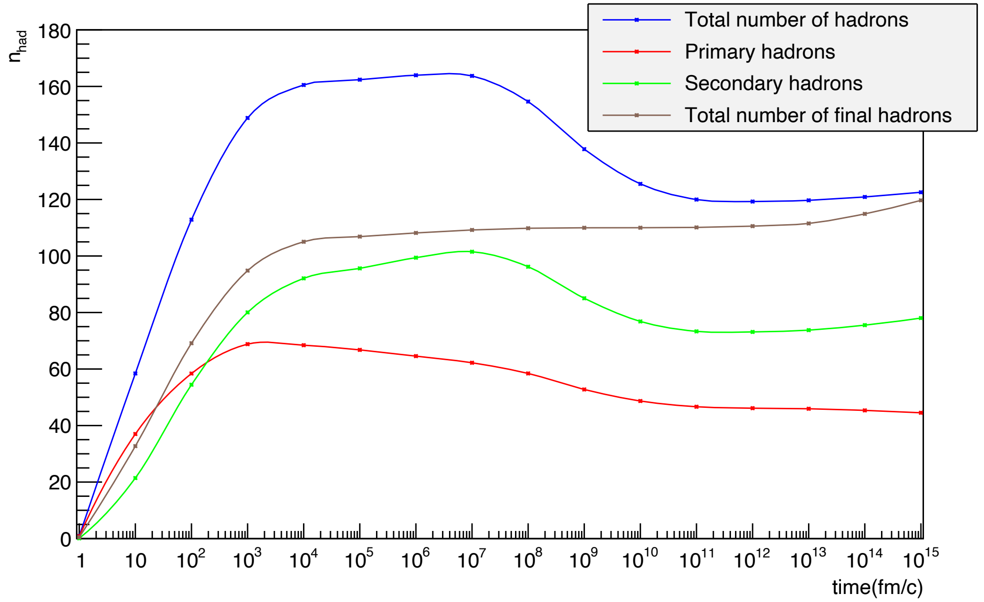
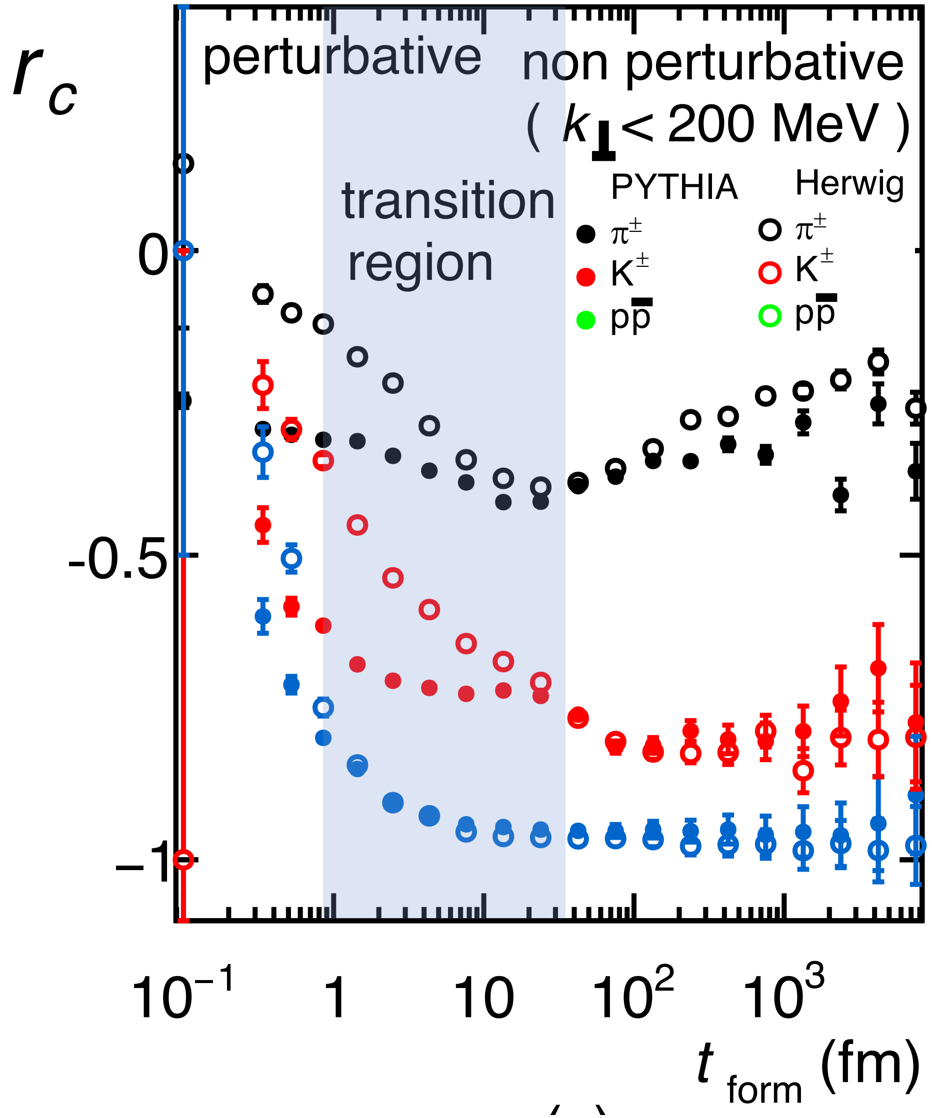


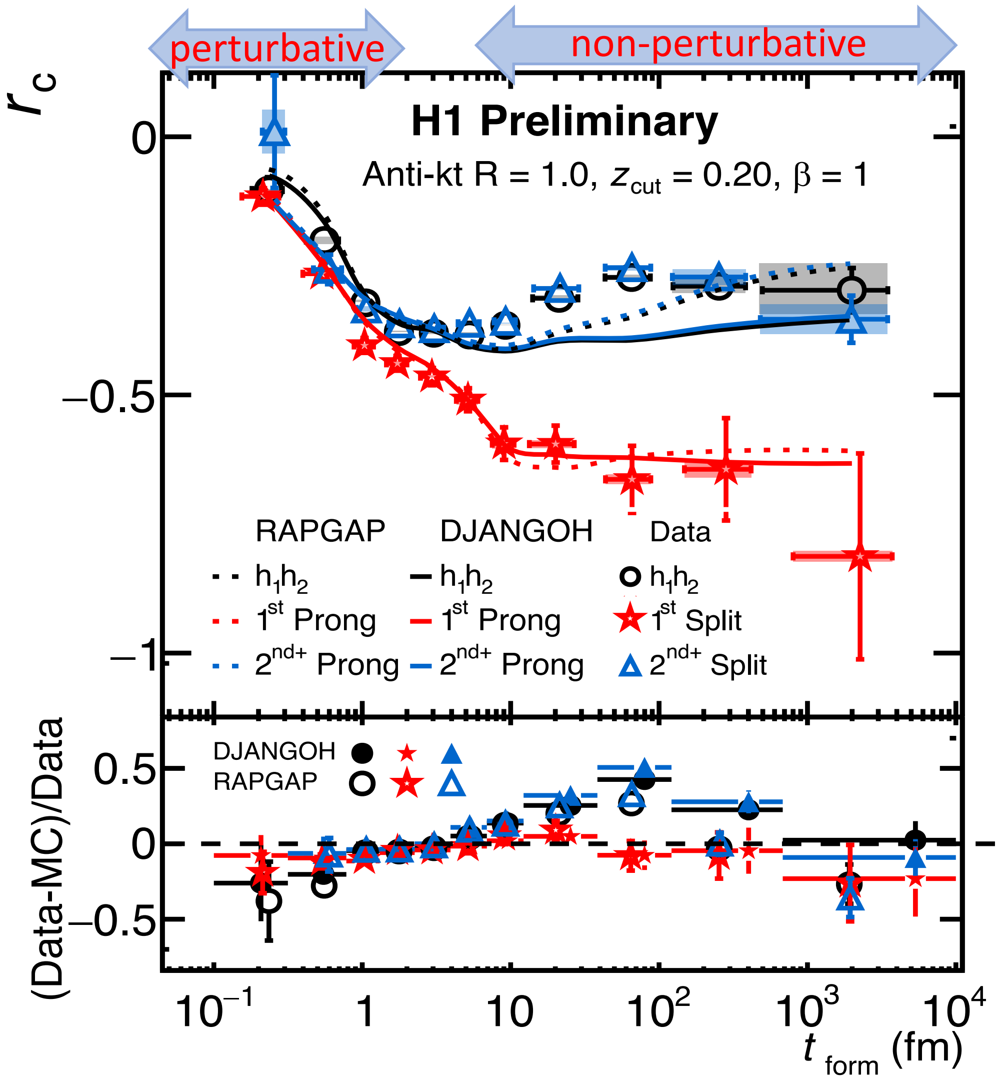
Figure 20: Hadron number per event as a function of time for 13 TeV pp collisions.

EIC



r_c
perturbative
non perturbative
($k_\perp$ < 200 MeV)
transition
region
PYTHIA
Herwig
$\pi^\pm$
$K^\pm$
$p\bar{p}$
0
-0.5
−1
10^{-1}
1
10
10^2
10^3
t_{form} (fm)

H1



perturbative
non-perturbative
r_c
H1 Preliminary
Anti-kt R = 1.0, z_{cut} = 0.20, β = 1
RAPGAP
DJANGOH
Data
h_1h_2
1^{st} Prong
2^{nd+} Prong
1^{st} Split
2^{nd+} Split
0
−0.5
−1
(Data-MC)/Data
DJANGOH
RAPGAP
0.5
0
−0.5
10^{-1}
1
10
10^2
10^3
10^4
t_{form} (fm)