Probing Hadronization Through Jet Substructure Analysis

ArXiv: arXiv:2212.11846v2

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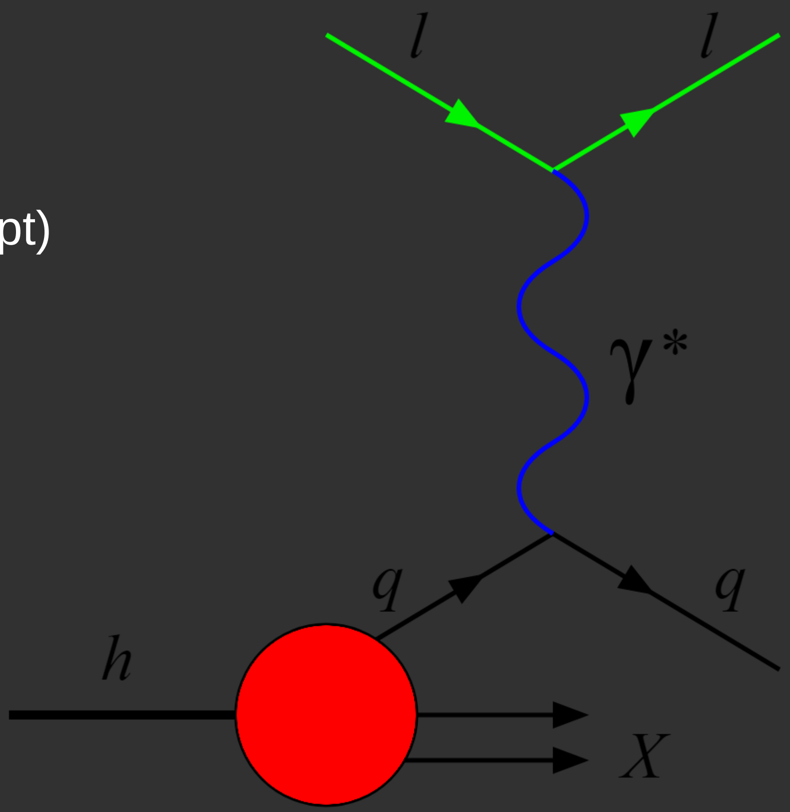

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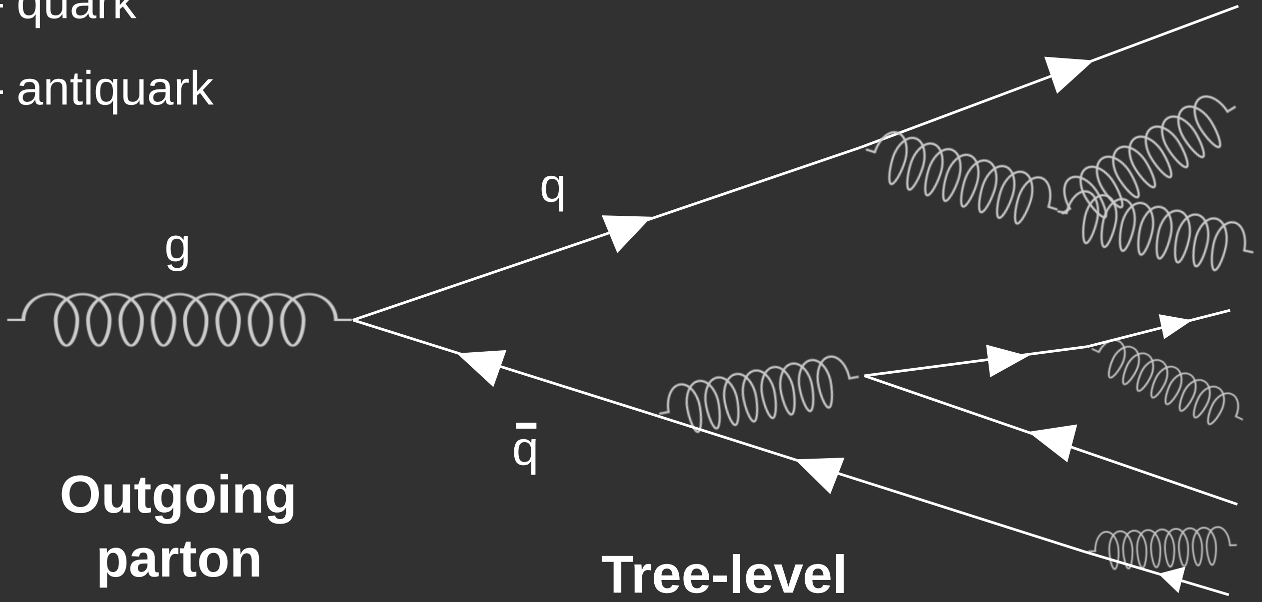
Collision Physics

g – gluon

q – quark

$\bar{q}$ – antiquark



Outgoing parton

Tree-level Parton Shower

Perturbative QCD

Collision Physics

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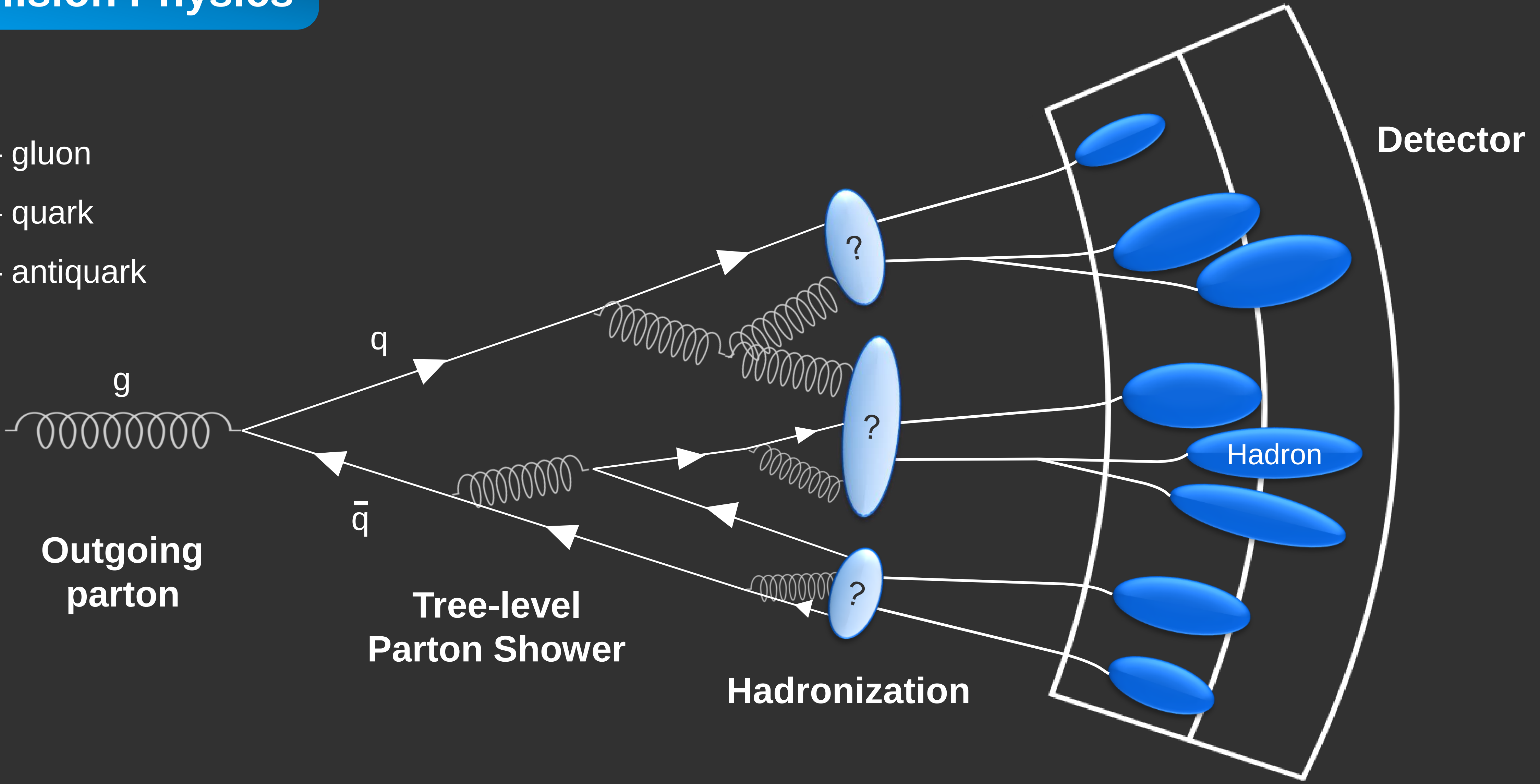


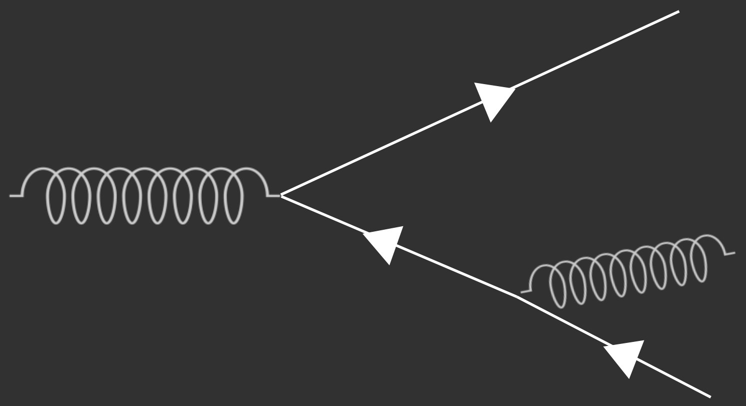
Perturbative QCD

Non-perturbative QCD

Hadronization Models

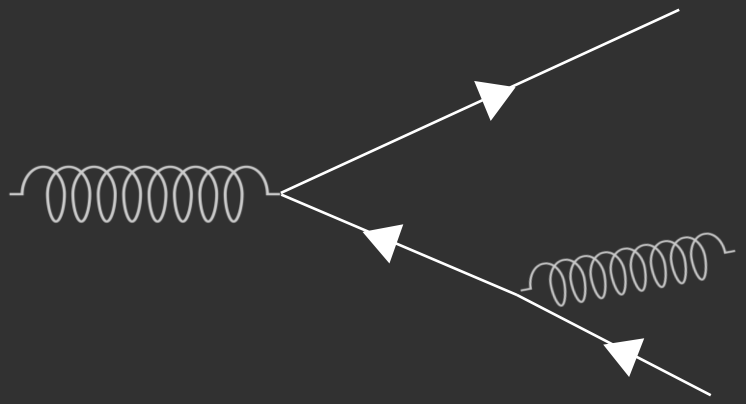
Lund String
(Pythia, Jetset)

[B. Andersson, G. Gustafson, and B. Soderberg, Z. Phys.C 20, 317 (1983)]



Cluster Fragmentation
(Herwig, Sherpa)

[D. Amati and G. Veneziano, Phys. Lett. B 83, 87 (1979)]



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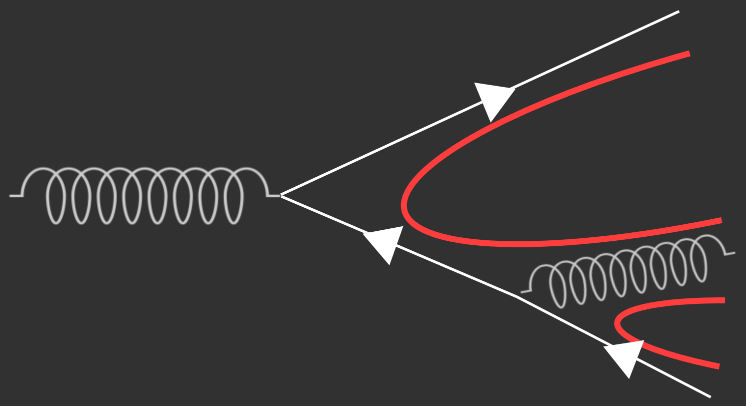

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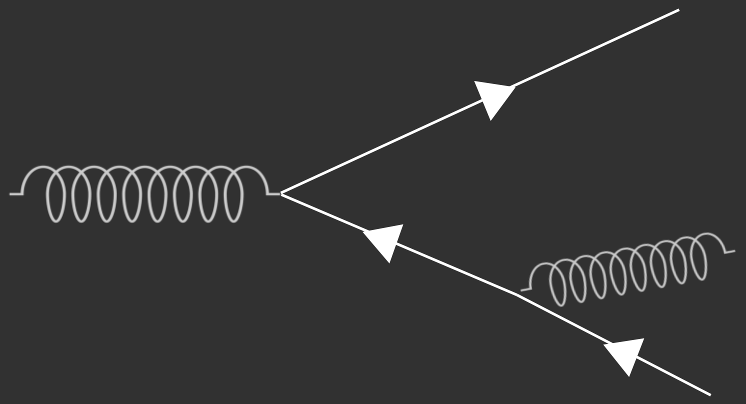

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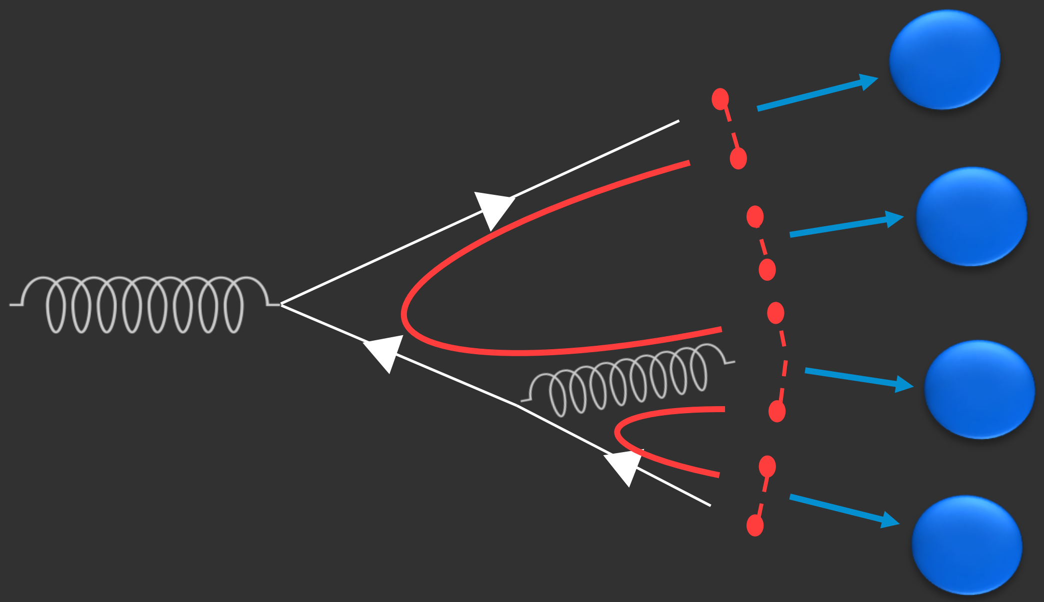

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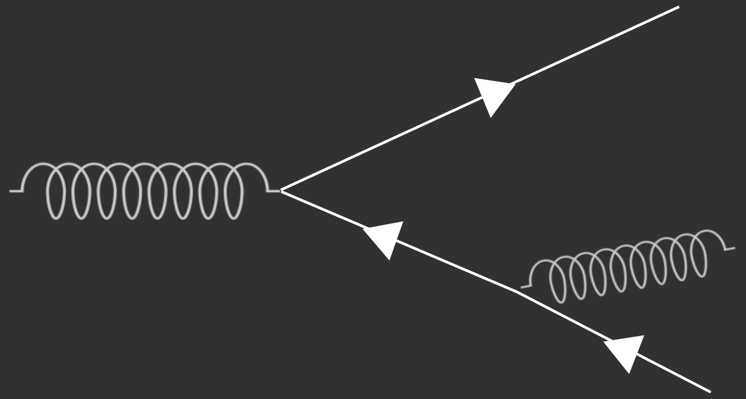

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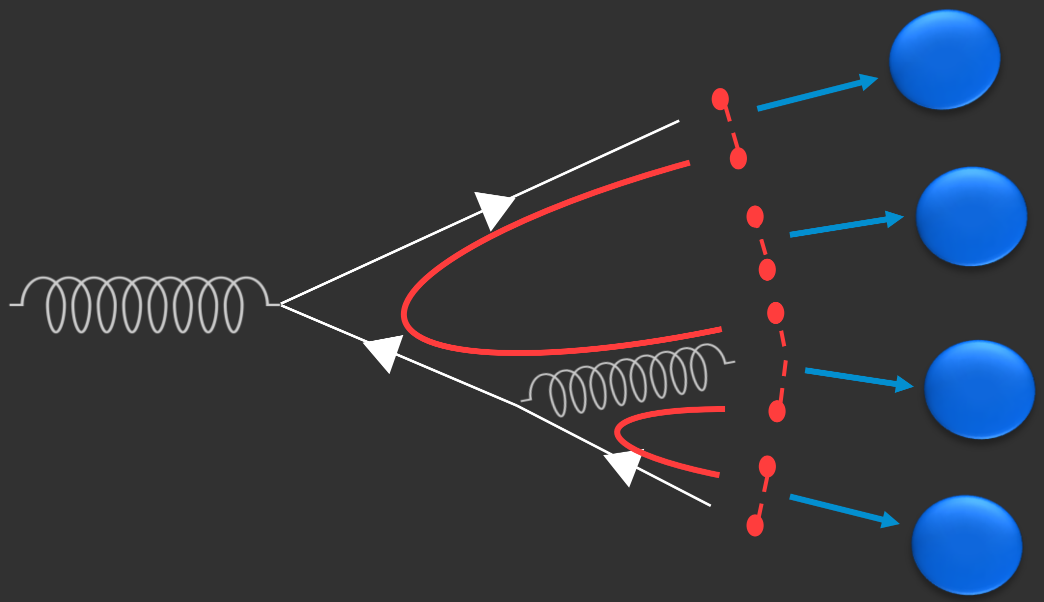

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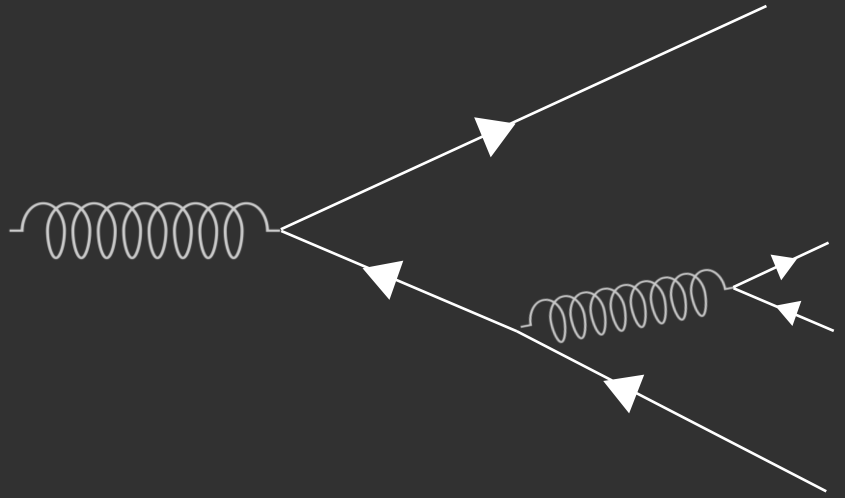

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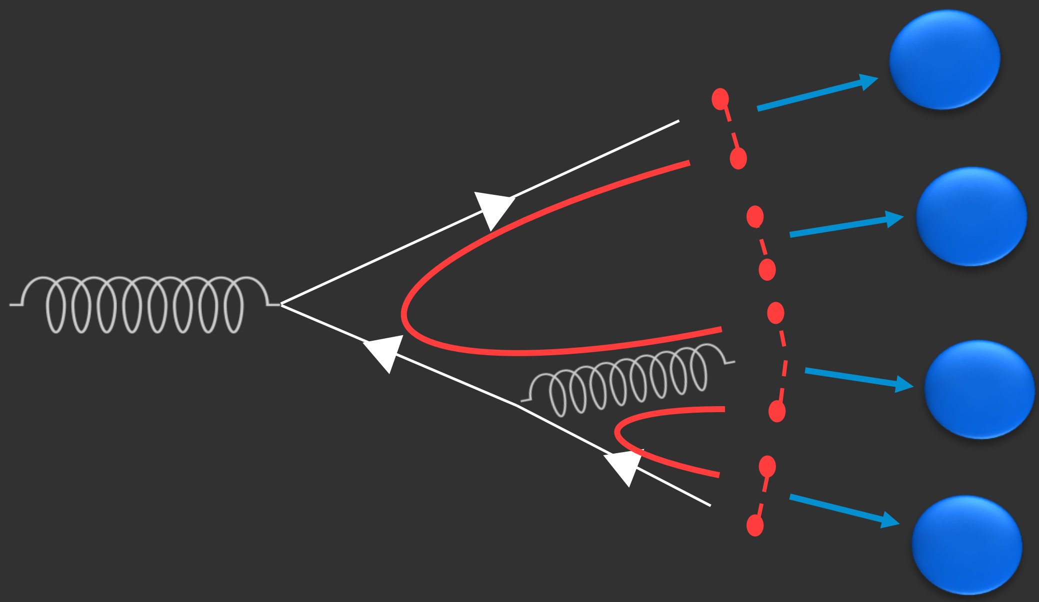

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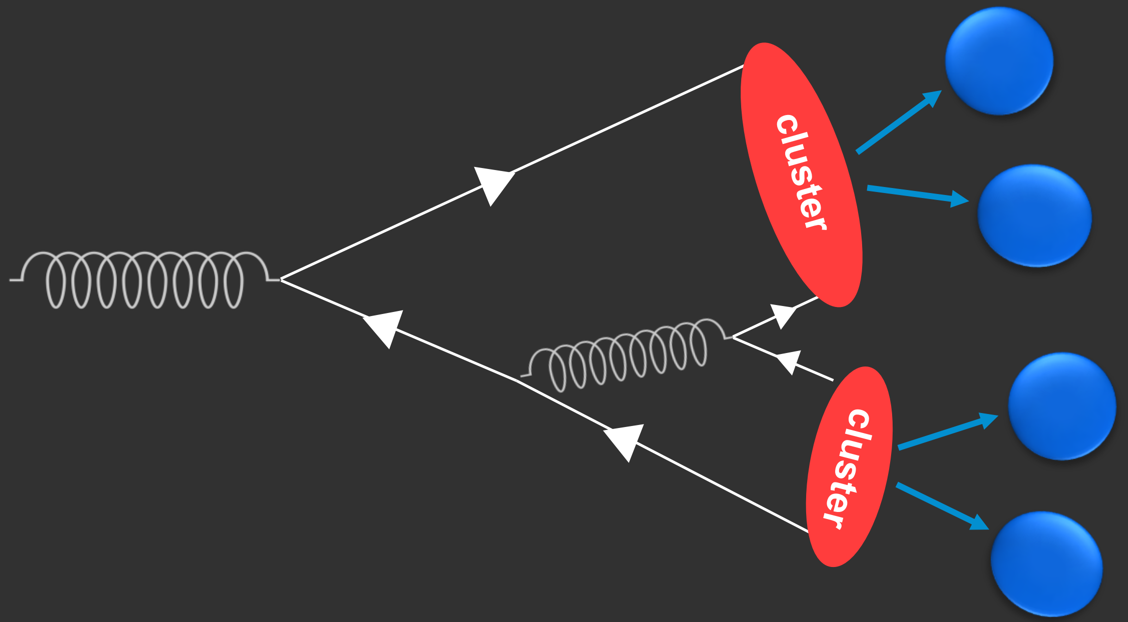
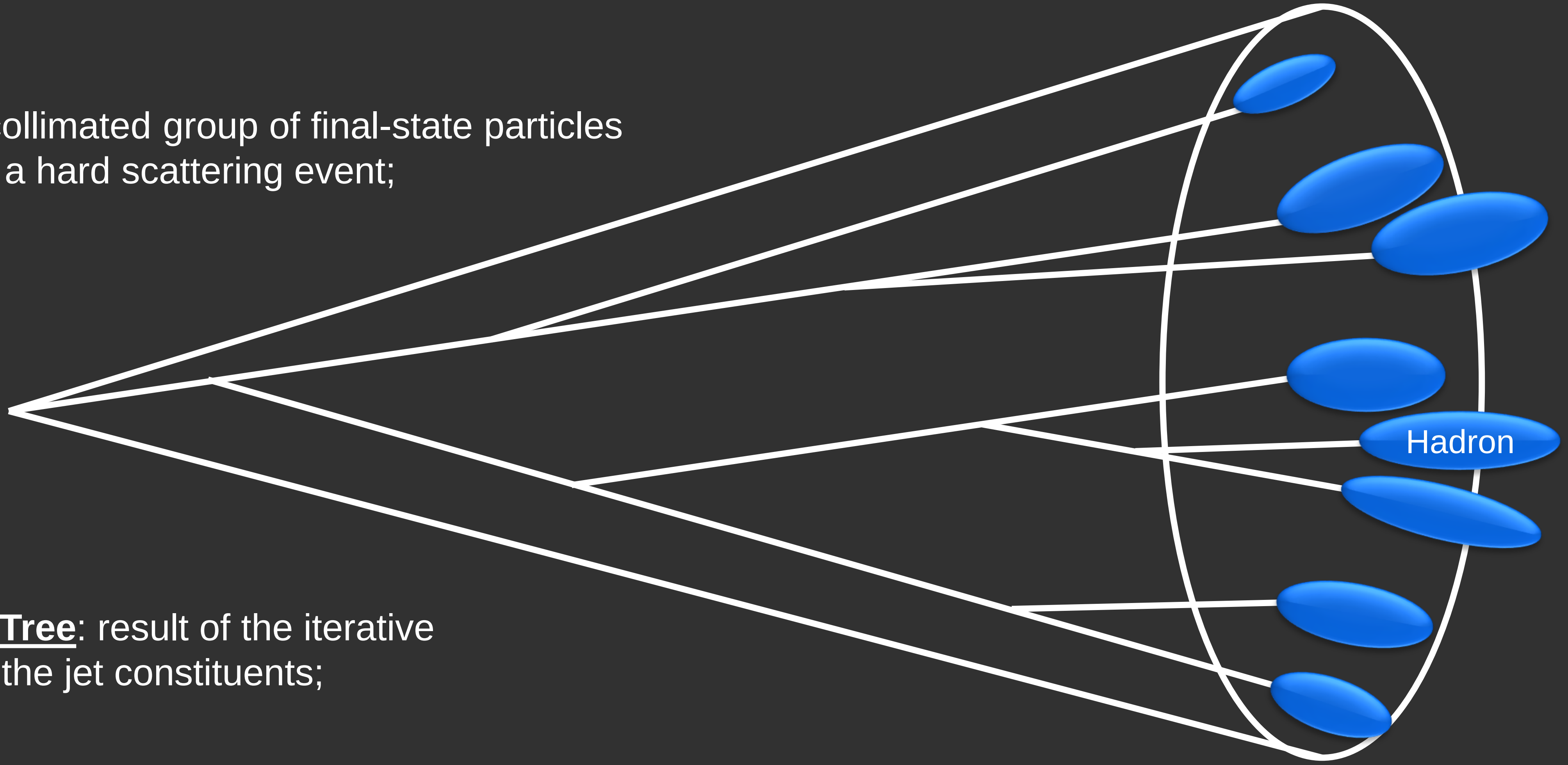


Jets

Jet: highly-collimated group of final-state particles produced in a hard scattering event;



Clustering Tree: result of the iterative grouping of the jet constituents;

➢ **Objective**: find substructure observables with increased sensitivity to hadronization effects!

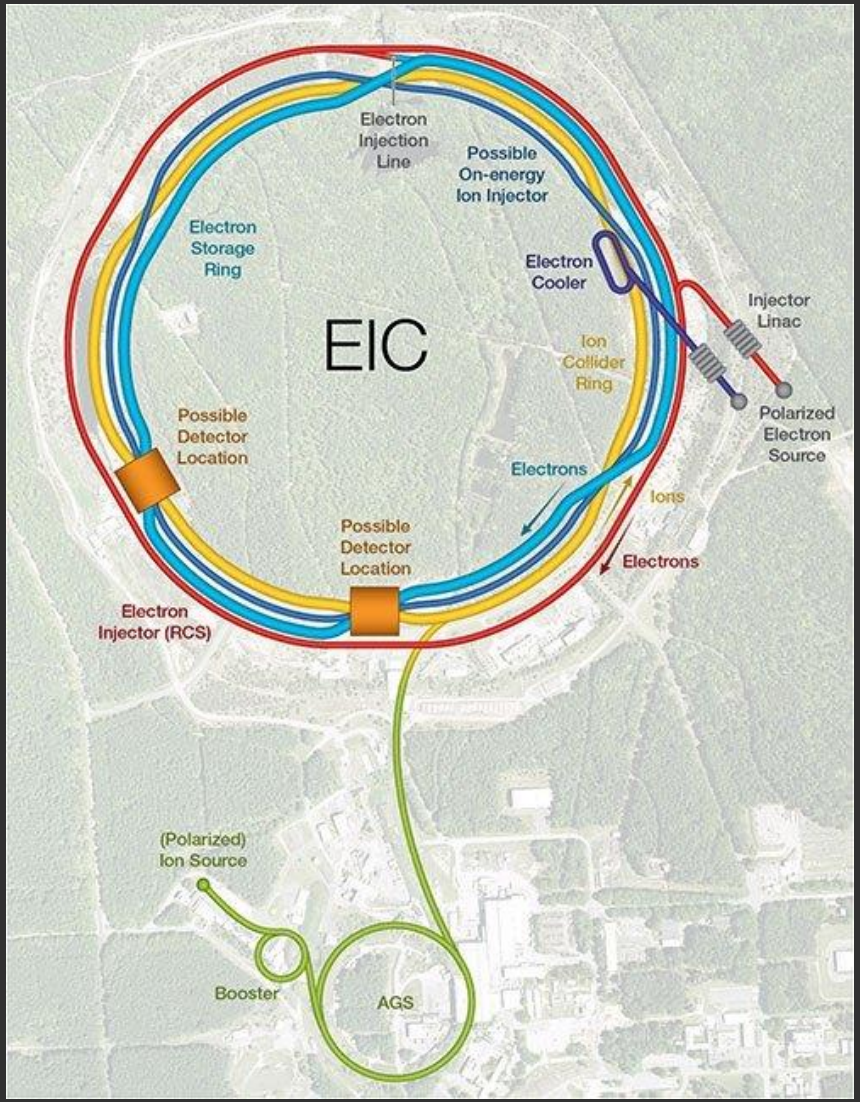
Simulation and Jet Analysis

- Monte Carlo event generators: **PYTHIA 8.306** and **HERWIG 7**;

Settings	Values
E_e	18 GeV
E_p	275 GeV
Q^2	> 50 GeV^2
$p_{T,part}$	> 0.2 GeV/c

- Jets are found using the anti-k$_T$ jet clustering algorithm and re-clustered using the τ algorithm with SoftDrop grooming.

Settings	Values
R	1
$p_{T,jet}$	> 5 GeV/c
η_{jet}	$-1.5 < \eta_{jet} < 3.5$
z_{cut}	0.1
β	0

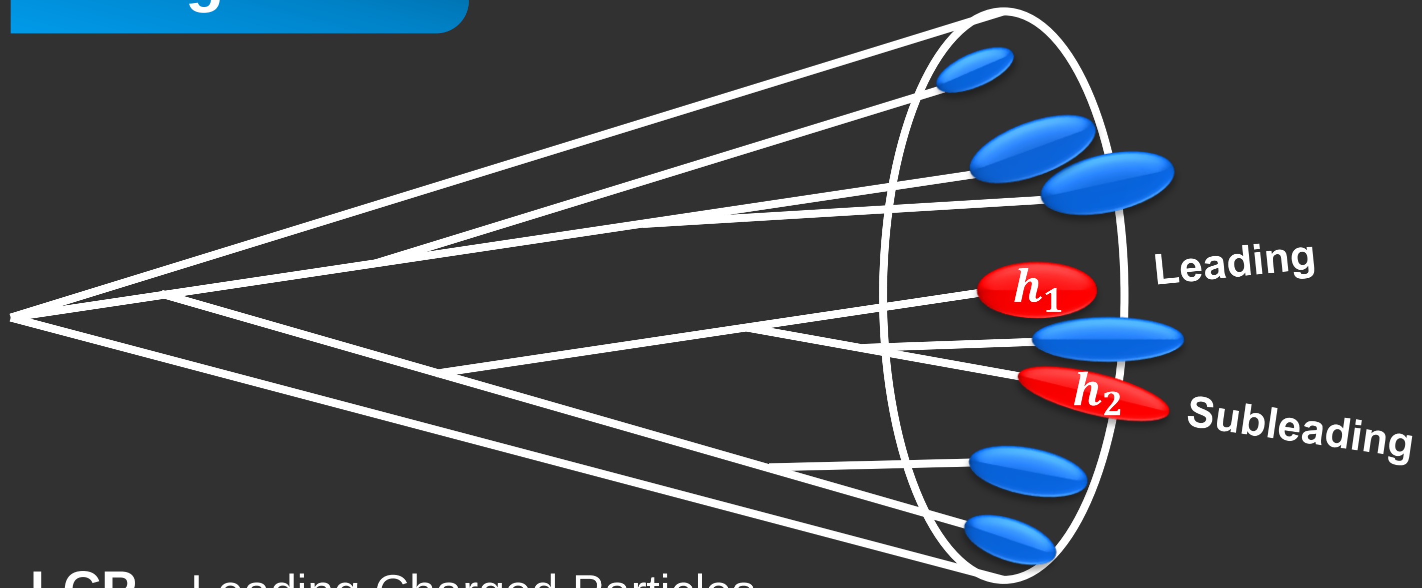


[A. J. Larkoski et al., arXiv:1402.2657v2]

SD criterion: $$\frac{min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

Charge Ratio

[Y.-T. Chien et al, arXiv:2109,15318]



LCP – Leading Charged Particles

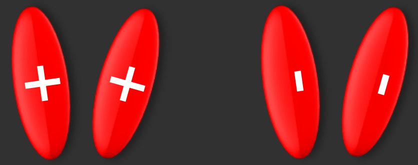
Charge Correlation Ratio:

$$r_c = \frac{\frac{d\sigma_{h_1 h_2}}{dX} - \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}{\frac{d\sigma_{h_1 h_2}}{dX} + \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}$$

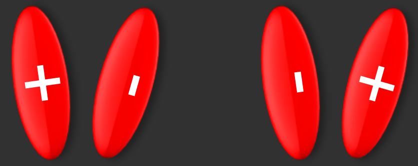
h_1, h_2 – pion (π), kaon (K), proton (p)

X – jet substructure variable of choice

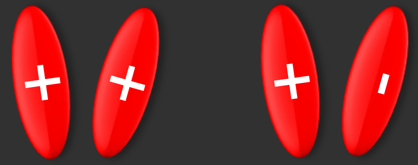
- $r_c > 0$: higher probability of producing jets with equally-charged LCP;



- $r_c < 0$: higher probability of producing jets with oppositely-charged LCP;



- $r_c = 0$: jets produced randomly with equally- or oppositelly-charged LCP.



Formation Time

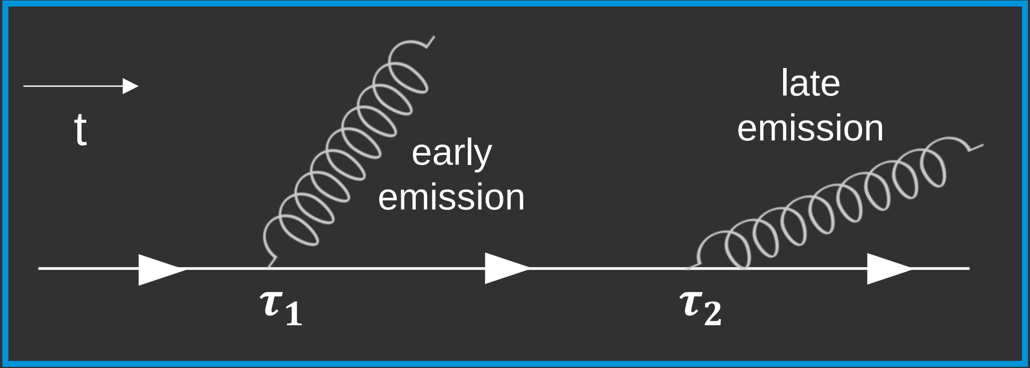
[L. Apolinário et al, arXiv:2012.021999]
[L. Apolinário et al, arXiv:2401.14229]

Formation Time

$$\tau_{form} = \frac{1}{2\,E\,z\,(1-z)\,(1\,-\,\cos\theta_{12})}$$

Estimate of the timescales involved in a particle splitting into 2 other particles that act as independent sources of additional radiation

E	source energy
θ_{12}	angle between the 2 emitted prongs
$z = \frac{min(E_1,E_2)}{E_1 + E_2}$	energy fraction

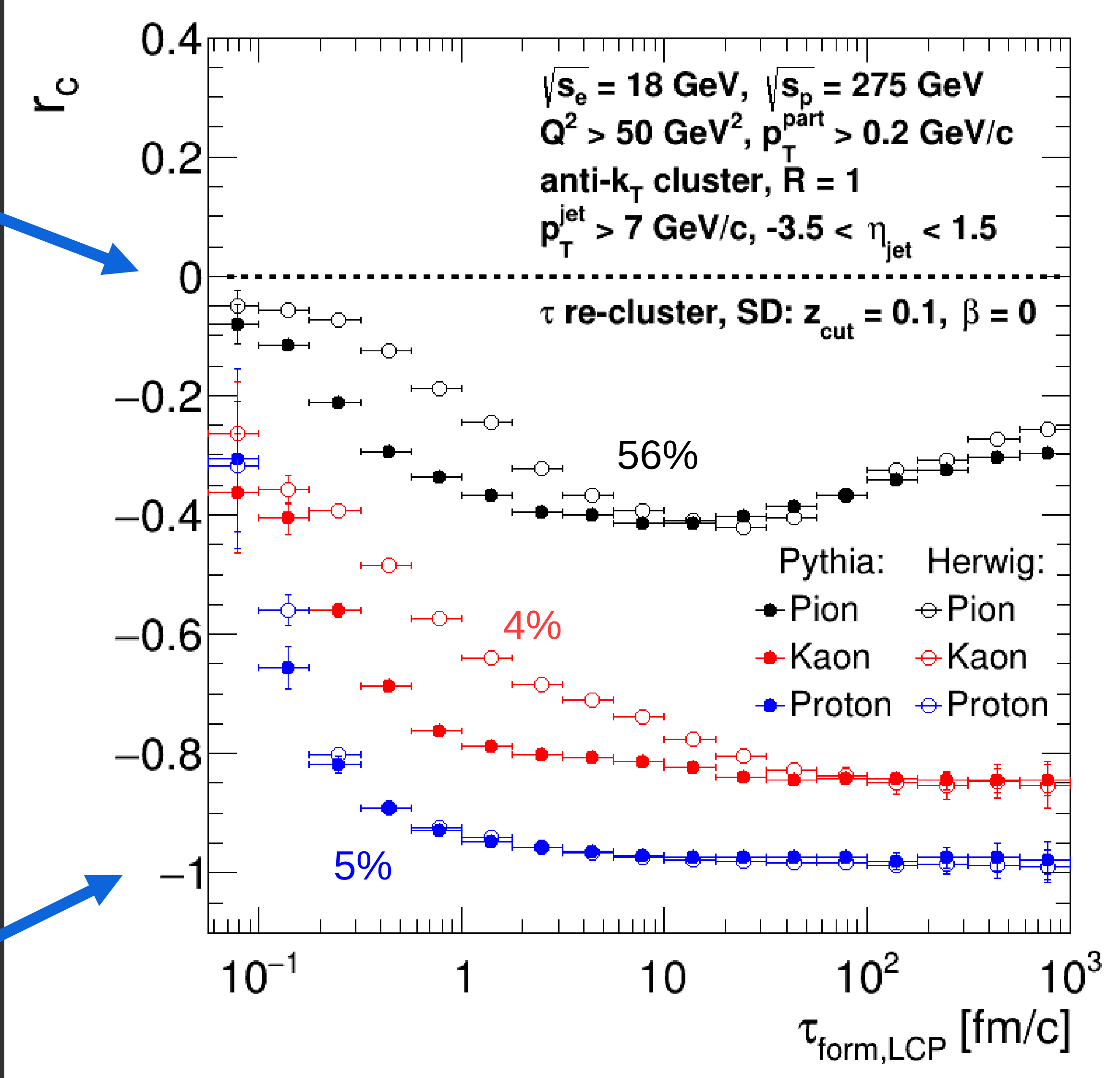


$\tau_1 < \tau_2$

Charge Ratio

$$r_c = \frac{\frac{d\sigma_{h_1h_2}}{dX} - \frac{d\sigma_{h_1\overline{h_2}}}{dX}}{\frac{d\sigma_{h_1h_2}}{dX} + \frac{d\sigma_{h_1\overline{h_2}}}{dX}}, \qquad X = \tau_{form}$$

50% same-sign, 50% opposite-sign jets



0% same-sign, 100% opposite-sign jets

[Similar to study in Y.-T. Chien et al, arXiv:2109,15318]

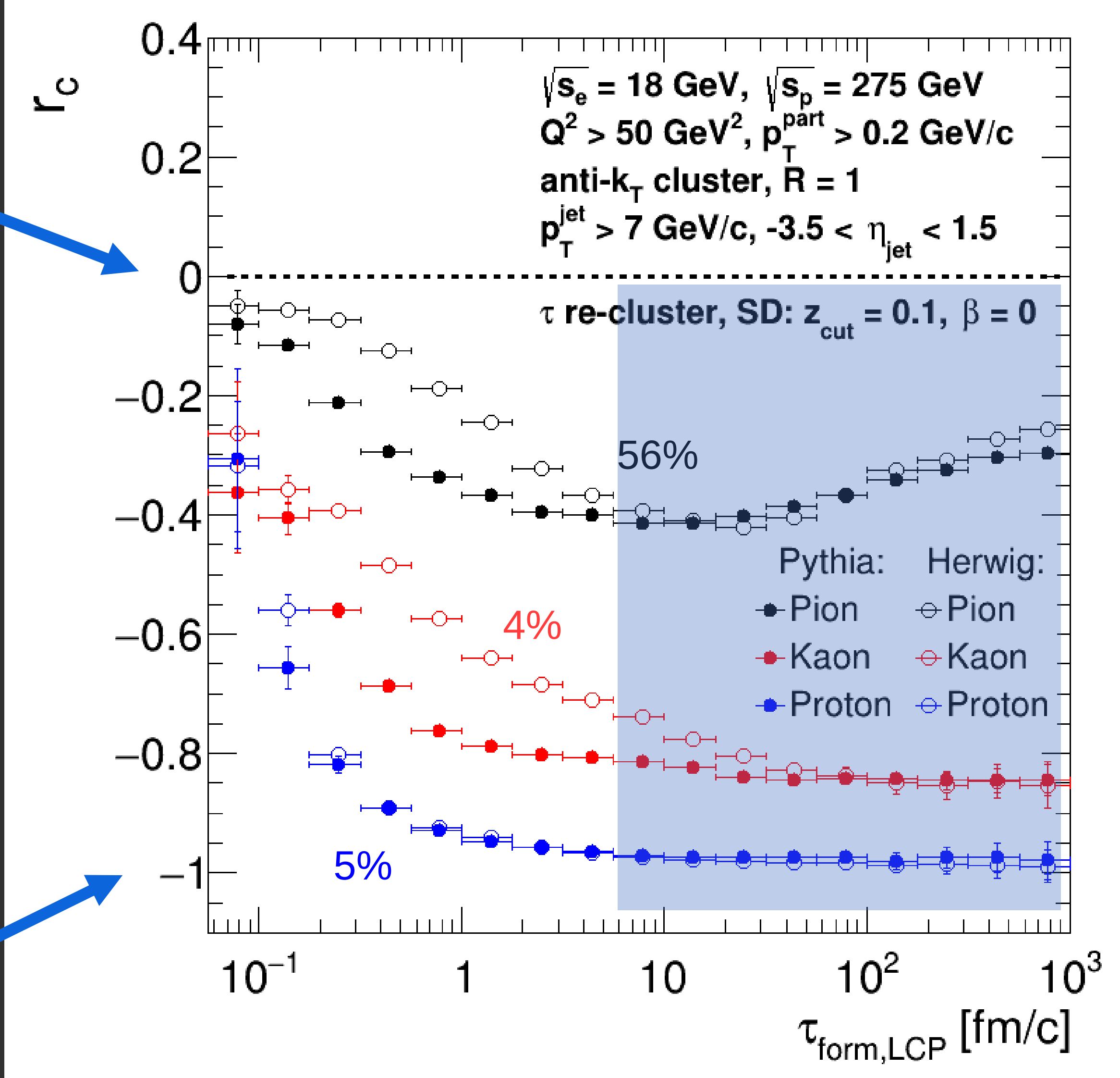
Charge Ratio

$$r_c = \frac{\frac{d\sigma_{h_1 h_2}}{dX} - \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}{\frac{d\sigma_{h_1 h_2}}{dX} + \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}, \qquad X = \tau_{form}$$

50% same-sign, 50% opposite-sign jets

- **Late time LCP**: r_c ~ constant and close to -1, meaning jets more likely to have opposite-sign LCP;

0% same-sign, 100% opposite-sign jets



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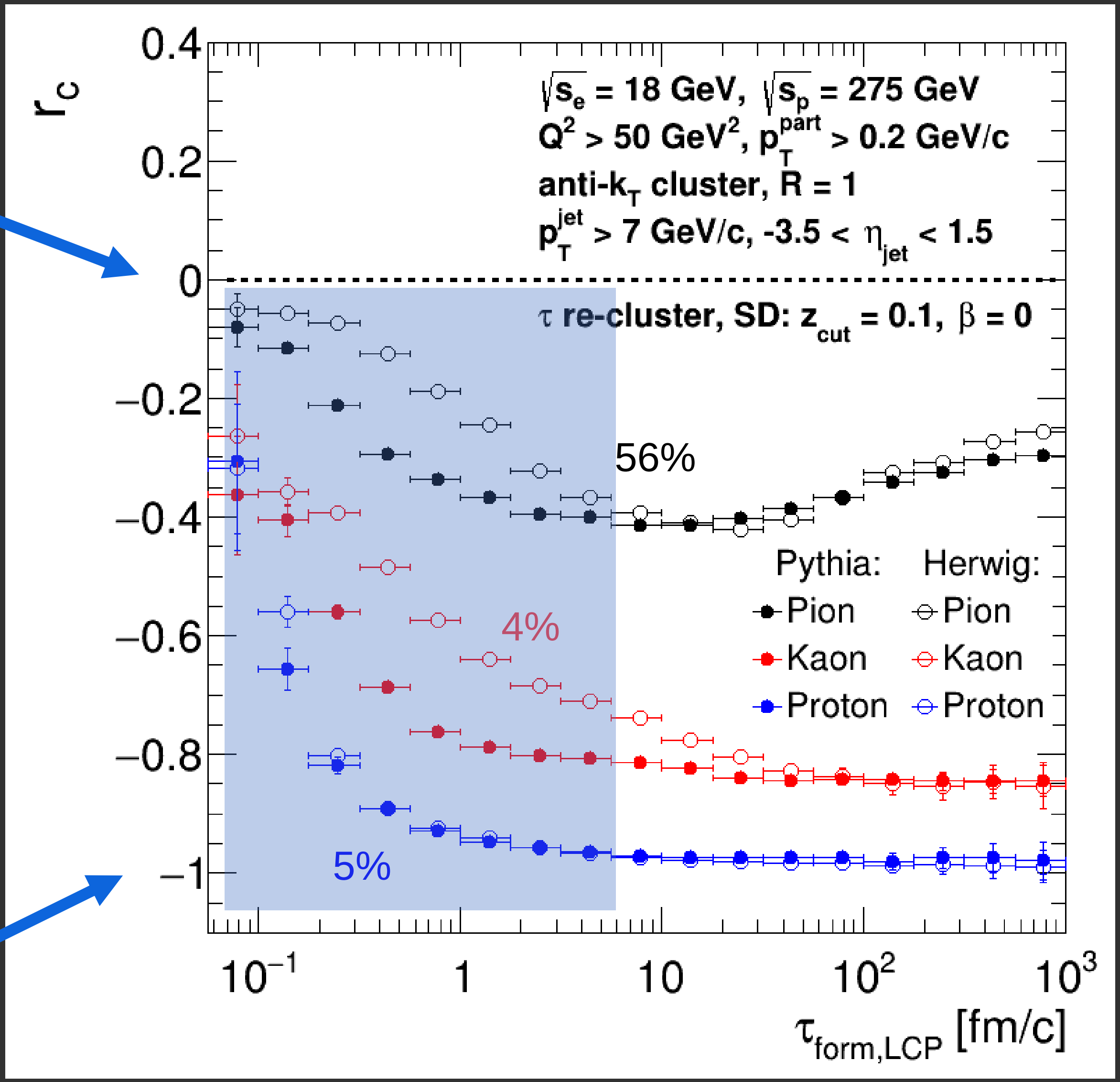
50% same-sign, 50% opposite-sign jets

- **Late time LCP**: r_c ~ constant and close to -1, meaning jets more likely to have opposite-sign LCP;
- **Early time LCP**: r_c closer to 0, meaning larger charge randomization of the leading particles;

0% same-sign, 100% opposite-sign jets



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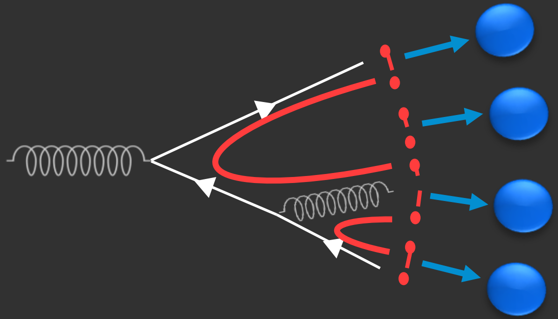
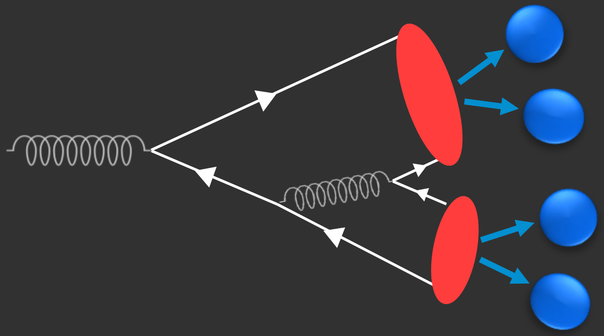
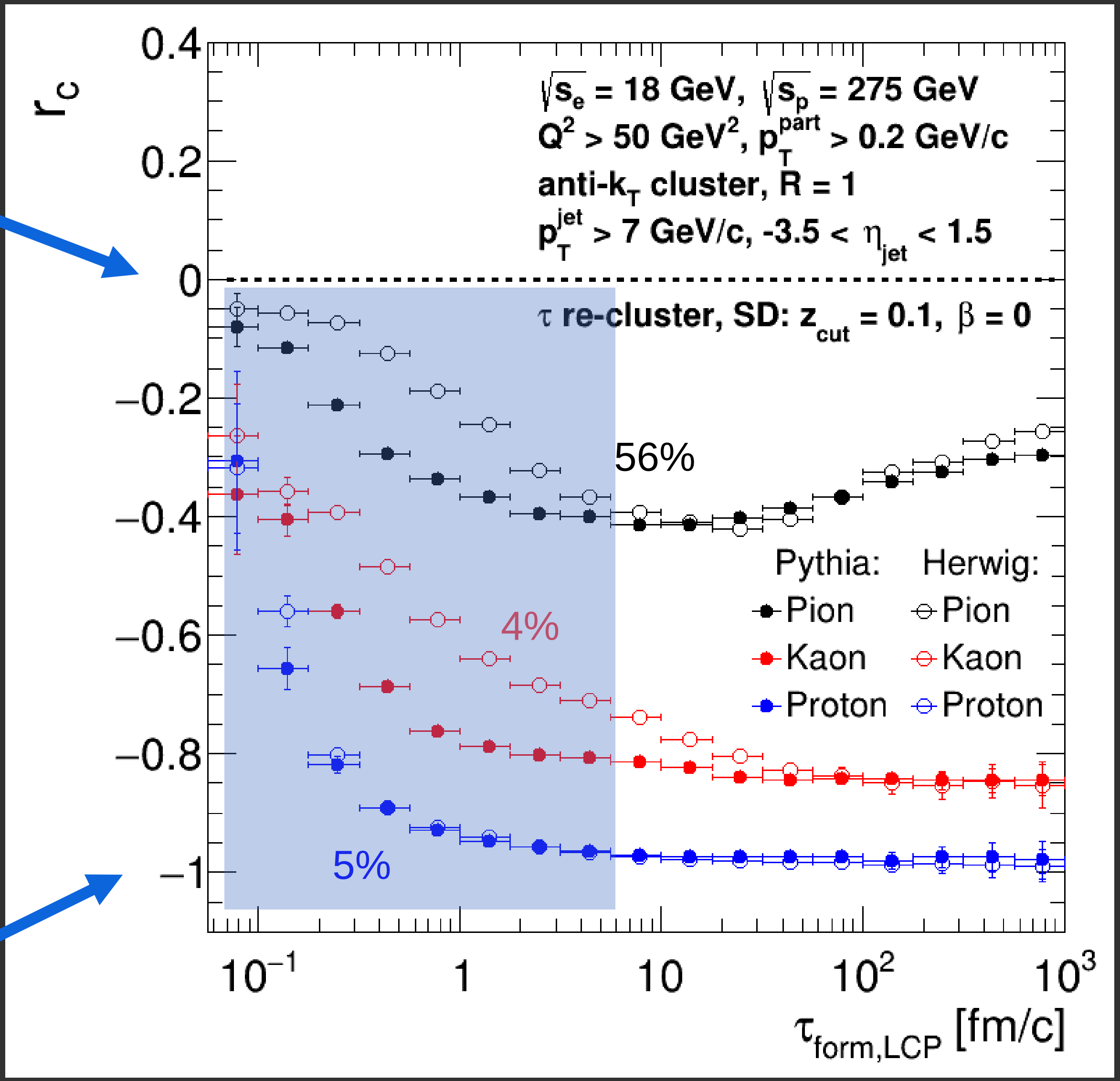
50% same-sign, 50% opposite-sign jets

Lund String



Cluster Fragmentation





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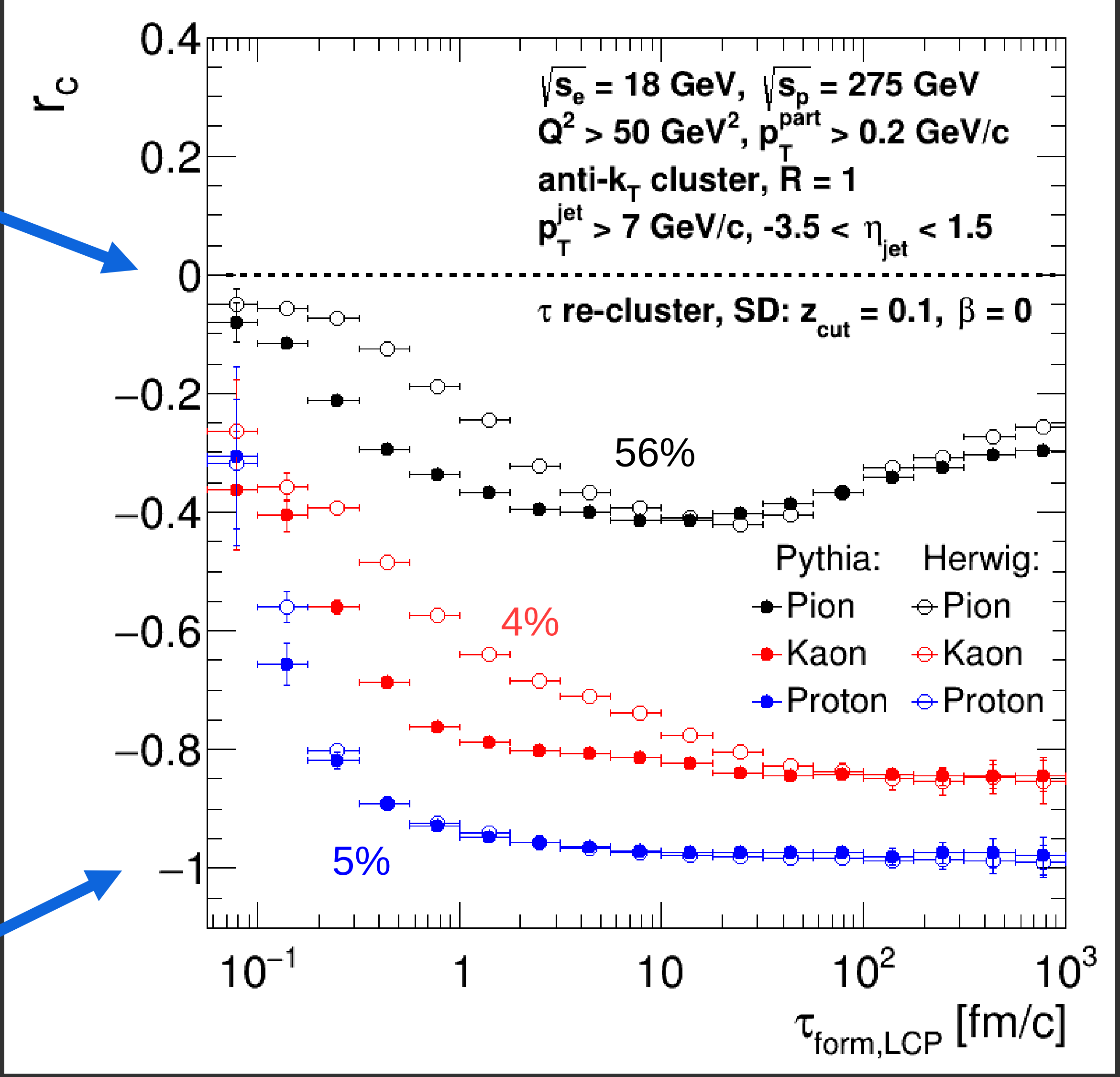
50% same-sign, 50% opposite-sign jets

$$z_{LCP} \sim 0.5$$

$$\tau_{form,LCP} = \frac{1}{2\,E\,z\,(1-z)\,(1 - \cos\theta_{12})} \sim \frac{1}{E\,\theta^2}$$

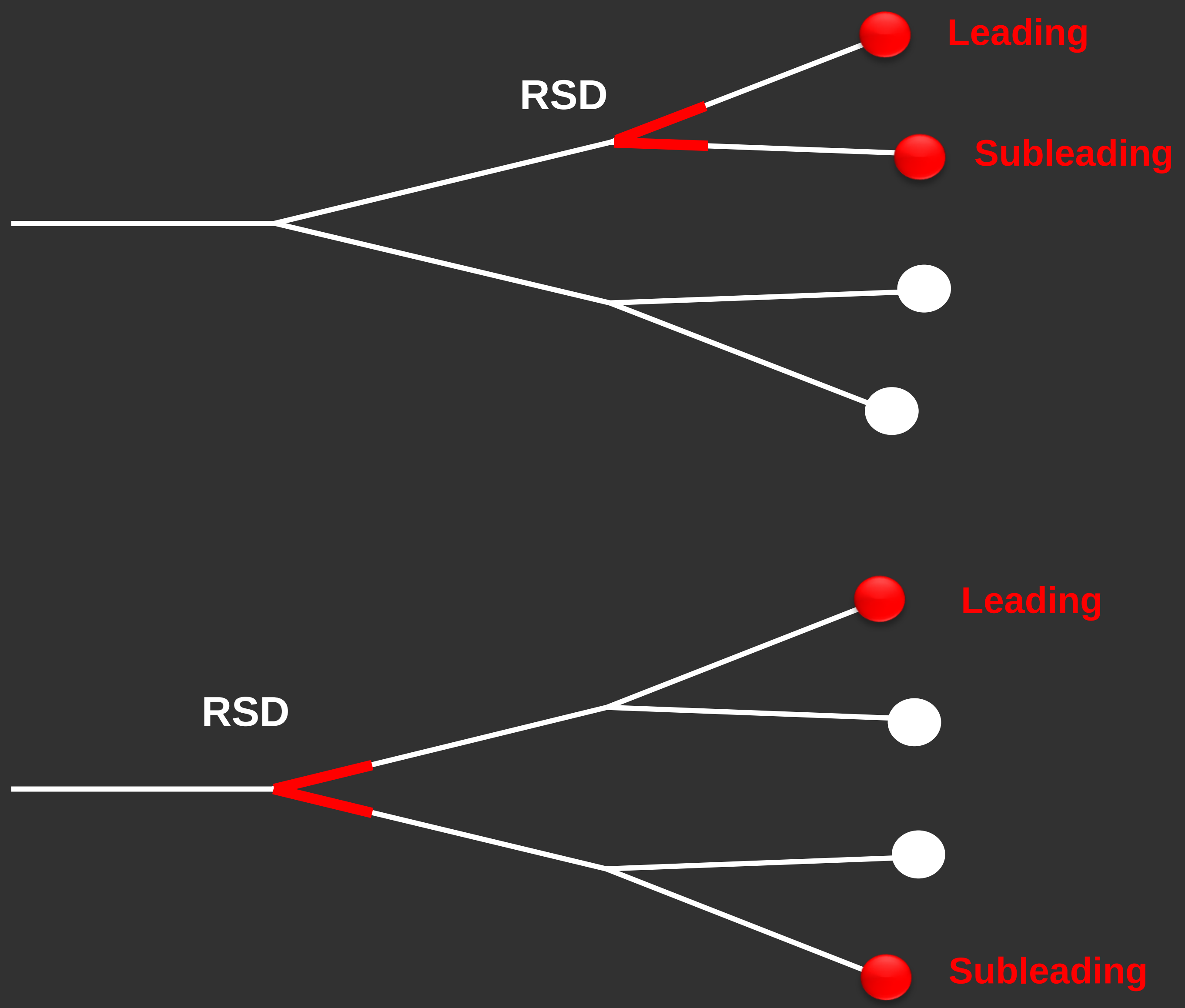
- Where in the clustering tree are the leading charged particles coming from?
- What is the r_c dependence on jet substructure?

0% same-sign, 100% opposite-sign jets



[Similar to study in Y.-T. Chien et al, arXiv:2109,15318]

Resolved SoftDrop Splitting – RSD



- The **RSD** is the SoftDrop splitting in the clustering tree where the leading charged particles get separated into 2 different subjets;

- **Top** clustering tree:
  - $N_{SD} = 2$
  - $N_{RSD} = 2$
  - RSD depth = $N_{RSD}/N_{SD} = 2/2$

- **Bottom** clustering tree:
  - $N_{SD} = 2$
  - $N_{RSD} = 1$
  - RSD depth = $N_{RSD}/N_{SD} = 1/2$

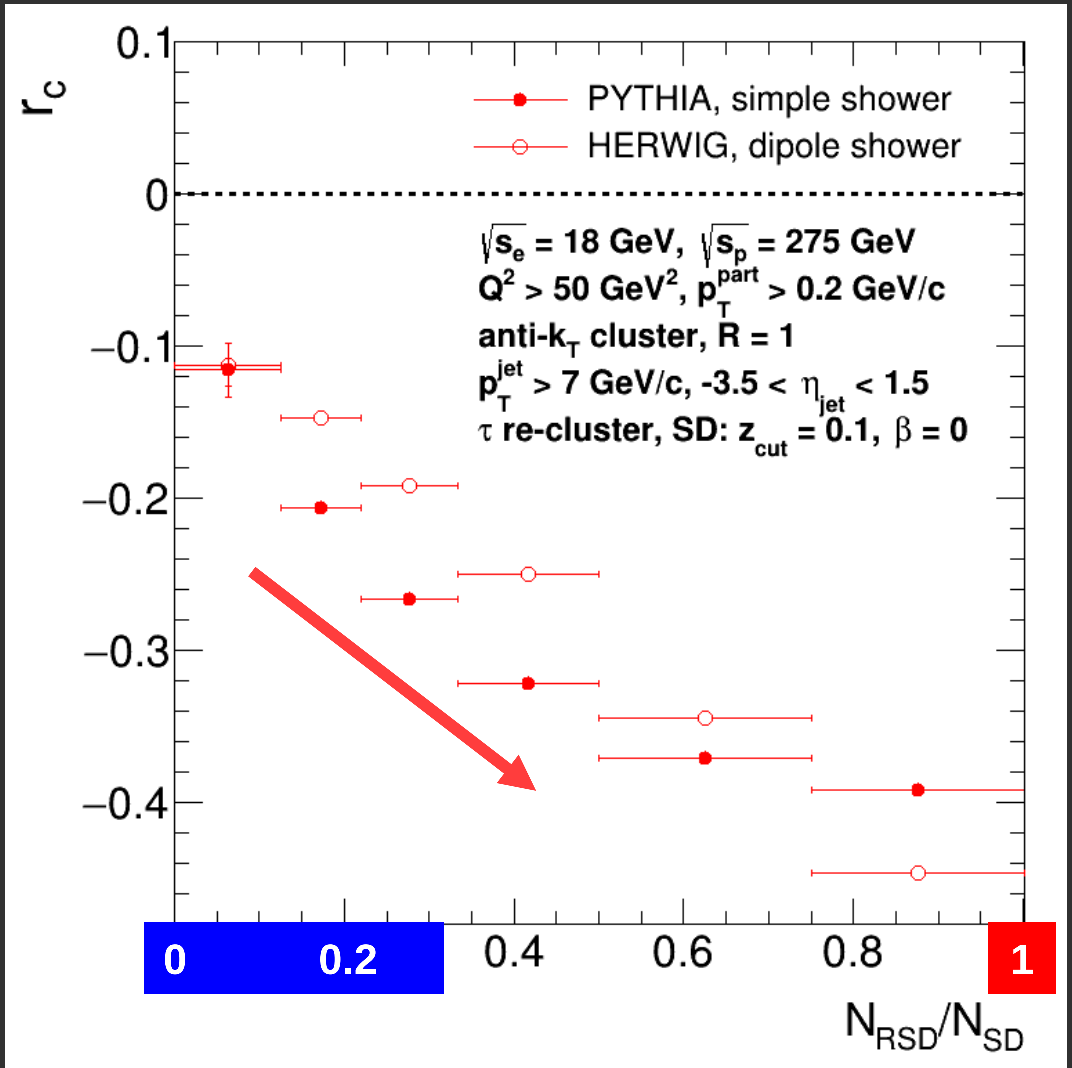
Nuno O., Madureira

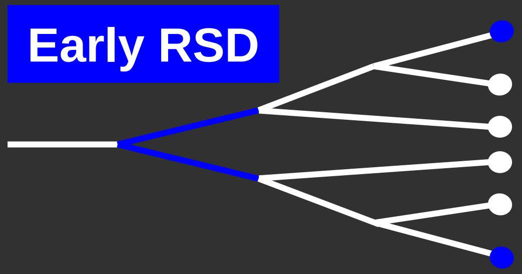
Charge Ratio vs RSD Depth

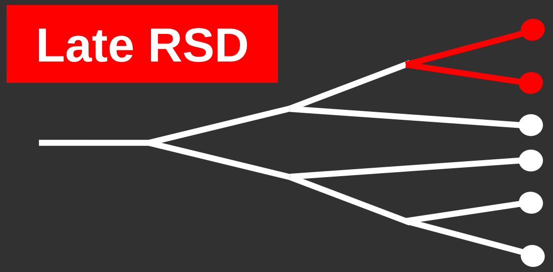
$$r_c = \frac{\frac{d\sigma_{h_1 h_2}}{dX} - \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}{\frac{d\sigma_{h_1 h_2}}{dX} + \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}, \qquad X = \frac{N_{RSD}}{N_{SD}}$$

- **Large RSD depths**: few subsequent branchings, "remembers" charge correlation of leading particles;
- **Small RSD depths**: several subsequent branchings, "forgets" charge correlation of leading particles

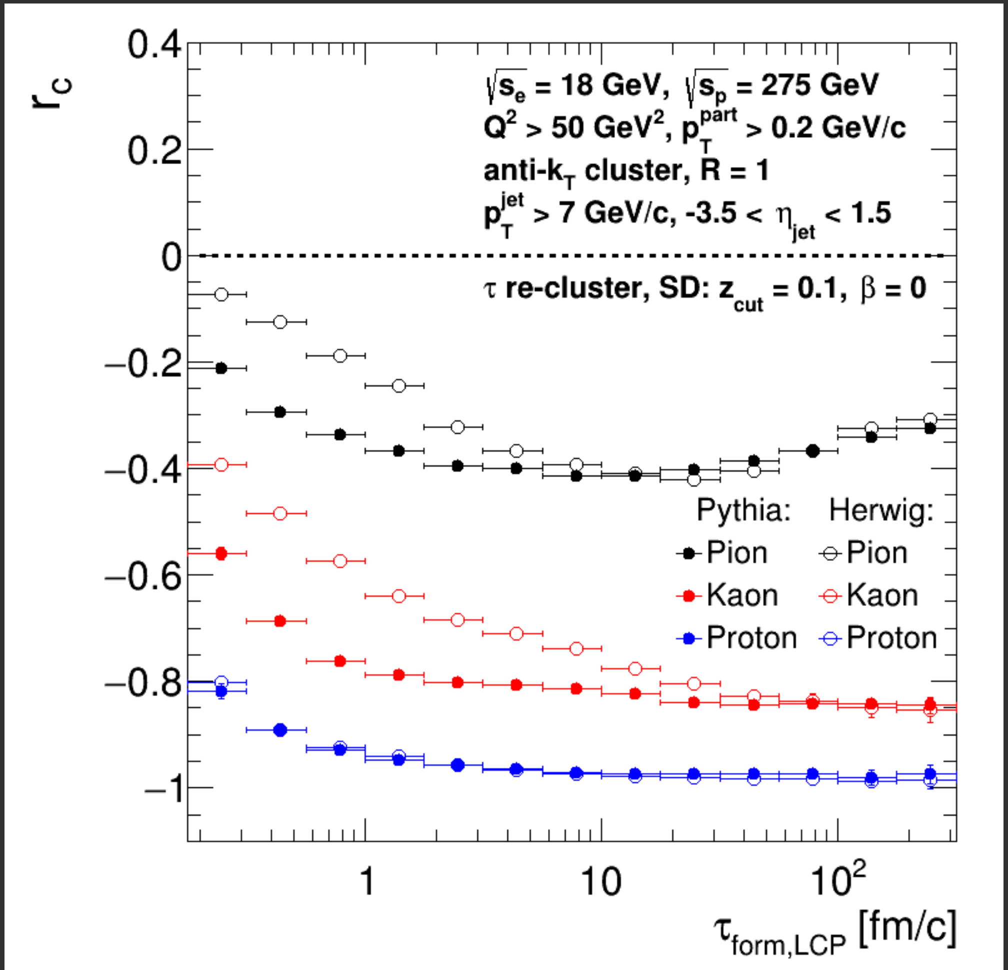
Conclusion: r_c depends strongly on jet substructure topology!



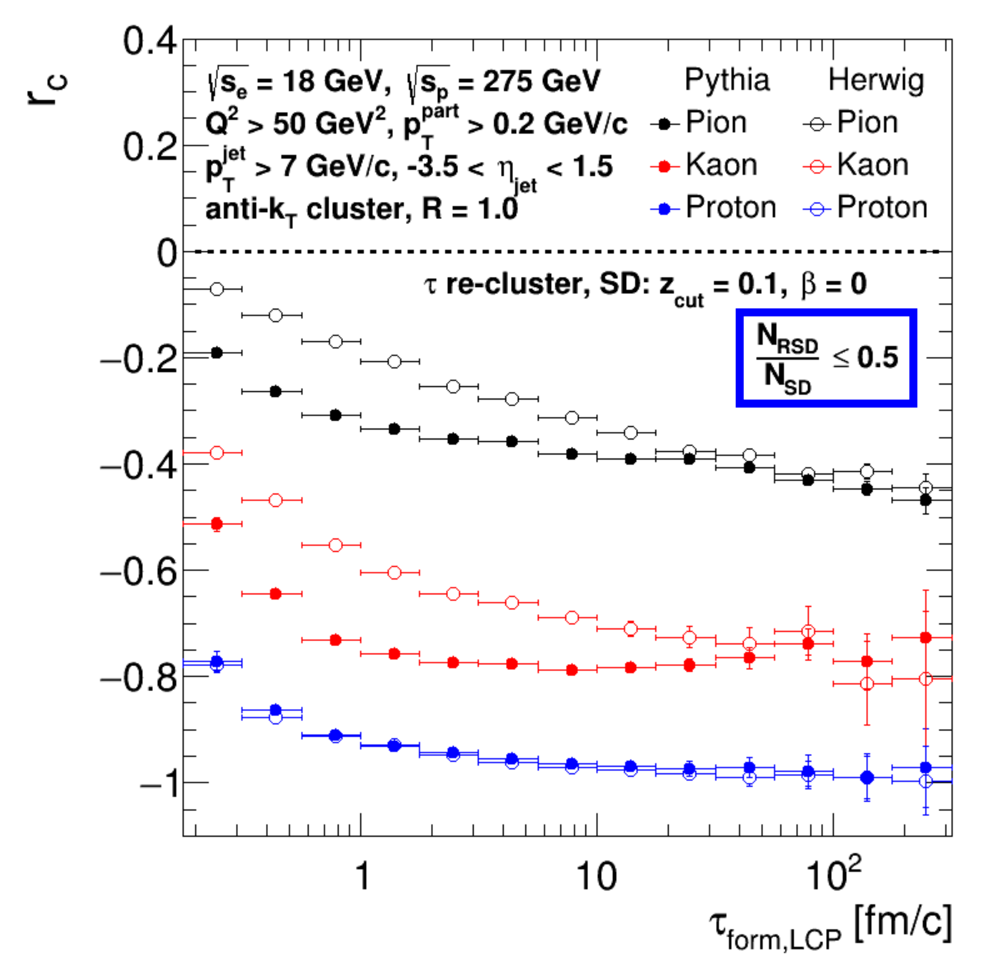




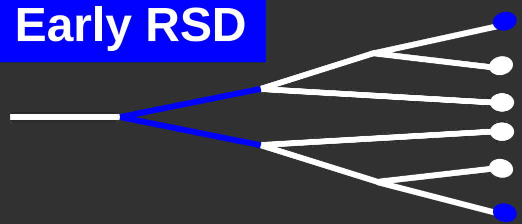
Charge Ratio with Selections



Inclusive Plot



Early RSD



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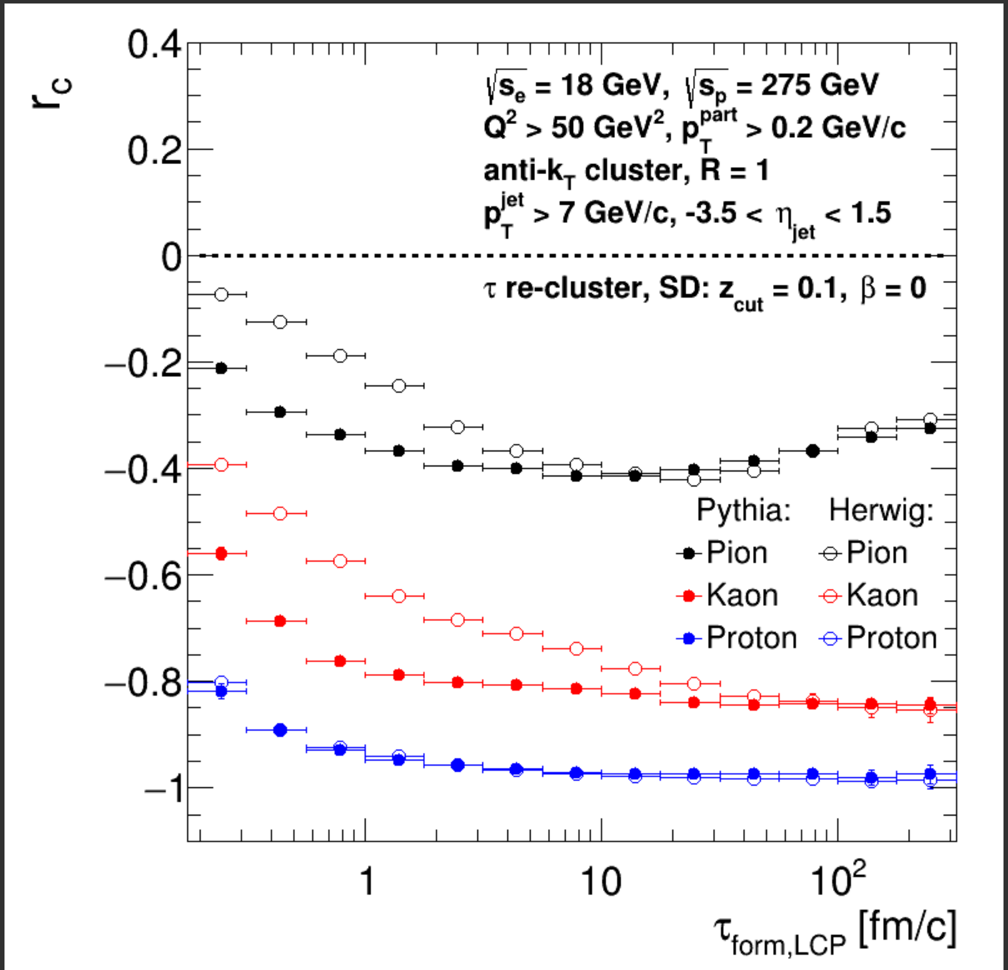

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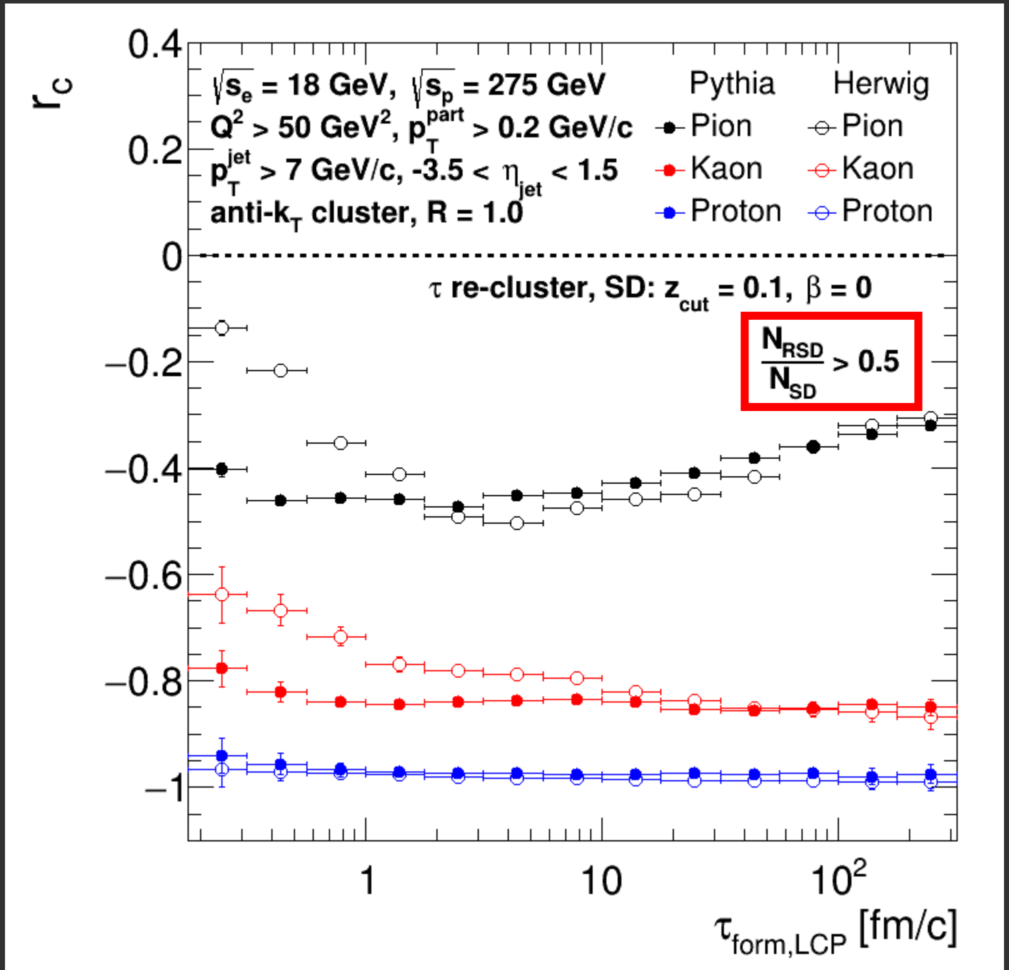
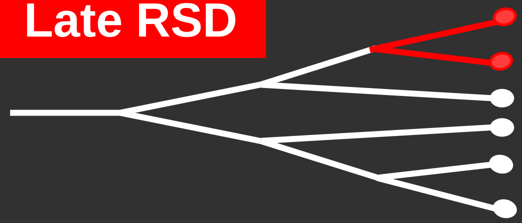
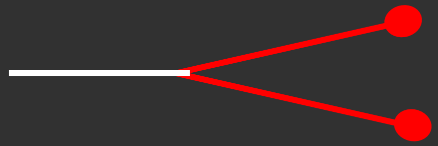


Late RSD



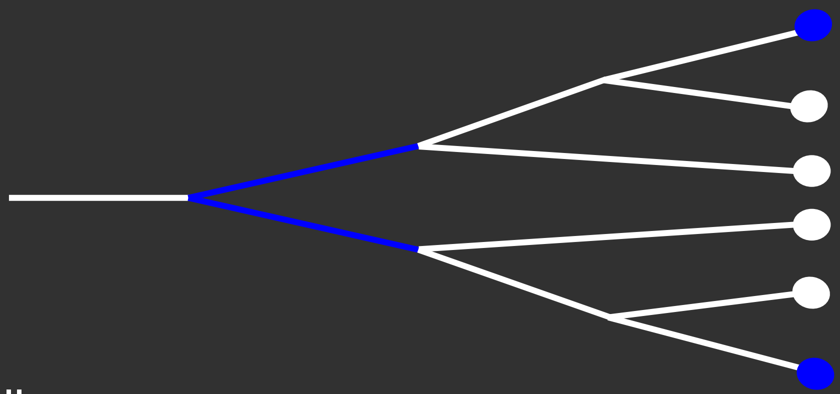
Charge Ratio with Selections

Example 1 of jet topology



- Small $\tau_{form,LCP}$
- Large RSD depth

Example 2 of jet topology



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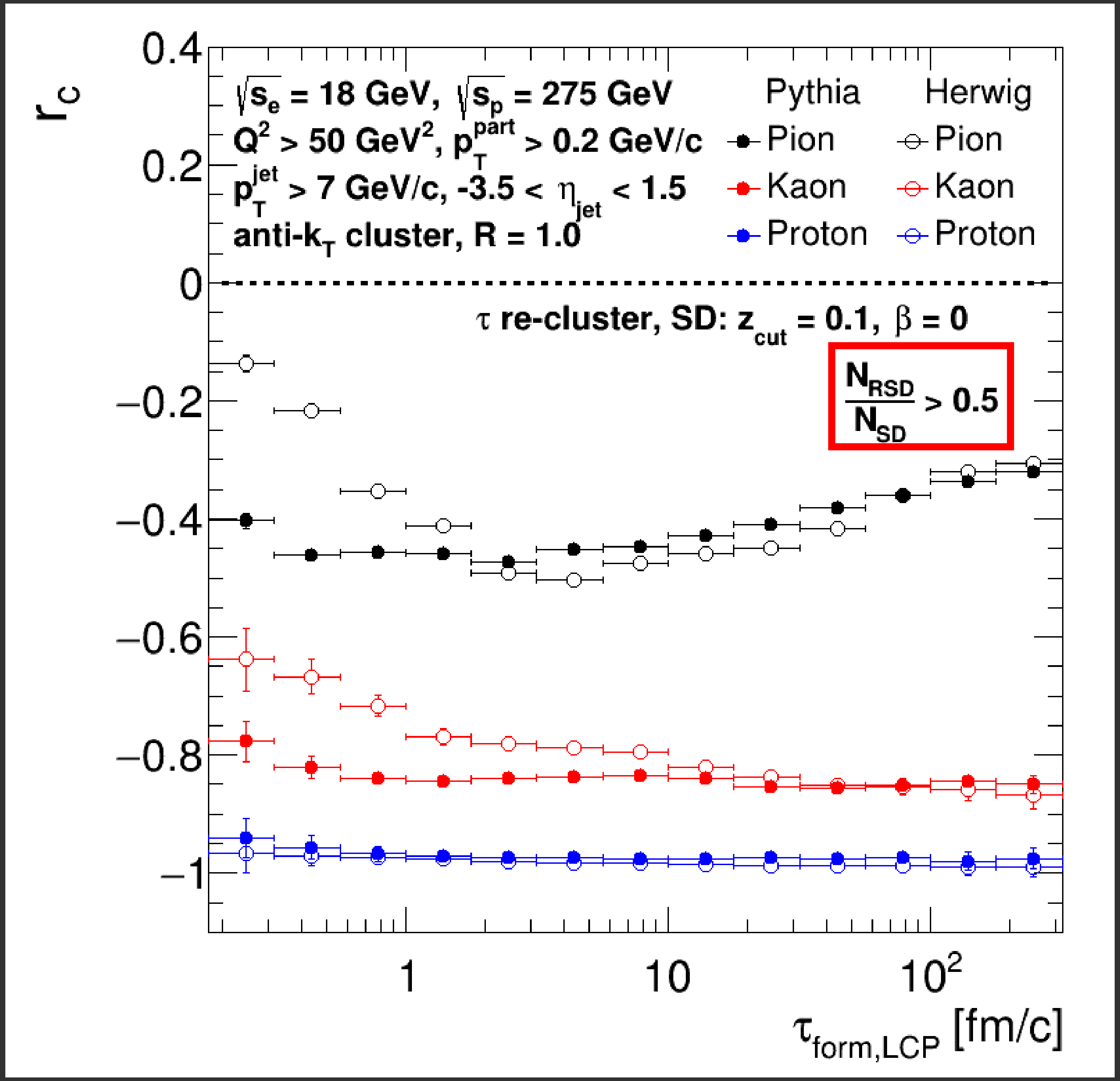

Charge Ratio with Selections

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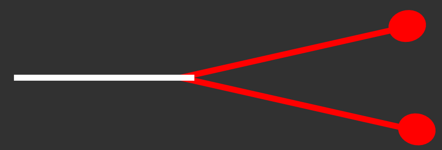

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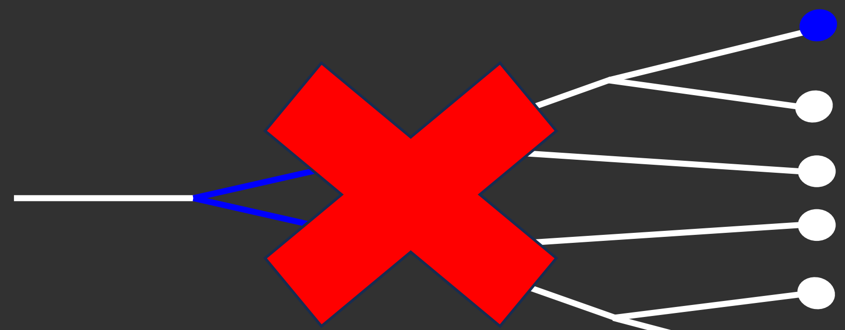

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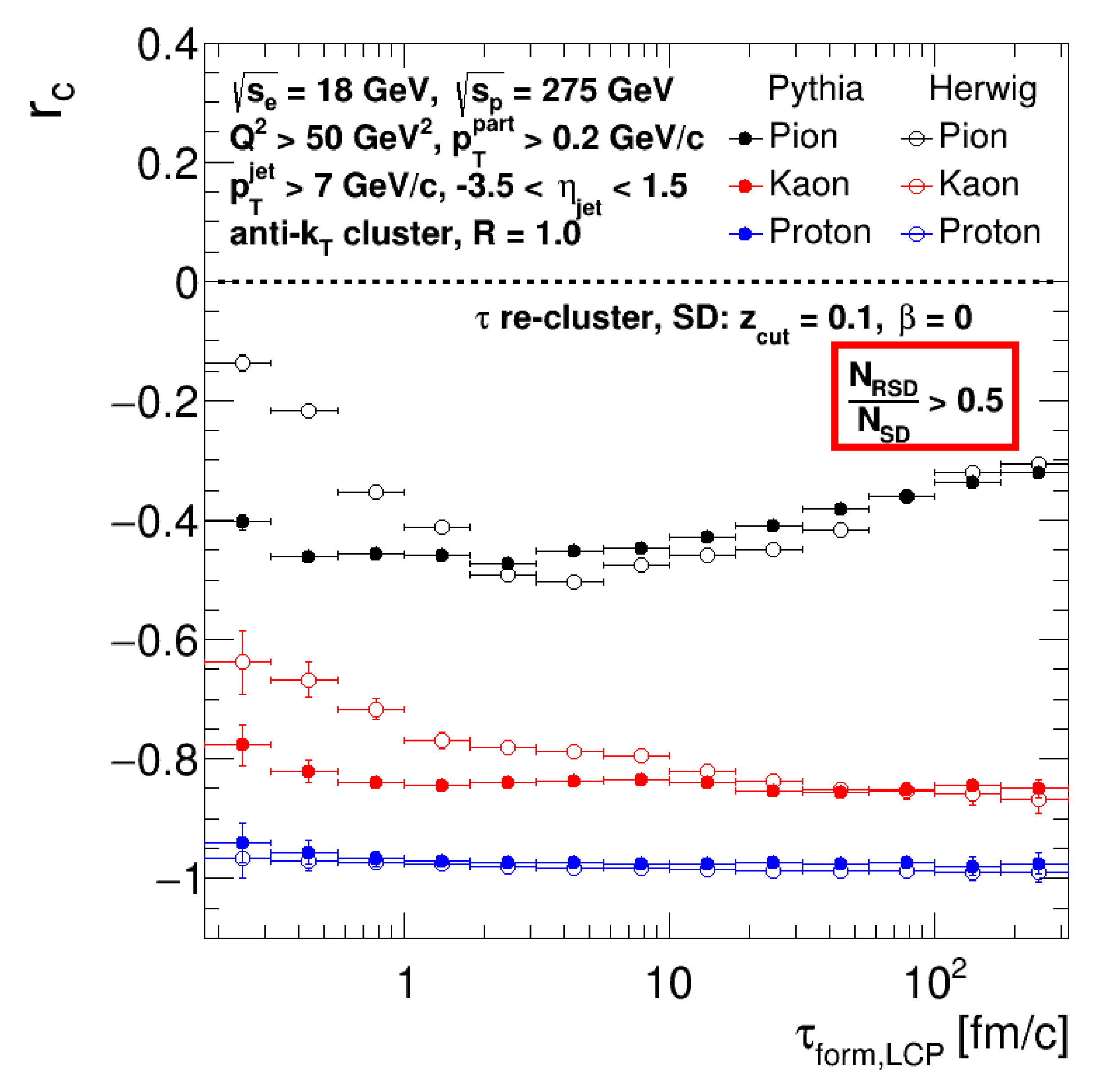
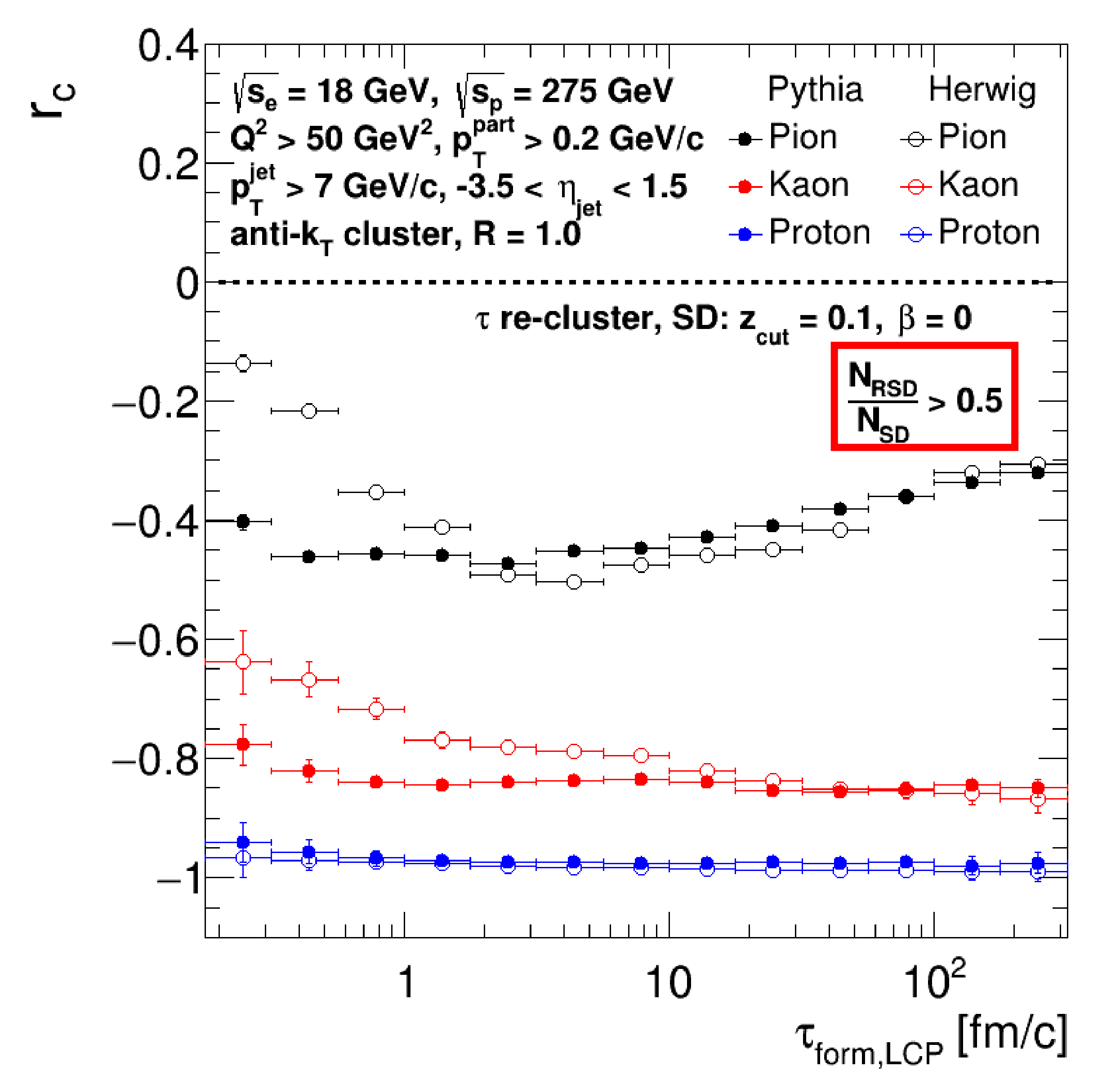


Conclusions

- RSD distinguishes different jet topologies, showing r_c is strongly dependent on substructure;

- Selection on late RSD reveals a qualitatively different behaviours of r_c from Pythia (Lund string) and Herwig (cluster fragmentation).



Thank you for your attention!

Questions?

Aknowledgements

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Backup Slides

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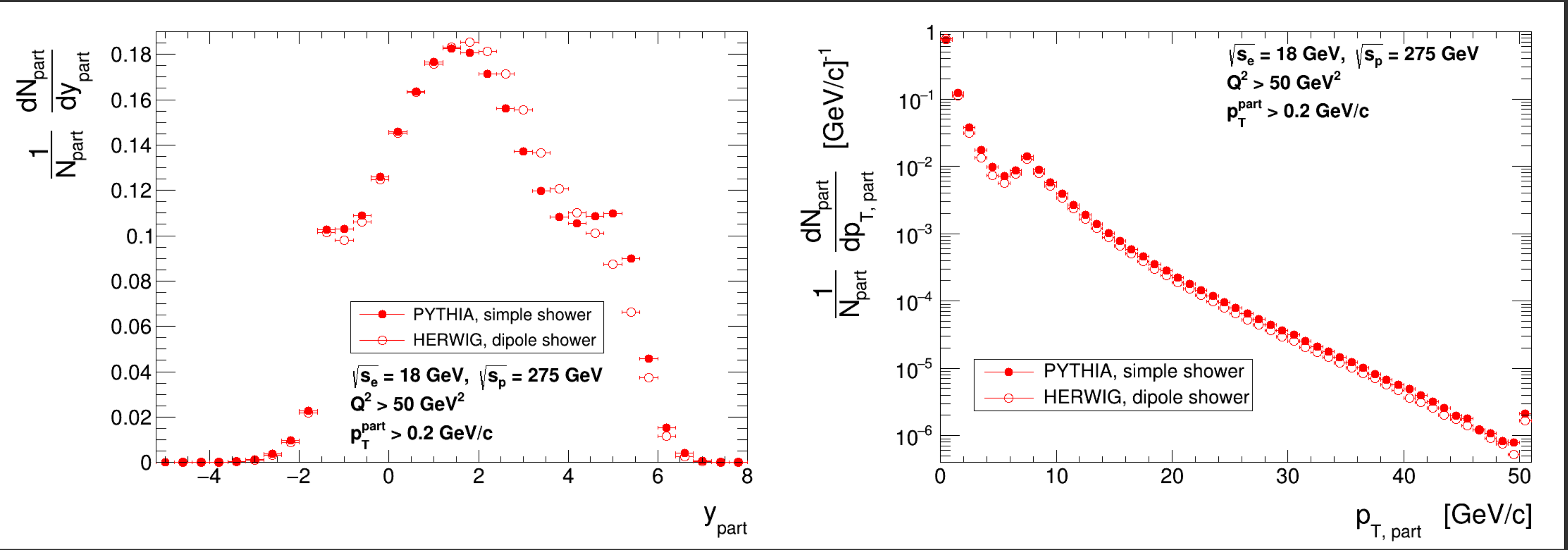
Parton Description Matching

- PYTHIA's simple shower and HERWIG's dipole shower are the parton shower descriptions that allow for the best case scenario matching between event-level variables on both Monte Carlos, such as particle rapidity, transverse momentum and azimutal angle.



Implementation

["Soft drop" (2014);
"Time reclustering for jet quenching studies" (2021)]

- Jet analysis is performed with **FastJet**

- **Distance measure** used to cluster pairs of particles together:

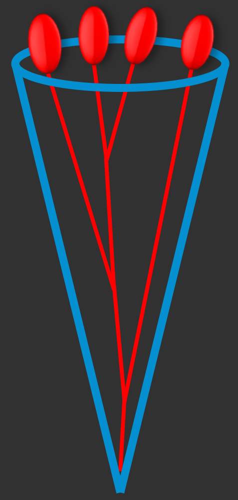
$$d_{ij} = min\left(p_{T1}^{2p}, p_{T2}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2}$$

p_T – particle transverse momentum
R – jet radius
ΔR_{ij} – measure of the angular distance

- **Anti-k_t** algorithm:
  - Sensitive to hard objects
  - Unphysical clustering trees

- **C/A** algorithm: Angular-ordered trees

- τ algorithm: Reverse time-ordered trees



Parameter $\boldsymbol{p}$ defines the **clustering algorithm**

$p = -1$	$p = 0$	$p = 0.5$
⇓	⇓	⇓
Anti-k_t algorithm	Cambridge/Aachen (C/A) algorithm	τ algorithm
⇓	⇓	⇓
Jet finding	Jet substructure studies	

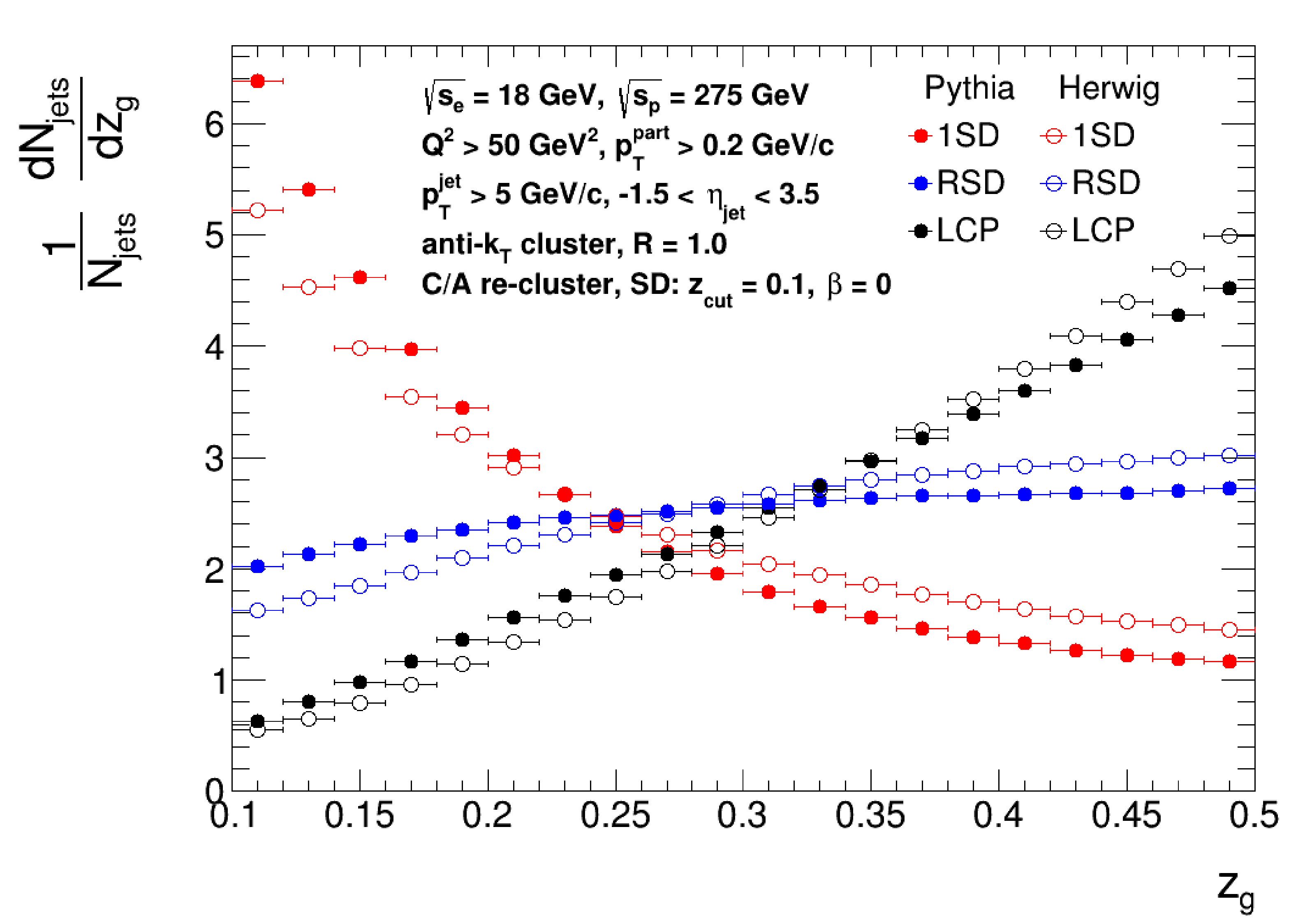
τ algorithm

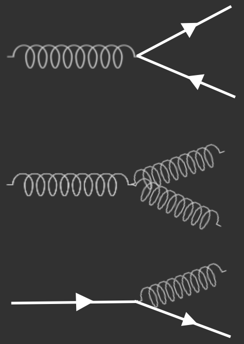
$$d_{ij}^{p=0.5} = min(p_{T1}, p_{T2})\frac{\Delta R_{ij}^2}{R^2} \sim E\, z\, \theta^2 \approx \frac{1}{\tau_{form}}$$

in the high-energy, soft and colinear limits!

Results – Groomed Momentum Fraction

$$z_g = \frac{min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$





$$P_{g\to q\bar{q}} = \frac{1}{2}(z^2 + (1-z)^2)$$

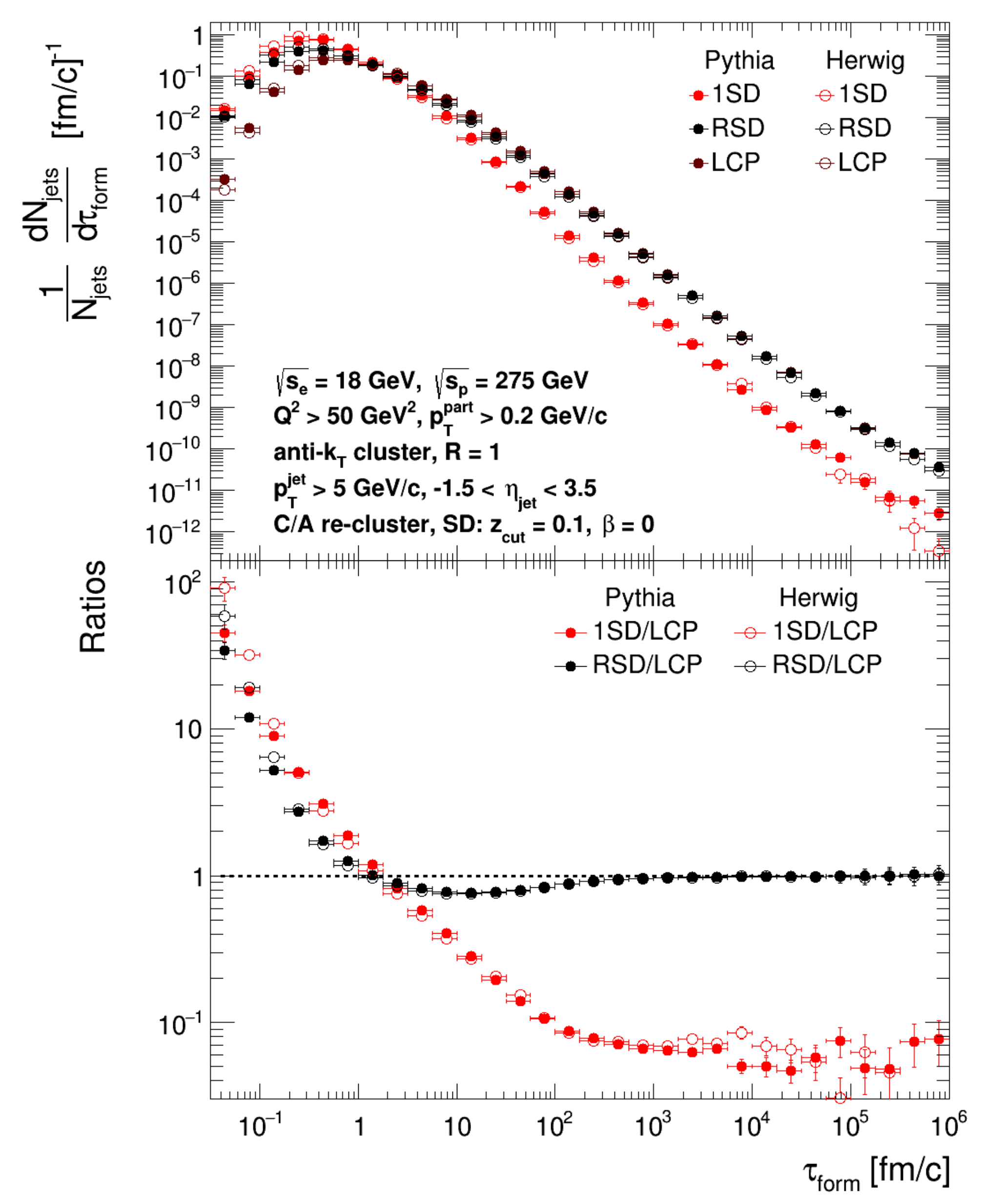
$$P_{g\to gg} = 3\frac{(1-z(1-z))^2}{1-z}$$

$$P_{q\to qg} = \frac{4}{3}\frac{1+z^2}{1-z}$$

- **1SD** is highly **asymmetrical**; distributions extremely peaked for small z_g
- **LCP** is highly **symmetrical**; distributions extremely peaked for large z_g
- **RSD** is more symmetrical than 1SD and more asymmetrical than LCP; more to the likes of the LCP splitting

Results – Formation Time

$$\tau_{form} = \frac{1}{2\,E\,z\,(1-z)\,(1\; - \;\cos\theta_{12})}$$

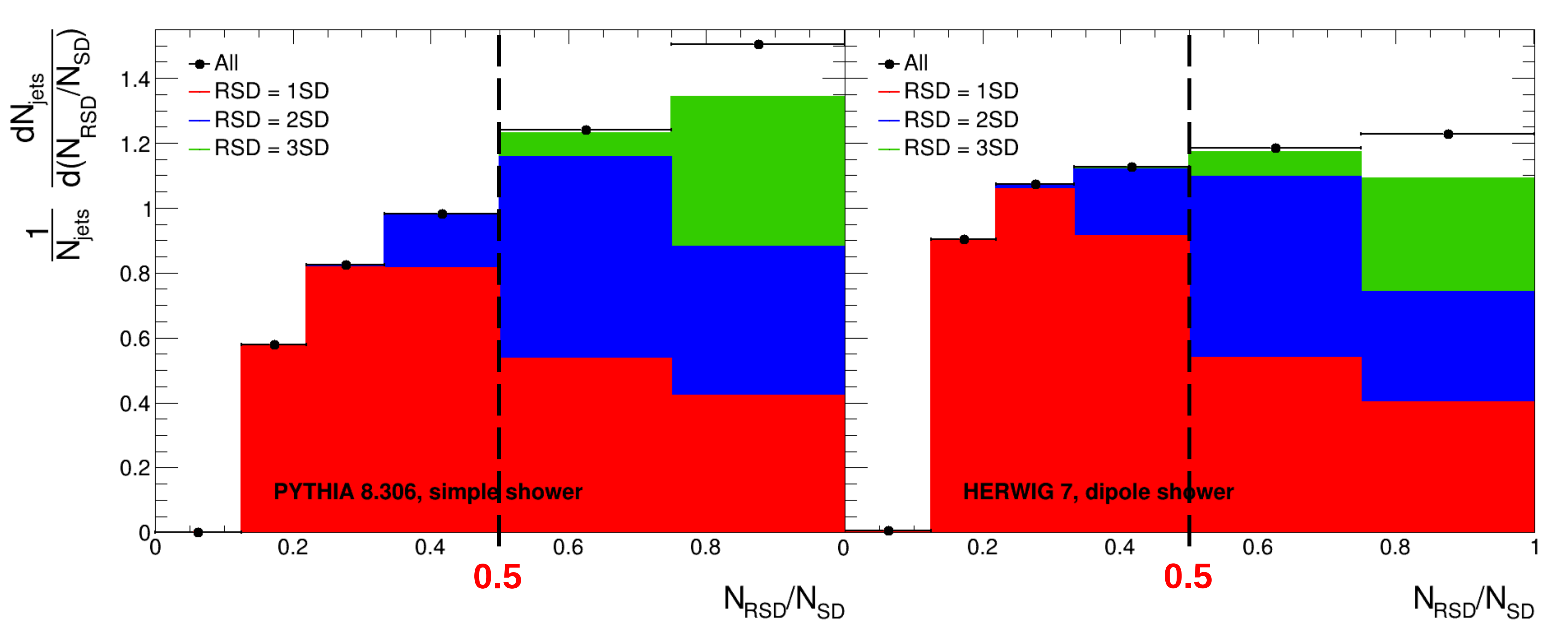


- **1SD** tends to have smaller τ_{form}
- **LCP** tends to have larger τ_{form}
- **RSD** sits between the 1SD and the LCP
- $\tau_{form,1SD} \neq \tau_{form,LCP}$
- $\tau_{form,RSD} \approx \tau_{form,LCP}$

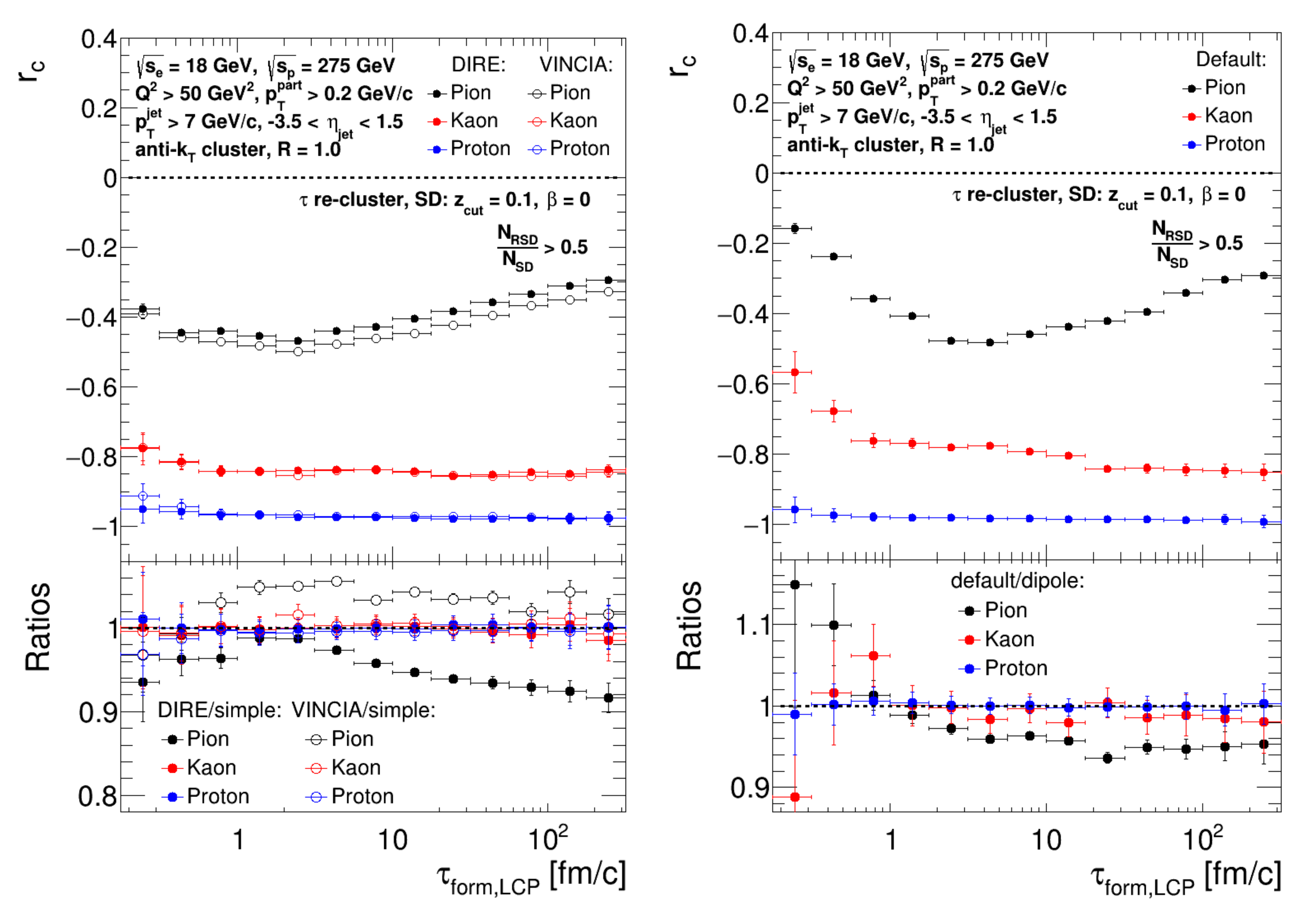
Conclusion: RSD splitting, an actual splitting from the clustering tree, is a good proxy for the LCP

RSD Depth

N_{RSD}/N_{SD}



Charge Ratio – Parton Shower Dependence



- The behaviour observed for these jet selections is robust against parton shower descriptions;
- **Since the** r_c is meant to be sensitive to hadronization physics, this is good news!