ECT* 2024 Workshop

Flavour correlations dependence on jet substructure

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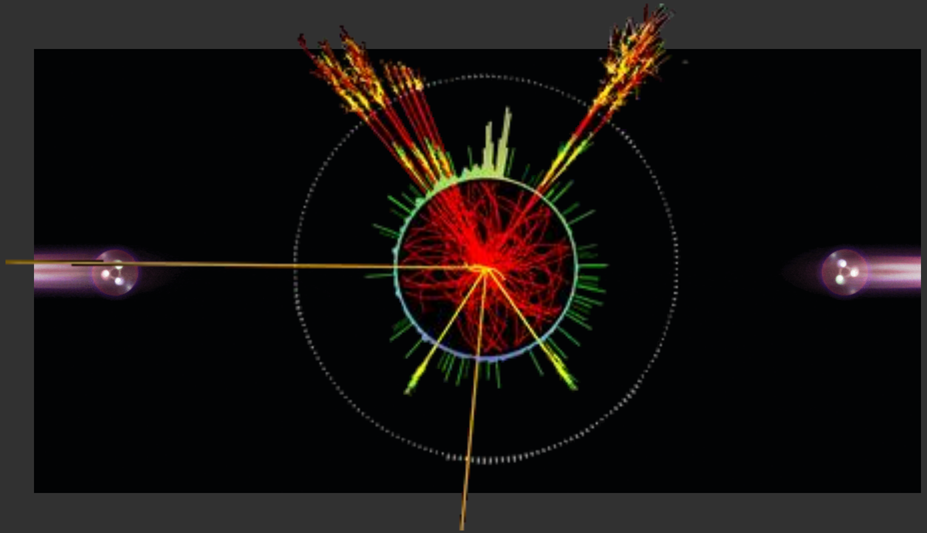

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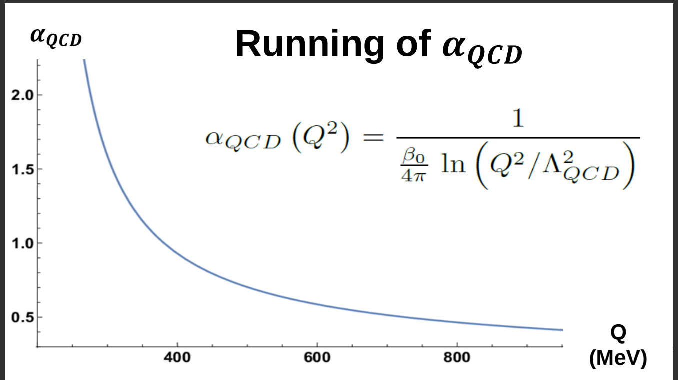
Collision Physics



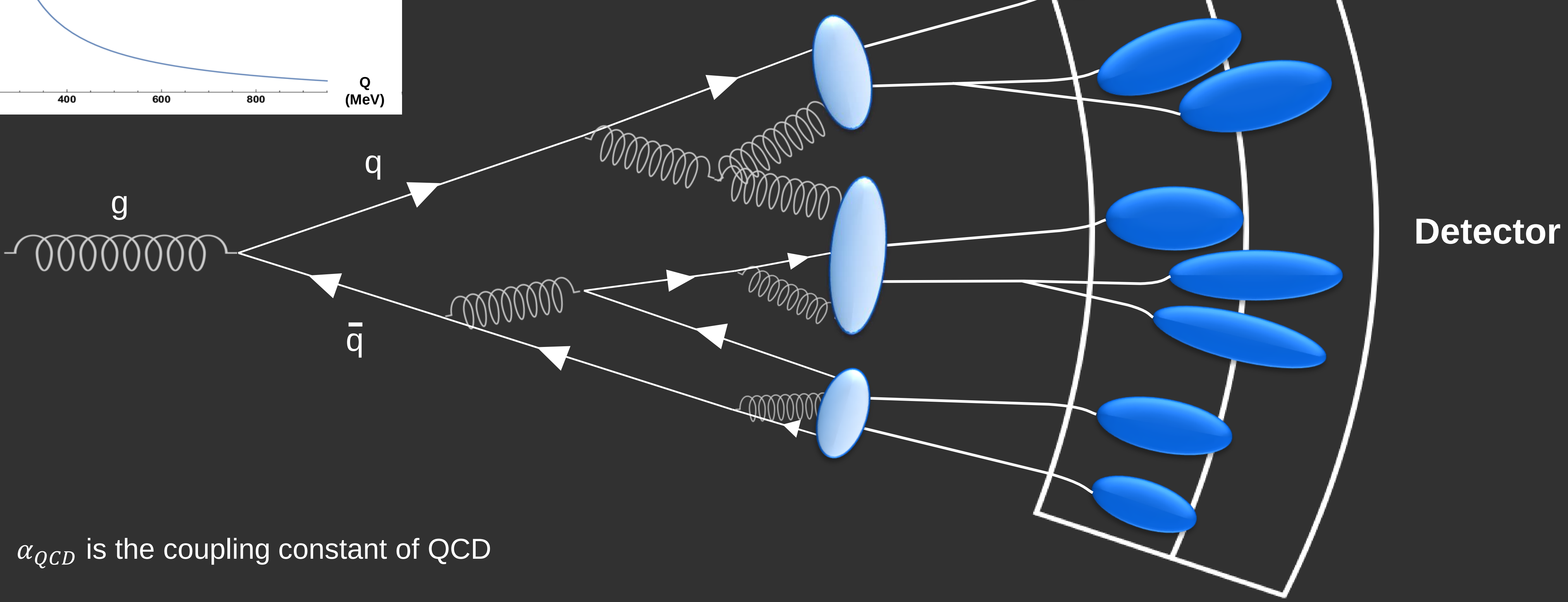
Hadronization

Process by which free partons bind to produce hadrons

g – gluon

q – quark

$\bar{q}$ – antiquark



- α_{QCD} is the coupling constant of QCD

Collision Physics

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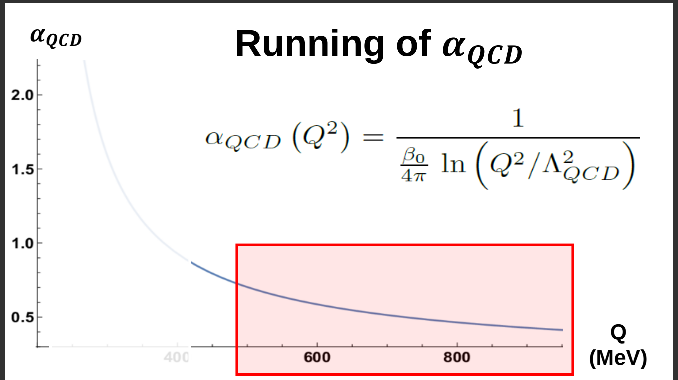
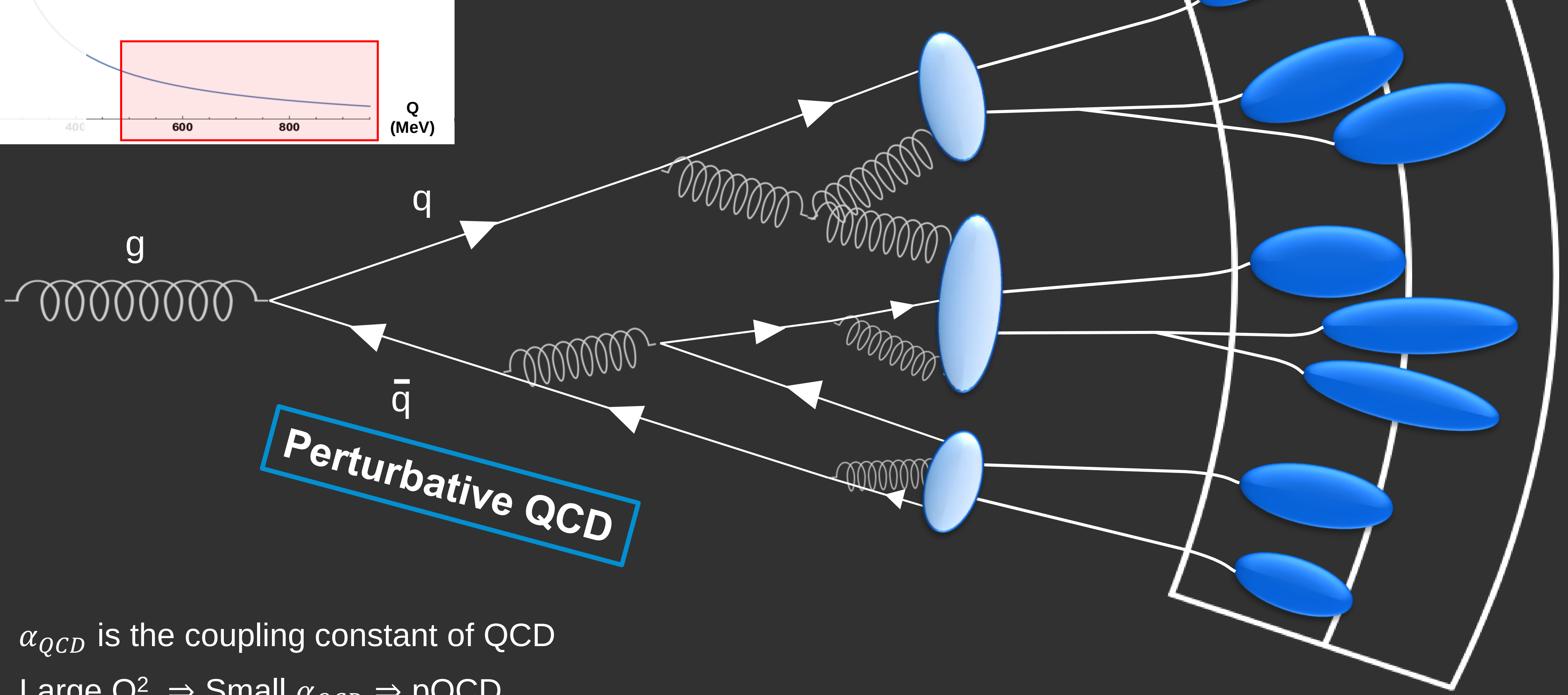
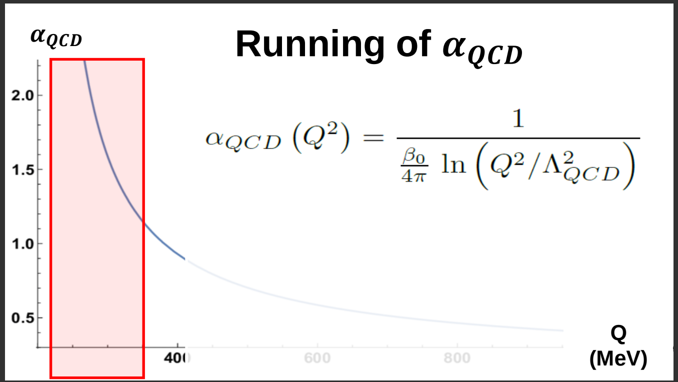
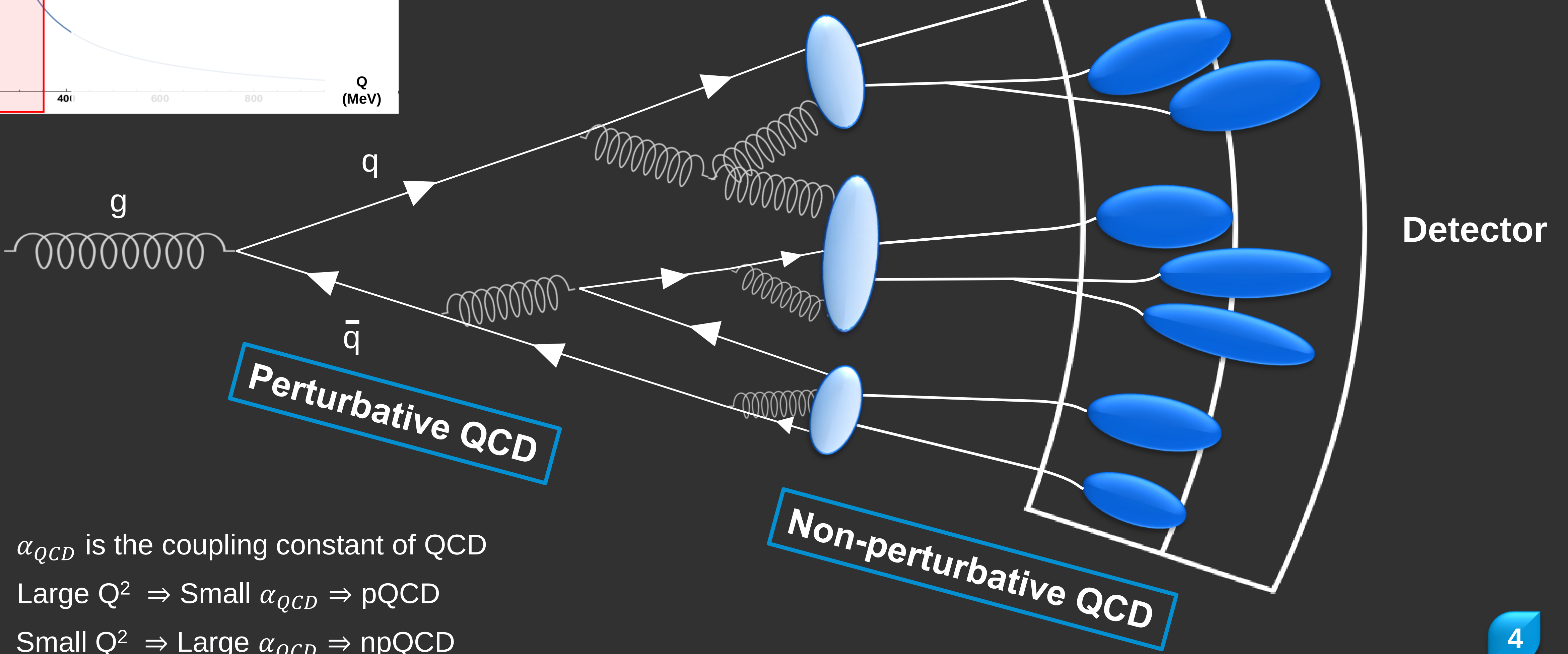




- α_{QCD} is the coupling constant of QCD
- Large Q^2 $\Rightarrow$ Small α_{QCD} $\Rightarrow$ pQCD

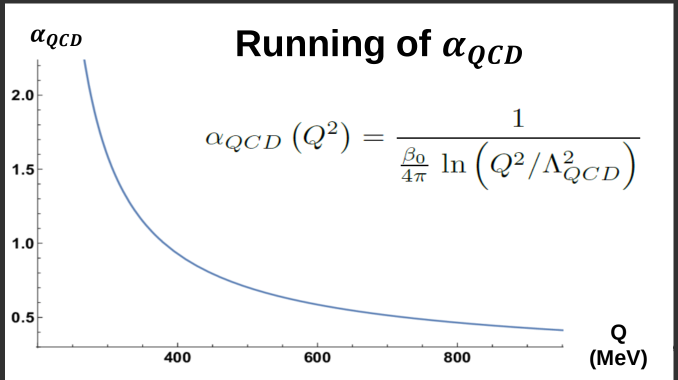
Collision Physics





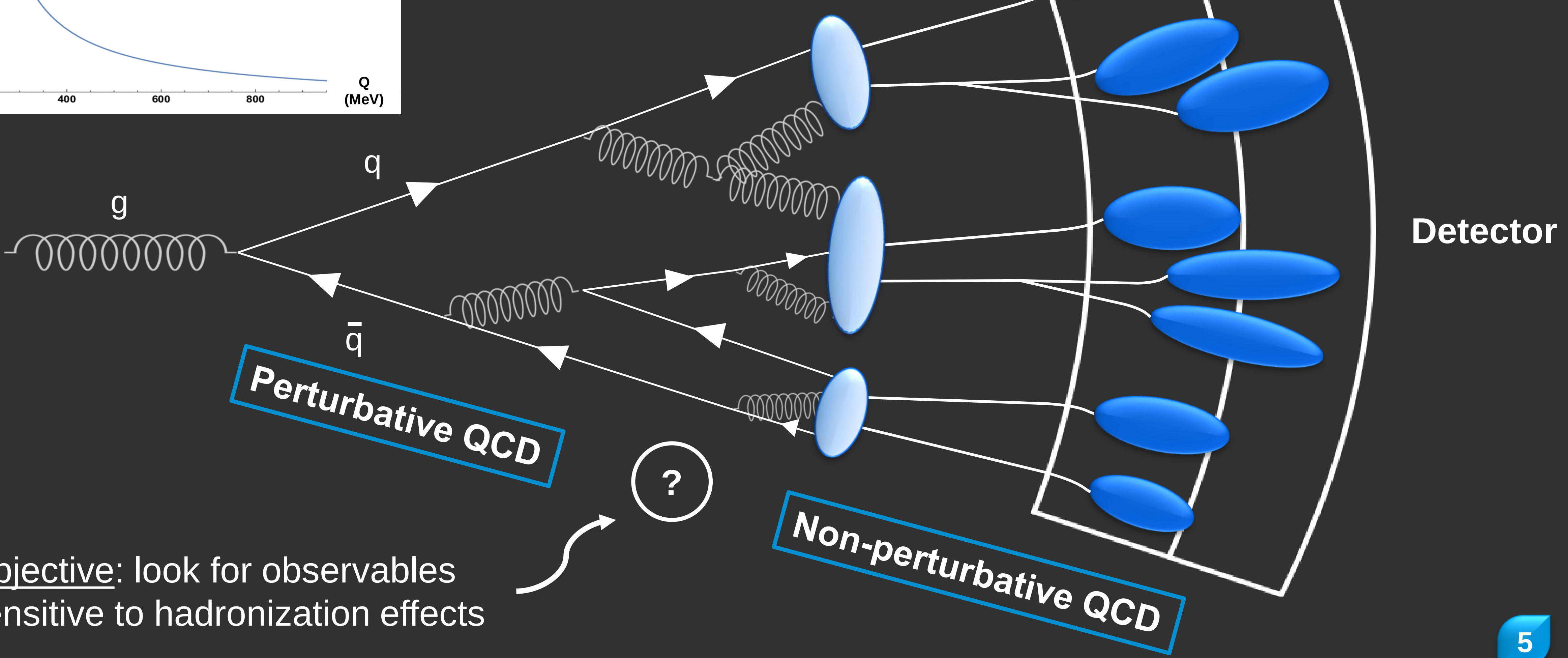
- α_{QCD} is the coupling constant of QCD
- Large Q^2 $\Rightarrow$ Small α_{QCD} $\Rightarrow$ pQCD
- Small Q^2 $\Rightarrow$ Large α_{QCD} $\Rightarrow$ npQCD

Collision Physics



Hadronization

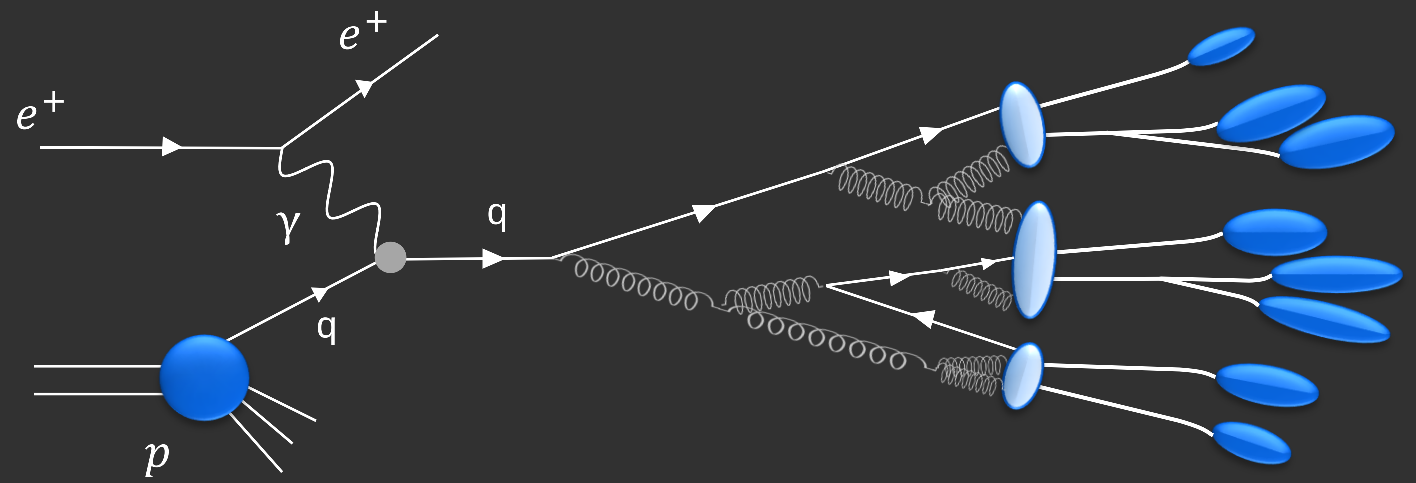
Process by which free partons bind to produce hadrons



Objective: look for observables sensitive to hadronization effects

Motivation

- Focus on Deep Inelastic ep Scatterings (DIS), with EIC beam energies, selected on high Q^2 to ensure hard processes;

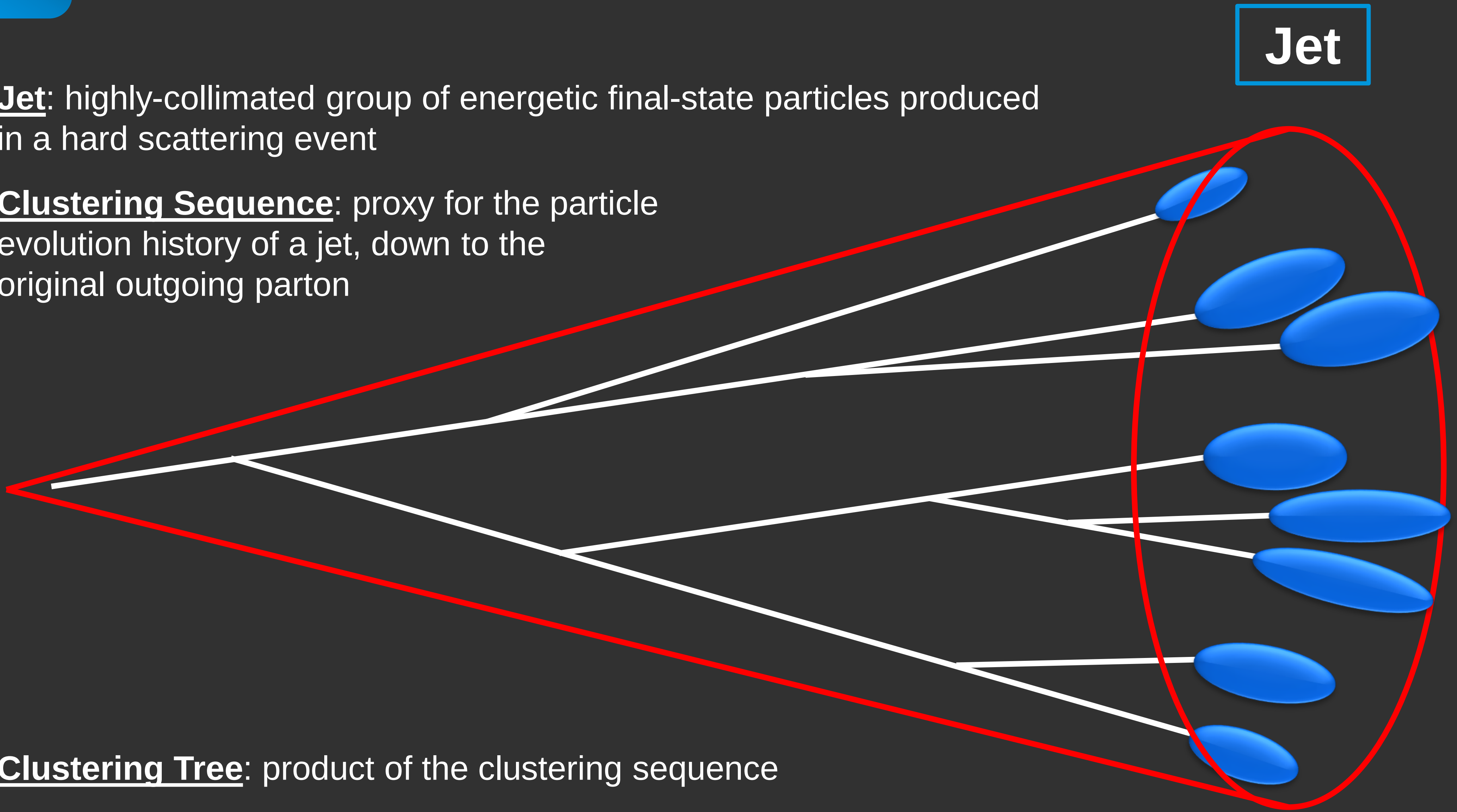


- DIS provides clean environment (more precise measurements) to study hadronization and confinement such as the hadronization timescales;

- Comparisons between vacum and nuclear DIS help the testing and calibration *e.g.* of Monte Carlo generators used to study the quark-gluon plasma produced in Heavy-Ion Collisions.

Jets

- **Jet**: highly-collimated group of energetic final-state particles produced in a hard scattering event
- **Clustering Sequence**: proxy for the particle evolution history of a jet, down to the original outgoing parton



- **Clustering Tree**: product of the clustering sequence
- Our work proposes jets as probing tools to investigate the transition from partons to hadrons

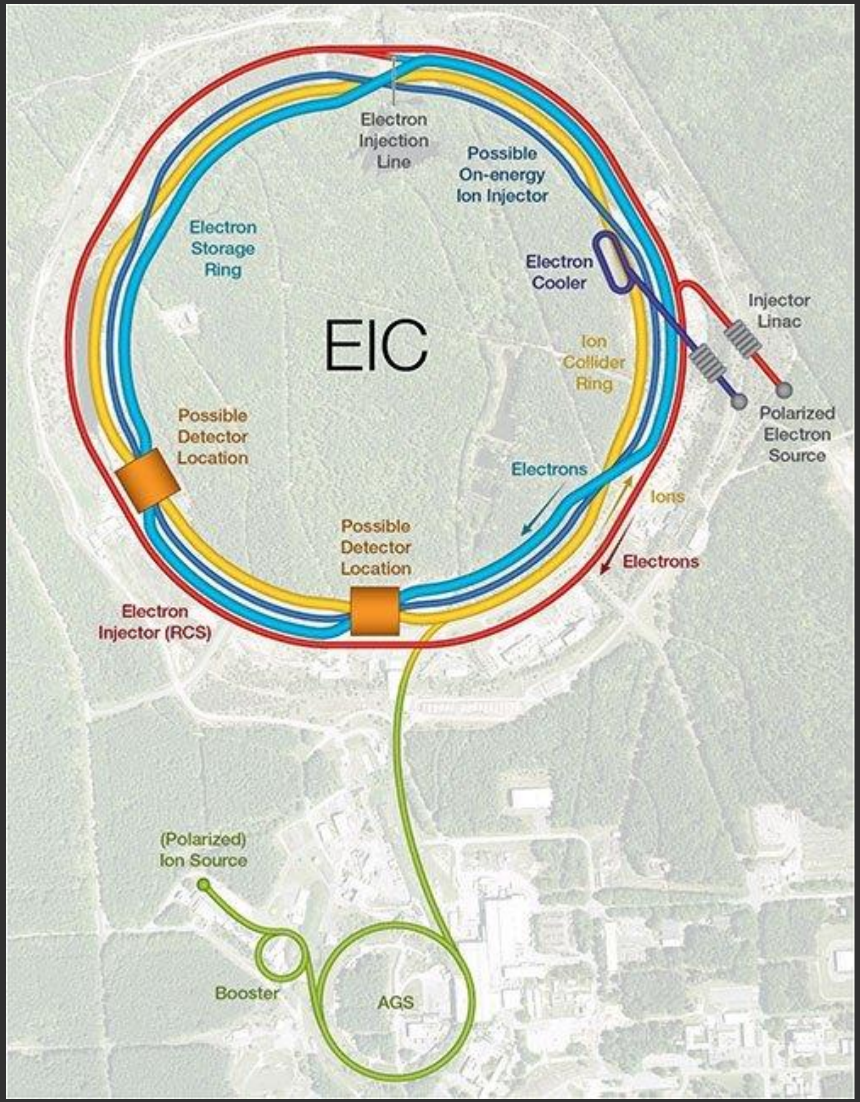
Simulation and Jet Analysis

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

Settings	Values
$\sqrt{s_e}$	18 GeV
$\sqrt{s_p}$	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 C/A algorithm with soft-drop grooming.

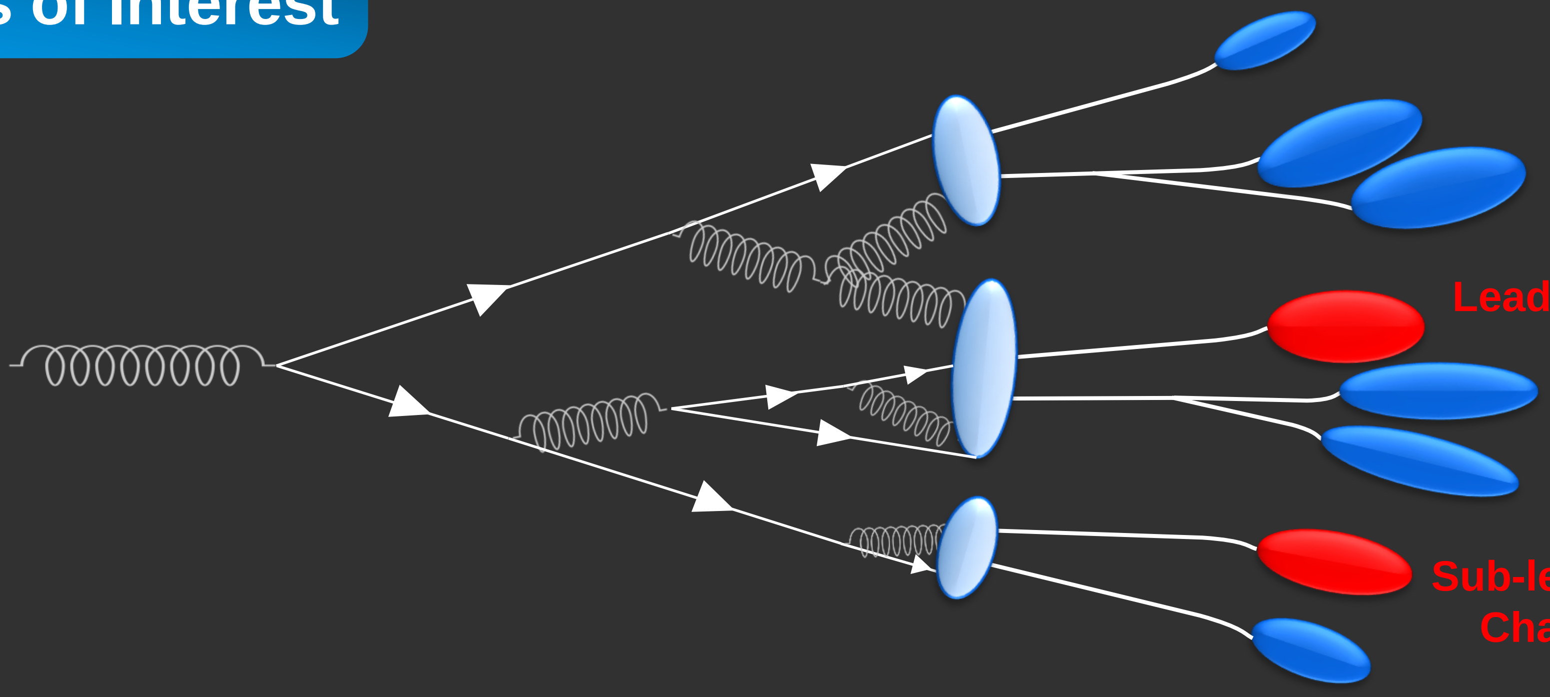
Settings	Values
R	1
$p_{T,jet}$	> 5 GeV/c
η_{jet}	$-1.5 < \eta_{jet} < 3.5$
z_{cut}	0.1
β	0



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

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

Splittings of Interest



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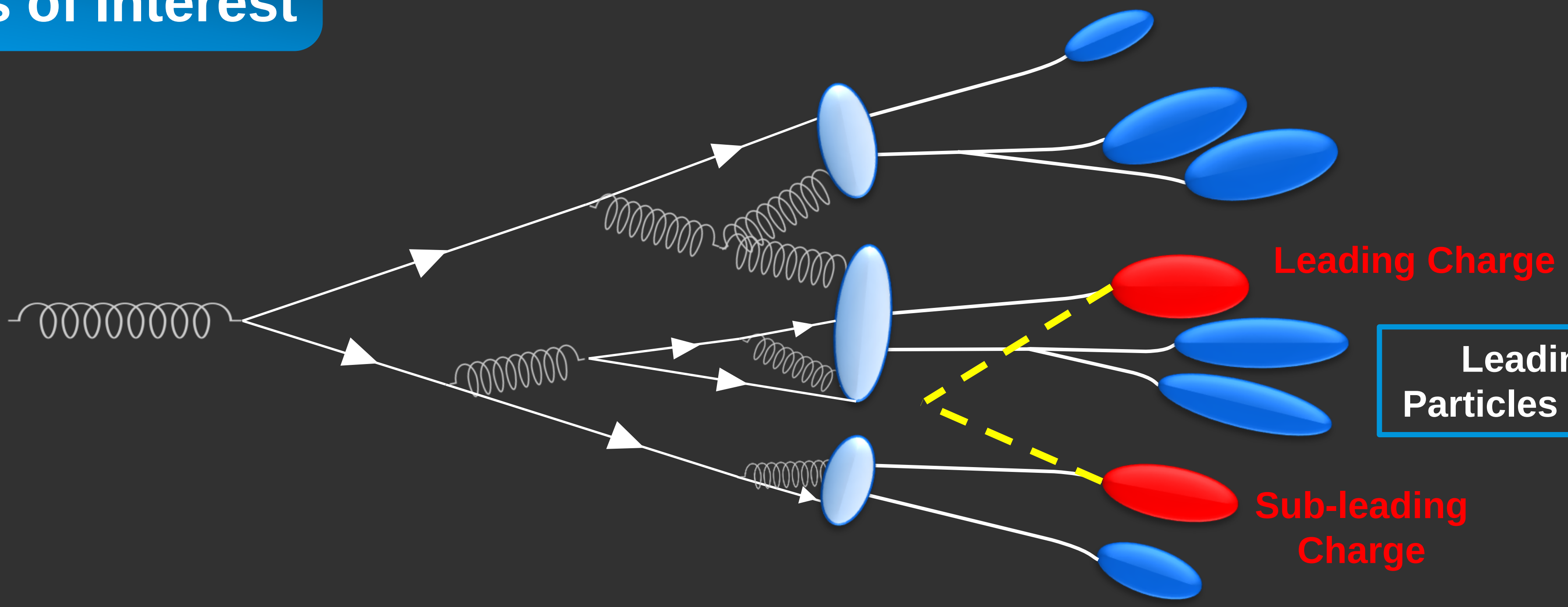


Leading Charged Particles splitting (LCP)

Charge Ratio

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

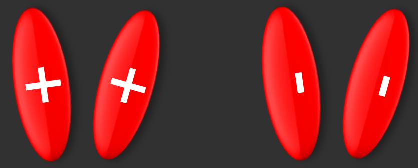
$$r_c = \frac{\frac{d\sigma_{h_1 h_2}}{dX} - \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}{\frac{d\sigma_{h_1 h_2}}{dX} + \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}$$

h_1 – leading charged hadron
h_2 – subleading charged hadron

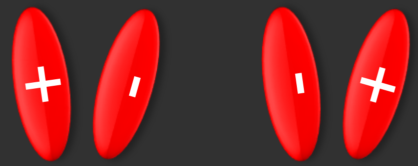
h_1, h_2 - pion (π), kaon (K), proton (p)

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.

Results – Formation Time

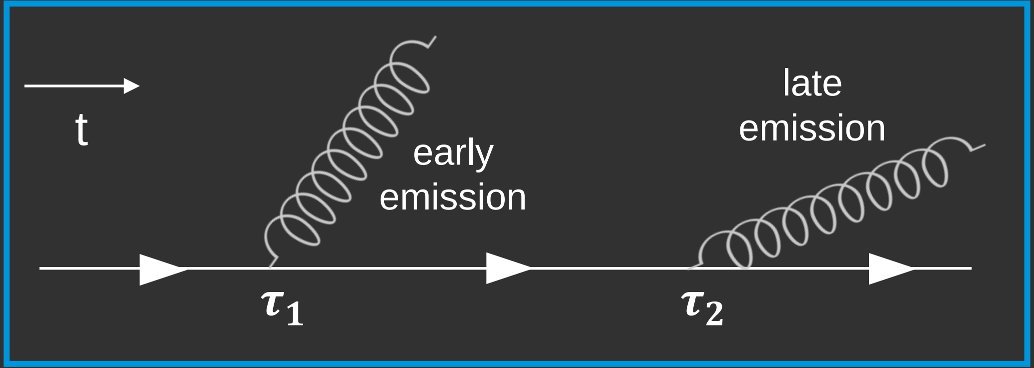
[Y.L. Dokshitzer et al., Basics of perturbative QCD]
[L. Apolinário et al, arXiv:2012.021999]

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

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

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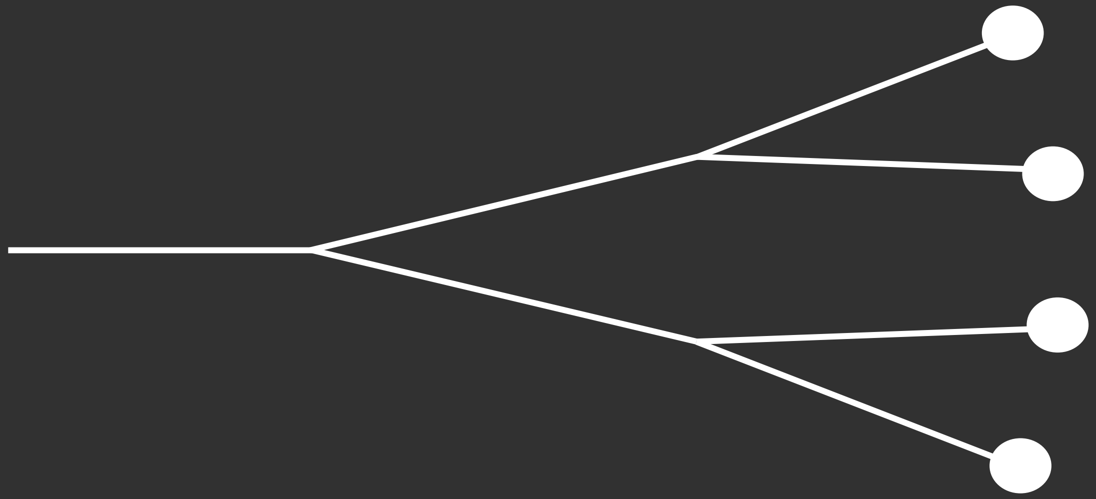

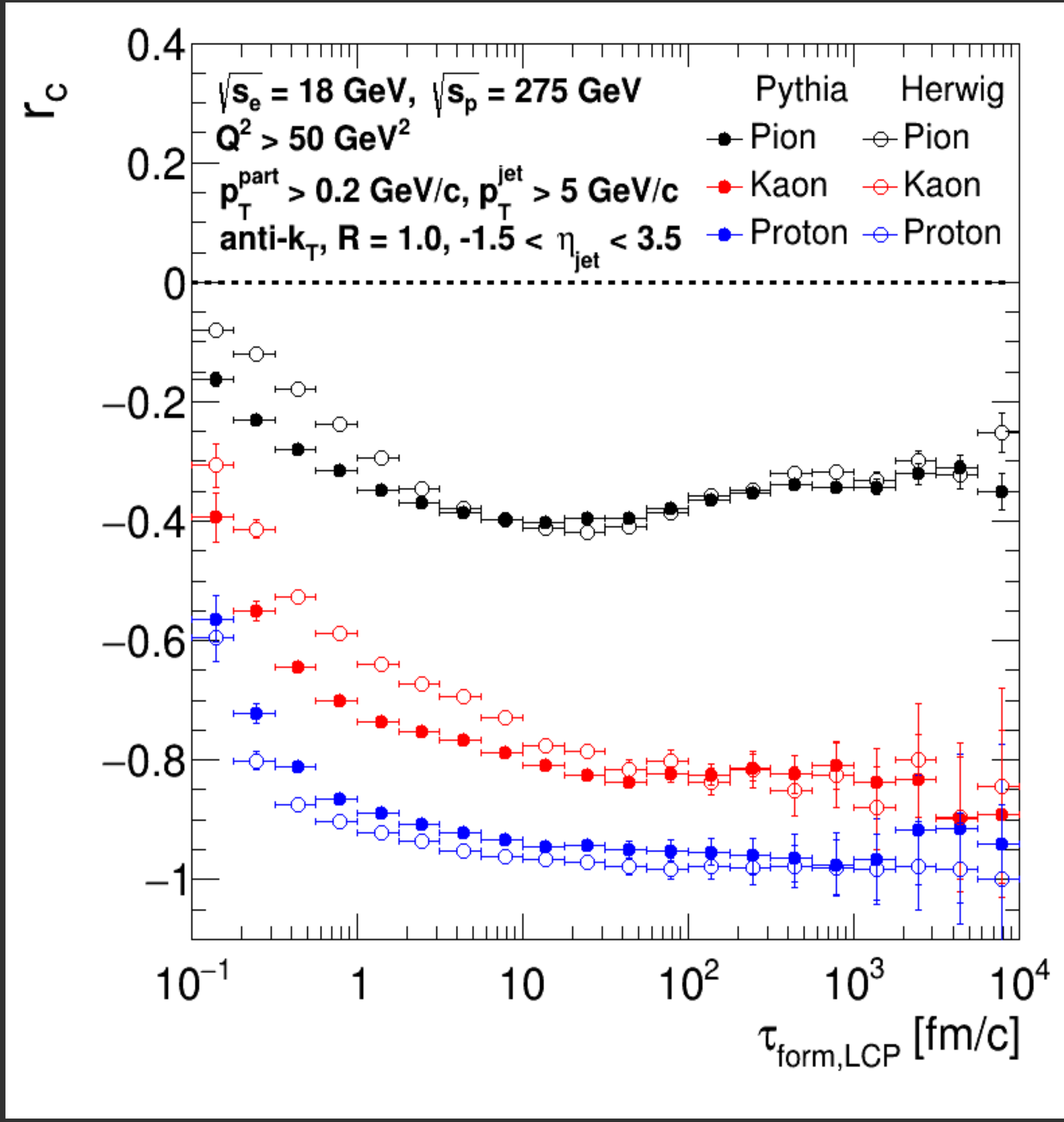

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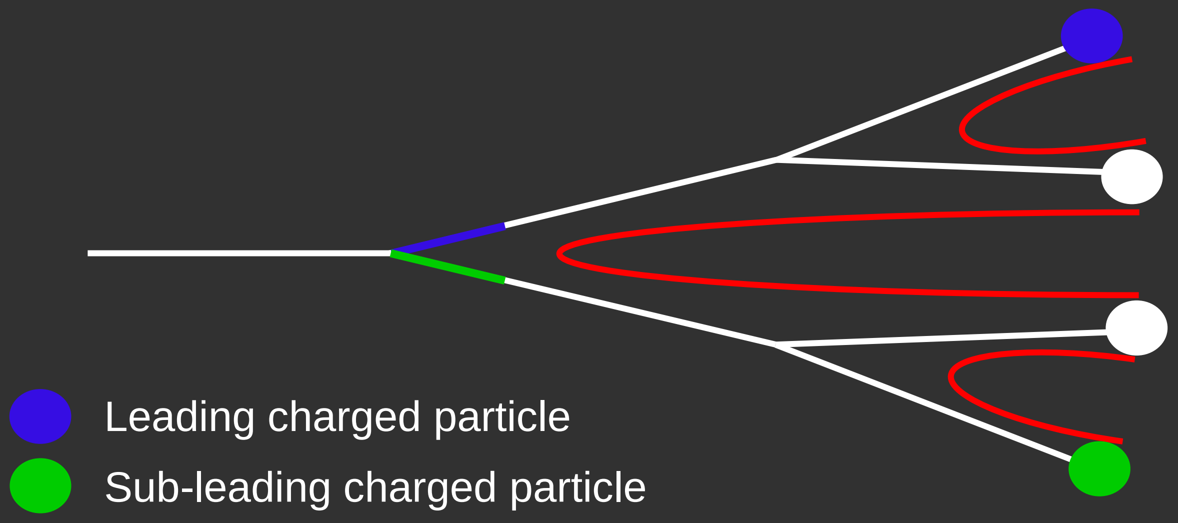

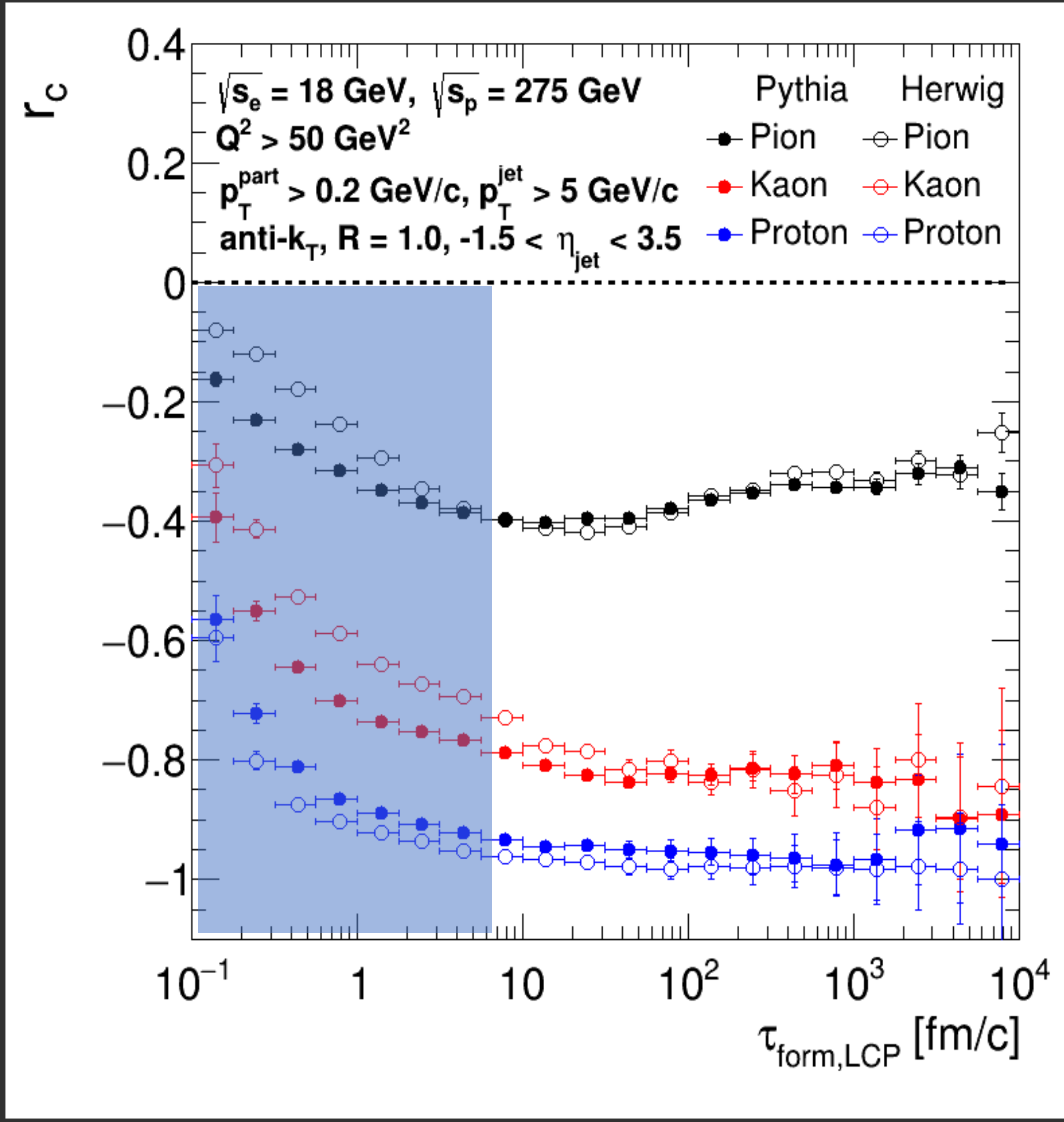

- LCP “produced” at earlier times, typical of the earlier splittings ⇒ subsequent splittings randomize the charge correlation ⇒ r_c closer to 0

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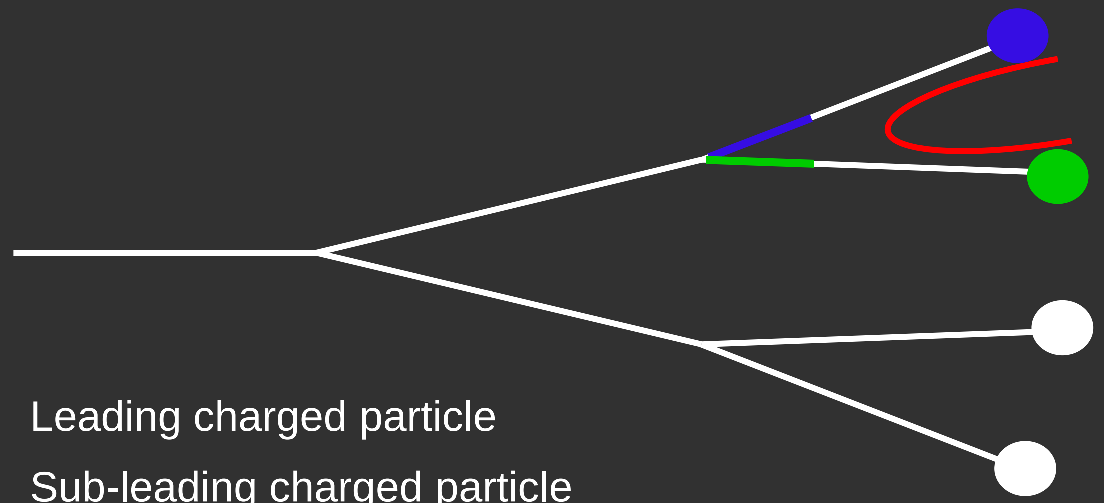
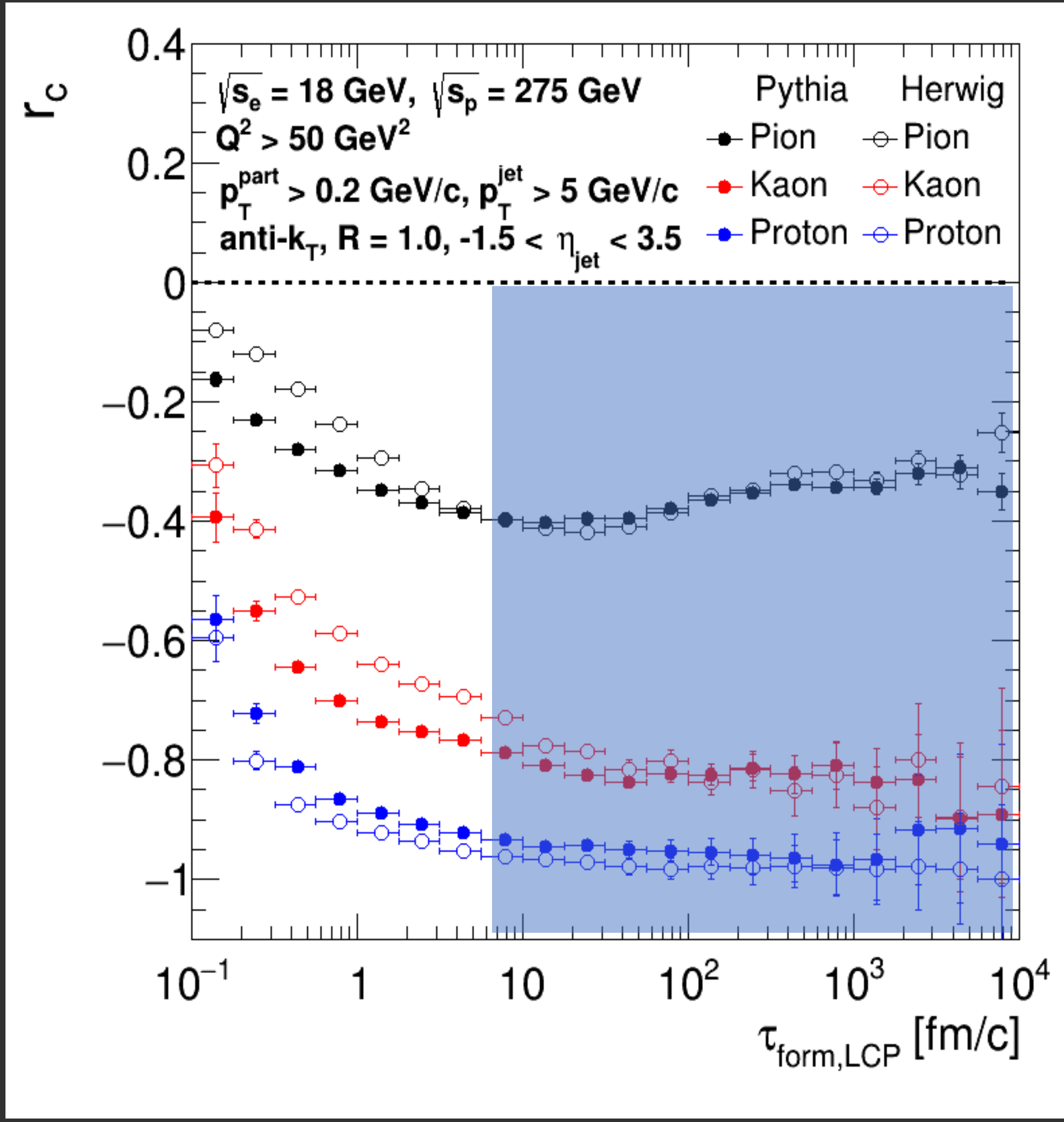


Leading charged particle

Sub-leading charged particle



- LCP "produced" at earlier times, typical of the earlier splittings ⇒ subsequent splittings randomize the charge correlation ⇒ r_c closer to 0

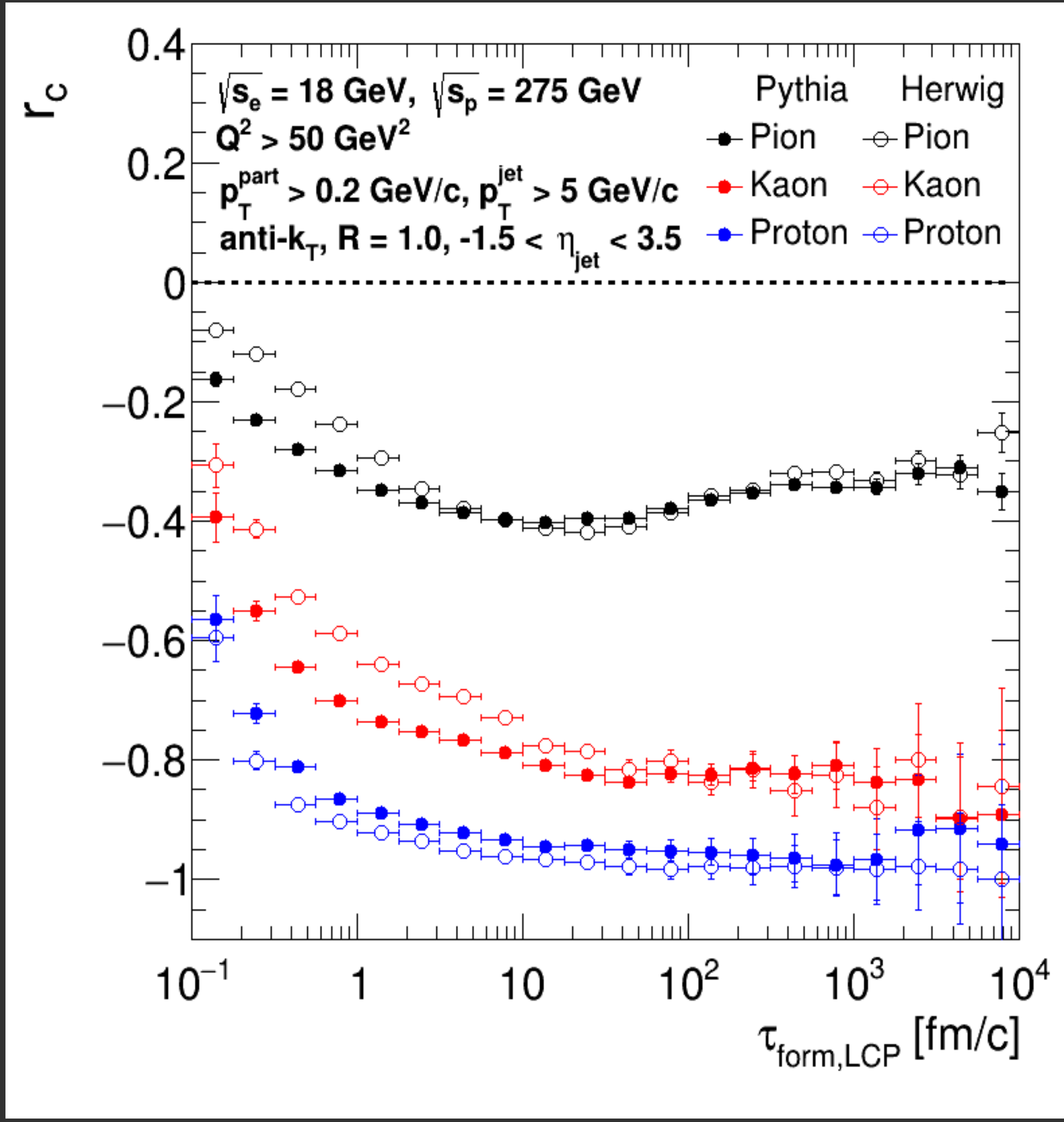
- LCP "produced" at later times, typical of later splittings ⇒ retain more information of the splitting where the LCP separate, which favours opposite charges ⇒ r_c more negative

Charge Ratio

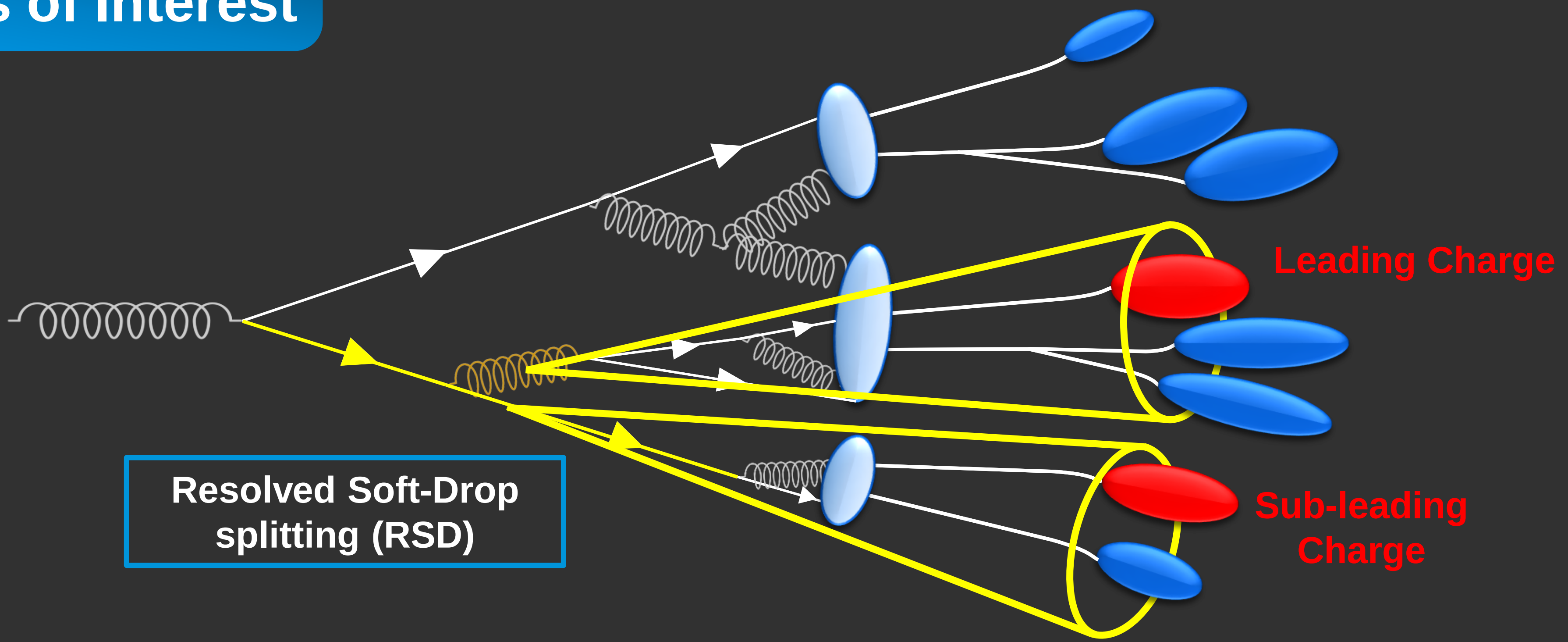
$$r_c = \frac{\frac{d\sigma_{h_1h_2}}{dX} - \frac{d\sigma_{h_1\overline{h_2}}}{dX}}{\frac{d\sigma_{h_1h_2}}{dX} + \frac{d\sigma_{h_1\overline{h_2}}}{dX}}, \qquad X = \tau_{form}$$

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

- How dependent is the r_c on the jet fragmentation pattern?

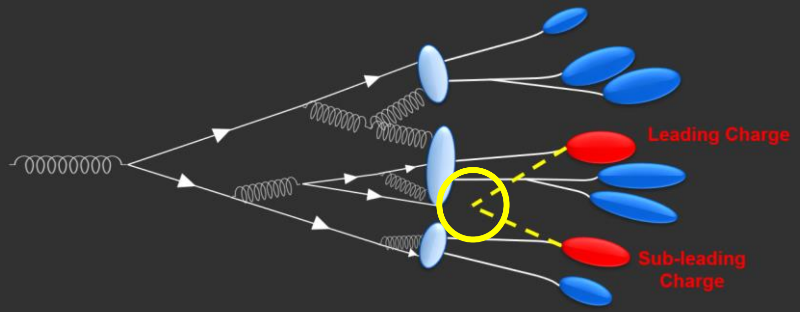


Splittings of Interest



Resolved Soft-Drop splitting (RSD)

Leading Charged Particles splitting (LCP)



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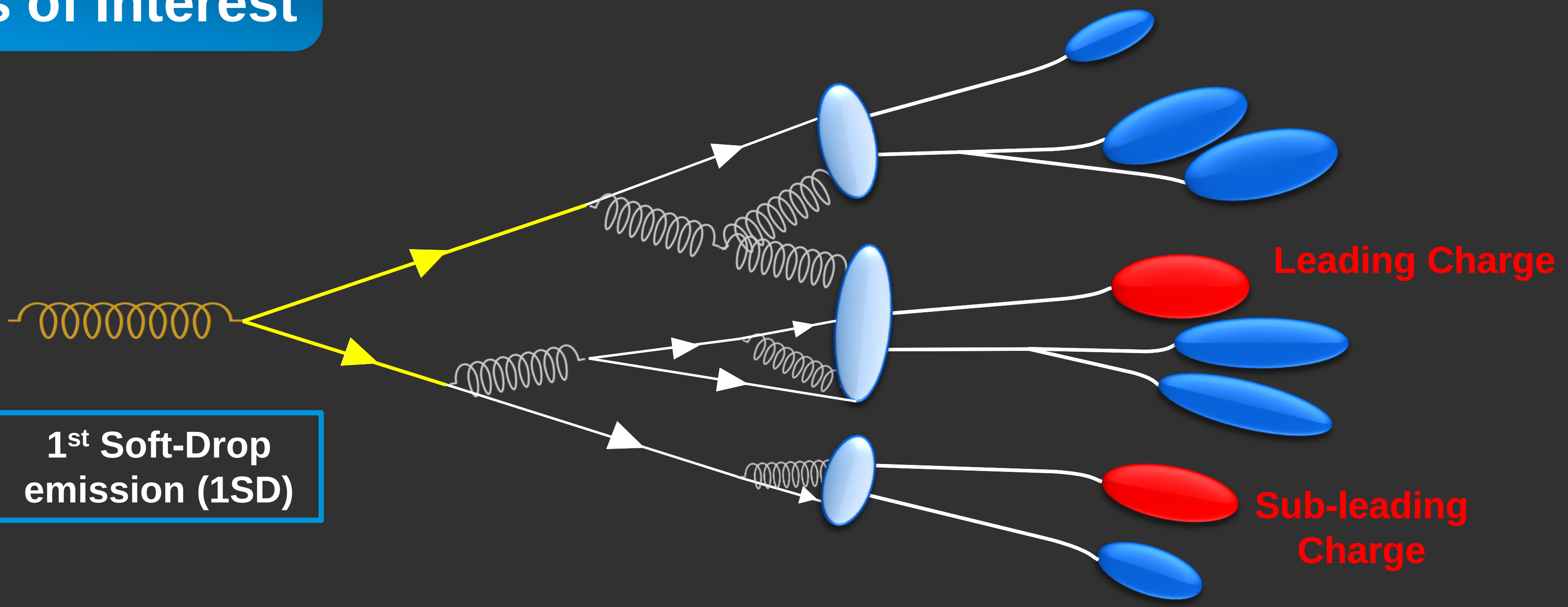
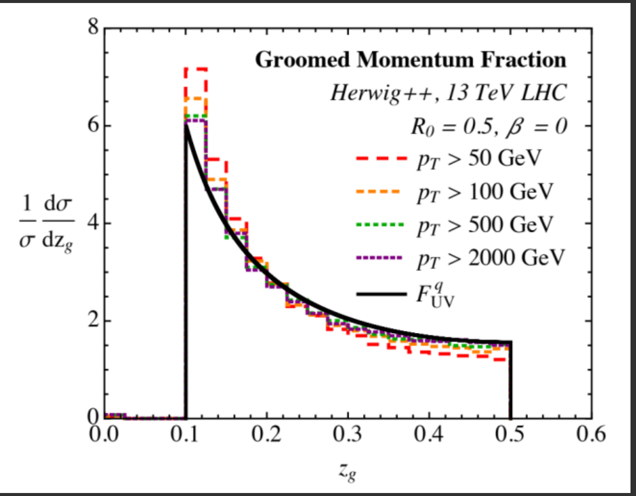


1st Soft-Drop emission (1SD)

[A.J. Larkoski et al, arXiv:1502.01719]



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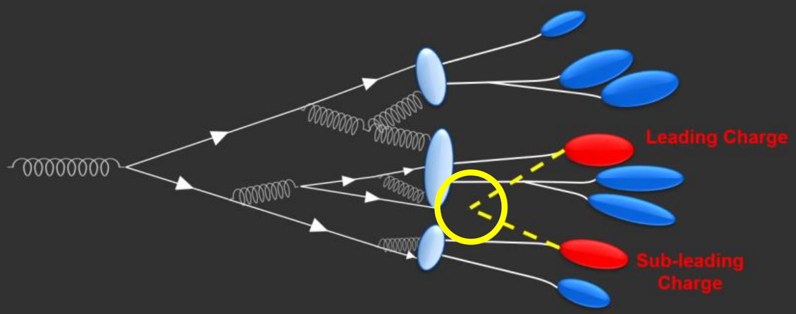

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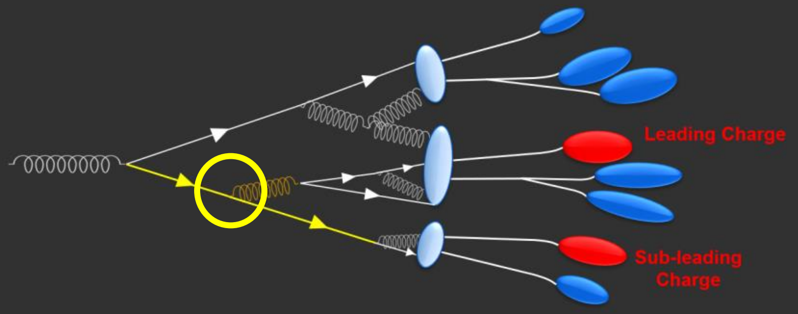
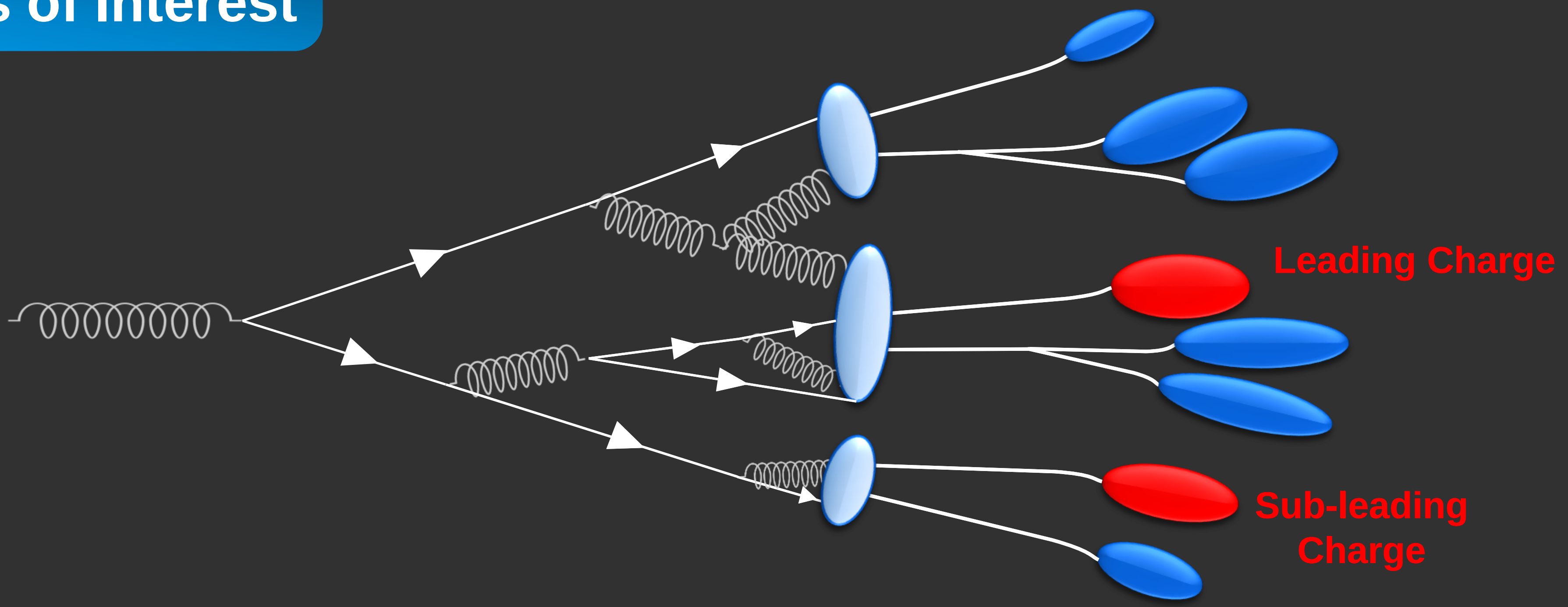
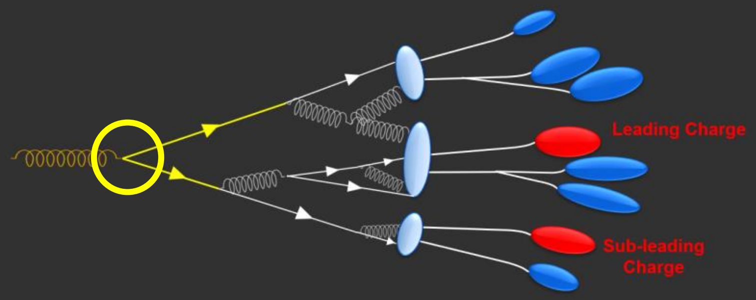
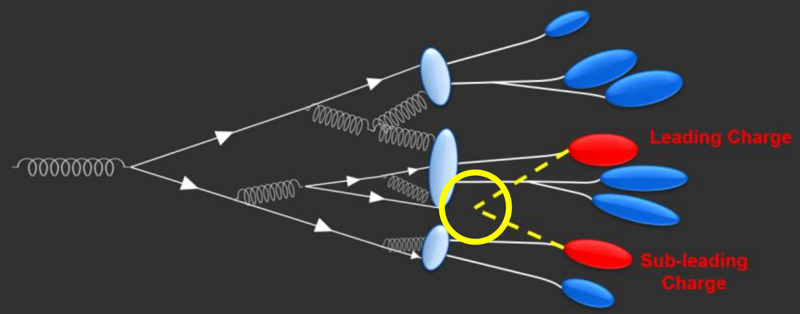


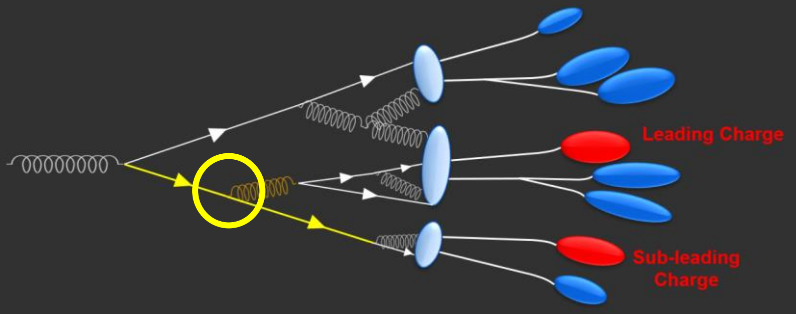
Splittings of Interest



1st Soft-Drop emission (1SD)	Leading Charged Particles splitting (LCP)	Resolved Soft-Drop splitting (RSD)

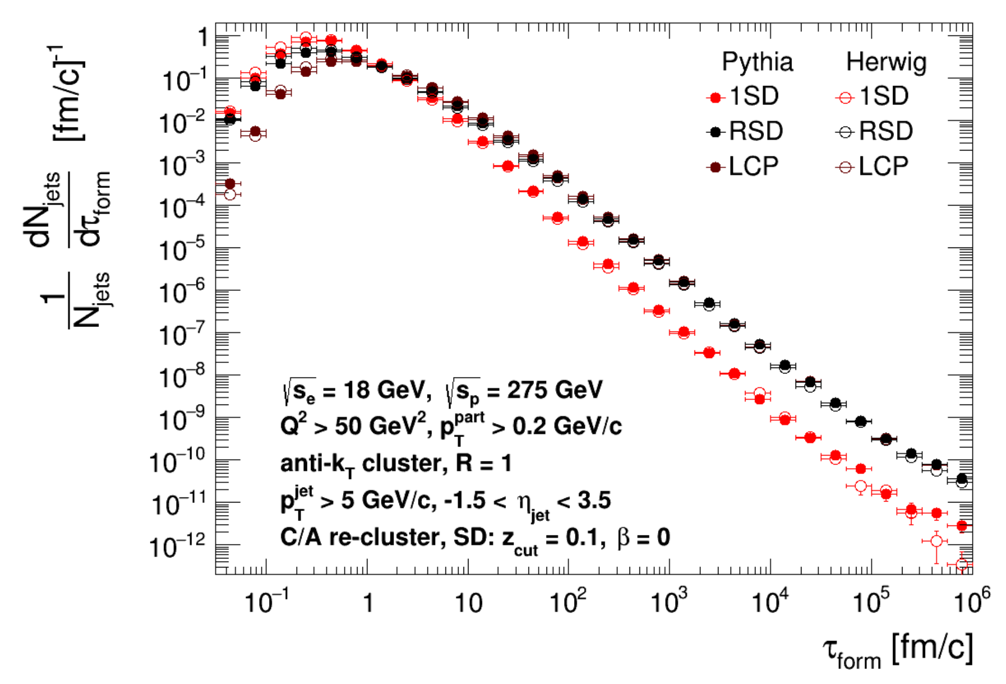






Results – Formation Time

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

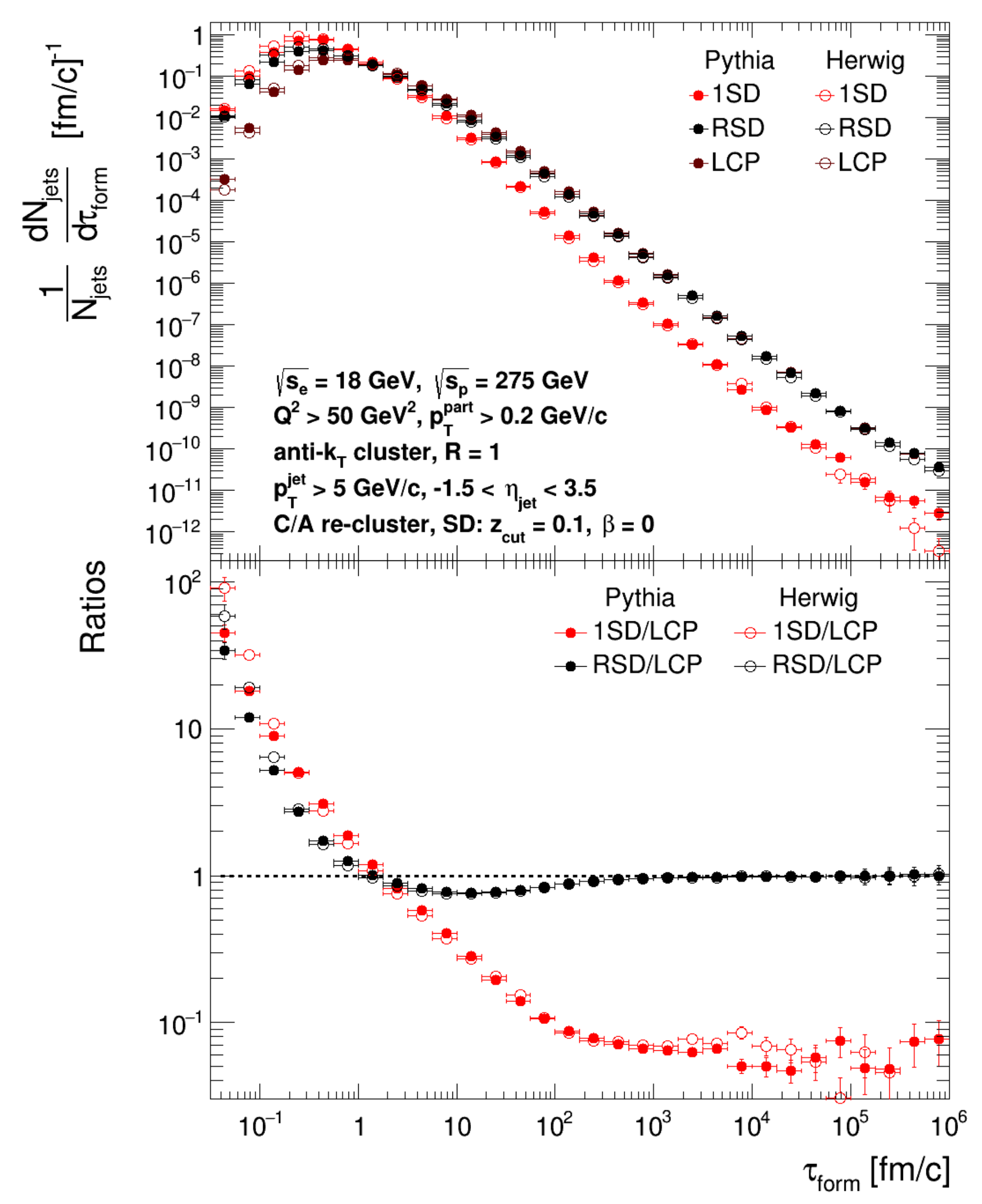


- **1SD** tends to have smaller τ_{form}
- **LCP** tends to have larger τ_{form}
- **RSD** sits between the 1SD and the LCP

$$\frac{fm}{c} \sim \frac{10^{-15}\,m}{10^{8}\,m/s} = \ 10^{-23}\ s$$

Results – Formation Time

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

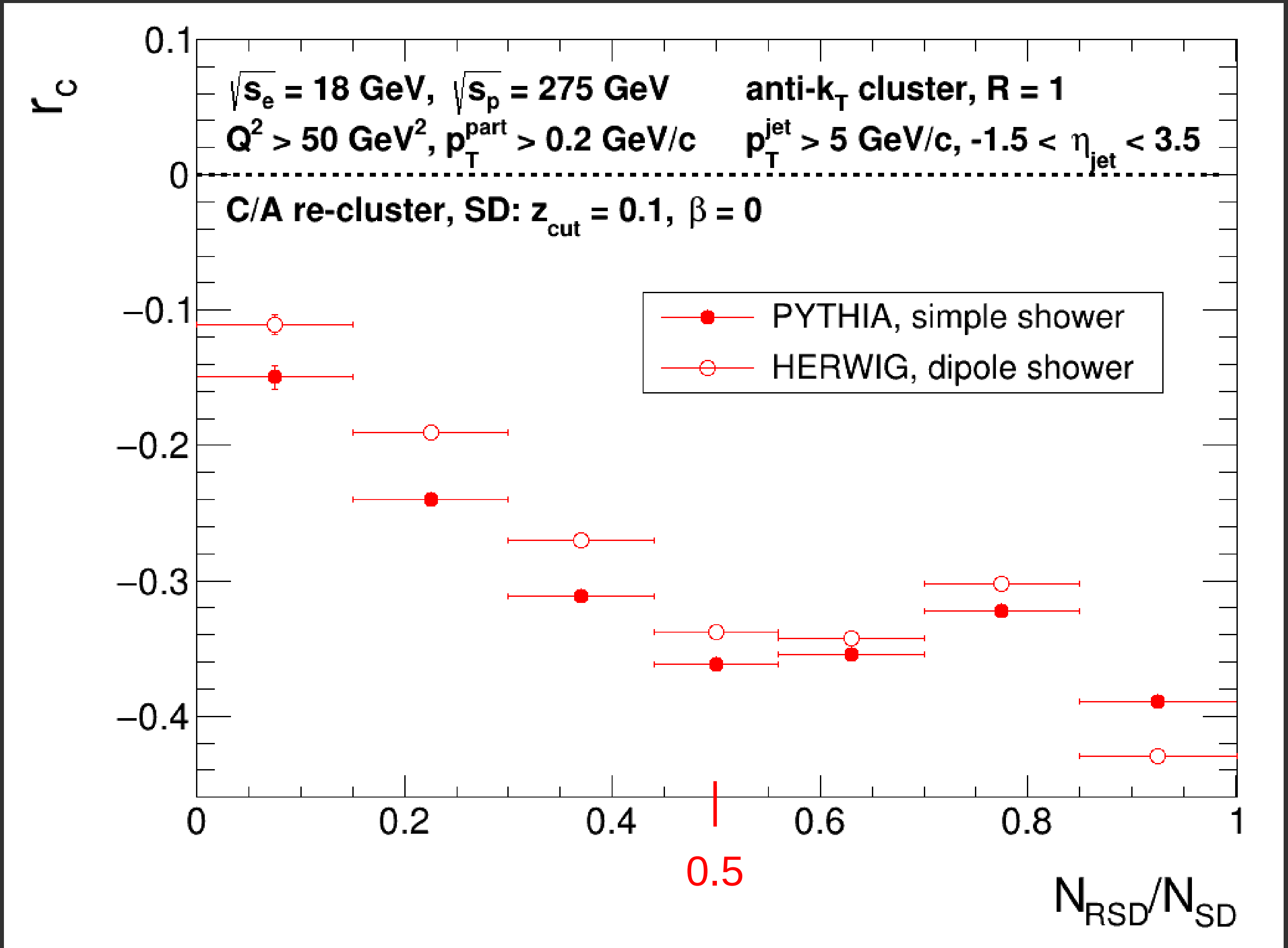


- **1SD** tends to have smaller τ_{form}
- **LCP** tends to have larger τ_{form}
- **RSD** sits between the 1SD and the LCP
- $\tau_{form,1SD} \neq \tau_{form,LCP}$
- $\tau_{form,RSD} \approx \tau_{form,LCP}$

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

Results – Charge Ratio

$$r_c = \frac{\frac{d\sigma_{h_1h_2}}{dX} - \frac{d\sigma_{h_1\overline{h_2}}}{dX}}{\frac{d\sigma_{h_1h_2}}{dX} + \frac{d\sigma_{h_1\overline{h_2}}}{dX}}, \qquad X = \frac{N_{RSD}}{N_{SD}}$$



- N_{RSD}/N_{SD} measures the depth/relative position of the RSD in the clustering tree

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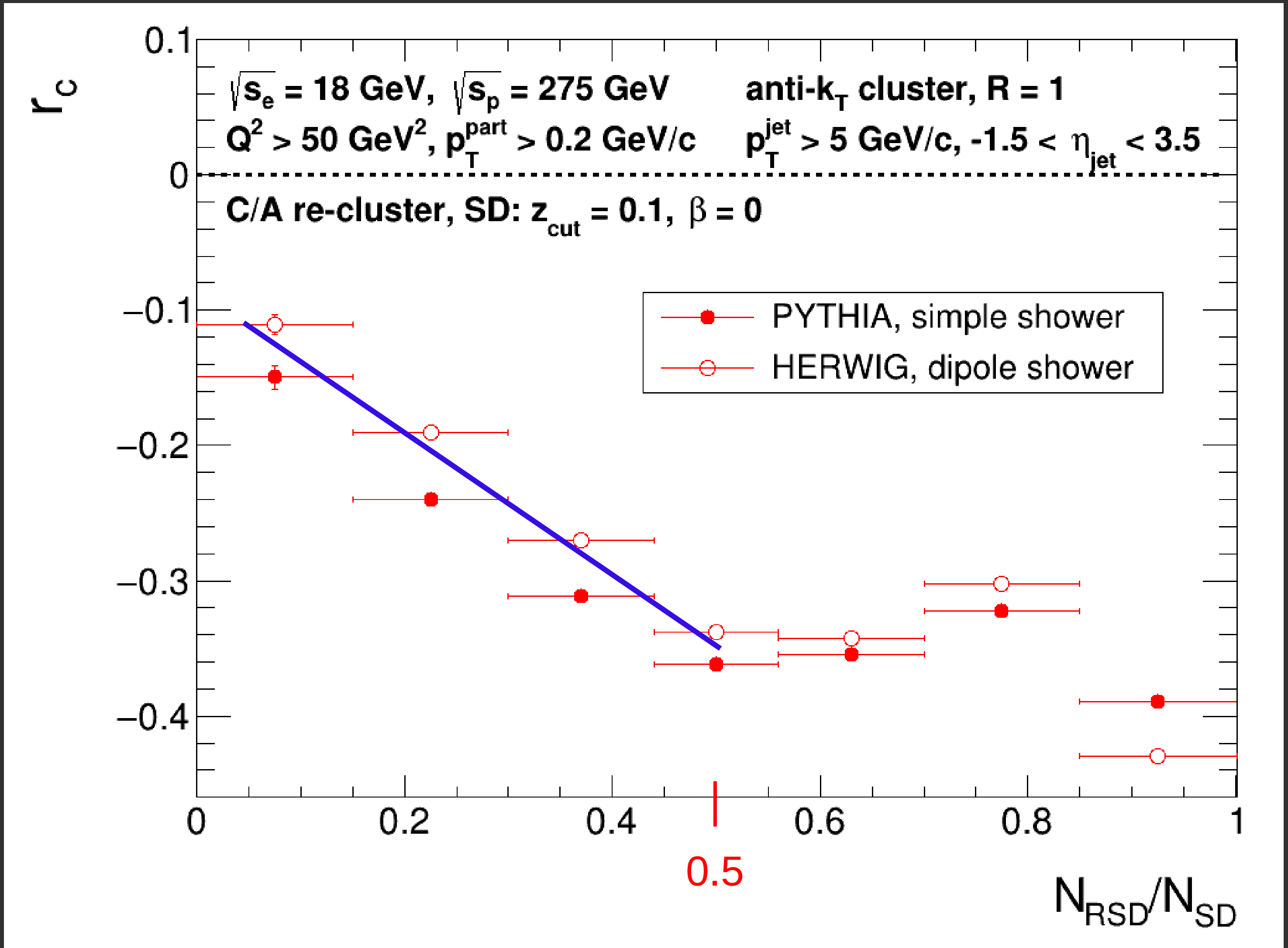

- N_{RSD}/N_{SD} measures the depth/relative position of the RSD in the clustering tree
- The charge ratio decreases, in general, with the increase of the RSD relative position

Conclusion: Yes! The r_c depends on the jet fragmentation pattern

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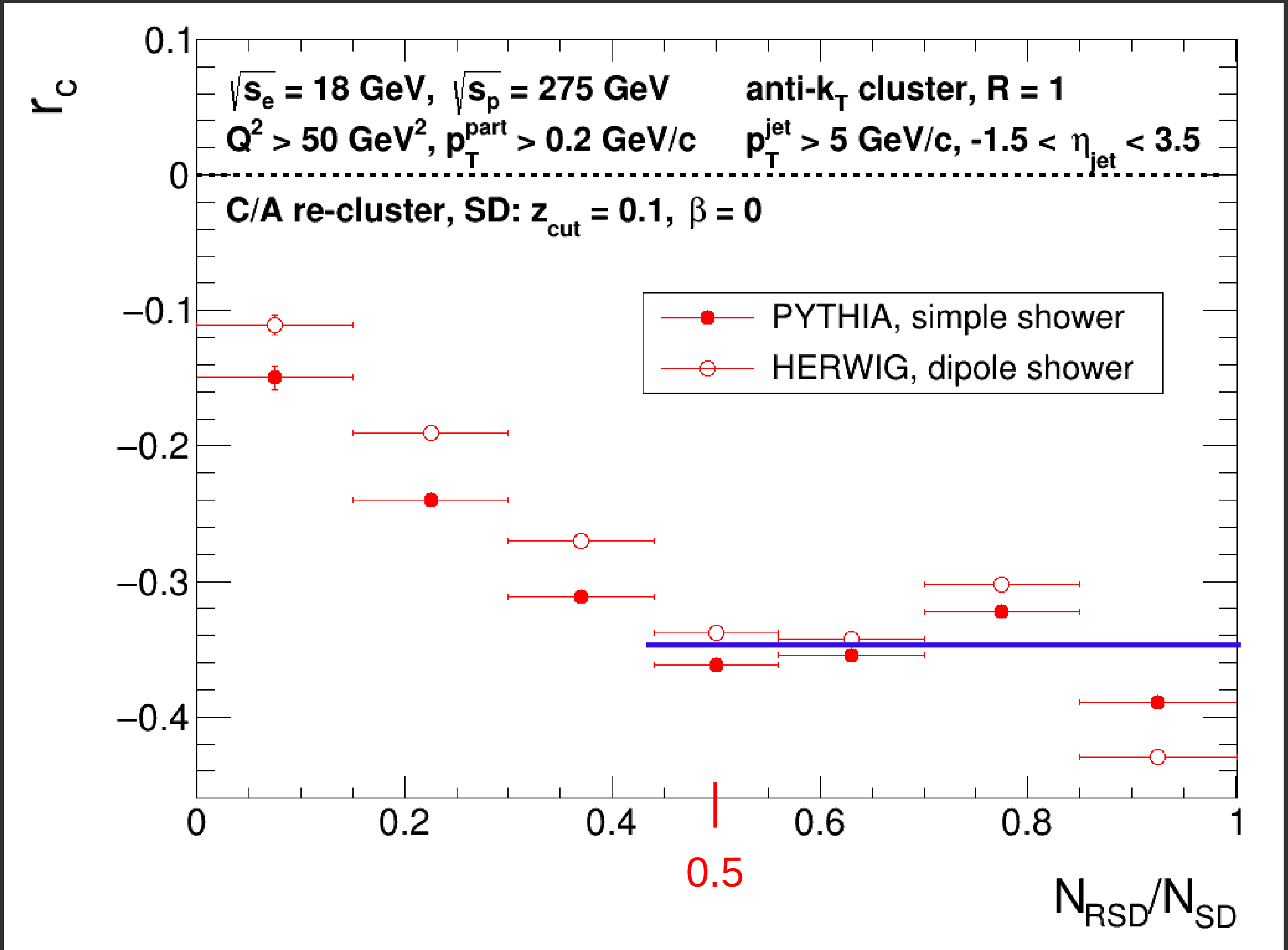
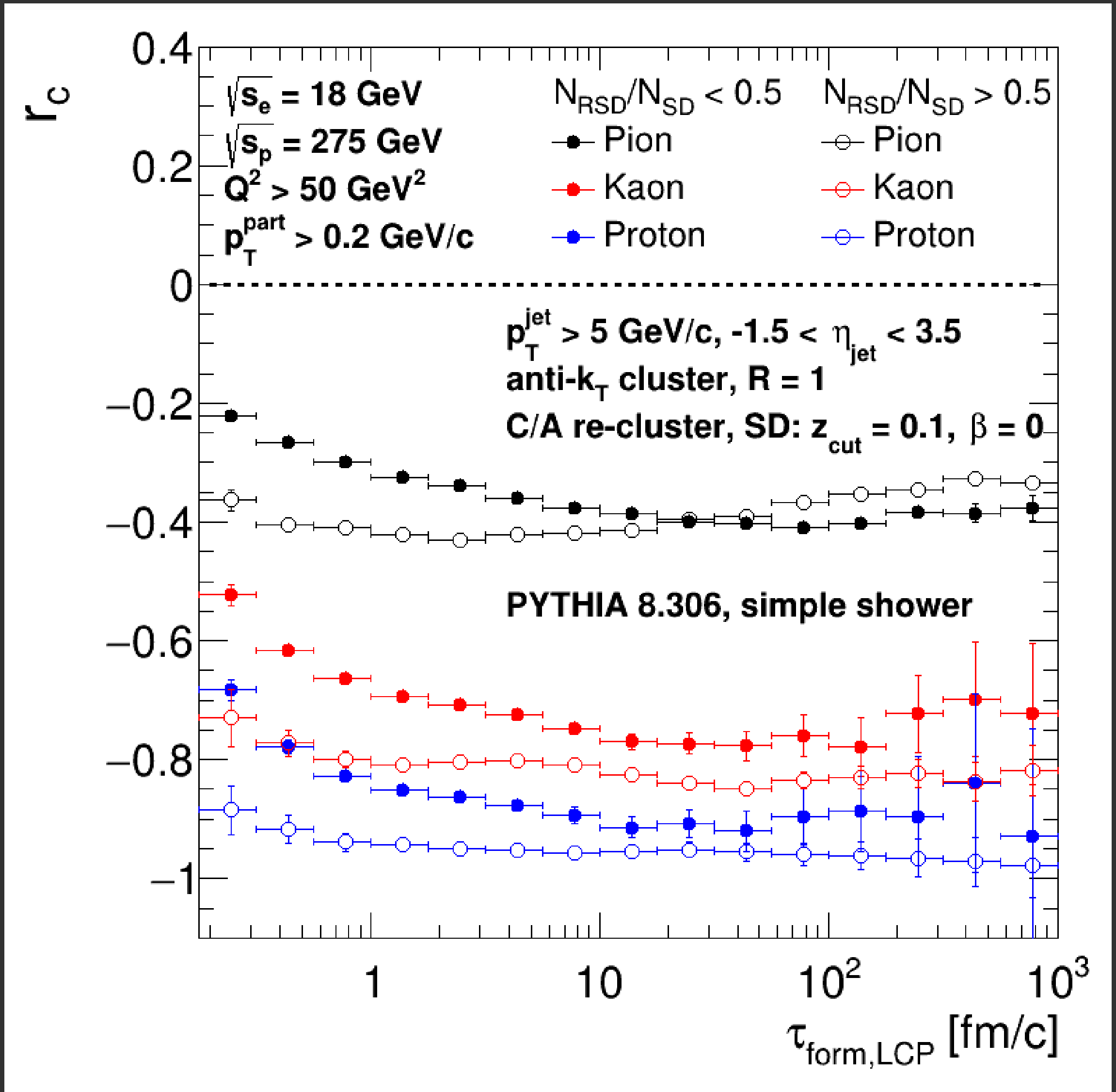


- N_{RSD}/N_{SD} measures the depth/relative position of the RSD in the clustering tree
- The charge ratio decreases, in general, with the increase of the RSD relative position
- For $N_{RSD}/N_{SD} > 0.5$, the descrease gives place to a plateau where r_c remains constant

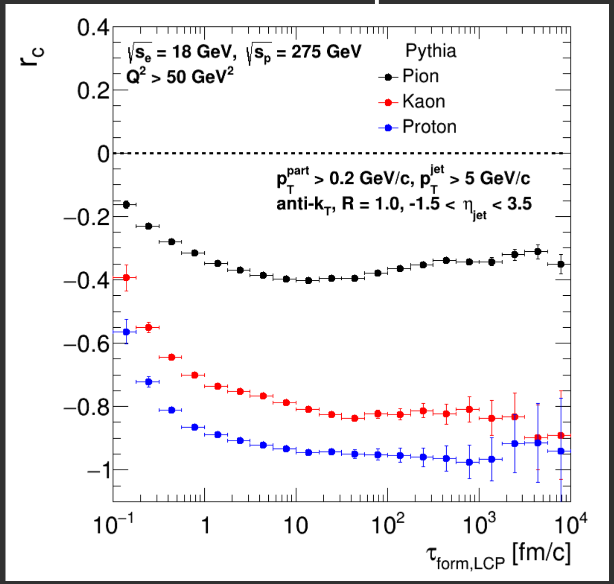
Conclusion: Yes! The r_c depends on the jet fragmentation pattern

Results – Charge Ratio



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

Inclusive plot

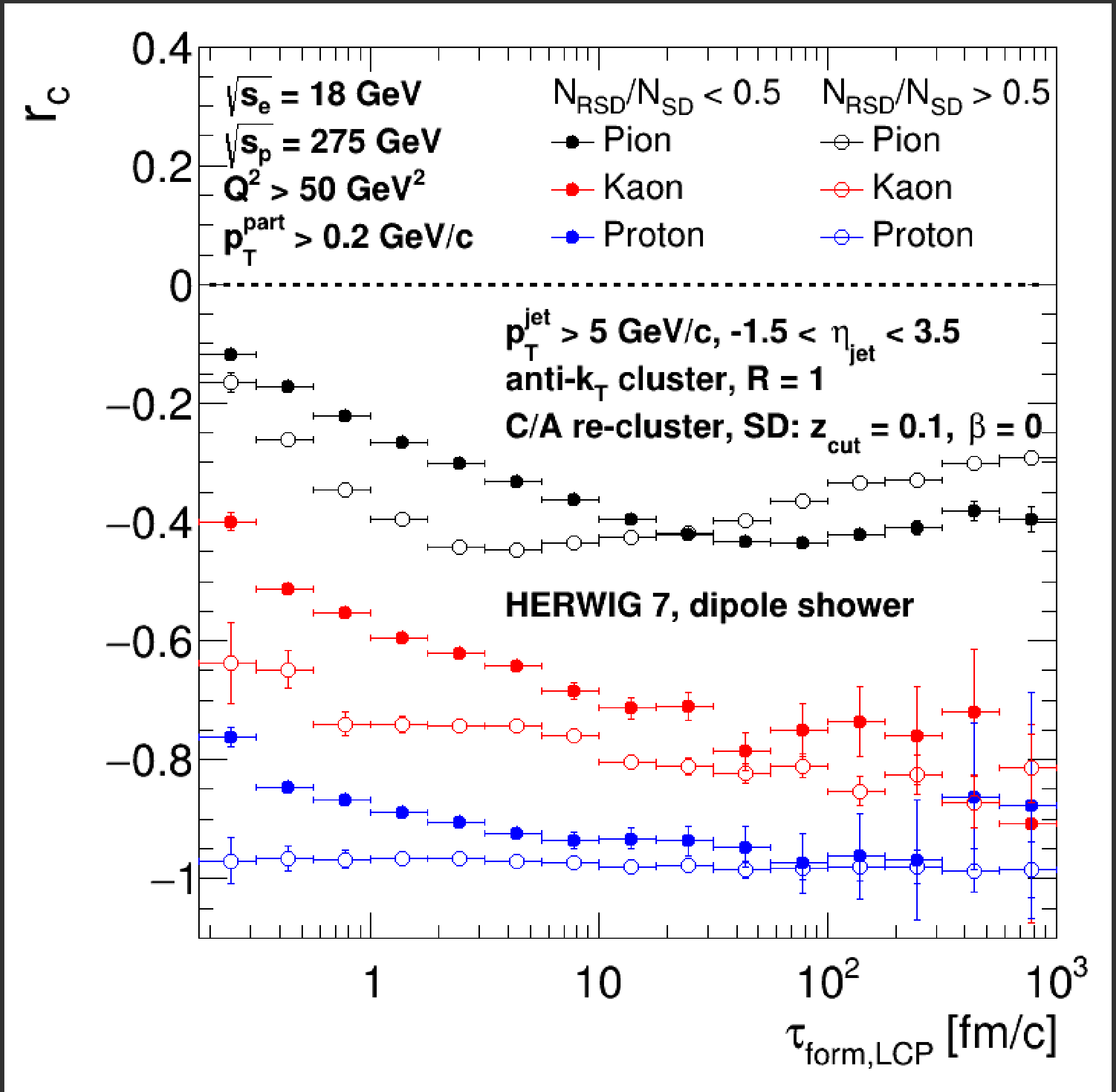


- For PYTHIA (Lund String Model),

⇒ $N_{RSD}/N_{SD} < 0.5$ cut keeps the qualitative behaviour of the generic $\boldsymbol{r_c}$;

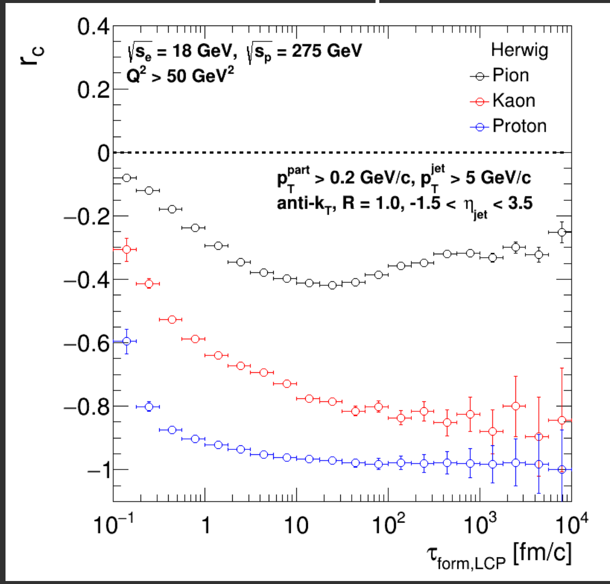
⇒ $N_{RSD}/N_{SD} > 0.5$ cut eliminates the time-dependence of the $\boldsymbol{r_c}$ for all hadronic species and selects jets with higher chance of having opposite LCP.

Results – Charge Ratio



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

Inclusive plot



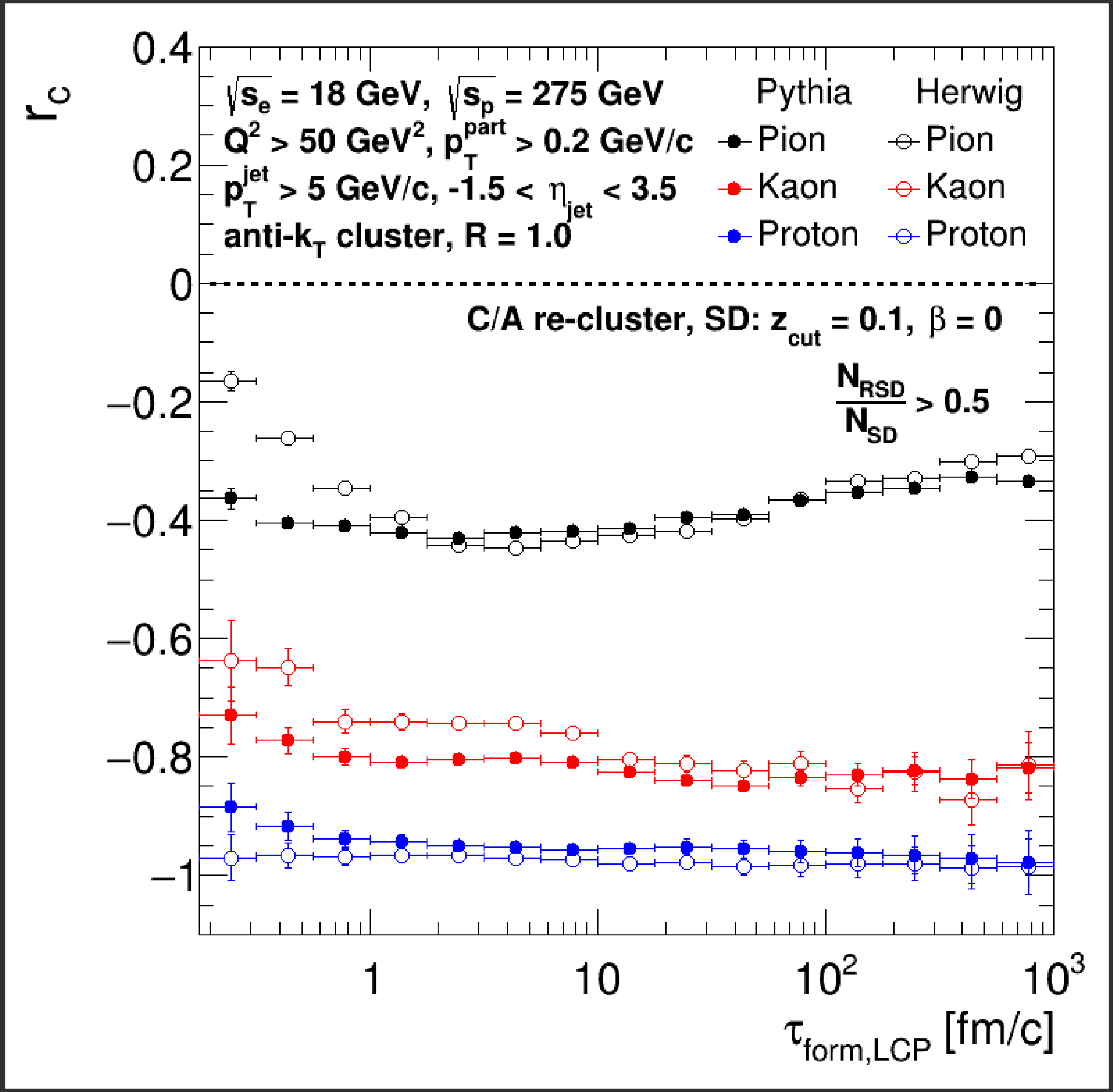
- For HERWIG (Cluster Model),

⇒ $N_{RSD}/N_{SD} < 0.5$ cut keeps the qualitative behaviour of the generic $\boldsymbol{r_c}$;

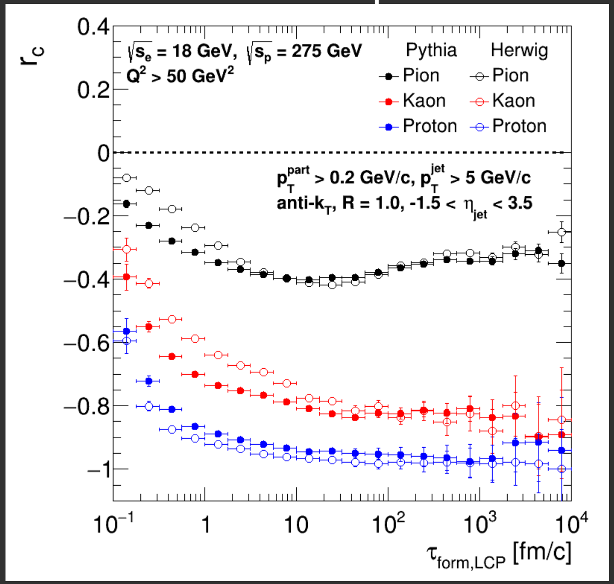
⇒ $N_{RSD}/N_{SD} > 0.5$ cut keeps the $\boldsymbol{r_c}$ close to 0 for earlier times, but also selects jets with overall higher chances of having opposite LCP.

Results – Charge Ratio

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



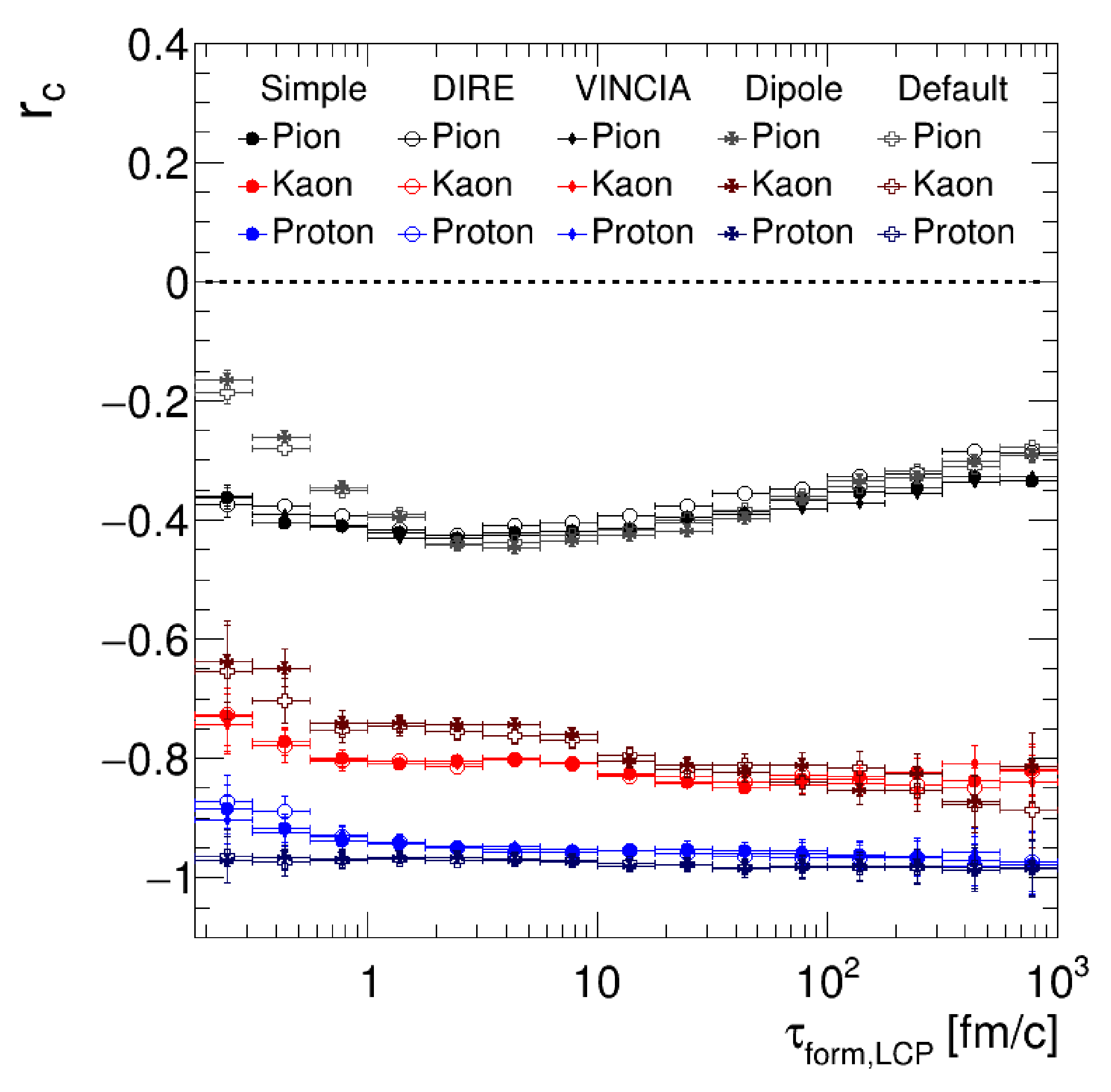
Inclusive plot



- Significant discrepencies between the predictions made by the two Monte Carlos, coming from the hadronization model;

Conclusion: the cluster model randomizes the charges of the LCP for earlier τ_{form}

Results – Charge Ratio



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

PYTHIA 8.306 offers the following 3 parton shower models:

- Simple
- DIRE
- VINCIA

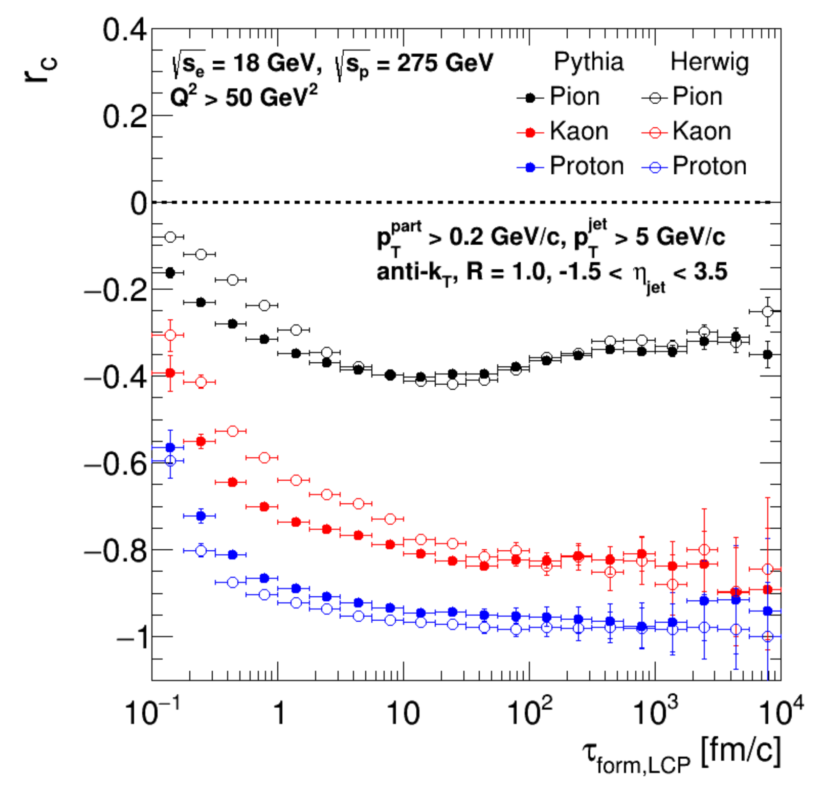
Herwig 7 offers the following 2 parton shower descriptions:

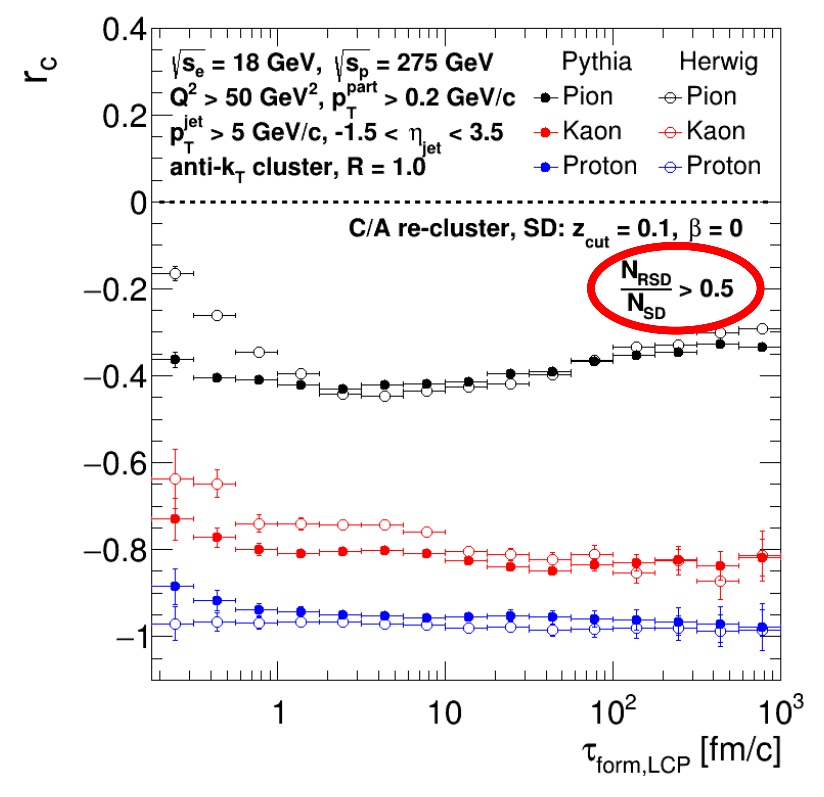
- Dipole
- Default

Conclusion: the r_c is roughly independent of the parton shower description in either Monte Carlo

Conclusions

- The charge ratio is not only dependent on the formation time of the LCP (leading charged particles), but also on the jet fragmentation pattern;
- A selection on $N_{RSD}/N_{SD} > 0.5$ reveals a qualitatively different behaviour of the charge ratio between the Monte Carlos – PYTHIA and HERWIG.





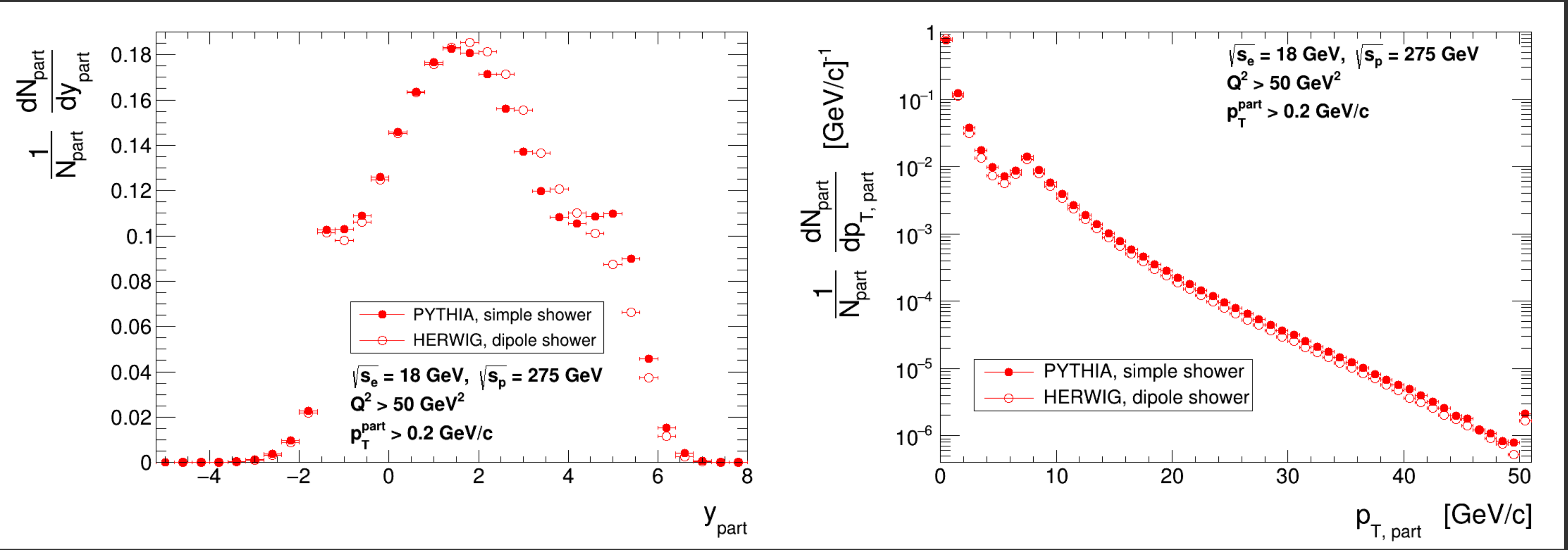
Thank you for your attention!

Questions?

Backup Slides

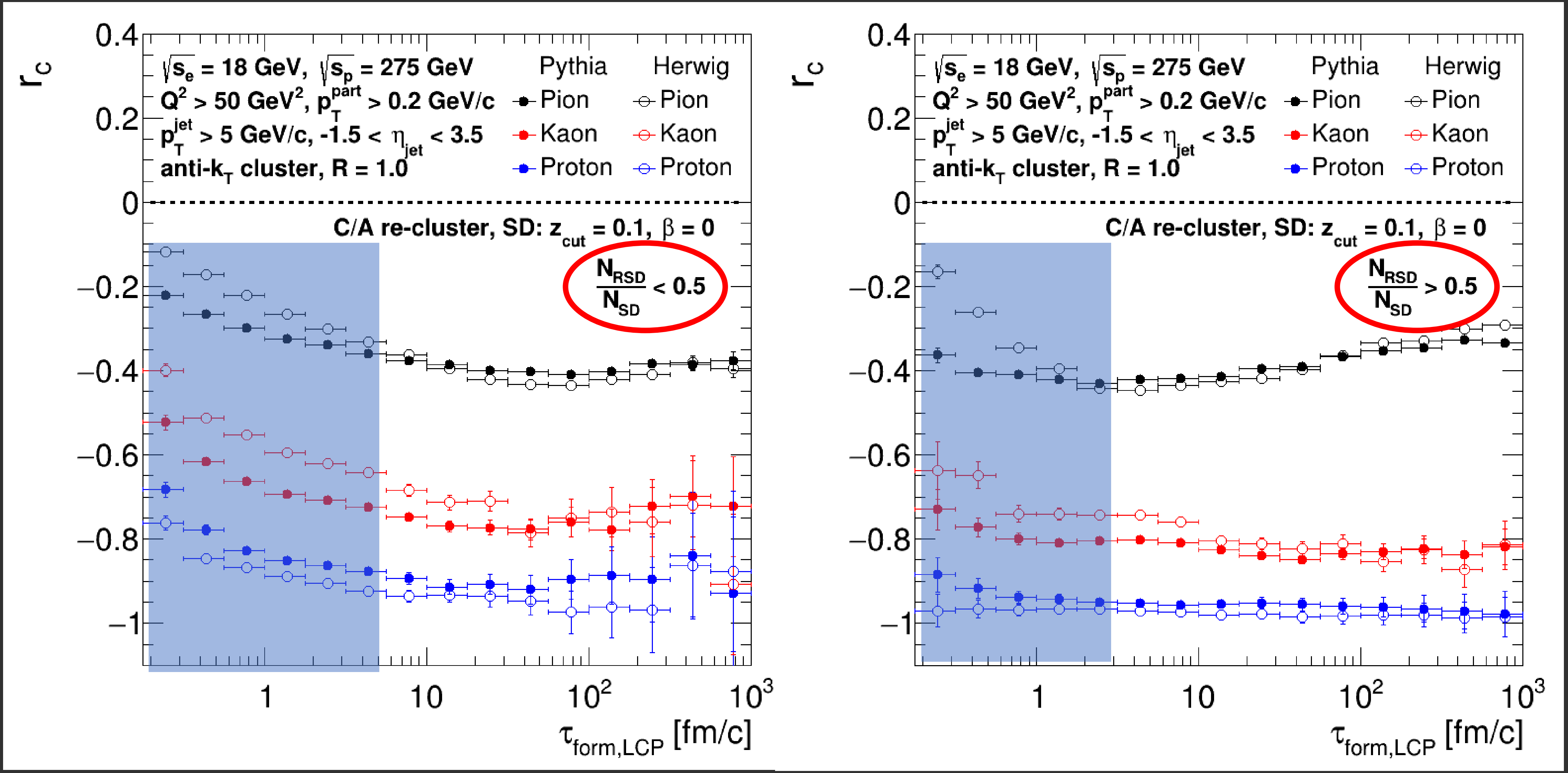
Parton Description Matching

- 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.



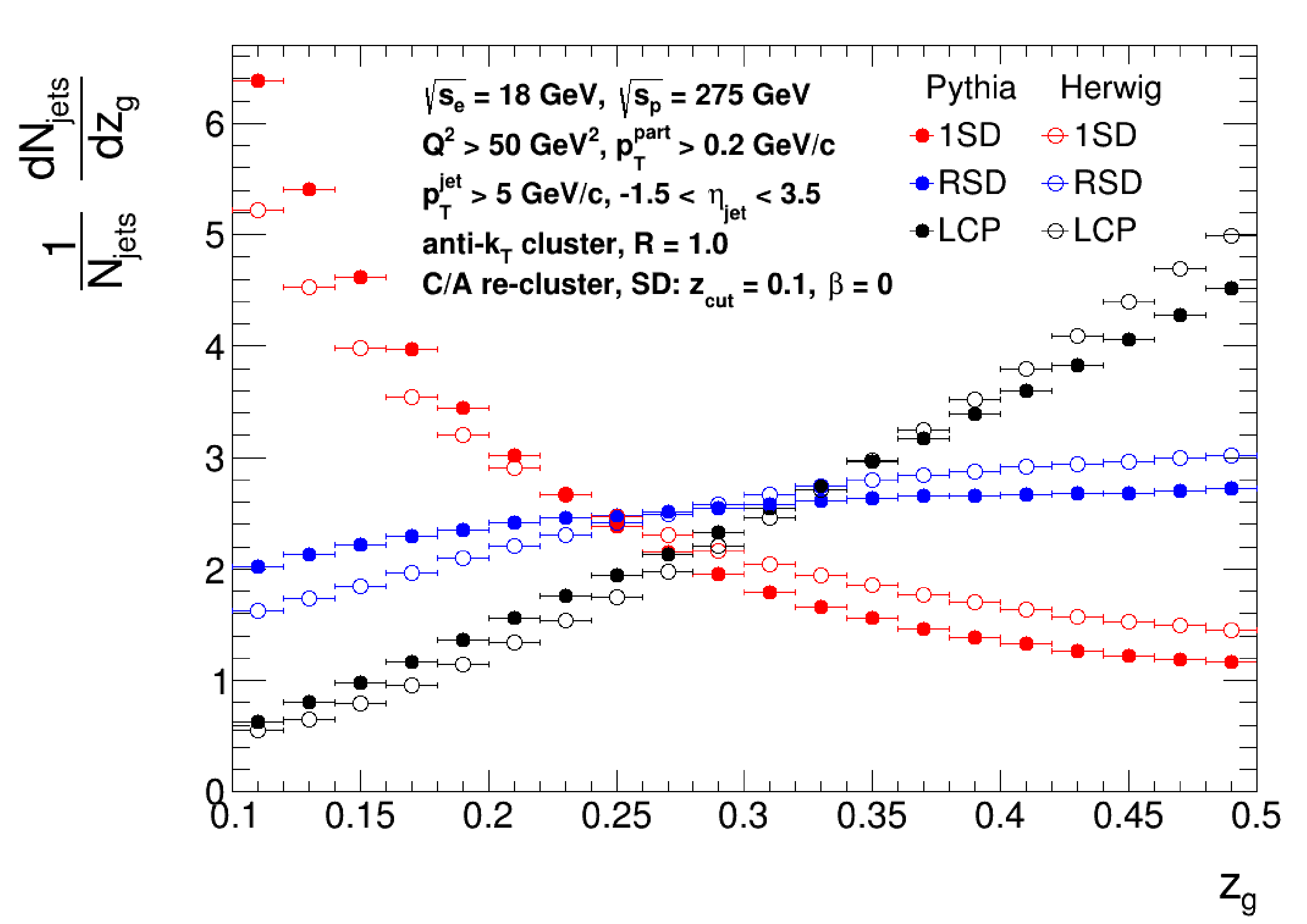
Results – Charge Ratio

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



Results – Groomed Momentum Fraction

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



- **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