Peering into the non-perturbative phase-space regions of jets

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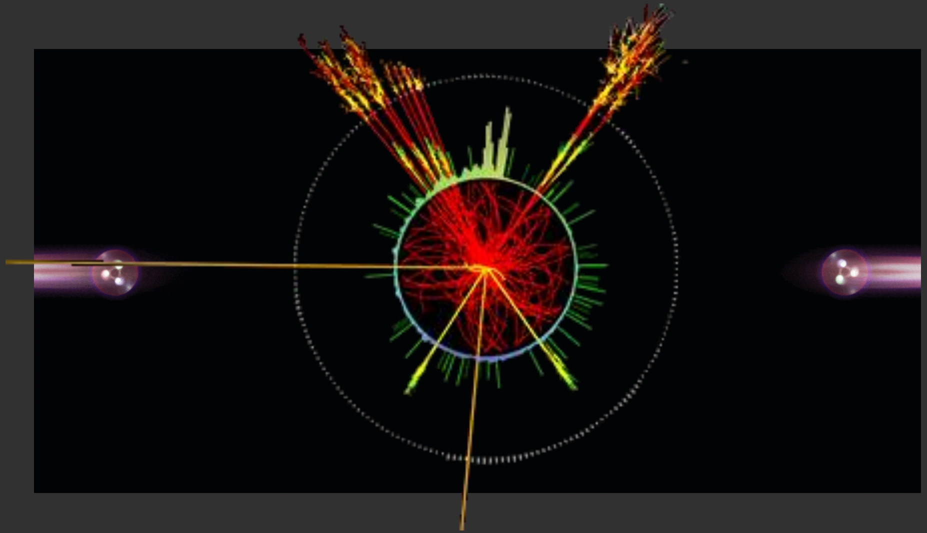

TÉCNICO LISBOA

LIP | LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Theoretical Introduction

Hard ~ high transverse momentum
Soft ~ low transverse momentum

Outgoing Parton

collision results in the ejection of hard partons

g

Partons

g – gluon

q – quark

q̄ – antiquark

Theoretical Introduction

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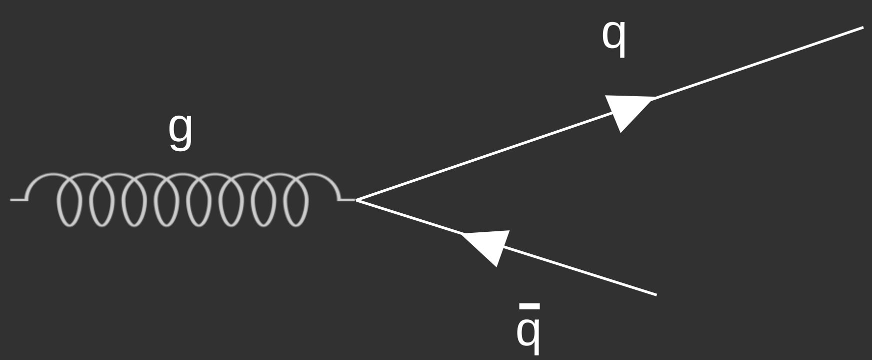
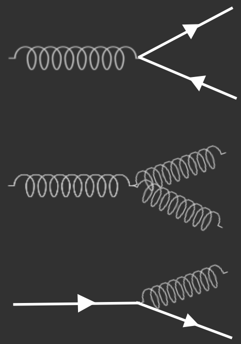
Outgoing Parton



collision results in the ejection of hard partons

Parton Branching



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

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

DGLAP splitting functions

Theoretical Introduction

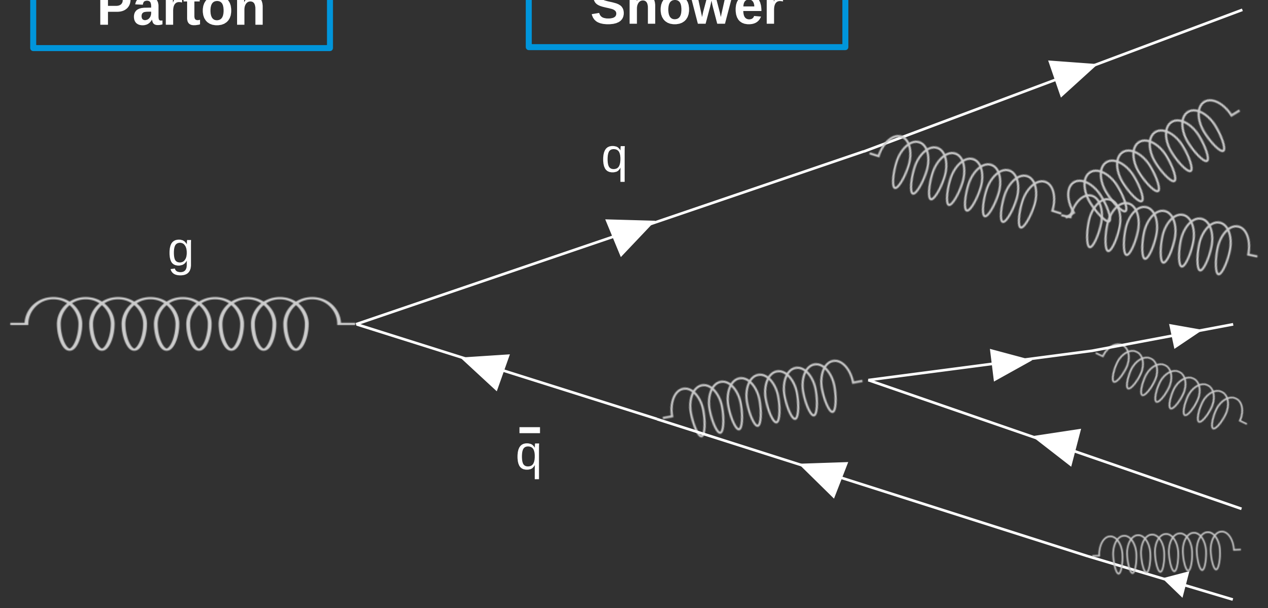
g – gluon

q – quark

$\bar{q}$ – antiquark

Outgoing Parton

Parton Shower



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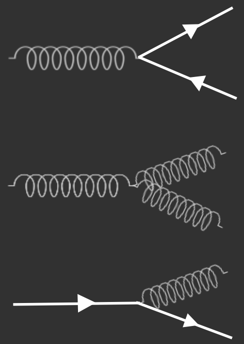

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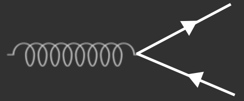
DGLAP splitting functions

Theoretical Introduction



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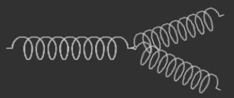

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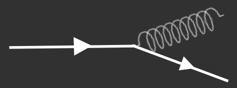

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Outgoing Parton

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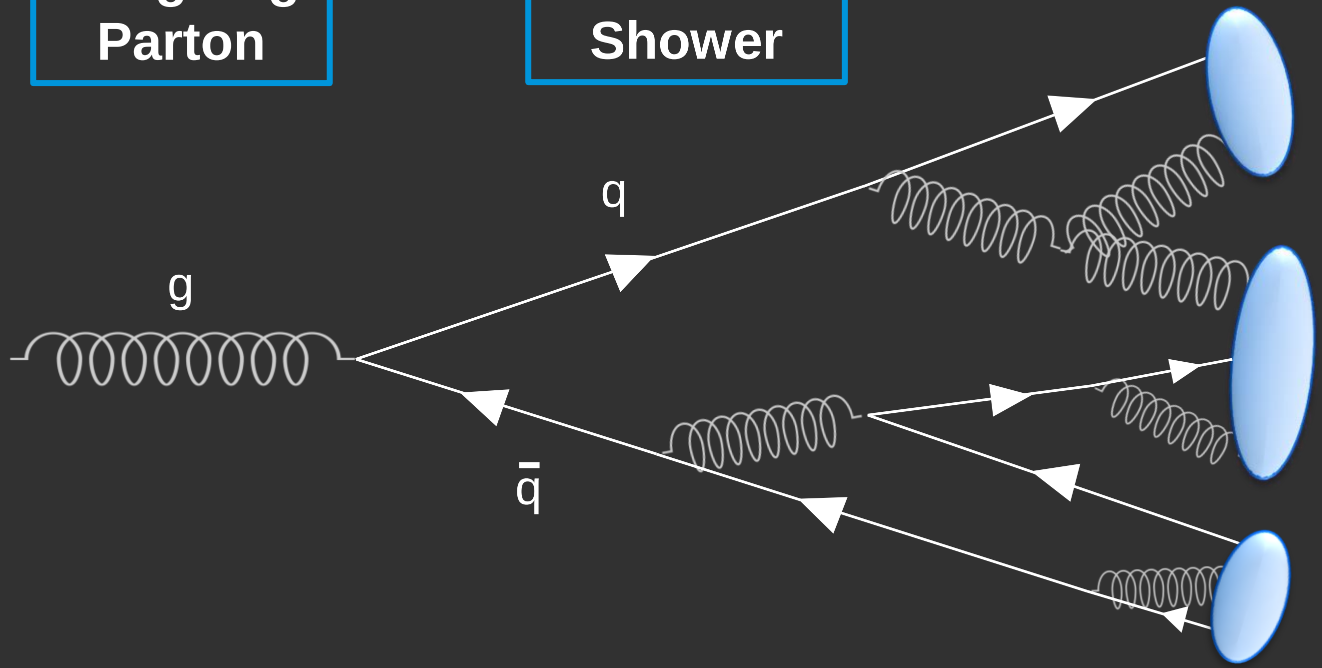
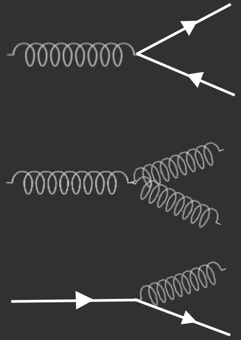


Hadronization

Process by which free partons bind to produce hadrons

collision results in the ejection of hard partons

Theoretical Introduction



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Detector

g – gluon

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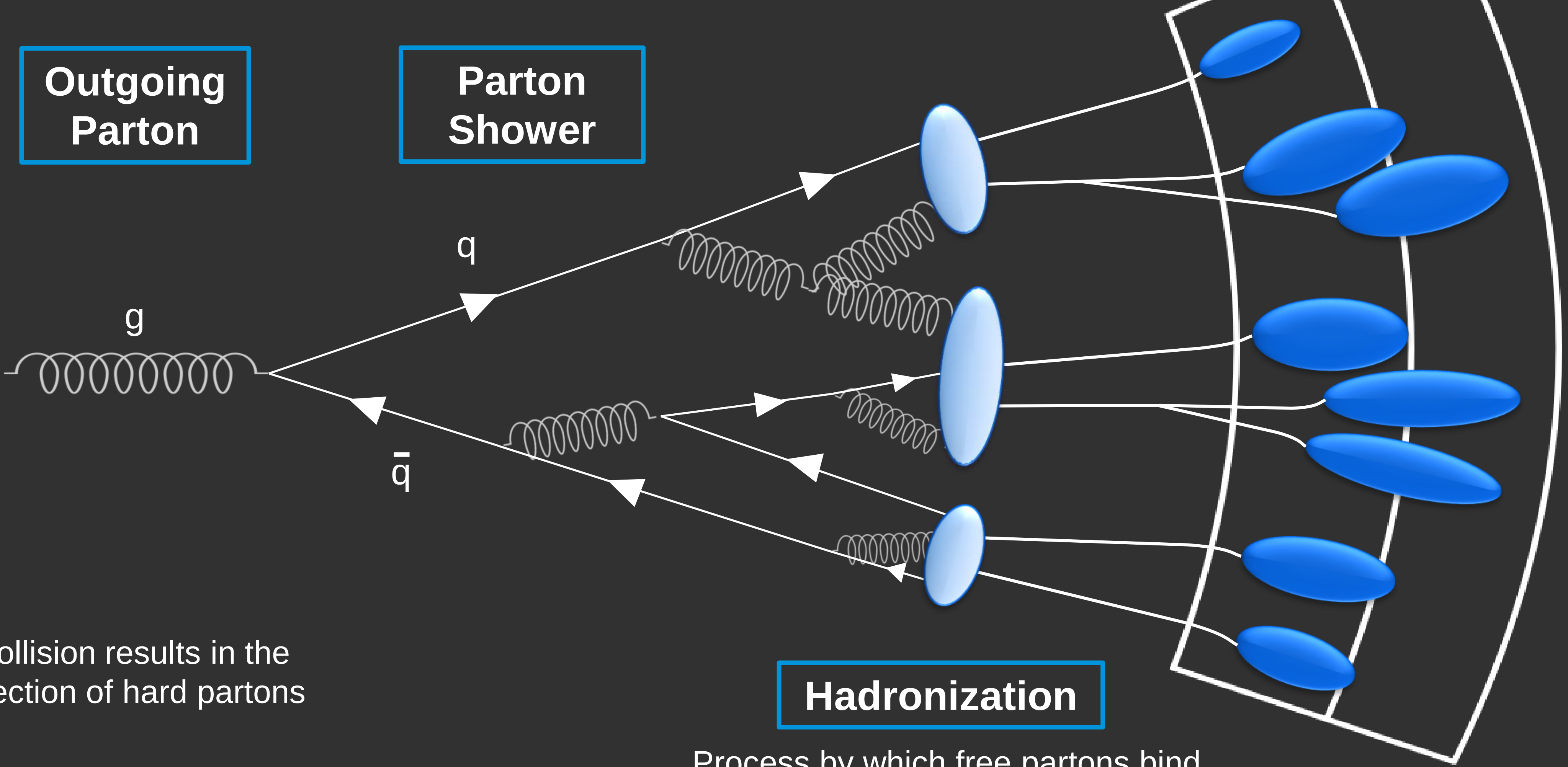
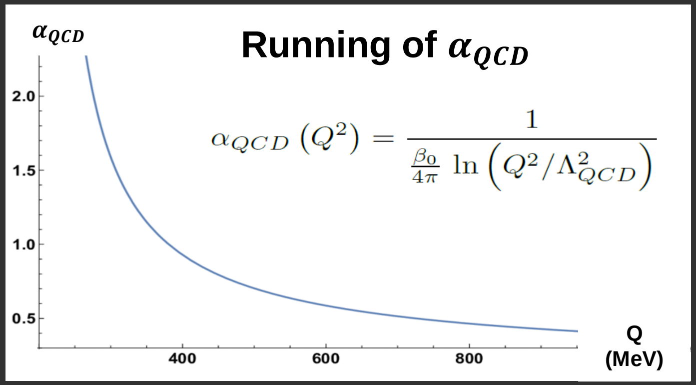
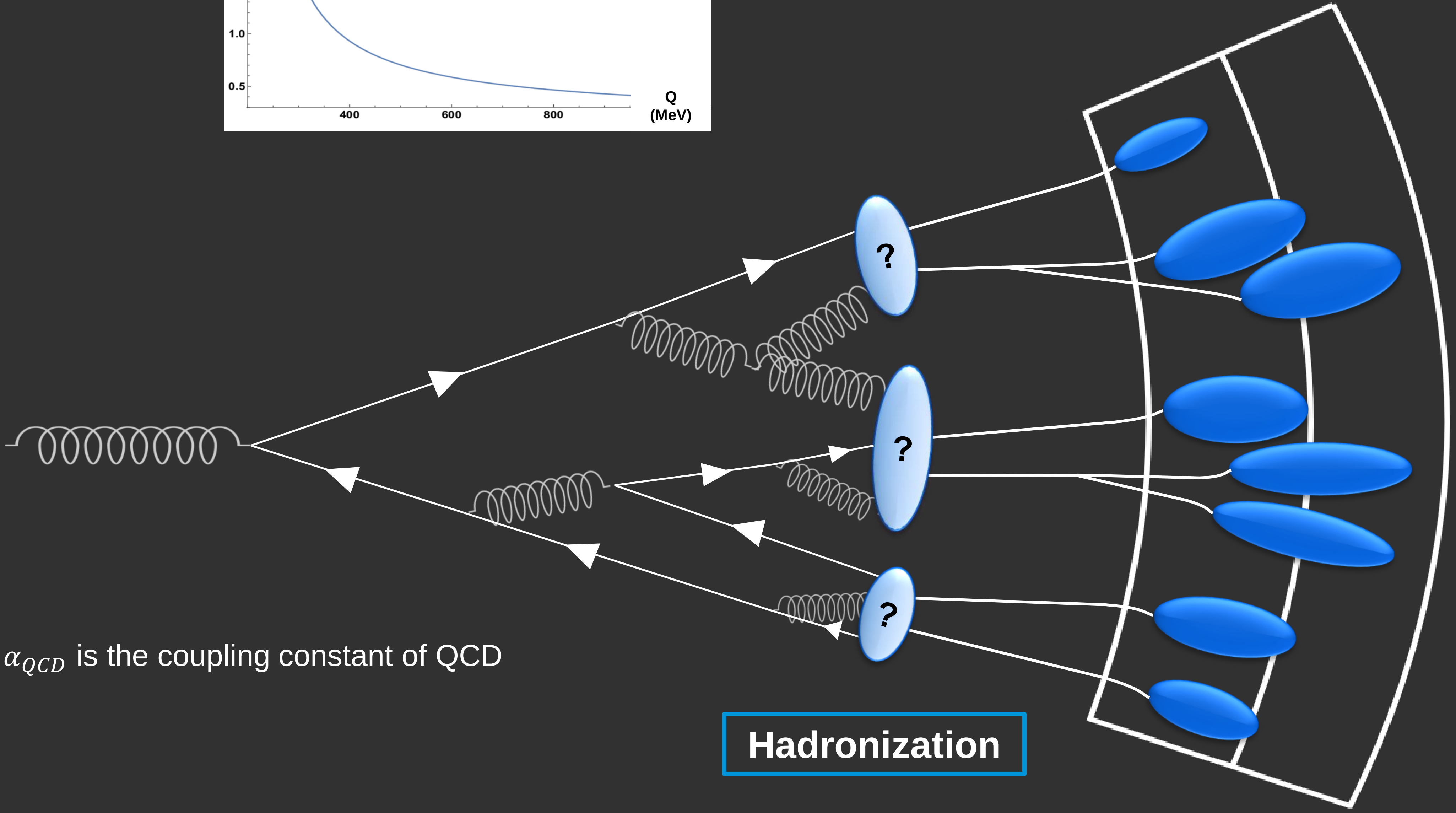


collision results in the ejection of hard partons

Process by which free partons bind to produce hadrons

Objective

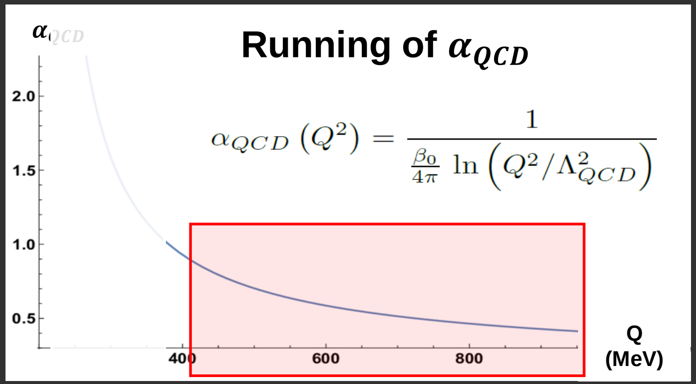


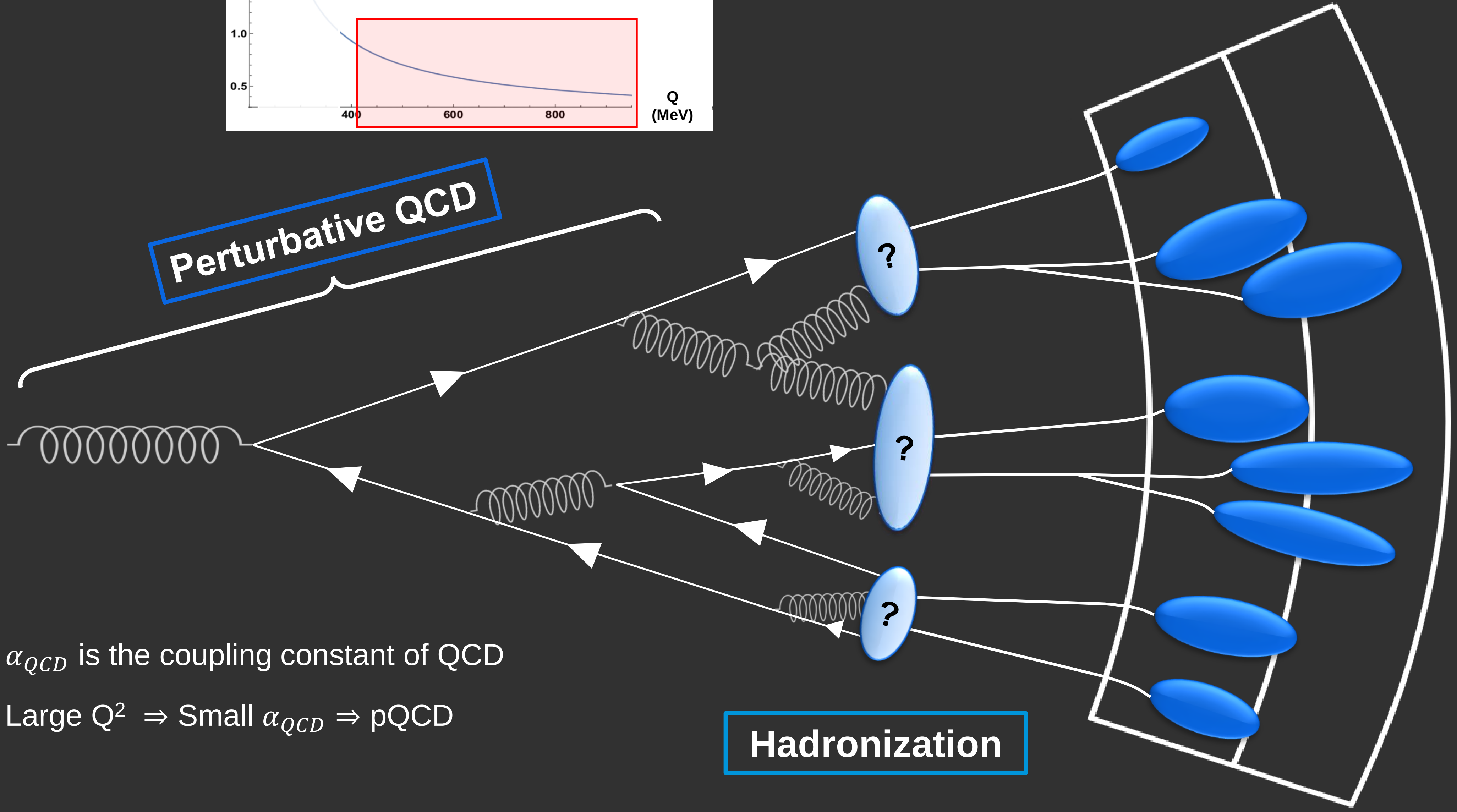


- α_{QCD} is the coupling constant of QCD

Hadronization

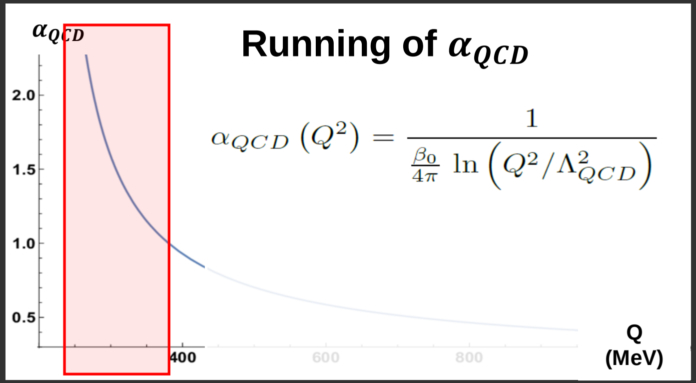
Objective

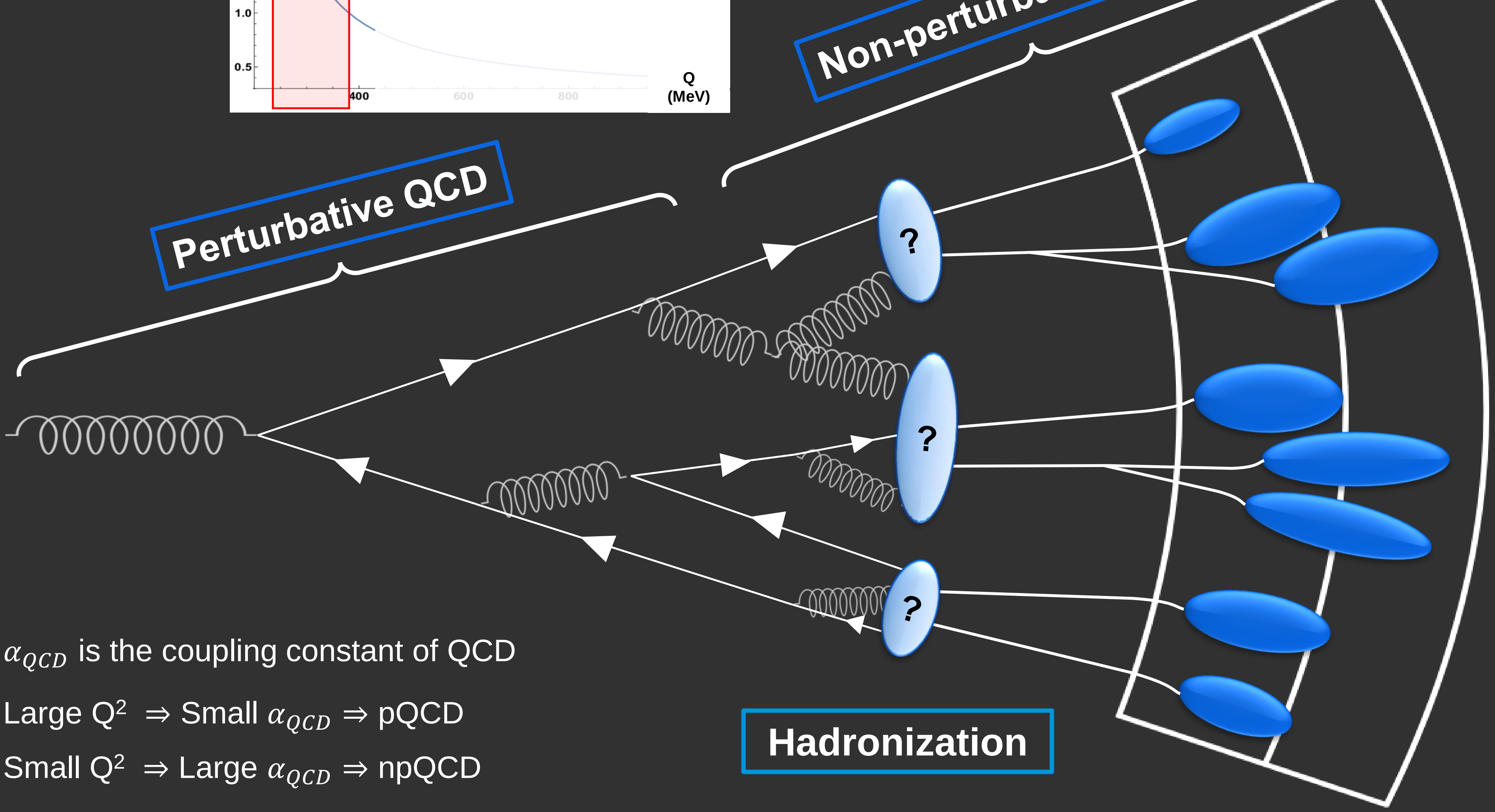




- ➢ α_{QCD} is the coupling constant of QCD
- ➢ Large Q^2 $\Rightarrow$ Small α_{QCD} $\Rightarrow$ pQCD

Objective

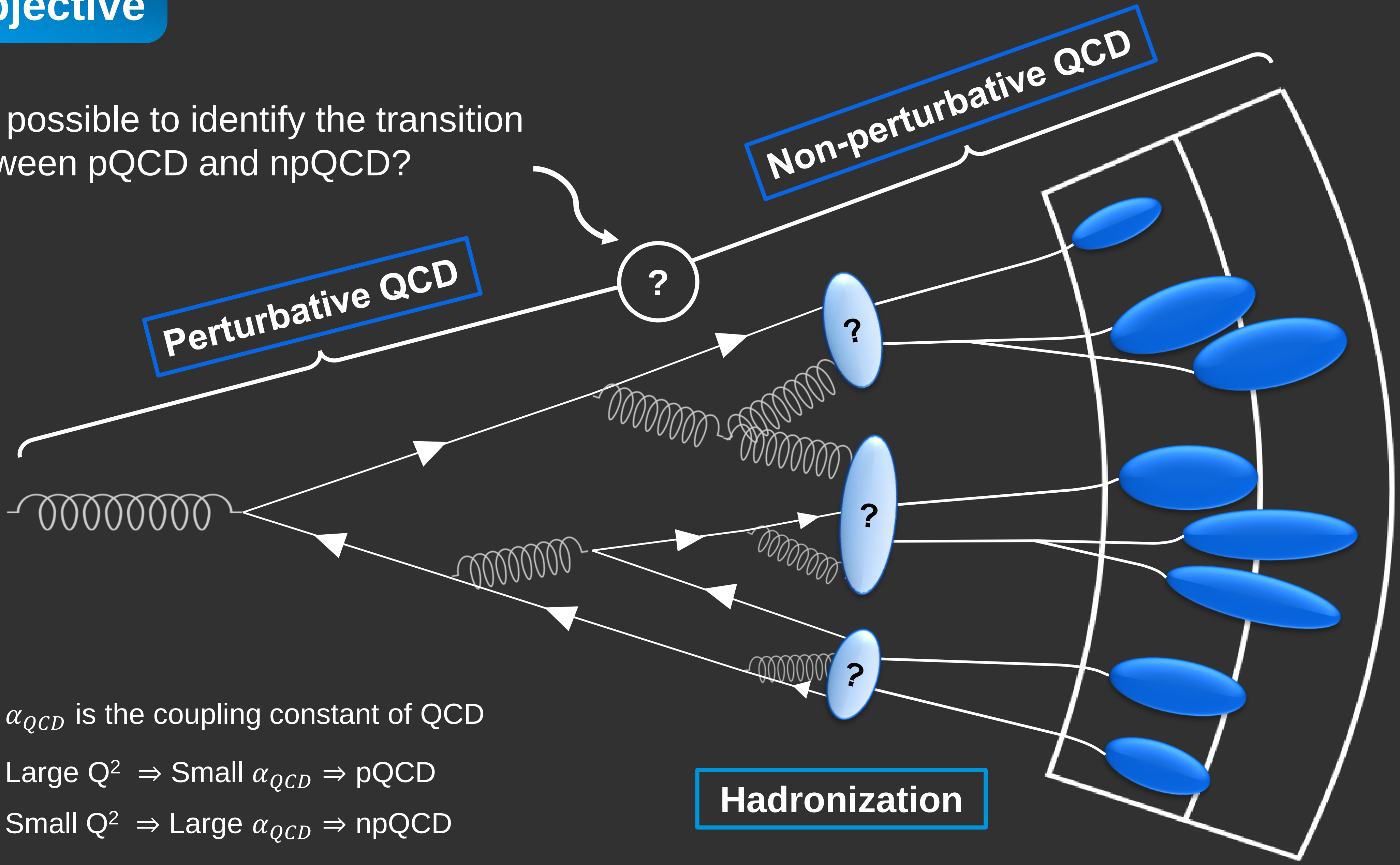




- α_{QCD} is the coupling constant of QCD
- Large Q^2 $\Rightarrow$ Small α_{QCD} $\Rightarrow$ pQCD
- Small Q^2 $\Rightarrow$ Large α_{QCD} $\Rightarrow$ npQCD

Objective

Is it possible to identify the transition between pQCD and npQCD?



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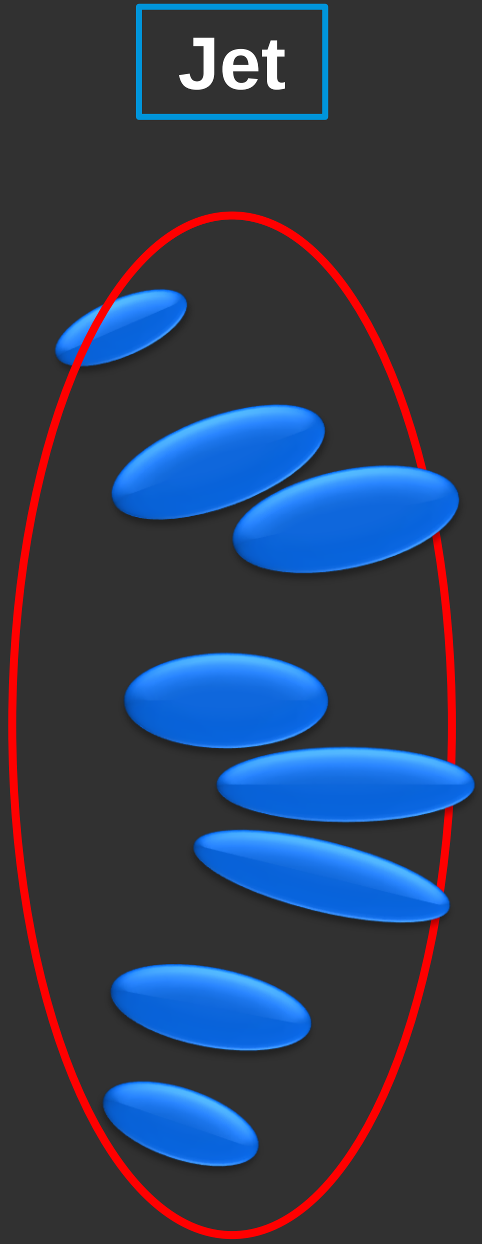
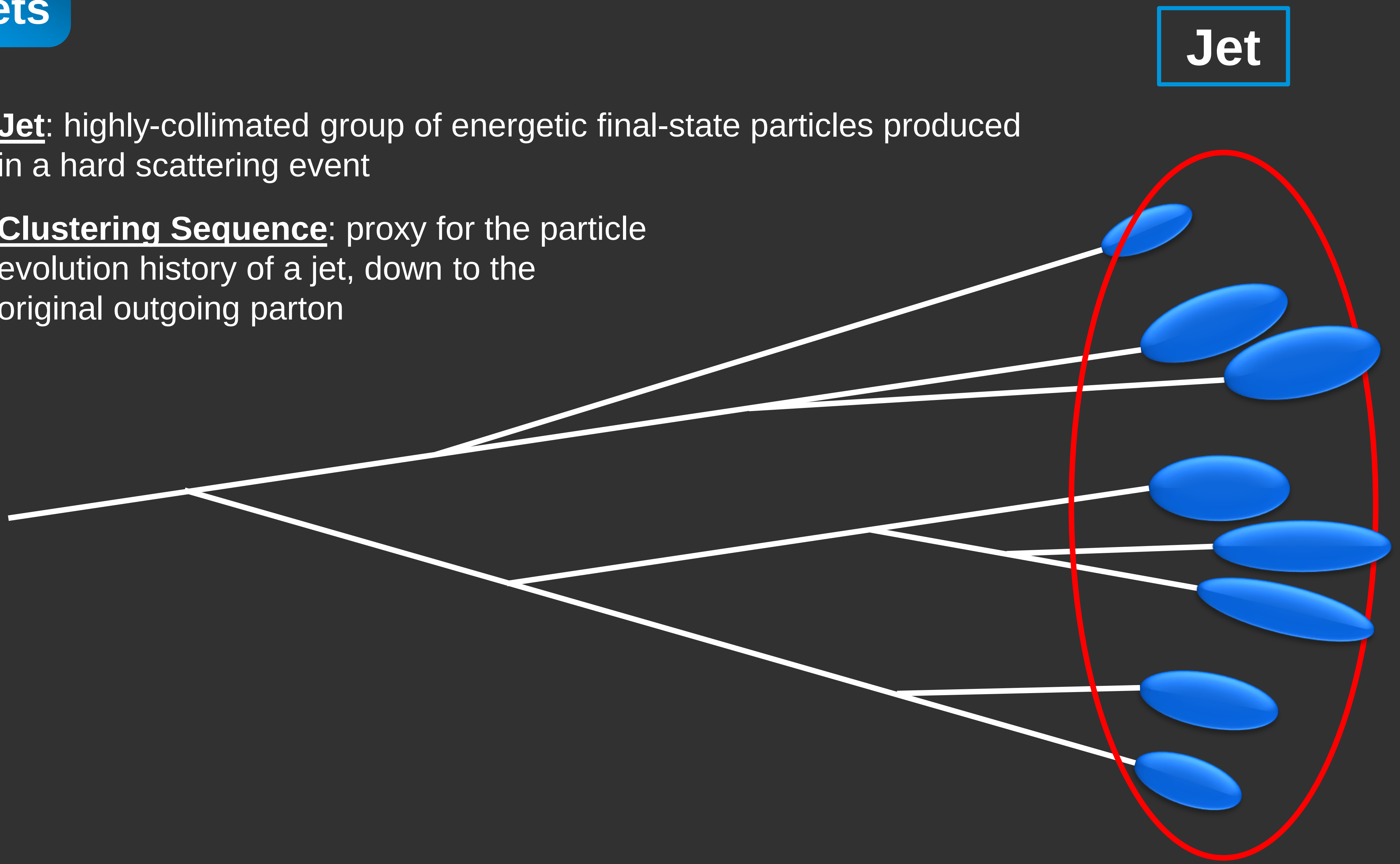
Jets

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



Jets

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



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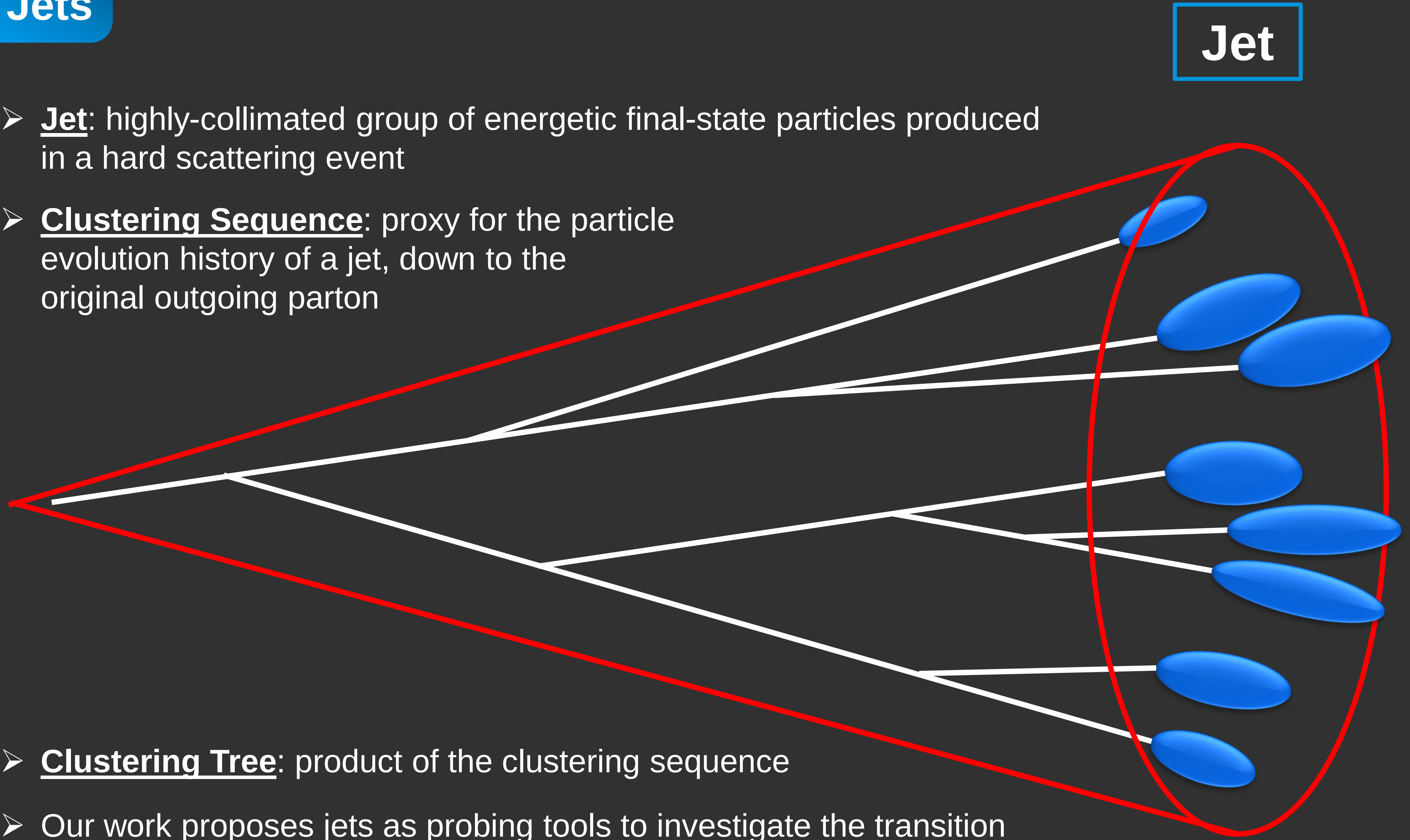


- **Clustering Tree**: product of the clustering sequence
- Our work proposes jets as probing tools to investigate the transition from partons to hadrons

Results – Formation Time

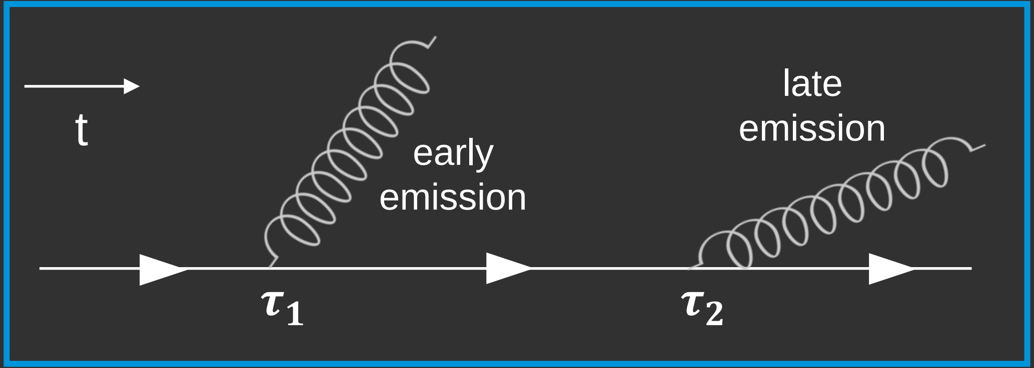
[Y.L. Dokshitzer et al., Basics of perturbative QCD]
[L. Apolinário et al, arXiv:2012.021999]

Formation Time

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

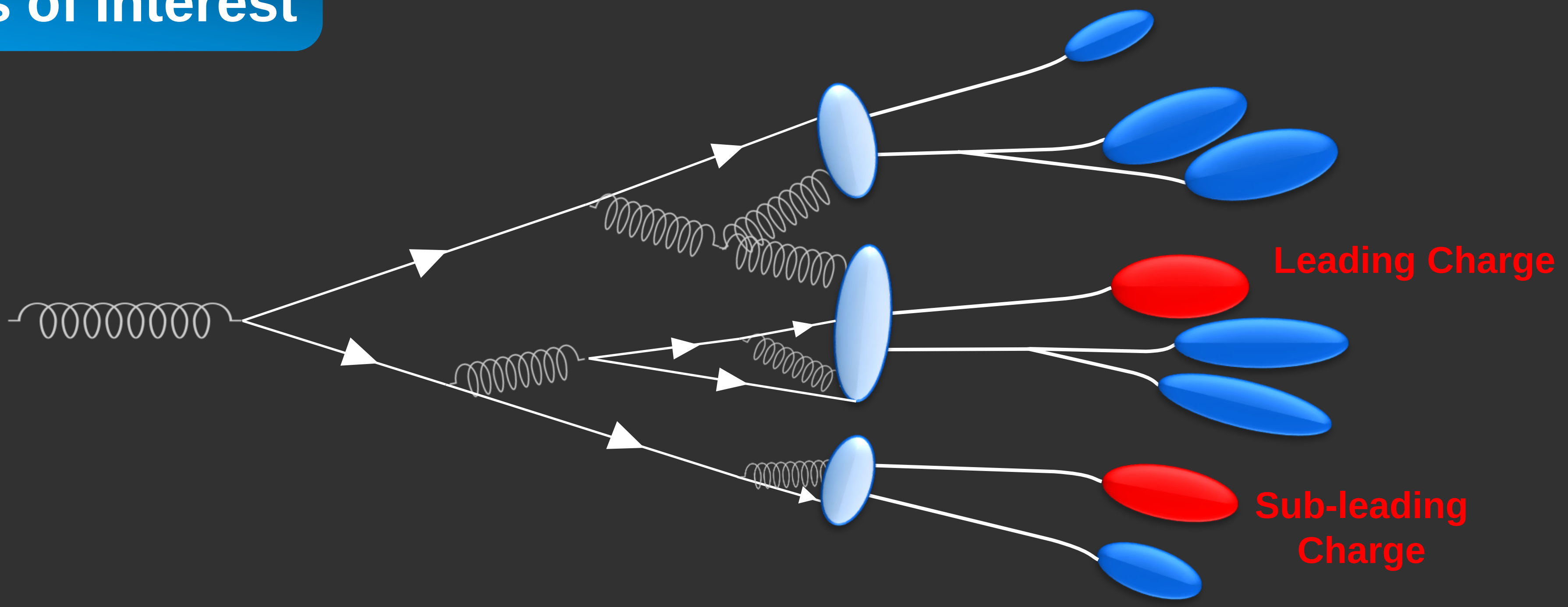
Estimate of the timescales involved in a particle splitting into 2 other particles that act as independent sources of additional radiation

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



$$\tau_1 < \tau_2$$

Splittings of Interest



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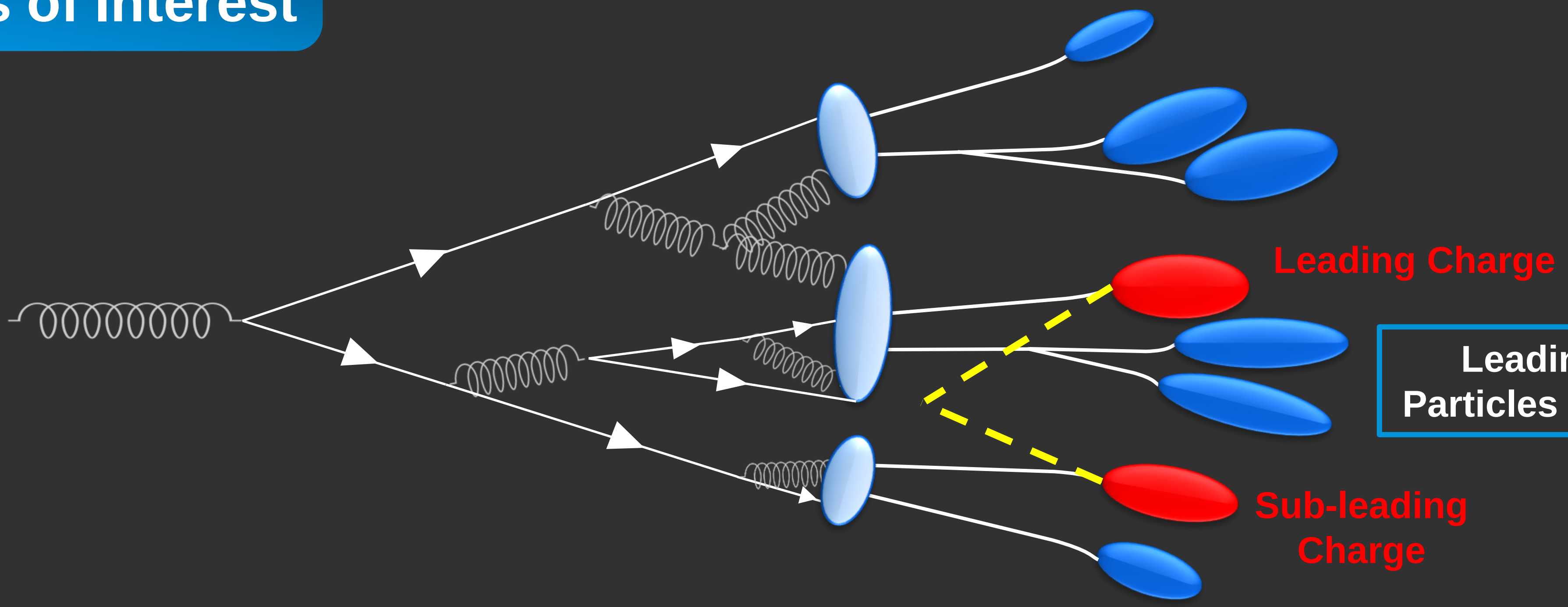


Leading Charged Particles splitting (LCP)

Charge Ratio

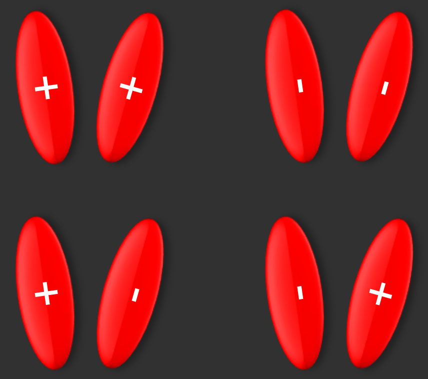
$$r_c = \frac{\frac{d\sigma_{h_1 h_2}}{dX} - \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}{\frac{d\sigma_{h_1 h_2}}{dX} + \frac{d\sigma_{h_1 \overline{h_2}}}{dX}}$$

h_1 – leading charged hadron
h_2 – subleading charged hadron

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

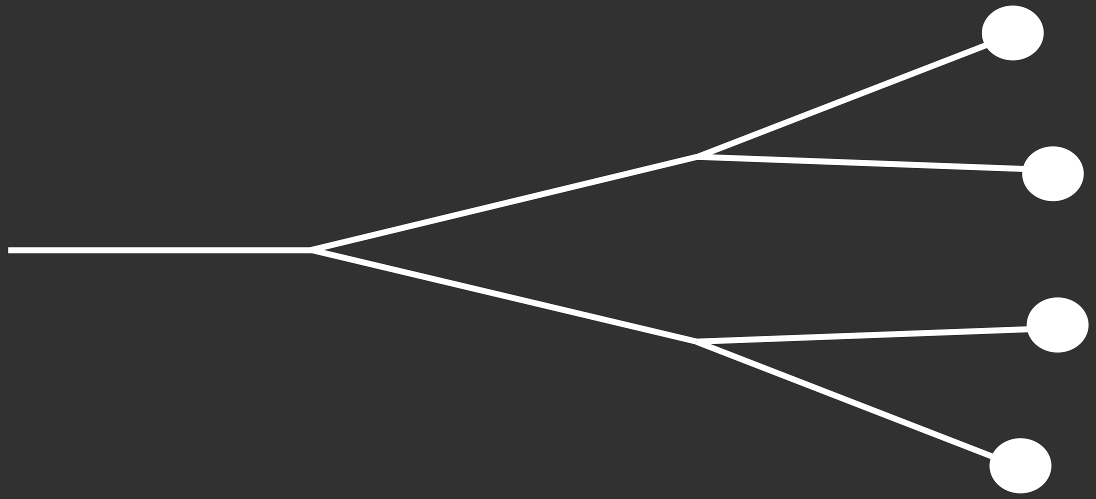
X – jet substructure variable of choice

- $r_c > 0$: 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.

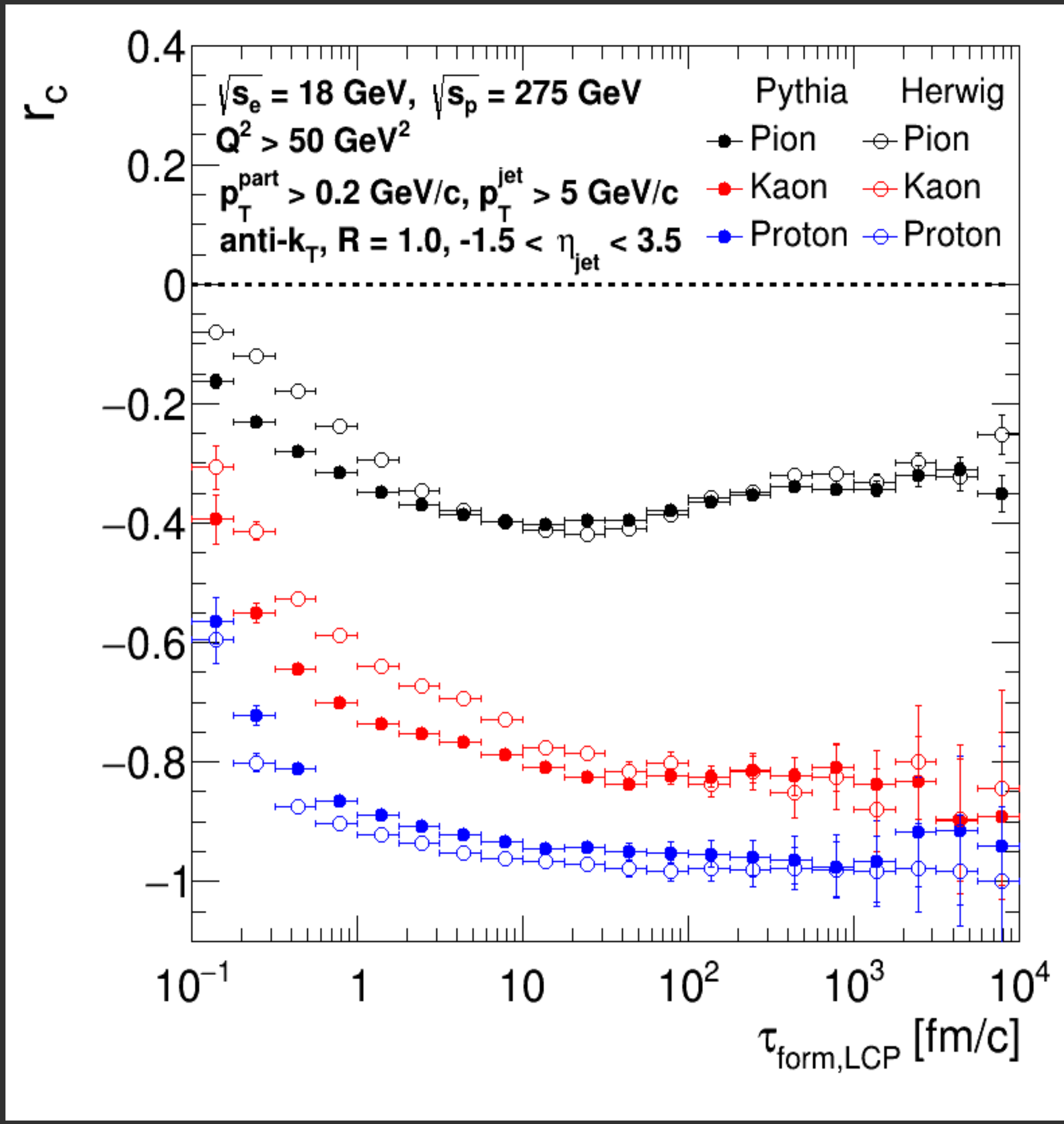


Charge Ratio

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



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



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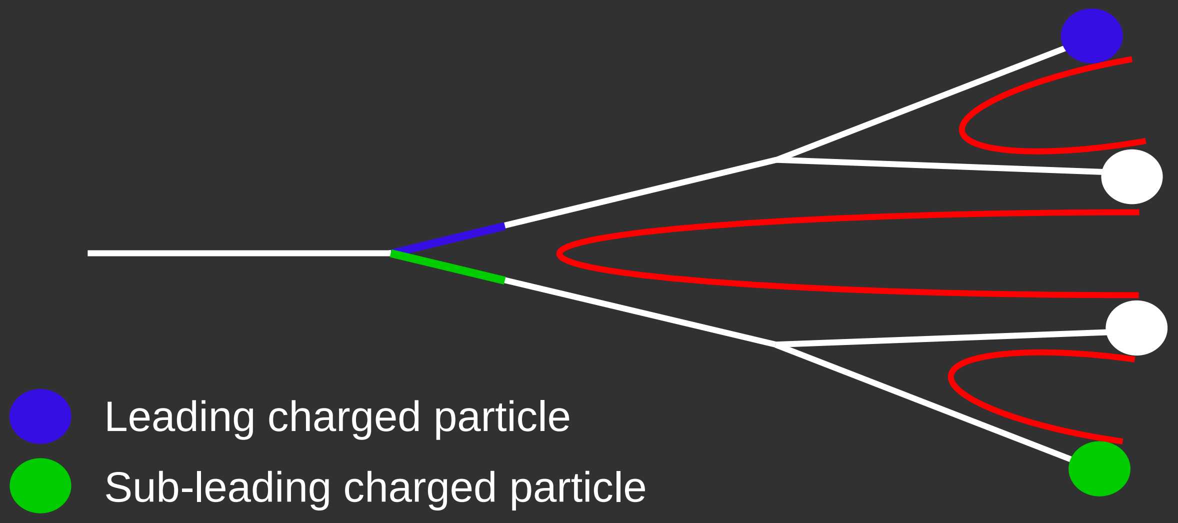
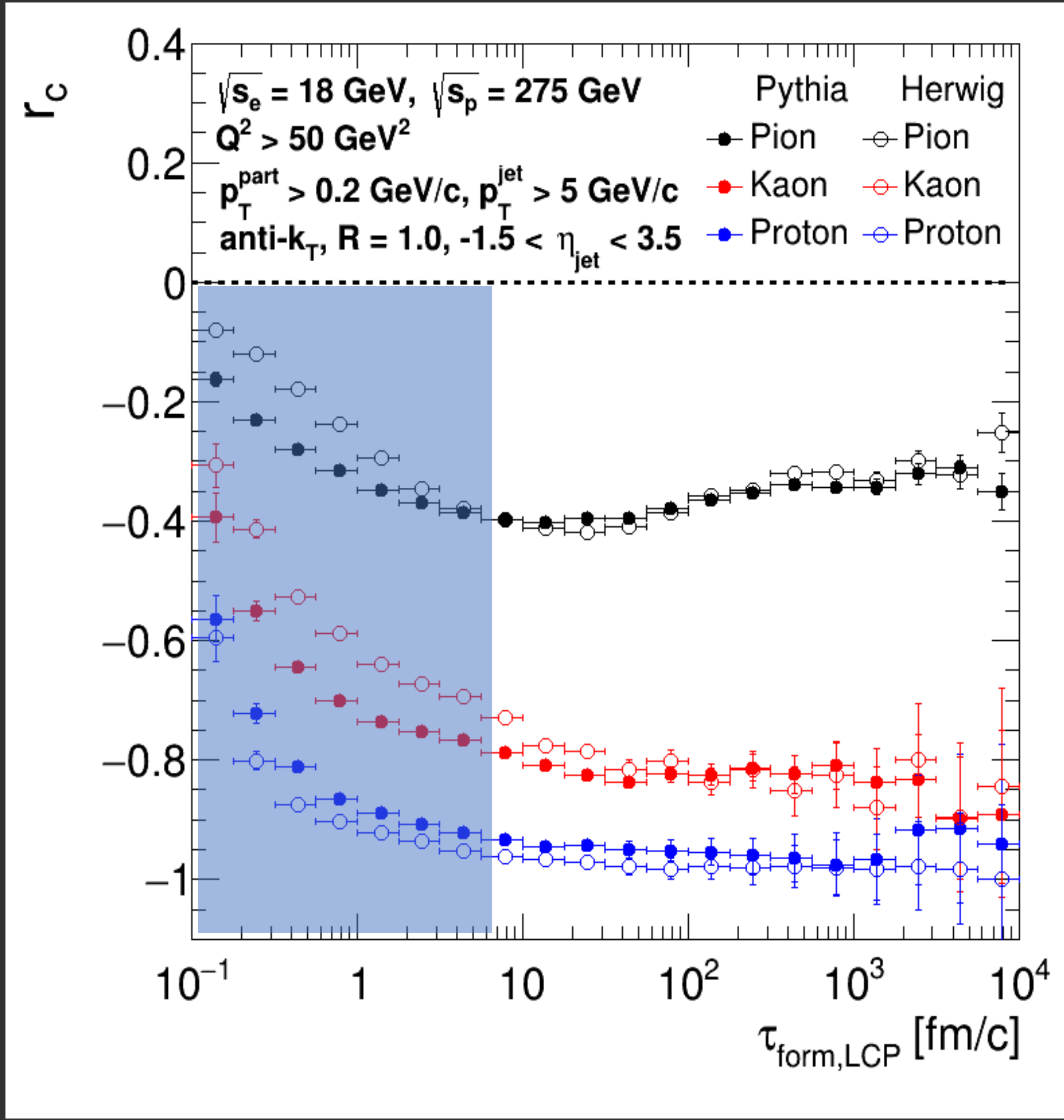


Leading charged particle

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

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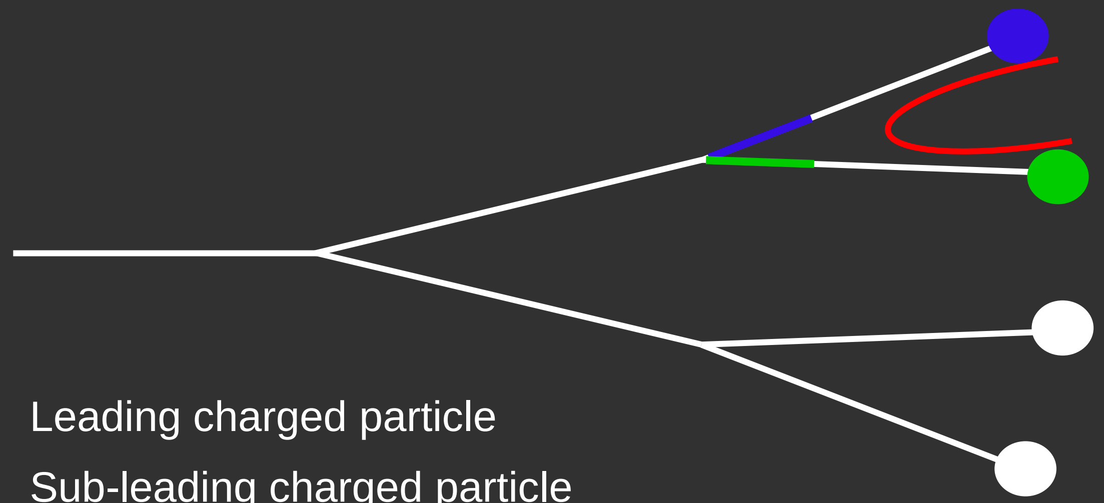

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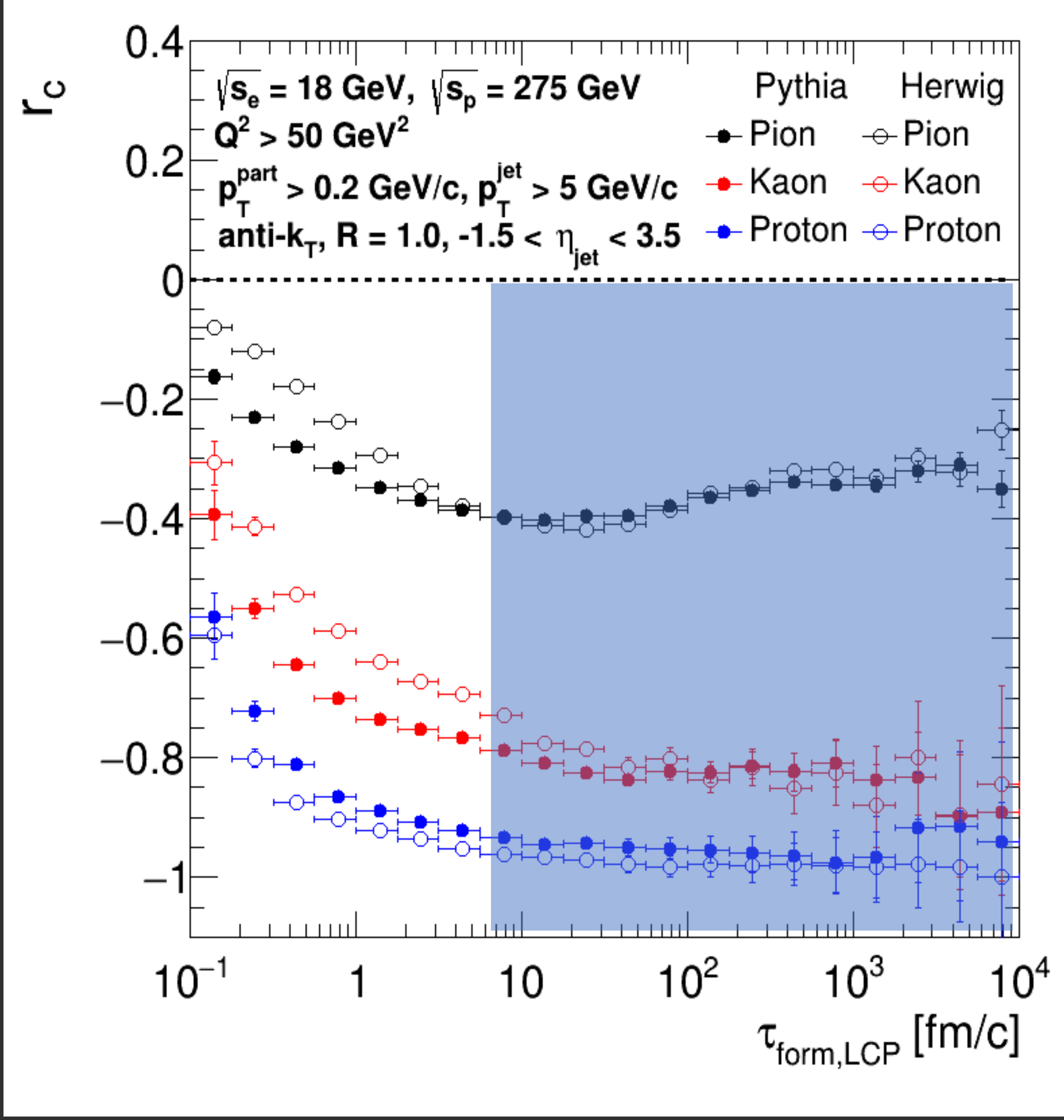


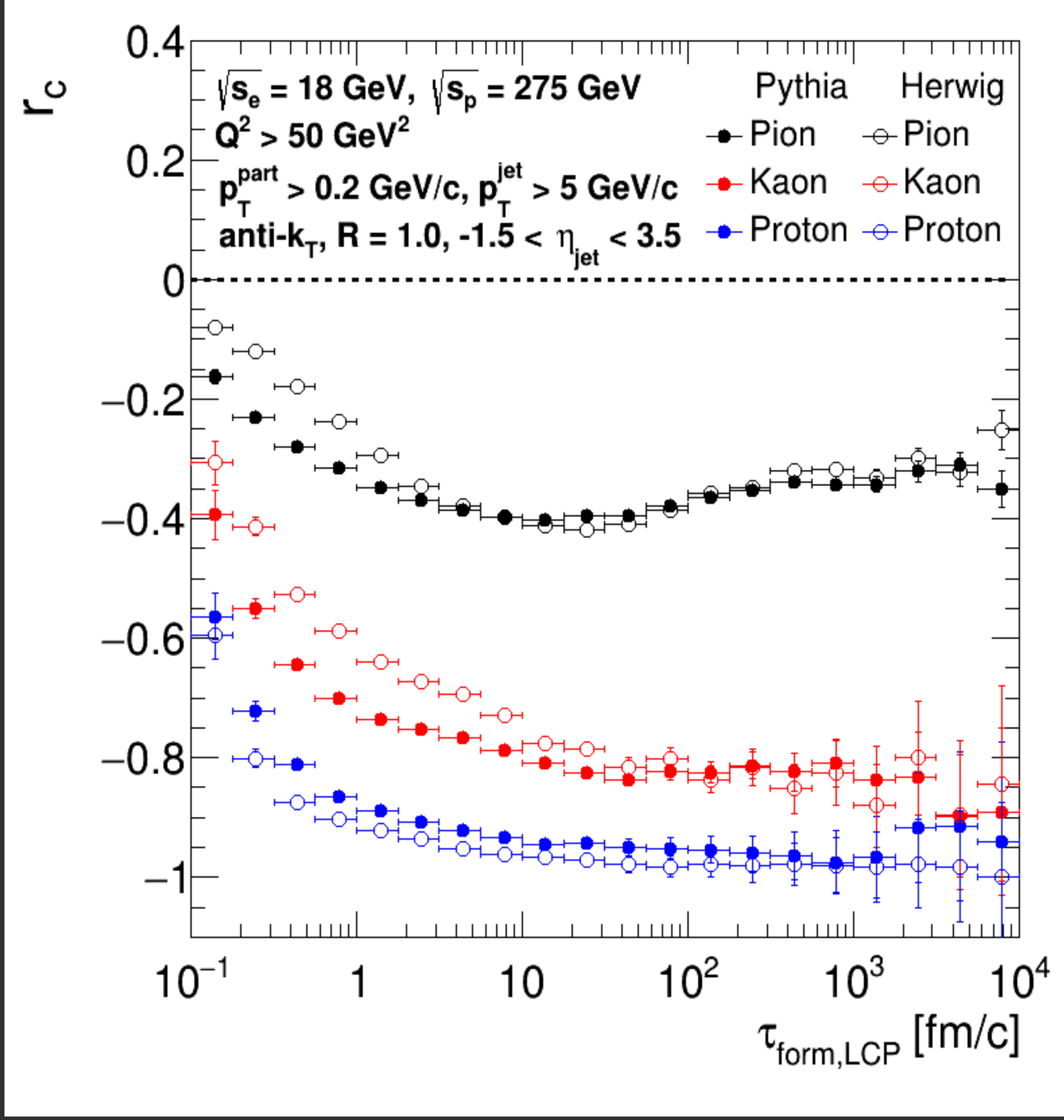
- LCP "produced" at earlier times, typical of the earlier splittings ⇒ subsequent splittings randomize the charge correlation ⇒ r_c closer to 0
- LCP "produced" at later times, typical of later splittings ⇒ retain more information of the splitting where the LCP separate, which favours opposite charges ⇒ r_c more negative

Charge Ratio

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

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

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



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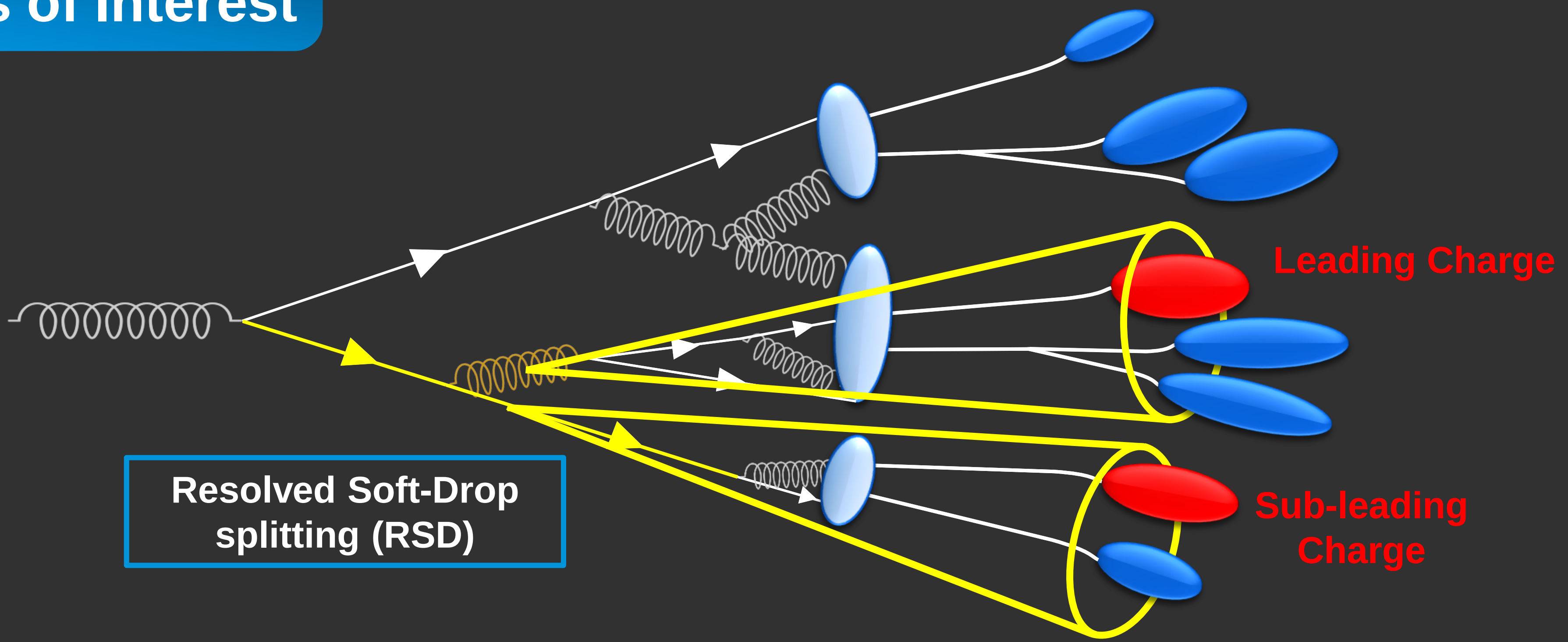
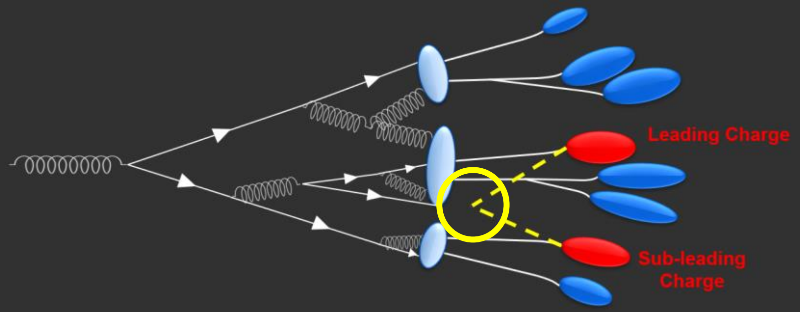


Resolved Soft-Drop splitting (RSD)

Leading Charged Particles splitting (LCP)



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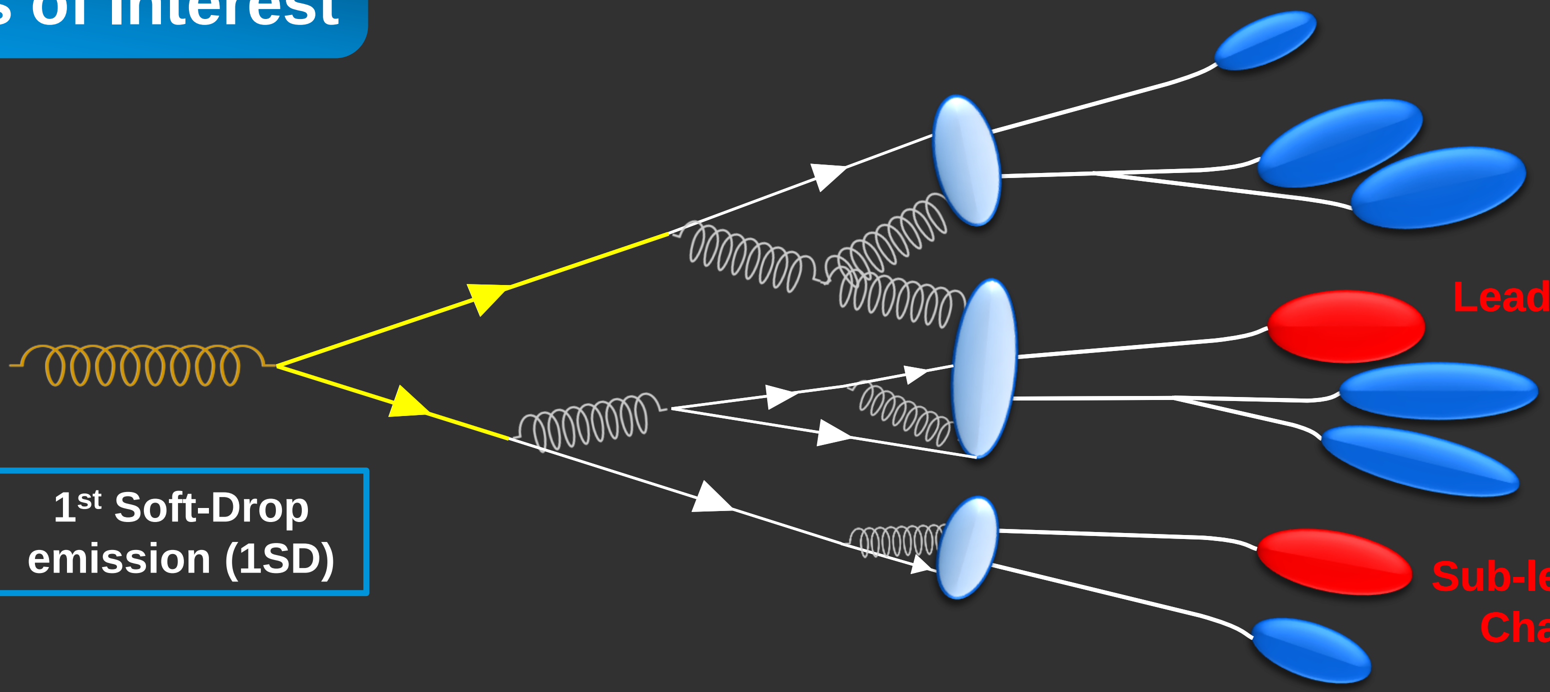
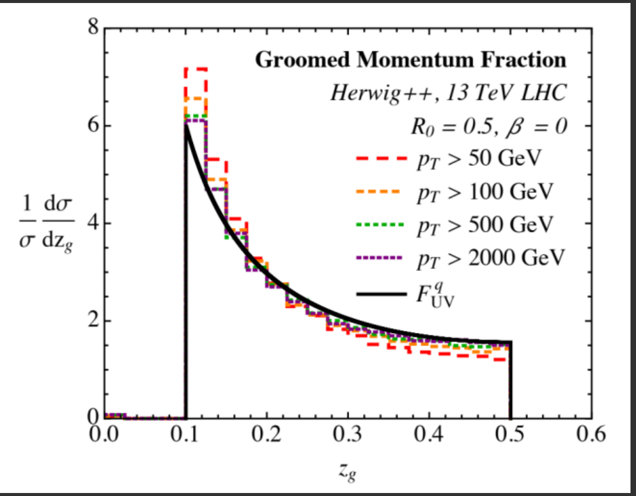


1st Soft-Drop emission (1SD)

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



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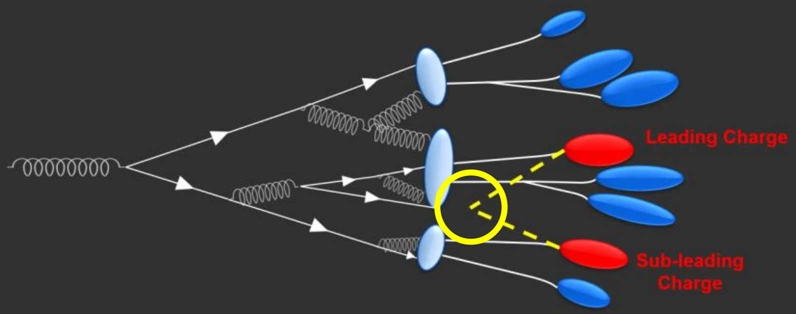

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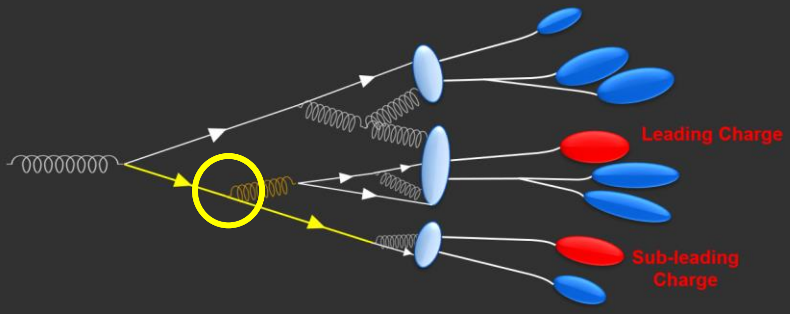

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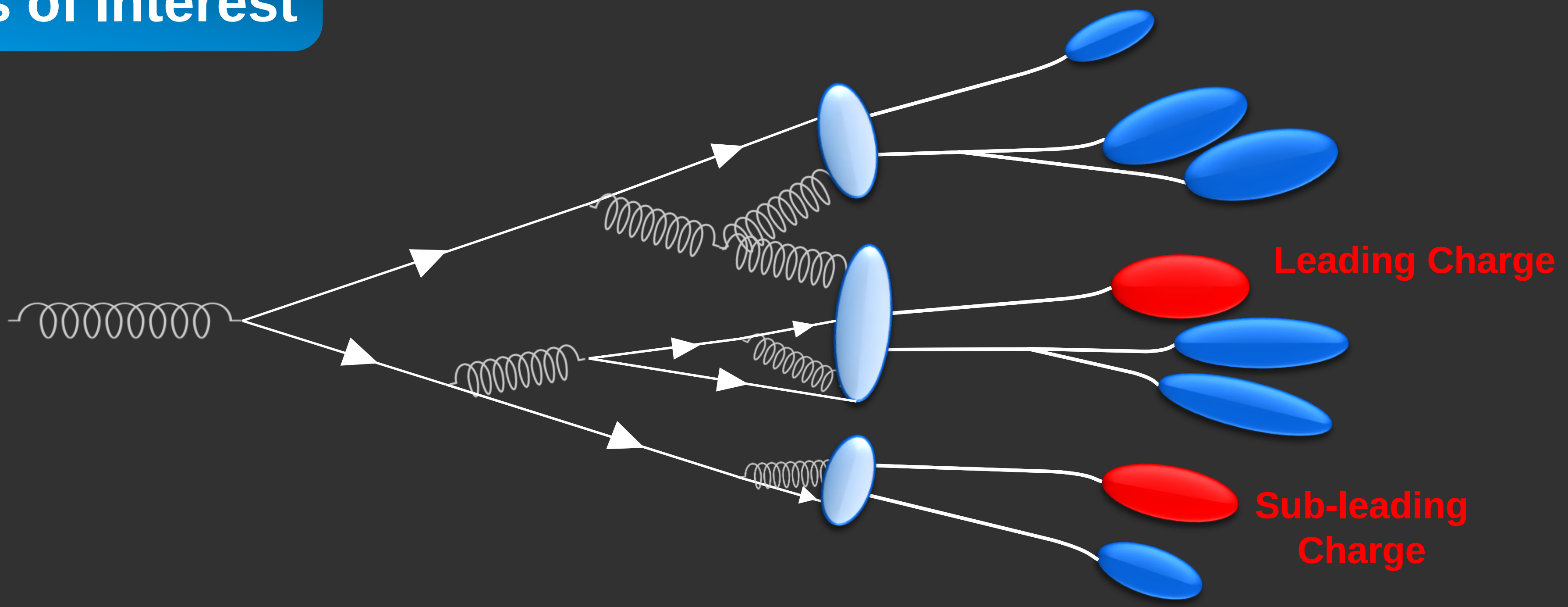
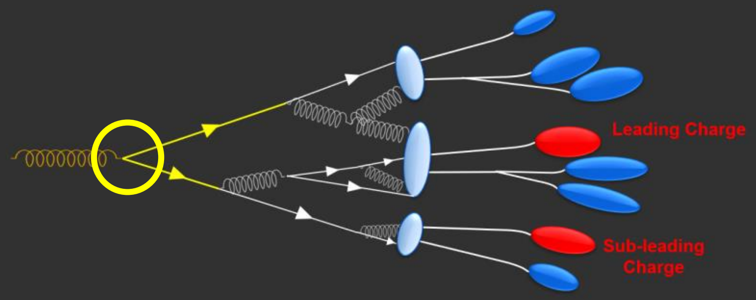
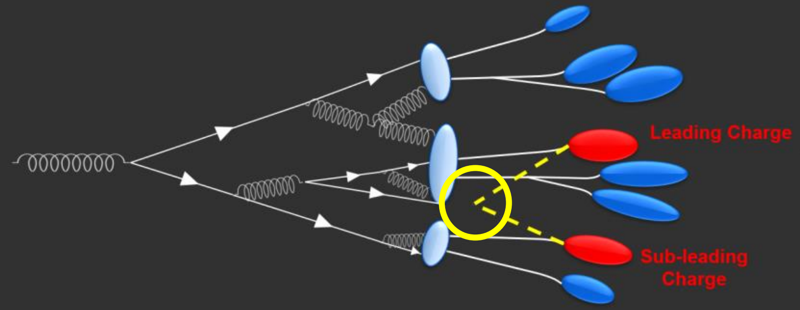
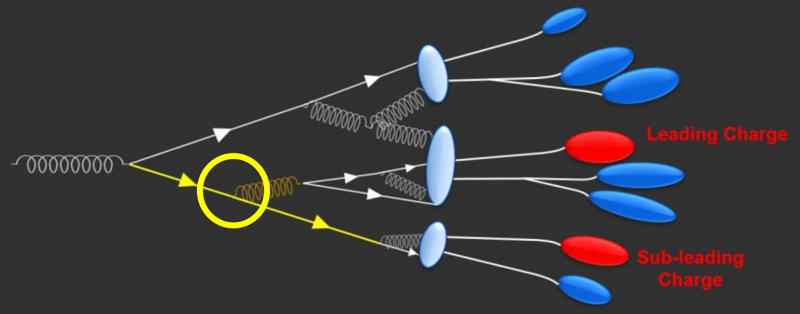


1st Soft-Drop emission (1SD)	Leading Charged Particles splitting (LCP)	Resolved Soft-Drop splitting (RSD)

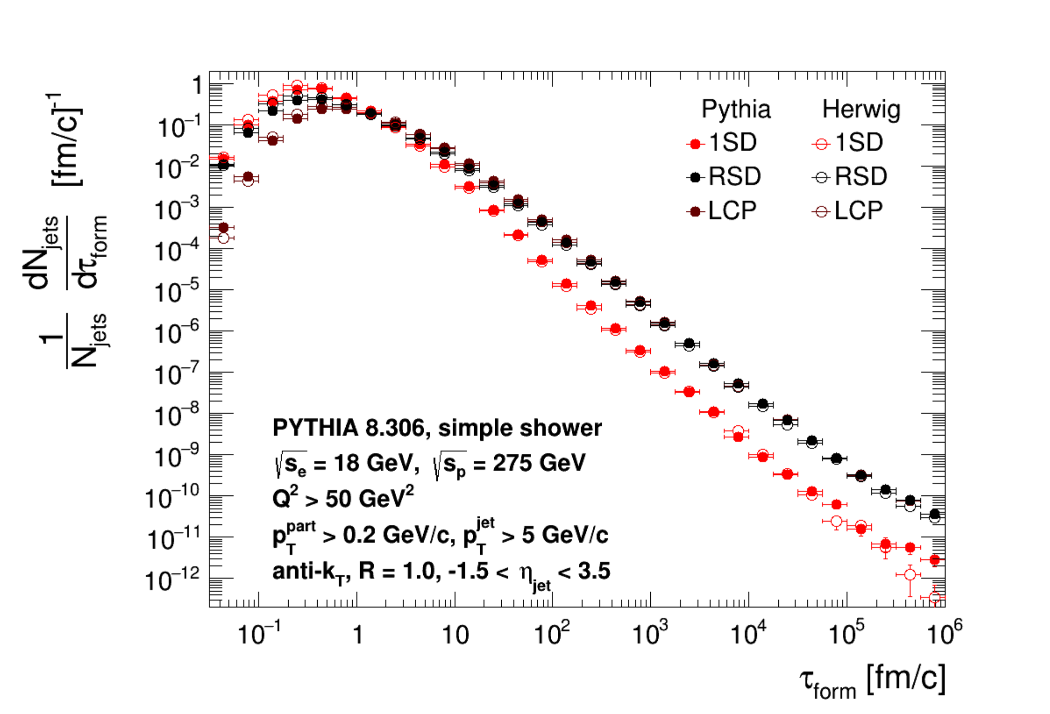






Results – Formation Time

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



- **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

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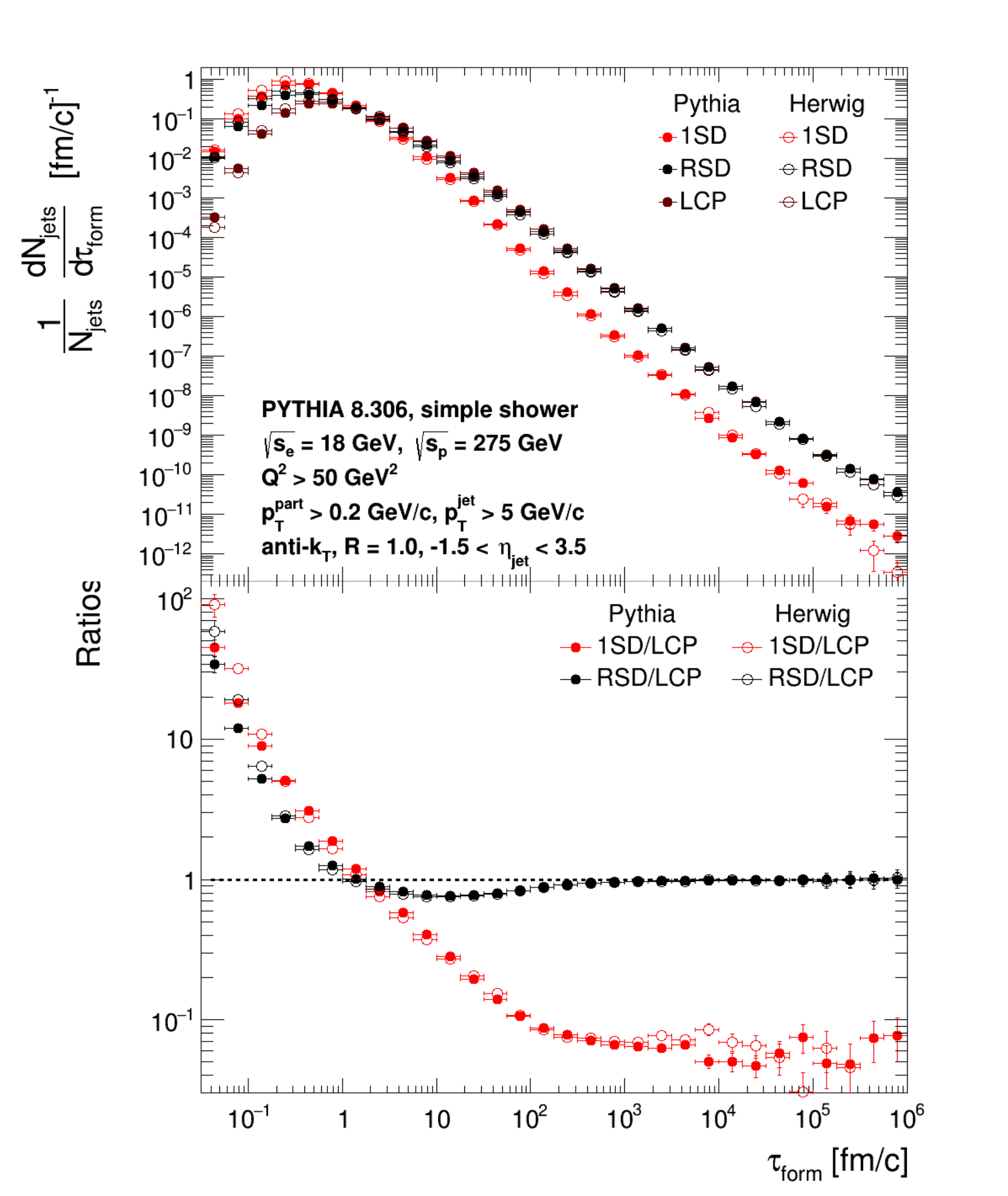


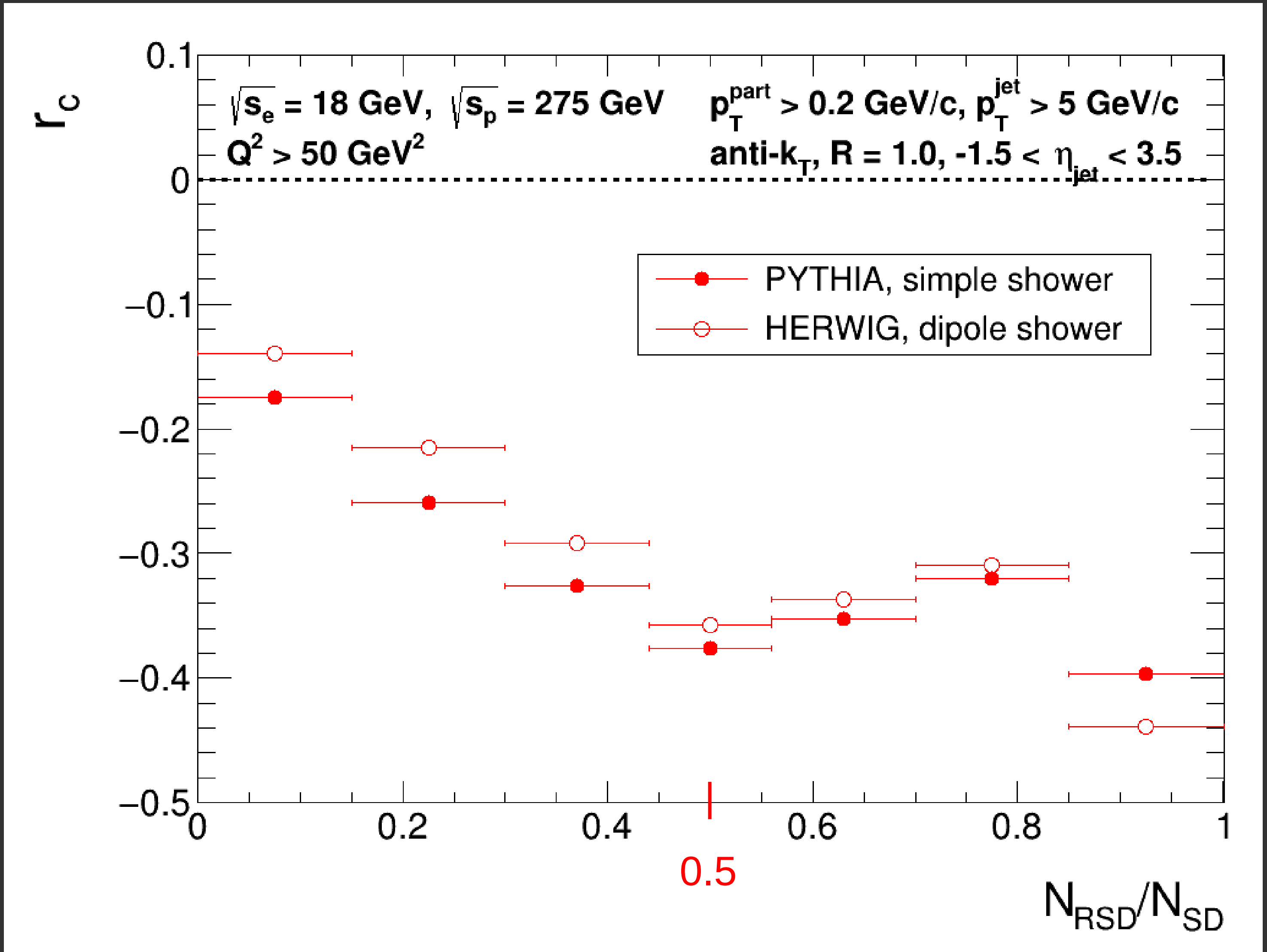
- **1SD** tends to have smaller τ_{form}
- **LCP** tends to have larger τ_{form}
- **RSD** sits between the 1SD and the LCP

- $\tau_{form,1SD} \neq \tau_{form,LCP}$
- $\tau_{form,RSD} \approx \tau_{form,LCP}$

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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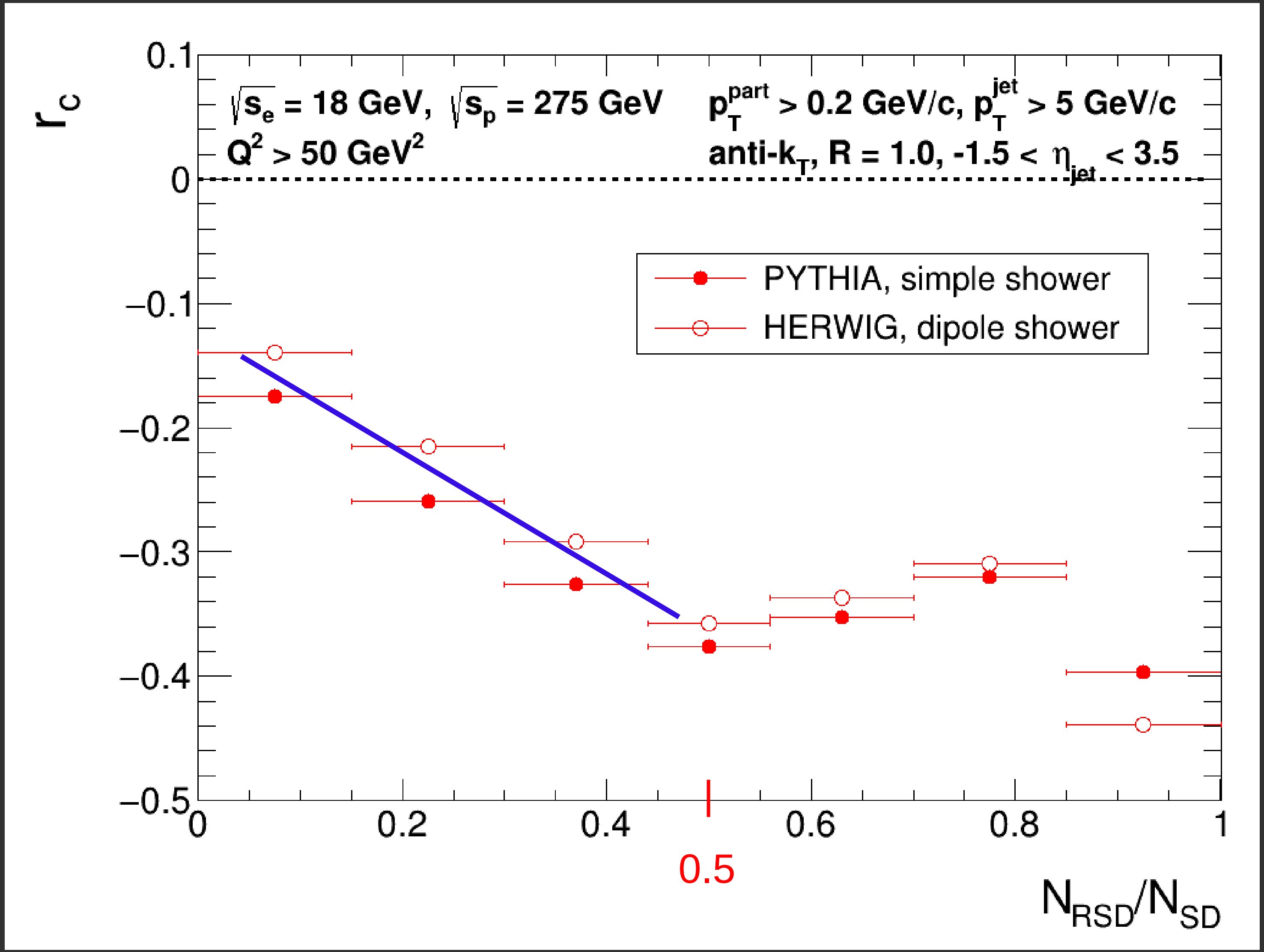

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- The charge ratio decreases, in general, with the increase of the RSD relative position

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

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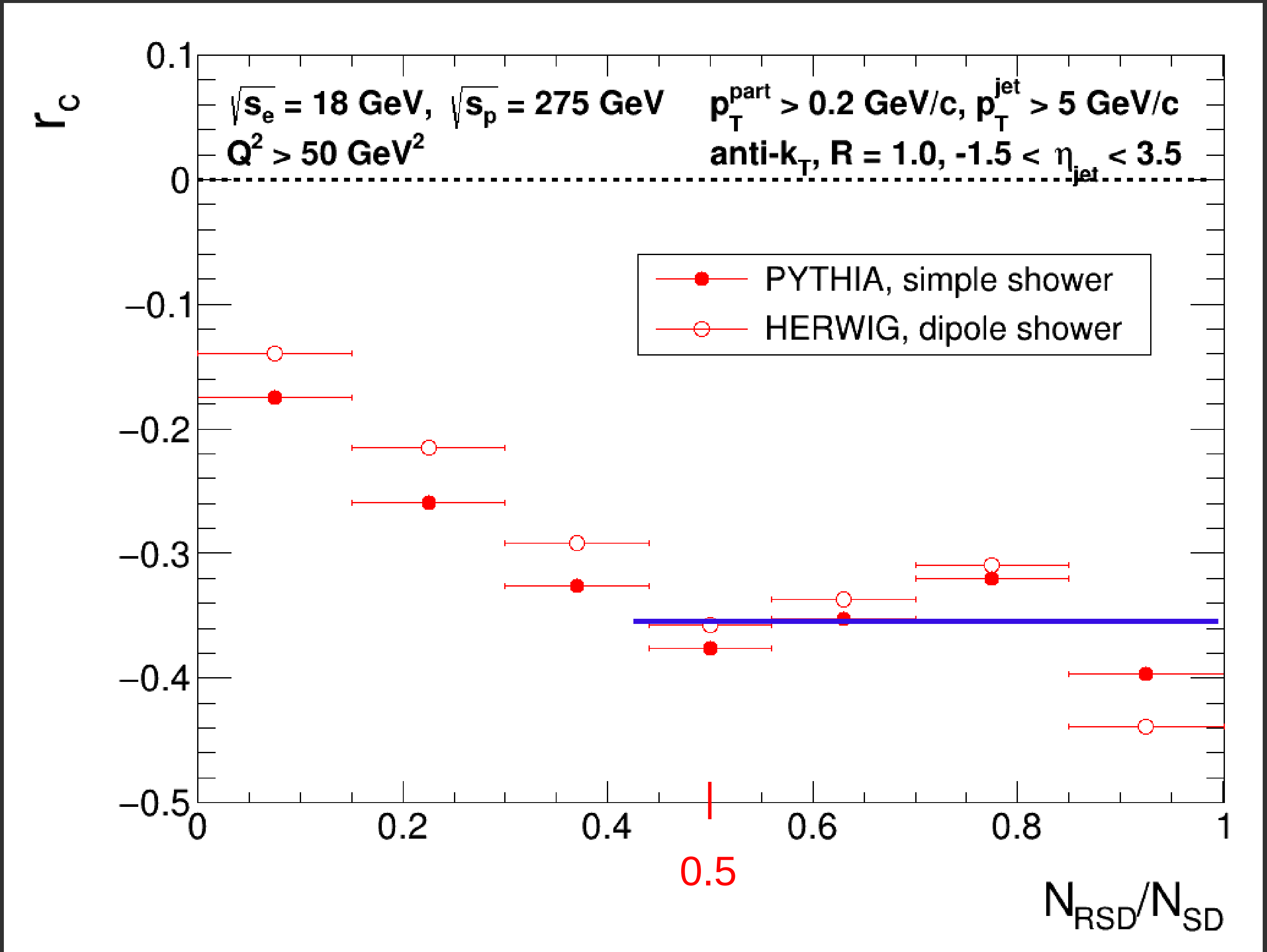
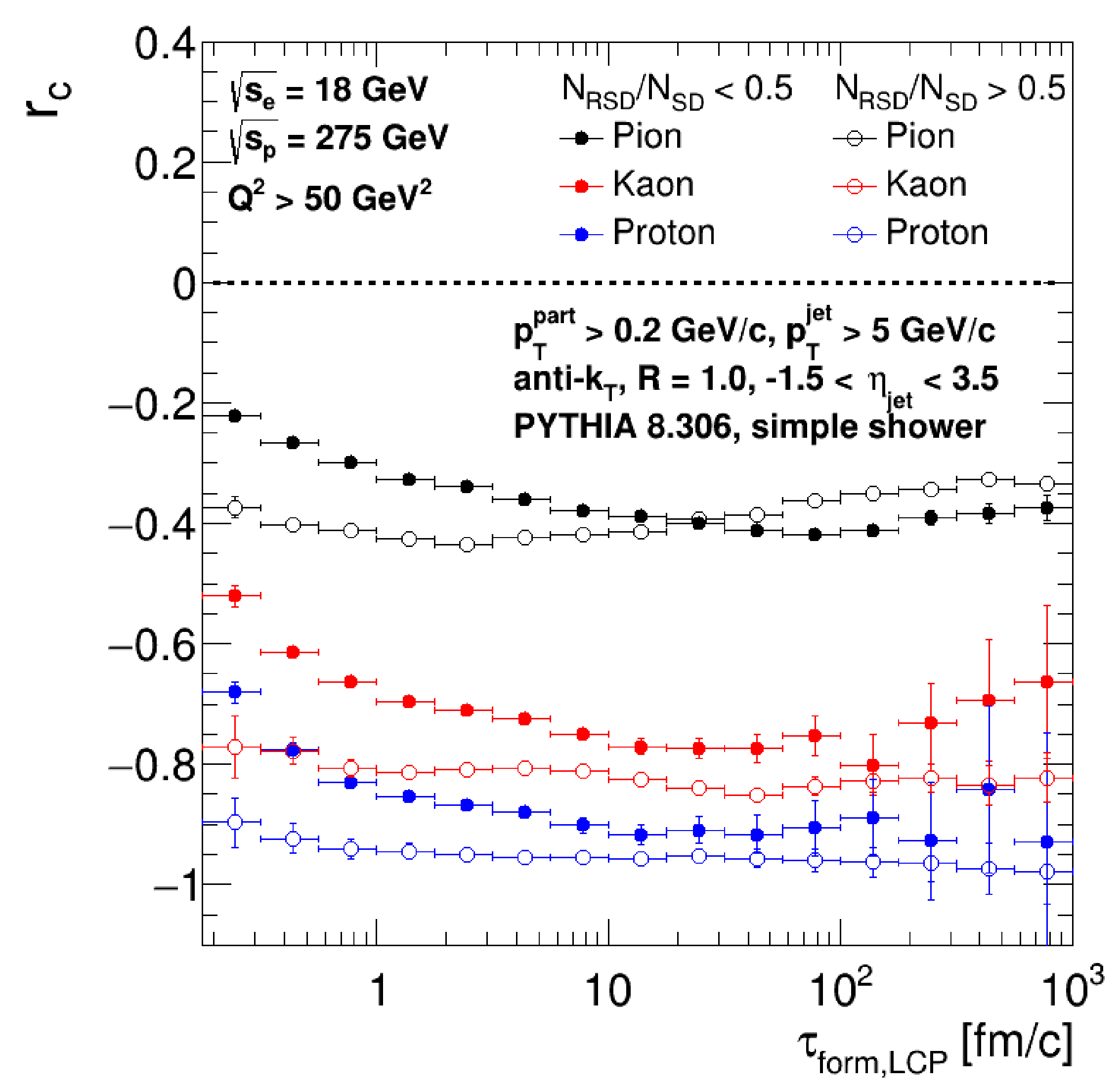


- N_{RSD}/N_{SD} measures the depth/relative position of the RSD in the clustering tree
- The charge ratio decreases, in general, with the increase of the RSD relative position
- For $N_{RSD}/N_{SD} > 0.5$, the descrease gives place to a plateau where r_c remains constant

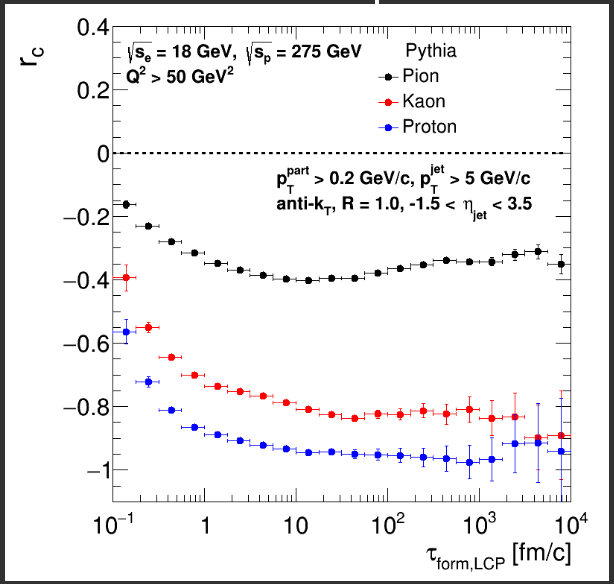
Conclusion: Yes! The r_c depends on the jet fragmentation pattern

Results – Charge Ratio



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

Inclusive plot

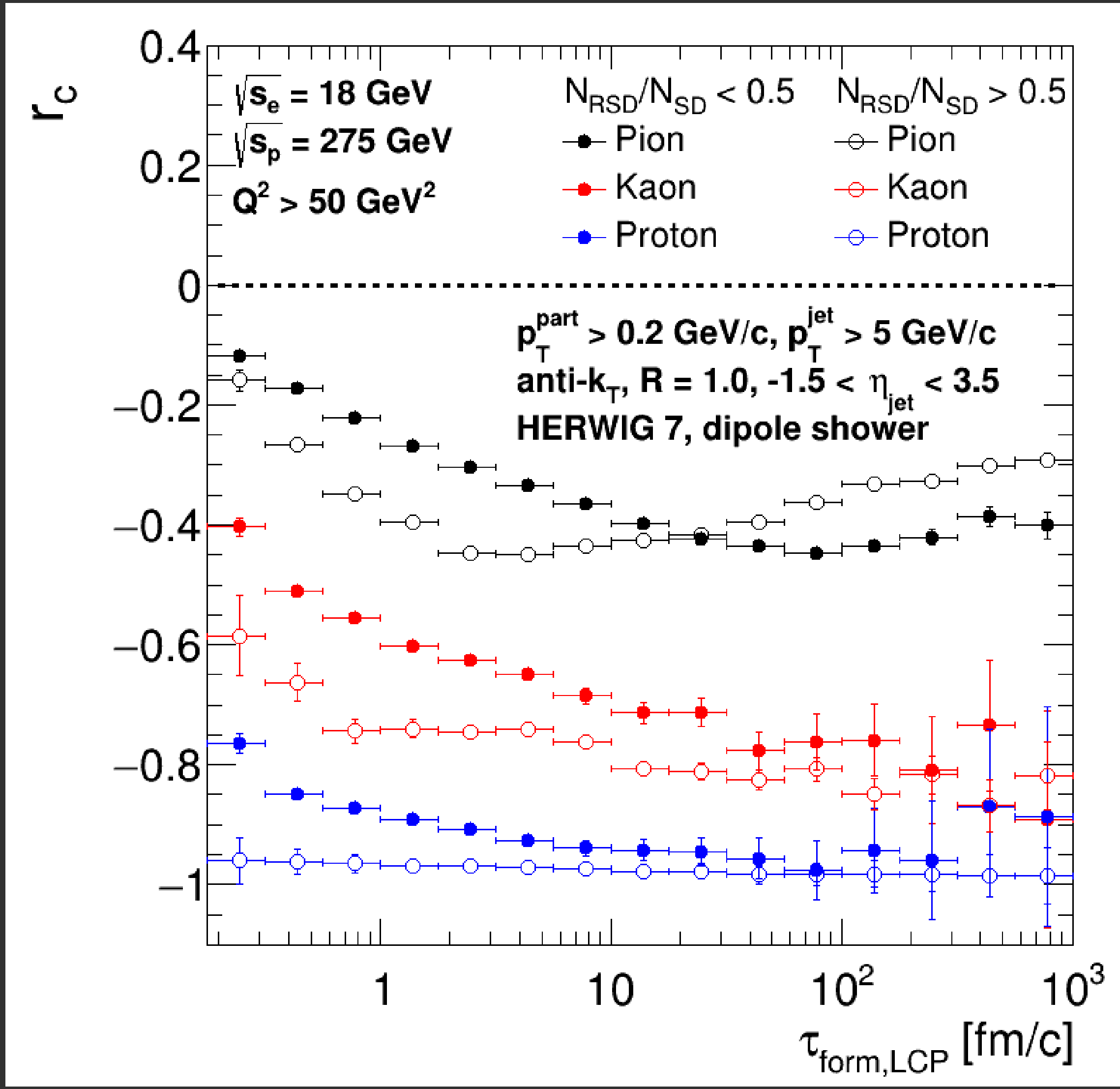


- For PYTHIA (Lund String Model),

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

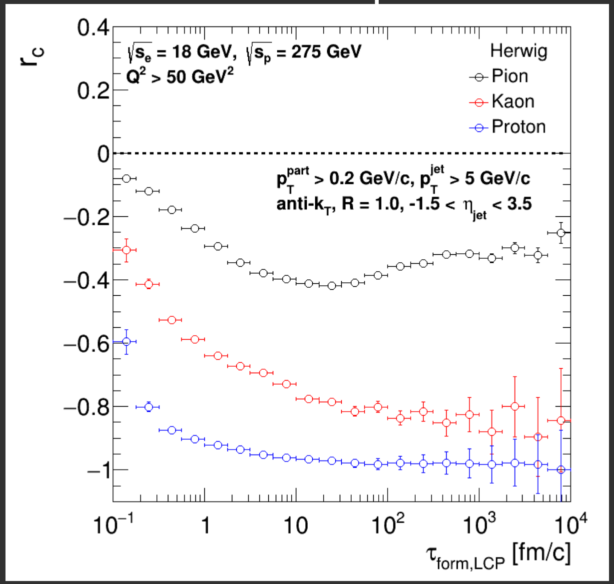
$\Rightarrow N_{RSD}/N_{SD} > 0.5$ cut eliminates the time-dependence of the r_c for all hadronic species and selects jets with higher chance of having opposite LCP.

Results – Charge Ratio



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

Inclusive plot

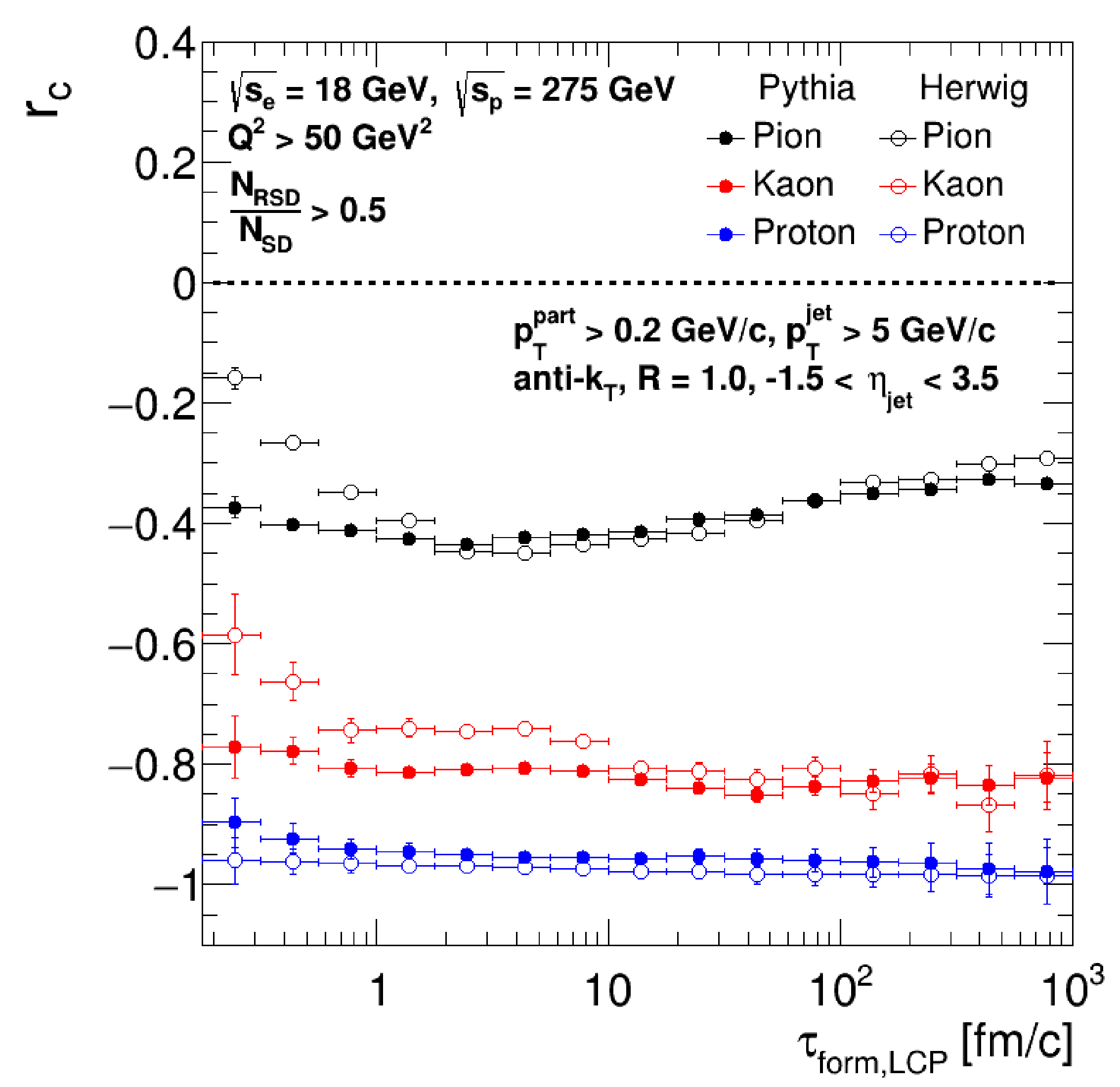


- For HERWIG (Cluster Model),

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

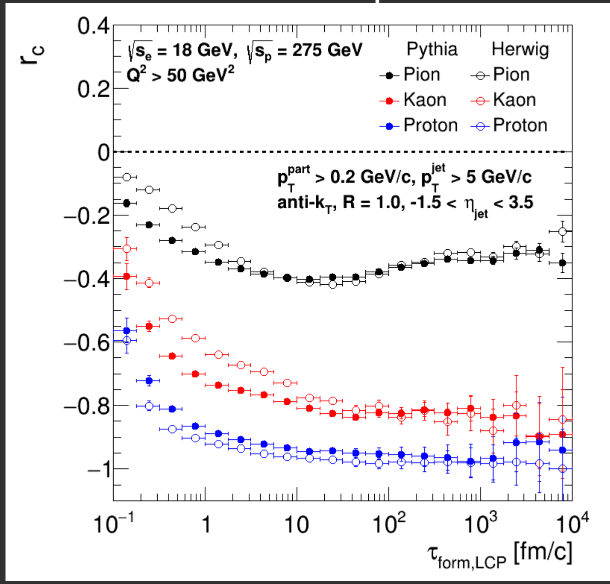
$\Rightarrow N_{RSD}/N_{SD} > 0.5$ cut keeps the r_c close to 0 for earlier times, but also selects jets with overall higher chances of having opposite LCP.

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

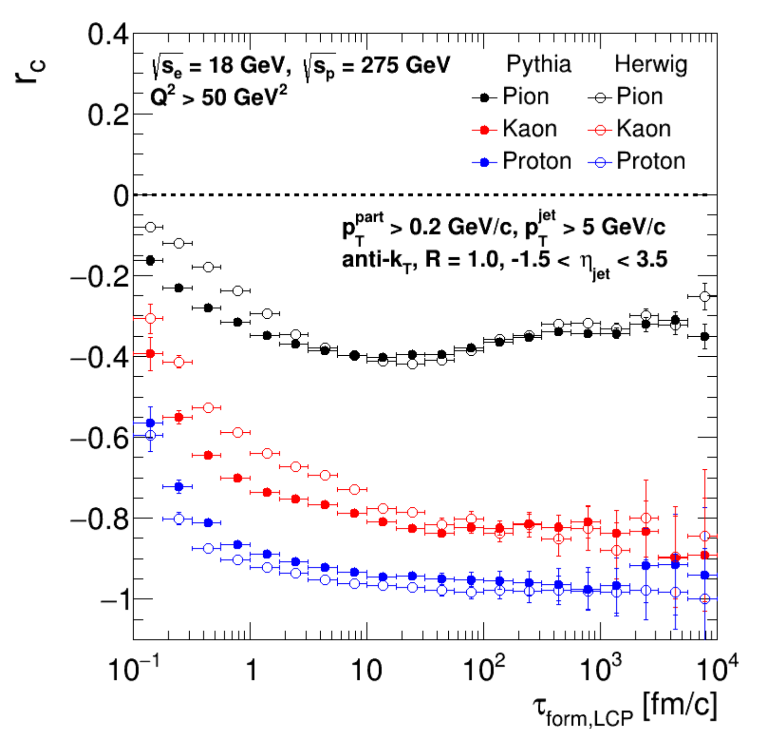


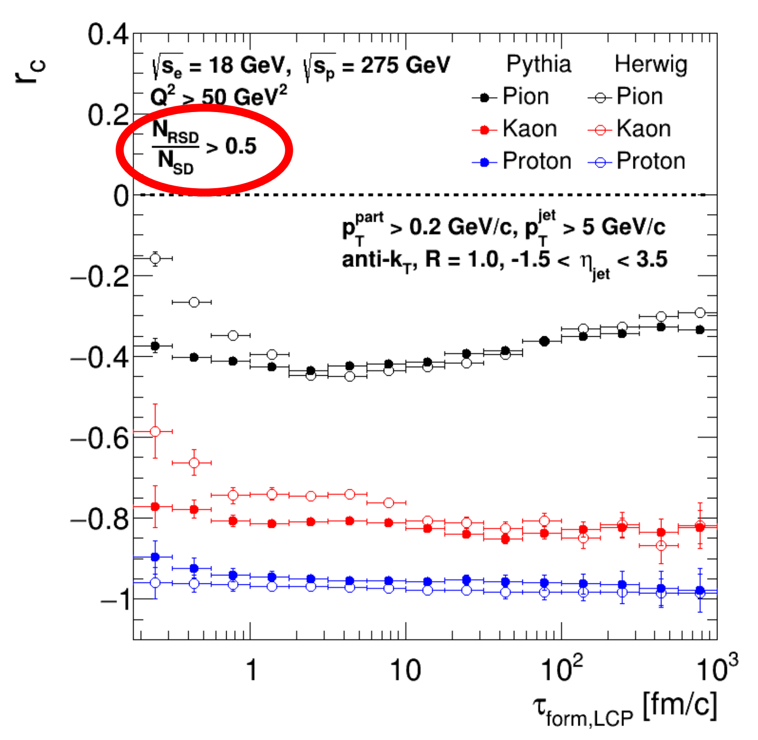
- Significant discrepencies between the predictions made by the two Monte Carlos, coming from the hadronization model;

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

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?

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LIP

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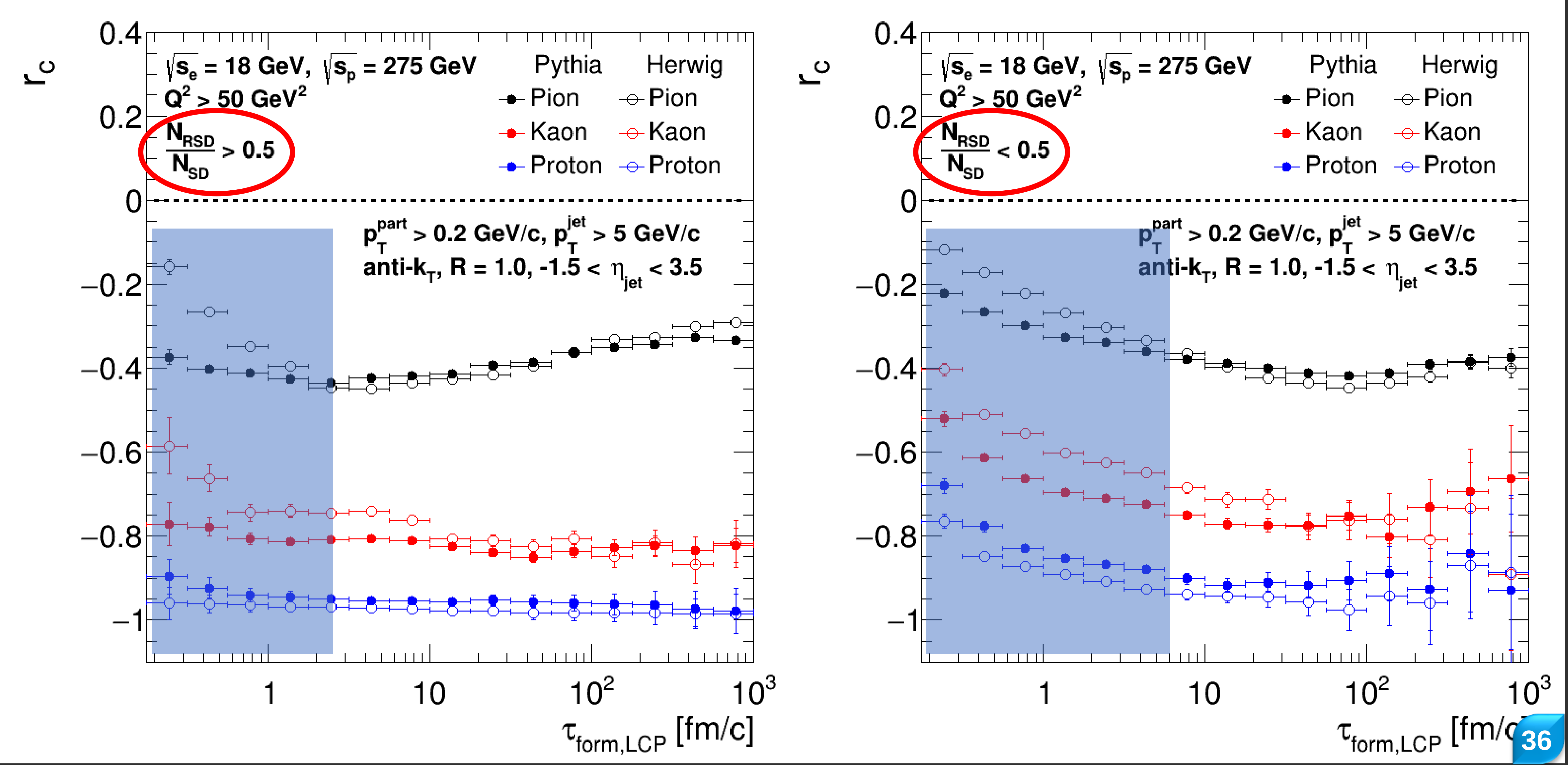
Results – Charge Ratio

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



Implementation

- **PYTHIA 8.306** and **HERWIG 7** are the event generators used in this work to simulate pp and ep collisions

Relativistic Heavy-Ion Collider (RHIC)

- 0.2 TeV pp collisions
- 0.2 TeV AuAu collisions

Large Hadron Collider (LHC)

- 5 TeV PbPb collisions
- 14 TeV pp collisions

Settings	CM energy	$p_{T,jet}$
RHIC	$\sqrt{s} = 200$ TeV	$20 < p_{T,jet} < 40$ GeV/c
LHC	$\sqrt{s} = 5$ TeV	$200 < p_{T,jet} < 300$ GeV/c
EIC	$\sqrt{s_e} = 18$ GeV $\sqrt{s_p} = 275$ GeV	$p_{T,jet} > 5$ GeV/c

- Jet analysis is performed with **FastJet**

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

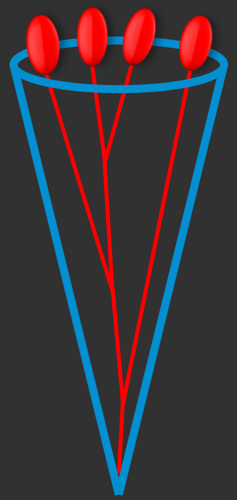
Clustering Algorithms

Anti-k_t | **Cambridge/ Aachen (C/A)** | τ

⇓ ⇓ ⇓

Jet finding | **Jet substructure studies**

- **Anti-k_t** algorithm:
  - Sensitive to hard objects
  - Unphysical clustering trees
- **C/A** algorithm: Angular-ordered trees
- τ algorithm: Reverse time-ordered trees



Groomed Momentum Fraction

Groomed Momentum Fraction

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

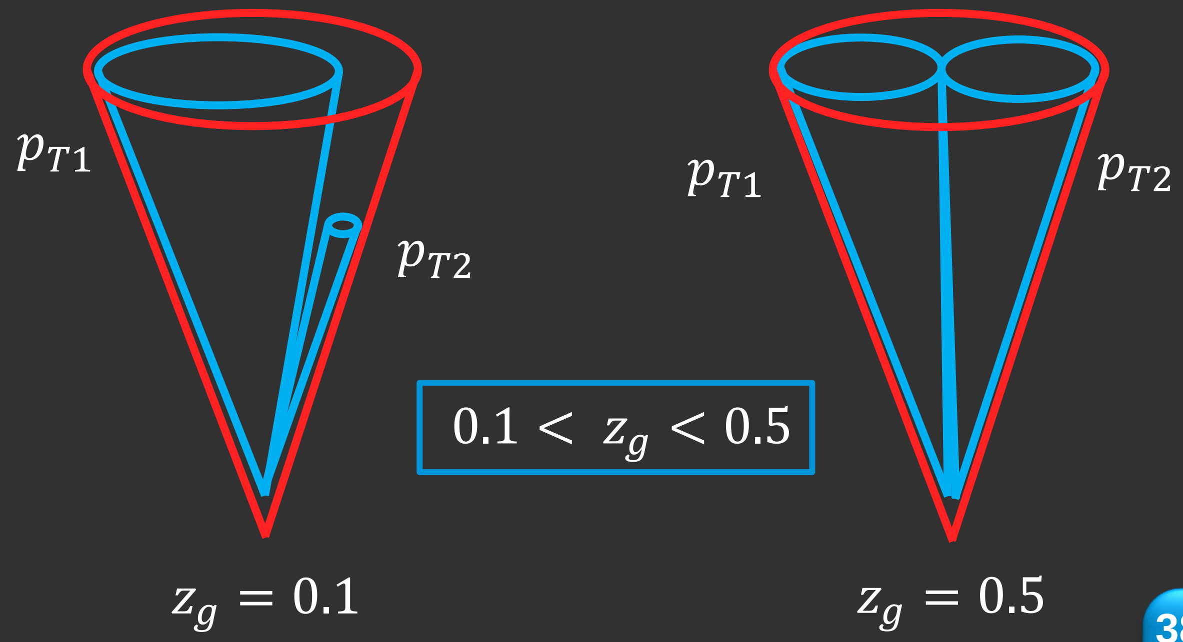
Fraction of the total transverse momentum of the source object that is carried out by the softest daughter of a SD emission

Soft-drop (SD) algorithm: remove soft wide-angle radiation; better comparisons between experiment and pQCD calculations

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

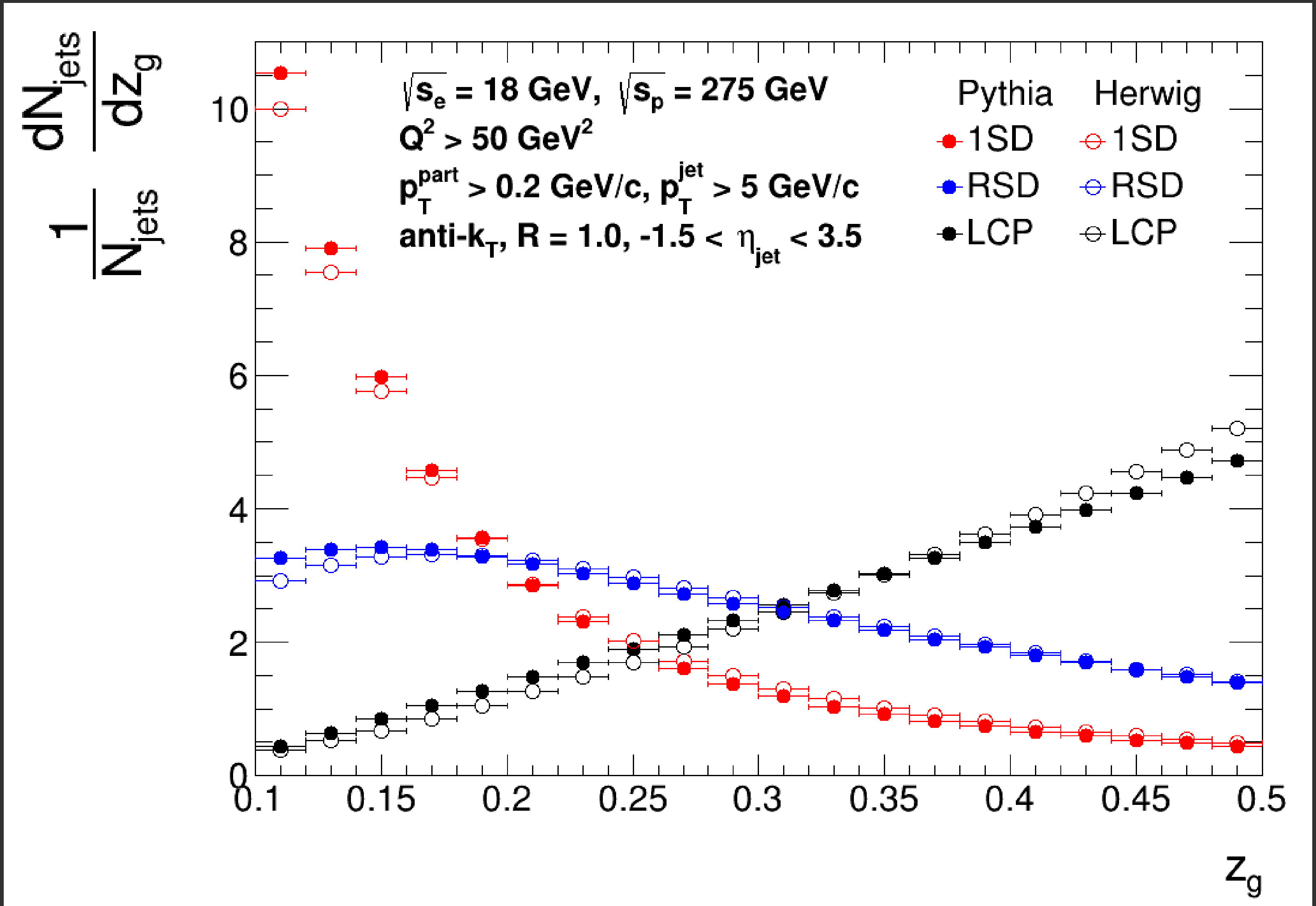
SD criterion: $z_g > 0.1$

$\Longrightarrow$



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