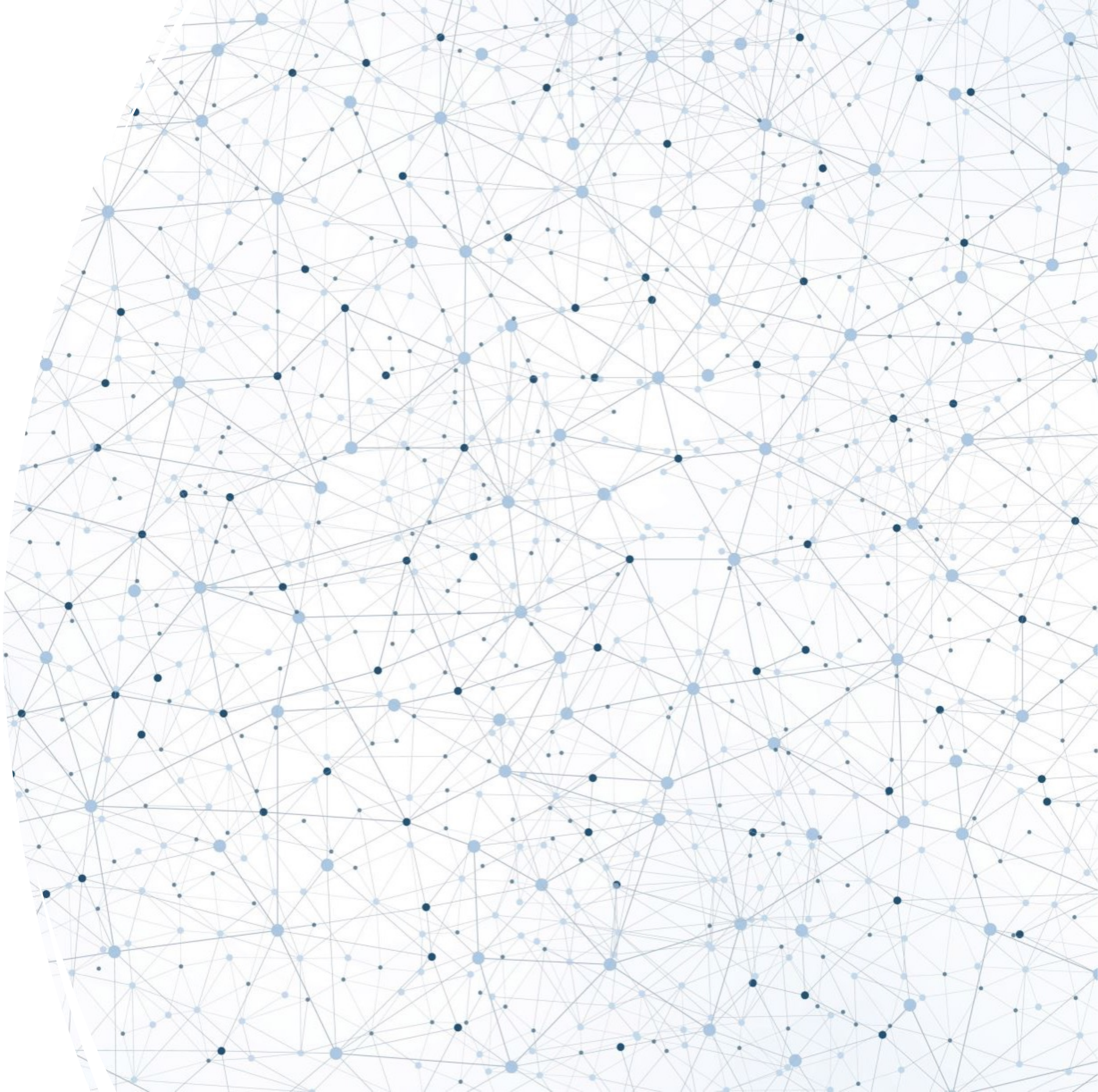
Studying hadronization mechanisms with spectator tagging of slow protons at Fermilab, Jefferson Lab, and EIC

Carolina Robles

GHP workshop, 14 April 2023

EX UMBRA IN SOLEM



Hadronization

It is the mechanism of hadron formation out of quarks and gluons

What it the hadronization process?

hadronization

In-medium hadronization

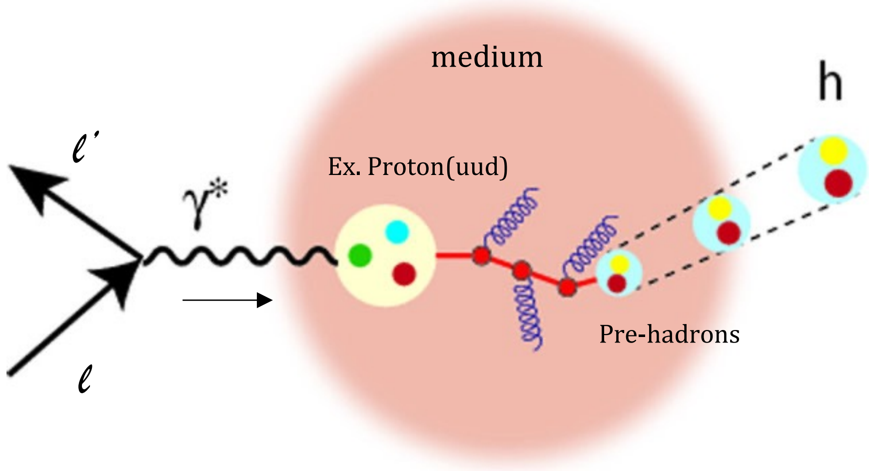


Fig.1: Propagation of a quark in the nucleus

Propagation of a quark in the nucleus:

- By the extraction of medium properties (QGP).
- Studying the spacetime development of the hadronization(L_P).
- Studying a geometrical approach after the hard interaction and before the hadronization (L, b).

B.Guiot and Z.Kopeliovich.
DOI: 10.1103/PhysRevC.102.045201

SPECTATOR TAGGING

Geometry tagging

Technique that will help to select our event samples and, on a statistical basis, **control the geometry of the collision**

Nuclear geometry can be constructed in different ways depending x_{Bj} values.

d , d_1 , d_2 : Medium average path length

b, b_1 , b_2 : Impact parameter

j, j_1 , j_2 : Final state hadrons

$$x_{Bj} = \frac{Q^2}{2M\nu}$$

“struck quark” scenario

$$\gamma^* + q \rightarrow q$$

$x_{Bj} > 0.1$

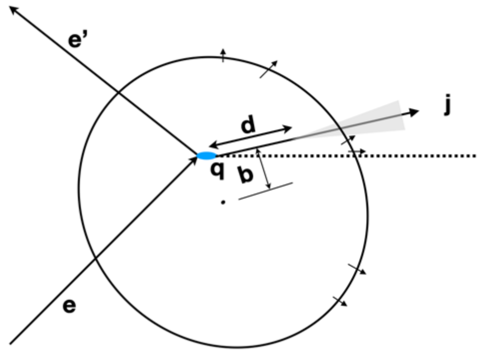


Fig. 3: High x_{Bj} Picture

“$q\bar{q}$ pair” scenario

$$\gamma^* + g \rightarrow q\bar{q}$$

$x_{Bj} < 0.1$

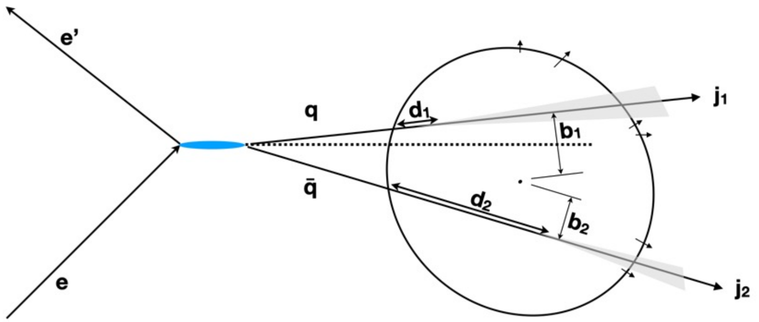
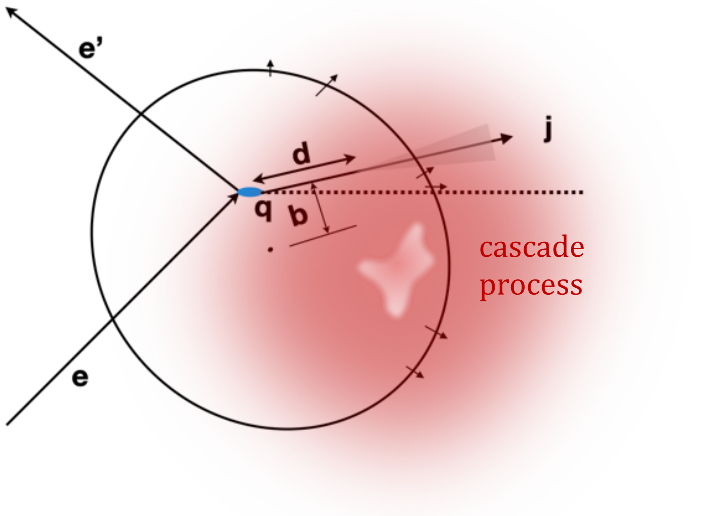


Fig. 4: Low x_{Bj} Picture

SLOW PROTONS : GREY TRACKS

- Protons, with a momentum range between: $\mathbf{0.2\ GeV < p < 0.6\ GeV}$
- Such protons may either originate directly from the projectile collision or they may have been knocked out in the cascade process.



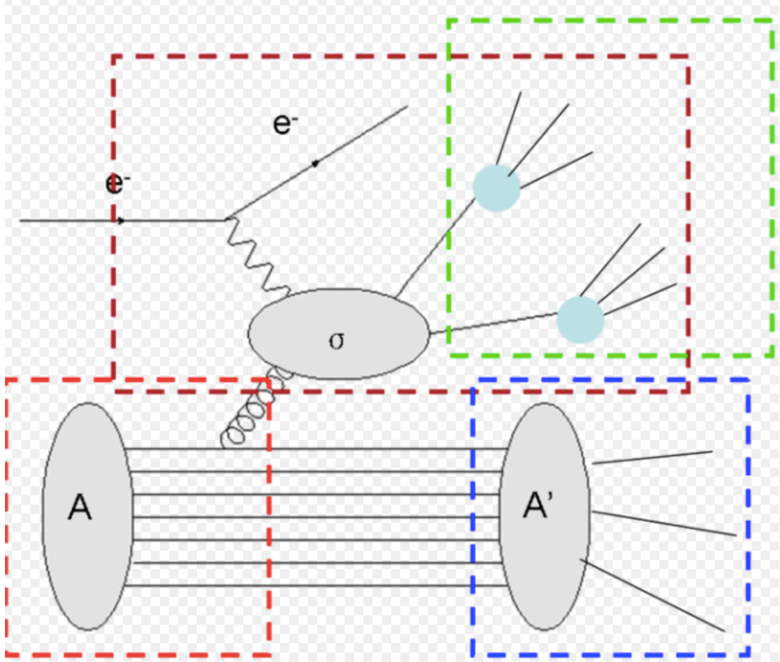
cascade process

Why are they important for us?

- They help us to understand the intranuclear mechanism for particle multiplication. How?
  - These knocked out protons give us a measure to calculate the average number of cascade interactions.
  - Slow protons will allow us to analyze better the region just after the collision.
  - Considering that they are also useful to identify those events where cascade interactions occur.

BeAGLE **B**enchmark **eA** **G**enerator for **LE**ptoproduction

Monte Carlo Event Generator for Leptoproduction



A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

Nuclear geometry by DPMJet and nPDF provided by EPS09.

Parton level interaction and jet fragmentation completed in PYTHIA.

Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

Complex software:

- DPMJet
- Pythia 6 ↔ PyQM
- Fluka
- PYTHIA PDF ↔ LHAPDF (linked)

↓

EPS09 Nuclear PDF routines

Fig. 5: **BeAGLE** technical scheme.

Classes Documentation: https://www4.rcf.bnl.gov/~eickolja/

Main info: https://wiki.bnl.gov/eic/index.php/BeAGLE → Input files and output files format

Gluon radiation in PyQM

Considering: $\Delta E = E_{parton}^{initial} - E_{parton}^{final}$

$$\omega \frac{dI}{d\omega dz} \cong \alpha_s \sqrt{\frac{\hat{q}}{\omega}} \quad \text{and} \quad N(\omega) \equiv \int_{\omega}^{\infty} d\omega' \frac{dI(\omega')}{d\omega'}$$

$$\omega'_{hard} = \frac{4\alpha_s^2 \hat{q}}{N^2} L^2$$

$$\omega_{hard} = \Delta E$$

For **one hard gluon**:

$$\omega'_{hard} = 4\alpha_s^2 \hat{q} L^2 \qquad \text{where} \qquad \omega'_{hard} \leq \Delta E$$

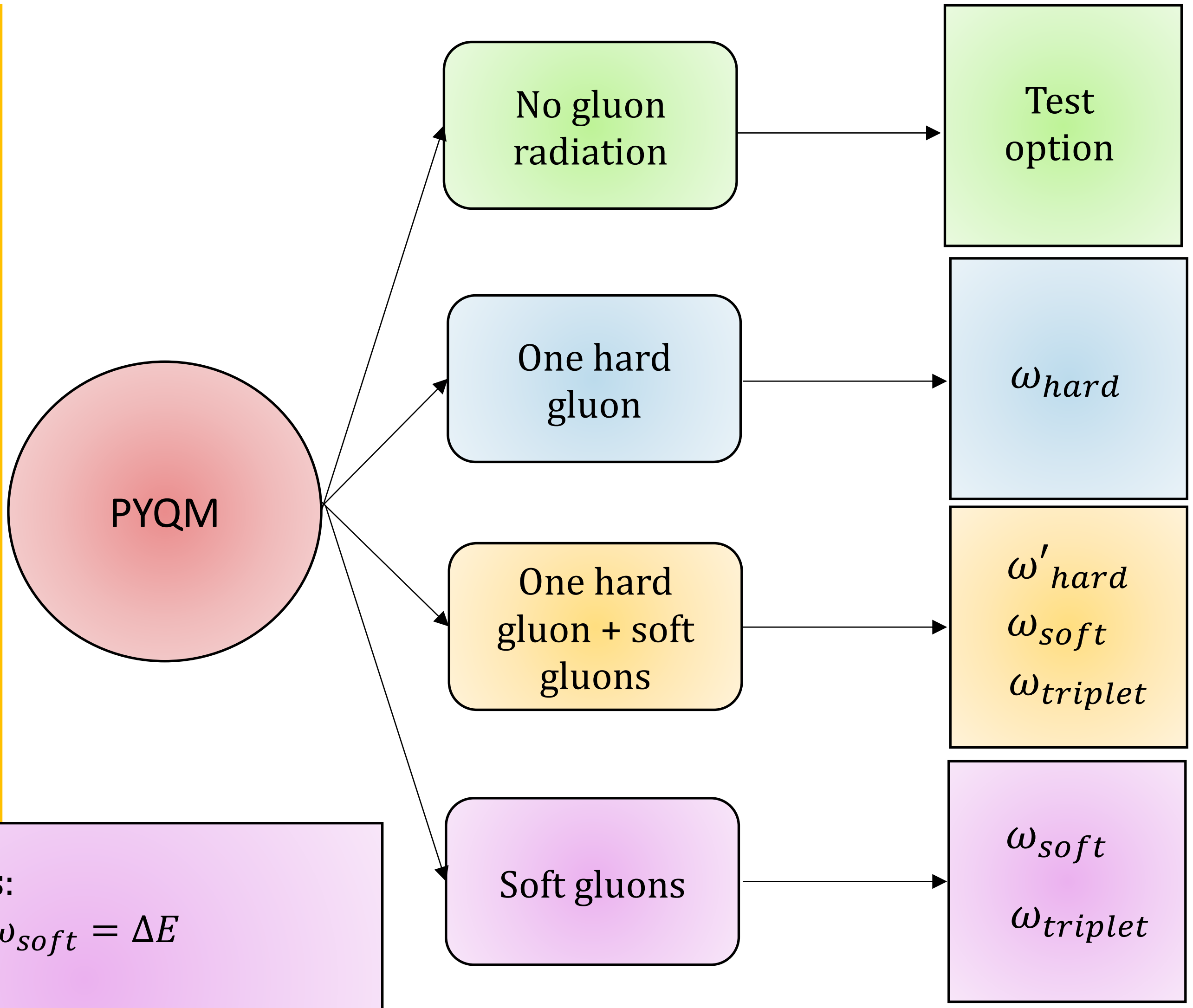
If $\omega'_{hard} < \Delta E$ then we add **soft gluons**:

$$\omega_{soft} = \Delta E - \omega'_{hard}$$

If $\omega_{soft} > 5\ GeV$, then we add a triplet (qg$\bar{q}$):

$$\omega_{triplet} = \omega_{soft} - 5\ GeV$$

Treating the medium-induced GLUON radiation


PYQM

No gluon radiation

Test option

One hard gluon

ω_{hard}

One hard gluon + soft gluons

ω'_{hard}

ω_{soft}

$\omega_{triplet}$

Soft gluons

ω_{soft}

$\omega_{triplet}$

Soft gluons:

$$\omega_{soft} = \Delta E$$

If $\omega_{soft} > 5\ GeV$ then we add a triplet $\omega_{triplet}$.

TESTING PyQM - FERMILAB

Why we chose the E665 experiment?

- Muon-nuclei fixed target experiment.
- Muon beam of 490 GeV and Xenon target.
- Analyzed grey tracks.

Average hadronic
multiplicity ratio

$$R = \frac{\langle n(n_g) \rangle_{\mu Xe}}{\langle n \rangle_{\mu D}}$$

Average number tracks for μXe, considering n_g

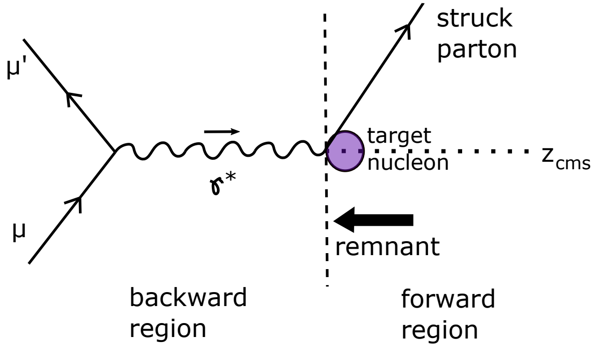
Average number tracks for μD

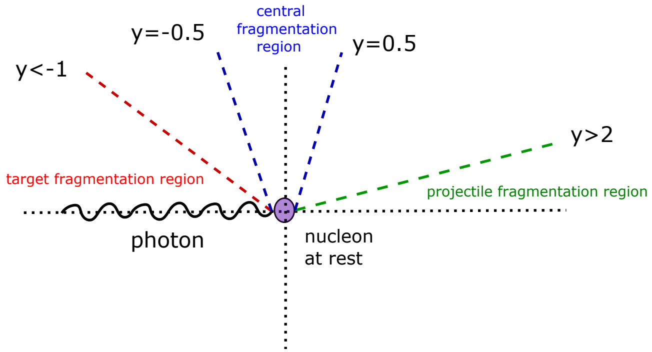
Analized by regions

We **have an insight** into the mechanism of hadron-production on nuclei by measuring:

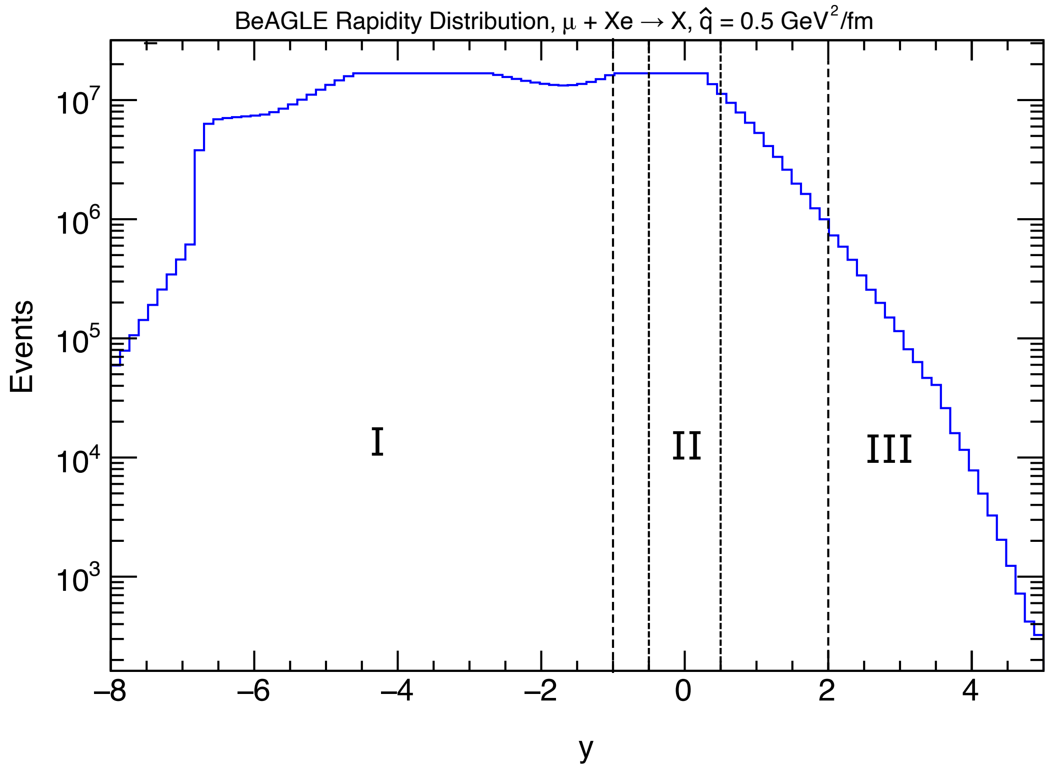
- Its **average hadronic multiplicity ratio** as a function of the number of grey tracks n_g (or cascade interactions).
- Correlation between the average in-medium path length and the impact parameter with the number of grey tracks.

ANALYZING BY REGIONS





Rapidity in the center of mass frame



I: Target Fragmentation Region

II: Central Fragmentation Region

III: Projectile Fragmentation Region

Multiplicity Ratio for ALL regions as a function of grey tracks

E665 Cuts:

- $x_F^* < -0.2$
- $Q^2 > 1 GeV^2$
- $8 < W < 30\ GeV$
- $50 < \upsilon < 400\ GeV$

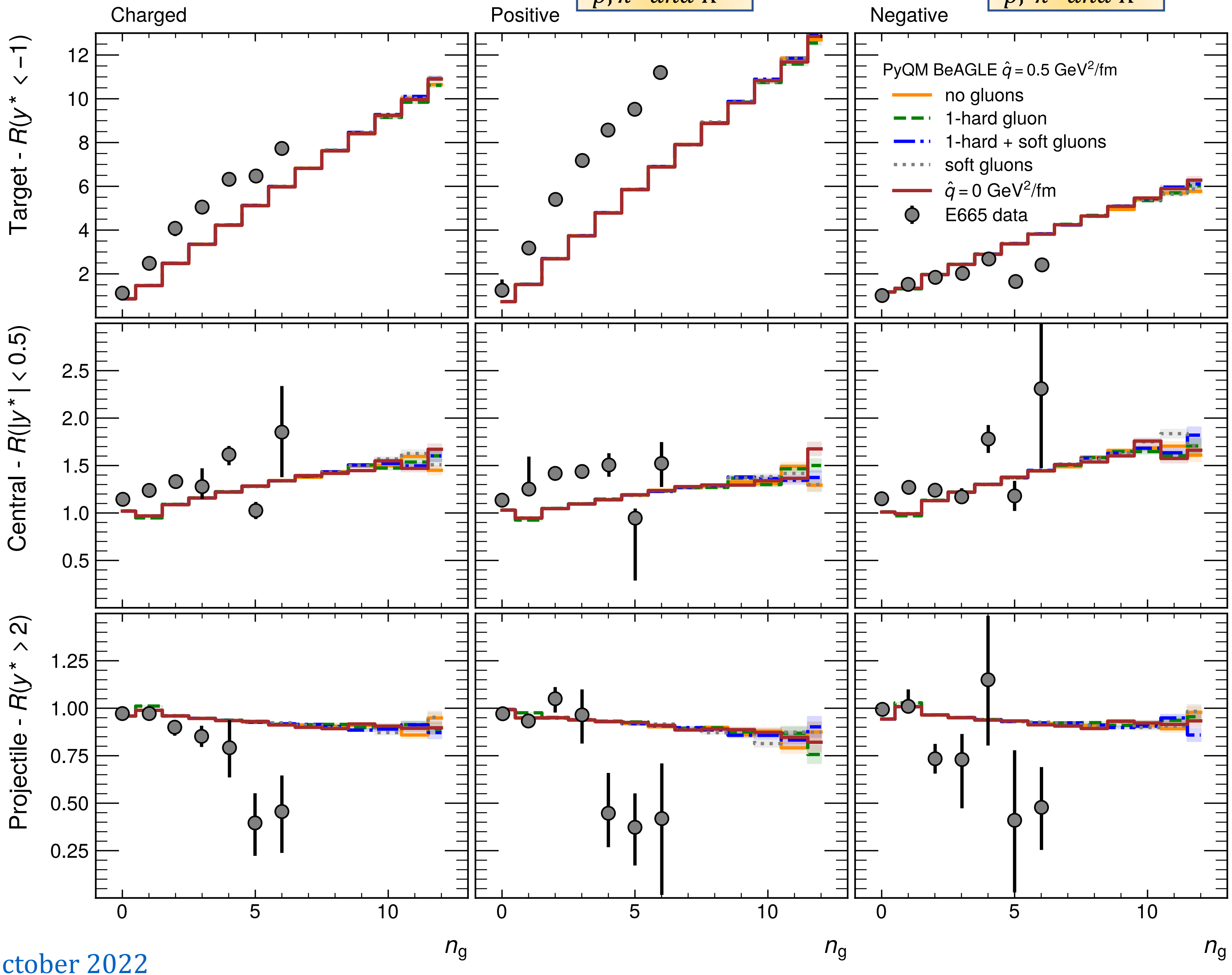
Simulation parameters:

- $Q^2 > 1 GeV^2$
- $8 < W < 30\ GeV$
- $50 < \upsilon < 400\ GeV$
- $\hat{q} = 0.5\ ^{GeV^2}/_{fm}$
- tau0 = 7 fm/c

Fast particles

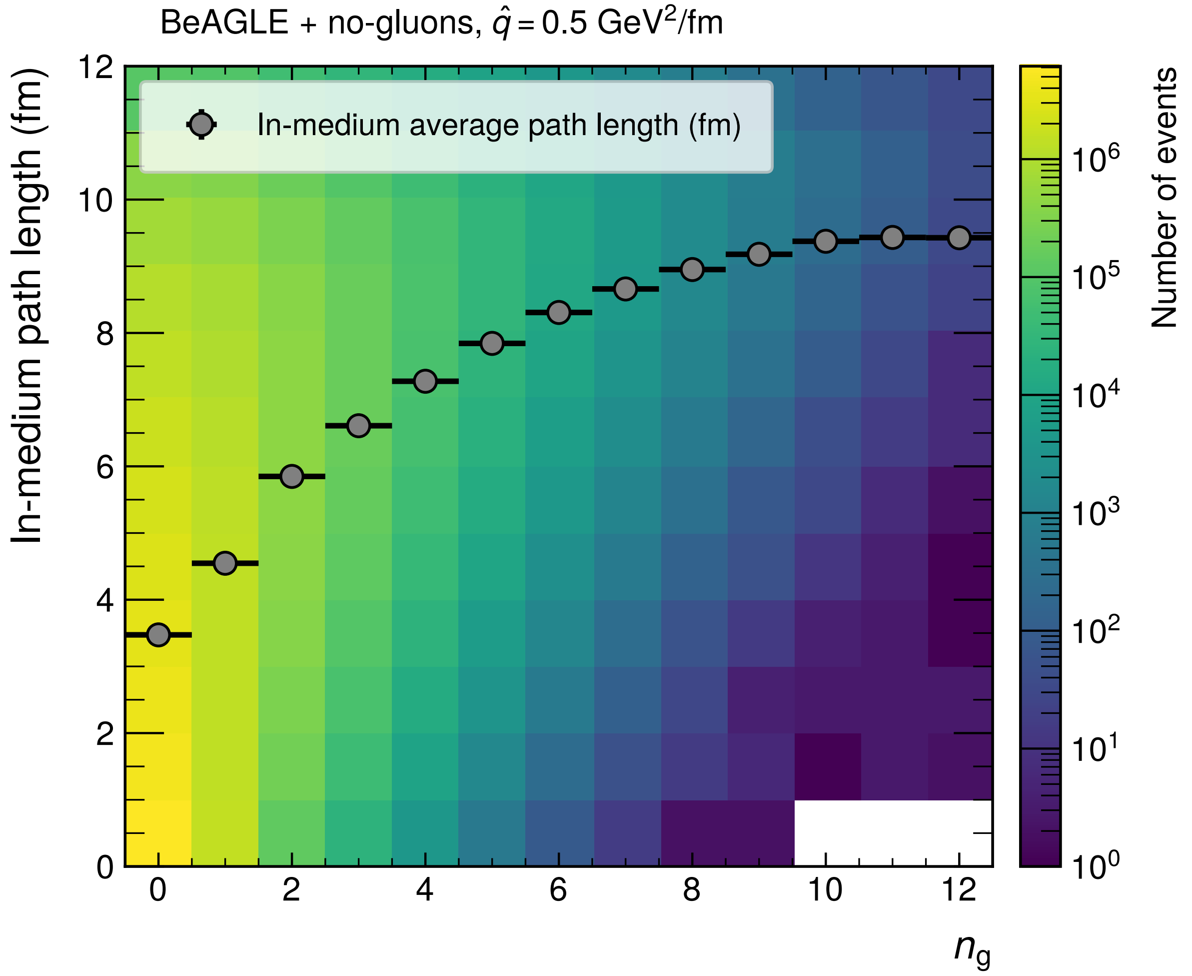
$p, \pi^+ and\ K^+$

$\bar{p},\ \pi^- and\ K^-$



Phys. Rev. C **106**, 045202 – Published 13 October 2022

In-medium path length as a function of grey tracks

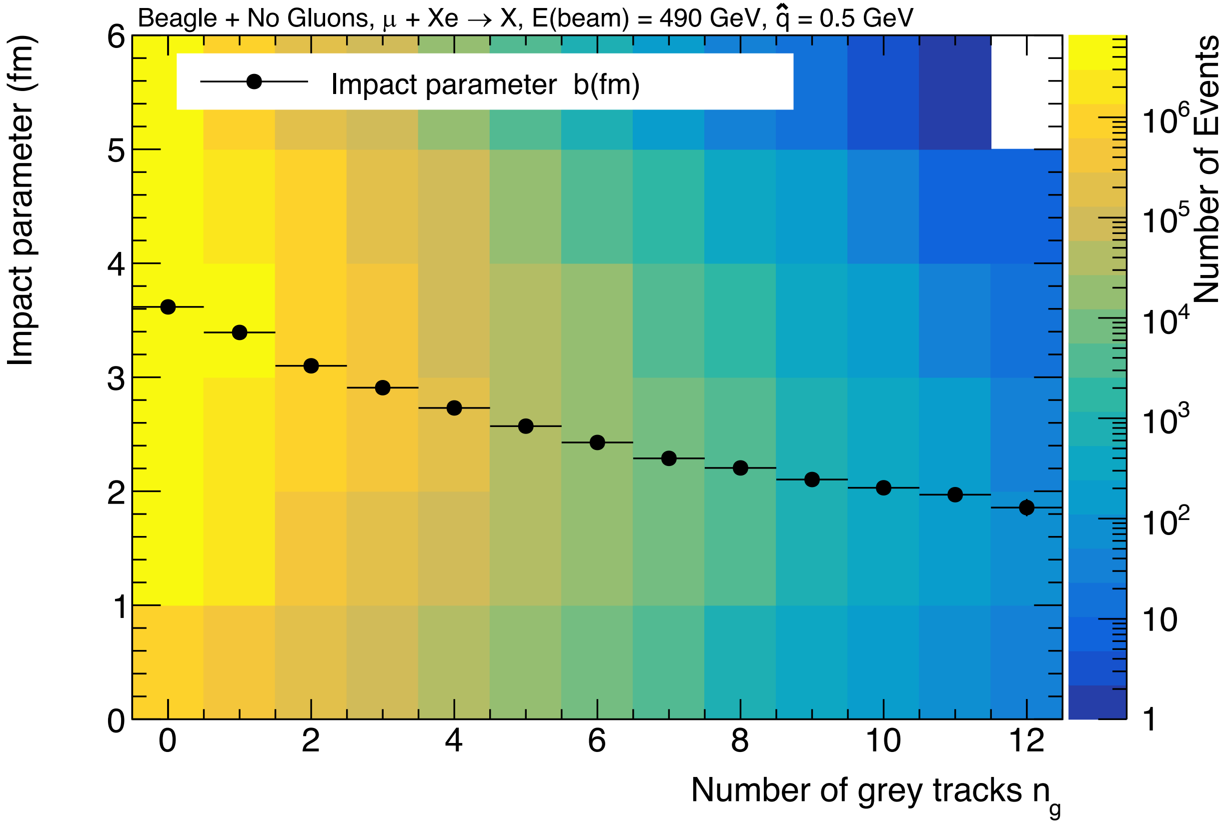


"Characterizing the geometry of the collision"

- Strong correlation between the in-medium path length and grey tracks.
- Most of the events show:
  - The in-medium path length goes up to ~8 fm having a good correlation with at least ~5 grey tracks.
  - Small traveling lengths are correlated with a small amount of n_g (less cascade interactions).
  - Longer traveling lengths are correlated with an increase in the cascade interactions.

Phys. Rev. C **106**, 045202 – Published 13 October 2022

Impact parameter as a function of grey tracks



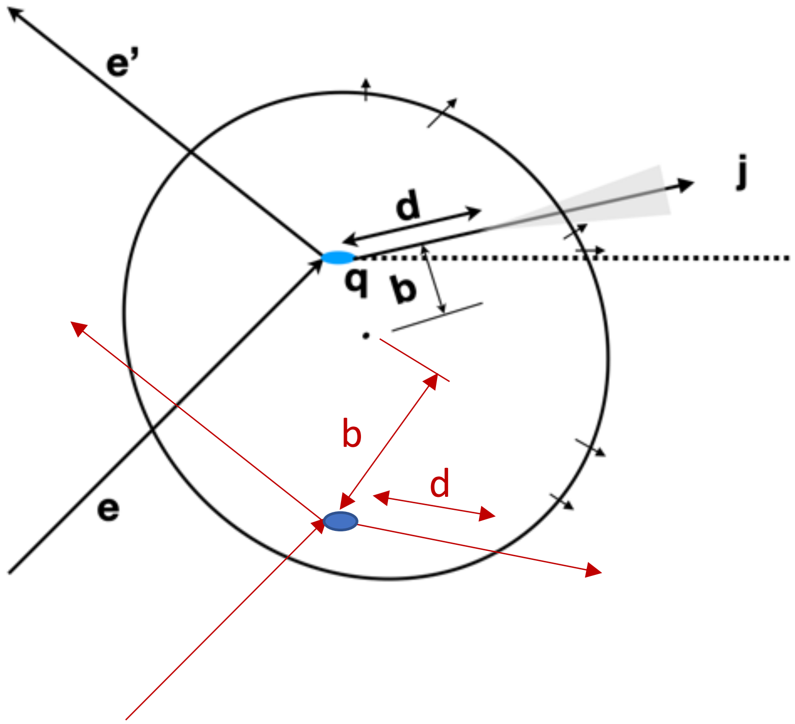
- Good correlation between the impact parameter and grey tracks.
- Most of the events show:
  - Higher values of b are correlated to small values of grey tracks, meaning that cascade interactions get smaller farther from **the center of the nucleus**.

  - Small values of b correlate to greater values of grey tracks, which means **that cascade interactions become important closest to the center of the nucleus**.

Preliminary results

- In – medium path length is proportional to the number of grey tracks
- The impact parameter is inversely proportional to the number of grey tracks

Bigger values of the in-medium path length are correlated to small values of b, and viceversa.



SUMMARY

- We have improved PyQM, the energy loss module of BeAGLE.
- Grey tracks production is **dominated** by interactions with in-medium hadrons in the **backward region**.
- Using a comparison of BeAGLE simulation to E665 grey track data, we find that grey tracks are **unaffected** by the **parton energy loss modifications** for the forward production.
- We see a strong correlation between the **number of grey tracks,** the **in-medium path length and the impact parameter . Grey tracks could be** an important quantity for modeling and interpret geometry-tagged data.
- These results lay an **important foundation** for future spectator tagging studies both with CLAS12 at Jefferson Lab, and at the Electron-Ion Collider.

Agencia
Nacional de
Investigación
y Desarrollo
Ministerio de Ciencia,
Tecnología, Conocimiento
e Innovación
Gobierno de Chile

EX UMBRA IN SOLEM

PONTIFICIA
UNIVERSIDAD
CATÓLICA DE
VALPARAÍSO

MILLENNIUM INSTITUTE
FOR **SUBATOMIC PHYSICS**
AT HIGH-ENERGY FRONTIER
SAPHIR

Thank you for your attention!

This work was supported in part by:

- National Agency for Research and Development(ANID)/DOCTORADO BECA NACIONAL, Chile/2017-21171926 (2017-2019),
- PUCV DEA 1-2020 (6 months 2020),
- UTFSM DGIIP 2-2020-2021,
- ANID-Millennium Science Initiative Program - ICN2019_044 (2021-2022)