# Hadronization studies in heavy ion collisions

Raghav Kunnawalkam Elayavalli (they/them)
Vanderbilt University

Measurements sensitive to Hadronization in Data

Hadronization implementation in models

# Measurements sensitive to Hadronization in Data

LHC

RHIC

JLab

GSI

AA, pA, eA

# Lets start with heavy flavor particles

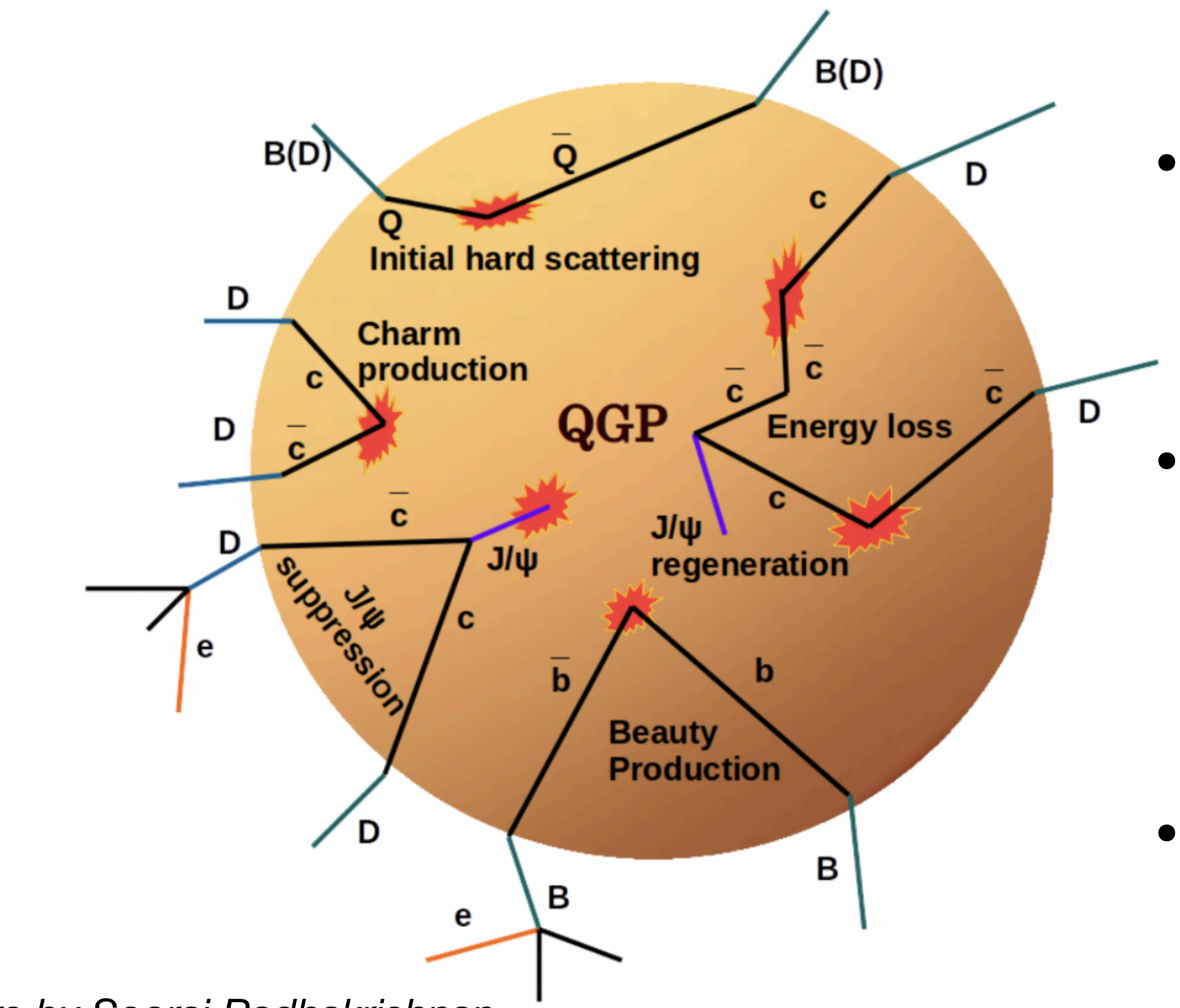
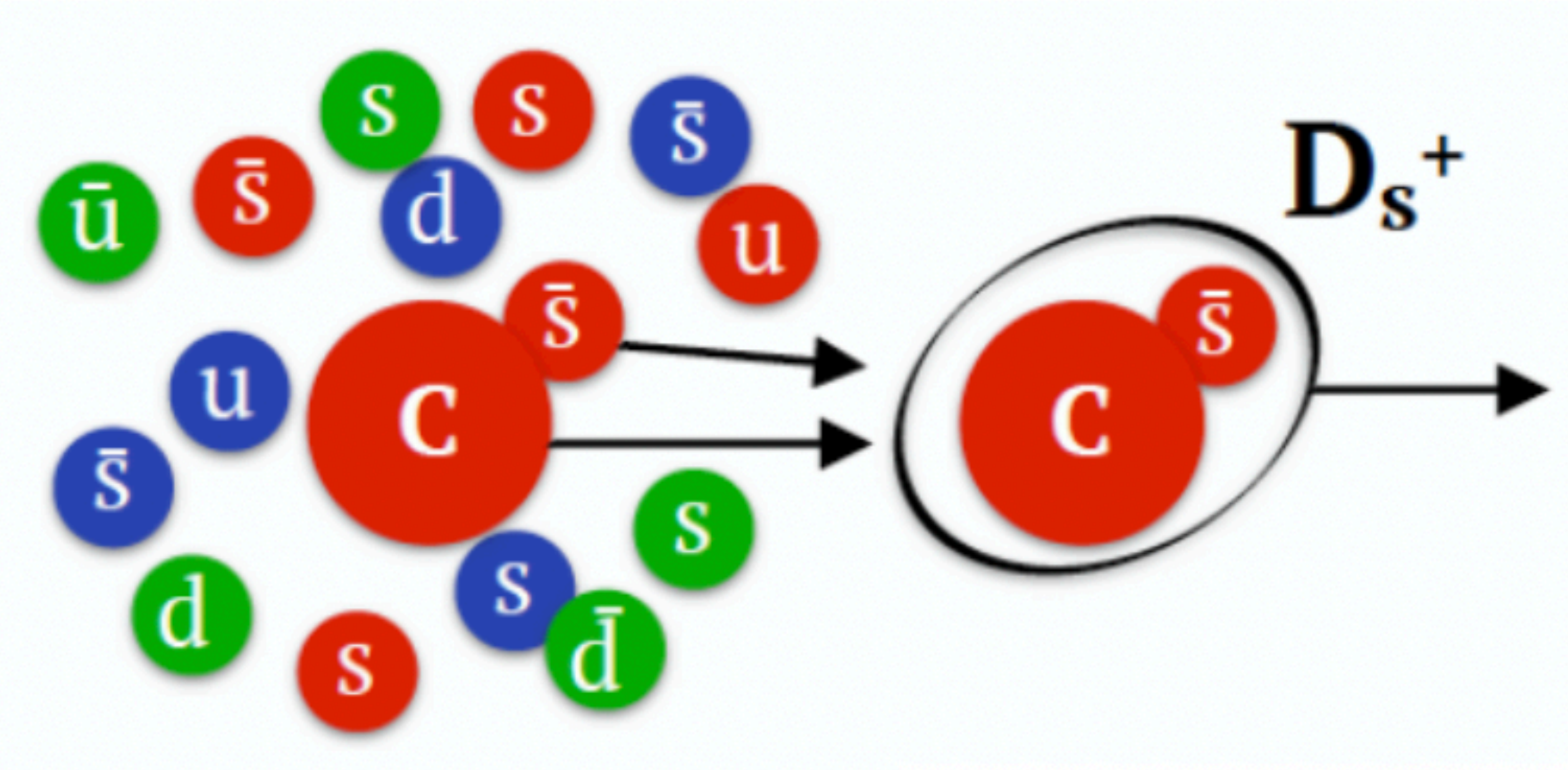



*Figure by Sooraj Radhakrishnan*

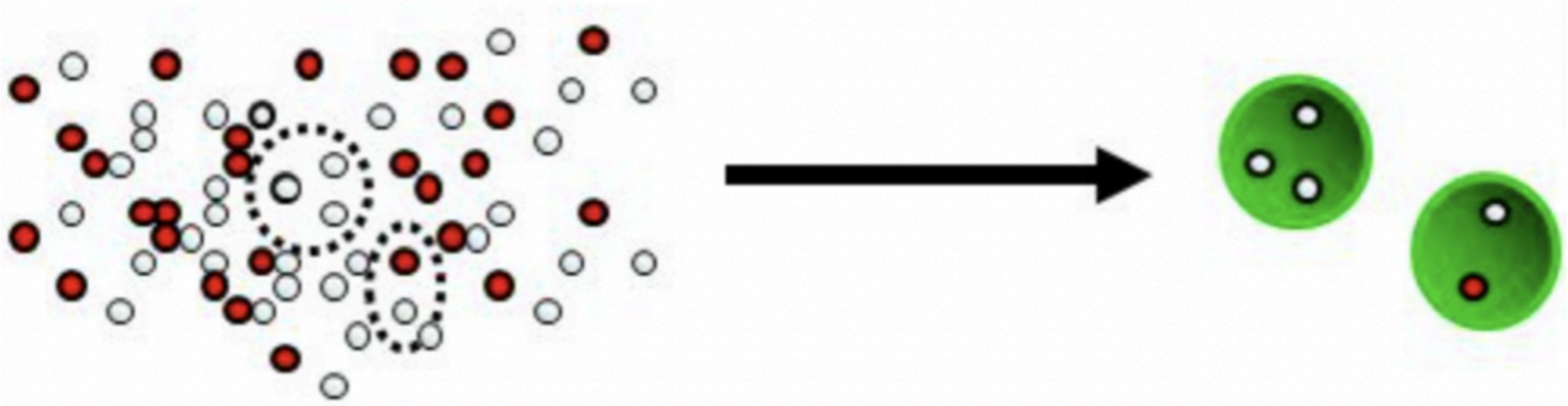
- Given the type of the heavy flavor quark, one can potentially study mass dependent energy loss
- Direct study on the resulting particle distribution after hadronization mechanism - regeneration and/or coalescence
- Mass dependence of hadron production and flow!

# Baryon to Meson ratio!

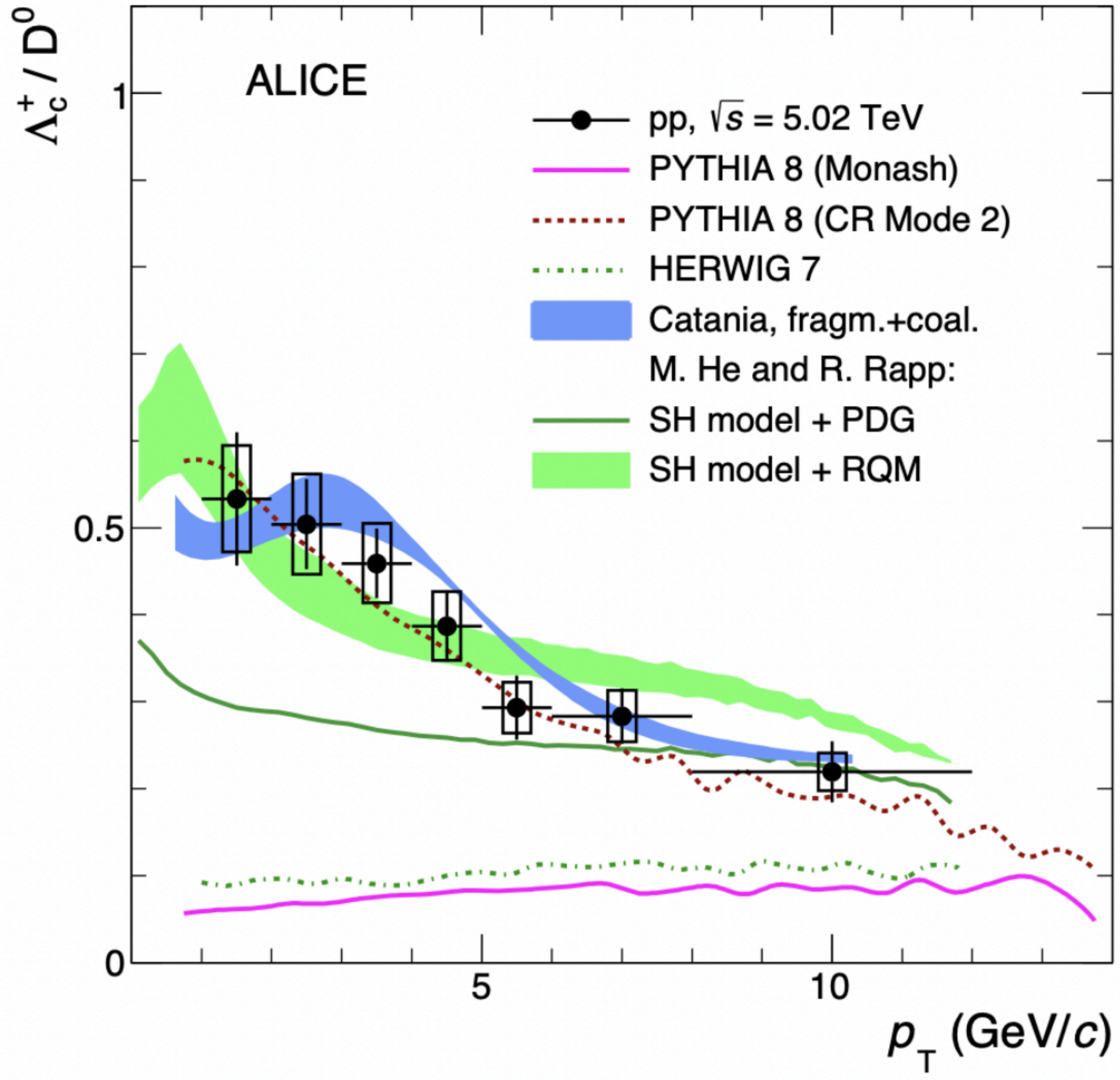



- What drives the production of a three-quark state versus a quark-antiquark state
- How is this production dependent on the environment its in?

Cartoon by Rainer Fries



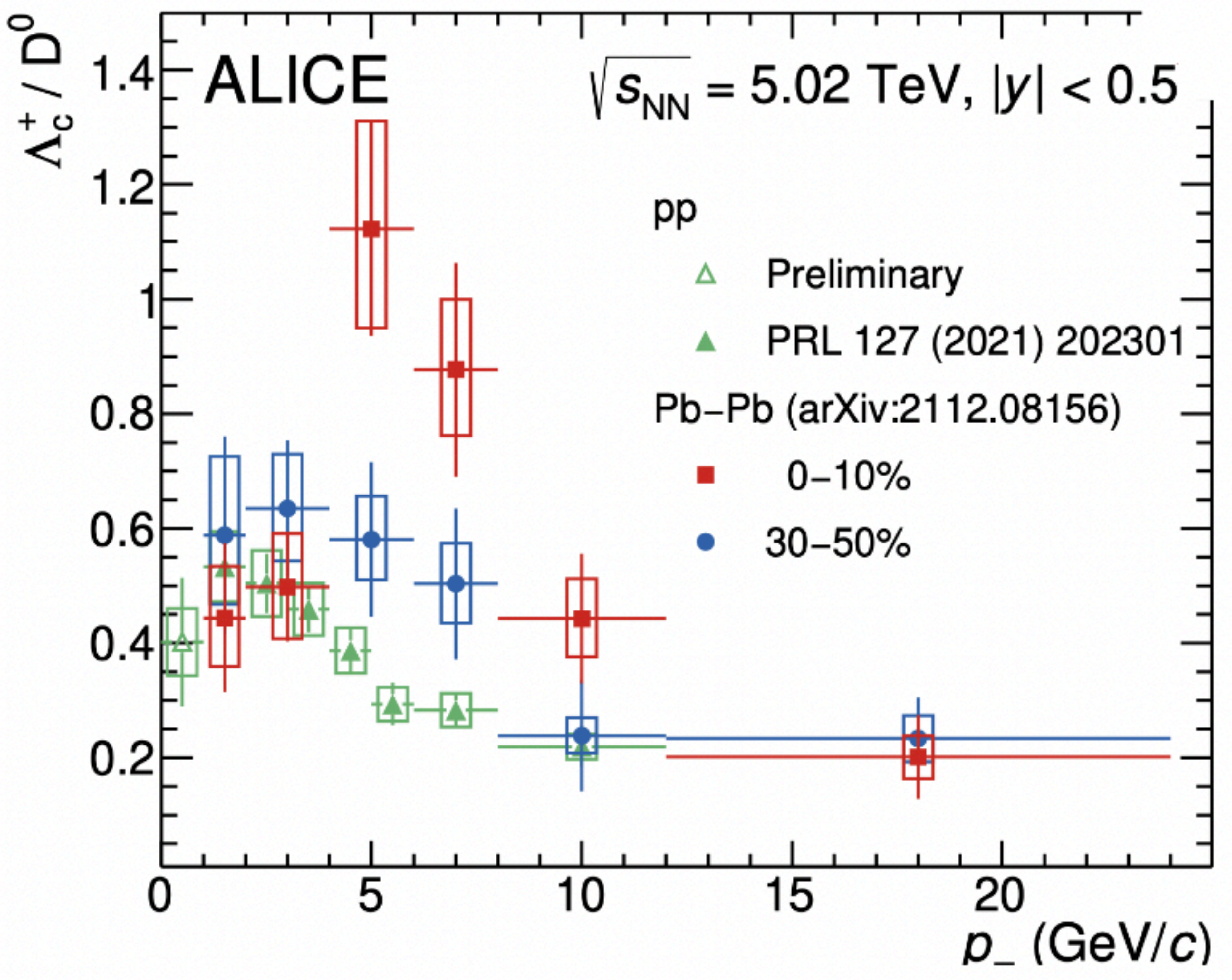
# $\Lambda_c/D^0$ - the puzzle!



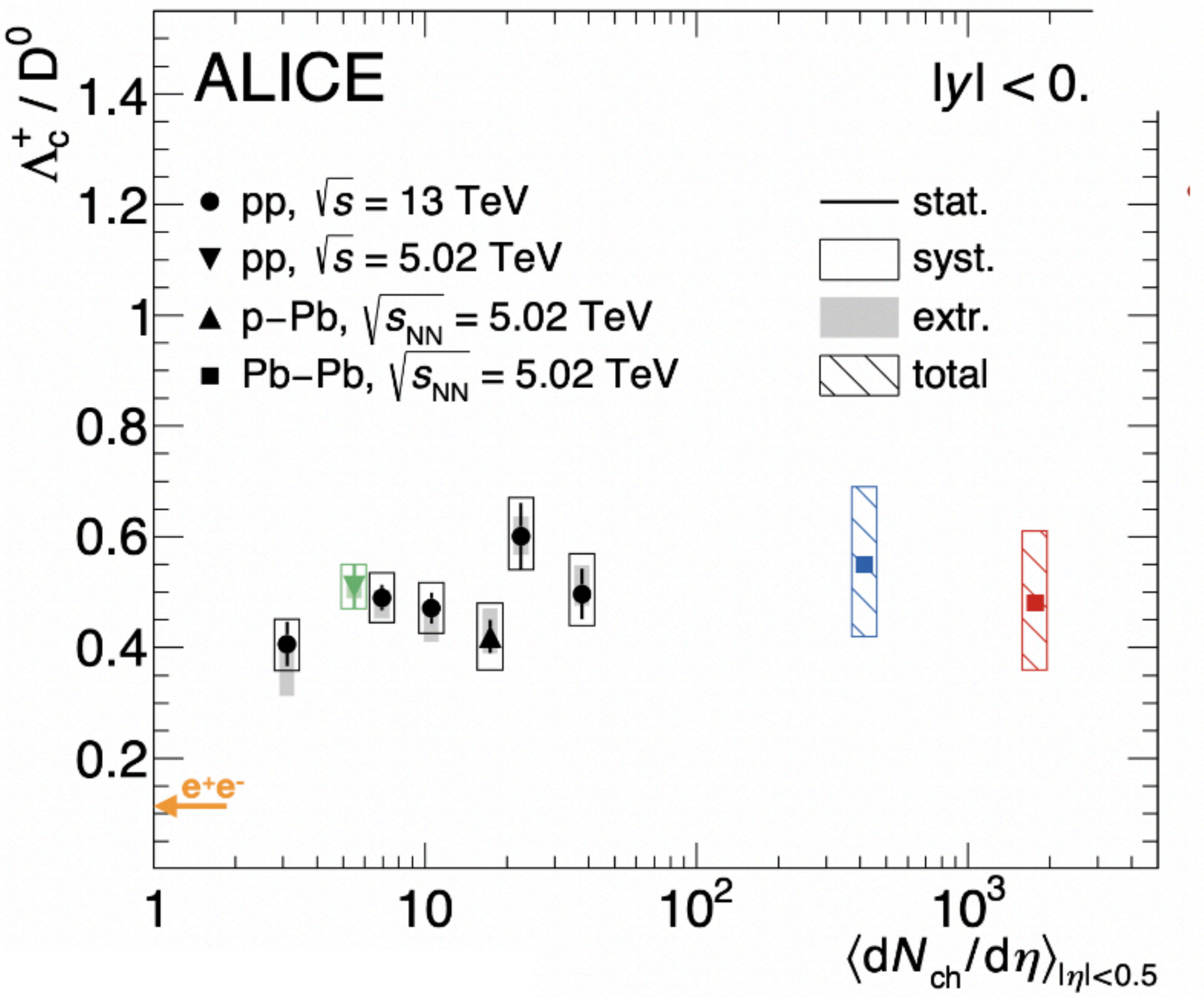

*Phys. Rev. Lett. 127 (2021) 202301*

- Breaking of universality of charm fragmentation fractions
- Strong enhancement of $\Lambda_c$ production in p+p and p+Pb collisions for $p_T < 8$ GeV/c compared to fragmentation ratios measured at high $p_T$
- PYTHIA with color reconnection and thermal model with feed down from excited charm states describe data
- Multiplicity dependence, QGP impact, rapidity, collision energy dependence?

# $\Lambda_c/D^0$ - the puzzle continues!

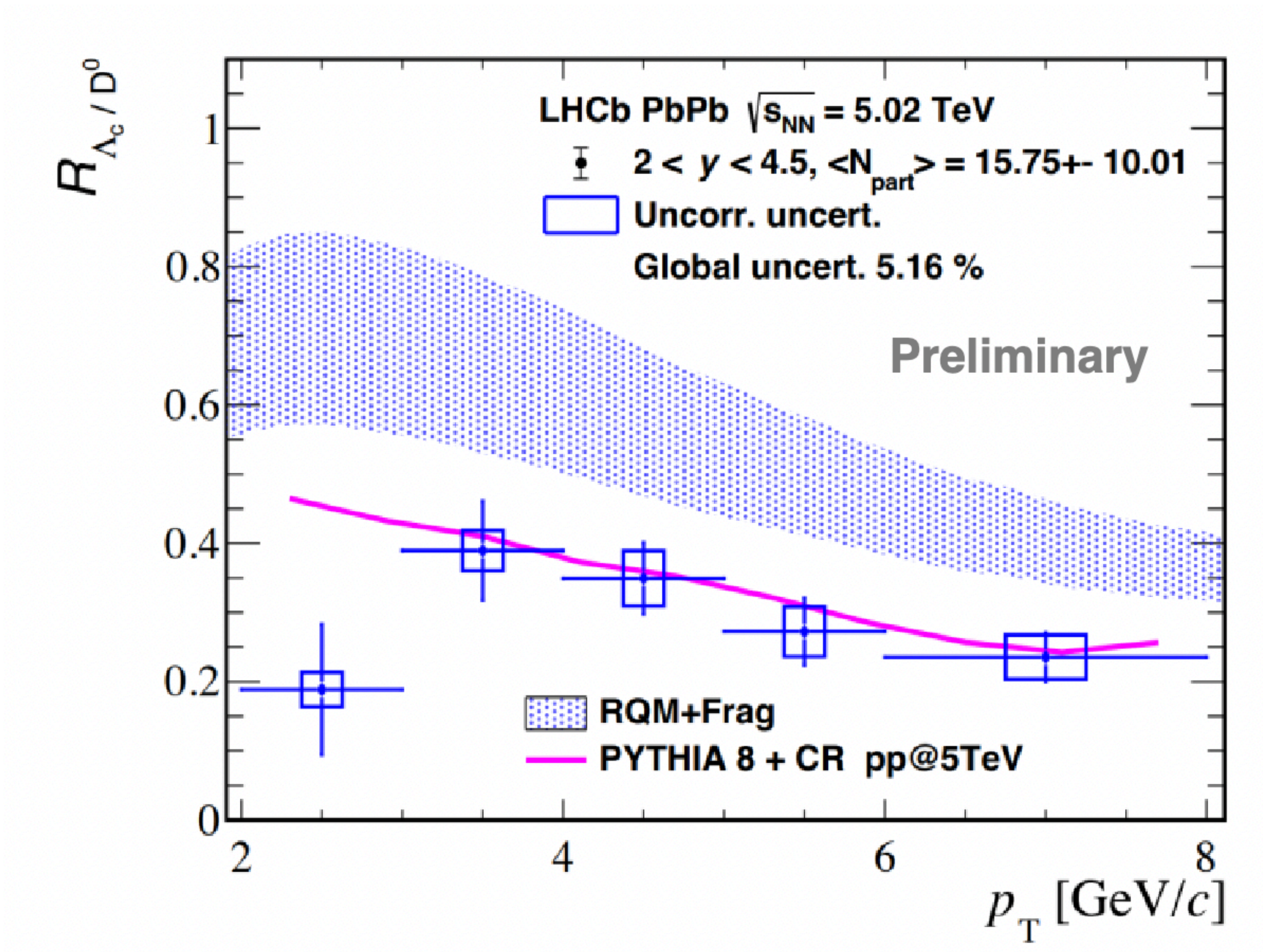



- Scanning across different systems - centrality and size dependence evident vs $p_T$
- Size dependence in integrated yield not as evident



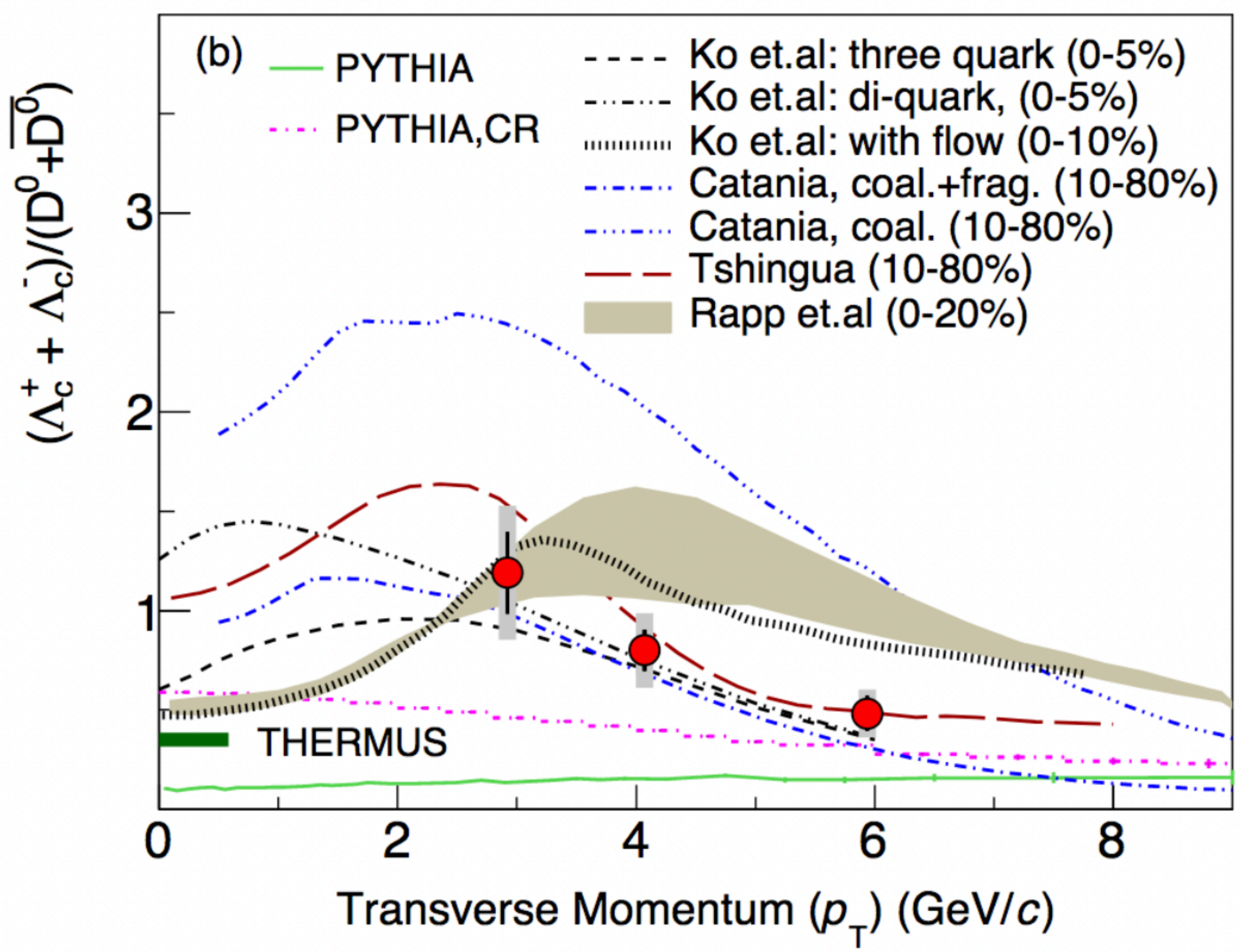

arXiv:2112.08156

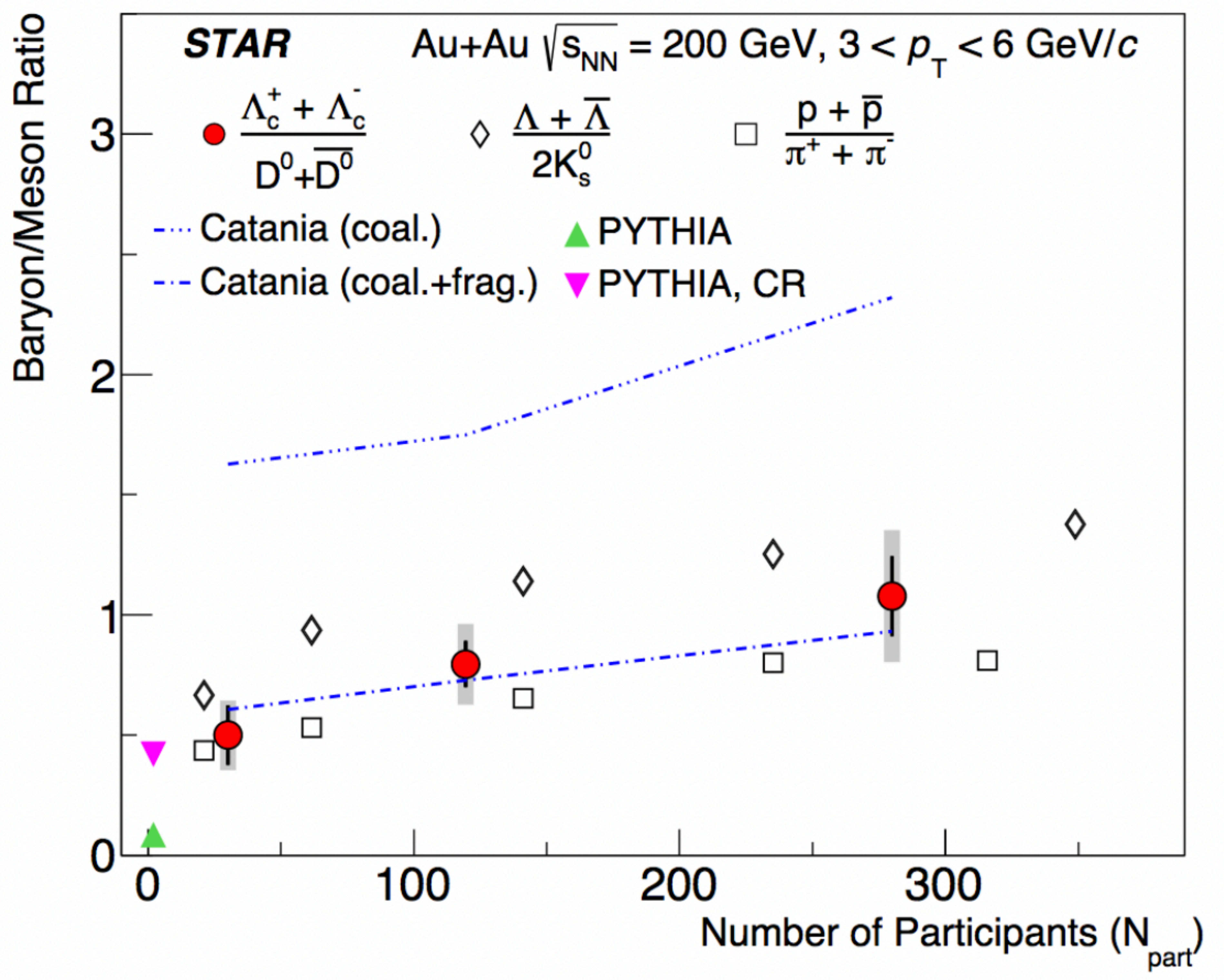
# Does the yield ratio change at larger rapidity?




- Statistical models are unable to predict the overall shape the distribution
- PYTHIA 8 with its varying tunes of color reconnection *in pp* describes the trend in PbPb data!
- Potential cancellation of effects and accidental comparison

# At RHIC?



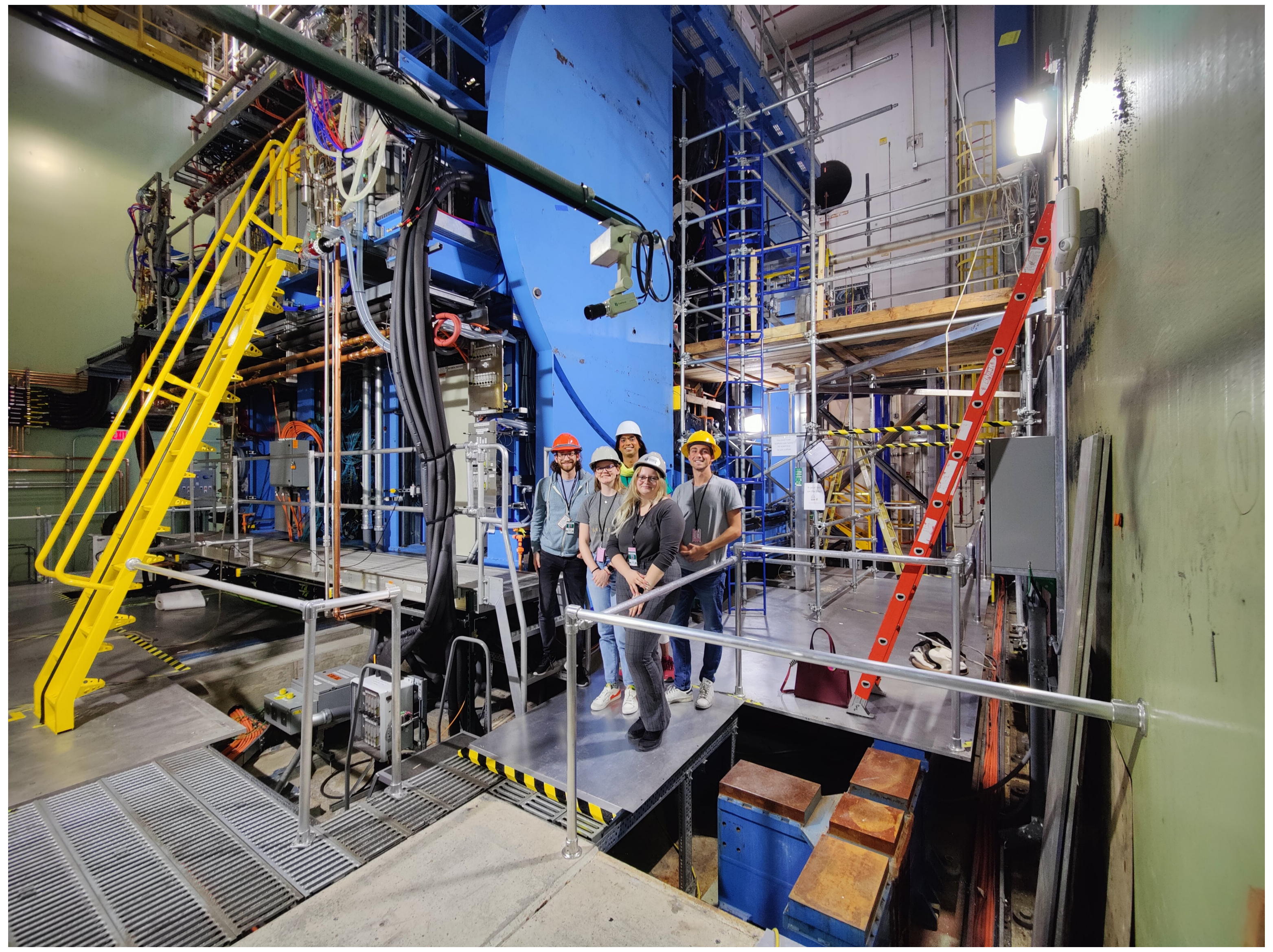

*Phys. Rev. Lett. 124, 172301 (2020)*

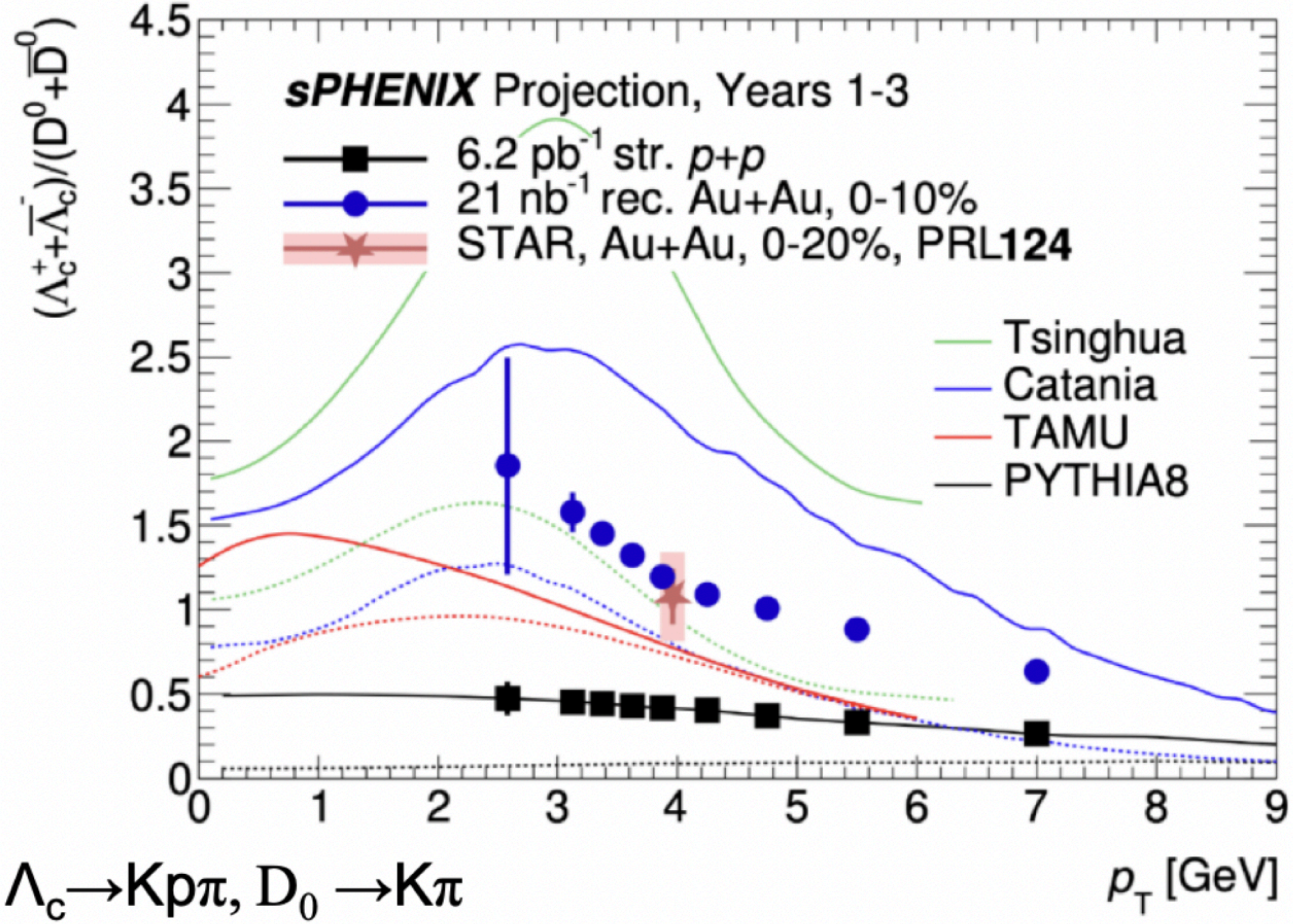
- Strong enhancement relative to PYTHIA in Au+Au collisions at RHIC
- Similar trend as seen for B/M ratio enhancement for light flavor hadrons
- Consistent with coalescence model calculations

*Slide by Sooraj Radhakrishnan*

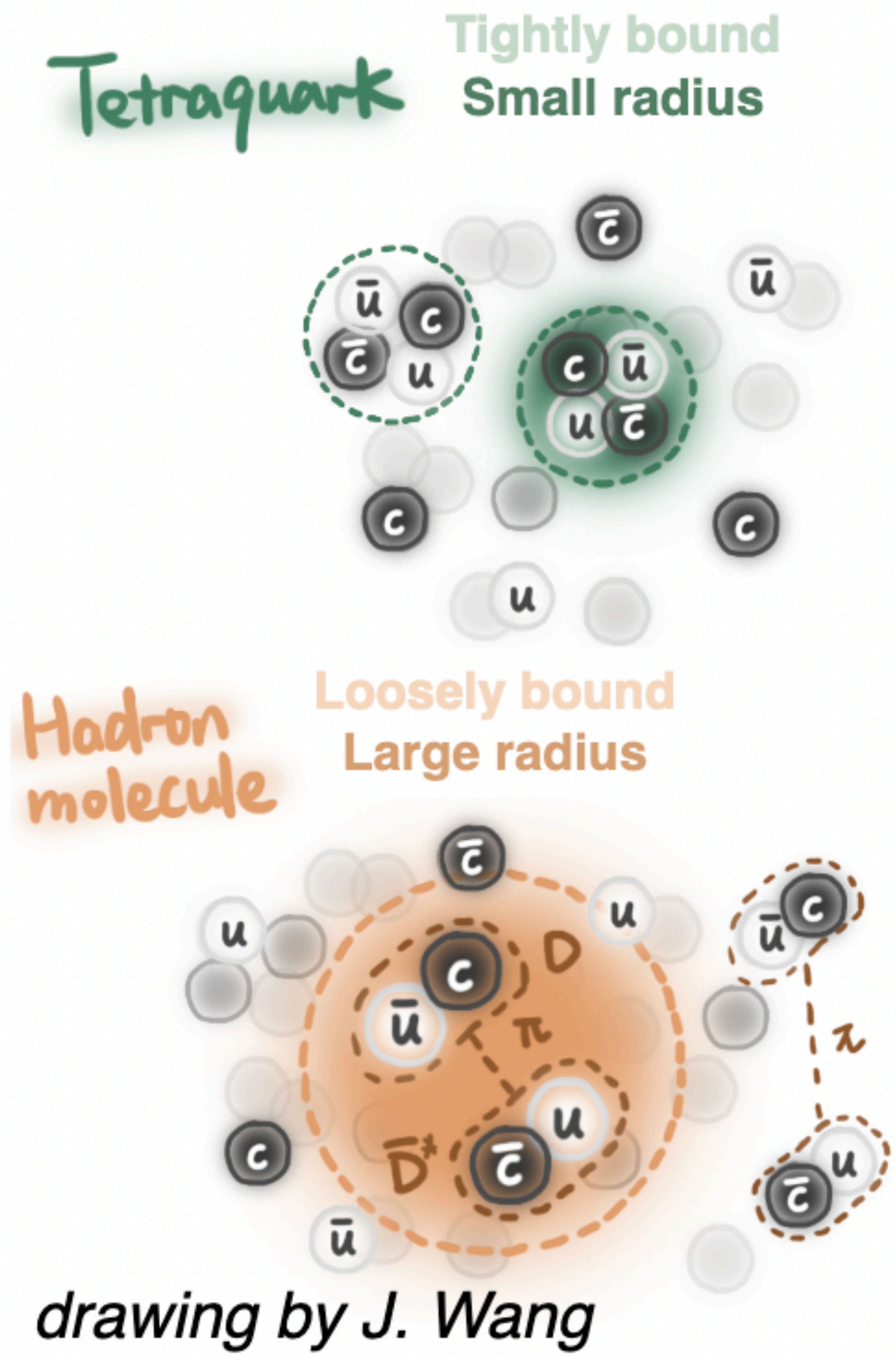
# sPHENIX's contribution

- Commissioning officially started this morning!

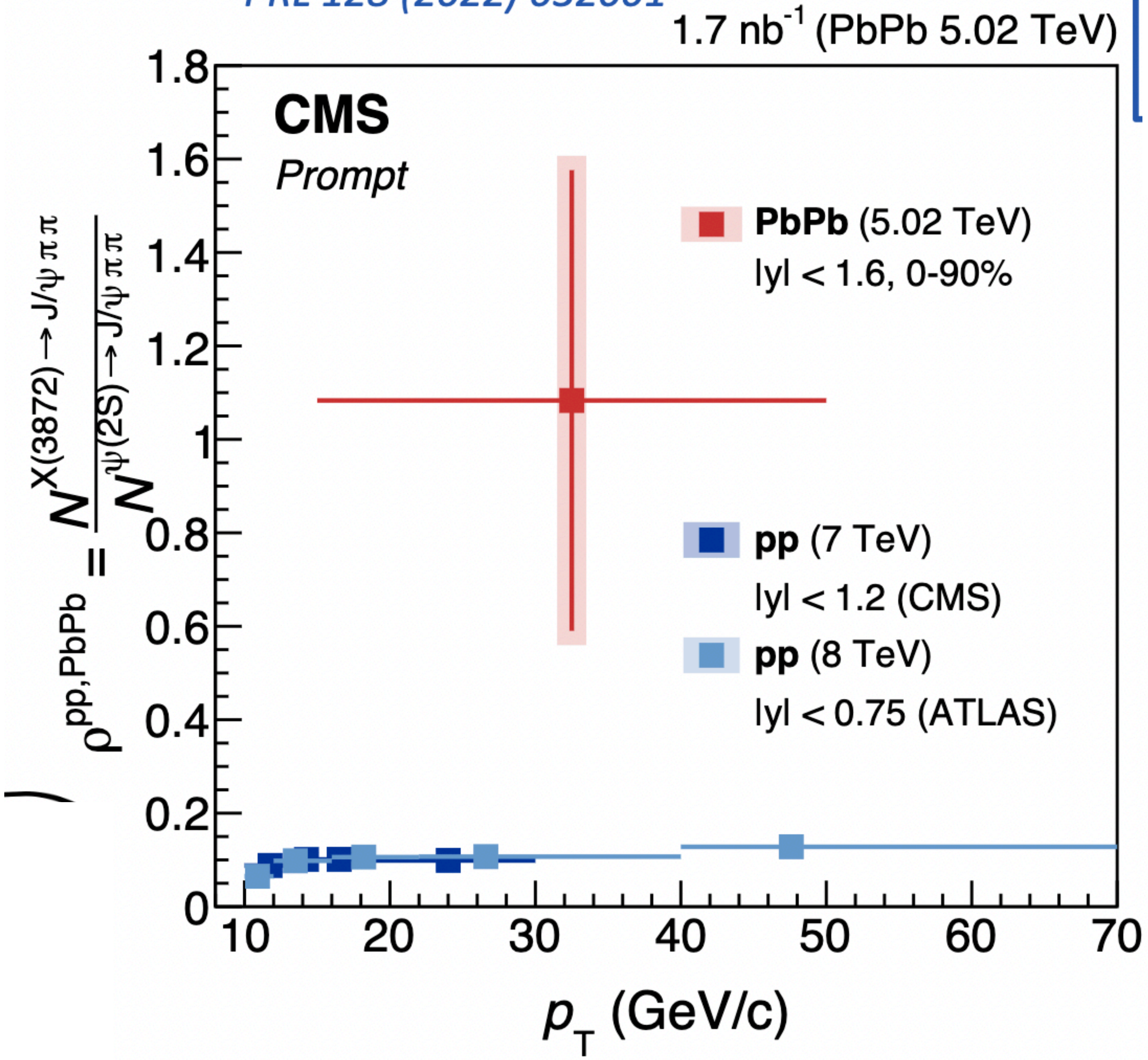





$\Lambda_c \rightarrow Kp\pi$, $D_0 \rightarrow K\pi$



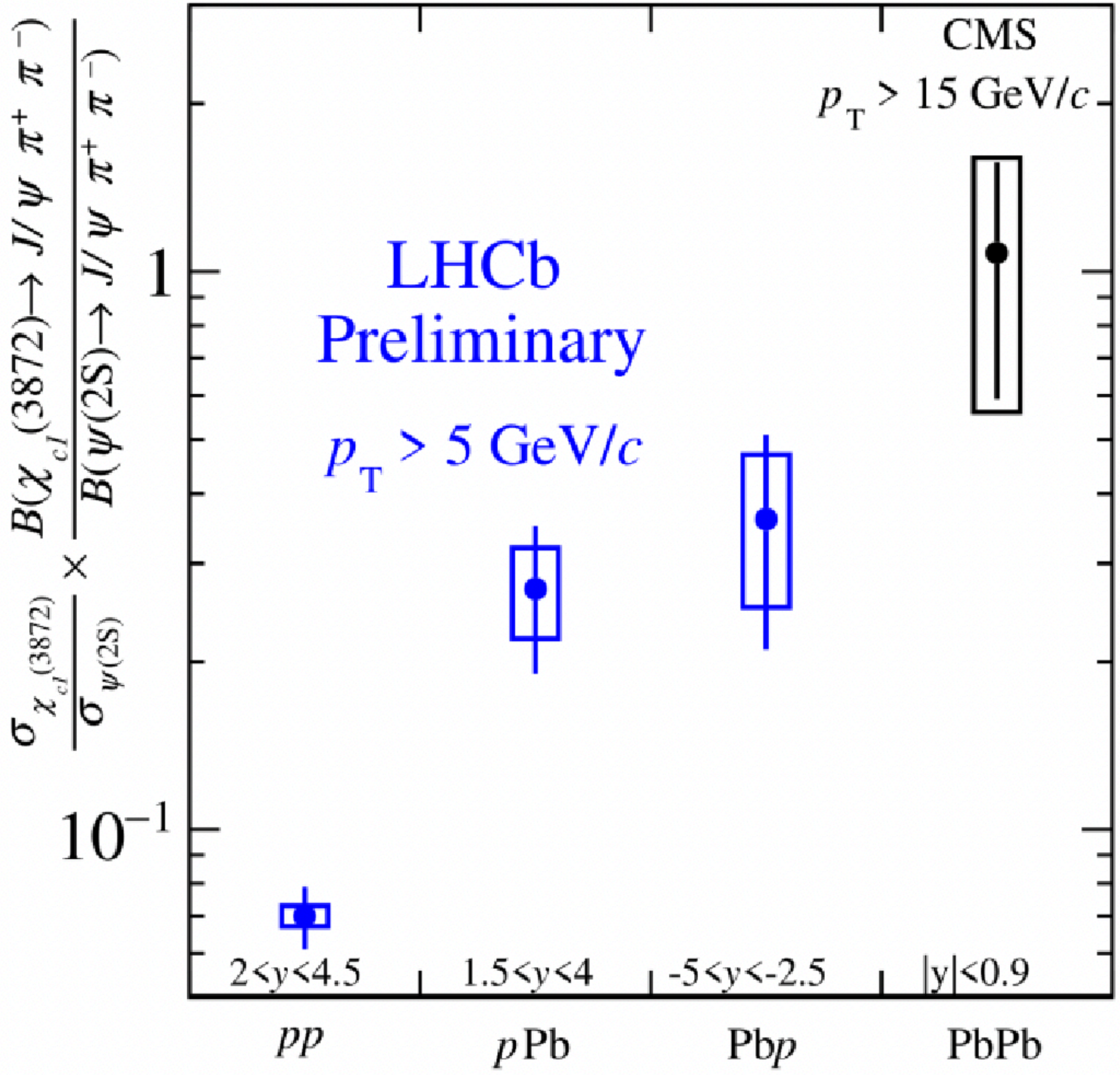

PRL 128 (2022) 032001



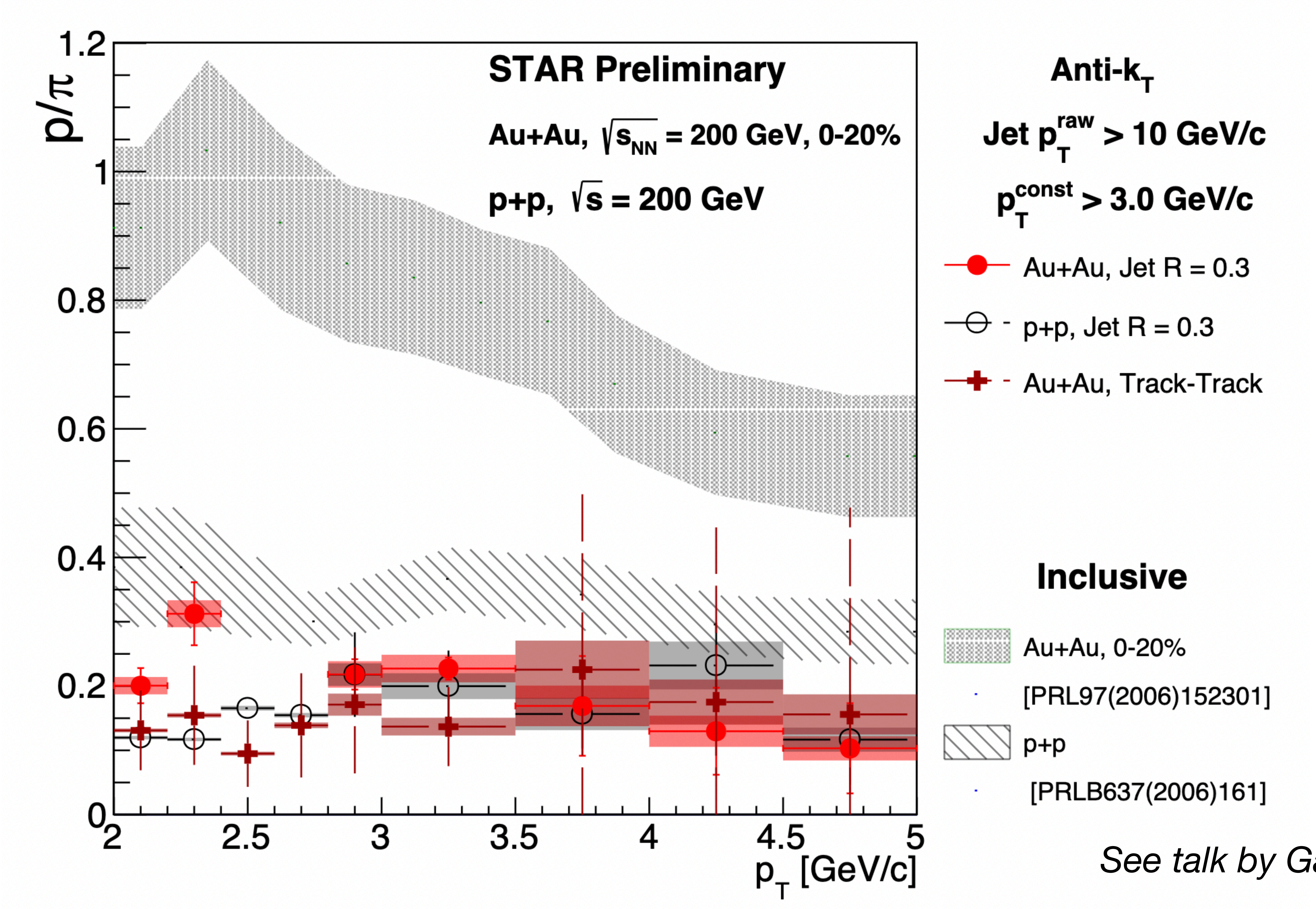
# System size dependence

- X(3872) must have a different production mechanism as compared to the $\psi$(2S)
- Potentially we produce less of $\psi$(2S) as compared to X in heavy ion collisions
- How does this compare with the production of other meson states?

[LHCb-CONF-2022-001]



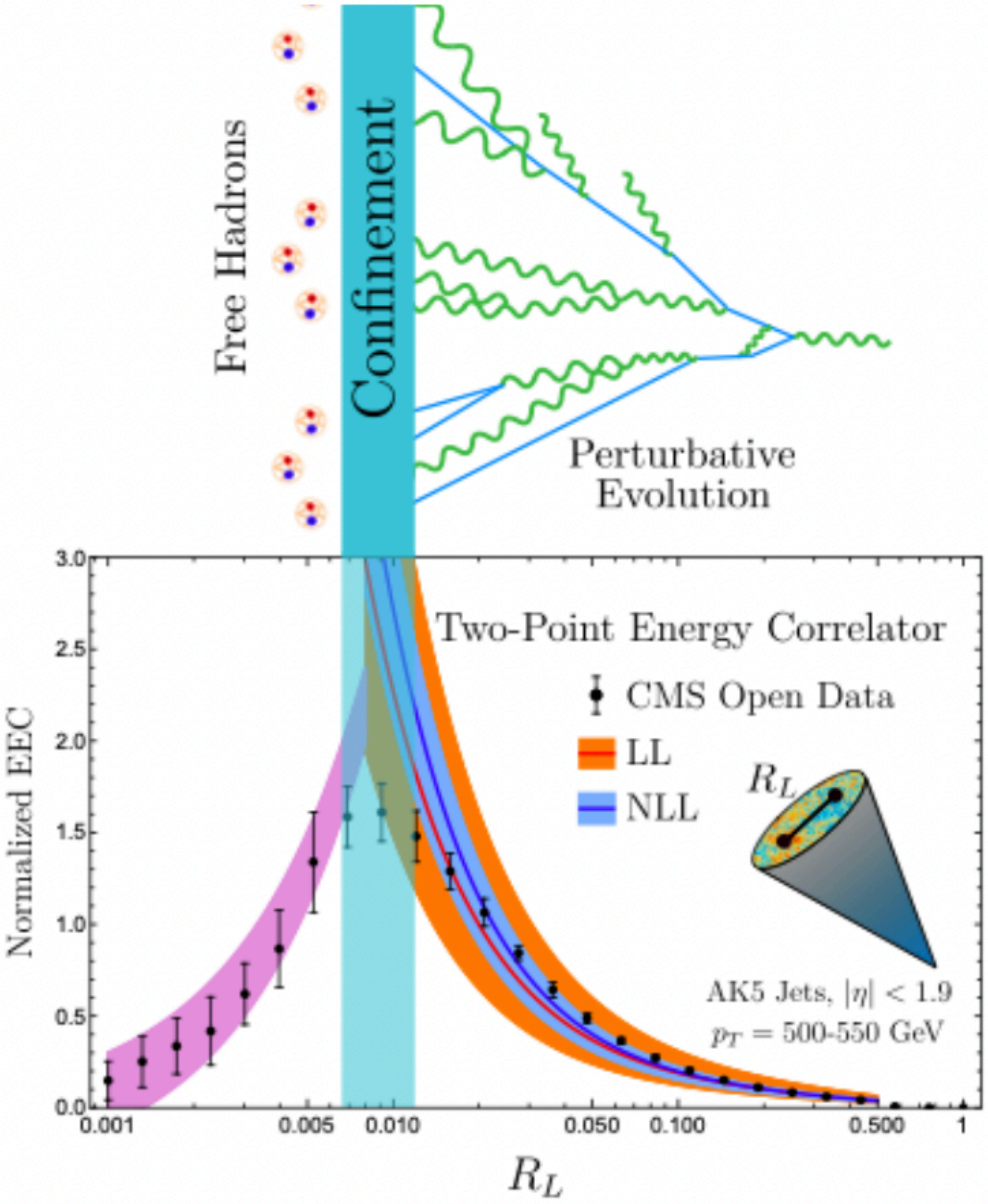
# Baryon to Meson in jets!



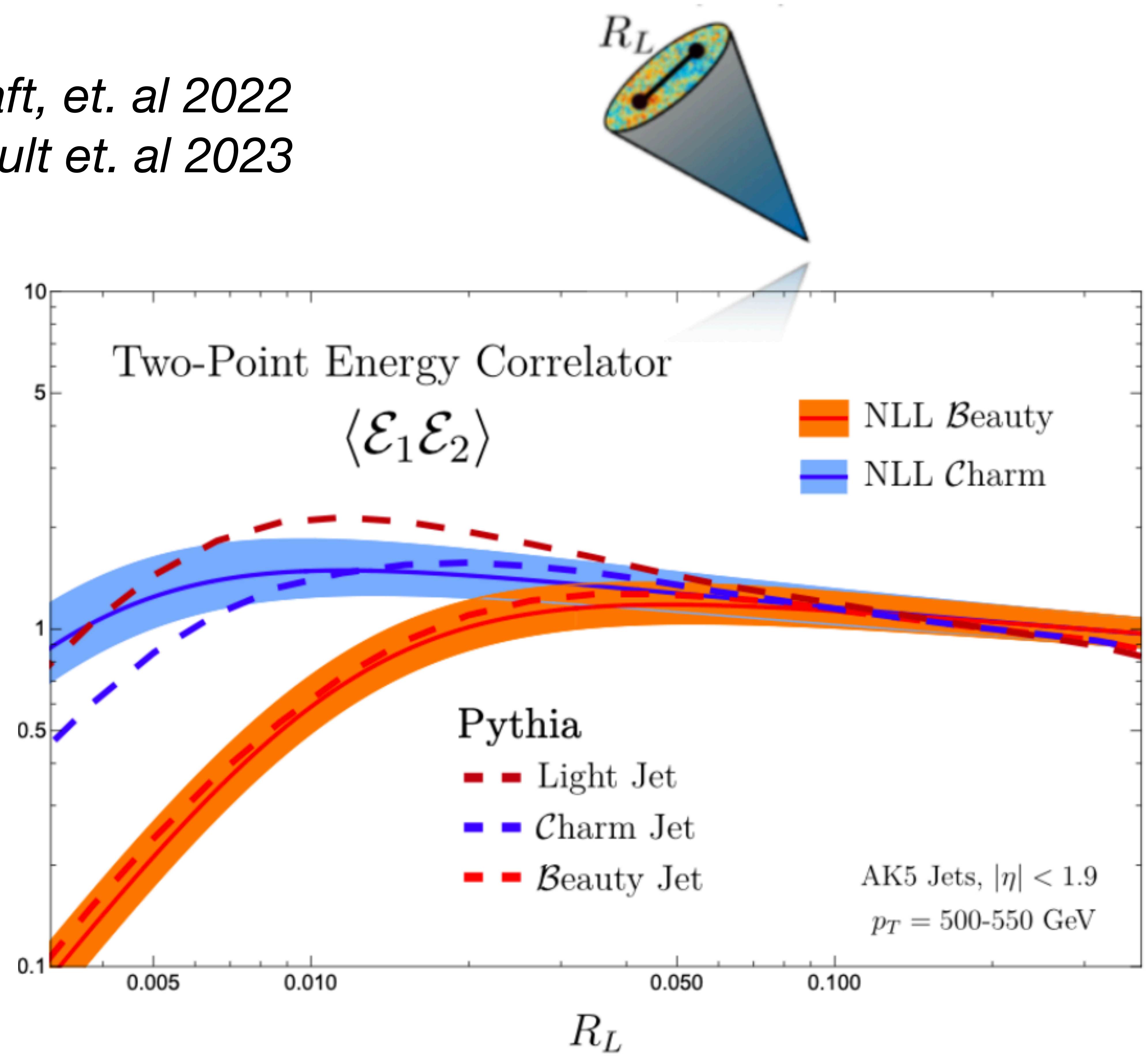

- Once you identify a particle - how often do you produce them in the bulk versus in/around the jet
- Jets start with a higher energy scale and thus particles produced in jets *might* occur 'after' other soft-uncorrelated particles produced

*See talk by Gabriel Dale-Gau, HP 2023*

# Energy-Energy Correlators

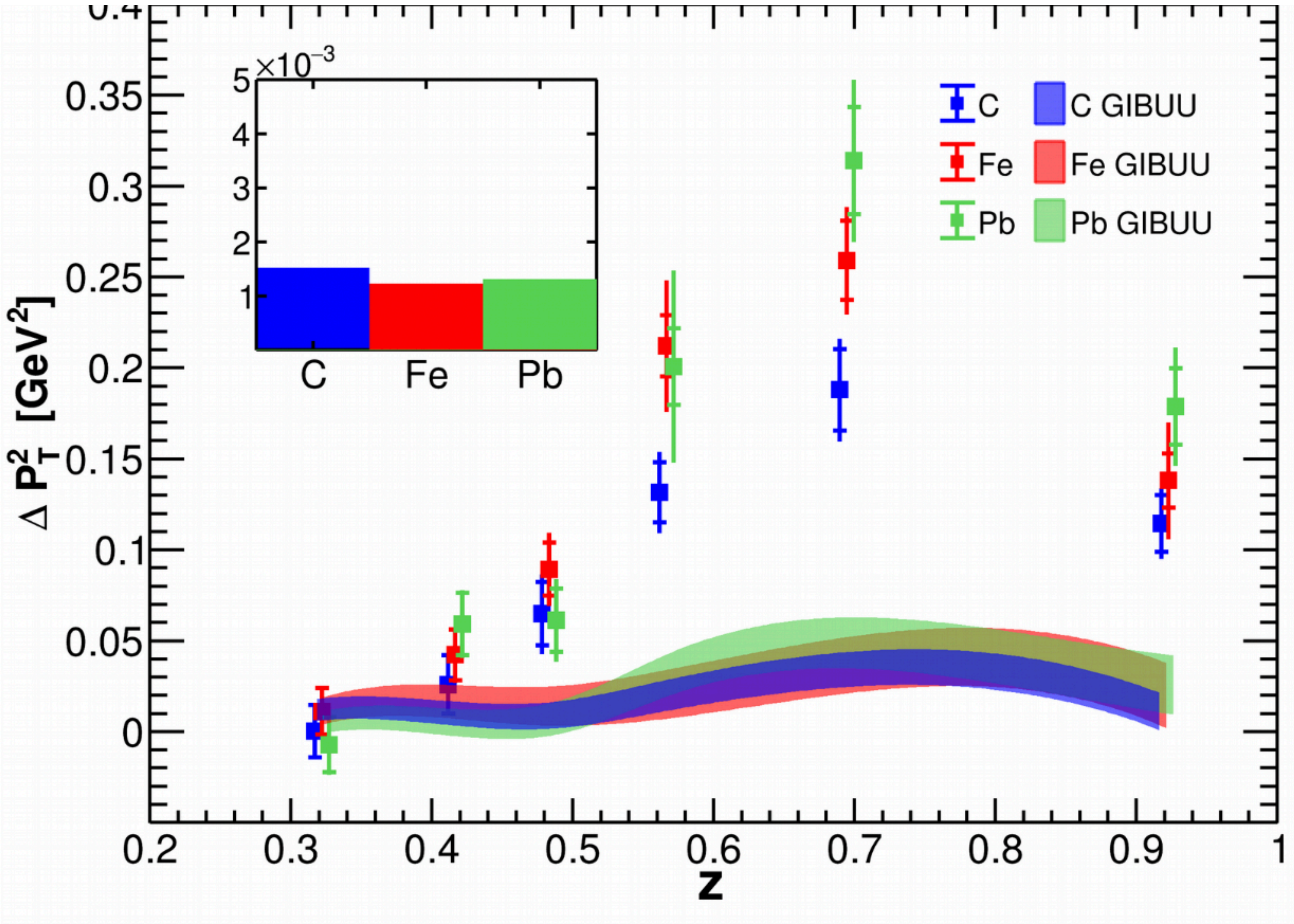


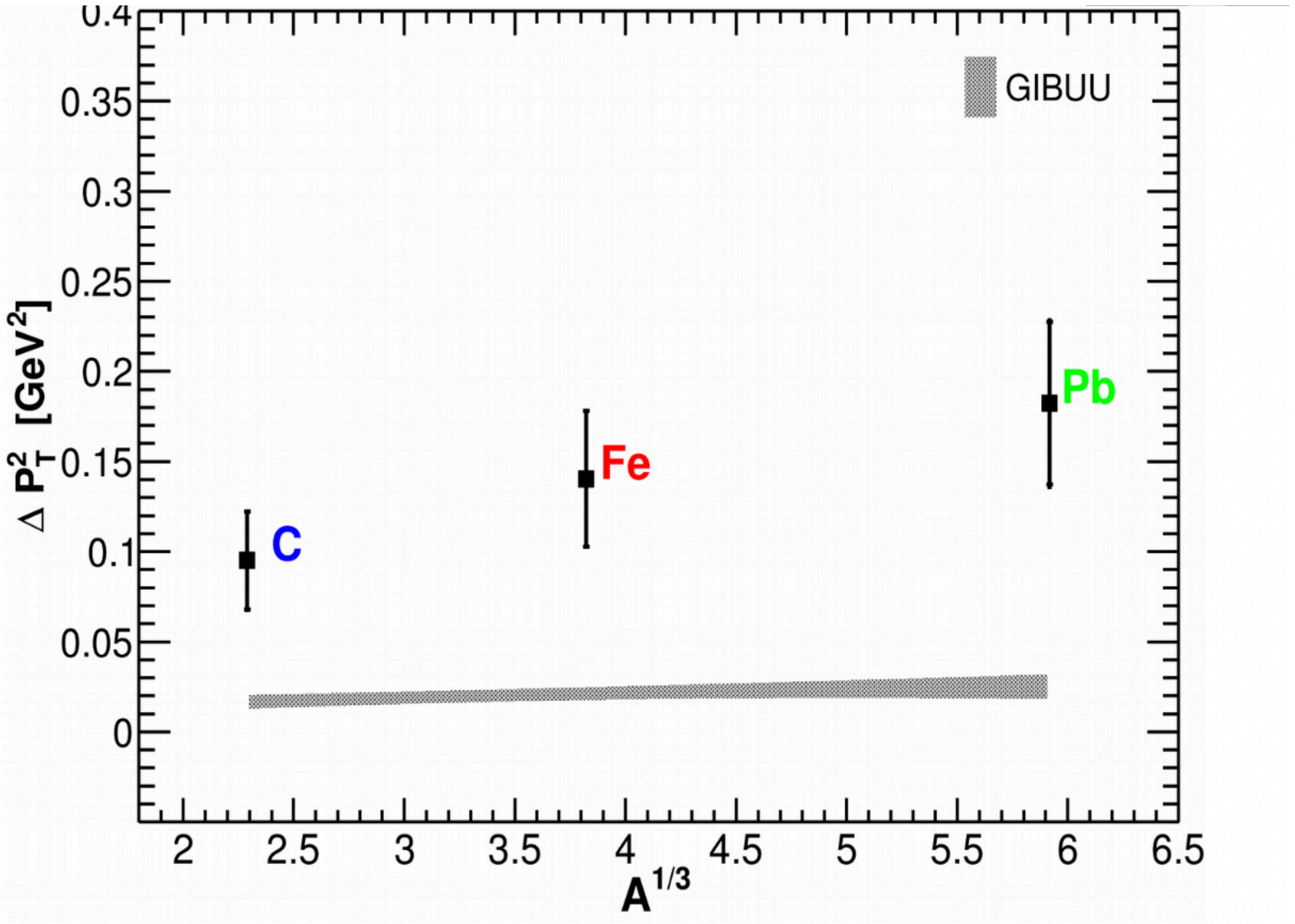

*Craft, et. al 2022*
*Moult et. al 2023*




- Dead-cone effect shows up in the correlation of hadrons within jets

# Current fragmentation @ CLAS6




Phys. Rev. Lett. **130**, 142301 (2023)

*See talk by Laamia El-Fassi, GHP 2023*

- Measured $p_T$ broadening increases with z and A;
- Trend favors $A^{1/3}$ dependence $\Longrightarrow$ Dominance of partonic stage within nuclei;

# Hadronization implementation in models

Lund

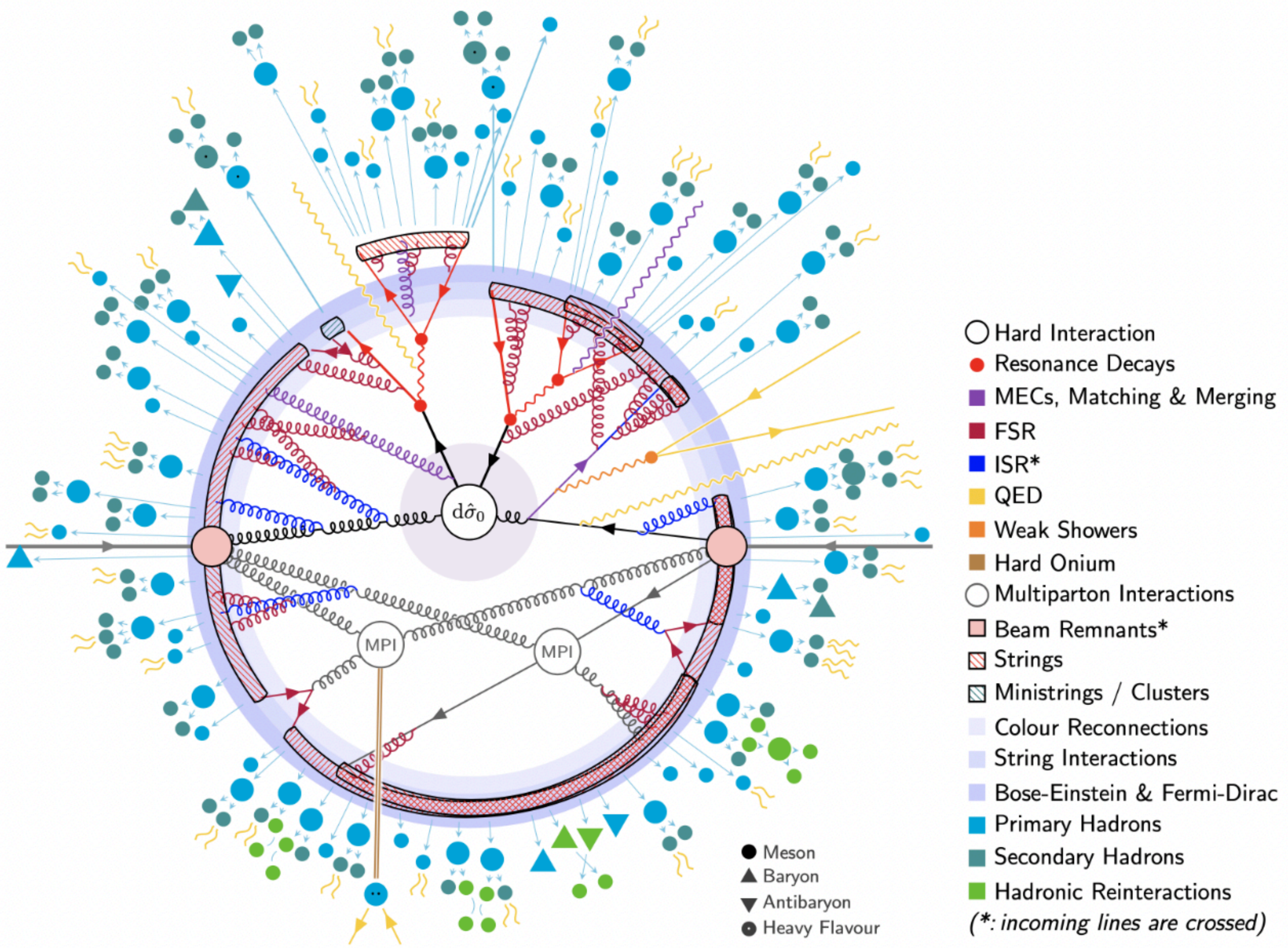
Cluster

Hybrid

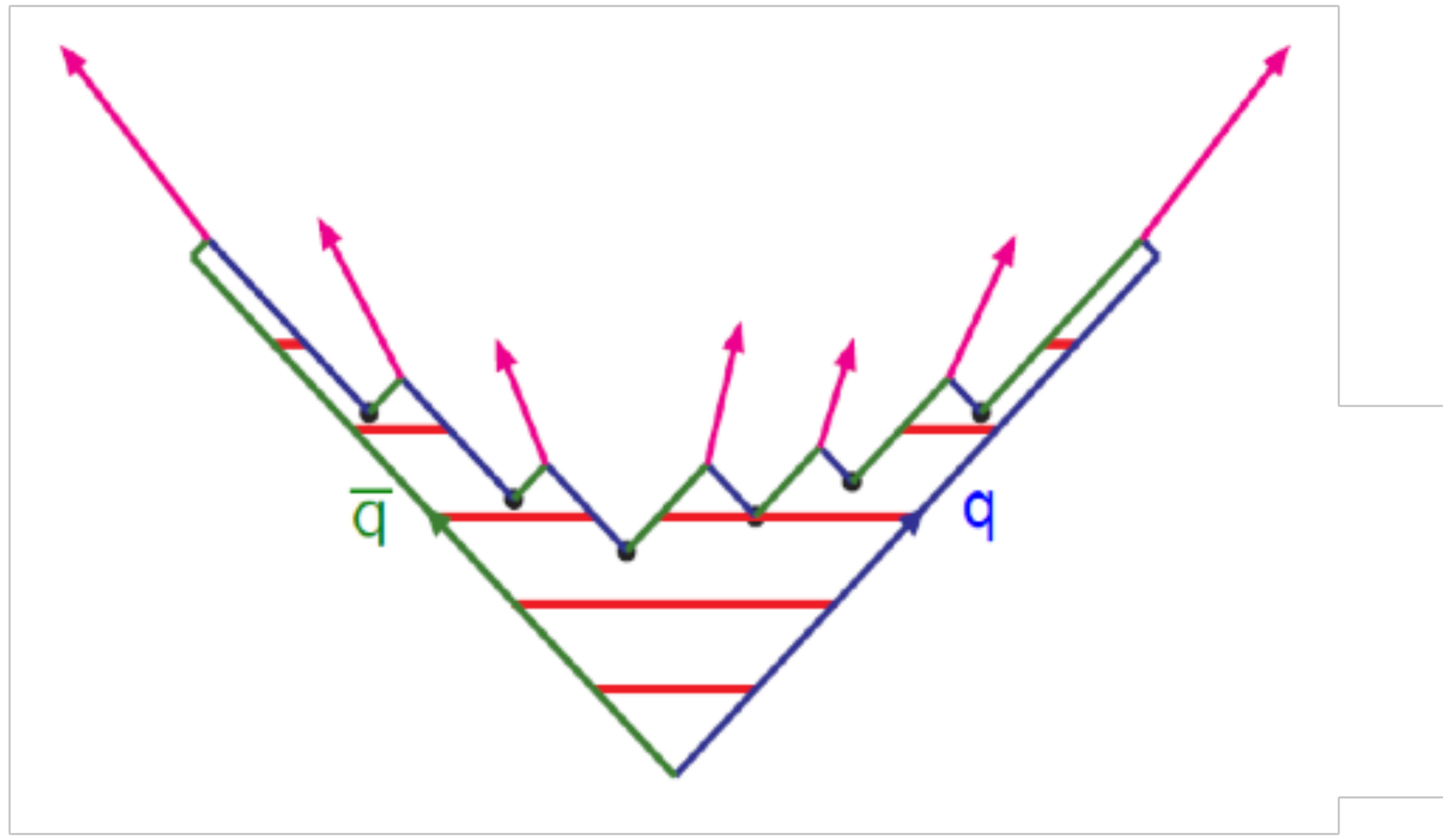
# Common assumption when we run heavy ion (jet/HF) simulations - Hadronization is unchanged compared to vacuum!

- Predominantly all initial-state and final-state interactions are deconvoluted from hadronization mechanisms
- For example - heavy ion jet quenching MC - JEWEL - assumed same hadronization mechanism as vacuum

# PYTHIA - Lund String




(figure by S. Chakraborty and P. Skands)




- One of the most commonly used models for hadronization
- Strings are attached to partons at the end of the evolution and depending on tension (and other parameters), you produce particles!

# PYTHIA - Strings/Ropes & Pushing/Shoving

✓ In transverse coordinate space ⟹ rope hadronization[1]
✓ In colour space ⟹ colour reconnection[2], colour swing[3]
✓ In 3 dimensional coordinate space ⟹ string shoving

**QGP signatures**

Final-state collective effects
Jet quenching
Strangeness enhancement

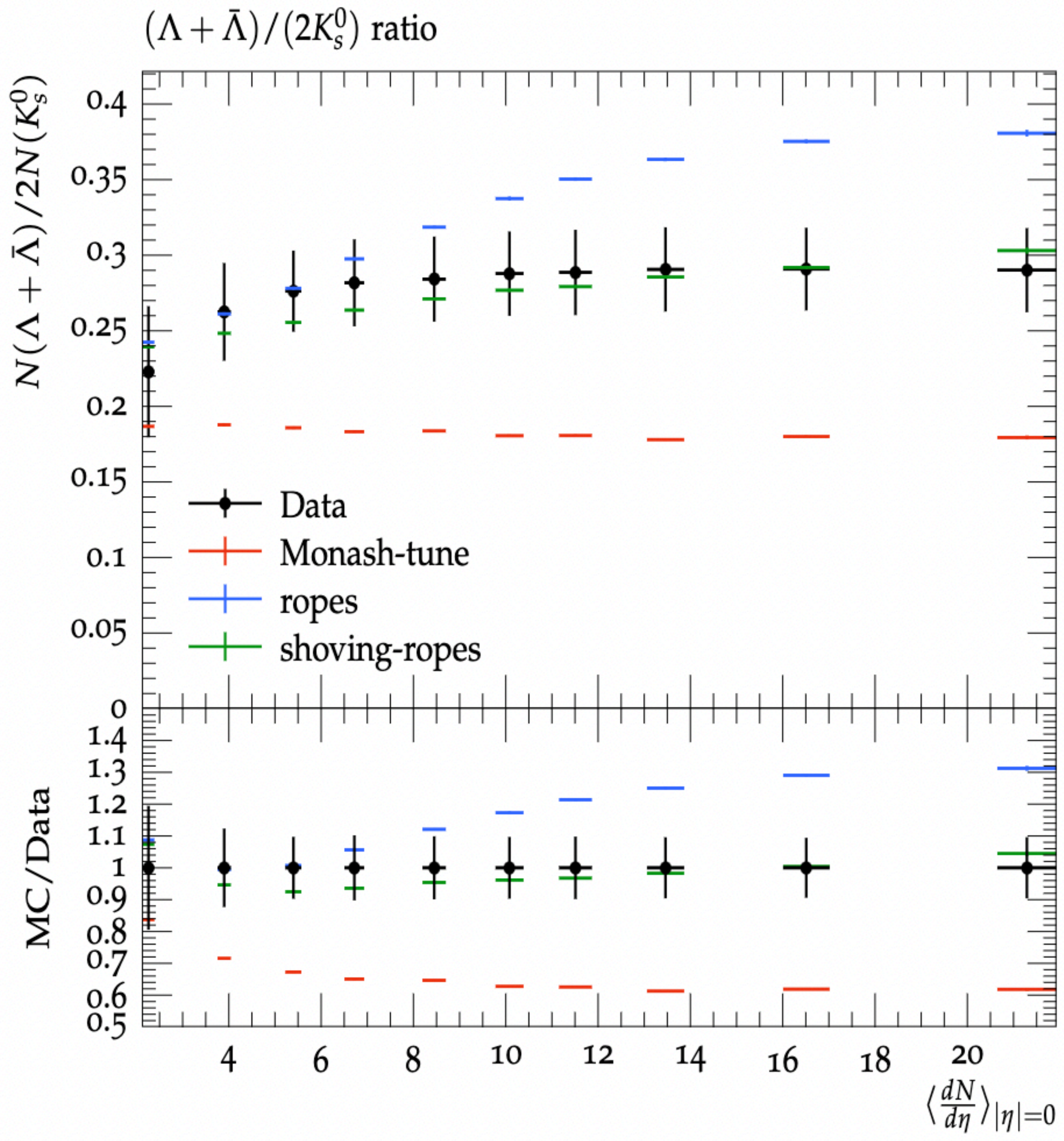
⇒

**Underlying mechanisms**

**String shoving**
Colour reconnection
**Rope hadronization**

*Slide by Smita Chakraborthy, ISMD 2022*

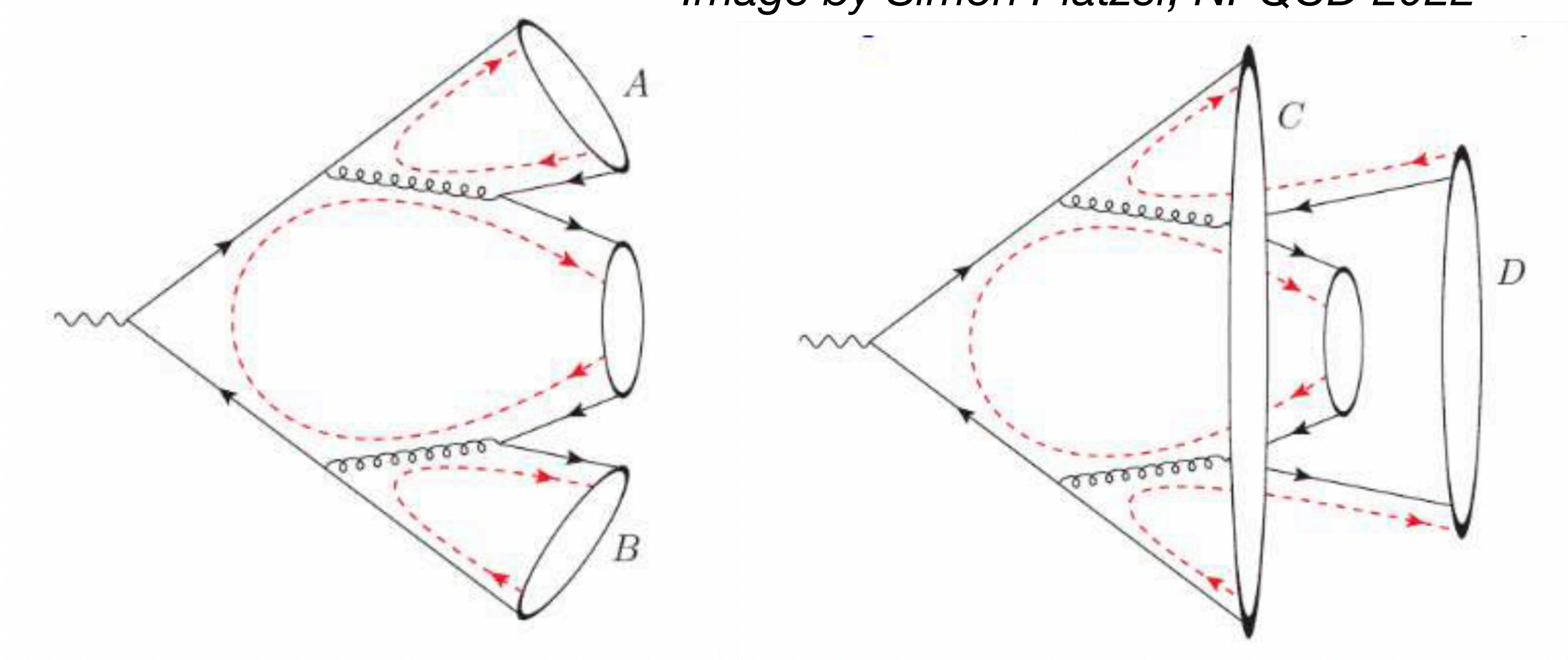
1. Bierlich C., Gustafson G., Lönnblad, L. et al., J. High Energ. Phys. 2015, 148 (2015).
2 .Christiansen, J.R., Skands, P.Z., J. High Energ. Phys. 2015, 3 (2015).
3. E. Avsar, Gustafson G., Lönnblad, L., JHEP 12 (2007) 012.

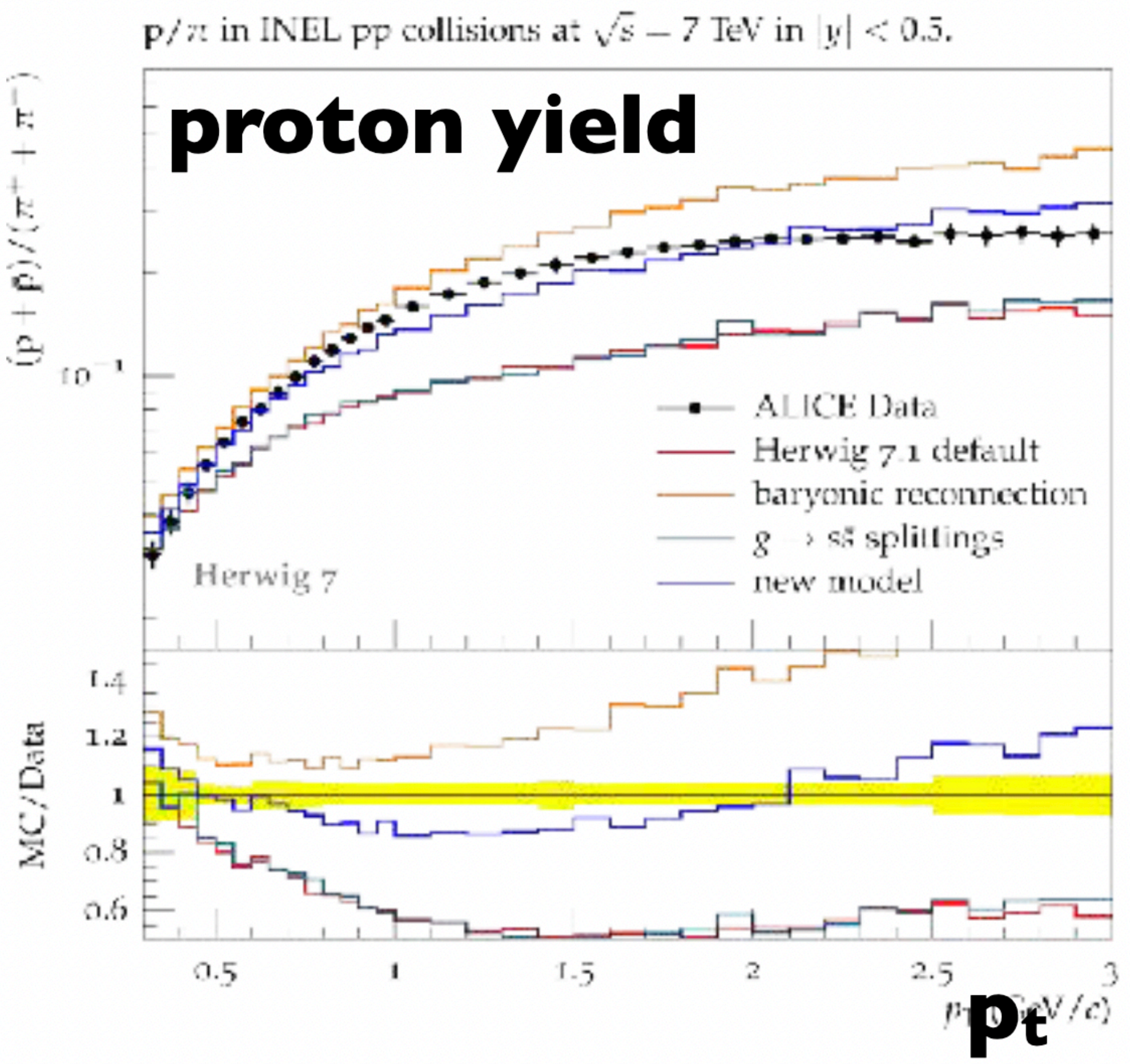



- In progress towards a unified description of particle production with both early and late time dynamics

# HERWIG Cluster Hadronization

*Image by Simon Platzer, NPQCD 2022*



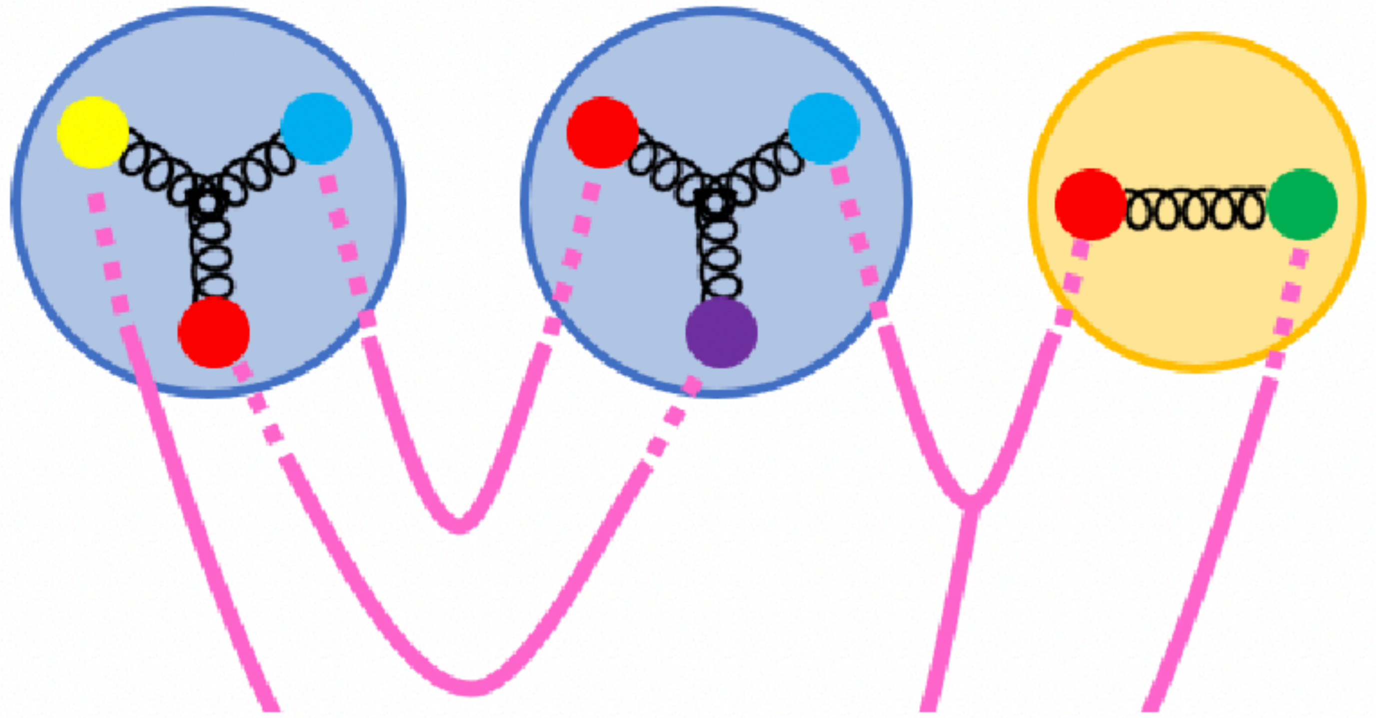




- Cluster model is currently being updated to better produce baryons/meson ratios - but still only applicable to small systems

# Hybrid Hadronization

**Hybrid Hadronization (HH)** combines two of these models:

1. **Quark recombination** (high-density systems)
   - Quarks can directly recombine into hadrons
2. **Lund string fragmentation** (low-density systems)
   - Color flux tubes in QCD vacuum at large distances → string-like behavior.
   - Quarks connected with strings; gluons are part of these strings – these strings are then broken to form hadrons.

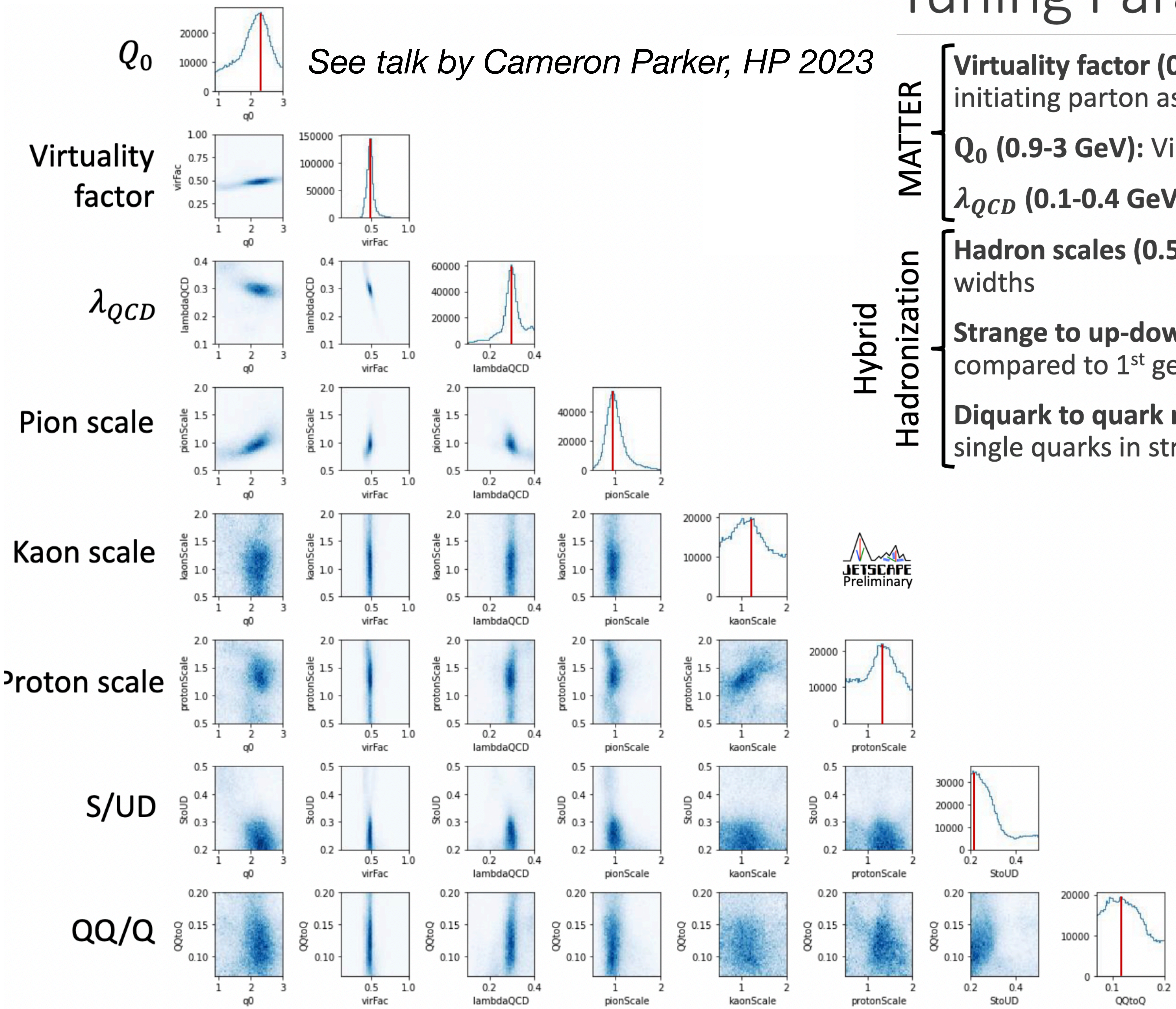


[4] K.C. Han et. al., Phys. Rev. C **93** (2016) 4, 045207

*Slide by Rainer Fries*

# Tuning Parameters

*See talk by Cameron Parker, HP 2023*

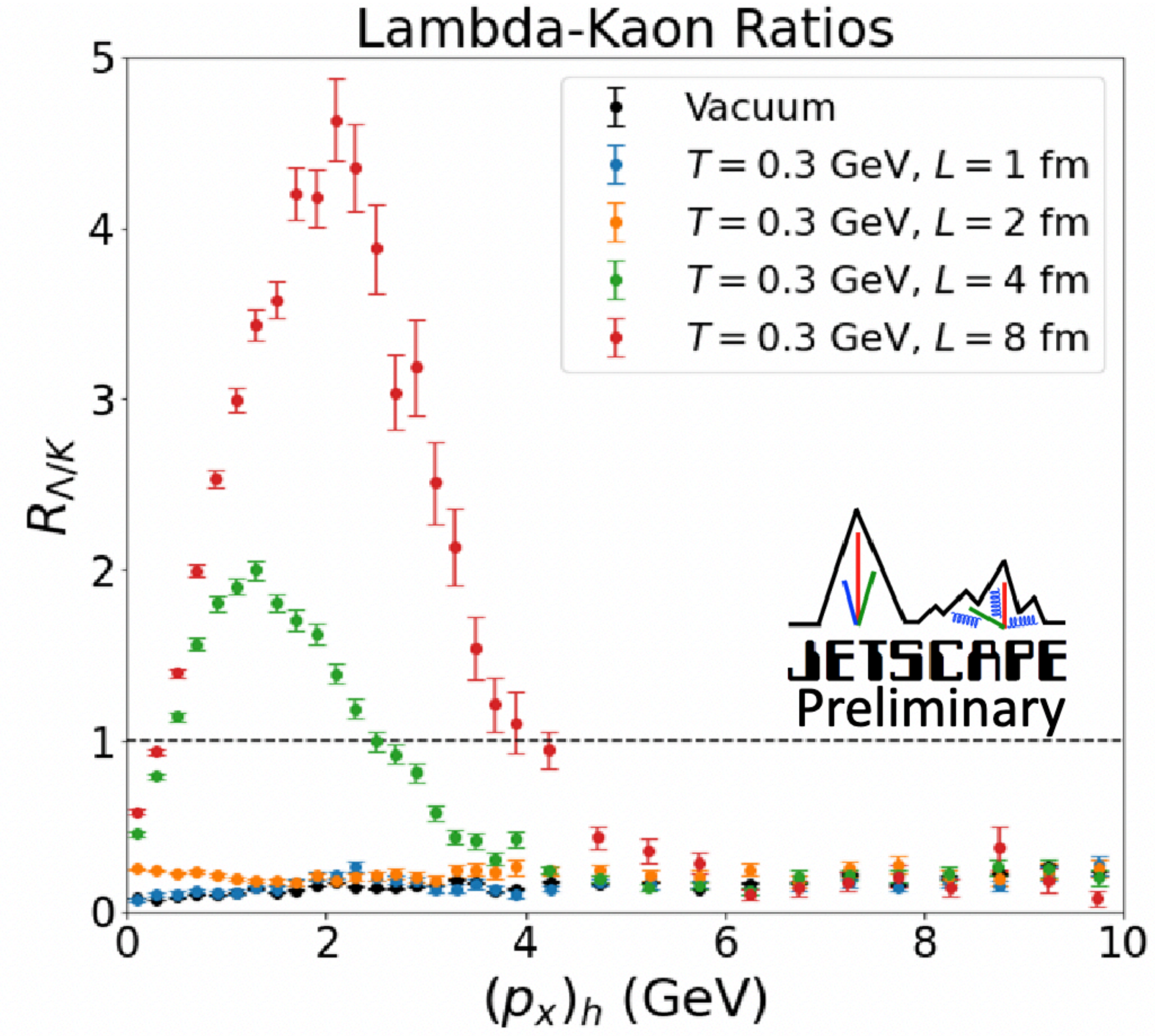



**MATTER**

- **Virtuality factor (0.1-1):** determines starting virtuality for every shower initiating parton as a portion of its initial momentum
- **$Q_0$ (0.9-3 GeV):** Virtuality threshold for when perturbative QCD stops
- **$\lambda_{QCD}$ (0.1-0.4 GeV):** strength of QCD interactions in MATTER

**Hybrid Hadronization**

- **Hadron scales (0.5-2):** factor multiplying the measured wavefunction widths
- **Strange to up-down ratio (0.2-0.5):** rate strange quarks are produced compared to 1st generation quarks in string fragmentation
- **Diquark to quark ratio (0.07-0.2):** rate diquarks are produced compared to single quarks in string fragmentation



# Where are we now?

- Data is leading the way towards potentially intriguing differences between various mass meson states and different parton flavors
- Heavy flavor hadron production, flow, quark content/composition, studies highlight impact of recombination, coalescence, scattering
- Particle production within the jet and outside in the bulk seems somewhat similar but uncertainties are large

# What are we doing next?

Higher statistics dataset, precision differential measurements, upgraded modeling, creating impactful observables sensitive to hadronization effects

- Advancing our understanding of npQCD using energy flows - First CFNS workshop - https://indico.bnl.gov/event/15664/contributions/

Advancing the Understanding of Non-Perturbative QCD Using Energy Flows

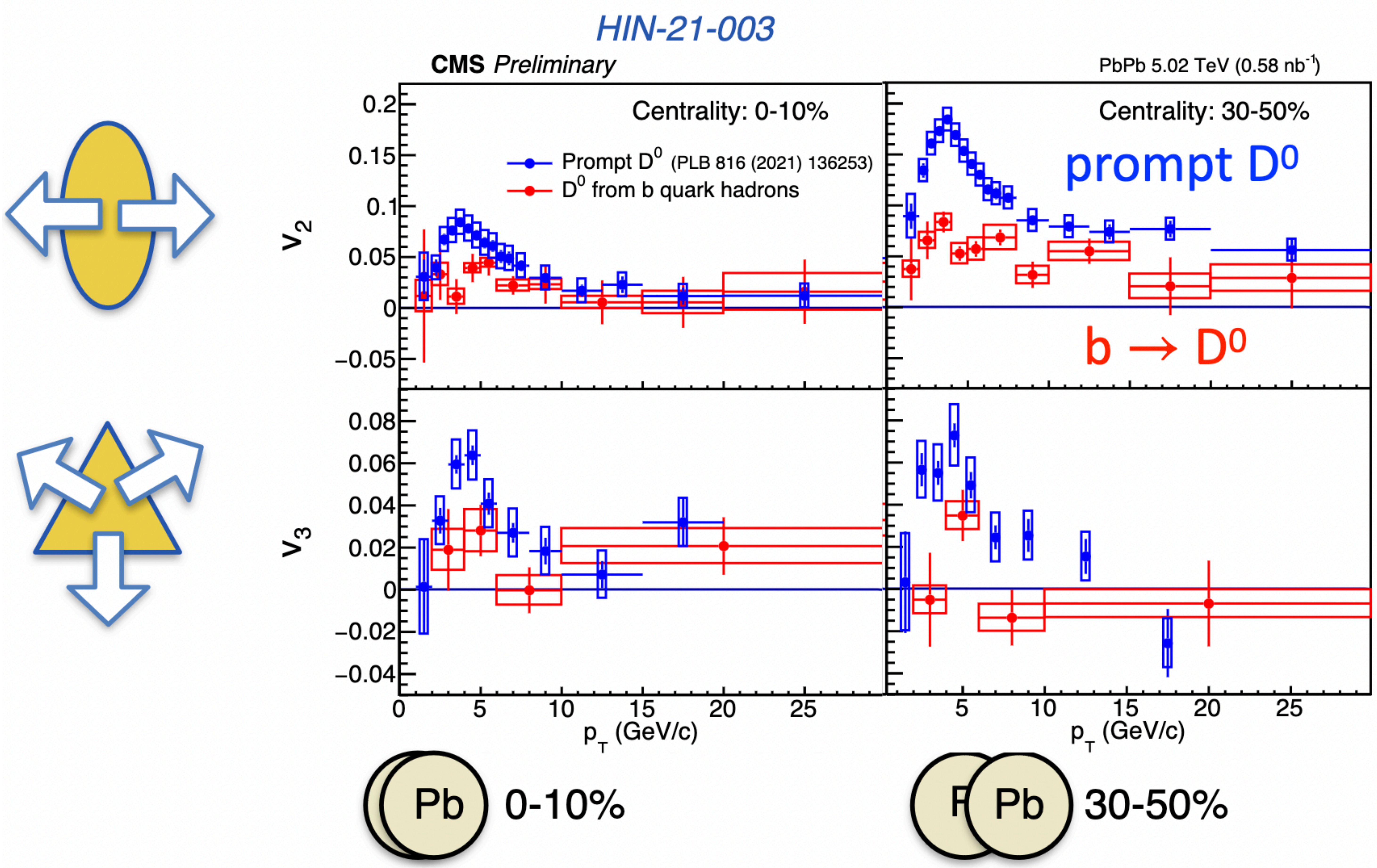
19–22 Sep 2022
Online/In-person
US/Eastern timezone

Enter your search term

- Second CFNS workshop on npQCD studies coming soon! Stay tuned!

# Backup Slides

# Meson production - direct vs decay

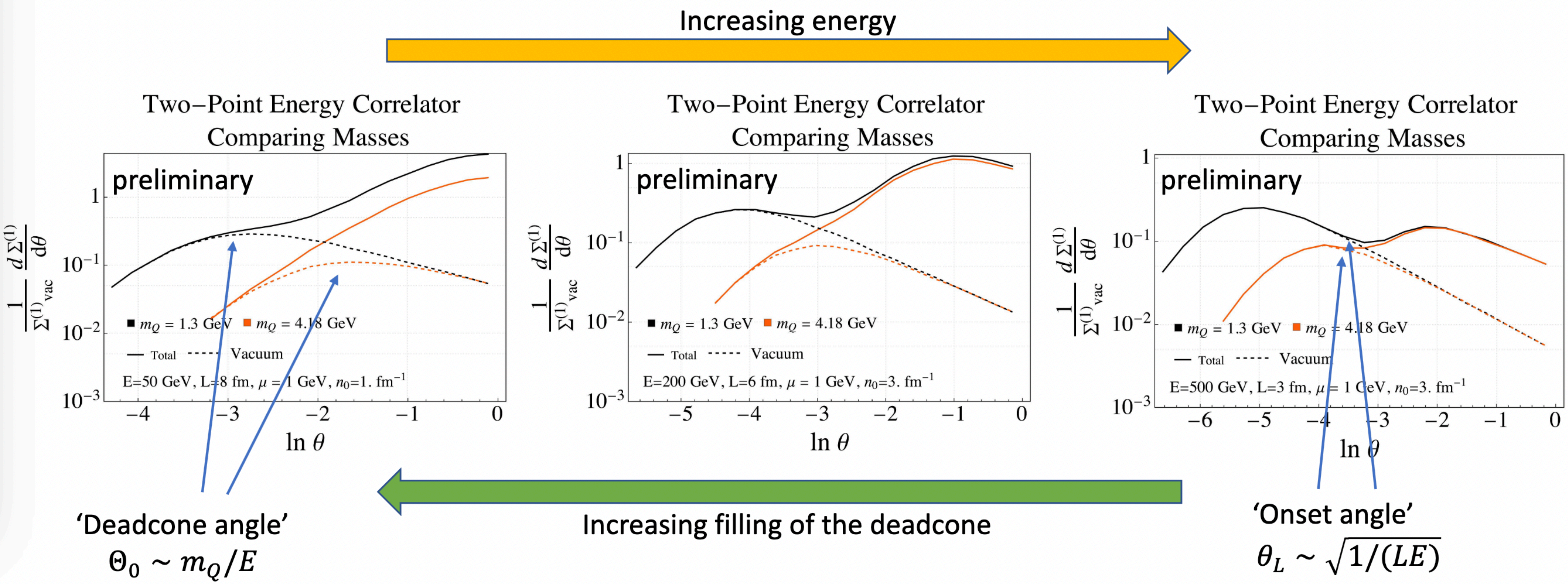



- Prompt $D^0$ produced earlier from the hard scattering - higher v2 at lower momentum
- $D^0$ from decays of b-hadrons occur later in time

*Slide by Yongsun Kim*

- Significant non-zero $v_3$ for b→D⁰ for all centrality bins
- Indicates the b hadron collectivity being sensitive to fluctuation of initial geometry

# The EEC on a *massive* quenched jet



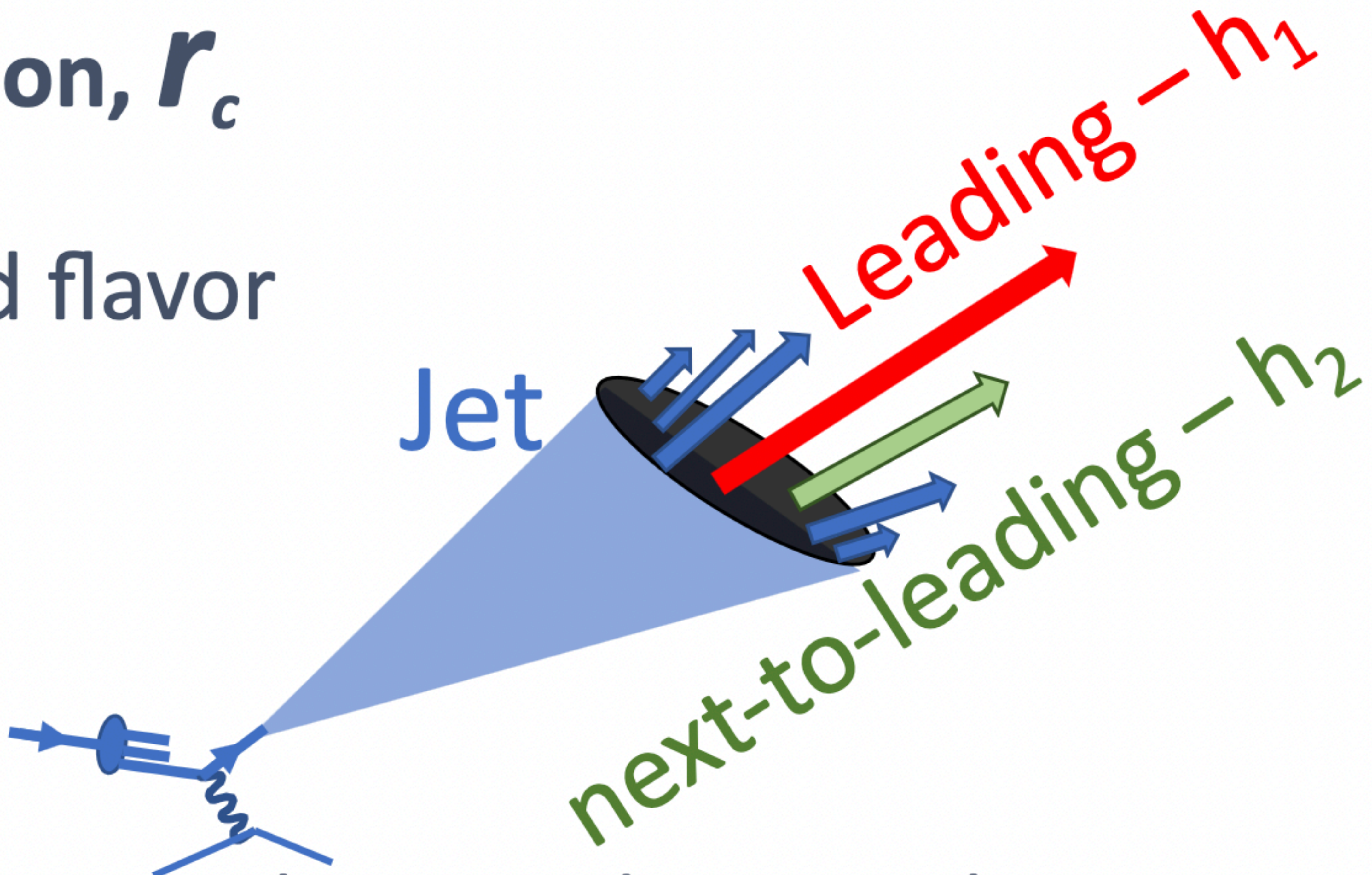

Threshold scales with $\sqrt{E/L} \sim m_Q$.

*See talk by Jack Holguin, HP 2023*

# 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

*Slide by Mriganka Mondal*

# Charge-energy correlations

**Observable : charge-momentum correla**

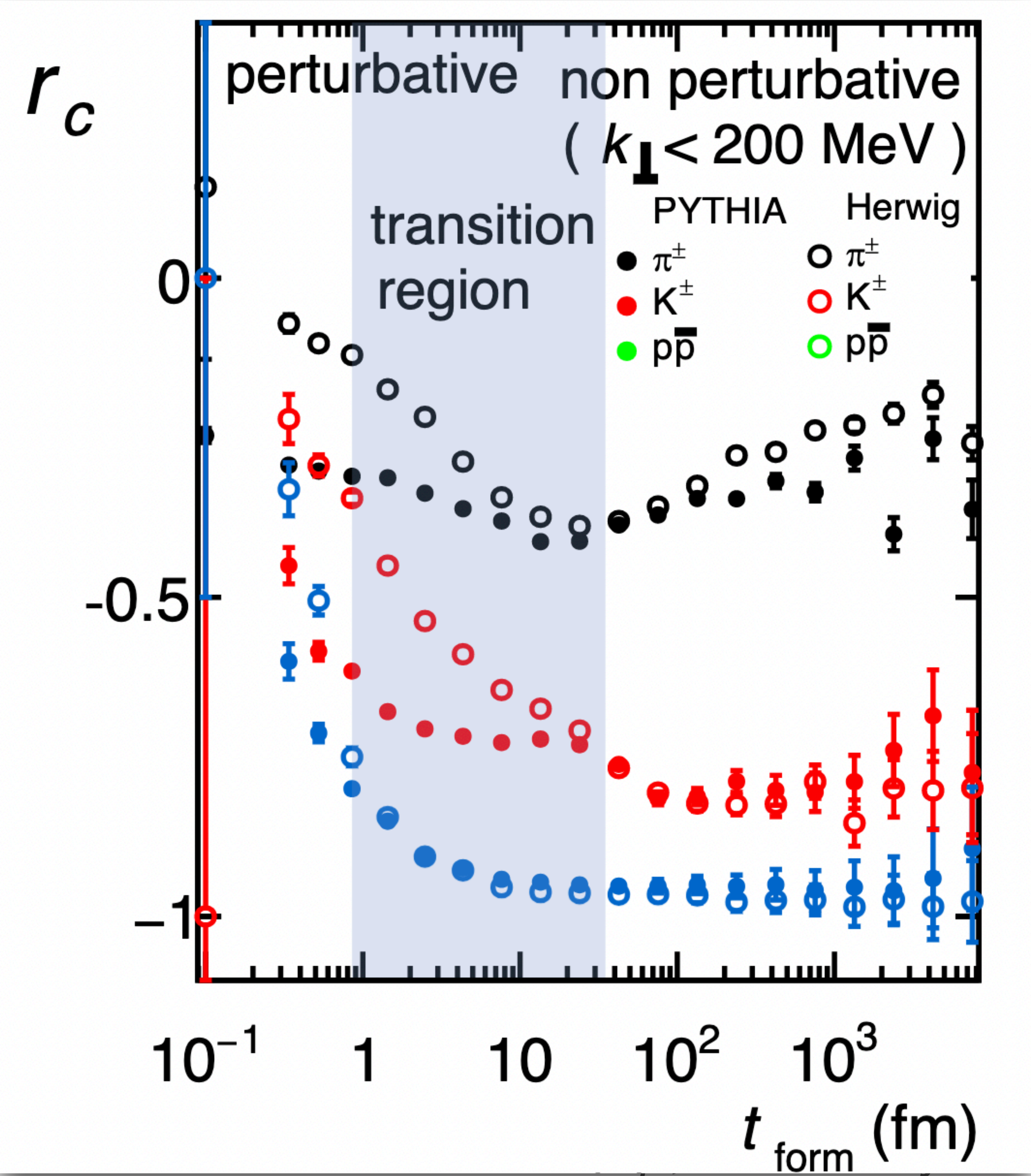
- Correlations in momentum, charge a
- **Leading(L)** and **next-to-leading (NL)** momentum particles in a jet
- **h1** and **h2** are charged hadrons only

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

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

$N_{CC}$

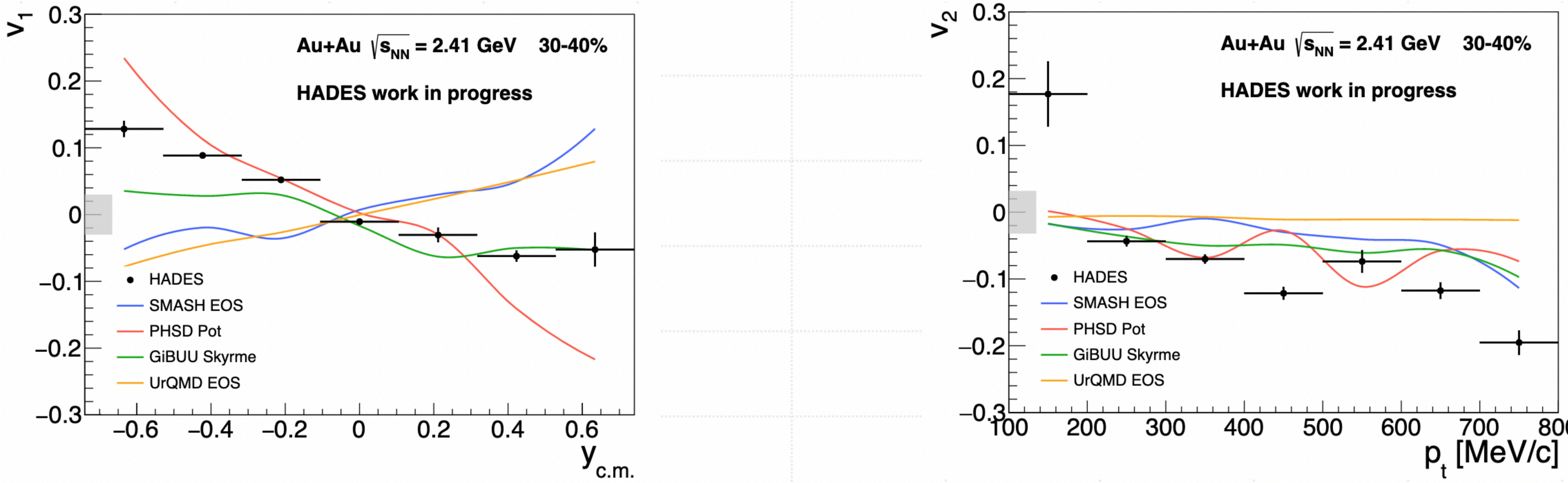
$N_{C\bar{C}}$



# Lower energies - identified particle flow

## Kaon anisotropy in Au+Au

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
30-40% centrality




- Good statistics to constrain models and equation of state
- There is room for improvement in the modeling

*Slide by Szymon Harabasz*