Gluon Junction Interactions and Ω-h Correlations

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Outline

1, Baryon Number Transport

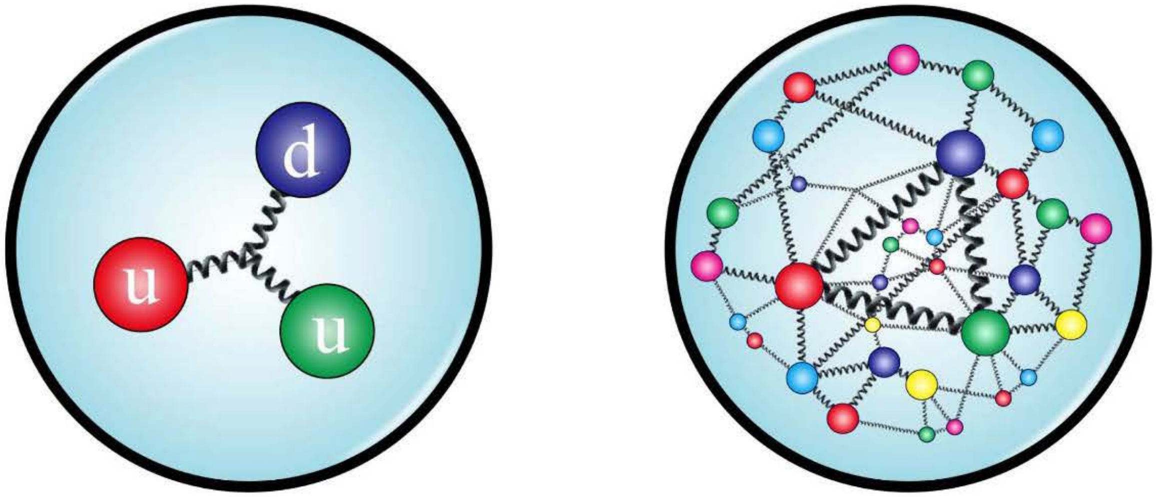
2, Net Baryon Number Transport to Ω Hyperon and Ω-h Correlation

3, p+A collisions

4, Future Perspective

Gluon Junction Concept – old, perhaps fundamental !

Traditional quark model **QCD**



(a) (b)

Figure 1. The internal structure of the proton from the viewpoints of (a) traditional quark model and (b) quantum chromodynamics (QCD).

Chen et al., Rep. Prog. Phys. 86 (2023) 026201

Baryon Number Transport Phenomenology

1) Fragmentation scheme

incoming baryons at beam rapidity → final state baryons at a rapidity y

How many fragmentation functions we should adopt?

Do we have enough data to constrain fragmentation functions?

Baryon number transported by a rapidity shift

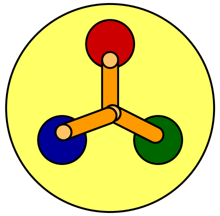
Dy = y_beam – y

2) The rapidity shift in p+A collisions depends on the target A thickness

in p+A collisions → parameterized using number of binary collisions

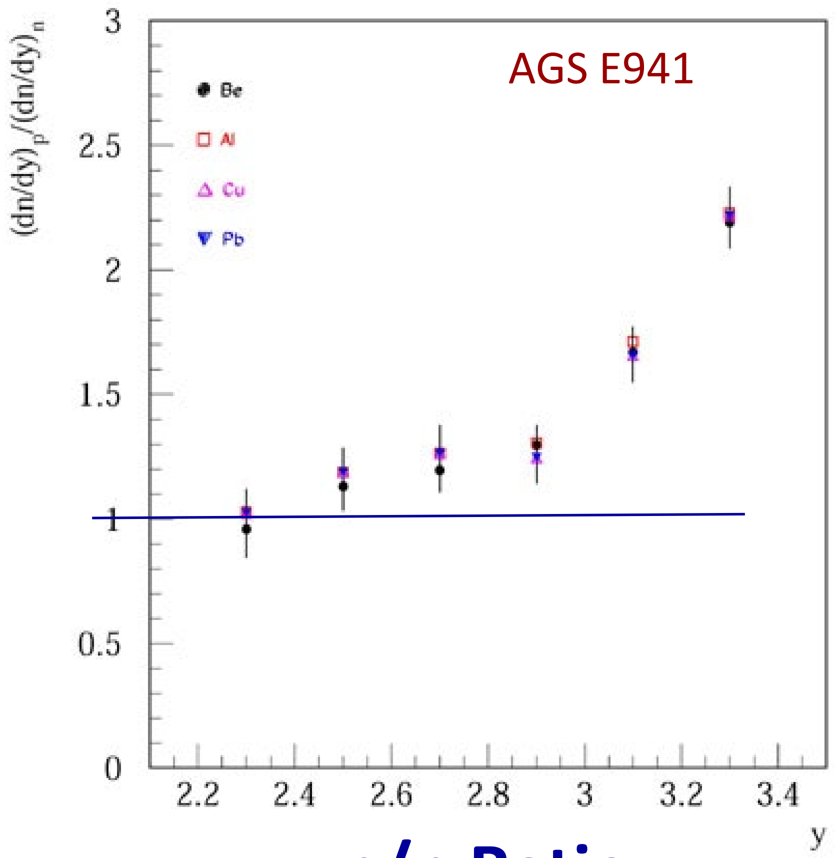
is the framework adequate for baryon number transport phenomenology?

Fragmentation Schemes – not Well Constrained yet



Proton Fragmentation Schemes:

1) Diquark-quark Fragmenation p/n = 2 (Flavor-biased)
2) Three-quark Fragmentation p/n = 1 (Flavor-neutral)
3) Gluon-junction Fragmenation p/n = 1 (Flavor-neutral) (unrelated to quark PDF)



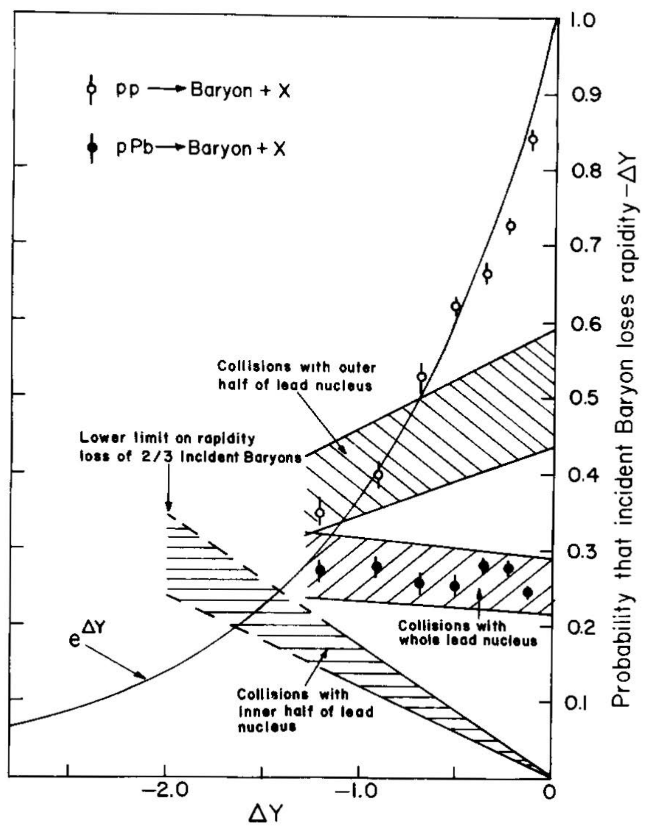
p/n Ratio

- Flavor-neutral processes increase hyperon production
- Gluon-junction interaction increases baryon-pair production as well (Kharzeev, Vance-Gyulassy)

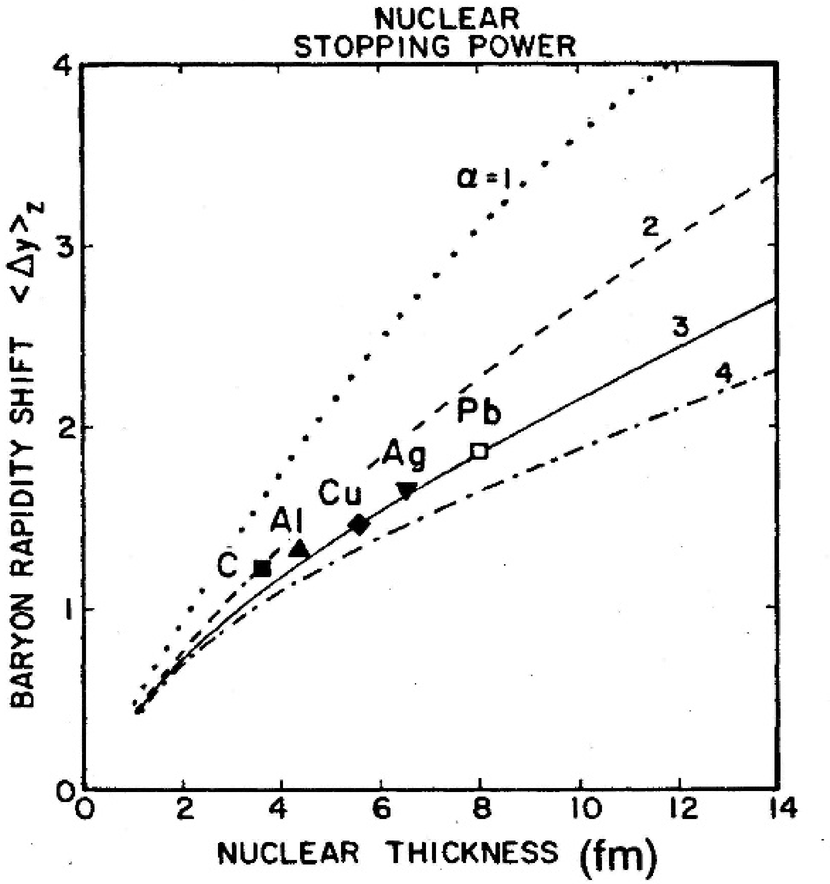
Protons are very brittle in high energy collisions!
Important to know the p/n ratios!

Longitudinal Dynamics in p+A Collisions

Busza and Goldhaber PLB139, 235 (1984)



Date, Gyulassy and Sumiyoshi, PRD32, 619 (1985)



p+p collisions:
final baryon distribution $e^{\Delta y}$
average rapidity shift ~ 1 unit

pA ansatz:
first collision $e^{\Delta y}$; sequential collisions $e^{\alpha \Delta y}$
average rapidity shift $1 + \frac{n-1}{\alpha}$

$$\alpha \approx 3$$

Experimental Challenges:

Modern collide experiments do not measure the baryon rapidity distribution over a large rapidity window (BHRAMS an rare exception) (many cannot identify protons at high rapidity)

If the neutron/proton ratio is a function of rapidity in p+A collisions in the proton hemi-sphere, there is no reason to expect that the n/p ratio will be flat in rapidity in heavy ion collisions !

Conceptually, is the number of binary collisions a valid framework? Is this longitudinal dynamics reflected on the different probabilities for di-quark, quark and gluon junction fragmentation schemes?

Baryon Formation Phenomenology

Traditional fragmentation scheme for hadron formation incomplete in heavy ion collisions!

Fragmentation scheme –

leading quark responsible for the hadron characteristics

final state hadron's other valence quarks – not paid any attention to in the past

Most particles are produced with no "leading" quark – all valence quarks matter !

Coalescence or recombination particle formation mechanism

There is clear evidence for hadron formation beyond traditional fragmentation.

We will use coalescence mechanism within the AMPT framework to study Ω and Ω-h

Ω Hyperons Carry the Baryon Number from the Colliding Nuclei

J. Adam et al. (STAR), Phys. Rev. C 102, 034909 (2020)

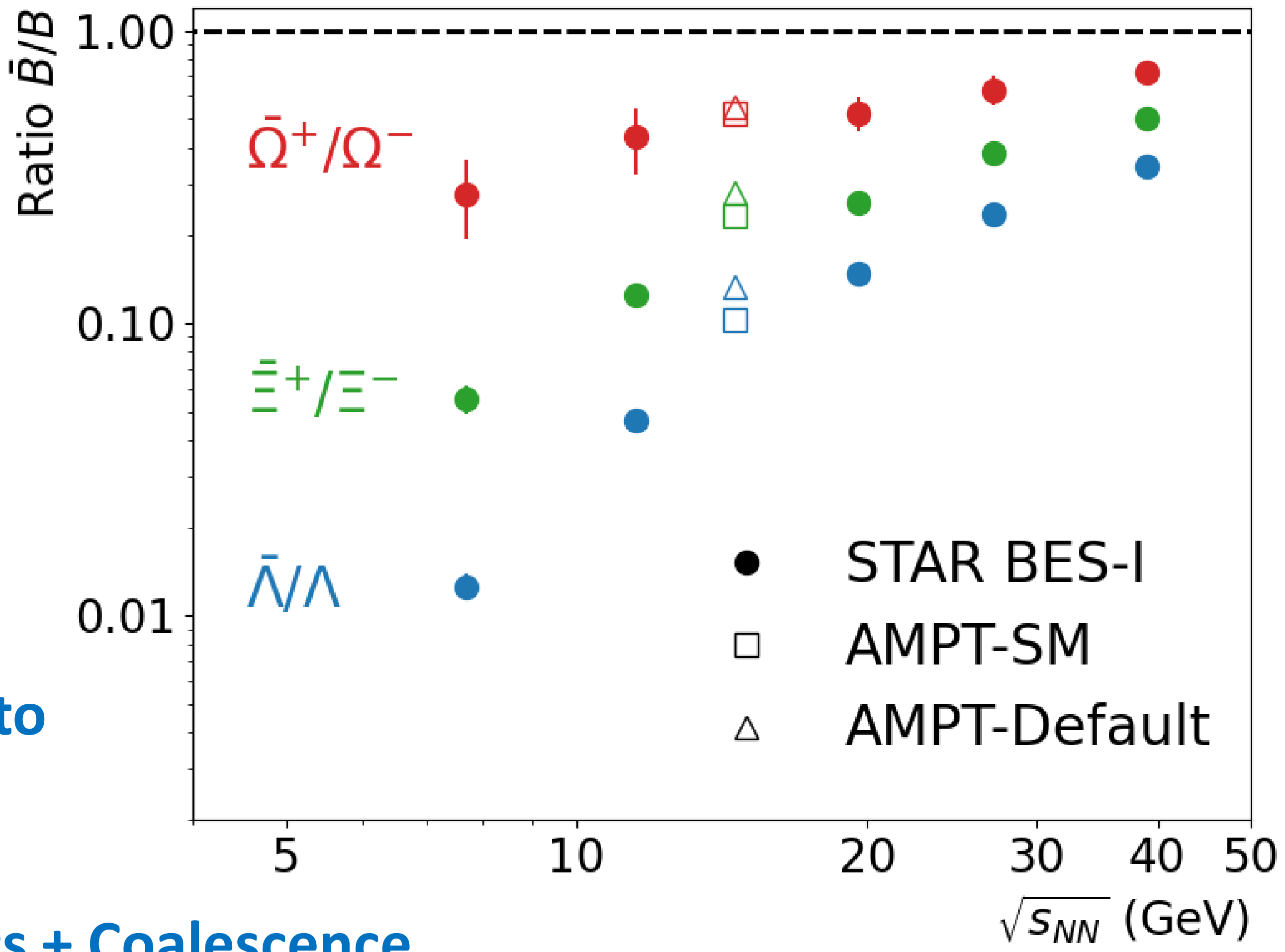
Strange and anti-strange quarks are pair-produced

Ratio of $\bar{\Omega}/\Omega < 1.0$

There is a net baryon number in Ω

What are the dynamics for the baryon number transport?

Use A Multi-Phase Transport (AMPT) model to guide the experimental investigation.

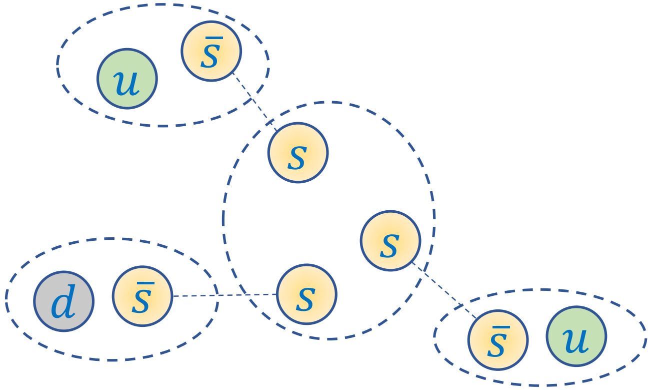


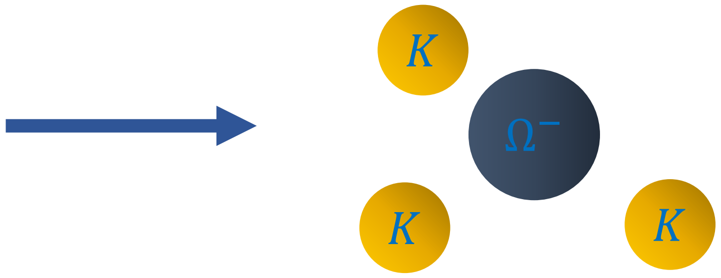
AMPT-SM (String Melting) – Parton Dynamics + Coalescence

AMPT-Default – fragmentation for particle formation

Strangeness Conservation (Scenario 1)

Generalized Associated production





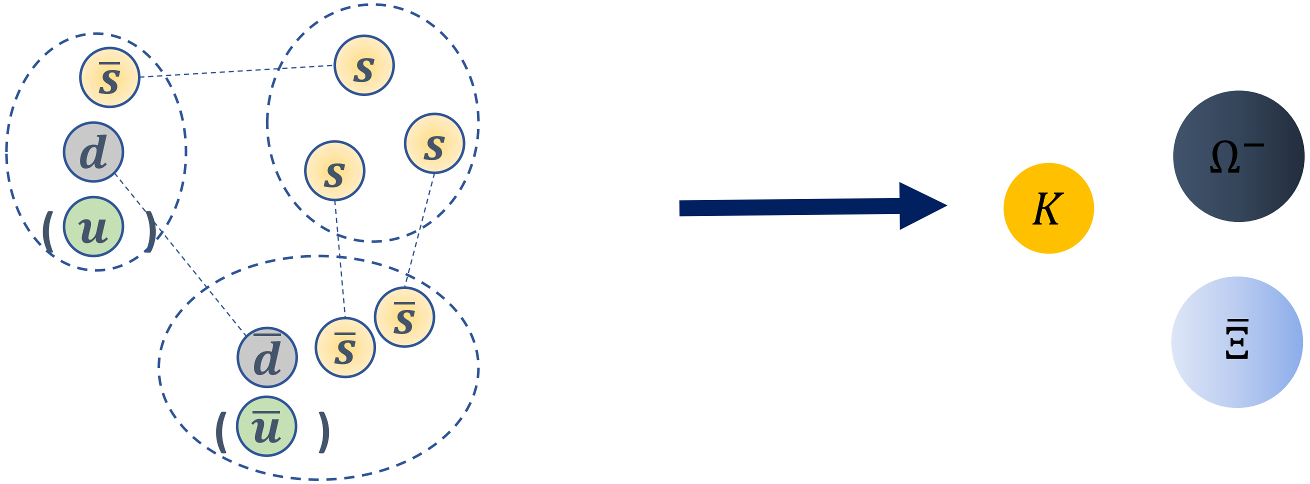
Now carries (a fraction of) baryon number from colliding nuclei!

(some u and d quarks come from colliding nuclei)

Gluon junction interaction could be one of the dynamics responsible for the mechanism

Strangeness Conservation (Scenario 2)

Generalized Baryon-Pair Production



Can replace $\bar{\Xi}$ with $\bar{\Lambda}$, $\bar{\Sigma}$, or $\bar{p}/\bar{n}$ with one or two extra Ks

net baryon number = 0

($u\bar{u}$ or $d\bar{d}$ from pair production)

Experimentally very challenging to measure, only recently ALICE measured hyperon-antihyperon correlation in p+p collisions.

Strangeness Conservation Expectations

Compare events with one Ω to events without any (assuming all the other non-Ω-related processes are the same), the first-order toy model gives:

- Scenario 1:
  - Ω carries baryon number from colliding nuclei
  - 3 extra K → $\Delta N_K = 3$
  - No $\overline{B}$ correlated with Ω → $\Delta N_{\overline{B}} = 0$
- Scenario 2:
  - Ω production not associated with net baryon number
  - 1, 2 or 3 extra K → $\Delta N_K = 1(\overline{\Xi}), 2(\overline{\Lambda}, \overline{\Sigma}), 3(\overline{p}, \overline{n})$
  - One anti-baryon correlated with Ω → $\Delta N_{\overline{B}} = 1$

$\Delta(\dots) \equiv \langle \dots \rangle_{\mathrm{w.}\Omega} - \langle \dots \rangle_{\mathrm{w.o.}\Omega}$

$\overline{B}$ refers to $\overline{\Lambda}$, $\overline{\Sigma}$, $\overline{\Xi}$, $\overline{p}$, and $\overline{n}$

Experimental approach:

Measure $K^{\pm} - \Omega$ and $\overline{\Xi}^{+}(\overline{\Lambda}^{0}, \overline{p}) - \Omega$ correlation

Strange Hadron Counts

AMPT – A Multi-Phase Transport dynamical model for heavy ion collisions

SM – String melting mode (parton degree of freedom and coalescence)
Default – string fragmentation for hadron formation

In the bracket: within STAR η acceptance

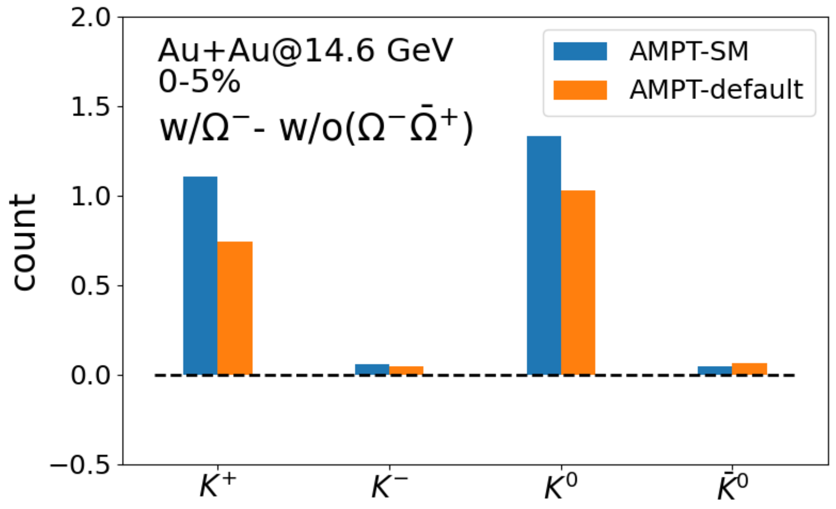
AMPT-SM:

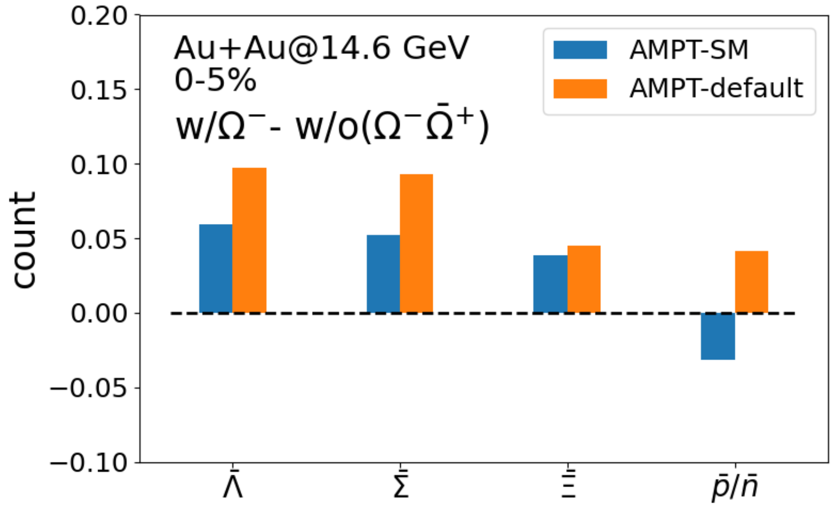
- $\Delta N_K \approx 2.44$ ($\Delta N_{K^+} \approx \mathbf{0.29}$)
  (3 for scenario 1)
- $\Delta N_{\bar{B}} \approx 0.12$ ($\mathbf{0.04}$)
  (0 for scenario 1)

AMPT-Default:

- $\Delta N_K \approx 1.76$ ($\Delta N_{K^+} \approx \mathbf{0.26}$)
  (1-3 for scenario 2)
- $\Delta N_{\bar{B}} \approx 0.28$ ($\mathbf{0.14}$)
  (1 for scenario 2)

Both models exhibit a mixture of the two scenarios, but AMPT-SM favors scenario 1





Difference in $K^{\pm} - \Omega$ Correlation

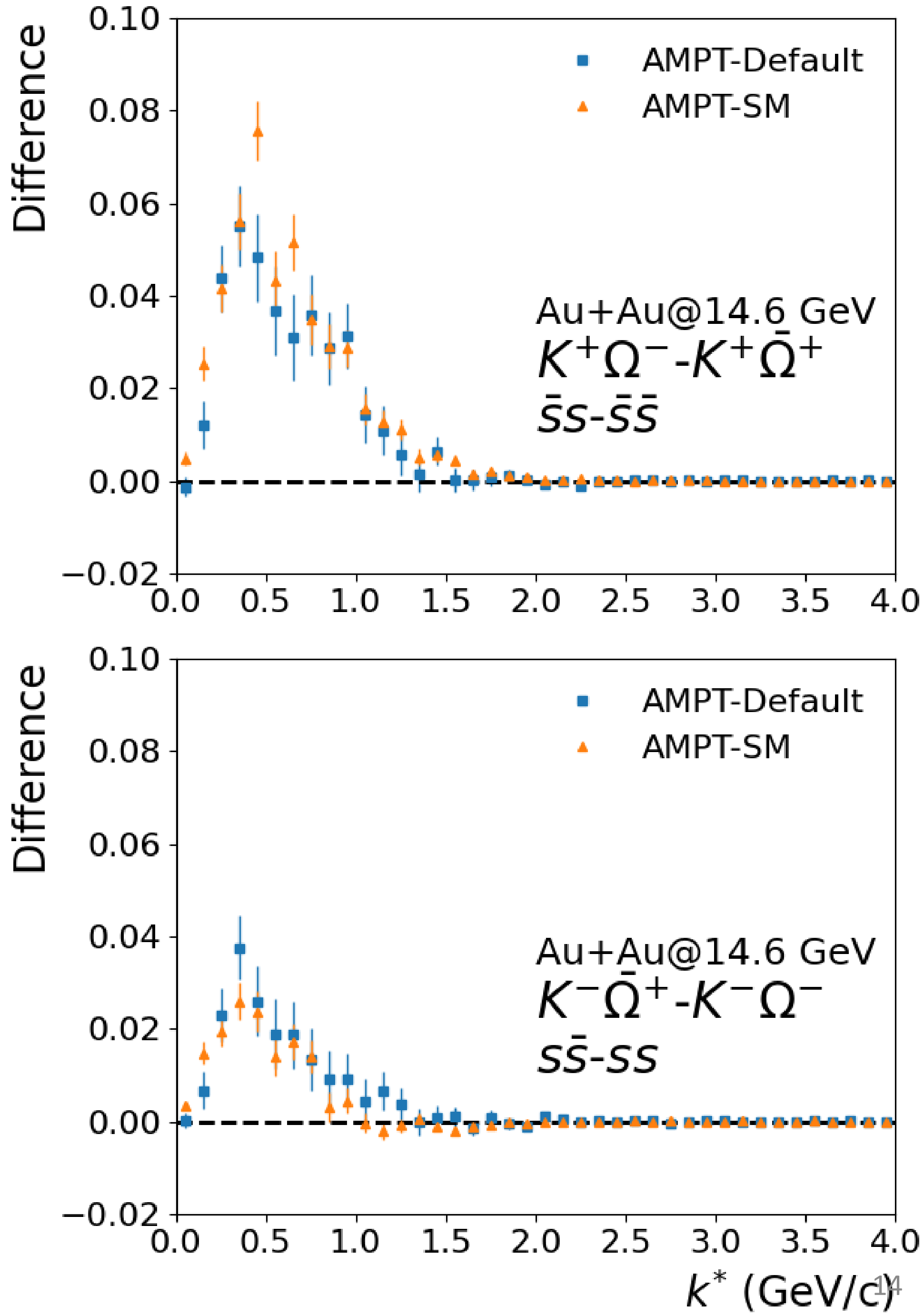
- Background Subtraction:

  opposite sign minus same-sign --

  $$s\bar{s} - s(\bar{s})s(\bar{s})$$

  - e.g., $K^{+}\Omega^{-} - K^{+}\overline{\Omega}^{+}$ and $K^{-}\overline{\Omega}^{+} - K^{-}\Omega^{-}$
  - Same event and track selection
  - Normalized by number of events, not by event-mixing

- Shows effects of transported quarks



Difference in baryon—Ω k* Correlation

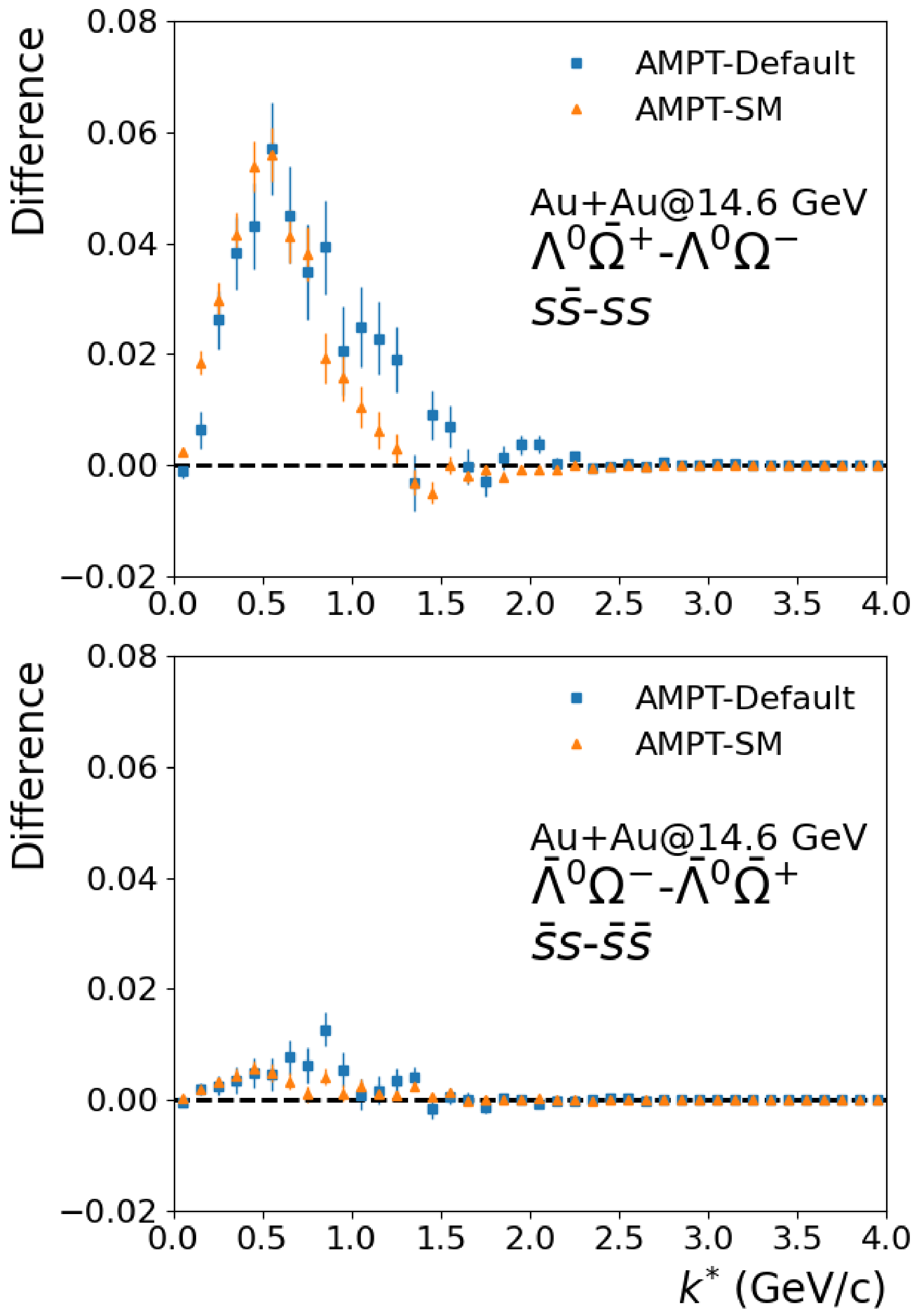
Background Subtraction: opposite-sign minus same-sign, $s\bar{s} - s(\bar{s})s(\bar{s})$

- e.g., $\bar{\Lambda}^0\Omega^- - \bar{\Lambda}^0\bar{\Omega}^+$ and $\Lambda^0\bar{\Omega}^+ - \Lambda^0\Omega^-$
- Same event and track selection

- **Two AMPT versions show noticeable difference in $s\bar{s}$ correlation widths**

  →Does such difference relate to the two Ω production scenarios?

- Again shows effects of transported quarks



Difference in baryon—Ω rapidity y Correlation

Background Subtraction:

opposite-sign minus same-sign, $s\bar{s} - s(\bar{s})s(\bar{s})$

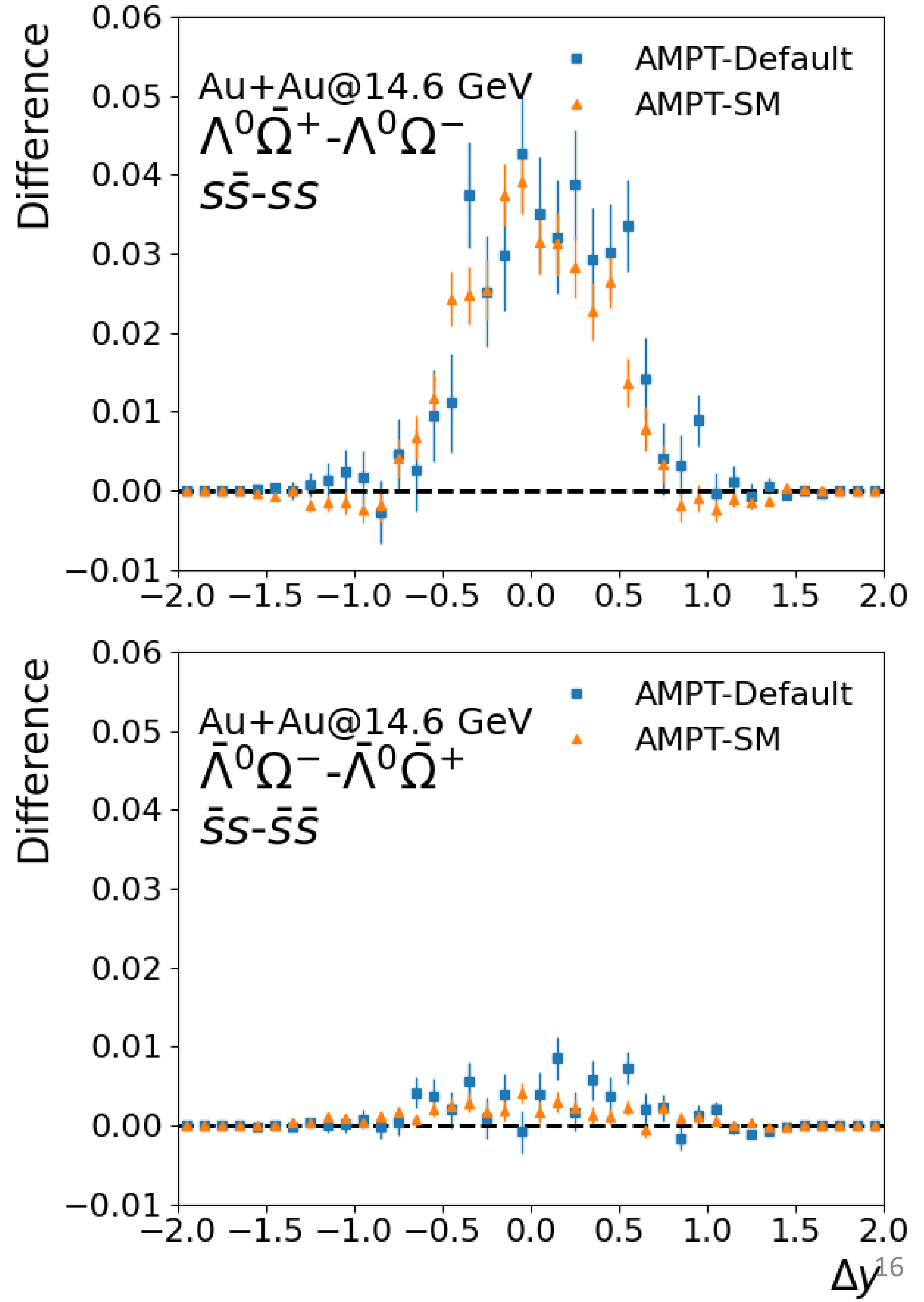
- e.g., $\bar{\Lambda}^0\Omega^- - \bar{\Lambda}^0\bar{\Omega}^+$ and $\Lambda^0\bar{\Omega}^+ - \Lambda^0\Omega^-$
- Same event and track selection

- **Two AMPT versions show noticeable difference in $s\bar{s}$ correlation widths**

  →Does such difference relate to the two Ω production scenarios?

- Again shows effects of transported quarks

We are analyzing the STAR BES II data



Comments on A+A Collisions

Baryon number transport in Au+Au collisions

Likely a combination of many mechanisms

If model calculations reliable, we can use model calculations to unfold for contributions of various components

We need to separate gluon junction interaction and generalized associated production for Omega

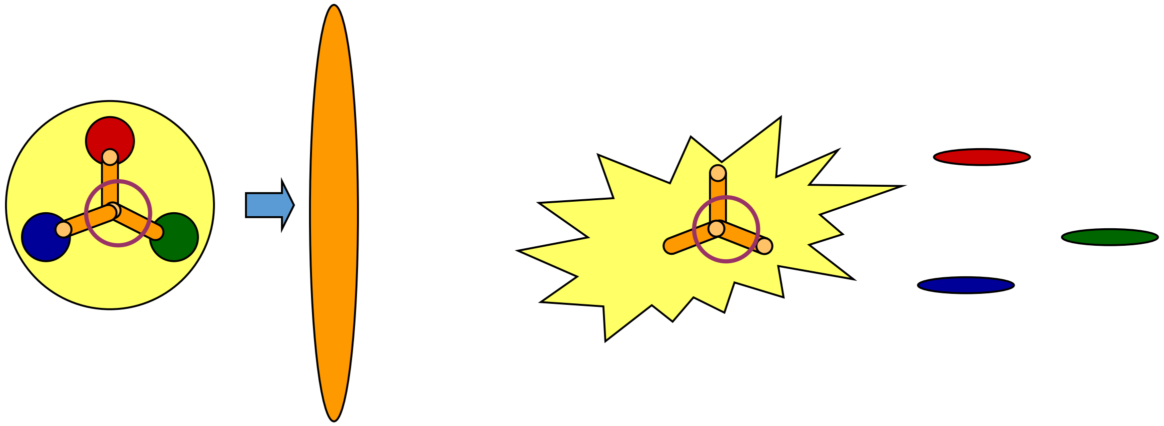
Which beam energy A+A collisions where Ω-h correlations would be more sensitive?

Too high energy → Ω = anti-Ω

Two low energy → valance quarks not separated in phase space

still trying to figure out the optimal energy with simulations

Gluon-Junction Interactions in p+A Collisions



Unique Features of Gluon-Junction Interaction in pA Collisions at High Energy:

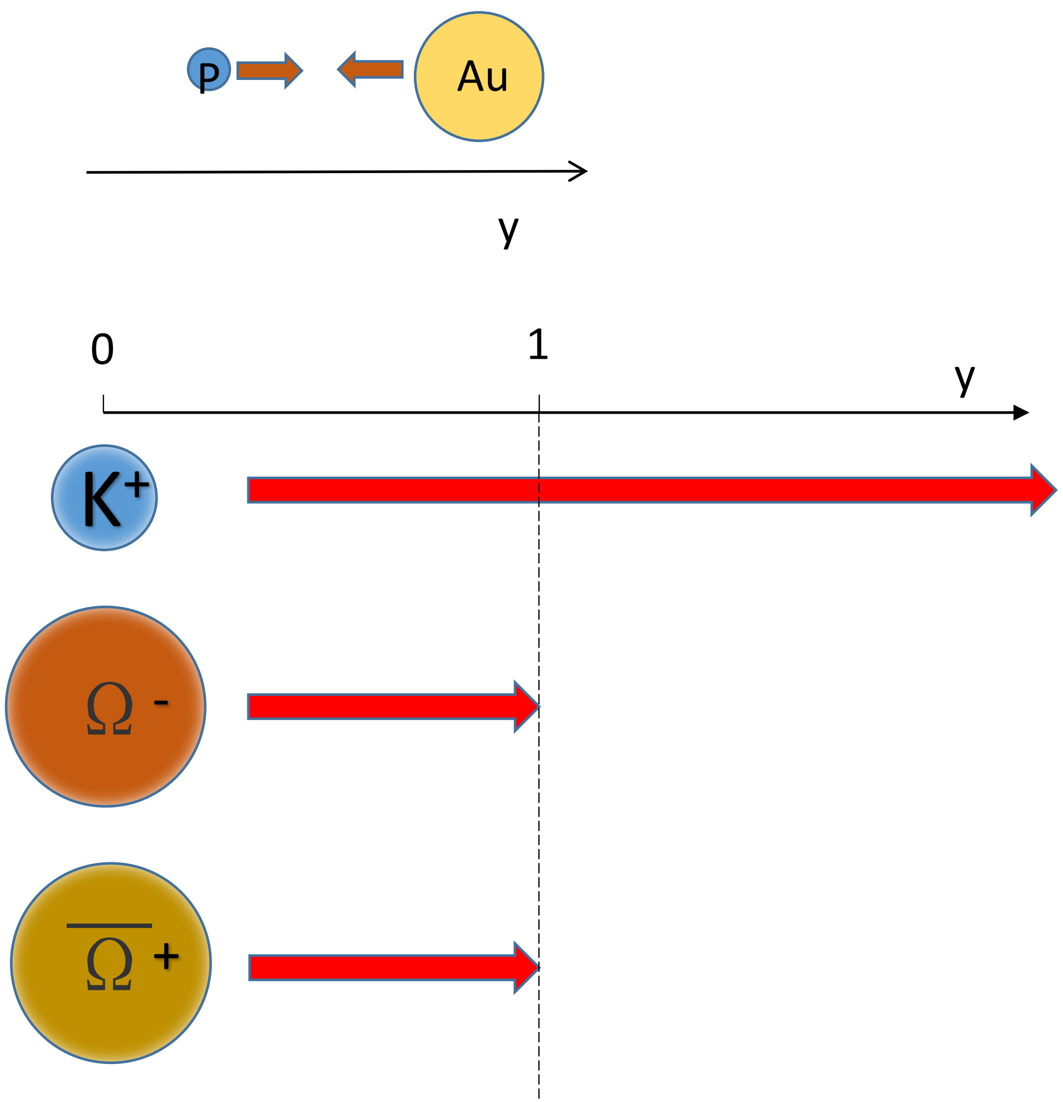
1) **Baryon number is carried by the gluon junction during the interaction**
2) **Valence quark jets emerge with leading mesons**

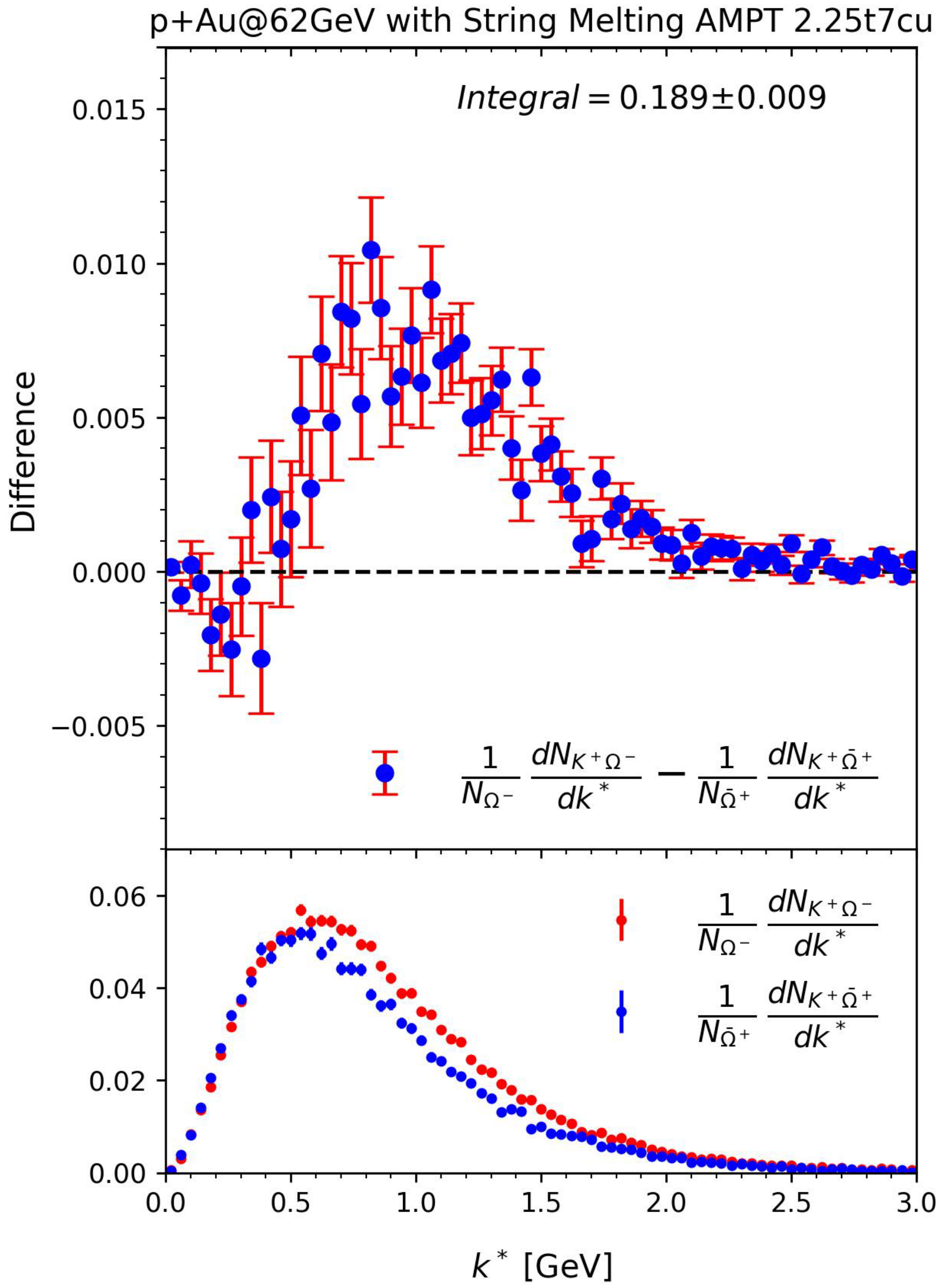
筛选： K^+的快度>0, \Omega^-和 \bar{\Omega}^+的快度介于0到1之间

String Melting AMPT

AMPT version: 2.25t7cu (StringMelting)

Energy: 62 GeV





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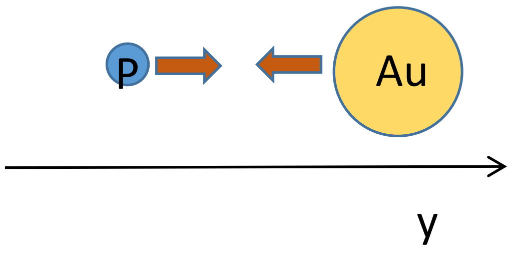

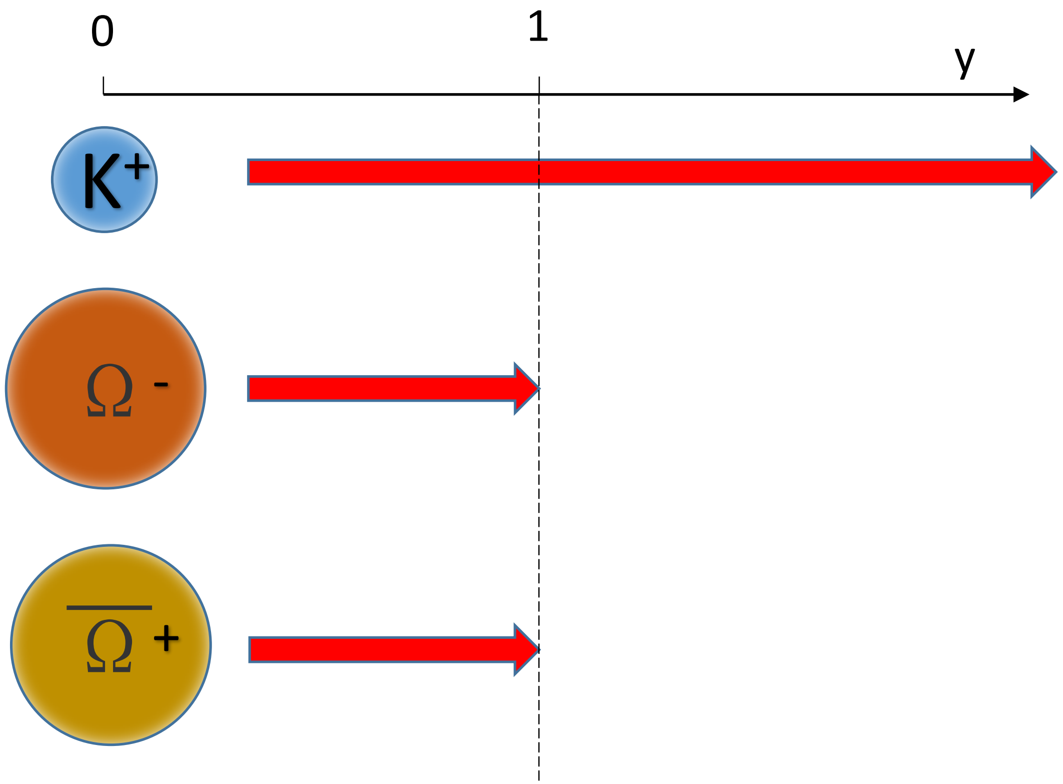

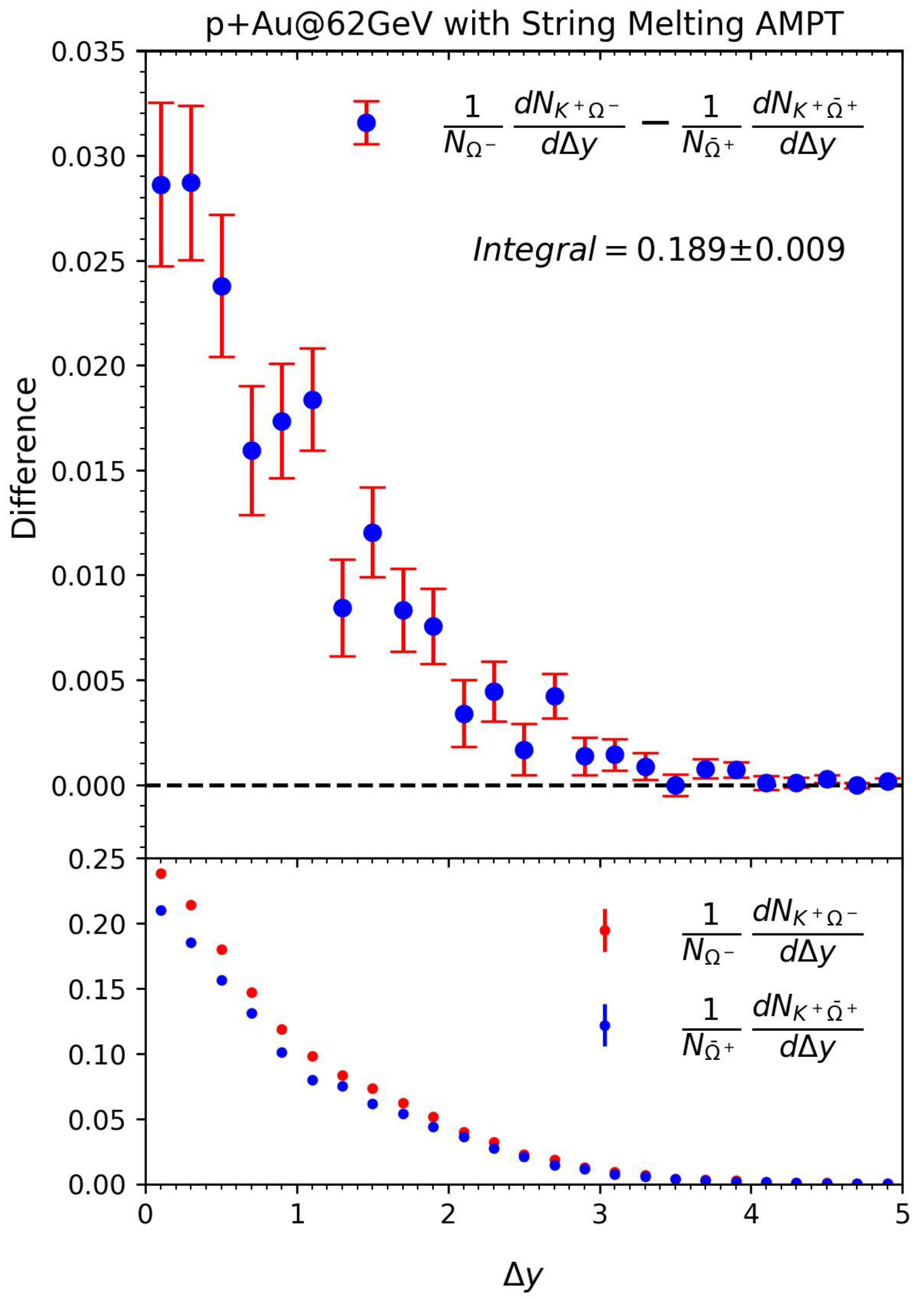

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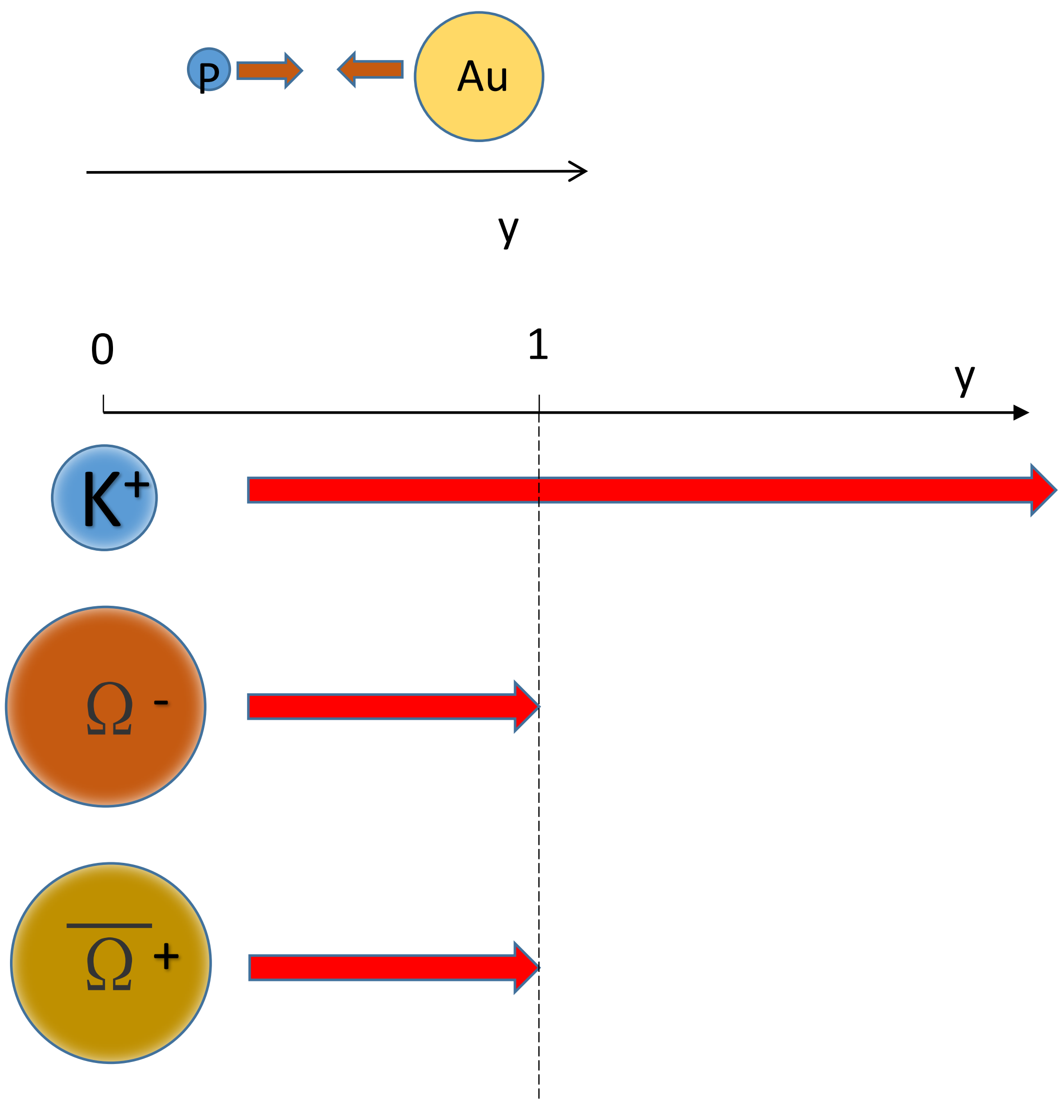

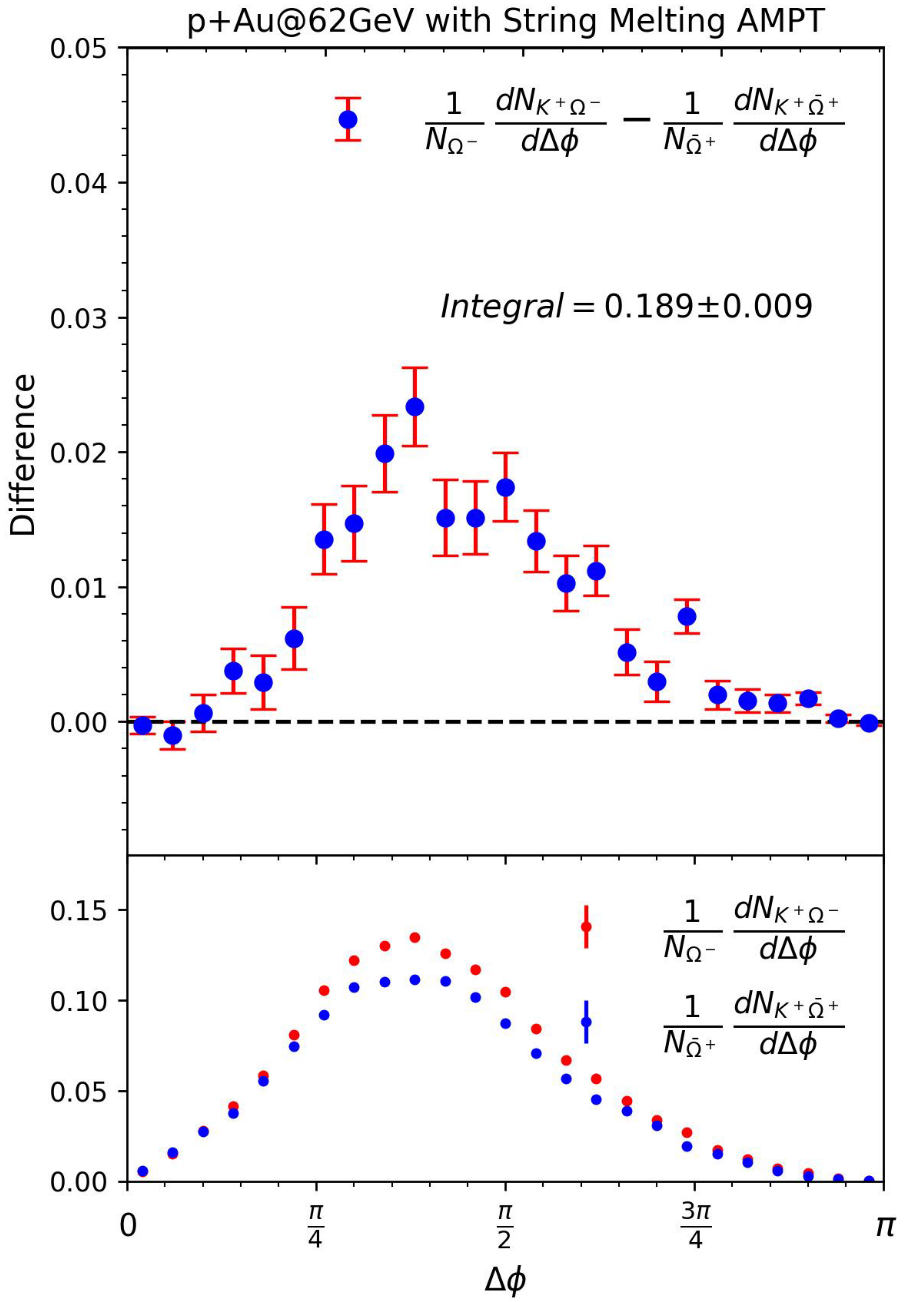

Near Term p(d)+A Studies

p+A collisions – promising venue to study possible gluon junction interactions

Ω-h correlation – sensitive probe of baryon number transport dynamics

Nuclear A → may act as a valence quark filter to study gluon junction interactions at mid-rapidity

STAR p+A and p+p data with the forward calorimeter system will be an interesting data set to analyze

Future Perspectives

Gluon junction → as an intrinsic non-perturbative QCD structure inside the nucleon
appealing QCD-inspired model theoretically
contributing dynamics for baryon number transport over a large rapidity gap
flavor neutral – possible dynamics for baryon number transport to Ω hyperons

STAR BES II data and p(d)+A will be unique data sets to study baryon number transport
dynamics and gluon junction interactions

Baryon number transport to Ω hyperon and Ω-hadron (K, anti-hyperons) correlations
from A+A and p+A collisions – sensitive to possible gluon junction interactions

Exciting physics topic for RHIC and EIC !

Thanks