Dependence of net-hyperon production at mid-rapidity on beam energy and its implication on baryon number carrier

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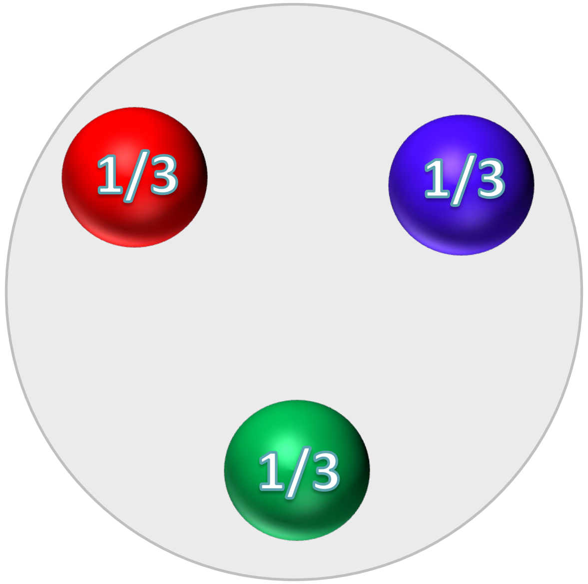
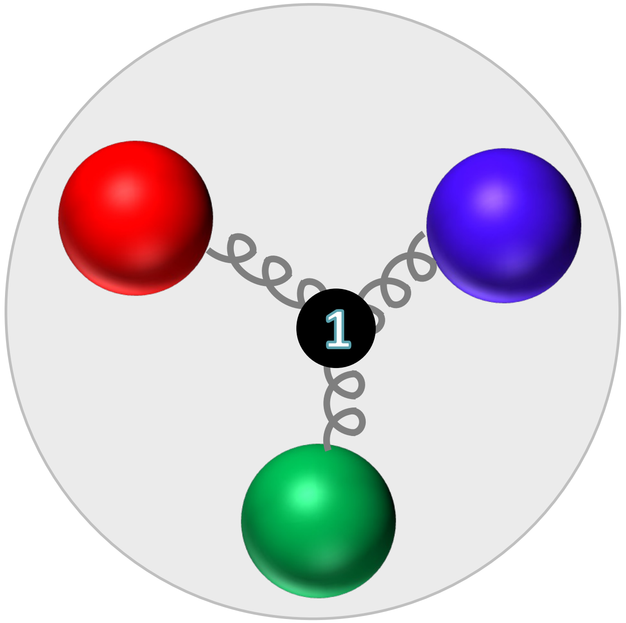
What carries baryon number?

Conventional quark model



Baryon junction



Artru, X. NPB 85, 442–460 (1975)
Rossi, G. C. & Veneziano. NPB 123, 507–545 (1977)

Baryon transport

- **Valence quarks carry large momenta**
  - Contracted into thin “pancakes”
  - Less interaction time
  - Hard to be stopped or transported

- **Junction carries small momentum**
  - Made of low-*x* gluons
  - Easier to be transported

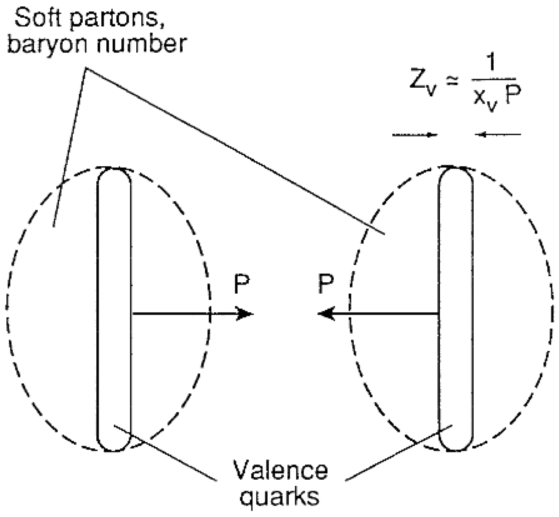
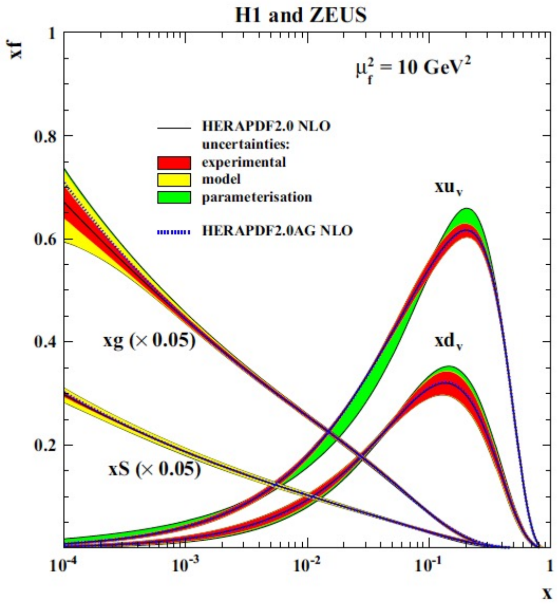


Fig. 2.

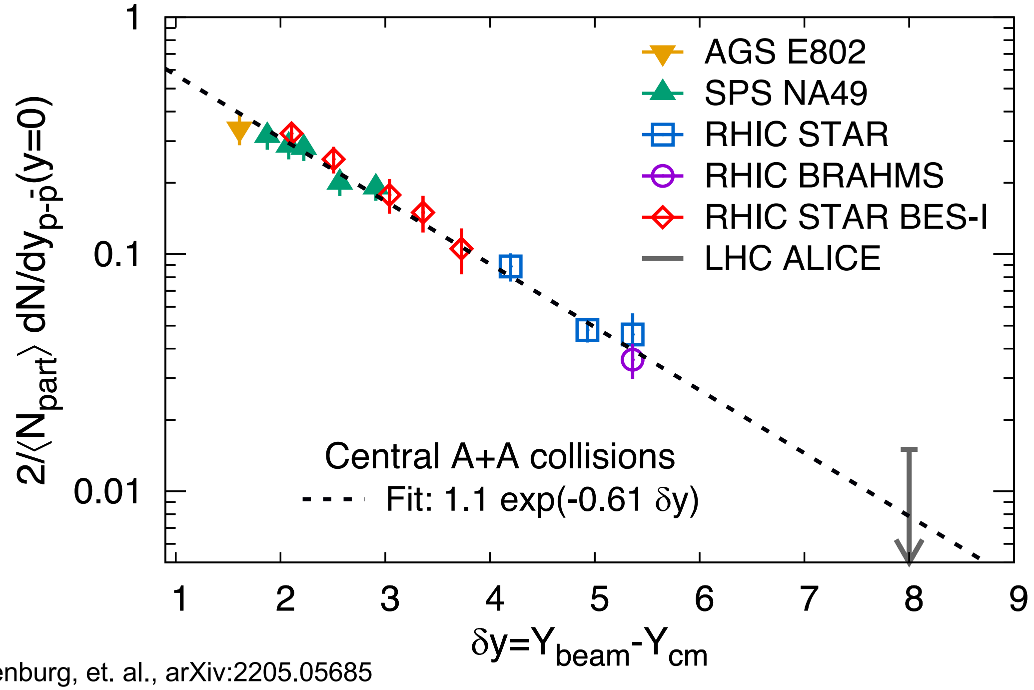
D. Kharzeev, PLB 378, 238 (1996)



H1 and ZEUS, EPJC 75, 580 (2015)

Baryon transport: rapidity slope

- **Expect:** $\frac{dN_B}{d\delta y} \propto e^{-\alpha_B \delta y}, \delta y = y_{beam} - y_{cm}$



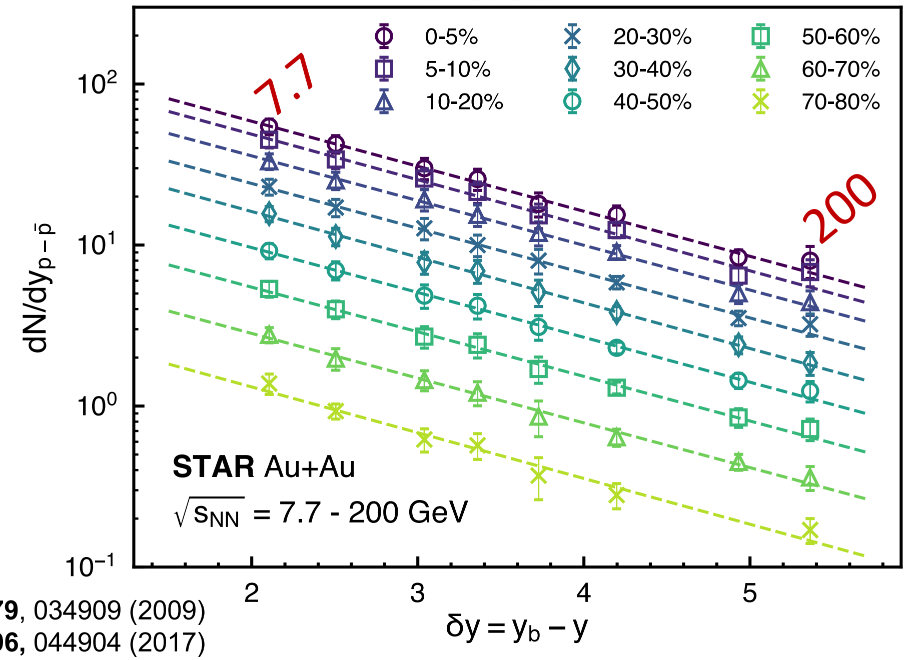
J. D. Brandenburg, et. al., arXiv:2205.05685

	α_B
Data (net-proton)	0.61 ± 0.03
Baryon junction theory	0.42 – 1.0

Theory: D. Kharzeev, PLB 378, 238 (1996

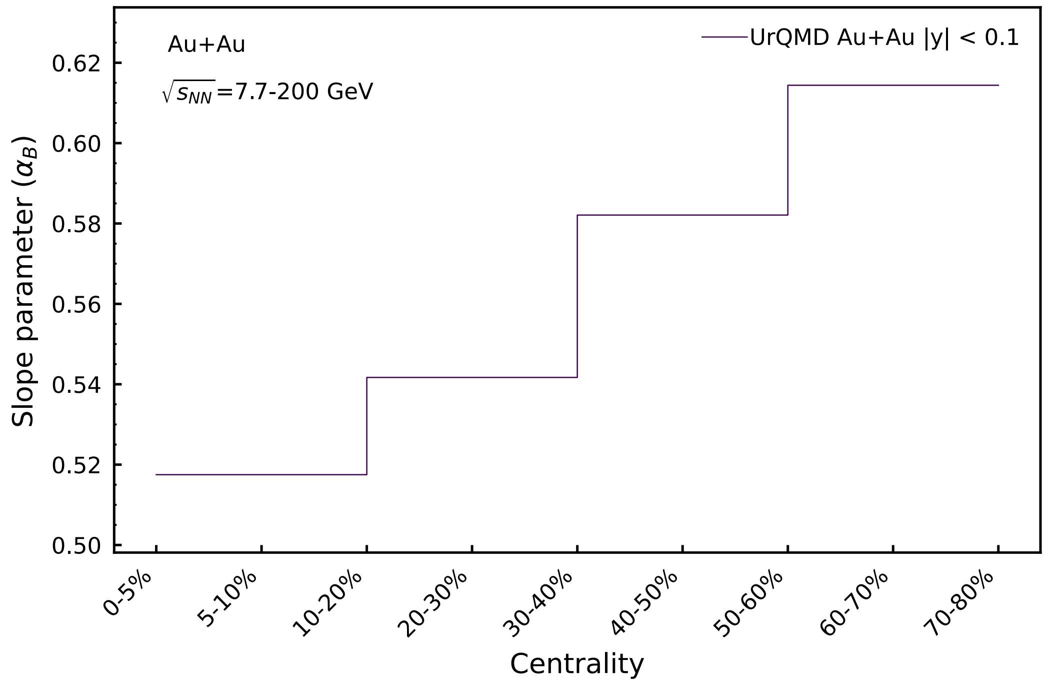
Baryon transport: centrality dependence

Data



STAR, PRC **79**, 034909 (2009)
STAR, PRC **96,** 044904 (2017)

UrQMD

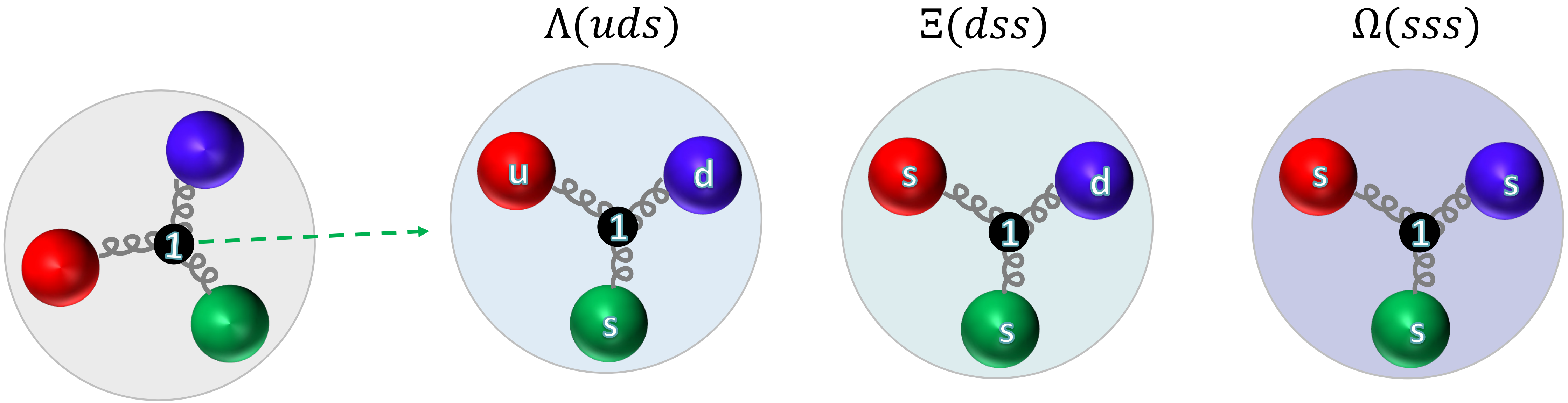


- **Data:** no centrality dependence
- **UrQMD (valence quark):** slope decreases from peripheral to central; more multiple scattering → more valence quark stopping

R.Ma Tue. 5:10pm

How about other types of baryons?

- **Valence quarks:** flavor preference
- **Baryon junction: flavor blind**



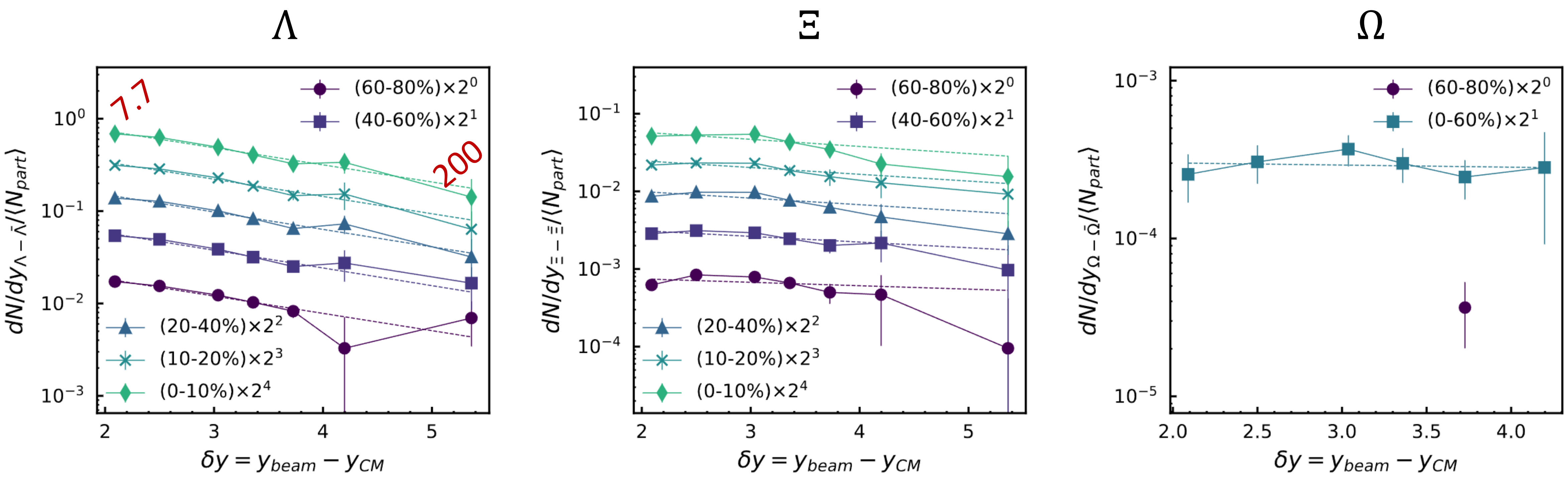
Net-hyperons: expectations

- **Hyperons: baryons with at least one valence strange quark**
  - $\Lambda^0(uds), \Xi^-(\mathrm{uss}), \Omega^-(\mathrm{sss})$
  - (Anti-)hyperons have baryon number +1(-1)
  - Net-hyperon = hyperon − antihyperon

- **Baryon junction: flavor blind → same transport behavior; same α_B for $\Lambda^0, \Xi^-, \Omega^-$**

- **Fit** $\frac{dN_B}{d\delta y} \propto e^{-\alpha_B \delta y}$ **for** net-Λ^0, net$-\Xi^-$, net$-\Omega^-$ **to extract the slope parameters**
  - Use published hyperon yields at mid-rapidity by STAR
  - $\delta y = y_{beam} - y_{cm}$, y_{cm} ~ 0 while y_{beam} varies with beam energy

Net-hyperons: first glance



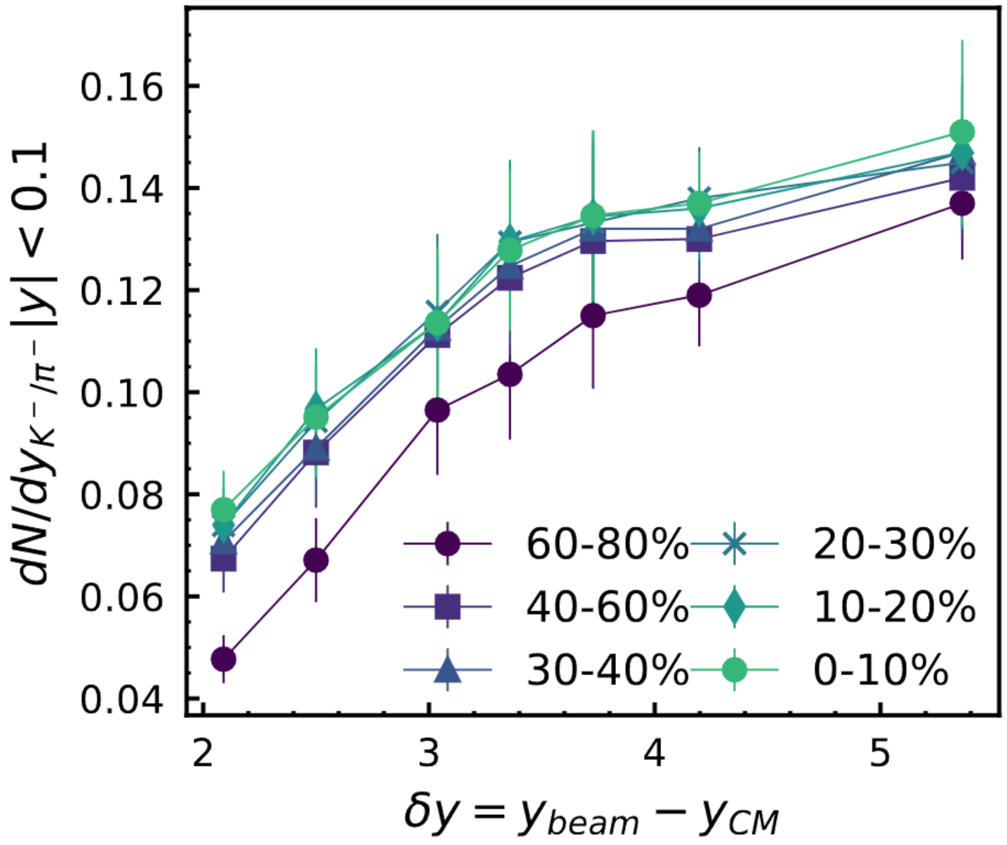
STAR data: PRL 98, 062301 (2007); PRL 108, 072301 (2012); PRC 102(3), 034909 (2020)

- Does not seem to follow the exponential function
- **Could it be due to the difficulty for producing strange quarks?**

Strange quark production suppresion

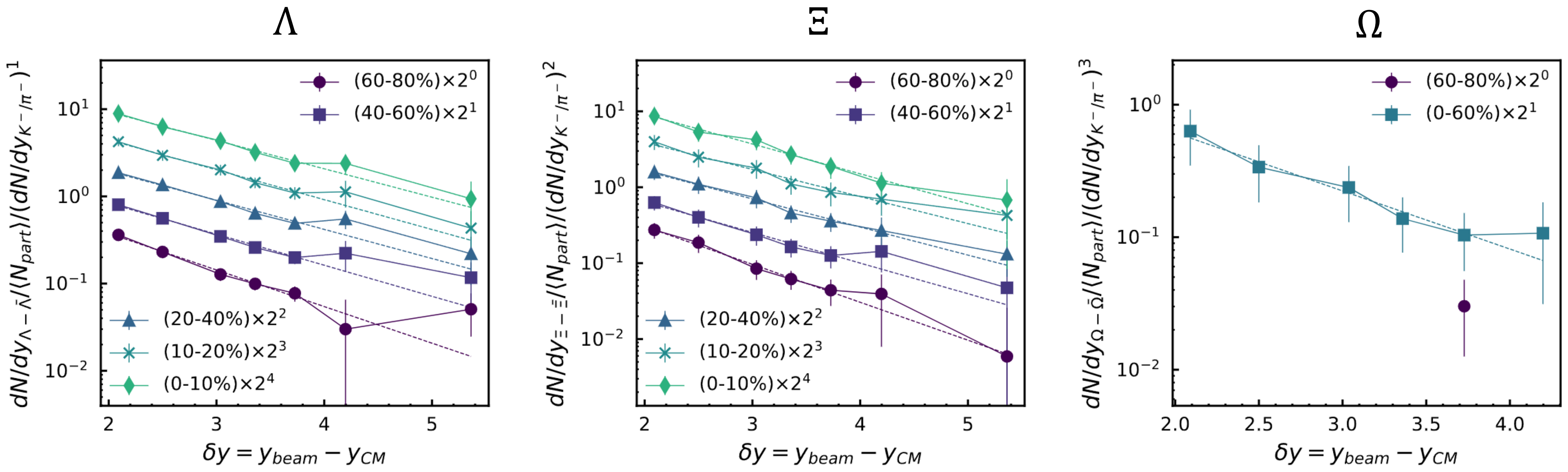
- **$K^-(s\bar{u})/\pi^-$: proxy for the rate of pair-produced s-quarks.**
  - K^+ is not used due to associated production ($p + N \rightarrow \Lambda + K^+ + N$)
  - Assume that *the QGP effects for strange mesons and baryons are the same*

- **Scale net-hyperon yields by $(K^-/\pi^-)^n$,** where n is the number of valence strange quarks



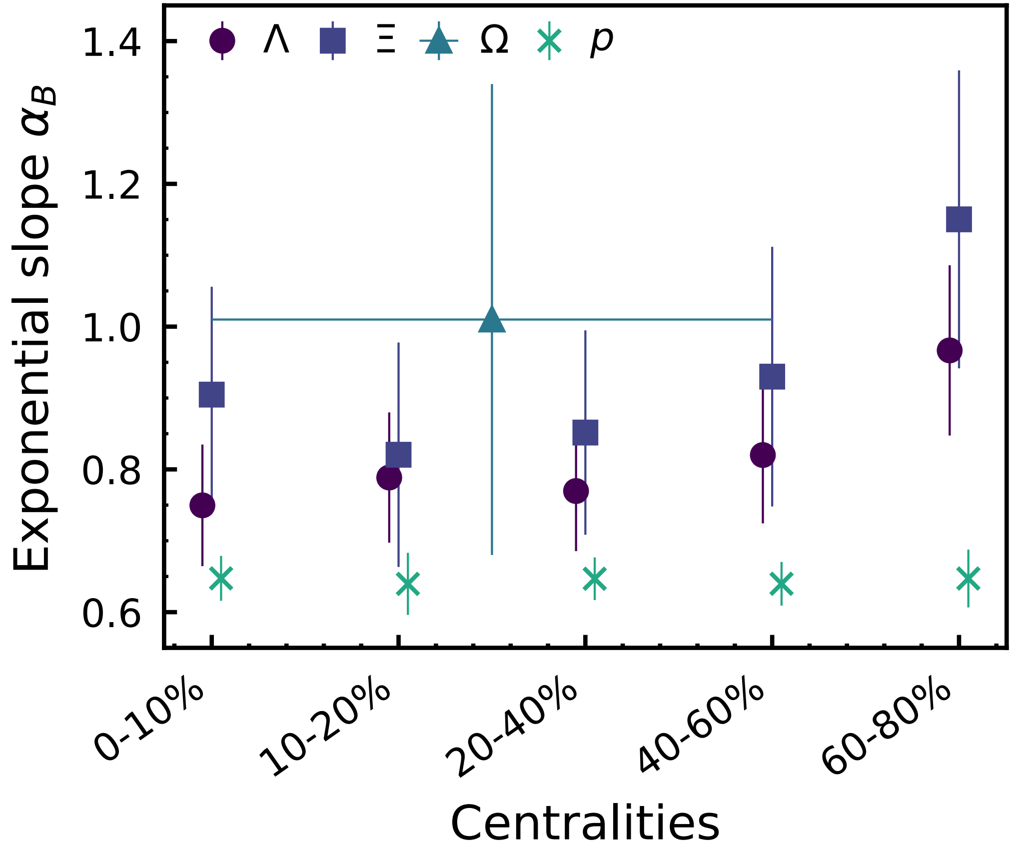
STAR, PRC 96(4):044904, 2017

Scaled net-hyperon yields



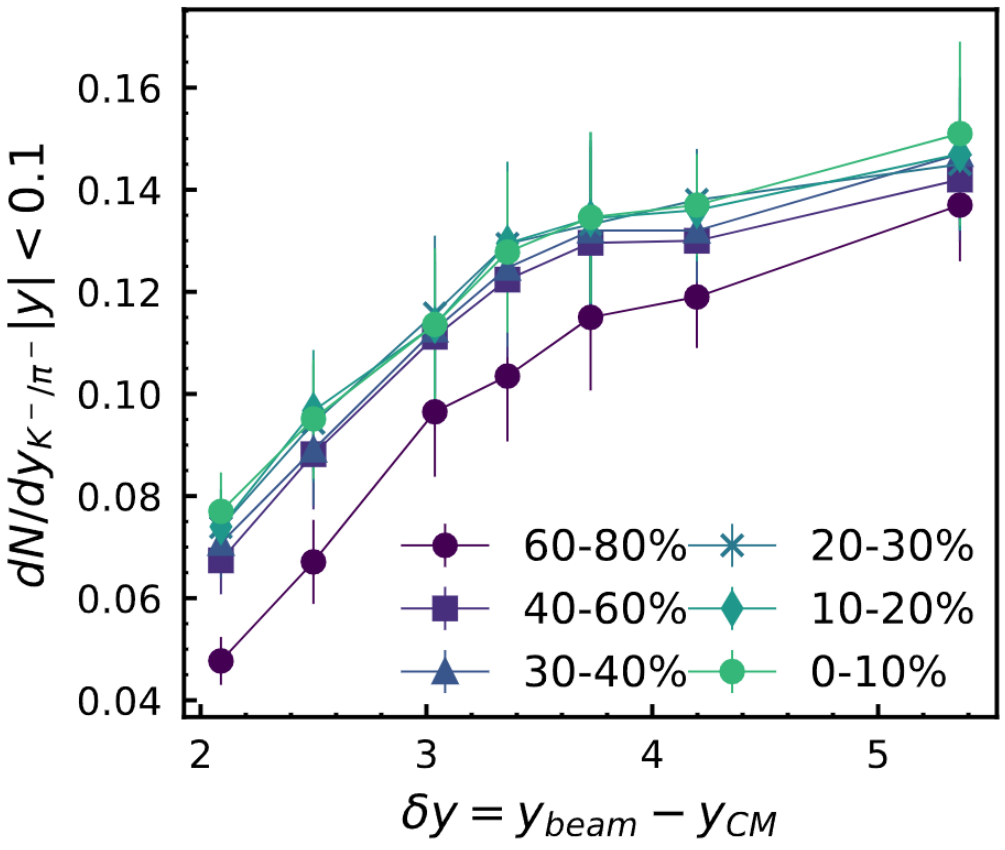
- **Follow exponential function much better**

Hyperon transport rapidity slope



- **Consistent among different hyperons within uncertainties → support the flavor blind prediction**
- Seems systematically higher than net-proton. **Maybe K^-/π^- is not the perfect proxy for s-quark production**
- **Also there seems a tendency to increase towards peripheral collisions?**

Possible effect of Δ baryon decays

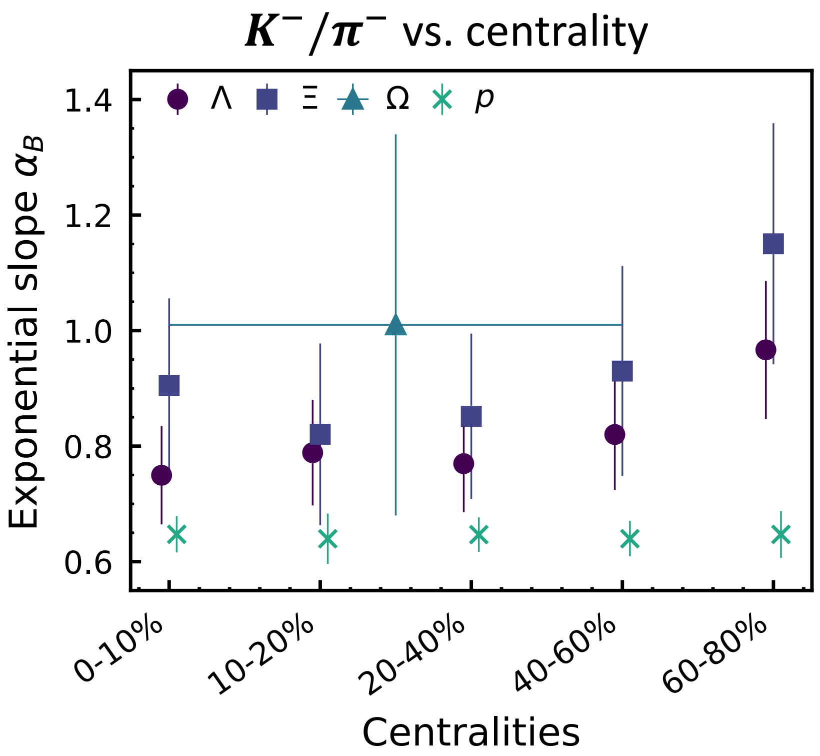


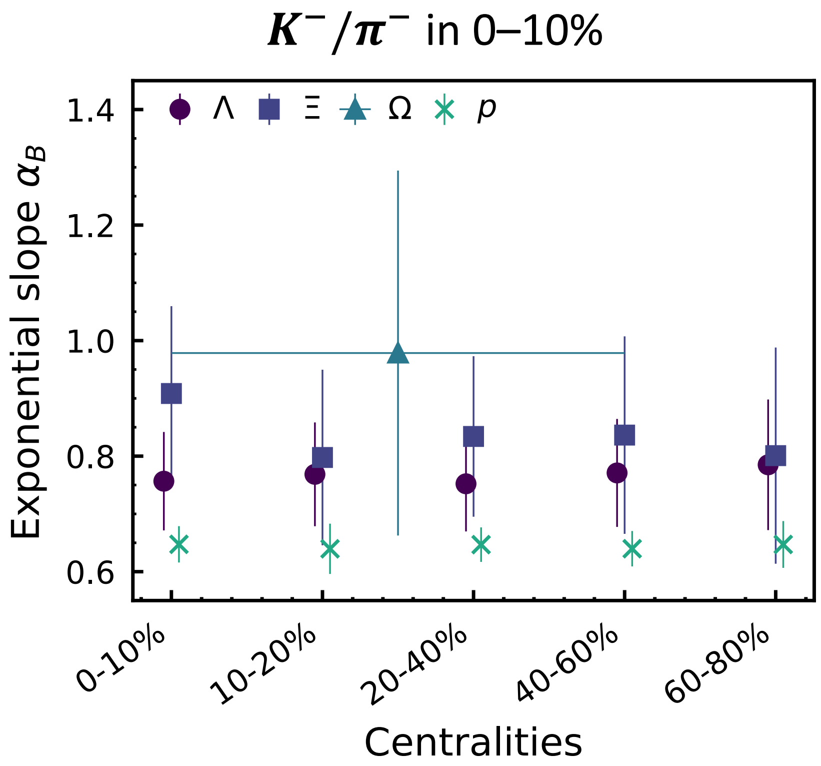
- K^-/π^- $vs. \delta y$ has **different magnitude and shape in peripheral collision**

  → **could be due to increased contribution of Δ baryon decays to pion yield**

- **We can use K^-/π^- from 0–10% for all centrality bins**

Hyperon rapidity slope vs. centrality

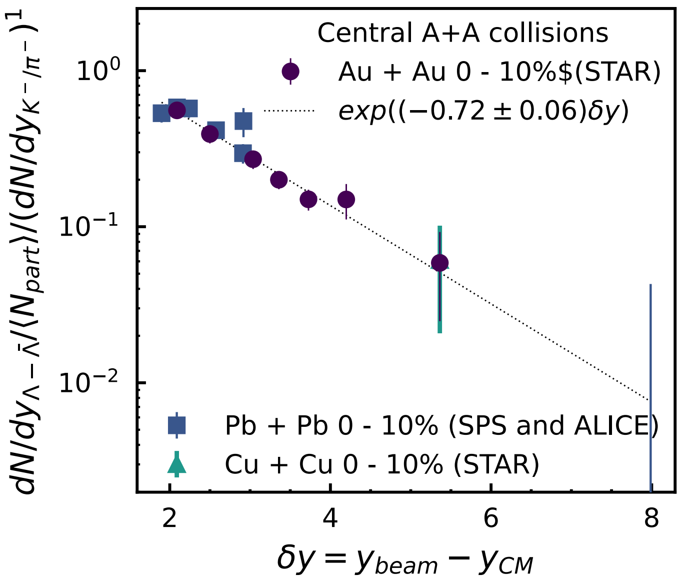




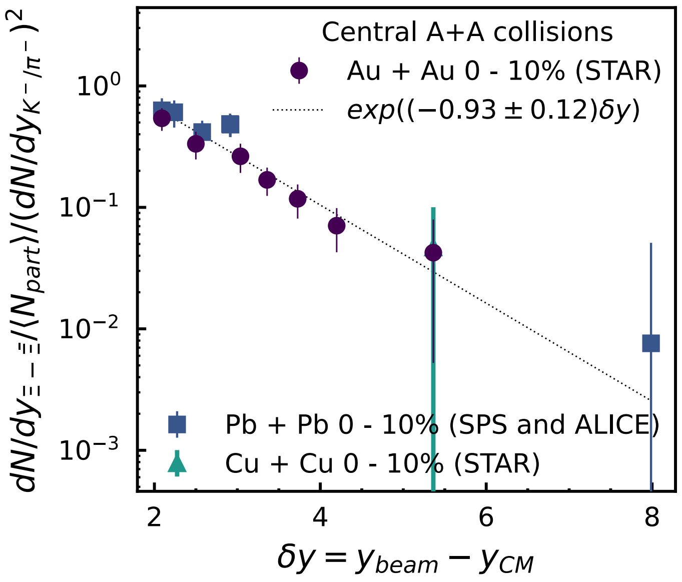
- **By using K^-/π^- from 0–10% only, α_B for Λ^0 and $\Xi^-$are independent of centrality, as for the case of proton**

How about non-STAR measurements?

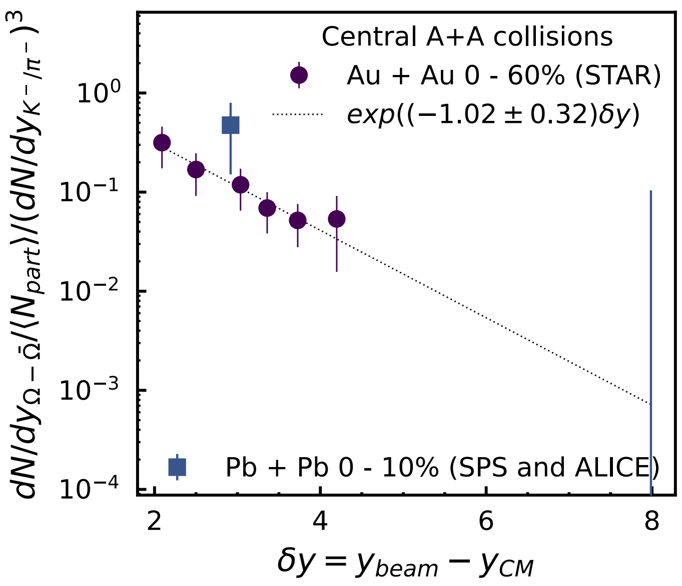
Λ



Ξ



Ω



- **Measurements in central Pb+Pb, Cu+Cu collisions follow those in Au+Au**

PRC, 78, 034918 (2008); JPG, 32, 427–442 (2006); PLB, 728, 216–227 (2014); PRL, 111, 222301 (2013);
PRC, 75, 064901 (2007); EPJC, 71, 1594 (2011); PRC, 66, 054902 (2002); PRC, 88, 044910 (2013); EPJC, 71, 1655 (2011)

Comparison to PYTHIA

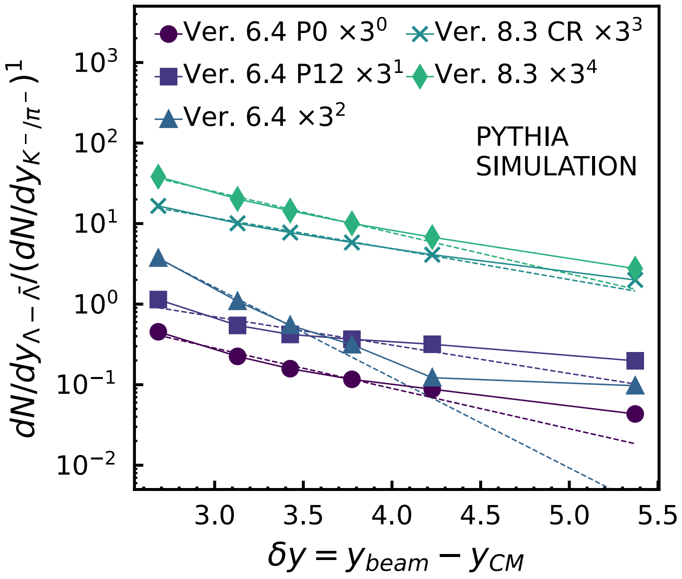
- **PYTHIA: no baryon junction in incoming protons**
  - Baryons produced mainly through “popcorn” mechanism
  - CR Mode 2: allow dynamical formation of baryon junction prior to hadronization

Event generator	Tune	Process	Hadronic decay
Pythia 6.428	Default	pysubs.msel = 1	ON
Pythia 6.428	Perugia0 (P0)	pysubs.msel = 1	ON
Pythia 6.428	Perugia2012 (P12)	pysubs.msel = 1	ON
Pythia 8.303	Default	SoftQCD:nonDiffractive = on	ON
Pythia 8.303	CR Mode 2	SoftQCD:nonDiffractive = on	ON

- Simulate p+p collisions at the same energies as Au+Au (7.7 – 200 GeV)

Fit PYTHIA distributions

Λ



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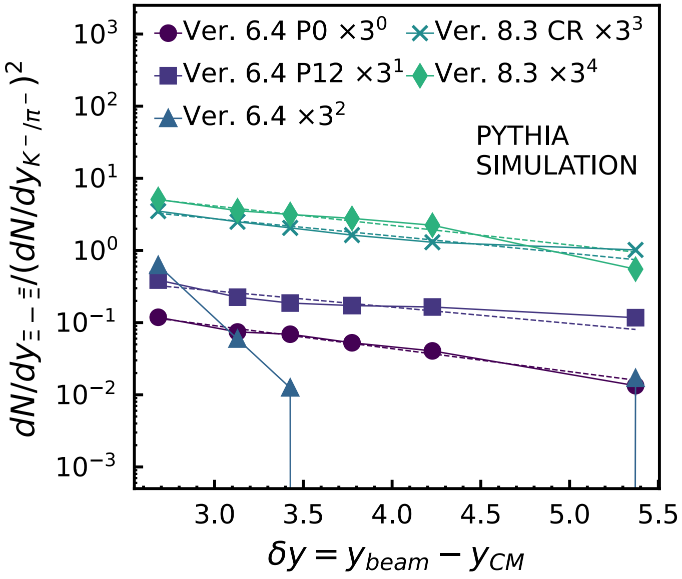
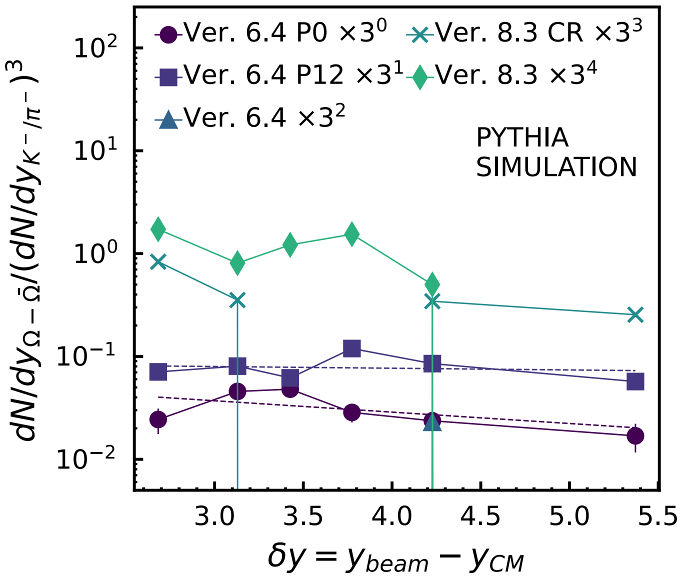


Ω



- **Exponential fit does not work as well as in data**
- There are cases of negative net-Ξ^- and net-Ω^- yields, for which no fitting is performed

PYTHIA vs. data

Species	Data (0-60%)	Ver. 6.4	Ver. 6.4 (P0)	Ver. 6.4 (P12)	Ver. 8.3	Ver. 8.3 CR Mode 2
Λ	0.72 ± 0.07	2.58 ± 0.03	1.15 ± 0.01	0.81 ± 0.01	1.18 ± 0.01	0.88 ± 0.01
Ξ	0.85 ± 0.13	N.A.	0.73 ± 0.05	0.52 ± 0.05	0.62 ± 0.08	0.55 ± 0.06
Ω	0.98 ± 0.32	N.A.	0.25 ± 0.10	0.04 ± 0.15	N.A.	N.A.
p	0.65 ± 0.07	0.74 ± 0.05	0.72 ± 0.02	0.35 ± 0.01	0.98 ± 0.02	0.69 ± 0.02

- Statistical errors only for PYTHIA predictions
- **Overpredict slope for net-Λ, but underpredict for net-Ξ^- and net$-\Omega^-$**
- **Stronger flavor dependence in PYTHIA than that in data**
- **CR Mode 2 improves agreement with data, but still not enough**

Summary

- **Recently, STAR collaboration presented multiple results that favor baryon junction over valence quarks as the baryon number carriers**
- **We test the baryon junction prediction of flavor blindness using hyperons**
  - STAR Au+Au data from 7.7-200 GeV
  - Need to account for s-quark production suppression for net-hyperon yields
- **Similar a_B values for different hyperons within uncertainties and independent of event centrality → consistent with baryon junction picture**
- **No PYTHIA versions or tunes can describe slope parameters for all baryons**
  - Including dynamical junction production helps, but not enough

Outlook

- STAR Beam Energy Scan Phase-II data can greatly improve precision of net-hyperon yield measurements, especially for Ω^-

- Measurements of hyperon yields in d+Au collisions at different energies can avoid the complication of QGP effects on strange hadrons

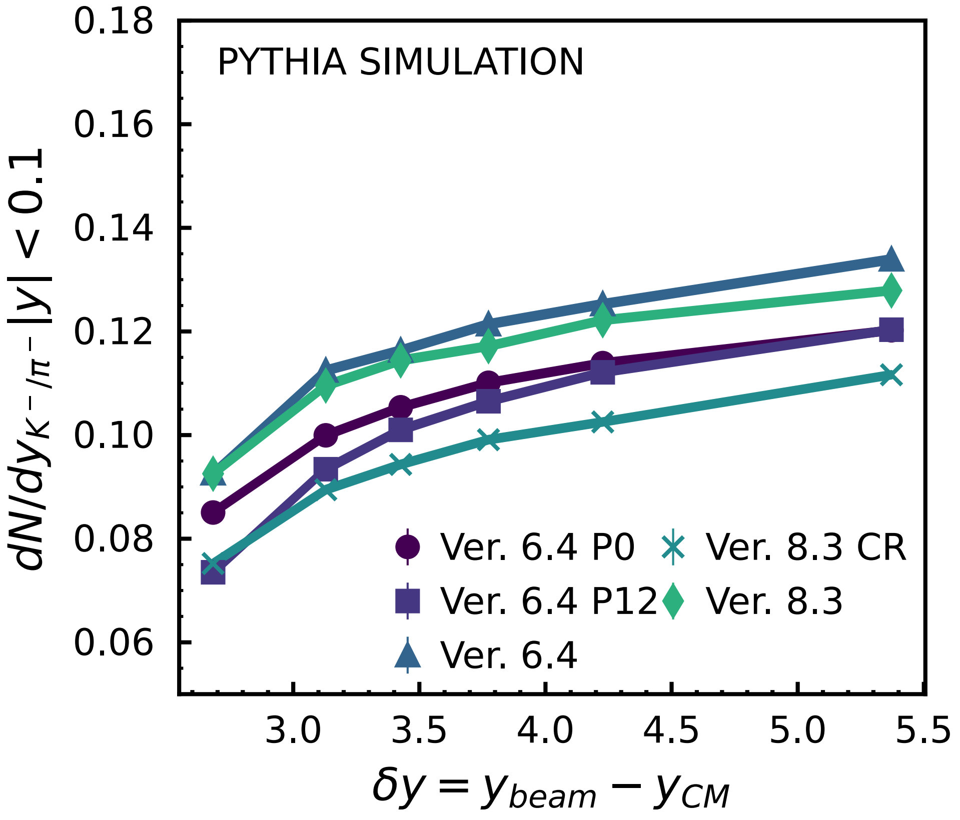
- Test the flavor blindness and associated forwad meson production at Electron-Ion Collider

D. Frenklakh, et. al. PLB 853, 138680 (2024)

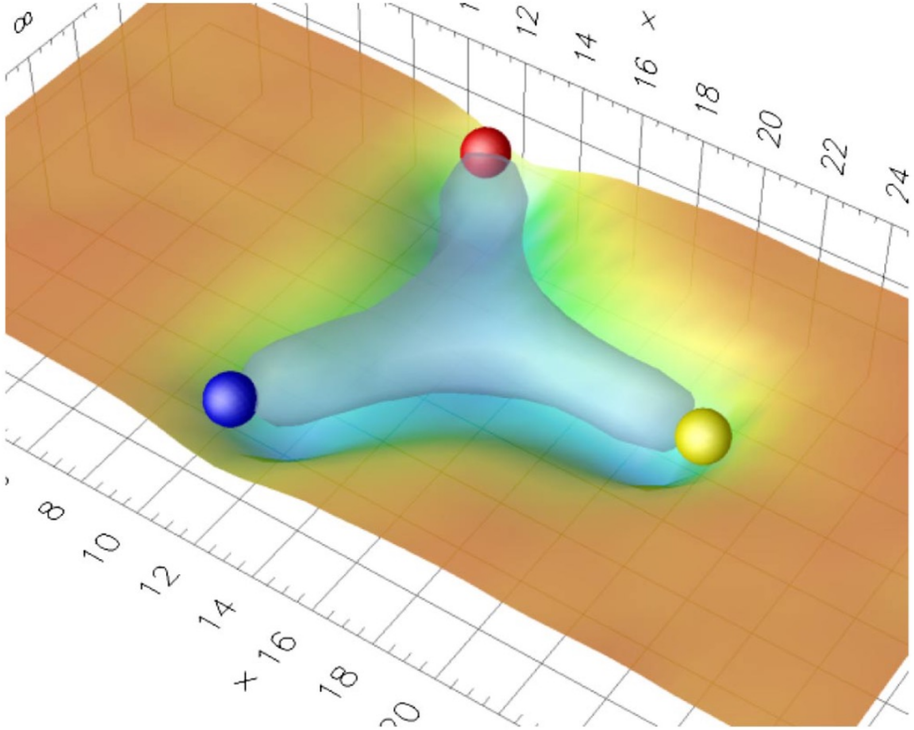
Backup slides

K^-/π^- ratio in PYTHIA

- **Reject pions from eta, D mesons, Lambda, Xi, and Omega baryon decays**



Y-Shaped baryon flux-tube in lattice QCD



F. Bissey, *et al* Phys. Rev. D **76**, 114512 (2007)

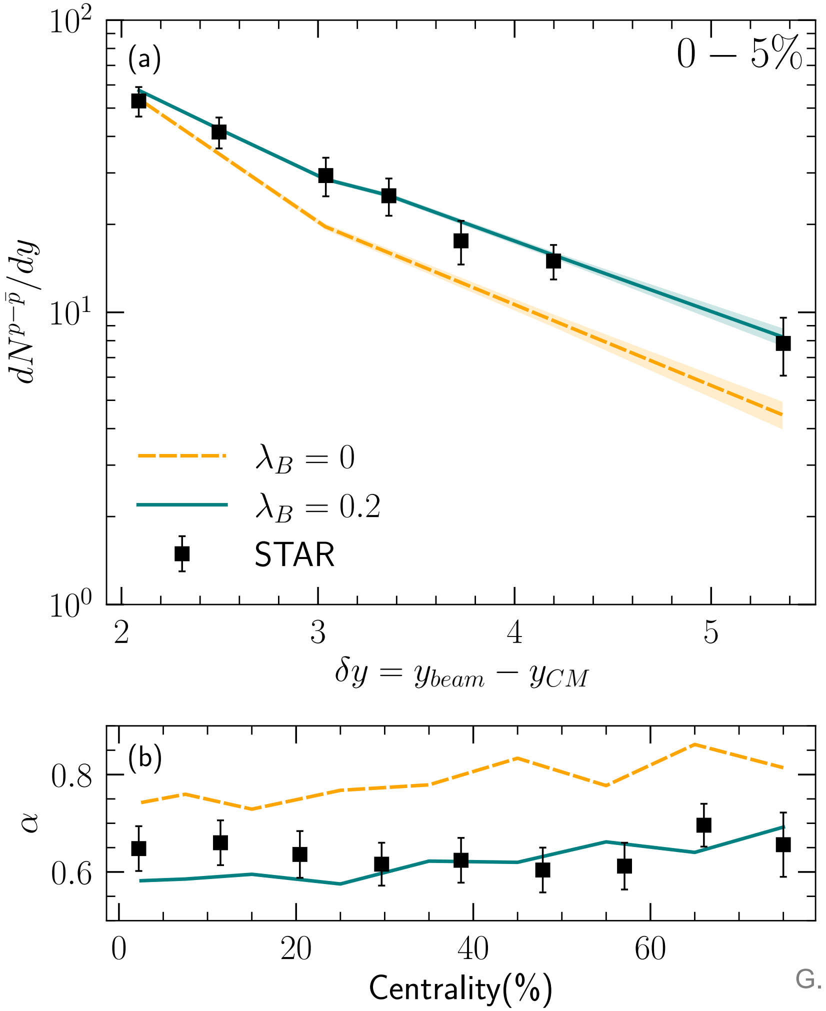
- **Some lattice calculations have suggested the formation of a Y-shaped color flux tube among the three quarks at long distances**

T. T. Takahashi, *et al* Phys. Rev. Lett. **86**, 18 (2001)

T. Takahashi, *et al*, Phys. Rev. D **65**, 114509 (2002)

String junction model

- **3+1D hybrid model:** GLAUBER + MUSIC + URQMD
- **String junction where the baryon charge of the string can fluctuate towards the center of the string with tuning parameter λ_B**
  - $\lambda_B = 0.2$ closer to the dN/dy of net-protons at STAR



G. Pihan, et. al., arXiv:2405.19439

Net-baryon (B) vs. net-charge difference (ΔQ)

- Isobar: ${}^{96}_{44}\boldsymbol{Ru} + {}^{96}_{44}\boldsymbol{Ru}$ and ${}^{96}_{40}\boldsymbol{Zr} + {}^{96}_{40}\boldsymbol{Zr}$.
- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$
- $\Delta Q = \left[(N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_{\bar{p}})\right]_{\mathrm{Ru}} - [\,]_{\mathrm{Zr}}$
- **Valence quarks picture:** $B/\Delta Q \approx A/\Delta Z$ **at |y| < 0.5**
- **Junction picture:** $B/\Delta Q > A/\Delta Z$
    - Enhanced mid-rapidity emission.