Chemical potential difference between isobar systems and net-hyperon yields dependence on beam energy

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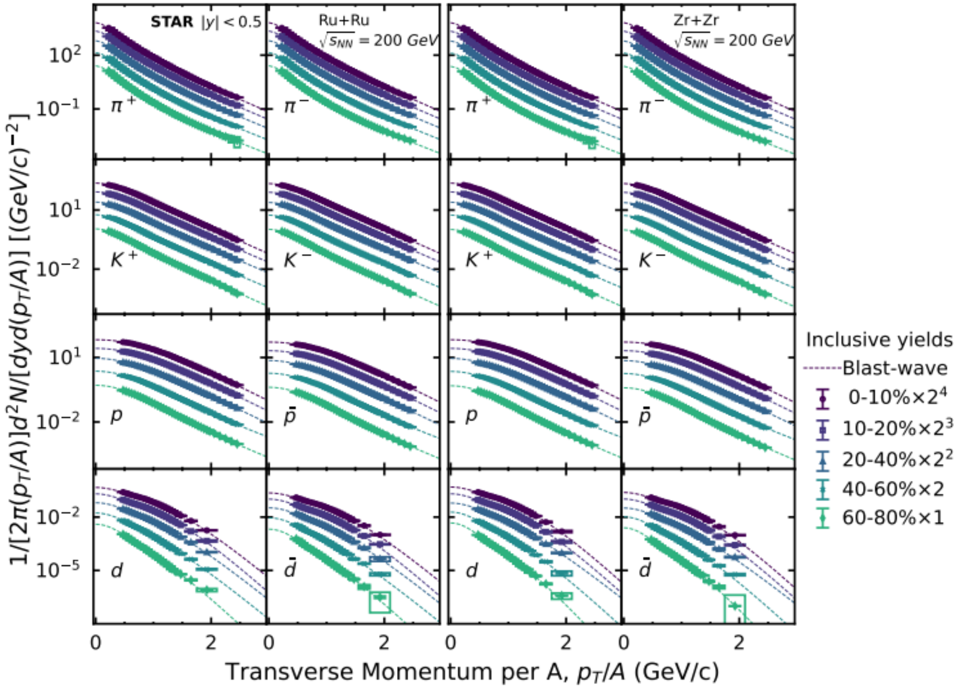
APS-GHP meeting

Supported in part by:

Motivation

- Study bulk properties of QCD matter.
- Fit particle yields to thermal model.
  - Was done for Au+Au and Pb+Pb [2-4].
  - $\pi^{\pm}, K^{\pm}, p$ and $\bar{p}$ transverse momentum spectrum.
  - Gives chemical freeze-out parameters.
- STAR measured spectrum for isobar (Ru+Ru and Zr+Zr) collisions [1].
  - $\sqrt{s_{NN}} = 200$ GeV, |y| < 0.5.
  - Originally used to studies **baryon junction** (!!! Important, will come back).



Isobar spectrum from Ref. [1]

[1]: arXiv:2408.15441
[2]: Phys. Rev. C 96 (2017) 44904
[3]: Phys. Rev. C 79 (2009) 34909
[4]: Phys. Rev. Lett. 133, 092301

Motivation (cont.)

- A step further: **Difference between Ru and Zr**.
  - Same mass (A=90), different N.O. protons.
  - Probes **isospin contribution**.

- Problem: Large uncertainty.
  - Ru - Zr parameters = small number $\pm$ large number.

- Solution: ΔQ tricks.
  - $Q \equiv (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} - N_{K^-} - N_{\bar{p}})$.
  - $\Delta Q \equiv Q_{Ru+Ru} - Q_{Zr+Zr}$.
  - **Measured in Ref. [1].**

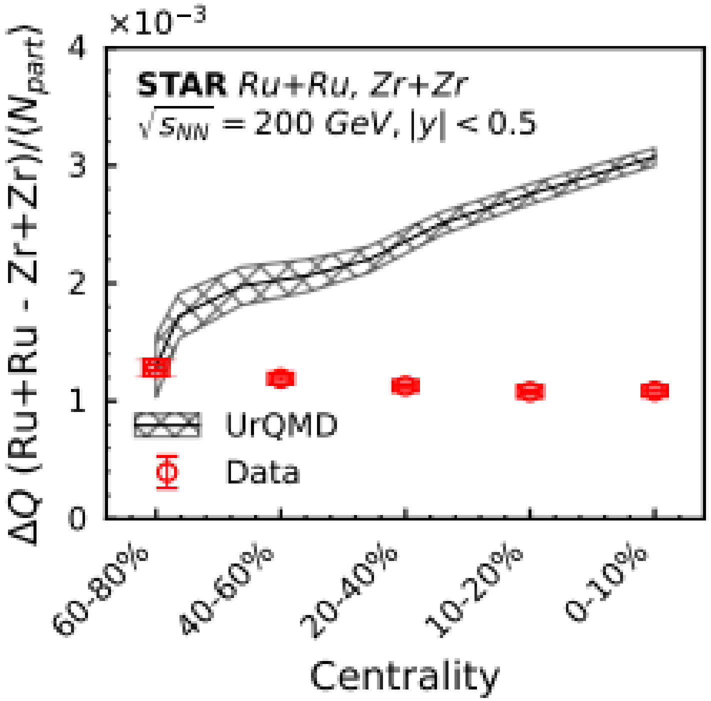


Figure from Ref. [1]

[1]: arXiv:2408.15441

Net-Charge difference (ΔQ)

- $\Delta Q = \left[\left(N_{\pi^+} + N_{K^+} + N_p\right) - \left(N_{\pi^-} + N_{K^-} + N_{\bar{p}}\right)\right]_{\text{Ru}} - []_{\text{Zr}},$
- Naïve estimation: $\Delta Q = 0 \pm$ large sys. Uncertainty.
- Define $R2_\pi = \frac{\left(N_{\pi^+}/N_{\pi^-}\right)_{Ru}}{\left(N_{\pi^+}/N_{\pi^-}\right)_{Zr}},$
- Let $N_\pi = 0.5 \times \left(N_{\pi^+} + N_{\pi^-}\right)$, then change of variable,
- $\Delta Q \approx N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p\left(R2_p - 1\right).$
- Double ratio cancels sys. Uncertainty => reduction in sys. Uncertainty for $\boldsymbol{\Delta} Q$.
- **Can also estimate ΔQ for pions, kaons and proton separately!**

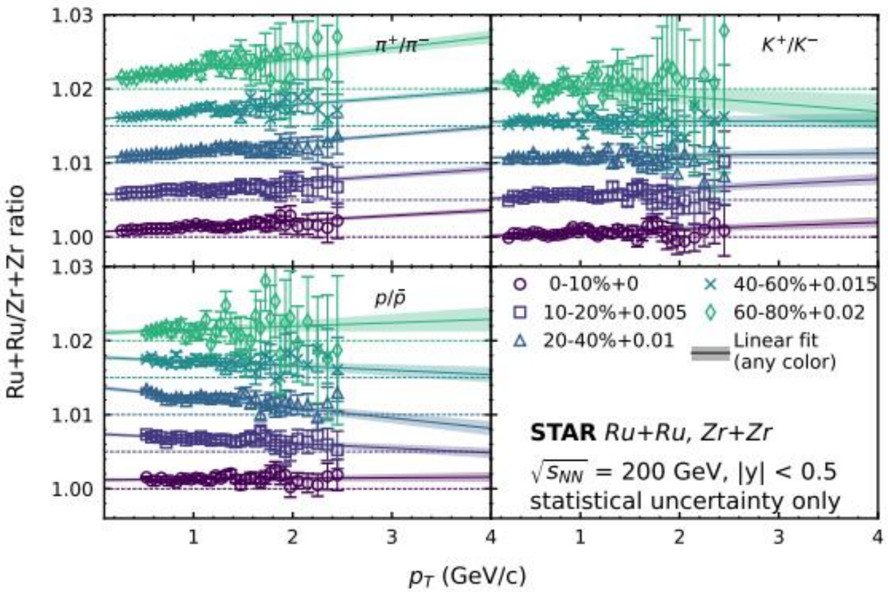
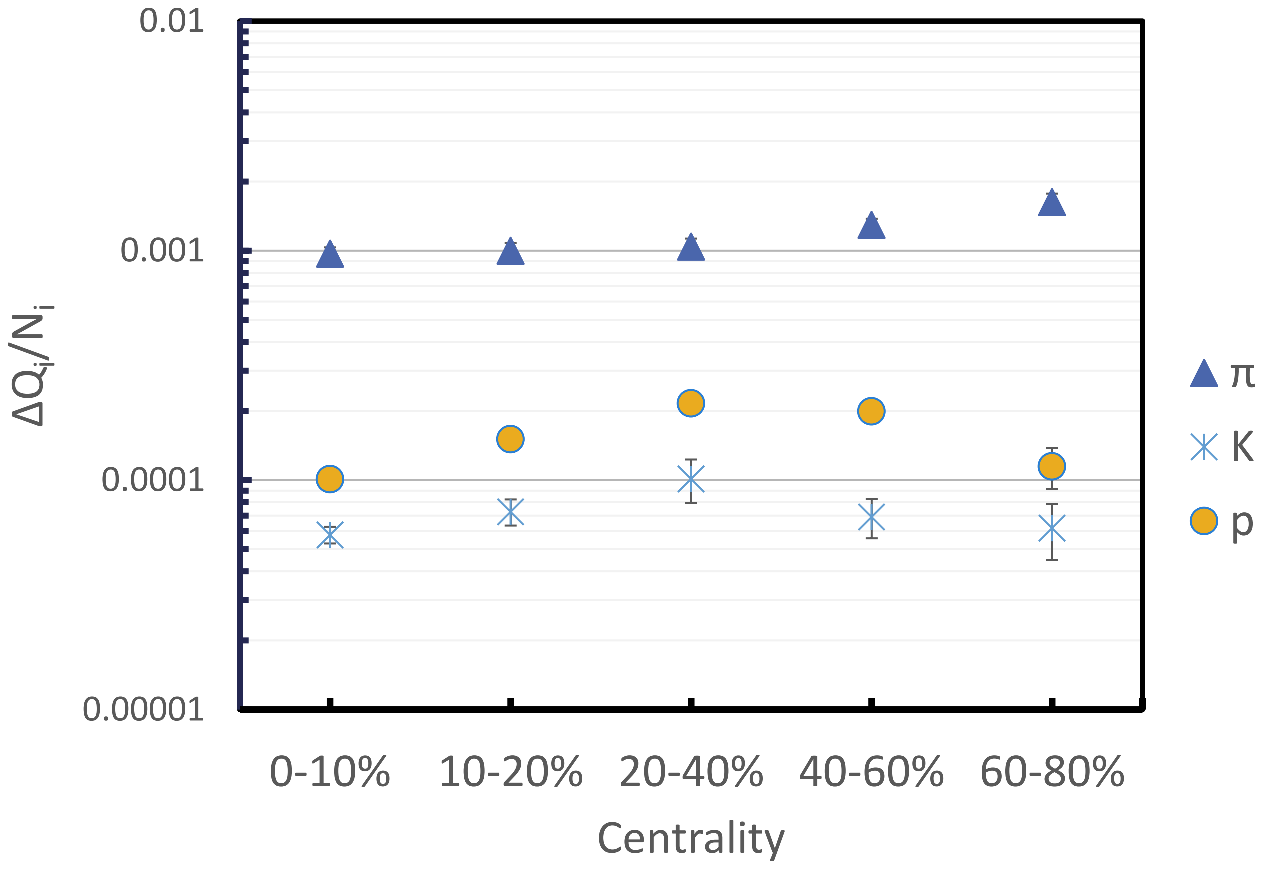


Figure from Ref. [1]

[1]: arXiv:2408.15441

$\Delta Q/N_i$ by species, $i = \pi, K$ and p



- Ref. [1] only shows ΔQ sum of all 3 particle species.
- Re-analyze data from Ref. [1] for ΔQ of each particle.
- $\boldsymbol{\Delta Q_i/N_i}$ places constrains on $\boldsymbol{\Delta\mu = \mu(Ru) - \mu(Zr)}$

[1]: arXiv:2408.15441

THERMUS thermal model settings Bayesian analysis, uniform prior

Parameters to fit

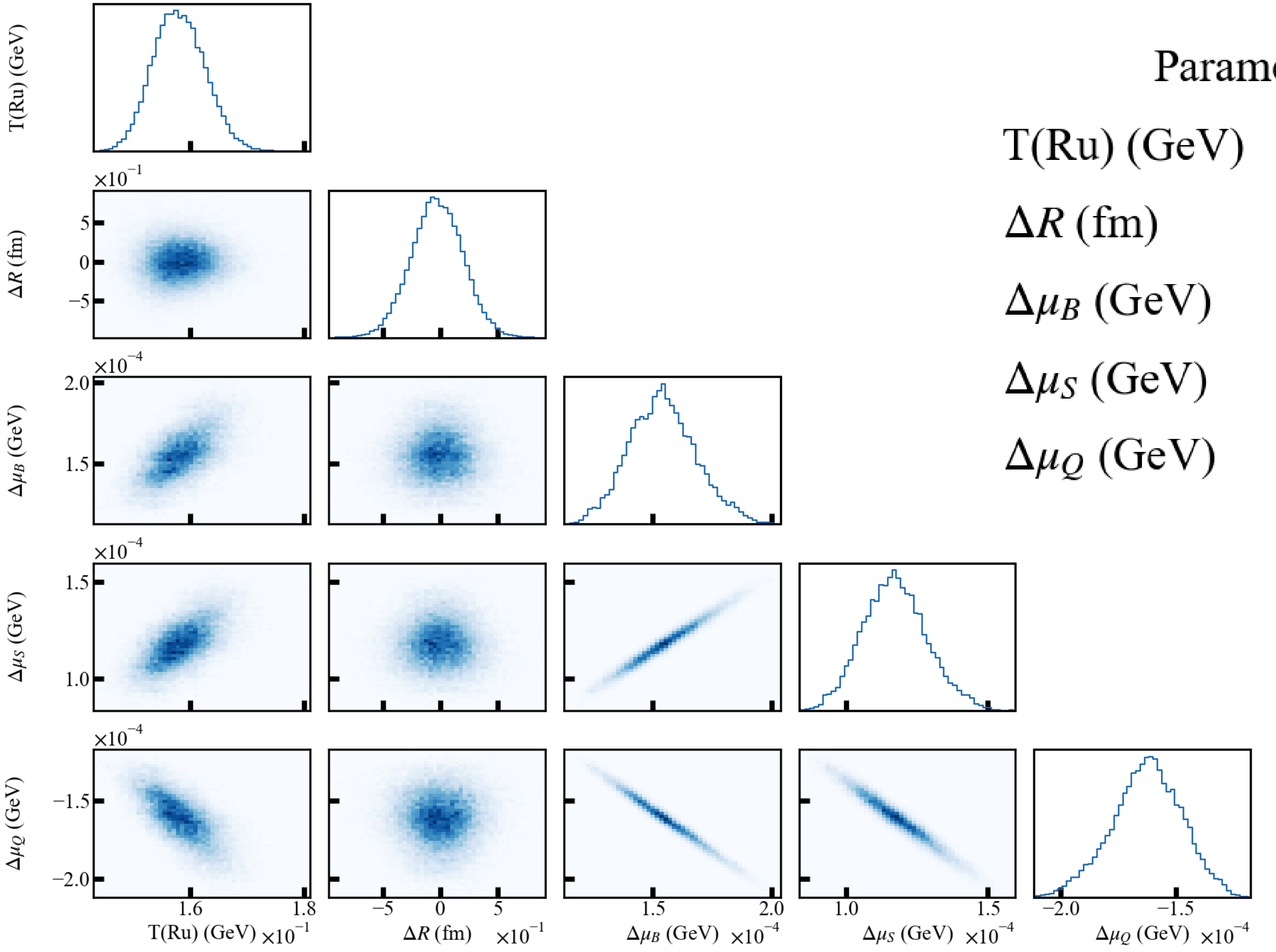
1. T(Ru and Zr)*: 0.13 – 0.17 GeV
2. μ_B(Ru): -0.05 – 0.05 GeV
3. μ_S(Ru): -0.01 – 0.01 GeV
4. μ_Q(Ru): -0.02 – 0.02 GeV
5. Υ_S(Ru): 0.5 – 1.0
6. R: 1 – 7.5 fm
7. **ΔR: -1.0 – 1.0 fm**
8. **$\Delta\mu_B = \mu_B$(Zr) – μ_B(Ru): -0.03 – 0.03 GeV**
9. **$\Delta\mu_S$: -0.003 – 0.003 GeV**
10. **$\Delta\mu_Q$: -0.002 – 0.002 GeV**

*T(Ru) = T(Zr) as chemical freeze-out temperature is universal

Experimental data

- N_{π^+}, $N_{\bar{p}}/N_p$, N_p/N_{π^+}, N_{π^+}/N_{π^-}, N_{K^+}/N_{K^-}, N_{K^+}/N_{π^+}.
- Inclusive yields and ratios.
  - Both Ru and Zr.
- $\Delta Q_\pi/N_\pi, \Delta Q_K/N_K, \Delta Q_p/N_p$
  - $\Delta Q_\pi/N_\pi = R2_\pi - 1.$
  - $\Delta Q_K/N_K = R2_K - 1.$
  - $\Delta Q_p/N_p = R2_p - 1.$

Bayesian analysis posterior at 0-10% centrality
(Selected parameters only)



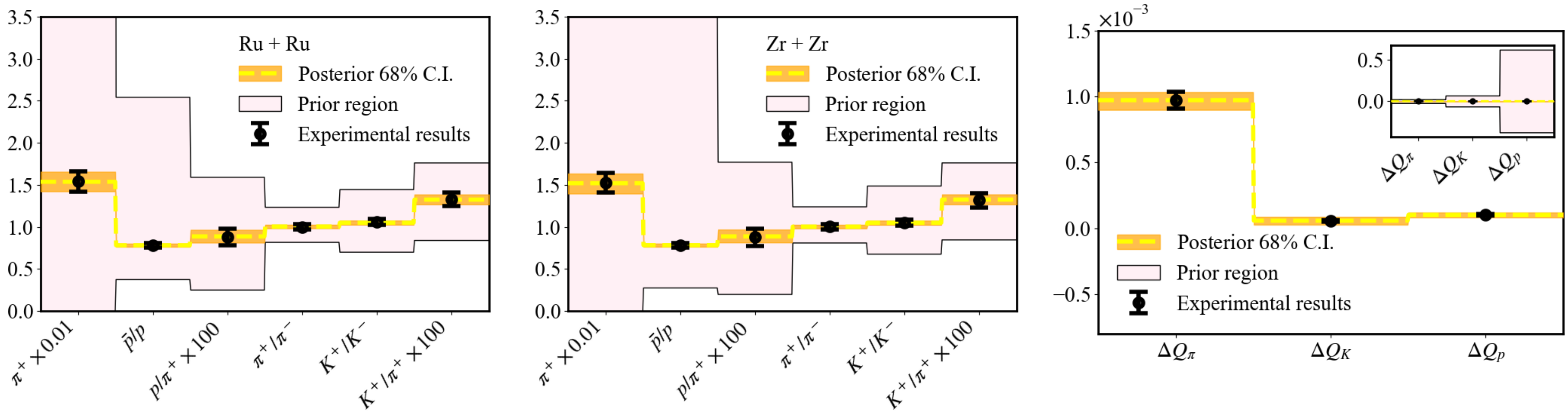
Parameter	Value
T(Ru) (GeV)	$=0.158^{+0.005}_{-0.004}$
ΔR (fm)	$=-0.01^{+0.22}_{-0.22}$
$\Delta\mu_B$ (GeV)	$=0.000155^{+1.4e-05}_{-1.4e-05}$
$\Delta\mu_S$ (GeV)	$=0.000118^{+1.2e-05}_{-1.1e-05}$
$\Delta\mu_Q$ (GeV)	$=-0.000161^{+1.5e-05}_{-1.5e-05}$

Positive $\Delta\mu_B$,
positive $\Delta\mu_S$,
negative $\Delta\mu_Q$

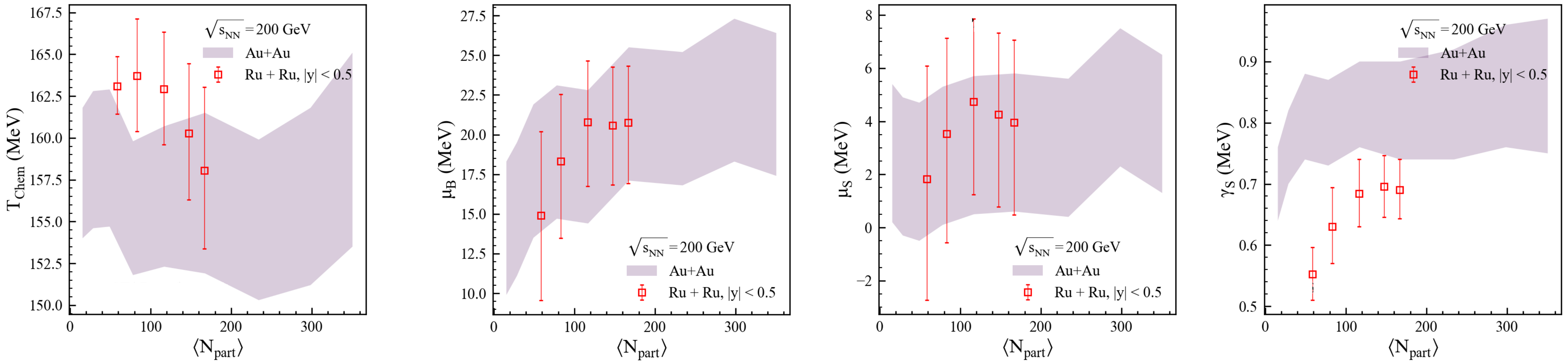
$\Delta\mu_B/\Delta\mu_Q$=-0.96+/-0.02

THERMUS agreement with data (0-10%)

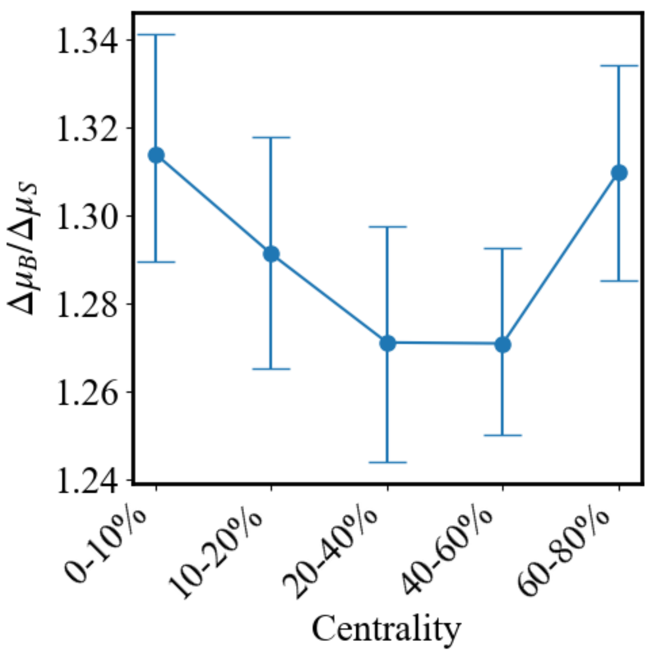
Credible interval (C.I.) on predictions

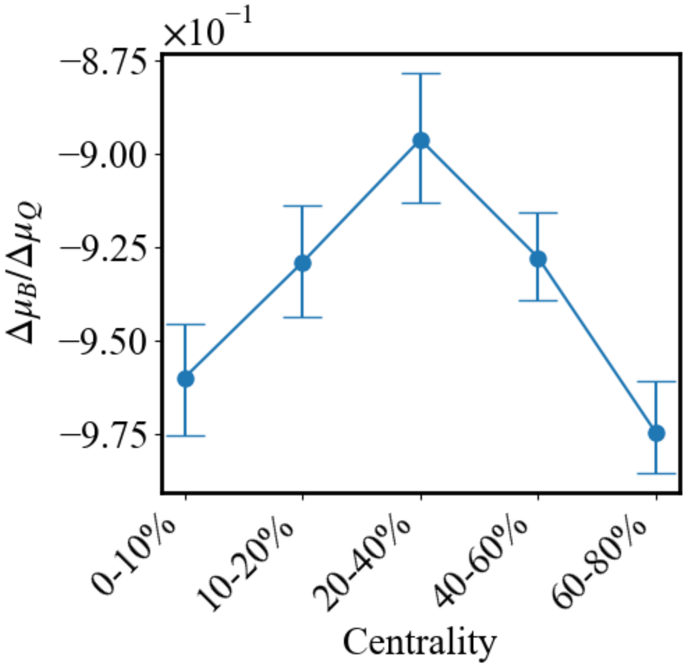


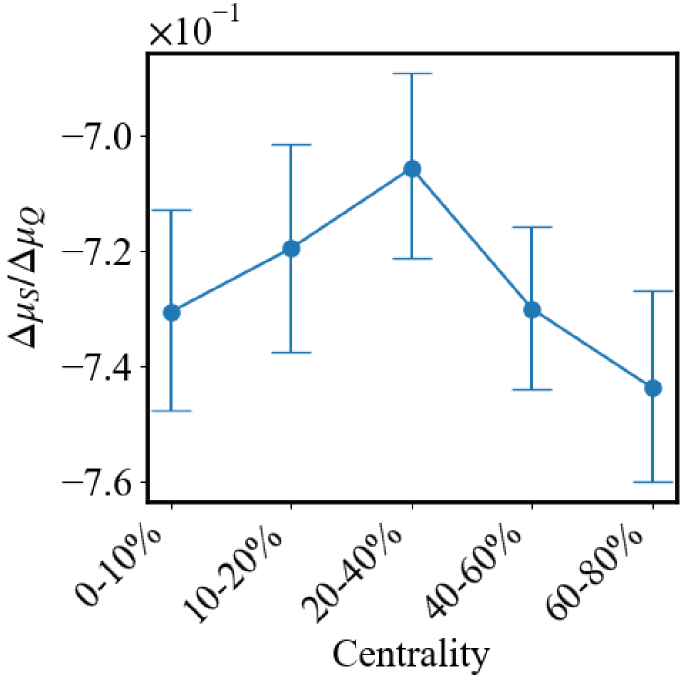
Compare parameters to published results



Implications (work in progress)



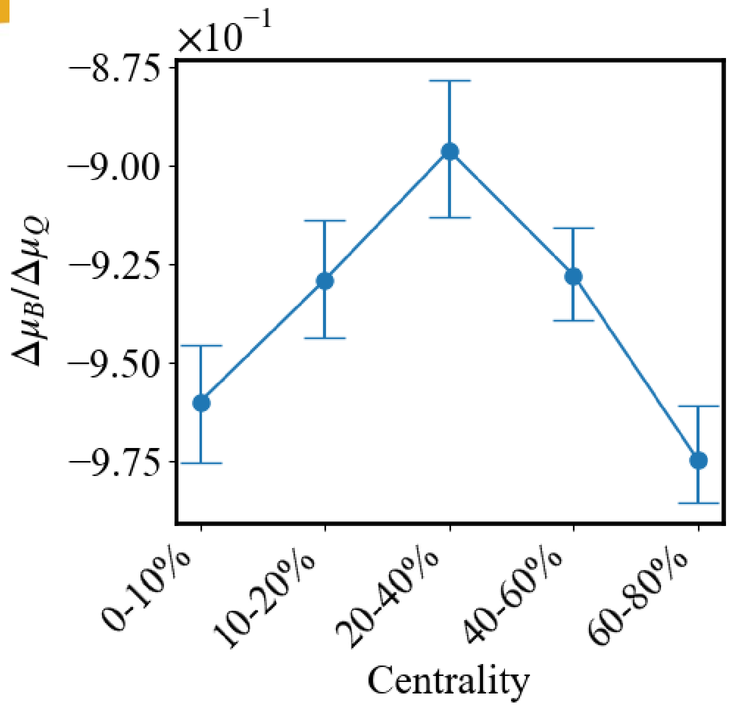


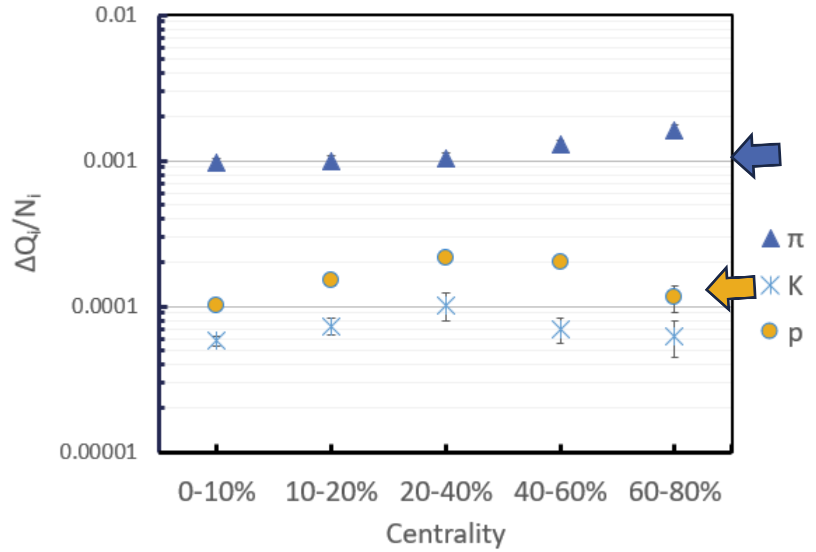


- **Accurate measurement on how chemical potentials changes with Z.**
- Ratios could be slopes along chemical freeze-out plane?
- Additional constraint on quark matter diagram?
- Curiously, $\Delta\mu_B/\Delta\mu_Q$ ~ -1. Any reasons?

$\Delta\mu_B/\Delta\mu_Q$ ~ -1 across centralities

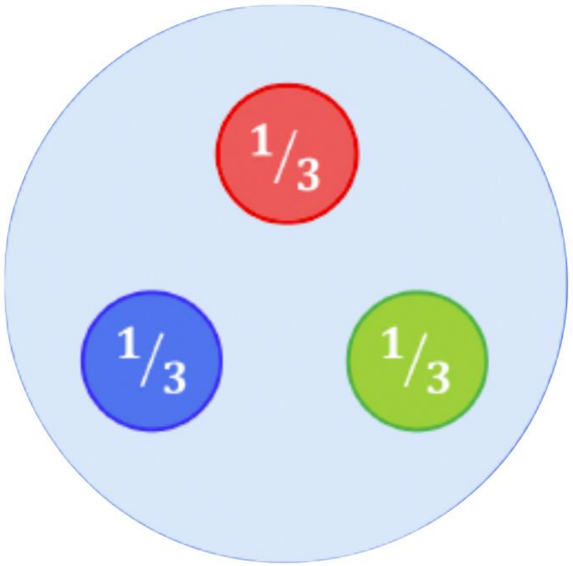
- $\frac{N_{\pi^+}}{N_{\pi^-}} = e^{2\mu_Q/T} \rightarrow N_{net-\pi} \equiv N_{\pi^+} - N_{\pi^-} \approx \frac{2\mu_Q}{T} N_{\pi^+}$
- Therefore, $\mu_Q = \frac{T}{2}\frac{N_{net-\pi}}{N_{\pi^+}} \rightarrow \Delta\mu_Q = \frac{T}{2}\frac{\Delta Q_\pi}{N_{\pi^+}}$.
- Similarly, $N_{net\ p} \approx \frac{2(\mu_Q+\mu_B)}{T} N_p, \Delta\mu_B = \frac{T}{2}\left(\frac{\Delta Q_p}{N_p} - \frac{\Delta Q_\pi}{N_{\pi^+}}\right)$.
- $\frac{\Delta\mu_B}{\Delta\mu_Q} = \frac{\Delta Q_p/N_p - \Delta Q_\pi/N_\pi}{\Delta Q_\pi/N_\pi}$ assuming $N_{\pi^+} \approx N_{\pi^-} \equiv N_\pi$
- $\Delta\mu_B/\Delta\mu_Q$ ~ -1 is a consequence of $\Delta Q_p/N_p$ << $\Delta Q_\pi/N_\pi$ (See plot).
  - Courtesy: David Frenklakh for derivation.
- **Implications**: Baryon number transport to mid-rapidity is independent of isospin, but **NOT** charge transport.
- **Baryon-number ≠??? Charge-number carriers in collisions.**





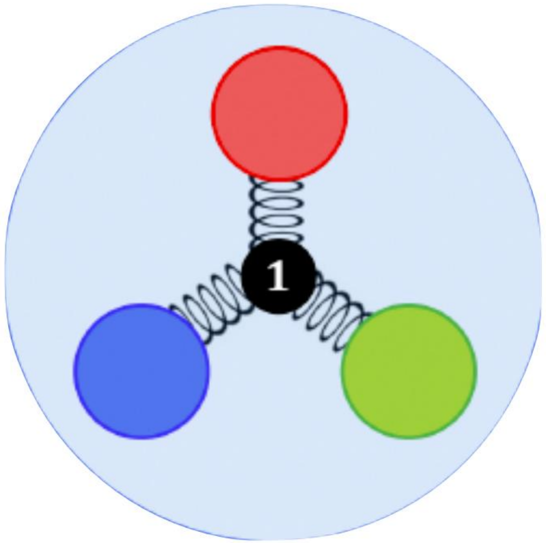
Valence quark vs. baryon junction

Valence quark



Conventional picture

Baryon junction [1, 2]



[1]: Artru, X. String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (1975).
[2]: Rossi, G. C. & Veneziano, G. A Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (1977)

Another evidence for junction: Net-hyperons vs beam energies

Physics Letters B, *860*, 139205.

Eur. Phys. J. C (2024) 84:590.

Baryon transport from junction

- Valence quarks carry most of the momentum.
  - contracted into thin “pancakes”.
  - Less time to interact => most pass right through.
- Junction carries lower momentum.
  - Made of low-x gluons
  - Enhanced baryon transport to mid-rapidity

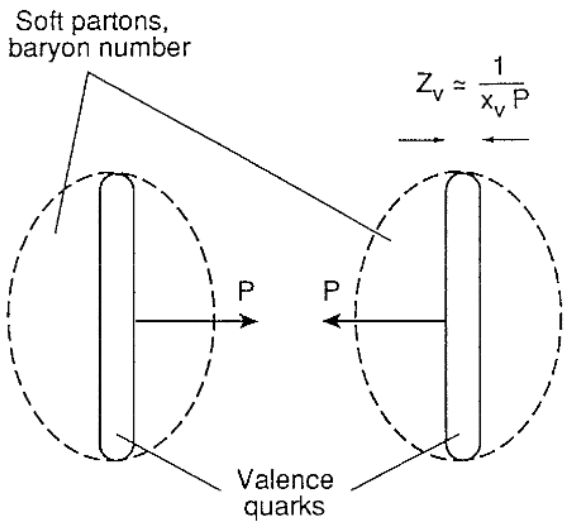
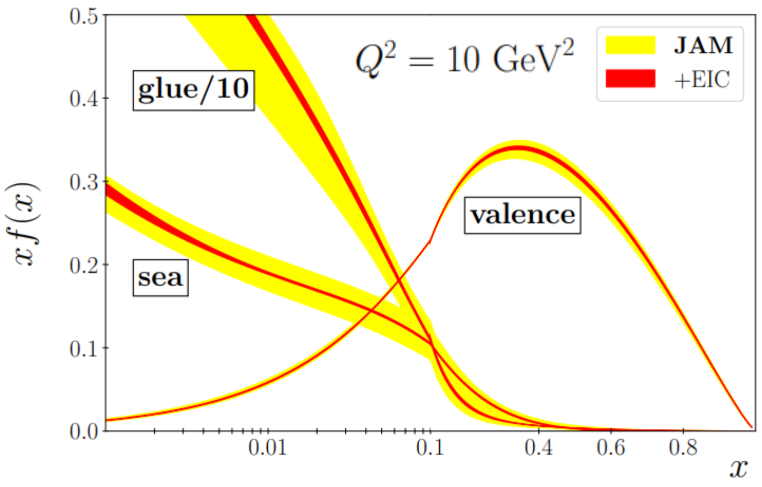


Figure from D. Kharzeev, Physics Letters B 378, 238 (1996)

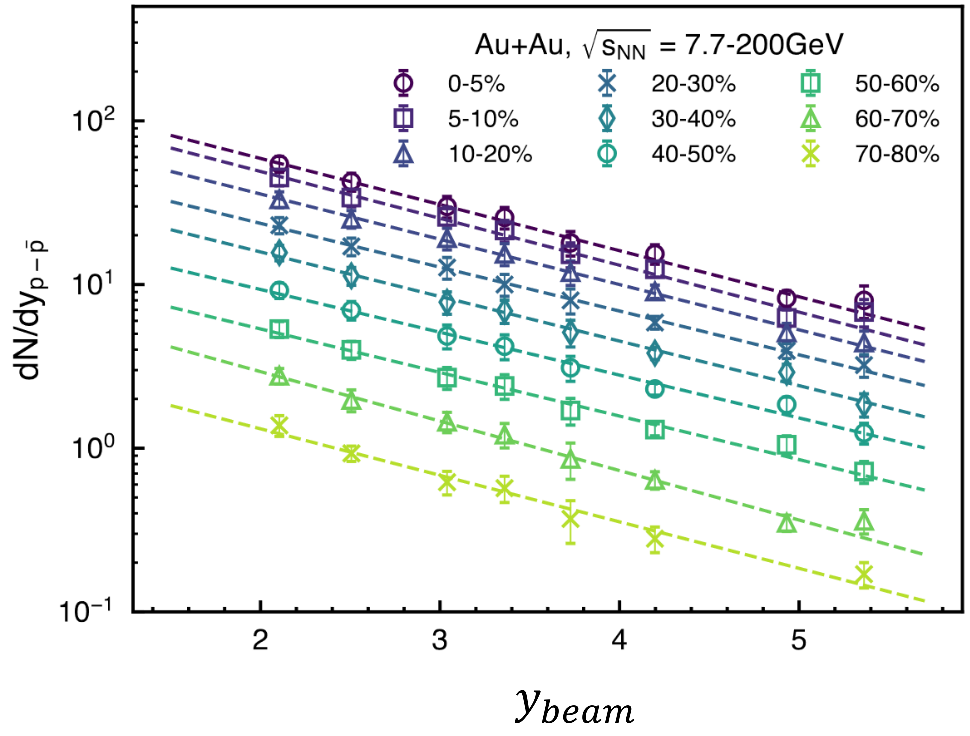


R. Abdul Khalek et al, arXiv:2103.05419 [physics.ins-det]

Mid-rapidity emission enhancement
Quantify by a_B

- Regge theory: $dN_{net-p}/dy \propto e^{-a_B y_{beam}}$.
- Measured $a_B \approx 0.65$.
- **Too small (flat)** compared to PYTHIA and HERWIG predictions [1].
- Slope does not depend on centrality
  - Valence quark transport depends on multiple scatterings and thus on centrality.
  - UrQMD shows centrality dependence [2].

Au + Au BES-I data [3, 4]



[1]: Eur. Phys. J. C (2024) 84:590
[2]: arXiv:2408.15441
[3]: PRC 79, 034909 (2009)
[4]: PRC 96, 044904

A step further: Net-hyperons

- **Expectation**: Same a_B for $\Lambda^0, \Xi^-, \Omega^-$ in junction picture.
  - Favor independent.
  - Test: $dN_{B-\bar{B}}/dy|_{|y|<0.5}$ $v.s. Y_{beam}$, fit with $y \propto e^{-a_B Y_{beam}}$.
  - Data from BES-I [1-4].

- **Complication**:
  - Below s-quark threshold $dN_{B-\bar{B}}/dy|_{|y|<0.5} = 0$ vs. model prediction $e^{-a_B Y_{beam}} > 0$.
  - $dN_{B-\bar{B}}/dy|_{|y|<0.5}$ depends on both baryon stopping **AND** s-quark production rate.

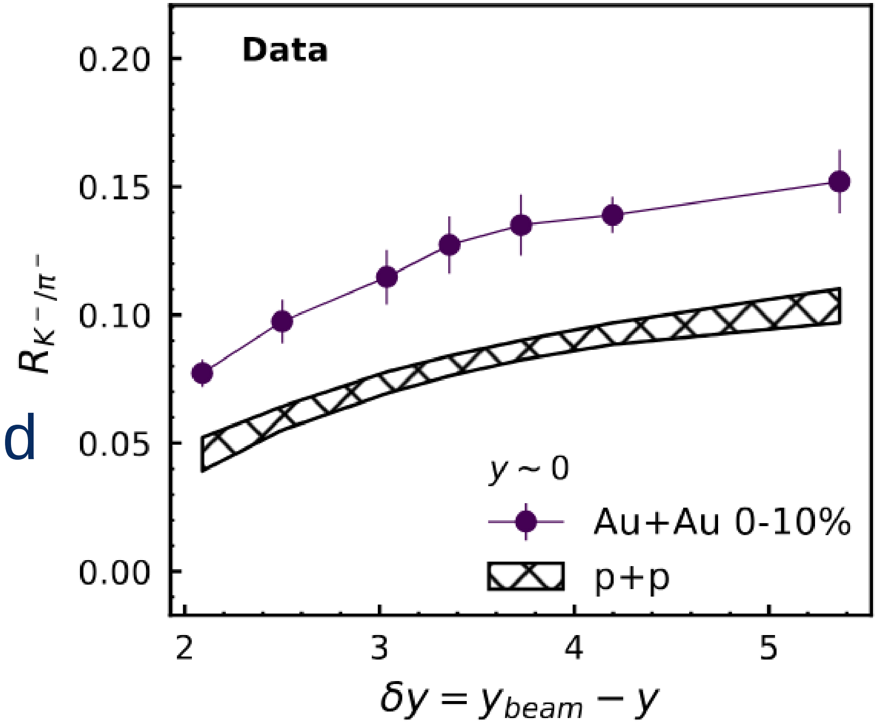
- **Solution**: Factor out s-quark effects → Normalize by production rate:
  - $\boldsymbol{dN_{B-\bar{B}}/dy|_{|y|<0.5}}$/(s-quark production rate) $\propto ???\, \boldsymbol{e^{-a_B Y_{beam}}}$

- **How to estimate s-quark production rates?**

[1]: Phys. Rev. Lett. 98 (2007) 062301
[2]: Phys. Rev. Lett. 108 (2012) 072301
[3]: Phys. Rev. C 102 (3) (2020) 034909
[4]: Phys. Rev. C 83 (2011)024901

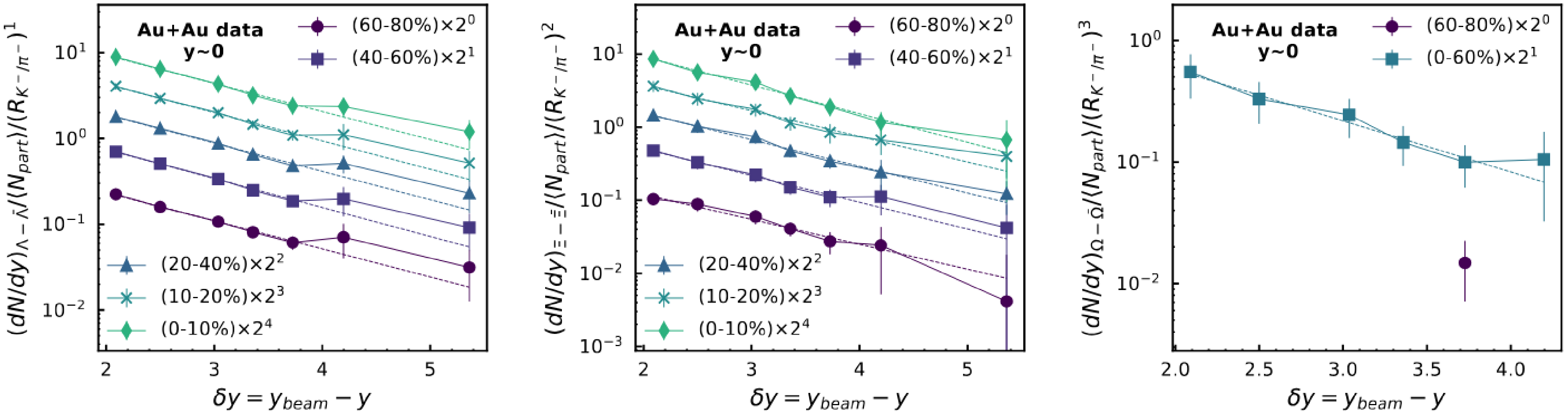
R_{K^-/π^-} ratio as a proxy for s-quarks production

- $K^-(s\bar{u})$ and $\pi^-(u\bar{d})$.
- Divide net-hyperons by $\left(R_{K^-/\pi^-}\right)^n$.
  - n is number of valence s-quark.
- R_{K^+/π^+} not used. K^+ is enhanced by associated production.
  - $p + N \rightarrow \Lambda + K^+ + N$.
- Try R_{K^-/π^-} from both Au+Au and p+p.
  - p+p has no QGP.



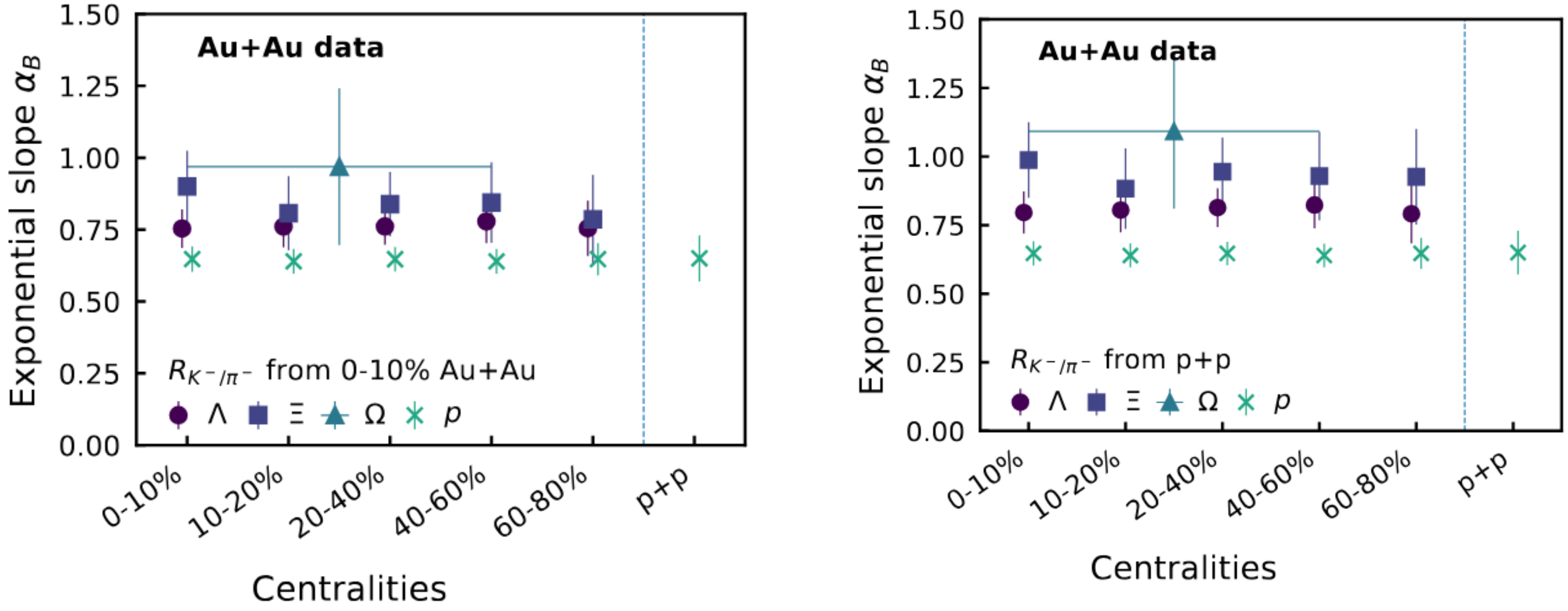
STAR data:
Phys. Rev. C, 96(4):044904, 2017

$dN_{B-\bar{B}}/dy|_{|y|<0.5}/R_{K^-/\pi^-}$ v.s. y_{beam} with STAR data [1-4]



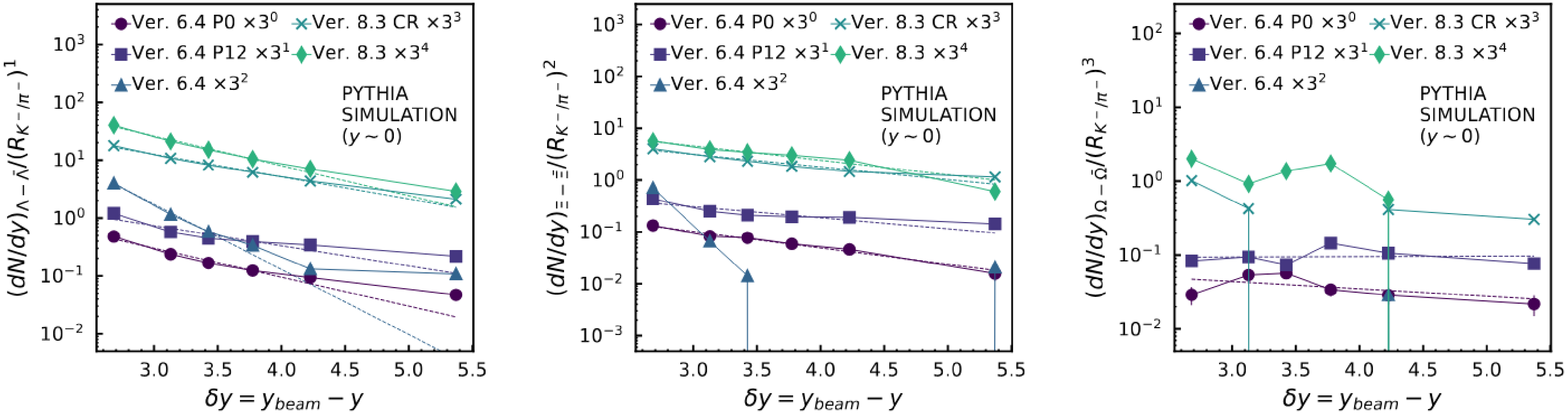
[1]: Phys. Rev. Lett. 98 (2007) 062301
[2]: Phys. Rev. Lett. 108 (2012) 072301
[3]: Phys. Rev. C 102 (3) (2020) 034909
[4]: Phys. Rev. C 83 (2011)024901

a_B for $\Lambda^0, \Xi^-, \Omega^-$, $dN_{B-\bar{B}}/dy|_{|y|<0.5} \propto e^{-a_B Y_{beam}}$



- Independent of centrality.
- a_B for $\Lambda^0, \Xi^-, \Omega^-$ are within uncertainties of each other.
- a_B for $\Lambda^0, \Xi^-, \Omega^-$ are larger than that for proton, but no more than twice the uncertainty.

PYTHIA doesn't work well



	Au+Au (0-80%)		PYTHIA				
Species	Au+Au R_{K^-/π^-}	p+p R_{K^-/π^-}	Ver. 6.4	Ver. 6.4 (P0)	Ver. 6.4 (P12)	Ver. 8.3	Ver. 8.3 CR Mode 2
p	0.64 ± 0.05	-	0.86 ± 0.05	0.76 ± 0.03	0.38 ± 0.02	1.01 ± 0.03	0.73 ± 0.02
Λ	0.72 ± 0.06	0.77 ± 0.06	2.58 ± 0.03	1.15 ± 0.01	0.80 ± 0.01	1.19 ± 0.01	0.89 ± 0.01
Ξ	0.86 ± 0.10	0.95 ± 0.11	N.A.	0.73 ± 0.05	0.49 ± 0.05	0.64 ± 0.08	0.56 ± 0.06
Ω	0.97 ± 0.28	1.09 ± 0.28	N.A.	0.23 ± 0.10	-0.01 ± 0.15	N.A.	N.A.

Conclusion

- Precise constraints on $\Delta\mu_{B,}$ $\Delta\mu_{Q}$ and $\Delta\mu_{S}$ between the isobar systems.
- Net-hyperon stopping (quantified by $\boldsymbol{\alpha}_{\mathrm{B}}$): no species dependence.
- Existing models fail to reproduce $\boldsymbol{\alpha}_{\mathrm{B}}$ of hyperons.
- Observations align with the baryon-junction framework.

Thanks

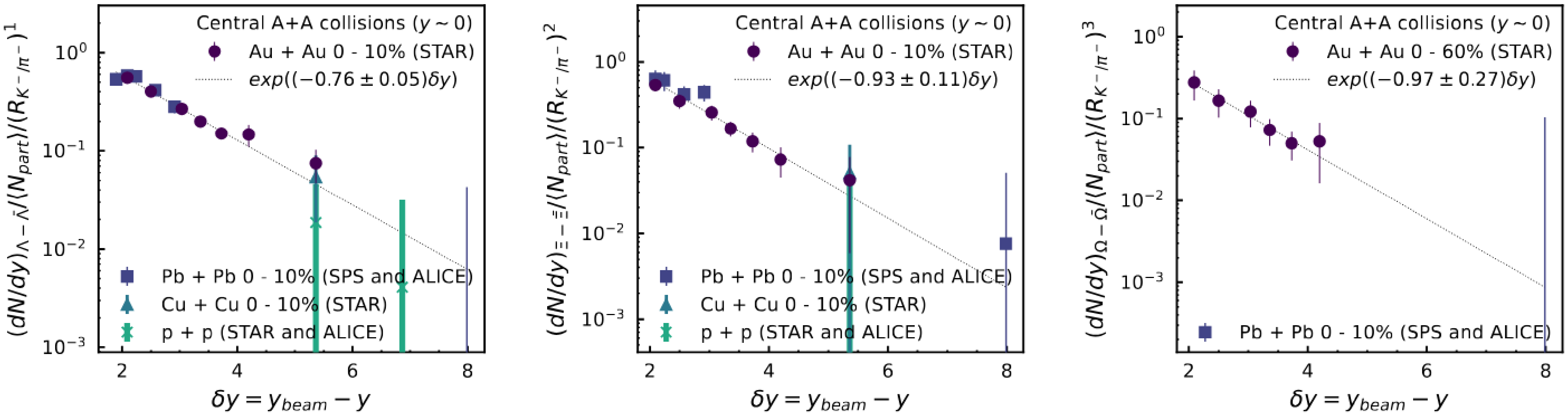
Comparison to PYTHIA

- **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

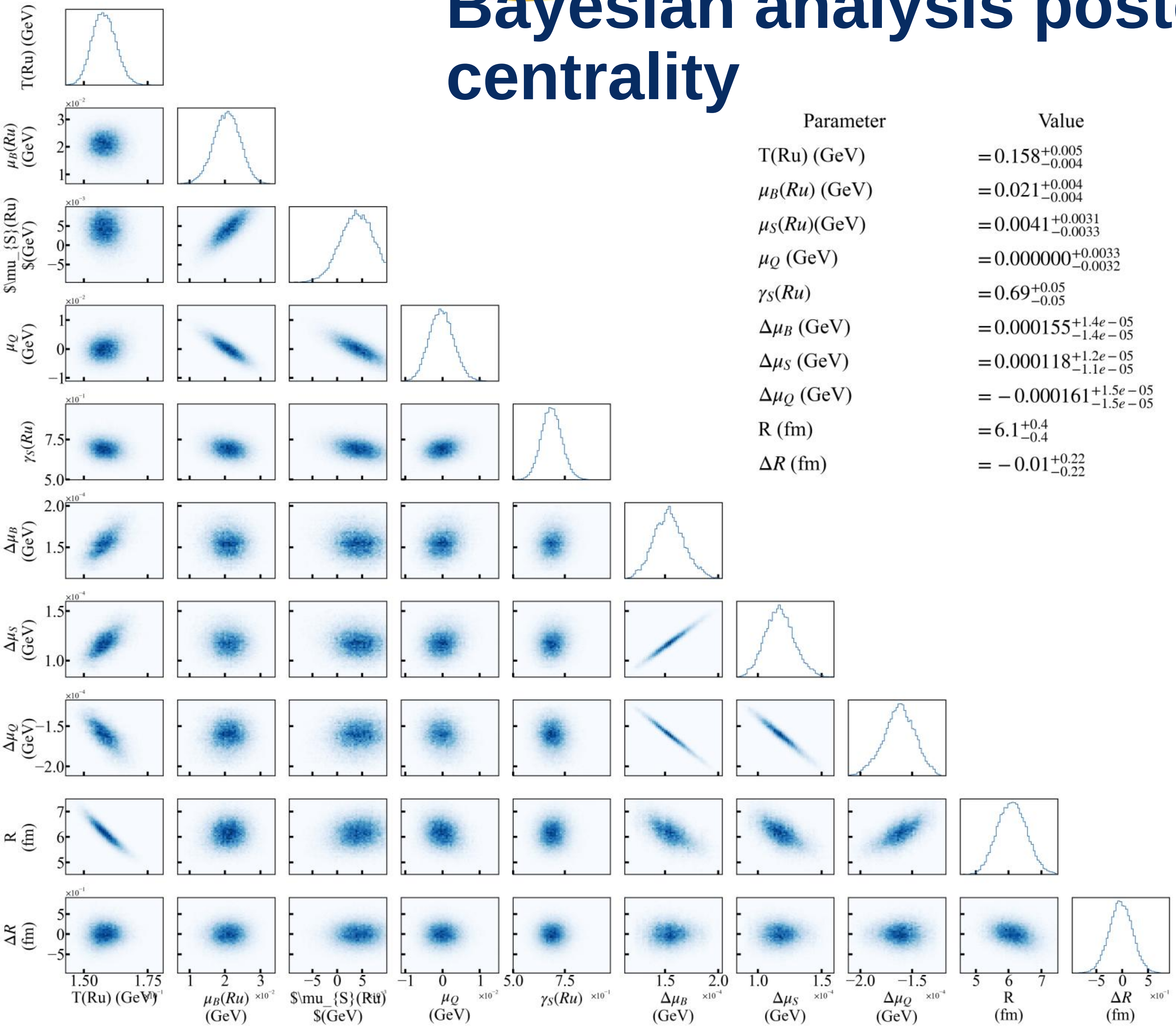
Courtesy:
Rongrong Ma

Include data from other reactions.



Phys. Rev. C, 78:034918, 2008
J. Phys. G, 32:427–442, 2006
Phys. Lett. B, 728:216–227, 2014.
Phys. Rev. Lett., 111:222301, Nov2013
Phys. Rev. C, 75:064901, 2007
Eur. Phys. J. C, 71:1594
Phys. Rev. C, 66:054902, 2002
Phys. Rev. C, 88:044910, Oct 2013
Eur. Phys. J. C, 71:1655,2011

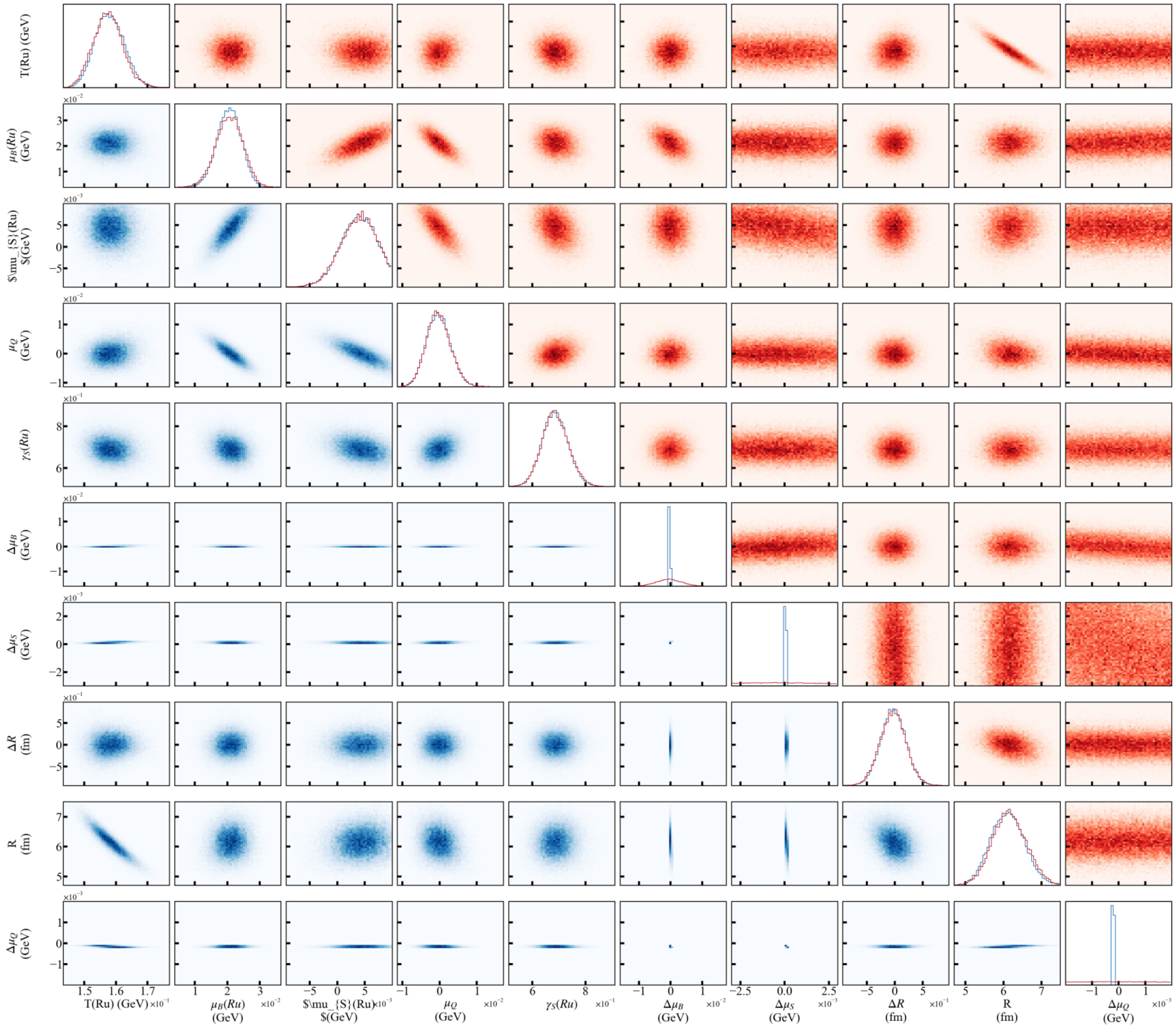
Bayesian analysis posterior at 0-10% centrality



Parameter	Value
T(Ru) (GeV)	$=0.158^{+0.005}_{-0.004}$
$\mu_B(Ru)$ (GeV)	$=0.021^{+0.004}_{-0.004}$
$\mu_S(Ru)$(GeV)	$=0.0041^{+0.0031}_{-0.0033}$
μ_Q (GeV)	$=0.000000^{+0.0033}_{-0.0032}$
$\gamma_S(Ru)$	$=0.69^{+0.05}_{-0.05}$
$\Delta\mu_B$ (GeV)	$=0.000155^{+1.4e-05}_{-1.4e-05}$
$\Delta\mu_S$ (GeV)	$=0.000118^{+1.2e-05}_{-1.1e-05}$
$\Delta\mu_Q$ (GeV)	$=-0.000161^{+1.5e-05}_{-1.5e-05}$
R (fm)	$=6.1^{+0.4}_{-0.4}$
ΔR (fm)	$=-0.01^{+0.22}_{-0.22}$

Positive $\Delta\mu_B$,
positive $\Delta\mu_S$,
negative $\Delta\mu_Q$

$\Delta\mu_B/\Delta\mu_Q$=-0.96+/-0.02



ΔQ is crucial for Δμ

- Lower triangular (blue): Posterior with ΔQ.
- Upper triangular (red): Posterior WITHOUT ΔQ.