1st Workshop on Baryon Dynamics from RHIC to EIC
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Study of Baryon and Charge Transport with UrQMD

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arXiv:2309.06445

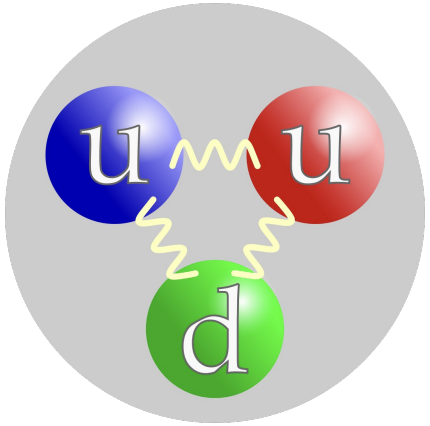
Does Quark Carry Baryon Number?

PDG particle data group

15.2 Quantum numbers of the quarks

As gluons carry no intrinsic quantum numbers beyond color charge, and because color is believed to be permanently confined, the quantum numbers of strongly interacting particles are given by the quantum numbers of their constituent quarks and antiquarks.

Quarks are strongly interacting fermions with spin 1/2 and, by convention, positive parity. Antiquarks have negative parity. Quarks have the additive baryon number 1/3, antiquarks -1/3.



https://en.wikipedia.org/wiki/Quark

- PDG says: Baryon number are carried by quarks (1/3 for each)
  - Any experimental evidence?

    NO! Simply because there are three valence quarks in a baryon
  - Is quark the only candidate?

    NO! Valence quarks are not the only objects in a baryon

Alternative Baryon Number Carrier

PDG particle data group

15.2 Quantum numbers of the quarks

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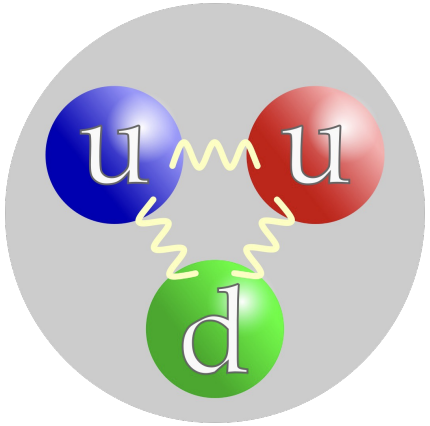
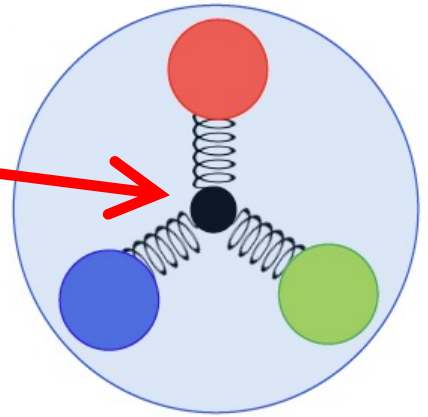


https://en.wikipedia.org/wiki/Quark

Alternative picture of a proton

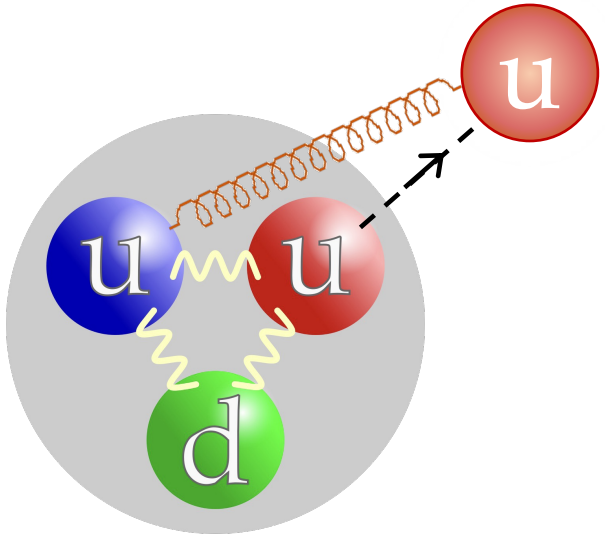
- A Y–shaped gluon junction topology carries baryon number (baryon junction)
- Valence quarks are connected to the end of the junction
- Valence quarks do not carry baryon number
- Proposed in 1970s

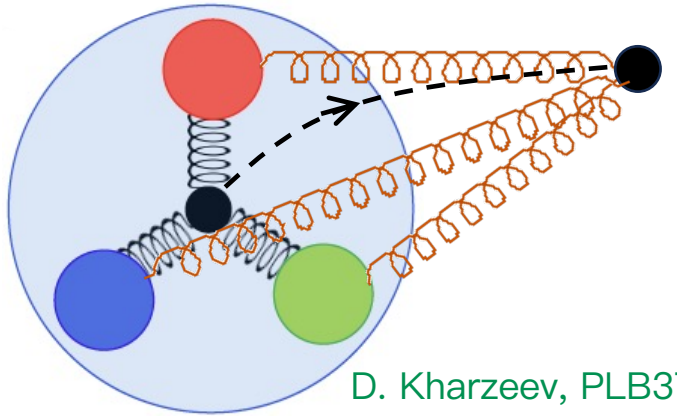


X. Artru, NPB85, 442 (1975)
G. Rossi and G. Veneziano, NPB123, 507 (1977)

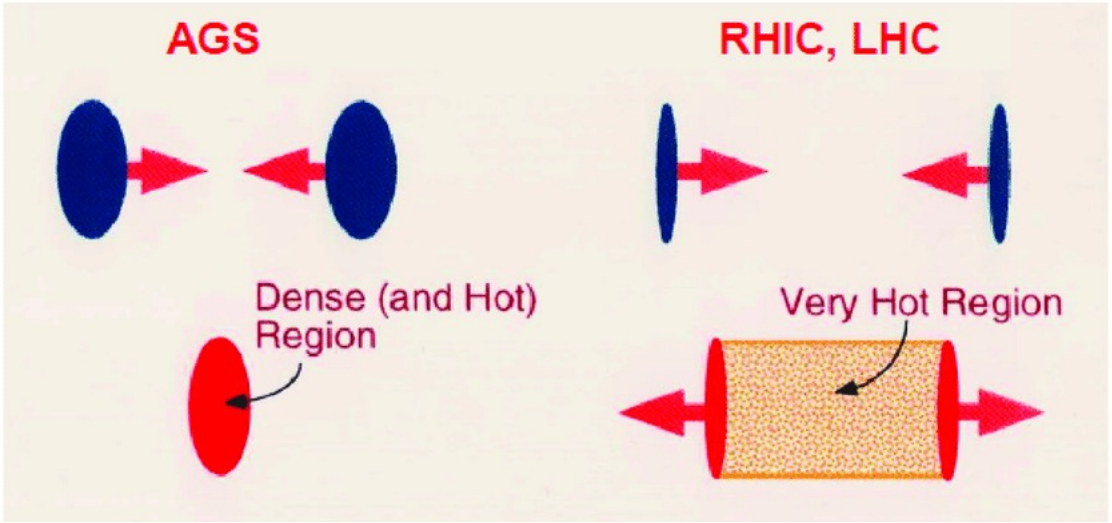
How to Probe the Baryon Number?

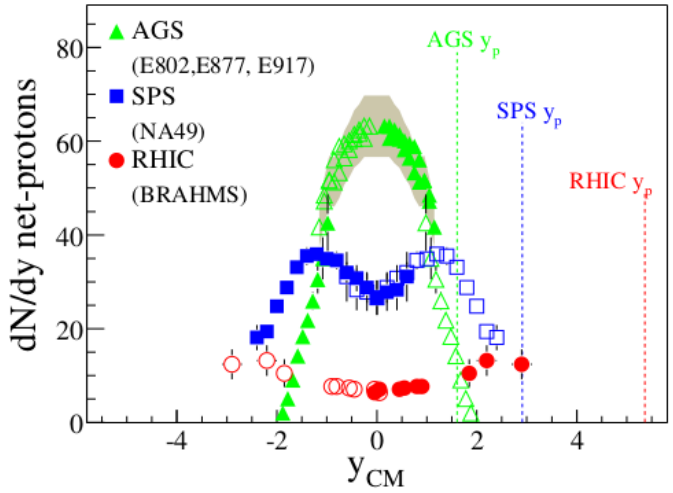
Pull them out: Measure baryon stopping at mid–rapidity in A+A collisions





D. Kharzeev, PLB378, 238 (1996)

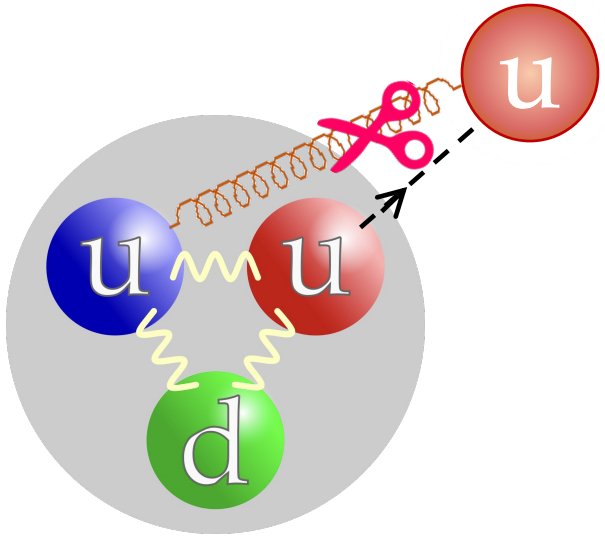




BRAHMS, PRL93, 102301 (2004) and references therein

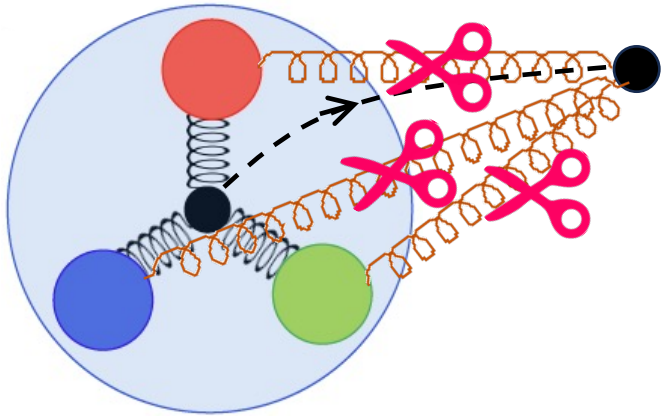
Net–Charges vs. Net–Baryons

Valence quark stopping



- Net quarks are all transported from projectile and target nuclei
- The ratio of net–charge and net–baryon should be highly correlated with Z/A of projectile and target

Baryon junction stopping

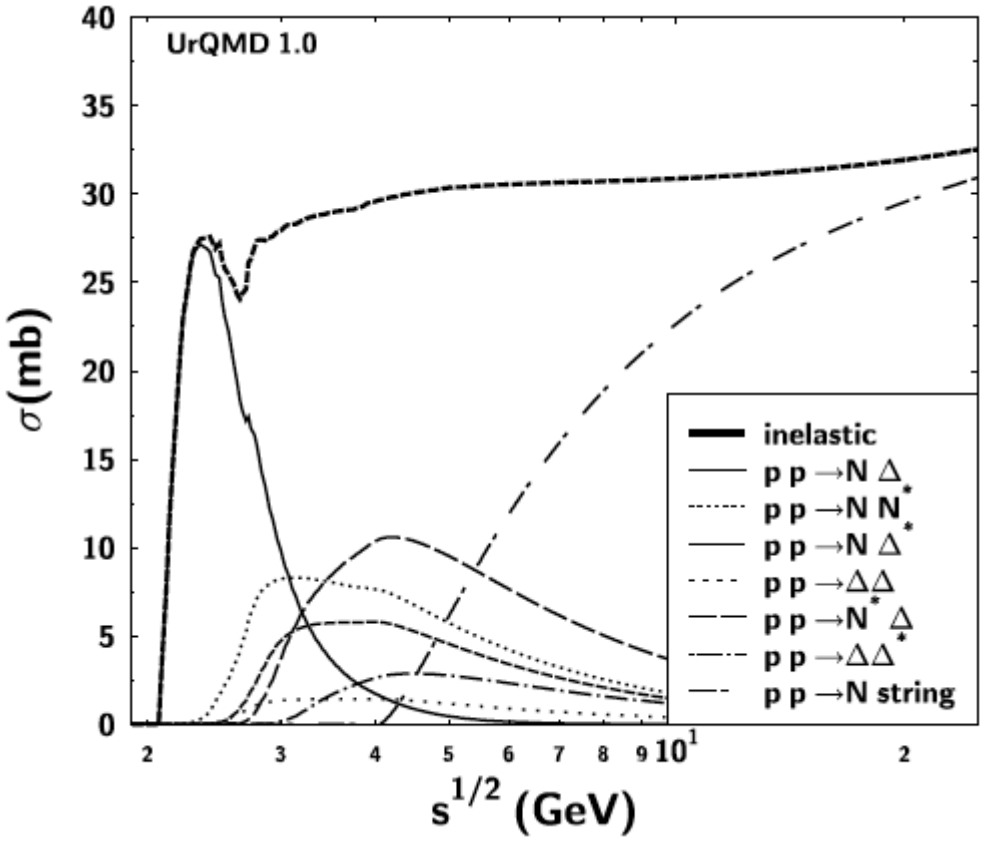


- Quarks connected to the stopped junction are sea quarks
- The ratio of net–charge and net–baryon is not related to the quark composition of projectile and target

Ultra-relativistic Quantum Molecular Dynamics

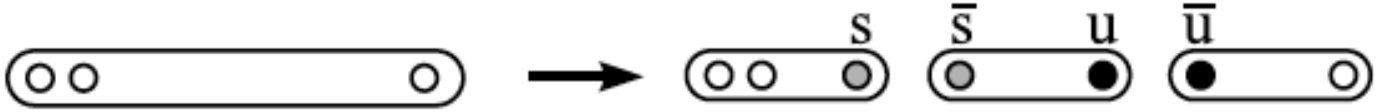
UrQMD is a non-equilibrium transport model

S. Bass et al., Prog. Part. Nucl. Phys. 41, 225 (1998)
M. Bleicher et al., J. Phys. G 25, 1859 (1999)



Particle production in UrQMD:

- Formation and decay of resonances
  - 55 baryon spices upto 2.25 GeV/c^2
  - 39 meson spices
  - and their antiparticles
- Excitation and fragmentation of strings
  - Pythia 6.4 for hard collisions
  - Multiple scattering of leading diquarks is implemented
  - Diquark breaking is taken into account but is minor important (10%)



Net Charge and Net Baryon Calculations

	Ru_Ru	
	PID	N
	-139	1
	-134	1195
	-133	53221
	-106	115938276
	-55	102151
	-49	1491036
	-40	4947811
	-27	5246547
	-1	34466495
N(938)	1	460529272
Λ(1116)	27	13781035
Σ(1192)	40	13317400
Ξ(1317)	49	2409775
Ω(1672)	55	112778
γ	100	82608
π	101	1723940742
η	102	68125421
K	106	134711106
D	133	50740
D^*	134	1127
J/ψ	135	17
χ_c	136	6
Ψ’	137	1

Net Charge (Q): Sum of the charge of all particles

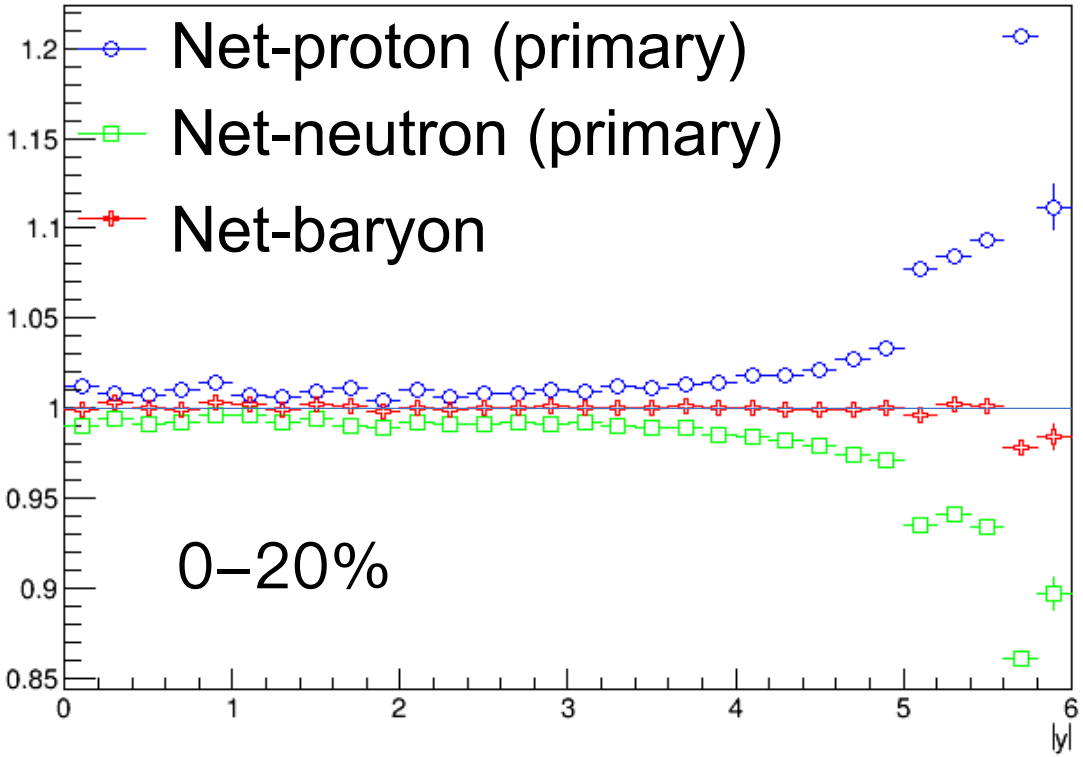
Net Baryon (B): Sum of the baryon number of p/n, Λ, Σ, Ξ and Ω

Integrate over all kinematic region

	Ru+Ru	Zr+Zr	Ru/Zr
B	*191.996* ±0.007	*191.996* ±0.007	1.0000
Q	*88.000* ±0.012	*80.000* ±0.012	1.1000

Net Baryon in Heavy Ion Collisions

$$\frac{{}^{96}_{44}Ru + {}^{96}_{44}Ru}{{}^{96}_{40}Zr + {}^{96}_{40}Zr}$$

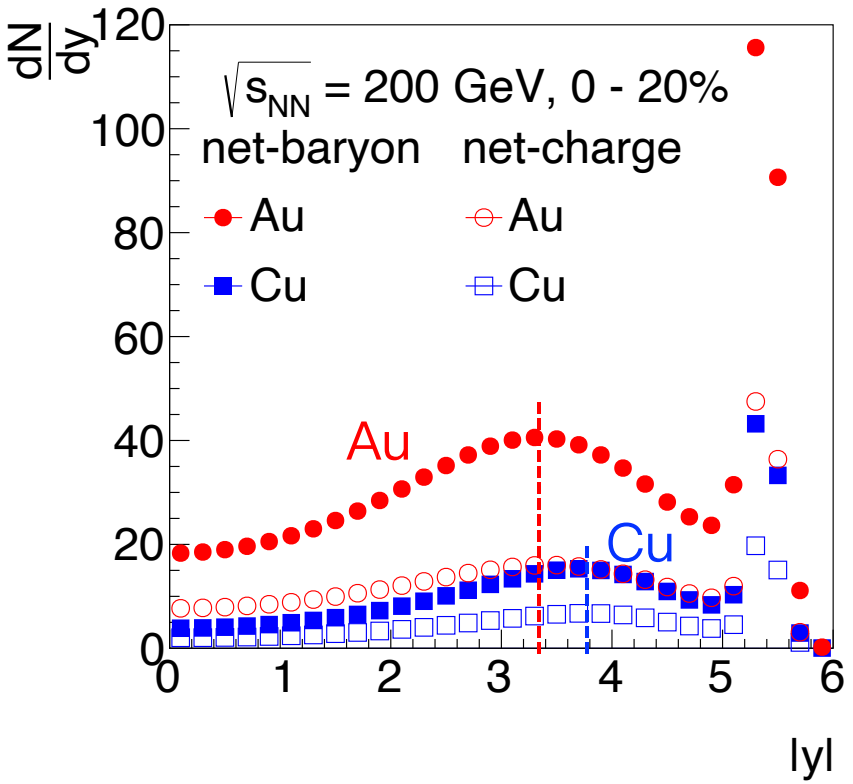


- Close to unity at mid–rapidity

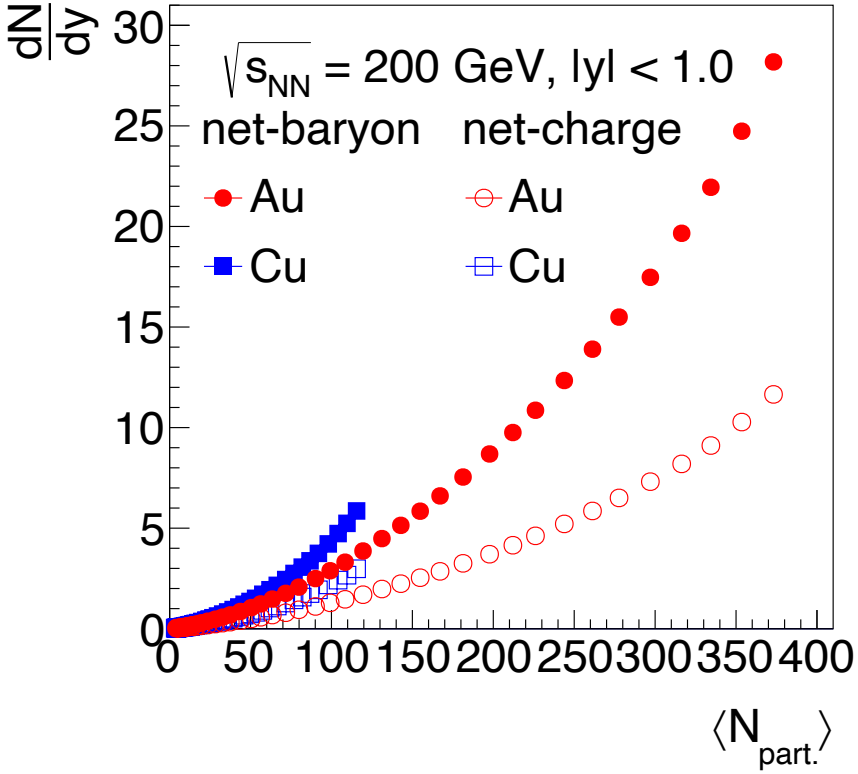
  → The initial isospin distribution of baryons are almost washed out
- But net–proton ratios are still slightly higher than neutron

Net–proton is a very good but not perfect proxy of net–baryon

B and Q in Au+Au and Cu+Cu Collisions



Larger y–loss in central Au+Au than in central Cu+Cu collisions

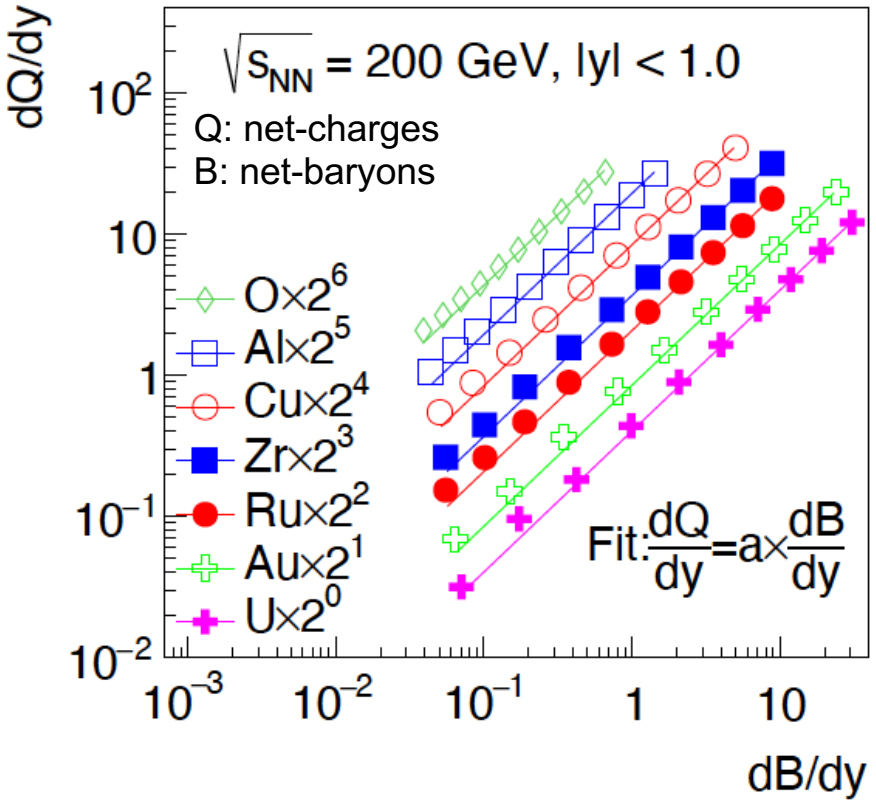


Larger B and Q in Cu+Cu than in Au+Au with the same N_{part}

Multiple scattering plays a role and will introduce centrality dependence

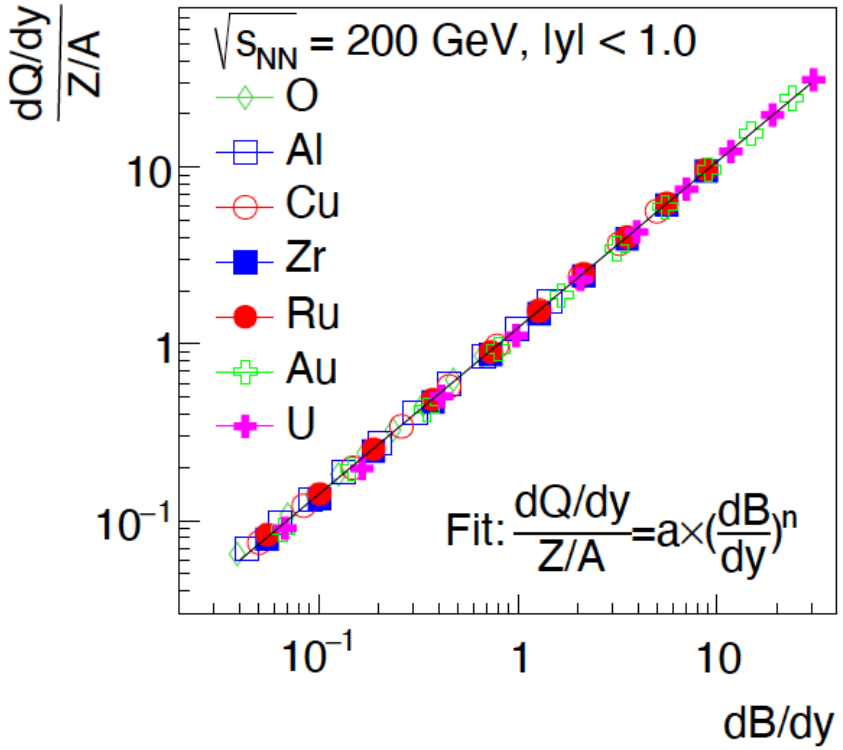
Net–Charges vs. Net–Baryons from UrQMD

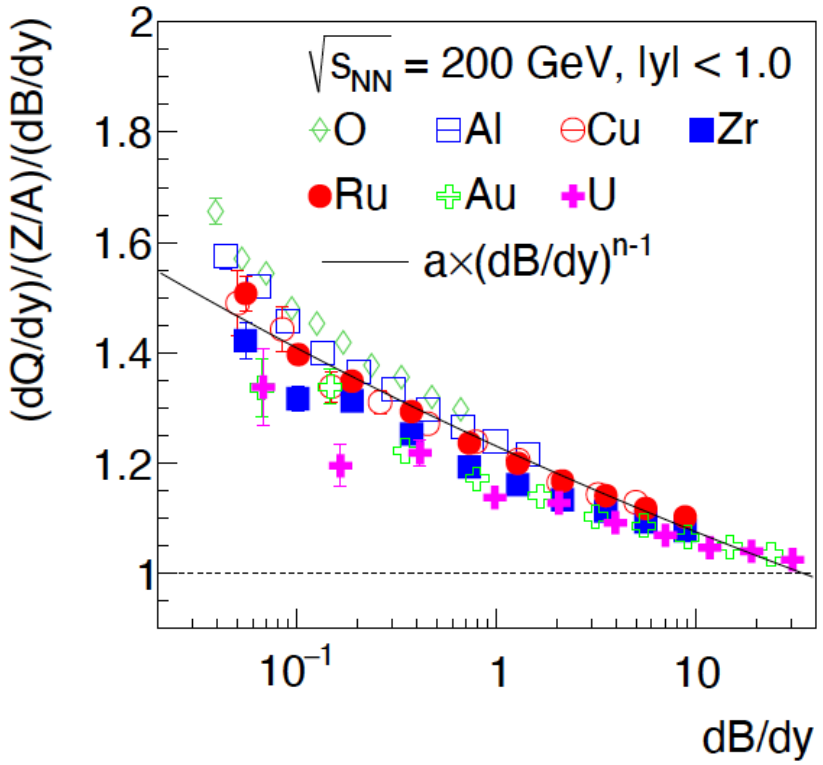
Nucleus	Z	A	Z/A
O	8	16	0.500
Al	13	27	0.481
Cu	29	64	0.453
Zr	40	96	0.417
Ru	44	96	0.458
Au	79	197	0.401
U	92	238	0.386



- Z/A varies from 0.4 to 0.5 (25%) from Au/U to O
- Strong correlation between *B* and *Q* at mid–y in all collision systems
- The slope *a* increases with Z/A

Net-Charges vs. Net-Baryons from UrQMD



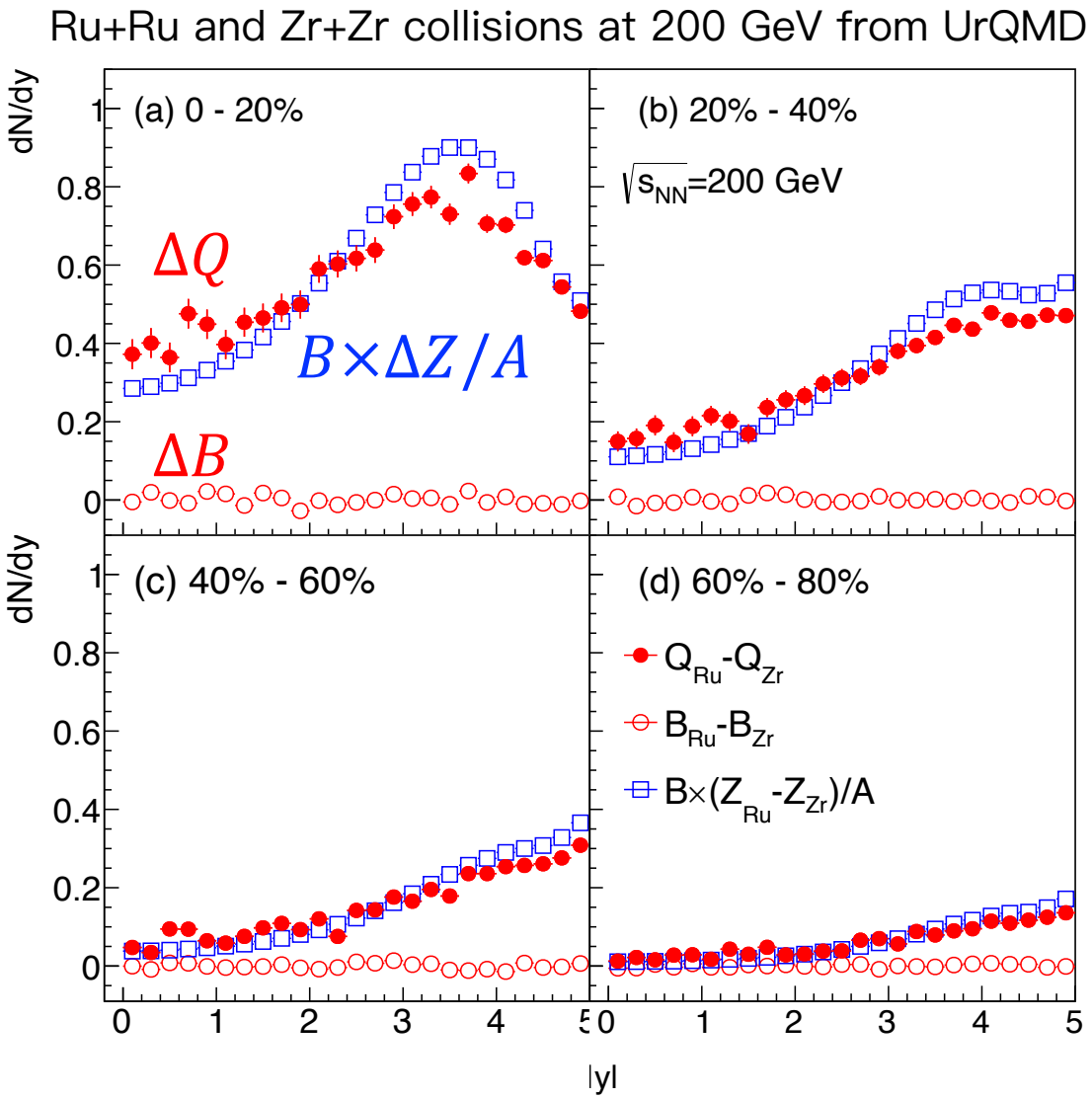


Q at mid-y scales with Z/A

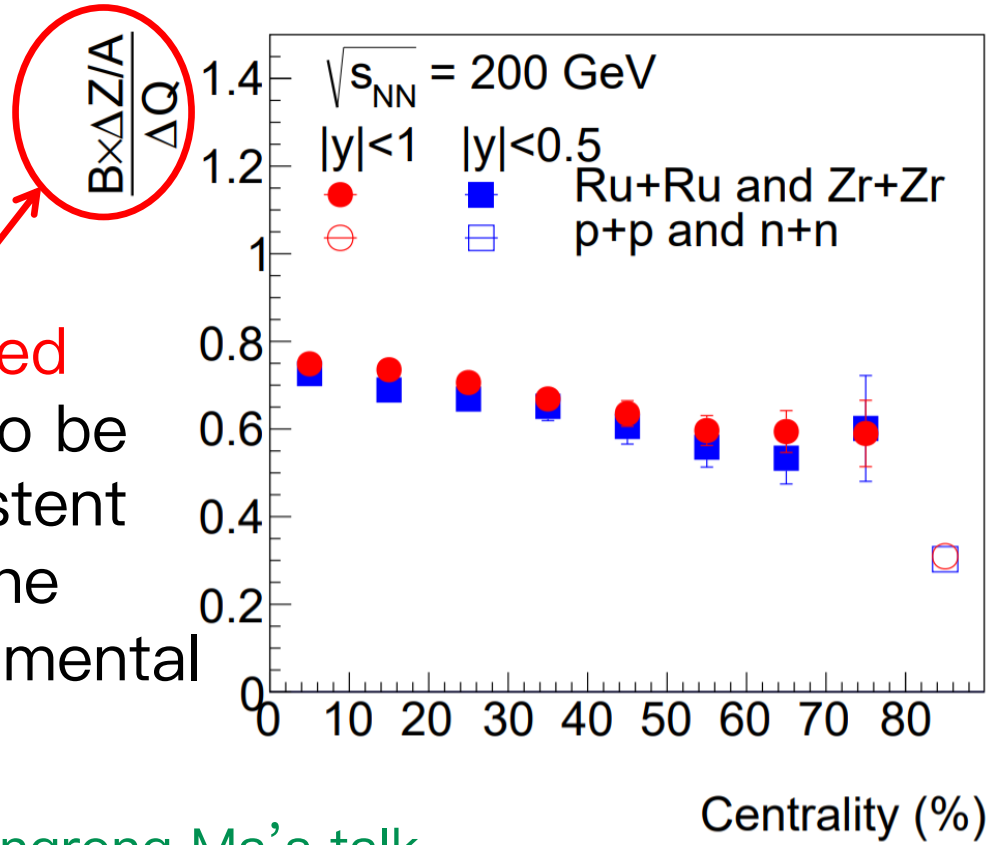
Q/B x A/Z approaches 1 for large system

Expect 25% difference of Q/B in O+O vs. Au+Au collisions
and 10% difference of Q/B in Ru+Ru and Zr+Zr collisions

Net-Charges and Net-Baryons in Isobaric Collisions



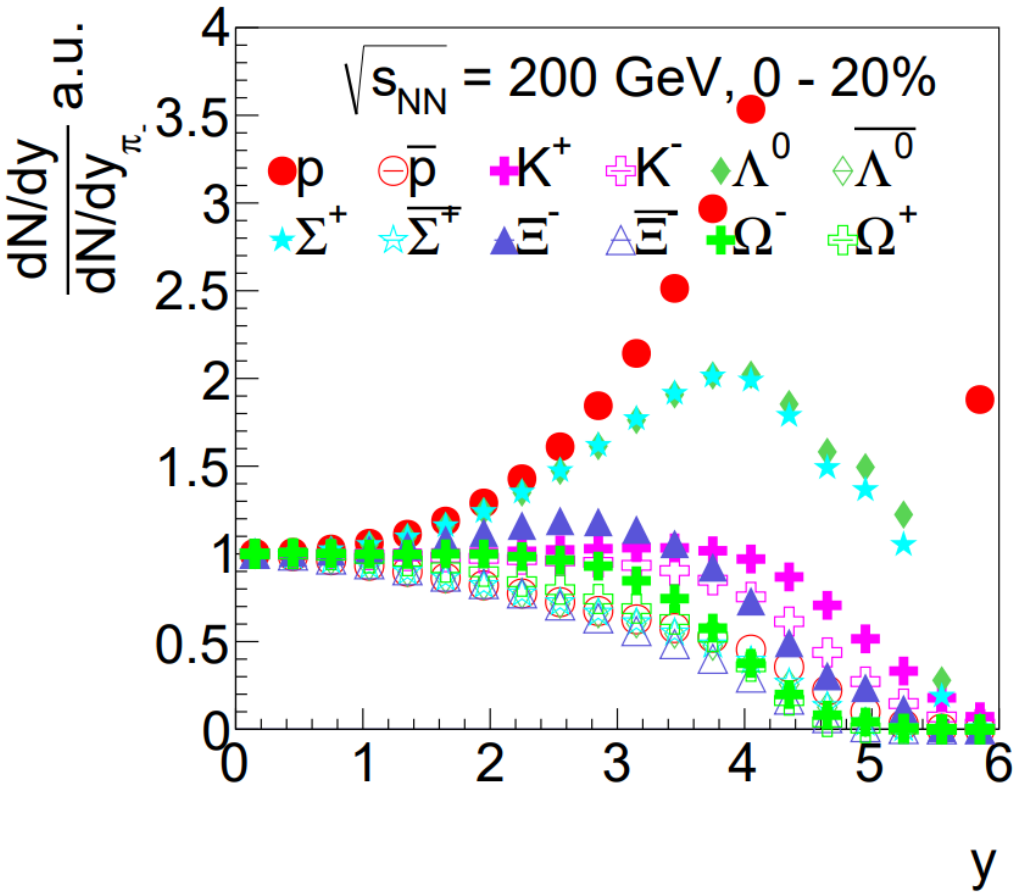
- Difference of B is almost zero
- Difference of Q is close to BxΔZ/A



Inversed here to be consistent with the experimental data

See Rongrong Ma's talk

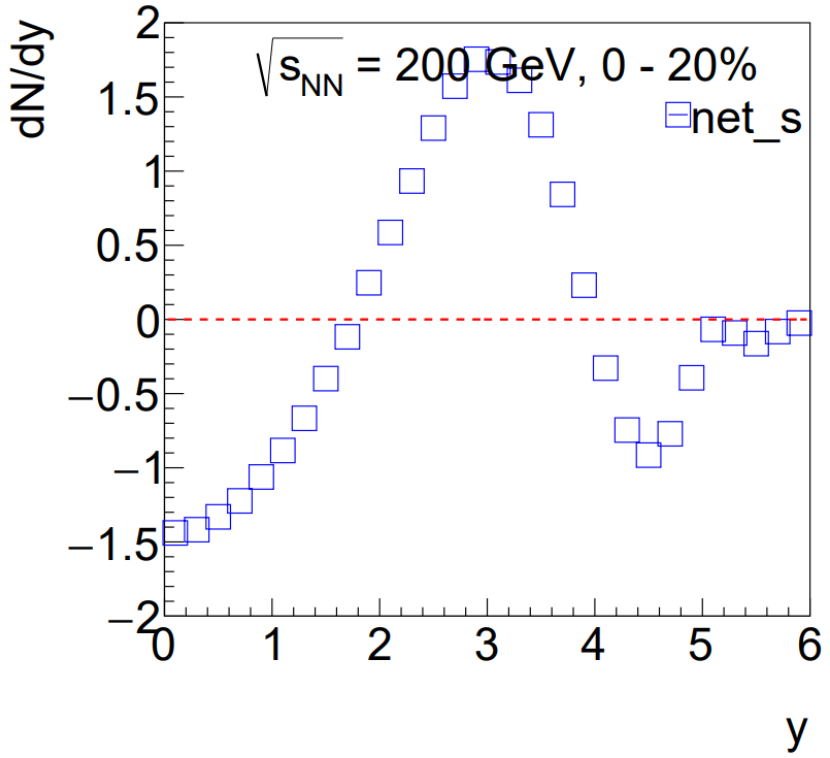
Why Q/B is More Than Naïve Expectation?

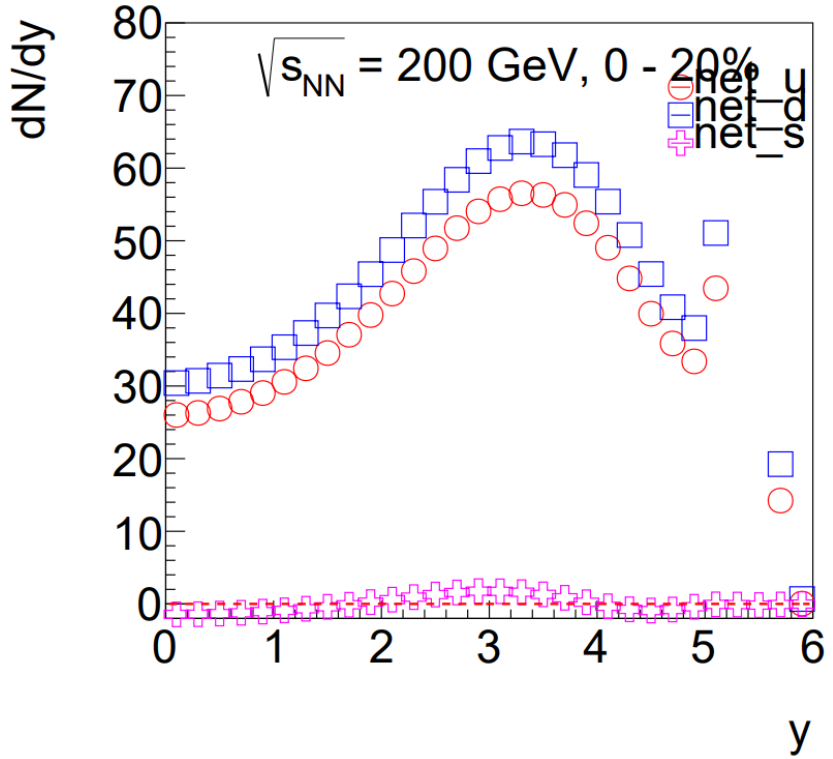


Width of the rapidity distribution:

p/n > Λ/Σ > Ξ ~ K ~ π > Ω > Anti–hyperon

Net–Quarks Rapidity Distribution

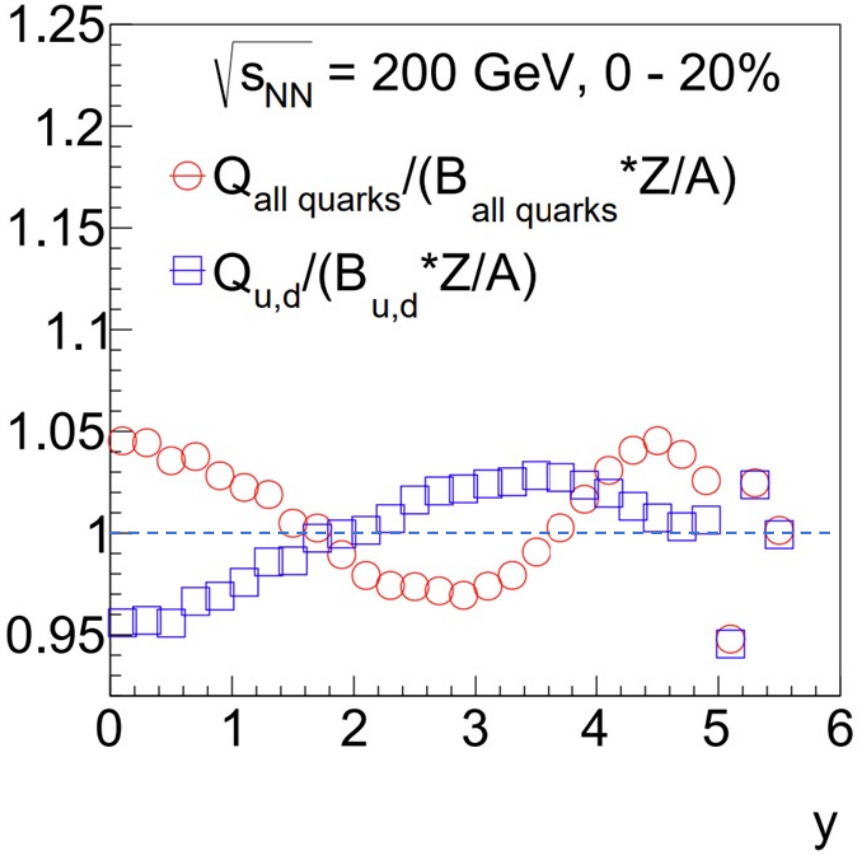


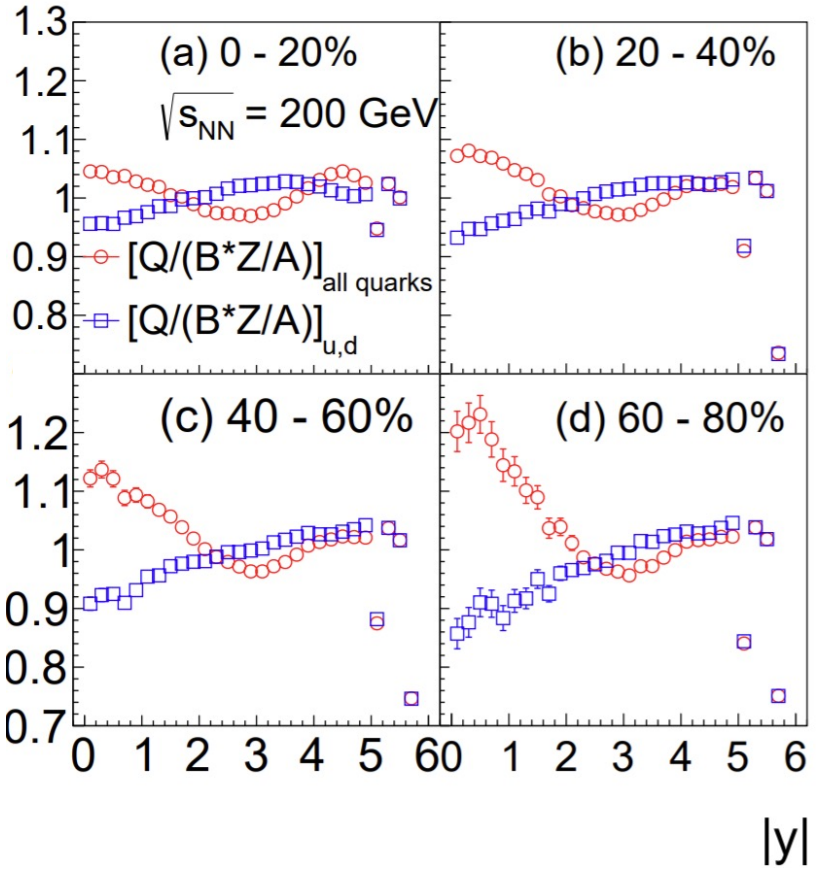


- Net–strange increases from negative at mid–y to positive at forward y

- The trend is similar as transported quarks
- Or affected by transported quarks

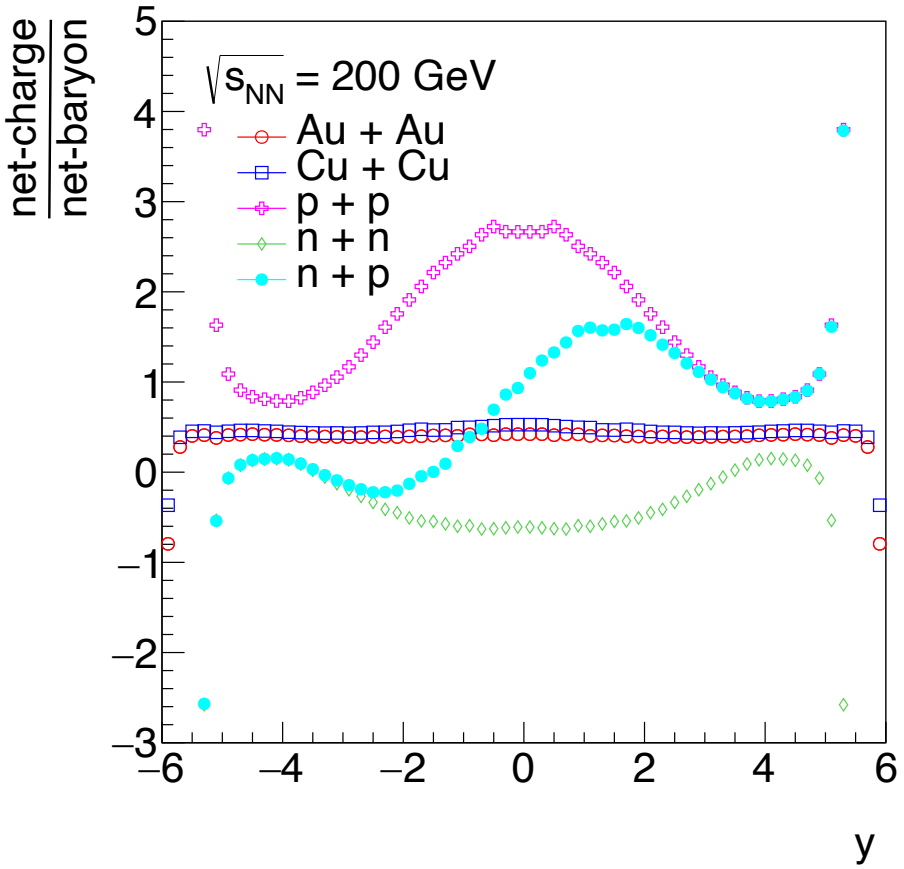
Q/B w/ and w/o Strangeness





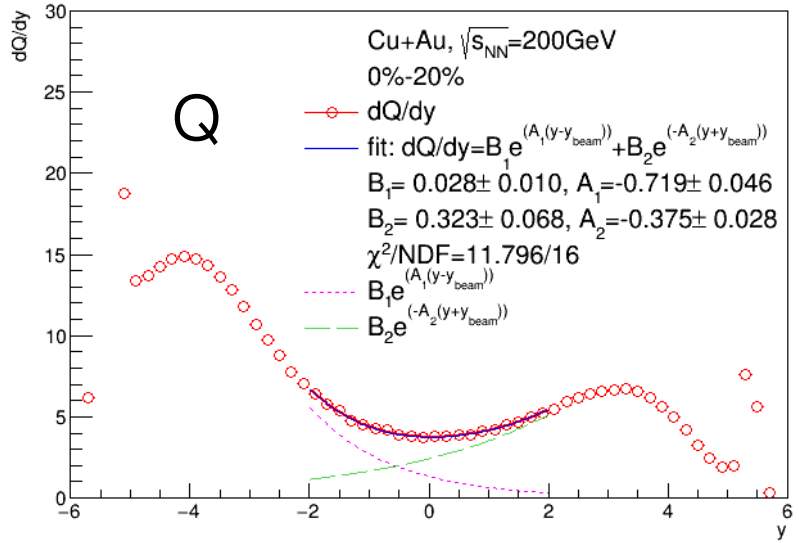
- Q/B ratio is different with or without strangeness
- The difference depends on rapidity
- The difference is smaller in central collisions, likely due to multiple scattering

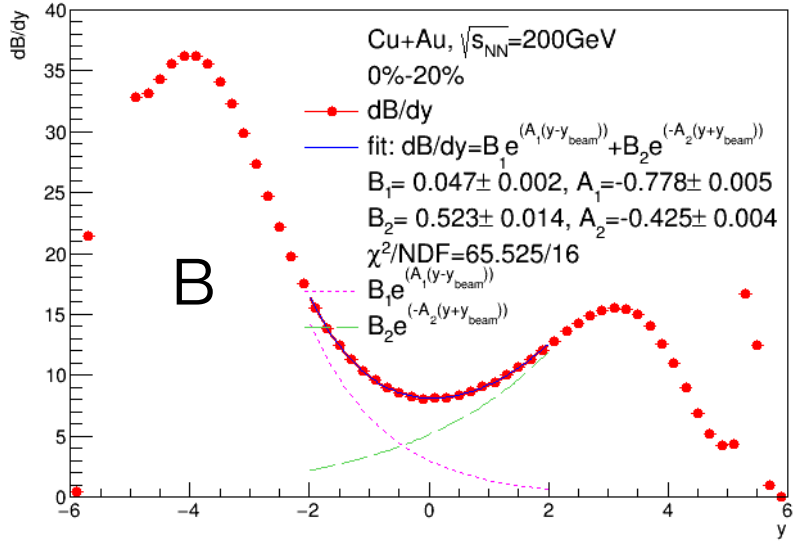
Q/B in Proton and Neutron Collisions

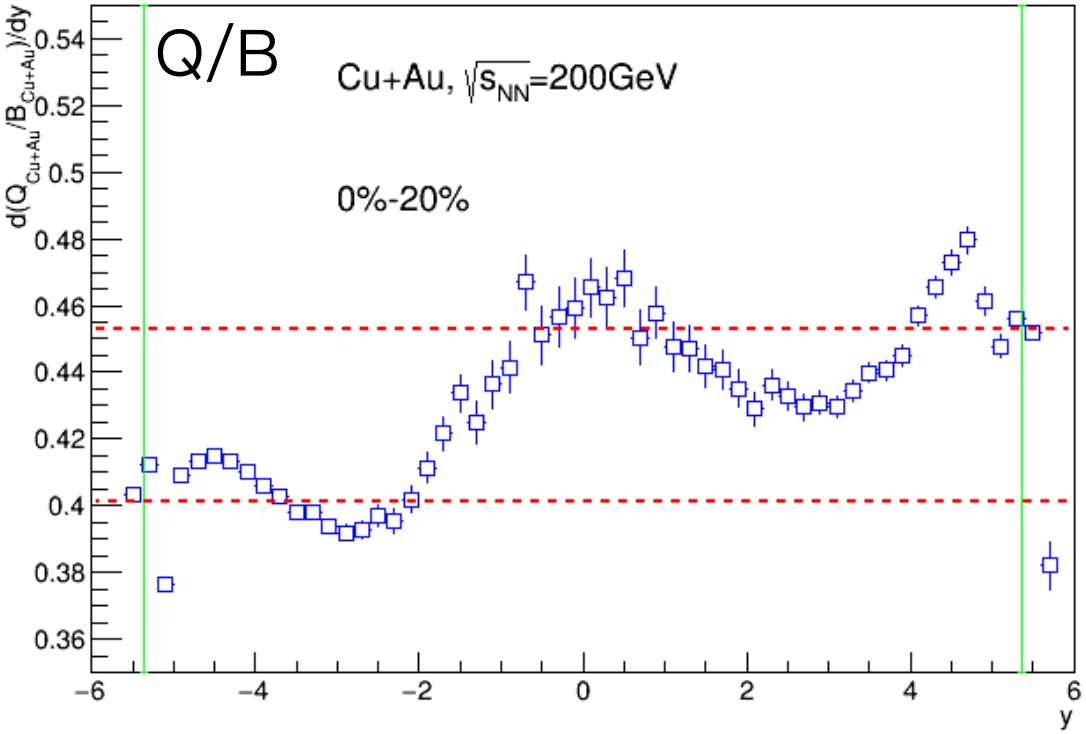


- The Q/B in p+p, n+n is different from the naïve expectation of valence quark stopping
- Detailed baryon transport need to be considered

Q/B in Cu+Au Collisions at 200 GeV

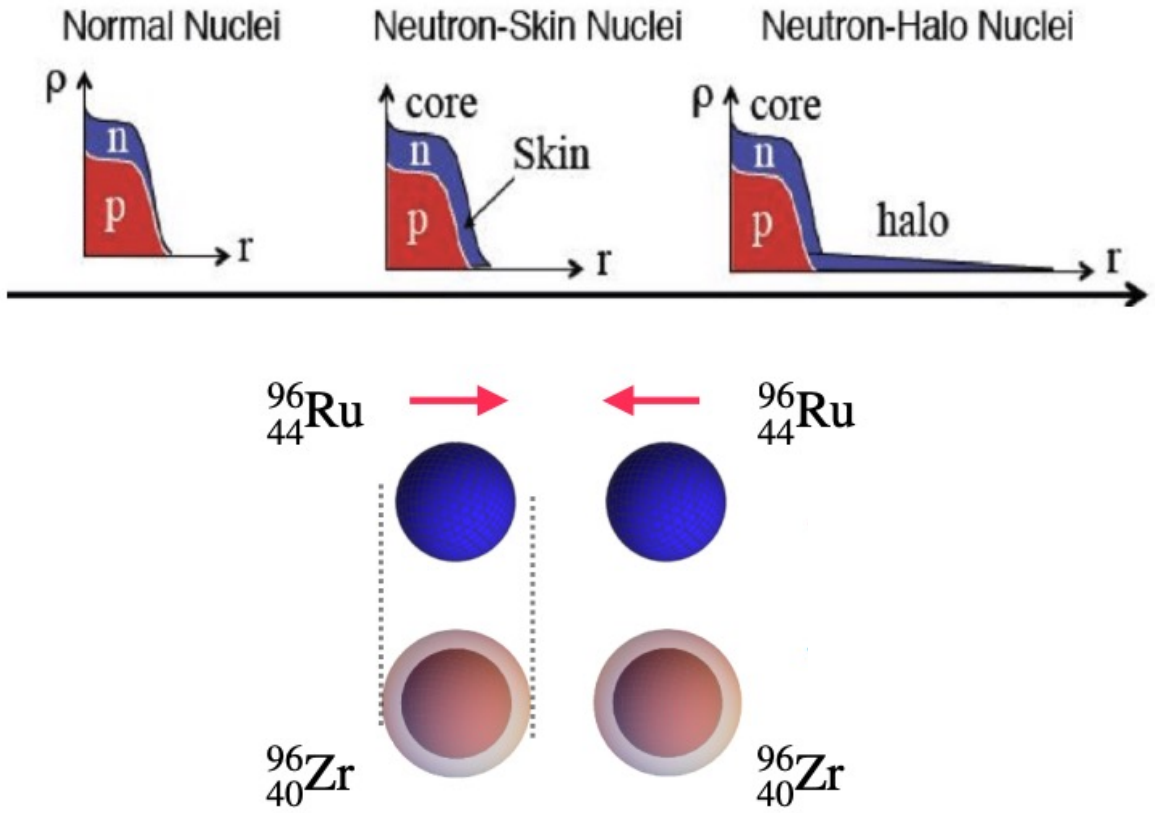






- Q/B significantly depends on rapidity in asymmetric collisions
- Large rapidity acceptance detector needed

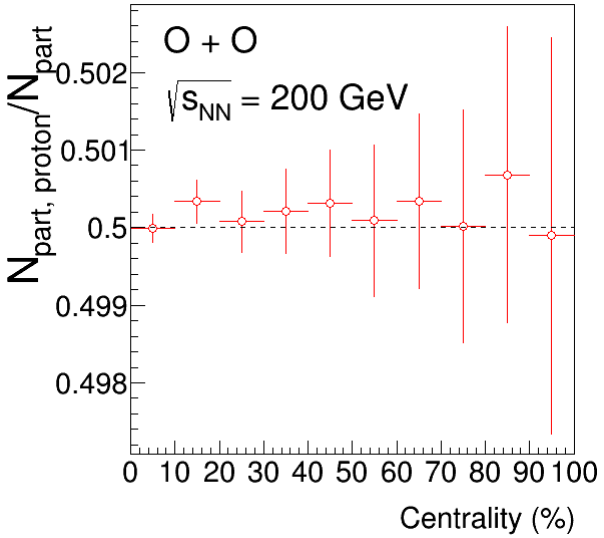
Neutron Skin Effect?

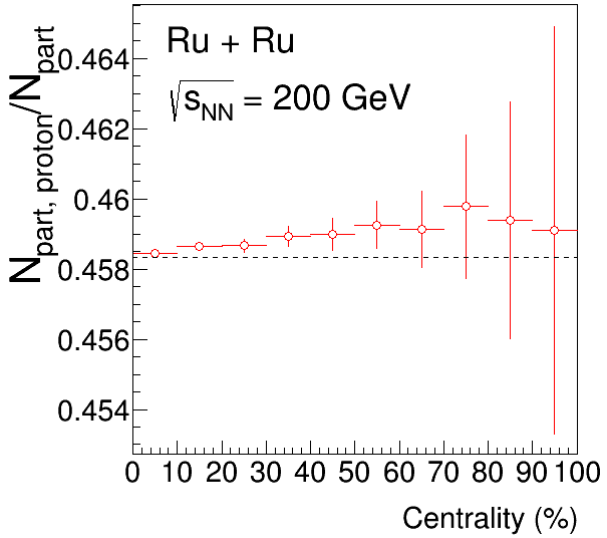


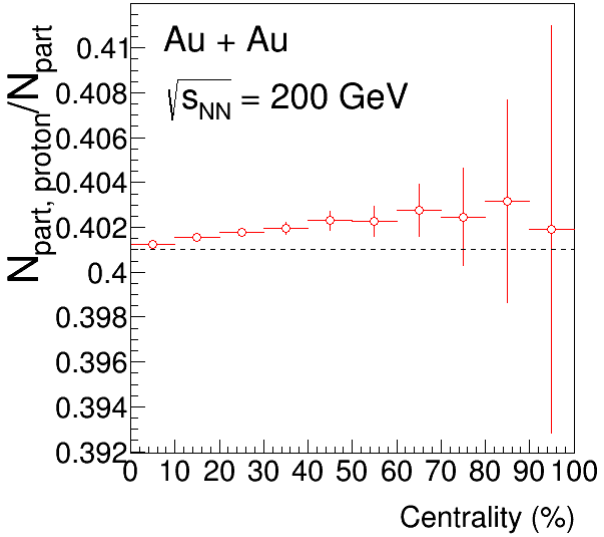
H. Xu et al, PRC105, L011901 (2022)

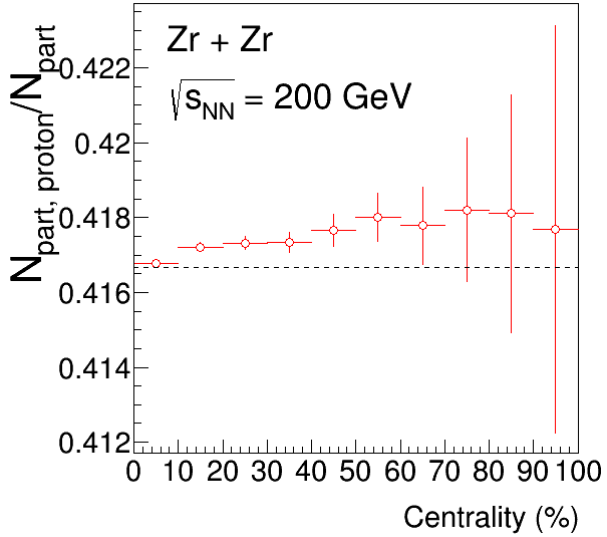
- Thick halo–type neutron skin in Zr
- More p+p collisions in central Zr+Zr

No Neutron Skin in UrQMD





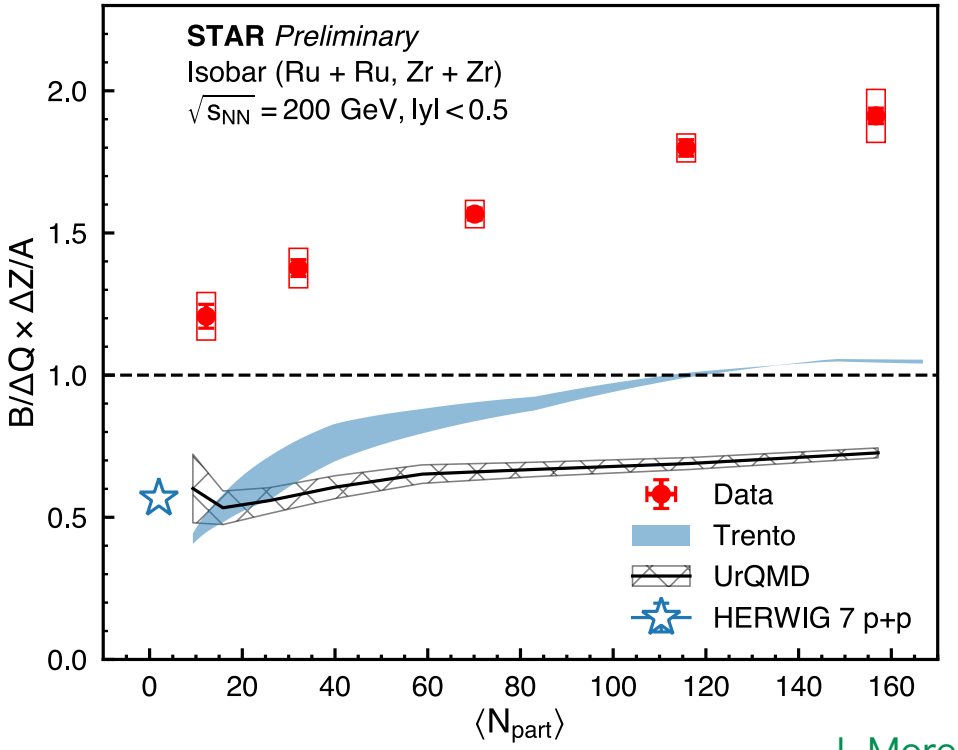




No neutron skin in UrQMD

Proton number density is different in Ru+Ru and Zr+Zr collisions

Neutron Skin Effect?



J. Moreland et al, PRC92, 011901(R) (2015)

- UrQMD + Neutron–skin explains the centrality dependence observed in data
- But not enough to explain the large ratio

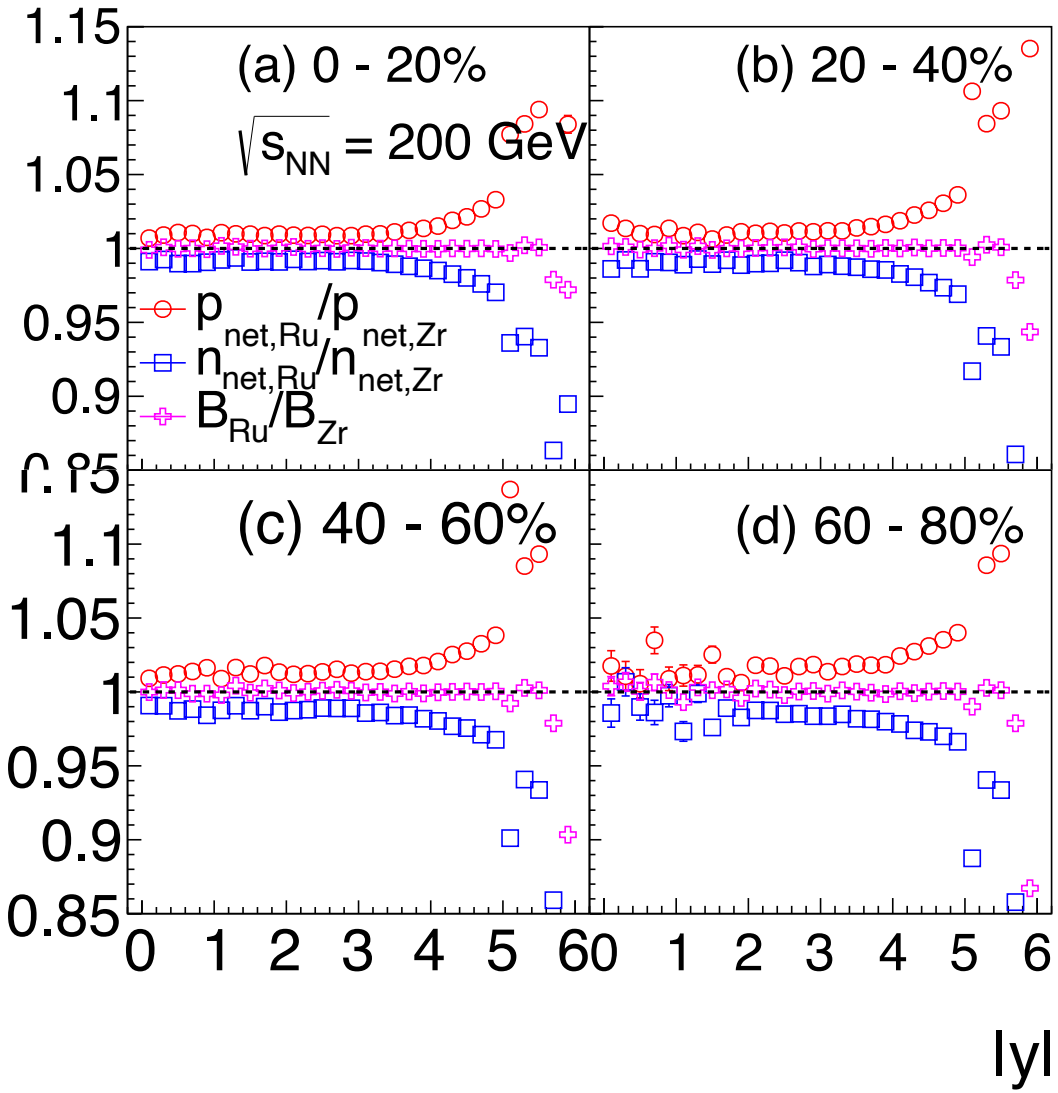
See Rongrong Ma's talk

Summary

- The transport of net-charges and net-baryons are studied in heavy-ion collisions with the UrQMD, in which valence quark carries baryon number
- Net-charges and net-baryons at mid-rapidity are found to be highly correlated
- Q/B ratio approximately scale with Z/A of the colliding nucleus
- Detailed transport need to be considered for the baseline of experimental search for baryon junction

Thanks!

Extra slides


(a) 0 - 20%
$\sqrt{s_{NN}}$ = 200 GeV
$p_{net,Ru}/p_{net,Zr}$
$n_{net,Ru}/n_{net,Zr}$
B_{Ru}/B_{Zr}
(b) 20 - 40%
(c) 40 - 60%
(d) 60 - 80%
1.15
1.1
1.05
1
0.95
0.9
0.85
0 1 2 3 4 5 6
|y|