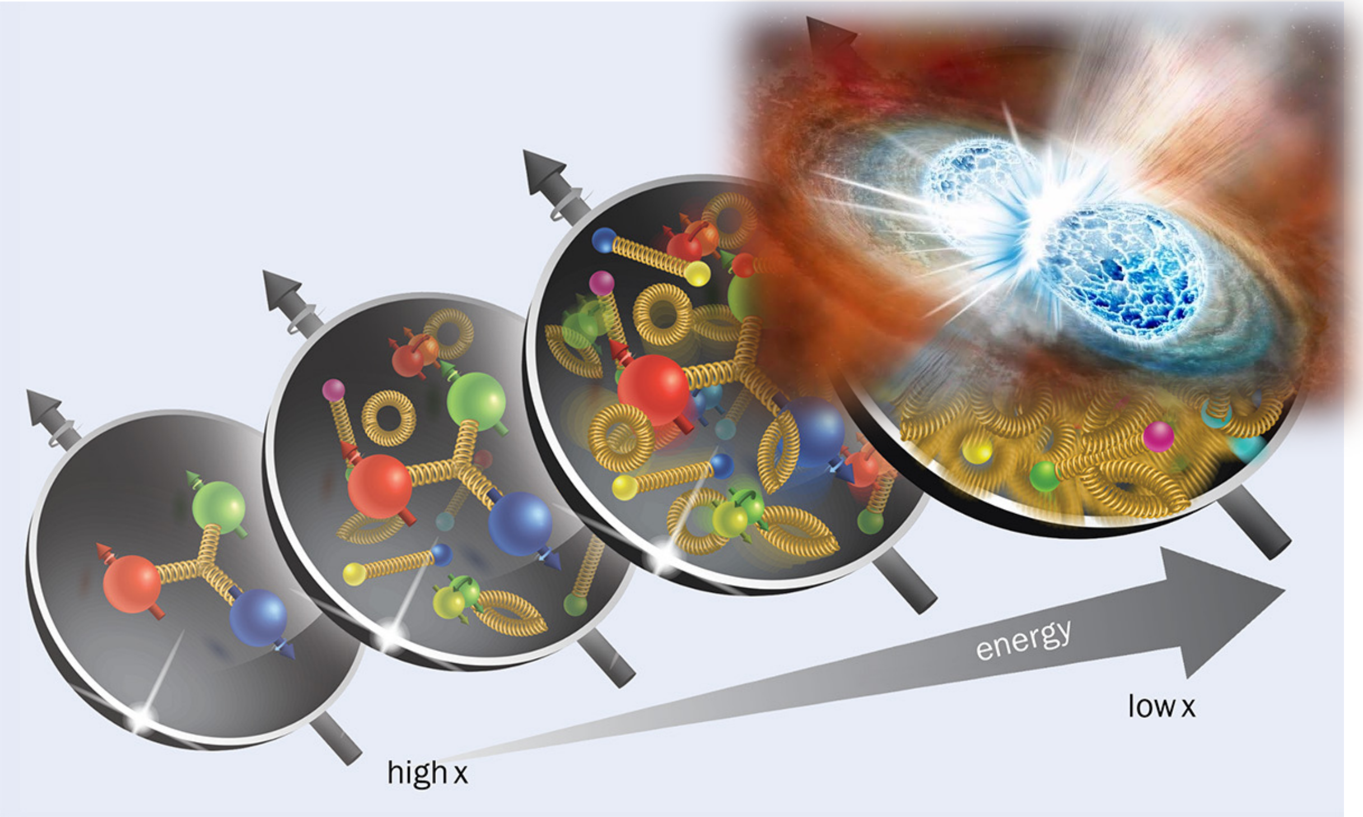
Recent Results on Nucleus Interactions from STAR



Zhangbu Xu
(Brookhaven National Lab)

- Discovery of B=-4 hypernucleus
- B=4,3 Hypernuclear properties
- B=3,2 nuclear yield ratio as probe of quantum wavefunction overlaps and Density Fluctuation
- B=1: simplest gluon topology in QCD

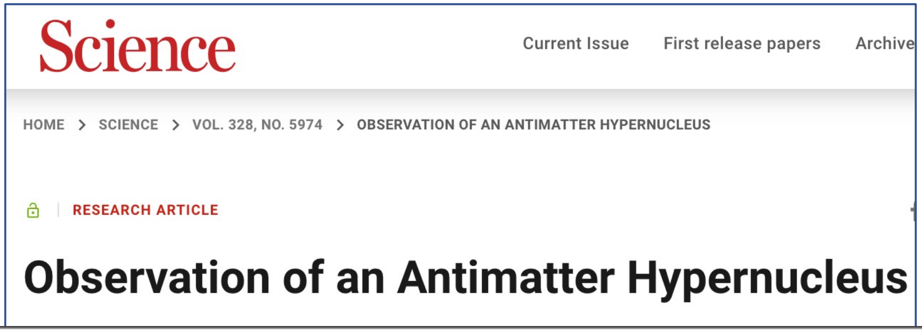
Neha Shah, Nu Xu, Kaijia Sun (talks)

N. Lewis, T. Tsang, Y. Li, H. Klest, W.B. Zhao, N. Magdy, R.R. Ma, P. Tribedy, J.D. Brandenburg, Z.B. Tang, Z.W. Lin, C. Shen, B. Schenke, D. Kharzeev, *et al.*

EMMI workshop on
"Bound states and particle interactions in the 21st century"

In part supported by
Brookhaven National Laboratory
U.S. DEPARTMENT OF ENERGY Office of Science

Search for heavier antimatter nuclear cluster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RESEARCH ARTICLE
Observation of an Antimatter Hypernucleus

B=-4


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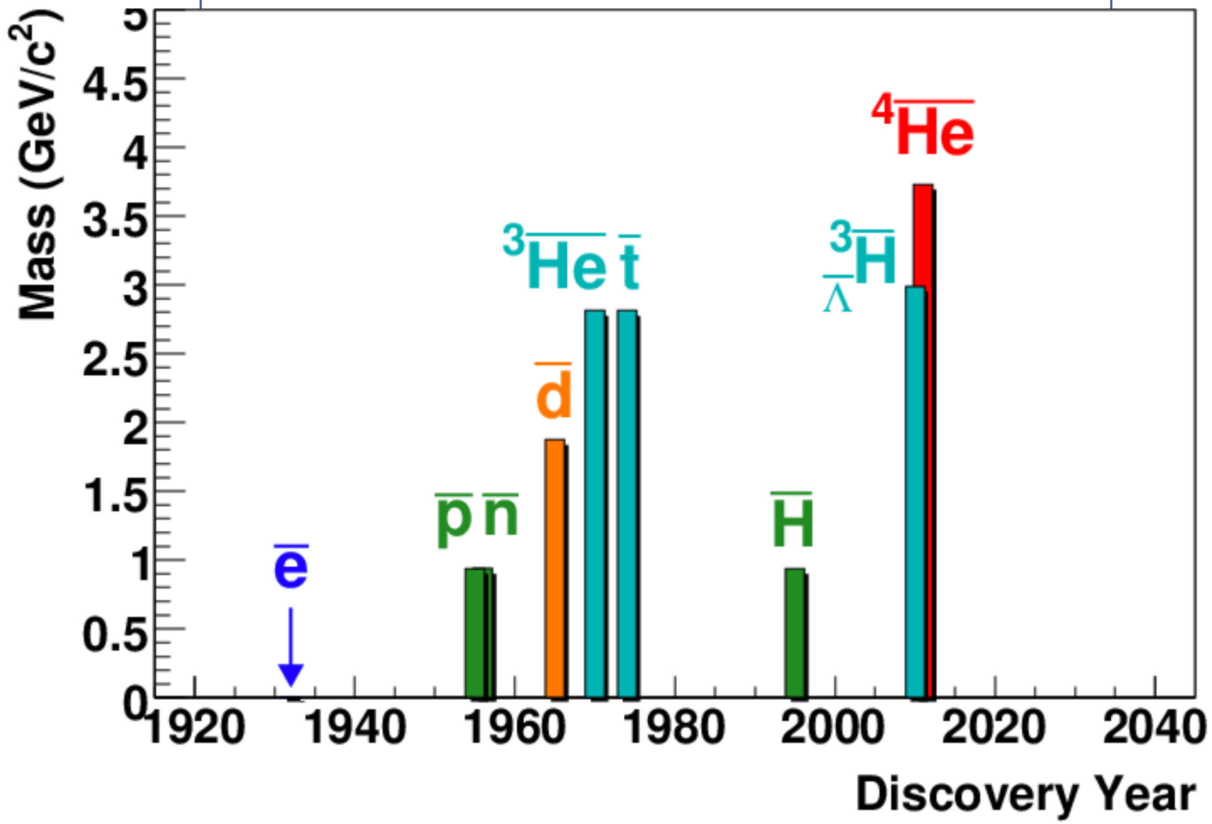
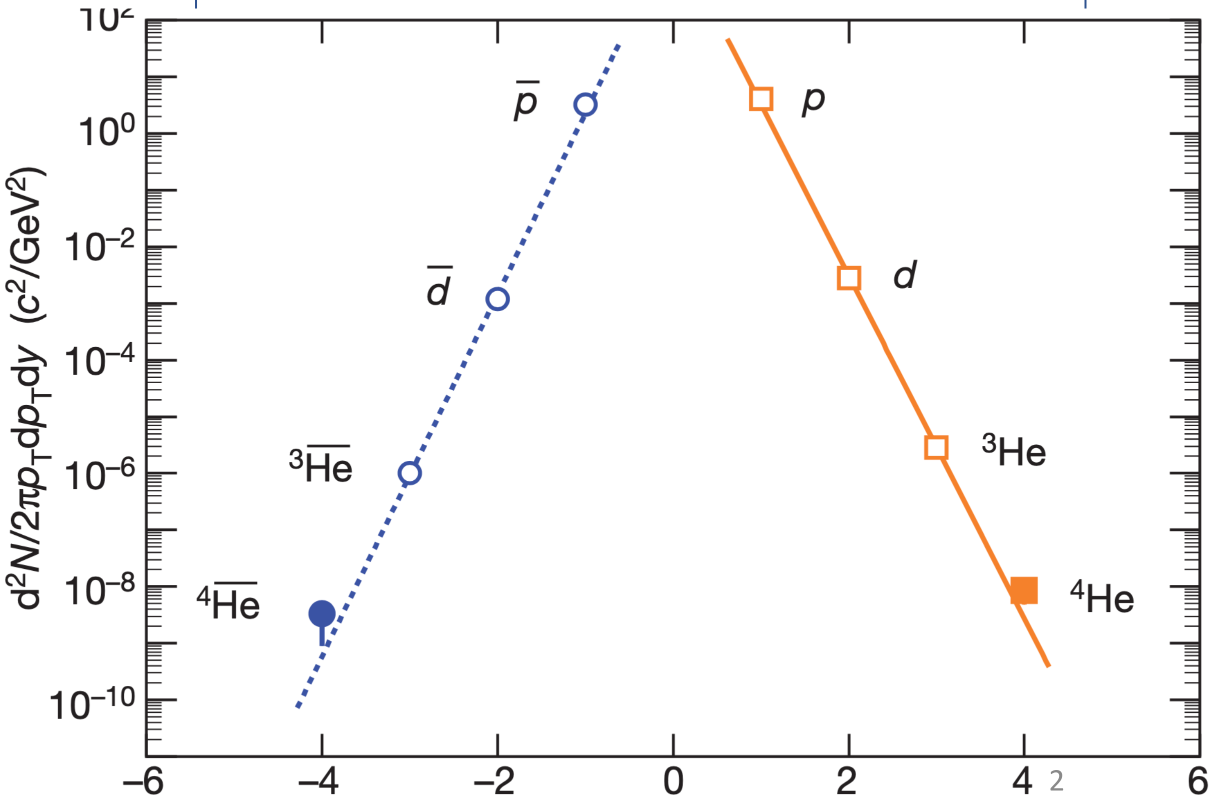
Published: 24 April 2011
Observation of the antimatter helium-4 nucleus

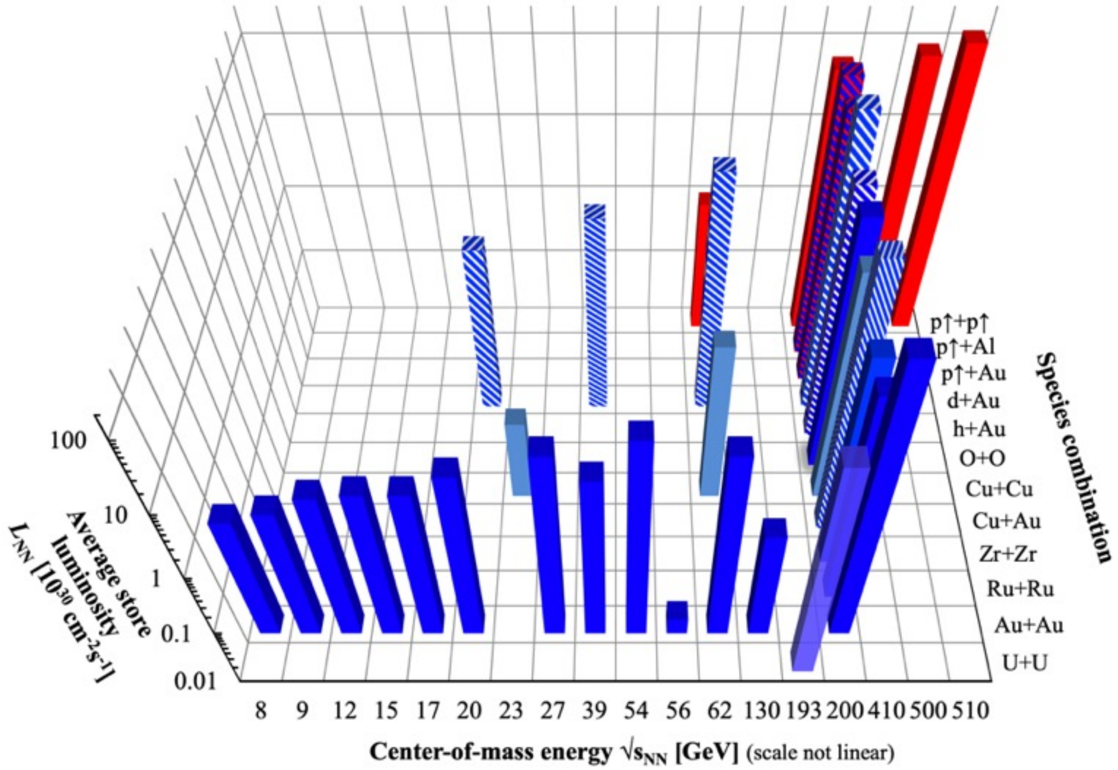




Example of versatile colliders and detectors

major upgrades over the last twenty years to improve particle identification and vertex reconstruction and is still evolving with an extension to forward rapidity as of today. pioneered in using new technologies: MRPC, MAPS, GEM and siPM.
Estimate 35M(initial) +75M(upgrades)$.

RHIC energies, species combinations and luminosities (Run-1 to 22)



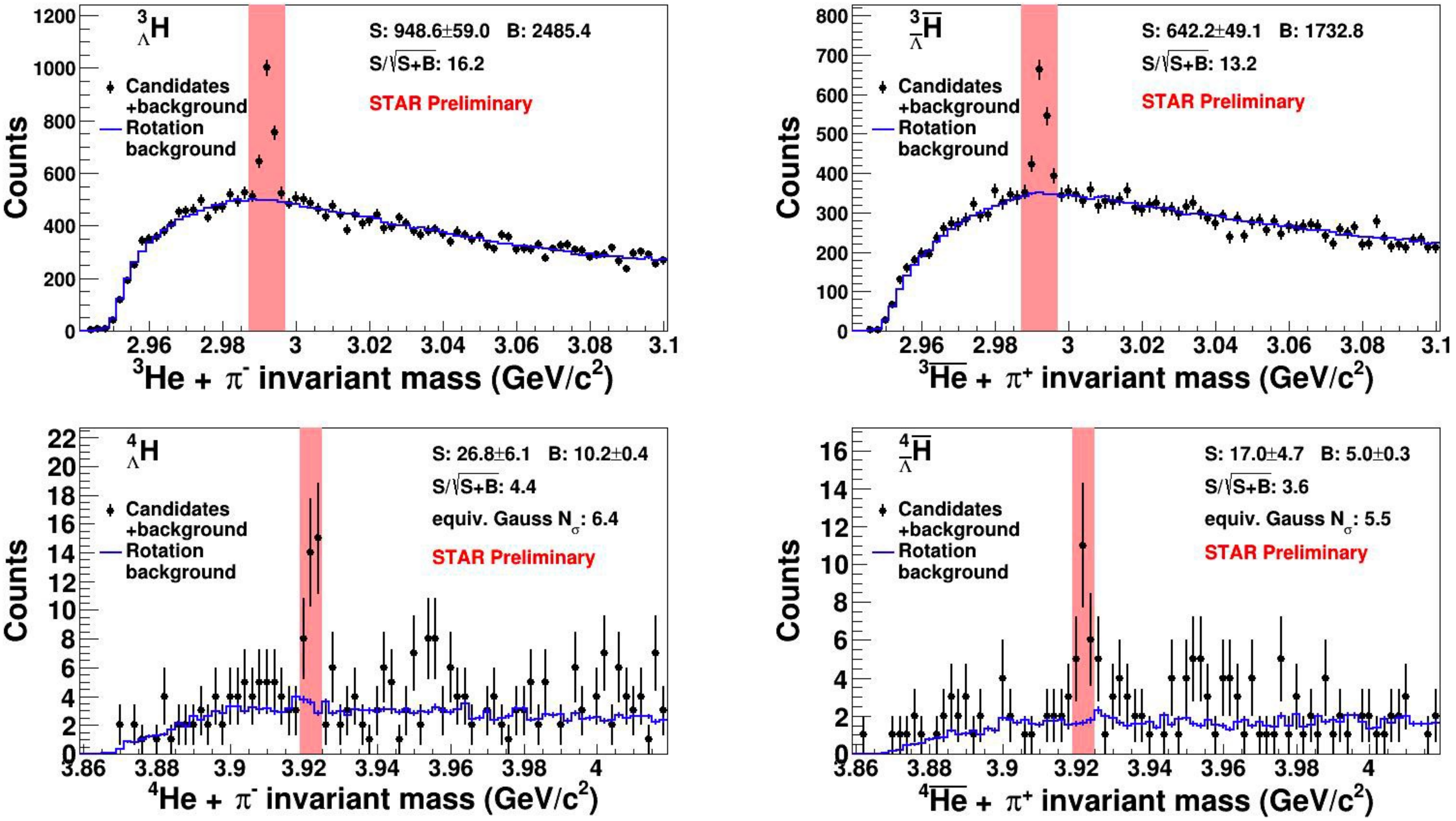
Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\lvert\eta\rvert < 1$ Tracking		1999-
Barrel EMC	$\lvert\eta\rvert < 1$ jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	$1 < \eta < 2$ jets/π^0/e	(NSF)	2005-
Roman Pots	diffractive		2009-
TOF	PID	(China)	2009-
FMS/Preshower	$2.5 < \eta < 4.2$	(Russia)	2008-2017
DAQ1000	x10 DAQ rate		2008-
HLT	Online Tracking	(China/Germany)	2012-
FGT	$1 < \eta < 2$ $W^{\pm}$		2012-2013
GMT	TPC calibration		2012-
HFT/SSD	open charm	(France/UIC)	2014-2016
MTD	muon ID	(China/India)	2014-
EPD	event plane	(China)	2018-
RHICf	$\eta > 5$ π^0	(Japan)	2017
iTPC	$\lvert\eta\rvert < 1.5$ Tracking	(China)	2019-
eTOF	$-2 < \eta < -1$ PID	(Germany/China)	2019-
FCS	$2.5 < \eta < 4$ calorimeter	(NSF)	2021-
FTS	$2.5 < \eta < 4$ Tracking	(NCKU/SDU)	2021-

8 new detectors added to STAR since 2014

Observation of antimatter H4Lambda

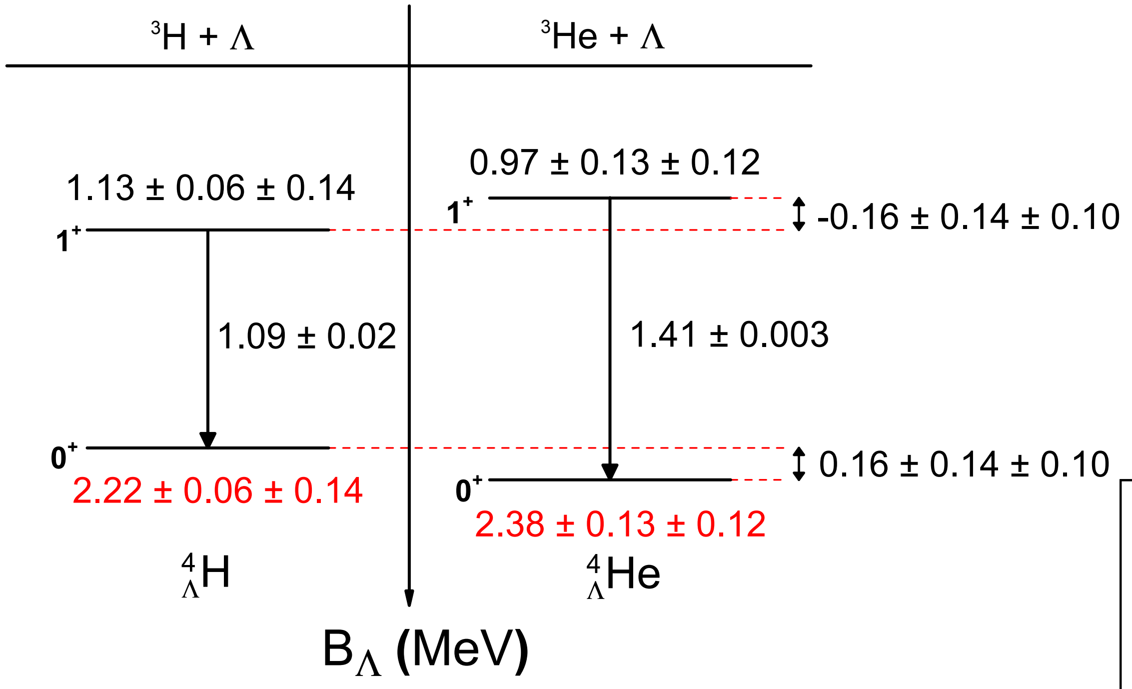
J.L. Wu (STAR), SQM2022

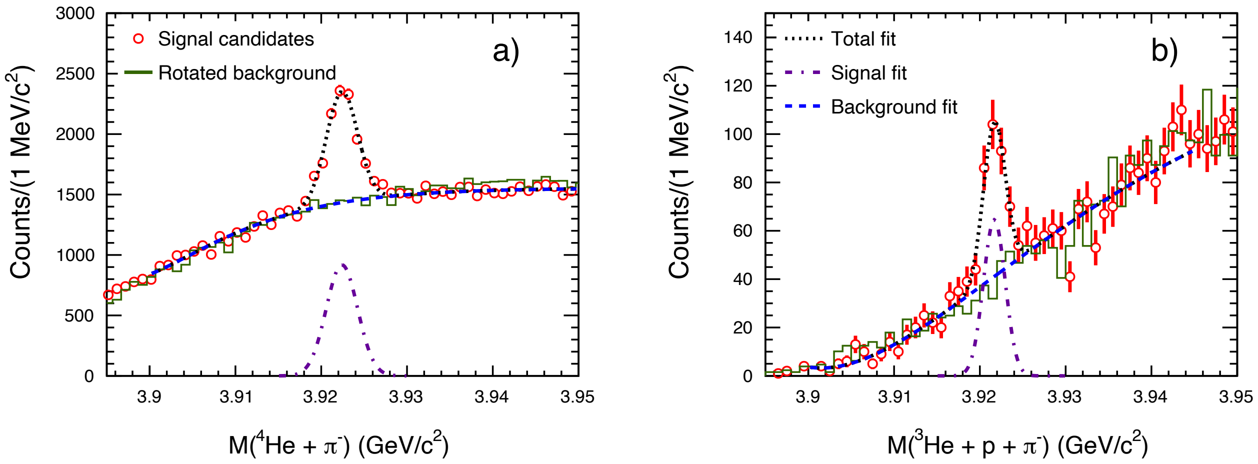
Au+Au: 2010+2011
U+U: 2012
Zr+Zr/Ru+Ru: 2018

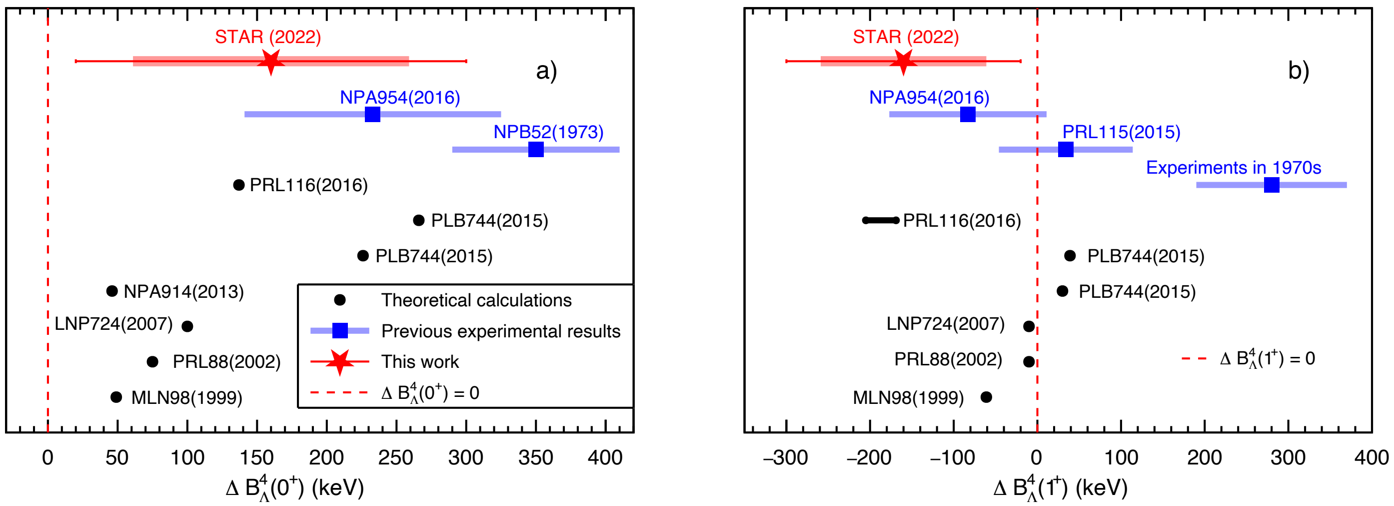


Charge Symmetry Breaking in B=4 hypernuclei

STAR, Phys. Lett. B **834** (2022) 137449



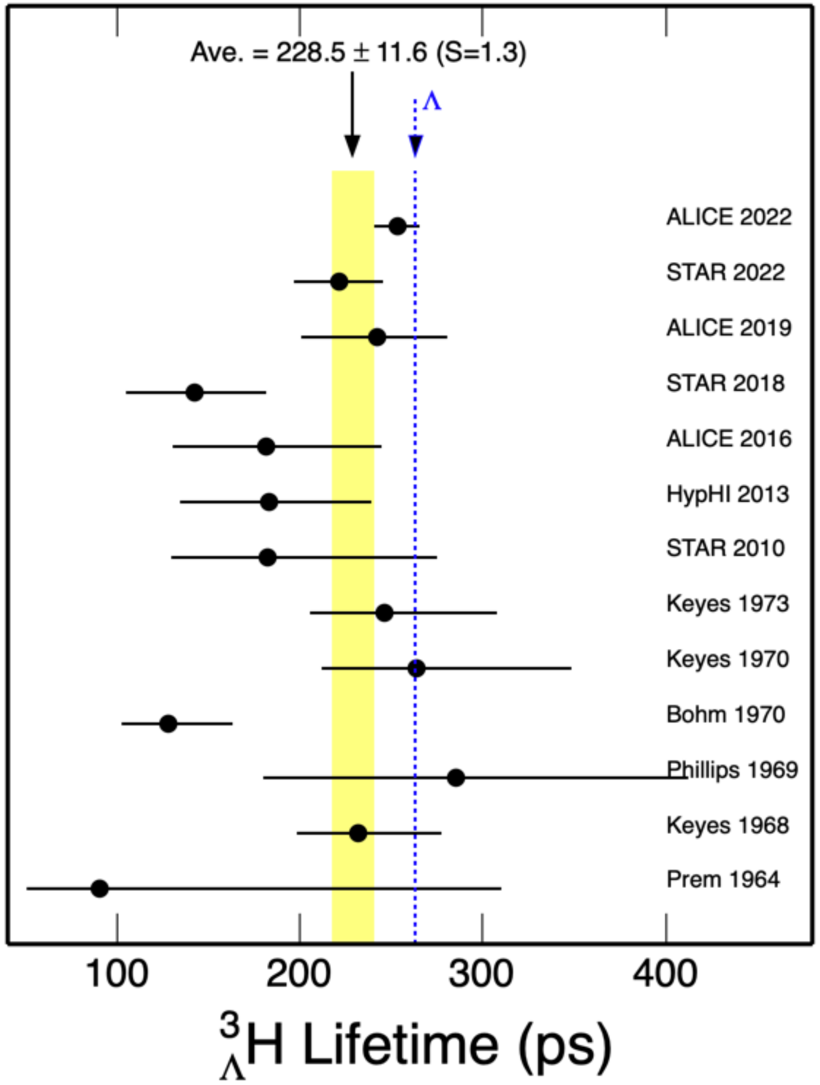


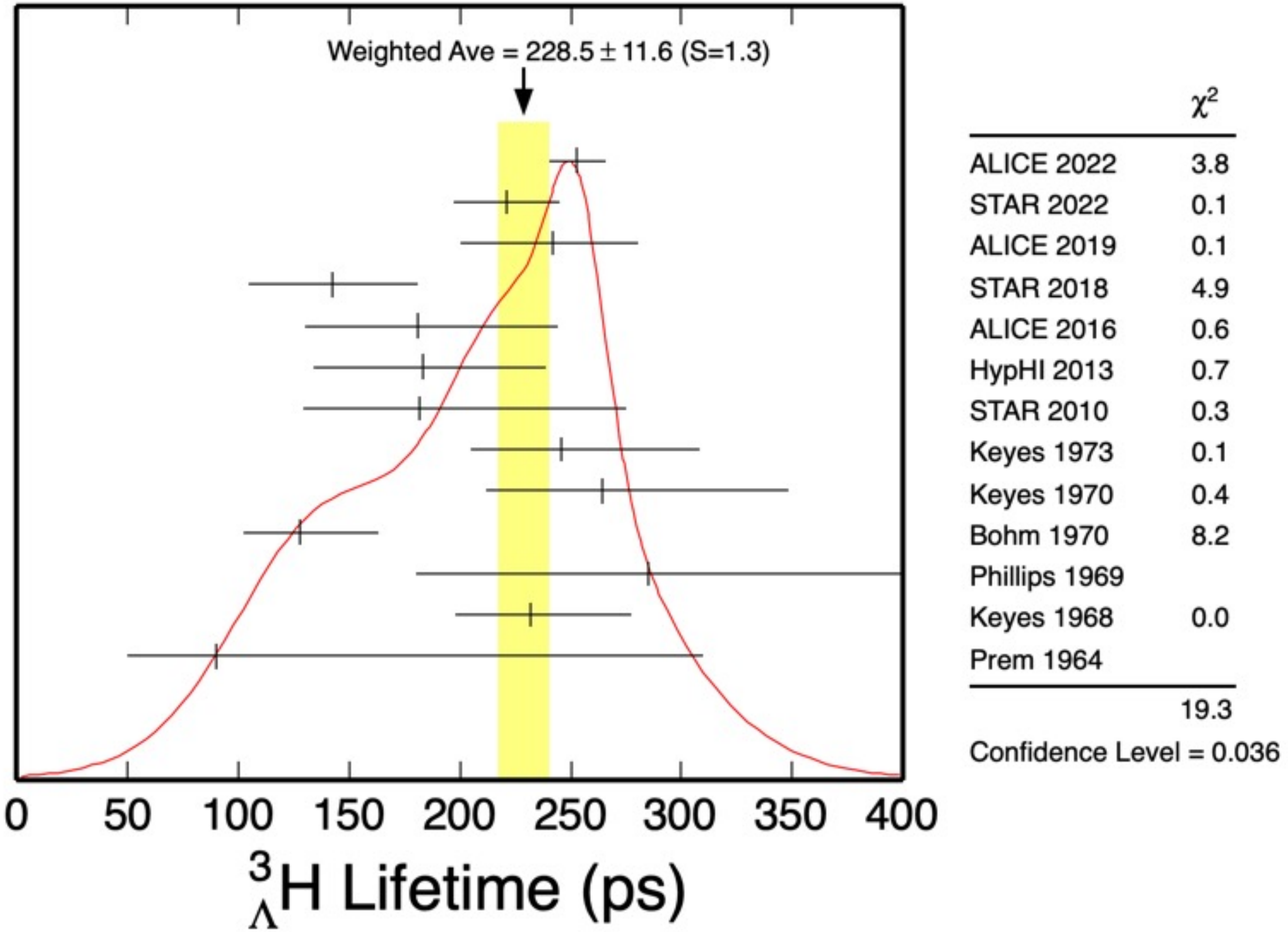


A puzzling CSB (70s):
both 0+ and 1+ large and positive ΔB

New measurements:
small and symmetric ΔB

|B|=3 hypertriton lifetime





Potential discrepancy?

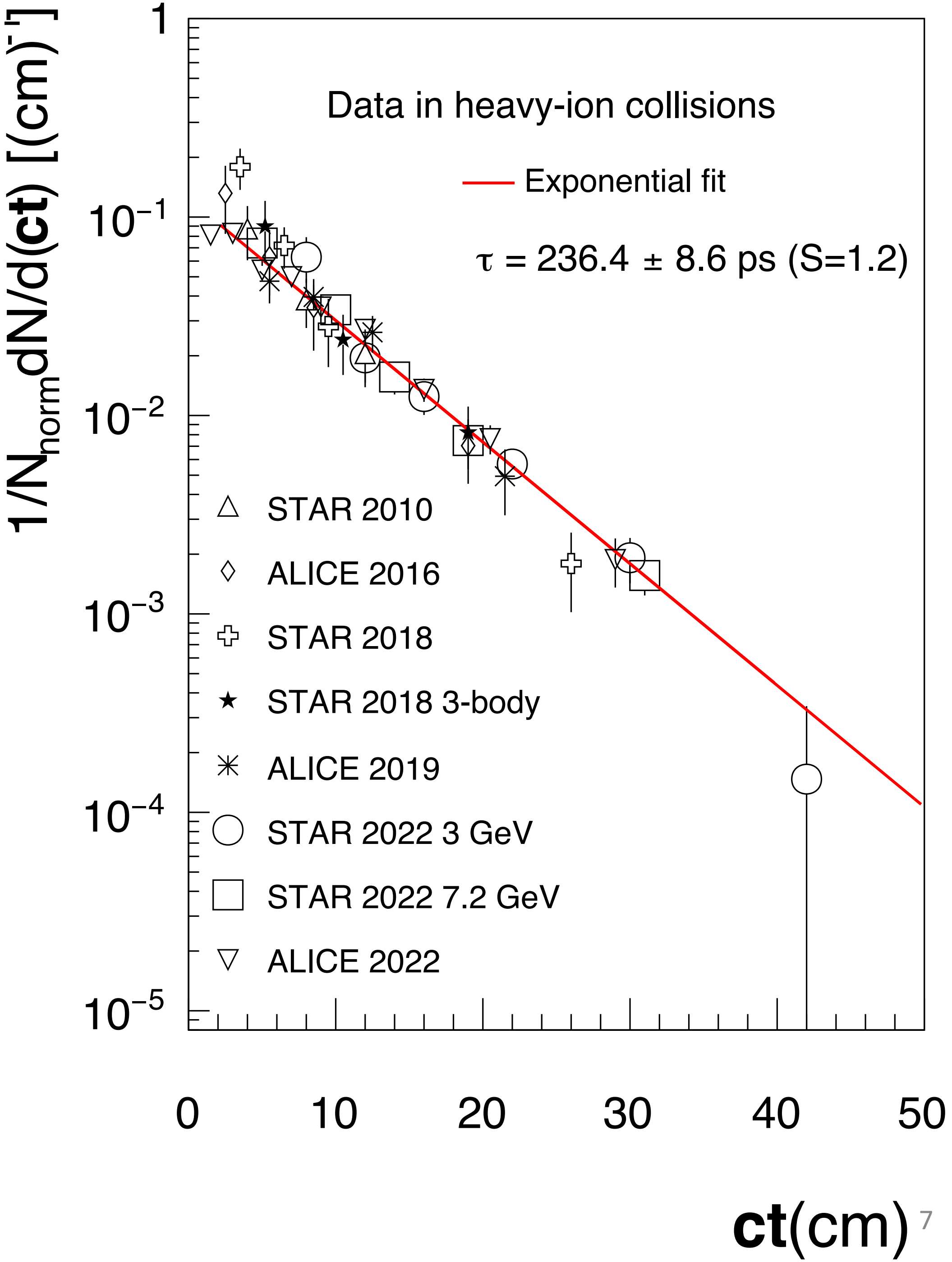
Simultaneous fit to all heavy-ion data

Scale yields to one common exponential function

Result consistent with other (average) methods

About 3σ smaller than Lambda lifetime

STAR 2018 first cτ point appears high
ALICE 2022 first cτ point appears low



B=1,2,3 nuclear yield ratios

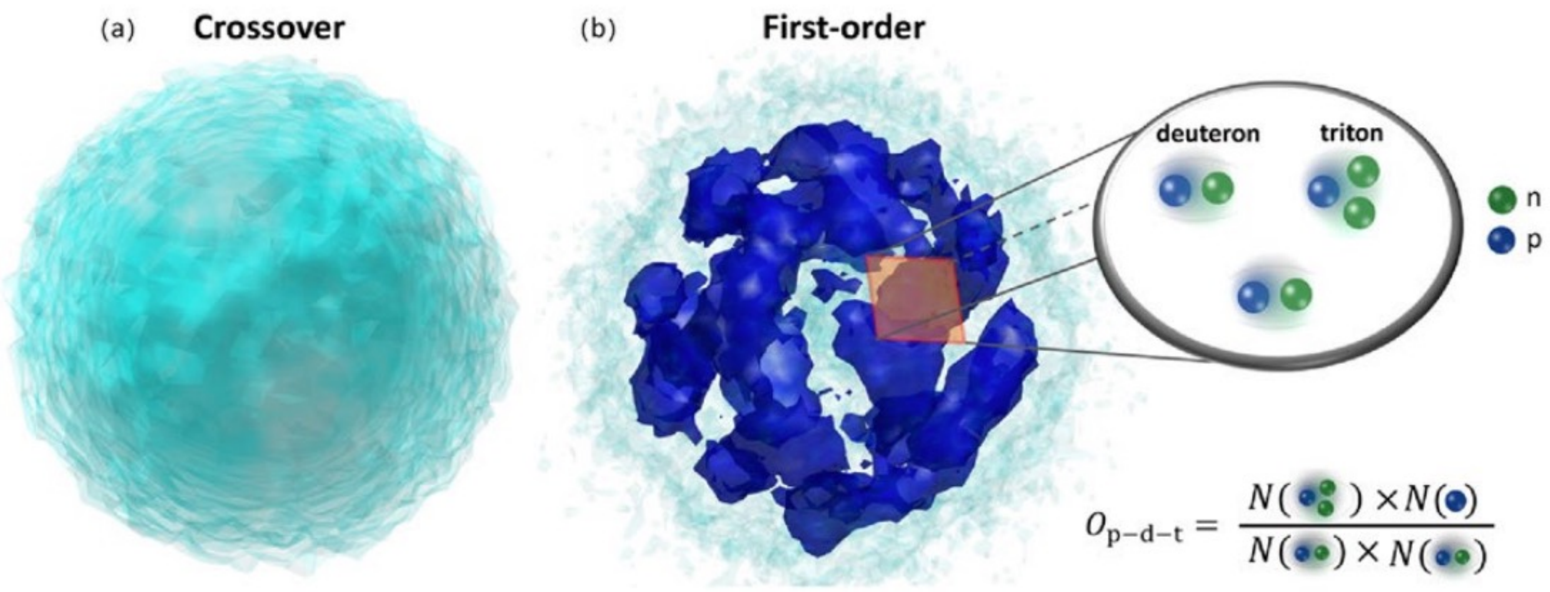


Fig. 1 (Color online) Density distribution of strongly interacting matter in a heavy ion collision after its expansion for the cases of crossover transition (panel **a**) and first-order chiral phase transition (panel **b**). Also shown for illustration of the latter case are deuterons and tritons produced from the density fluctuating hadronic matter and their yield ratio $\mathcal{O}_{\text{p-d-t}} = N_t N_p / N_d^2$, which depends on the magnitude of neutron density distribution as discussed in the text

- Light nuclei production as a probe of the QCD phase diagram

K.J. Sun, et al., PLB 781 (2018) 499

- Probing QCD critical fluctuations from light nuclei production in relativistic heavy-ion collisions

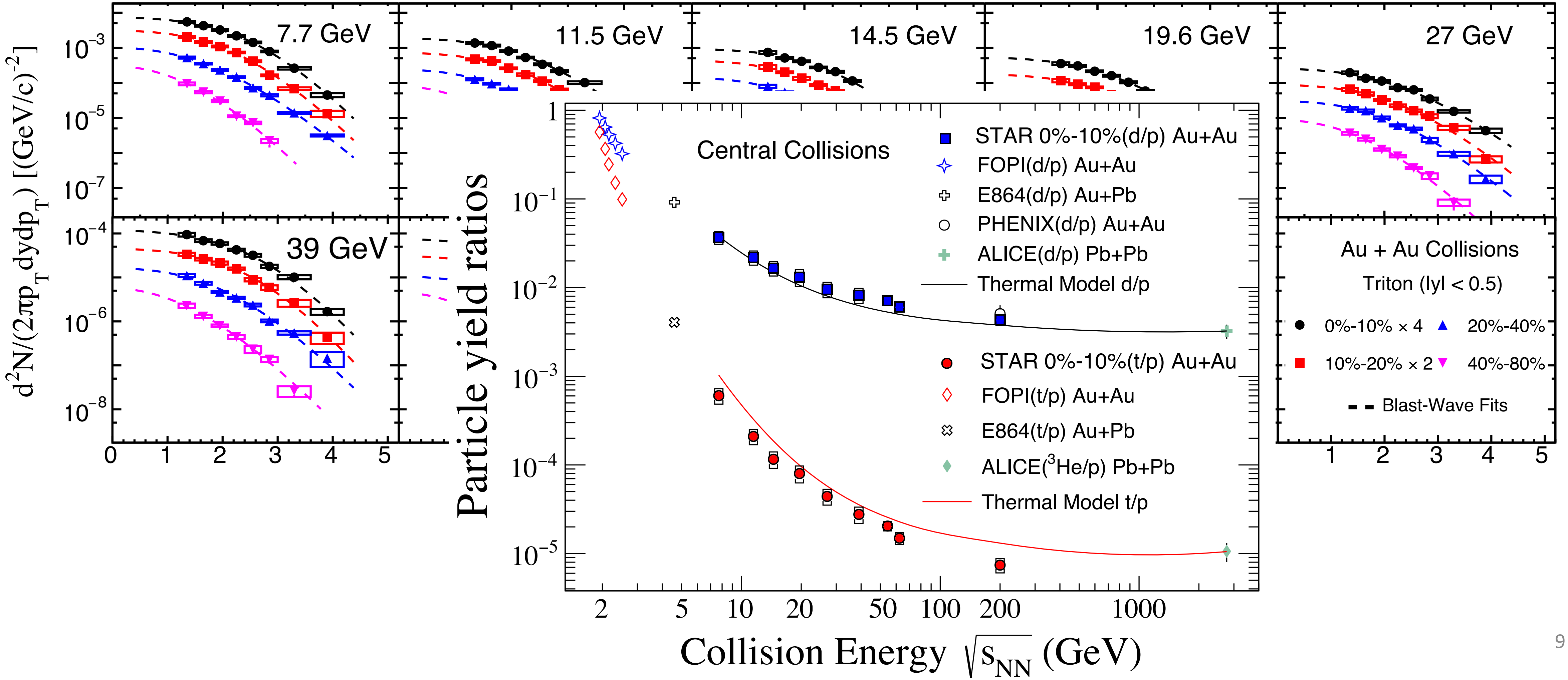
K.J. Sun, et al., PLB 774 (2017) 103

C.M. Ko, NST 34 (2023) 80

$$\mathcal{O}_{\text{p-d-t}} = \frac{N_{^3\text{H}} N_p}{N_d^2} = g\frac{1+(1+2\alpha)\Delta n}{(1+\alpha\Delta n)^2}$$

Spectra and two-particle ratios

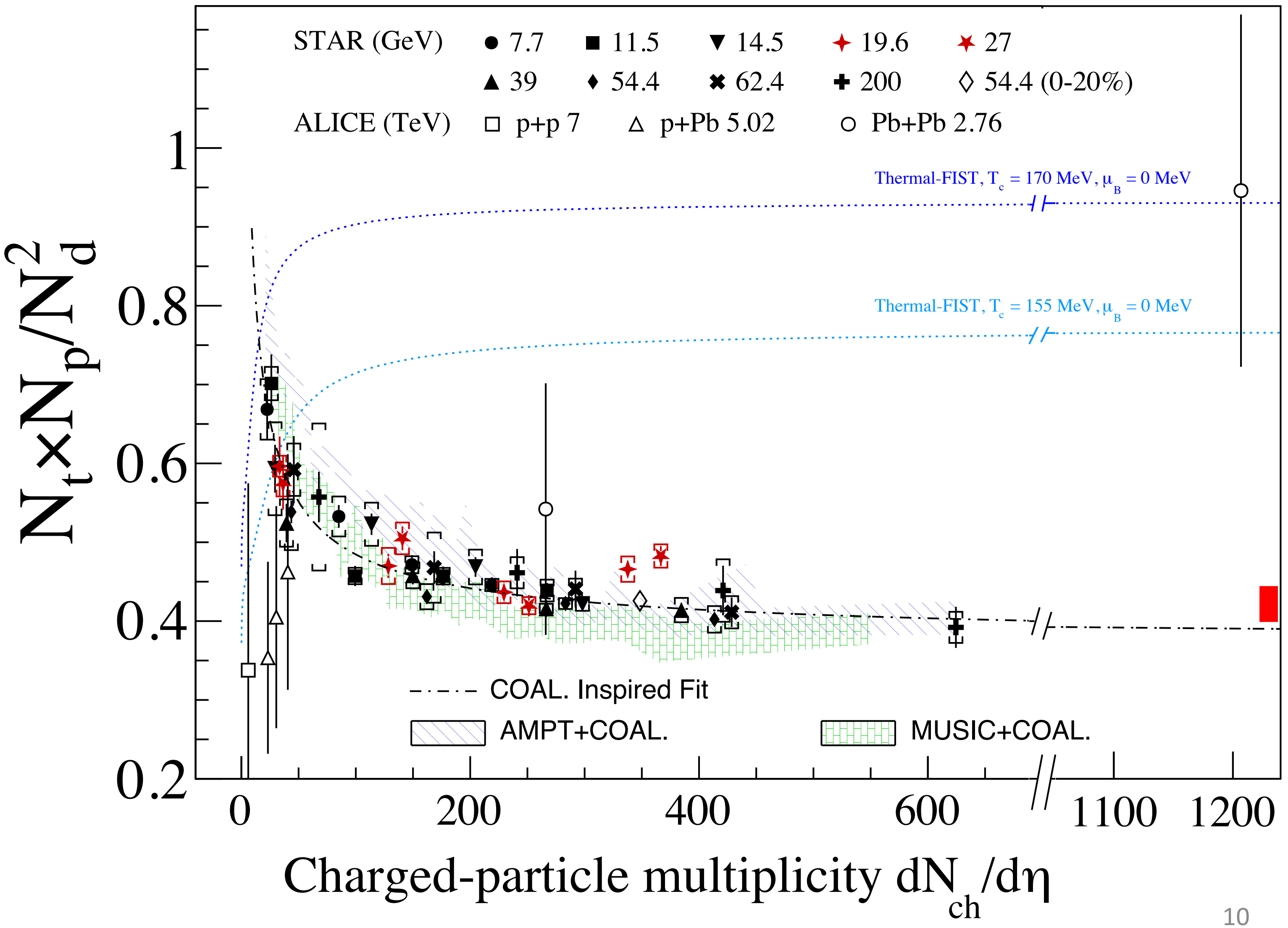
STAR, Phys.Rev.Lett. 130 (2023) 202301



Quantum Wavefunction overlap efficiency

$$\frac{N_t \times N_p}{N_d^2} = p_0 \times \left(\frac{R^2 + \frac{2}{3} r_d^2}{R^2 + \frac{1}{2} r_t^2} \right)^3$$

STAR, Phys.Rev.Lett. 130 (2023) 202301

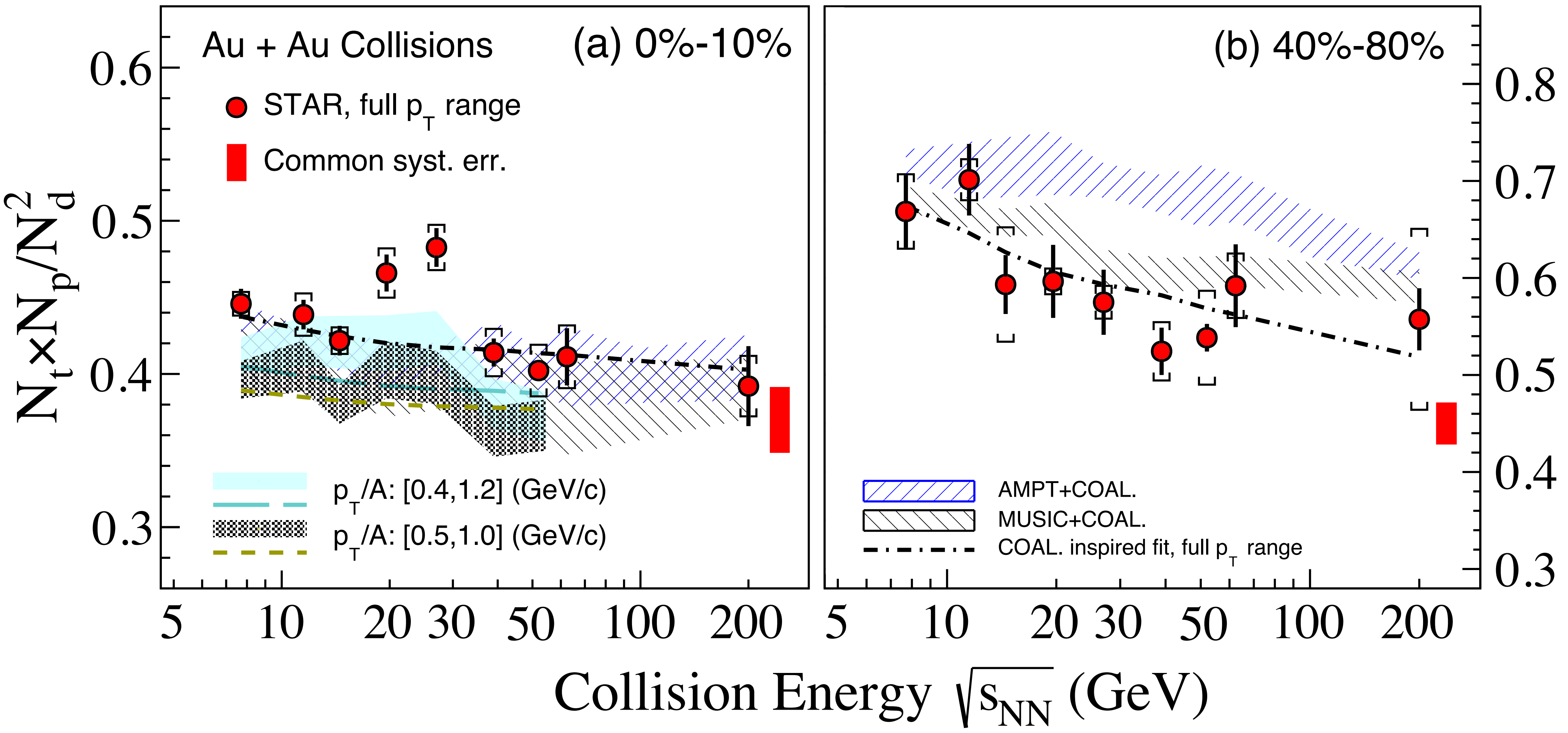


Coalescence wavefunction overlap between nucleus and nucleons

Possible sign of Density Fluctuation

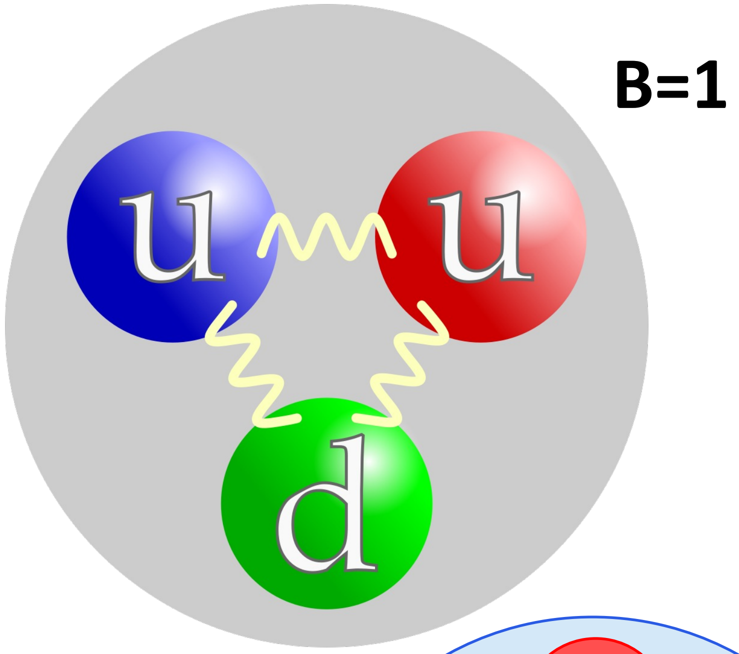
4σ effect, BES-II data x10 statistics

STAR, Phys.Rev.Lett. 130 (2023) 202301



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

Baryon Number (B) Carrier



- Textbook picture of a proton
  - Lightest baryon with strictly conserved baryon number
  - Each valence quark carries 1/3 of baryon number
  - Proton lifetime $>10^{34}$ years
  - Quarks are connected by gluons
- Alternative picture of a proton
  - Proposed at the Dawn of QCD in 1970s
  - A Y-shaped gluon junction topology carries baryon number (B=1)
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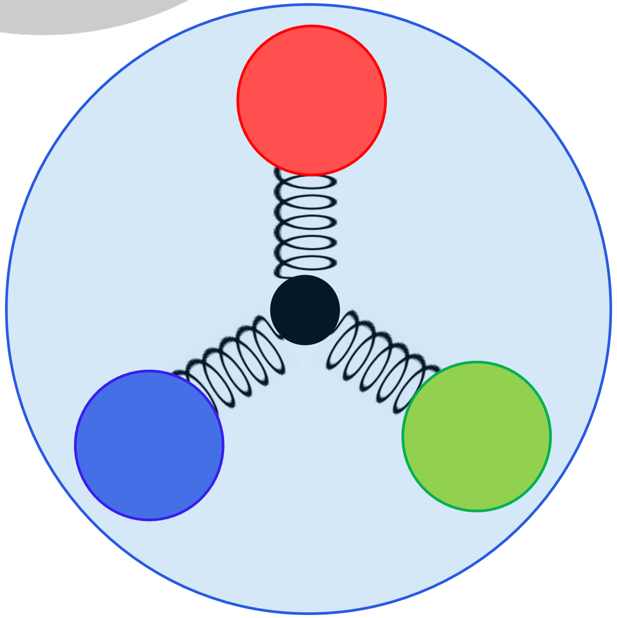

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[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (**1977**)

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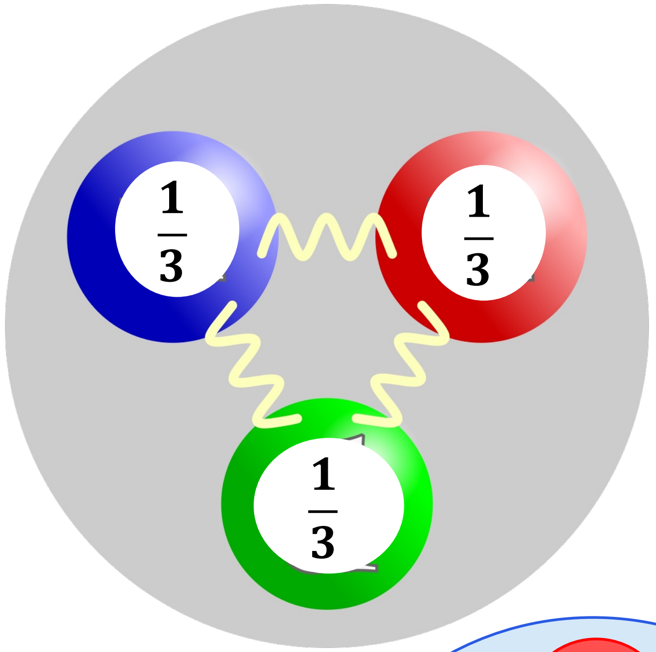

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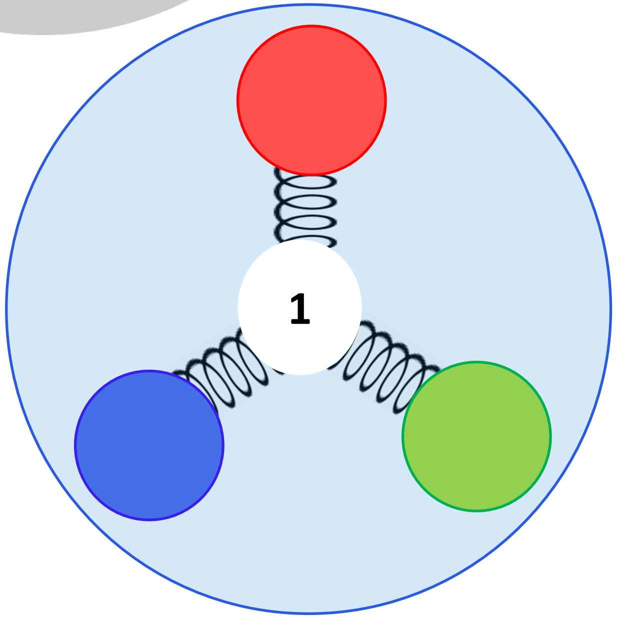

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Model implementations of baryons at RHIC

- Many of the models used for heavy-ion collisions at RHIC (HIJING, AMPT, UrQMD) have implemented a nonperturbative baryon stopping mechanism

V. Topor Pop, *et al,* Phys. Rev. C **70**, 064906 (2004)

Zi-Wei Lin, *et al*, Phys. Rev. C **72**, 064901 (2005)

M. Bleicher, *et al,* J.Phys.G **25,** 1859-1896 (1999)

- Baryon Stopping
  - Theorized to be an effective mechanism of stopping baryons in pp and AA

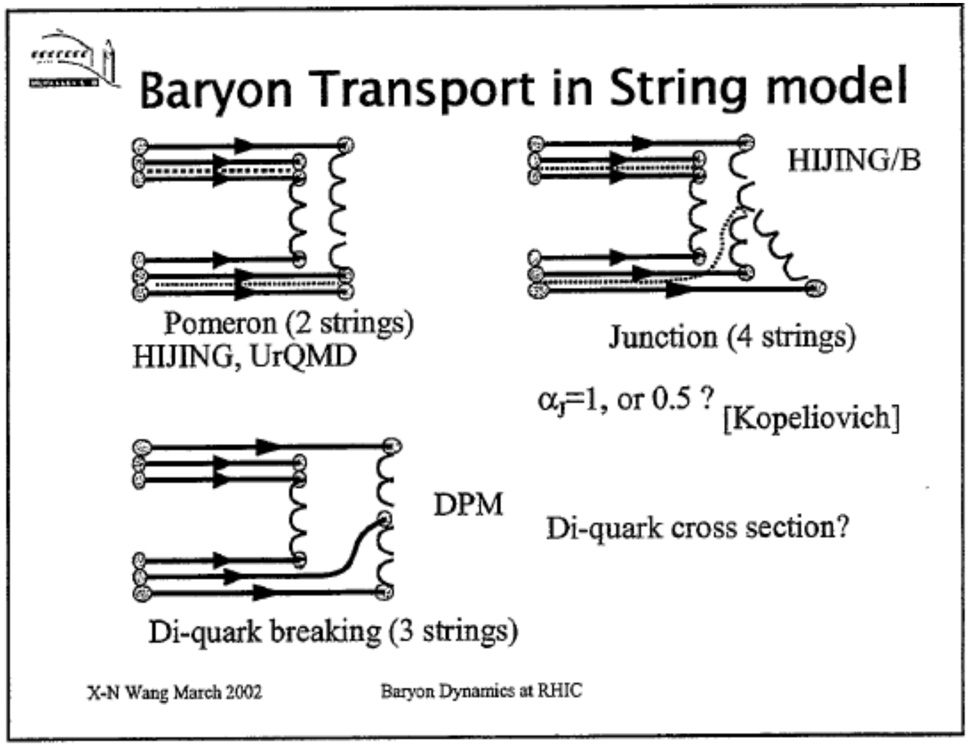
D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

- Specific rapidity dependence is predicted:

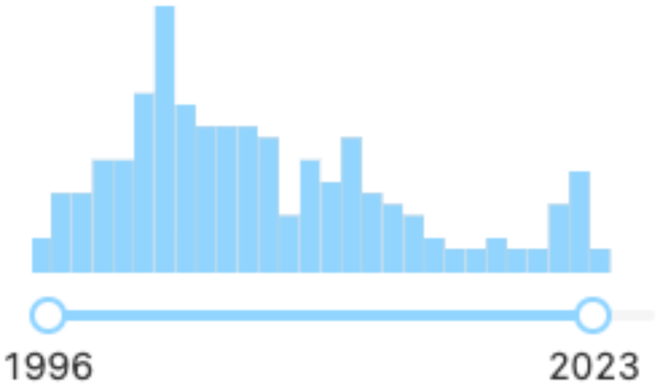
$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5

2003 RBRC Workshop on "Baryon Dynamics at RHIC"



D. Kharzeev, Physics Letters B **378**, 238-246 (1996)
"Can gluons trace baryon number?"



"Science, however, is never conducted as a popularity contest..." --- Michio Kaku

BUT citations ARE

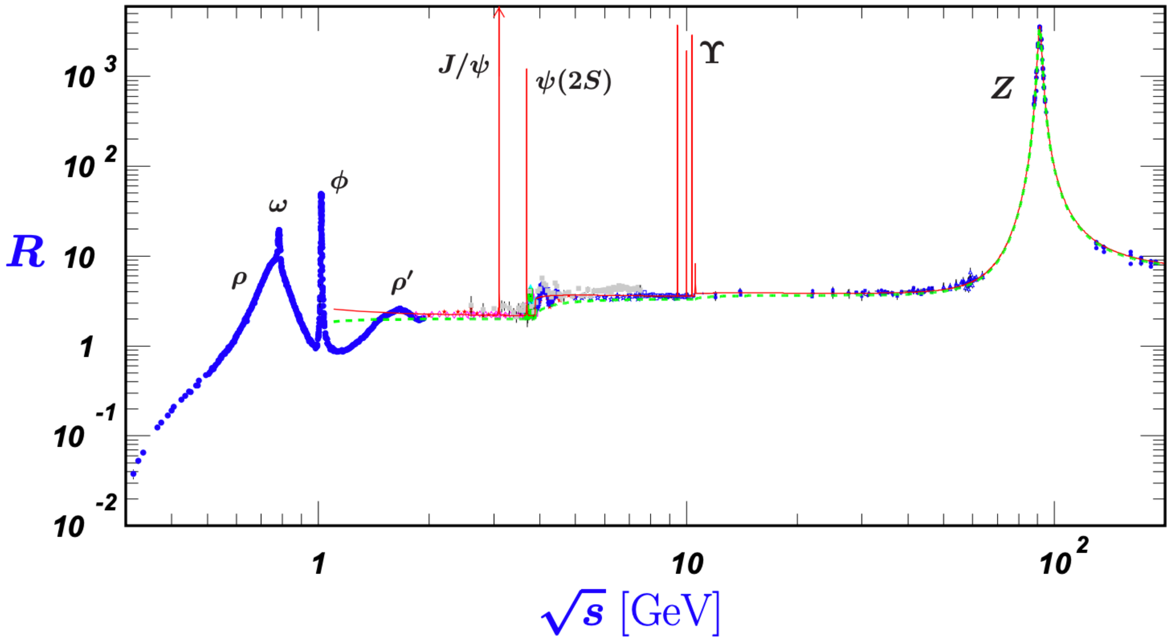
Measurements of quark electric charges

Scattering cross section $\sigma \propto e_q^2$

$(2/3)^2+(1/3)^2+(1/3)^2=2/3$

$(2/3)^2+(2/3)^2+(1/3)^2=1$

$(1/3)^2+(1/3)^2+(1/3)^2=1/3$



PDG

Figure 53.2: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model

Riordan, Science 1992

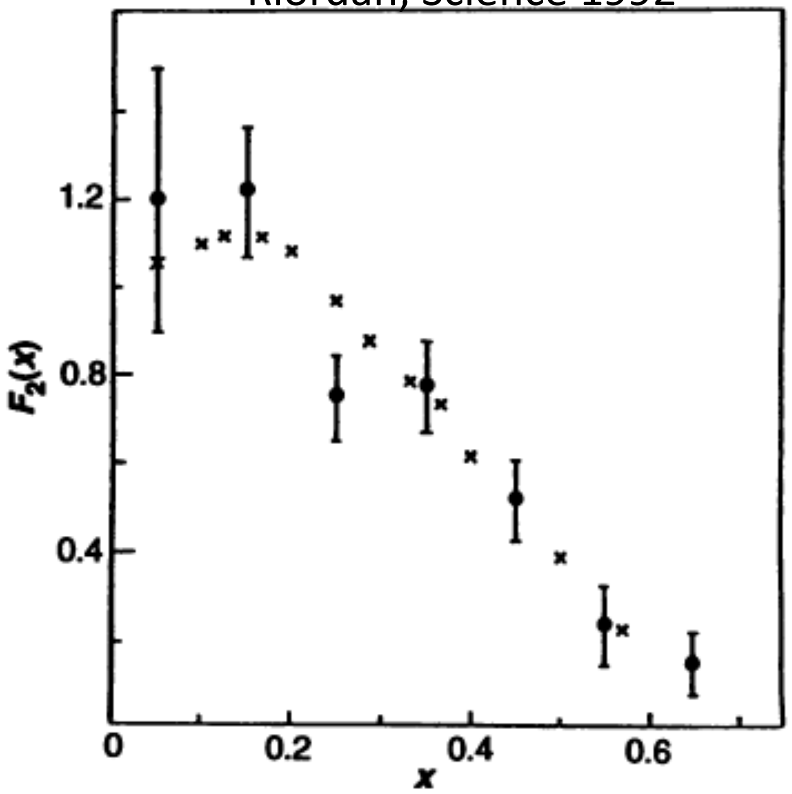
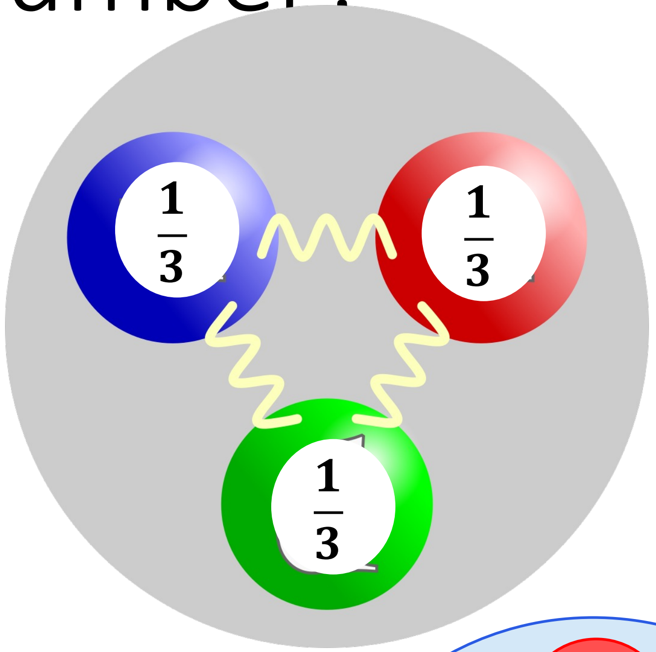


Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (×), MIT-SLAC, $(18/5)F_2^{eN}$]. When multiplied by 18/5, a number specified by the quark-parton model, the electron scattering data coincide with the neutrino data.

Measurements of quark baryon number?



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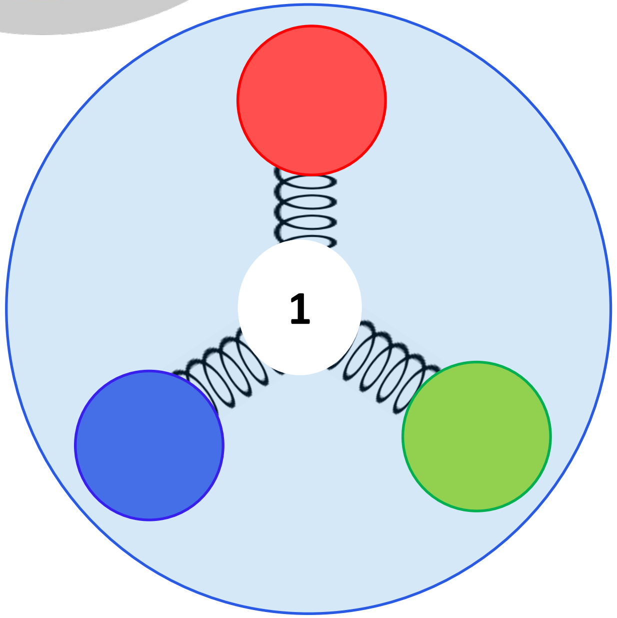

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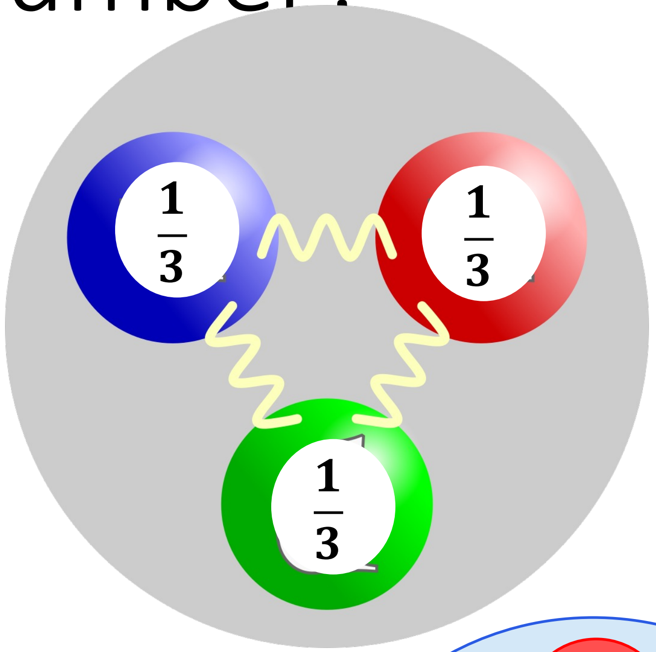
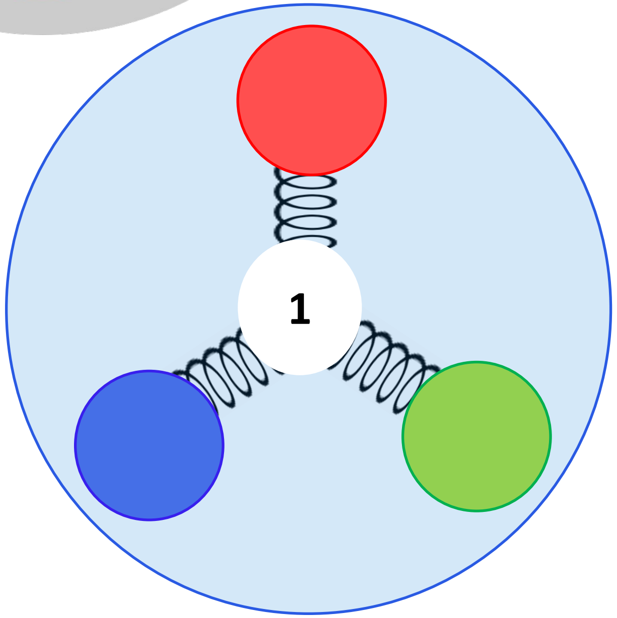
- **Neither of these postulations has been verified experimentally**





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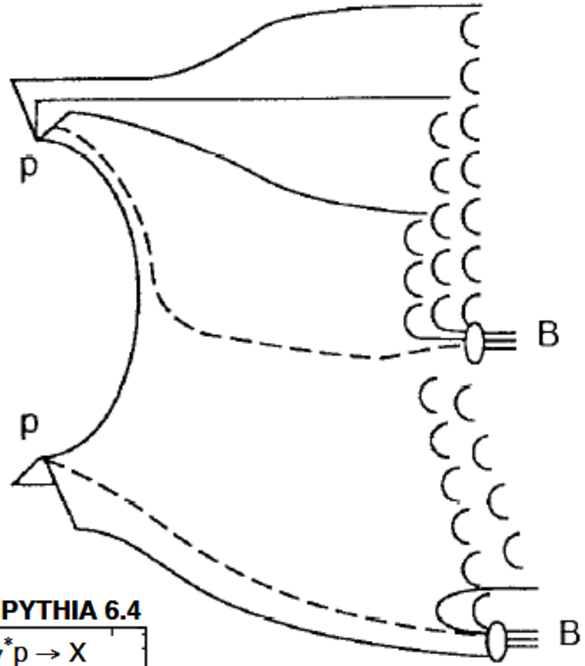
Three approaches toward tracking the origin of the baryon number

1. STAR Method:
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity

D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685

Proposed to use double ratio in Zr+Zr and Ru+Ru isobar collisions to cancel al the detector effects, the signal is at the level of 10^{-3}

Nicole Lewis (BNL), CFNS seminar 05/25

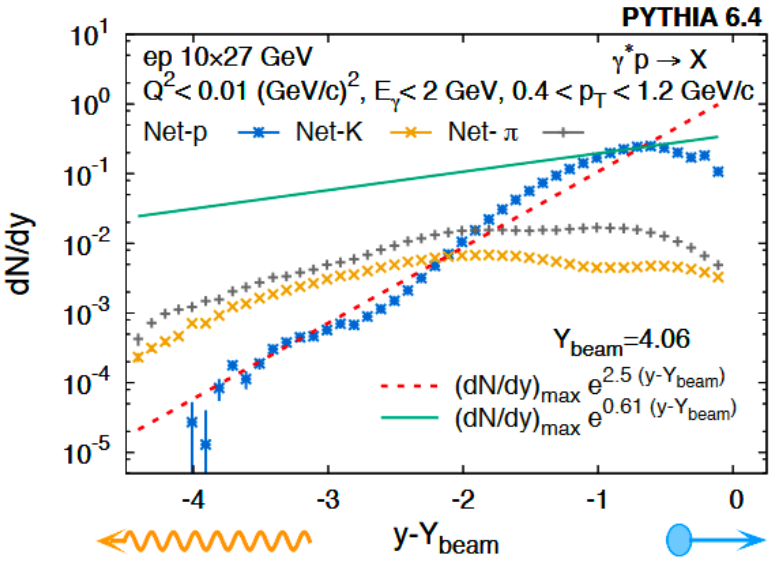


2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory

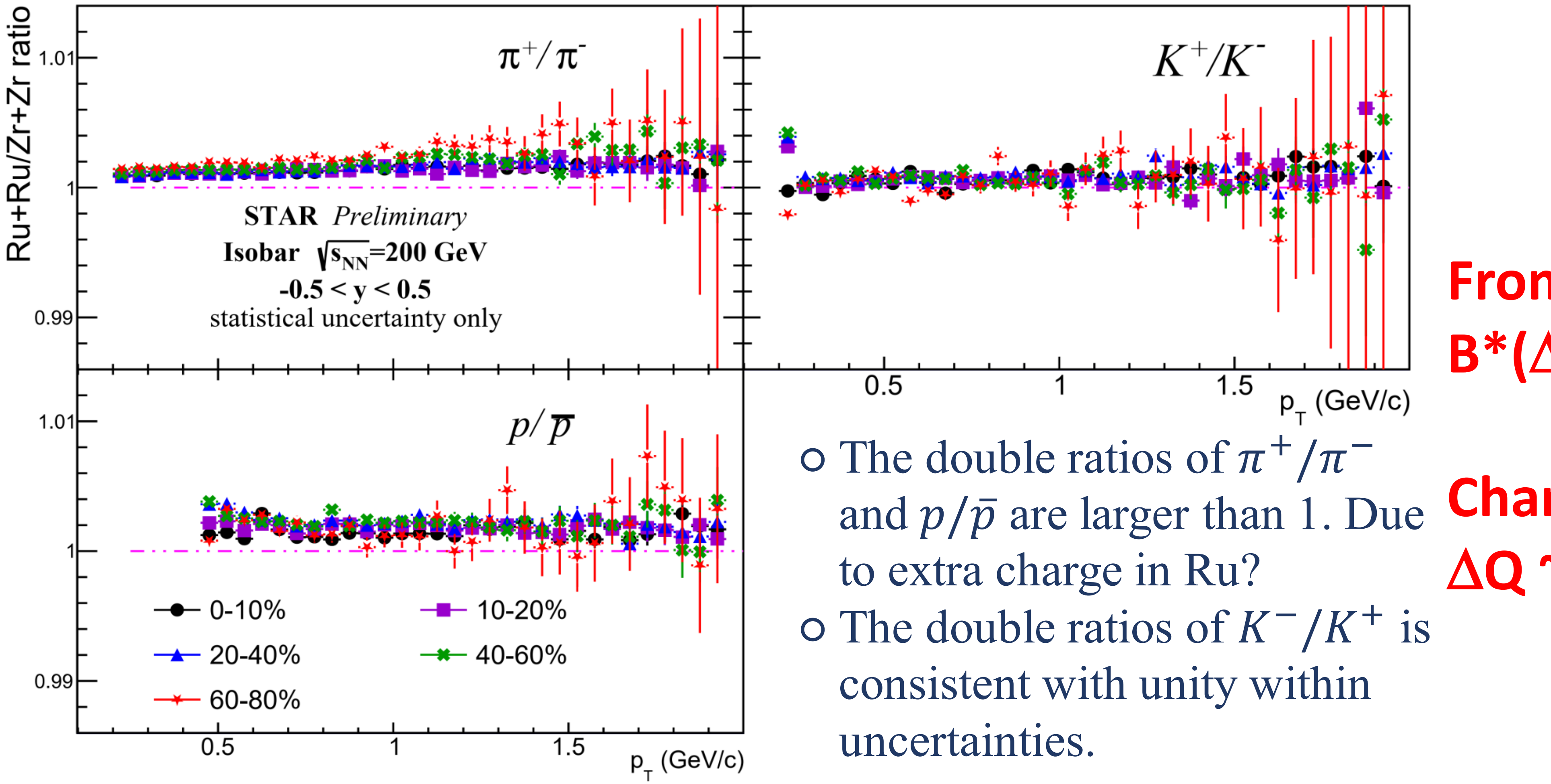
$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5

3. Artru Method:
   In γ+Au collision, rapidity asymmetry can reveal the origin



Double ratios between Ru+Ru and Zr+Zr collisions



- The double ratios of π^+/π^- and $p/\bar{p}$ are larger than 1. Due to extra charge in Ru?
- The double ratios of K^-/K^+ is consistent with unity within uncertainties.

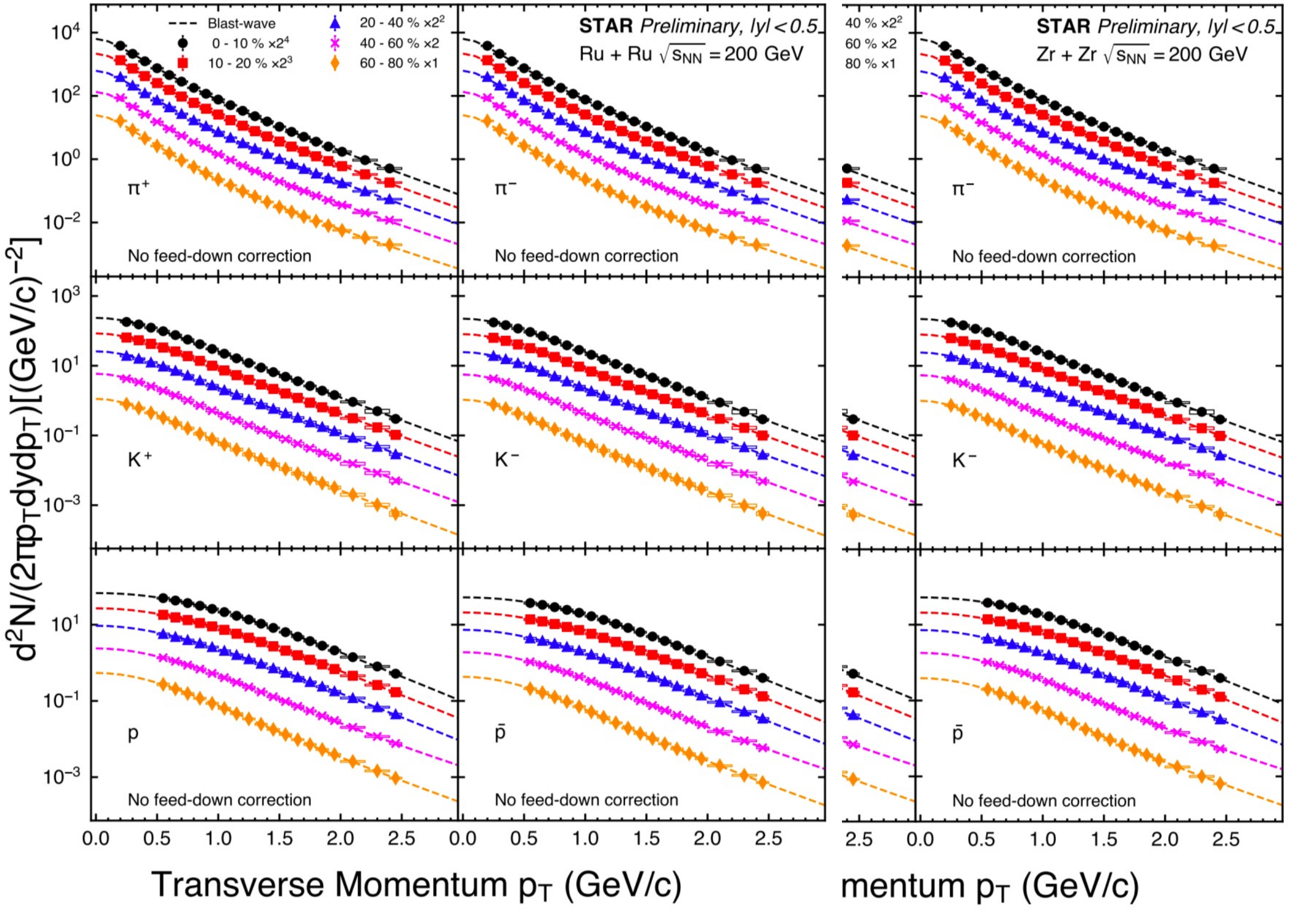
From baryon stopping: B*(ΔZ/A)~=2x10^{-3}

Charge stopping: ΔQ ~=1x10^{-3}

Identified hadron spectra to low momentum

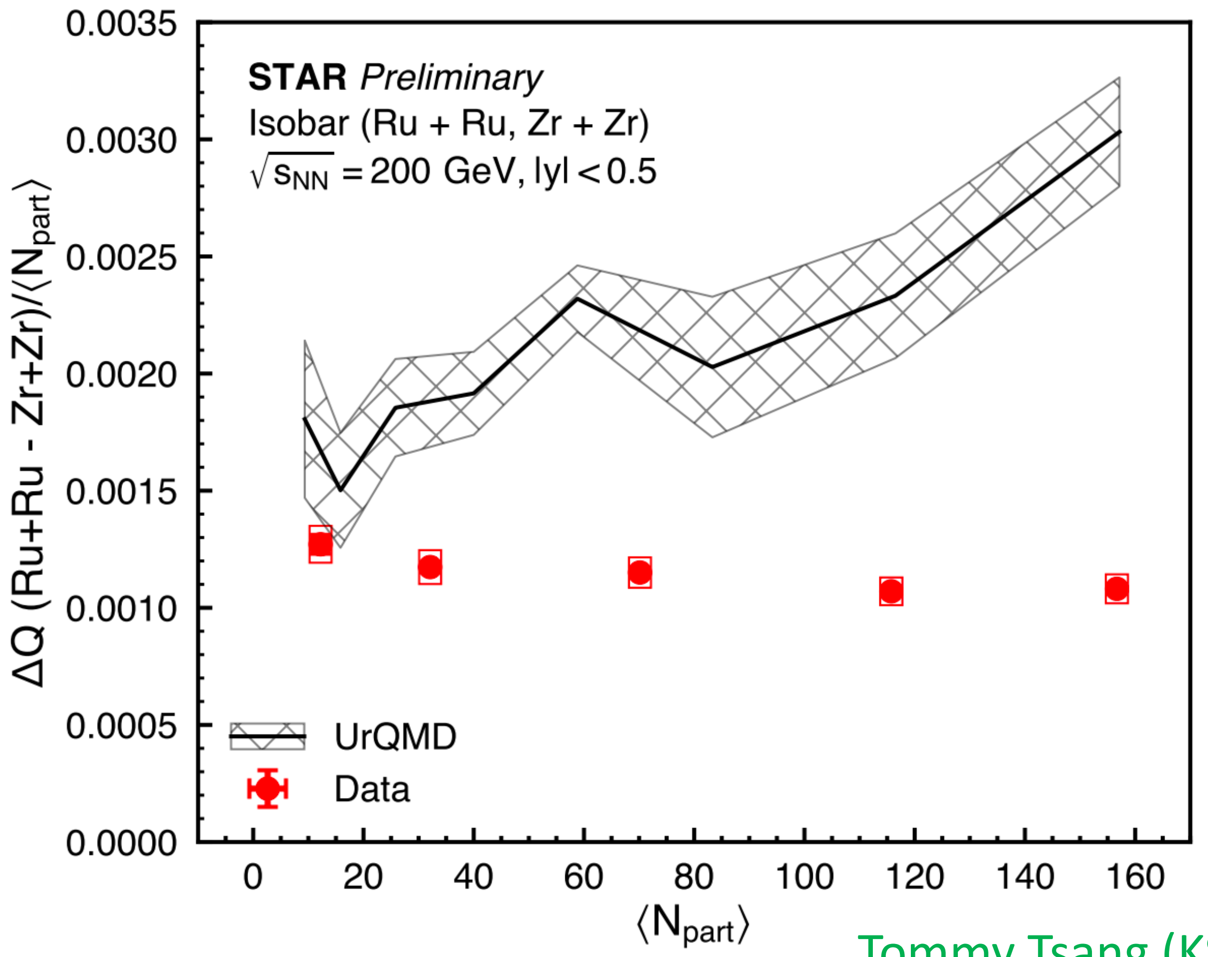
Net-charge difference (Ru+Ru – Zr+Zr)

- $R2_\pi = \frac{(N_\pi^+/N_\pi^-)_{Ru}}{(N_\pi^+/N_\pi^-)_{Zr}} \approx \frac{[1+(N_\pi^+ - N_\pi^-)/N_\pi]_{Ru}}{[1+(N_\pi^+ - N_\pi^-)/N_\pi]_{Zr}} = \frac{1+\Delta \mathrm{R_{Ru}}}{1+\Delta \mathrm{R_{Zr}}} \approx 1 + \Delta \mathrm{R_{Ru}} - \Delta \mathrm{R_{Zr}}$
- $\Delta Q = \left[\left(N_\pi^+ + N_K^+ + N_p\right) - \left(N_\pi^- + N_K^- + N_{\bar{p}}\right)\right]_{\mathrm{Ru}} - [\,]_{\mathrm{Zr}}$
- **Focus on pion terms,**
- $(N_\pi^+ - N_\pi^-)_{Ru} - (N_\pi^+ - N_\pi^-)_{Zr} = N_{\pi,Ru} \times \Delta \mathrm{R_{Ru}} - \mathrm{N}_{\pi,Zr} \times \Delta \mathrm{R_{Zr}}$
- $\approx N_\pi(\Delta \mathrm{R_{Ru}} - \Delta \mathrm{R_{Zr}}) = \mathrm{N}_\pi \times (R2_\pi - 1$
- **Where** $N_\pi = 0.5 \times (N_\pi^+ + N_\pi^-)$
- **Therefore,** $\Delta Q = \mathrm{N}_\pi(\mathrm{R2}_\pi - 1) + N_K(R2_K - 1) + N_p(R2_p - 1)$

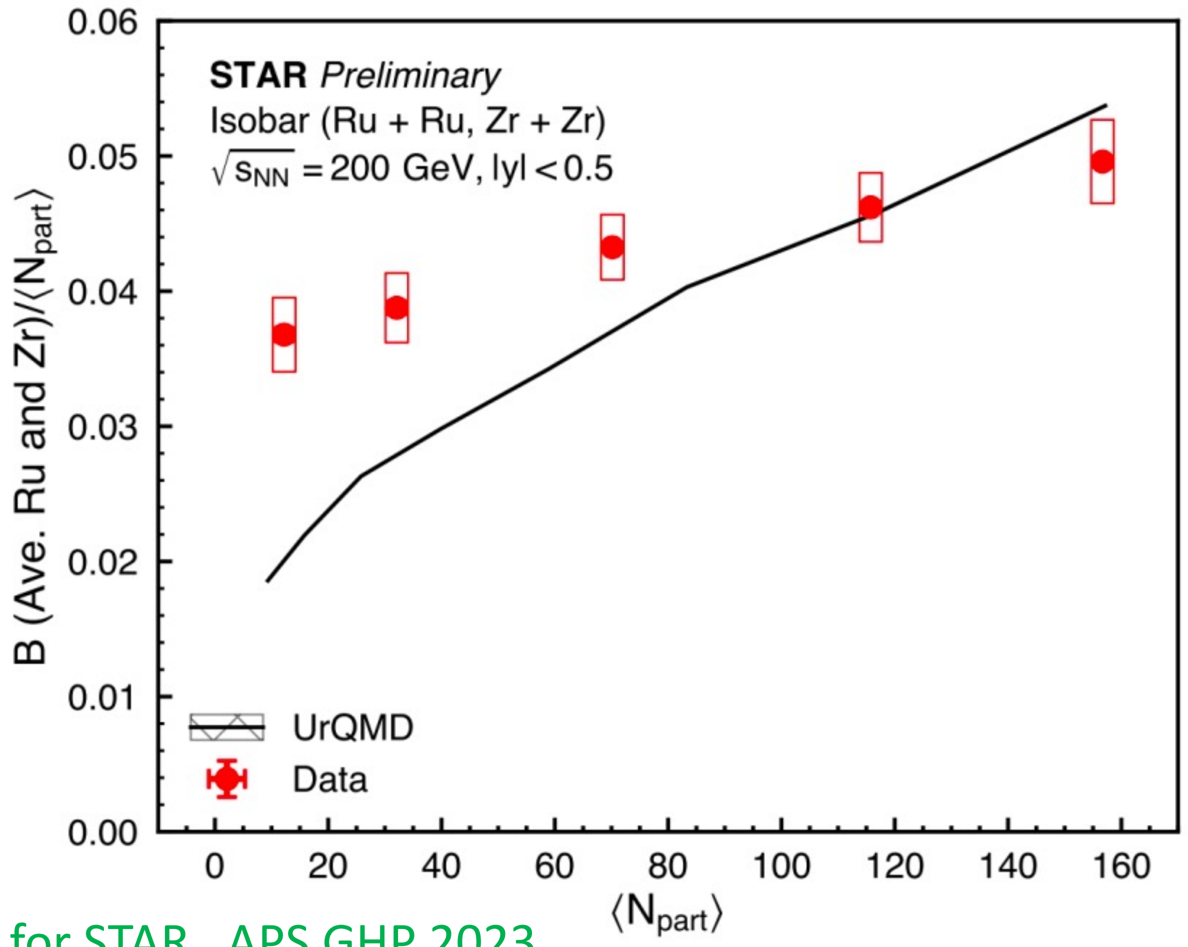


Separate charge and baryon transports

Charge number transport



Baryon number transport



Tommy Tsang (KSU) for STAR, APS GHP 2023

UrQMD matches data on charge stopping better in peripheral; better on baryon stopping in central
overpredicts charge stopping in central; underpredicts baryon stopping in peripheral

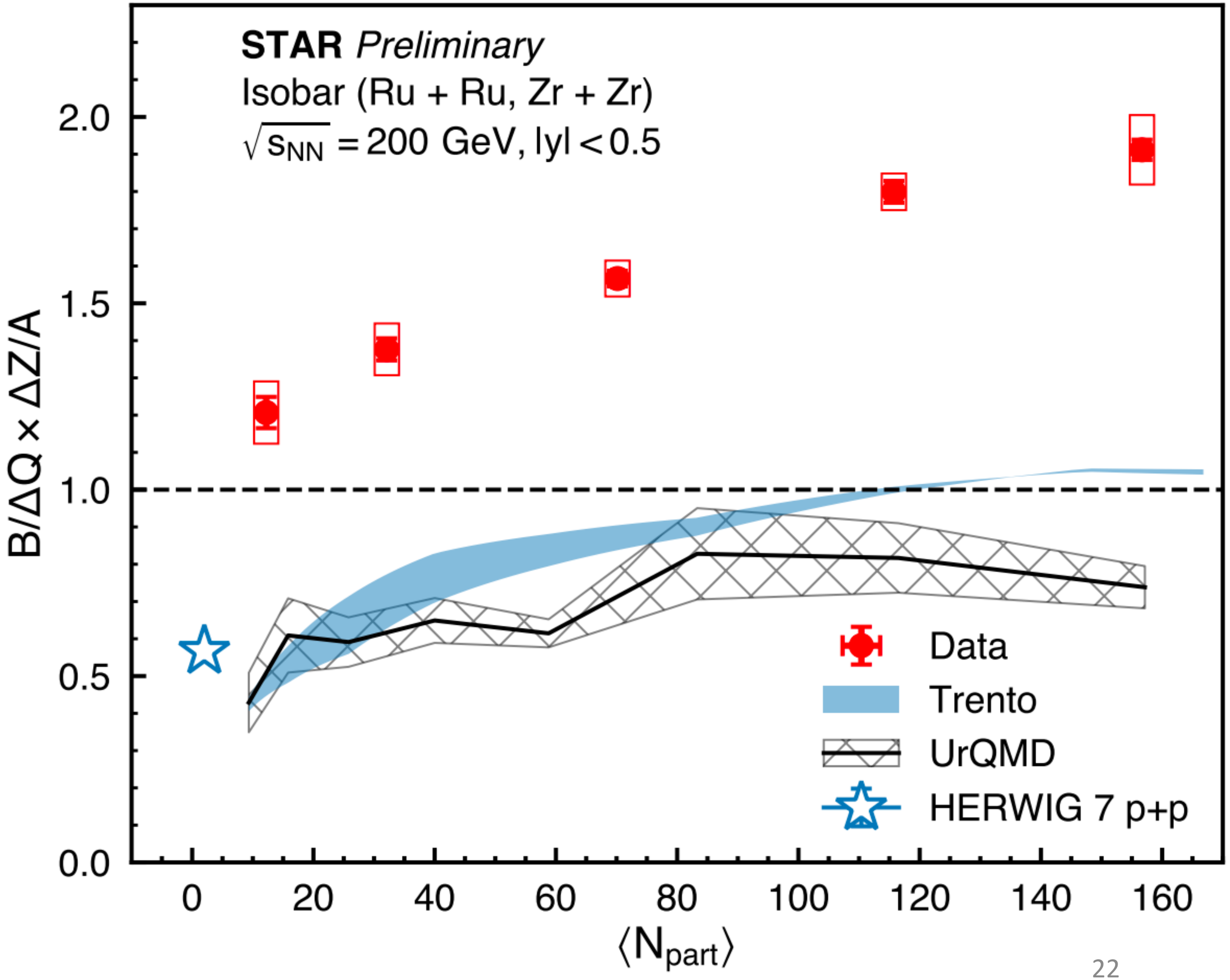
Ratio of baryon over charge transports

Tommy Tsang (KSU) for STAR, APS GHP 2023

- **Experimental data**:
  More baryon transported to C.O.M than charge by about a factor of 2

- **Model simulations**:
  Less baryon transported to C.O.M frame than charge

- Pure geometry:
  with neutron skin predicts the right centrality dependence (Trento)

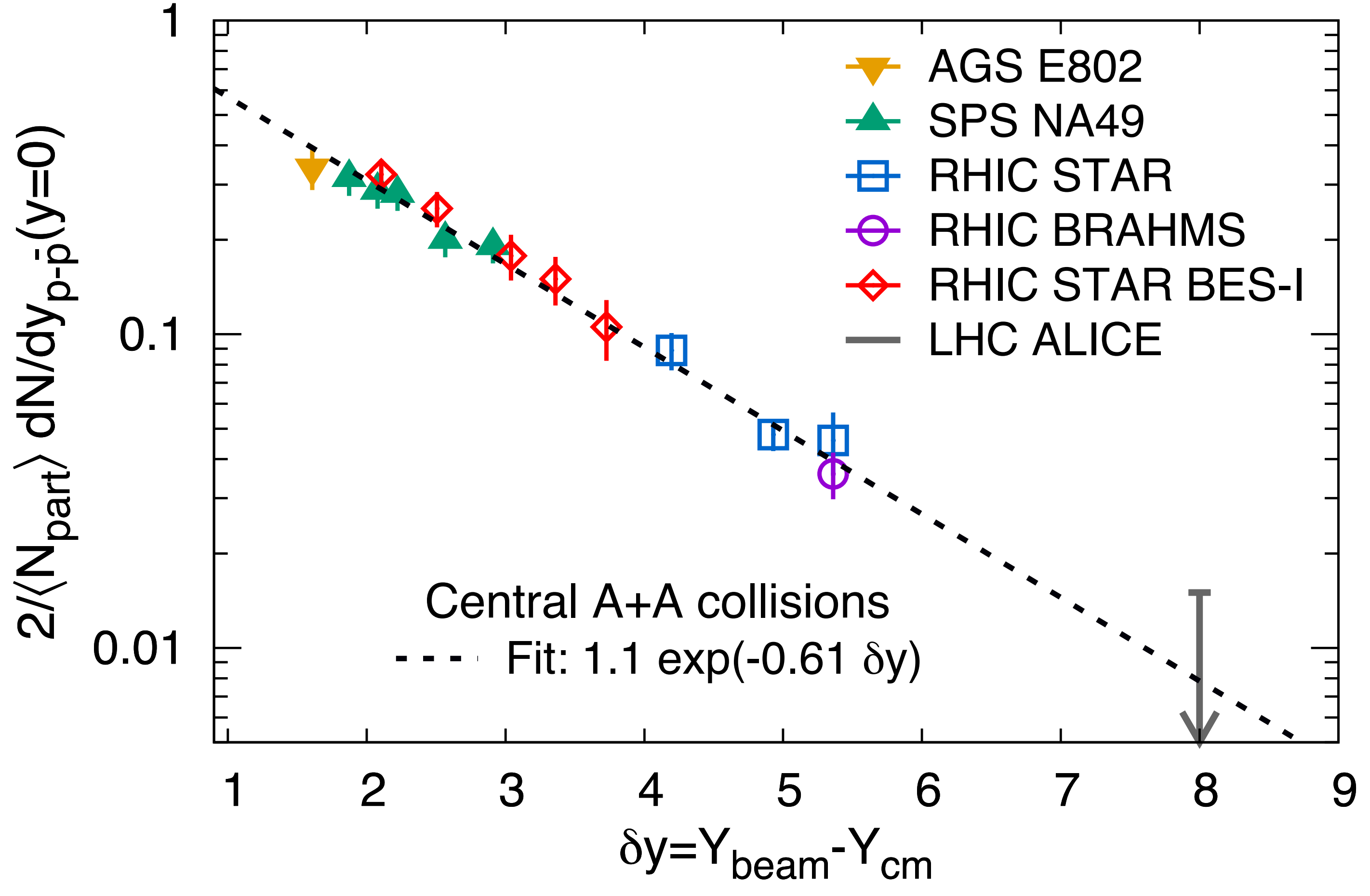


Quantifying baryon number transport

- RHIC Beam Energy Scan (BES-I) span large range of rapidity shift
- Exponential with slope of α_B =0.61±0.03
- Consistent with the baryon junction transport by gluons: α_B~=0.5+Δ
  Δ~=0.1

STAR, Phys. Rev. C **79** (2009) 34909; **96** (2017) 44904

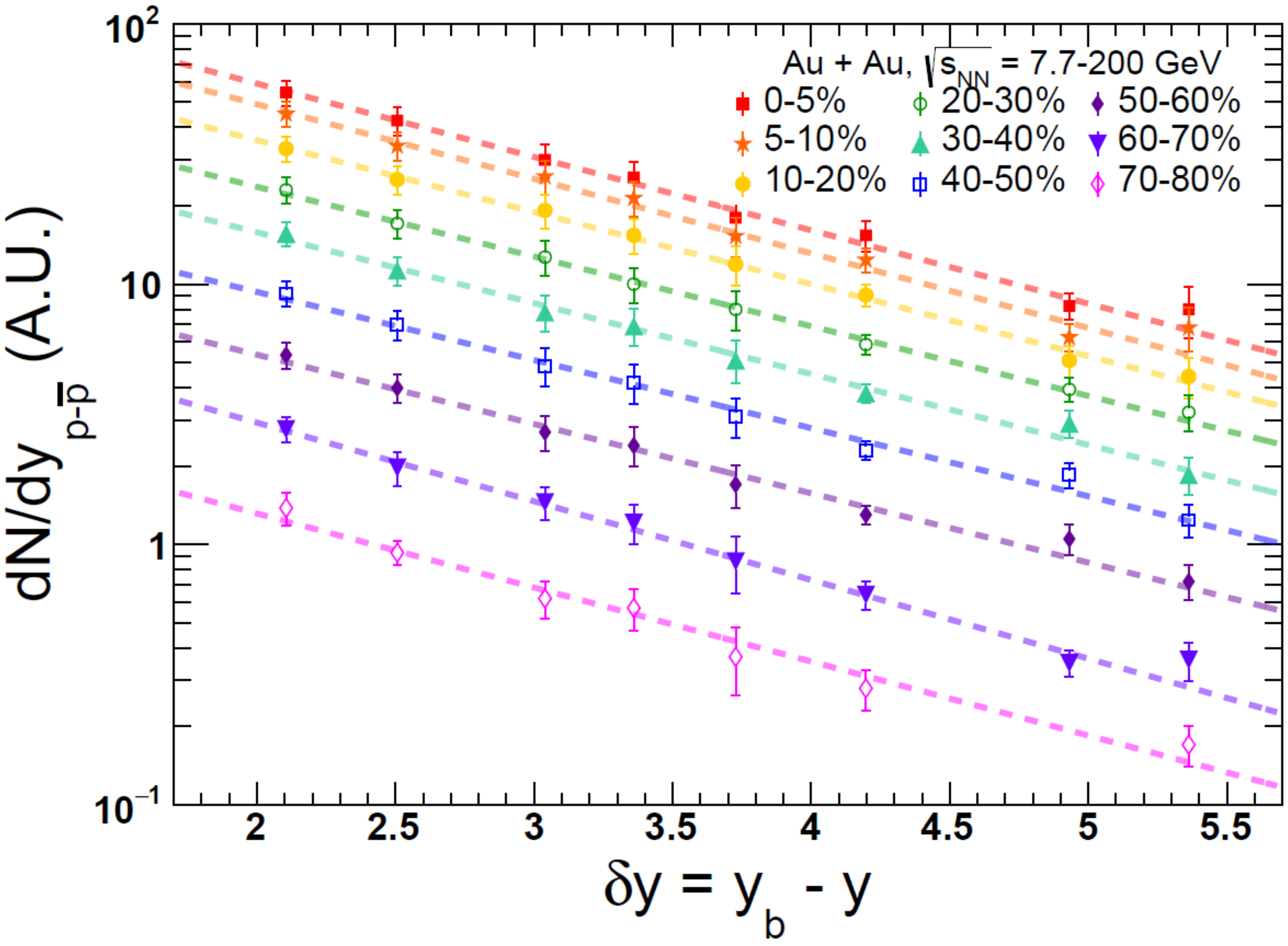
D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685



Quantifying baryon number transport

- Striking scaling for all centralities and collision beam energies from central A+A to p+p
- Expect slope to change if stopping is through multiple scattering of quarks
- New heavy-ion simulation require baryon junction to match data

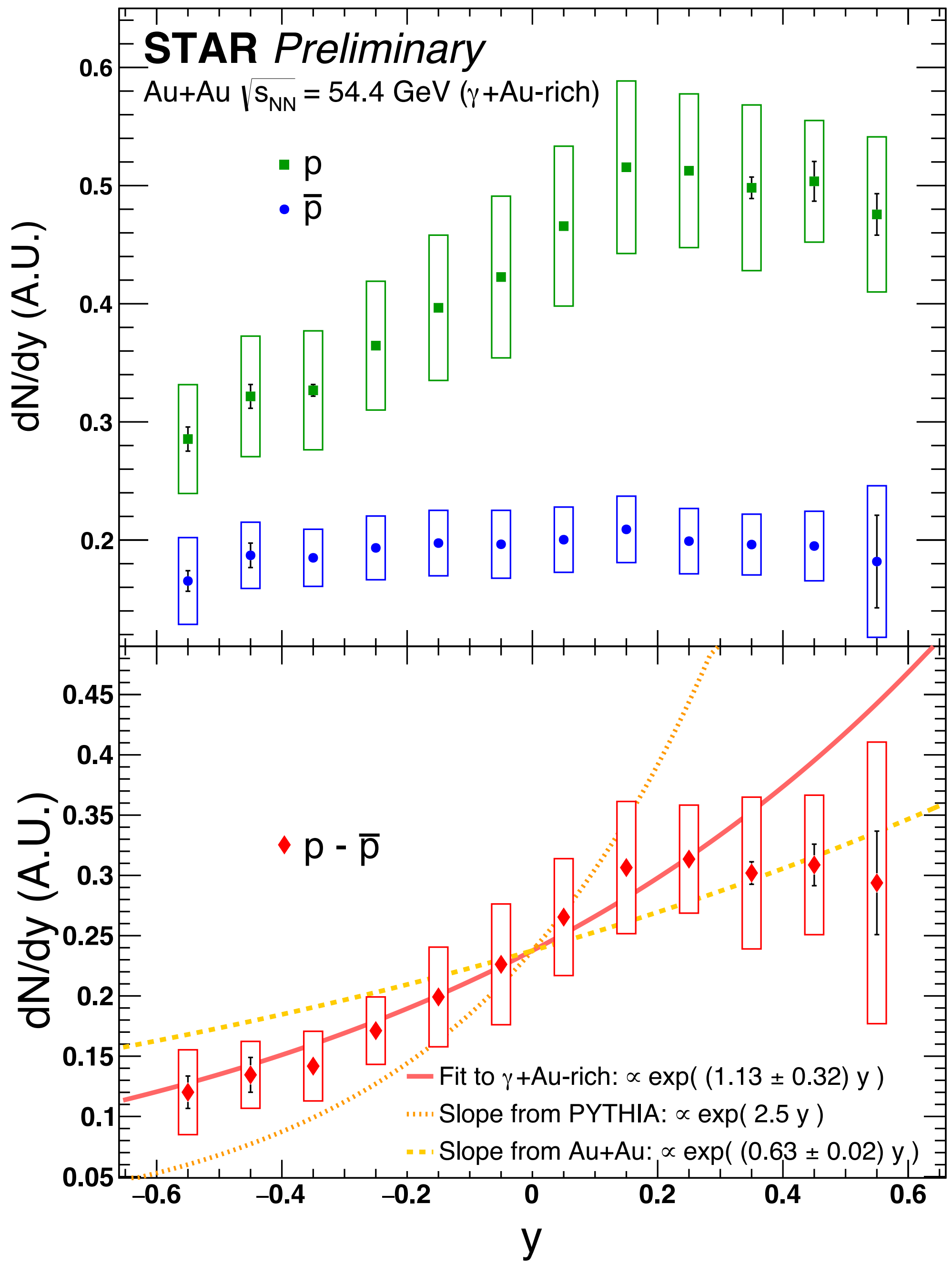
C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.



Nicole Lewis (BNL) for STAR, DIS2023

Rapidity asymmetry in photon-nucleus collision

- Selection of photon+Au collisions from Au+Au at 54.4GeV ultra-peripheral collisions
- Antiproton shows flat rapidity distribution
- Proton shows the characteristic asymmetry increase toward nucleus side
- Slope is closer to the slope of the beam energy dependence
- PYTHIA shows much larger slope

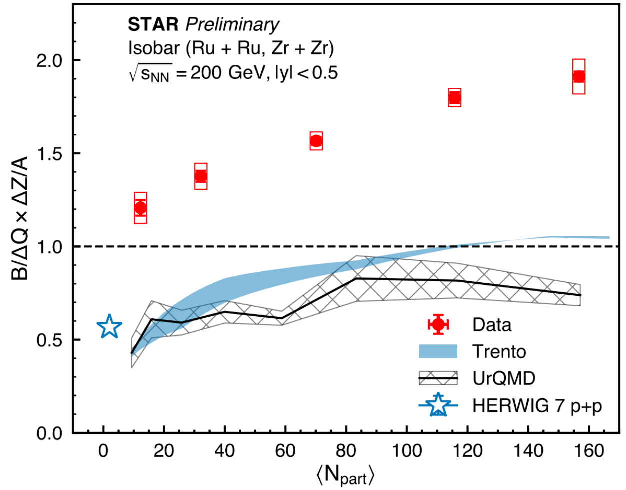


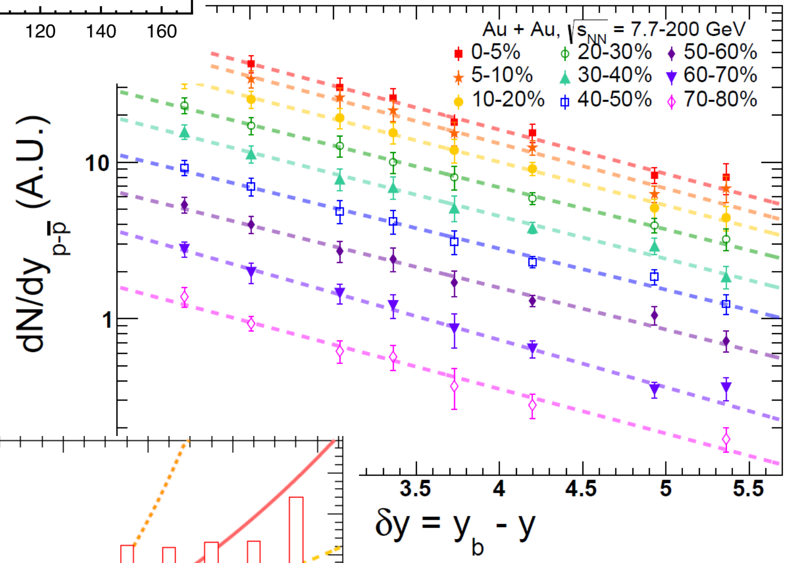
Three approaches toward tracking the origin of the baryon number

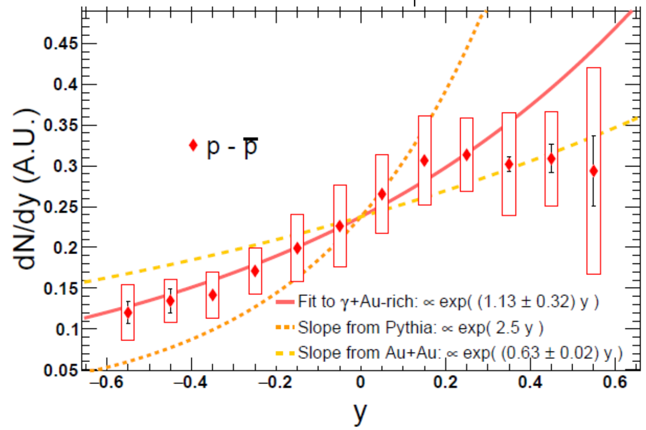
1. STAR Method:
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity
   B/Q=2
2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory
   α_B=0.61
3. Artru Method:
   In γ+Au collision, rapidity asymmetry can reveal the origin
   α_B(A+A)=0.61< α_B(γ+A)=1.1< α_B(PYTHIA)

$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5

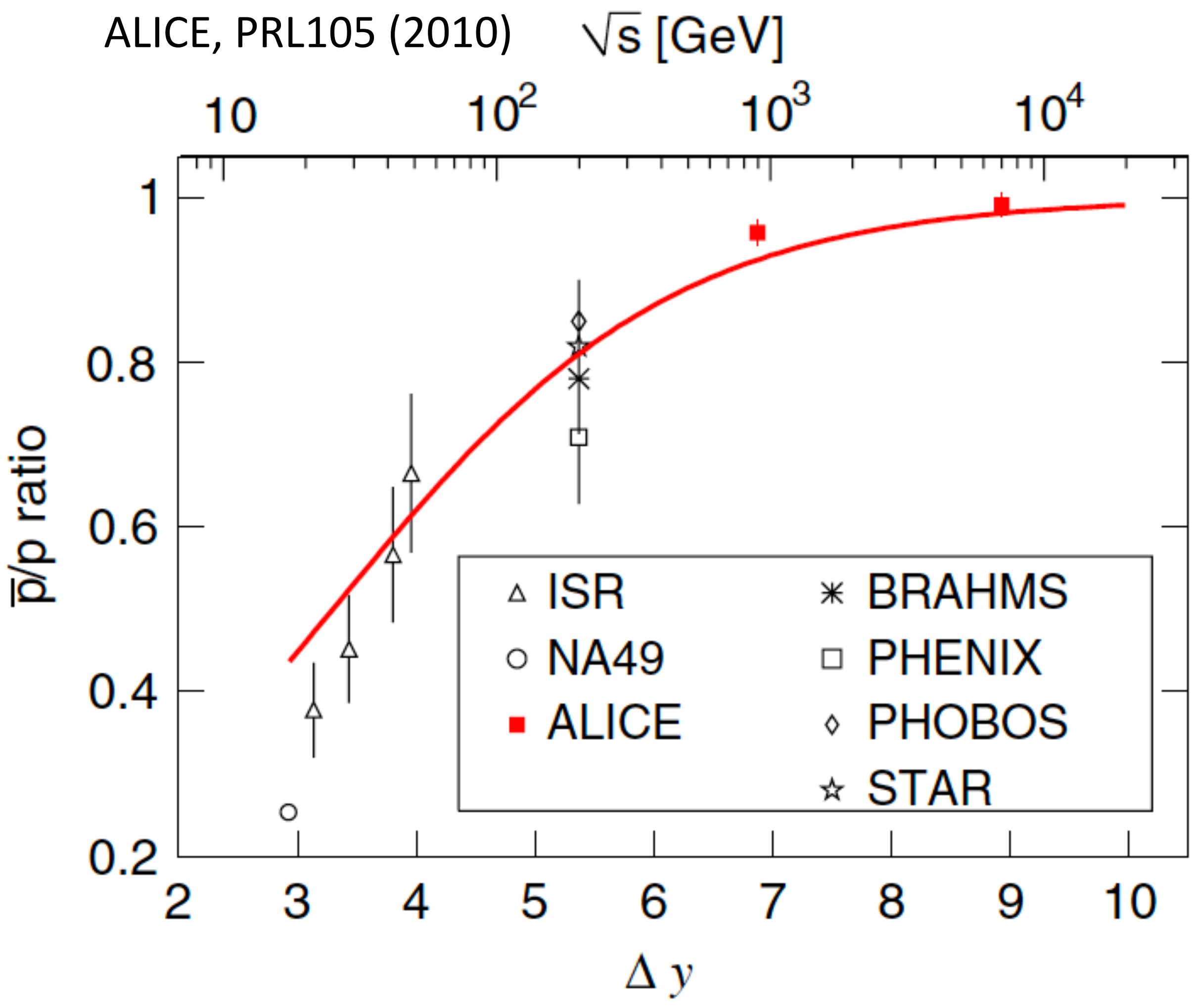






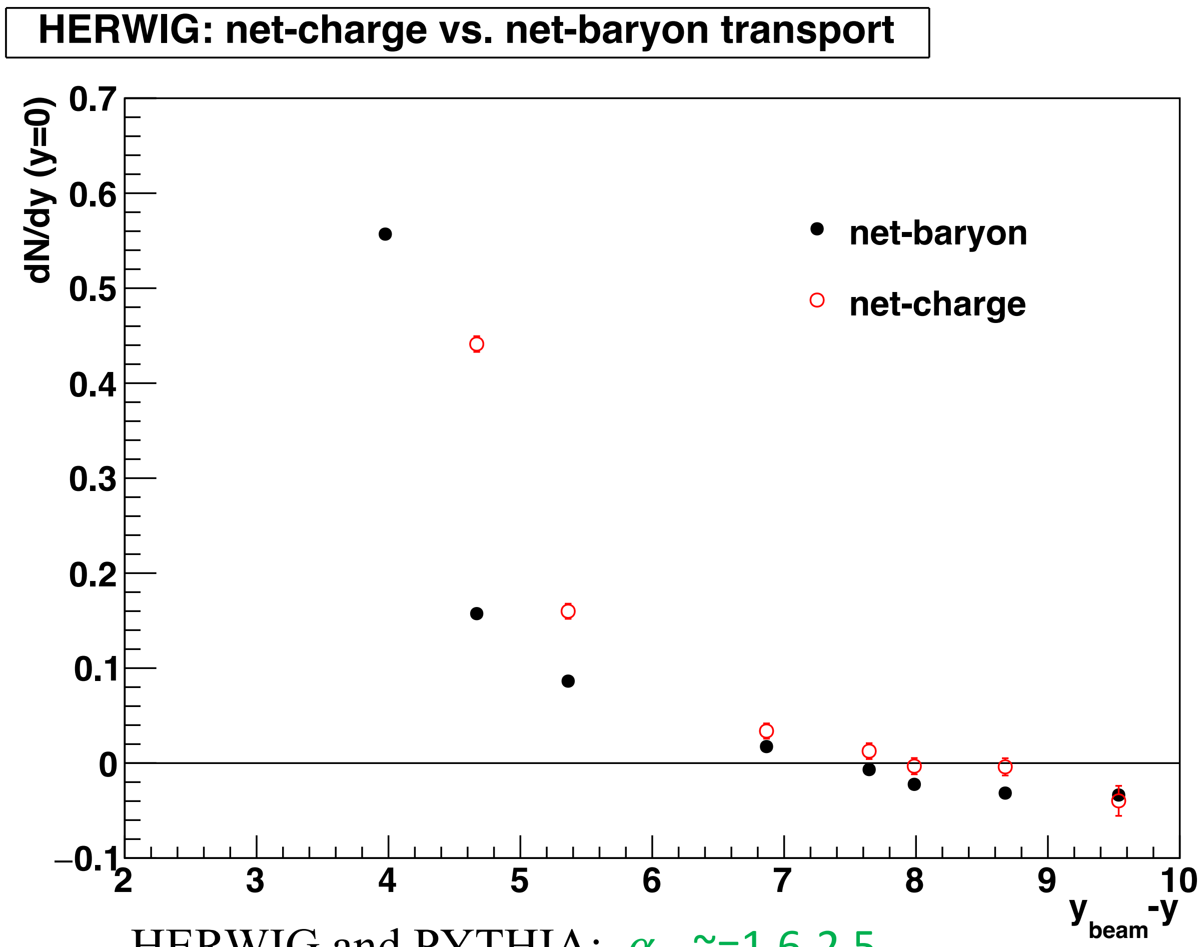
What do we know about pp collisions?

ALICE, PRL105 (2010)



read curve consistent with α_B =0.6

Rongrong Ma (BNL)



HERWIG and PYTHIA: α_B ~=1.6-2.5

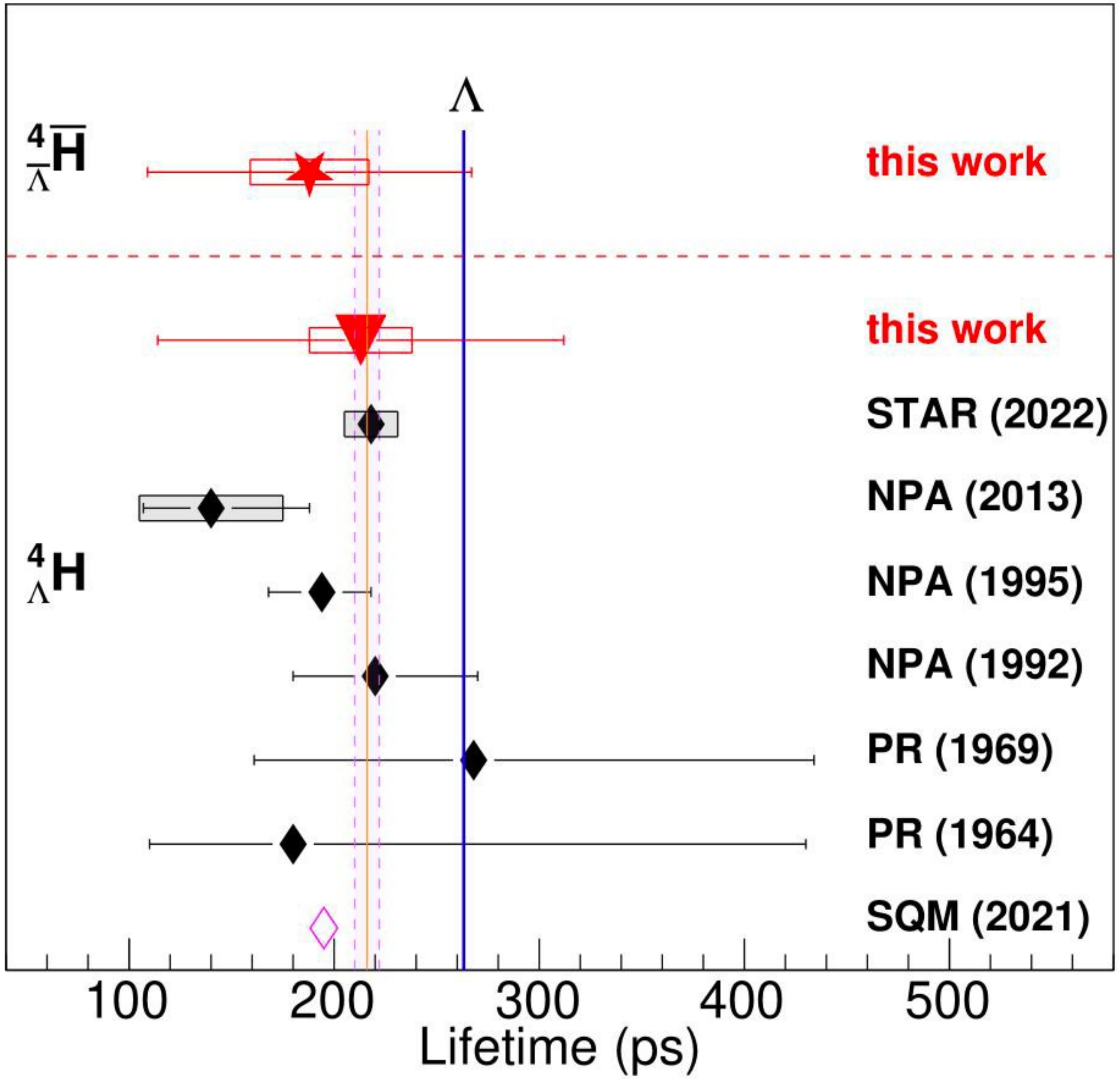
Negative (pbar>p) at LHC energy

Conclusions

- Discovery of the heaviest antimatter nuclear cluster (hyperhydrogen 4)
- Continue to improve our measurements on hypernuclear lifetime and binding energy (CSB)
- Use nuclear yields to study production mechanism, quantum wavefunction overlap: thermal vs coalescence model
- Use nuclear yield ratios as a sensitive probe of nucleon density fluctuation

- Baryon number is a strictly conserved quantum number, keeps the Universe as is
- We did not know what its carrier is; It had not been experimentally verified one way or the other until now;
- Discovery of the simplest QCD topology: the baryon gluon junction
- Explore other signatures

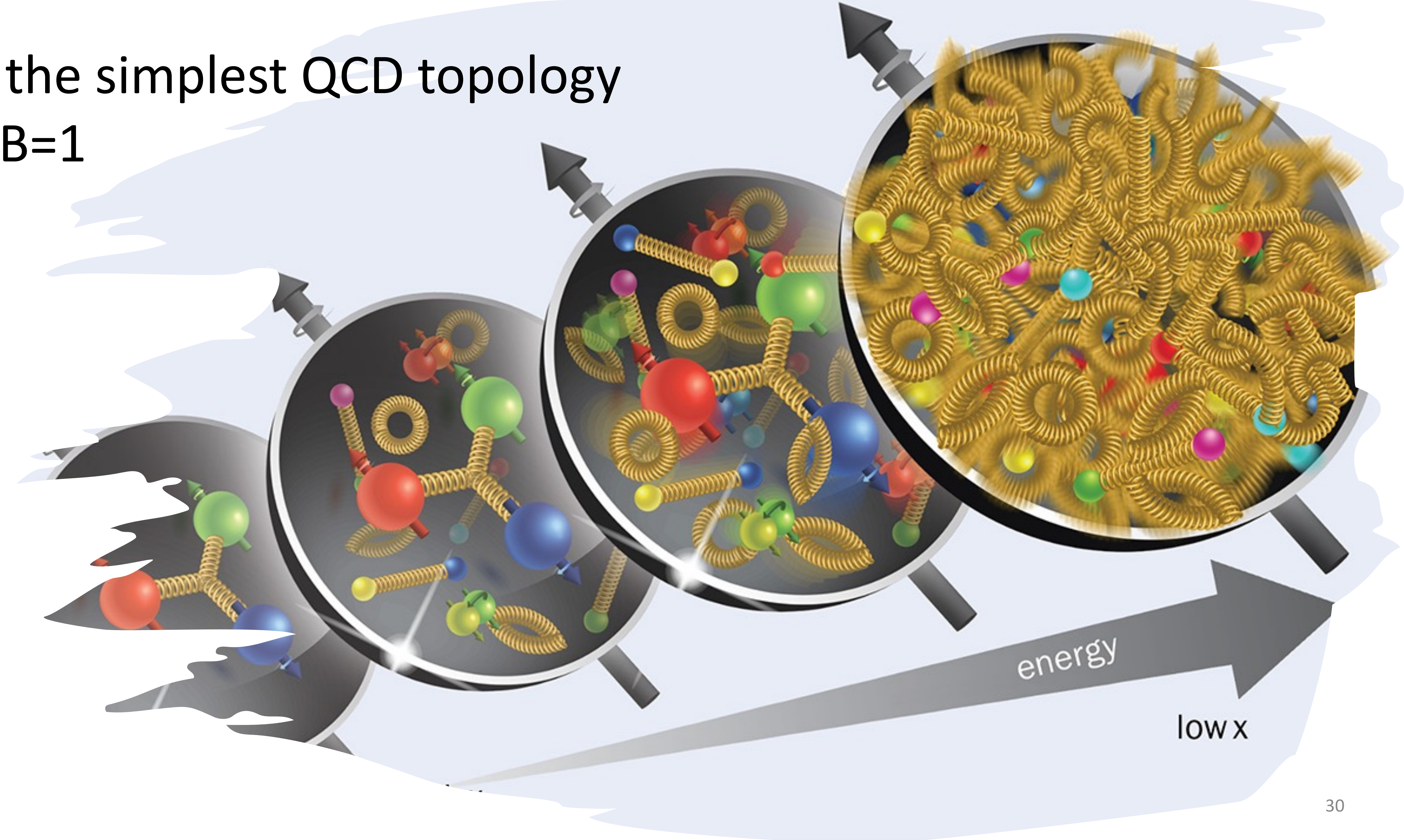
Lifetime of |B|=4 hypernucleus



J.L. Wu (STAR), SQM2022

the simplest QCD topology

B=1



Baryon stopping in UrQMD

M. Bleicher, *et al.*, JPG 25 (1999); hep-ph/9909407

$$z^{\pm} = t \pm z \quad \text{and} \quad p^{\pm} = E \pm p \quad . \tag{33}$$

The light cone momentum $p^{\pm}_{\rm hadron}$ given to the newly produced hadron is:

$$p^{\pm}_{\rm hadron} = z^{\pm}_{\rm fraction}\, p^{\pm}_{\rm total} \tag{34}$$

The fragmentation of a baryonic string reads:

$$p^{-}\underbrace{(qq\,q\bar{q}\,q)}_{\text{String}} = z^{-}_{\rm fraction}p^{-}\underbrace{(qqq)}_{\text{Baryon}} + (p^{-} - z^{-}_{\rm fraction}p^{-})\underbrace{\bar{q}q}_{\text{String}} \quad . \tag{35}$$

The main input is the fragmentation function which yields the probability distribution $p(z^{\pm}_{\rm fraction}, m_t)$. This function regulates the fraction of energy and momentum given to the produced hadron in the stochastic fragmentation of the color string. For newly produced particles the Field-Feynman function [41]:

$$p(z^{\pm}_{\rm fraction}) = \text{constant} \times (1 - z^{\pm}_{\rm fraction})^2, \tag{36}$$

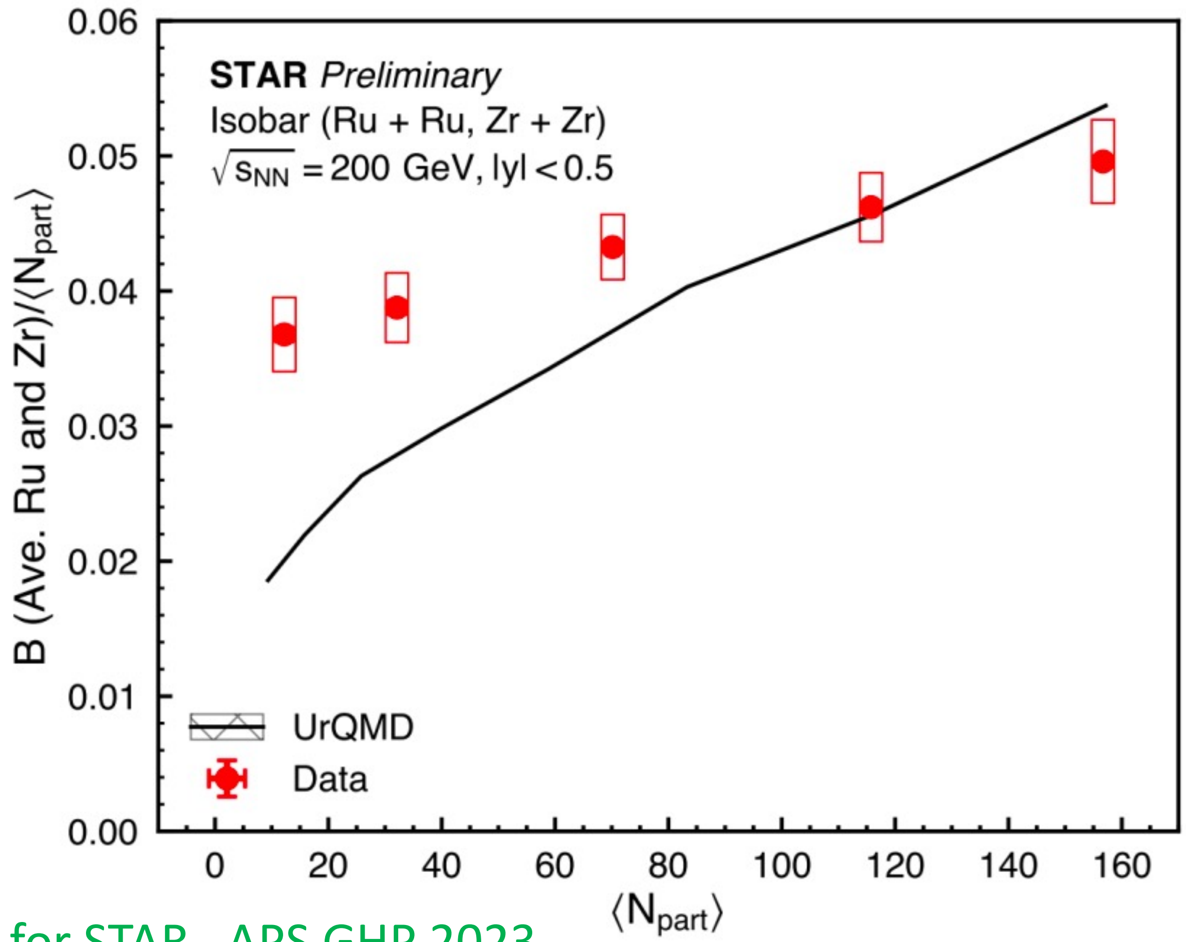
is used. $P(z)$ drops rapidly with increasing z (Fig. 29). Therefore, the longitudinal momenta of e.g. produced antibaryons (Fig. 30) and pions (Fig. 31) are small (they stick to central rapidities), in line with the experimental data. The rapidity spectra of these particles have a characteristic Gaussian-like shape, in contrast to the baryon spectra in pp, as it is clearly seen in Figure 30.

The proton is on average less stopped, since it is build up from the leading diquark in the string (leading particle effect). Fig. 32 compares the x_F distribution of protons and Λ's for the Feynman scaling variable $x_F = 2p_{\|}/\sqrt{s}$ measured in pp reactions at 205 GeV/c. The data on leading baryons can only be reproduced when a modified fragmentation function is used for the leading baryons (cf. Fig. 29, dashed curve). This leading baryon fragmentation function is of Gaussian form:

$$p(z^{\pm}_{\rm fraction}) = \text{constant} \times \exp\left[-\frac{(z^{\pm}_{\rm fraction} - b)^2}{2a^2}\right] \quad , \tag{37}$$

with parameters $a = 0.275$ and $b = 0.42$.

Baryon number transport



J) for STAR, APS GHP 2023

better on baryon stopping in central

baryon stopping in peripheral

Baryon rapidity loss

The average close to beam rapidity does not reflect the "tail" at high rapidity

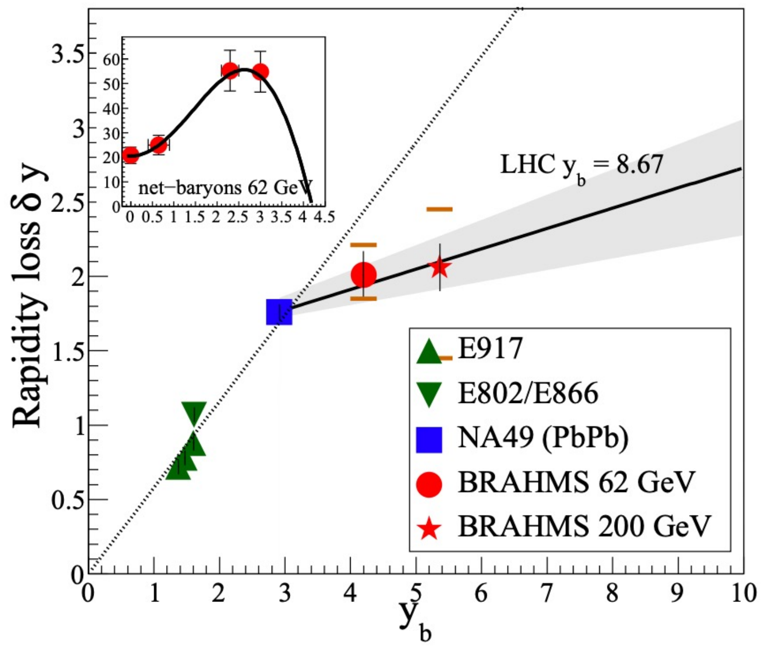


Figure 3: Rapidity losses from AGS, SPS and RHIC as a function of beam rapidity. The solid line is a fit to SPS and RHIC data, and the band is the statistical uncertainty of this fit. The dashed line is a linear fit to AGS and SPS data from [15].

BRAHMS 2009

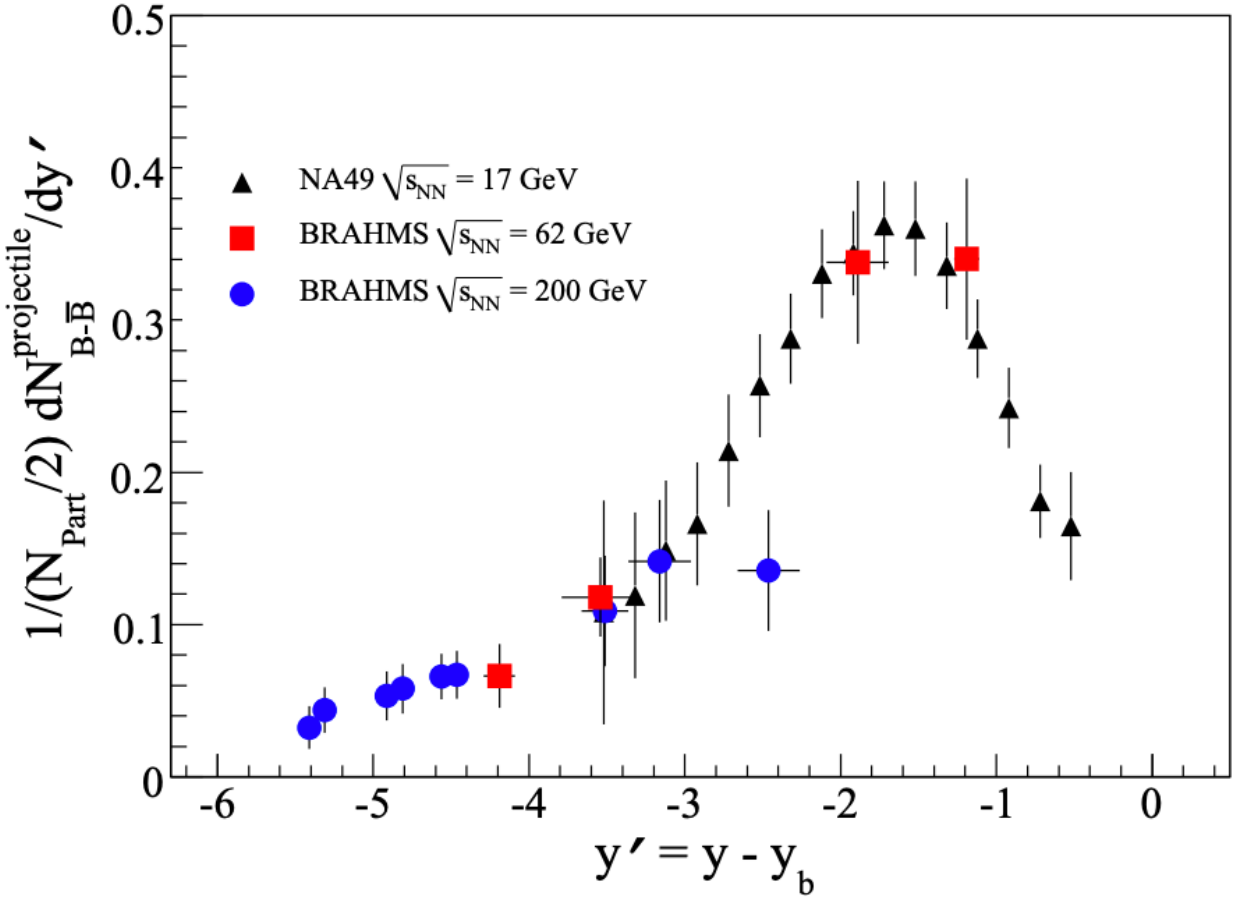
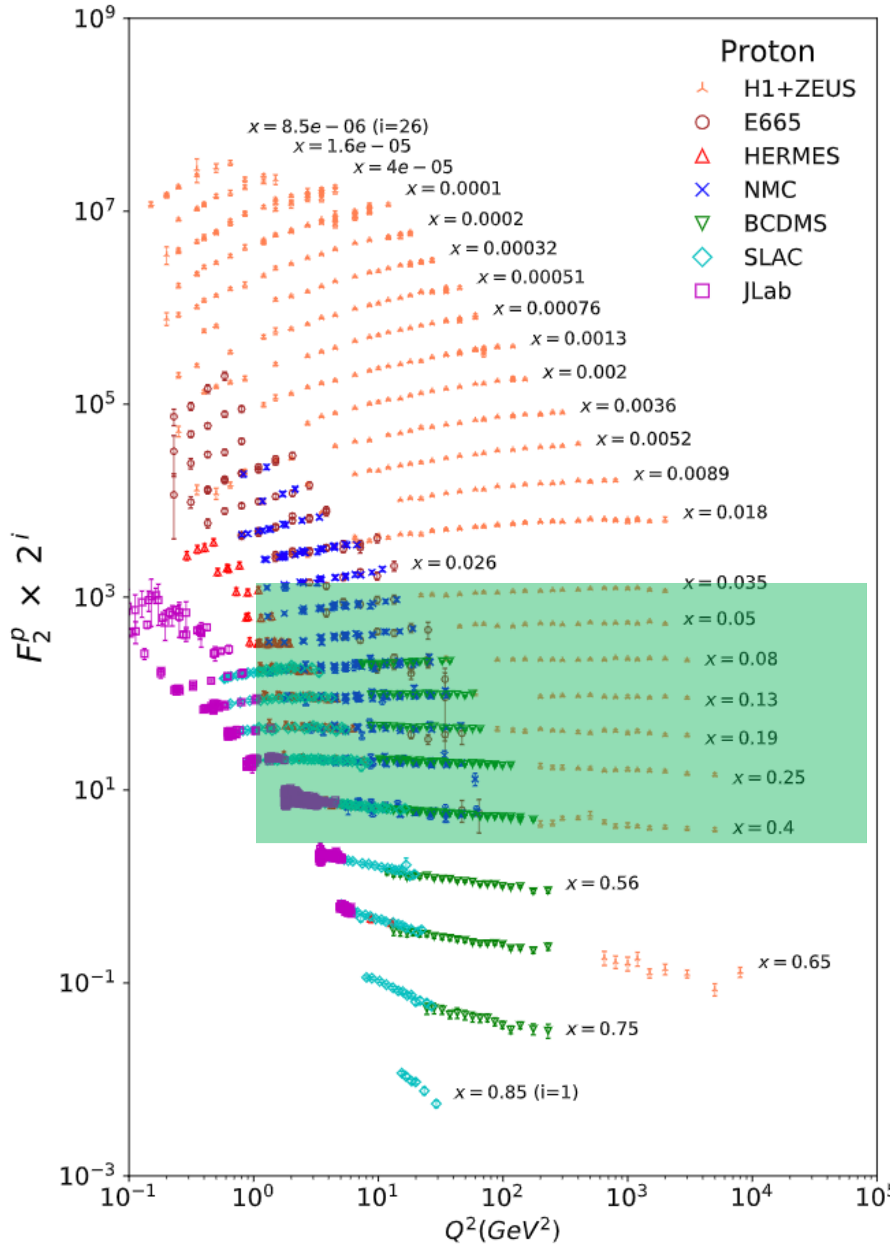


Figure 5: Projectile net-baryon rapidity density $(1/N_{part}/2)dN^{projectile}_{B-\bar{B}}/dy'$ from SPS and RHIC after subtraction of the target net-baryon contribution (see Fig. 4).

Bjorken Scaling for quarks

- Scaling at certain x range, quarks behave as point-like particles
- Evolution with x due to gluons
- At DIS (high Q^2>1 GeV^2)



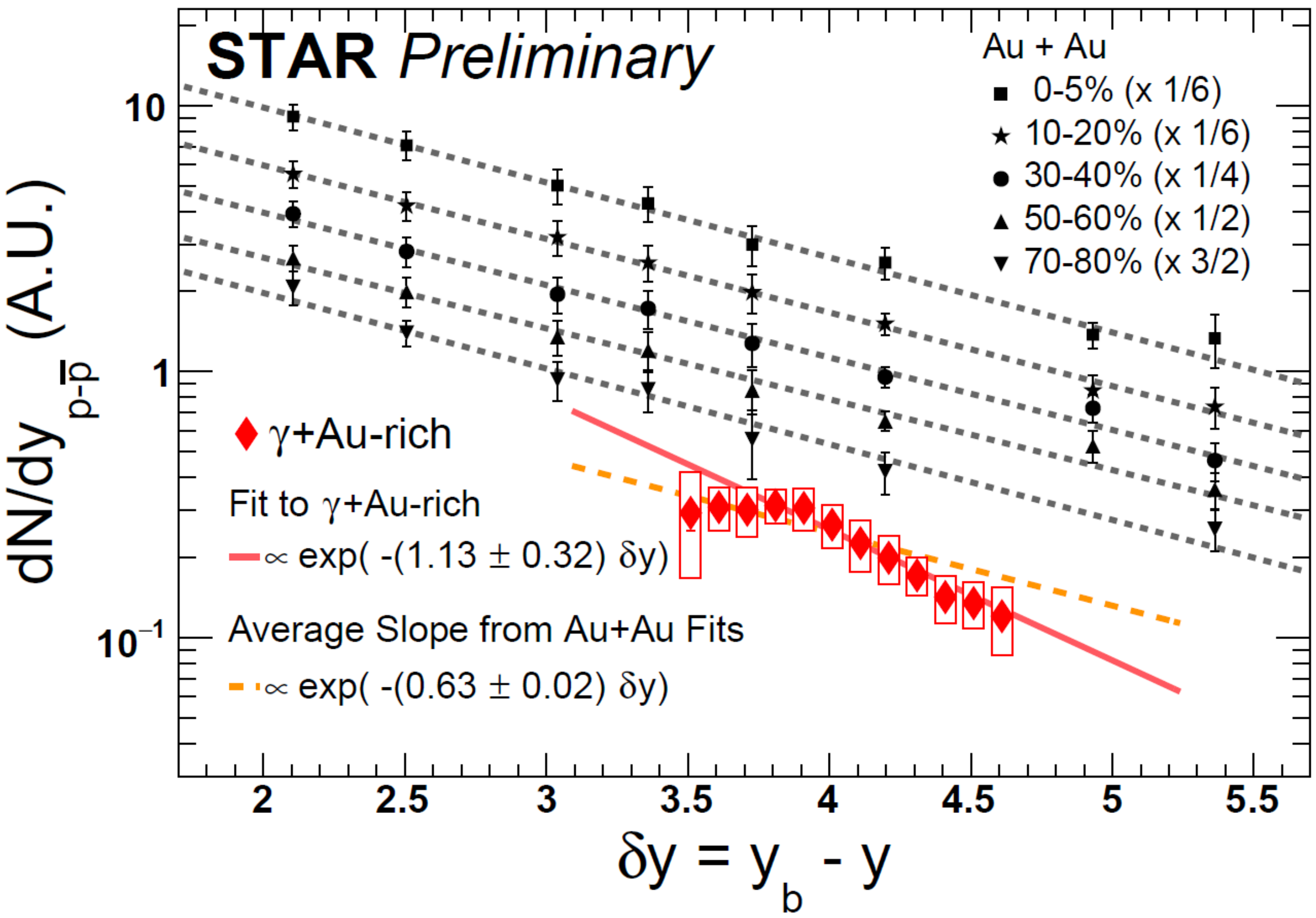
PDG

Figure 18.10: The proton structure function F_2^p measured in electromagnetic scattering of electrons and positrons on protons, and for electrons/positrons (SLAC,HERMES,JLAB) and muons (BCDMS, E665, NMC) on a fixed target. Statistical and systematic errors added in quadrature are shown. The H1+ZEUS

Tracking the origin of baryon number at RHIC

- RHIC nuclear energy is at a sweet spot
  - U+U, Au+Au, O+O, Cu+Au, Cu+Cu, He3+Au, d+Au,p+Au, p+p
- LHC and HERA energy are too high with small baryon excess (<1%)
- Isobar collisions with a beam-energy scan at RHIC to study the charge and baryon transports

Nicole Lewis (BNL) for STAR, DIS2023



Tracking the origin of baryon number at EIC

- RHIC nuclear energy is at a sweet spot
  - U+U, Au+Au, O+O, Cu+Au, Cu+Cu, He3+Au, d+Au,p+Au, p+p
- LHC and HERA energy are too high with small baryon excess (<1%)
- Isobar collisions at EIC with low Q^2 and low-p_t PID to study the charge and baryon transports
- EIC: extend to large range of rapidity shift from 2.5 to 6
  at the same time, measure the charge (model, RHIC) transport as well as baryon transport (BeAGLE B/Q=0.2, Niseem)

Nicole Lewis (BNL) for STAR, DIS2023