From junctions to entanglement – the long road to understanding hadronization

R. Bellwied (University of Houston)

Never at Rest: A Lifetime Inquiry of QGP
Bad Honnef, Physikzentrum, Feb.10-12th, 2025

A Gentleman never mentions a woman's age…..

(but I was here 10 years ago for Johanna's 60th celebration)

Flavor fluctuations and their relevance to the understanding of hadronization

R. Bellwied (University of Houston)

Thanks to:
C. Ratti, S. Jena, D. McDonald (University of Houston)
P. Alba, V. Mantovani (Torino University & INFN)
M. Bluhm, M. Nahrgang (North Carolina & Duke)
S. Borsanyi, Z. Fodor, S. Katz (Wuppertal & Budapest)

EMMI Workshop: Imprints of the QGP
16-17 April 2015
MPI for Nuclear Physics & Heidelberg University


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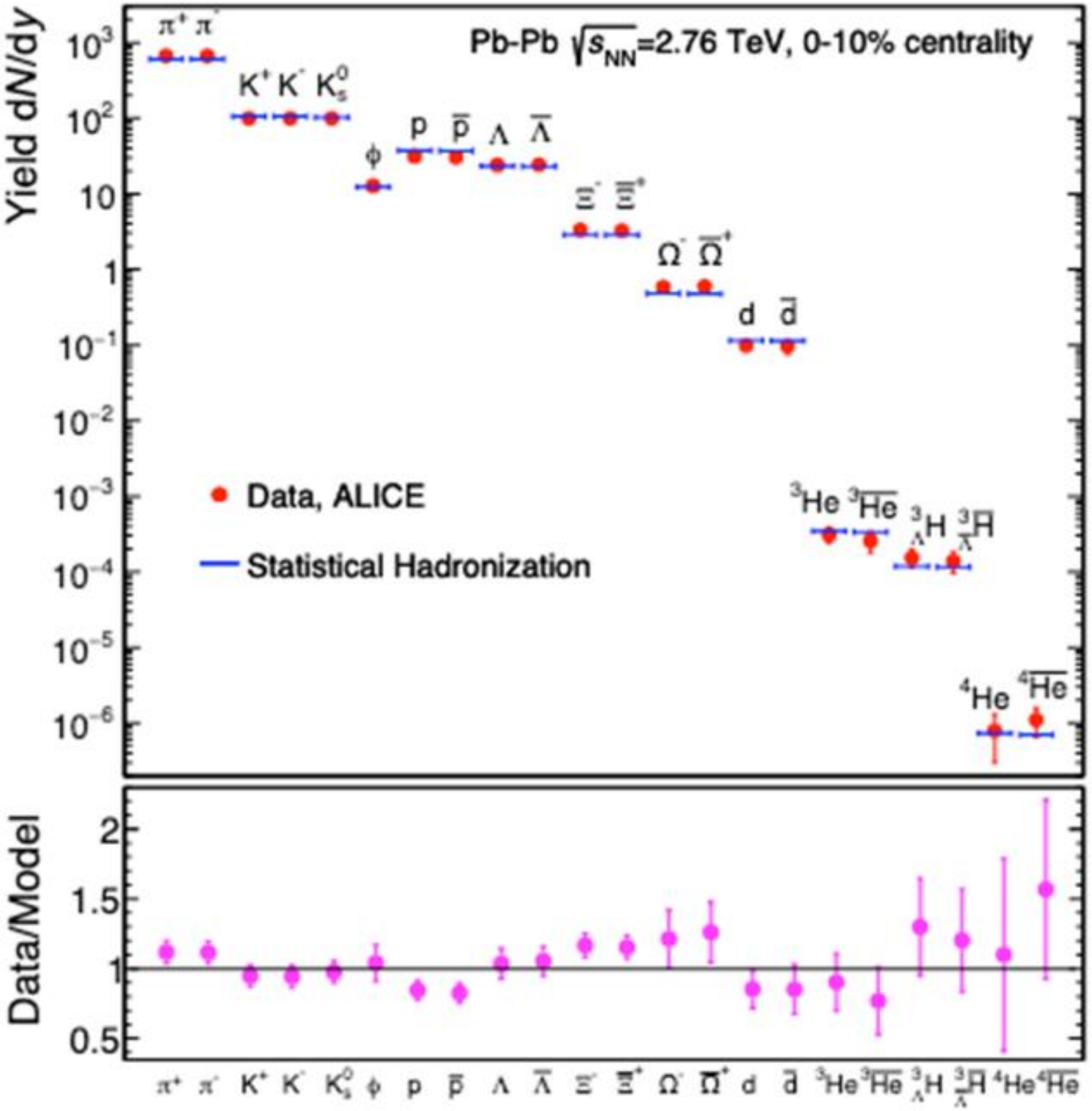
ALICE
PRELIMINARY

What still keeps me up at night when I think of our research ?

- **Relativistic Heavy Ion Physics:** The field is more than 50 years old.
- I joined more than 30 years ago.
- The big discovery (Quark-Gluon Plasma) happened 20 years ago.
- You have assembled an amazing group of experts around here, so I presume you have already had enough talks about it. Why give you another one ?
- Is there anything left ? Is anybody still interested ?
- *W. Reisdorf, GSI (1989): If during your lifetime as a physicist you will only do research in one field of physics, consider yourself extremely privileged (and maybe a little under-utilized).* Is EIC and LHC physics the same field ?

Here is a plot that kept me up at night a few years ago.

We still disagree on that one, but you can't argue with 750 citation in 6 years



A. Andronic et al., Nature 561, 321 (2018)

But rather than rolling up its validity let's ask the next level questions:

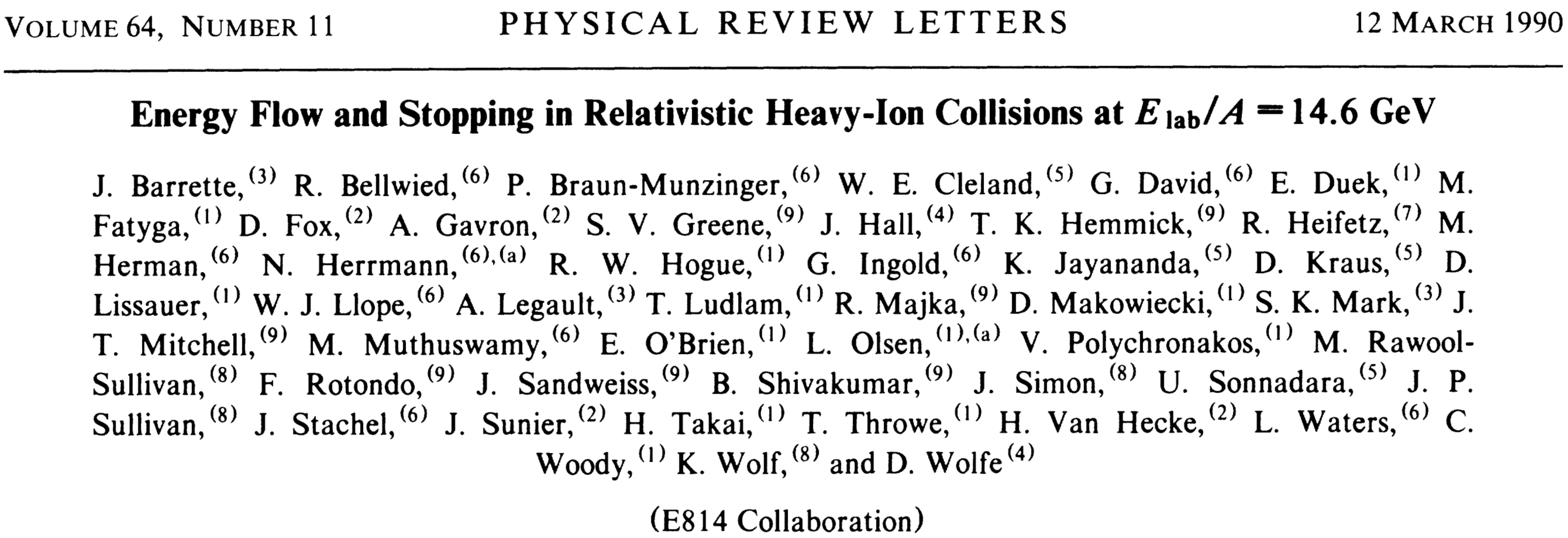
How can the partons thermalize fast enough that hydrodynamical and statistical hadronization models are applicable ?

How can the final state particles in elementary collisions be thermal ?

How come that there seems to be a one to one relation between the initial parton density and the final state particle density ?

Do partonic degrees of freedom really carry fractional quantum numbers.

My first postdoc paper



VOLUME 64, NUMBER 11 PHYSICAL REVIEW LETTERS 12 MARCH 1990

Energy Flow and Stopping in Relativistic Heavy-Ion Collisions at $E_{\mathrm{lab}}/A = 14.6$ GeV

J. Barrette,(3) R. Bellwied,(6) P. Braun-Munzinger,(6) W. E. Cleland,(5) G. David,(6) E. Duek,(1) M. Fatyga,(1) D. Fox,(2) A. Gavron,(2) S. V. Greene,(9) J. Hall,(4) T. K. Hemmick,(9) R. Heifetz,(7) M. Herman,(6) N. Herrmann,(6),(a) R. W. Hogue,(1) G. Ingold,(6) K. Jayananda,(5) D. Kraus,(5) D. Lissauer,(1) W. J. Llope,(6) A. Legault,(3) T. Ludlam,(1) R. Majka,(9) D. Makowiecki,(1) S. K. Mark,(3) J. T. Mitchell,(9) M. Muthuswamy,(6) E. O'Brien,(1) L. Olsen,(1),(a) V. Polychronakos,(1) M. Rawool-Sullivan,(8) F. Rotondo,(9) J. Sandweiss,(9) B. Shivakumar,(9) J. Simon,(8) U. Sonnadara,(5) J. P. Sullivan,(8) J. Stachel,(6) J. Sunier,(2) H. Takai,(1) T. Throwe,(1) H. Van Hecke,(2) L. Waters,(6) C. Woody,(1) K. Wolf,(8) and D. Wolfe(4)

(E814 Collaboration)

My first postdoc conference

Stopping and forward baryon distributions in relativistic heavy ion collisions

WWND 1991, Key West, 1991

Collisions of ^{28}Si+Al, Cu, Pb at $E_{\mathrm{lab}}/A = 14.6$ GeV were studied in a calorimetry-based experiment at the BNL Alternating Gradient Synchrotron. Transverse-energy production was measured for pseudorapidities $-0.5 < \eta < 0.8$. Correlations with the spectra and multiplicity of neutrons and protons emitted into a forward 0.8° cone demonstrate quantitatively the large amount of nuclear stopping observed in these reactions. Calculations in hadronic-fireball or nucleon-nucleon based models underpredict the measured transverse-energy production for Si+Pb and indicate the need to include rescattering of secondaries and/or contributions from target fragmentation.

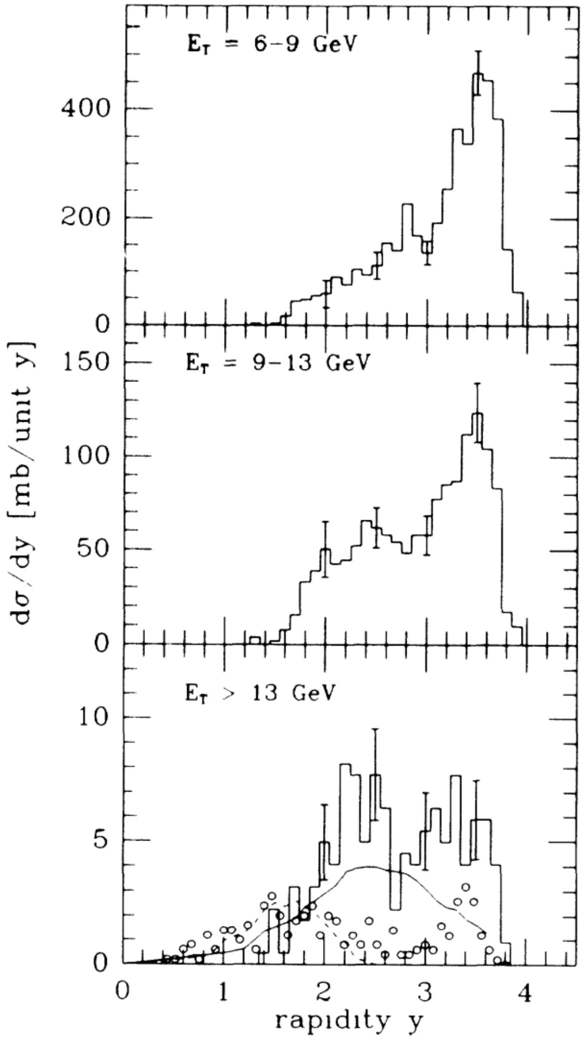


FIG. 3. Inclusive neutron-rapidity spectra measured in a forward 0.8° cone for 14.6 GeV/nucleon ^{28}Si+Pb and different transverse energies in TCal. Experimental threshold 1.3 GeV. Open circles, HIJET (Ref. 9); dashed line, isotropic fireball (Ref. 6); solid line, Landau fireball (Ref. 6).

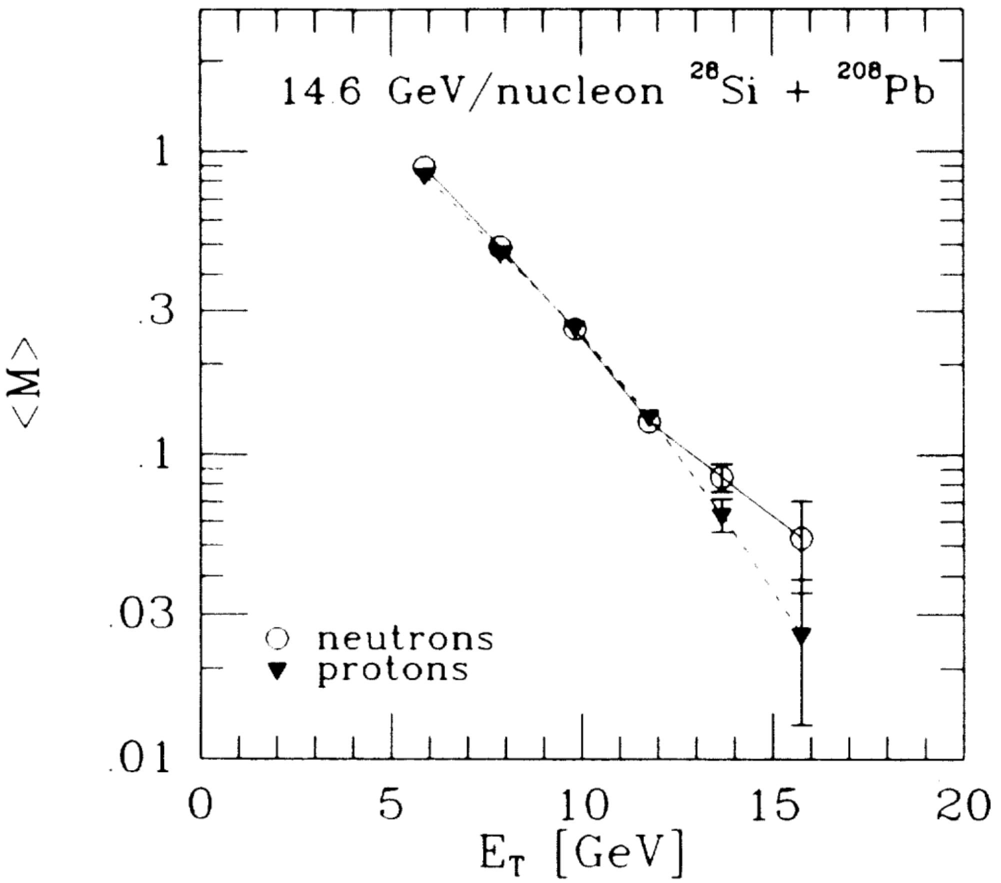


FIG. 4. Multiplicity of beam-rapidity baryons measured in a forward 0.8° cone as a function of transverse energy in TCal. Lines are drawn to guide the eye.

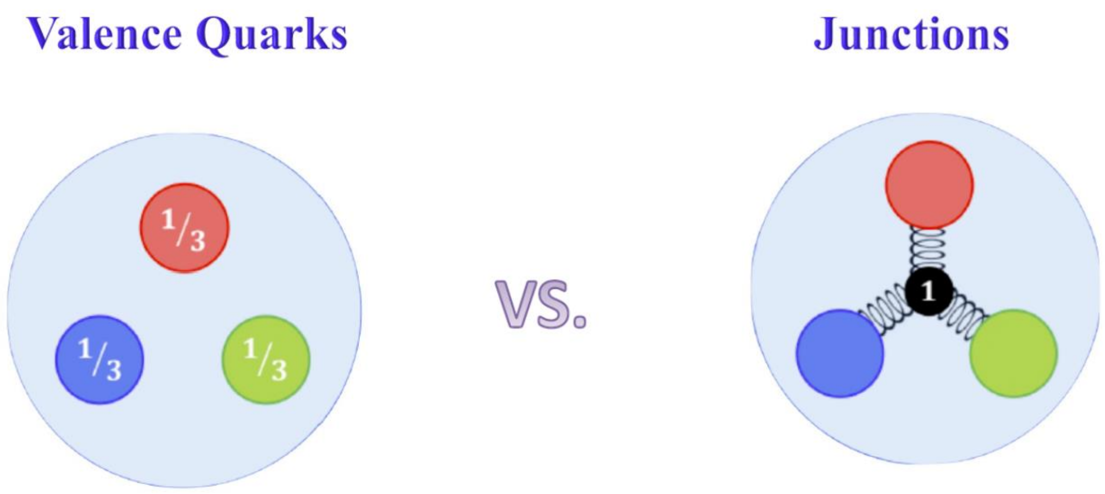
Baryon junctions

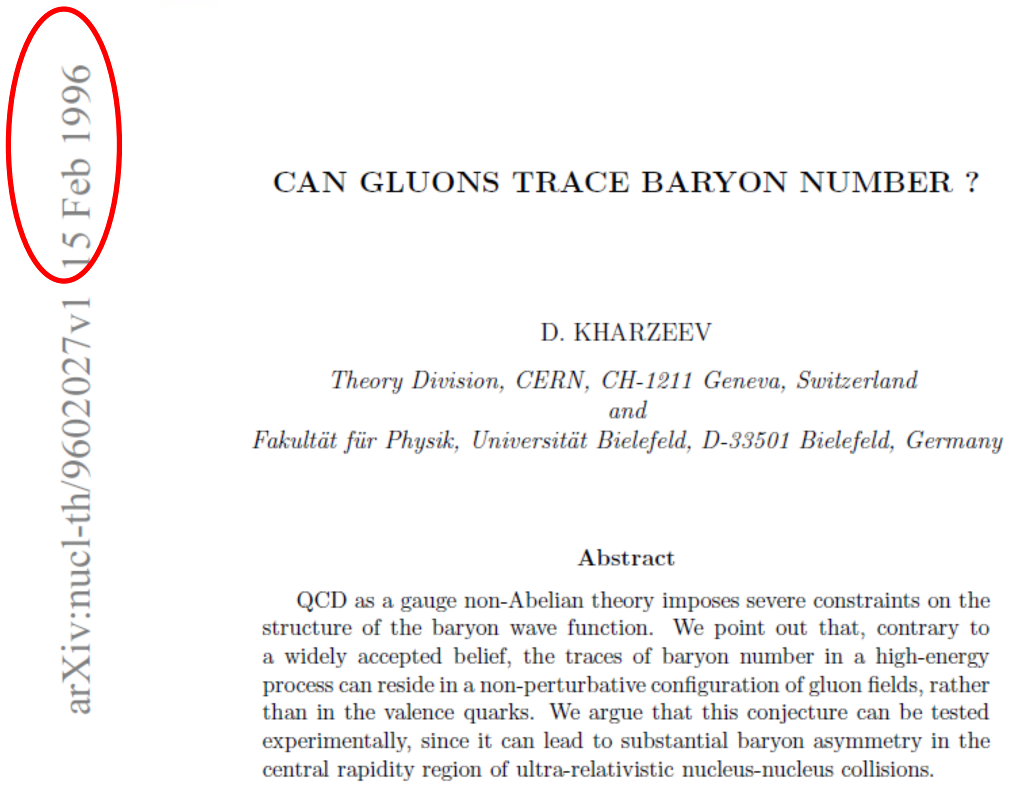
The idea that nonperturbative three color flux junctions could play an important role in baryon and anti-baryon production at high energies was proposed long ago by Rossi and Veneziano on the basis of dual regge theory. This idea was extended and applied by Kharzeev to nuclear collisions.

Unlike conventional diquark fragmentation models, a baryon junction allows the diquark to split with the three independent flux lines tied together at a junction.

Who carries the baryon number?

Fundamental Work:
1.) G.C. Rossi and G. Veneziano, Nucl. Phys. B123, 507 (1977); Phys. Rep. 63, 153 (1980)
2.) D. Kharzeev, Phys. Lett. B 378, 238 (1996)





CAN GLUONS TRACE BARYON NUMBER ?

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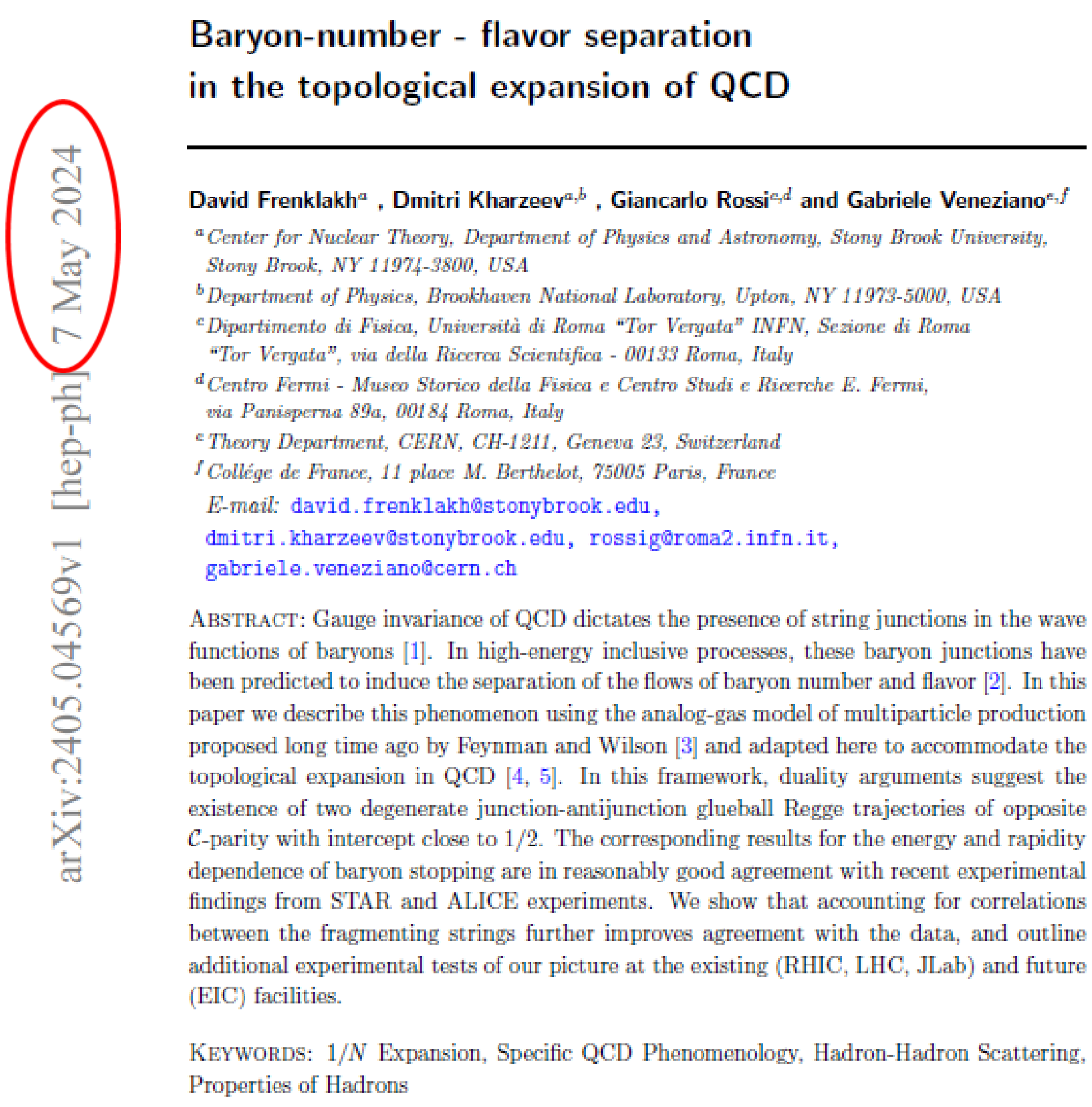
Abstract

QCD as a gauge non-Abelian theory imposes severe constraints on the structure of the baryon wave function. We point out that, contrary to a widely accepted belief, the traces of baryon number in a high-energy process can reside in a non-perturbative configuration of gluon fields, rather than in the valence quarks. We argue that this conjecture can be tested experimentally, since it can lead to substantial baryon asymmetry in the central rapidity region of ultra-relativistic nucleus-nucleus collisions.



Baryon-number - flavor separation in the topological expansion of QCD

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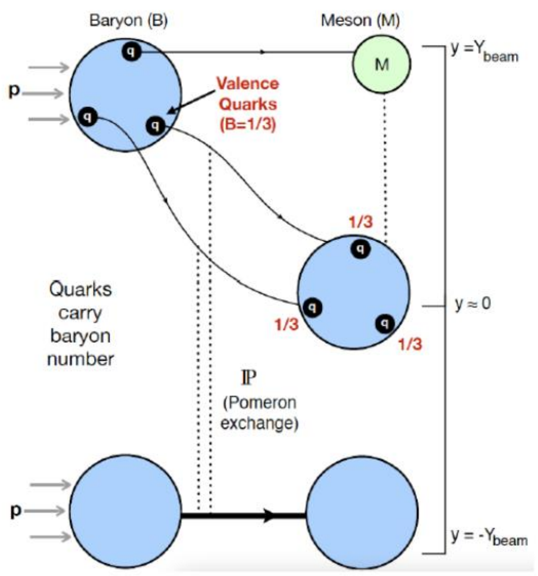
ABSTRACT: Gauge invariance of QCD dictates the presence of string junctions in the wave functions of baryons [1]. In high-energy inclusive processes, these baryon junctions have been predicted to induce the separation of the flows of baryon number and flavor [2]. In this paper we describe this phenomenon using the analog-gas model of multiparticle production proposed long time ago by Feynman and Wilson [3] and adapted here to accommodate the topological expansion in QCD [4, 5]. In this framework, duality arguments suggest the existence of two degenerate junction-antijunction glueball Regge trajectories of opposite $\mathcal{C}$-parity with intercept close to $1/2$. The corresponding results for the energy and rapidity dependence of baryon stopping are in reasonably good agreement with recent experimental findings from STAR and ALICE experiments. We show that accounting for correlations between the fragmenting strings further improves agreement with the data, and outline additional experimental tests of our picture at the existing (RHIC, LHC, JLab) and future (EIC) facilities.

KEYWORDS: $1/N$ Expansion, Specific QCD Phenomenology, Hadron-Hadron Scattering, Properties of Hadrons

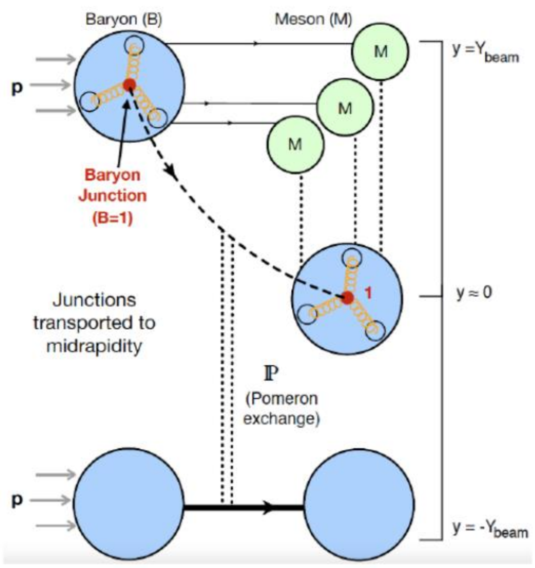
I moved from baryons to strangeness, but the junction stayed with me….

Valence Quarks



VS.

Junctions

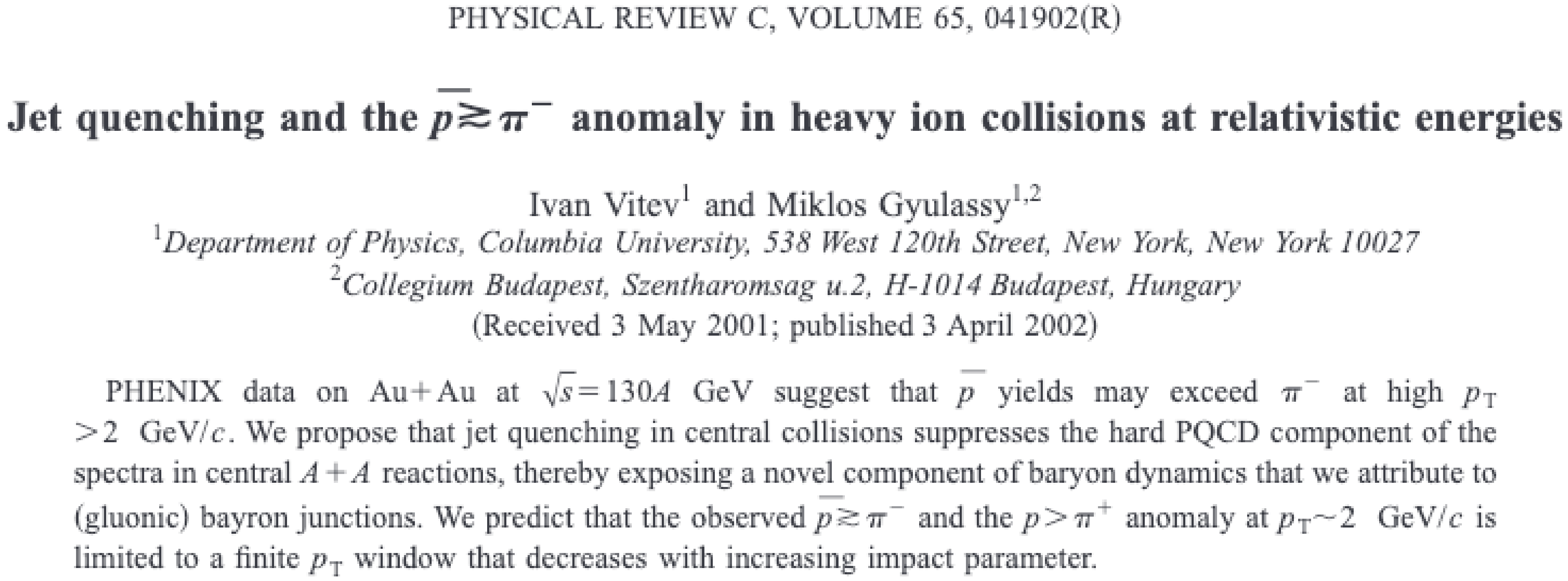


HIJING B-Bbar:

3.) S.E. Vance, M. Gyulassy, and X.N. Wang, Phys. Lett. B443, 45 (1998)
4.) S.E. Vance, M. Gyulassy, Phys. Rev. Lett. 83, 1735 (1999)
5.) I. Vitev, M. Gyulassy, PRC65, 041902® (2002)
6.) V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, X.N. Wang, N. Xu, and K. Filimonov, *Phys.Rev. C* 68, 054902 (2003)
7.) V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, X. N. Wang, N. Xu, *Phys.Rev.C* 70, 064906 (2004)
8.) V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, R. Bellwied, *Phys.Rev.C* 72 (2005) 054901

I worked with Vasile on understanding hyperon enhancement using baryon junctions

The main reason for baryon junctions at the time: the p/π anomaly at mid-p_T



PHYSICAL REVIEW C, VOLUME 65, 041902(R)

Jet quenching and the $\bar{p} \gtrsim \pi^-$ anomaly in heavy ion collisions at relativistic energies

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(Received 3 May 2001; published 3 April 2002)

PHENIX data on Au+Au at $\sqrt{s} = 130A$ GeV suggest that $\bar{p}$ yields may exceed π^- at high $p_T > 2$ GeV/c. We propose that jet quenching in central collisions suppresses the hard PQCD component of the spectra in central $A+A$ reactions, thereby exposing a novel component of baryon dynamics that we attribute to (gluonic) bayron junctions. We predict that the observed $\bar{p} \gtrsim \pi^-$ and the $p > \pi^+$ anomaly at $p_T \sim 2$ GeV/c is limited to a finite p_T window that decreases with increasing impact parameter.

Baryon and antibaryon production may in fact dominate the moderate high p_T hadron flavor yields, a phenomenon never before observed.

The assumption, in contrast to recombination models, is that strings survive and propagate

An attractive dynamical model that explains copious midrapidity baryon and antibaryon production is based on the existence of topological gluon field configurations (baryon junctions).

Other relevant measurements

Besides *mid-p_T baryon enhancement* other measurements point to novel baryon transport dynamics playing role in nucleus-nucleus (AA) reactions.

STAR data revealed a high *valence proton rapidity density (~10), five units from the fragmentation regions, and a pbar/p=0.65 at midrapidity.*

Junctions predict long-range baryon number transport in rapidity as well as *hyperon enhancement (including Ω)* and considerable p_T relative to conventional diquark-quark string fragmentation (large anti-hyperon enhancement at SPS energies).

Single baryon junction vs JJbar loops, Vance1998

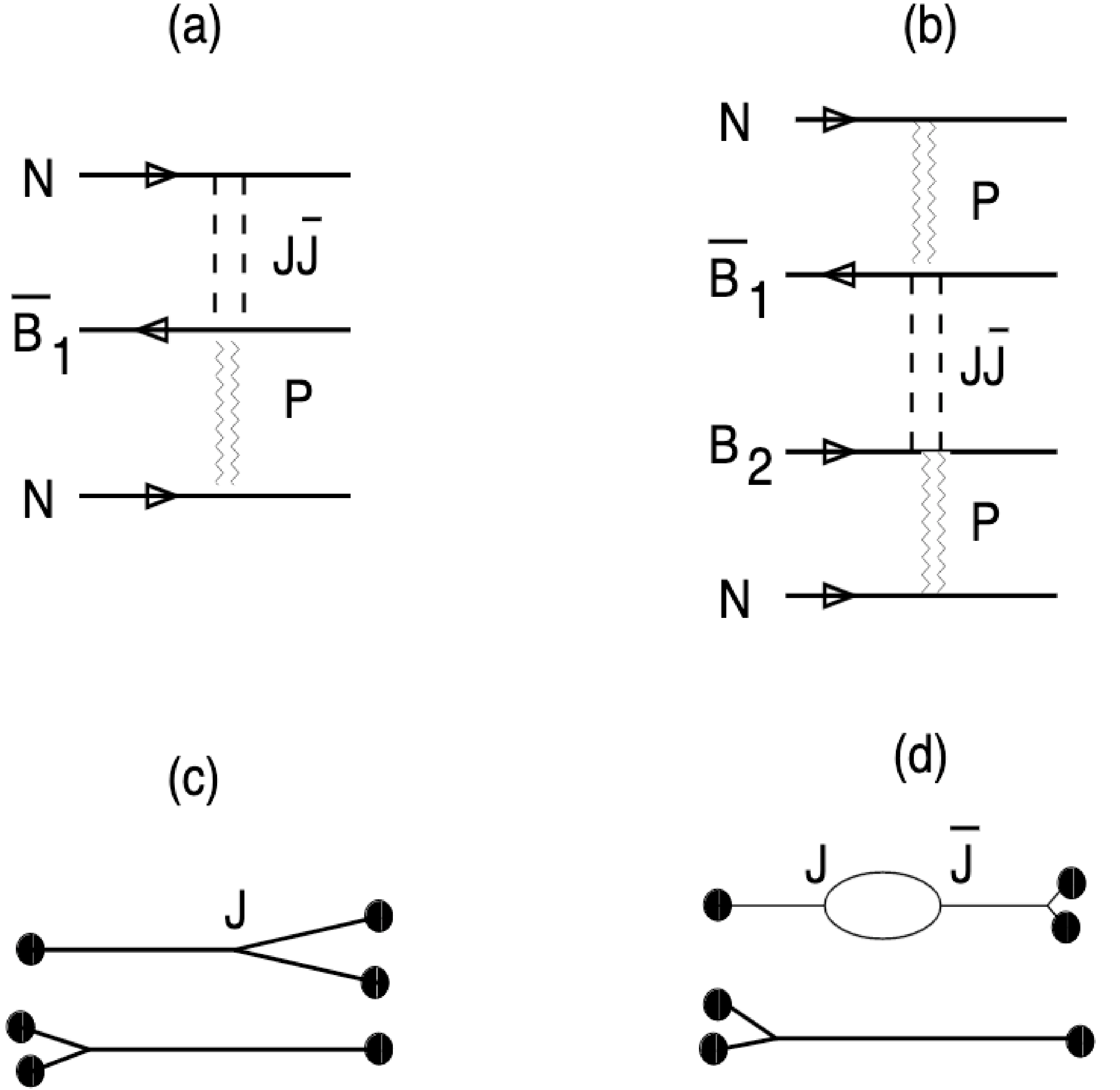


FIG. 1. The Regge diagrams for the single baryon junction exchange and $J\bar{J}$ loops are shown in (a) and (b), respectively. The string model implementation of each Regge diagram are shown in (c) and (d).

HIJING/B HIJING/BBar

Difference between HIJING and HIJING/B at SPS energies (Vance et al.,1998)

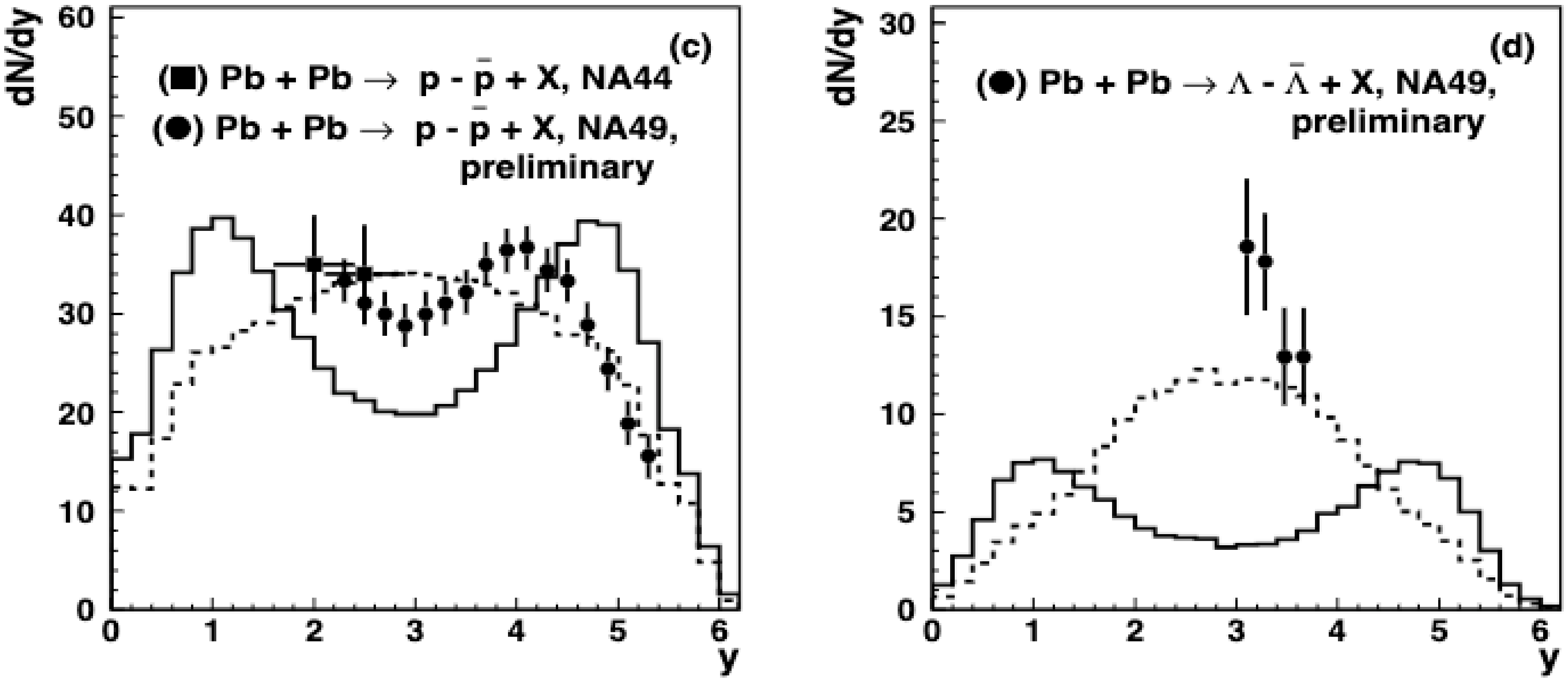


FIG. 1. HIJING (solid) and HIJING/B (dashed) calculations of the valence proton and hyperon rapidity distributions are shown for minimum bias $p+S$ collisions at 200 AGeV and central $Pb+Pb$ collisions at 160 AGeV. The data are from measurements made by the NA35 [1,2], NA44 [3] and NA49 [5] collaborations.

Hyperons in HIJING (Topor-Pop)

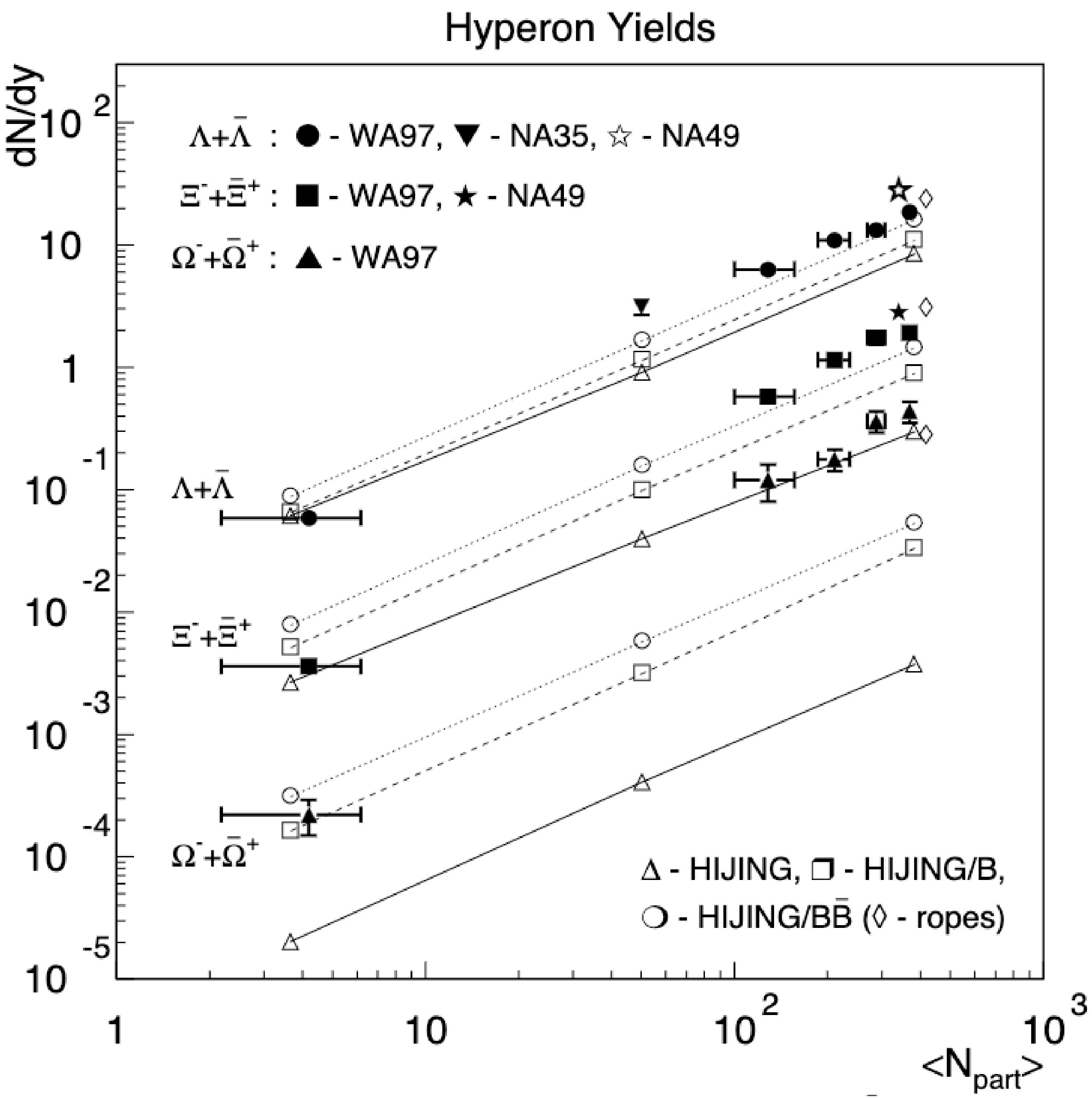


FIG. 2. Hyperon yields from HIJING, HIJING/B and HIJING/$B\bar{B}$ for $p + Pb$, $S + S$ and $Pb + Pb$ at incident momentum $p_{lab} = 160$ AGeV are shown along with data from the NA35 [26], the NA49 [2,3] and the WA97 [1] collaborations.

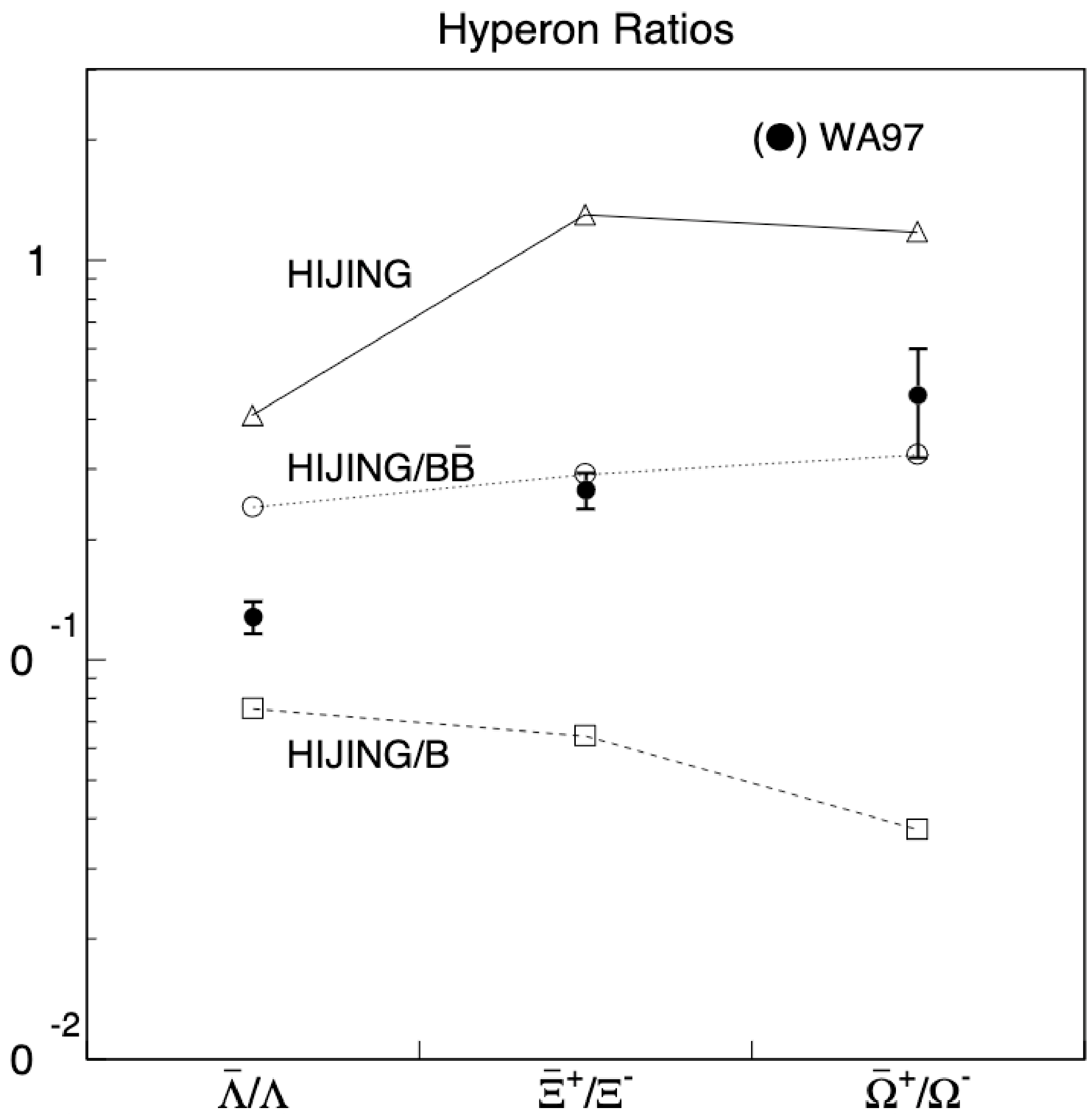


FIG. 3. The ratios of the yields of antihyperons to hyperons are shown for HIJING, HIJING/B d HIJING/$B\bar{B}$ for $p + Pb$, $S + S$ and $Pb + Pb$ at incident momentum $p_{lab} = 160$ AGeV along ith data from the WA97 [1] collaboration.

Quantitative gluon junction implementation

Many of the early phenomena at SPS and RHIC could be explained with ‘the right’ implementation of gluon junctions:

1.) baryon transport
2.) hyperon enhancement
3.) hyperon to anti-hyperon ratios
4.) proton/pion ‘anomaly’ and R_{AA} differences between species

The right implementation had several ‘free’ parameters:

- Not only junctions (J) but also JJbar loops
- Di-quark suppression factor
- Shadowing and quenching mechanisms (yqs/nqs)
- String tension to parametrize strong color fields (SCF)
- Enhanced di-quark p_T kick (f=3)

The new junction measurements

Valence Quarks

- Carry large momentum fractions
- Hard to be stopped at midrapidity
  - $dN/d\Delta y \sim \exp(-2.4\Delta y)$ (PYTHIA)
  - $\Delta y = Y_{\text{beam}} - y$
- Ensemble basis: $Q \sim B \times Z/A$

Junctions

- Consist of low-momentum gluons
- Easier to be stopped at midrapidity
  - $dN/d\Delta y \sim \exp(-0.5\Delta y)$ (theory)

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

- Ensemble basis: $Q < B \times Z/A$

✓ **THREE TESTS**

1) Compare Q vs. $B \times Z/A$ in Ru+Ru and Zr+Zr collisions
2) Net-proton $dN/d\Delta y$ in γ+Au events
3) Net-proton $dN/d\Delta y$ in hadronic Au+Au collisions

Net-charge vs. net-baryon

- ➢ Measured within midrapidity: $|y| < 0.5$

✓ Charge transport: net-charge number

$$Q = (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_{\bar{p}})$$

✓ Baryon transport: net-baryon number

$$B = (N_p + N_n) - (N_{\bar{p}} + N_{\bar{n}})$$

- ○ Almost all particles decay to π, K, p, n
  - ○ Missing deuteron contribution to $B \sim 0.8\%$
- ○ Measured spectra include resonance and weak decays (DCA < 3 cm)
  - ○ Missing weak decays contribute ~ 1%
- ○ Neutron yield estimated using proton and deuteron yields in thermal/coalescence picture
  - ○ Uncertainty ~ 3-5%

- ➢ Very difficult to measure net-charge with needed precision
- ➢ Instead, we can measure the net-charge difference between ${}^{96}_{44}Ru$+${}^{96}_{44}Ru$ and ${}^{96}_{40}Zr$+${}^{96}_{40}Zr$ collisions

$$\Delta Q = Q_{\text{Ru+Ru}} - Q_{\text{Zr+Zr}} \approx N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p(R2_p - 1)$$

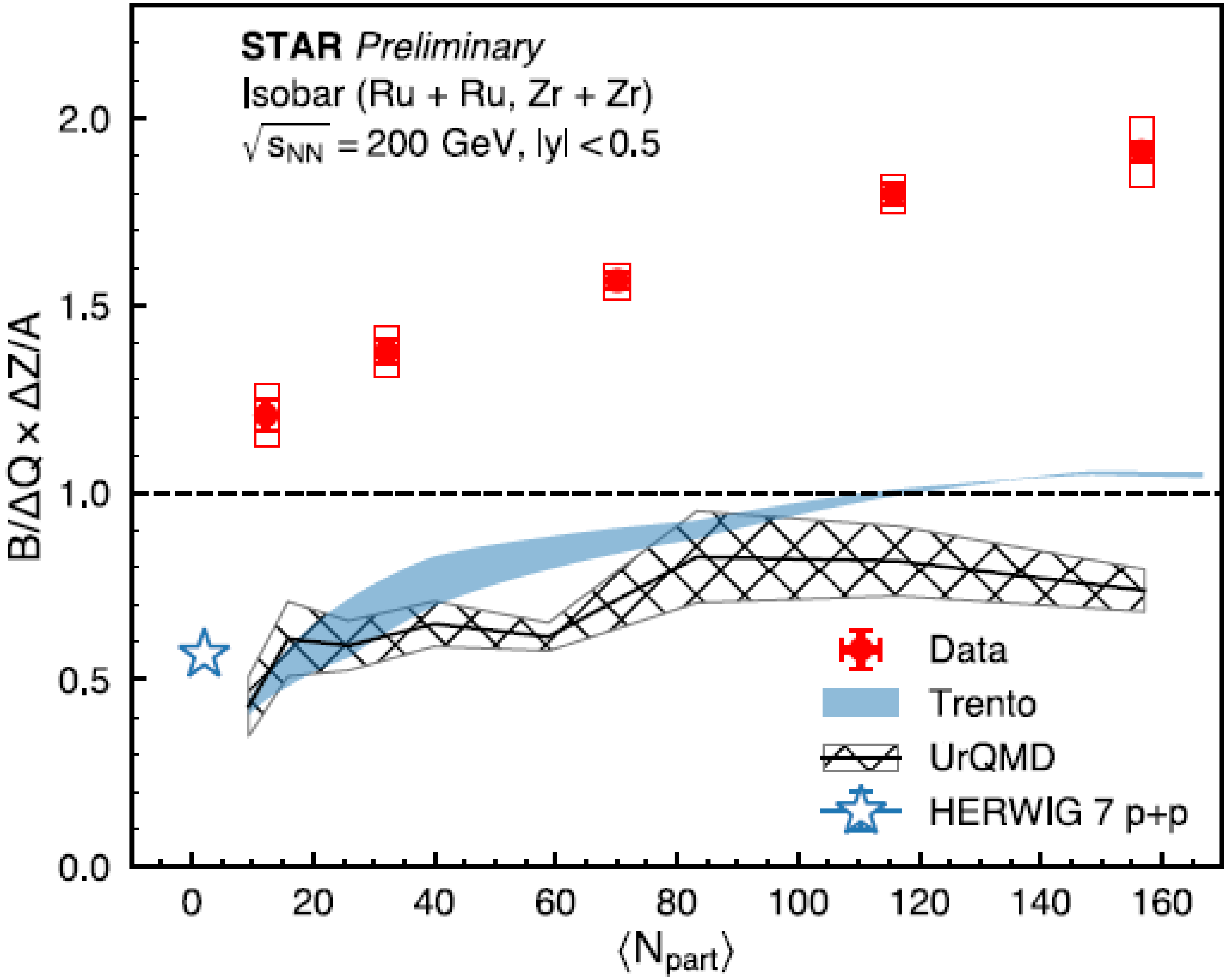
$$R2_\pi = (N_{\pi^+}/N_{\pi^-})_{\text{Ru+Ru}}/(N_{\pi^+}/N_{\pi^-})_{\text{Zr+Zr}}$$

- ○ Double ratios take care of multiplicity mismatch between two isobar collisions for a given centrality

✓ We compare:

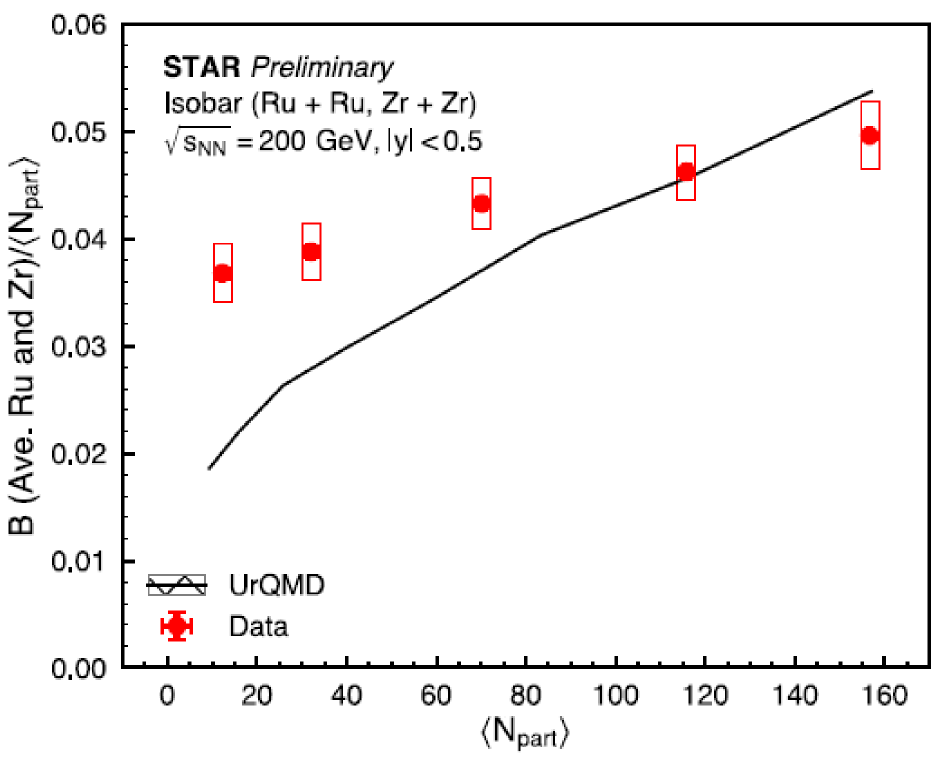
$$\Delta Q \text{ vs. } B \times \frac{\Delta Z}{A} \qquad \Delta Z = 44 - 40 = 4,\ A = 96$$

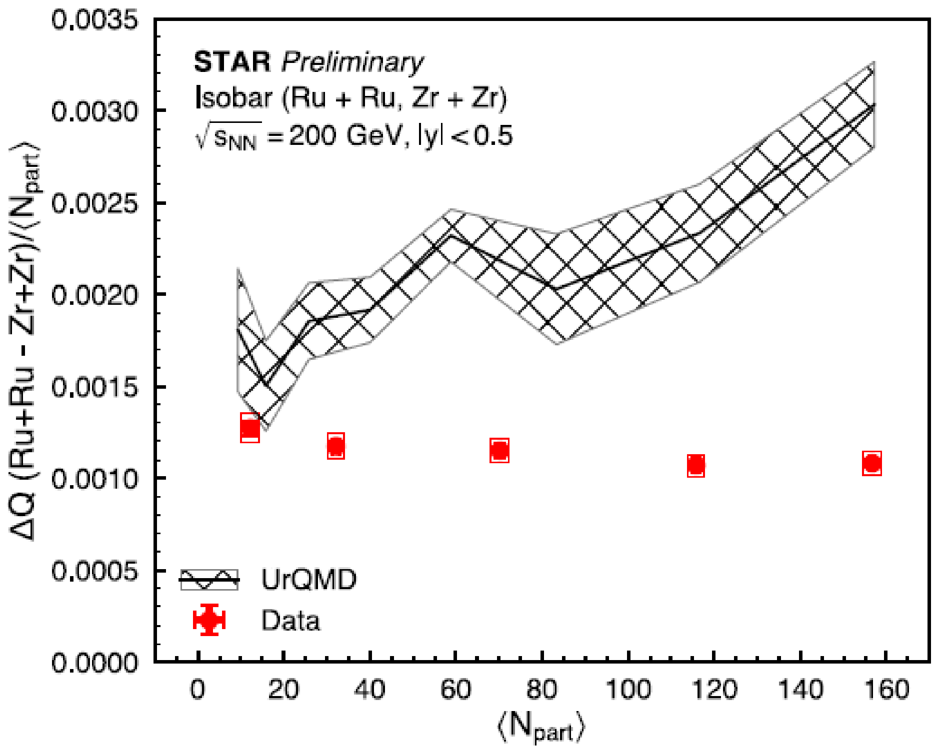
Net-baryon significantly larger



- Trento: decreasing towards peripheral due to different neutron skins between Ru and Zr

Compare <B> and ΔQ individually

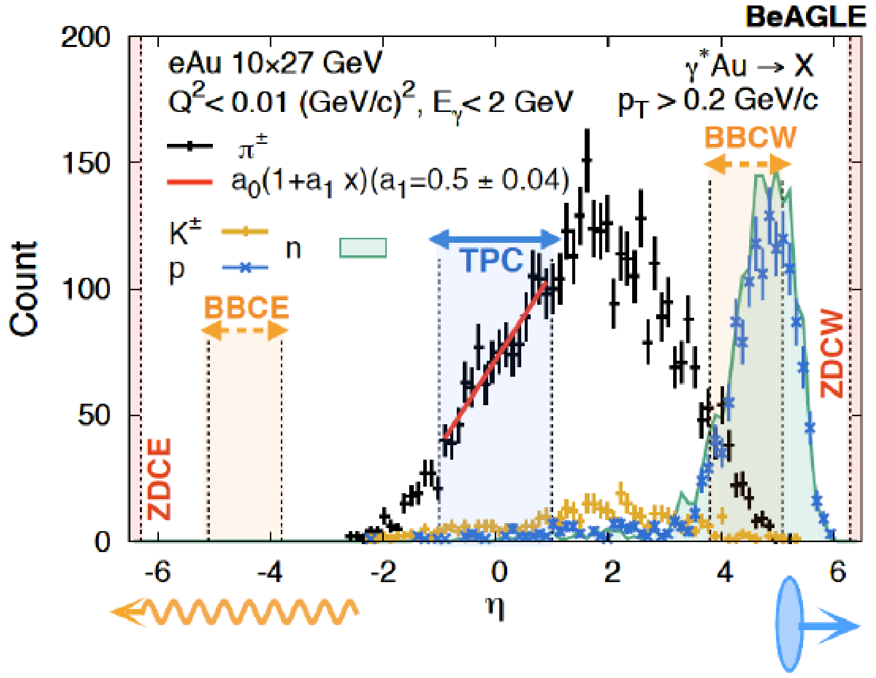




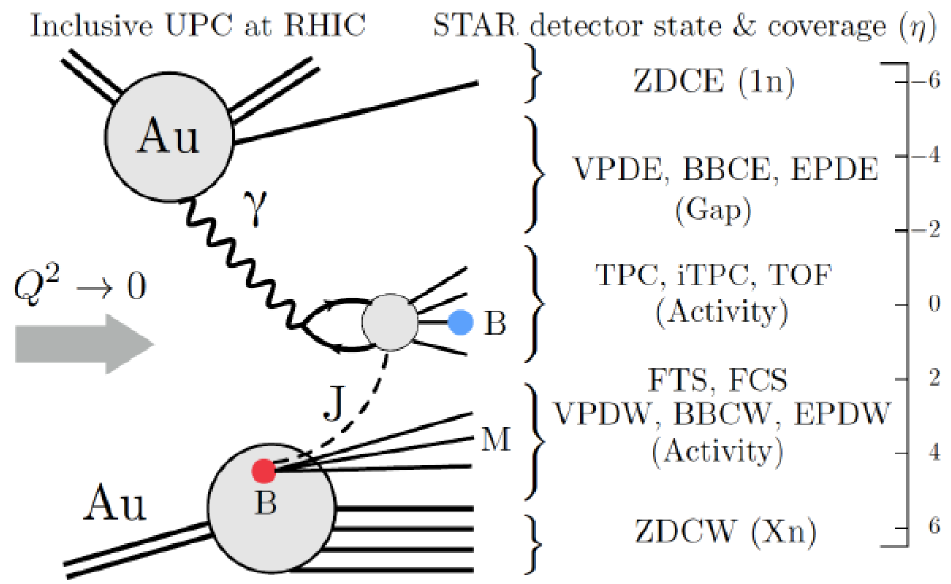
- Central collision: UrQMD can describe baryon number, but significantly overshoots charge number → enhancing baryon transport results in too many quarks stopped at midrapidity
- Correct model should describe both simultaneously

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

γ-Au events



BeAGLE: W. Chang, et. al., PRD 106 (2022) 012007



Inclusive UPC at RHIC

STAR detector state & coverage (η)

ZDCE (1n)

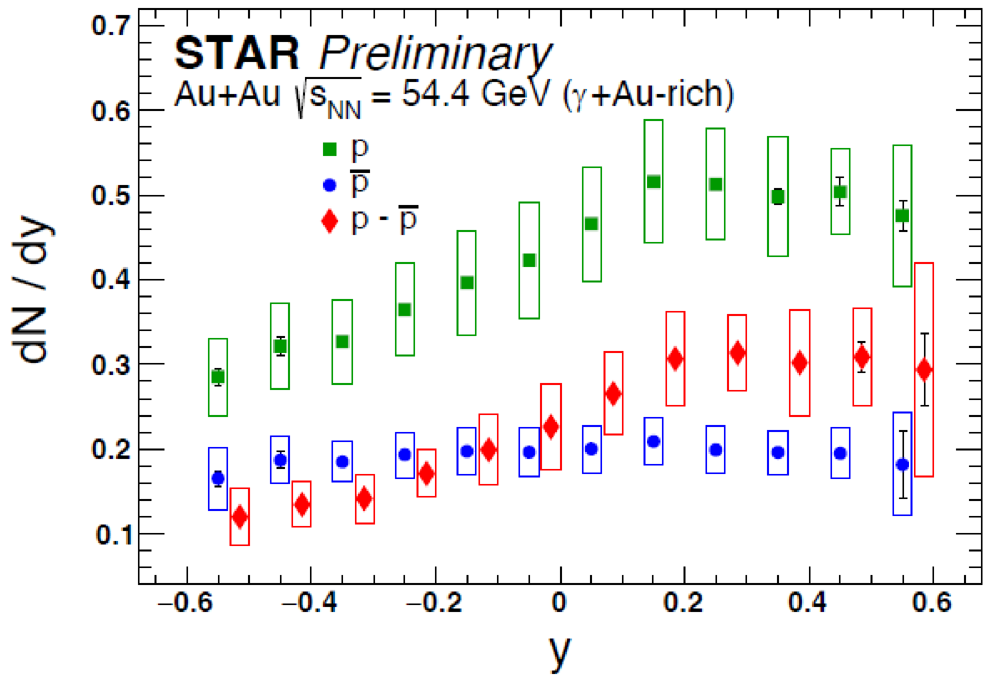
VPDE, BBCE, EPDE (Gap)

TPC, iTPC, TOF (Activity)

FTS, FCS VPDW, BBCW, EPDW (Activity)

ZDCW (Xn)

J. Brandenburg, N. Lewis, et. al., arXiv:2205.05685

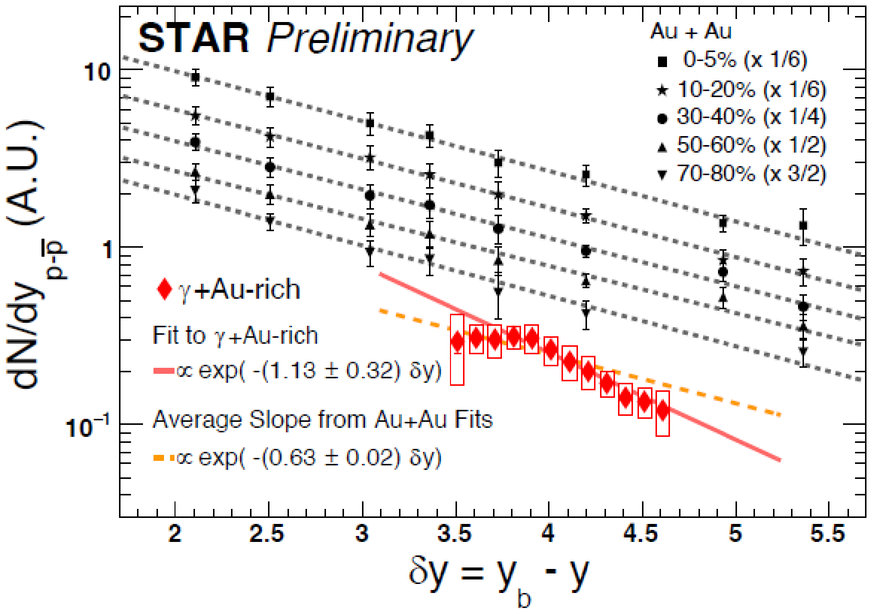


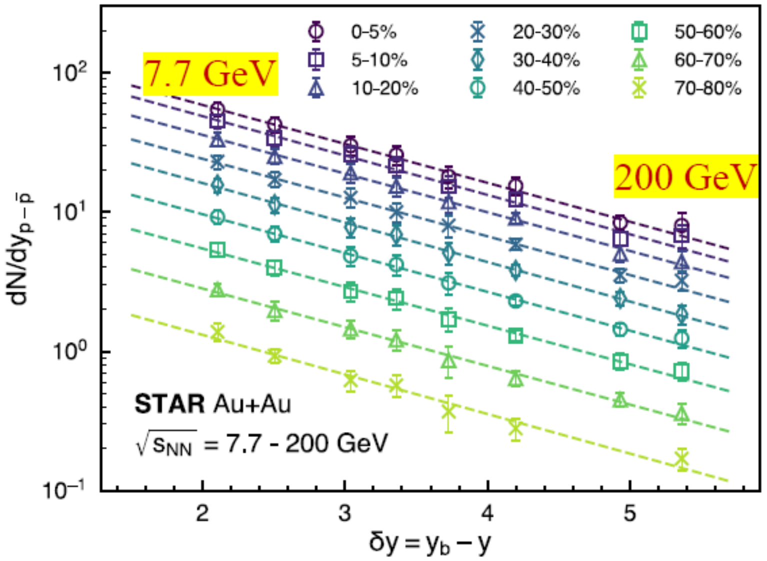
$$y = Y_{\text{beam}} - \Delta y$$

- Clear excess of *p* over anti-*p* → incoming photons can stop baryon number
- Flat distribution of anti-*p* → net-*p* slope is not created artificially by event selection

Rapidity slope of net-protons

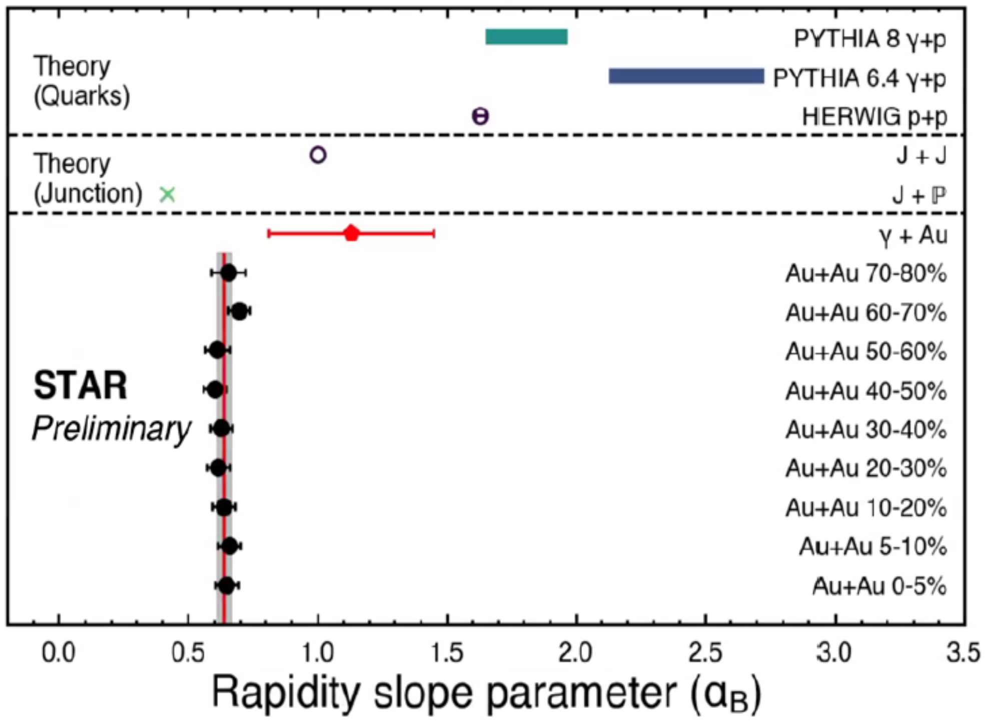
○ $\Delta y = Y_{\text{beam}} - y$: Y_{beam} changes with energy while $y \sim 0$ is fixed





J. Brandenburg, N. Lewis, et. al., arXiv:2205.05685

- ➢ Fit with an exponential function



Junction theory: D. Kharzeev, PLB 378 (1996) 238

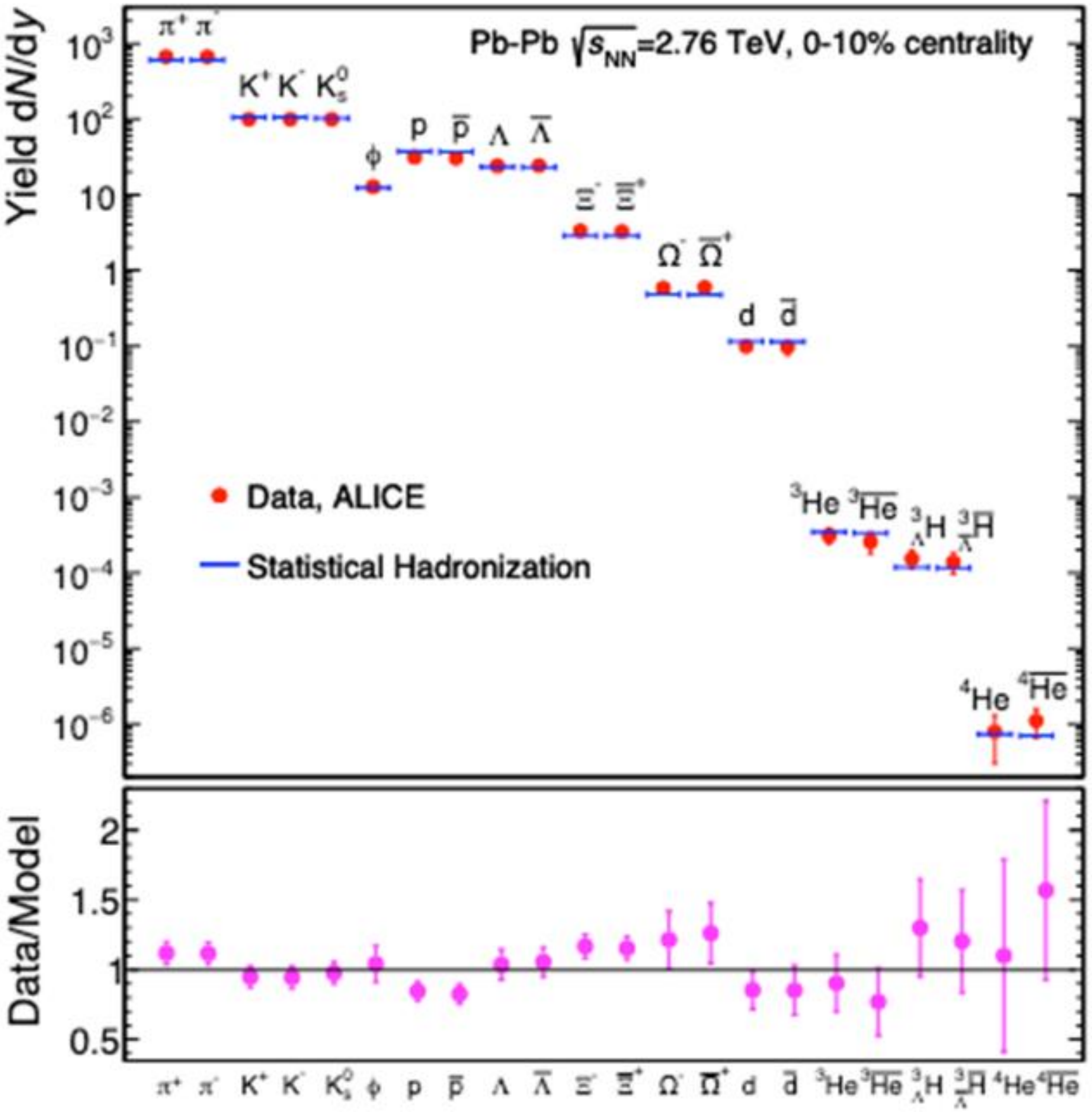
- ➢ No centrality dependence of the slope → not expected for valence quark stopping
- ➢ $Slope_{\gamma+\text{Au}} >\sim Slope_{\text{Au+Au}}$: possibly collision energy or process dependence

  X. Artru, M. Mekhfi, Nucl. Phys. A 532 (1991) 351
- ➢ Qualitatively consistent with baryon junction prediction
- ➢ Smaller than HERWIG and PYTHIA predictions

Quantum collectivity

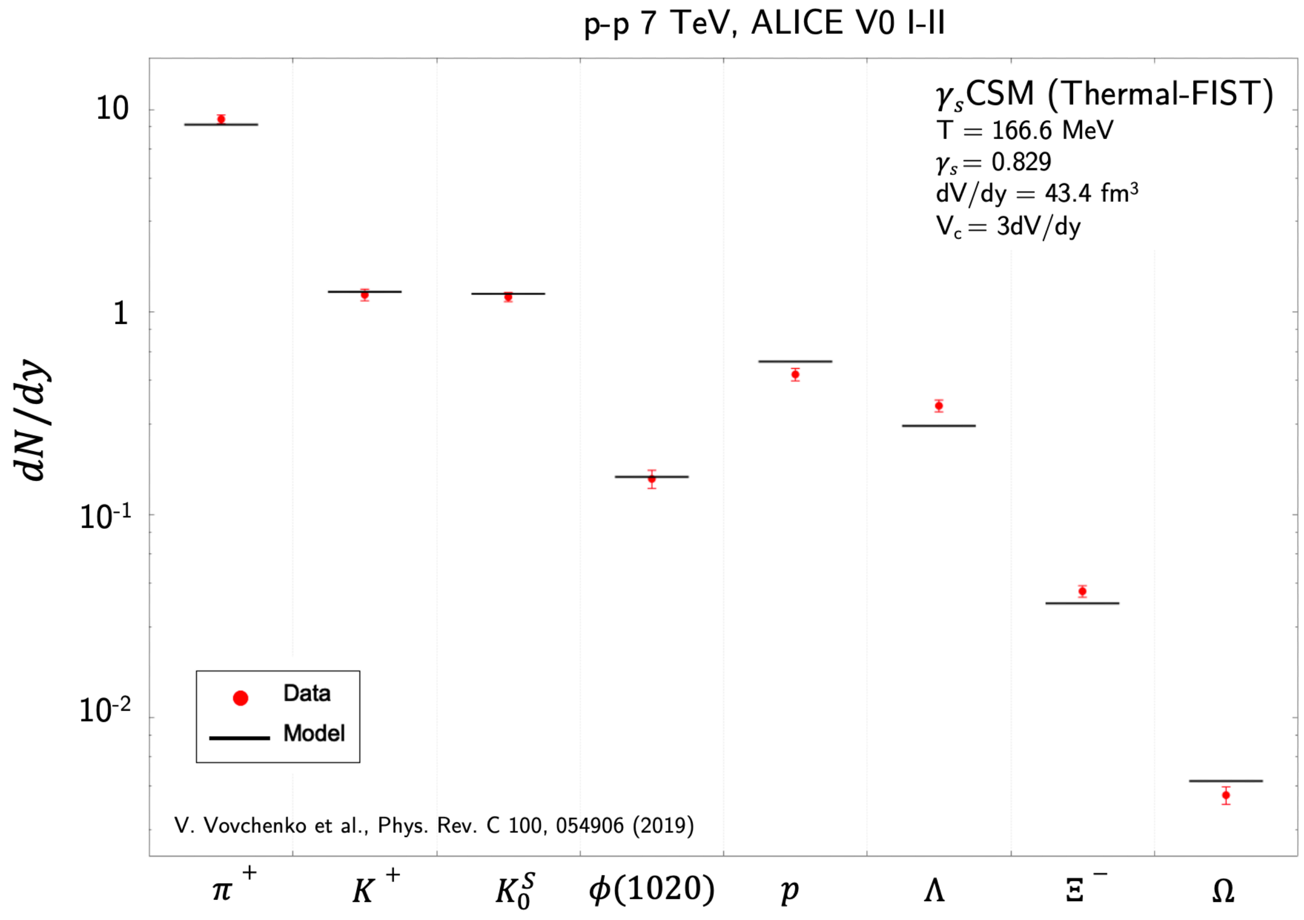
Kharzeev, Levin (1702.03489)
Baker, Kharzeev (1712.04558)
Berges, Floerchinger, Venugopalan (1707.05338)
Berges, Floerchinger, Venugopalan (1712.09362)
Bellwied (1807.04589)
Tu, Kharzeev, Ullrich (1904.11974)
Hentschinski, Kutak, Kharzeev, Tu (2305.03069)
Hutson, Bellwied (2410.17429)

Statistical hadronization models are extremely successful at finite T (under the assumption of thermal equilibration)



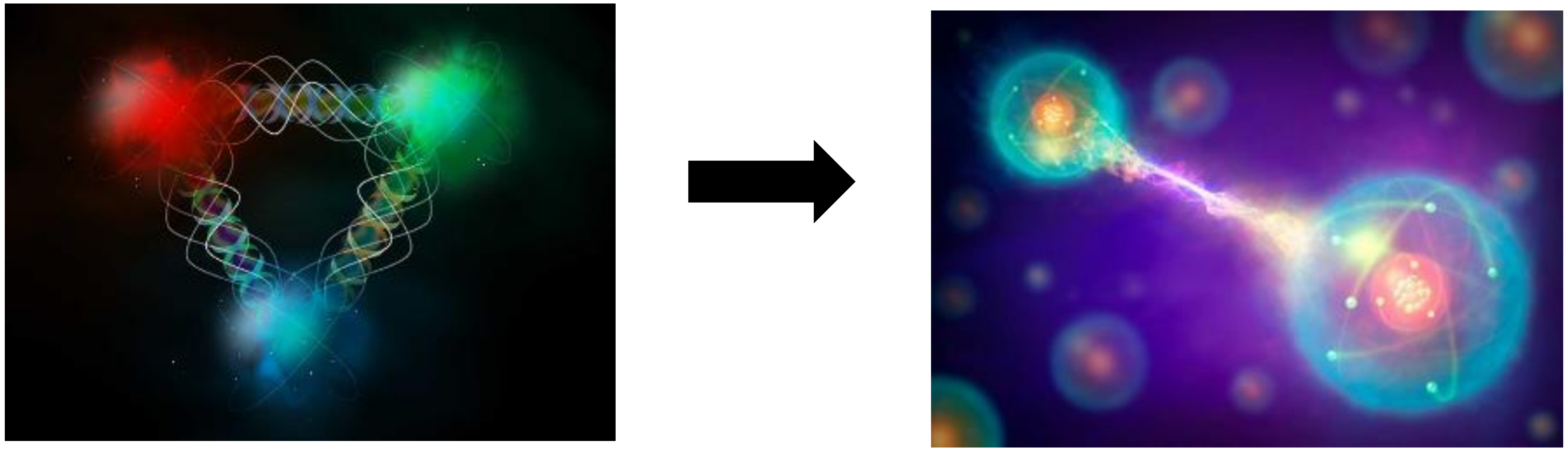
A. Andronic et al., Nature 561, 321 (2018)

Not only in AA, but also pp



V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)

Can we measure signs of quantum entanglement in pp (ep) or even PbPb collisions ?



> "...we never experiment with just one electron or atom or (small) molecule. In thought experiments, we sometimes assume that we do; this invariably entails ridiculous consequences ... ."

Erwin Schrödinger, 1952

<u>**Idea:**</u> initial state is entangled transversely (proton confinement) and longitudinally (string formation). Can we measure remnants of coherence ? Are final state multiplicities due to initial state entanglement (all the way out to light nuclei) ?

Entanglement entropy = thermodynamic entropy ? (parton-hadron duality). Is the system not driven by thermalization but by initial coherence, which looks thermal ?

‘Thermalization’ through quantum entanglement ?

Groundbeaking paper (experimental) (published in Science):

A.M. Kaufman et al., (Harvard), arXiv:1603.04409

Quantum thermalization through entanglement in isolated many-body system, but cold and small (quantum quench in BE condensate of ^{87}Rb atoms), effective T = 5-10 J, study impact on neighboring atoms

Even more groundbreaking paper (experimental) (published in Nature Comm):

J. Kong et al., May 2020

nature COMMUNICATIONS

ARTICLE

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Measurement-induced, spatially-extended entanglement in a hot, strongly-interacting atomic system

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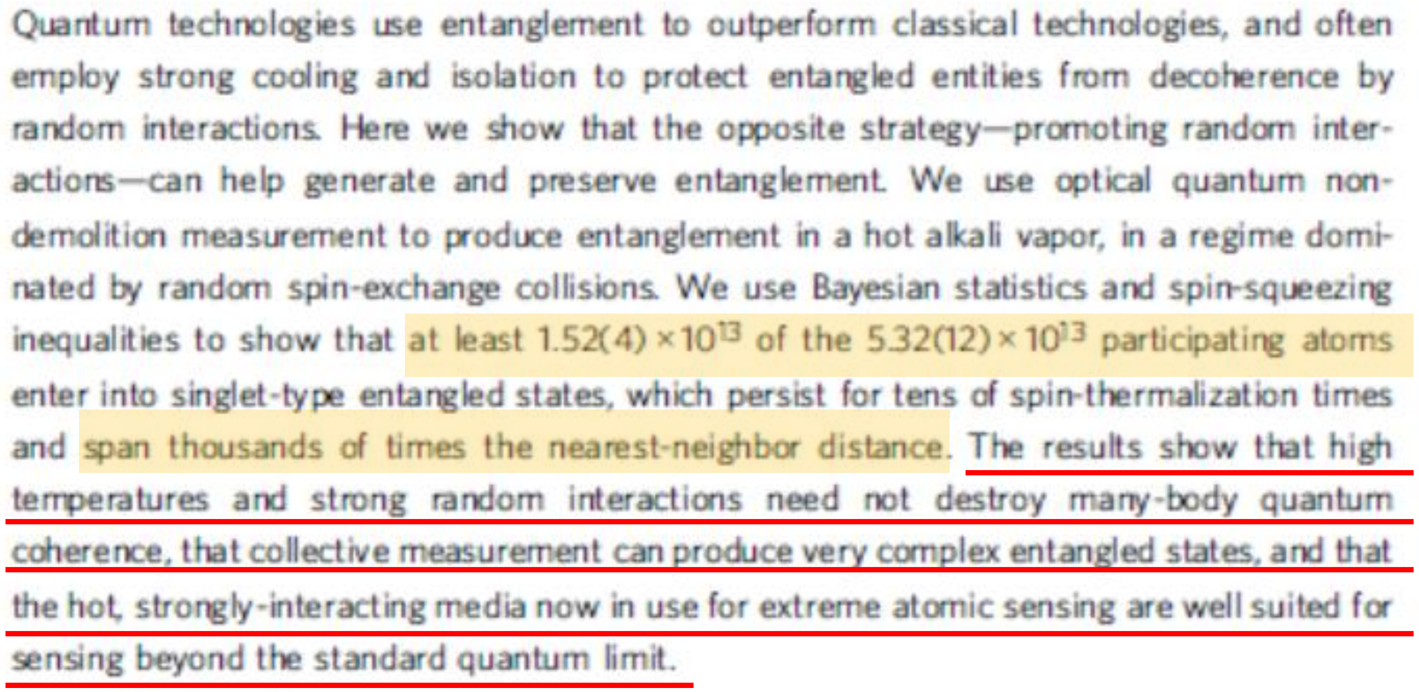


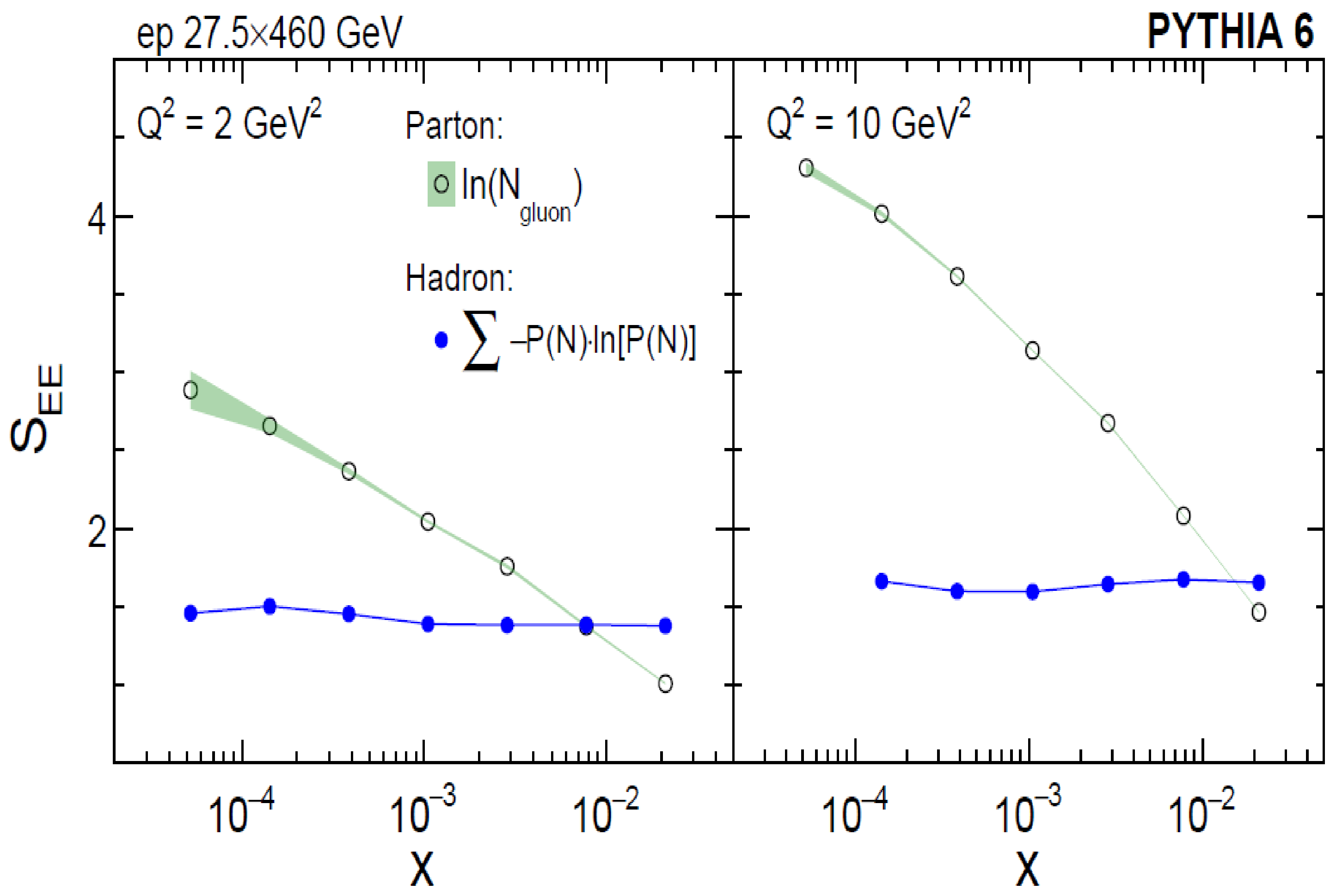
Quantum technologies use entanglement to outperform classical technologies, and often employ strong cooling and isolation to protect entangled entities from decoherence by random interactions. Here we show that the opposite strategy—promoting random interactions—can help generate and preserve entanglement. We use optical quantum nondemolition measurement to produce entanglement in a hot alkali vapor, in a regime dominated by random spin-exchange collisions. We use Bayesian statistics and spin-squeezing inequalities to show that at least $1.52(4) \times 10^{13}$ of the $5.32(12) \times 10^{13}$ participating atoms enter into singlet-type entangled states, which persist for tens of spin-thermalization times and span thousands of times the nearest-neighbor distance. The results show that high temperatures and strong random interactions need not destroy many-body quantum coherence, that collective measurement can produce very complex entangled states, and that the hot, strongly-interacting media now in use for extreme atomic sensing are well suited for sensing beyond the standard quantum limit.

How to map parton entanglement to parton distribution functions and experiment (from 1904.11974)

Model Calculations

- First we obtain the number of gluons, N_{gluon}, by integrating the gluon distribution $xG(x)$ over a given x range at a chosen scale Q^2. We use the leading order Parton Distribution Function (PDF) set MSTW at the 90% C.L. -> Entanglement Entropy in green

- The Boltzmann entropy of the final-state hadrons is shown as blue filled circles. It is calculated from the multiplicity distribution, P(N), in a rapidity range determined by the x range used to derive N_{gluon}. P(N) is taken from ep DIS events created with the PYTHIA 6 or 8 event generator



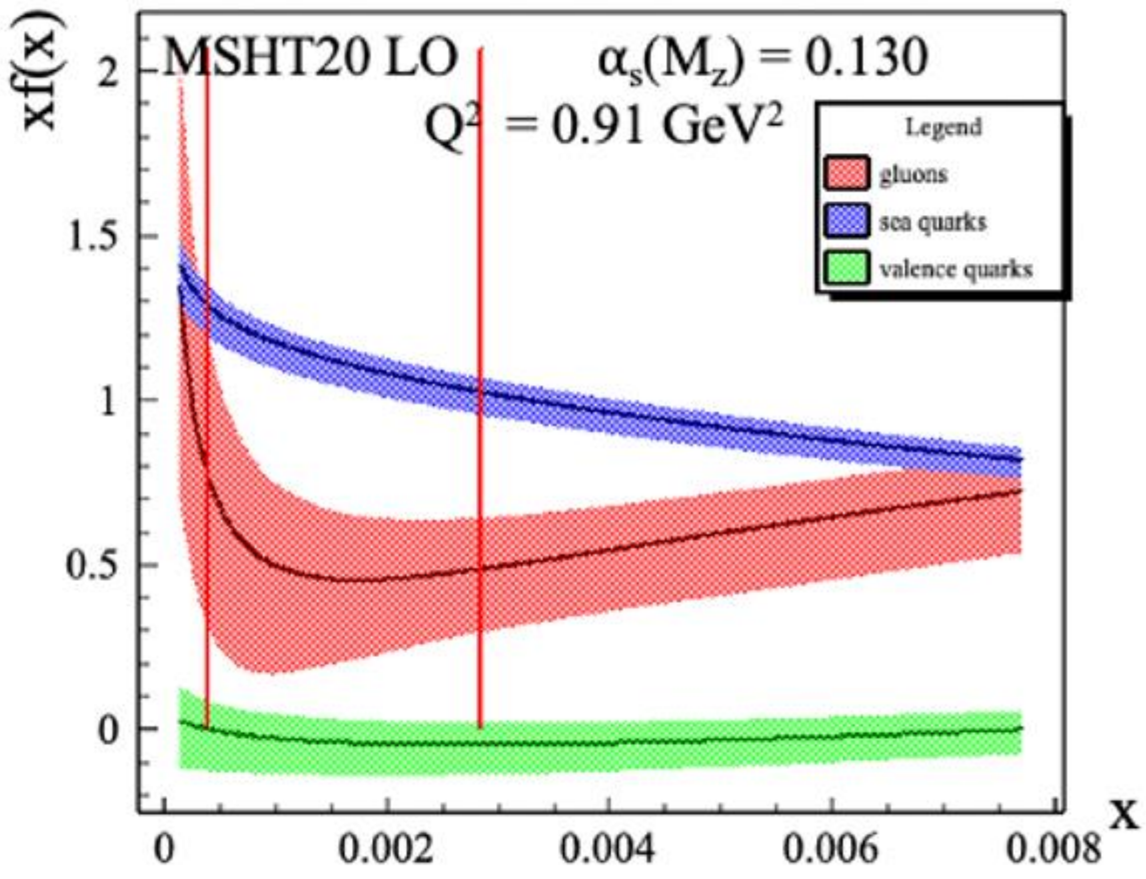
- Since x and momentum transfer scale Q^2 are not directly available in pp collisions, an alternative way of comparing the entropy at similar x and scales are used.

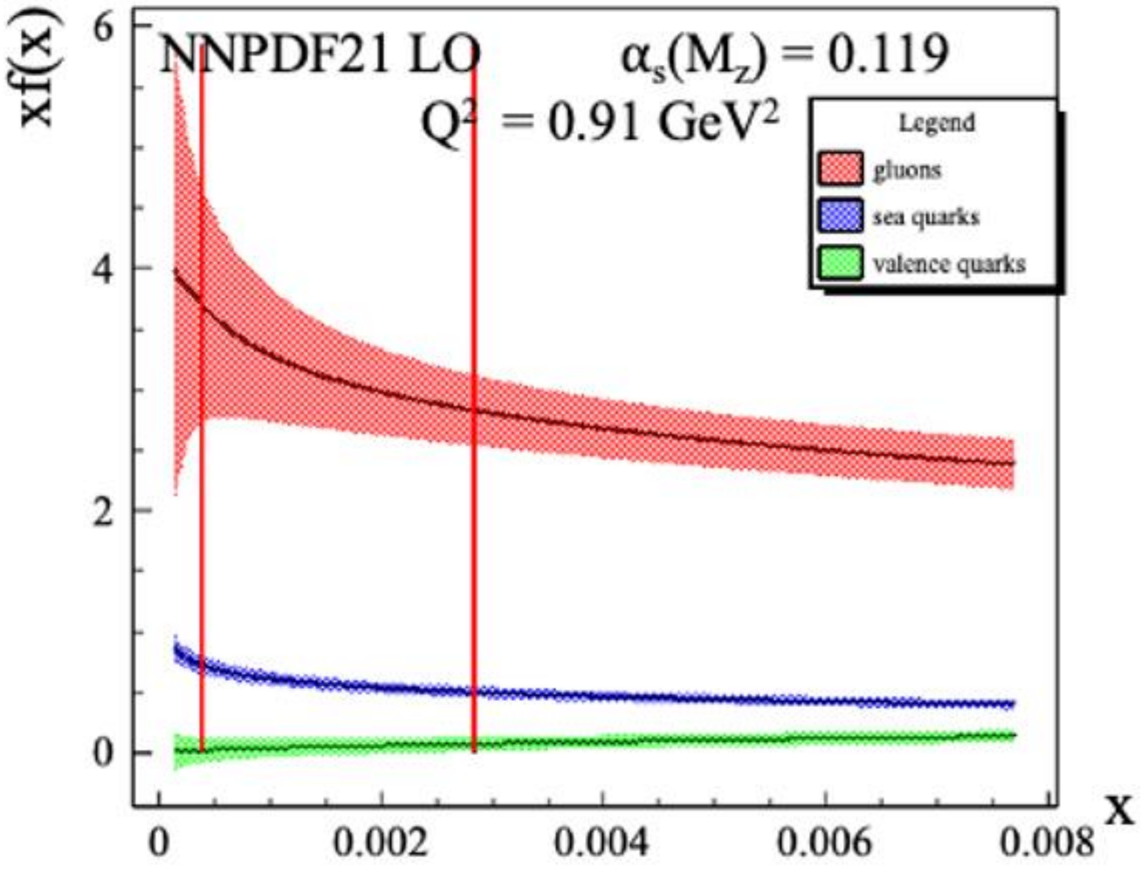
$$\ln(1/x) \sim y_{proton} - y_{hadron}$$

- **In ep collisions:** y_{proton} is the proton beam rapidity and y_{hadron} is the final-state hadron rapidity. For example, events with 27.5 GeV electrons scattering off 460 GeV protons with x between 3×10^{-5} and 8×10^{-5} correspond to a rapidity range of $-3.5 < y < -2.5$.

Different Parton Distribution Functions

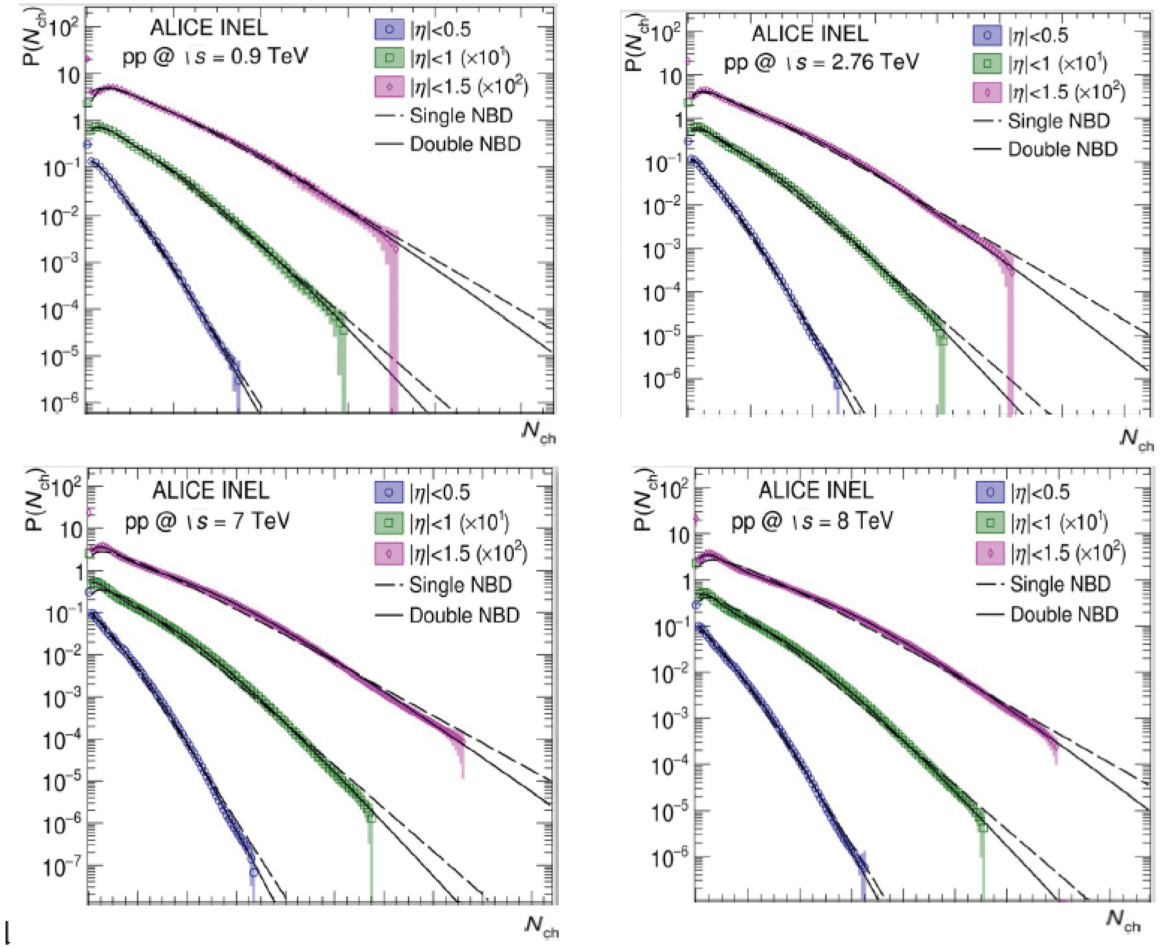
- Contributions from quarks might still be relevant at low x





This is slightly more complicated in pp

In pp collisions: two gluon distributions are involved, one from each proton, while we calculate the entanglement entropy from one distribution. Instead of altering the definition of the entanglement entropy, one can modify the P(N) distributions by extrapolating the P(N) distribution to reflect a single proton similar to that in ep collisions, by fitting a generalized Negative Binomial Distribution (NBD) to the P(N) distributions. The final P(N) is then taken as the same NBD function but with only half of the average multiplicity. This approach relies on the assumption that the final-state hadrons are produced coherently by the two colliding protons instead by incoherent and independent fragmentation.



Now that we understand how to calculate the initial state entropy we would like to compare this to the entropy of the final state hadrons.

We measure the hadron entropy using Gibbs entropy formula and summing over the probability distribution P(N).

$$S_{final} \propto \Sigma P(N_h) ln(P(N_h))$$

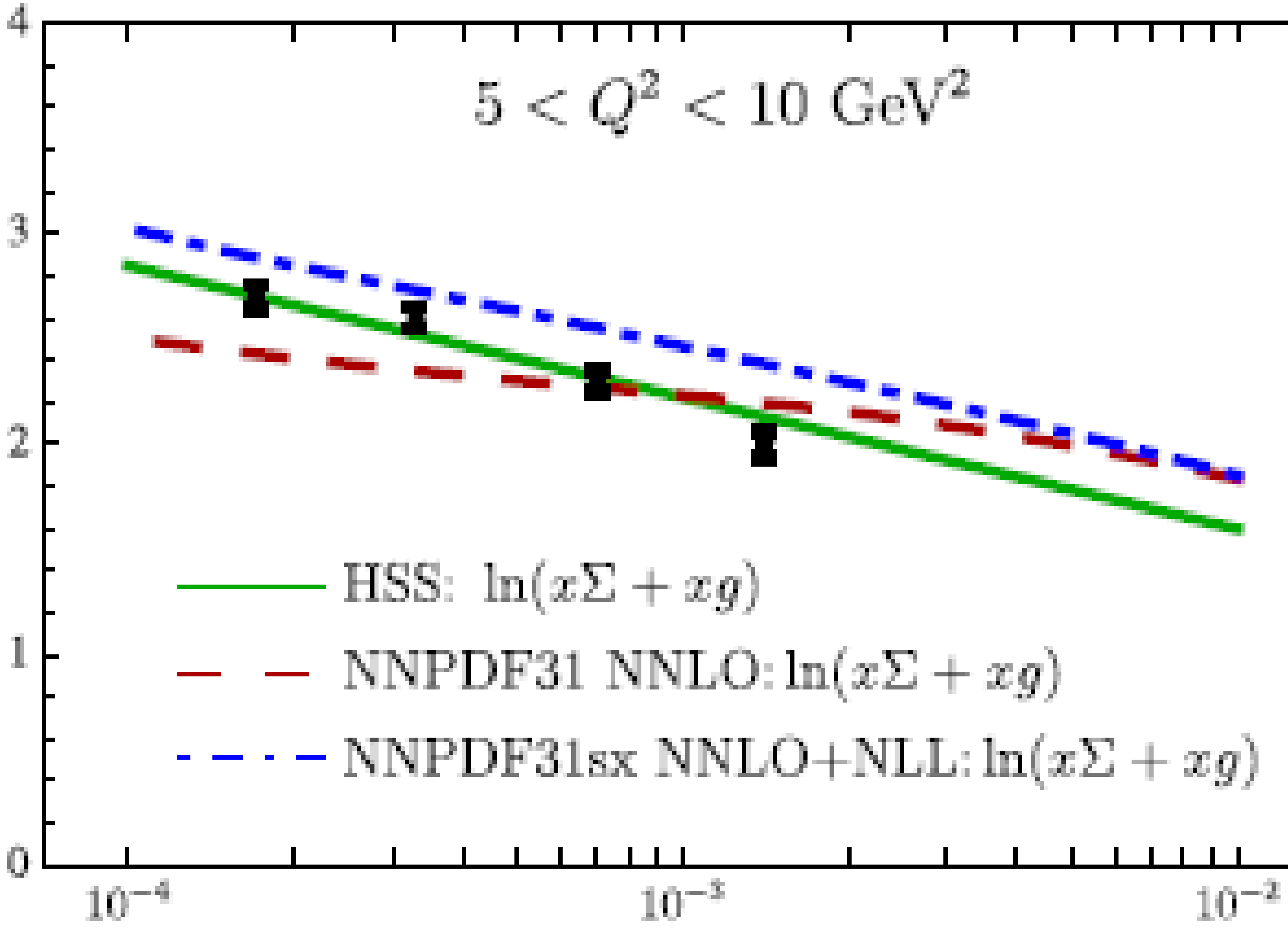
Procedure:
1.) measure multiplicity distributions In a fixed rapidity range

2.) calculate x-value distribution

3.) calculate entropy distribution

The impact of quark contributions

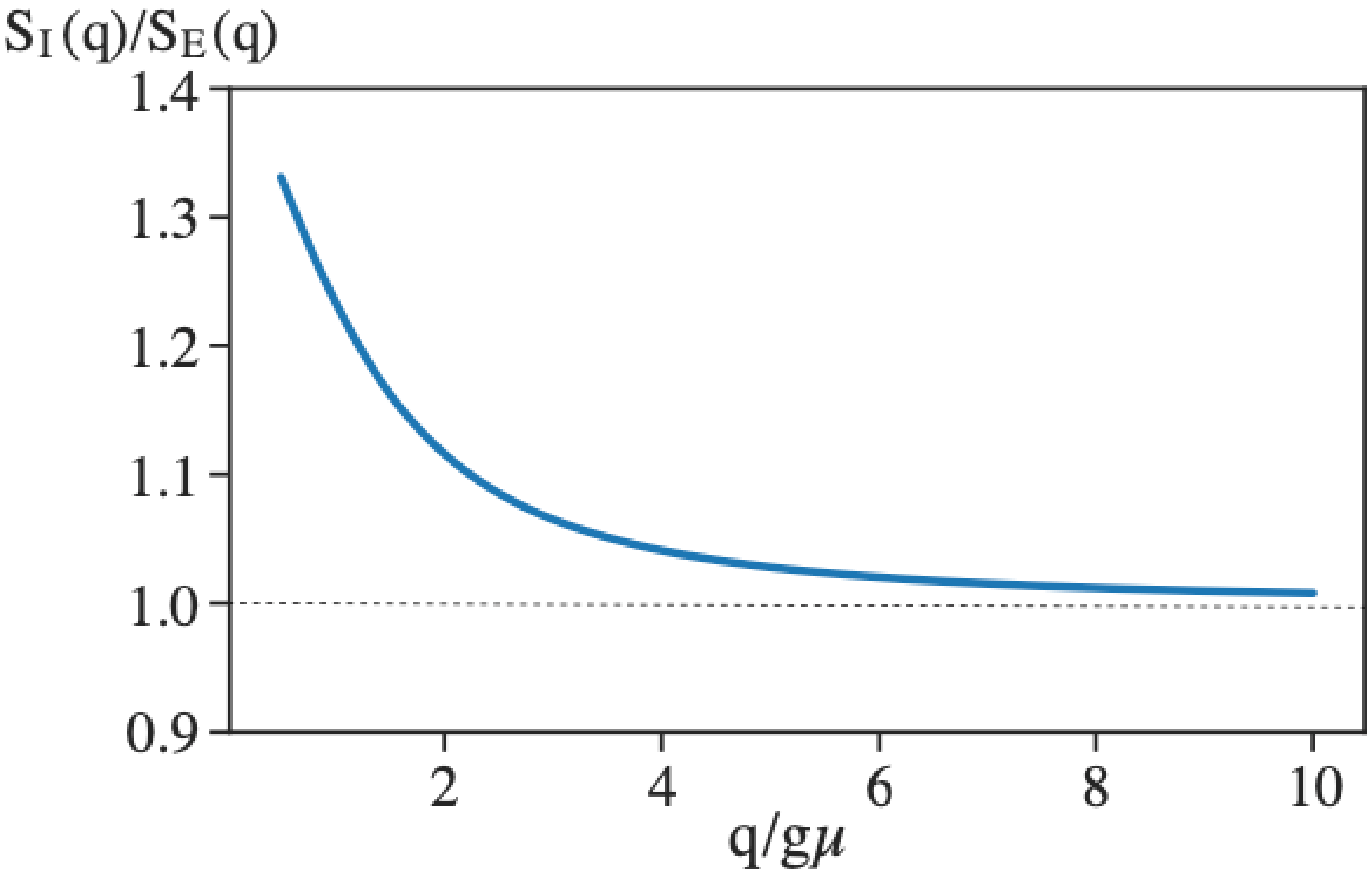
Hentschinski & Kutak (2021):Disagreement at higher x could be due to significant sea-quark contributions (shown here in comparison to H1 data)



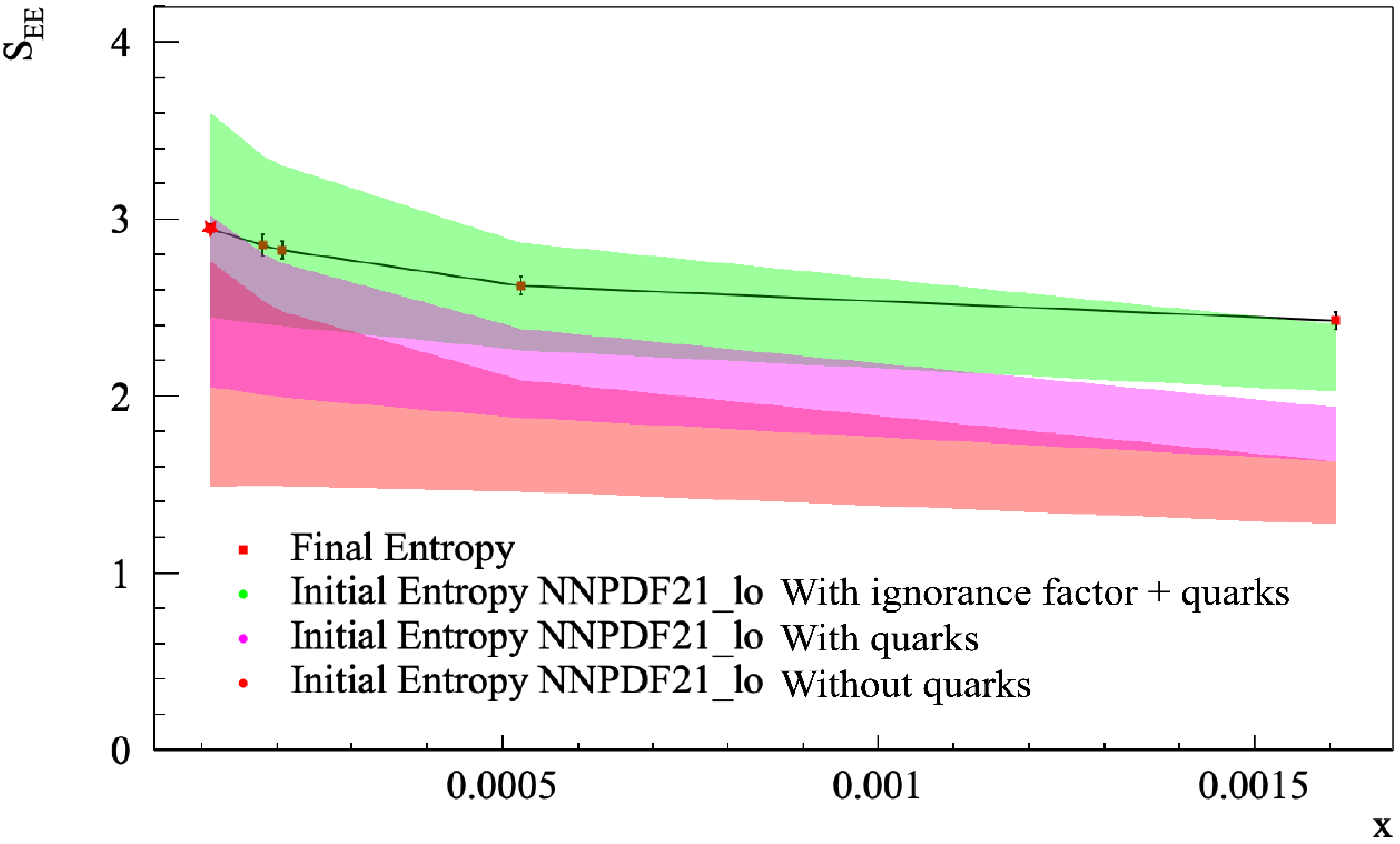
‘Ignorance’ scaling

A calculation by Duan, Akkaya, Kvoner, Skokov (arXiv:2001.01726)
based on the Page curve of limited acceptance (Mueller, Schaefer (arXiv: 2211.16265))

S_E is based on the set of observables (only sensitive to the diagonal matrix elements of the density matrix). S_I takes into account off-diagonal elements

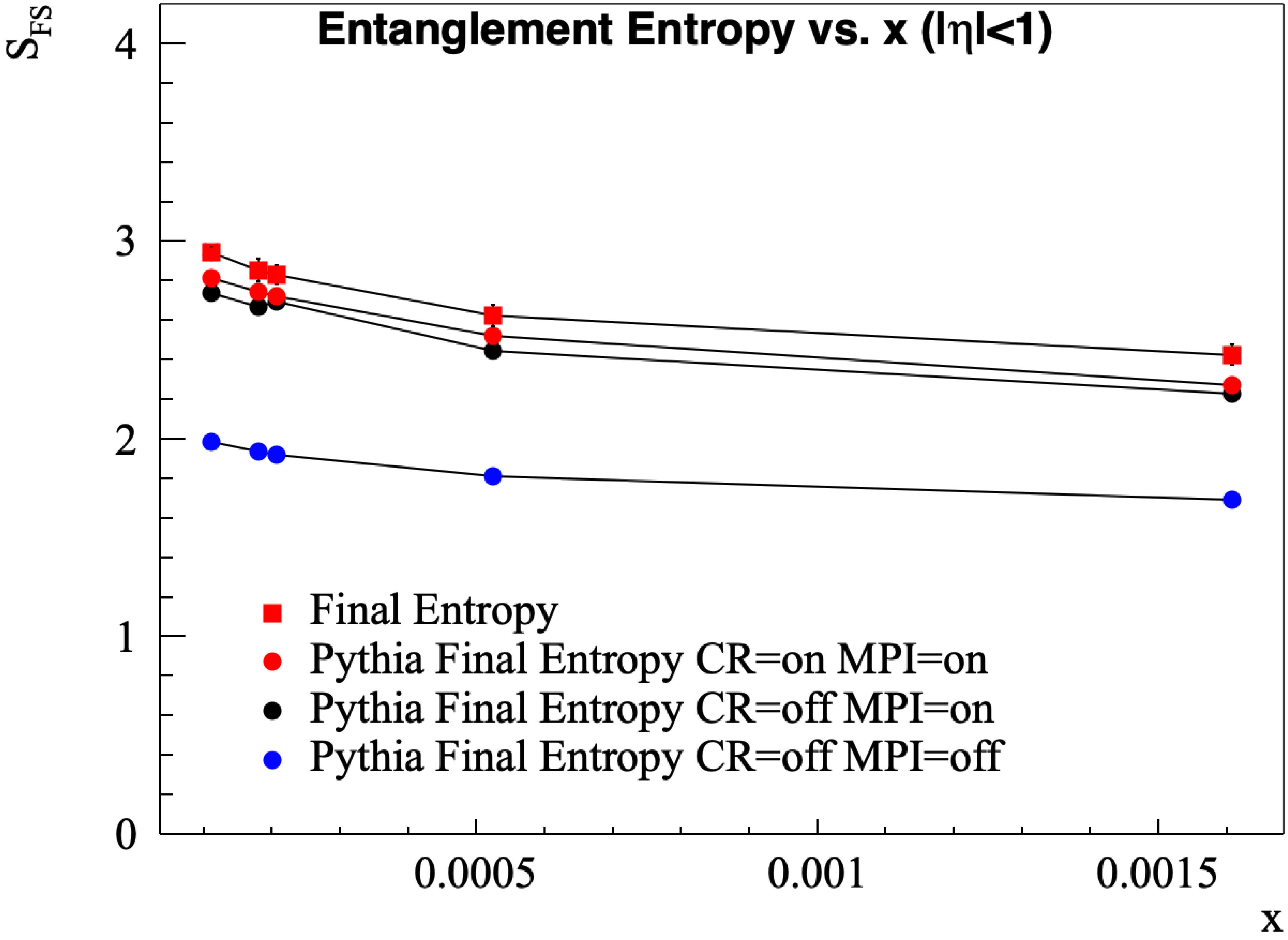


Entanglement entropy vs. ALICE final state entropy



Hutson, Bellwied (2410.17429)

The alternative (PYTHIA Monash Tune)



Hutson, Bellwied (2410.17429) & Holmganga CLASH workshop

Conclusions and outlook

- There are still open and interesting questions to be answered regarding hadronization and particle production. Theory has shifted from static models to dynamic models and quantum problems.
- Quantization issues such as baryon number transport and gluon entanglement complement the picture of global thermalization and add a microscopic quantum description to the formation of matter.
- For more than 40 years Johanna has been a leader in our field, and I am honored to have accompanied her journey for most of that time.
- Let’s not stop here, there is still much to come, at the LHC and the EIC.

Thanks to the Stony Brook Gang for a great meeting