Formation of a fireball, (and clustering near CP)

Edward Shuryak
Center for Nuclear Theory, Stony Brook University

How the idea of RAPID NONLINEAR QGP fireball formation was developing

0.phenomenology of centrality dependence:
multiplcity/wounded nucleons indicate
an unexpected jump between light and heavy ions

1.The holography and use of the idea of trapped surface
(from Gubser et al, 2008)

2. Finding trapped surface for non-central
collisions (Shu Lin+ ES 2009) and discovery
of critical impact parameter

3.deriving string-string interaction
(Tigran Kalaydzhyan and ES, 2014)

4.collective effects in “spaghetti” multistring system
in the transverse plane (Tigran Kalaydzhyan and ES, 2014)

5. Strings and multistrings in holography
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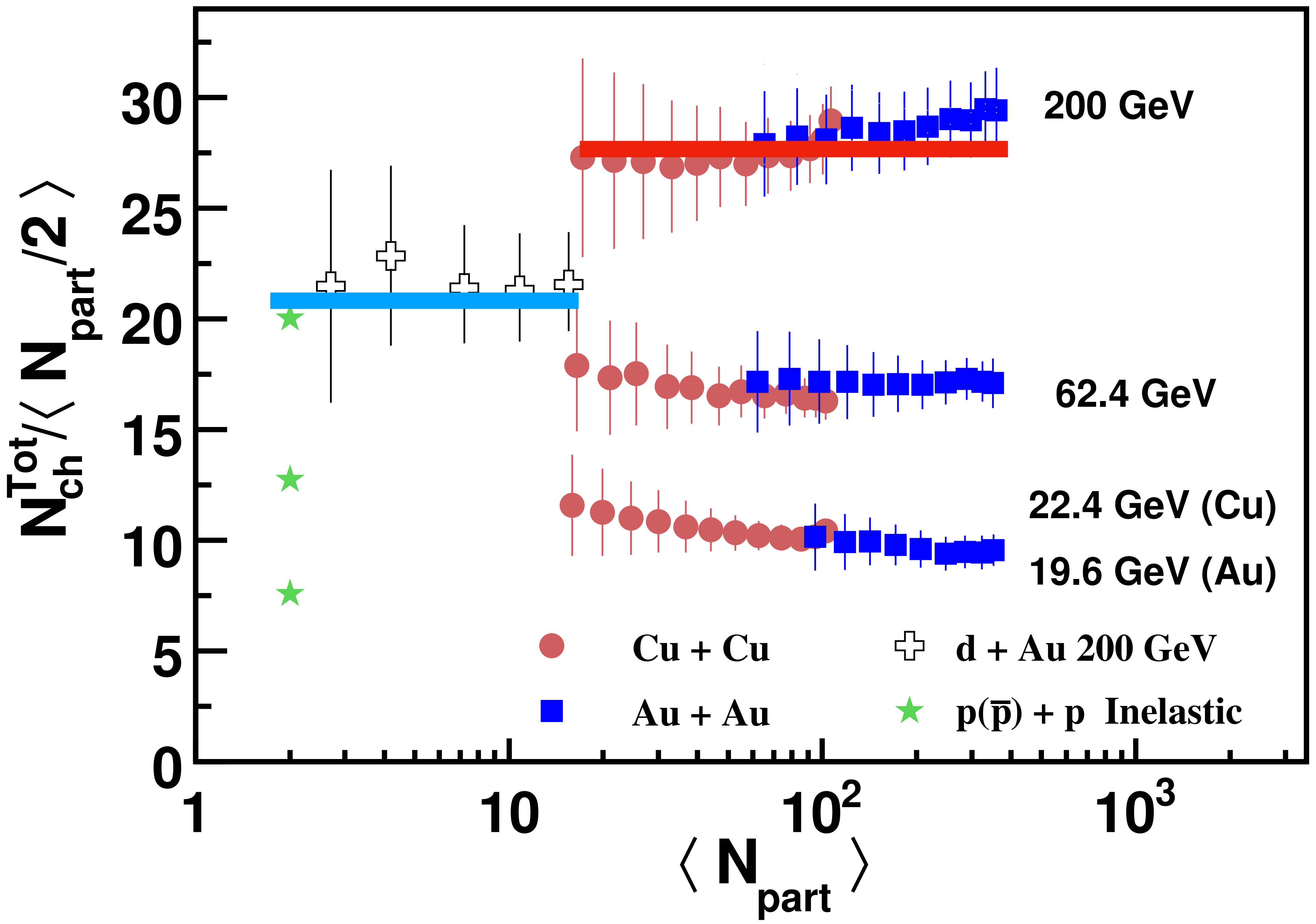
If I still have time, I will tell
you what I worked on recently
in connection to hypothetical critical point

To keep you interested, I start with phenomenology of light/heavy ion collisions



a 20-year old PHOBOS data on multiplcity per participant

there seems to be two horisontal lines on this plot ,

one for light

and one for heavy ions,

independent of centrality

jump at about 15 participants?

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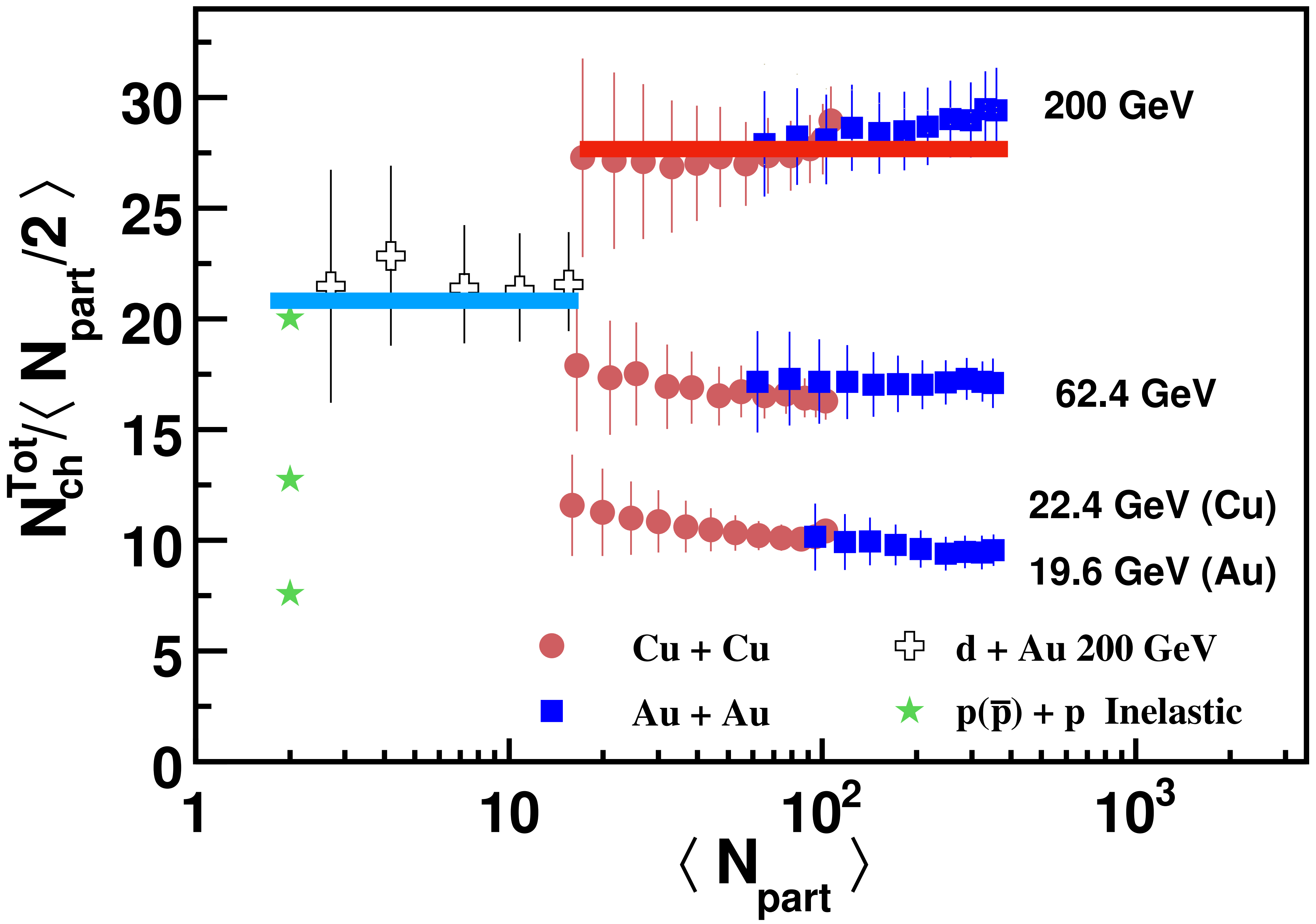

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Is there some sharp transition between two regimes?

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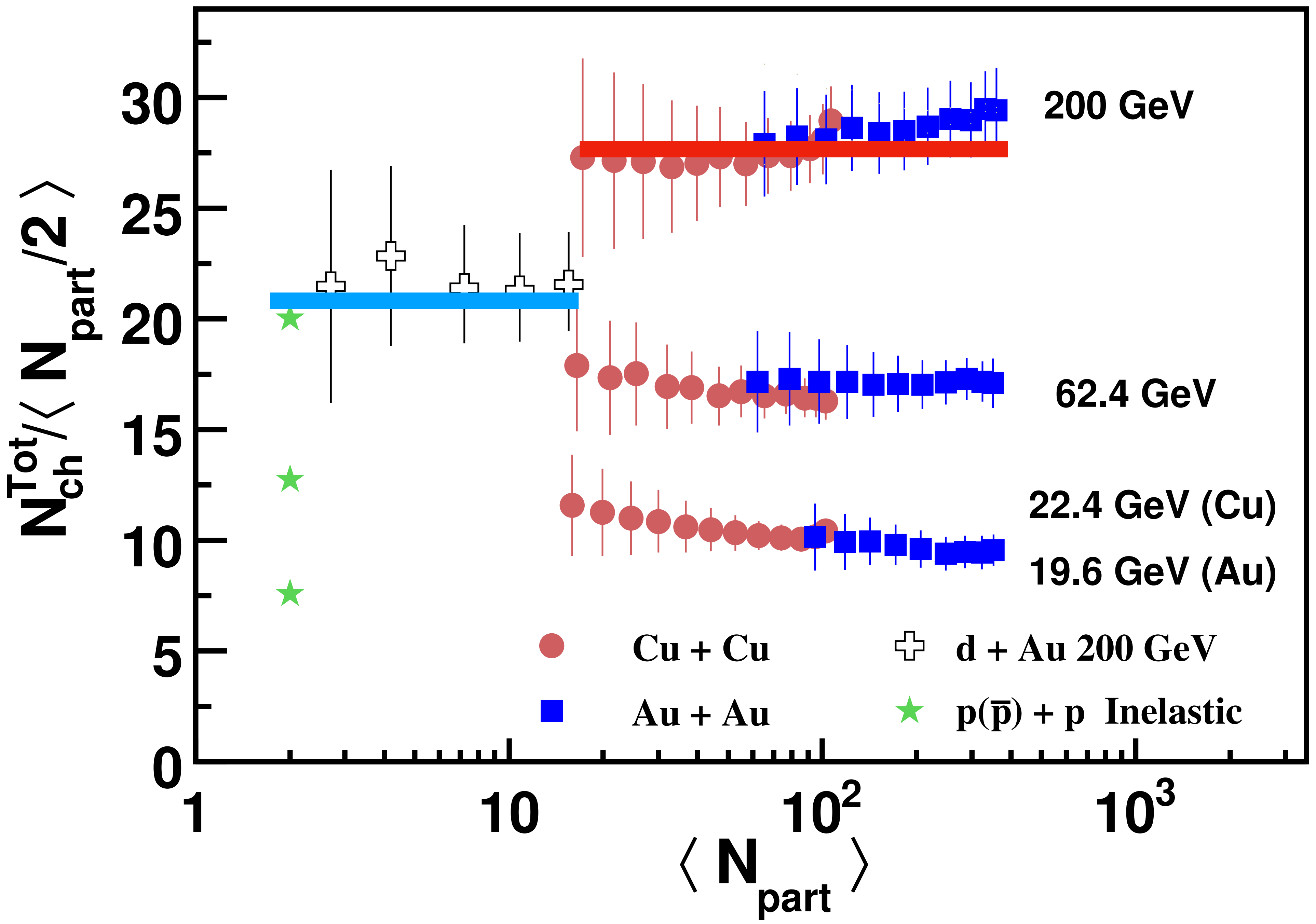

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Is there some sharp transition between two regimes?

Recent results from SHINE:
central Be Be is nearly the same as pp
but already Ar
(atomic weight about 40)
is already close to PbPb
Again, a hint for rapid transition…

arXiv:0805.1551v1 [hep-th] 12 May 2008

Entropy production in collisions of gravitational shock waves and of heavy ions

Steven S. Gubser,[1,*] Silviu S. Pufu,[1,†] and Amos Yarom[2,‡]

By that time it was clear that formation of QGP fireball in holographic models corresponds to formation of black hole out of some falling objects in the "bulk"
e.g. Shu Lin and myself propose falling membrane as a model of thermalization

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Bekenstein

it is inequality
because the surface we find
at time zero, and it may grow later

Here is the setting: a central collision of two relativistic masses (black holes) their field is a gravitational "shock wave"

the flat surface is a boundary where we live

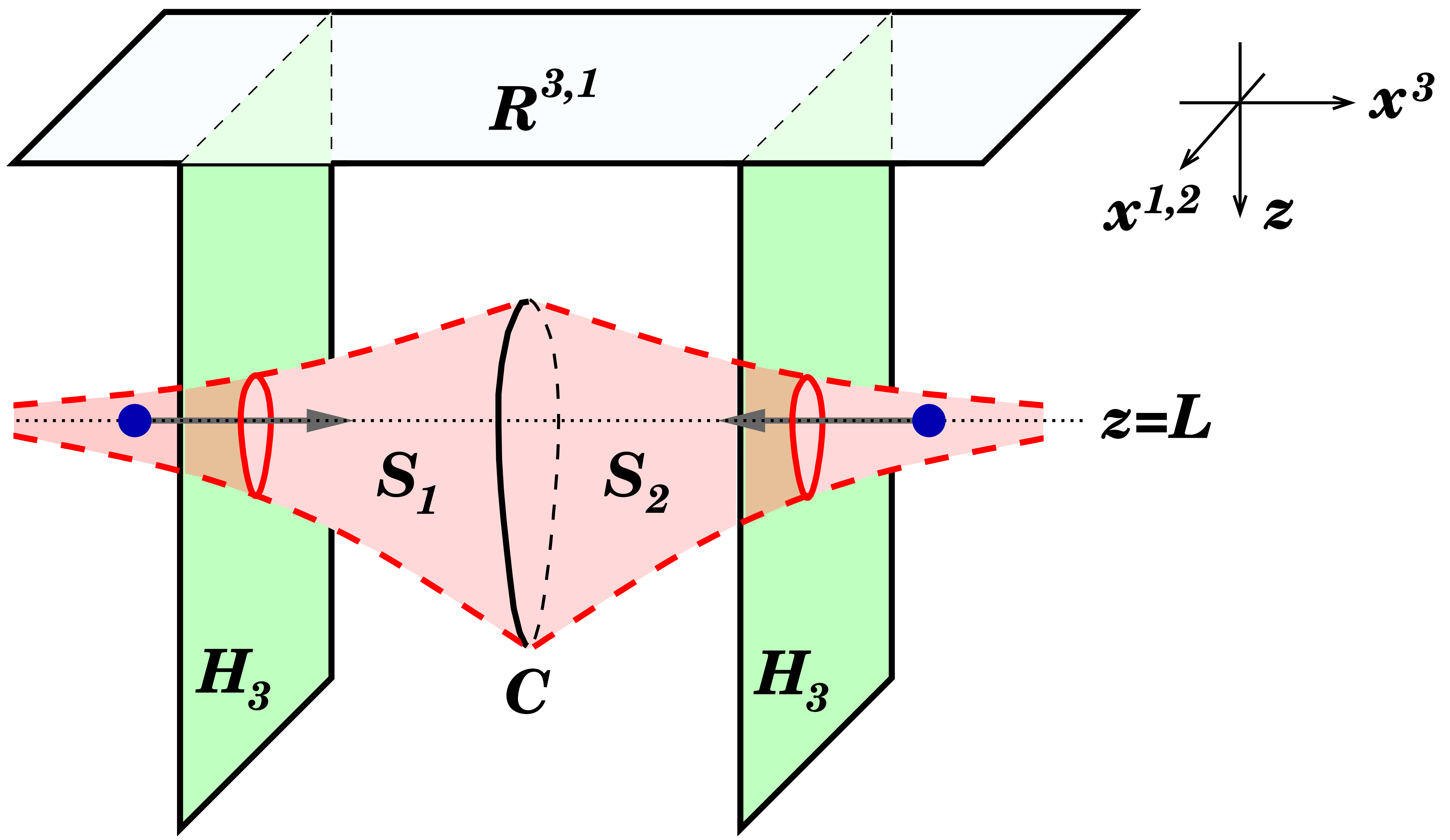


Figure 1: A projection of the marginally trapped surface that we use onto a fixed time slice of the AdS_5 geometry. The size of the trapped surface is controlled by the energy of the massless particles that generate the shock waves. These particles are shown as dark blue dots.

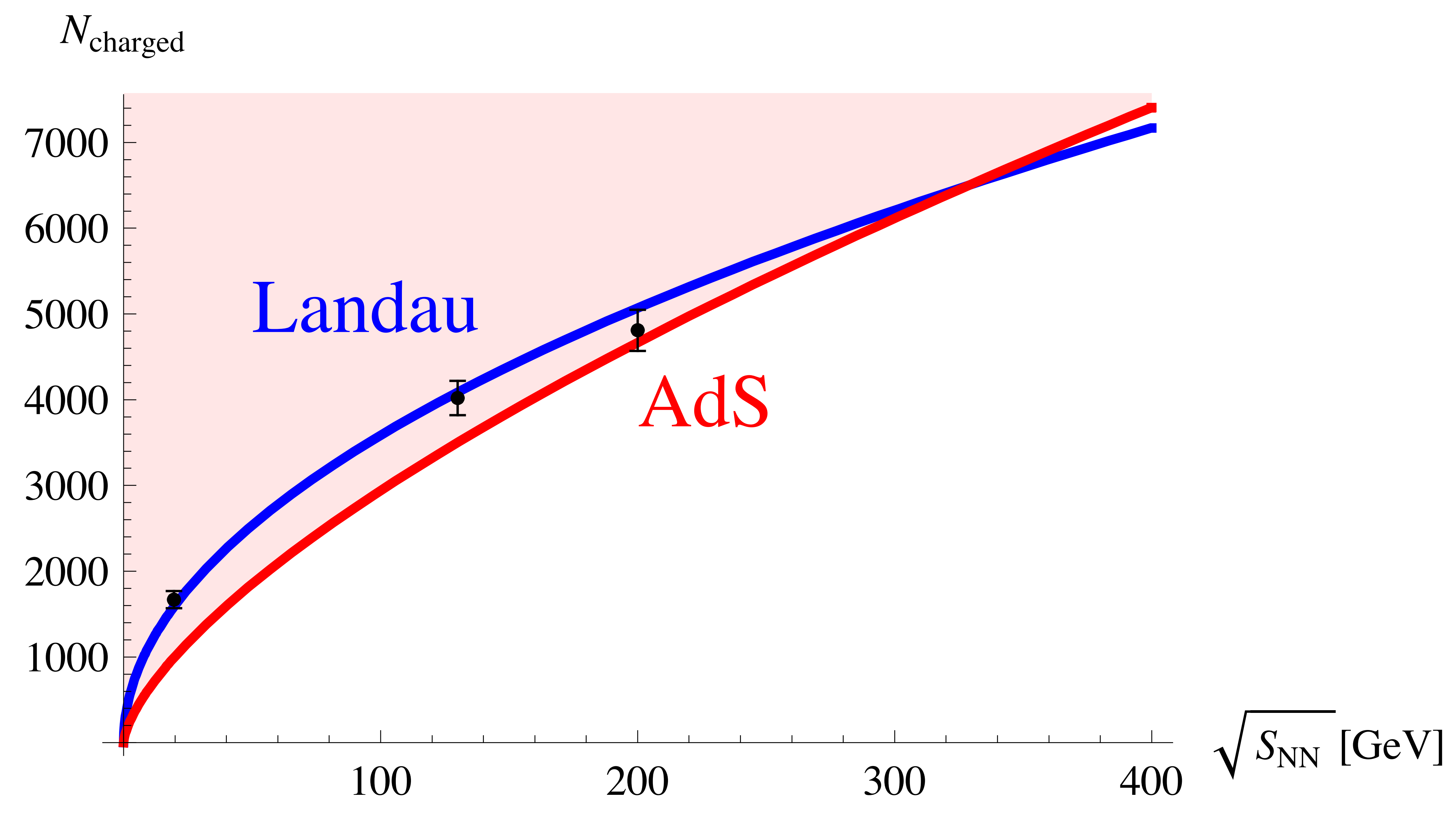
the main result: multiplcity should grow as E(cm)^(2/3)

$$S_{\text{trapped}} \approx \pi \left(\frac{L^3}{G_5}\right)^{1/3} (2EL)^{2/3} .$$

Famout Fermi-Landau initial condition
— the instant equilibration —
gives E(cm)^(1/2) or s^(1/4)
worked better for RHIC,
Gubser et al show

but the model is very schematic…

(it was before LHC)



Grazing Collisions of Gravitational Shock Waves and Entropy Production in Heavy Ion Collision

Shu Lin[1], and Edward Shuryak[2]

we started much more complicated project:
nonzero impact parameter
then trapped surface is not a sphere!
one needs to find it from complicated eqn,
which we turned to integral eqn and
solved it numerically

we found that there is a
critical trapped surface
and at impact parameter
b>bc no such surface exists!
no black hole =
no QGP fireball

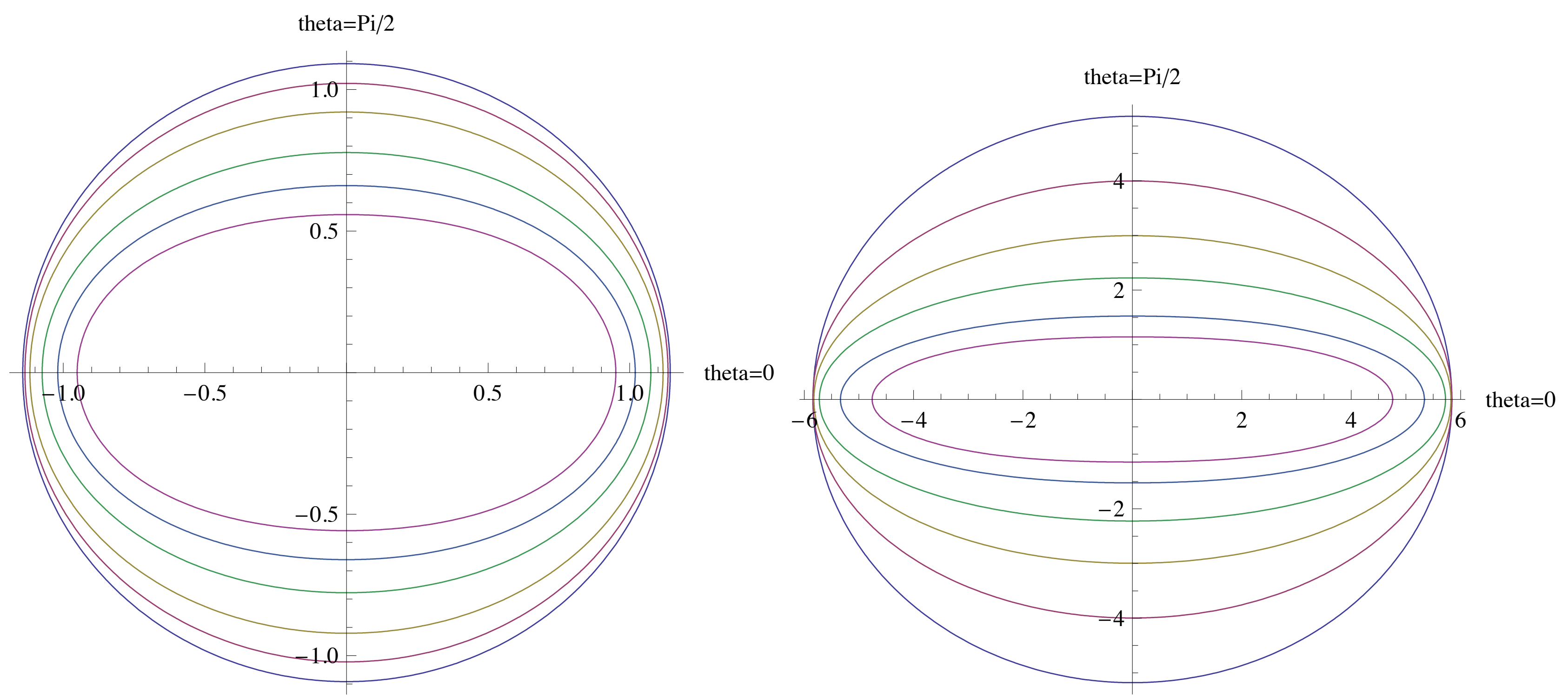


Figure 1: (left)The shapes of $\mathcal{C}$ (the trapped surface at $u = v = 0$) at $\frac{G_5 E}{L^2} = 1$. The impact parameters used in the plot are $0.4L$, $0.6L$, $0.8L$, $1.0L$, $1.1L$, $1.14L$ from the outer to the inner. The innermost shape being the critical trapped surface. (right)The shapes of $\mathcal{C}$ (the trapped surface at $u = v = 0$) at $\frac{G_5 E}{L^2} = 100$. The impact parameters used in the plot are $1.0L$, $2.0L$, $3.0L$, $4.0L$, $5.0L$, $5.3L$ from the outer to the inner. The innermost shape being the critical trapped surface. As collision energy grows, the trapped surface gets elongated in the axis of mismatch.

For the first time ever we managed to do so
BEFORE Gubser et al also did it
in their second paper,

Here is a comparison from
lines are theirs,
the black dots are our numerical solution
as you see, they match perfectly

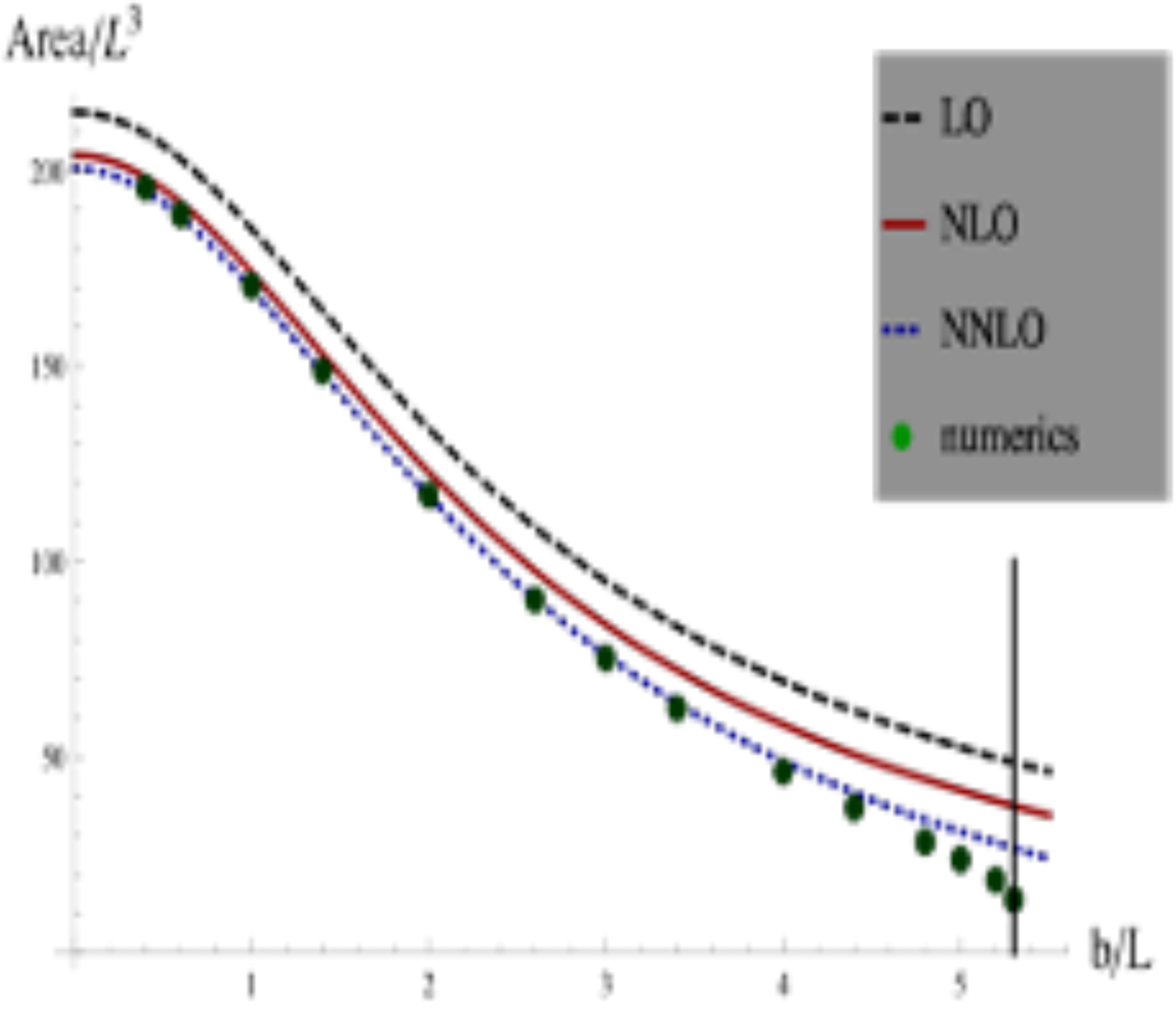


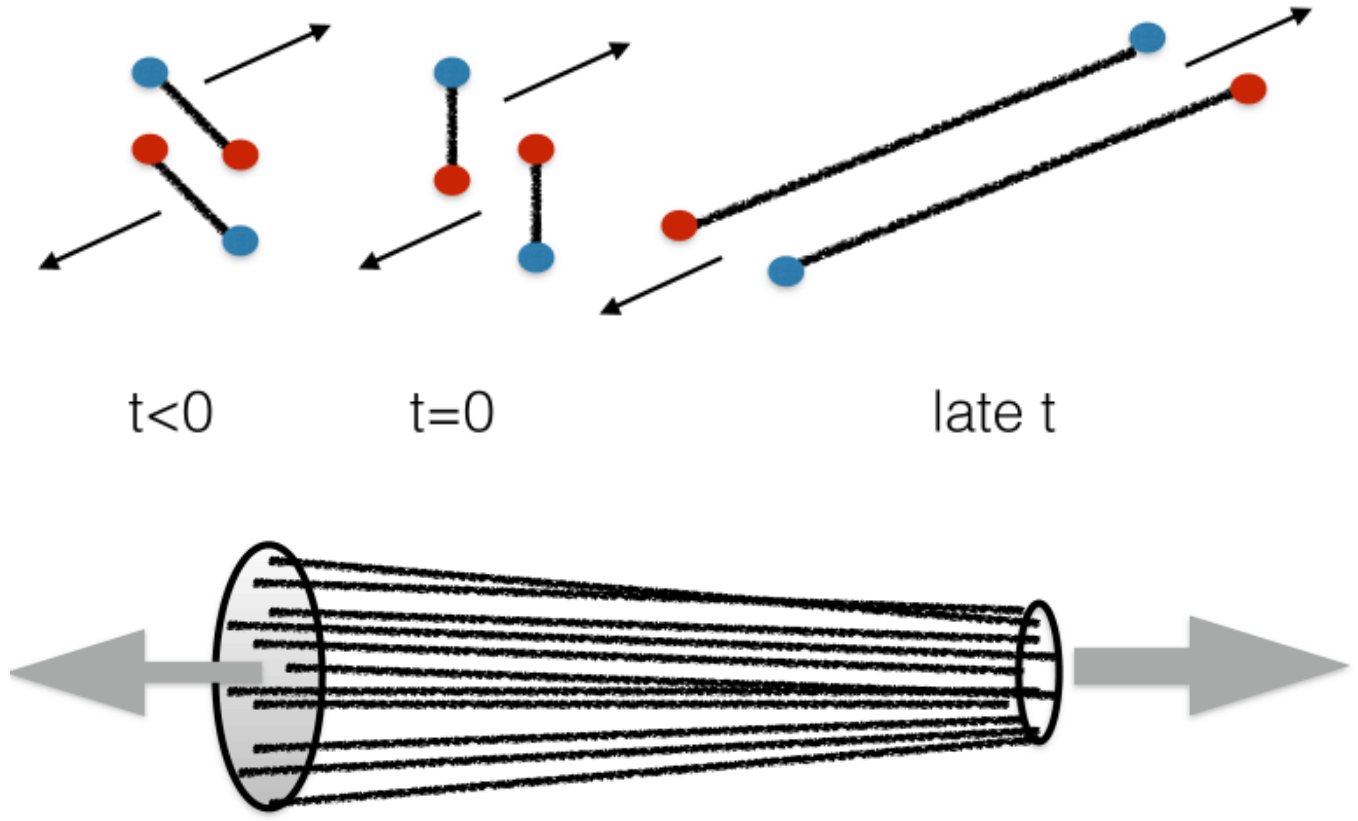
Figure 1: (Color online.) Comparisons between the numerics of [36] and the analytic formula (58). The black dashed curve represents the leading term in (58); the solid red curve corresponds to the first two terms in (58); the dotted blue curve represents the expression (58), which is correct up to a term of order $\mathcal{O}(1/\zeta^2)$; the green dots represent the numerical evaluations used in figure 3 of [36]; lastly, the vertical green line marks the place where, according to [36], the maximum impact parameter b_{max}/L occurs. We thank S. Lin and E. Shuryak for providing us with the results of their numerical evaluations.

It is the area (=entropy=multiplcity)
versus the impact parameter
the vertical line is the location
of the critical value b_c

very peripheral collisions do
NOT produce a fireball

Collective interaction of QCD strings and early stages of high multiplicity pA collisions

Tigran Kalaydzhyan and Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA



basic mechanism of production of QCD strings
(also called flux tubes)

multistring configuration after collision,
(spaghetti)
when strings are extended longitudinally
Lund model (Pythia etc) true for pp and light nuclei assumes string are broken INDEPENDENTLY
This cannot be true of the number is large…

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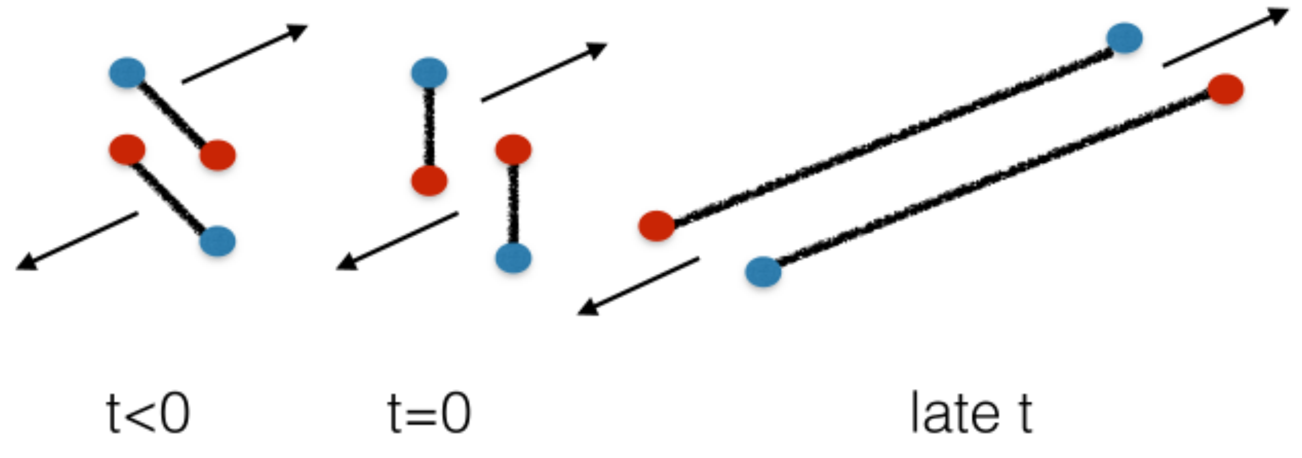

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Original discussion was for pPb collisions at LHC
for which collective explosion similar to PbPb
was observed (radial and elliptic flows)

Note that its center bin corresponds to collision with about 16 nuclons
thus we speak about > 30 strings
the same applies to central collisions of light nuclei

QCD flux tubes were studied on the lattice

Classification of flux tube in superconductor:
(Abrikosov)
type I are attractive at large distances due to which they are glued together to macroscopic domain in which there is no superconductivity
Type II REPEL EACH OTHER
and form a lattice
(therefore used in superconducting magnets)

The QCD vacuum is weak Type I

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here a group in Japan studied various operators in conjunction to the flux tube
here is depletion of quark chiral condensate
the curve is our formula for m(sigma)=600 MeV like in nuclear forces

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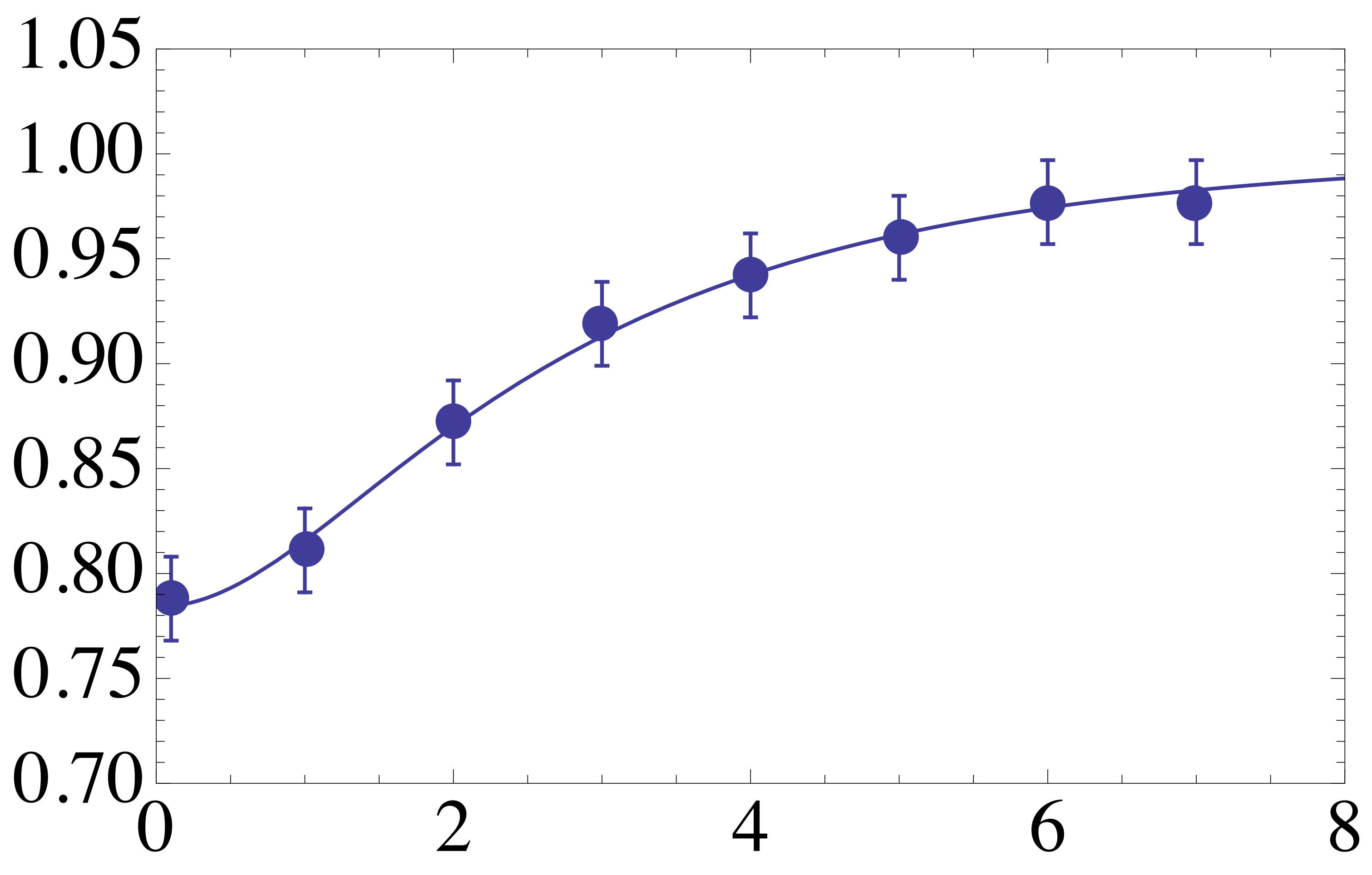

FIG. 3: (Color online) Normalized chiral condensate as a function of the radial coordinate transverse to the QCD string. Points are from the lattice data [23]. The curve is expression (7) with $C = 0.26$ and $s_{string} = 0.176\,\text{fm}$.

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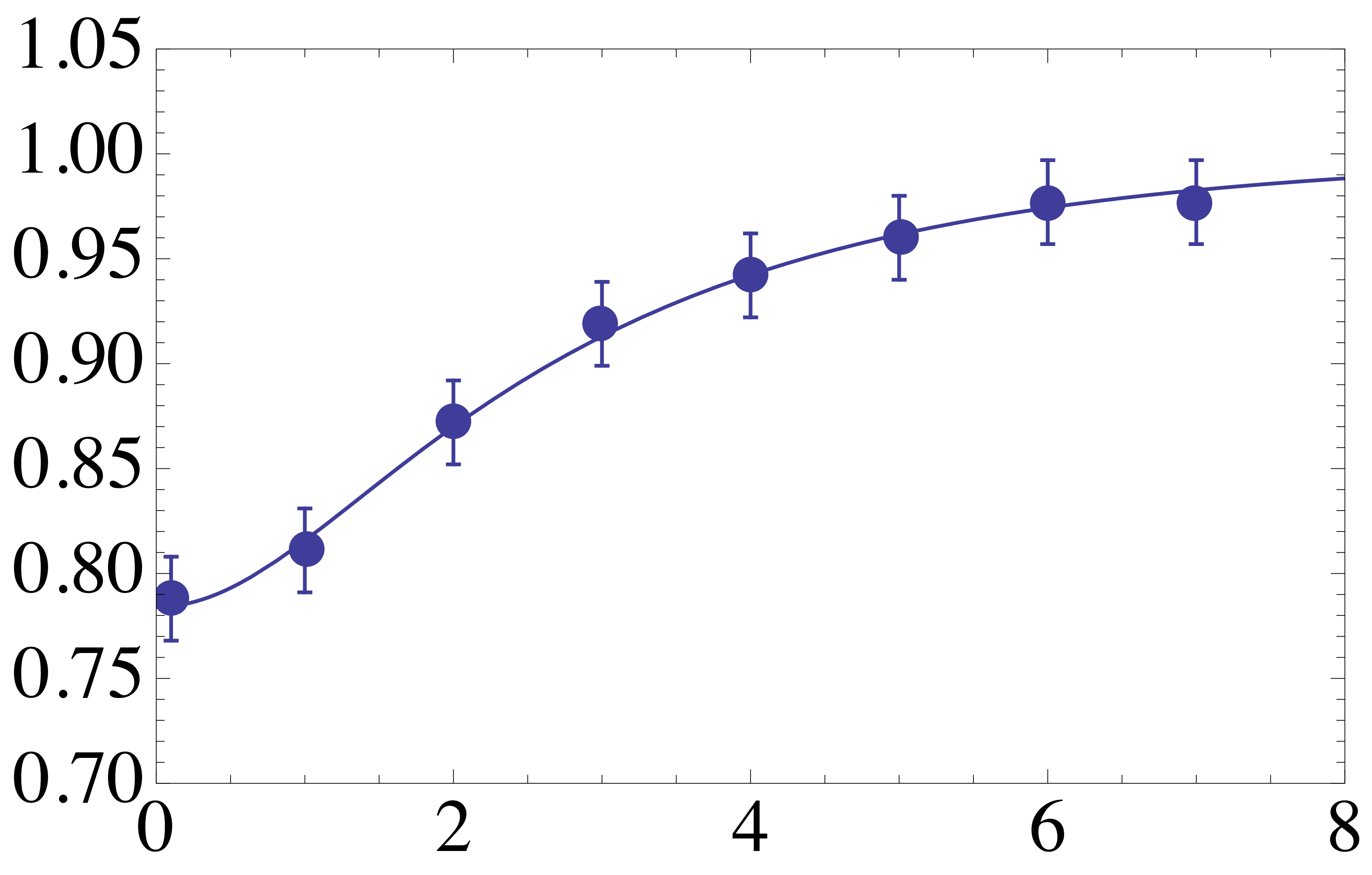

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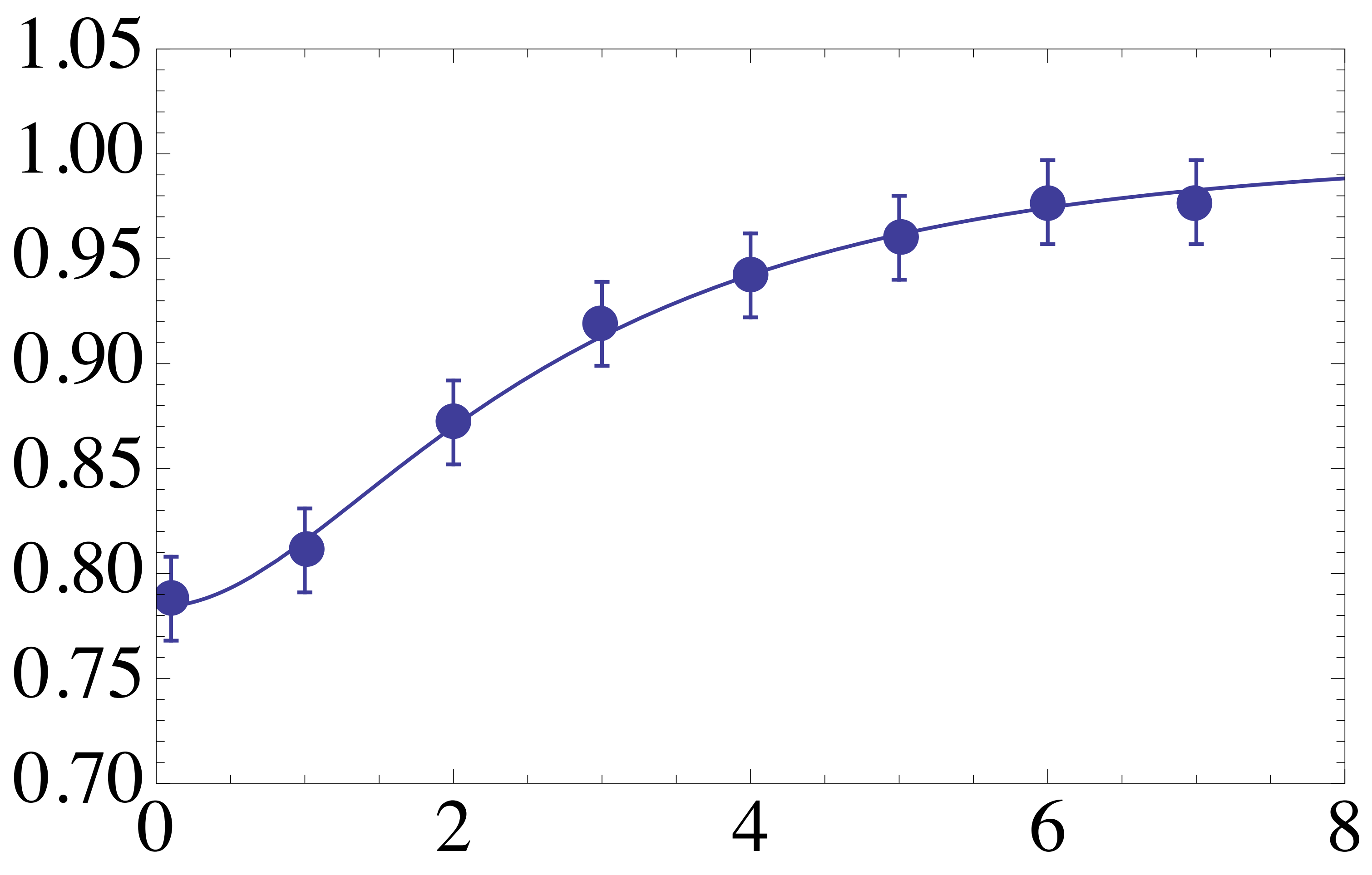

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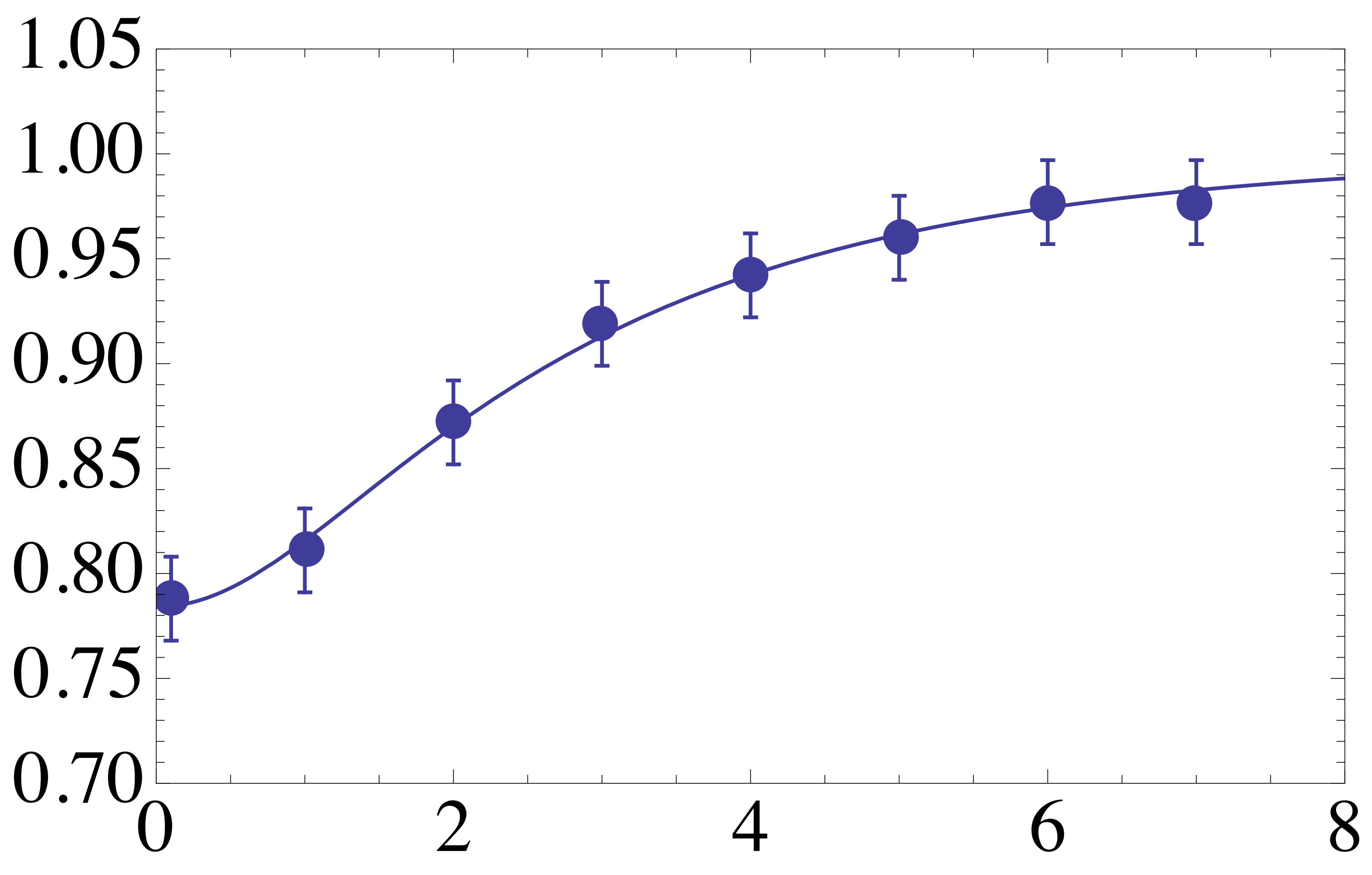

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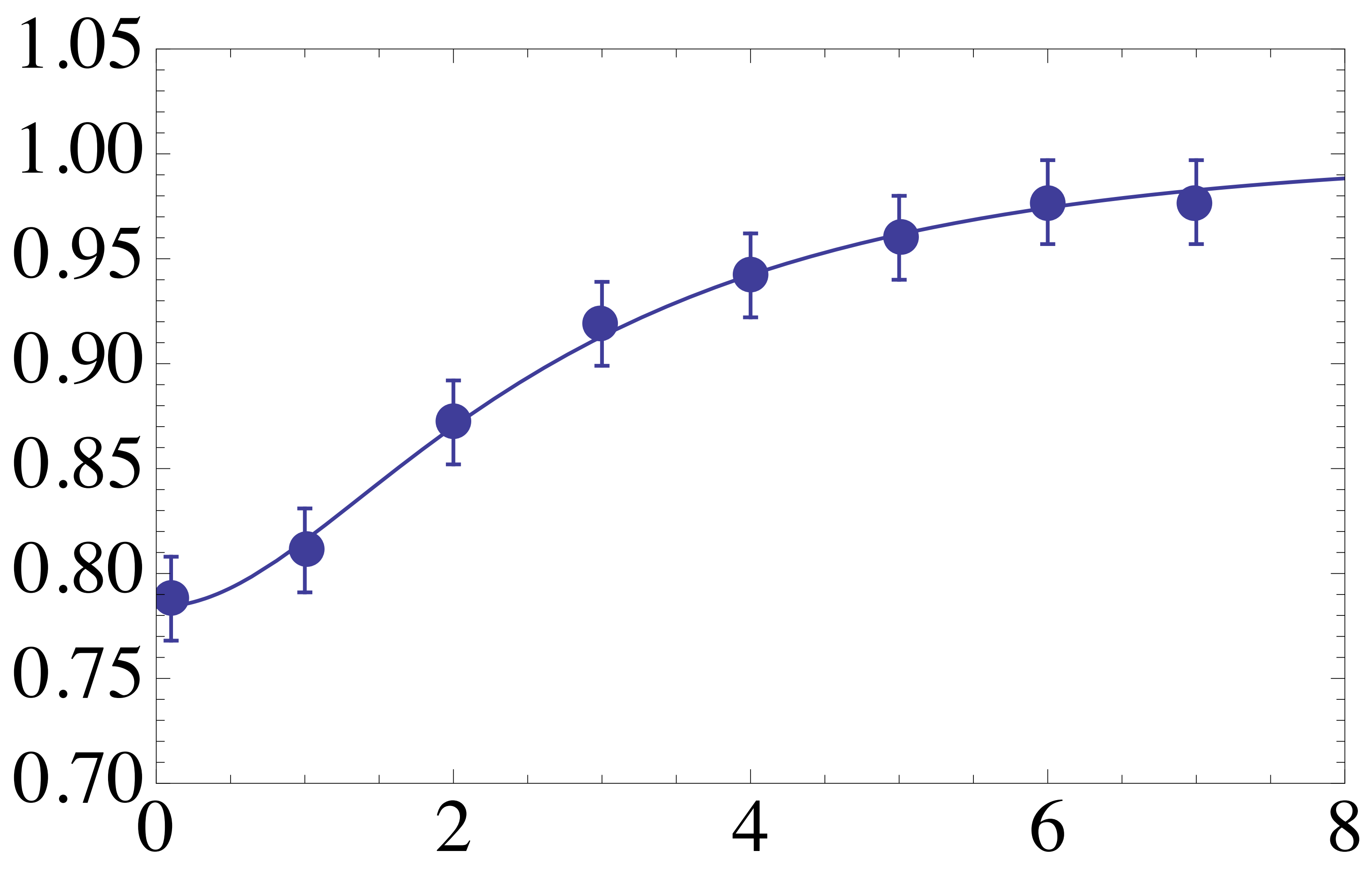

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A SCALAR EXCHGE IS ATTRACTIVE AND CANNOT BE SCREENED correctly neglected in situations for which the Lund model was originally invented – when only O(1) strings are created , but not for spaghetti!

MOLECULAR DYNAMICS STUDY

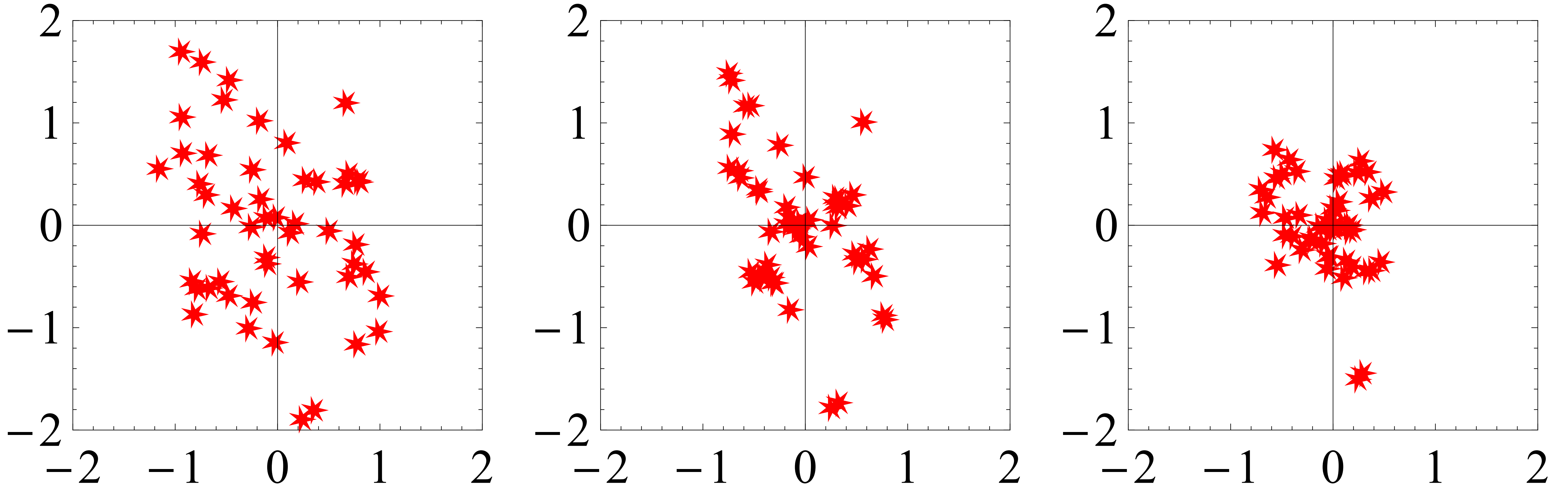

Table 1

Example of changing transverse positions of the 50 string set: the plots correspond to initial configuration evolved to times τ = 0.1, 0.5 and 1 fm/c

the formation of chirally restored fireball

In the white region quarks become massless
which means they have full
pressure like in QGP
AND THERE IS AN EXPLOSION

**WE ESTIMATED
THAT THE EFFECT
GETS IMPORTANT FOR
N STRING > 30**

**(each pair of wounded nucleons
mean 2 strings)**

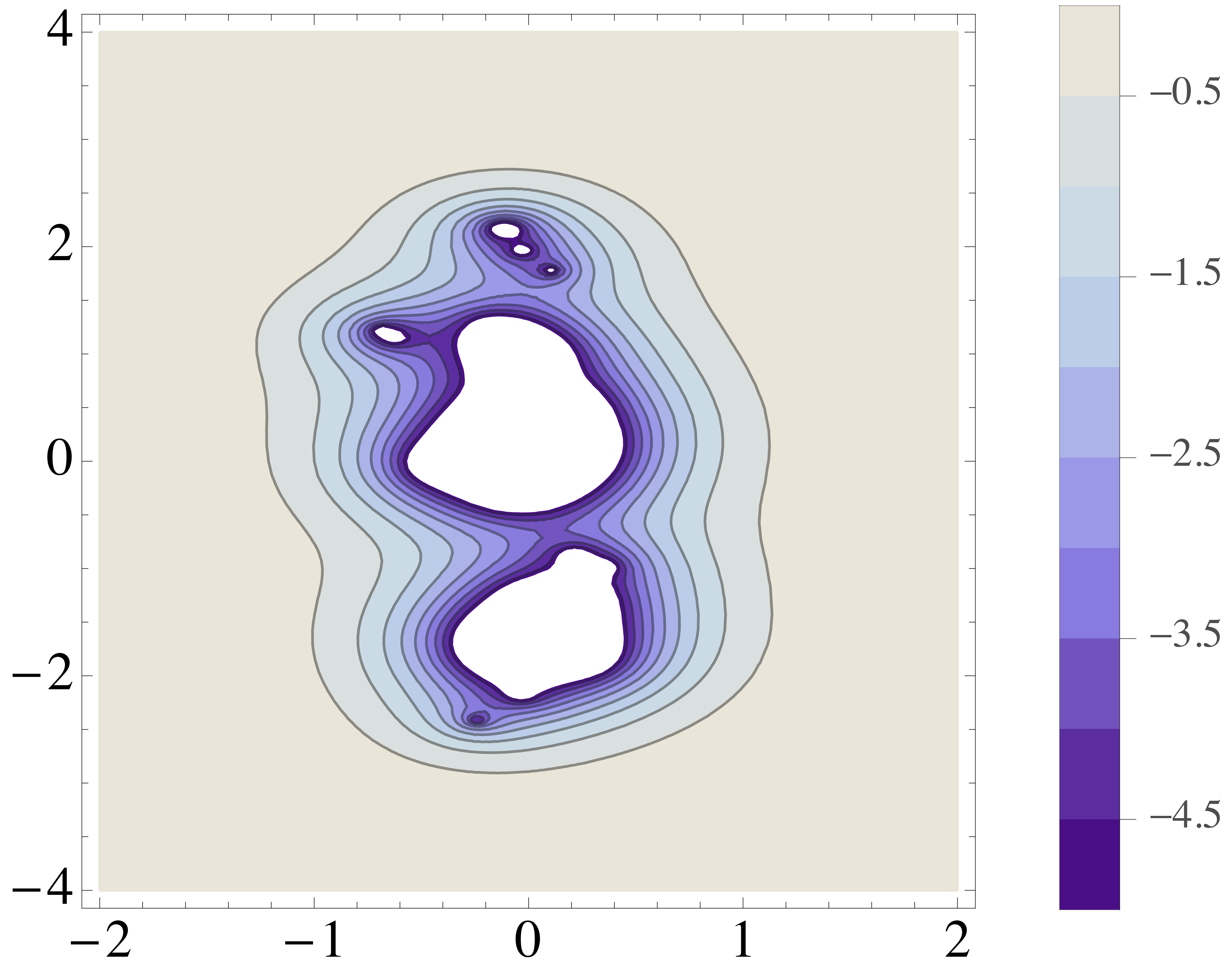

FIG. 10: (Color online) Instantaneous collective potential (in units of $2g_N\sigma_T$) for an AA configuration with $b = 11\,\mathrm{fm}$, $g_N\sigma_T = 0.2$, $N_s = 50$ at the moment in time $\tau = 1\,\mathrm{fm}/c$. White regions correspond to the chirally restored phase.

Collective String Interactions in AdS/QCD and High Multiplicity pA Collisions

Ioannis Iatrakis,* Adith Ramamurti,† and Edward Shuryak‡

to calculate string interactions one needs to understand one of the most diffucult subject in hadronic spectroscopy meson-glueball mixing in scalar 0++ channel

without mixing, strings interact only by glueball exchange, and the lightest scalar glueball has mass of about 1.6 GeV

the mass of lightest scalar meson sigma is only 0.4-0.6 GeV

sigma is the crucial element for nuclear attractive force and its binding

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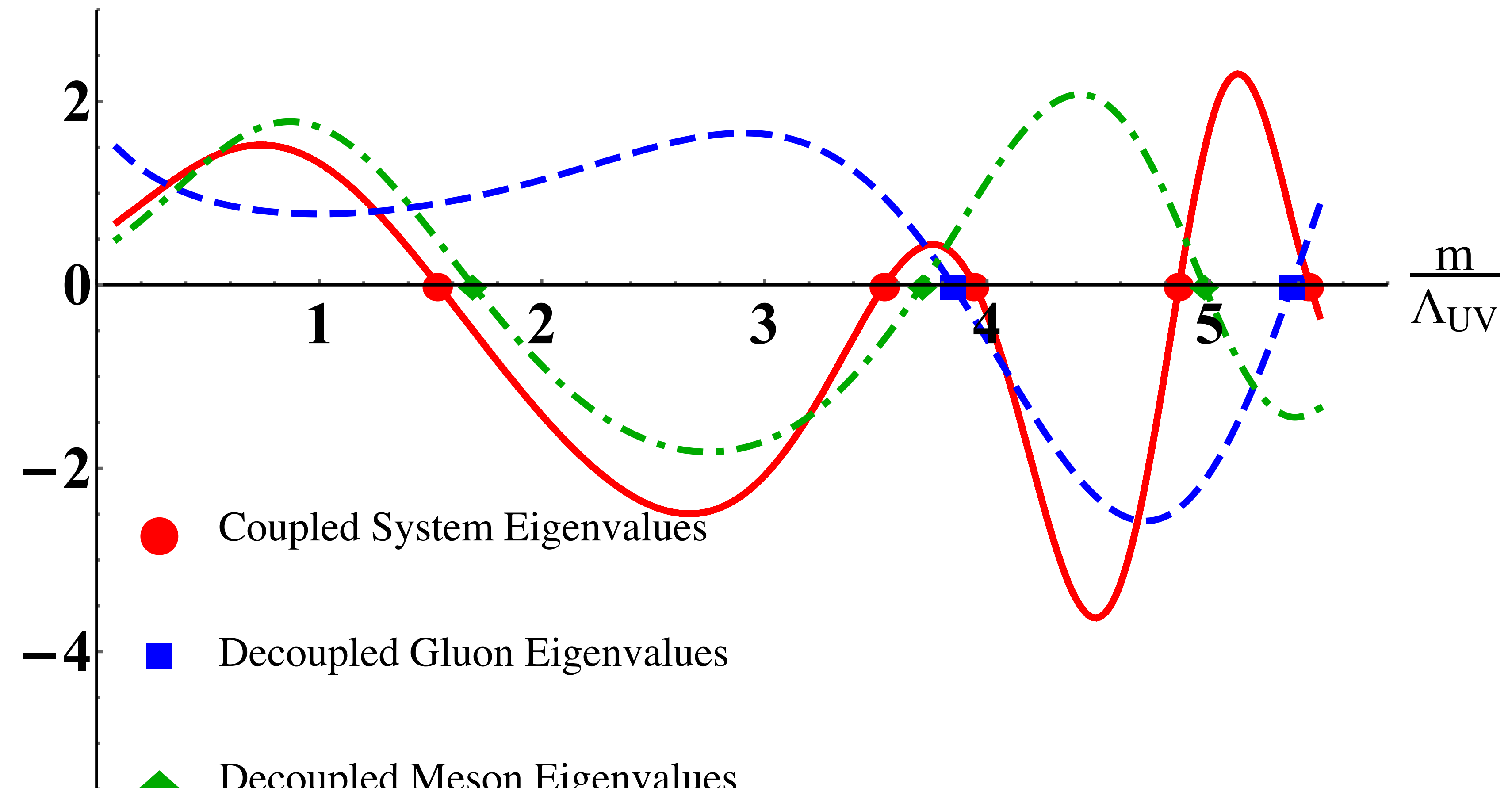

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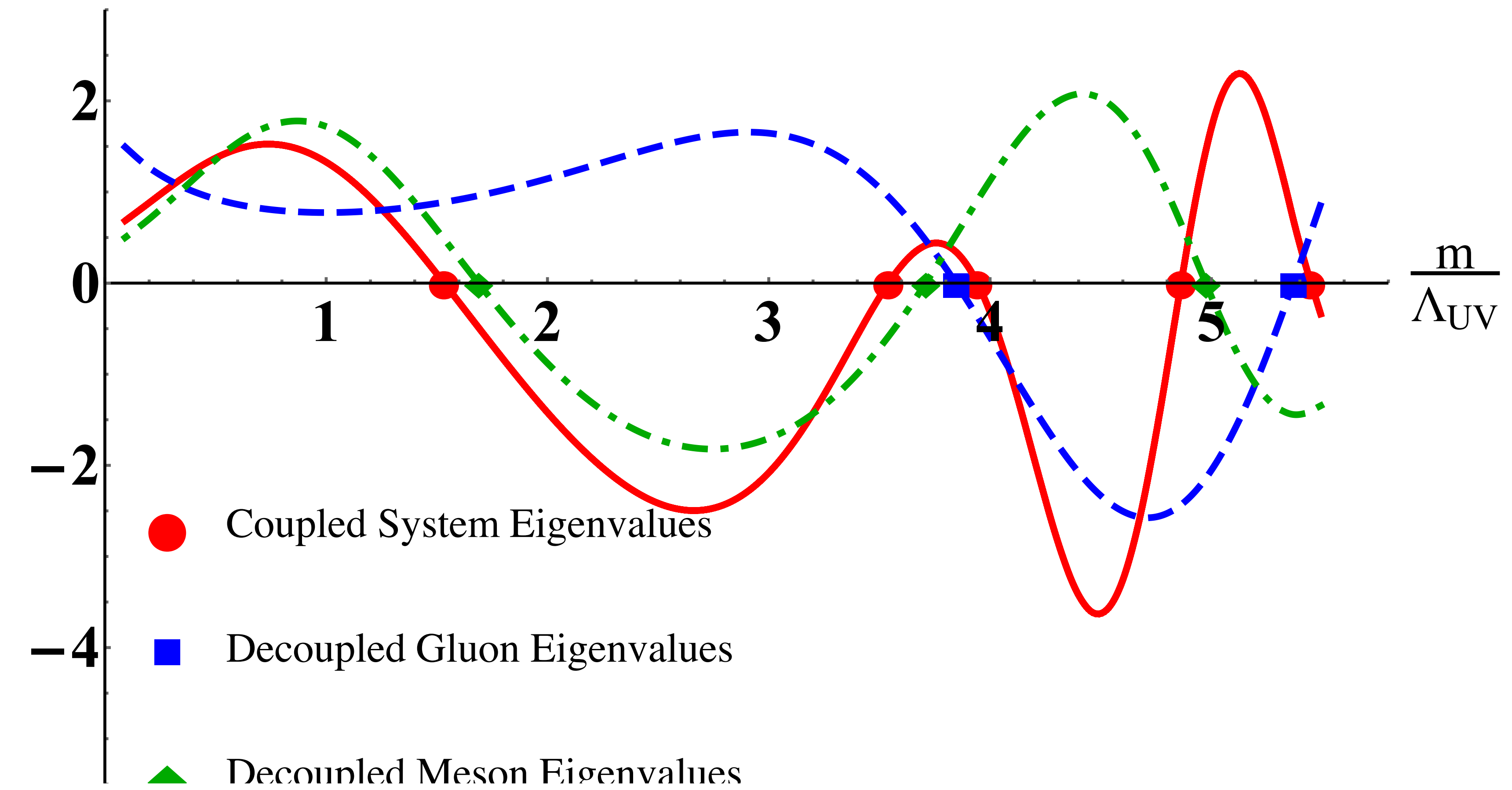

effective model AdS/QCD WAS DEVELOPED BY Kiritsis et al in great details we had all the parameters, and just calculated the mixing of scalars

the results agreed with lattice finding of the coupling

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arXiv:1503.04759v2 [hep-ph] 4 Aug 2015

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snapshots of string in x-z plane: going to larger z is falling toward AdS center its hologram means that strings get fatter with time! the factor is so big that it appears as a fireball at z=0 (our world) arXiv:1503.04759v2 [hep-ph] 4 Aug 2015

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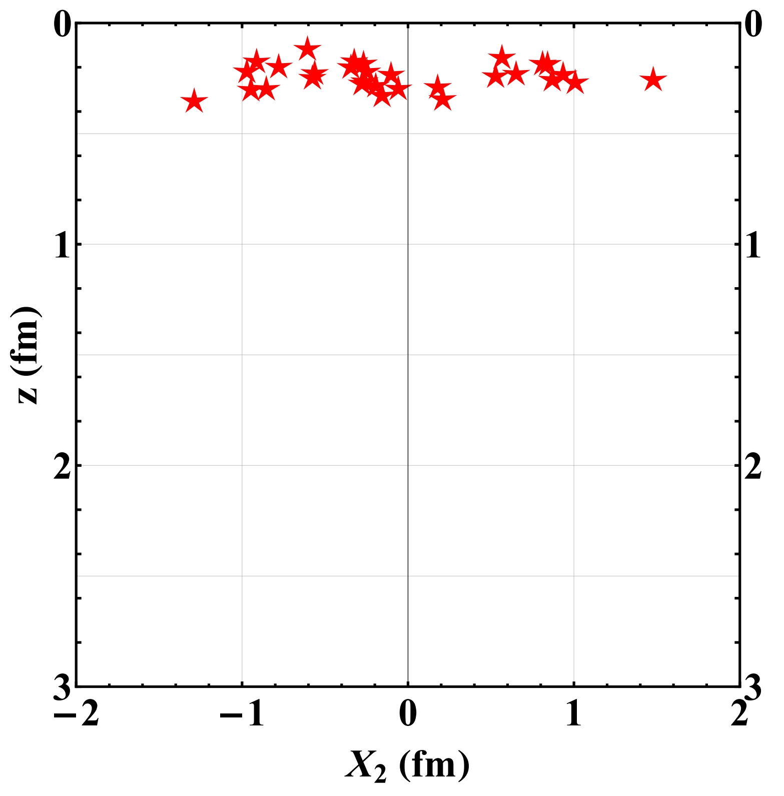

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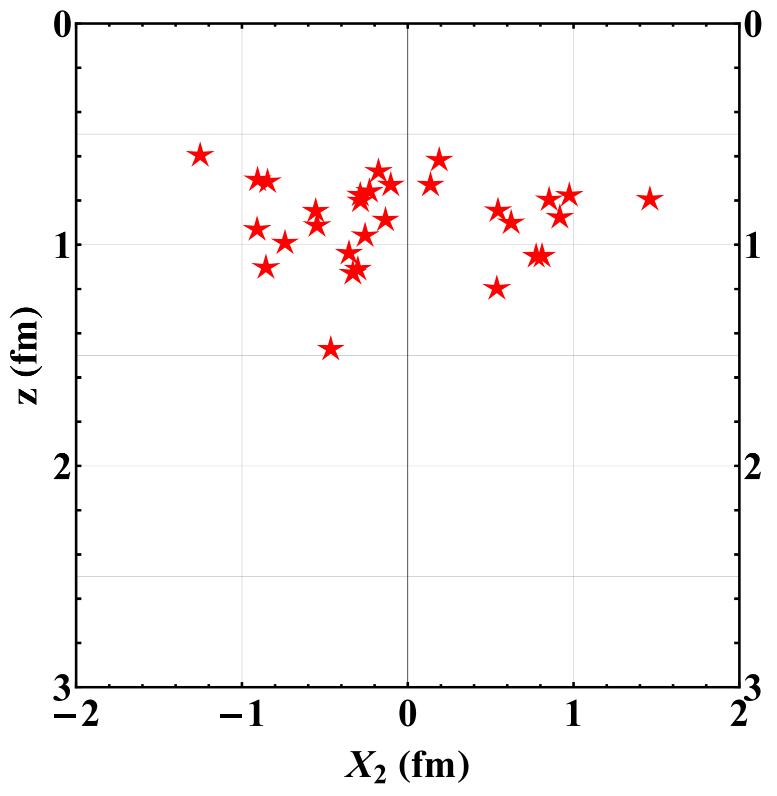

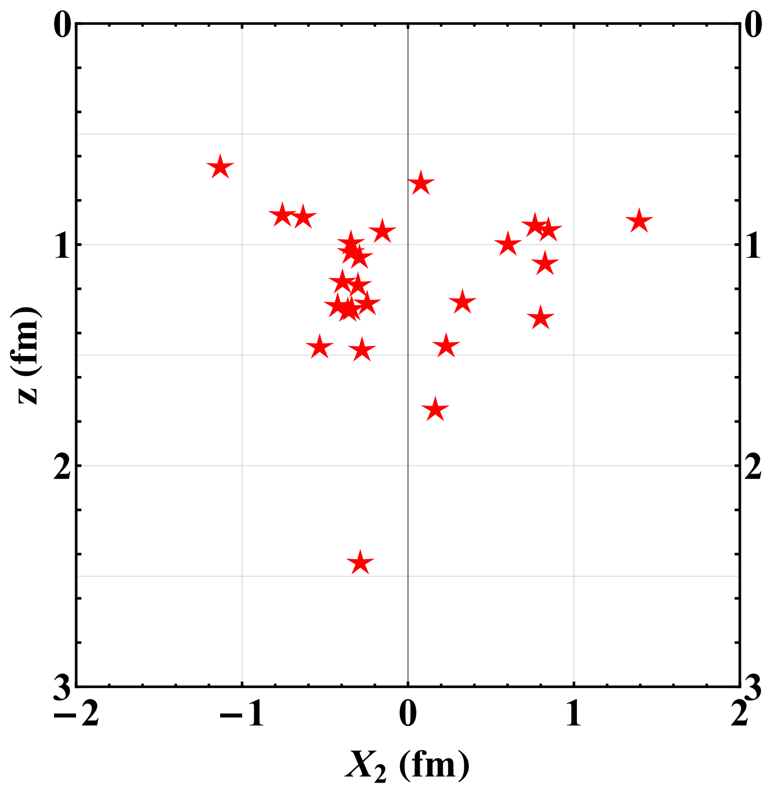

Many-body forces and nucleon clustering near the QCD critical point

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ES and J. M. Torres-Rincon, Phys. Rev. C100, 024903 (2019), arXiv:1805.04444 [hep-ph].

ES and J. M. Torres-Rincon, Phys. Rev. C101, 034914 (2020), arXiv:1910.08119 [nucl-th].

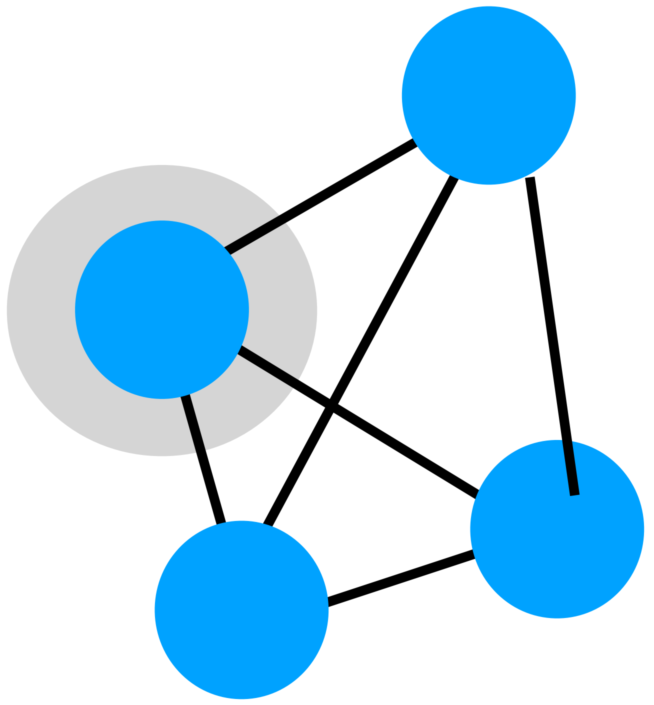
D. DeMartini and ES (2020), arXiv:2007.04863 [nucl-th].

Many-body forces and nucleon clustering near the QCD critical point D. DeMartini and E. Shuryak, e-Print: 2010.02785

•The main idea of this work:

Suppose the CP indeed exists, and is located in the part of the phase diagram near the freezeout line of BES program collisions. Furthermore, while scanning this line, for some specific beam energy one happens to be in a state in which the correlation length reaches a value ξmax ~ 1.5-2fm. What observables are sensitive to such scale of ξ?

$\xi_{min} \sim 1/m_\sigma \sim 0.4\, fm$



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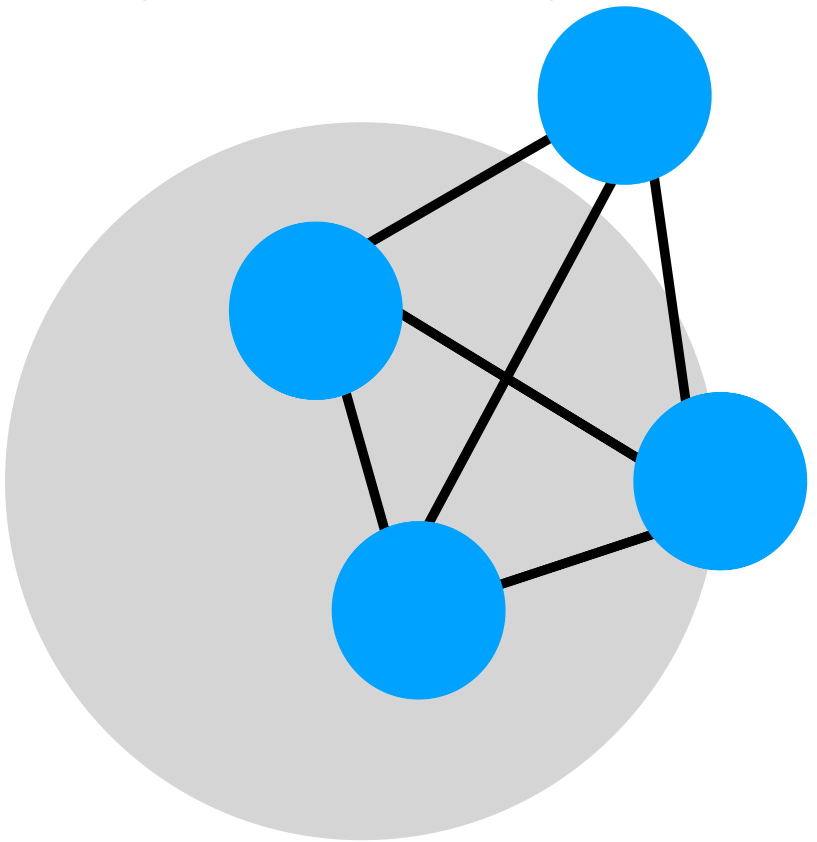

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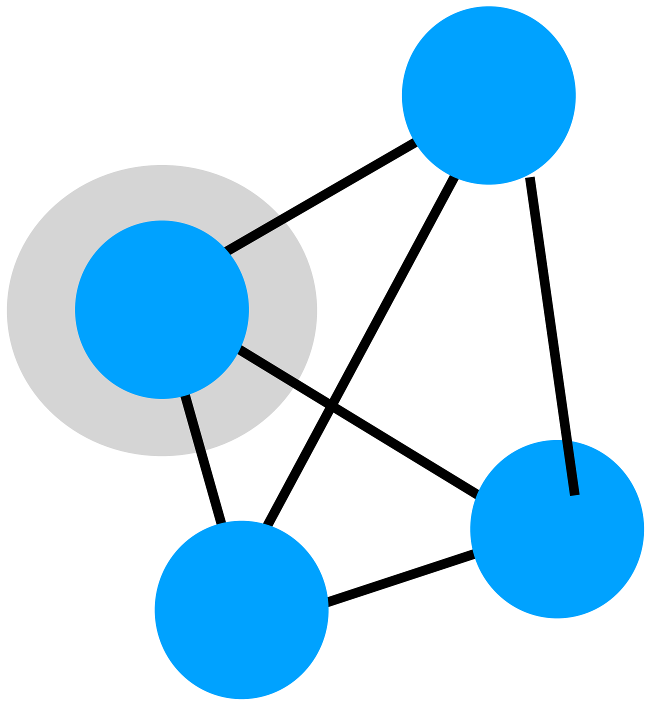

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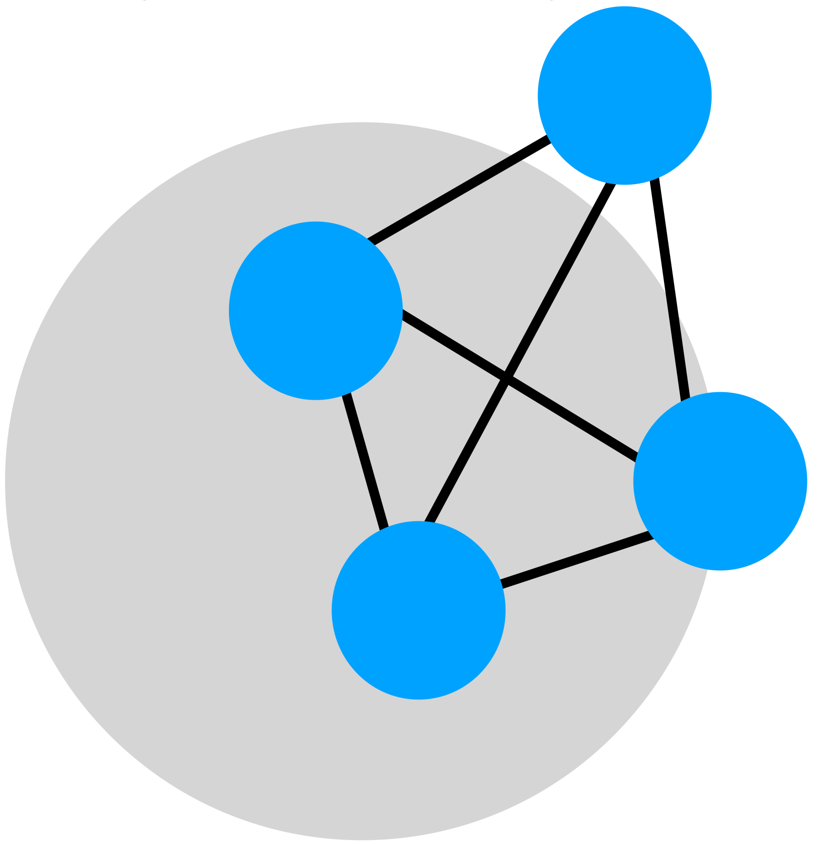

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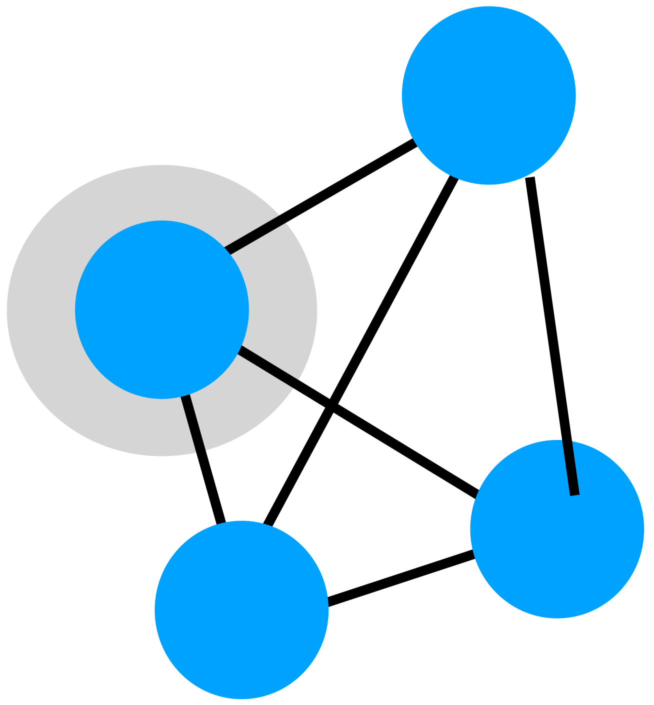

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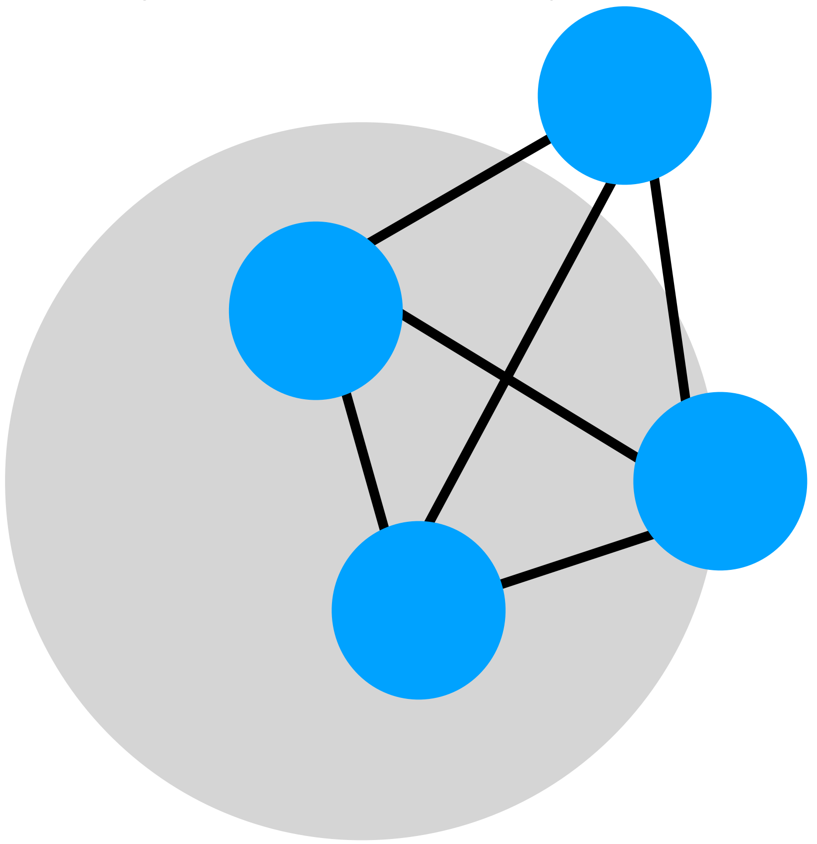

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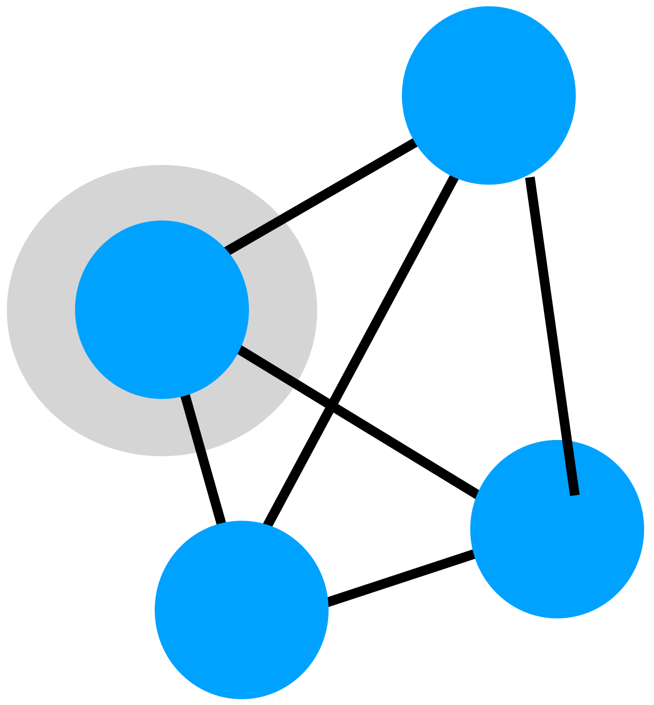

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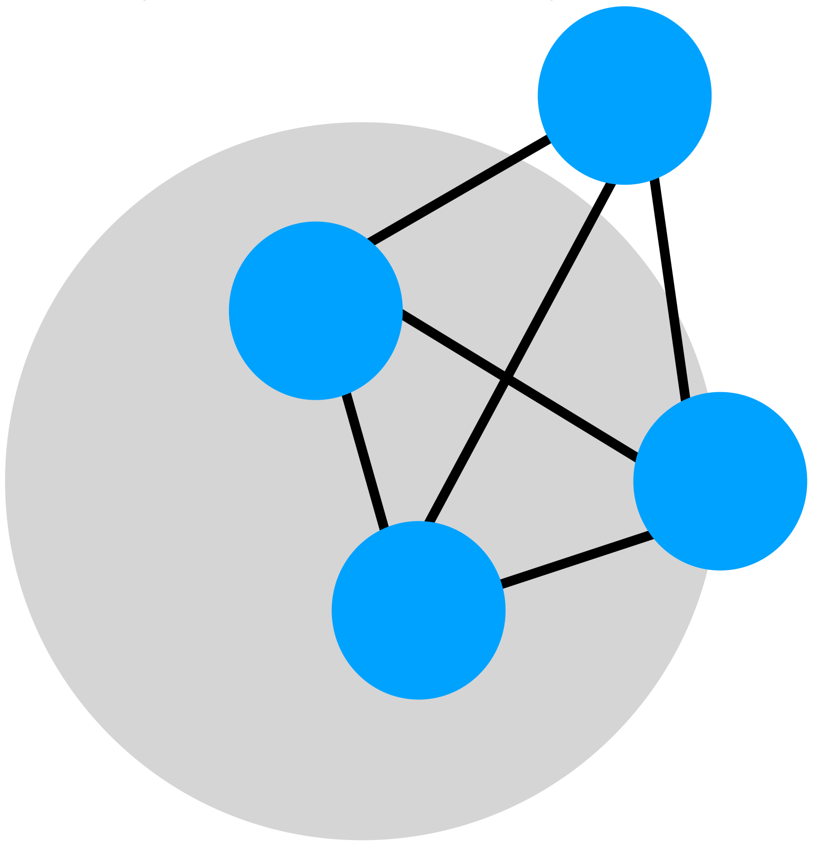

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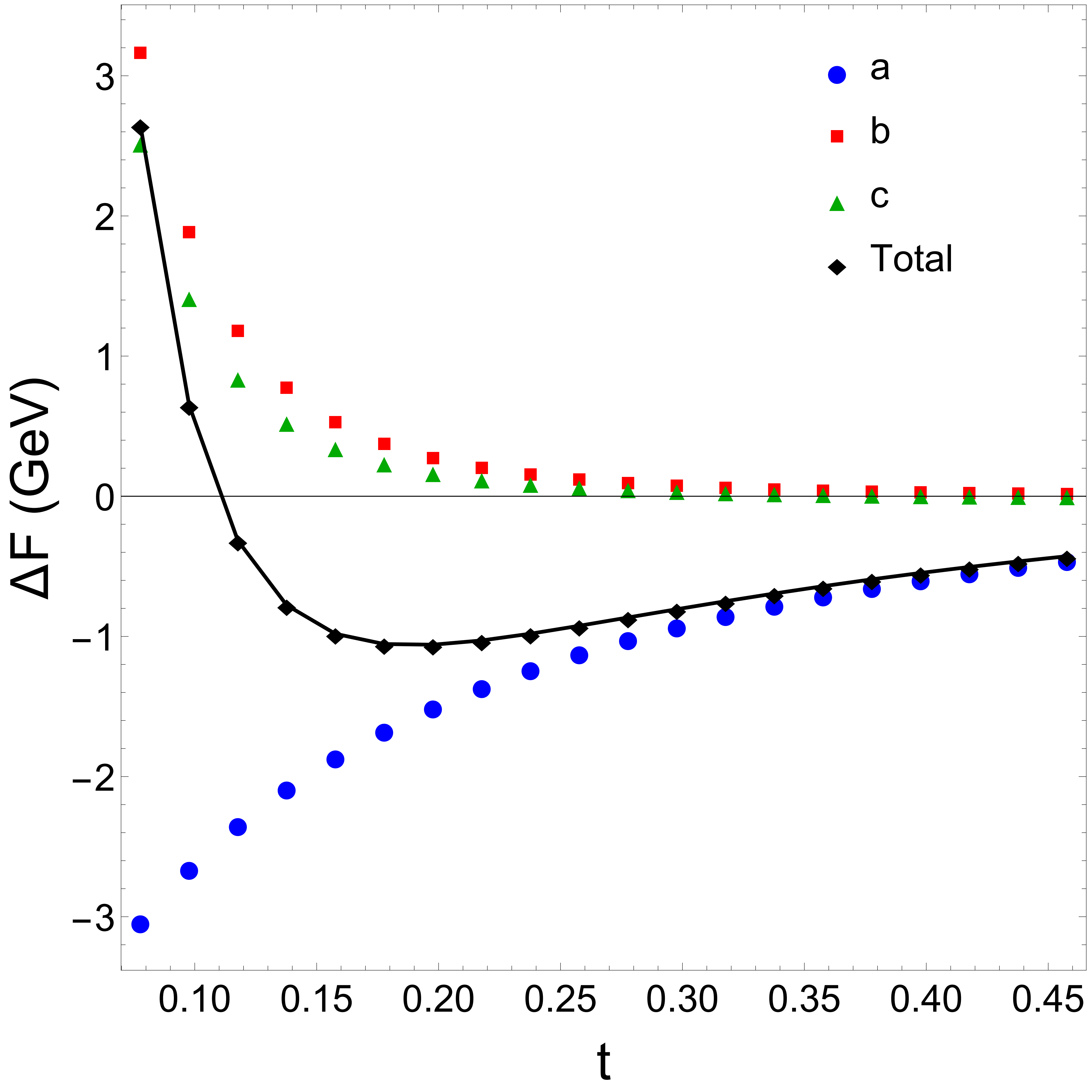
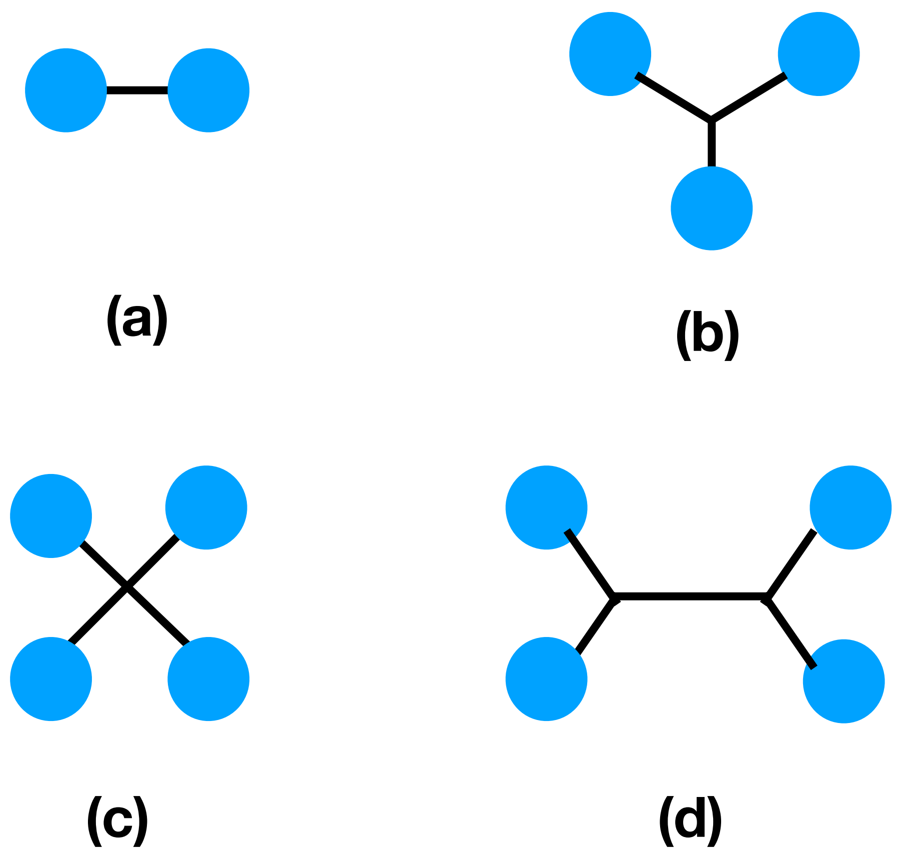
Pre-clustering of nucleons create objects of the right scale ! Their energy — and therefore production yield — is very sensitive to correlation length

As we will show, the interplay of attractive binary And repulsive manybody forces Will lead to very non-monotonous signal

Energy of 4-N cluster
rho=2 fm
t=T/Tc-1



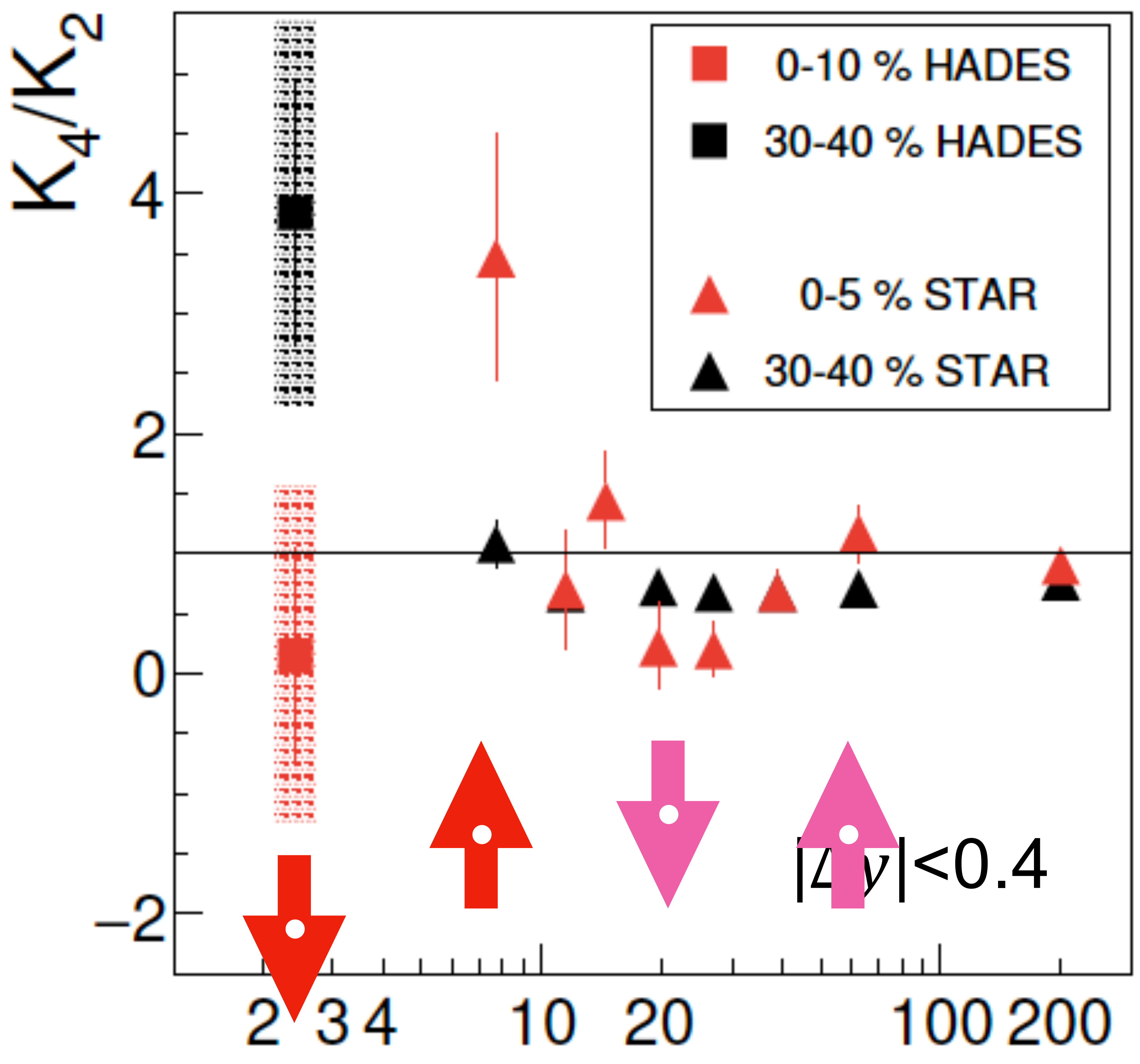
$$V = -\frac{4\cdot 3}{2}\frac{g_c^2}{4\pi}\frac{exp(-r_{ij}/\xi)}{r_{ij}} + 4\cdot 3!\lambda_3(\frac{g_c}{4\pi})^3 V_b$$
$$+4!\lambda_4(\frac{g_c}{4\pi})^4 V_c - 4!\frac{\lambda_3^2}{8\pi}(\frac{g_c}{4\pi})^4 V_d$$



Repulsive three and four
Body forces overcome
Attraction near CP
and kill clustering

•Let us now look at experimental **kurtosis**

•Older STAR data have shown large effect



Two dips for central bins
large at 2 and smaller at 20 GeV?
Errors still large => BESII

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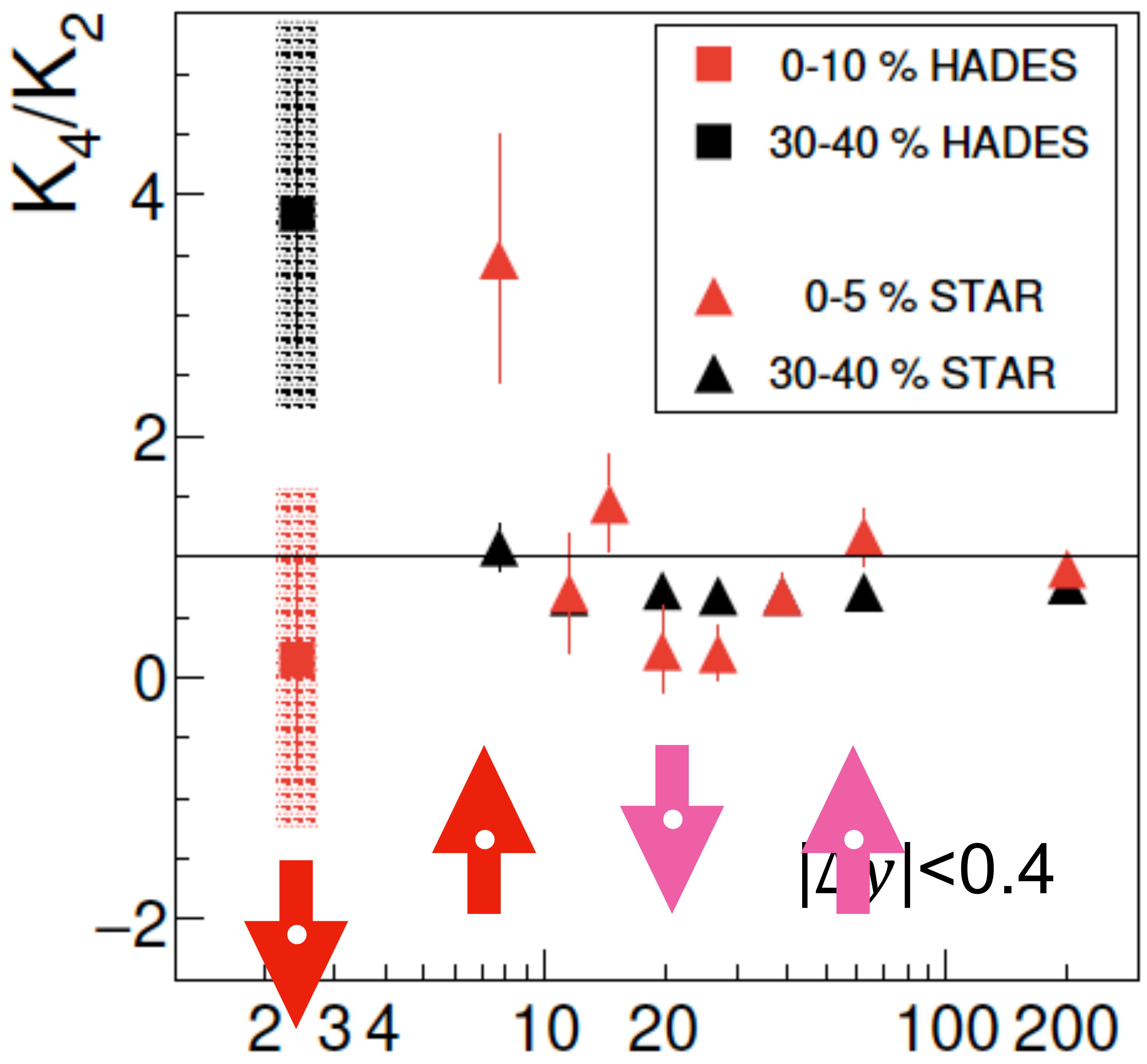

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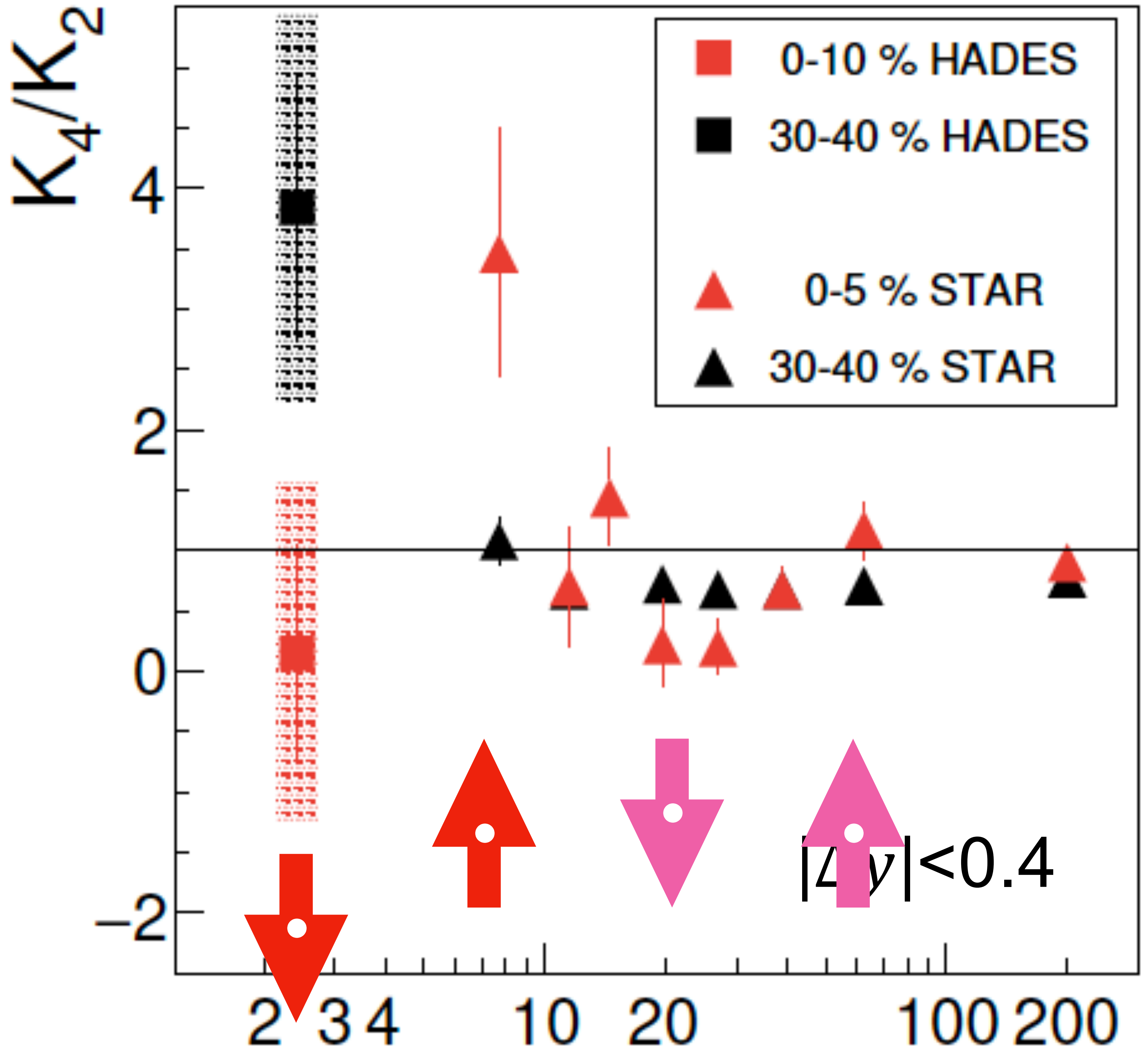

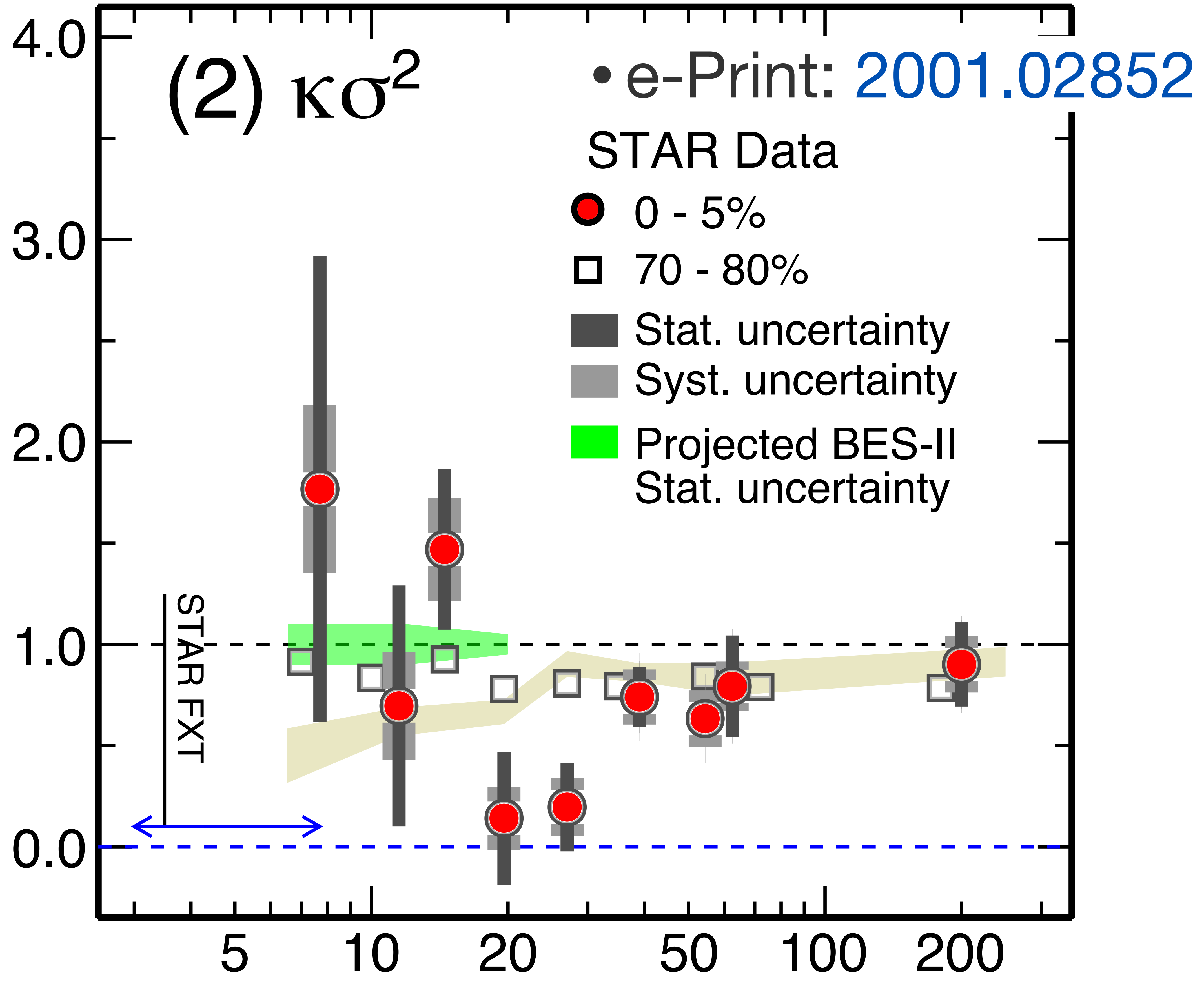

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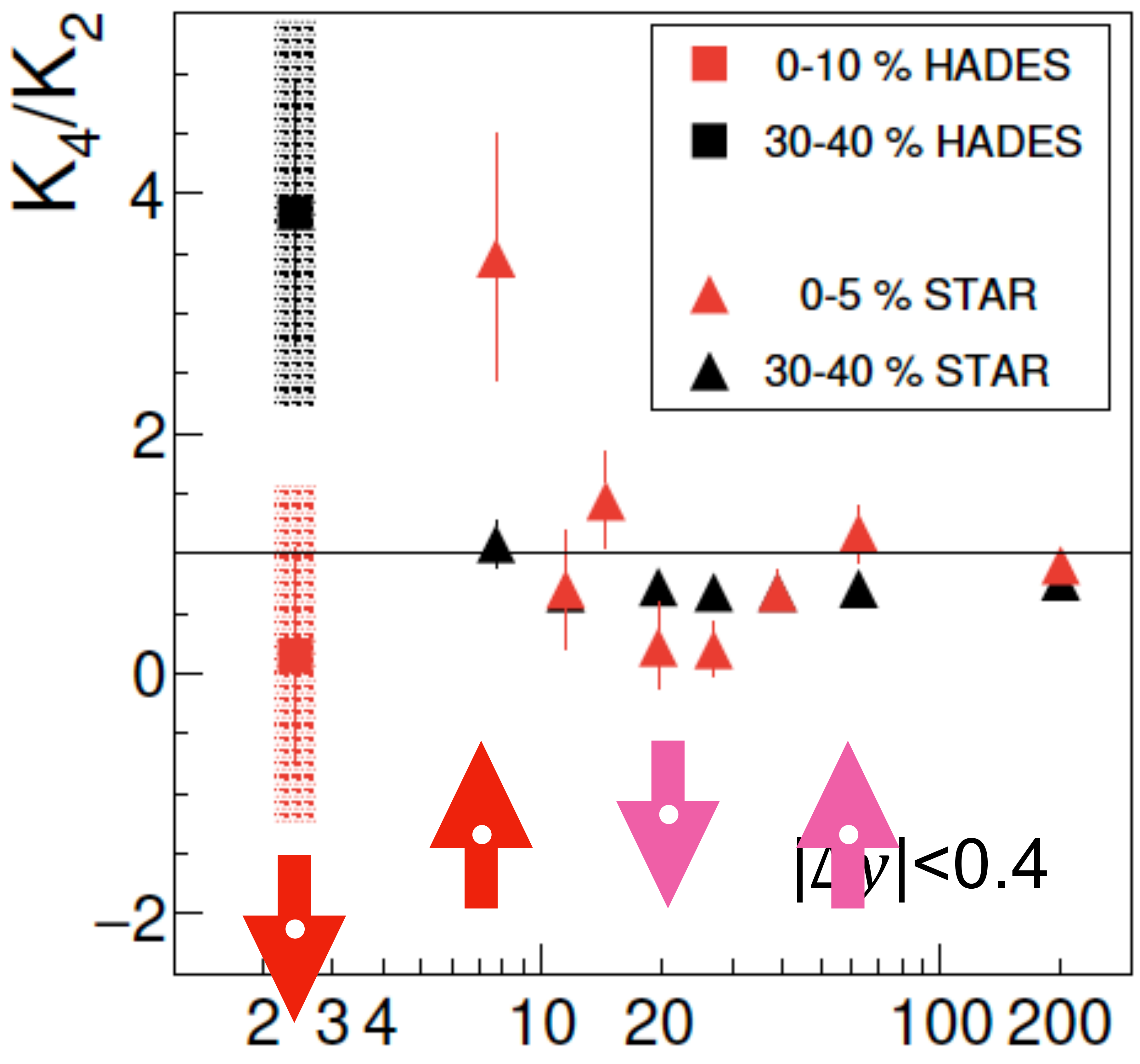

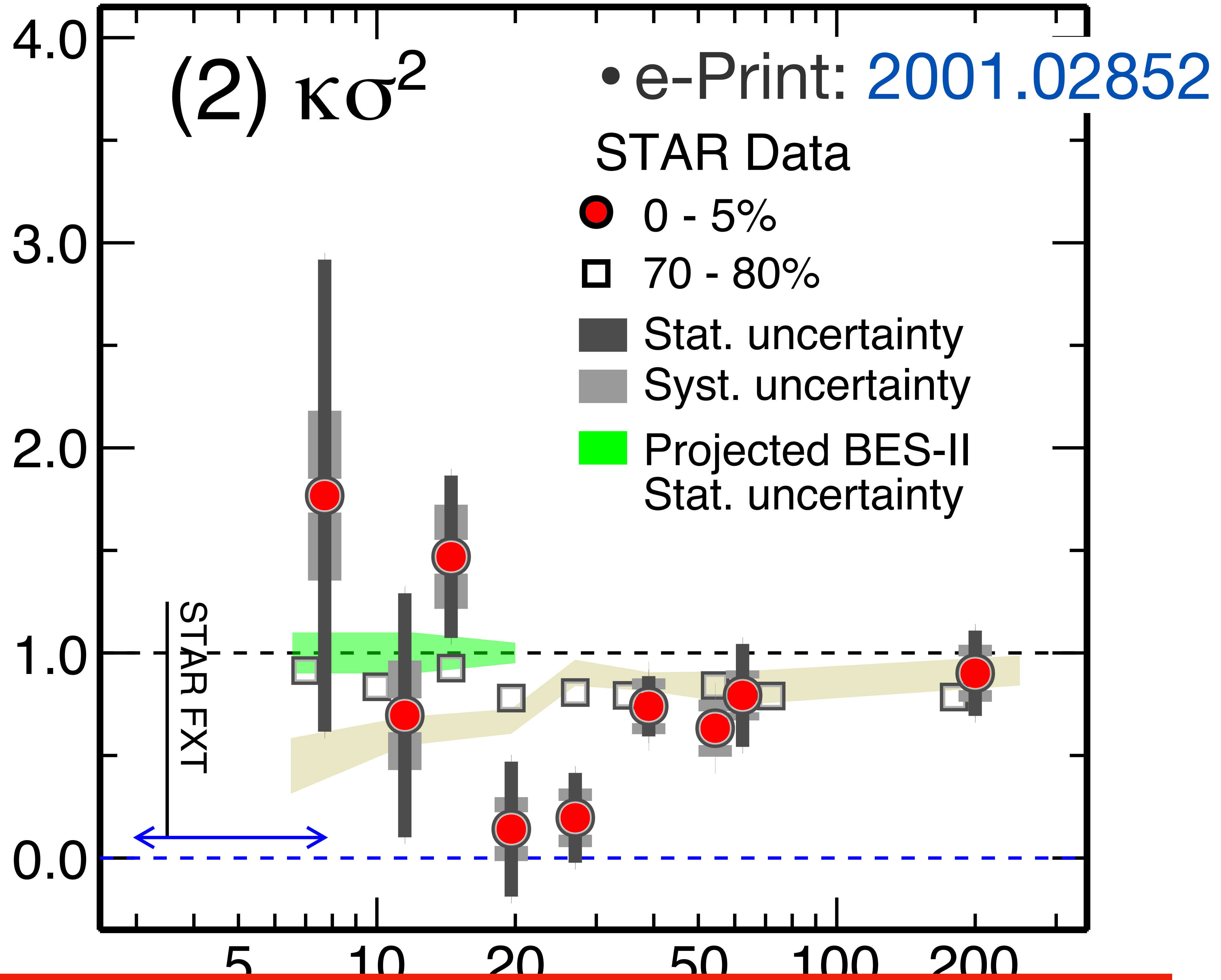

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Still non-monotonous signal?
Clearly much more accurate measurements from BeS-II are needed

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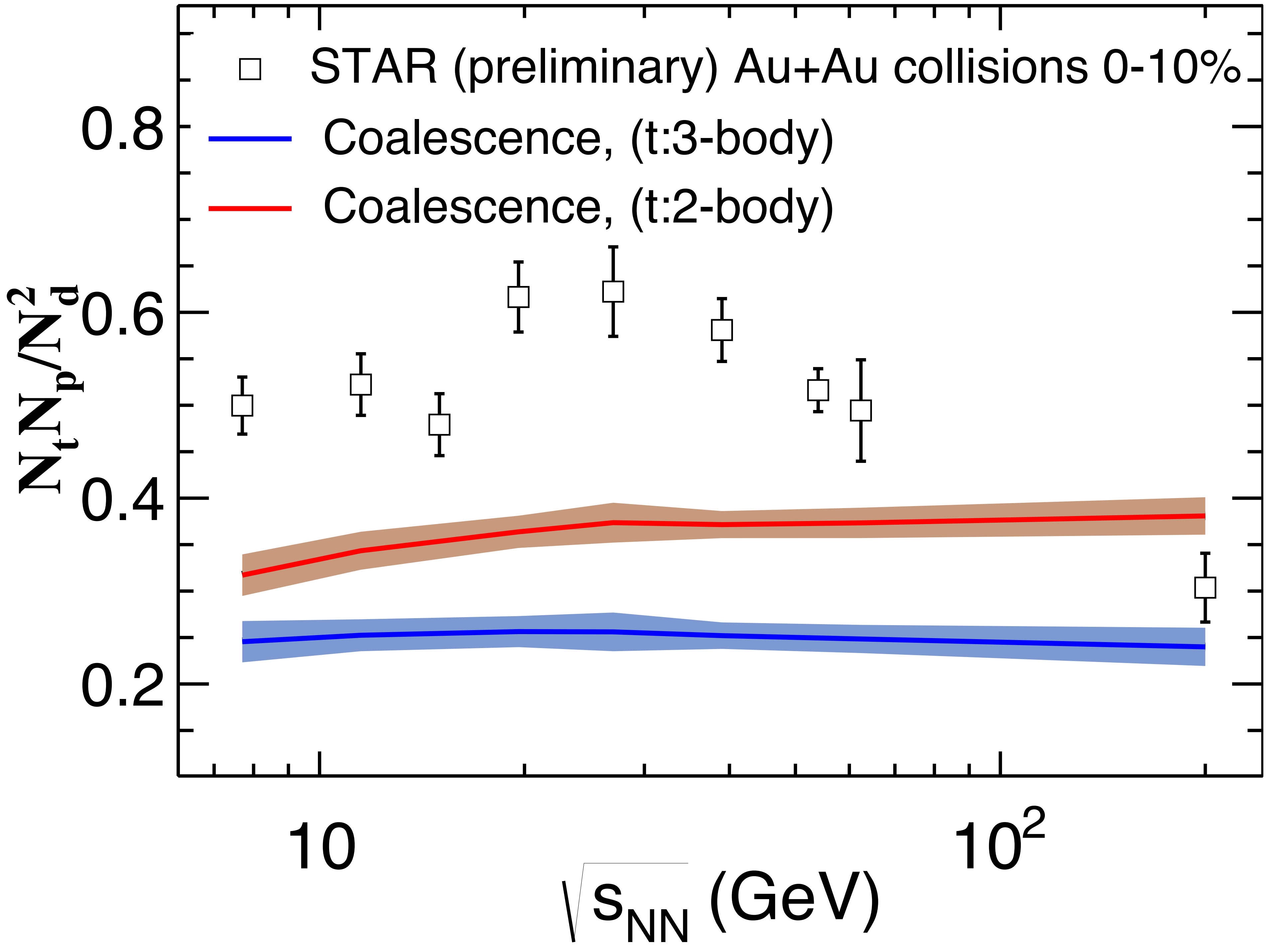
In this ratio the main driver — fugacity exp(mu/T) - Cancels out



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Extra source of t is needed:
4-N reclusters =>
50 states of He4 =>
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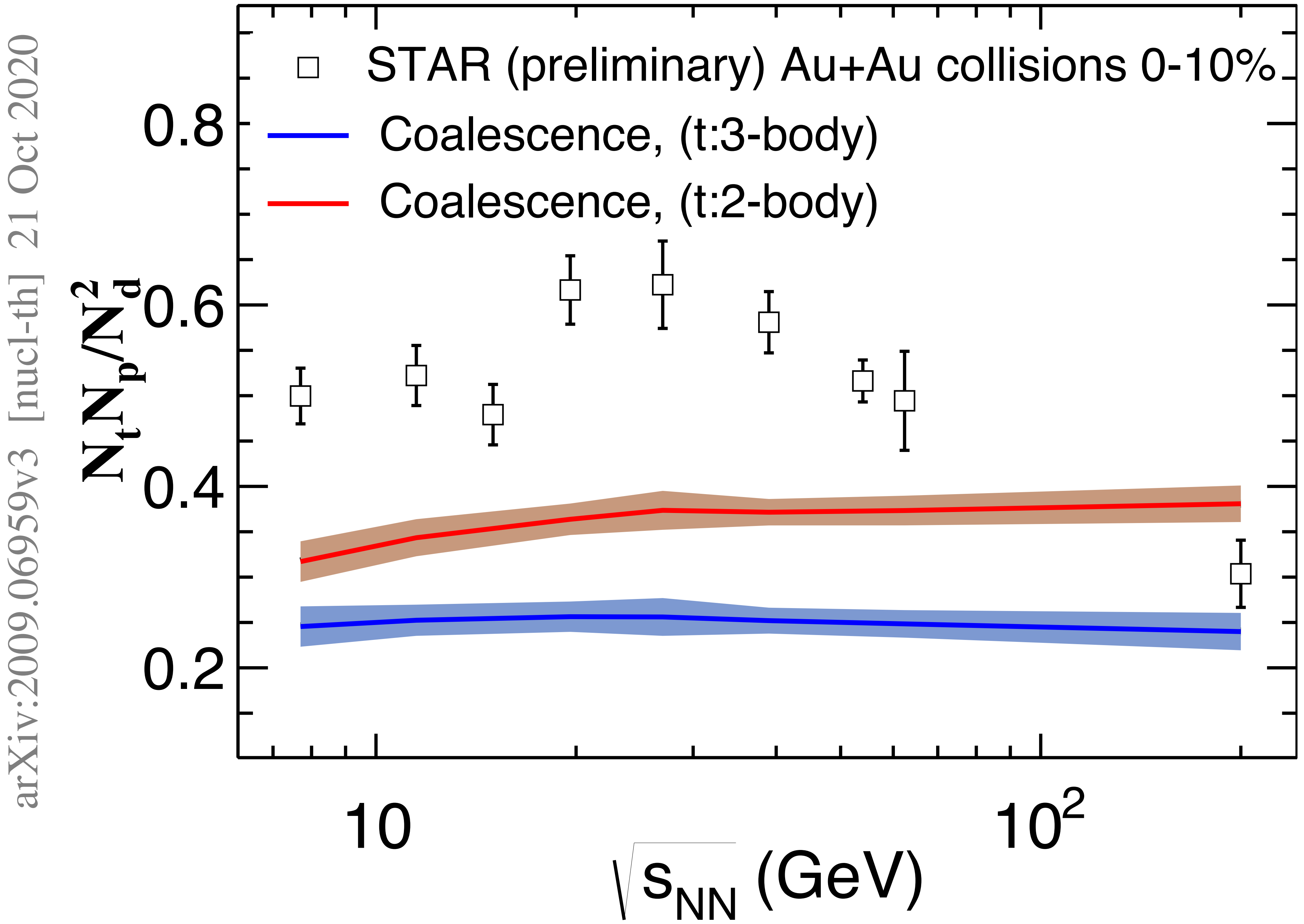

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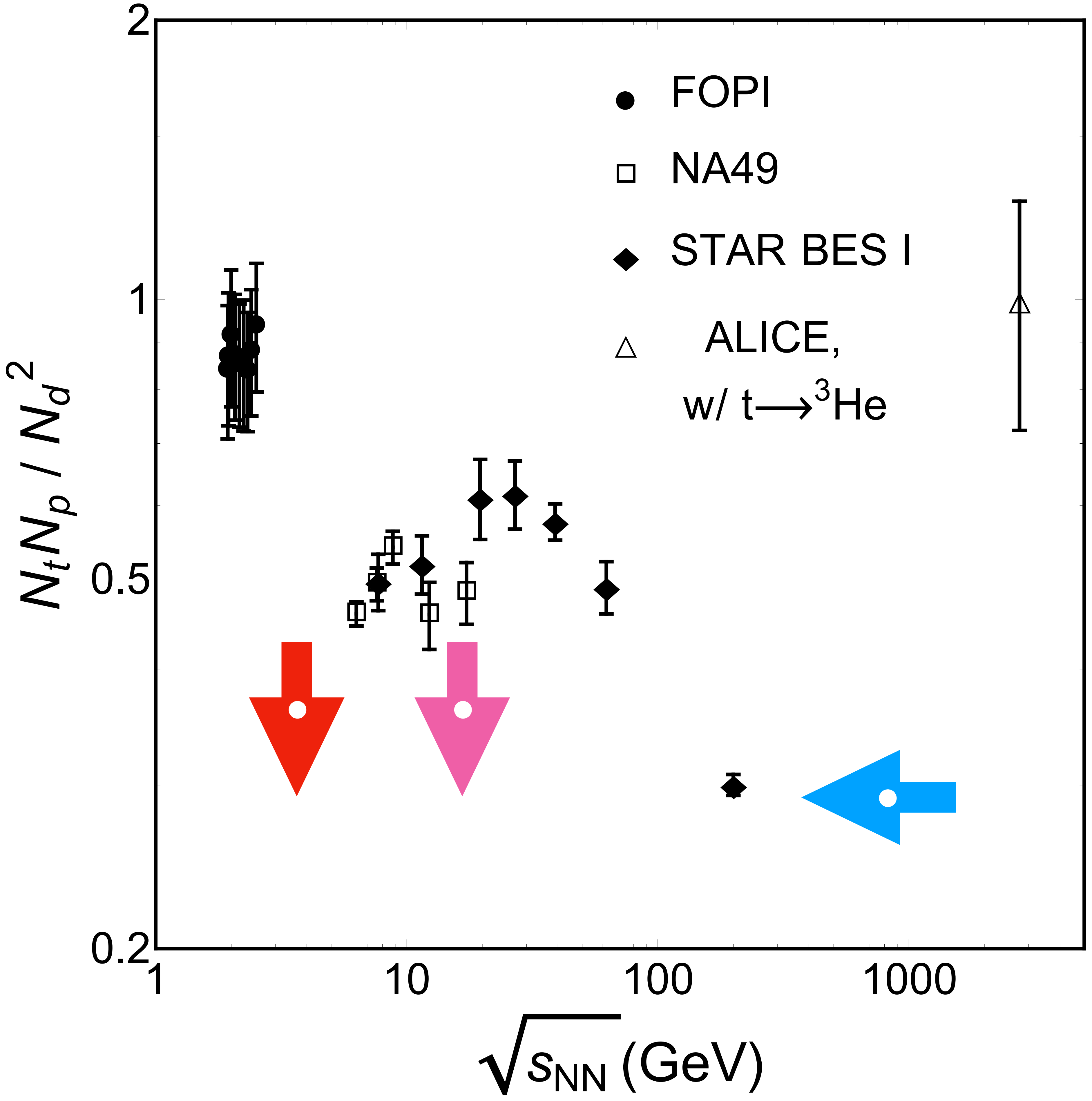

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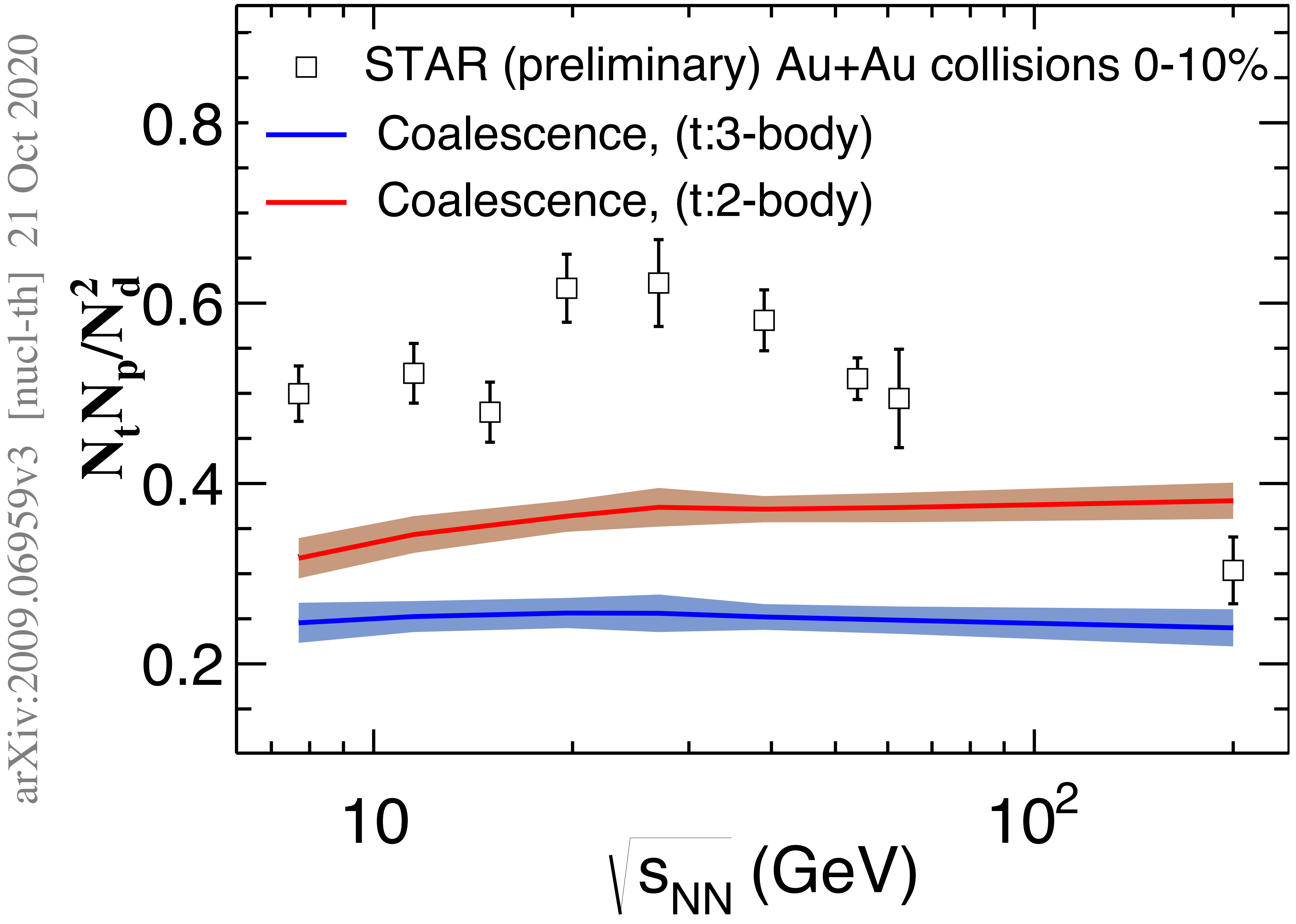

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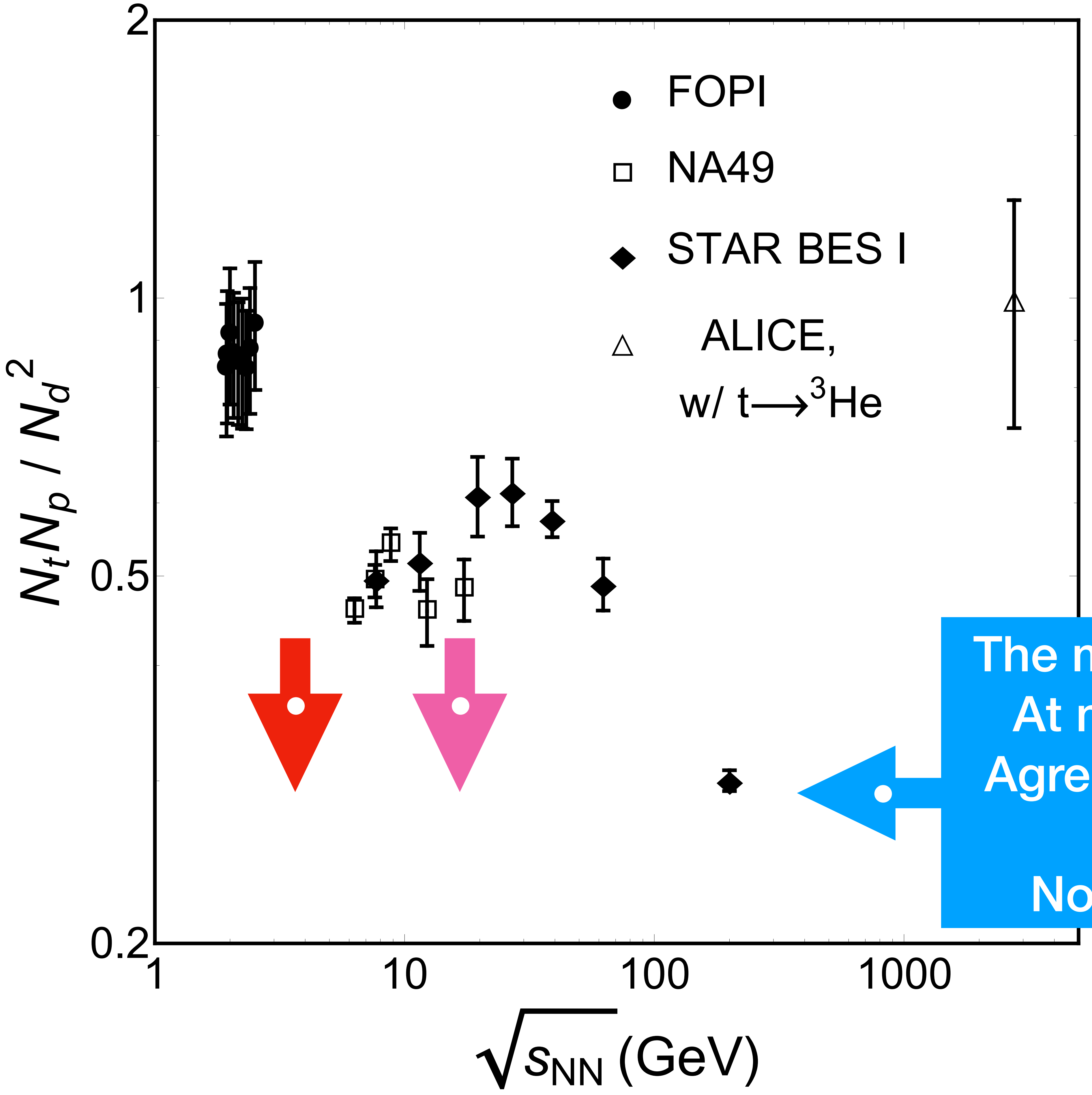

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At main RHIC energy
Agrees with stat weight
Ratio 0.29 =>
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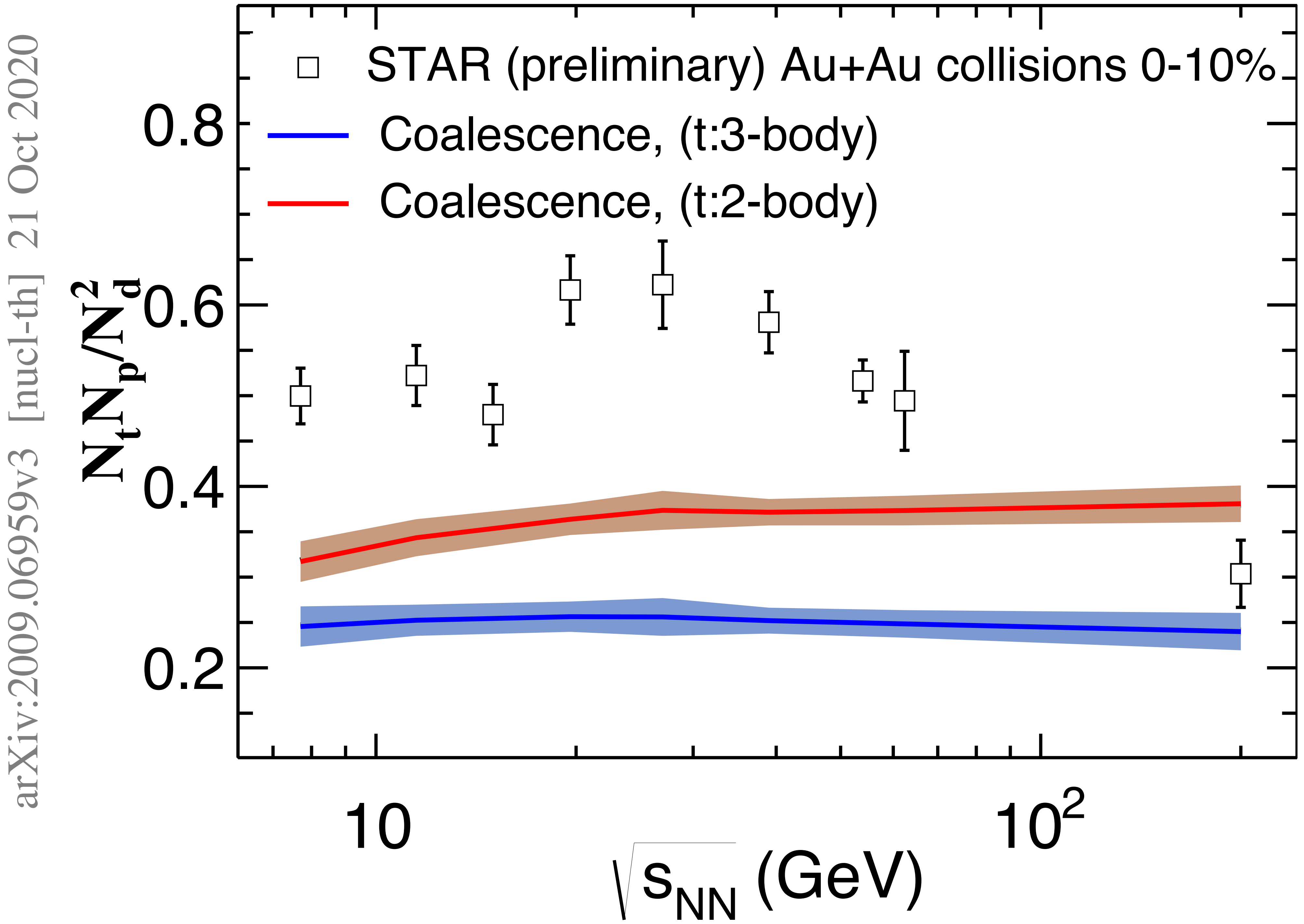

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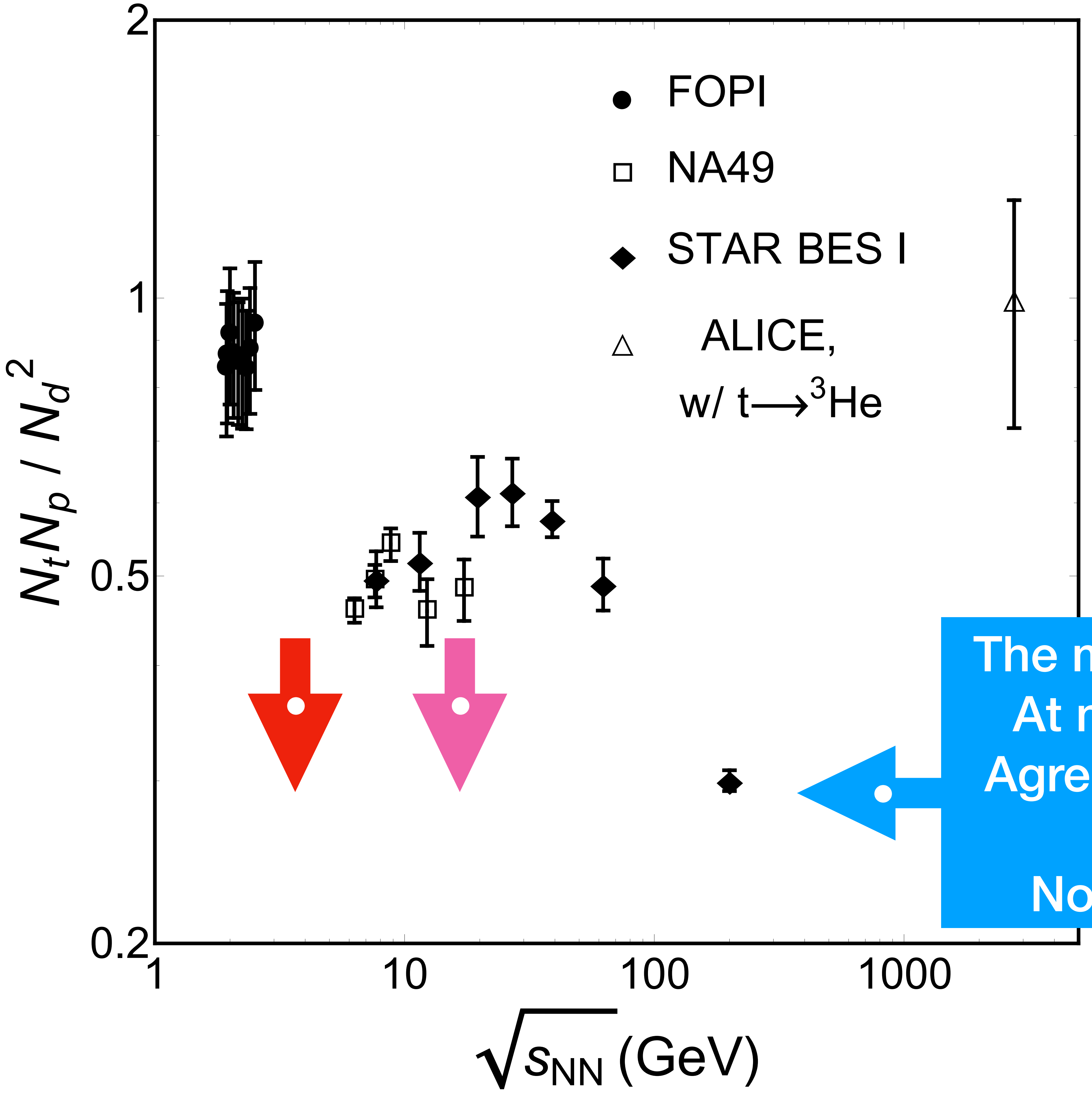

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