Triple Nuclear Collisions (TNC) - a New Method To Explore the Matter Properties Under New Extreme Conditions

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in Collaboration with

Theoretical Modeling

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A+A Collision Are the Main Tool to Study the QCD Phase Diagram

High Energy Nuclear Physics mission:

1. **We want to find the QCD phase transition(s) experimentally**

2. **We want to locate (tri)CEP experimentally**

3. **We want to convince the colleagues from our community and physicists from other communities that goals 1. and 2. are achieved**

But after almost 40 years several groups realized that we need Independent and Reliable EXPERIMENTAL
Source of Information about QCD phase diagram

In Addition to A+A Reactions We Need Independent and Reliable Source of Information about QCD matter EoS

Otherwise the HENP mission will take 40 more years!

1. **Astrophysical processes like neutron star mergers**

   Good probe, but for the neutron matter EoS!

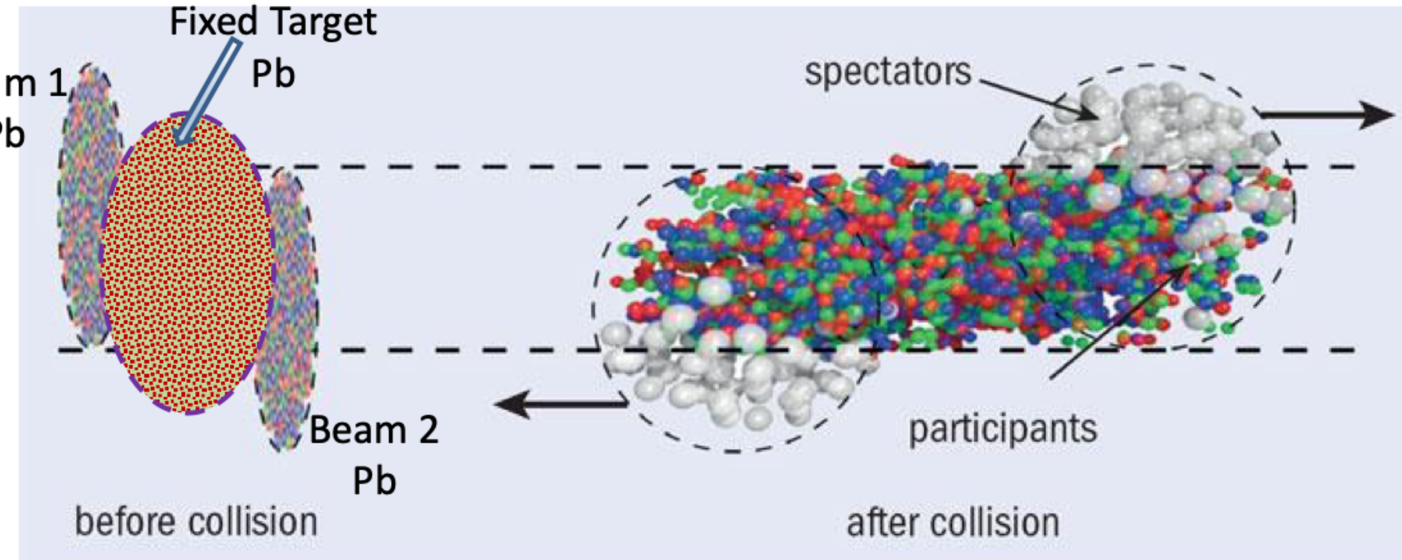
   The neutron matter EoS is necessary as input for Such modeling, but it is less known than the nuclear matter EoS (recall the tetra-neutron problem!)

See: Most, Weih, Papenfort, Dexheimer, Hanauske, Motornenko, Steinheimer, Stoecker, Rezzolla

And Bauswein, Bastian, Blaschke, Chatziioannou, Clark, Fischer, Oertel

2. **Triple nuclear collisions: A+T+B reactions**

Main Idea of TNC: install the target at the interaction region of two colliding beams



http://images.iop.org/objects/ccr/cern/53/4/18/CCfir5_04_13.jpg

22.06.2017
V.M. Pugatch
presentation at GSI

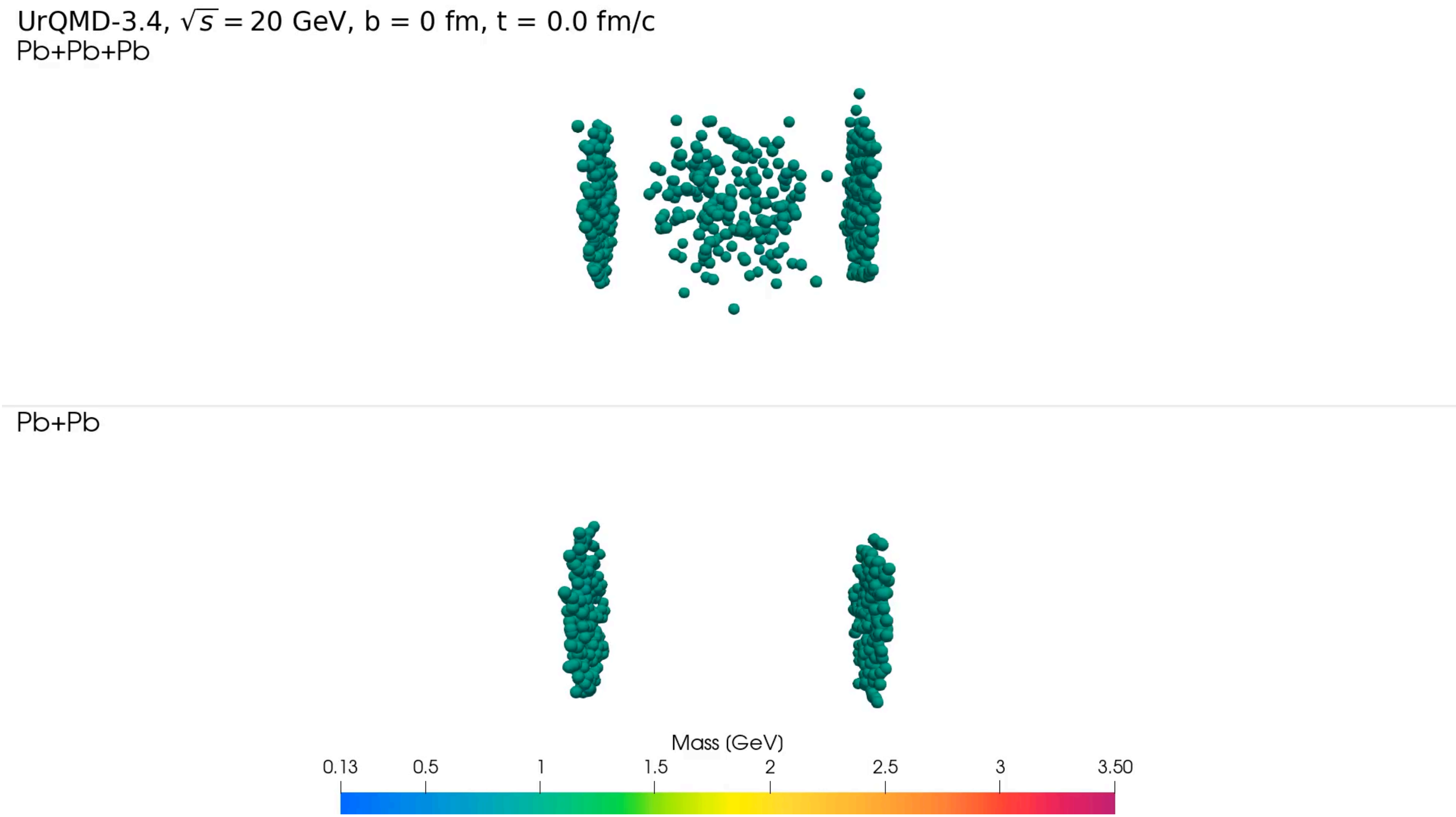
Events with three Pb nuclei interaction !

15.05.2018
Valery Pugatch
presentation at
The Kharkiv
CERN-Ukraine
Meeting

I was there, but was
Preparing my talk…

Example $\sqrt{s} = 20$ GeV

Modeling the TNC with UrQMD 3.4



Video: V~m (Bag Model) made by Oleksandr Vitiuk

Ultra-relativistic Quantum Molecular Dynamics (UrQMD 3.4)

Hadron cascade (standard mode)

- Based on the propagation of hadrons
- Rescattering among hadrons is fully included
- String excitation/decay (LUND picture/PYTHIA) at higher energies
- Provides a solution of the relativistic Boltzmann eq.:

$$p^{\mu} \cdot \partial_{\mu} f_i(x^{\nu}, p^{\nu}) = \mathcal{C}_i$$

The collision term C includes more than 100 hadrons

M. Bleicher et al, J.Phys. G25 (1999) 1859-1896

Very well-known transport approach, but first we have to Find out whether and how it works at LHC energies!

Normalizing UrQMD 3.4 on A+A data

Although UrQMD is a hadronic cascade the heavy resonances (strings) can be considered as the bags of QGP plasma!

Our main task is to study the general properties of hadron production in TNC. Hence UrQMD is the right tool.

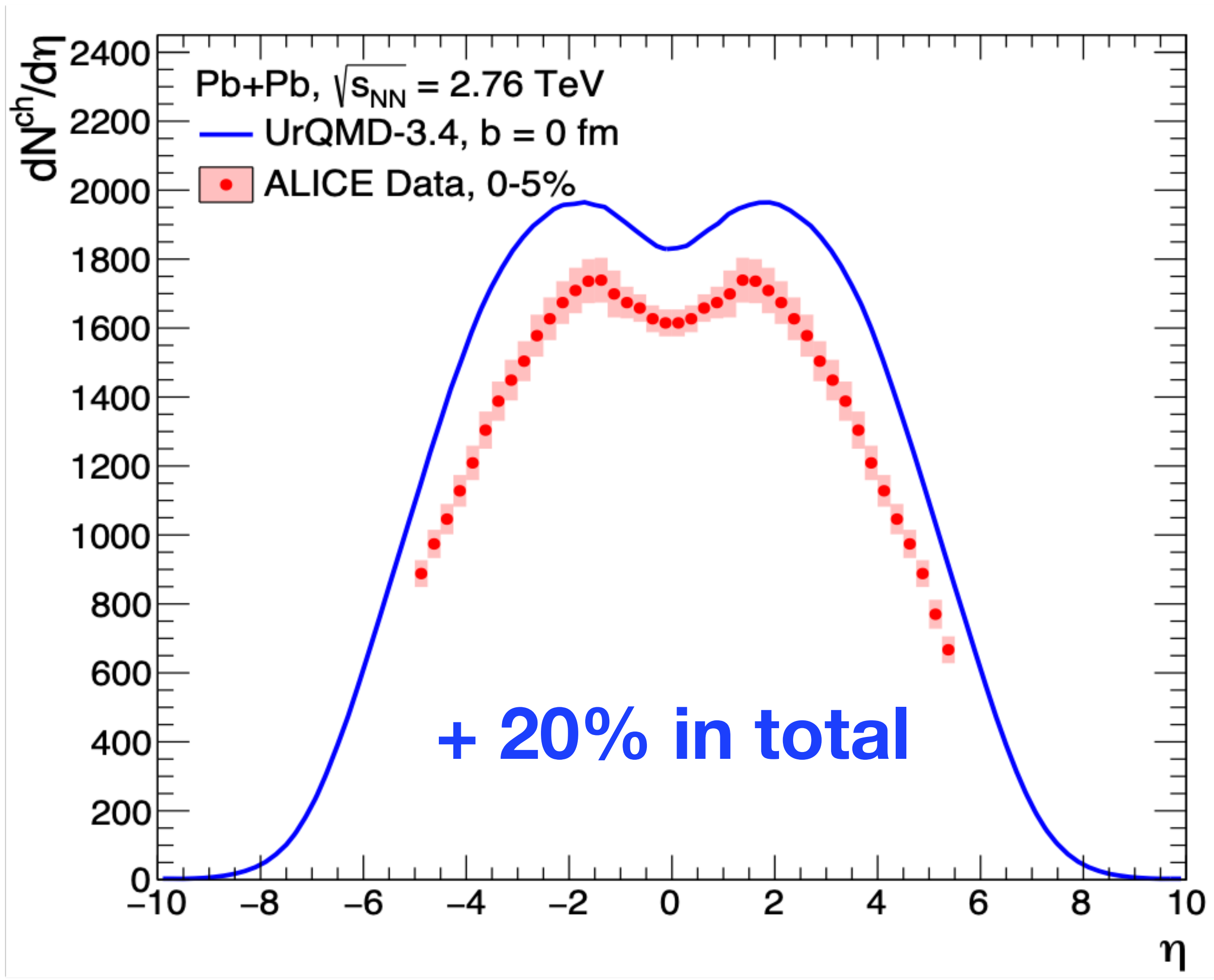


Figure 1: Pseudorapidity distribution of charged particles $\frac{dN_{ch}}{d\eta}$ measured in 0-5% most central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (symbols) [29] vs. the UrQMD results (curve).

A+A LHC data vs UrQMD

Table 1: Comparison of the ALICE CERN midrapidity hadronic yields measured in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [30] with the results of UrQMD 3.4 output for the same energy.

Data	π^+	π^-	K^+	K^-	p	$\bar{p}$
ALICE	669.5 ±48	668 ±47	100 ±8	99.5 ±8.51	31 ±2.5	30.5 ±2.5
UrQMD	933.7	934.5	121.6	117.4	31.7	26.5

for impact parameter b=0 fm

=> Pions are strongly overestimated,
Kaons on ~ + 20%,
protons - well described!
Antiprotons ~ - 15%

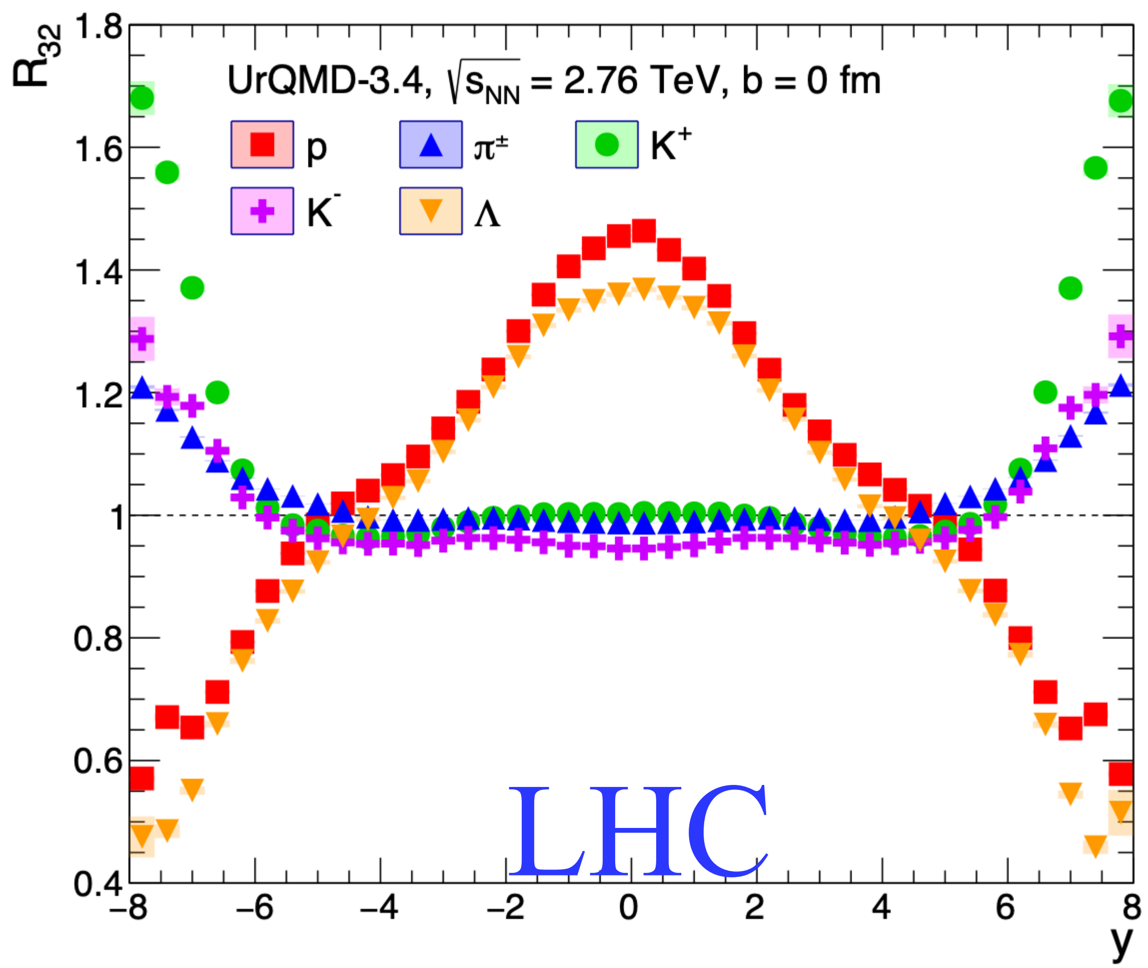
Ratios of (A+A+A)/(A+A) Results

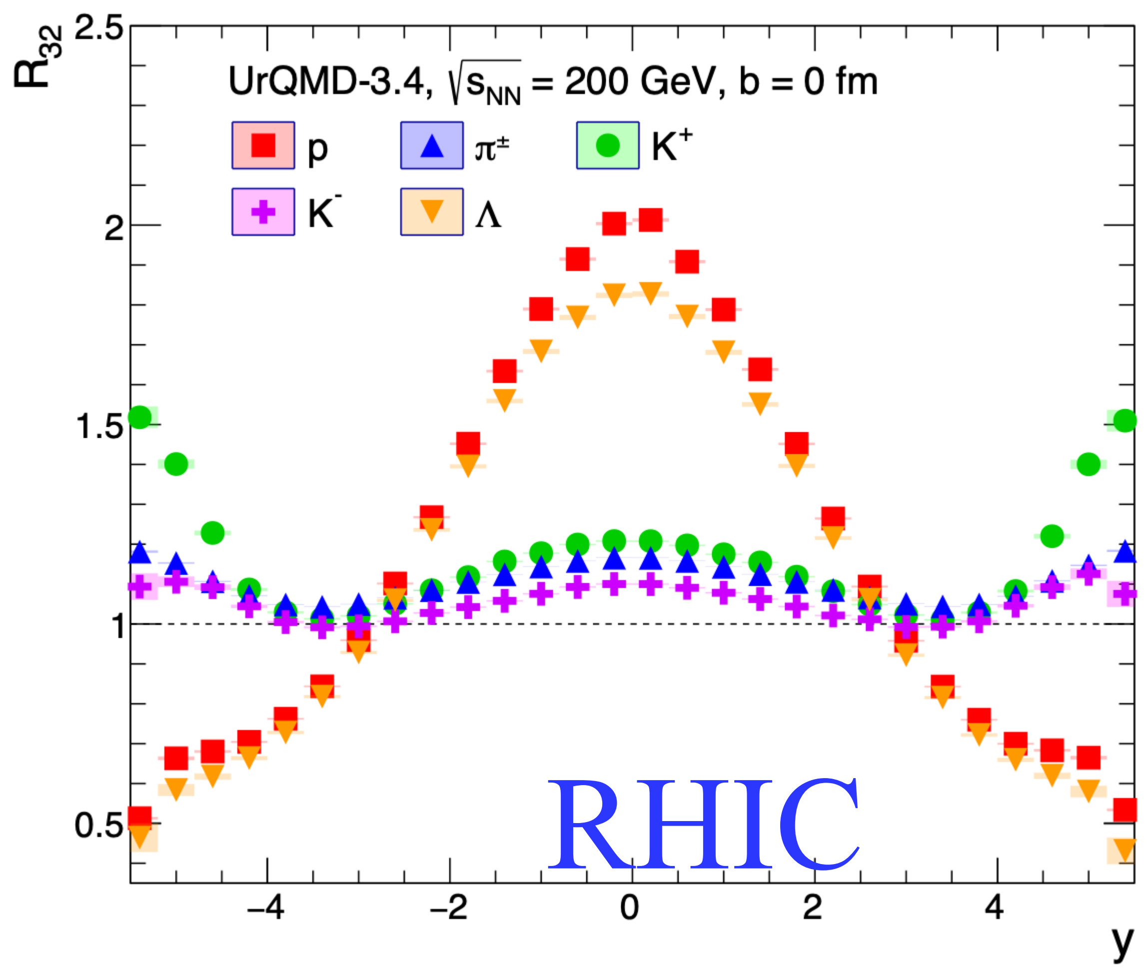
* Our main interest is the baryon production in most central collisions.

* Both (A+A) results and (A+A+A) results contain the same deviations compared to the data

=>

In the ratios the (A+A+A)/(A+A) results must be less affected by these deviations!

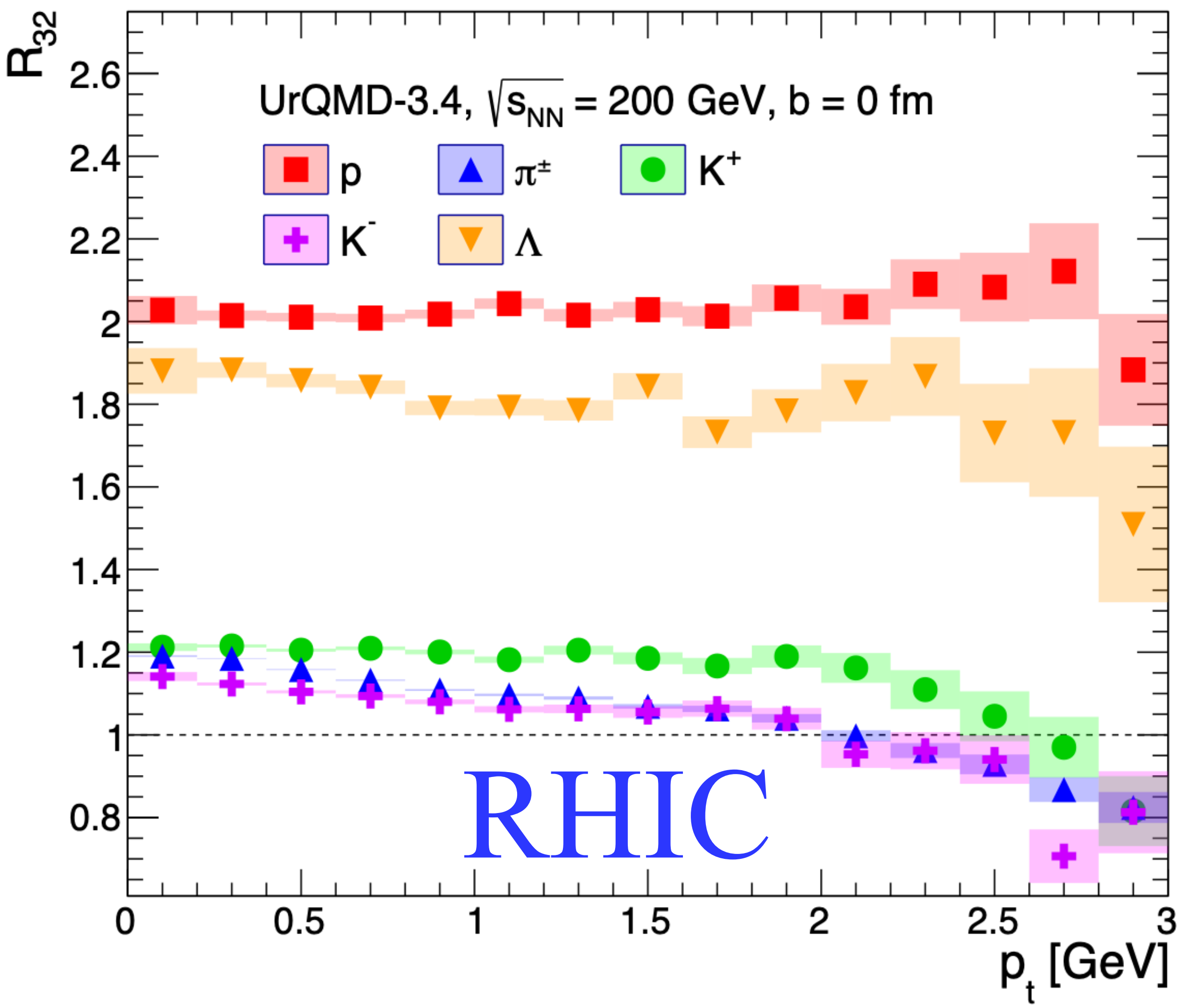


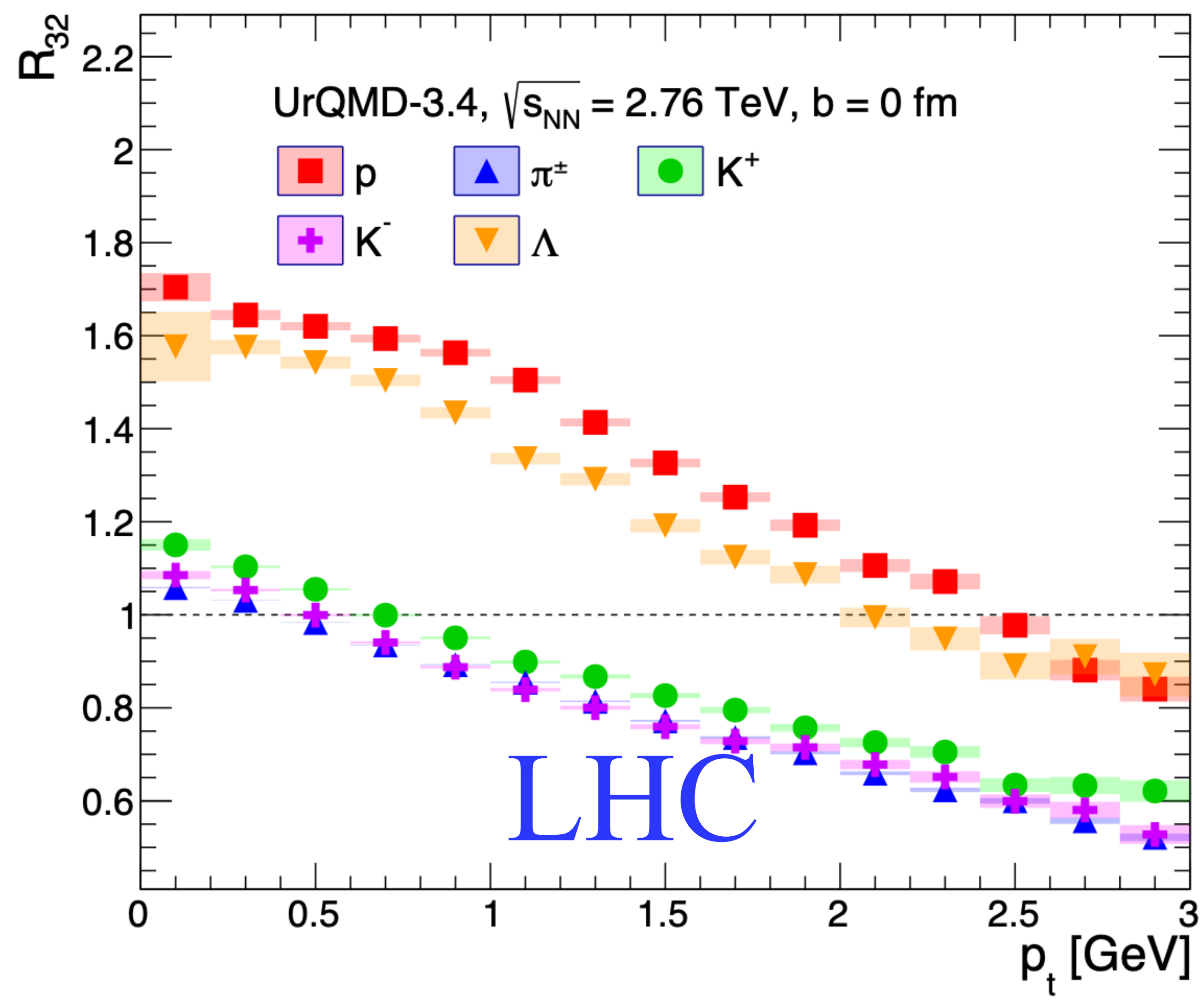


In (A+A+A) reactions p and Λ-hyperons are strongly enhanced at midrapidity!

(A+A+A)/(A+A) Ratios for Transversal Spectra at Midrapidity

In (A+A+A) reactions the pT-spectra of particles at RHIC and LHC energies behave differently!



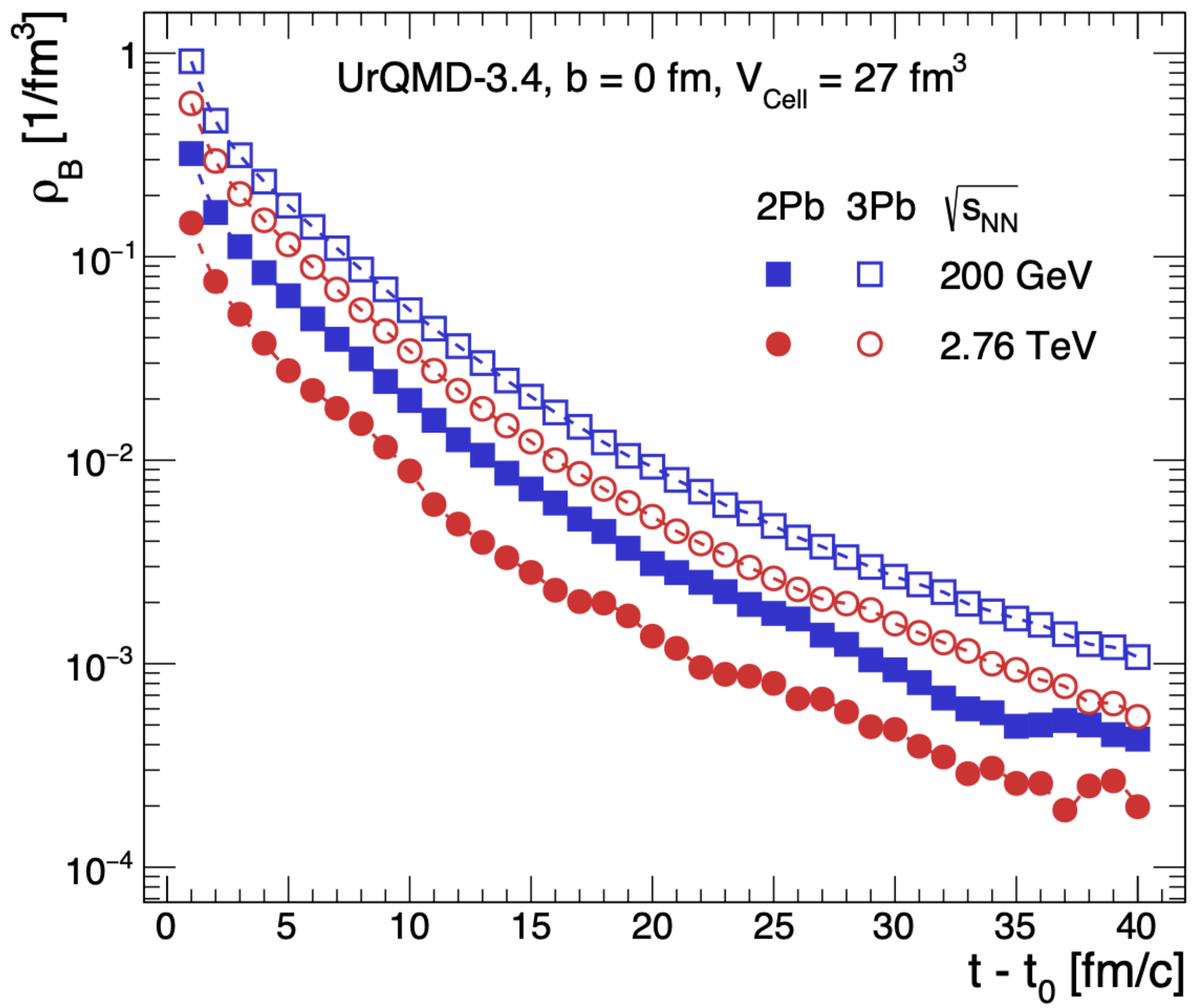


Spectra are modified by a constant factor!

Number of slow hadrons Is enhanced stronger! => Density trap? => Should be investigated

Central Cell Evolution 1

Different sizes of central cell were investigated.
For 3x3x3 fm^3 the fluctuations are less strong => shown below



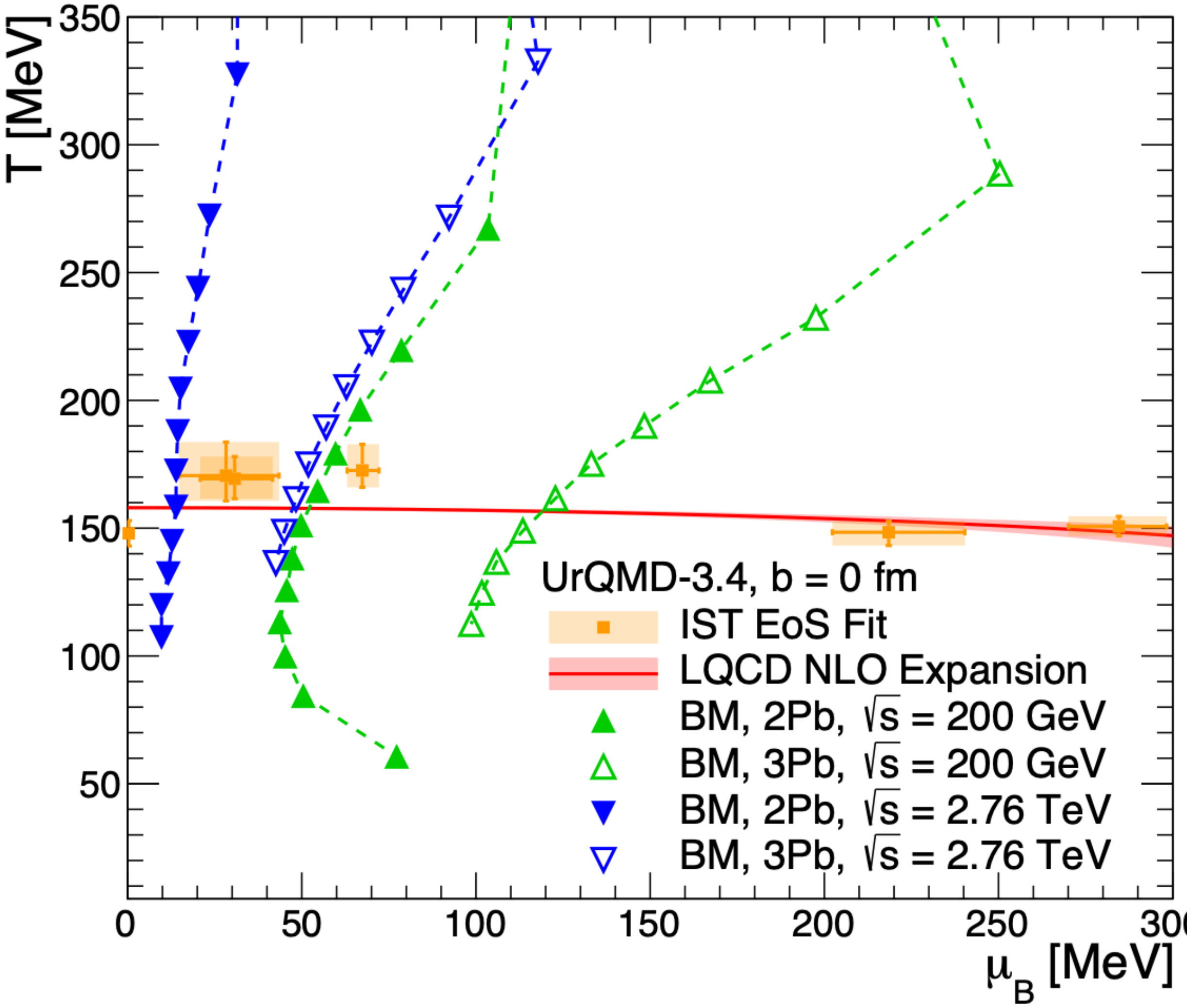
t_0 is the time, when the remnants of projectile nuclei have passed through each other.

In TNC the initial baryonic charge density is 3 times higher than in A+A collisions!

The energy density in TCN is similar to A+A collisions.

Central Cell Evolution 2

To quantify the parameters of central cell evolution, we used The MIT Bag Model EoS:



$$p^{BM} = \frac{95}{180}\pi^2 T^4 + \frac{T^2\mu_B^2}{6} + \frac{\mu_B^4}{108\,\pi^2} - B_{vac}\,, \qquad (1)$$

where the vacuum pressure B_{vac} was chosen as $B_{vac}^{\frac{1}{4}} = 206$ MeV

From EoS one can find baryonic charge density *ρ* and Energy density *ε*

$$\rho_B^{BM} = \frac{\partial p^{BM}}{\partial \mu_B}\,, \quad s^{BM} = \frac{\partial p_{BM}}{\partial T}\,,$$

$$\epsilon^{BM} = T\,s^{BM} + \mu_B\,\rho_B^{BM} - p^{BM}\,.$$

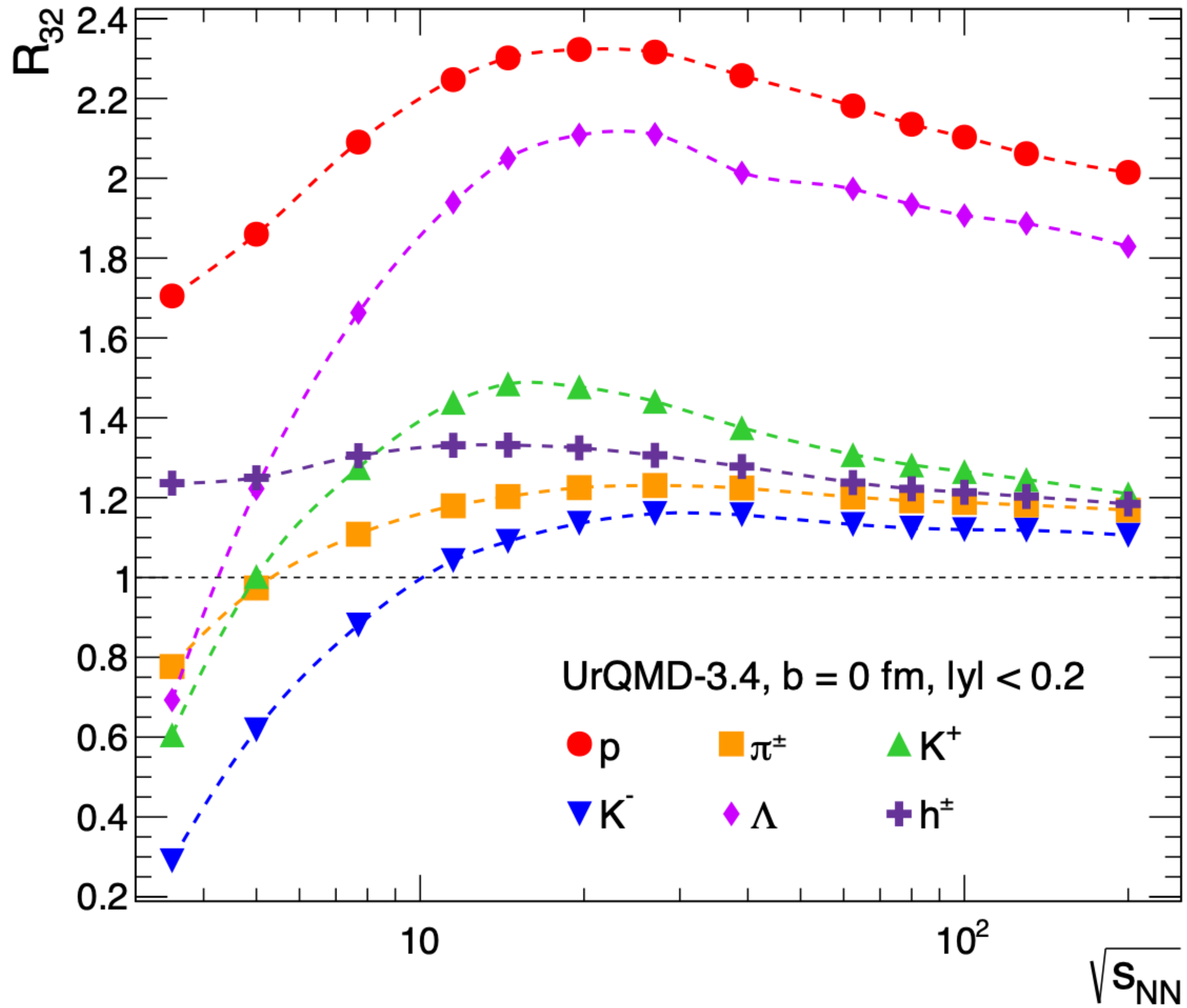
Equating *ρ* and *ε* found by UrQMD to the ones of MIT Bag Model => μ_B and T of central cell

Filled symbols - A+A collisions
Open symbols - TNC.
Comparing to chemical freeze-out => accuracy of μ_B ~ 15 MeV
=>
Much higher μ_B can be reached In TNC!

Central cell parameters at LHC are similar to A+A at RHIC, but initial Baryonic density is 2 times higher!

At Lower Collision Energies the Effects Should be Stronger!

Ratio (3A)/(2A) of particle yields as the function of collision energy



In the cm energy range 10-40 GeV one can expect NEW phenomena!
=> Colleagues from RHIC, NICA and FAIR may be interested in our results!

Main Conclusions

Very interesting Physics of TNC Awaits for us!

Combining the results of A+A collisions and TNC
We have a real chance to accomplish the HENP mission
And to get the QCD phase diagram from experiments

But what are the TNC rates?

Are the TNC the dreams of theoreticians?

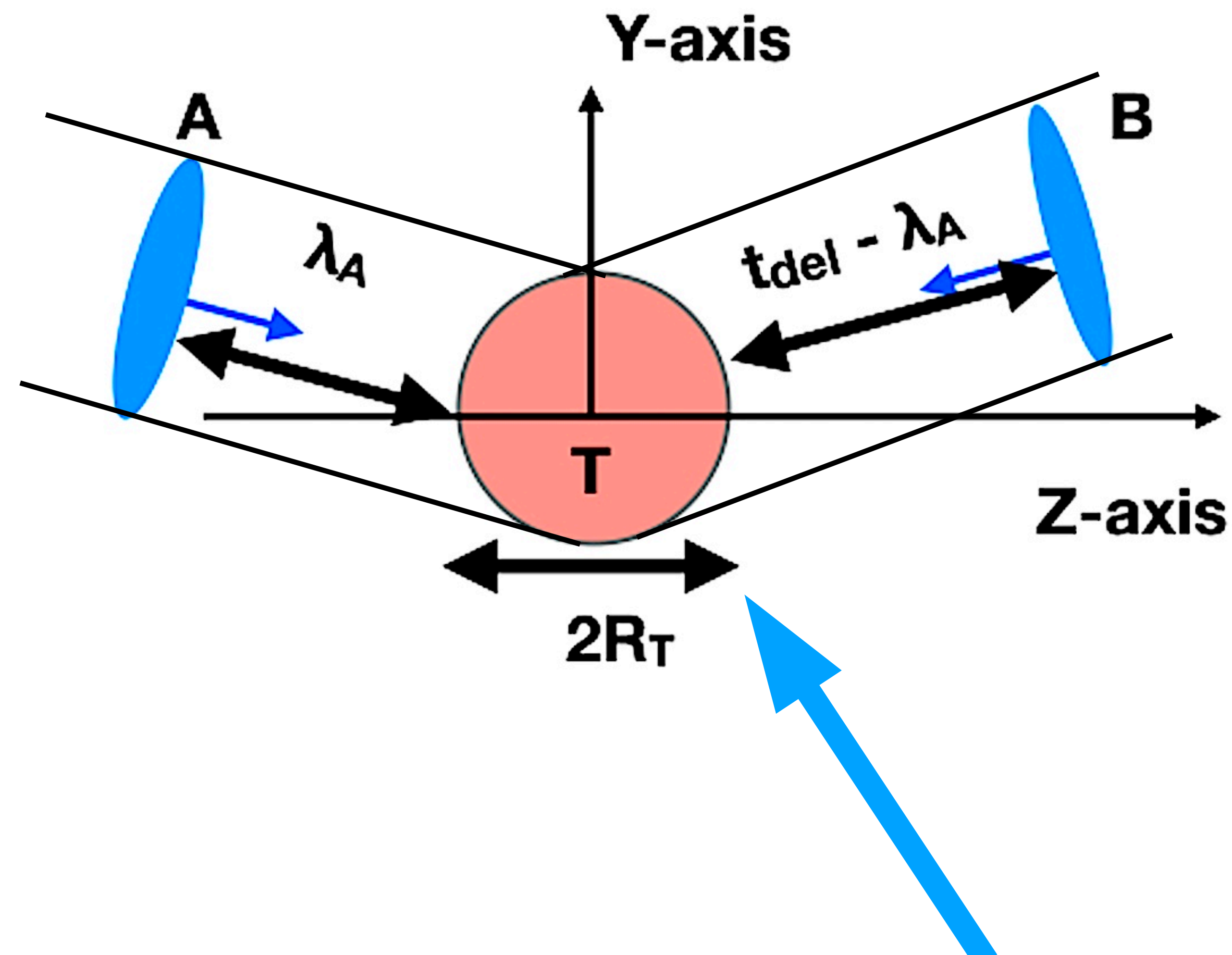
Rates for Central TNC (highly idealized case!)

General Formulae for TNC:

For thin target T of thickness $h \geq 2R_b \simeq 3.2\,\mu\text{m}$

R_b is mean beam radius

Collision rate of $A+T+B$ with time delay $t_{del} \leq 10$ fm



$$\frac{dN_{A+T+B}}{dt} \simeq \underbrace{L^{A+B}}_{luminosity} \cdot \underbrace{\sigma^{A+B}}_{cross-sect} \cdot N_T^{int}$$

here N_T^{int} is number of TNC with t_{del}

$$N_T^{int} = \underbrace{\rho_T}_{density} \cdot \underbrace{V_{A+T+B}^{int}}_{volume\ of\ inter}$$

On geometrical grounds one can write (for a single event)

$$V_{A+T+B}^{int} \leq \pi \left[(\max\{R_A; R_T\})^2 + (\max\{R_B; R_T\})^2 \right] \cdot [2R_T + t_{del}/2]$$

R_B is radius of nuclei in beam B

For very thin targets $h < 2R_b \simeq 3.2\,\mu\text{m}$ the corrections diminish the rate

TNC Rates 2

Consider p+C reactions, first

Assume: inelastic cross-section of p+C is

$$\sigma_{p+C} \simeq 100 \text{ mb} \simeq 10^{-25} \text{ cm}^{-2}$$

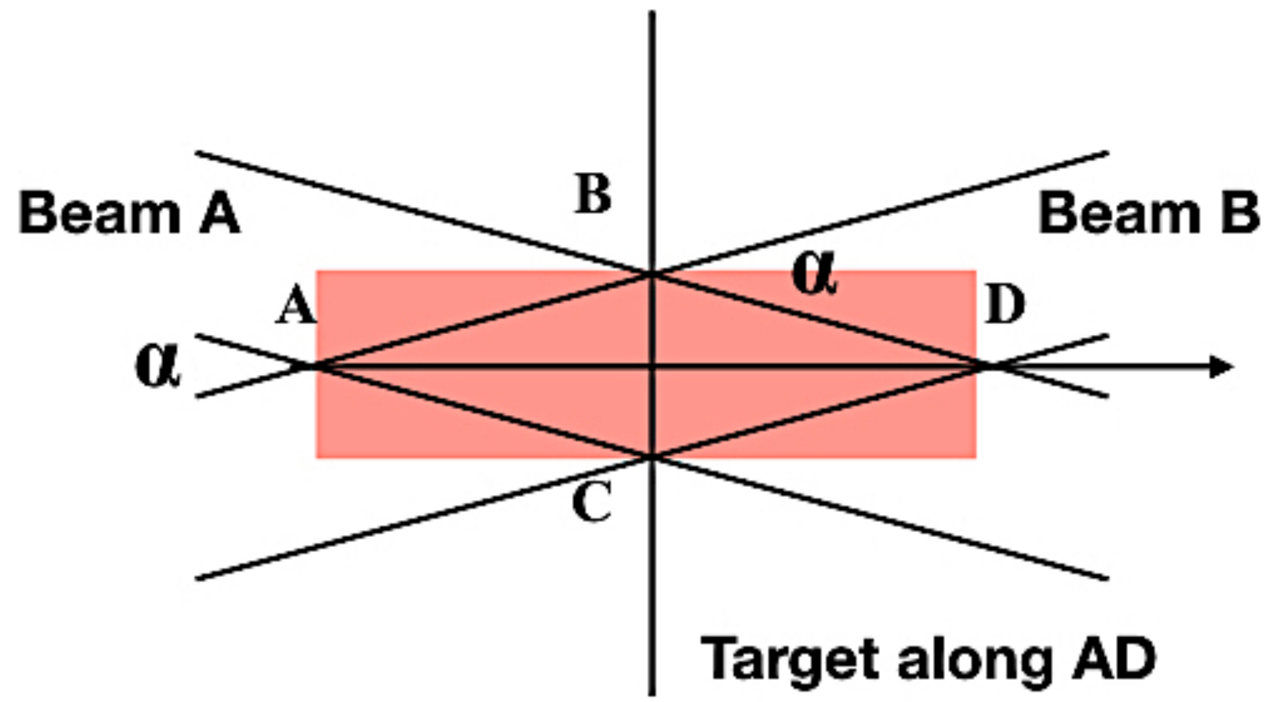
It agrees with the geometrical formula

$$\sigma_{A+T} \simeq \sigma_{p+p} \left[\frac{A^{\frac{1}{3}} + T^{\frac{1}{3}}}{1^{\frac{1}{3}} + 1^{\frac{1}{3}}} \right]^2 \Longrightarrow$$

$$\sigma_{p+C} \simeq 33.5\text{mb} \left[\frac{1^{\frac{1}{3}} + 12^{\frac{1}{3}}}{1^{\frac{1}{3}} + 1^{\frac{1}{3}}} \right]^2 \simeq 91\text{mb}\,,$$

$\sigma_{p+p} = 33.5\text{mb for } \sqrt{s} = 60 \text{ GeV}$

was taken from PDG



Results for target T being along AD

$$V^{int}_{p+C+p} \leq 2\pi \left(1.25 \cdot 12^{\frac{1}{3}} fm\right)^2 \cdot \left[2.5 \cdot 12^{\frac{1}{3}} fm + 5 fm\right] \simeq 505 \text{ fm}^3$$

$$V^{int}_{3Pb} \leq 2\pi \left(1.25 \cdot 208^{\frac{1}{3}} fm\right)^2 \cdot \left[2.5 \cdot 208^{\frac{1}{3}} fm + 5 fm\right] \simeq 6828 \text{ fm}^3$$

TNC Rates 3

For the luminosity of p-beams $L^{p+p} = 10^{36} \frac{1}{s \cdot cm^2}$ we get

$$\frac{dN_{p+C+p}}{dt} \simeq 10^{36} \frac{1}{s \cdot cm^2} \cdot 10^{-25} cm^2 \cdot 6 \cdot 10^{-14} nucl. \simeq 6 \cdot 10^{-3} \frac{1}{s}$$

For the luminosity of Pb-beams $L^{Pb+Pb} = 9 \cdot 10^{32} \frac{1}{s \cdot cm^2}$
(for # of Pb ions in bunch is 10^9) we get

$$\frac{dN_{3Pb}}{dt} \simeq 9 \cdot 10^{32} \frac{1}{s \cdot cm^2} \cdot 1.3 \cdot 10^{-24} cm^2 \cdot 2.25 \cdot 10^{-13} nucl.$$

$$\simeq 2.63 \cdot 10^{-4} \frac{1}{s}$$

If one day the luminosity of Pb-beams will be $L^{Pb+Pb} = 10^{36} \frac{1}{s \cdot cm^2}$

$$\frac{dN_{3Pb}^{future}}{dt} \simeq 3 \cdot 10^{-2} \frac{1}{s} \text{ !}$$

IMPORTANT: if we use the cross-sections from EPOS generator T.Pierog et al., Phys. Rev. C 92, 034906, then
the rates above should be increased by factor 4!

For semi-central TNC the the rates should be higher!

The Present Day Problem with TNC

Is not that TNC are rather rare events!

But a huge energy deposition to the target!

For # of protons hitting the carbon target per second is

$$\frac{dN_p}{dt} \simeq 10^{18}\ \mathrm{s}^{-1}$$

one can find that energy deposition per second

$$\frac{dE_{p+C+p}}{dt} \simeq 1.76 \cdot 10^6 \frac{J}{s} \Leftrightarrow \text{explosion of } 420\ \frac{g}{s} \text{ of TNT!}$$

How to resolve this problem?

1. Use super-thin target, which is restorable. $\Rightarrow$ target will evaporate and not explode.

2. Make a jet target of the micro-particles like SMOG-2 to remove the heat from reaction zone.

Second Main Conclusion: new ideas are necessary!

Thank you very much for your attention!