Fixed Super-thin Solid Target and Colliding beams in a single experiment – a novel approach to study the matter under new extreme conditions

Kyrill Bugaev

in Collaboration with

Theoretical Modeling

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Offshell-2021, July 7, 2021

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!

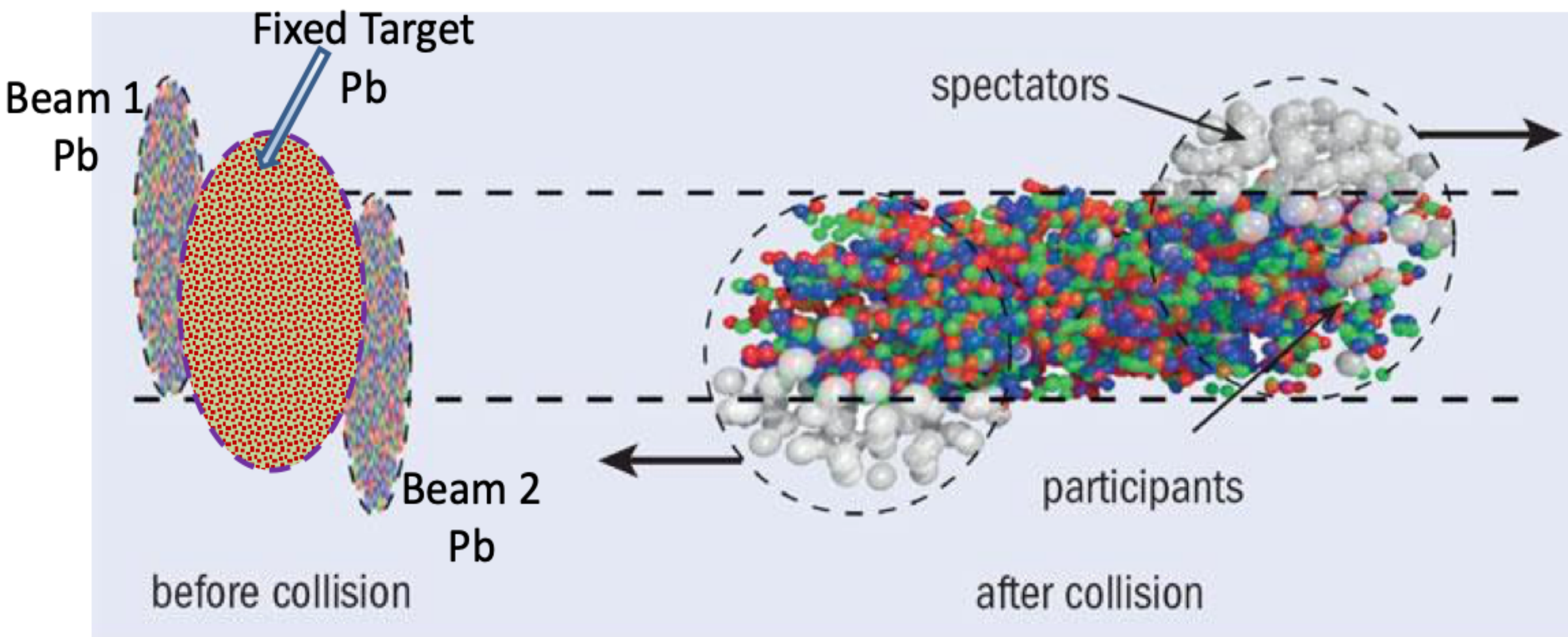
   The neutron matter EoS is necessary as input for Such modeling, but it is less known than the nuclear matter EoS (recall the tetra-neutron problem!)

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

Events with three Pb nuclei interaction !

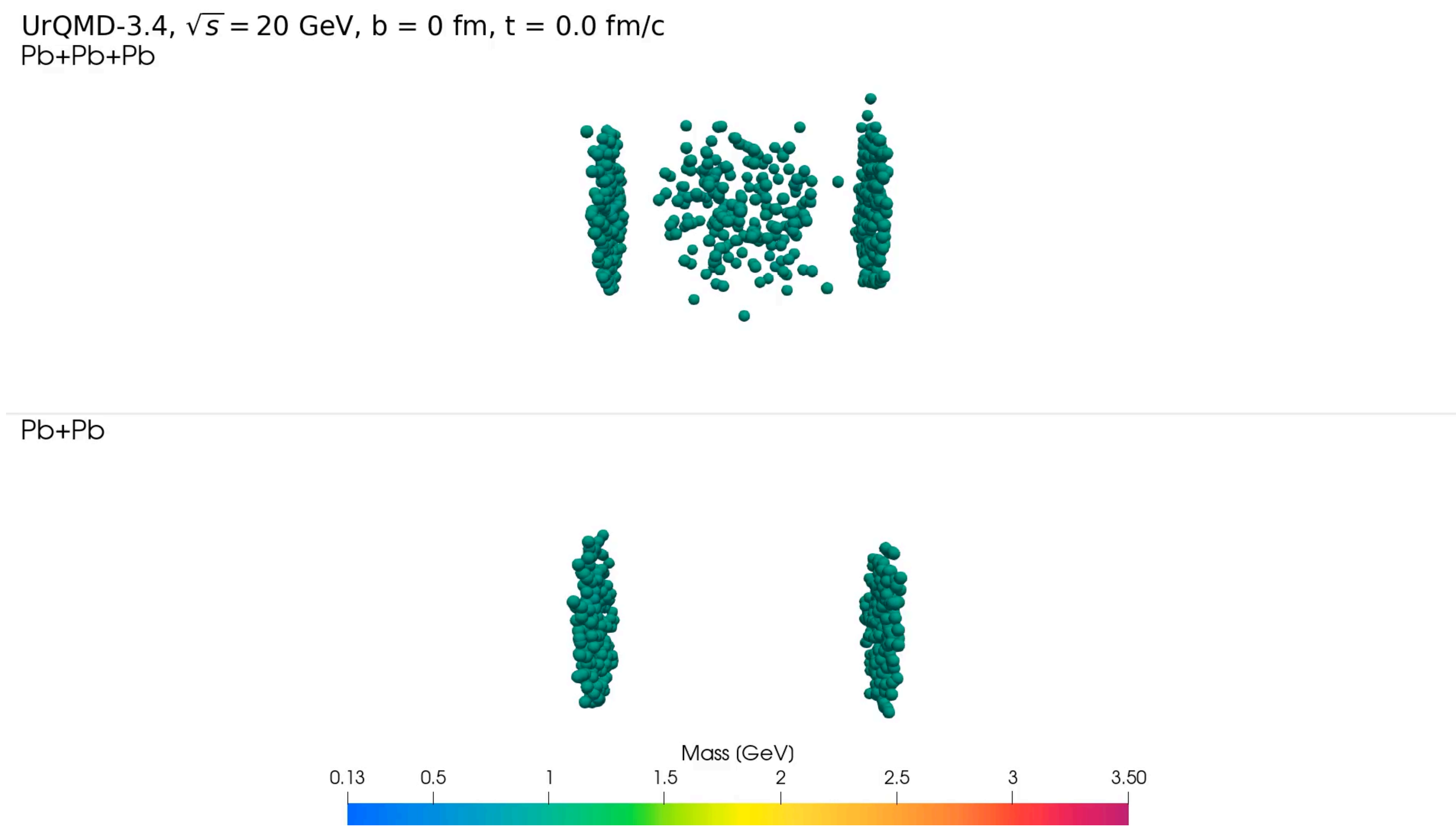
22.06.2017
V.M. Pugatch
presentation at GSI

15.05.2018 Valery Pugatch presented this idea 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.

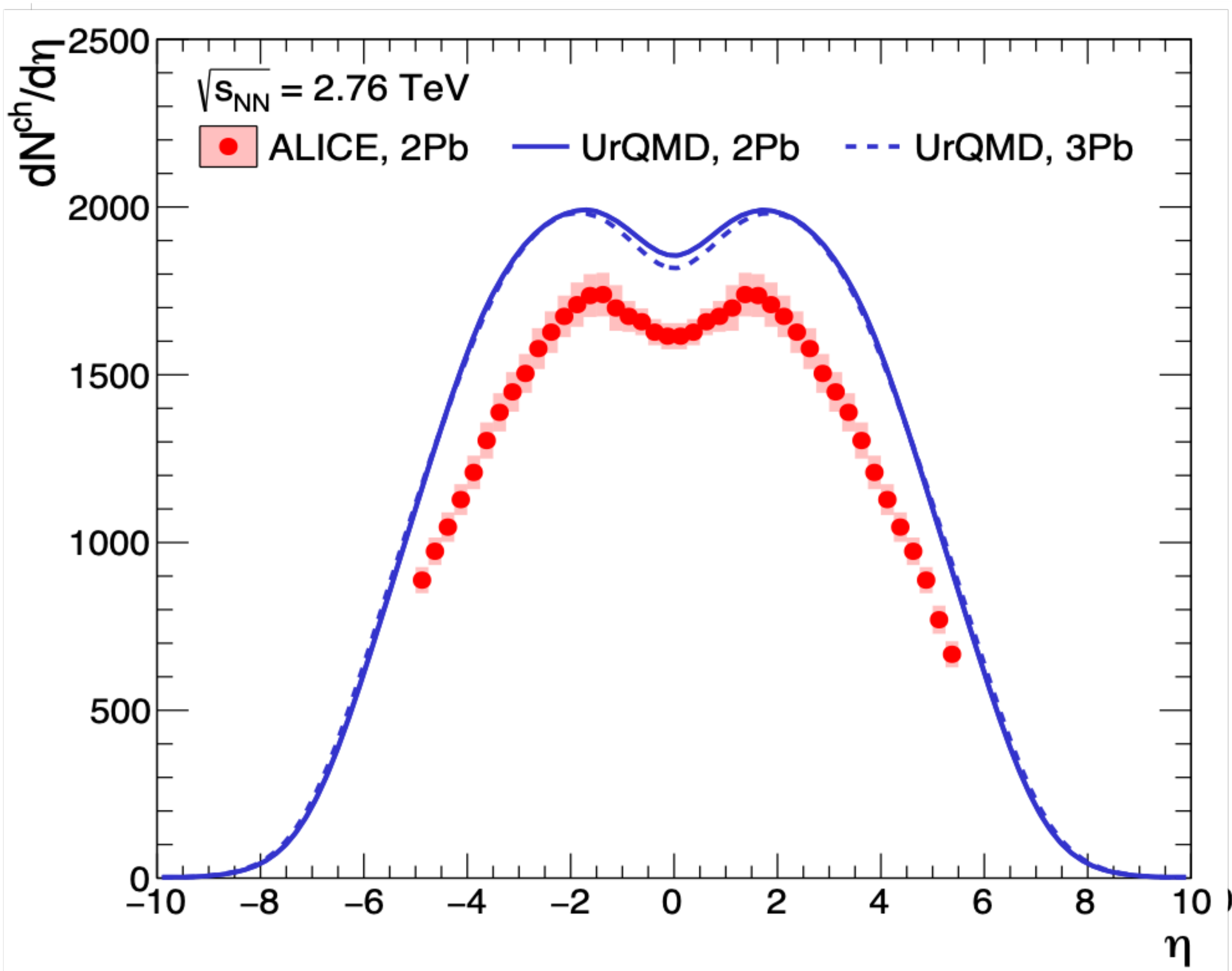


Figure 1: Pseudorapidity distribution of charged particles $\frac{dN_{ch}}{d\eta}$ measured in 0-5% most central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (symbols) [29] vs. the UrQMD results (curve).

Pb+Pb 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%

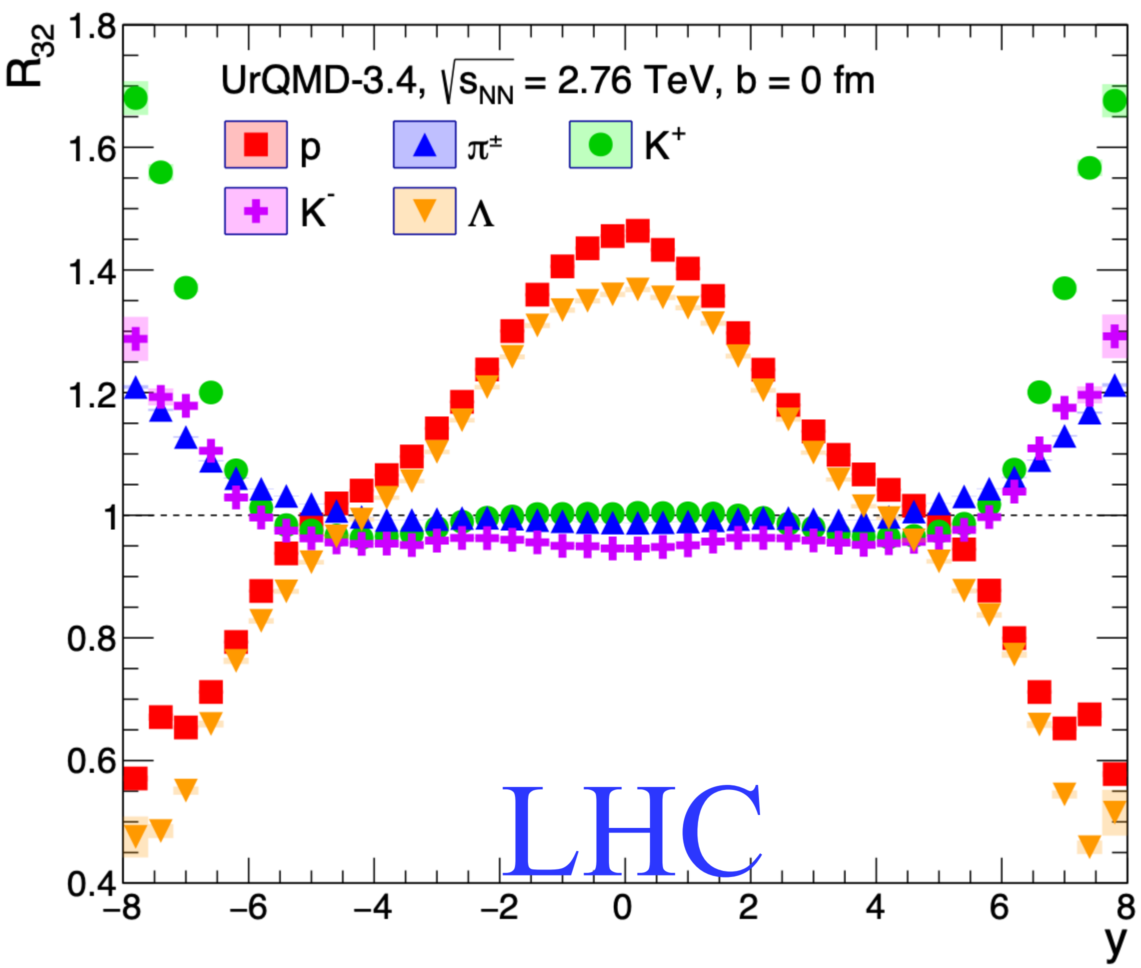
Ratios of (Pb+Pb+Pb)/(Pb+Pb) Results

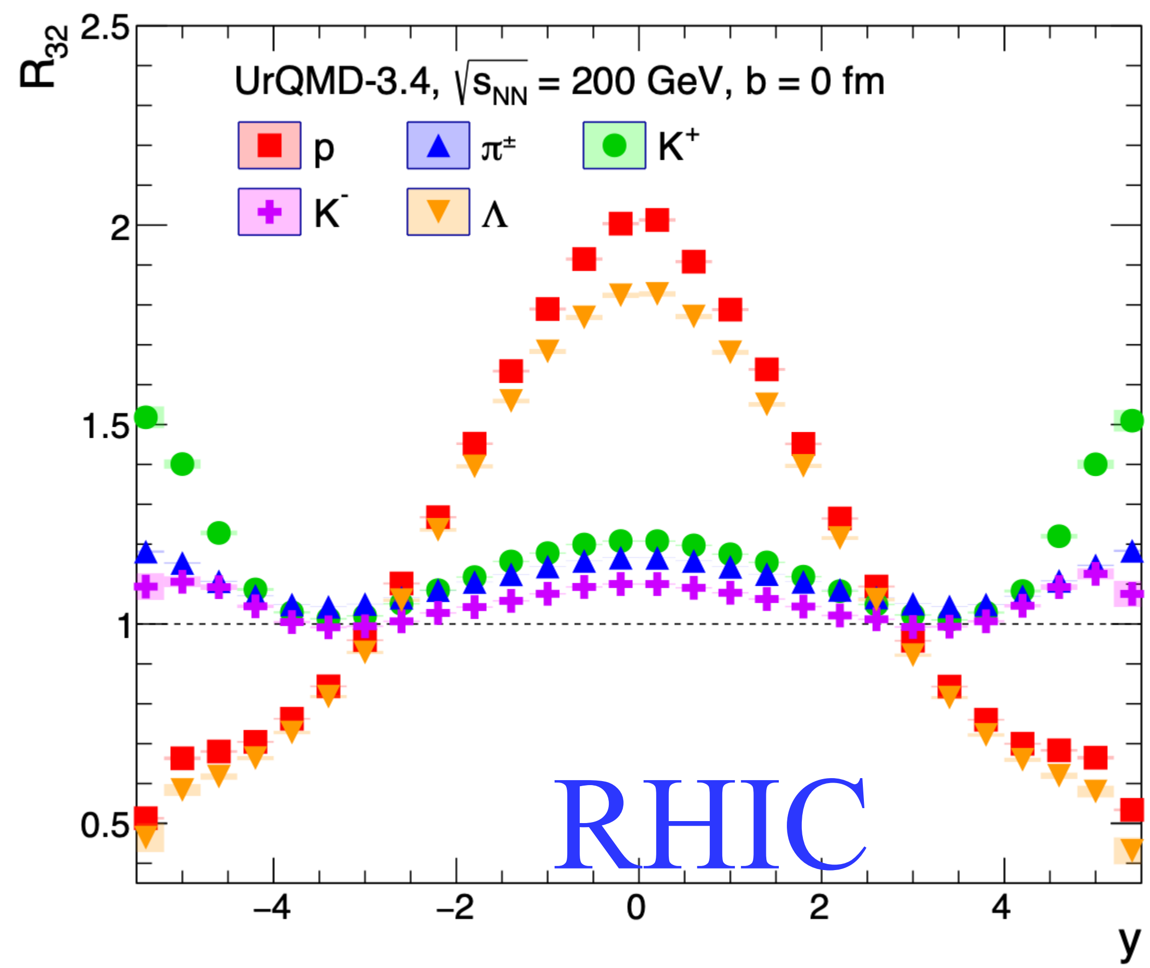
* Our main interest is the baryon production in most central collisions.

* 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!

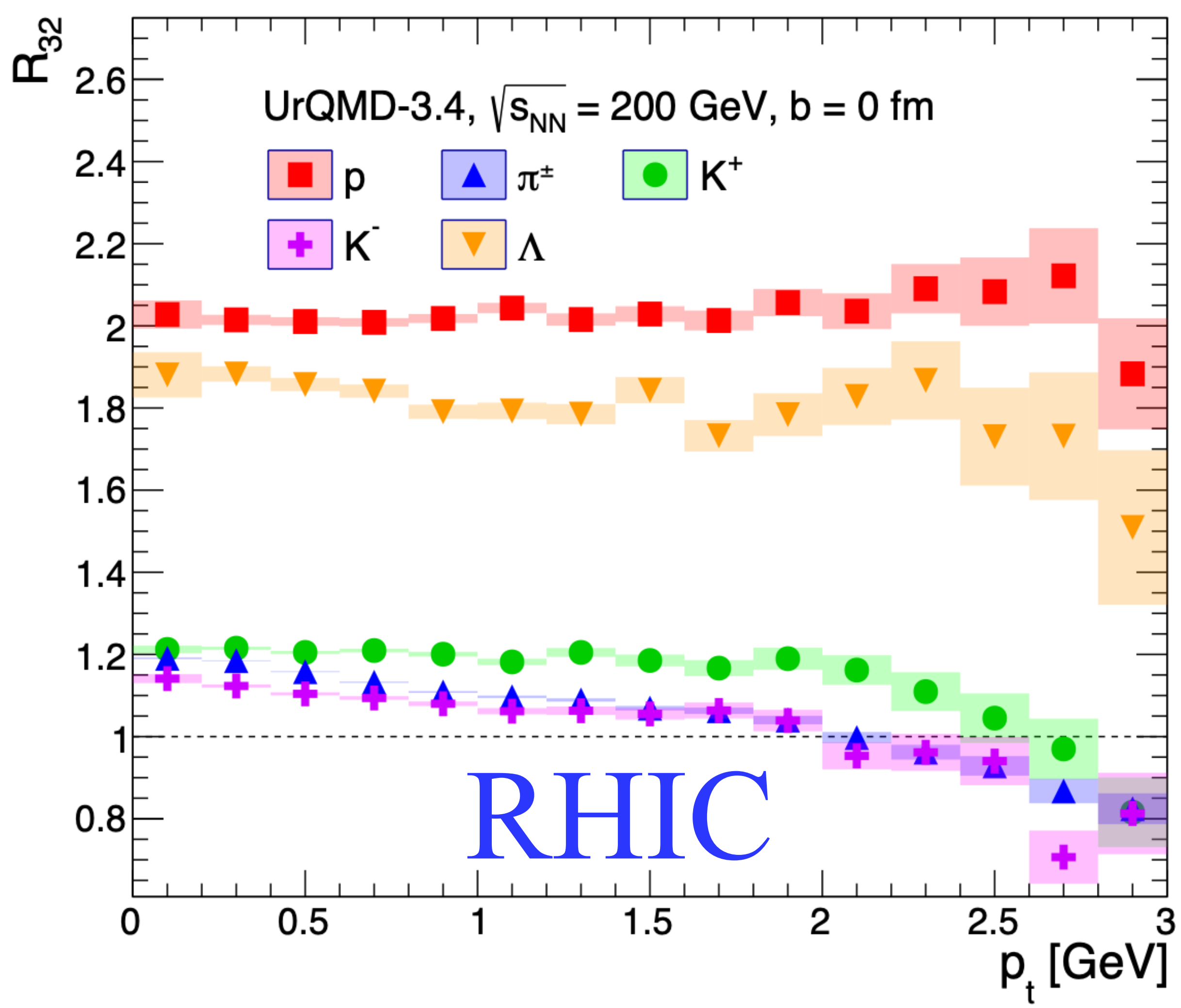


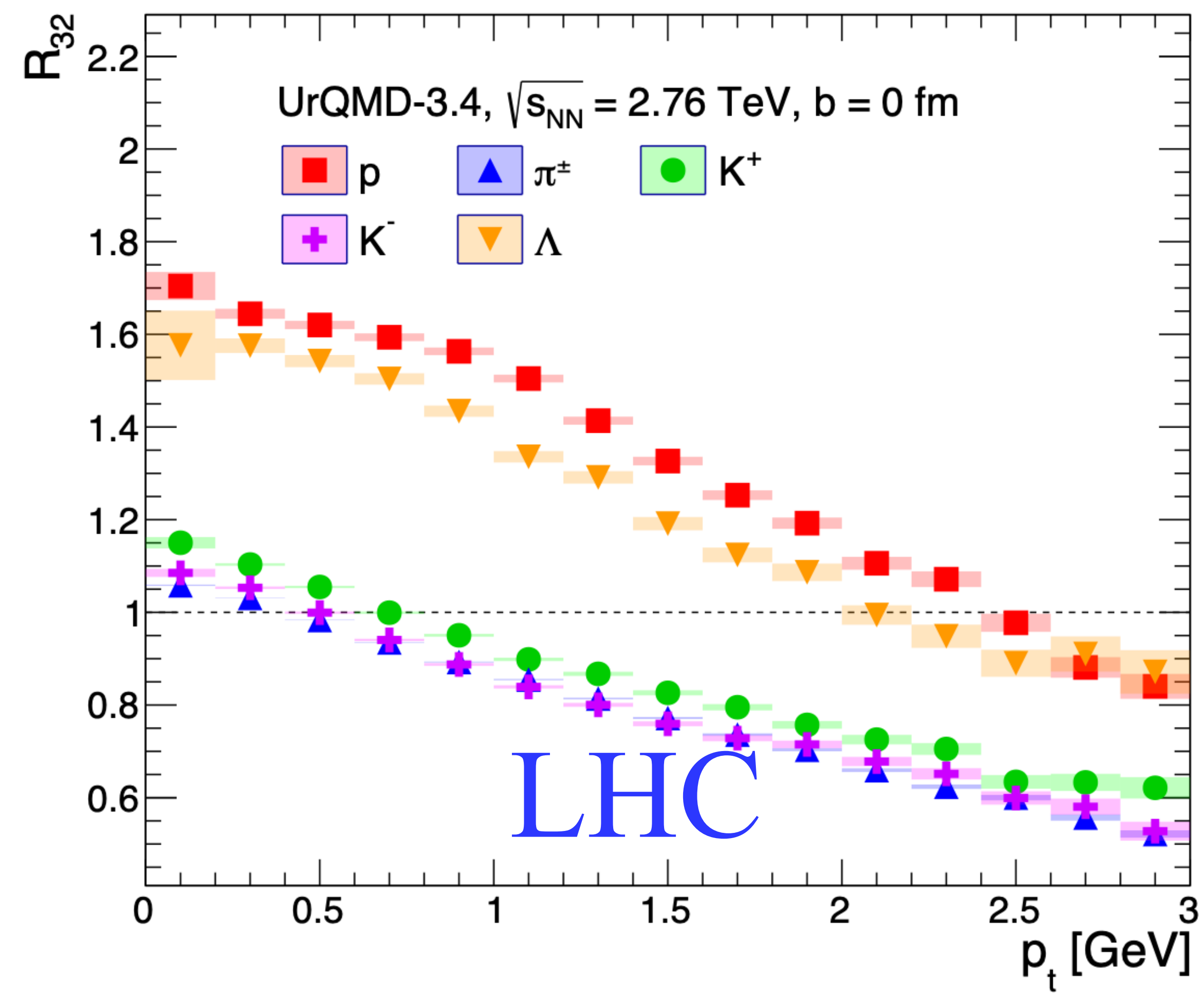


In (Pb+Pb+Pb) reactions p and Λ-hyperons are strongly enhanced at midrapidity!

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

In (A+A+A) reactions the p_T-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

Normalizing UrQMD 3.4 on A+A data 2

To understand the UrQMD results for Pb+PB+Pb TNC consider p+C+p collisions at 2.76 TeV for proton beams!

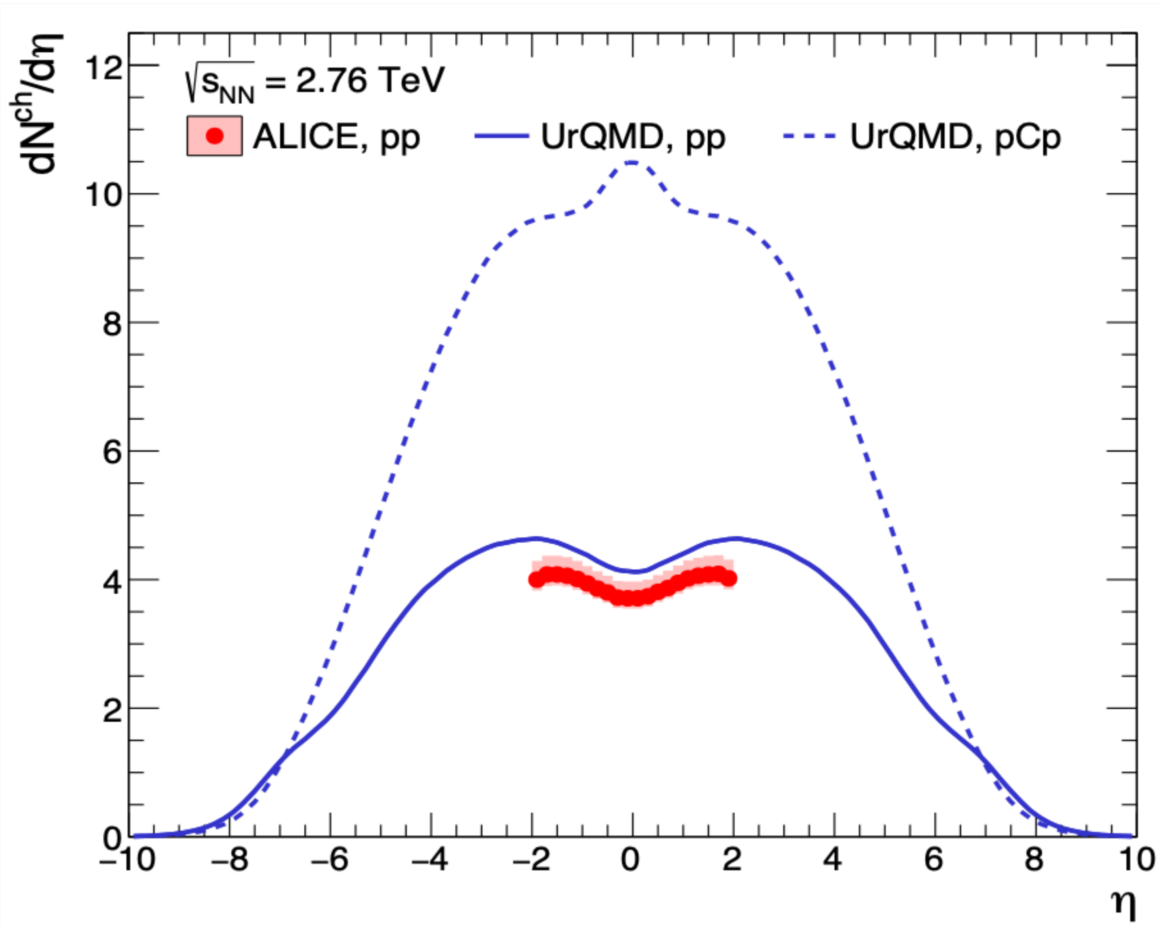
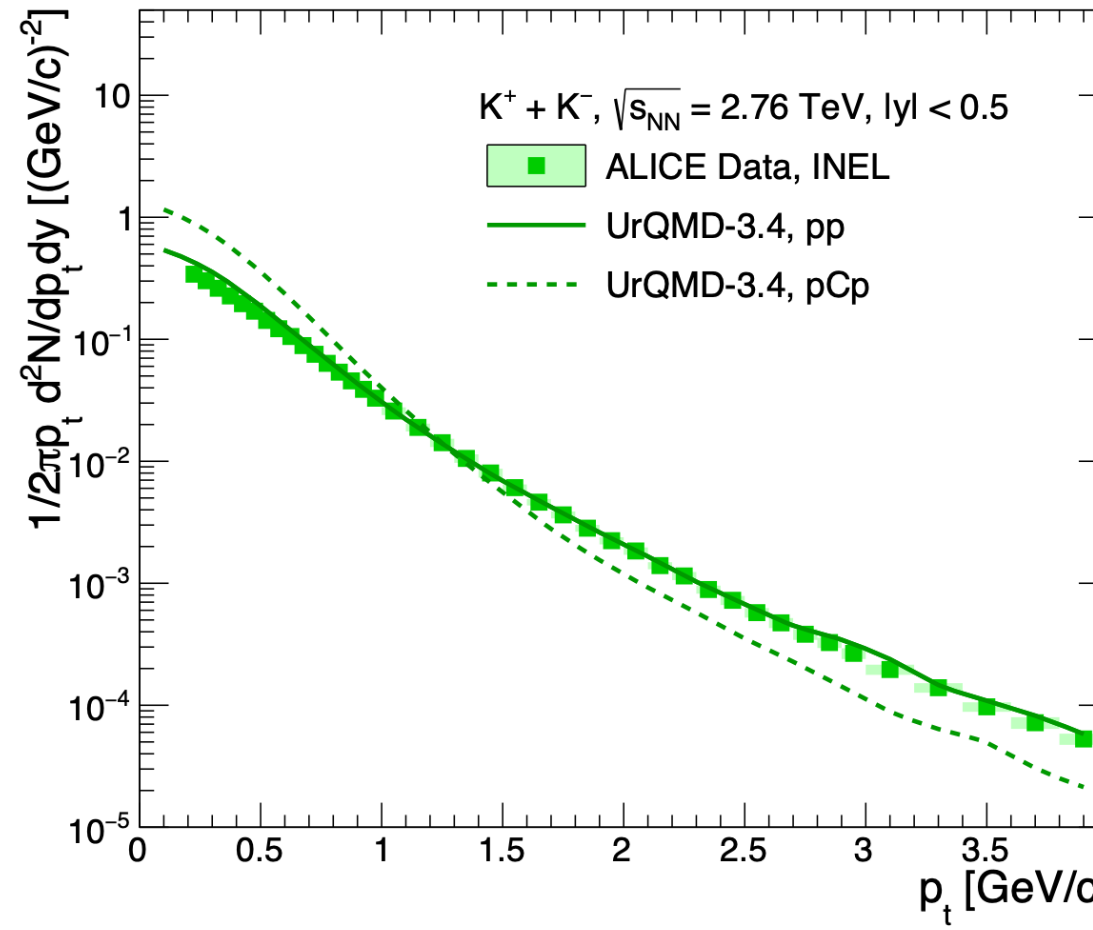


Fig. 5 Comparison of the pseudorapidity distributions of charged particles $\frac{dN_{ch}}{d\eta}$ found in the experiments with the ones obtained by the UrQMD simulations. **Upper panel:** ALICE data on inelastic p+p collisions of Ref. [38] measured at minimum bias at $\sqrt{s_{NN}}$ = 2.76 TeV (symbols) vs. the UrQMD results (solid curve). For comparison, the dashed curve shows the same distribution for the p+C+p



Typical example: Inelastic kaons in p+p Collisions are overestimated < 10%.
Protons - reasonably well described,
Pions are overestimated

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

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

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

=>

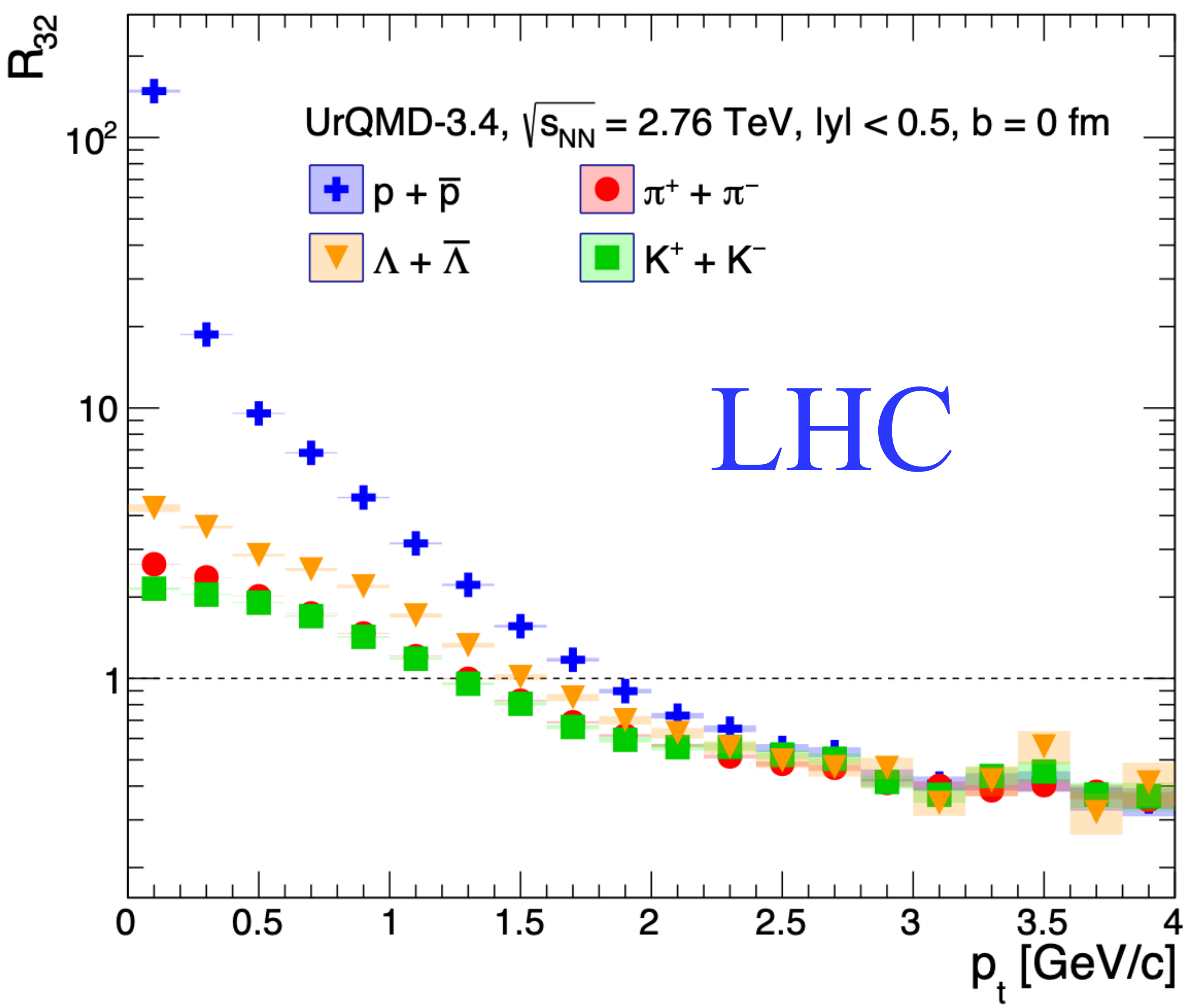
In the ratios the (A+B+A)/(A+A) results must be less affected by these deviations!

In (p+C+p) reactions p and Λ-hyperons are strongly enhanced at low p_T and Suppressed for p_T > 2 GeV!

=> Measuring the ratio

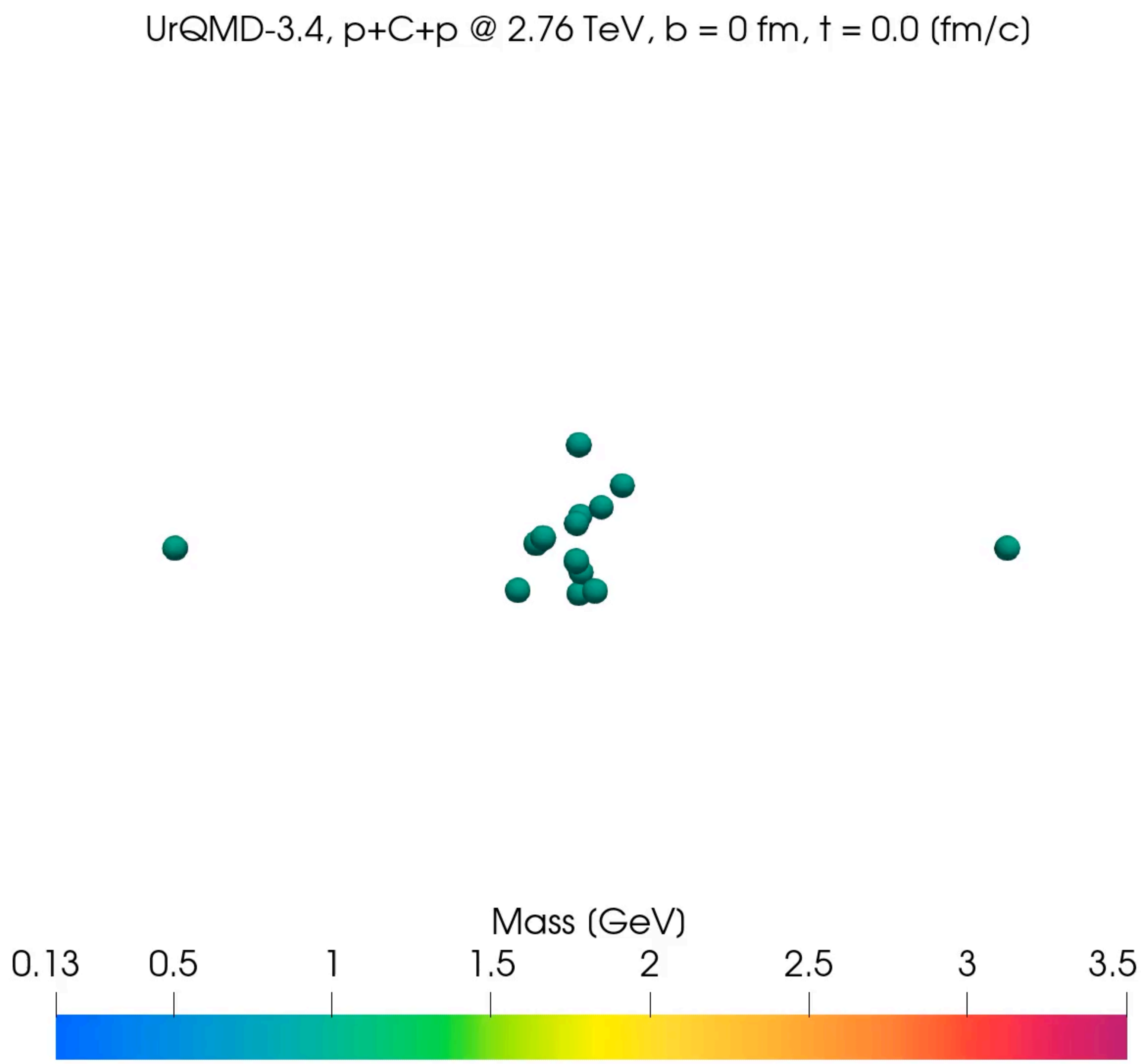
$$R(\text{low p}_\text{T} \text{ to high p}_\text{T}) \equiv$$

$$\equiv \left.\frac{d^2N}{p_T dp_T dy}\right|_{p_T<1\text{GeV}} \Bigg/ \left.\frac{d^2N}{p_T dp_T dy}\right|_{p_T>2.5\text{GeV}}$$



One can distinguish p+C+p collisions from p+p ones!

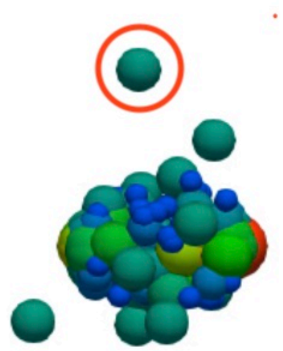
Transverse momentum redistribution effect In p+C+p TNC



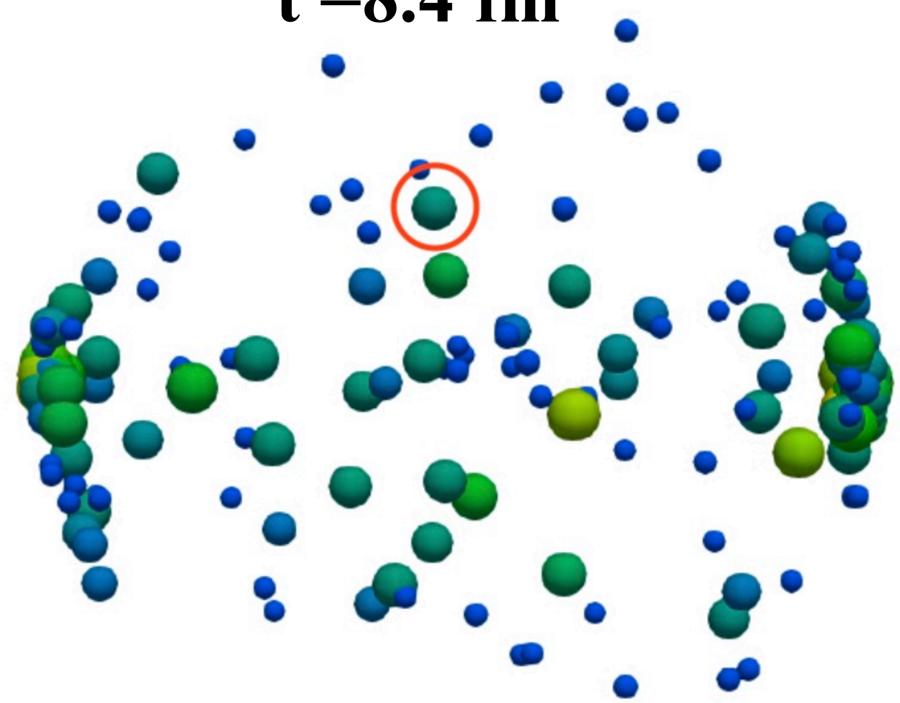
Video: V~m (Bag Model) made by Oleksandr Vitiuk

Transverse momentum redistribution effect In p+C+p TNC

t =5 fm



t =8.4 fm



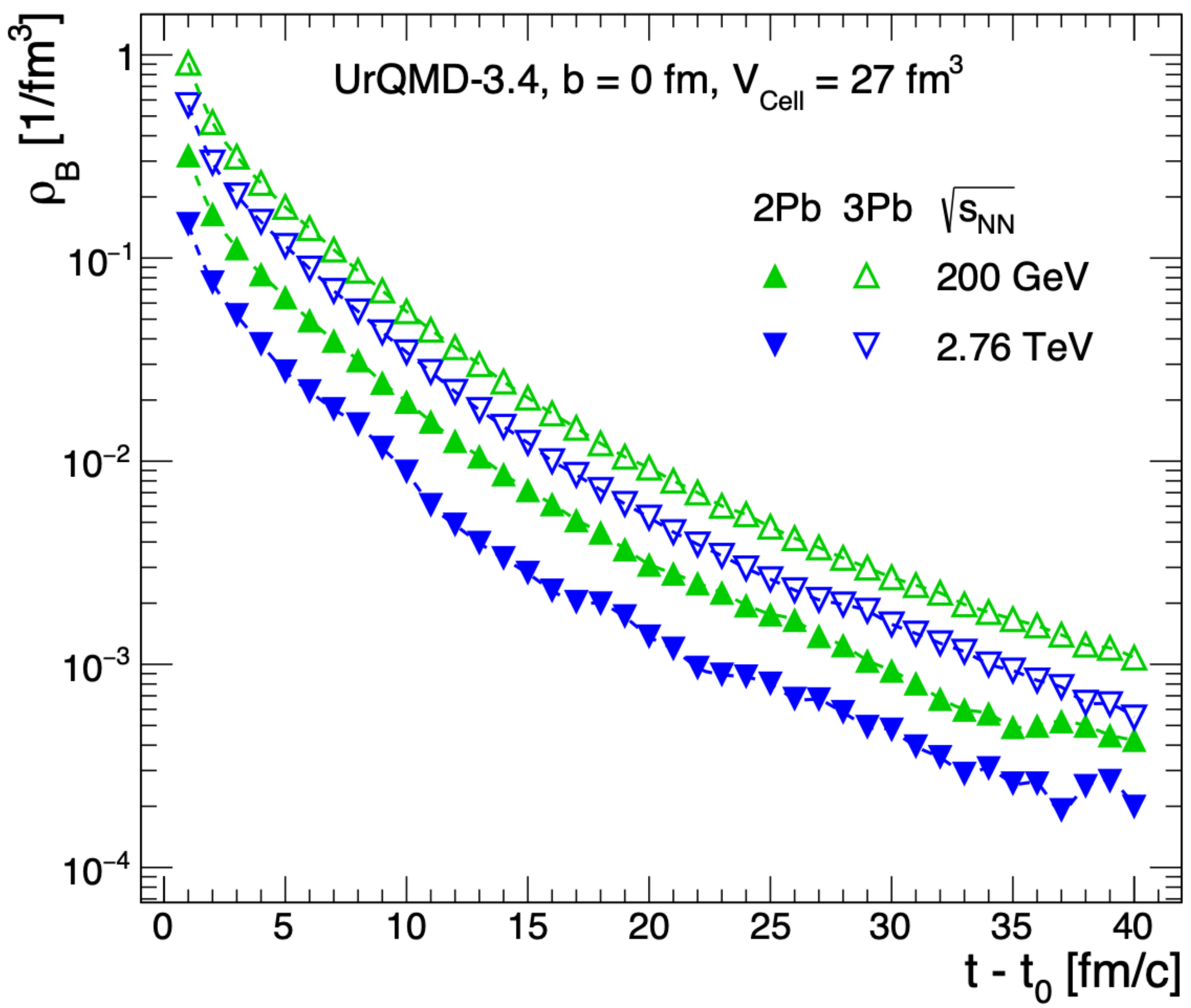
The primary hadrons from p+p (or p+p+p) collision re-scatter on the nucleons of C-nucleus and lose the part of their p_T momentum!

Encircled nucleon of C-nucleus practically does not move during the whole reaction!

=> Strong enhancement of soft particles!
Similar effect at RHIC, but at higher p_T ~ 3 GeV

Central Cell Evolution in Pb+Pb+Pb TNC 1

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



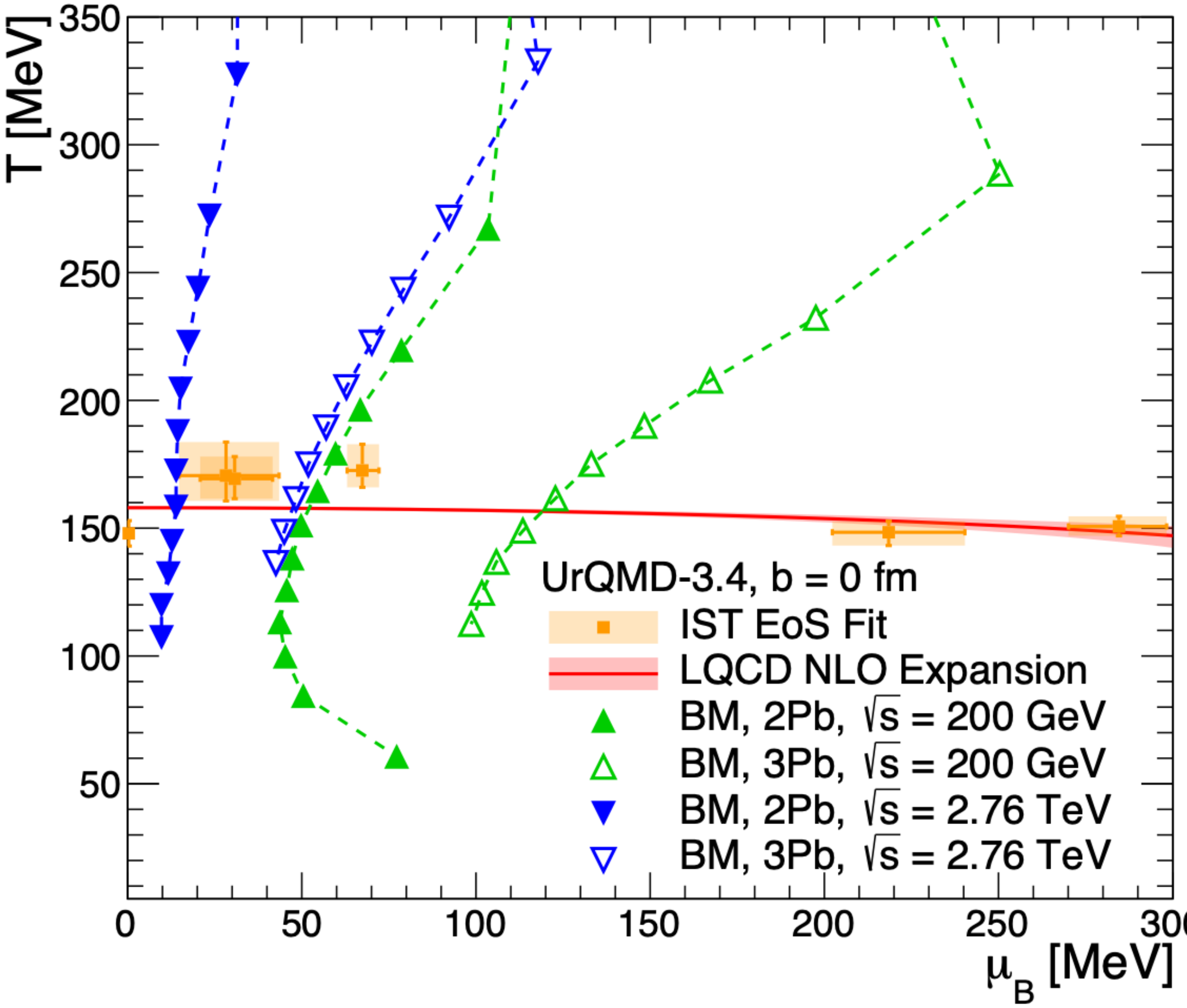
t_0 is the time, when the remnants of projectile nuclei have passed through each other.

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 in Pb+Pb+Pb TNC 2

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



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

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

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

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

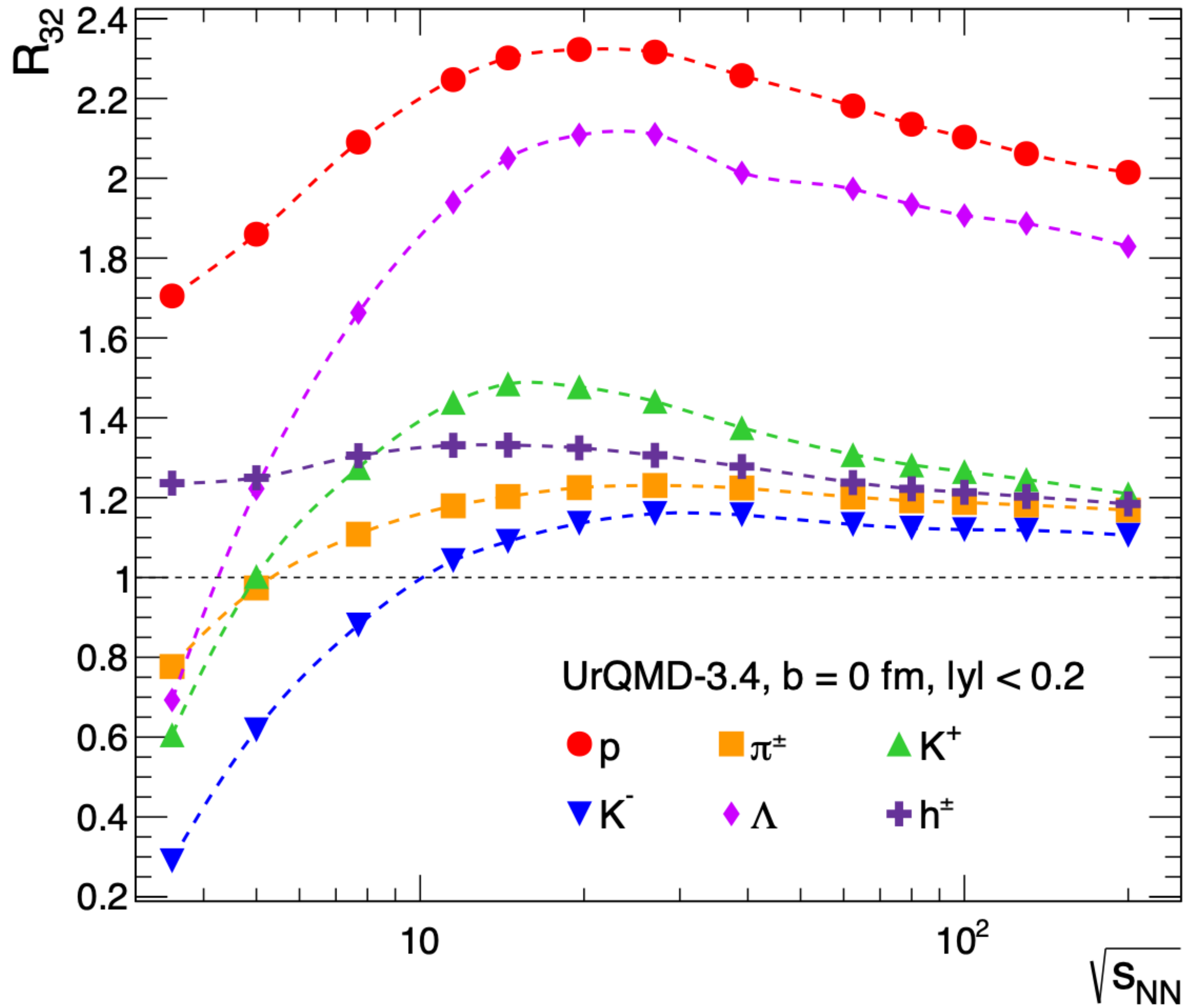
Equating ρ and ε found by UrQMD to the ones of MIT Bag Model => μ_B and T of central cell

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!
With TNC we can probe very high densities of baryonic and electric charges

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 $h \geq 2R_b \simeq 3.2\,\mu\mathrm{m}$

R_b is mean beam radius

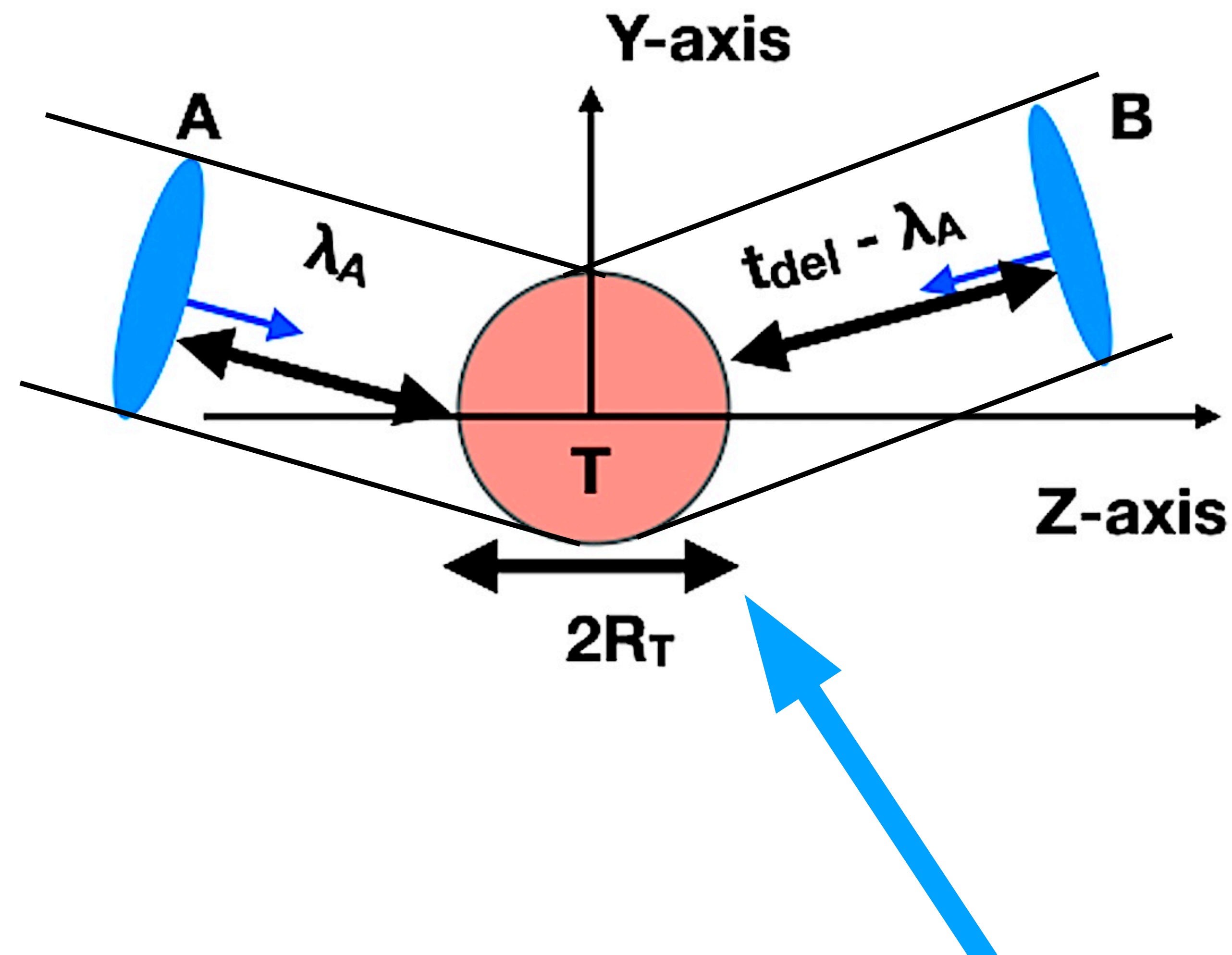
Collision rate of $A+T+B$ with time delay $t_{del} \leq 10$ fm

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

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 $h < 2R_b \simeq 3.2\,\mu\mathrm{m}$ 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

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

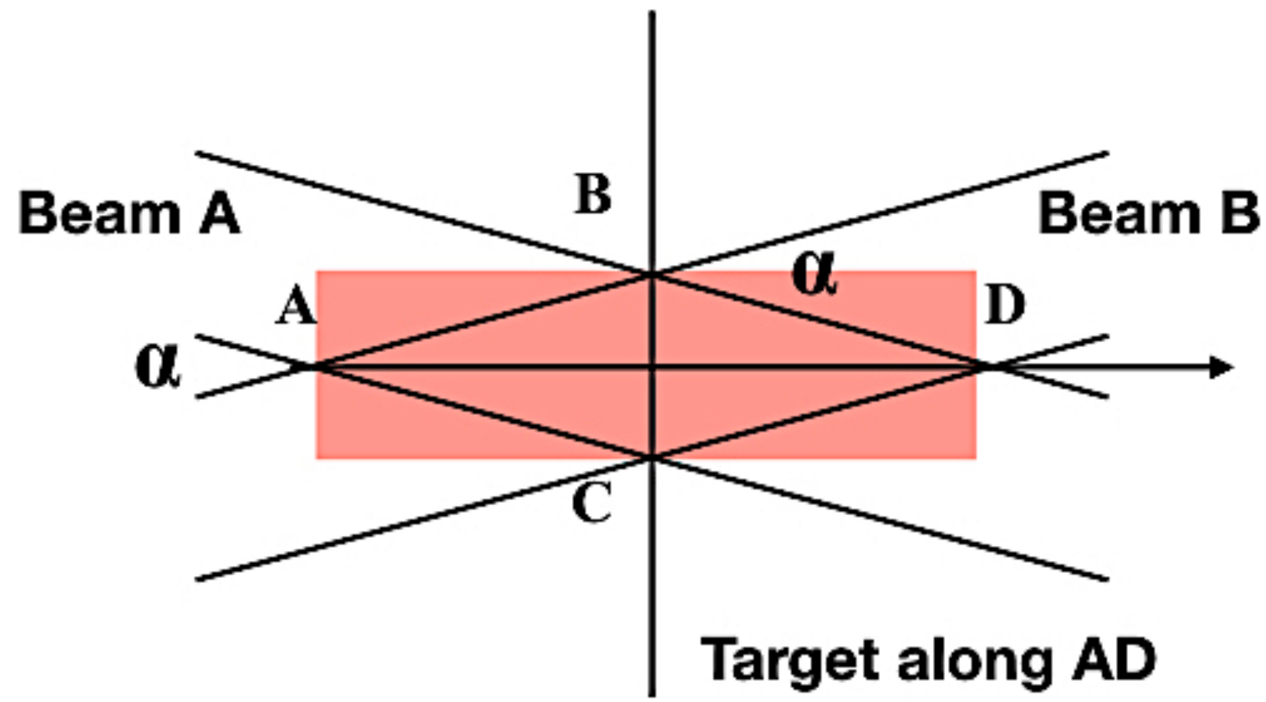
$$\sigma_{p+C} \simeq 33.5\text{mb} \left[\frac{1^{\frac{1}{3}} + 12^{\frac{1}{3}}}{1^{\frac{1}{3}} + 1^{\frac{1}{3}}} \right]^2 \simeq 91\text{mb},$$

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

was taken from PDG

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

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



Results for target T being along AD

TNC Rates 3

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

$$\frac{dN_{p+C+p}}{dt} \simeq 10^{36} \frac{1}{s \cdot cm^2} \cdot 3.5 \cdot 10^{-26} cm^2 \cdot 6 \cdot 10^{-14} nucl. \simeq 2 \cdot 10^{-3} \frac{1}{s}$$

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

$$\frac{dN_{3Pb}}{dt} \simeq 9 \cdot 10^{32} \frac{1}{s \cdot cm^2} \cdot 1.3 \cdot 10^{-24} cm^2 \cdot 2.25 \cdot 10^{-13} nucl. \simeq 3 \cdot 10^{-4} \frac{1}{s}$$

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

$$\frac{dN_{3Pb}^{future}}{dt} \simeq 0.3 \frac{1}{s} \ !$$

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 these 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 (rotating). ⇒ target will evaporate and not explode.

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

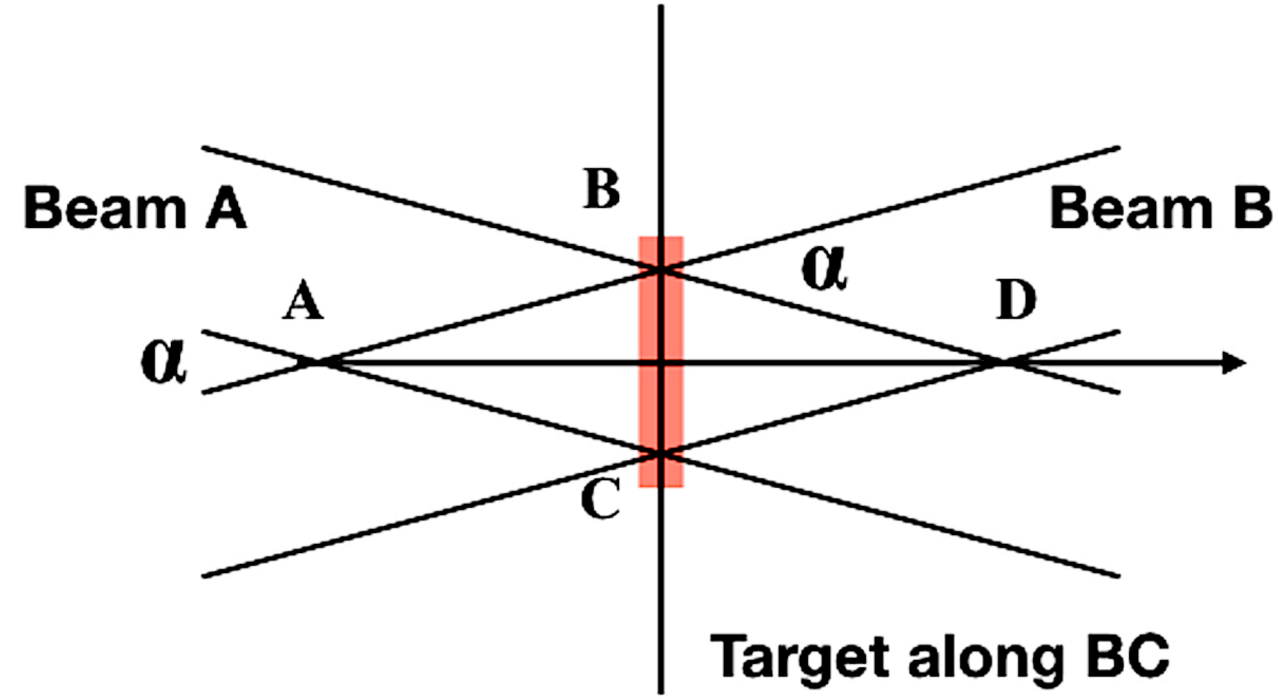
3. Cardinal solution is to make the third (low energy) ring with proper synchronisation of collisions

Second Main Conclusion: new ideas are necessary!

TNC Rates for Traditional Arrangement of Target

In this case TNC rates should be reduced by a factor

$$\frac{\text{V(irrad)}}{\text{V(beams)}} = h\,\frac{\sin(\alpha)}{4R_b} \simeq 7\cdot 10^{-5}$$



Hence in this case TNC rates will be too small

$$\frac{dN_{p+C+p}}{dt} \simeq 1.4\cdot 10^{-7}\,\frac{1}{s}$$

$$\frac{dN_{3Pb}}{dt} \simeq 2.4\cdot 10^{-8}\,\frac{1}{s}$$

Nevertheless, experiments with traditional target arrangement are necessary to develop the prototype of restorable target

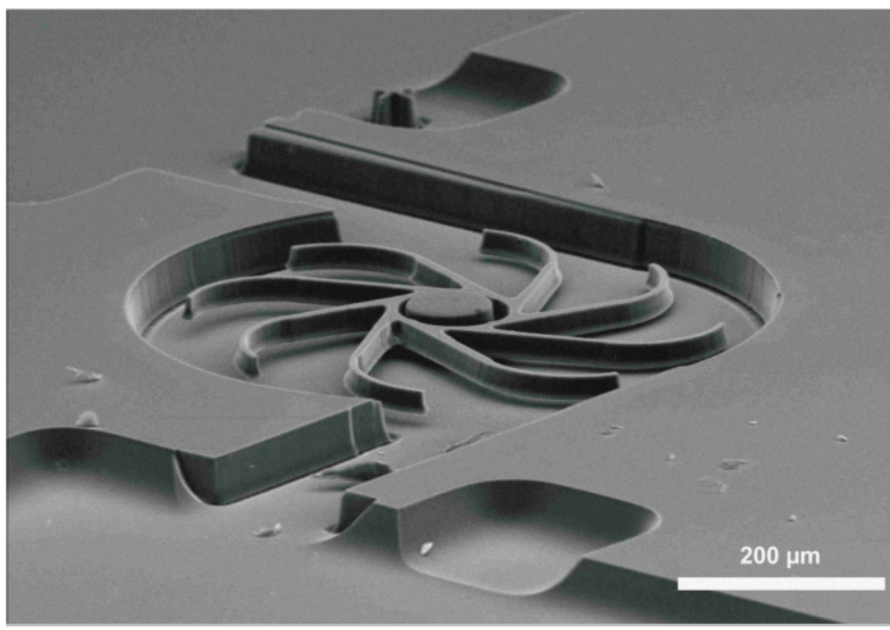
Our Colleagues at Kyiv Institute for Nuclear Research Are Working on Super-thin (graphen) Target

For more details see poster No 99

«The super-thin fixed target for the LHCb experiment in Run4»

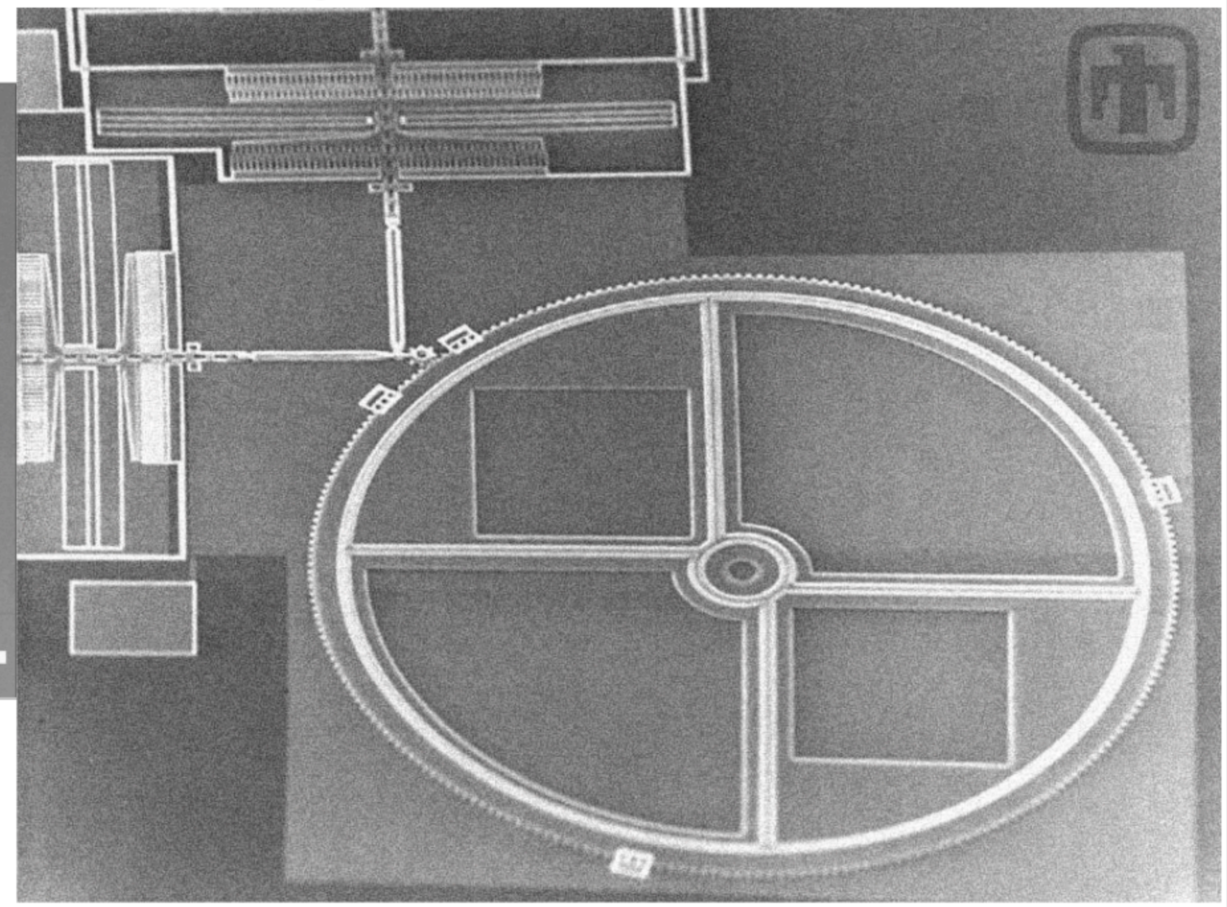
by **Serhii Chernyshenko et al**

Microelectromechanical systems



МЭМС-насос.

(MEMS pump)



Оптический МЭМС-затвор

(Optical MEMS shutter)

2

MEMS (used by NASA for cosmic apparata) provide nanometer precision which is necessary for target insertion into the beam.

Conclusions 1

1.Very interesting Physics of TNC Awaits for us! With TNC we can probe very high densities of baryonic and electric charges

It seems that TNC may be helpful in observing:

the chiral magnetic effect (due to stronger el-m. fields)
K. Fukushima, D. E. Kharzeev H. J. Warringa, Phys. Rev. D 78, (2008) 074033.

the chiral vortical effect (due to larger baryonic charge density)
O. Rogachevsky, A. Sorin and O. Teryaev, Phys. Rev. C 82, (2010) 054910.

a possible pion (kaon?) condensation [in p+C+p TNC] at LHC

a formation of droplets of strange (Λ) matter due strong enhancement of Λ-hyperons

and ….

Conclusions 2

2. 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

3.There are many technological problems to be solved before the TNC will become a reality and, therefore, we need new and original ideas

Thank you very much for your attention!

Ultra-relativistic Quantum Molecular Dynamics (UrQMD 3.4)

nucleon	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1192}	Ξ_{1317}	Ω_{1672}
N_{1440}	Δ_{1600}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	
N_{1520}	Δ_{1620}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1700}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1900}	Λ_{1670}	Σ_{1775}	Ξ_{1950}	
N_{1675}	Δ_{1905}	Λ_{1690}	Σ_{1790}	Ξ_{2025}	
N_{1680}	Δ_{1910}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1920}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1930}	Λ_{1820}	Σ_{2030}		
N_{1720}	Δ_{1950}	Λ_{1830}			
N_{1900}		Λ_{1890}			
N_{1990}		Λ_{2100}			
N_{2080}		Λ_{2110}			
N_{2190}					
N_{2200}					
N_{2250}					

0^{-+}	1^{--}	0^{++}	1^{++}
π	ρ	a_0	a_1
K	K^*	K_0^*	K_1^*
η	ω	f_0	f_1
η'	ϕ	f_0^*	f_1'
1^{+-}	**2^{++}**	**$(1^{--})^*$**	**$(1^{--})^{**}$**
b_1	a_2	ρ_{1450}	ρ_{1700}
K_1	K_2^*	K_{1410}^*	K_{1680}^*
h_1	f_2	ω_{1420}	ω_{1662}
h_1'	f_2'	ϕ_{1680}	ϕ_{1900}

List of included particles in the hadron cascade

- Binary interactions between all implemented particles are treated
- Cross sections are taken from data or models
- Resonances are implemented in Breit-Wigner form
- No in-medium modifications