Triple Nuclear Collisions (TNC) and new perspectives to explore the QCD matter properties under new extreme conditions

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in Collaboration with

Theoretical Modeling

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ICNFP 2021, Crete, September 1, 2021
1. Present status of binary A+A collisions vs problems on a large scale

2. What are the alternatives to binary A+A collisions?

3. Normalization of UrQMD at LHC energies for Pb+Pb+Pb and p+C+p reactions

4. Results for TNC at LHC and highest RHIC energies

5. Some results at lower collision energies: Pb+Pb+Pb collisions

6. Estimates for the TNC rates and related problems

7. Conclusions
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

Events with three Pb nuclei interaction!
Example $\sqrt{s} = 20$ GeV

Modeling the TNC with UrQMD 3.4

UrQMD-3.4, $\sqrt{s} = 20$ GeV, $b = 0$ fm, $t = 0.0$ fm/c
Pb+Pb+Pb

Pb+Pb

Video: $V_\sim m$ (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.: 

\[ p^\mu \cdot \partial_\mu f_i(x^\nu, p^\nu) = C_i \]

The collision term C includes more than 100 hadrons


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.

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.

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for impact parameter $b=0$ fm

=> Pions are strongly overestimated, kaons on $\sim + 20\%$, protons - well described! Antiprotons $\sim - 15\%$

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).
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

\[ \Rightarrow \]

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

In \((Pb+Pb+Pb)\) reactions \(p\) and \(\Lambda\)-hyperons are strongly enhanced at midrapidity!
In (A+A+A) reactions the $p_T$-spectra of particles at RHIC and LHC energies show enhancement of slow hadrons and deficit of fast ones!

Spectra are modified by a constant factor!

Number of slow hadrons is enhanced stronger! => 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 $\frac{dN_{\text{ch}}}{d\eta}$ 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

\[ \text{In the ratios the } (A+B+A)/(A+A) \text{ results must be less affected by these deviations!} \]

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

\[ \Rightarrow \text{Measuring the ratio} \]

\[ R(\text{low } p_T \text{ to high } p_T) \equiv \frac{d^2 N}{p_T dp_T dy \mid p_T < 1 \text{GeV}} / \frac{d^2 N}{p_T dp_T dy \mid p_T > 2.5 \text{GeV}} \]

One can distinguish \(p+C+p\) collisions from \(p+p\) ones!

LHC
Transverse momentum redistribution effect
In p+C+p TNC

UrQMD-3.4, p+C+p @ 2.76 TeV, b = 0 fm, t = 0.0 (fm/c)

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

$\Rightarrow$ Strong enhancement of soft particles!
Similar effect at RHIC, but at higher $p_T \sim 3$ 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

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

\[
p^{BM} = \frac{95}{180} \pi^2 T^4 + \frac{T^2 \mu_B^2}{6} + \frac{\mu_B^4}{108 \pi^2} - B_{vac},
\]

here the vacuum pressure \( B_{vac} \) was chosen as \( B_{vac}^{1/4} = 206 \) MeV

From EoS one can find

**baryonic charge density** \( \rho \) and

**Energy density** \( \varepsilon \)

\[
\rho_B^{BM} = \frac{\partial p^{BM}}{\partial \mu_B}, \quad s_B^{BM} = \frac{\partial p^{BM}}{\partial T},
\]

\[
\varepsilon^{BM} = T s_B^{BM} + \mu_B \rho_B^{BM} - p^{BM}.
\]

Equating \( \rho \) and \( \varepsilon \) found by UrQMD to the ones of MIT Bag Model => \( \mu_B \) and \( T \) of central cell

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 Conclusion

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

But what are the TNC rates?

Are the TNC the dreams of theoreticians?
TNC Rates for Most Central Collisions

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

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

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

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

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

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

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

\[ \frac{dN_p}{dt} \sim 10^{18} \text{ s}^{-1} \]

one can find that energy deposition per second

\[ \frac{dE_{p+C+p}}{dt} \sim 1.76 \cdot 10^6 J \text{ s}^{-1} \iff \text{explosion of } 420 \text{ } \frac{g}{s} \text{ of TNT!} \]

How to resolve this problem?
1. Use super-thin target, which is restorable (rotating). \(\Rightarrow\) 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!
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)

   the **chiral vortical effect** (due to larger baryonic charge density)

   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)

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

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Rates for Central TNC (highly idealized case!)

General Formulae for TNC:

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

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

$$\frac{dN_{A+T+B}}{dt} \simeq L^{A+B} \cdot \sigma^{A+B} \cdot N_{T}^{int}$$

here $N_{T}^{int}$ is number of TNC with $t_{del}$

$$N_{T}^{int} = \rho_T \cdot V_{A+T+B}^{int}$$

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

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

$R_B$ is radius of nuclei in beam $B$

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

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

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

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

was taken from PDG

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

$$V_{3P_0}^{int} \leq 2\pi \left( 1.25 \cdot 208^{\frac{1}{3}} \text{ fm} \right)^2 \cdot \left[ 2.5 \cdot 208^{\frac{1}{3}} \text{ fm} + 5 \text{ fm} \right] \simeq 6828 \text{ fm}^3$$
In this case TNC rates should be reduced by a factor

\[
\frac{V(\text{irrad})}{V(\text{beams})} = \hbar \frac{\sin(\alpha)}{4R_b} \approx 7 \cdot 10^{-5}
\]

Hence in this case TNC rates will be too small

\[
\frac{dN_{p+C+p}}{dt} \approx 1.4 \cdot 10^{-7} \frac{1}{s}
\]

\[
\frac{dN_{3Pb}}{dt} \approx 2.4 \cdot 10^{-8} \frac{1}{s}
\]

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

Microelectromechanical systems

МЭМС-насос.

(MEMS pump)

Optical MEMS shutter

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