Prospects for the (hyper)nuclei study at the NICA energy range

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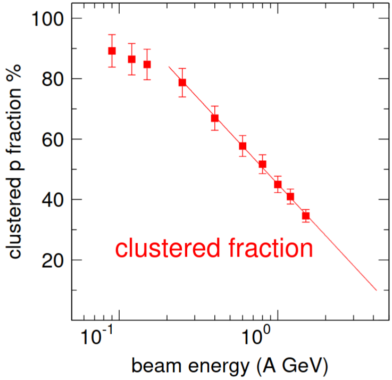
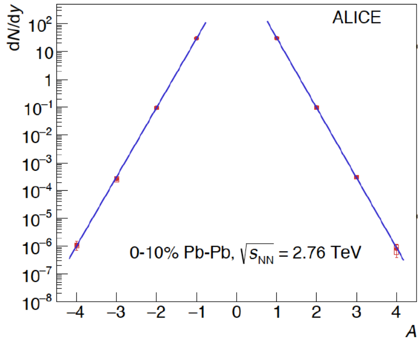
Introduction



Nucl.Phys.A 848 (2010) 366-427

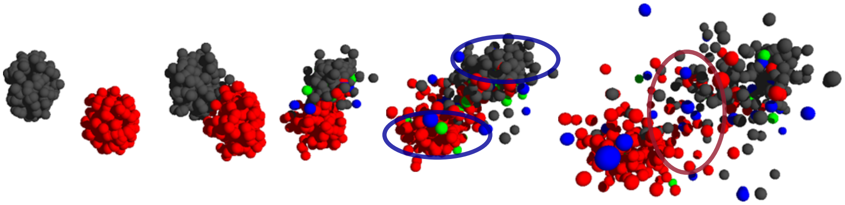
Low energy: up to 20% of protons in central Au+Au collisions at NICA energies are bound into the clusters.



Nucl.Phys.A 971 (2018) 1-20

High energy HIC – "ice in a fire" puzzle: **how the weakly bound objects can be formed in a hot environment?**

Projectile/target spectators: heavy cluster formation
Midrapidity: light clusters



IQMD: Ch. Hartnack

(Anti)hypernuclei production:

- at mid-rapidity by Λ coalescence during expansion
- at projectile/target rapidity by re-scattering/absorption of Λ by spectators

Static approaches: cluster multiplicity determined at a fixed time or temp

- coalescence (early, assumption: no collisions later)
- statistical model (V,T,N) very late $\rho << \rho_0$

Dynamical approaches: cluster multiplicity is function of time

- minimum spanning tree (correlation in coordinate space)
- simulated annealing (correlation in momentum and coordinate space)
- time-dependent perturbation theory using Wigner densities

In order to understand the microscopic origin of clusters formation one needs:

- a realistic model for the dynamical time evolution of the HIC
- dynamical modeling of cluster formation based on interactions

Cluster formation is sensitive to nucleon dynamics $\longrightarrow$ one needs to keep initial and final nucleon correlations by realistic nucleon-nucleon interactions in transport models:

- Quantum-Molecular Dynamics (QMD) – allows to keep correlations.
- Mean-field (MF) based models – correlations are smeared out.

PHQMD transport approach

The goal: to develop a unified n-body microscopic transport approach for the description of heavy-ion dynamics and dynamical cluster formation from low to ultra-relativistic energies.

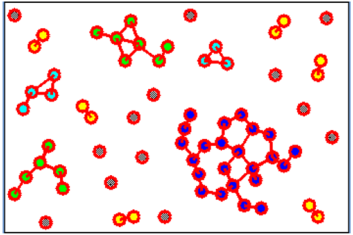
Realization: combined model **PHQMD** = (PHSD & QMD) & MST and SACA

Phys. Rev. C 101, 044905

- **Initialization & propagation of baryons**: Quantum-Molecular Dynamics
- **Propagation of partons (quarks, gluons) and mesons + collision integral** = interactions of hadrons and partons (QGP) from Parton-Hadron-String Dynamics (PHSD) Phys. Rev. C 78 (2008) 034919; Nucl. Phys. A 831 (2009) 215-242
- **Clusters recognition**: Minimum Spanning Tree (MST) or Simulated Annealing Clusterization Algorithm (SACA)

In elementary reactions PHQMD = PHSD.

The **Minimum Spanning Tree (MST)** procedure is a cluster recognition method applicable for the (asymptotic) final states where coordinate space correlations may only survive for bound states.

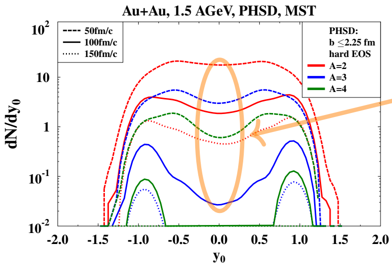


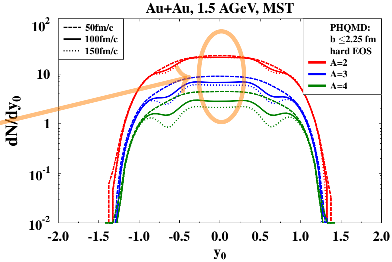
J. Aichelin, Phys.Rept. 202 (**1991**) 233-360

The MST algorithm searches for accumulations of particles in coordinate space:

- Two particles are "bound" if their distance in coordinate space fulfills $|r_i - r_j| \leq 4.0$ fm.
- Particle is bound to a cluster if it bounds with at least one particle of the cluster.
- (new) Cluster binding energy E_{bind} is calculated, clusters only with $E_{bind} < 0$ are taken.

Inclusion of an additional momentum cuts (coalescence) lead to a small changes: particles with large relative momentum are mostly not at the same position.





QMD propagation: number of clusters are stable vs. time (MST finds at 50 fm/c almost the same clusters as at 150 fm/c).

MF propagation:

- Number of fragments is strongly time dependent.
- Fragments disappear with time.
- Midrapidity fragments disappear early, projectile/target fragments later – no common time for coalescence.

The Simulated Annealing Clusterization Algorithm (SACA):

based on idea by Dorso and Randrup (Phys.Lett. B301 (1993) 328)

- Take the positions and momenta of all nucleons at time t.
- Combine them in all possible ways into all kinds of clusters or leave them as single nucleons.
- Neglect the interaction among clusters.
- Choose that configuration which has the highest binding energy.

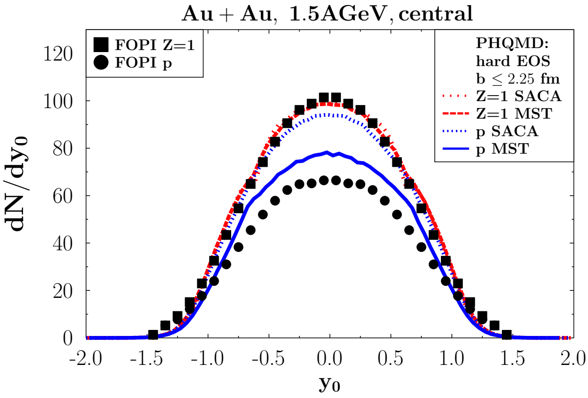
Repeat this procedure many times ("Metropolis" algorithm): **leads automatically to the finding of the most bound configurations**.

R. K. Puri, J. Aichelin, PLB301 (1993) 328, J.Comput.Phys. 162 (2000) 245-266;

P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

Results and ongoing work

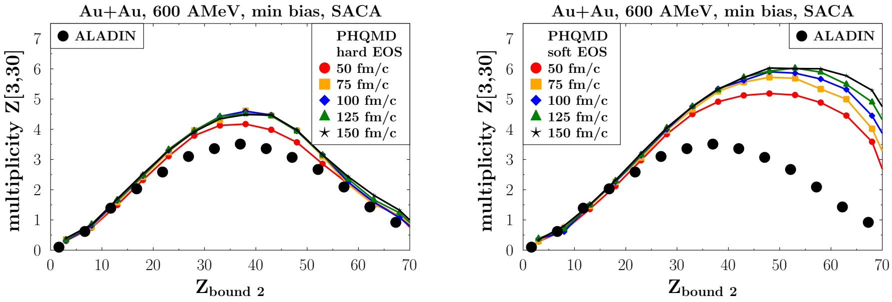
Published in: Phys.Rev.C 101 (**2020**) 4, 044905, arXiv: 1907.03860 [nucl-th]



Scaled experimental rapidity distribution, $y_0 = y/y_{proj}$, of all bound and unbound protons ($Z = 1$), and free (unbound) protons.

The MST algorithm is less sensitive (as SACA) to the potential interaction of nucleons and comes closer to the data $\longrightarrow$ better for the light nuclei description.

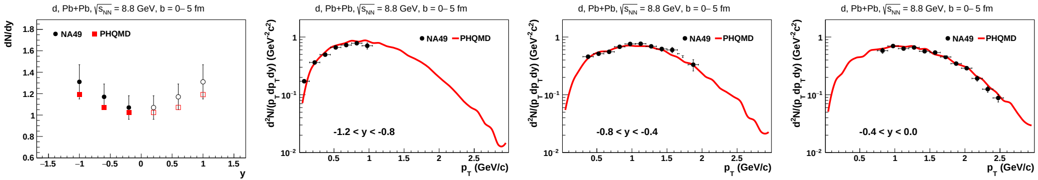
Published in: Phys.Rev.C 101 (**2020**) 4, 044905, arXiv: 1907.03860 [nucl-th]



'Rise and fall' of the multiplicity of clusters with $Z \in [3, 30]$ as a function of the total bound charge $Z_{\text{bound 2}}$.

The clusters identified by SACA are stable for time larger than 50 fm/c. PHQMD with "hard" EoS reproduces experimental data. "Rise and fall" depends strongly on the nuclear EoS: the spectator matter is much less stable with "soft" EoS.

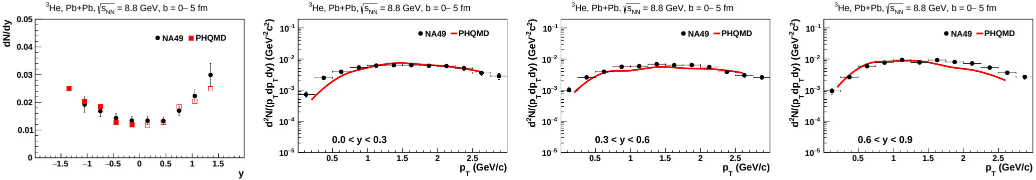
Published in: Phys.Rev.C 105 (**2022**) 1, 014908, arXiv: 2106.14839 [nucl-th]



The rapidity distribution and transverse momentum spectra of deuterons for Pb+Pb central collisions at $\sqrt{s_{NN}} = 8.8$ GeV for different rapidity intervals.

In the whole p_T range the transverse momentum spectra for different rapidity bins are remarkable well reproduced by PHQMD with MST.

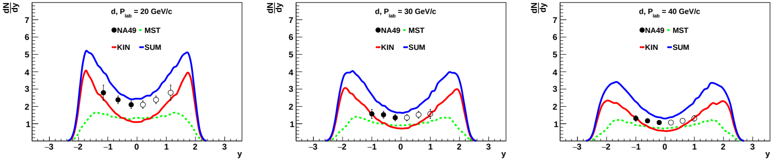
Published in: Phys.Rev.C 105 (**2022**) 1, 014908, arXiv: 2106.14839 [nucl-th]



The rapidity distribution and transverse momentum spectra of ^3He for Pb+Pb central collisions at $\sqrt{s_{NN}} = 8.8$ GeV.

The PHQMD rapidity distribution of ^3He shows a good agreement with the experimental data over the whole rapidity range. p_T distributions for different rapidity intervals are also well reproduced.

Kinetic mechanism deuteron production by $3 \to 2$ hadronic reactions.
(Gabriele Coci)

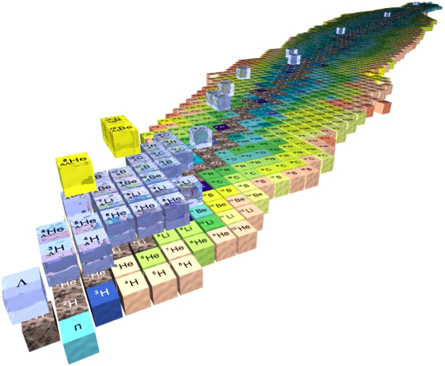


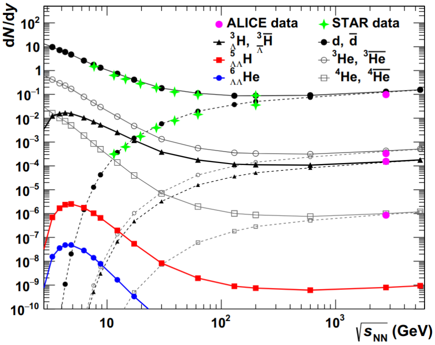
$$\pi^{\pm,0} + p + n \leftrightarrow \pi^{\pm,0} + d$$
$$\pi^{-} + p + p \leftrightarrow \pi^{0} + d$$
$$\pi^{+} + n + n \leftrightarrow \pi^{0} + d$$
$$\pi^{0} + p + p \leftrightarrow \pi^{+} + d$$
$$\pi^{0} + n + n \leftrightarrow \pi^{-} + d$$

The p_T distribution of deuterons produced by potential interactions (MST) – green line, $3 \to 2$ hadronic reactions (KIN) – red line, the sum of both mechanisms is shown by the blue line (SUM).

Paper in progress!

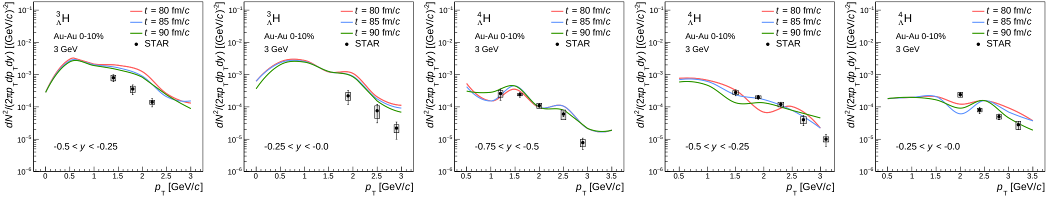
$^{A}_{Y}Z$, Y = Hyperon, $Z = Z_p + (N_y * q_y)$, $A = N_n + N_p + N_y$





Benjamin Dönigus, Eur.Phys.J.A 56 (2020) 11, 280

Published in: Phys.Rev.C 105 (**2022**) 1, 014908, arXiv: 2106.14839 [nucl-th]



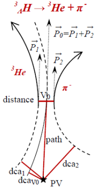
Transverse momentum distribution of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H for different rapidity intervals as indicated in the legends in central Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV.

The calculations show that the trend of the experimental p_T spectra is well reproduced.

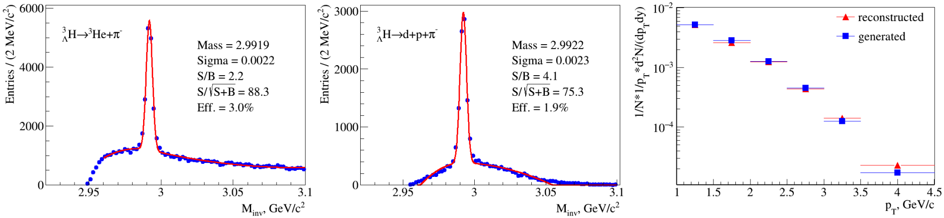
PHQMD is a good starting point for the hypernuclei production studies. $\Downarrow$

Reconstruction of hypertritons in MPD:

A. Zinchenko, V. Vasendina, A.Mudrokh, I.Rufanov, V.Kolesnikov



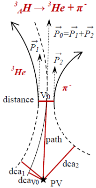
- 40M events Bi+Bi at 9.2 GeV, $|y| < 1$
- Full event simulation and reconstruction
- A set of topological cuts aimed at maximizing significance

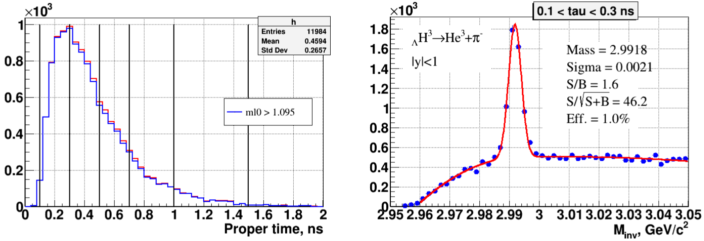


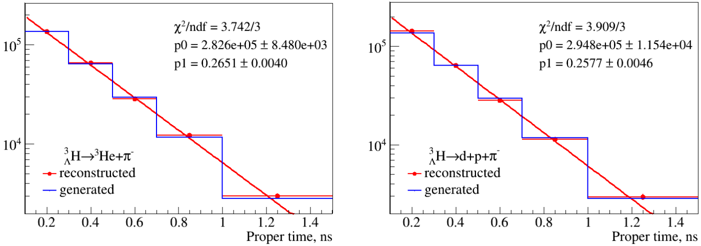
- Invariant spectrum of hypertritons is reconstructed up $p_T = 4.5$ GeV/c
- With a larger data sets, pT-spectra and rapidity densities can be obtained in centrality selected Bi+Bi collisions over a large phase space shedding light to the formation details and collective behavior of hypernuclei

Hypertriton lifetime study:

- Hypertritons are reconstructed in several τ bins
- 2- and 3-prong decay modes were studied separately to estimate systematics







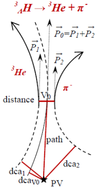
$\tau = ML/p$, where p – momentum, M – hypertriton mass, L – track length.

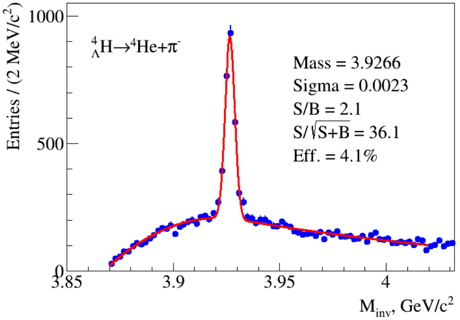
$$N(\tau) = N(0)exp(-\frac{\tau}{\tau_0}) = N(0)exp(-\frac{ML}{cp\tau_0})$$

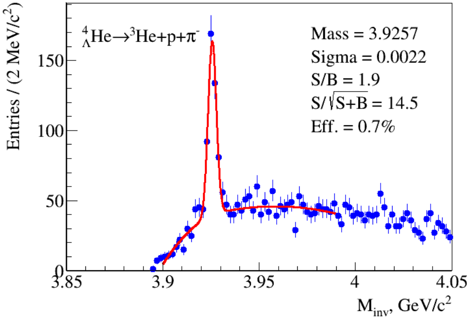
Results for different decay modes are consistent

Results for heavier hypernuclei in MPD:

- Signal embedding: the PHQMD data set was enriched by signal particles distributed according to the $\eta - p_T$ phase space.
- Equivalent statistics: ~140M events for ${}^4_\Lambda H$ and ${}^4_\Lambda He$







Good MPD performance for heavier hypernuclei in Bi+Bi at 9 GeV

Why can clusters survive?

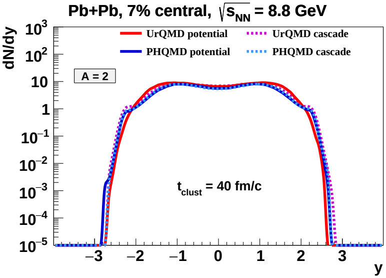
Phase-space Minimum Spanning Tree (psMST):

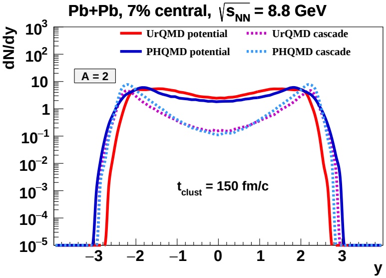
- Model-independent.
- Cross-platform.
- Stand-alone library easy to integrate.
- Implements MST procedure and the coalescence algorithm (only for deuterons)
- Extends MST by the optional inclusion for the momentum space
- Allows to study:
  - the influence of the momentum correlations of nucleons and hyperons for the formation of (hyper)nuclei.
  - the sensitivity of the (hyper)nuclei production on the baryon dynamics implementation.

Applied to 4 different models (PHQMD, PHSD, SMASH and UrQMD) to check the influence of the momentum correlation and baryon dynamics on the cluster formation:
"Cluster dynamics studied with the phase-space Minimum Spanning Tree approach"
V. Kireyeu, *Phys. Rev. C 103, 054905 (**2021**), arXiv:2103.10542*

Used to study MST and Coalescence predictions at the "freeze-out" (the time of the last elastic or inelastic collision, after which only potential interaction between baryons occurs):
"Deuteron Production in Ultra-Relativistic Heavy-Ion Collisions: A Comparison of the Coalescence and the Minimum Spanning Tree Procedure"
V. Kireyeu, J. Steinheimer, J. Aichelin, M. Bleicher and E. Bratkovskaya, *Phys. Rev. C 105, 044909 (**2022**), arXiv: 2201.13374*

Published in: Phys.Rev.C 105 (**2022**) 4, 044909, arXiv: 2201.13374 [nucl-th]

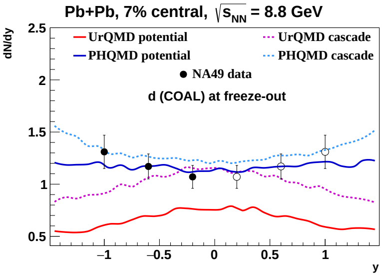


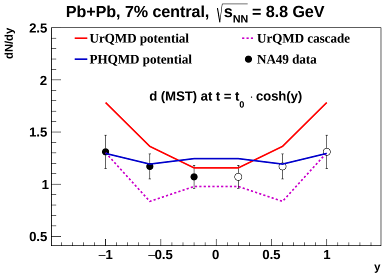


Rapidity distributions for clusters with the mass number $A = 2$ identified within the MST procedure in central Pb+Pb reaction at $\sqrt{s_{NN}} = 8.8$ GeV.

Only simulations including the nucleon-nucleon potential are able to keep the clusters bound. Without the attractive nucleon-nucleon potential interaction, the proton and neutron increase their spatial distance with time.

Published in: Phys.Rev.C 105 (**2022**) 4, 044909, arXiv: 2201.13374 [nucl-th]

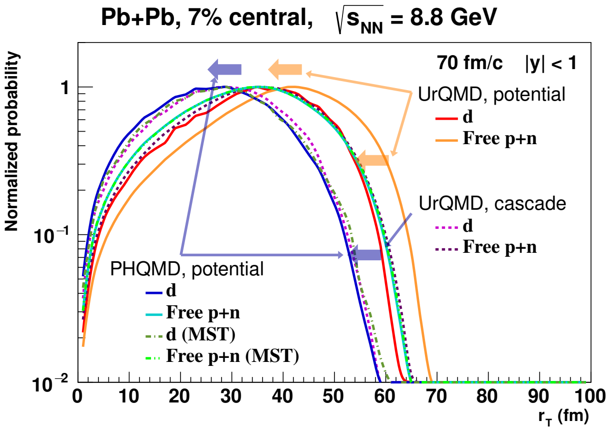




Rapidity distributions of deuterons (coalescence and MST) in central Pb+Pb reaction at $\sqrt{s_{NN}} = 8.8$ GeV.

Different algorithms applied to different models shows similar results.

Published in: Phys.Rev.C 105 (**2022**) 4, 044909, arXiv: 2201.13374 [nucl-th]



The transverse distance of unbound $p + n$ and deuterons at 70 fm/c.

Deuterons remain in transverse direction closer to the center of the heavy-ion collision than free nucleons!

Summary

- The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and with clusters identification by the Minimum Spanning Tree procedure. PHQMD predicts the dynamical formation of clusters in wide energy range due to the interactions among the nucleons and reproduces cluster data in HI collisions.
- The results of MPD feasibility studies indicate good hypernuclei reconstruction performance of the detector. Future high statistics data from NICA/MPD can provide better constrains for hypernuclei production models in the high baryon density regime.
- Coalescence and MST give very similar deuteron distributions within the PHQMD and UrQMD transport approaches. A detailed analysis reveals that stable clusters are formed:
  - shortly after elastic and inelastic collisions have ceased
  - behind the front of the expanding energetic hadrons

  Since the "fire" is not at the same place as the "ice", cluster can survive.
- In progress: PHQMD with potential (MST) + kinetic mechanisms for deuteron production.

Thank you for your attention!

Thanks to the Organizers!