Physics and phenomenology
(the ALICE and heavy-ion theory perspectives)

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QGP properties using charmonium and beauty hadrons

**J/ψ measurements provides access to key measurements**
- Charmonium production
- Beauty hadrons via non-prompt decays to J/ψ

**Physics**
- Modification of the QCD force in deconfined medium
- Thermalization of heavy quarks
- Flavor dependence of parton energy loss in QGP
Photoproduction in ultra-peripheral heavy-ion collisions

Nuclei interacting only via EM fields \((B_{\text{max}} \sim 10^{15} \text{ T})\)

- Photo-production of vector mesons in ultra-peripheral collisions
  - sensitive to gluon density at low-\(x\)
- Light-by-light scattering
  - test for the Standard Model, sensitive to BSM physics
Nuclear gluon PDFs and gluon saturation (with ALICE FOCAL)

- Forward production of isolated photons
- Forward J/ψ photo-production in ultra-peripheral collisions
J/psi production in jets

- Non-prompt J/psi tagged jets provide direct access to the beauty quark kinematics
  - Study parton flavor dependence of the QGP transport properties
- Prompt J/psi jets and their modification in QGP
  - Provide information on the mechanisms of J/psi nuclear suppression

ALICE - work in progress
High multiplicity pp collisions: multi-parton interactions and QGP

- Investigate multi-parton interactions phenomenology
- Onset of QGP in small systems using hard probes, i.e. open and hidden heavy flavor hadrons
  - existing measurements suggest final state effects in light flavor measurements
  - theoretically cleaner probes involving heavy flavor observables can be employed (so far suffer from large statistical uncertainties)
Nature of the X(3872)

Nuclear suppression pattern of X(3872) is thought to be sensitive to its internal structure (strongly bound tetraquark or a D meson molecule)
Heavy-ion theory: jets and hard probes

Probing the inner workings of QGP with hard (jets) or heavy (quarkonium) probes.

Jet quenching: main activity in UiB (Konrad Tywoniuk)

Quarkonium dynamics: main activity in UiS (Alexander Rothkopf)
Jet quenching: ongoing projects

Radiative processes in QGP

Understanding jet transport parameters

Barata, Mehtar-Tani, Soto-Ontoso, KT 2106.07402

Space-time picture of jet evolution

Takacs, Isaksen, KT (in preparation)
Jet quenching: ongoing projects

Full jet quenching

Jet thermalization in medium

Mehtar-Tani, Pablos, KT 2101.01742
Takacs, KT 2103.14676

Blanco, Kutak, Placzek, Rohrmoser, KT 2109.05918
Jet quenching: ongoing projects

Dipole shower

Pablos, Takacs, KT 2009.02936

Grooming & substructure techniques

Mehtar-Tani, Soto-Ontoso, KT 2005.07584
Jet quenching: ongoing projects

Machine learning

Bayesian inference

Du, Pablos, KT 2106.11271
Du, Pablos, KT 2012.07797

Falcao, Nielsen, KT (in preparation)
Jet quenching: future plans

Precision calculations of jet observables:

1) unified, perturbative, analytical framework
2) MC with additional non-perturbative elements
3) Bayesian, data-driven tools for designing optimal observables.

Interested in high-pT jets, substructure -> need higher statistics, more systematic searches.

Interested in small systems, connection between jet quenching & onset of hydrodynamic flow.

Quarkonium: Interested in J/ψ at high-pT (hard & heavy) - a large fraction are created in jet fragmentation.

Electron-ion: Comparison between jets (final-state radiation) and DIS (initial-state radiation) processes.
Quarkonium: ongoing projects

Two independent approaches used to solve the singlet 1d Lindblad equation

- Start either with single ground state or single excited state and monitor survival probability
- Late-time results independent of initial conditions: steady-state
- Steady state characterized by Boltzmann distributed occupation numbers. Quarkonium temperature very close to medium temperature.
- First OQS real-time approach that can thermalize quarkonium states

Solving the 1D Lindblad equation
- Thermalization requires balance of fluctuations and dissipation.

- Naïve expectation: dissipation does not play an important role at early times

- In absence of dissipation, fluctuations heat up quarkonium system until fully randomized

- Note that dissipative effects are relevant for ground state from beginning of the evolution

- Our recent results challenge pNRQCD based OQS approaches, which do not incorporate dissipative effects and do not accommodate thermalization

Effects of dissipation
Quarkonium: plans

How to go beyond the current approximations involved in deriving the Lindblad equation, including non-perturbative effects?

Plans to restart these studies, possibly with new postdoc via Marie Curie Actions stipend.
For the first time, the difference between global polarization of $\Lambda$ and anti-$\Lambda$ is obtained within the thermal approach. This difference is naturally explained by the difference in space-time distributions of both hyperons and different freeze-out with respect to the thermal vorticity field.
The global polarization, $2<\Pi_{0y}>_p$, in our PICR model (red circle) and STAR BES experiments (green triangle), at energies $\sqrt{s}$ of 11.5, 14.5, 19.6, 27.0, 39.0, 62.4, and 200 GeV.

$$<\Pi_{0y}>_p = \frac{\int dp d\Pi_{0y}(p,x) n_F(x,p)}{\int dp d n_F(x,p)} = \frac{\int dp \Pi_{0y}(p)n_F(p)}{\int dp \ n_F(p)}$$

We use the same simulation data, but vary the freeze-out time for different collision energies.
SHEAR VISCOSITY (GREEN-KUBO METHOD)

M. Teslyk, L.B. et al., PRC101 (2020) 014904; NPA1005 (2021) 121861

\[ \eta(t_0) = \frac{V}{T} \int_{t_0}^{\infty} \langle \pi(t) \pi(t_0) \rangle_t dt \]

\[ \pi^{ij}(t) = \frac{1}{V} \sum_{k=1}^{\text{particles}} \frac{p_k^{(i)} p_k^{(j)}}{E_k(t)} \]

\[ \langle \pi(t) \pi(t_0) \rangle_t \approx \langle \pi(t_0) \pi(t_0) \rangle \exp \left( -\frac{t-t_0}{\tau} \right) \]

\[ \eta(t_0) = \frac{V \tau}{T} \langle \pi(t_0) \pi(t_0) \rangle \]

For the first time, we got the evolution of shear viscosity as function of energy density, net baryon density, and net strangeness density simultaneously.
At high transverse momenta $p_T > 10$ GeV/c the cumulants are sensitive to both the anisotropy due to jet quenching, $v^{RP}$, and the particle correlations with the jet axis, $v_2^{\text{jet}}$. In the collisions with centrality up to 30–40% the four-cumulant method “measures” mainly the azimuthal anisotropy due to jet quenching, whereas in more peripheral collisions it is affected primarily by the particle correlations inside jets.
Even a small fraction of data is enough to achieve satisfactory results. Training time depends strongly on data fraction used for the training, and on the employed algorithm.
The main results and topics:

1. the phenomenological transport model

PACIAE 2.2.1: An updated issue of the parton and hadron cascade model PACIAE 2.2. Z.L. She et al., CPC 274(2022)108289

The PACIAE 2.2.1 model is upgraded by the global chiral magnetic effect (CME)-induced initial charge separation mechanism, to mimic the CME-related physics.

Charge azimuthal correlator $\gamma$

\[ \gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \]
The main results and topics:

2. (Anti-)nuclei and (anti-)hypernuclei production in A+A collisions

Collision system size dependence of light (anti-)nuclei and (anti-)hypertriton production in high energy nuclear collisions. Z.L. She et al., EPJA 58(2022)15

The production of light (anti-)cluster in a scan of symmetric nuclear collision systems (from atomic mass number $A = 10 - 238$) is studied by PACIAE + DCPC model at RHIC energy; and the suppress-ion of yield ratios for (hyper)nuclei-to-hadron is also considered.

**Strangeness population factor $s_3$:**

$$s_3 = \left( \frac{^3H \times p}{^3He \times \Lambda} \right)$$

The non-smooth $A$ dependence may be mainly related to a size effect.
The main results and topics:

3. Exotic states production in high-energy nuclear collisions

(1) Investigation of exotic state $X(3872)$ in pp collisions at $\sqrt{s} = 7, 13$ TeV.

H.G. Xu et al., EPJC 81 (2021) 784

**FREEZE-OUT AND EVOLUTION OF $\varepsilon$ AND $T$**

- **pentaquark state**
- **nucleus-like state**
- **molecular state**

Rapidity distributions of $X(3872)$ of different structures produced for different $D\bar{D}^*$ clusters in pp collisions at $\sqrt{s} = 7, 13$ TeV.
The main results and topics:

3. Exotic states production in high-energy nuclear collisions

(2) A study on the exotic state $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ in pp collisions at $\sqrt{s} = 7, 13$ TeV. C.H. Chen et al., arXiv:2111.03241. Accepted by PRD

The exotic state $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ are considered to be three kinds of possible structures, i.e. pentaquark state, nucleus-like state, and molecular state based on $P_c^{\pm} \rightarrow J/\Psi p(\bar{p})$ bound state, and their productions are predicted by PACIAE+DCPC model.

Transverse momentum distribution of exotic states $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ with three different structures ($P_{cp}$, $P_{cn}$, $P_{cm}$) in pp collisions at $\sqrt{s} = 7, 13$TeV
Thermal production of Sexaquarks in heavy ion collisions

Multipartonic states can be produced in enhanced way in heavy ion collisions via thermal production and coalescence mechanisms


Sexaquarks are produced at relatively high rates for both 0.0 and 0.4 fm radii and for masses of 1700 and 1960 MeV.
At 170 MeV the ratio of thermal Sexaquark with mass 1950 GeV to thermal deuteron ratio is about 0.45.
HI phys. spin-off to Laser Induced Fusion BGO 2021-2022

Validation tests – Target manufacturing

Two basic principles are tested on non-fusion material targets at low energies

- Implanted with nano-antennas  □ Amplified absorption
- Multilayer targets □ Simultaneous Ignition (in progress)

[M. Csete, A. Bonyár, I. Papp, P. Rácz, et al.]

Soon!

Csernai, L.P. [NAPLIFE]
Future plans:

- QGSM + String Fusion Model for pp and A+A collisions
- HYDJET++ for AA collisions: flow and RAA
- UrQMD + Thermal Model for calculation of vorticity, polarisation, viscosity
- Thermal model and Coalescence model for anti-hypernuclei and exotics

Sexaquarks

- Study of X(3872), Pc(4312), PC(4440), Pc(4457) in pp collisions at 7 and 13 TeV in PACIAE+DCPC model in three possible structures: pentaquark state, nucleus-like state and molecular state

- Machine learning
- Laser Fusion