

# Exploring the Perfect Liquid

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Max Planck Institute for Astrophysics (MPA)



## Book of Abstracts



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**Small Systems / 21****Anatomy of Azimuthal Angle correlations in Large and Small Systems**Roy Lacey<sup>1</sup><sup>1</sup> *Stony Brook University (US)***Corresponding Author(s):** roy.lacey@stonybrook.edu

no text

**Flow / 8****Automatic computation of n-subset n-particle correlators and new applications**Jacopo Margutti<sup>None</sup>**Corresponding Author(s):** jacopo.margutti@cern.ch

Multi-particle cumulants are a widely used experimental method to disentangle few-body short-range azimuthal correlations, usually called non-flow, from many-body long-range ones, which carry information on collective dynamics. Cumulants can be defined in terms of correlators, which can be efficiently computed from  $Q$ -vectors via the Generic Framework (GF) algorithms, especially when direct implementation of analytic formulae is unpractical. One limitation of the GF algorithms is that correlators must be computed from one common set of particles, whereas in some cases one would wish to correlate particles from disjoint or intersecting subsets. For some of those cases, analytic solutions have been previously derived, e.g. the so-called differential cumulants and subevent cumulants. Here, we present a generalization of the GF algorithms which enables to automatically compute  $n$ -particle correlators between  $n$  or less arbitrary subsets, with  $n = 2, \dots, \infty$ , without the need of lengthy analytic formulae. We discuss possible applications and limitations of cumulants built from such correlators, taking as a case study the Chiral Magnetic Effect.

**Femtoscopia and Fluctuations / 9****Baryon–baryon femtoscopy in pp and p-A collisions**Andreas Mathis<sup>1</sup> ; on behalf of the ALICE collaboration<sup>None</sup><sup>1</sup> *TUM***Corresponding Author(s):** andreas.mathis@ph.tum.de

Femtoscopia is a method relating particle correlations to their emission source and interaction potential. Applying this technique to a small collision system, such as pp, has the advantage of probing the inner part of the interaction potential. In order to allow for an accurate determination of the correlation function for small sources, we have developed a new C++ analysis tool called "Correlation Analysis Tool using the Schrödinger equation" (CATS), which will be presented in this talk. We also present ALICE results on baryon–baryon correlations obtained from the RUN 2 operation of the LHC in pp collisions at 13 TeV and p-Pb collisions at 5.02 TeV. The statistics of RUN 2 data provides a higher precision in the analysis of the p–p, p– $\Lambda$  and  $\Lambda$ – $\Lambda$  correlations, and additionally makes it possible to probe the interaction of more exotic pairs like p– $\Xi$ . Thanks to ongoing collaborations with theory groups working on chiral and lattice calculations, we are in the position to compare the predicted correlation functions with the experimental data.

**Quarkonia / 12**

## Charmonium production within the Statistical Hadronisation Model

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We will report on recent developments of charmonium production within the statistical hadronisation model. Charmonium production as a function of centrality, rapidity and transverse momentum will be presented and compared to available LHC data. The model can be extended to all charmed mesons and baryons. Predictions for the transverse momentum spectra of exotic charmonium states are made for future heavy-ion data at the LHC.

**Open Heavy Flavour / 32**

## DREENA framework: high pt predictions and proposal of a new observable

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I will present our newly developed DREENA framework, which allows predicting energy loss of high pt partons traversing quark gluon plasma (QGP). The framework is based on dynamical energy loss formalism, and is applied to both the medium with constant temperature (DREENA-C) and to evolving medium modeled by Bjorken 1+1D expansion (DREENA-B). The formalism allows to generate predictions for both light and heavy flavor observables, for different centralities and collision energies, as well as different experiments and collision systems. Accordingly, I will first show that our predictions agree well with a wide range of data at different centralities. Furthermore, I will show that the predictions, which were published well before the data became available, agree very well with these data, again explaining some of the experimentally observed, but intuitively unexpected, suppression patterns. I will also propose a new observable, which allows clearly distinguishing between different energy loss mechanisms, as well as numerical predictions and simple scaling arguments that support this proposal. The first steps in our work towards the application of this model as a novel high-precision tomographic tool of QGP medium, will also be discussed.

**Femtoscopy and Fluctuations / 29**

## Do we really understand flow fluctuations in central A+A collisions?

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Dummy abstract

**Flow / 6**

## Does eta/s depend on EoS?

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In hydrodynamical modeling of heavy-ion collisions, the equation of state (EoS) is usually taken to be lattice QCD EoS. However, the still often used parametrisation for lattice QCD EoS, s95p, is strictly speaking not compatible with the contemporary lattice QCD results. We have devised a new family of EoS parametrisations based on hotQCD and Budapest-Wuppertal data, and different lists of resonances in the hadronic phase, and carry out Bayesian analysis to find out whether these different EoSs will lead to different favoured values of eta/s.

**Flow / 1**

## Experimental Constraints on the Physics in Small Systems

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There is now a wealth of experimental data from RHIC and the LHC in small collision systems ranging from p+p, p+A, d+Au, 3He+Au that should help for constraining the underlying physics mechanisms at play. We detail a number of the key observables (<https://arxiv.org/abs/1801.03477>) and give a critical assessment of various theoretical interpretations. We attempt to provide a map forward in terms of both experiment and theory.

**Femtoscopy and Fluctuations / 28**

## Exploring the QCD phase diagram via event-by-event fluctuations of identified-particle yields

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In a thermal system, fluctuations of particle yields are directly encoded in the equation of state of the system under the study. By measuring event-by-event fluctuations over an ensemble of events via cumulants or moments of particle multiplicity distributions, one can study the freeze-out conditions in heavy-ion collisions and clarify their relation to the QCD phase transition.

In this contribution, recent studies of measured event-by-event fluctuation signals of identified pions, kaons and protons are discussed. The experimental results are confronted with corresponding

signals from dynamical models, and the dependence of fluctuation measurements on phase-space coverage of detected particles are addressed in view of the calculations from Lattice QCD (LQCD) and the Hadron Resonance Gas (HRG) model. Moreover, several experimental challenges, such as particle detection efficiency losses, volume fluctuations etc., for the measurement of fluctuation signals are briefly discussed.

### Femtoscopy and Fluctuations / 23

## Femtoscopy in heavy ions

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Overview talk on femtoscopy in heavy ions

### Flow / 24

## Flow overview

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Overview talk on flow

### Open Heavy Flavour / 30

## Heavy flavour constraints on nuclear PDFs

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Dummy title+abstract. To be updated

### Small Systems / 7

## Hydrodynamic Collectivity in Proton–Proton Collisions at 13 TeV

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In this paper, we investigate the hydrodynamic collectivity in proton–proton (p–p) collisions at 13 TeV, using vishnu hybrid model with hijing initial conditions. With properly tuned parameters, our model simulations can remarkably describe all the measured 2-particle correlations, including integrated and differential elliptic flow coefficients for all charged and identified hadrons ( $K_S^0$ ,  $\Lambda$ ). However, our model calculations show positive 4-particle cumulant  $c_2\{4\}$  in high multiplicity pp collisions, and can not reproduce the negative  $c_2\{4\}$  measured in experiment. Further investigations on the \hijing initial conditions show that the fluctuations of the second order anisotropy coefficient  $\varepsilon_2$  increases with the increase of its mean value, which leads to a similar trend of the flow fluctuations. For a simultaneous description of the 2- and 4- particle cumulants within the hydrodynamic framework, it is required to have significant improvements on initial condition for pp collisions, which is still lacking of knowledge at the moment.

**Open Heavy Flavour / 17**

## Measurements of heavy-flavour correlations and jets with ALICE

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This contribution will focus on the latest heavy-flavour correlation and jet measurements with the ALICE detector in pp, p–Pb and Pb–Pb collisions at the LHC.

In particular, the results of azimuthal correlations of D mesons with charged particles in pp collisions at  $\sqrt{s} = 7$  and 13 TeV and in p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV will be presented. Measurements of multiplicity and centrality dependent azimuthal correlations of heavy-flavour hadron decay electrons with charged particles in p–Pb and Pb–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV will be shown together with the heavy-flavour electron  $v_2$  in p–Pb collisions.

Furthermore, measurements of D-meson tagged jet production in pp collisions at  $\sqrt{s} = 7$  TeV including studies of the jet-momentum fraction carried by the D meson will be presented. The recent results in p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV will be reported. The first measurement of the nuclear modification factor of D-tagged jet in Pb–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV will be also discussed.

**Small Systems / 16**

## Non-Bessel-Gaussianity and Flow Harmonic Fine-Splitting

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Both collision geometry and event-by-event fluctuations are encoded in the experimentally observed flow harmonic distribution  $p(v_n)$  and  $2k$ -particle cumulants  $c_n\{2k\}$ . In the present talk, we systematically connect these observables to each other by employing Gram-Charlier A series. Also we quantify the deviation of the flow harmonic distribution from Bessel-Gaussianity in terms of the flow harmonic fine-splitting. This study helps us to disentangle the effect of the collision geometry and fluctuations in  $v_n\{2k\}$ . After that we introduce two applications for this study. We first introduce several estimators for the averaged ellipticity and second we restrict the  $v_2\{2\}$ ,  $v_2\{4\}$  and  $v_2\{8\}$  phase space.

**Flow / 22**

## Non-Gaussian flow fluctuations in heavy-ion collisions

Giuliano Giacalone<sup>1</sup><sup>1</sup> *Université Paris-Saclay***Corresponding Author(s):** giulianogiacalone@gmail.com

I present the state-of-the-art of anisotropic flow fluctuations in heavy-ion collisions. Event-by-event fluctuations of flow coefficients are investigated experimentally by means of multi-particle cumulants, which are indicators of the non-Gaussian behavior of the  $v_n$  distributions. After a brief review of the theoretical basis underlying cumulants and the related observables, I use selected Pb+Pb and Xe+Xe measurements to show that flow fluctuations are the key probes of the initial fluctuating geometry of the quark-gluon plasma. Eventually, I discuss what the future of flow fluctuations is in view of upcoming large-statistics LHC3 and LHC4 data.

**Quarkonia / 4**

## On nonequilibrium quarkonium evolution in the QGP fireball

Antonio Vairo<sup>1</sup> ; Nora Brambilla<sup>2</sup> ; Peter Vander Griend<sup>3</sup> ; Yan Zhu<sup>1</sup><sup>1</sup> *TUM*<sup>2</sup> *Physik Department, TU Munich*<sup>3</sup> *Technical University of Munich***Corresponding Author(s):** vanderriend@tum.de, antonio.vairo@ph.tum.de, nora.brambilla@ph.tum.de, yanzhu.zhu@tum.de

A Lindblad equation for the evolution of heavy quarkonia in QGP has recently been derived from potential non-relativistic QCD (pNRQCD) and open quantum system framework. We derive the classical limit of the evolution equations for color-singlet and color-octet quarkonia states. Within the classical approximations, we are able to write the evolution equations respectively as a Langevin equation and Boltzmann equations in two different regimes. This allows us to identify the difference between quantum and classical evolution, and examine the effect of classical approximations. Applications to the study of the quarkonium evolution in QGP are presented.

**Open Heavy Flavour / 26**

## Open heavy flavour production in heavy ions

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Overview talk on open heavy flavour production in heavy ions

**Quarkonia / 27**

## Overview on Quarkonia

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Overview talk on quarkonia

### Femtoscopy and Fluctuations / 18

## Polarization in relativistic fluids

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The observation of a finite global polarization in agreement with theoretical predictions has opened a new dimension in relativistic heavy ion physics as well as in relativistic hydrodynamics, with several intriguing connections to chiral and electromagnetic effects. Very recent experimental observations seem to challenge the hydrodynamic predictions. In this talk, the status of the theory of polarization in relativistic fluids is reviewed and possible developments in the field are discussed.

### Quarkonia / 5

## Recent Results on Lattice QCD at non-zero temperature and density

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I will discuss recent lattice QCD results on equation of state, transition temperature, fluctuations of conserved charges and color screening at vanishing and non-zero baryon density. I will show new results on the equation of state in 2+1 flavor QCD up to temperature 2000 MeV and recent results from Taylor expansion in baryon chemical potential for equation of state and the transition temperature. I will discuss the comparison of the lattice results with weak coupling calculations at high temperatures and hadron resonance gas at low temperature. Finally, I will discuss the length scale of onset of color screening and the effective coupling constant at non-zero temperature.

### Small Systems / 25

## Small systems overview

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Overview talk on small systems

**Small Systems / 31**

## **Some comments about jet quenching in small collision systems**

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I'd like to have 5 minutes to discuss two slides with hydrodynamic freeze-out surfaces for various "small" collision systems that may help to explain the absence (so far) of jet quenching effects in p-Pb and p-p collisions.

**Wrap up / 34**

## **Summary: Femtoscopy and Fluctuations**

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**Wrap up / 35**

## **Summary: Flow**

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**Wrap up / 37**

## **Summary: Open Heavy Flavour**

**Wrap up / 36**

## **Summary: Quarkonia**

Flow / 19

## Symmetric cumulants: Overview of experimental results so far and future directions

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Symmetric cumulants, the novel flow observables which quantify the correlations between event-by-event fluctuations of two different flow harmonics, have been utilized extensively by the experimentalists in recent flow analyses in ultra-relativistic nuclear collisions, both at RHIC and LHC.

These observables provide the strong constraints for the details of QGP's temperature dependence of  $v_n/s$ , which is currently heavily studied by the theorists, and to which the individual flow harmonics are nearly insensitive. In addition, symmetric cumulants have a potential to disentangle for the first time the two contributions to anisotropic flow stemming from initial conditions and from the transport properties of the QGP. This in turn could enable the theorists to perform independent modelling and tuning of initial configurations of nuclear collisions and of the system properties of the produced QGP.

In this talk the overview of experimental results collected so far for symmetric cumulants, over a wide range of different collision systems and colliding energies, will be presented. The possibility how to generalize these observables to extract even further independent constraints on initial conditions and QGP properties will be discussed at the end.

Flow / 14

## Systematic formulation of far-from-equilibrium relativistic fluid dynamics

Jorge Noronha<sup>1</sup><sup>1</sup> *University of Sao Paulo***Corresponding Author(s):** jorgenoronha@gmail.com

We show that far-from-equilibrium relativistic fluid dynamics may be systematically defined, for arbitrary flow profiles, in terms of a generalized tensorial expansion with transport coefficients that contain an all order resummation in gradients. In this formulation, the transport coefficients of far-from-equilibrium fluid dynamics depend not only on the microscopic properties of the system but also on the nonlinear properties of the underlying state of the fluid itself. In contrast to previous works, no additional assumptions about the symmetries of the flow are necessary. A concrete example of this proposal is constructed using the slow-roll expansion in conformal Israel-Stewart theory. In this case, the novel resummed shear viscosity and relaxation time coefficients decrease with increasing Knudsen number according to formulas that can be readily investigated in current numerical simulations of the quark-gluon plasma formed in ultrarelativistic heavy ion collisions.

Open Heavy Flavour / 2

## Temperature- and momentum dependence of the heavy quark diffusion coefficient

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Recent years have seen significant theoretical progress in the transport description of open heavy quarks in QCD matter - a number of models are now able to simultaneously describe a subset of the most important heavy flavor observables - a simultaneous description of a comprehensive set of observables at all available collision energies still poses a challenge. A global analysis encompassing all available collision systems and energies as well as an improved treatment of known uncertainties for different observables would significantly improve our ability to distinguish between different theoretical models and constrain the heavy quark diffusion coefficient in an unbiased way.

In this study, we utilize two hybrid heavy quark transport models, a radiation improved Langevin approach and a hybrid linearized Boltzmann model with diffusive non-perturbative contributions, to extract the temperature- and momentum-dependence of the heavy quark transport coefficient via a Bayesian model-to-data analysis. In both cases the QGP medium is given by a state of the art viscous hydrodynamic evolution, which has been calibrated to soft flow observables in the light hadron sector.

The constrained diffusion coefficient is validated by comparing  $B$ -meson measurements along with  $D$ -meson  $R_{AA}$  in pPb collisions. New observables are proposed to further constrain the diffusion coefficient.

**Open Heavy Flavour / 20**

## Transport properties and hadronization of Heavy Quarks from $R_{AA}$ and $v_n$ and their correlations to the bulk collective dynamics

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We study the propagation of charm and bottom quarks in the quark-gluon plasma (QGP) by means of a relativistic Boltzmann transport approach. The non-perturbative interaction of heavy quarks is described by means of a quasi-particle approach that entails only a weak dependence of the drag on the temperature. This features, along with hadronization by coalescence, plays a fundamental role to describe simultaneously the experimental data for the nuclear suppression factor  $R_{AA}$  and the elliptic flow  $v_2(p_T)$  of D mesons at both RHIC to LHC energies.

In particular an hadronization by coalescence predict a very large  $\Lambda_c$  baryon production that impact also the determination of the  $R_{AA}$ . In the same scheme, we present predictions for B mesons that allow also a determination of the space-diffusion coefficient that is practically independent on the transport scheme for HQ: Boltzmann vs Langevin.

Focusing on the role of initial state fluctuations to generate high order anisotropic flows  $v_3(p_T)$  and  $v_4(p_T)$  of D mesons, it will be discussed the role of QCD interaction in developing correlations between the light and the heavy flavor anisotropic flows ( $v_n^{light}, v_n^{heavy}$ ) providing novel and powerful constraints for the transport coefficients.

Finally we show how  $v_1$  provides a probe of the very strong initial electro-magnetic (e.m.) fields are created in Ultra-relativistic Heavy-Ion Collision (HIC) that induce a vorticity in the reaction plane that is odd under charge exchange. Even more it can induce a splitting of uncharged  $D^0$  meson and antimeson providing a proof of the QGP phase.

**Small Systems / 11**

## Understanding long-range correlations in small systems from ATLAS

Jiangyong Jia<sup>1</sup> ; ATLAS Collaboration<sup>None</sup>

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ATLAS has performed comprehensive measurement of two-particle and multi-particle long-range azimuthal correlations in pp, p+Pb and peripheral Pb+Pb collisions at various energies. This talk provides a comprehensive review of results from these measurements, and it discusses their implications for understanding the mechanism and time scale for the generation of the long-range correlations in small collision systems.

**Start of the Workshop / 33**

### Welcome

Torsten Dahms<sup>1</sup> ; Laura Fabbietti<sup>1</sup> ; Jean-Philippe Lansberg<sup>None</sup> ; Jean-Yves Ollitrault<sup>None</sup>

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**Quarkonia / 13**

### sPHENIX at RHIC: Science mission and status

Gunther Roland<sup>1</sup> ; sPHENIX collaboration<sup>None</sup>

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The science mission of the sPHENIX experiment, outlined in the 2015 US Nuclear Physics long range plan, calls for studies of the microscopic structure of the QGP through state-of-the-art jet, upilon and heavy flavor measurements at RHIC, complementing similar measurements at LHC. We will discuss highlights of the proposed sPHENIX science program and describe the design and construction status of the key sub detectors, as the collaboration prepares for commissioning the detector in 2022 and the first science run in 2023. We will also describe the path to a future EIC detector based on sPHENIX.

**Quarkonia / 10**

### $\Upsilon$ -meson dissociation in Pb+Pb collisions at LHC energies and the role of the electromagnetic field

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We investigate the suppression of  $\Upsilon$  mesons in the hot quark–gluon plasma (QGP) created in Pb+Pb collisions at energies available at the CERN Large Hadron Collider using a centrality- and transverse-momentum-dependent model that encompasses screening, collisional damping, and gluodissociation in the QGP. For  $\Upsilon(1S)$ , the model prediction is compatible with experimental data from the CMS collaboration whereas it cannot explain the  $\Upsilon(2S)$  yields observed in peripheral collisions.

To improve the description of peripheral collisions, an estimate of the electromagnetic field strength experienced by  $\Upsilon$  mesons embedded in the expanding QGP and its consequences on  $\Upsilon$  dissociation is made. Our results, however, point at a relative insignificance of these electromagnetic field effects compared to the established strong-interaction suppression mechanisms.

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