Extreme QCD matter: fluid description versus experimental data

Theory-Experiment Collaboration

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GSI

Quantum Systems in Extreme Conditions (QSEC2019)

September 23-27, 2019

Collaboration within **ISOQuant**

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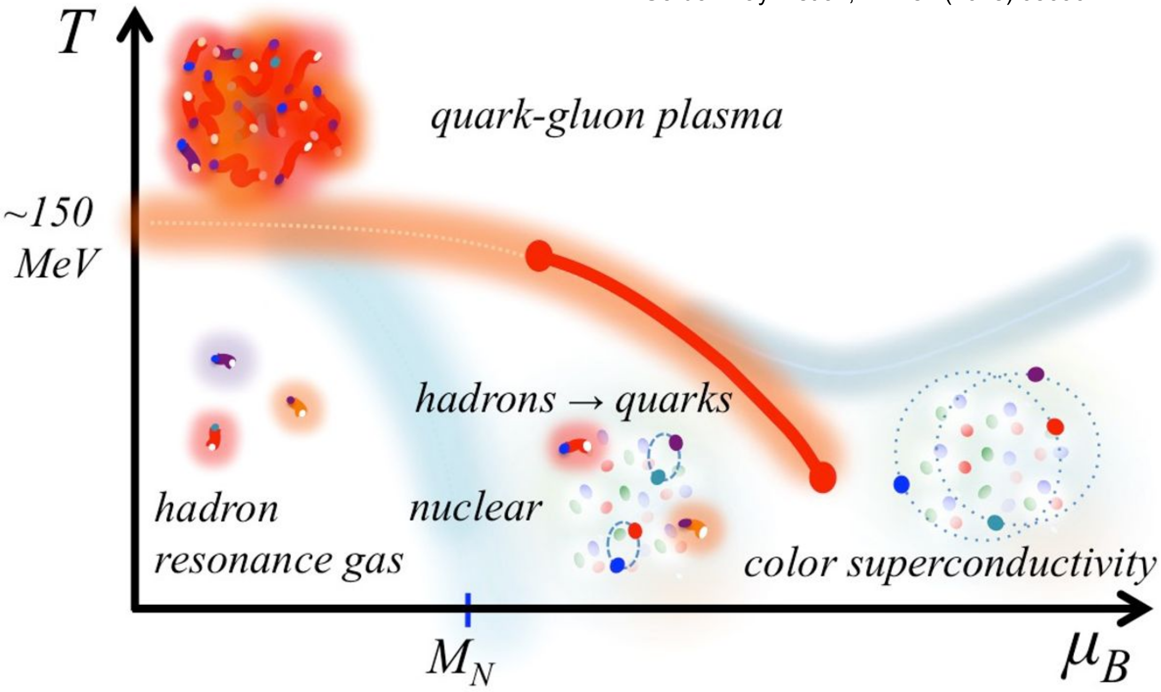
QCD phase diagram

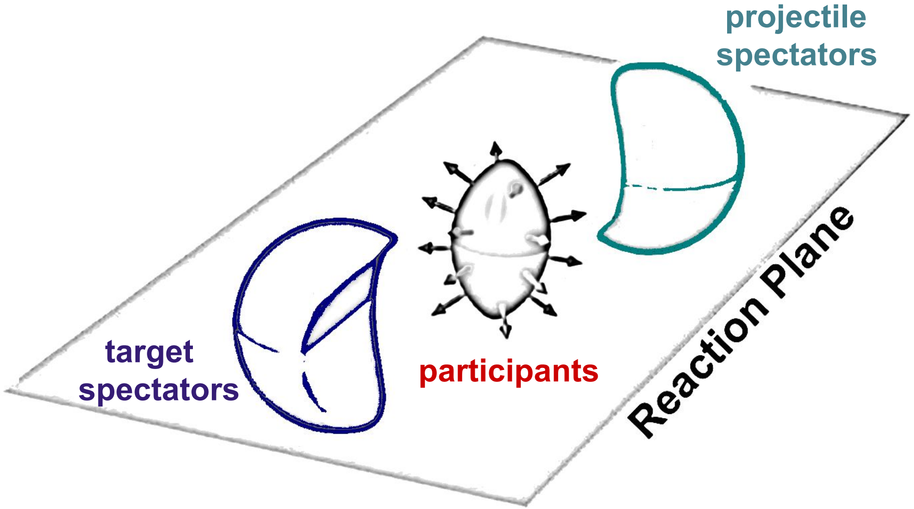
Gordon Baym et al., RPP81 (2018) 056902



early universe → $\mu_B \sim 0$

very high temperature

Collisions at Ultra-relativistic (TeV) energies

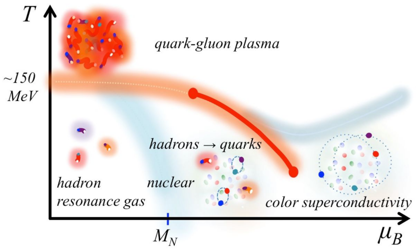


Abundant soft QCD particle production
→ symmetric matter - anti-matter

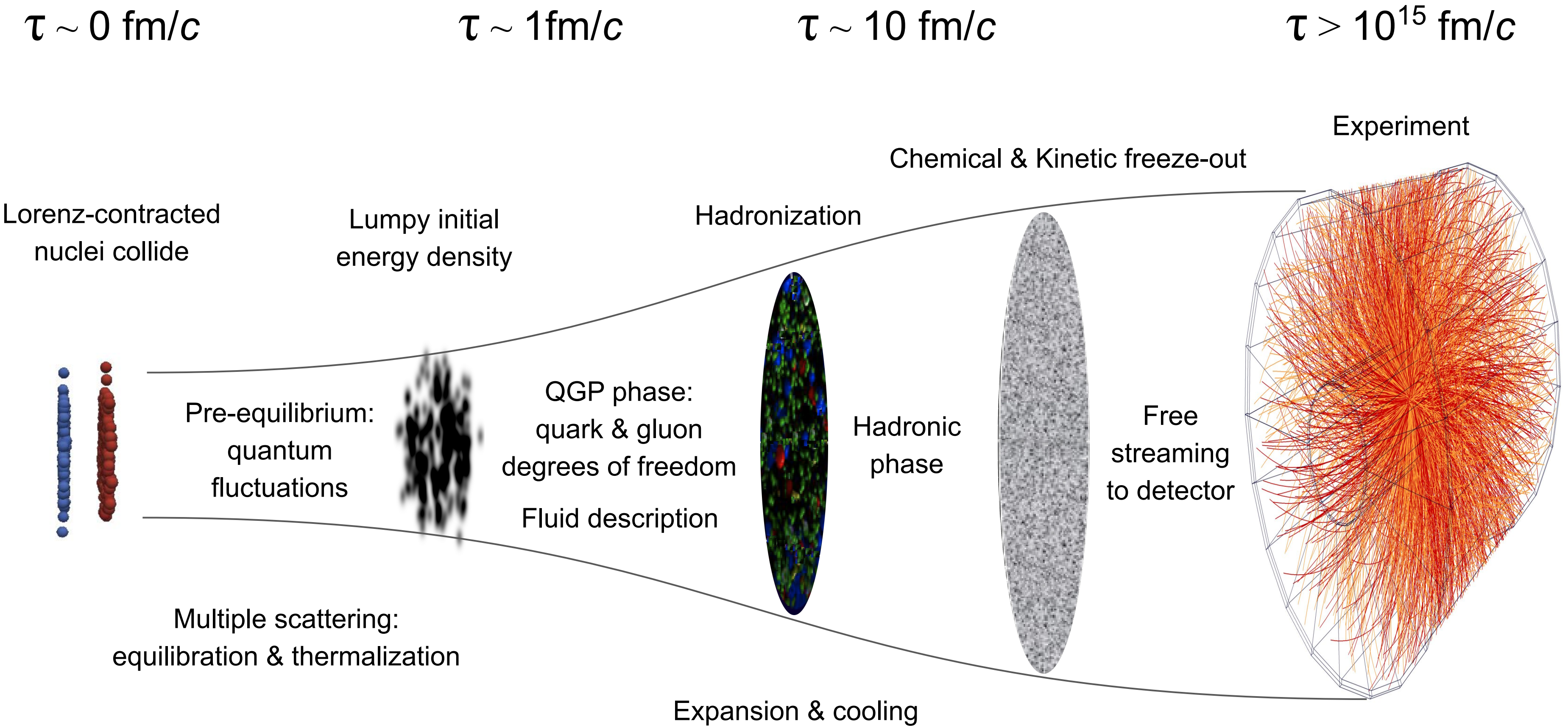
Multiple interaction & collective expansion
→ justifies macroscopic (fluid) description

Symmetric matter - anti-matter production
→ $\mu_B \sim 0$ (early universe conditions)

Temperature T > 150 MeV
→ access Quark-Gluon Plasma (QGP)

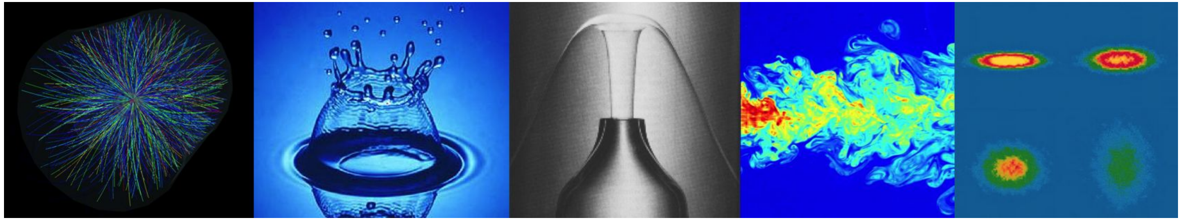


Evolution of a heavy-ion collision



Fluid dynamics

- Long distances, long times or strong enough interactions
- Matter or quantum fields form a fluid
- Macroscopic fluid properties
    - Thermodynamic equation of state $p(T,\mu)$
    - Shear viscosity $\eta(T, \mu)$
    - Bulk viscosity $\zeta(T, \mu)$
    - Heat conductivity $k(T, \mu)$
    - Relaxation times, …
- Ab initio calculation of fluid properties difficult
  but fixed by microscopic properties of the QCD lagrangian



Motivation for Fluid*u*M

- Relativistic fluid approximation to QCD dynamics
  which is a close-to-local-equilibrium, but out-of-global-equilibrium
- Analyze spectrum of perturbations around symmetric configurations
  - Characterize perturbations through symmetry properties
    (azimuthal & longitudinal wave numbers) and Bessel expansion (radial wave number)
  - Symmetries allow to reduce complexity of partial differential equations
- Efficient and precise numerical calculations (based on pseudo-spectral method)
  - Numerical evolution is done independent of initial state model for perturbations
- New method for resonance decays based on symmetries and mode expansion

Fluid*u*M:
Fluid dynamics of heavy-ion collisions with Mode expansion

- Solves evolution equations for relativistic QCD fluid
- Expands in perturbations around event-averaged solution
  - Leads to linear + non-linear response formalism
- Good convergence properties
- Very fast numerical calculations

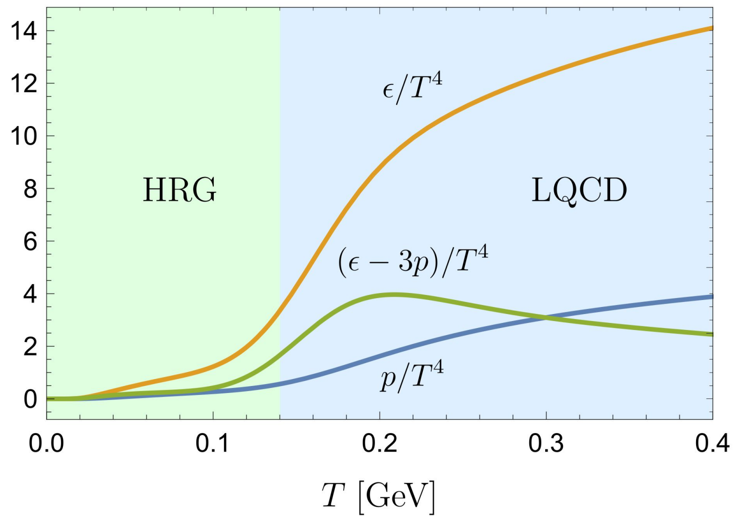
Currently profit from:
efficient (and precise) numerics and detailed theory-experiment comparison

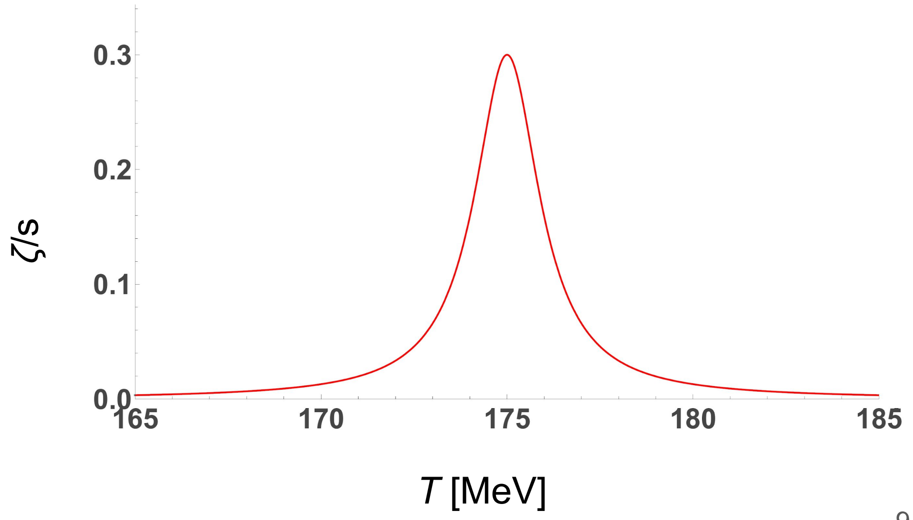
In future:
study perturbations, include thermal & quantum fluctuations of the fluid fields

S. Floerchinger & U. Wiedemann, PLB 728, 407 (2014)
S. Floerchinger, E. Grossi, J. Lion, PRC 100, 014905 (2019)

Fluid*u*M: hydrodynamic evolution

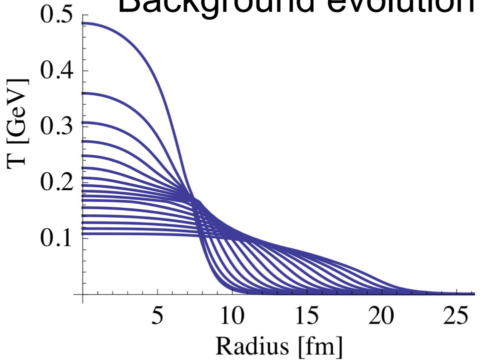
- Relativistic viscous fluid model
  - Energy-momentum conservation
  - State-of-the-art thermodynamic equation of state
  - Shear and temperature dependent bulk viscous dissipation



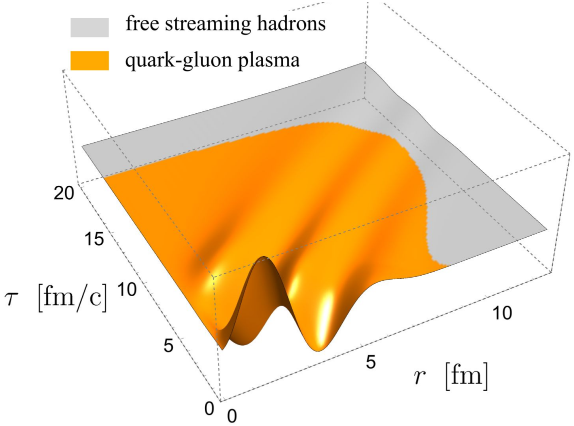


Fluid*u*M: Splitting background and perturbations

Background evolution



Perturbations evolution



Decompose fluid fields into two components

$$\Phi(\tau, r, \varphi, \eta) = \Phi_0(\tau, r) + \Phi_1(\tau, r, \varphi, \eta)$$

Background: $\Phi_0(\tau, r)$

- azimuthally and Bjorken boost symmetric

Perturbations: $\Phi_1(\tau, r, \varphi, \eta)$

- azimuthally and rapidity dependent

Procedure replaces event-by-event approach in relativistic fluid formalism

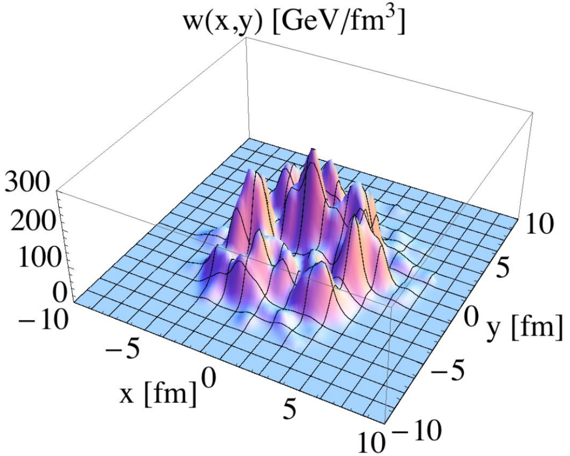
Fluid*u*M: Evolving perturbation modes

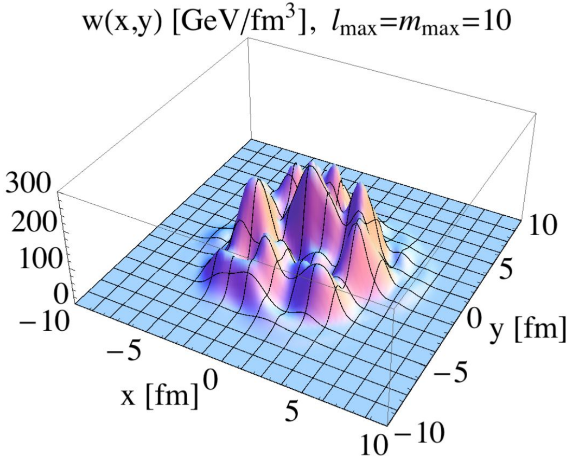
Longitudinal and azimuthal fluctuations are characterized by Fourier expansion

$$w(\tau_0, r, \phi, \eta) - w_{\mathrm{BG}}(\tau_0, r) = \int \frac{dk_\eta}{2\pi} \sum_{m=-\infty}^{\infty} e^{ik_\eta \eta + im\phi}\, w^{(m)}(\tau_0, r, k_\eta)$$

Radial fluctuations by Bessel expansion

$$w^{(m)}(\tau_0, r) = w_{\mathrm{BG}}(\tau_0, r) \sum_{l=1}^{\infty} J_m\left(k_l^{(m)} r\right) \tilde{w}_l^{(m)}$$

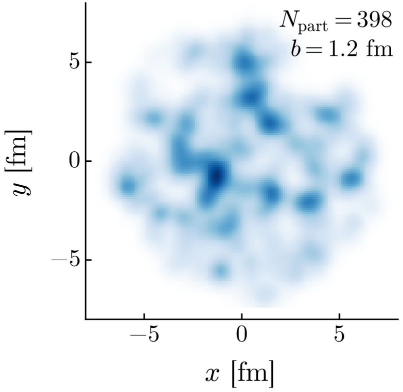




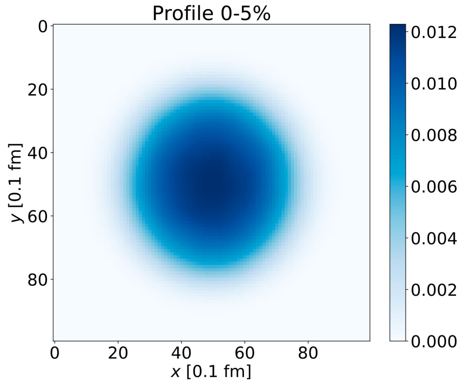
Initial conditions

TRENTo: Reduced Thickness Event-by-event Nuclear Topology

Event-by-event fluctuations



Average for 10^7 events split in 1% centrality classes



TRENTo configuration:

p = 0 (geometric)

k = 1.4

σ = 0.6 fm

$\sigma^{NN}_{inel} = 6.4\ \mathrm{fm}^2$

$$s(r) = \frac{\mathrm{Norm}_i}{\tau_0} \langle T_{\mathrm{R}}(r, \phi) \rangle$$

J. Moreland, J. Bernhard, S. Bass:
PRC 92, 011901 (2015); PRC 94, 024907 (2016)

BS thesis
K. Yousefnia

Hadronization: Cooper-Frye particlization

For T < 150 MeV use Cooper-Frye formula

$$E_{\mathbf{p}} \frac{dN_a}{d^3\mathbf{p}} = \frac{\nu_a}{(2\pi)^3} \int_\Sigma f_a(\bar{E}_{\mathbf{p}}) p^\mu d\Sigma_\mu$$

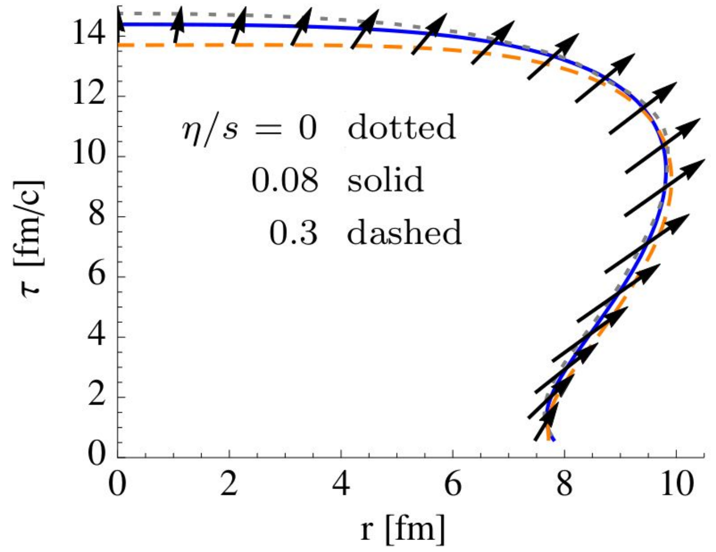
with viscous corrections

$$f = f_{\mathrm{eq}} + \delta f^{\mathrm{bulk}} + \delta f^{\mathrm{shear}}$$

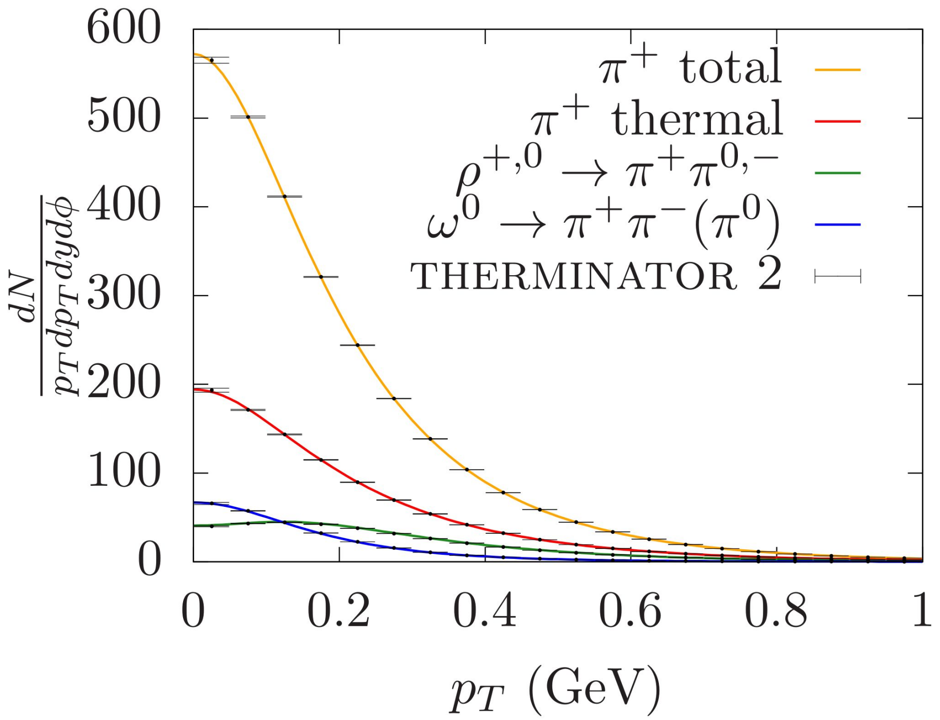
to equilibrium distribution

$$f_{\mathrm{eq}}\left(\frac{p\cdot u}{T}\right) = \frac{1}{e^{p\cdot u/T} \pm 1}$$

Background freeze-out line



Resonance decays with FastReso



Important to account for feed-down of resonance decays to particle yields at/after hadronization

Reduce Cooper-Frye integrals to 1D
~700 resonances from PDG-2016 with M < 3GeV

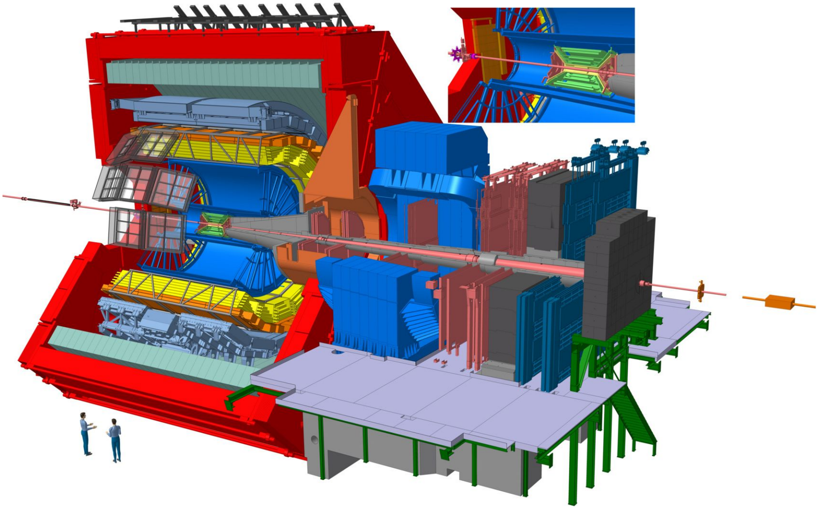
A. Mazeliauskas, S. Floerchinger, E. Grossi, D. Teaney
EPJC 79, 284 (2019)
https://github.com/amazeliauskas/FastReso

Comparison of Fluid*u*M calculations with LHC data

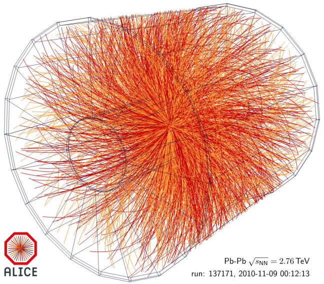
Model ingredients and parameter overview

Collision stage	Model	Configuration	Free parameter(s)	Pars.
Initial state	TRENTo	Thickness: p=0 (geometric) No initial radial flow No initial shear stress No bulk pressure Radially symmetric average	Centrality dependent initial entropy normalization Fluid initialization time	Norm_i τ_0
Fluid description	FluiduM	Relativistic fluid Lattice-QCD EoS Background: radially symmetric Perturbations: none	Shear & bulk viscosity over entry density (temperature dependent)	η/s $(\zeta/s)_{max}$
Hadronization (particlization)	Cooper-Frye + FastReso	Viscous corrections ~ 700 resonances (Mass < 3GeV) from PDG-2016		None
Freeze-out	Surface of constant T	Common chemical & kinetic freeze-out	Common freeze-out temperature	T_{fo}

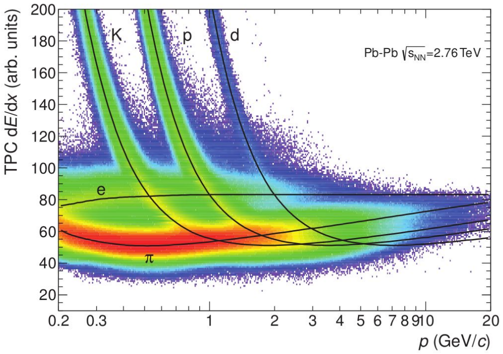
Experimental data from ALICE@LHC

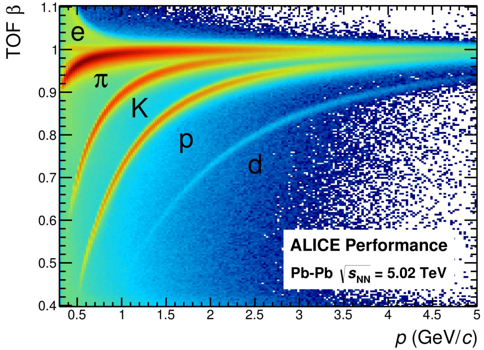


16 × 16 ×26 m^3
10,000 tons
20 subsystems



Charged particle identification over wide p_T range





Available ALICE data for particle yields

particle species	Energy (TeV)	PID	reference
Charged hadrons	2.76	$h^{\pm}$	PRC 88, 044910 (2013)
	5.02		PRL 116, 222302 (2016)
Identified charged hadrons	2.76	$\pi^{\pm}$, $K^{\pm}$, p	PRC 88, 044910 (2013)
Multi-strange baryons	2.76	Λ, Σ, Ω	PRL 111, 222301 (2013) PLB 728, 216 (2014)

Global fit procedure

- Calculations with Fluid*u*M + FastReso
  4 parameters + centrality dependent normalization: in total 10^5 configurations

Norm_i	τ_0 (fm/c)	η/s	$(\zeta/s)_{\mathrm{max}}$	T_{fo} (MeV)
30-60	0.2-0.6	0.1-0.25	0.005-0.1	130-155

- Phase space of the global fit
  - p_T < 3 GeV/c
  - 3 species (pions, kaons, and protons)
  - 5 centrality classes:
    0-5%, 5-10%, 10-20%, 20-30%, 30-40%

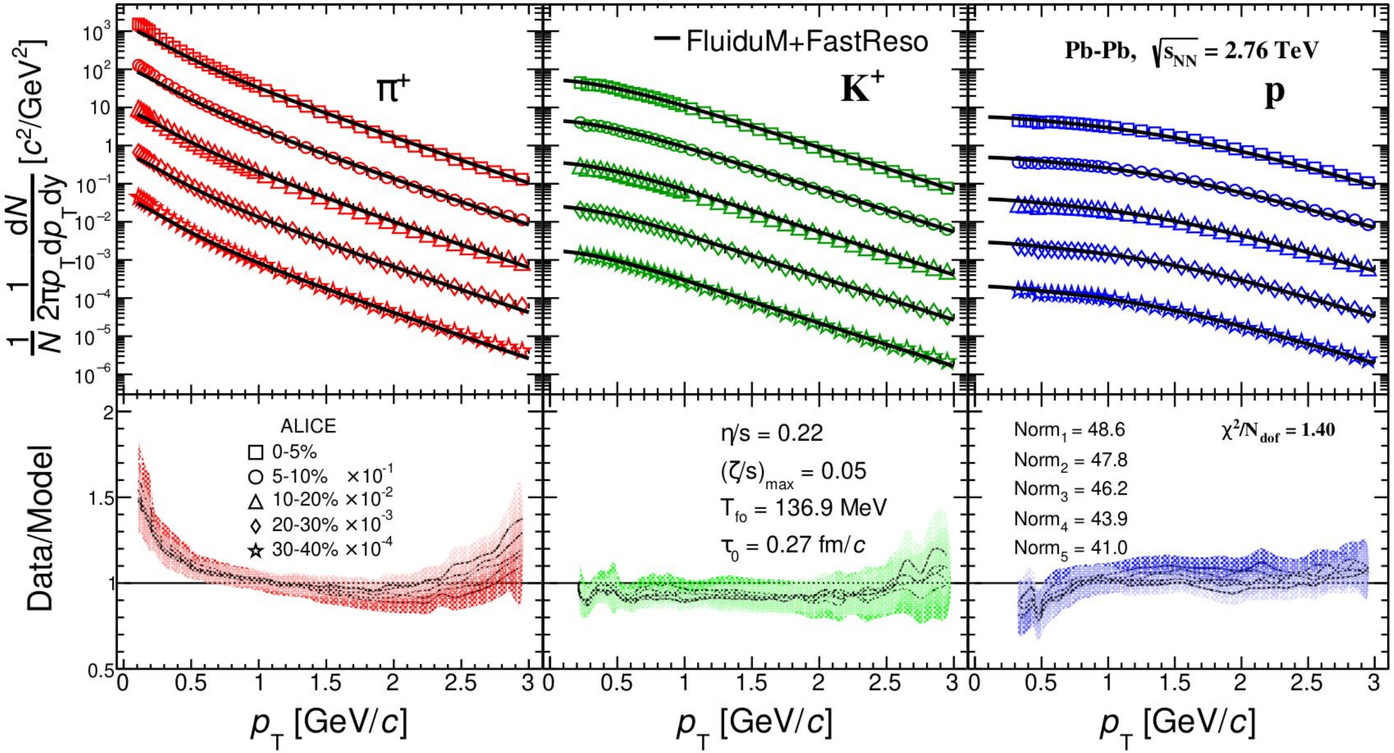
- Minimization with gradient descent algorithm

$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - y_i)^2}{\sigma_i^2}$$

- Using stat. and syst. uncertainties of the data

$$\sigma_i = \sqrt{\sigma_{i,\mathrm{sys}}^2 + \sigma_{i,\mathrm{stat}}^2}$$

Best fit for $\pi^{\pm}$, $K^{\pm}$, and p spectra



For a first time a p_T dependent fit

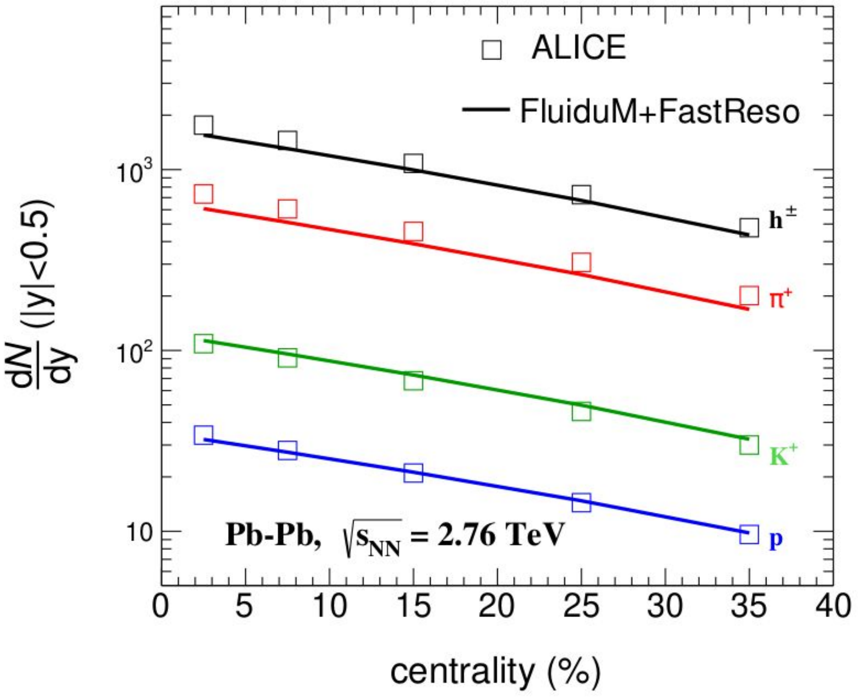
$\chi^2/N_{dof} = 1.4$

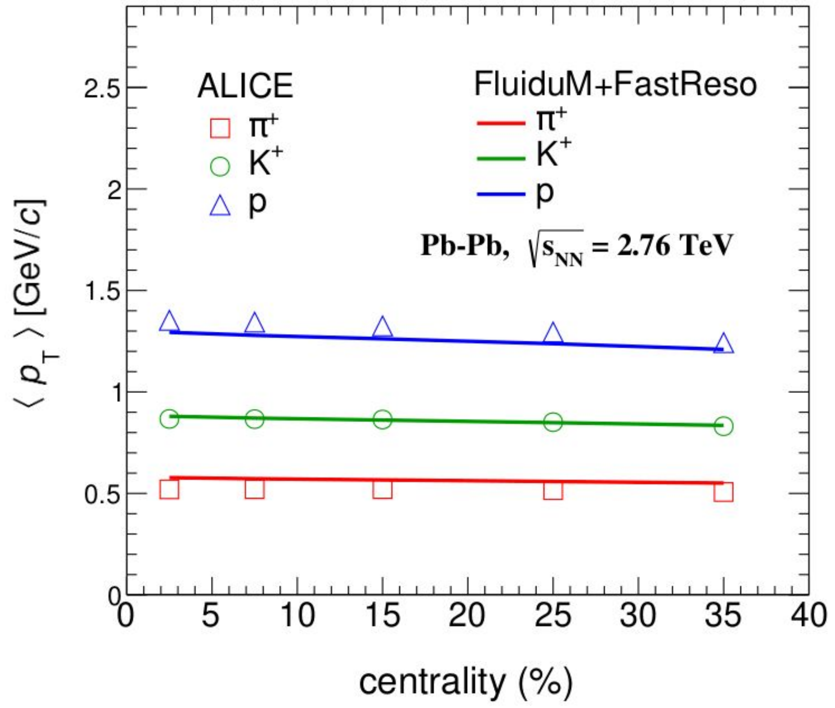
$N_{dof} = 546$

$\pi^{\pm}$ at low p_T are significantly underestimated

Resonances or non-thermal production from evolving coherent fields

Total yields and $\langle p_T \rangle$ vs. centrality



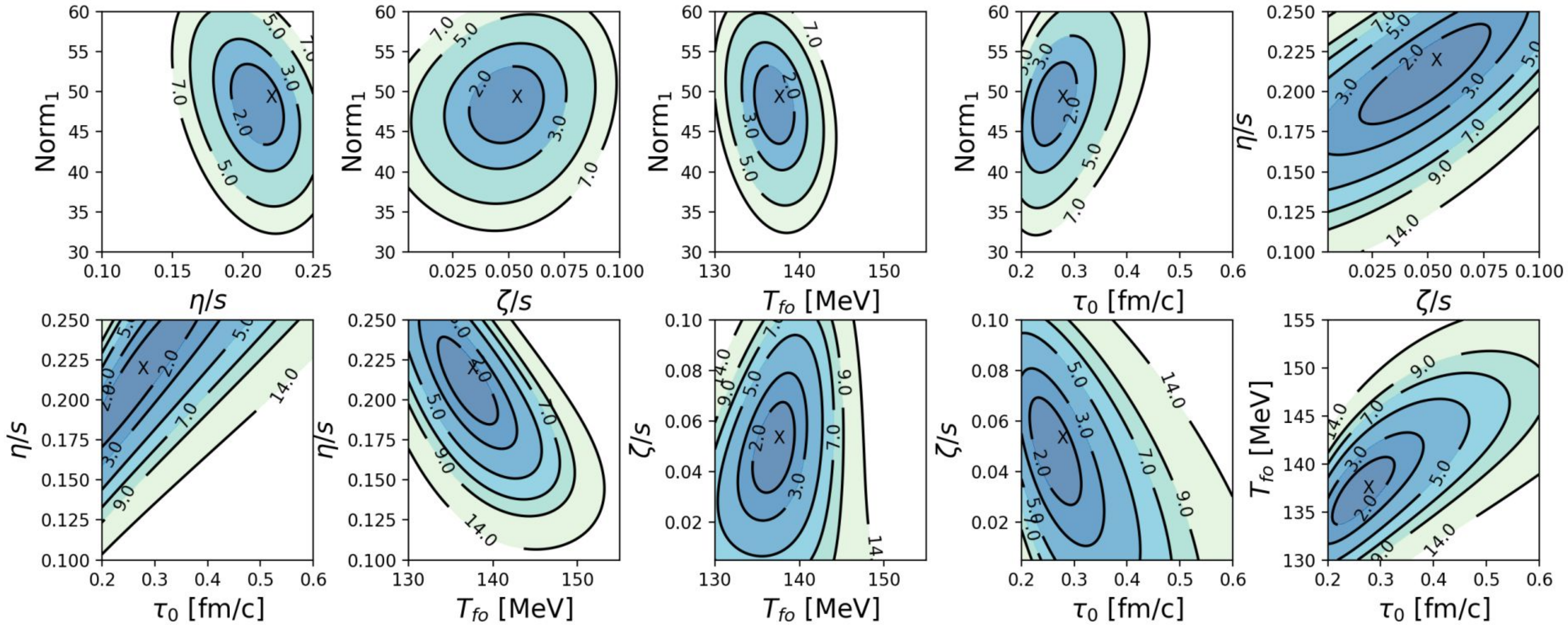


Total yields of $\pi^{\pm}$ are significantly underestimated due to differences at low p_T

$\langle pT \rangle$ for protons is not reproduced

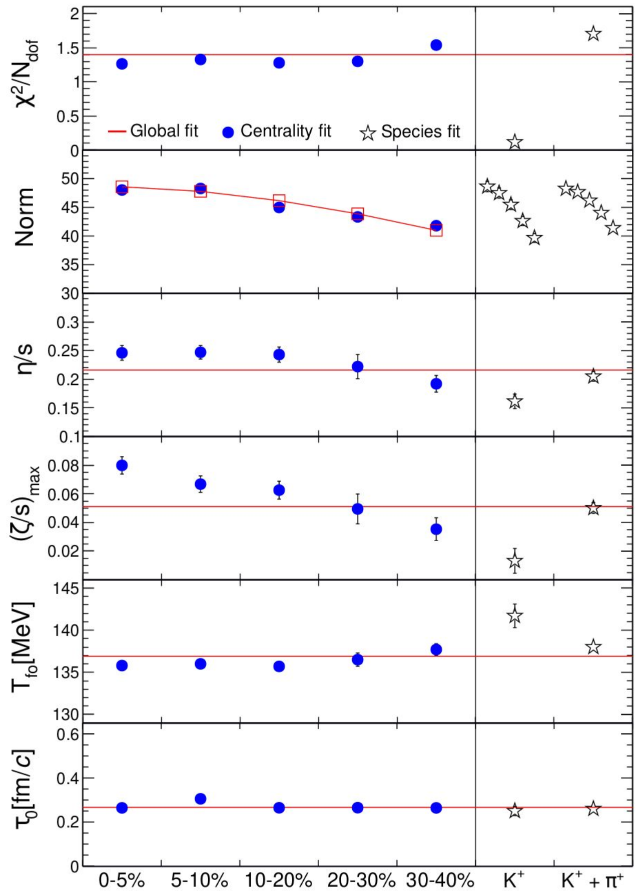
Correlations of model parameters

Contour plots of χ^2/N_{dof} for pairs of model parameters



Global minimum is seen for each individual pair of parameters

Systematic uncertainties

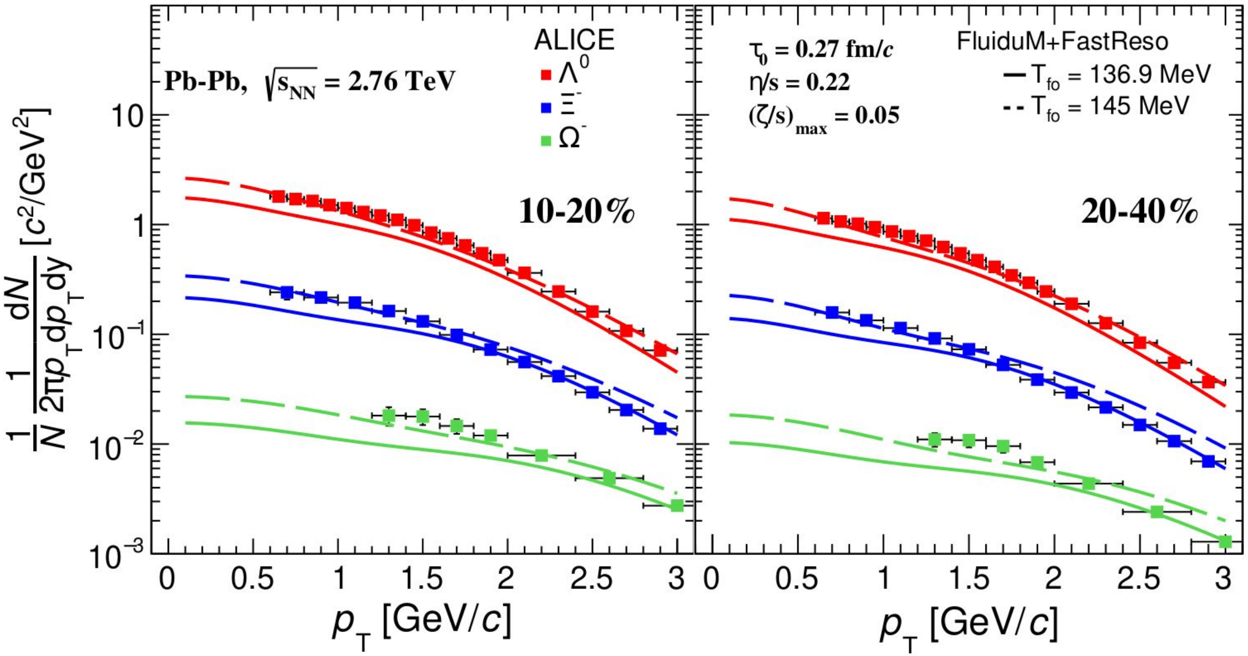


Variations:

- Global vs. individual fits for 5 centrality classes
- $K^\pm$ and $\pi^\pm$ (without p)
- $K^\pm$ (without $\pi^\pm$ and p)

Model parameter	Best fit value	Uncertainty from χ^2 landscape	Uncertainty from fit variations
Norm_1	48.6	0.3	0.6
Norm_2	47.8	0.3	0.5
Norm_3	46.2	0.3	1.2
Norm_4	43.9	0.3	1.3
Norm_5	41.0	0.3	1.3
τ_0 [fm/c]	0.27	0.003	0.04
η/s	0.22	0.006	0.05
$(\zeta/s)_{\max}$	0.05	0.003	0.04
T_{fo} [MeV]	136.9	0.2	4.8

Best fit derived calculations for (multi-)strange hyperon



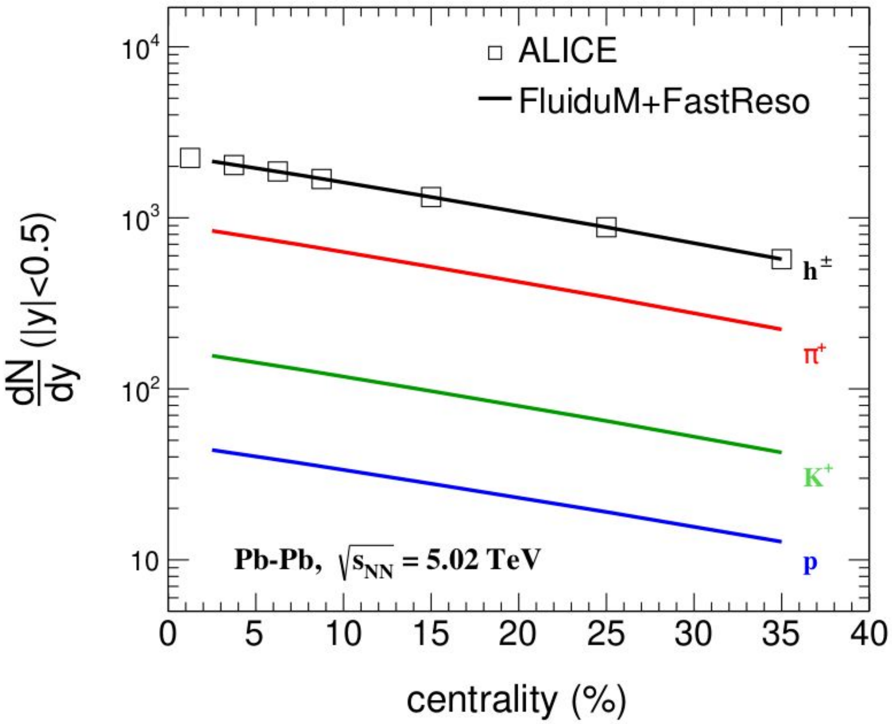
(multi-)strange hadrons prefer higher freeze-out temperature (T_{f0} = 145 MeV)

- sequential hadronization at different temperatures for different flavours?

  R. Bellwied et.al. PRL 111, 202302 (2013)

- additional resonance feed-down might improve the agreement with data

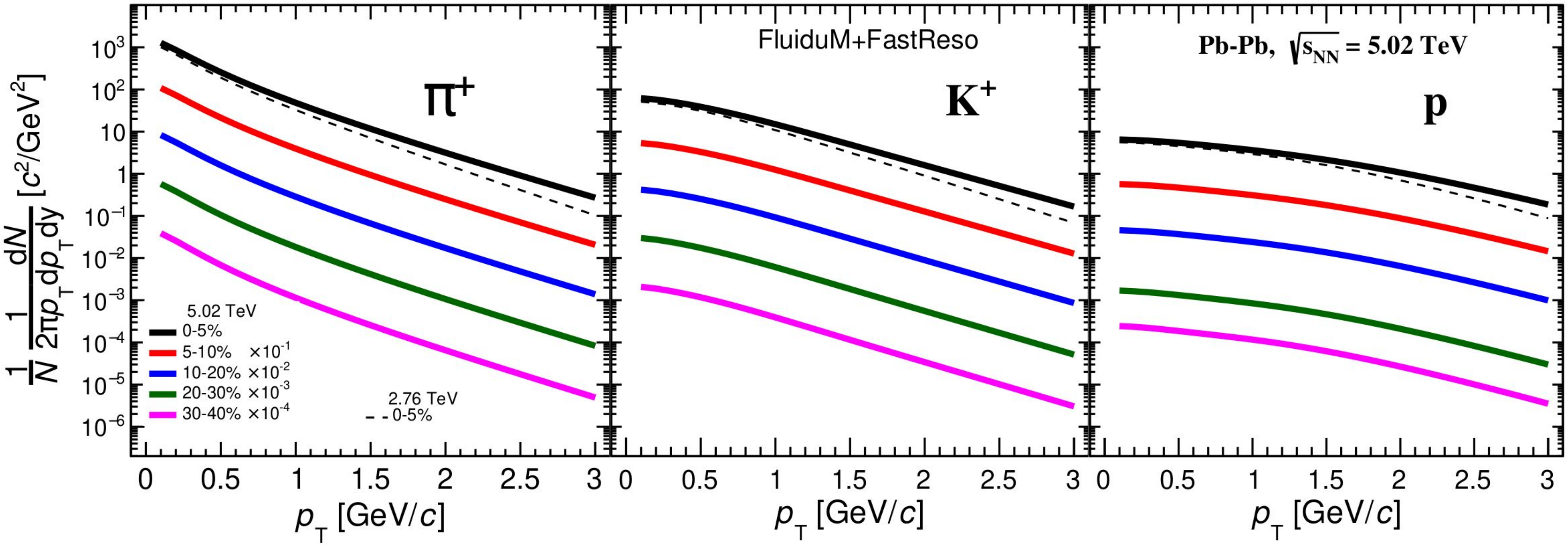
Predictions: total yields in Pb-Pb @ 5 TeV



Same global fit parameters as for 2.76 TeV

Only adjust the initial entropy density normalization (Norm_i) to fit to ALICE $h^{\pm}$ yields vs. centrality

Predictions: p_T yields of in Pb-Pb @ 5 TeV



Higher and flatter p_T-spectra at $\sqrt{s_{NN}}$= 5.02 TeV than at 2.76 TeV
→ stronger radial flow (increasing final state multiplicity with collision energy)

Results are available online: arXiv:1909.10485

Global fluid fits to identified particle transverse momentum spectra from heavy-ion collisions at the Large Hadron Collider

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[1] *Physikalisches Institut, Universität Heidelberg, 69120 Heidelberg, Germany*
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[3] *Institut für Theoretische Physik, Universität Heidelberg, 69120 Heidelberg, Germany*

(Dated: September 23, 2019)

Transverse momentum spectra of identified particles produced in heavy-ion collisions at the Large Hadron Collider are described with relativistic fluid dynamics. We perform a systematic comparison of experimental data for pions, kaons and protons up to a transverse momentum of 3 GeV/c with calculations using the FluiduM code package to solve the evolution equations of fluid dynamics, the TrENTo model to describe the initial state and the FastReso code to take resonance decays into account. Using data in five centrality classes at the center-of-mass collision energy per nucleon pair $\sqrt{s_{\rm NN}} = 2.76\,$TeV, we determine systematically the most likely parameters of our theoretical model including the shear and bulk viscosity to entropy ratios, the initialization time, initial density and freeze-out temperature through a global search and quantify their posterior probability. This is facilitated by the very efficient numerical implementation of FluiduM and FastReso. Based on the most likely model parameters we present predictions for the transverse momentum spectra of multi-strange hadrons as well as identified particle spectra from Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02\,$TeV.

Summary

- Fluid*u*M+FastReso approach has been compared to the experimental data for the charged and identified hadron in Pb-Pb collisions at the LHC

- For the first time using p_T-differential yields for global fit analysis

- χ^2/N_{dof} = 1.4 indicates that fluid description is incomplete

Model parameter	Best fit value	Uncertainty from χ^2 landscape	Uncertainty from fit variations
Norm_1	48.6	0.3	0.6
Norm_2	47.8	0.3	0.5
Norm_3	46.2	0.3	1.2
Norm_4	43.9	0.3	1.3
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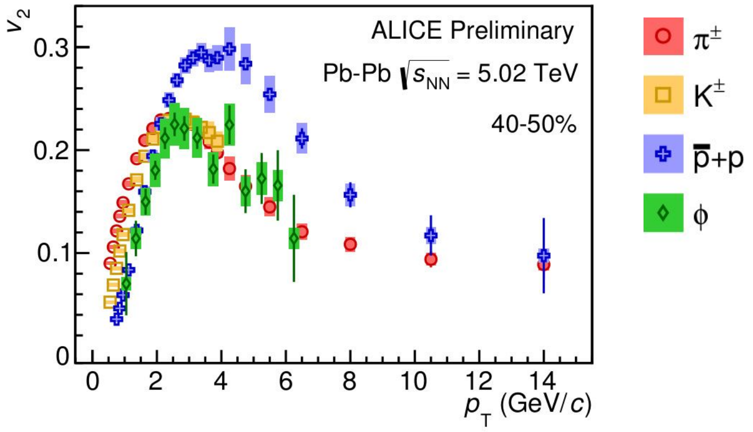
τ_0 [fm/c]	0.27	0.003	0.04
η/s	0.22	0.006	0.05
$(\zeta/s)_{\max}$	0.05	0.003	0.04
T_{fo} [MeV]	136.9	0.2	4.8

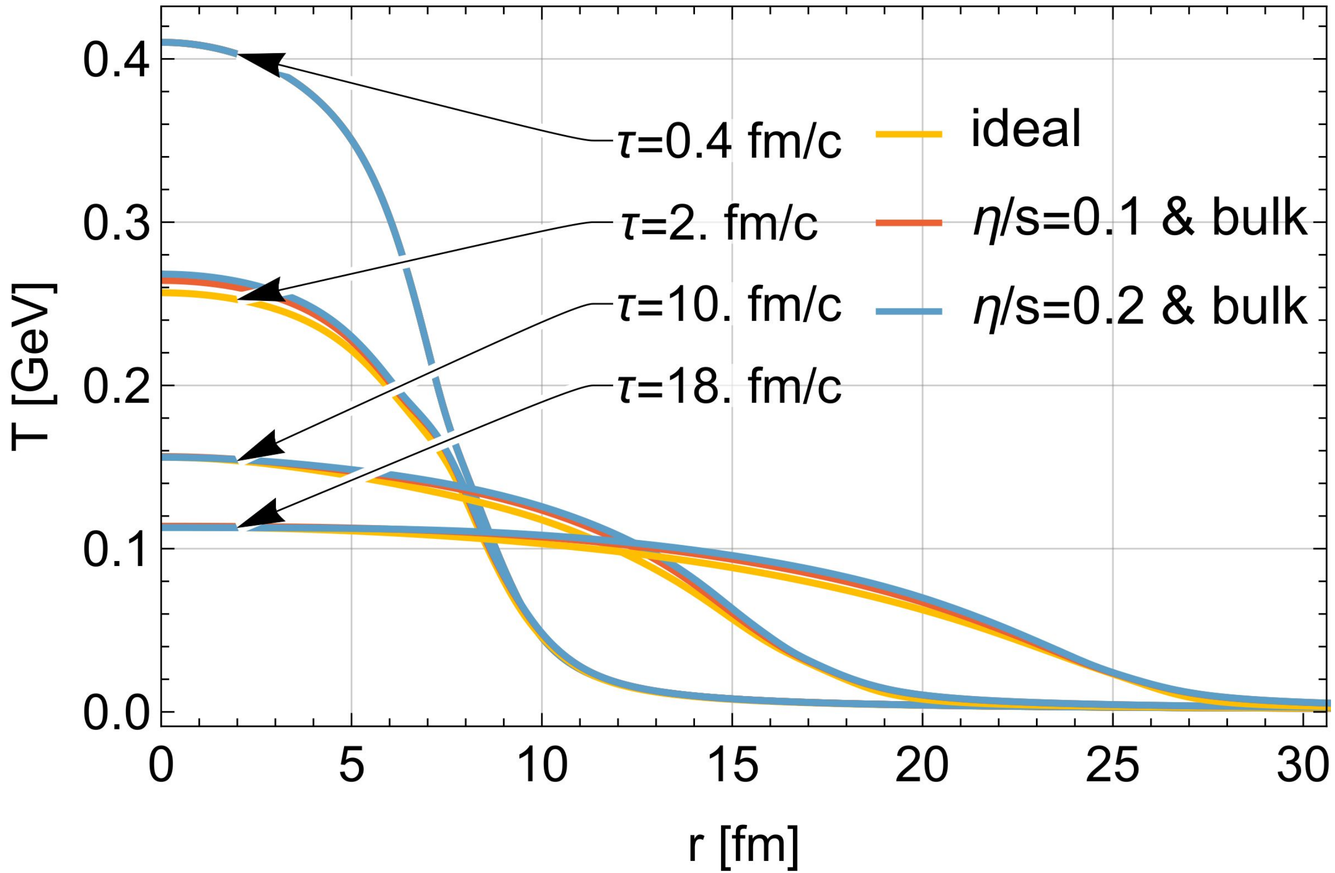
Outlook

- Investigate very low p_T region
- Separate chemical and kinetic freeze-out
- Implement coherent fields in Fluid*u*M
- Implement flow harmonics calculations within Fluid*u*M and compare with experimental data
- Investigate small systems (p-Pb, pp, *e*-p)
- High μ_B (beam energy scan at RHIC & SPS)

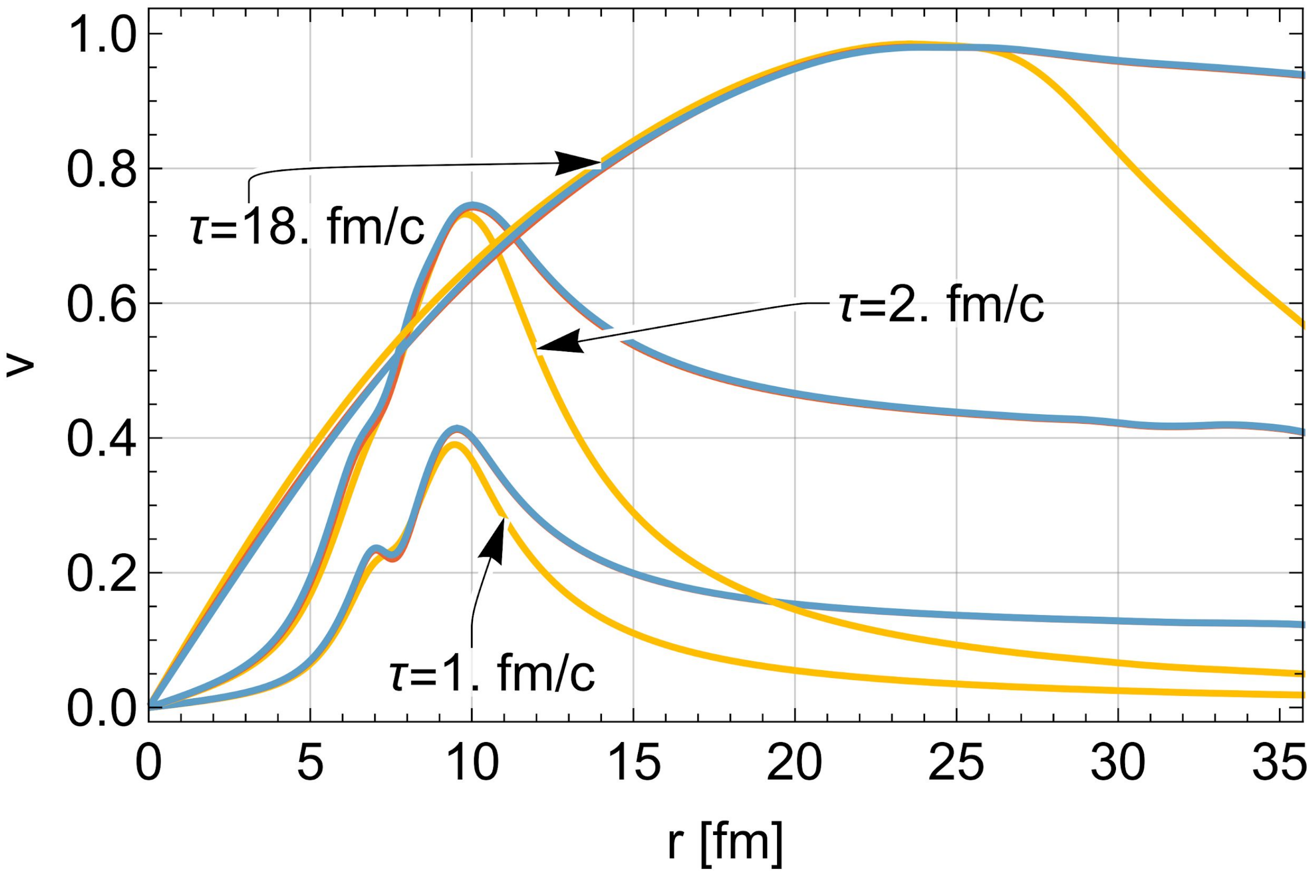


BACKUP

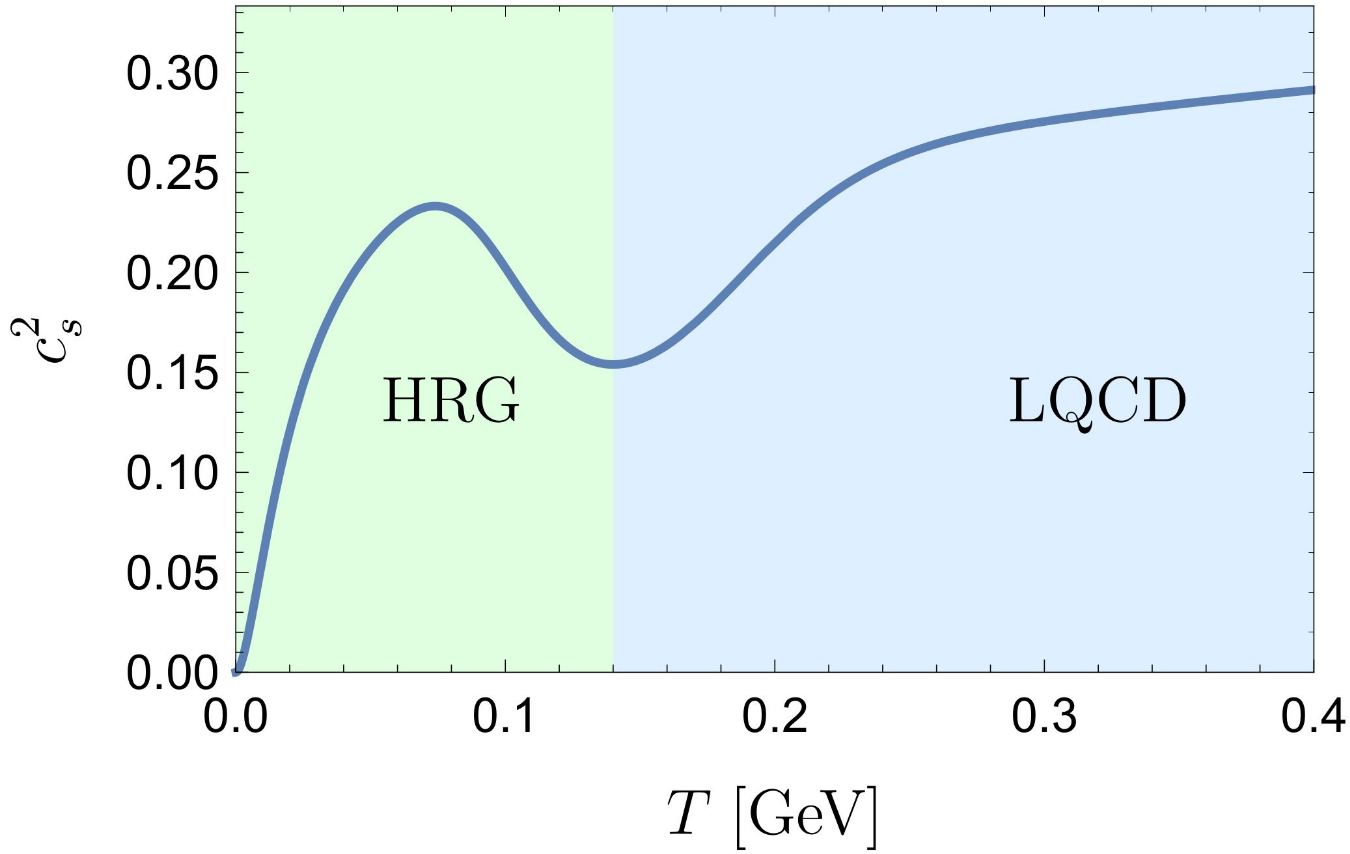
Fluid*u*M: Temperature profile with time



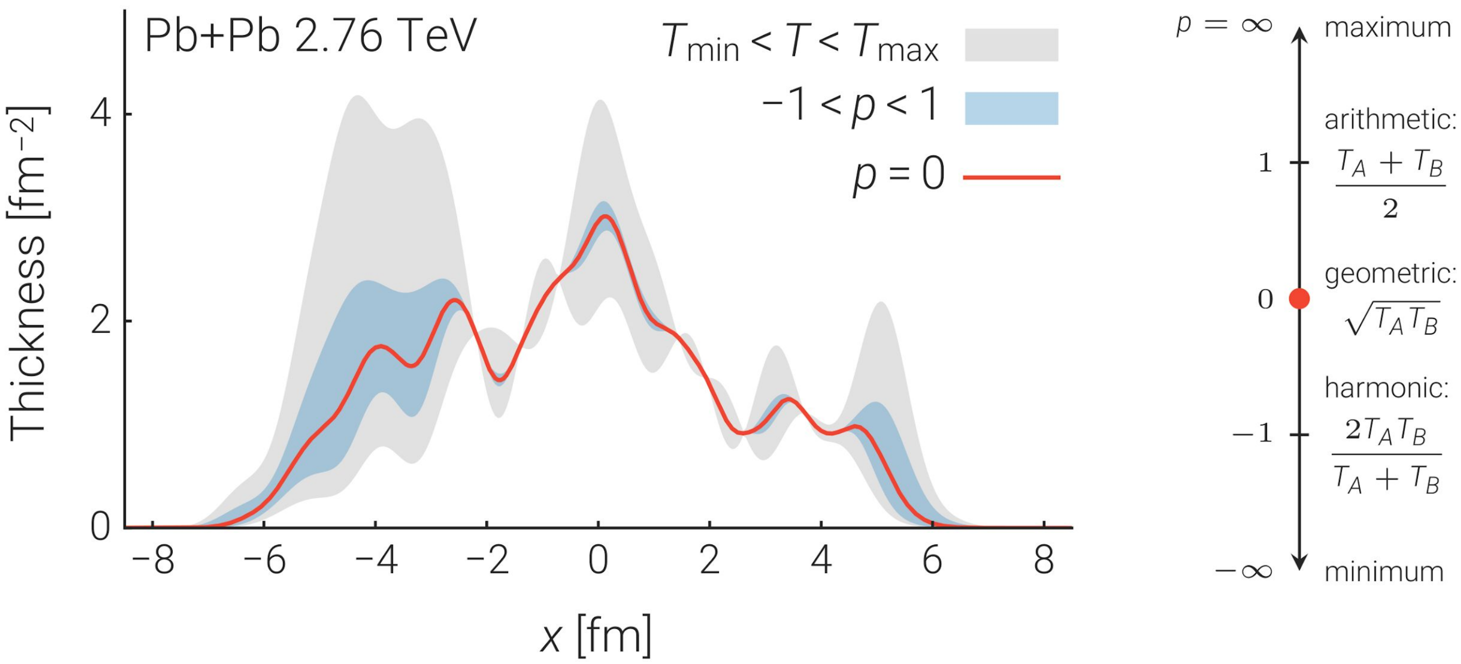
Fluid*u*M: velocity profile



Fluid*u*M: speed of sound vs. Temperature



TRENTo: Reduced Thickness Event-by-event Nuclear Topology



J. Moreland, J. Bernhard, S. Bass:
PRC 92, 011901 (2015); PRC 94, 024907 (2016)

Correlation matrix ρ_{ij} between the fitted parameters

Norm_1	Norm_2	Norm_3	Norm_4	Norm_5	η/s	$(\zeta/s)_{\text{max}}$	T_{fo}	τ_0
1.	0.85	0.85	0.85	0.85	-0.83	-0.85	0.76	0.25
0.85	1.	0.85	0.85	0.85	-0.83	-0.84	0.75	0.25
0.85	0.85	1.	0.84	0.85	-0.83	-0.84	0.74	0.25
0.85	0.85	0.84	1.	0.84	-0.82	-0.84	0.74	0.24
0.85	0.85	0.85	0.84	1.	-0.82	-0.84	0.73	0.23
-0.83	-0.83	-0.83	-0.82	-0.82	1.	0.98	-0.92	0.14
-0.85	-0.84	-0.84	-0.84	-0.84	0.98	1.	-0.91	0.036
0.76	0.75	0.74	0.74	0.73	-0.92	-0.91	1.	-0.02
0.25	0.25	0.25	0.24	0.23	0.14	0.036	-0.02	1.