Neural network enhanced Bayesian global analysis of heavy-ion observables using EbyE-EKRT model and hydrodynamics with dynamical freeze-out

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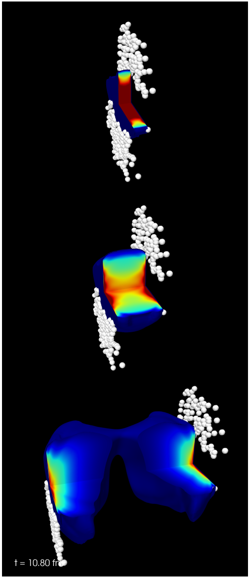
with

Jussi Auvinen, **Kari J. Eskola**, **Henry Hirvonen**

based on

J. Auvinen, K. J. Eskola, H. Hirvonen and H. Niemi, "Neural-network-enhanced Bayesian global analysis of relativistic heavy-ion collisions," Phys. Rev. C **114**, no.1, 014904 (2026) [arXiv:2603.26413 [hep-ph]].



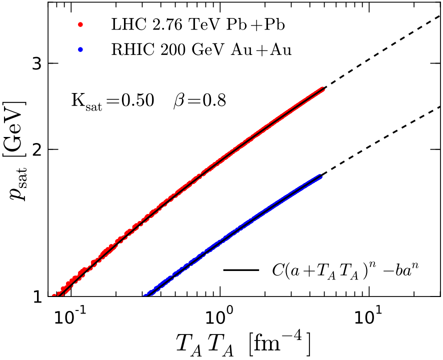
Ultrarelativistic heavy ion collisions: stages

- Initial particle production: Create small droplet of quark-gluon plasma (QGP)
- Secondary interactions of quarks and gluons: QGP evolution
- Formation of hadrons: QCD (phase) transition
- Secondary interactions of hadrons: Hadronic evolution
- Decoupling to free hadrons (**freeze-out**)
- **Fluid dynamics (Hydrodynamics)**: unified description of QGP, hadronization and Hadronic evolution: *microscopic details integrated in the equation of state and transport coefficients*

- Details of the interactions $\rightarrow$ experimental observables

Initial energy density from the Ebye-EKRT model

- NLO pQCD calculation of transverse energy E_T
- EPS09 nuclear parton distributions (Eskola et. al. JHEP **0904**, 065 (2009)) with impact parameter dependence (Helenius et. al. JHEP **1207** 073 (2012))

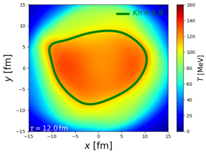


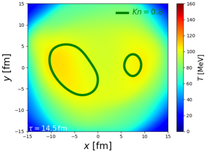
- The full calculation can be summarized by a simple parametrization
- Event-by-event fluctuations through fluctuations in nuclear overlap density ($T_A T_A$).

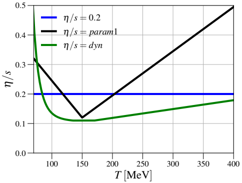
Energy density at time $\tau_0 = 1/p_{\rm sat}$

$$e(\mathbf{s}, \tau_0 = 1/p_{\rm sat}) = K_{\rm sat}\, p_{\rm sat}(\mathbf{s})^4/\pi$$

- $K_{\rm sat}$ free parameter that need to be fixed once.







Dynamical decoupling and viscosity

- Local decoupling condition:
  expansion rate $(\theta) \sim$ scattering rate $1/\tau_\pi$

$$\mathrm{Kn} = \tau_\pi \theta = \mathrm{C}_{\mathrm{Kn}}$$

- Global condition:
  mean free path $(\propto \tau_\pi) \sim$ size of the system (R)

$$\frac{\gamma \tau_\pi}{R} = C_R, \quad R = \sqrt{A/\pi}$$

- C_{Kn} and C_R are free parameters, fitted from data
- Shear and bulk viscosity $\eta/s(T)$, $\zeta/s(T)$
- Interplay between $\eta/s(T)$ and decoupling:

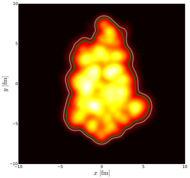
$$\tau_\pi = \frac{5\eta}{e+p} \sim 5\frac{\eta}{s}\frac{1}{T}$$

- In total 15 parameters to control viscosities (10), decoupling (3) and initial conditions (2)

EbyE-EKRT + dynamical FO: Hirvonen, Eskola, HN, Phys. Rev. C **106** (2022) 044913, arXiv:2206.15207

Neural networks

- One collision event relatively fast to compute
- Experimental observables are averages of millions of events
- Simulations need to performed for each event and parametrization separately $\longrightarrow$ computational challenge
- Employ neural networks (NN) to obtain the final results of fluid dynamical evolution:

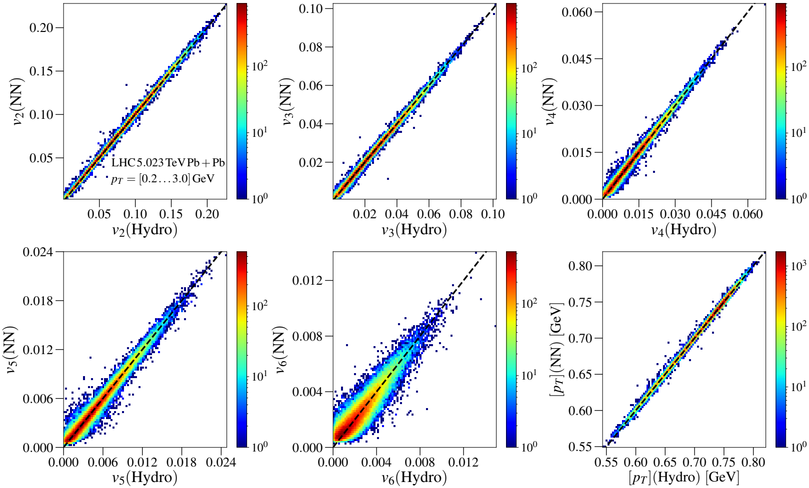


$\longrightarrow$ Neural Networks (DenseNet) $\longrightarrow$ v_n, dN/dy, $\langle p_T \rangle$

- Train NN to predict observables event-by-event from the initial energy density profile
- Create statistics (collision events) using NN
- Average events to compute final measurable observables

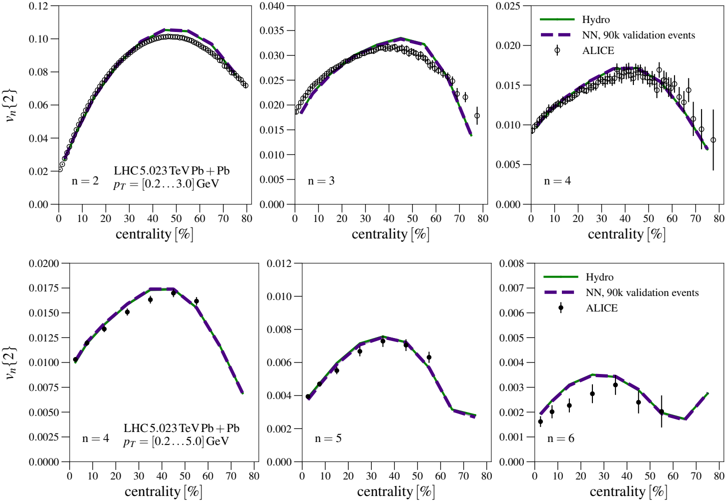
EbyE-EKRT + NN: Hirvonen, Eskola, HN, Phys. Rev. C **108** (2023) 034905, arXiv:2303.04517
DenseNet: G. Huang, Z. Liu, L. van der Maaten, and K. Q. Weinberger, arXiv:1608.06993

Neural networks validation: EbyE



EbyE-EKRT + NN: Hirvonen, Eskola, HN, Phys. Rev. C **108** (2023) 034905, arXiv:2303.04517

Neural networks validation: event-averages



EbyE-EKRT + NN: Hirvonen, Eskola, HN, Phys. Rev. C **108** (2023) 034905, arXiv:2303.04517

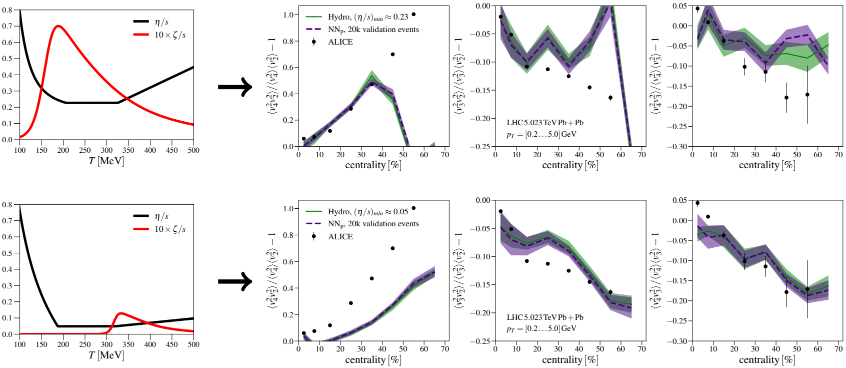
Global analysis with neural networks

Global analysis with neural networks

- I. Train neural networks using hydro by varying initial conditions, viscosity and freeze-out criterion (950 parameter points, 40 events per point/collision energy = 152k events)
  - 5.02 & 2.76 TeV Pb+Pb, 5.44 TeV Xe+Xe, 200 GeV Au+Au
- II. For each parameter point for each system create events using Neural network (here 100k events for each) – much faster than hydro code
- III. Compute event-averaged centrality dependent observables (v_n, dN/dy, $NSC(m,k)$, ...)
- IV. Use the generated data to train Gaussian Process Emulator: fast way to predict event-averaged observables in 15-D parameters space $\longrightarrow$ use in global Bayesian analysis
- **Dramatic speed-up of the analysis: Creating 100k events per parameter point/collision energy using hydro would be 2000 times slower**
- **Creating 10M events per point using hydro would be $\approx$ 100 000 times slower – Game changer!**

Auvinen, Eskola, Hirvonen, HN, Phys. Rev. C **114**, no.1, 014904 (2026) [arXiv:2603.26413 [hep-ph]]

Neural networks with viscosities and dynamical freeze-out conditions as input: validation



- Large and small viscosity cases are well reproduced by the neural networks

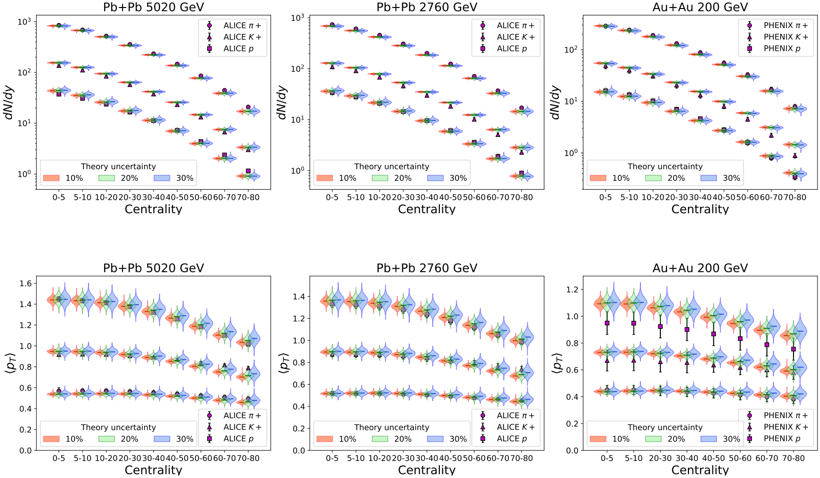
Hirvonen, Eskola, HN, EPJ Web Conf. **296** (2024), 02002, arXiv:2404.02602

Bayesian global analysis

- Find the posterior distributions of the model parameters (viscosity, decoupling, initial conditions) based on experimental data
- Exeperimental data: multiplicities, average p_T, azimuthal asymmetries v_n, NSC(4,2) flow correlators, 4 different systems at RHIC and LHC
- Use Gaussian process emulators to predict the observables $\longleftarrow$ trained using neural networks
- Consider theoretical errors 10 %, 20 %, 30 %: check the stability of the results
- Check the emulator quality: generate 100 more training points from the posterior distribution

Auvinen, Eskola, Hirvonen, HN, Phys. Rev. C **114**, no.1, 014904 (2026) [arXiv:2603.26413 [hep-ph]]

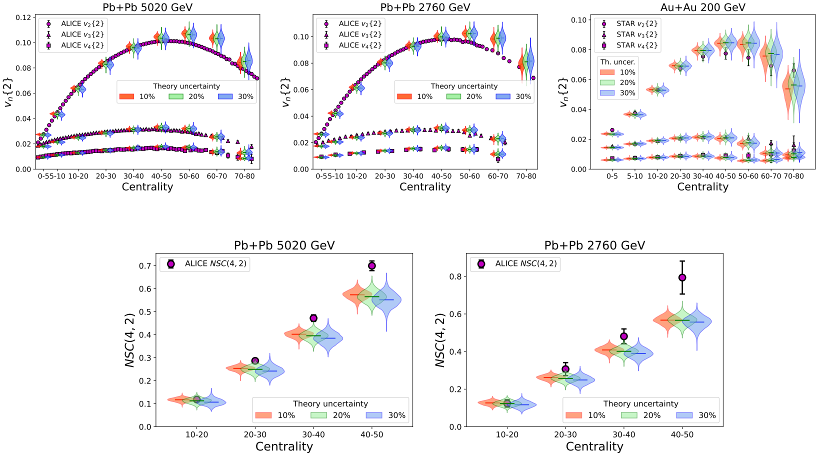
Results: Multiplicity and average p_T



- $\sqrt{s}$ dependence of multiplicity essentially prediction of Ebye-EKRT

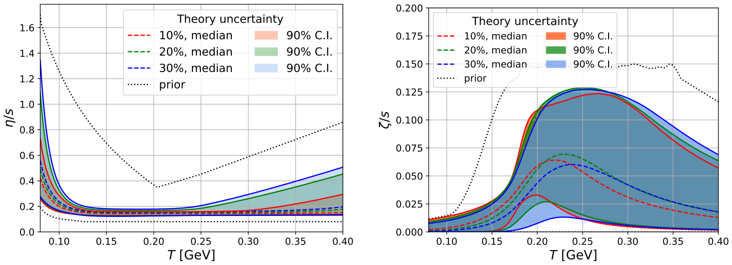
Auvinen, Eskola, Hirvonen, HN, Phys. Rev. C **114**, no.1, 014904 (2026) [arXiv:2603.26413 [hep-ph]]

Results: v_n and $NSC(2,4)$



Auvinen, Eskola, Hirvonen, HN, Phys. Rev. C **114**, no.1, 014904 (2026) [arXiv:2603.26413 [hep-ph]]

Results: Shear and bulk viscosity



- Well constrained $\eta/s(T)$
- Bulk viscosity less constrained
- Results very stable against theoretical errors

Auvinen, Eskola, Hirvonen, HN, Phys. Rev. C **114**, no.1, 014904 (2026) [arXiv:2603.26413 [hep-ph]]

Conclusions

- We can create event-by-event hydrodynamic simulation results using neural networks **A dramatic speed-up of the analysis**
- First results of global analysis using EbyE-EKRT with neural networks
- Shear viscosity is quite well constrained, bulk viscosity not so well
- Both constraints are quite insensitive to theoretical errors

Extra Slides

Parameter	Range
Initial state	
K_{sat}	0.2 – 1.0
σ_n	0.35 – 0.60 fm
QCD matter	
T_H	120 – 250 MeV
$(\eta/s)_{\mathrm{min}}$	0.08 – 0.22
P_H	2.0 – 10.0
$\Delta(\eta/s)_H$	0.1 – 1.5
S_Q	0.0 – 3.0 GeV^{-1}
W_{min}	0 – 300 MeV
$(\zeta/s)_{\mathrm{max}}$	0.0 – 0.15
$T_{\mathrm{max}}^{\zeta/s}$	180 – 350 MeV
$a_{\zeta/s}$	−2.0 – 0.0
$(\zeta/s)_{\mathrm{width}}$	10 – 100 MeV
Decoupling	
T_{chem}	135 – 165 MeV
$C_{\mathrm{Kn}}/(\eta/s)_{\mathrm{min}}$	2.0 – 15.0
$C_R/(\eta/s)_{\mathrm{min}}$	0.5 – 7.5

TABLE II: Free parameters of the model and their prior ranges.

	Theoretical uncertainty σ_{th}		
Parameter	10%	20%	30%
K_{sat}	$0.57^{+0.10}_{-0.09}$	$0.53^{+0.12}_{-0.11}$	$0.51^{+0.16}_{-0.13}$
σ_n [fm]	$0.38^{+0.03}_{-0.02}$	$0.38^{+0.05}_{-0.03}$	$0.40^{+0.07}_{-0.04}$
T_H [MeV]	181^{+61}_{-59}	178^{+61}_{-55}	178^{+63}_{-54}
$(\eta/s)_{\mathrm{min}}$	$0.14^{+0.01}_{-0.02}$	$0.15^{+0.02}_{-0.02}$	$0.15^{+0.03}_{-0.03}$
P_H	$8.4^{+1.5}_{-3.9}$	$8.4^{+1.5}_{-3.7}$	$8.3^{+1.5}_{-3.8}$
$\Delta(\eta/s)_H$	$0.3^{+0.3}_{-0.2}$	$0.3^{+0.6}_{-0.2}$	$0.4^{+0.8}_{-0.3}$
S_Q [GeV^{-1}]	$1.2^{+1.6}_{-1.1}$	$1.3^{+1.5}_{-1.2}$	$1.4^{+1.5}_{-1.2}$
W_{min} [MeV]	225^{+68}_{-130}	183^{+104}_{-151}	165^{+120}_{-144}
$(\zeta/s)_{\mathrm{max}}$	$0.09^{+0.05}_{-0.05}$	$0.09^{+0.05}_{-0.06}$	$0.08^{+0.06}_{-0.06}$
$T_{\mathrm{max}}^{\zeta/s}$ [MeV]	215^{+66}_{-31}	223^{+59}_{-37}	230^{+76}_{-43}
$a_{\zeta/s}$	$-0.5^{+0.4}_{-1.1}$	$-0.7^{+0.7}_{-1.1}$	$-0.8^{+0.7}_{-1.0}$
$(\zeta/s)_{\mathrm{width}}$ [MeV]	57^{+38}_{-43}	60^{+36}_{-43}	61^{+35}_{-43}
T_{chem} [MeV]	147^{+3}_{-4}	148^{+5}_{-5}	149^{+7}_{-6}
C_{Kn}	$1.2^{+0.6}_{-0.4}$	$1.4^{+0.7}_{-0.5}$	$1.5^{+0.8}_{-0.6}$
C_R	$0.7^{+0.3}_{-0.4}$	$0.7^{+0.3}_{-0.4}$	$0.8^{+0.4}_{-0.4}$

TABLE IV: Summary of the median values and 90% credible intervals from the marginal posterior distributions of the model parameters, for three different values of theoretical uncertainty.

Basic quantities in relativistic fluid dynamics

- State of matter given by the energy-momentum tensor:

$$T^{\mu\nu} = e u^{\mu} u^{\nu} - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

- "Primary" : energy density (e), thermal pressure (p), fluid 4-velocity (u^{μ})
- Dissipation: bulk viscous pressure (Π), and shear-stress tensor ($\pi^{\mu\nu}$)
- in equilibrium $\Pi = \pi^{\mu\nu} = 0$ (off-equilibrium corrections)

Energy and momentum conservation

$$\partial_{\mu} T^{\mu\nu} = 0$$

- Fluid evolution driven by pressure gradients, and counteracted by viscosity

$$\frac{\mathrm{d}u^{\mu}}{\mathrm{d}\tau} = \frac{\nabla^{\mu}(p + \Pi)}{e + p + \Pi} - \Delta^{\mu\nu}\partial_{\lambda}\pi^{\lambda}_{\nu}$$

- Need to express Π and $\pi^{\mu\nu}$ in terms of primary quantities (and their gradients)

Basic assumptions in fluid dynamics

- Close to thermal equilibrium:

inverse Reynolds number $R^{-1} = \frac{|\pi^{\mu\nu}|}{p} \ll 1$

- Weak gradients (separation of microscopic and macroscopic scales):

Knudsen number $\mathrm{Kn} = \ell_{\mathrm{micr}}/L_{\mathrm{macr}} \overset{e.g.}{=} \lambda_{\mathrm{mfp}}\theta \ll 1$
($\theta = \partial_\mu u^\mu =$ volume expansion rate)

- Simplest theory (Newtonian fluids in classical fluid dynamics)

$$\Pi = -\zeta\theta \qquad\qquad \pi^{\mu\nu} = 2\eta\partial^{\langle\mu}u^{\nu\rangle}$$

- $\zeta =$ bulk viscosity (Resistance to volume changes)
- $\eta =$ shear viscosity (Resistance to non-isotropic fluid deformations)
- Equilibrium enters through equation of state: $p = p(T)$

QCD matter properties are in $\eta(T)$, $\zeta(T)$ and $p(T)$

- Current estimate: minimum shear viscosity to entropy density ratio $\eta/s \sim 0.1 - 0.2 \longrightarrow$ mean-free path $\lambda_{\rm mfp} \sim 4\frac{\eta}{sT} \sim 0.5 - 1.0$ fm
- Size of the QGP droplet $L \sim 10$ fm $\longrightarrow \mathrm{Kn} \sim 0.05 - 0.1 \ll 1$
- However: Smallest structures in QGP: $L \lesssim 1$ fm $\longrightarrow \mathrm{Kn} \sim 0.5 - 1$

Need to go beyond simple approximation: $\Pi = -\zeta\theta$ and $\pi^{\mu\nu} = 2\eta\partial^{\langle\mu}u^{\nu\rangle}$

2nd order transient fluid dynamics (Israel-Stewart):

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\begin{aligned} \tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = \quad & 2\eta\sigma^{\mu\nu} + 2\tau_\pi \pi_\alpha^{\langle\mu}\omega^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} \\ & + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} \end{aligned}$$

- Resolves explicitly microscopic relaxation (or thermalization) timescales (τ_Π and τ_π) + second order contributions: $\mathrm{Kn}\mathrm{R}^{-1}$ and $(R^{-1})^2$