



Machine Learning for QCD Matter Properties, Initial Condition and Flow Studies

Kai Zhou (FIAS) Initial Stages2023 Copenhagen

#### Challenge in HIC and Machine Learning



See talk by Govert Nijs@Thu16:00 See poster by Yilin Cheng; Yuuka Kanakubo,; Niklas Gotz; Dong Jo Kim; Carlisle Aurabelle Casuga; etc,.

- Uncertainties in HIC modeling
- Multiple parameters <u>entangle</u> with multiple observables
- How to disentangle different factors to reveal fundamental physics from the dynamical environment?



See talk by Hannah Bossi@Tue12:00 See talk by Henry Hirvonen@Wed17:30 Z. Liu, W. Zhao, H. Song, EPJC79,870; P. Xiang, Y. Zhao, X. Huang, CPC46,074110; J. He, W. He, Y. Ma, S. Zhang, PRC104,044902; H. Hirvonen, K. Eskola, H. Niemi, 2303.04517; Y. Huang, L. Pang, X. Luo, X. Wang, PLB827,137001;



# 1, QCD matter EoS identification from Heavy Ion Collisions with Deep Learning

With Longgang Pang, Nan Su, Yilun Du, Jan Steinheimer, Lijia Jiang, Lingxiao Wang, Hanna Peterson, Horst Stoecker, Xinnian Wang, etc.,

Nature Communications 9 (2018), no.1, 210 JHEP 12 (2019) 122 Eur.Phys.J.C 80 (2020) 6, 516 Phys. Lett. B 811 (2020) JHEP 21 (2021) 184 Phys. Rev. D 103 (2021) 11, 116023 arXiv:2211.11670

#### Direct inverse mapping? CNN make the road



• Robust to initial conditions, eta/s

**Conclusion :** Information of early dynamics can survive to the end of the hydrodynamics and encoded with in the final state raw spectra, immune to evolution's uncertainties, with deep CNN we can decode it back.

#### L.G.Pang, K. Zhou, N.Su et al., Nature Commu.9 (2018), no.1, 210

#### Into more realistic cases

U+U 23 GeV/A



M.O.K, J.S, K. Zhou, et at., Phys. Lett. B 811, 135872 **JHEP** 21 (2021) 184

#### The EoS parameterization, the flow and transverse kinetic energy measurements

- Hadronic cascade dominant
- UrQMD model adapted to any density dependent EoS →

via density dependent potential Eur.Phys.J.C82(2022)5,417

**Evidence :** proton's v2

data

2.5

3.0

3.5

 $\sqrt{s_{\rm NN}}$  [GeV]

0.02

0.00

ട്<sup>−0.02</sup> റ

-0.04

-0.06

-0.08



M.OK, J. Steinheimer, H. Stoecker, K. Zhou, arXiv:2211.11670

4.5

#### EoS reconstruction Closure tests, with real data, Predictability



#### With real experimental data



Test the extracted EoS on different observables (not used in Bayesian analysis)



# 2, Initial Condition Inference

With Manjunath O.K, Jan Steinheimer, Andreas Redelbach, Horst Stoecker, Yi-Lin Cheng, Shuzhe Shi, Long-Gang Pang, Xin-Nian Wang, Yu-Gang Ma

Phys.Lett.B 811 (2020) 135872 Particles 2021, 4(1), 47-52 arXiv:1906.06429 arXiv:2301.03910

#### CBM Centrality-Meter with PointNet

- Experimental data has inherent point cloud structure
  - **collection of particles** as 2D array : each row = a particle (point) in one cloud each column = a feature of point
- PointNet based models learn directly from point clouds.
  - respects the order invariance of point clouds
  - direct processing of experimental data from detector ⇒ ideal online analysis algorithm
  - optimal for higher dimensional data

- We consider the CBM experiment as a use case
  - Au-Au collisions
  - 10 AGeV
  - CBM Challenges →

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## End-to-End Online Event Characteristics for CBM with PointNet

- b is not measurable
- Final state obs to obtain likely distribution with e.g., MC Glauber and percentiles of Nch



participants before collision after collision Impact Parameter

Polyfit

M-hits

S-hits MS-tracks

12.5

10.0

HT-combi

15.0

- Data: UrQMD + cbmROOT
- With hits/tracks, end-to-end ٠ online EbE b-meter: PointNet



- Quantifies accuracy
- DL: -0.3 0.2 fm for b = 2-14 fm
- Polyfit fluctuating



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#### Nuclear Deformation Inference from HIC with DL

• <u>Nuclear structure (deformation) imaging from High Energy Heavy Ion Collisions</u>



[see talk by Jiangyong@Wed09:00, Giuliano@Wed09:30]

#### **Deep Learning Nuclear Deformation via regression**



#### **DCNN Regression and Attention Mask Analysis**

ReLu

Squeeze Excite

Batch Norm

Conv2D(3x3)

ReLu

Batch Norm

Conv2D(3x3)

1 Residual Block-II

Conv 1x1

add 🕁



- 51  $\beta_2 \in [-0.5, 0.5] \times 51 \beta_4 \in [-0.2, 0.2] = 2601$  groups
- Each generate 100k events with random geometries in centrality range : 0 ~ 50%

L. Pang, K. Zhou and X. Wang, arXiv:1906.06429





### Bayesian Imaging for Nuclear Structure in Isobar Collisions

- How it works for single system ? (caveat: model dependent)
- Simultaneous inference for isobar systems with ratio?
- **Bayesian Inference:** Gaussian Process emulator + PCA dim reduction + MCMC Data: MC-Glauber + Matching (linear response approximation)







#### Simultaneous Reconstruction for Isobar Systems using Ratios of Obs.



• With purely the Isobar-Ratios, MCMC can not converge to a stationary inference of the nuclear structure

#### arXiv:2301.03910

#### **Ratios Plus Single-System Multiplicity Distribution**



- The  $d_{\perp}$  information is redundant for the inference
- More realistic model, AMPT-based in progress



# 3, Flow analysis & Unsupervised Outlier Detection

With Han-Sheng Wang, Shuang Guo and Guo-Liang Ma, Punnathat Thaprasop, Jan Steinheimer and Christoph Herold

arXiv:2305.09937 Phys. Scripta 96(2021)6,064003

#### Small or Large collision system distinction?

Data: list of (Px, Py, Pz, E) from AMPT







- Using 4-momentum point cloud the PCN can classify the two systems well
- discrepancy mainly at the p-going direction, consistent with : larger rapidity distribution diff. at larger Nch

## Small or Big collision system ?

- Data: list of (Px, Py) from AMPT ٠ (a) unnormalized (1) unnormalized  $(p_x, p_y)$ Accuracy (a) 0 mb (b) 3 mb (c) 10 mb (2) random rotation : remove flow effect 0.8 (GeV/c)  $p_{\rm v}^{\rm rand}$  $= p_{\rm x} \times \cos \phi_{\rm rand} - p_{\rm y} \times \sin \phi_{\rm rand},$ p+Pb 5.02 TeV, 3 mb or Pb+Pb 5.02 TeV, 3 mb 0.6  $= p_{\rm x} \times \sin \phi_{\rm rand} - p_{\rm y} \times \cos \phi_{\rm rand},$ 0.5 (b) normalized ^⊥ v 0.4  $p_{\rm x}^{\rm norm} = \frac{p_{\rm x}}{p_{\rm T}},$ (3) Normalized : w/o random rotation Accuracy 0.00 0.55 Pb+Pb *remove pT effects* 0.2  $p_{\rm v}^{\rm norm} = \frac{p_{\rm y}}{2}$ w/ random rotation -- p+Pb ml<2.4 150 150 200 100 150 (4) Normalized and random rotated 100 200 100 200 flow N<sub>ch</sub> N<sub>ch</sub> N<sub>ch</sub>  $p^{\text{norm,rand}} = \frac{p_{\text{x}} \times \cos \phi_{\text{rand}} - p_{\text{y}} \times \sin \phi_{\text{rand}}}{p_{\text{y}} \times \sin \phi_{\text{rand}}}$ 0.50 120 150 180 210 90  $p_{\rm v}^{\rm norm, rand} = \frac{p_{\rm x} \times \sin \phi_{\rm rand} - p_{\rm y} \times \cos \phi_{\rm rand}}{p_{\rm y} \times \cos \phi_{\rm rand}}$ N<sub>ch</sub>
- With unnormalized 2-momentum, PCN will first fully exploit the pT distribution characteristic of the two systems for their distinguishment
- PCN can also capture the **flow differences** in classifying the two systems (though worse than unnormalized case, but works in ensemble manner)

#### Small or Big collision system ?

- Many-body interactions makes *contrast medium* in identifying the two systems' features
- Isolating flow effects in the distinguishment



 p-Pb and Pb-Pb ensemble distinguishment may reflect the v2 and v3 discrepancies



### **Outlier Detection for HIC**

• Use centrality misclassification as example



• PCA to reduce dim while keep some **reconstruction**  $\rightarrow$ 









### **Outlier detection for HIC**

- Reconstruction Error separate the outlier from background
- Other reduced representation methods: autoencoder with FC or CNN





• Receiver Operating Curve (ROC) quantify outlier detection ability





- Physics Priors are needed, coult be put into :
- 1, training data (Implicit) : DL (network) learn the inverse mapping directly : <u>general mapping</u>, avoid case-specific retraining
- 2, **inference process (Explicit) :** Chi2 fit+**Bayesian** inference+Gradient Descent : <u>Automatic differentiation</u> and <u>Network representation</u>

If interested, for more discussion for QCD matter exploration with ML see Review: arXiv:2303.15136





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