Bridging Physical Simulations of HICs with AI for Scientific Discovery

汇报人：Long-Gang Pang

Central China Normal University

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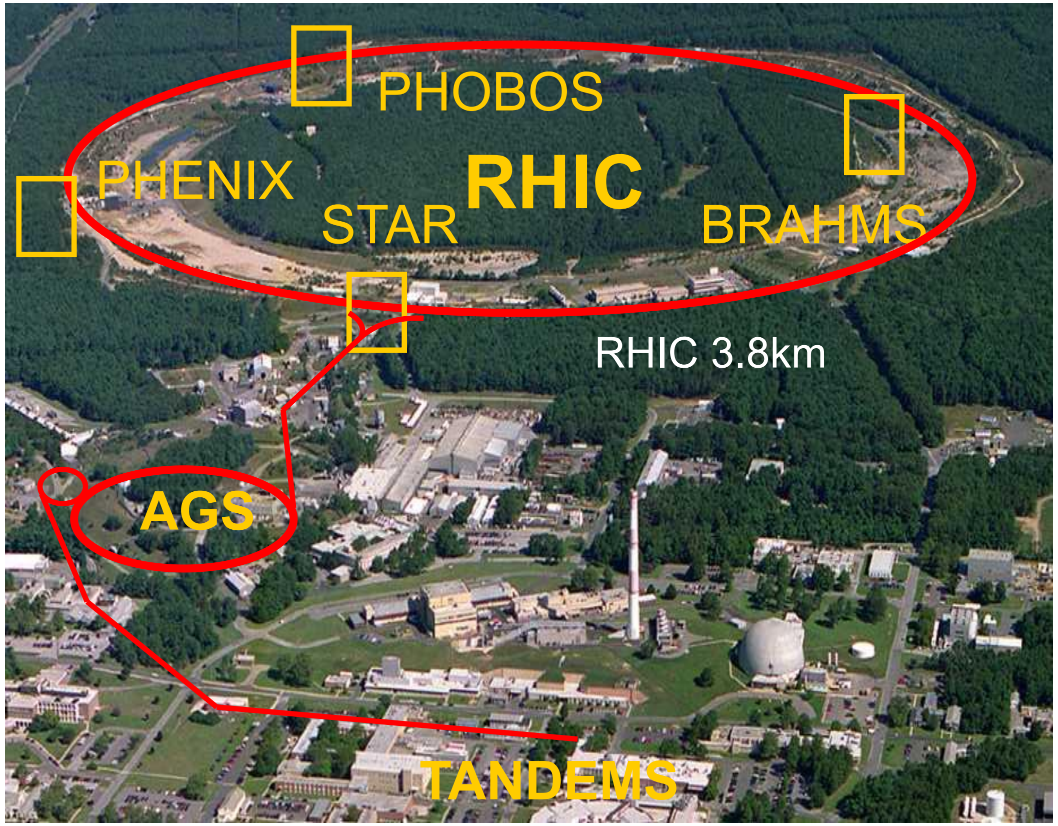
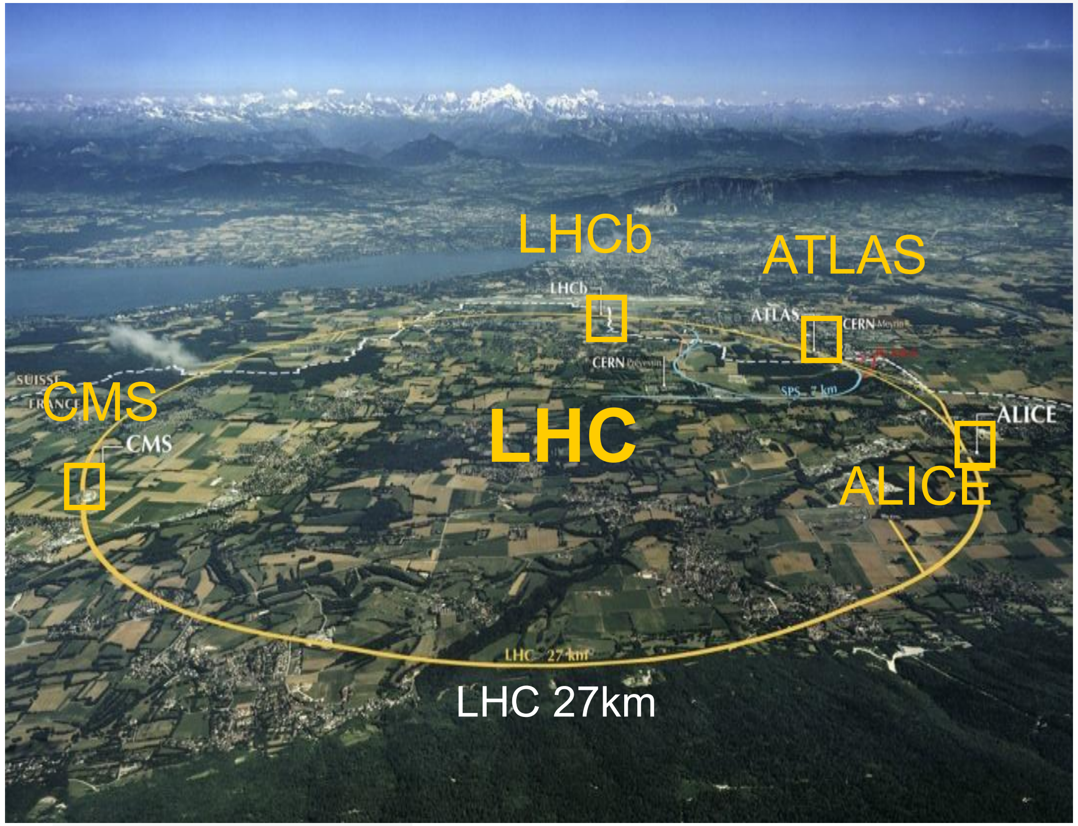
Nuclear Matter at extreme conditions

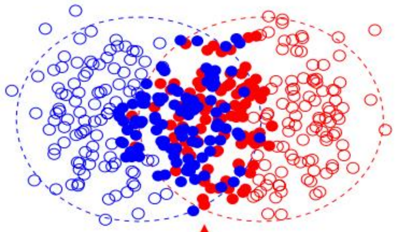




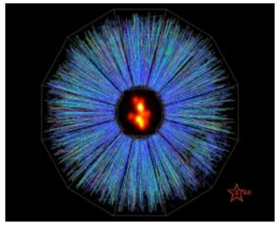
Au speed ～99.99% c

Pb speed～99.9999% c

相对论流体力学：CLVisc



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



$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \pi^{\mu\nu}$$

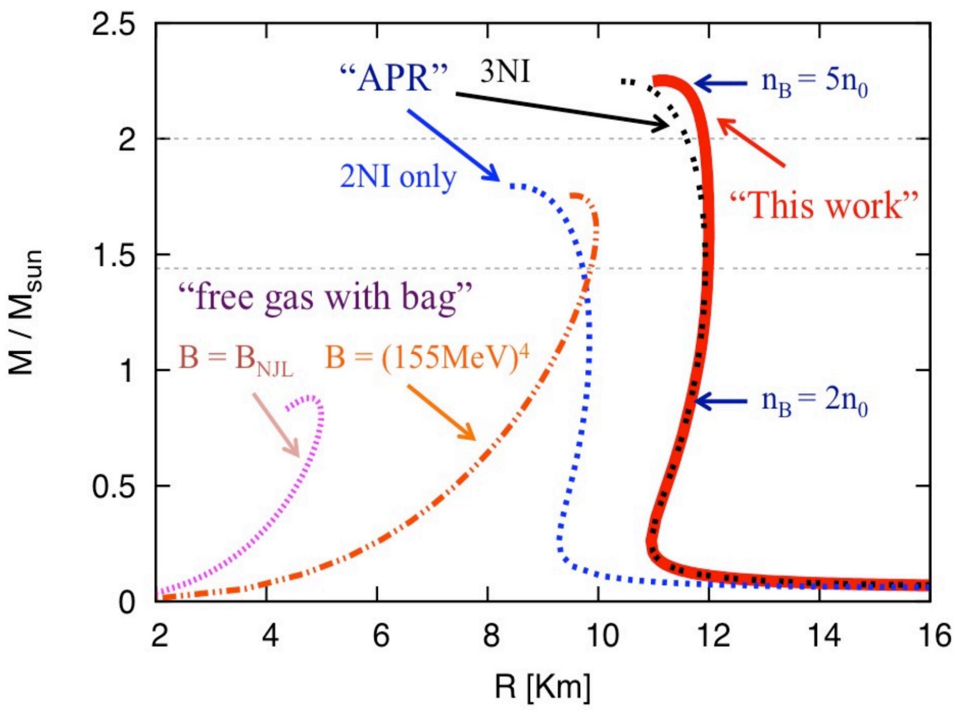
初始条件　　**状态方程 $P(\varepsilon)$**　　输运系数

- 名字起源：
  1. 指代 CCNU-LBNL Viscous Hydro：其中 CCNU是华中师范大学英文缩写
  2. 使用OpenCL实现 GPU 并行加速的粘滞（Viscous）流体力学程序
- 用途：描述高温高密核物质的非平衡态动力学演化
- 特点：运行速度快，单事例相对 CPU 加速 100 倍

L.G. Pang, Q. Wang and X. N. Wang, PRC 86 (2012) 024911
L.G. Pang, B.W. Xiao, Y. Hatta, X.N.Wang, PRD 2015
L.G. Pang，H.Petersen, XN Wang, PRC97(2018)no.6,064918

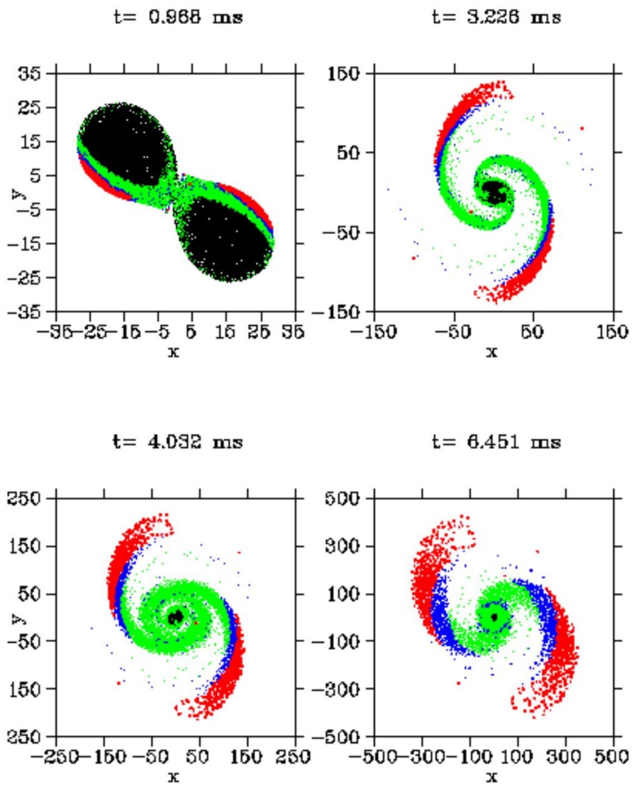
Astrophysics with different nuclear EoS

Neutron Star M-R

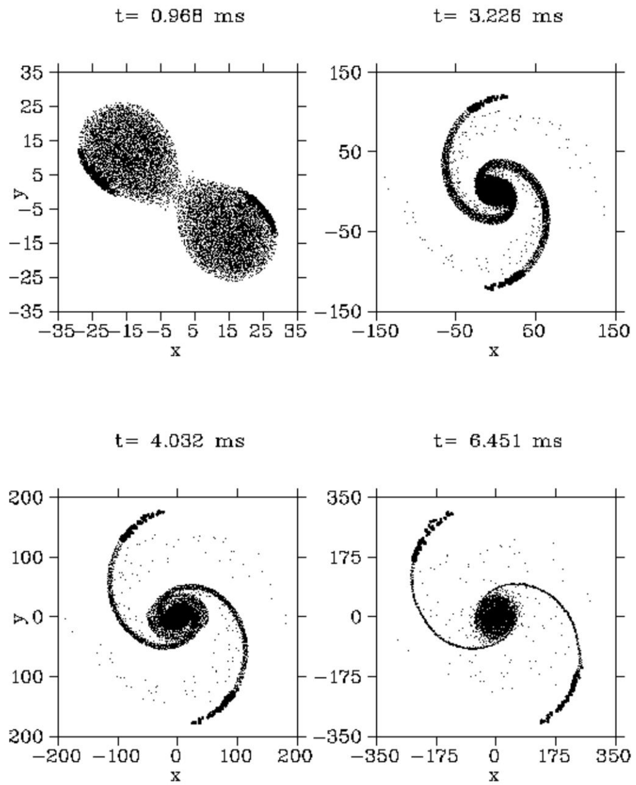


T Kojo, PD Powell,YF Song,and G Baym, 2015

Soft nuclear EoS

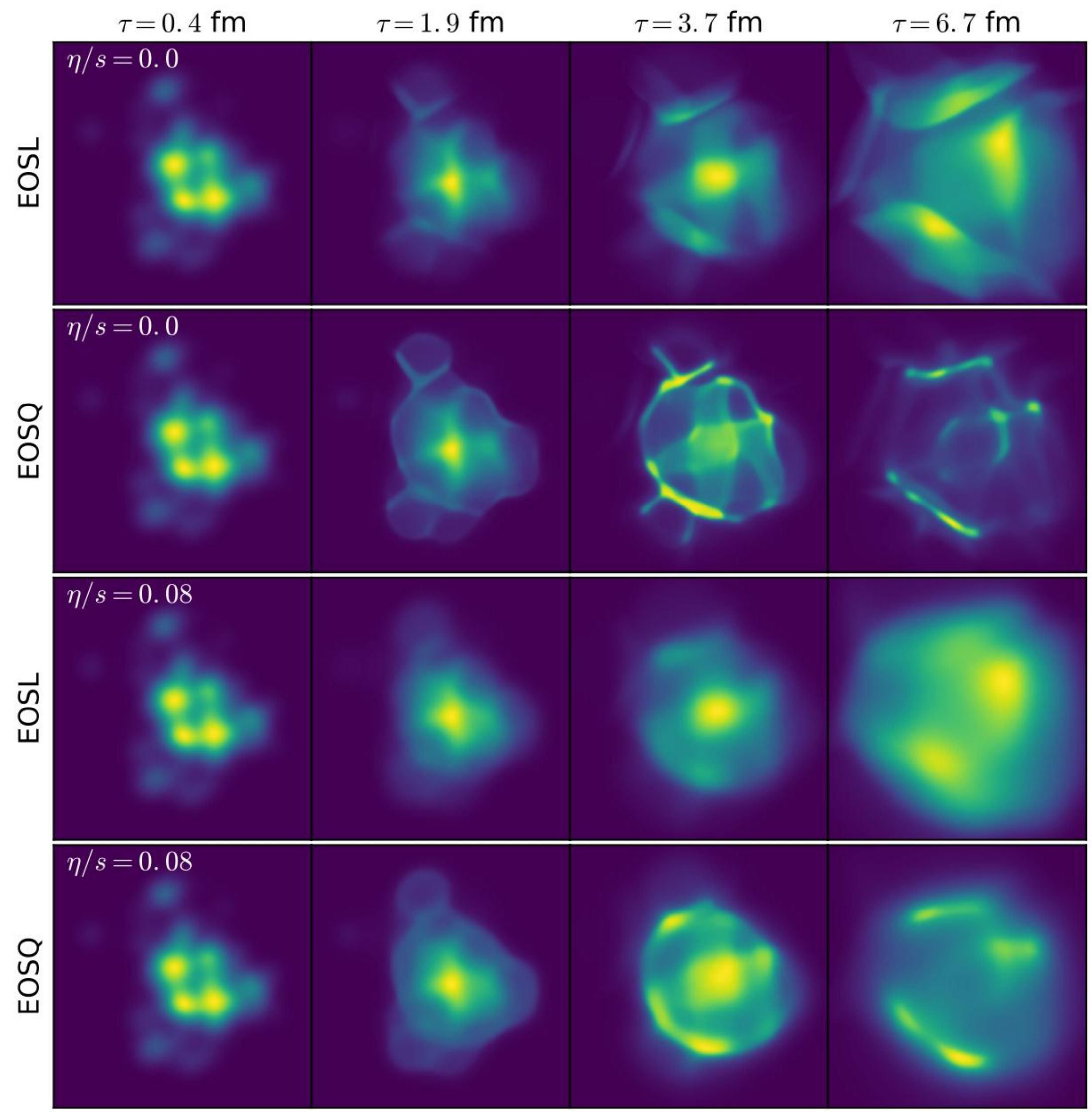


Stiff nuclear EoS

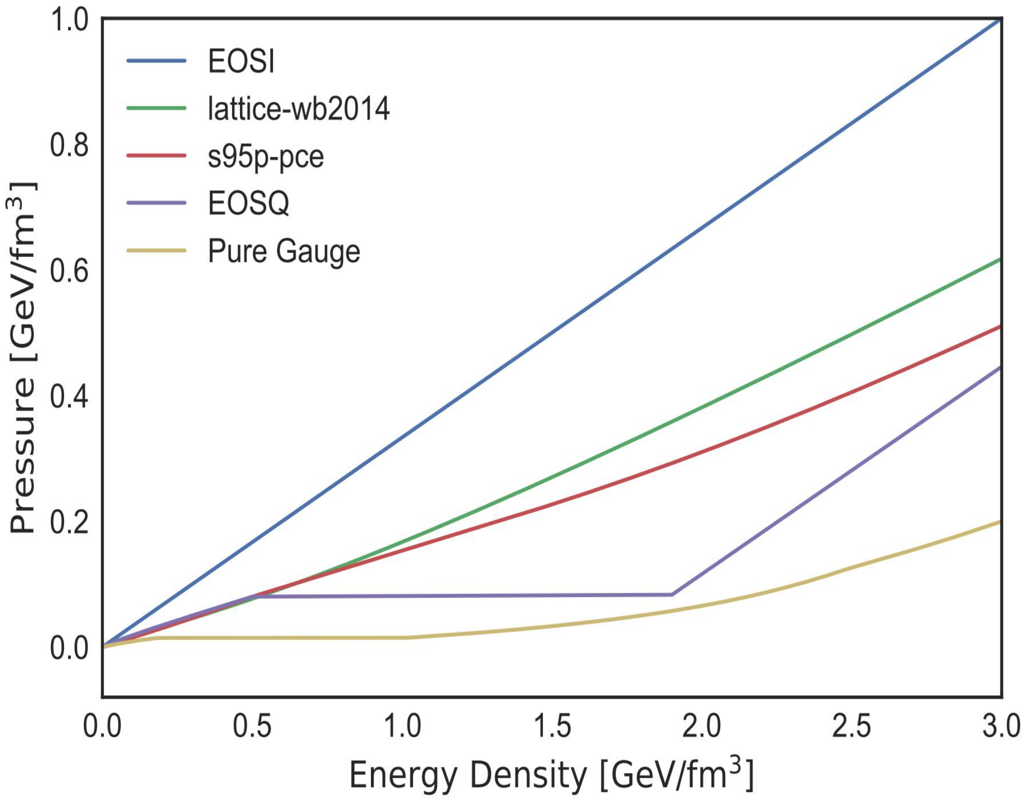


S. Rosswog et al., Astronomy and Astrophysics 341, 499 (1999).

Different Nuclear EoS used in CLVisc



Nuclear EoS employed in HIC physics



LG Pang, H Petersen, XN Wang, PRC 2018

Large scale simulations of our universe

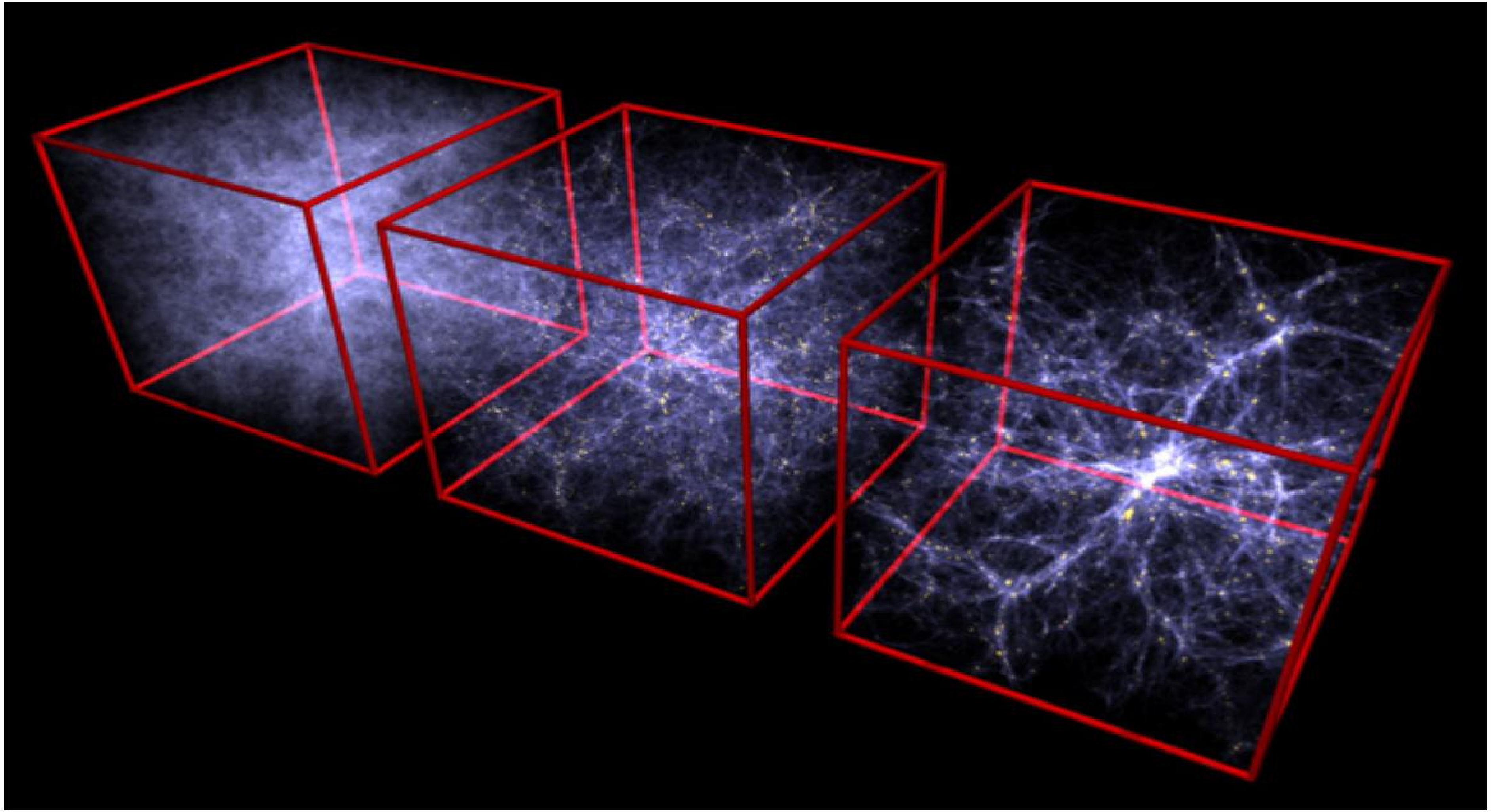
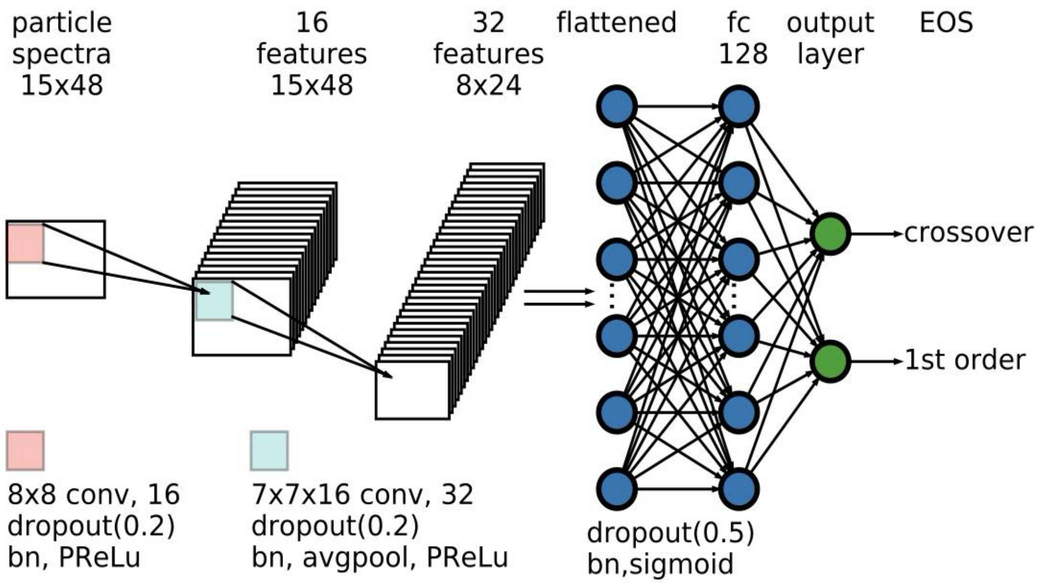


Figure 28: Small fluctuations in density in the far left box collapse into large structures on the right in this computer simulation of the universe.
Source: © Courtesy of V. Springel, Max-Planck-Institute for Astrophysics, Germany.

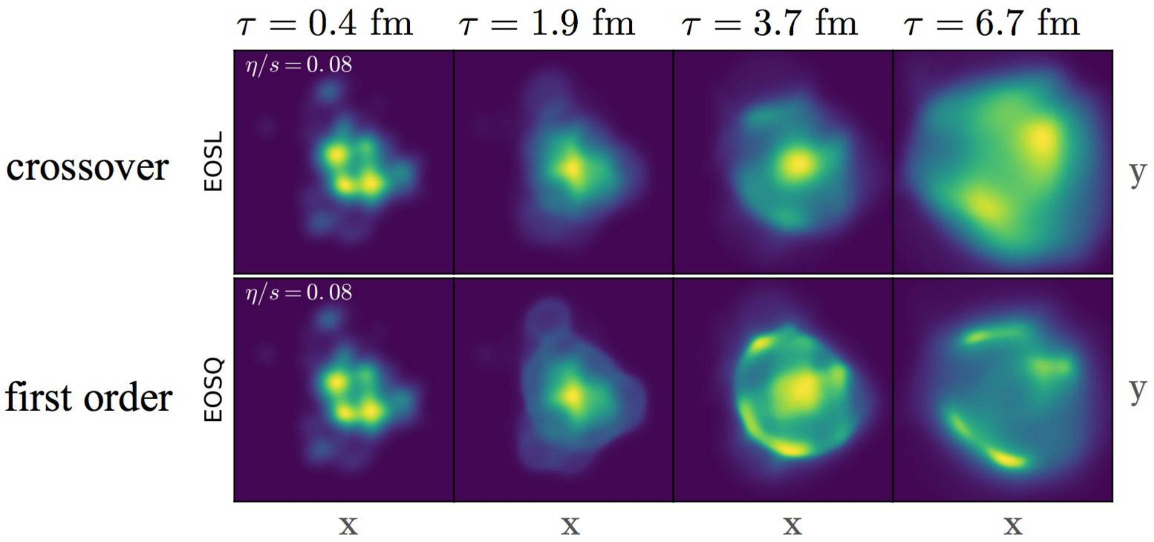
Determine nuclear phase transitions



$$l(\theta) = -\frac{1}{N}\sum_{i=1}^{N}[y_i \log \hat{y}_i + (1-y_i)\log(1-\hat{y}_i)] + \lambda||\theta||_2^2$$

cross entropy loss　　L2 regularization

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

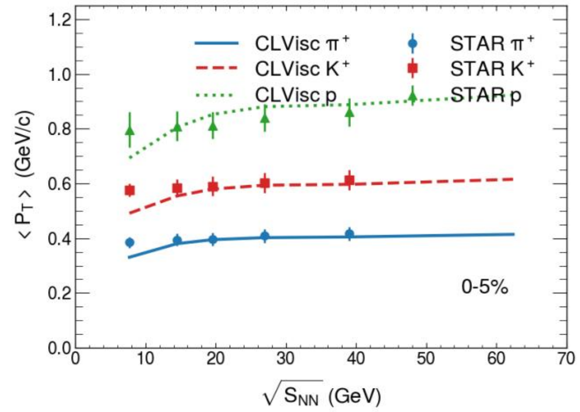


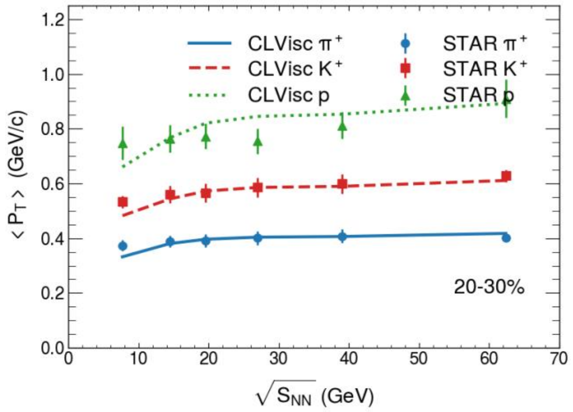
CLVisc 3+1D relativistic hydrodynamics

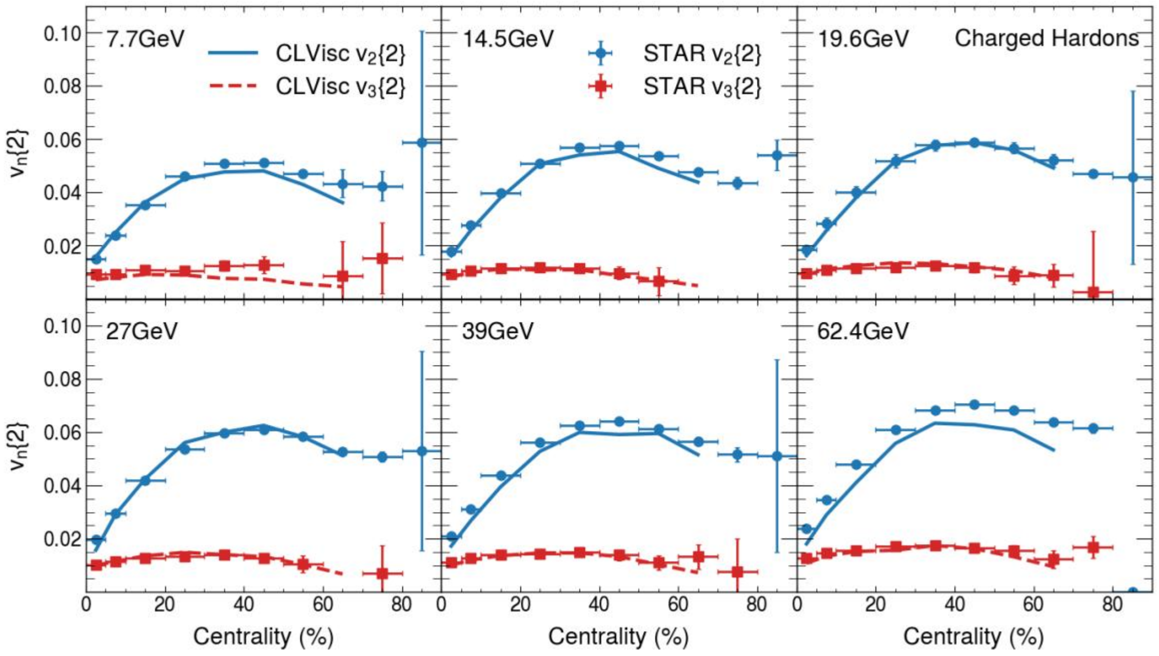
DL： 93% Classification Accuracy!

Nature Communications 2018, LG. Pang, K.Zhou, N.Su, H.Petersen, H. Stoecker, XN. Wang.

CLVisc2.0 For Beam Energy Scan







$$\nabla_\mu T^{\mu\nu} = 0\,, \qquad T^{\mu\nu} = eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}\,,$$

$$\nabla_\mu J^\mu = 0\,, \qquad J^\mu = nU^\mu + V^\mu\,,$$

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - \eta_v \sigma^{\mu\nu}\right) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha<\mu}\sigma^{\nu>}_{\alpha} + \frac{9}{70}\frac{4}{e+P}\pi^{<\mu}_{\alpha}\pi^{\nu>\alpha}\,, \tag{10}$$

$$\Delta^{\mu\nu} DV_\nu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}, \tag{11}$$

- 加入了净重子数守恒方程
- 添加了净重子扩散流满足的驰豫方程
- 新代码可以描述中低能核碰撞 （BES 能区）

XY Wu, 秦广友，庞龙刚，王新年，PRC 105 (2022) 3, 034909

CLVisc3.0 开发

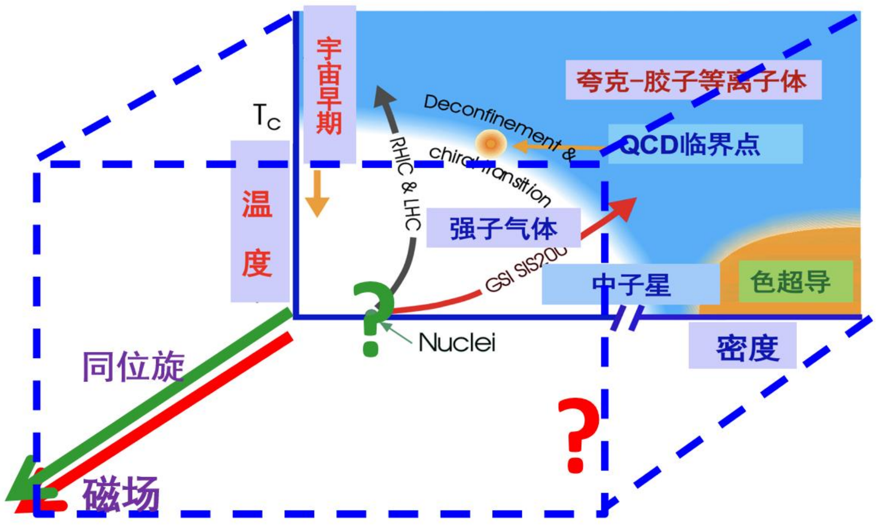
新版本：

$$\nabla_\mu T^{\mu\nu} = 0, \qquad T^{\mu\nu} = eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu},$$

$$\nabla_\mu J^\mu = 0, \qquad J^\mu = nU^\mu + V^\mu,$$

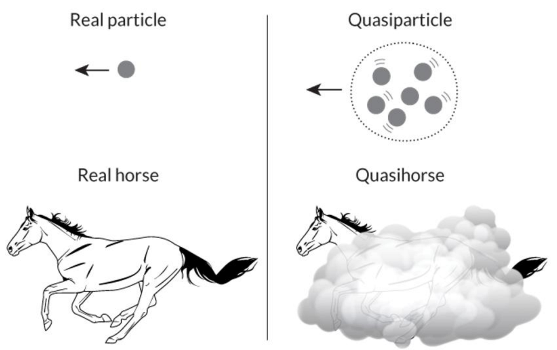
$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - \eta_v \sigma^{\mu\nu}\right) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha<\mu}\sigma^{\nu>}_{\alpha} + \frac{9}{70}\frac{4}{e+P}\pi^{<\mu}_{\alpha}\pi^{\nu>\alpha}, \tag{10}$$

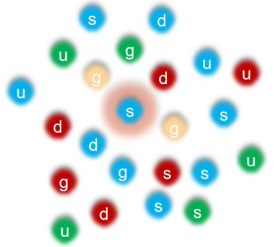
$$\Delta^{\mu\nu} DV_\nu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}, \tag{11}$$



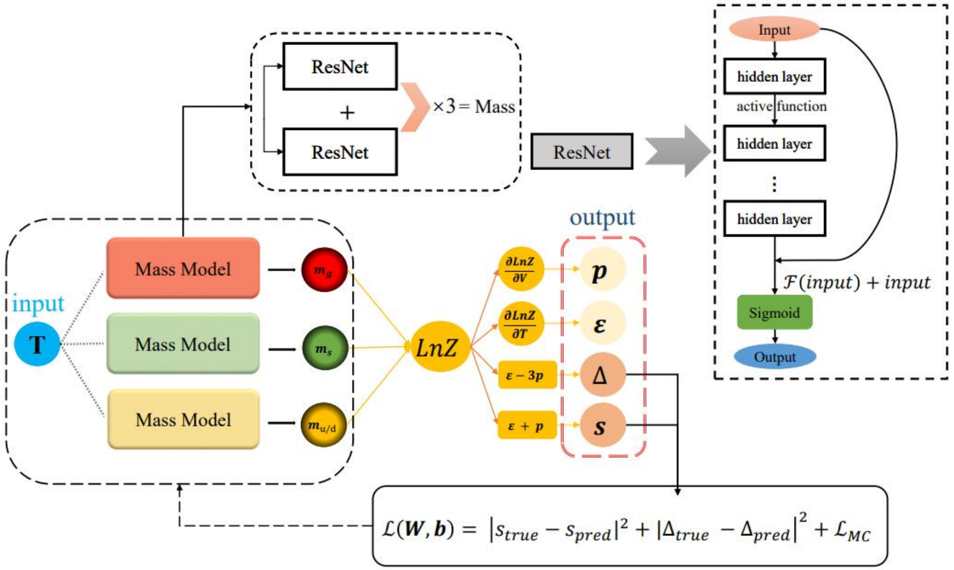
- 更好的文档和易用性 + LLM Agent 集成
- 加入净电荷数守恒方程
- 加入净奇异数守恒方程
- 更好的描述中低能核碰撞区不同强子产额比
- 四维状态方程和自洽的输运系数
- 加入涨落和关联随时间的演化方程
- 研究重子-超子关联
- 研究重子数和电荷数输运

DL Quasi Parton Model for nuclear EoS





screened, dressed, regularized, quasi particle



FuPeng Li, HL Lu, LG Pang, GY Qin, PLB 2023

$$\ln Z(T) = \ln Z_g(T) + \ln Z_{u,d}(T) + \ln Z_s(T),$$

Fermi-Dirac distributions,

$$\ln Z_g(T) = -\frac{16V}{2\pi^2}\int_0^\infty p^2 dp \ln\left[1-\exp\left(-\frac{1}{T}\sqrt{p^2+m_g^2(T)}\right)\right], \quad (2)$$

$$\ln Z_{q_i}(T) = +\frac{12V}{2\pi^2}\int_0^\infty p^2 dp \ln\left[1+\exp\left(-\frac{1}{T}\sqrt{p^2+m_{q_i}^2(T)}\right)\right], \quad (3)$$

quarks, $m_s(T,\theta_2)$ for strange quark and $m_g(T,\theta_3)$ for gluons, where θ_1, θ_2 and θ_3 are the parameters in DNN shown in Fig. 1.

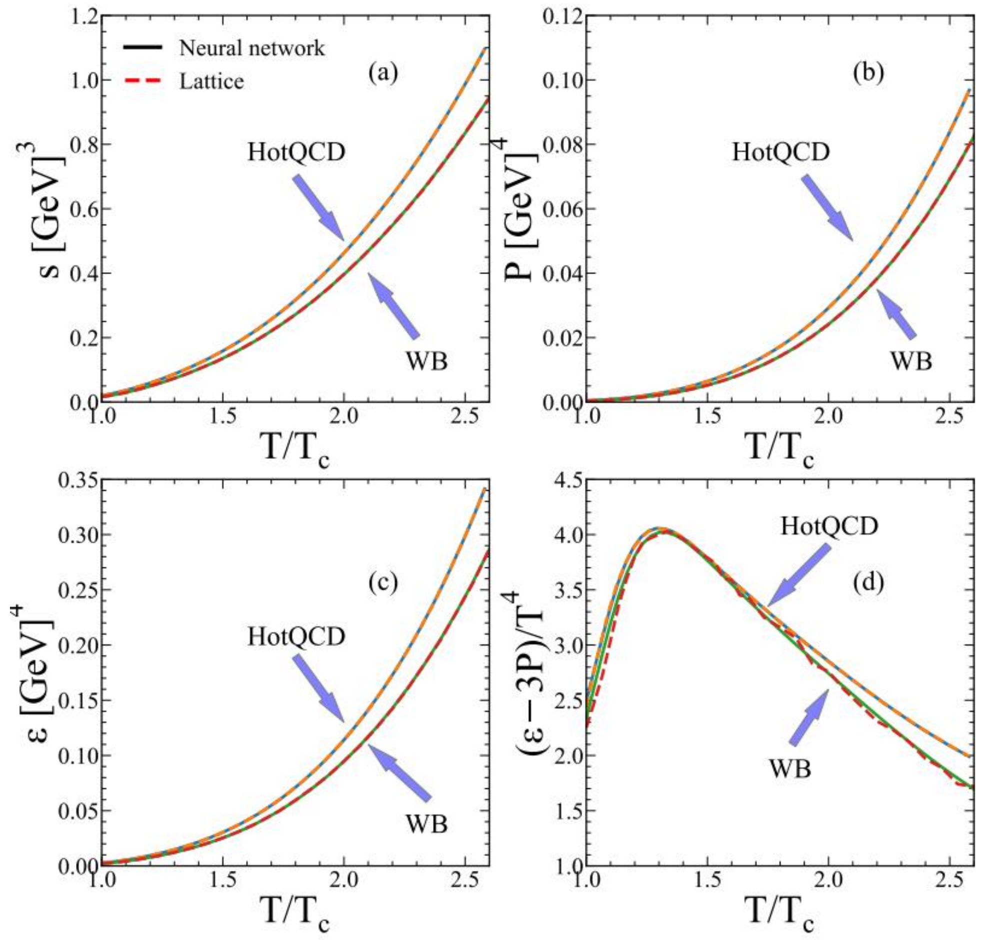
The resulting pressure and energy density are computed using the following statistical formulae,

$$P(T) = T\left(\frac{\partial \ln Z(T)}{\partial V}\right)_T, \quad (5)$$

$$\epsilon(T) = \frac{T^2}{V}\left(\frac{\partial \ln Z(T)}{\partial T}\right)_V, \quad (6)$$

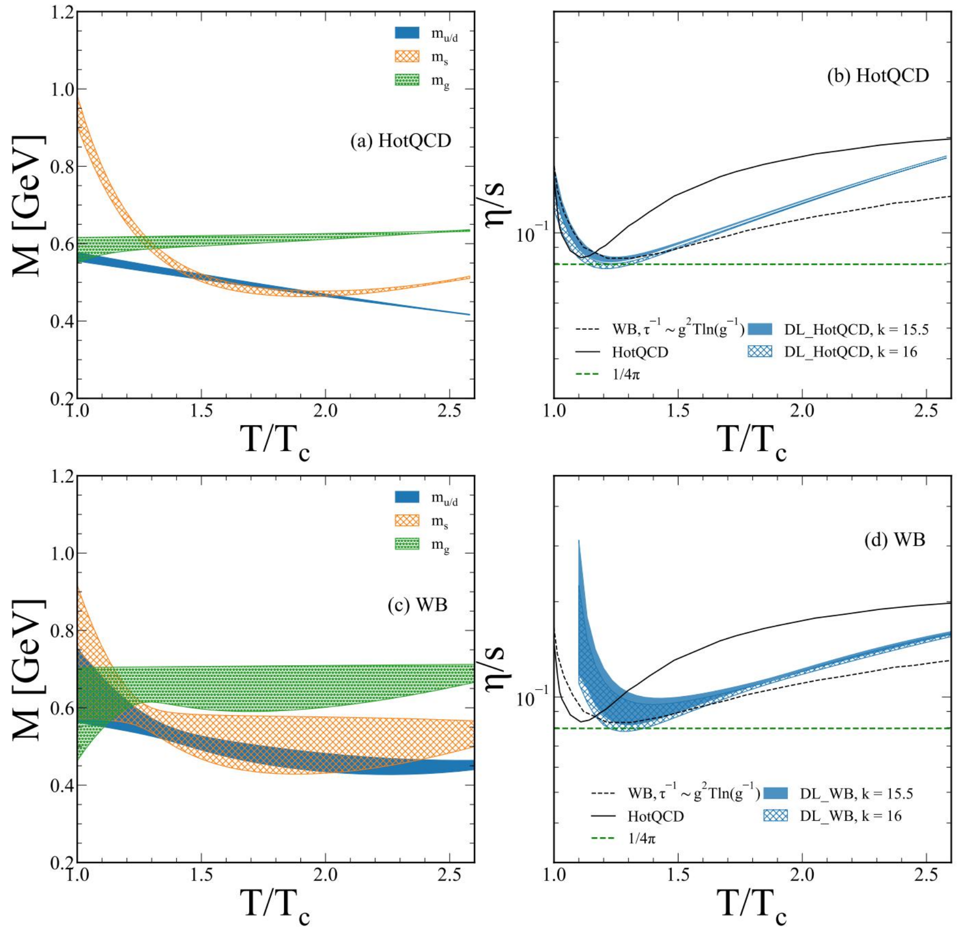
The learned quasi parton mass

EoS vs Lattice QCD



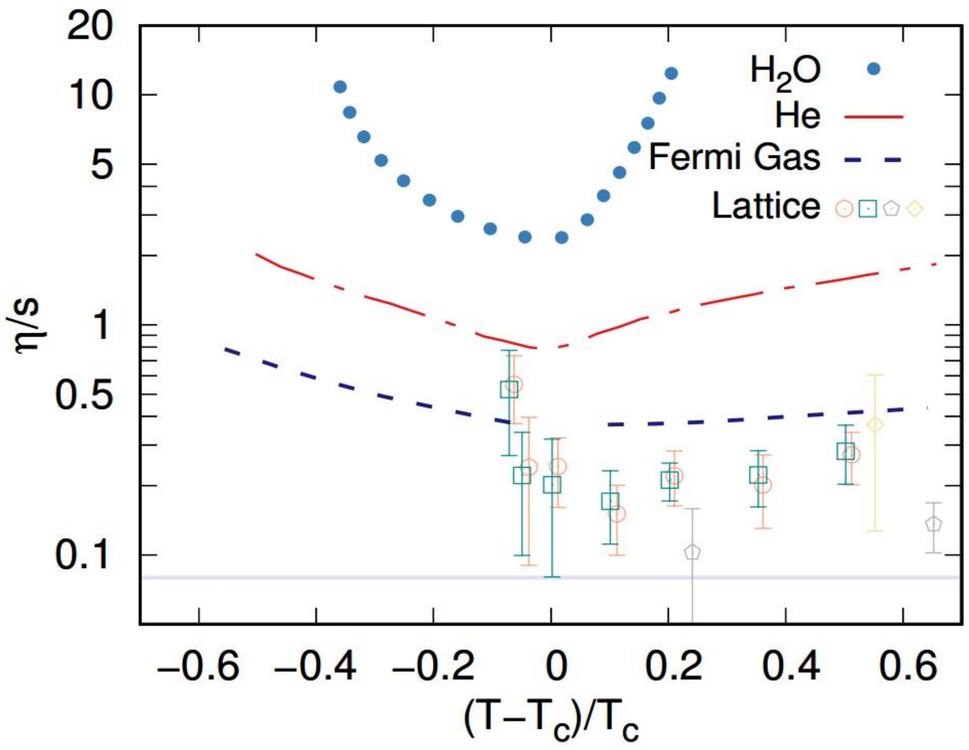
Learned Mass

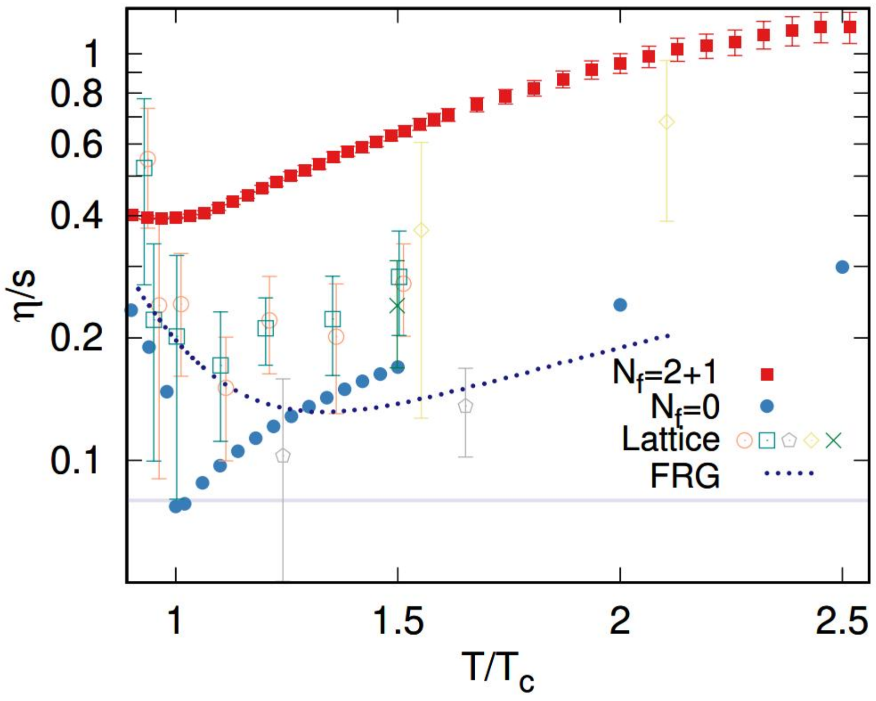
η/s



FuPeng Li, HL Lu, LG Pang, GY Qin, PLB 2023

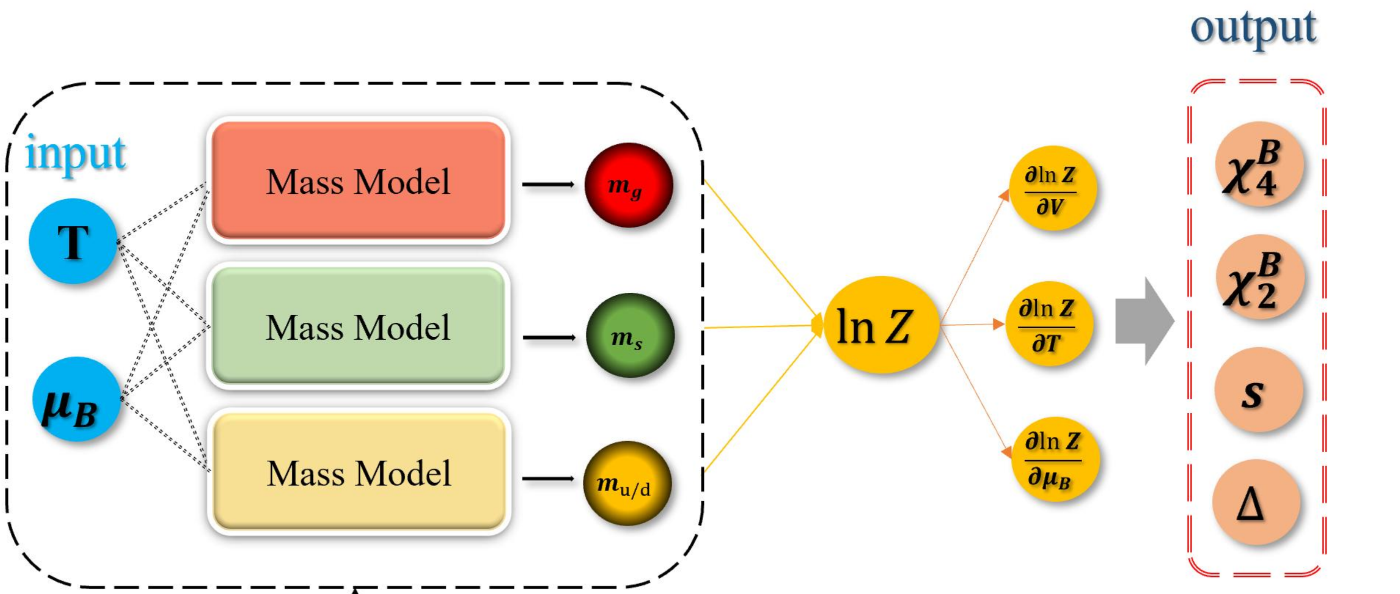
Location of minimum eta/s



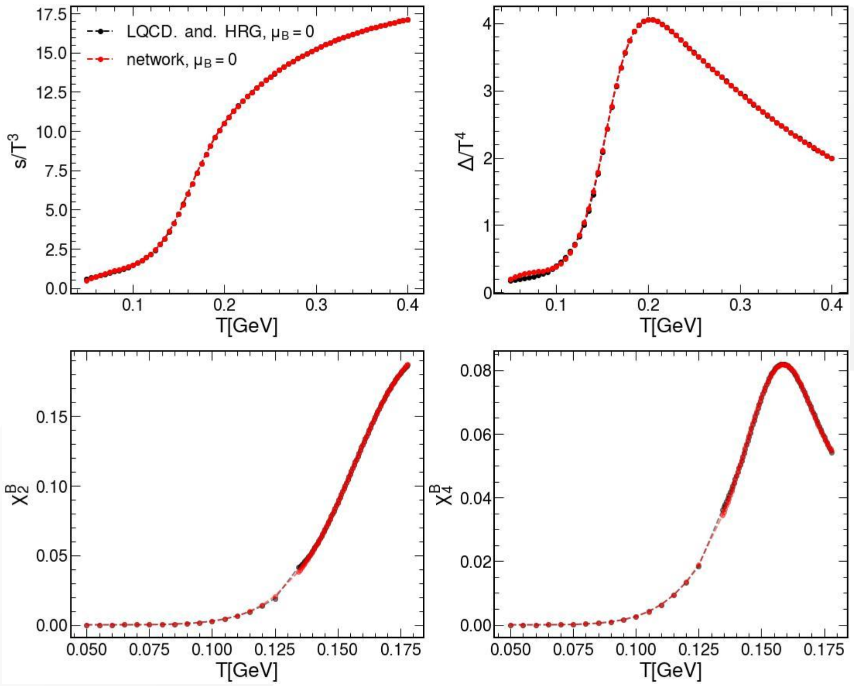


Thesis of Valeriya Mykhaylova, 2023

Extend Quasi Parton Model to finite muB



$$\mathcal{L}(\boldsymbol{W}, \boldsymbol{b}) = |s_{NN} - s_{input}| + |\frac{|\Delta\ _{NN} - \Delta\ _{input}}{T}| + |\chi^B_{2,NN} - \chi^B_{2,input}| + |\chi^B_{4,NN} \text{ - } \chi^B_{4,input}| + \mathcal{L}_{MC}$$



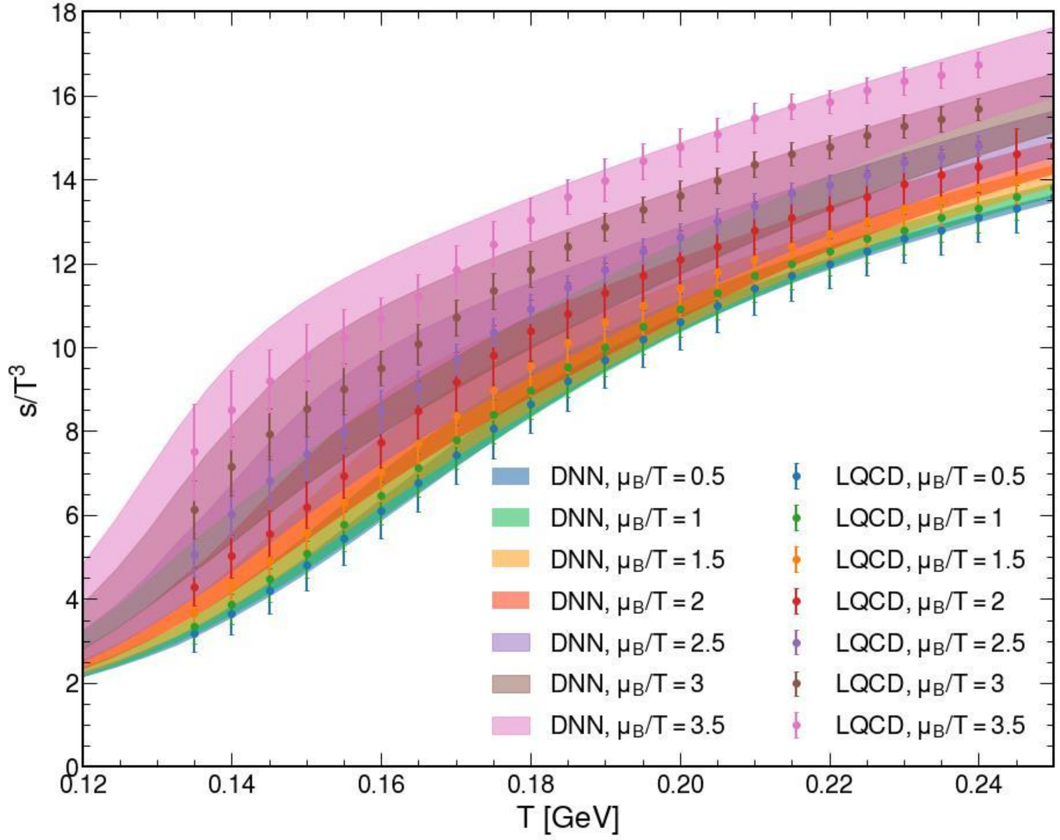
Model:
Deep learning Quasi Parton Model
Effective theory of strongly coupled QGP and nuclear matter at finite baryon density

Training data: Lattice QCD + HRG
PRD 95, 054504 (2017)
PRL118, 182301 (2017)
PRD 90, 094503 (2014)

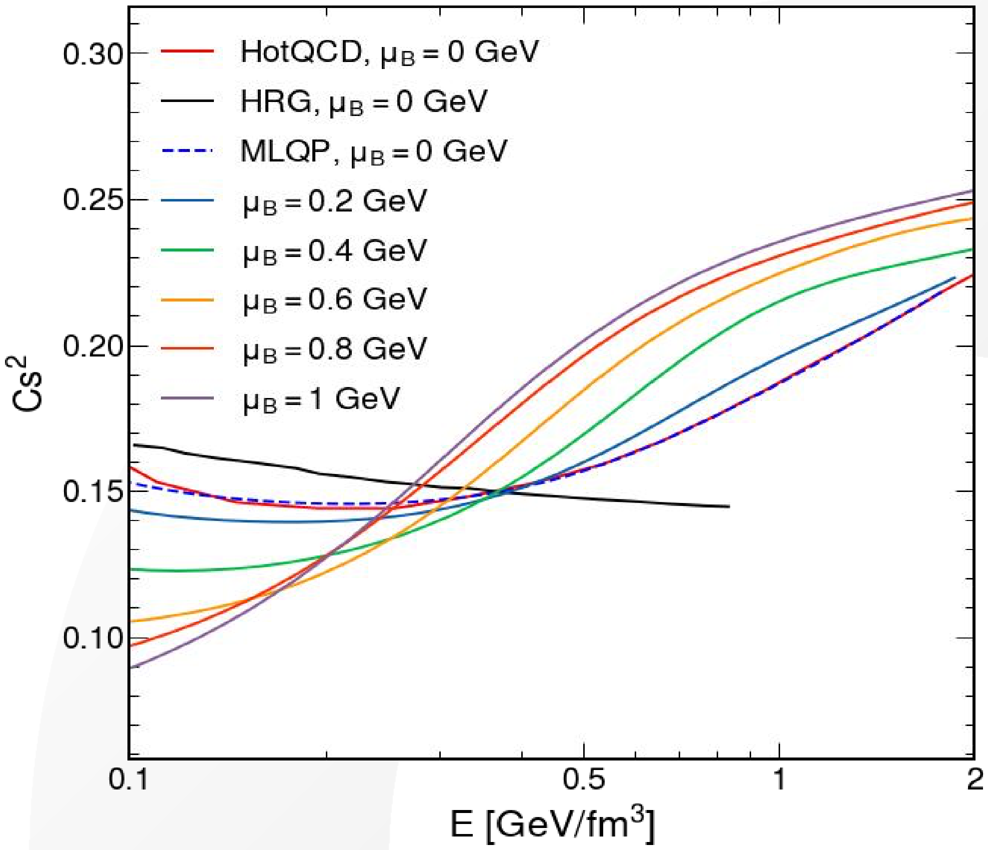
FuPeng Li, Long-Gang Pang, Guang-You Qin, arxiv: 2501.10012

Predictions of DL quasi parton model

Entropy density



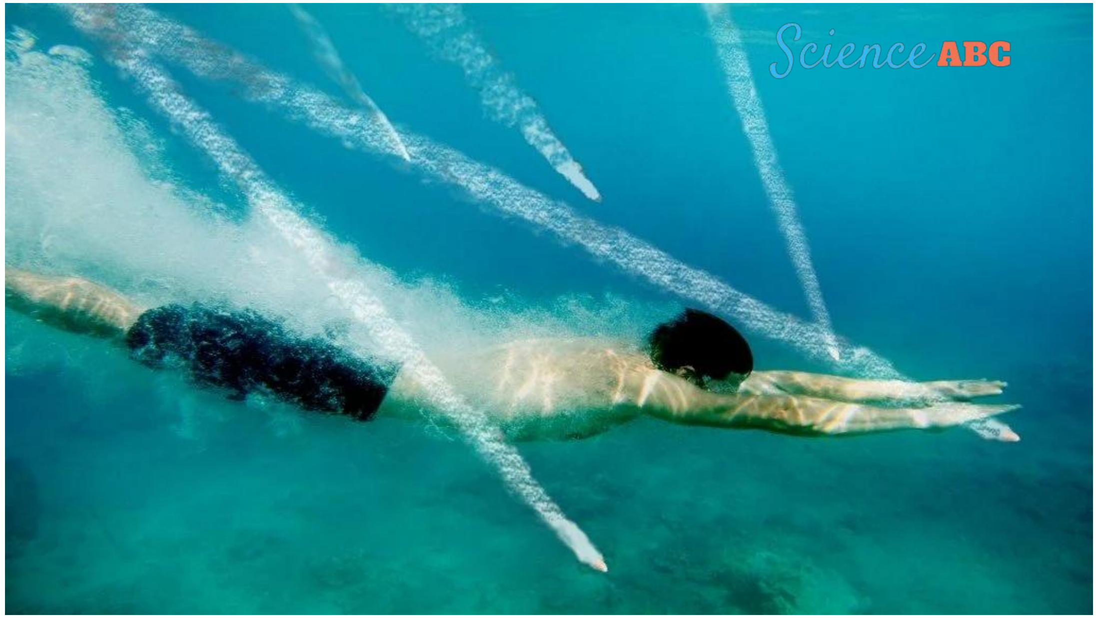
Speed of sound



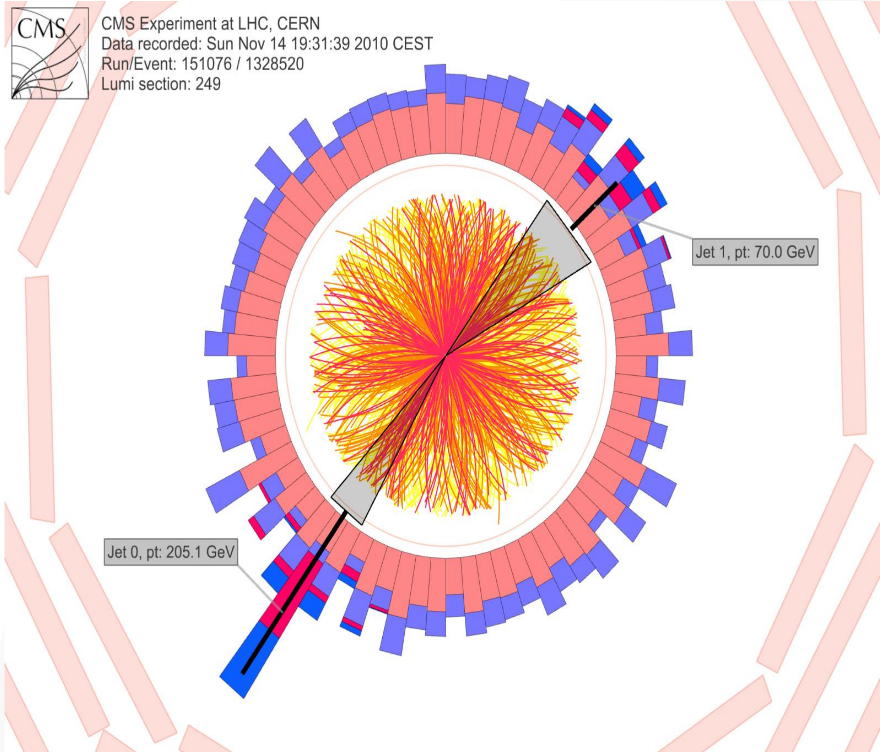
Next step: 4D EoS, $P(\epsilon, n_b) \rightarrow P(\epsilon, n_b, n_c, n_s)$

Jet eloss and medium response

Can Being Underwater Protect You From Bullets?

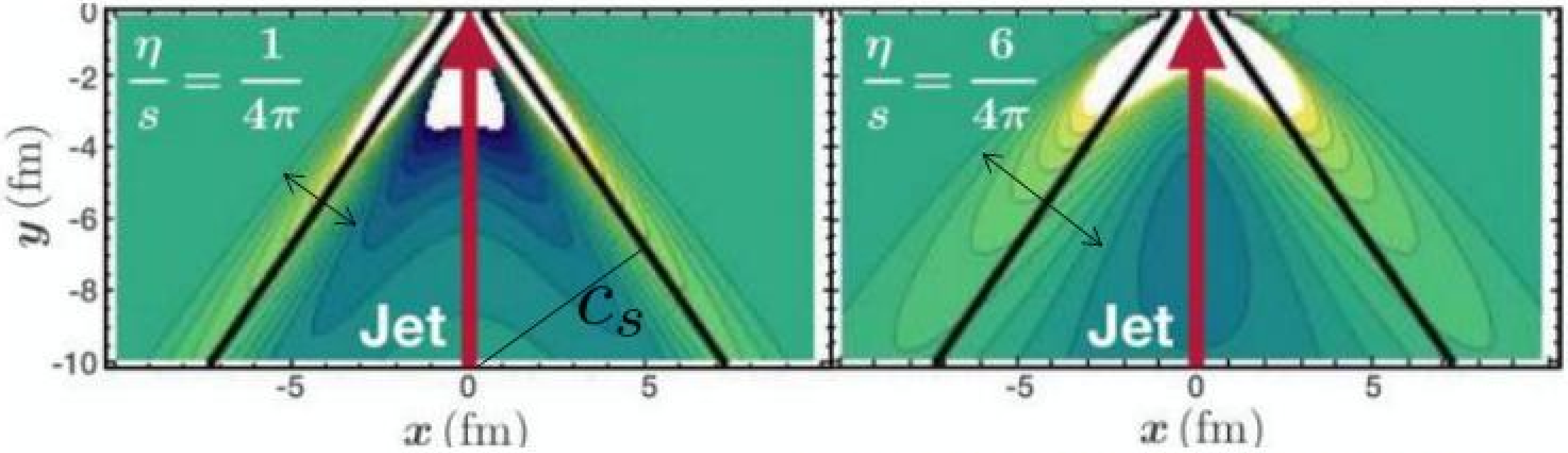


If the bullet is shot from an angle of 30 Degrees, then being underwater in the range of 3-5 feet (0.9-1.5 meters) can ensure safety from most guns.



Jet quenching in hot QGP

The nuclear EoS and Mach Cone



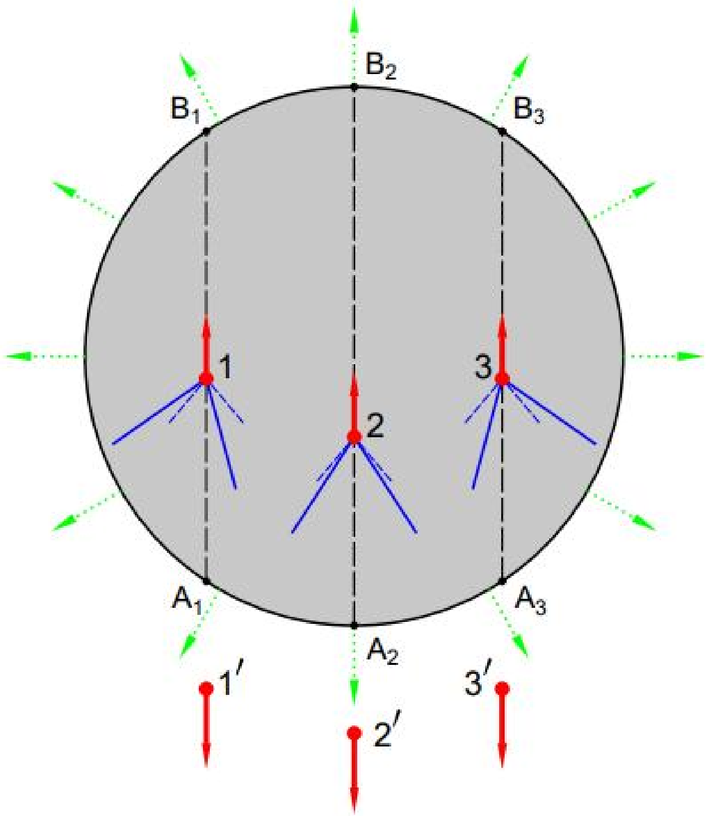
R.B.Neufeld. PRC79,054909(09')

Nuclear EoS： $c_s^2 = \frac{dP}{d\epsilon} = \sin^2\theta$

Shear Viscosity： width of the shock wave

Difficulties in looking for Mach Cones in HIC

- Random production locations and propagating directions relative to collective flow
- Tilted by different path length and collective flow



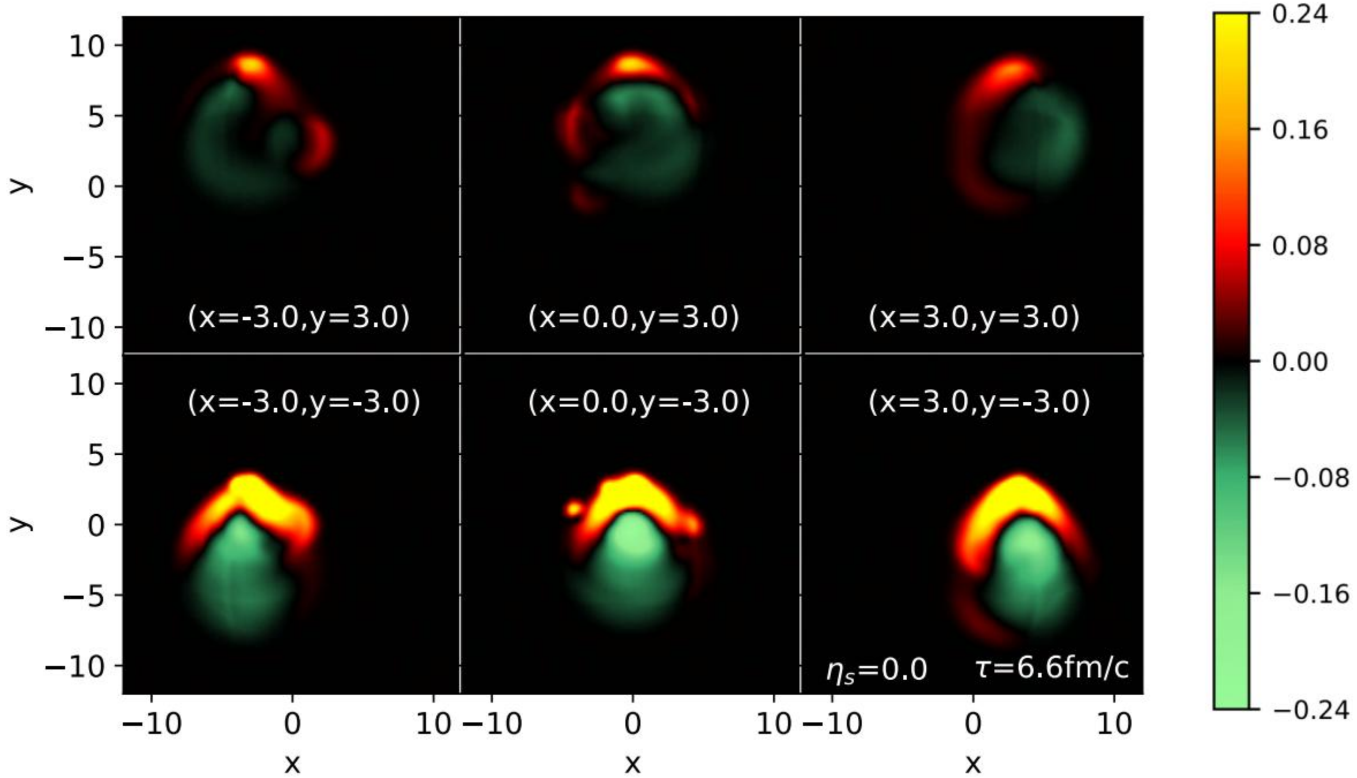
L.M. Satarov, H. Stoecker, I.N. Mishustin, PLB 627 (2005) 64-70

Training data: CoLBT(LBT + CLVisc)

$$p\partial f(p) = -C(p) \quad (p\cdot u > p^0_{cut})$$

$$\partial_\mu T^{\mu\nu}(x) = j^\nu(x)$$

$$j^\nu = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p\cdot u)$$



LBT: YY He, T Luo, XN Wang, Y Zhu,
PRC 91 (2015) 054908, PRC 97 (2018) 1, 019902

CLVisc:
LG Pang, Q Wang, XN Wang, PRC 86 (2012) 024911
LG Pang, H Petersen, XN Wang, PRC 97 (2018) 6, 064918
XY Wu, GY Qin, LG Pang, XN Wang,PRC 105 (2022) 3, 034909

CoLBT:

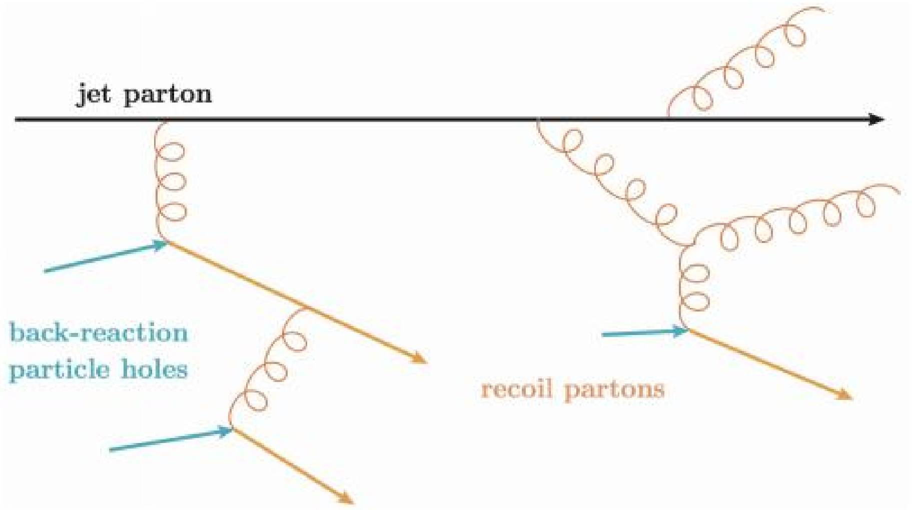
W Chen, T Luo, SS Cao, LG Pang, XN Wang,
PLB 777 (2018) 86-90

LBT: Linear Boltzmann Transport

$$p_1 \partial f_1 = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) \left| M_{12\to 34} \right|^2 (2\pi)^4 \delta^4 (\sum_i p^i) + inelastic$$

Medium-induced gluon(HT):

$$\frac{dN_g}{dz d^2 k_\perp dt} \approx \frac{2 C_A \alpha_s}{\pi k_\perp^4} P(z) \hat{q} (\hat{p} \cdot u) sin^2 \frac{k_\perp^2 (t - t_0)}{4z(1-z)E}$$

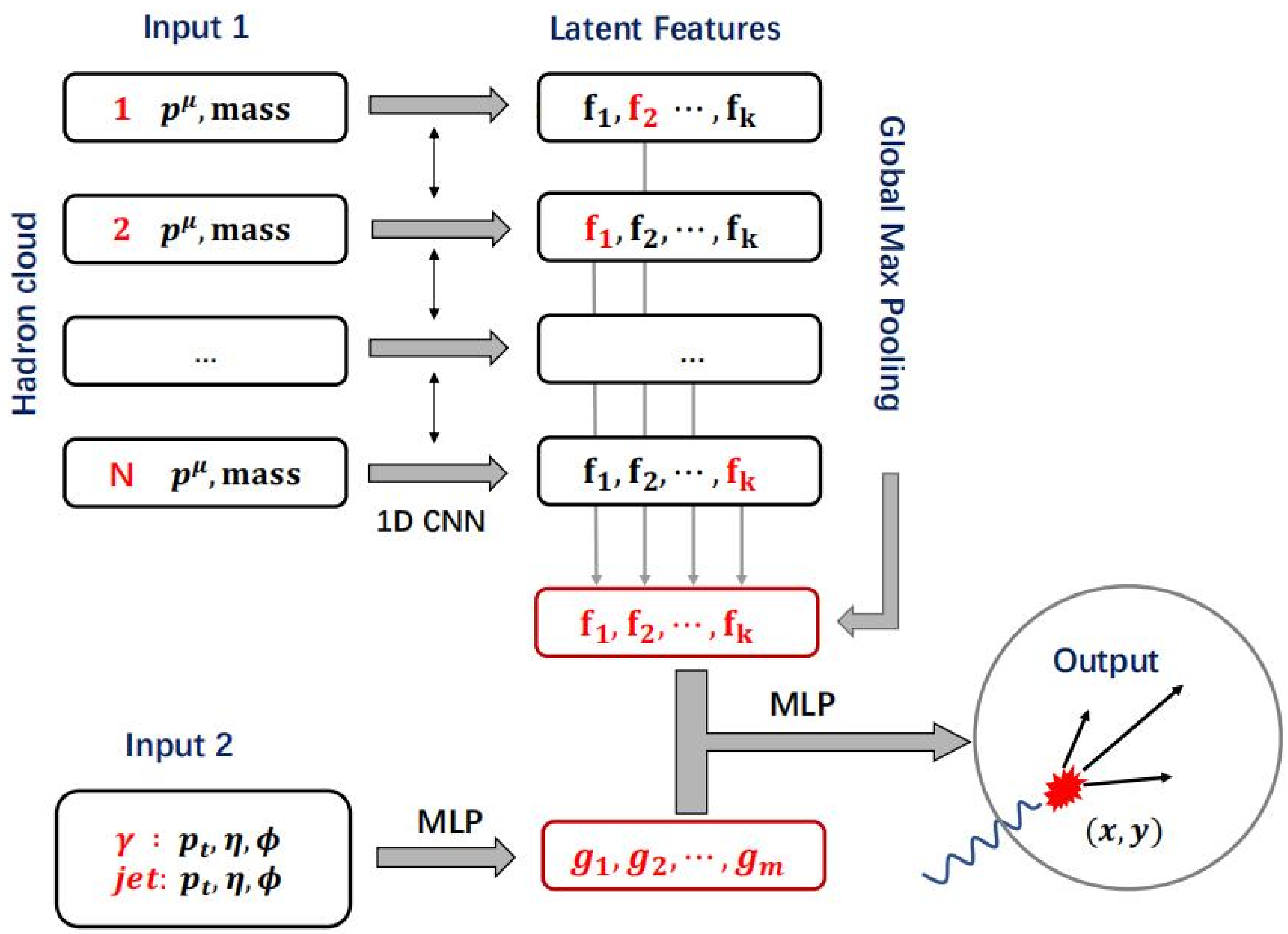


Tracked partons:

- Jet shower partons
- Thermal recoil partons
- Radiated gluons
- Negative partons(Back reaction induced by energy-momentum conservation)

YY He, T Luo, XN Wang, Y Zhu, PRC 91 (2015) 054908, PRC 97 (2018) 1, 019902

DL assisted jet tomography (gamma-jet)

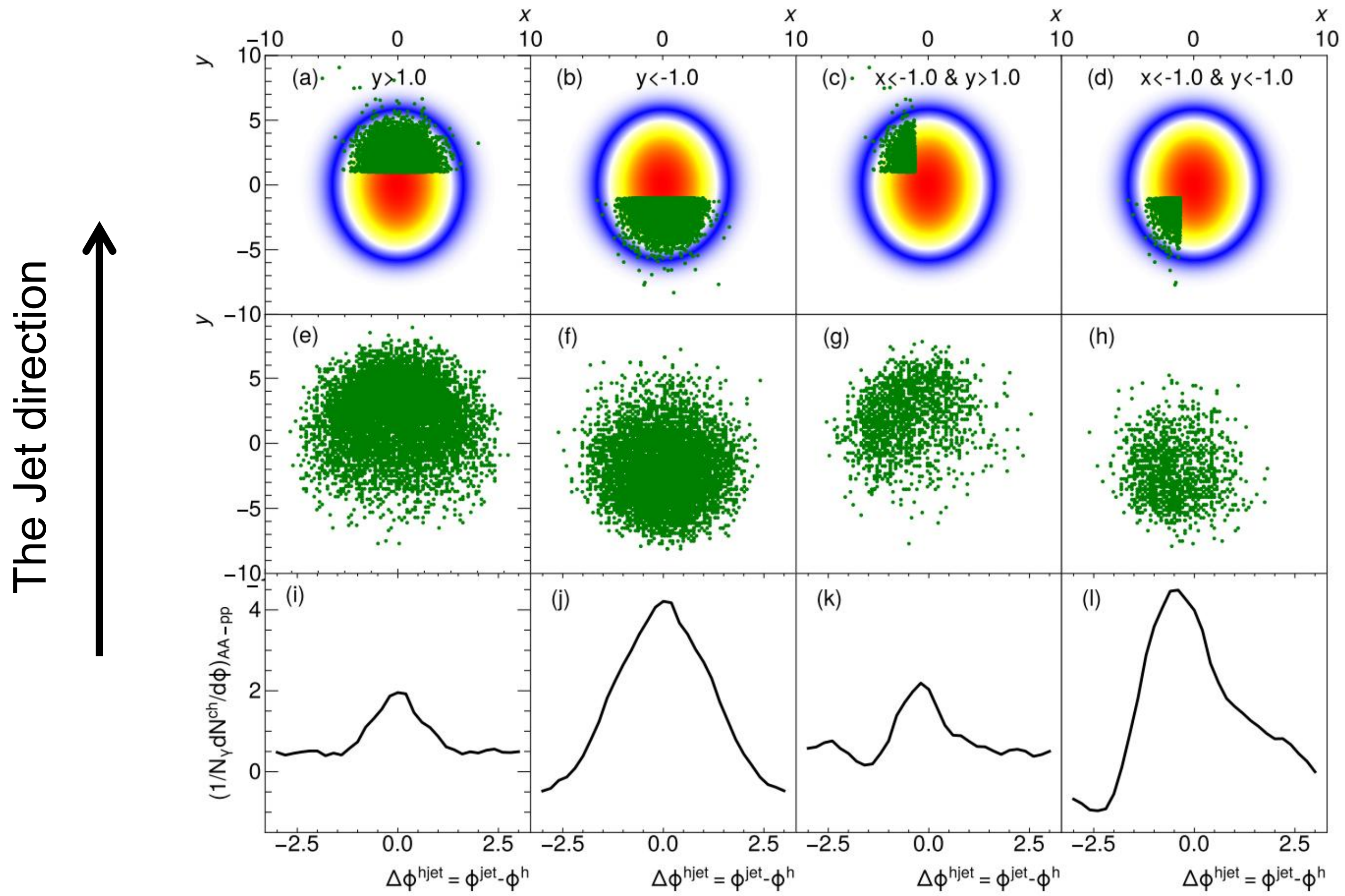


$ij \to kl$	$\lvert M\rvert^2_{ij\to kl}$	
$gg \to gg$	$\frac{9}{2}g_s^4\left(3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2}\right)$	(A-1)
$gg \to q\bar{q}$	$\frac{3}{8}g_s^4\left(\frac{4}{9}\frac{t^2+u^2}{tu} - \frac{t^2+u^2}{s^2}\right)$	(A-2)
$gq \to gq$ $g\bar{q} \to g\bar{q}$	$g_s^4\left(\frac{s^2+u^2}{t^2} - \frac{4}{9}\frac{s^2+u^2}{su}\right)$	(A-3)
$q_iq_j \to q_iq_j$ $q_i\bar{q}_j \to q_i\bar{q}_j$ $\bar{q}_iq_j \to \bar{q}_iq_j$ $\bar{q}_i\bar{q}_j \to \bar{q}_i\bar{q}_j$	$\frac{4}{9}g_s^4\frac{s^2+u^2}{t^2}, \quad i \neq j$	(A-4)
$q_iq_i \to q_iq_i$ $\bar{q}_i\bar{q}_i \to \bar{q}_i\bar{q}_i$	$\frac{4}{9}g_s^4\left(\frac{s^2+u^2}{t^2} + \frac{s^2+t^2}{u^2} - \frac{2}{3}\frac{s^2}{tu}\right)$	(A-5)
$q_i\bar{q}_i \to q_j\bar{q}_j$	$\frac{4}{9}g_s^4\frac{t^2+u^2}{s^2}$	(A-6)
$q_i\bar{q}_i \to q_i\bar{q}_i$	$\frac{4}{9}g_s^4\left(\frac{s^2+u^2}{t^2} + \frac{t^2+u^2}{s^2} - \frac{2}{3}\frac{u^2}{st}\right)$	(A-7)
$q\bar{q} \to gg$	$\frac{8}{3}g_s^4\left(\frac{4}{9}\frac{t^2+u^2}{tu} - \frac{t^2+u^2}{s^2}\right)$	(A-8)

$$(x_i^{\text{net}}, y_i^{\text{net}}) = f(\{\vec{p}\}_i, \theta),$$

Z Yang, YY He, W Chen, WY Ke, LG Pang, XN Wang, EPJC 83 (2023) 7, 652

DL assisted jet tomography

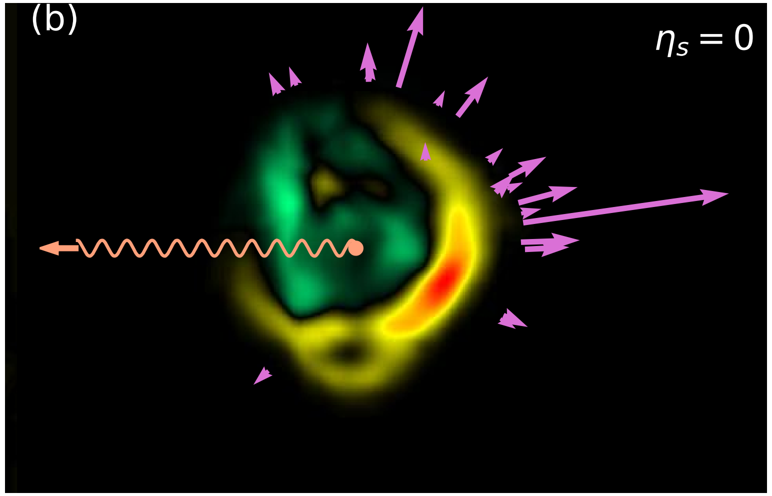


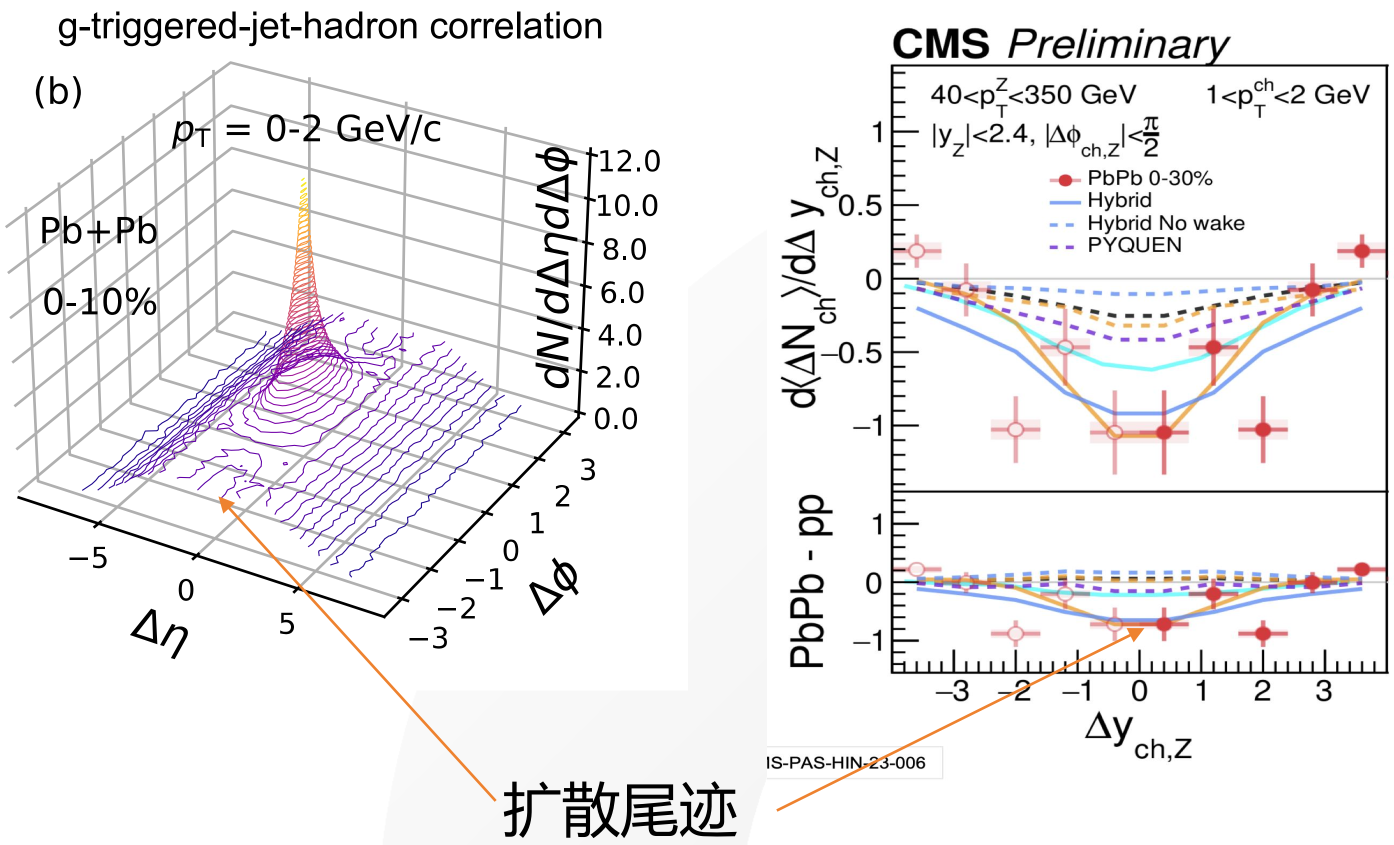
- ➢ **Network Prediction**
- ➢ **True Locations**
- ➢ **Jet hadron correlation for seleted events by deep learning**

Z Yang, YY He, W Chen, WY Ke, LG Pang, XN Wang, EPJC 83 (2023) 7, 652

Jet induced sound wave in QGP

- **扩散尾迹（Diffusion Wake, DF）：流体动力学中的普遍现象，伴随高速物体诱导的马赫尾迹。**
- **影响：扩散尾迹导致软强子产额在喷流方向的后方出现减少**

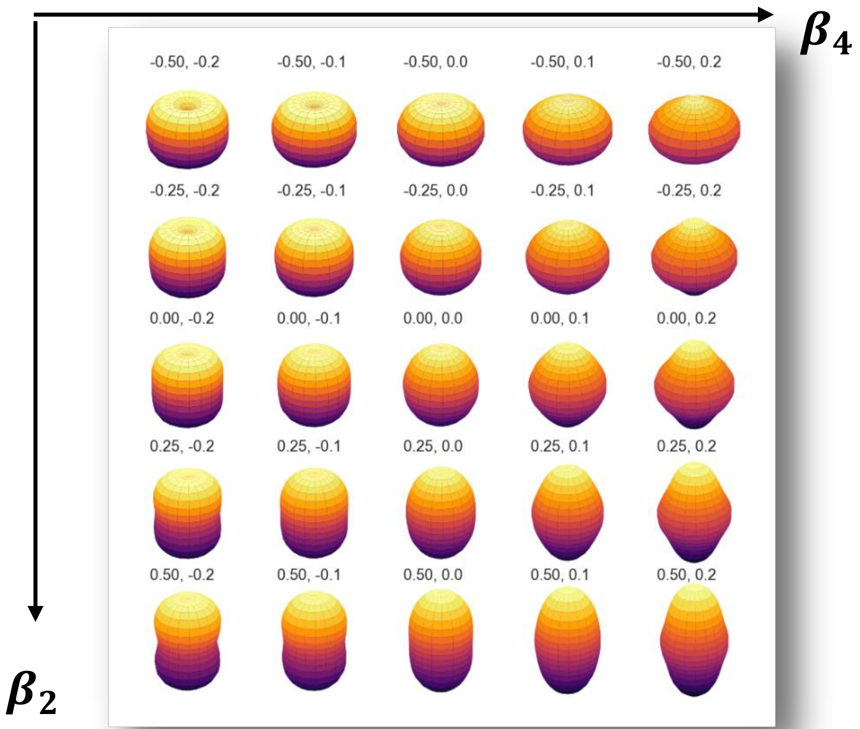




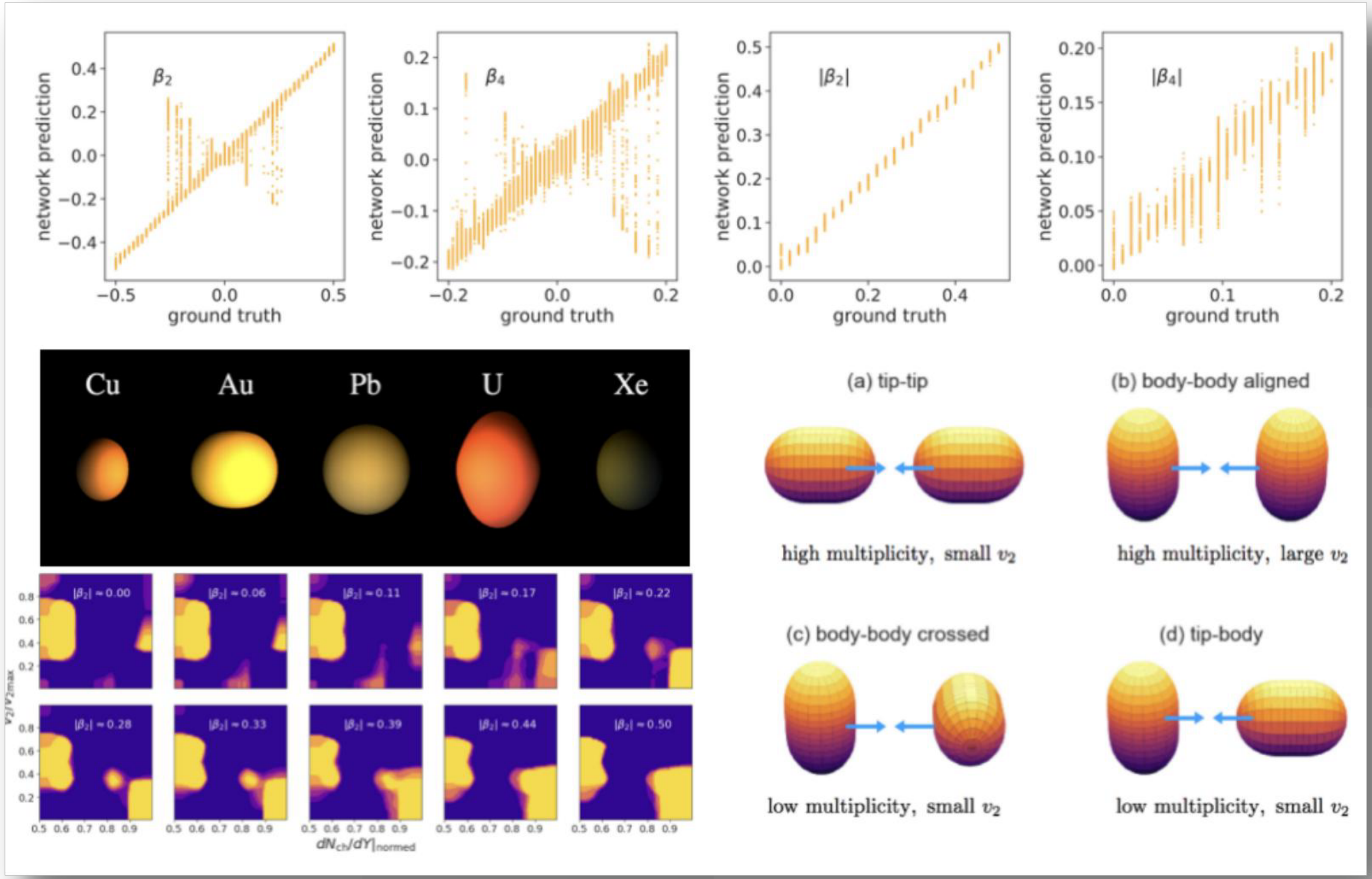
我们使用相对论流体力学 CLVisc 和线性玻尔兹曼输运模型 LBT 以及 CoLBT 预测的扩散尾迹首次在LHC的Pb+Pb碰撞中被CMS实验观测到!

杨忠, 罗覃, 陈巍, 庞龙刚，王新年, PRL, 130 (2023) , 052301

Determining nuclear deformation



Data: Trento + Matching



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

Nucleon nucleon short range correlation

Correlation hole at short range

For all the nuclei using AV18+UIX potential

Nucleon-Nucleon Correlations, Short-Lived Excitations, and the Quarks Within

Hen, Or, Gerald A. Miller, Eli Piasetzky, and Lawrence B. Weinstein. 2017. Reviews of Modern Physics 89 (4).

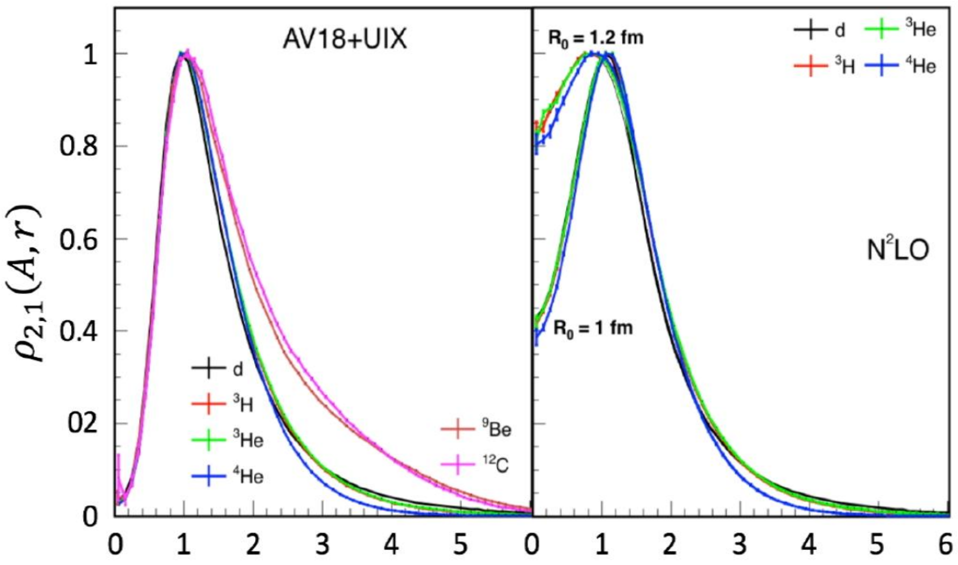
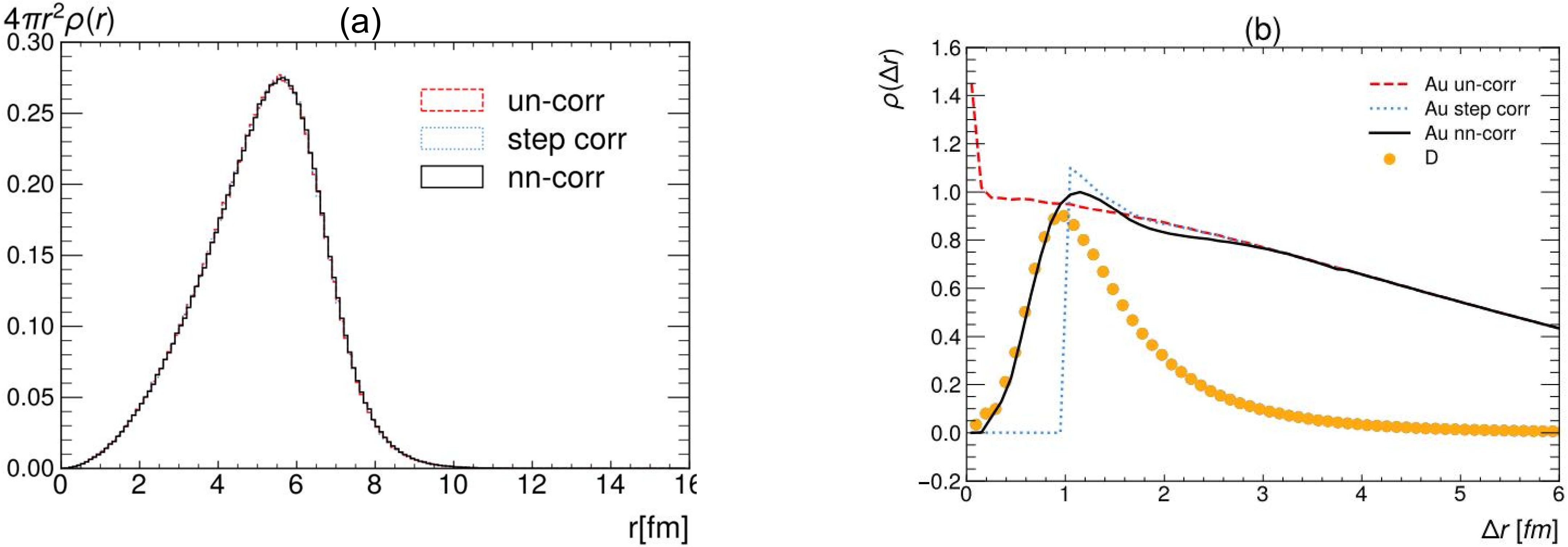


FIG. 5. Scaled two-body distribution function $\rho^A_{2,1}(r)/A$ [see Eq. (A11)] for nuclei with $A = 2$, 3, and 4. A correlation hole is seen for all of these nuclei. The two sets of curves are obtained with the (left) AV18 + UIX and (right) N^2LO potentials. The

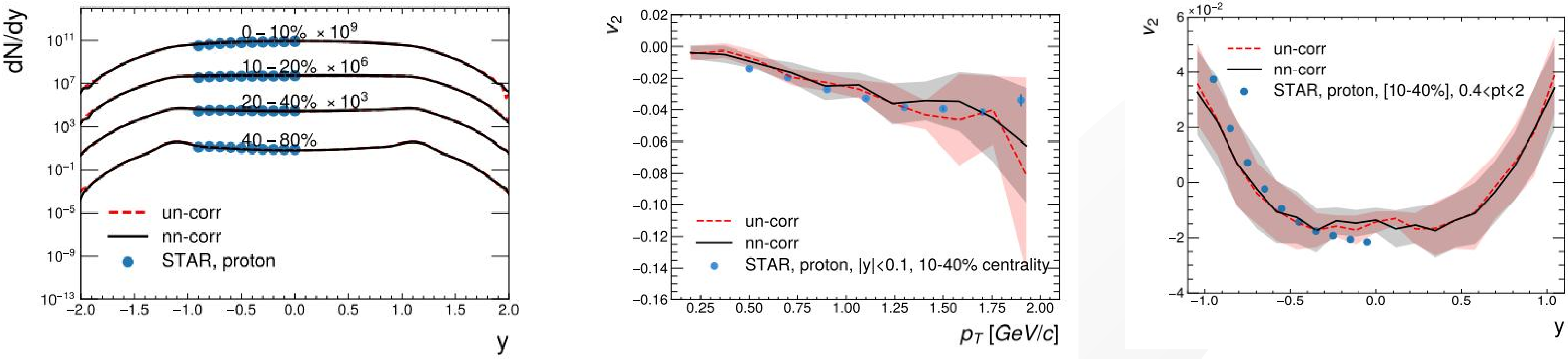
Monte Carlo Sampling



We developped a Monte carlo method to sample nucleons in Au nucleus obeying not only the single nucleon distribution $\rho(r)$ but also the two-nucleon distribution $\rho(\Delta r)$

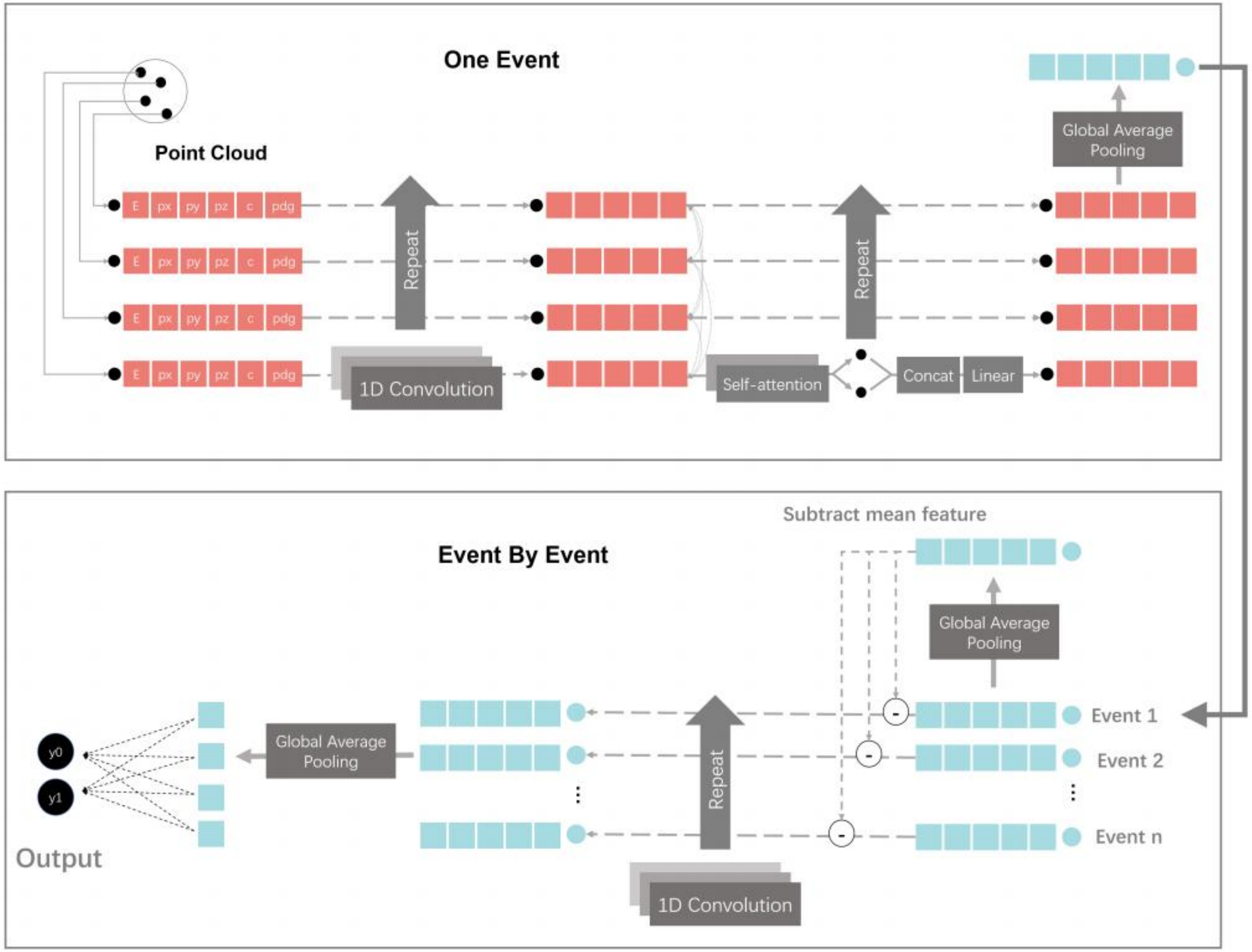
Y.J. Huang, Z. Meng, L.G. Pang, X.N. Wang, arXiv:2504.00790

Failure of traditional observables



Traditional observables for SMASH simulations of Au+Au 3GeV collisions fail to distinguish un-corr from nn-corr.

A novel neural network to detect nn correlations



Network structure

- ➢ Point cloud network
- ➢ Self attention (used in large language models like chatgpt and deepseek)
- ➢ Multi-event mixing

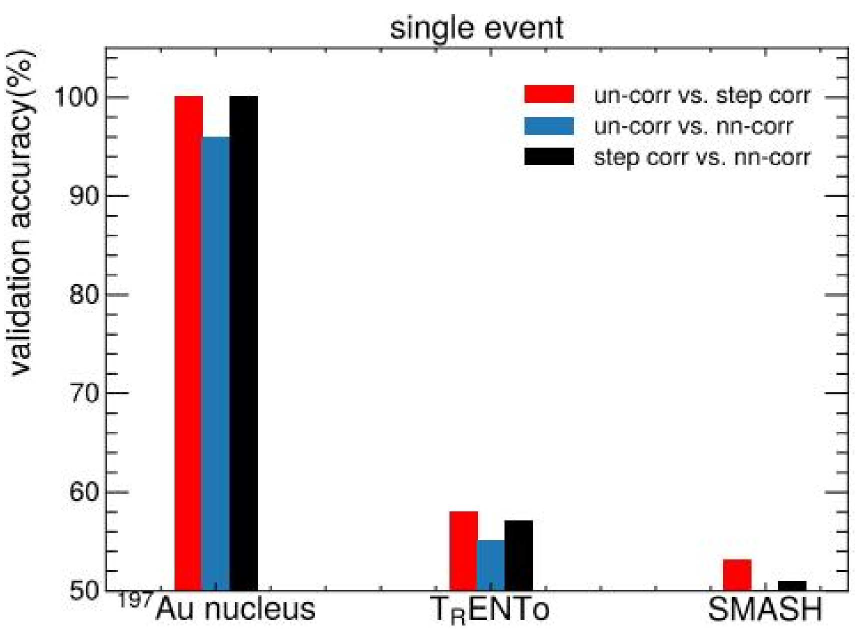
Correlations of latent features

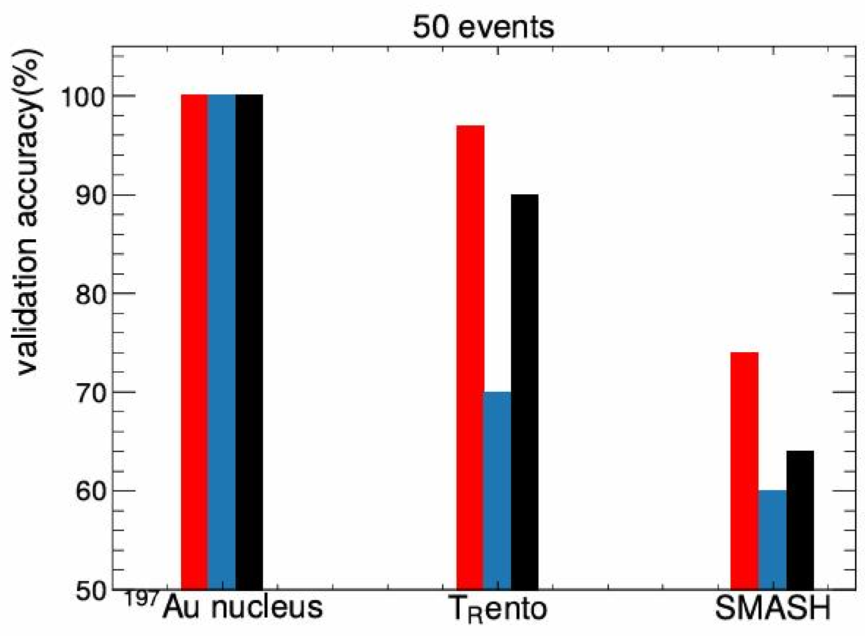
$$\overline{f(z_1 - \bar{z}_1, z_2 - \bar{z}_2, \cdots, z_n - \bar{z}_n)}$$

where z_i is the i-th latent feature
f(...) reprents the 1D convolution

Y.J. Huang, Z. Meng, L.G. Pang, X.N. Wang, arXiv:2504.00790

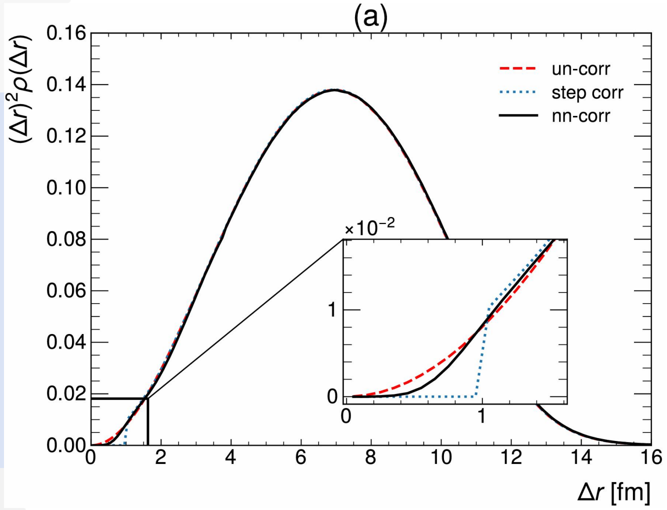
Classification accuracy



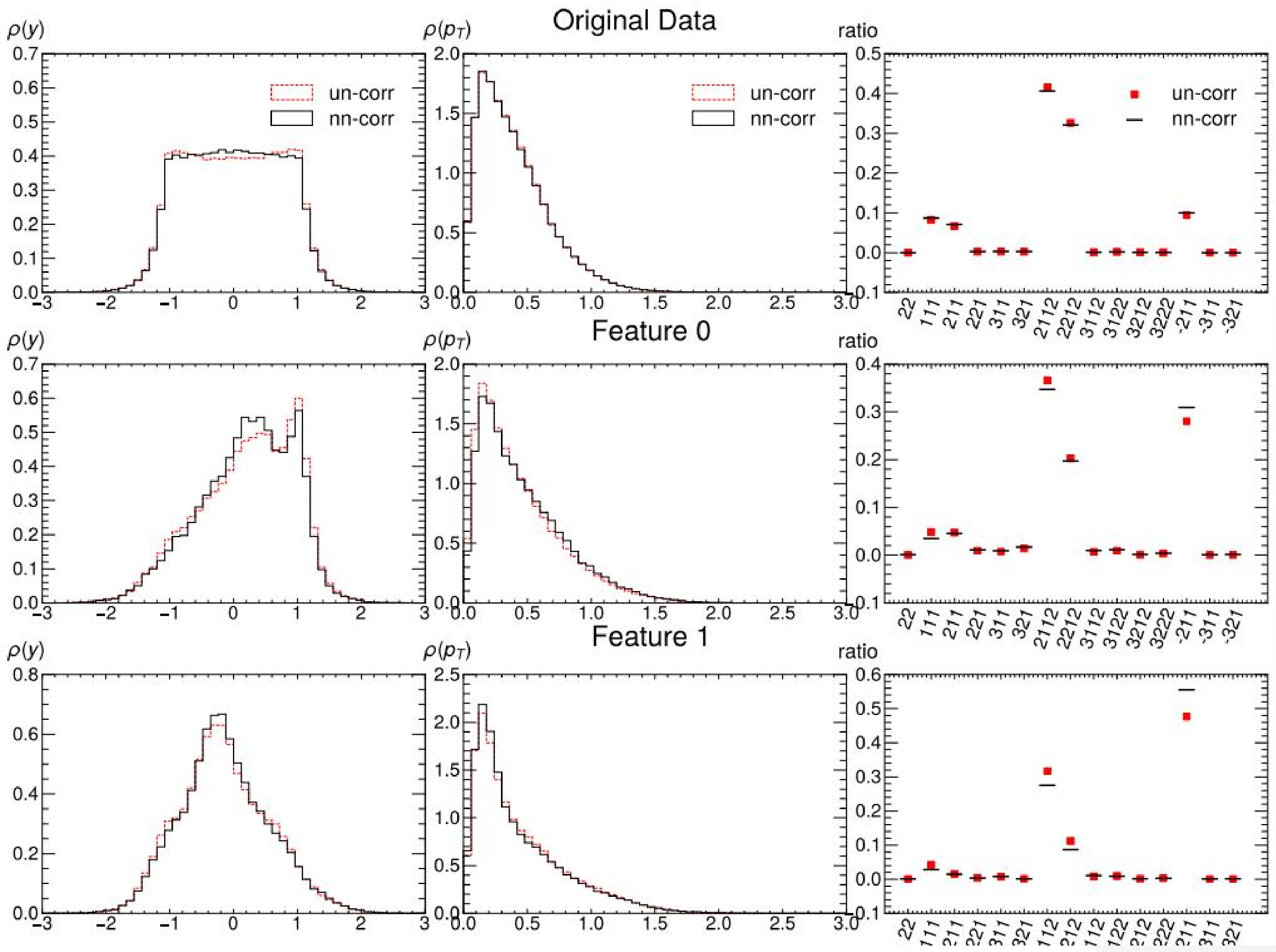


Accuracies

- lowest for un-corr vs nn-corr
- Decreases: Initial nucleus → Trento → SMASH
- Indicating information loss during dynamical evolution



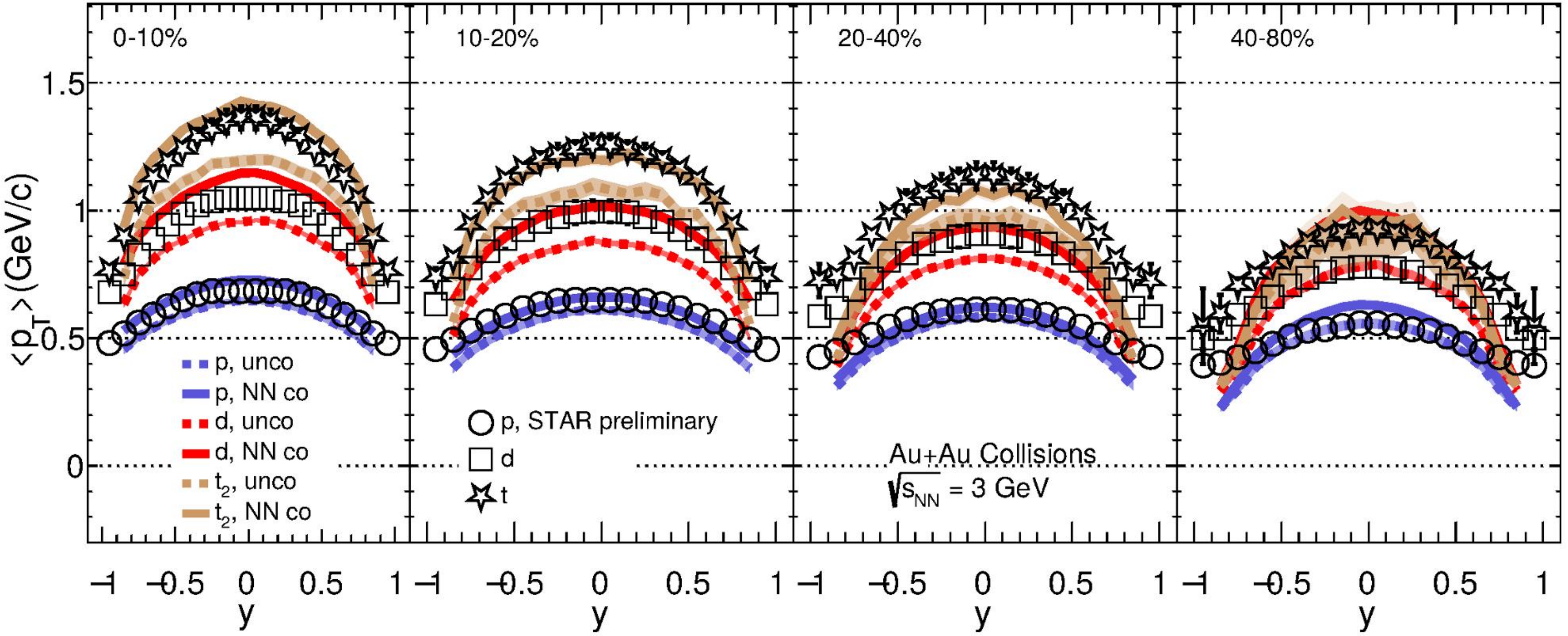
Interpretation of the ML model



Feature combinations

- Different features select particles from different momentum regions
- After selection, the particle ratio changes a lot
- Feature 0 uses particles at forward rapidity
- Feature 1 uses particles from mid-rapidity and low pt
- Both selected more pi-

Effect of NN Correlation on light nuclei production



Triton and deuteron yields depend on the spatial separation of nucleon pairs (Δr) in Wigner functions. With NN correlation, several observables align with experimental data better.

Q.R.Lin, Y.J. Huang, L.G. Pang, X.F. Luo, X.N. Wang. arxiv:2503.01128

ArXiv Vector Database

Cornell University Open sourced arXiv datasets.

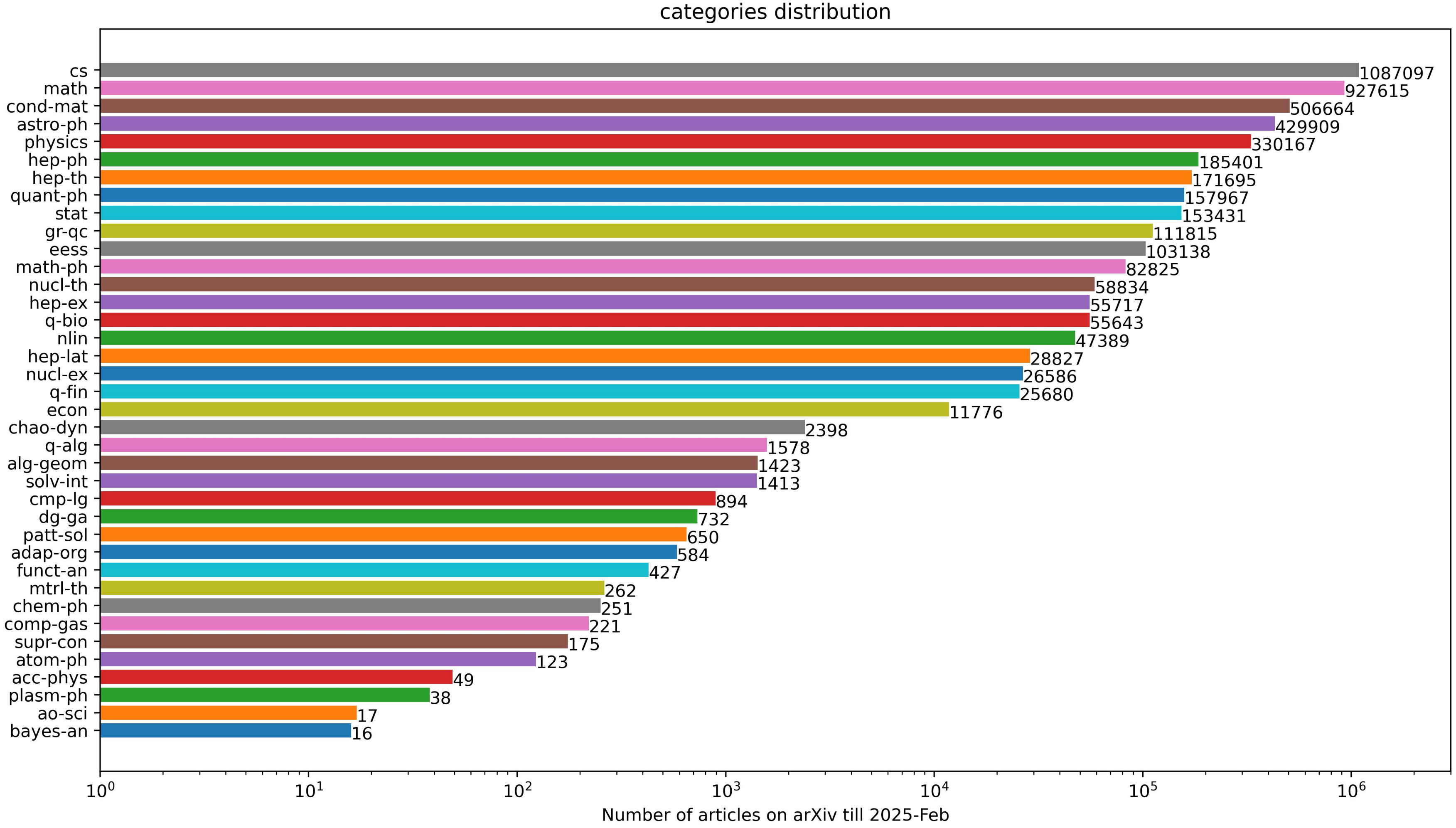
Till 2025-Feb.

Nuth-th: **58,834** articles

Nucl-ex: **26,586** articles

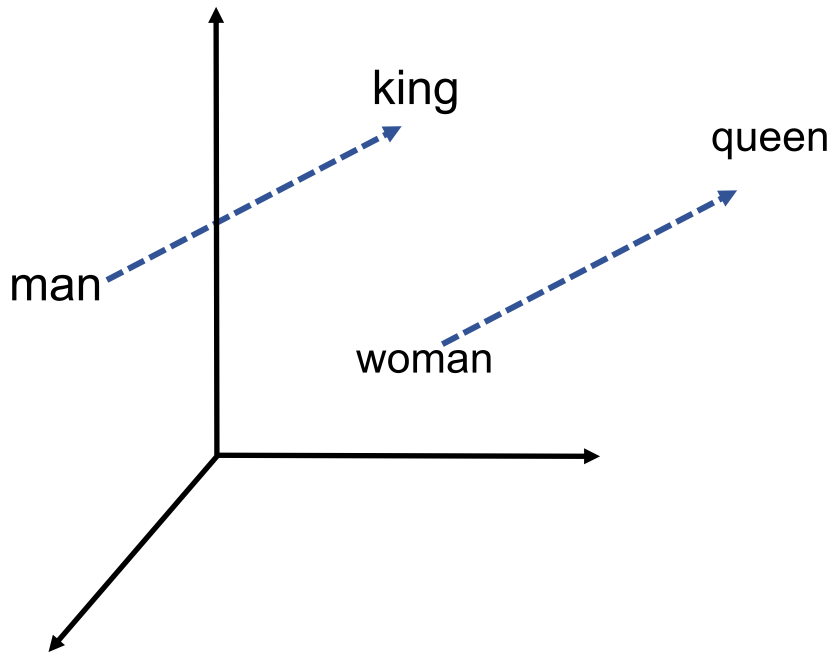
Hep-ph: **185,401** articles

Hep-th: **171,695** articles



Difficult to get all relavant papers, especially from interdisciplinary fields.

ArXiv Vector Database and LLM agents



word vector → sentence vector

Semantic search rather than keyword search

We have build and open sourced a Vector Database for arxiv papers

https://gitee.com/lgpang/arxiv_vectordb.git

2.666 Million articles (title + abstract)

2.666 million vectors (1024 elements each)

Size on disk: 30 GB

Query using the cosine similarity

Deepseek LLM agents

- relevance score
- read the downloaded pdf
- find future work directions from the discussion

Usage

科研助理

请输入您的问题:

what can we learn from relativistic isobar collisions

提交

生成的检索问题: ["What are the differences in nuclear structure be
isobars?", "What experimental results from relativistic isobar collisions (e.g., Ru
reported by the STAR collaboration?", "How do relativistic isobar collisions hel
effect (CME) in quark-gluon plasma studies?", "What are the theoretical predicti... (v_2)
differences in Ru+Ru vs. Zr+Zr collisions?", "How does nuclear deformation in isobars influence
observables in relativistic heavy-ion collisions?"]

论文: Title: Search for the chiral magnetic effect in collisions between two isobars with deformed and
neutron-rich nucl
background and c
(CME) in relativisti
did not observe th
Ru and $^{96}_{40}$Zr +
from different nuc
find out that seve
experiment. Cons
demonstrate that
the presence or a
state interactions
CME observables
the possible small

信息: ['2203.1521
PhysRevC.106.034

相关性得分: 1

论文: Title: Impact of initial fluctuations and nuclear deformations in isobar collisions Abstract: Relativistic isobar ($^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr) collisions have revealed intricate differences in their nucl size and shape, inspiring unconventional studies of nuclear structure using relativistic heavy ion collisions. In this study, we investigate the relative differences in the mean multiplicity ($R_{\langle N_{ch}\rangle}$) and th second- ($R_{\epsilon_2}$) and third-order eccentricity (R_{ϵ_3}) between isobar collisions using initial state models. It found that initial fluctuations and nuclear deformations have negligible effects on $R_{\langle N_{ch}\rangle}$ in most cent collisions, while both are important for the R_{ϵ_2} and R_{ϵ_3}, the degree of which is sensitive to the underl nucleonic or sub-nucleonic degree of freedom. These features, compared to real data, may probe the particle production mechanism and the physics underlying nuclear structure.)

信息: ['2305.17114', 'Jian-fei Wang, Hao-jie Xu, Fuqiang Wang', 'Nucl. Sci. Tech. 35, 108 (2024)', '10.1007 s41365-024-01480-8', '2024-07-08']

这篇知识库文章研究了相对论性同位素（isobar）碰撞中的初始波动和核形变对集体流的影响。文 探讨了这些因素如何影响粒子产生机制，并揭示核结构的物理特性。

用户的提问直接询问"我们能从相对论性同位素碰撞中学到什么？"，而知识库文章正是研究这类碰 及其科学意义。两者在研究主题上完全一致，内容高度相关。

相关性分析:

1. **研究领域**: 两者都在研究相对论性重离子/核碰撞。
2. **问题和内容**: 文章探讨了同位素碰撞中可以学到的信息（初始波动、形变对集体流的影响）。
3. **目标**: 用户想了解能从这些碰撞中学到的知识，而文章正好在分析这一主题。

相关性得分:

1.0

Summary

Physical simulations of HICs provide us good opportunity to explore rich physics of hot nuclear matter

- nuclear equation of state
- nuclear structure
- transport coefficients

AI is helpful in extracting subtle features from the final state of HICs

LLM agents may help us more in the future scientifc research