Workshop on Advances, Innovations, and Prospects in High-Energy Nuclear Physics

Deep Learning for nuclear EoS at extreme conditions

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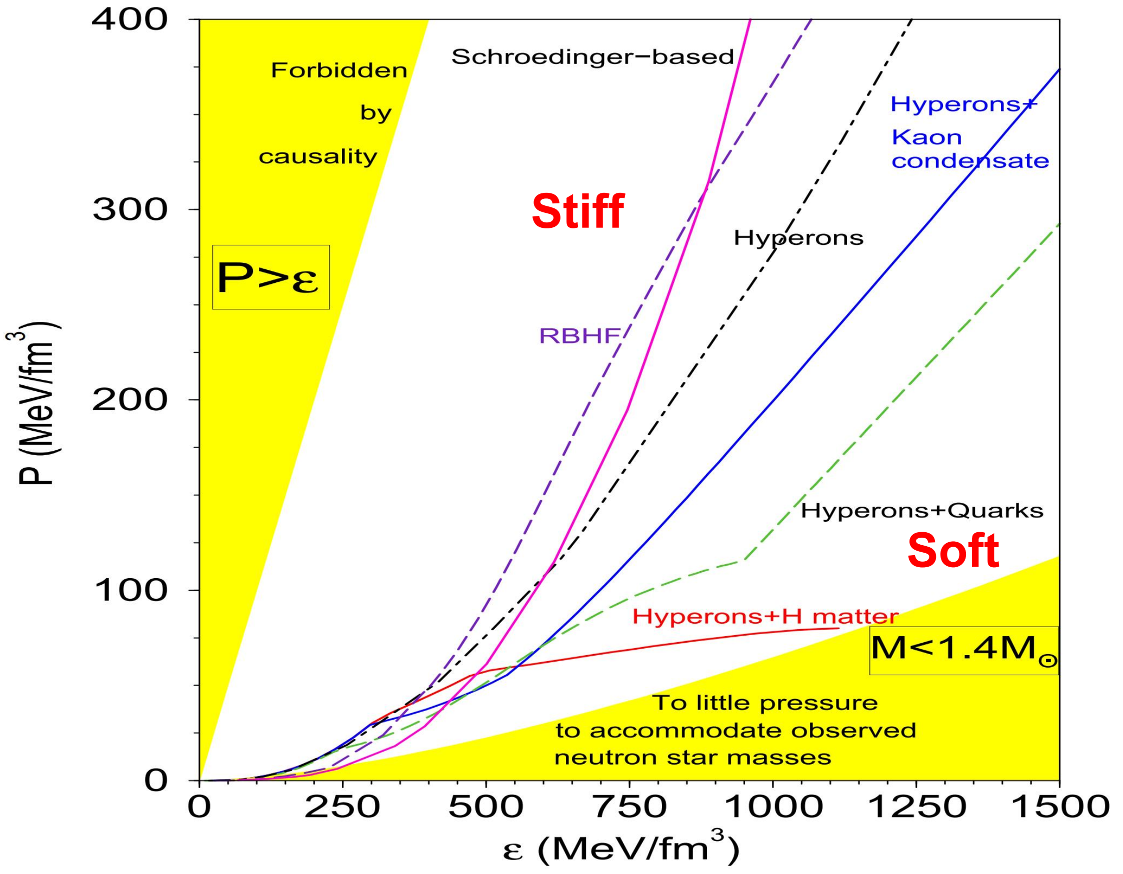
Central China Normal University

Oct. 20-24，WuHan

What is nuclear equation of state

- The nuclear EoS describes the relationships between **pressure p**, **energy density e**, **temperature T**, **net baryon density ρ** and **chemical potential μ**. For instance, p(ρ, T), p(μ, T) and e(ρ, T)
- Crucial for understanding the **evolution of early universe**, **supernova explosions**, **neutron star stability**, **heavy element synthesis**, and **heavy-ion collision experiments**
- It also constrains two-body and three-body nuclear interactions as well as non-perturbative Quantum Chromodynamics (QCD).

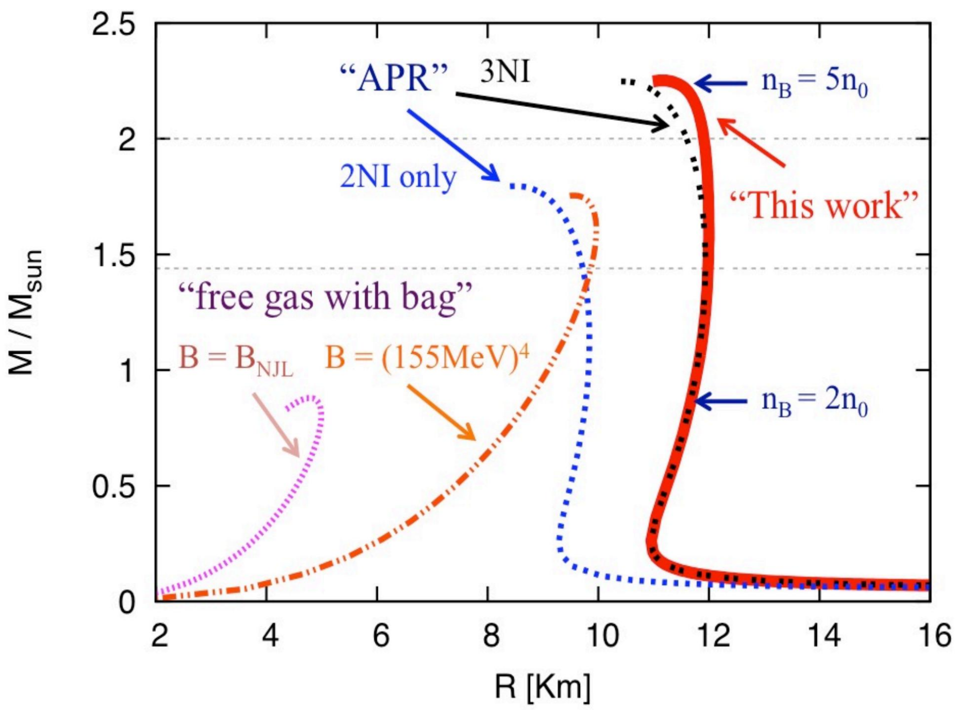
Nuclear EoS employed in astrophysical studies



F. Weber, IoP Publishing, Bristol(1999)

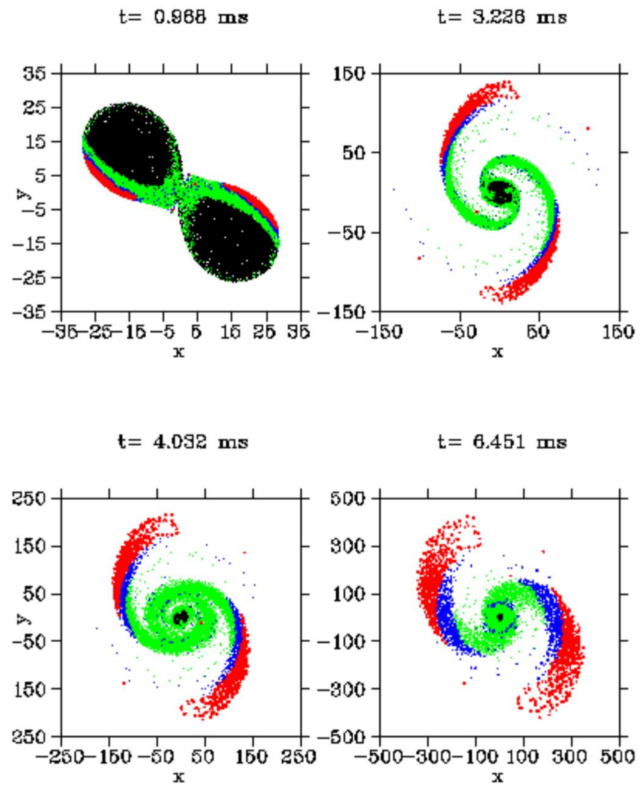
Astrophysics with different nuclear EoS

Neutron Star M-R

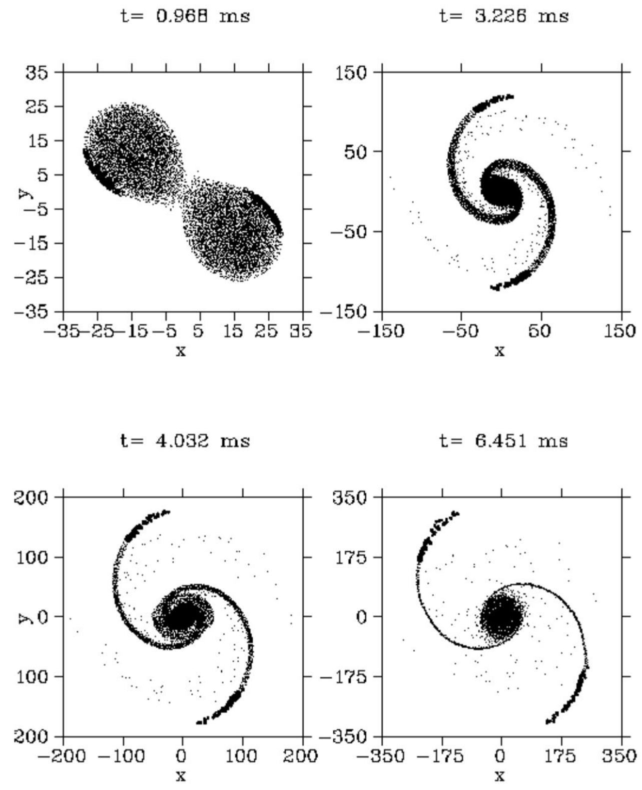


T Kojo, PD Powell,YF Song,and G Baym, 2015

Soft nuclear EoS



Stiff nuclear EoS

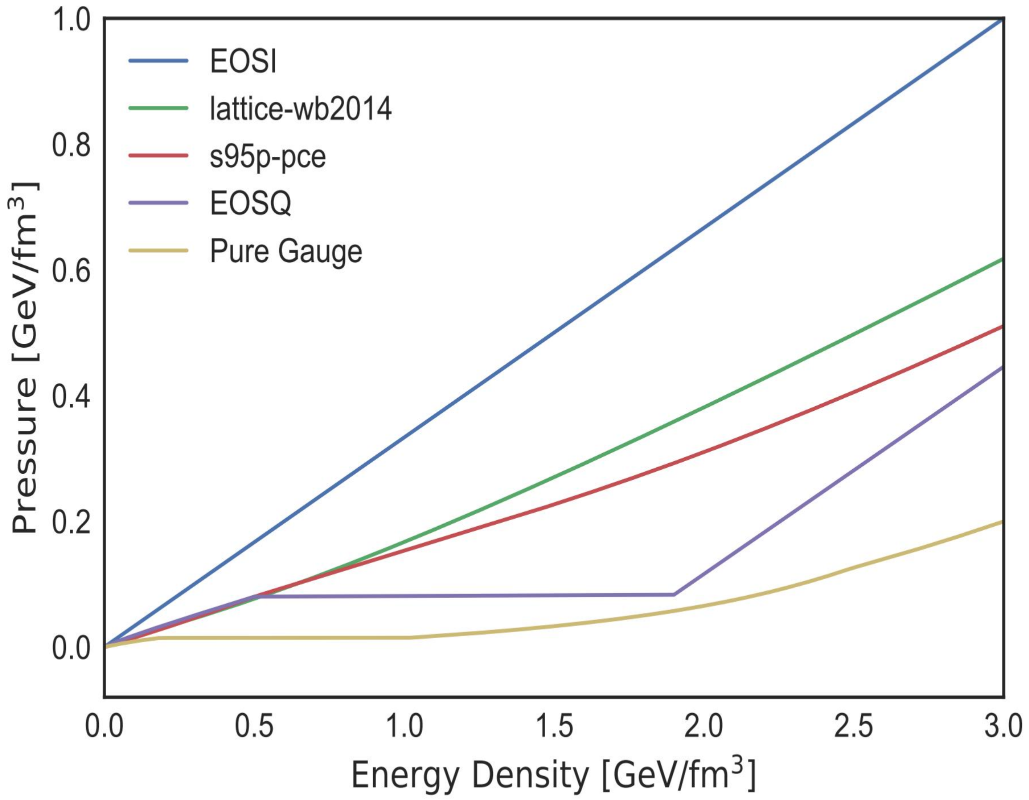


S. Rosswog et al., Astronomy and Astrophysics 341, 499 (1999).

Nuclear EoS at high temperature region

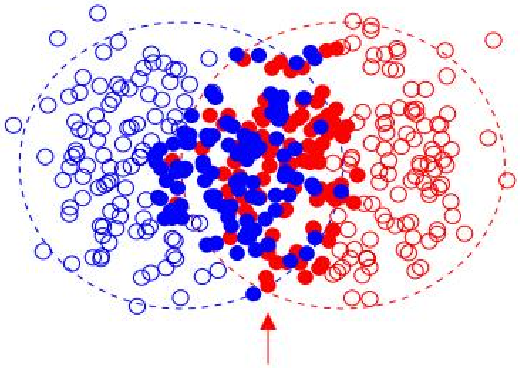
- The nuclear EoS describes the relationships between **pressure p**, **energy density e**, **temperature T**, **net baryon density ρ** and **chemical potential μ**. For instance, p(ρ, T), p(μ, T) and e(ρ, T)
- Crucial for understanding the **evolution of early universe**, **supernova explosions**, **neutron star stability**, **heavy element synthesis**, and **heavy-ion collision experiments**
- It also constrains two-body and three-body nuclear interactions as well as non-perturbative Quantum Chromodynamics (QCD).

Nuclear EoS employed in HIC physics



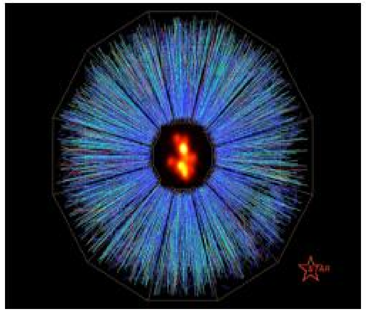
LG Pang, H Petersen, XN Wang, PRC 2018

Nuclear EoS in relativistic hydrodynamics



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

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



Initial condition EoS Viscosity

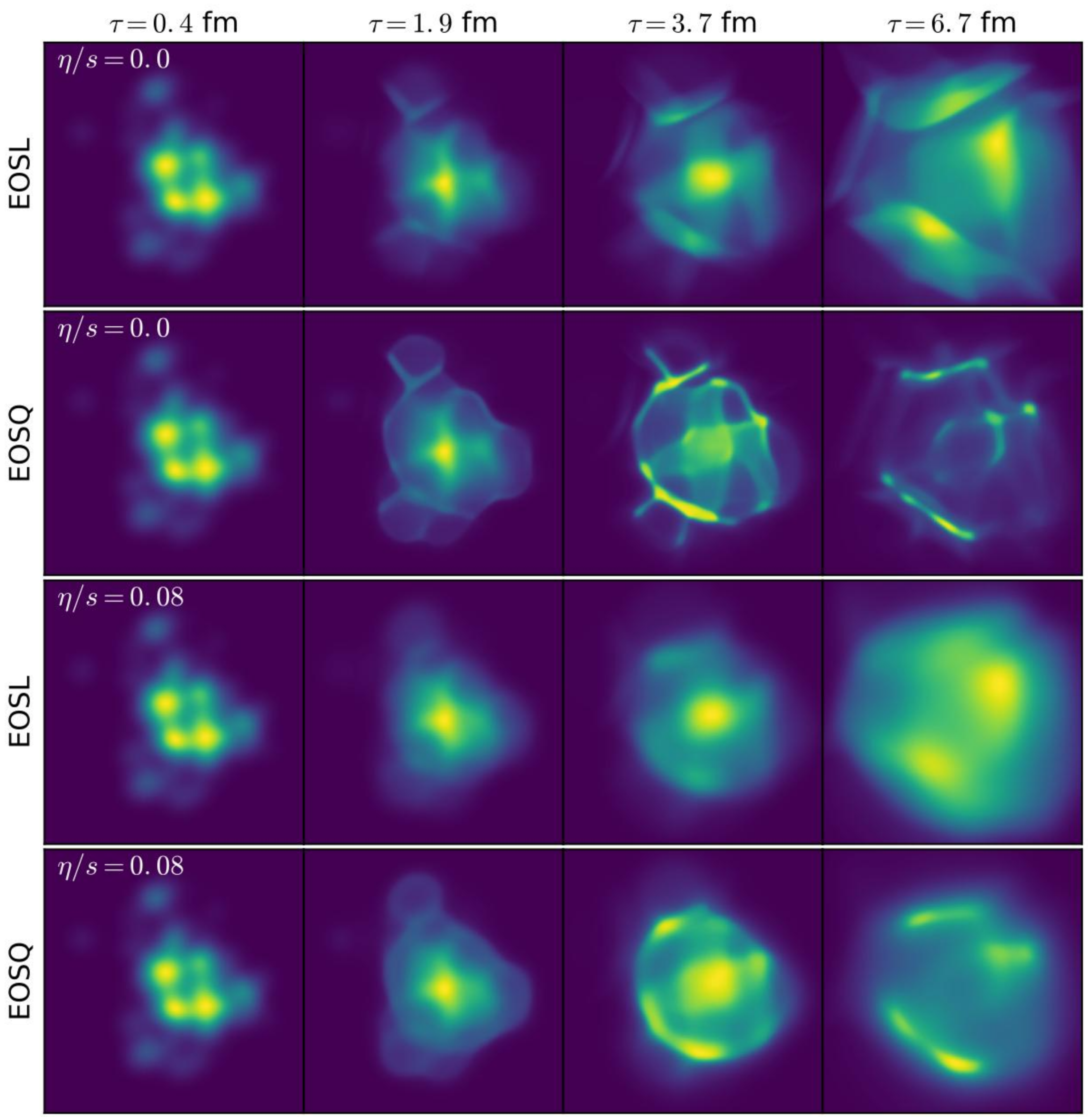
Name of CLVisc:

1. CCNU-LBNL Viscous Hydro, CCNU = Central China Normal University
2. A 3+1D viscous hydro parallized on GPU using OpenCL

Purpose: Describe the non-equilibrium space-time evolution of hot QCD matter
Feature: **60 times faster** for hydrodynamic evolution, **100 times faster** for hadronization

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

CLVisc for different EoS



eta/s = 0
Lattice QCD EoS
(smooth cross over)

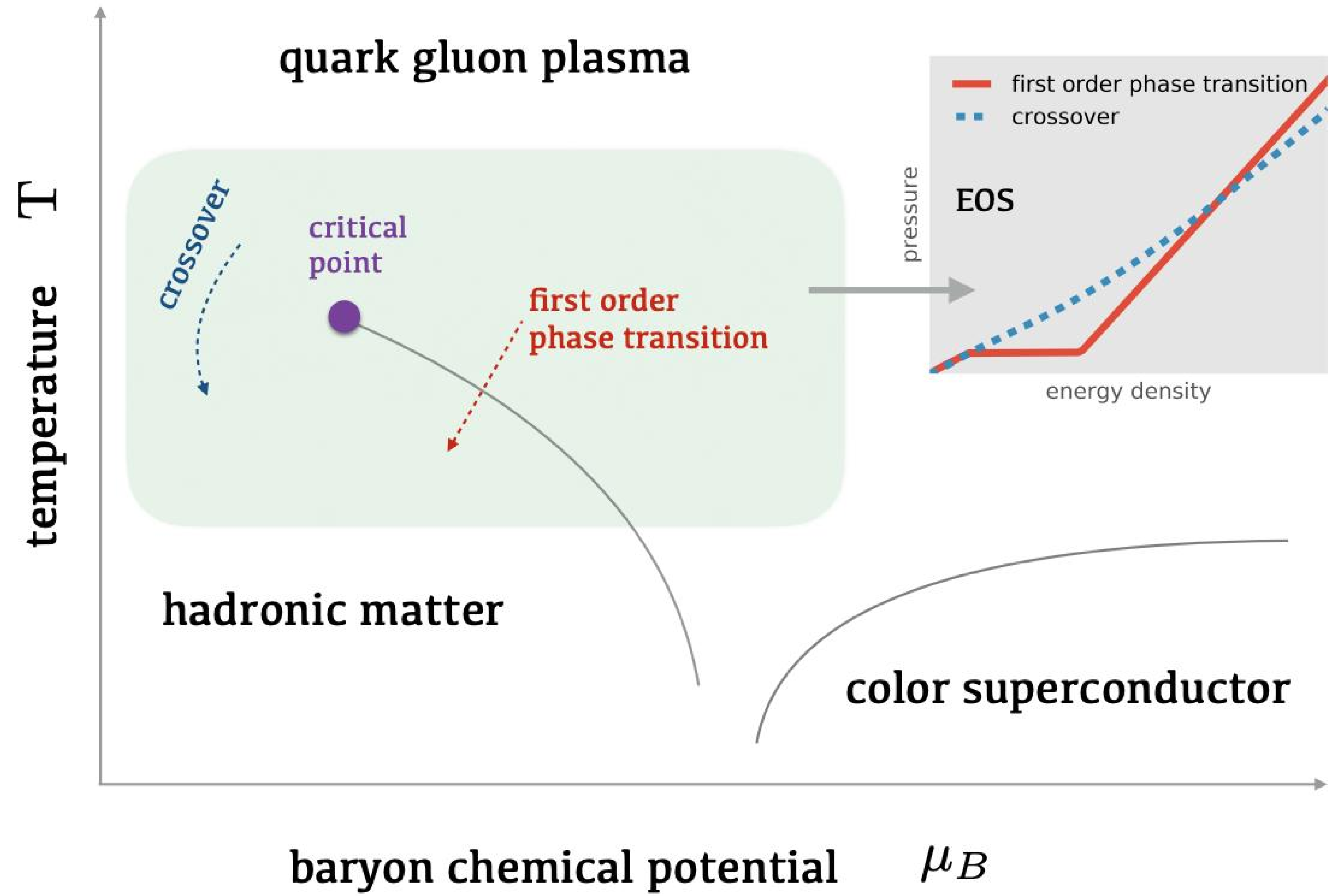
eta/s = 0
First order phase transition

eta/s = 0.08
Lattice QCD EoS

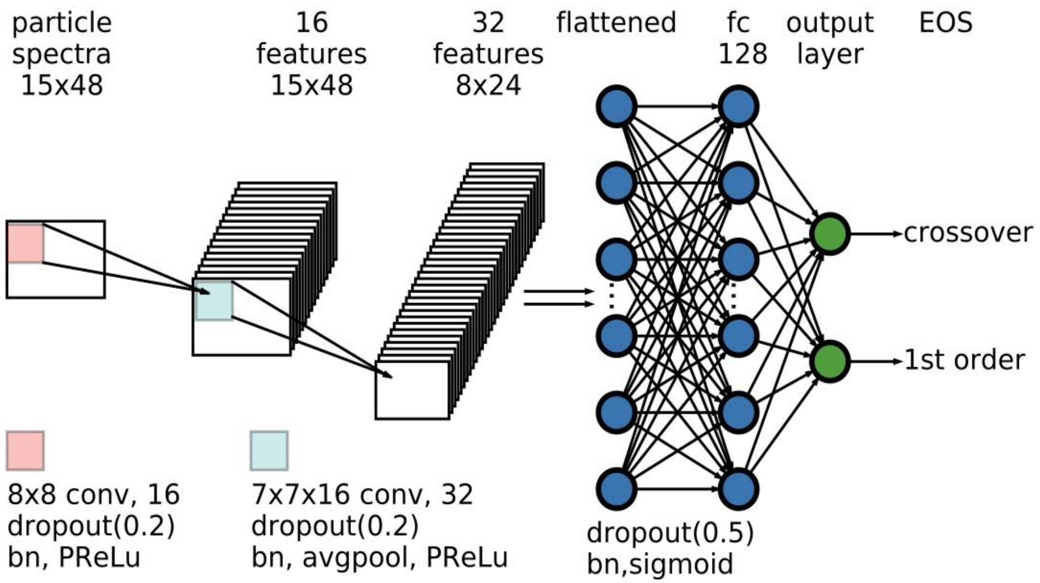
eta/s = 0.08
First order phase transition
eta/s: shear viscosity / entropy density

Will the effect of EoS survive the dynamical evolution and exist in the final state hadrons?

EoS for different phase transition types



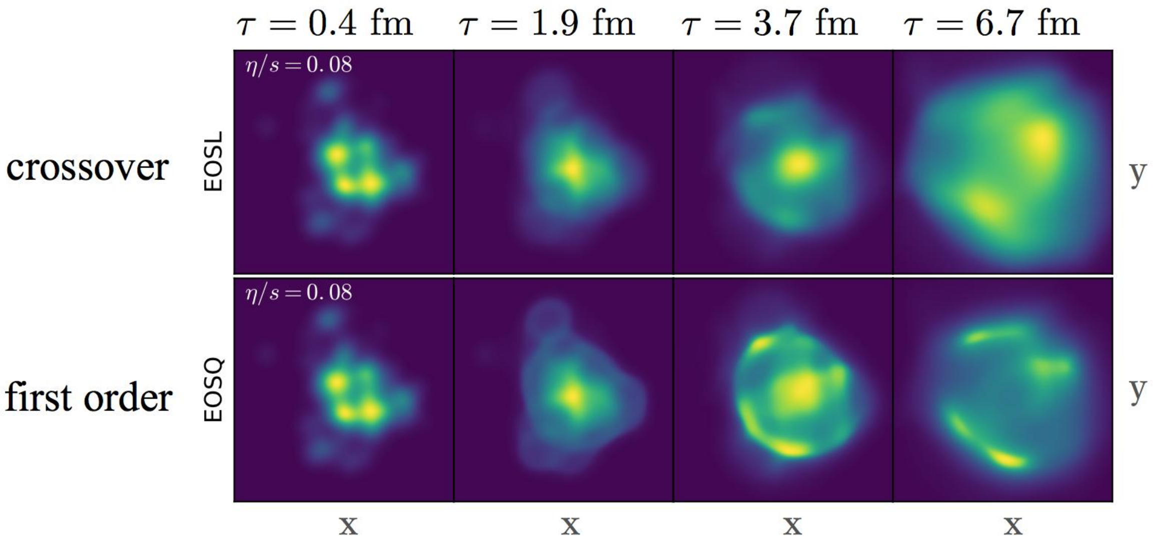
Determine nuclear phase transitions



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

cross entropy loss L2 regularization

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

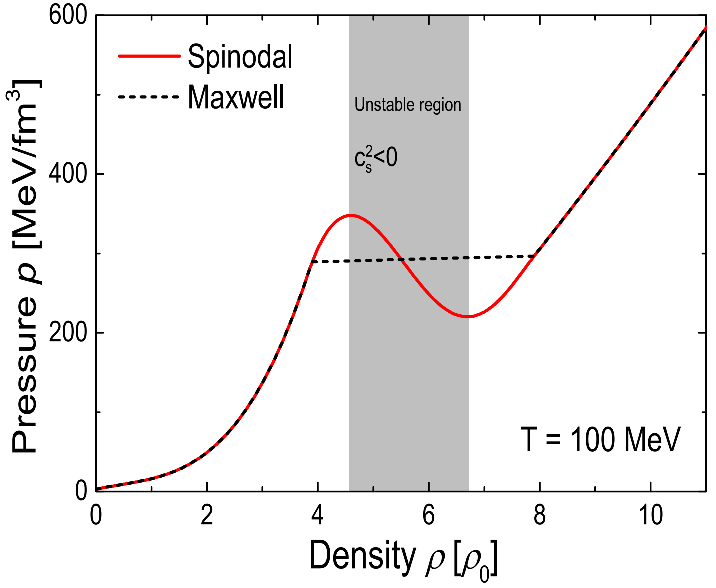


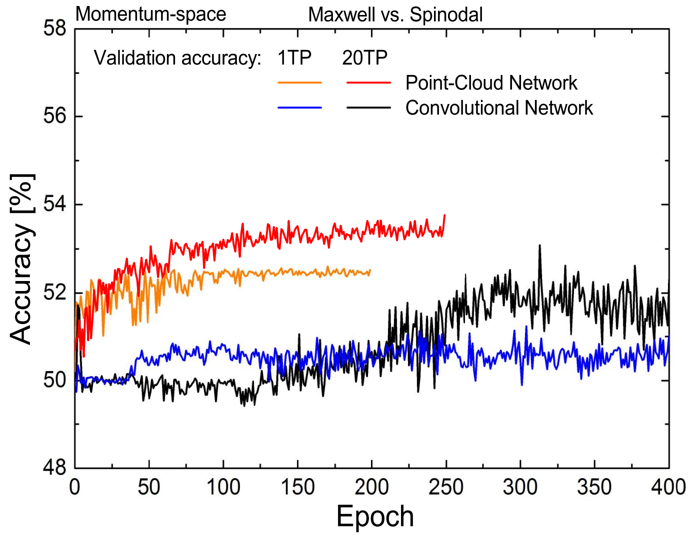
CLVisc 3+1D relativistic hydrodynamics

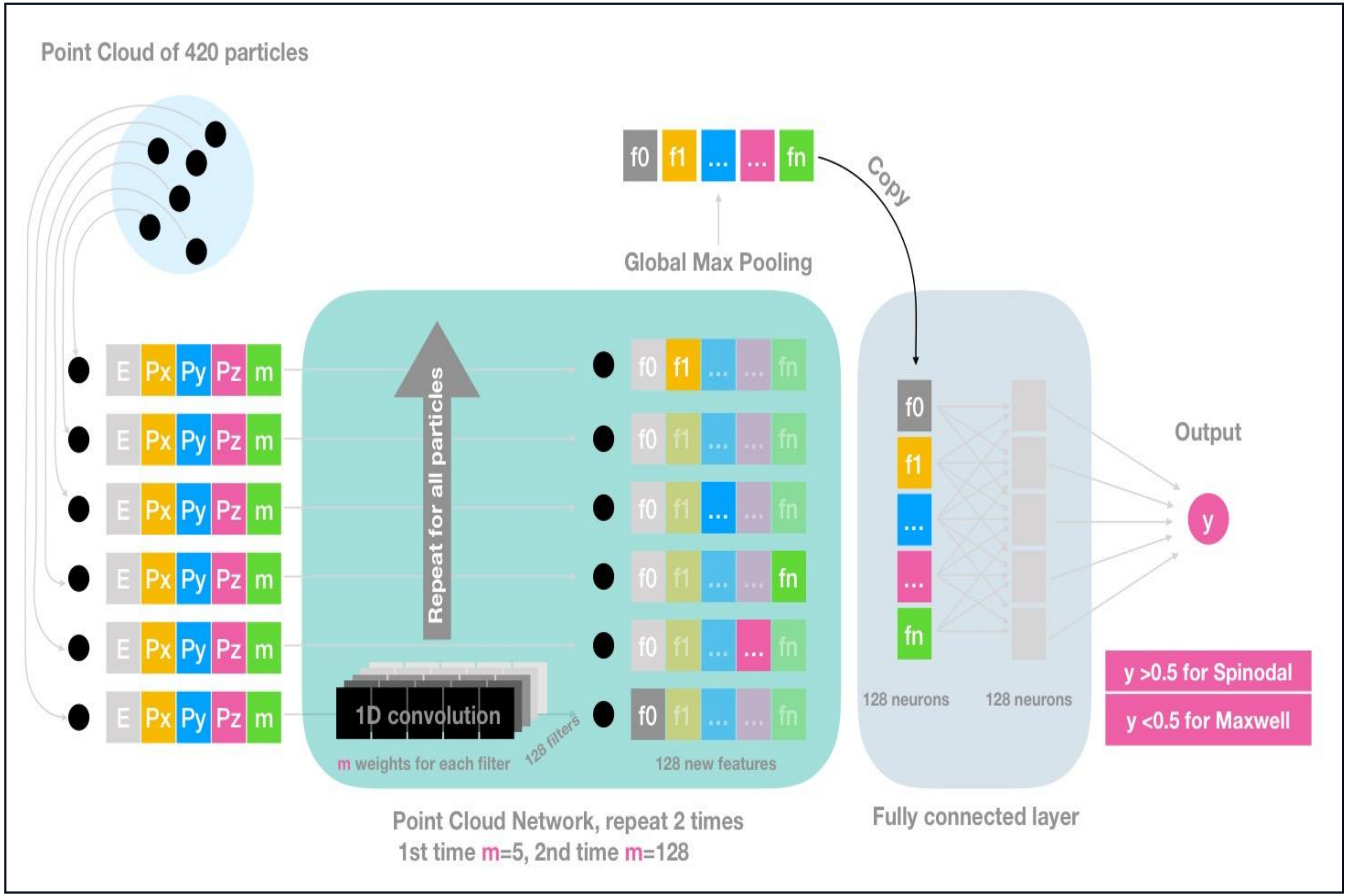
DL： 93% Classification Accuracy!

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

Spinodal vs Maxwell 1st order phase transition

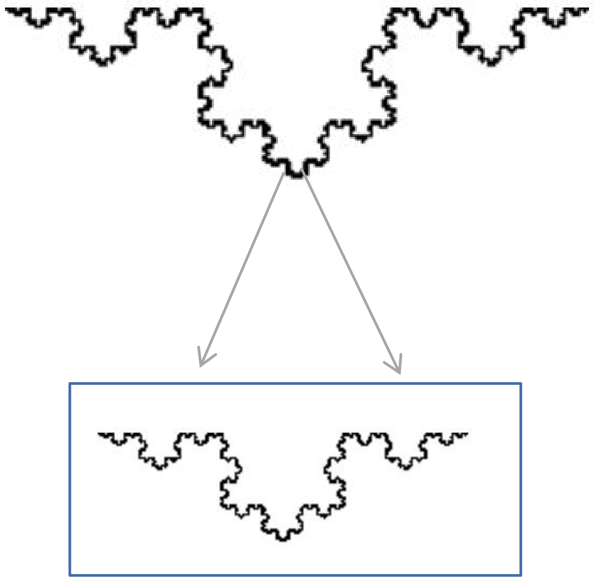






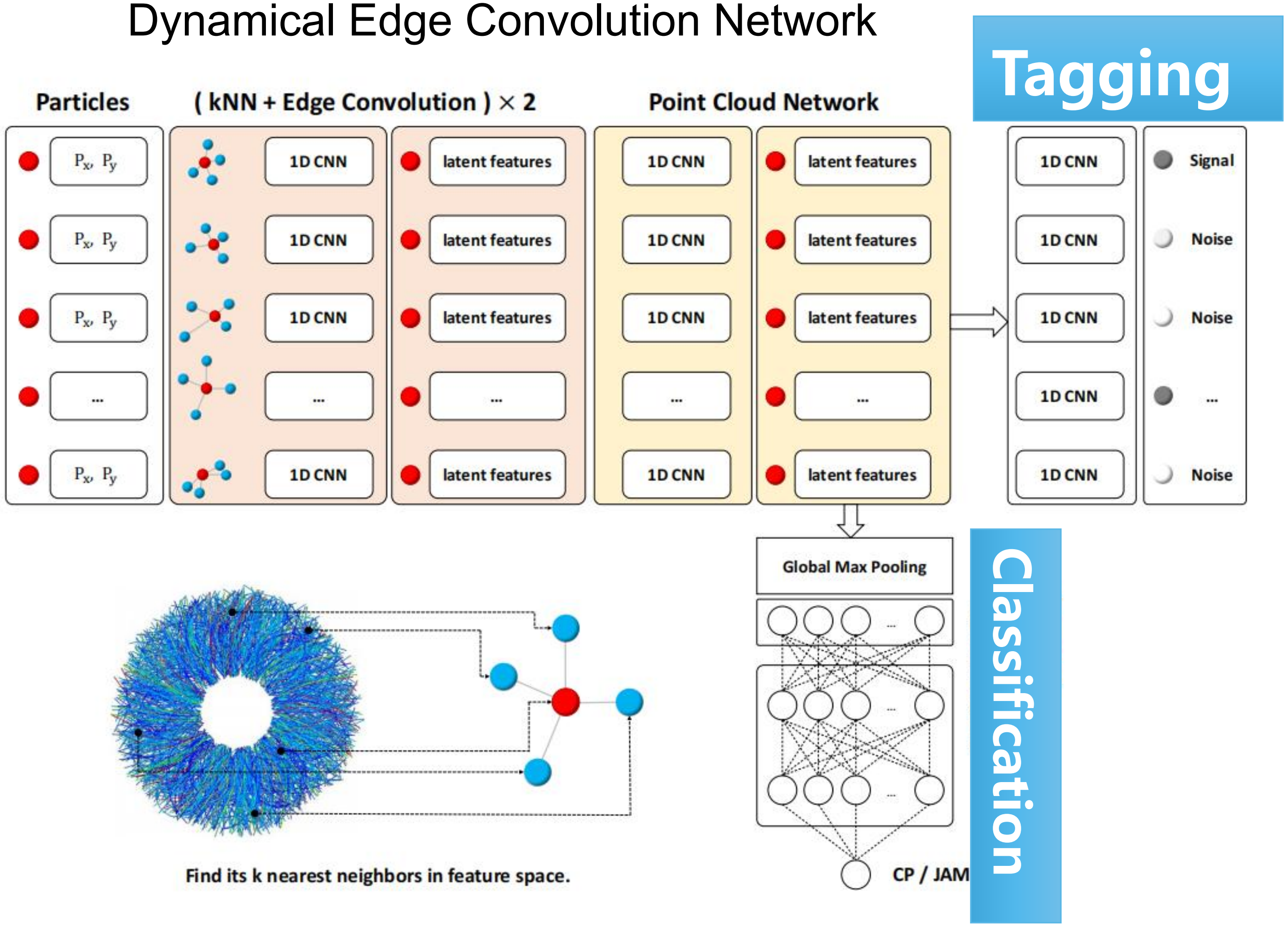
J. Steinheimer, L.G. Pang, K. Zhou, V. Koch and J. Randrup, JHEP 12 (2019) 122

Looking for self similarity in momentum space



Self similarity, scaling invariance

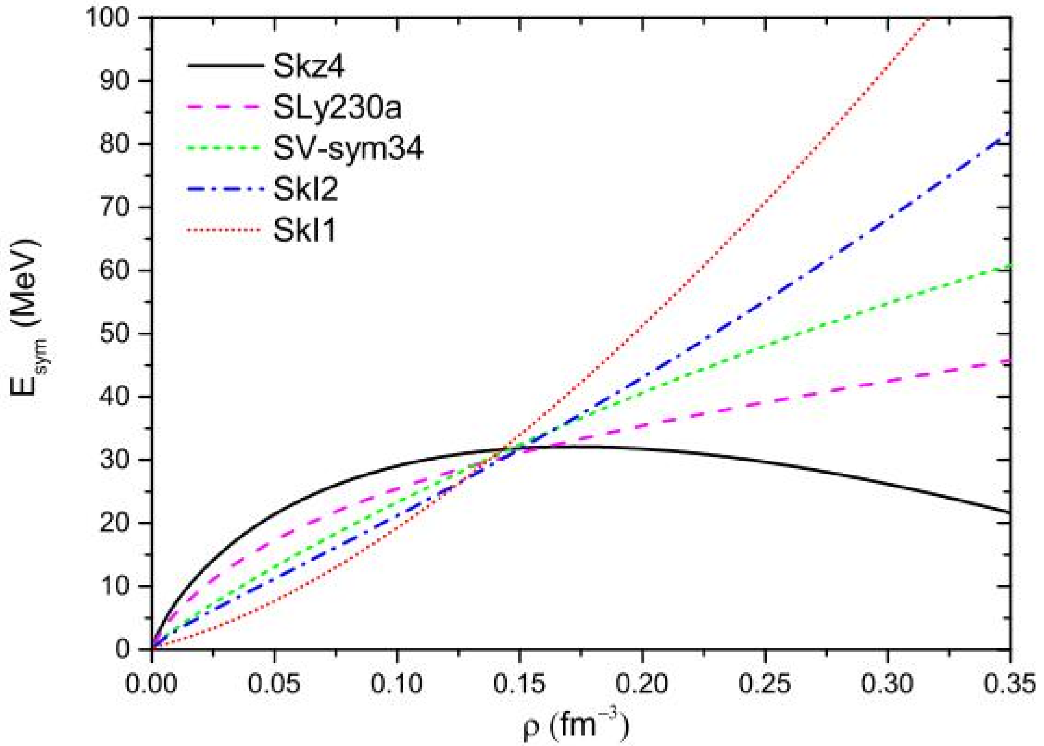
Dynamical Edge Convolution Network



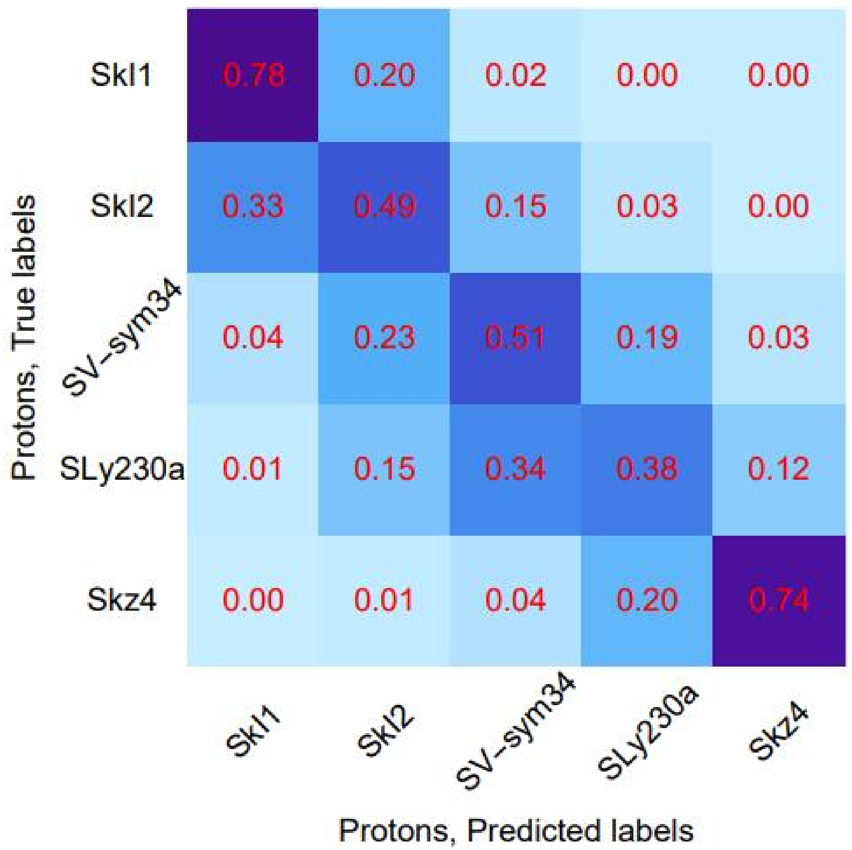
PLB 827(2022) 137001, Y.-G. Huang, L.-G. Pang, X.F. Luo and X.-N. Wang

Nuclear EoS at high density region

Skyrme potential + IMQMD



off-diagonal = misclassified



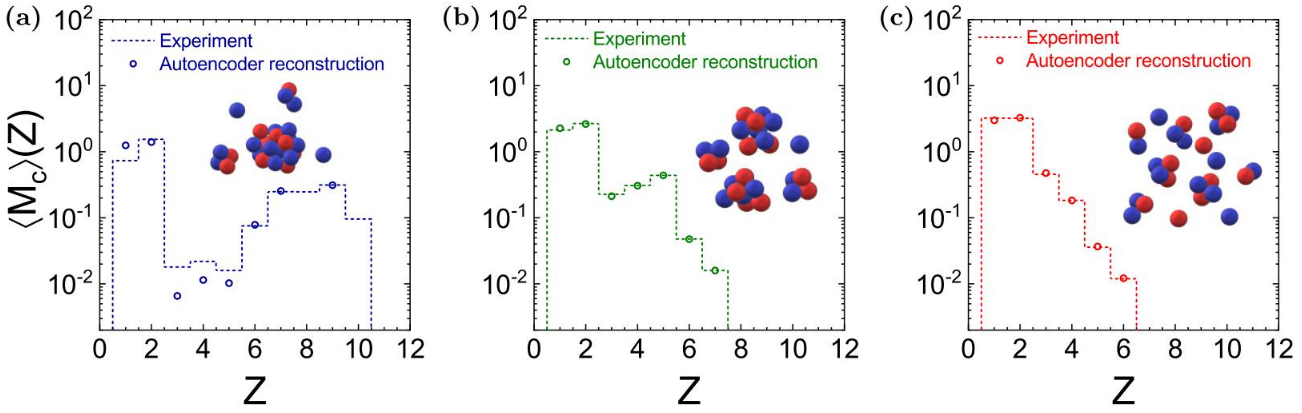
PLB 822 (2021) 136669, Y.J Wang, F.P. Li, Q.F. Li, H.L. L¨u, and K. Zhou

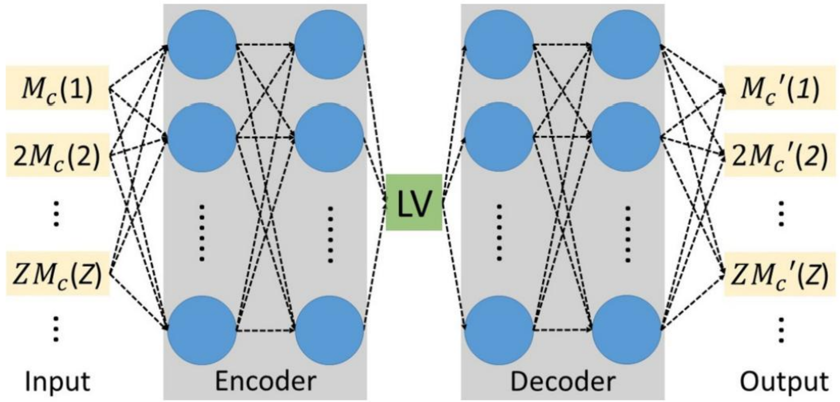
Auto Encoder for order parameter

PHYSICAL REVIEW RESEARCH **2**, 043202 (2020)

Nuclear liquid-gas phase transition with machine learning

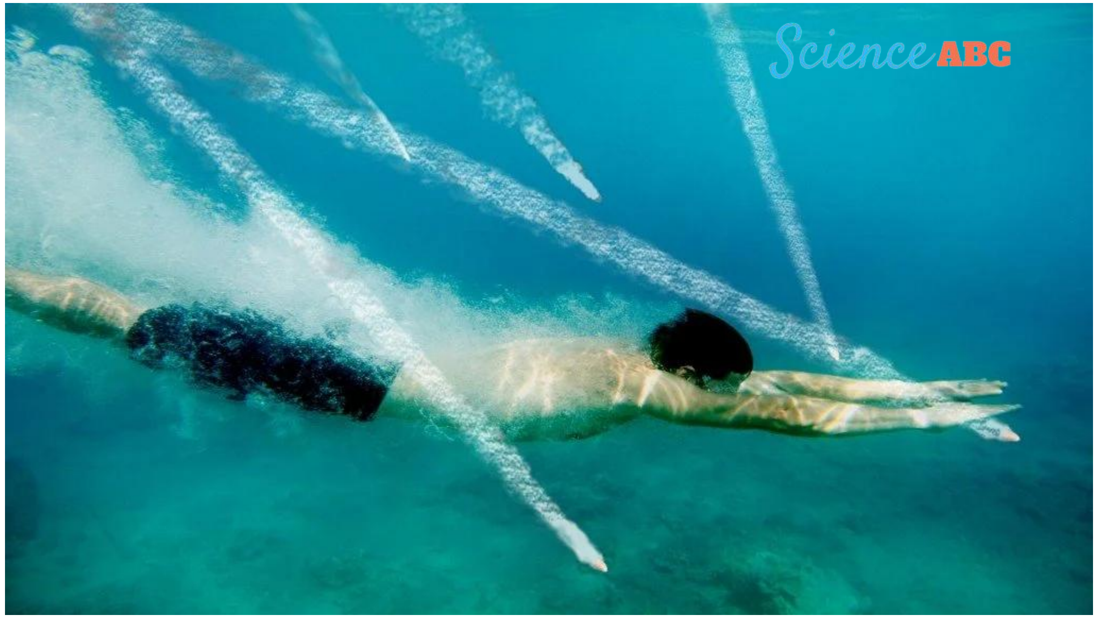
Rui Wang,[1,2,*] Yu-Gang Ma,[1,2,†] R. Wada,[3] Lie-Wen Chen,[4] Wan-Bing He,[1] Huan-Ling Liu,[2] and Kai-Jia Sun[3,5]



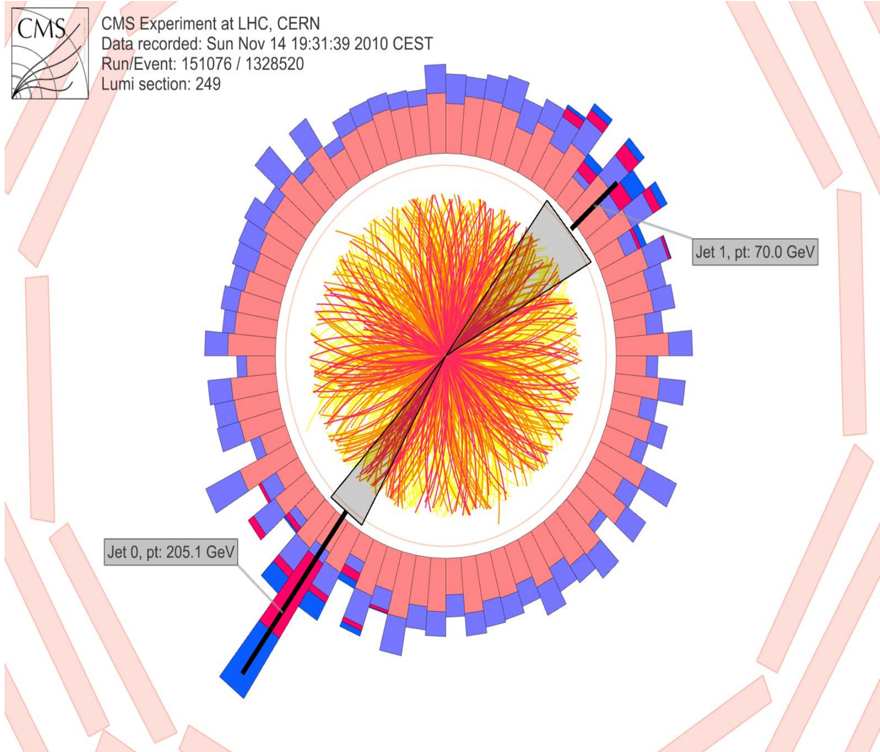


Jet eloss and medium response

Can Being Underwater Protect You From Bullets?

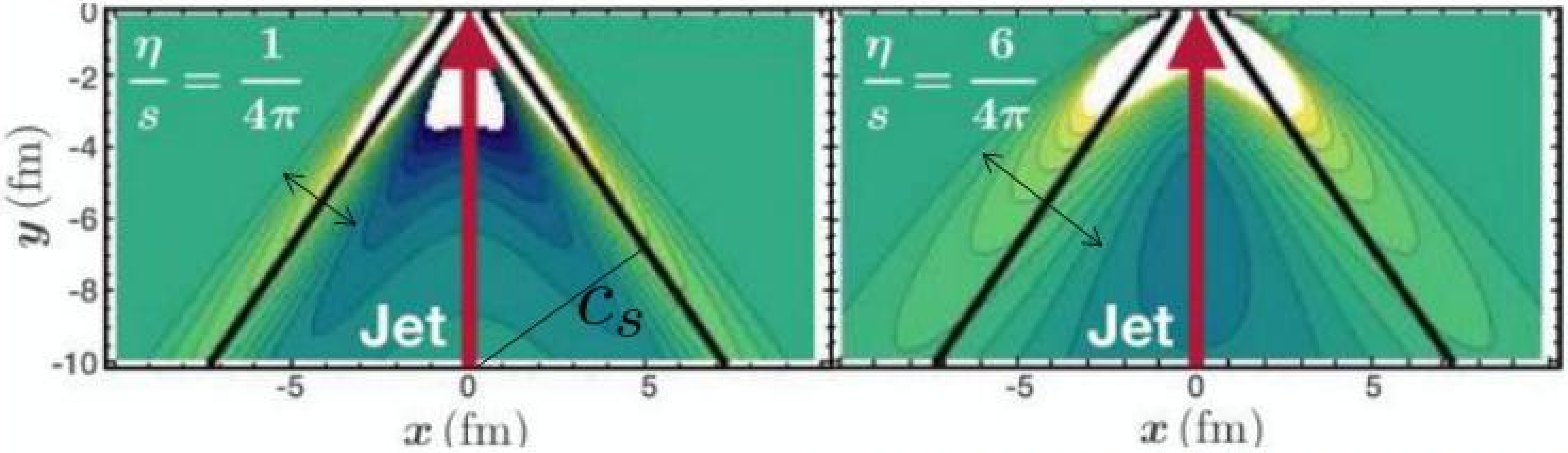


If the bullet is shot from an angle of 30 Degrees, then being underwater in the range of 3-5 feet (0.9-1.5 meters) can ensure safety from most guns.



Jet quenching in hot QGP

The nuclear EoS and Mach Cone



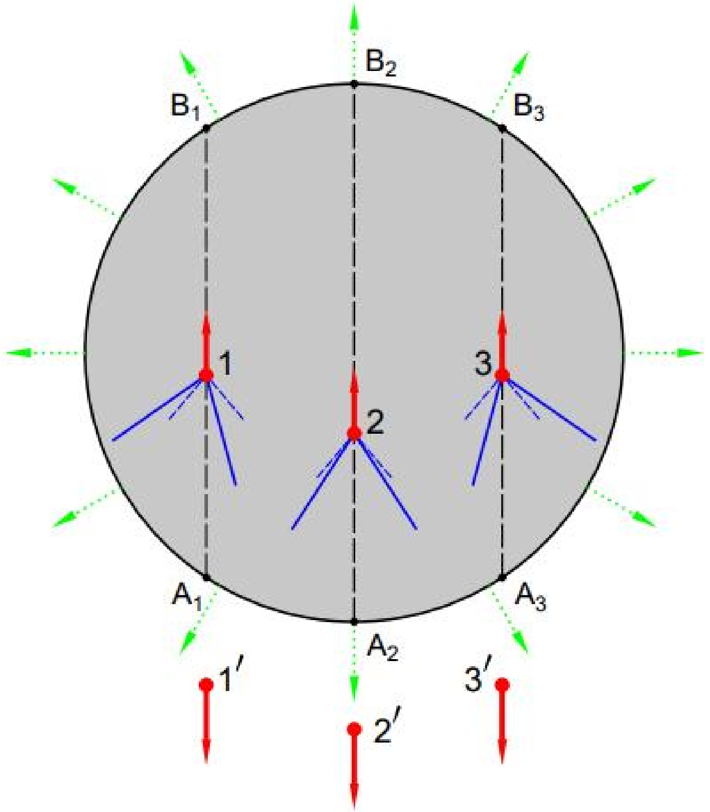
R.B.Neufeld. PRC79,054909(09')

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

Shear Viscosity： width of the shock wave

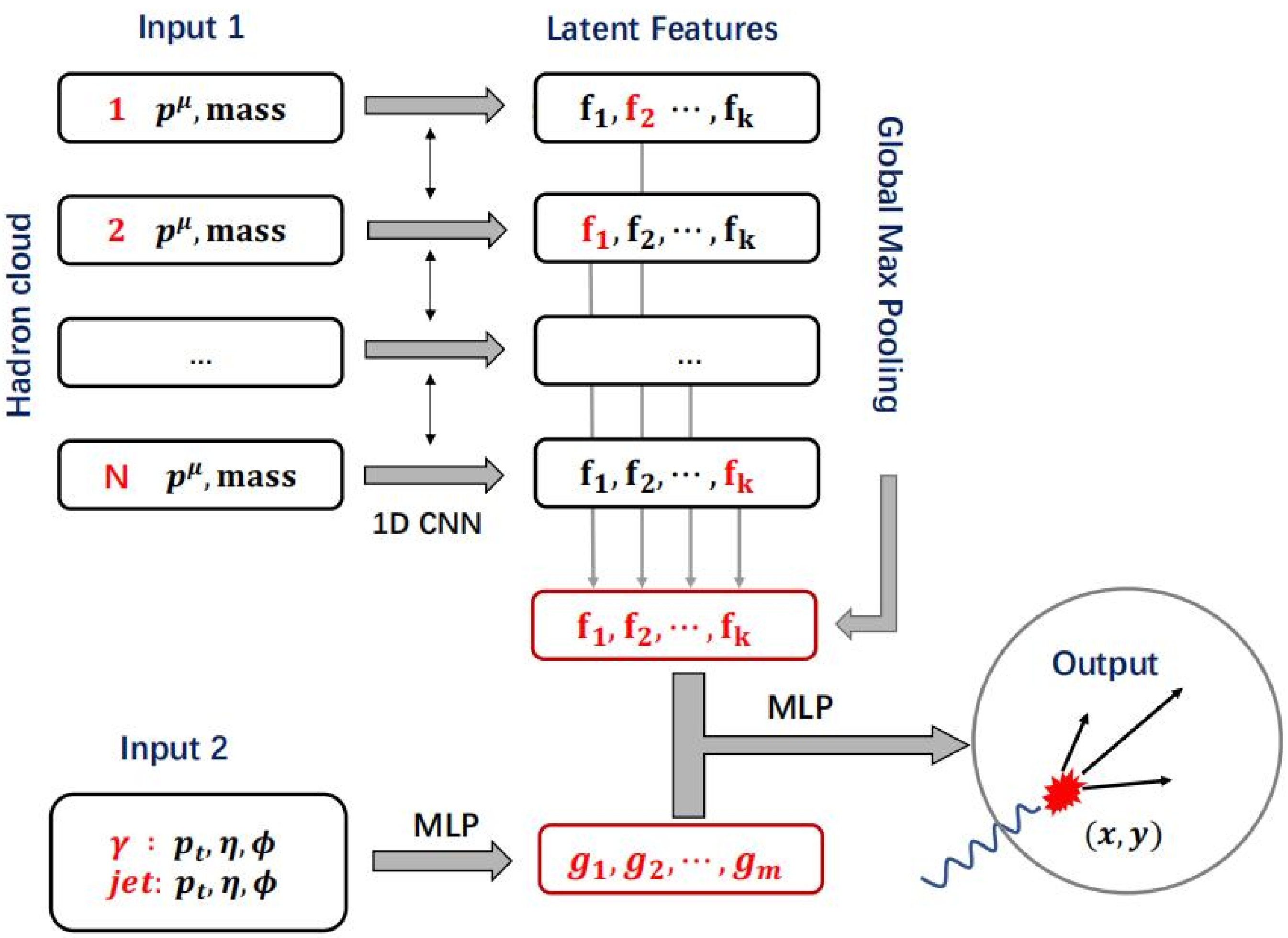
Difficulties in looking for Mach Cones in HIC

- 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

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)

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

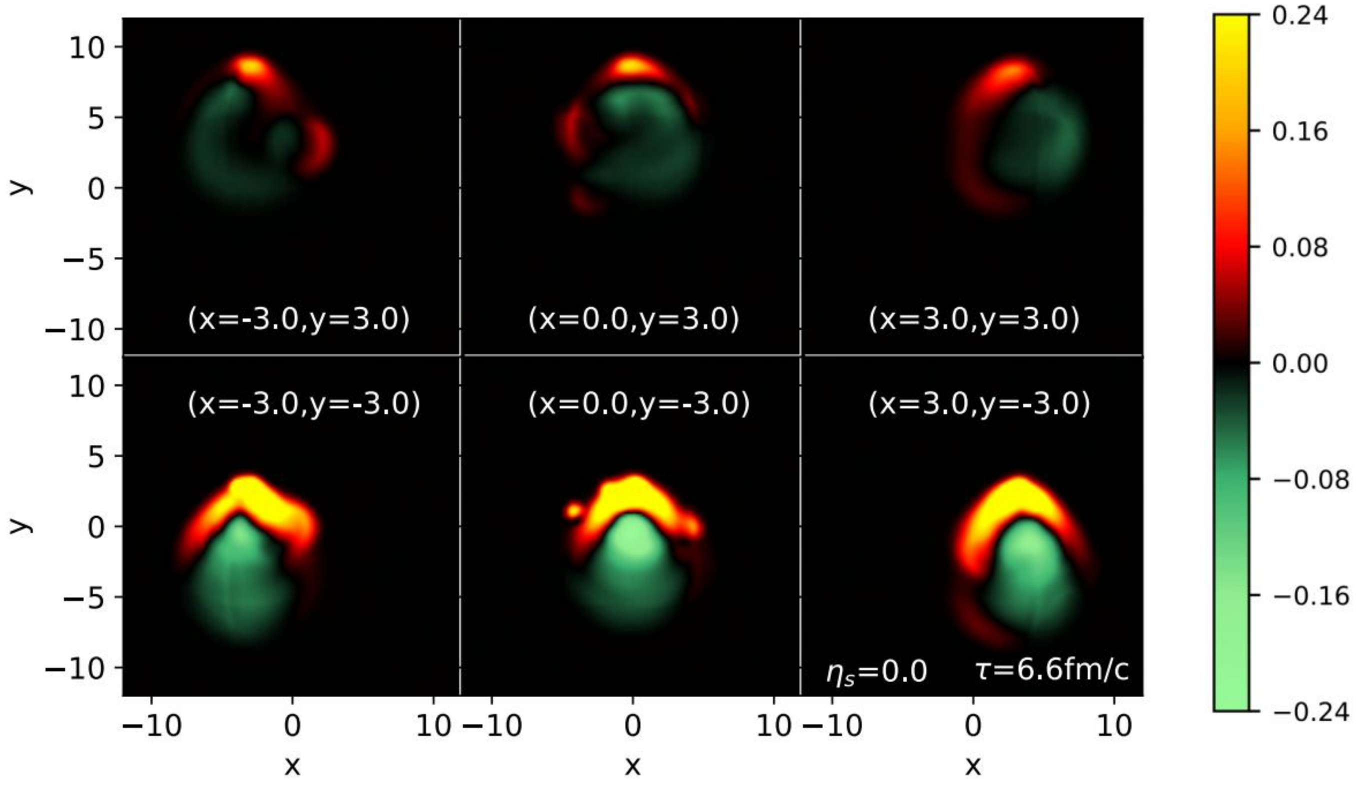
Z Yang, YY He, W Chen, WY Ke, LG Pang, XN Wang, EPJC 83 (2023) 7, 652

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

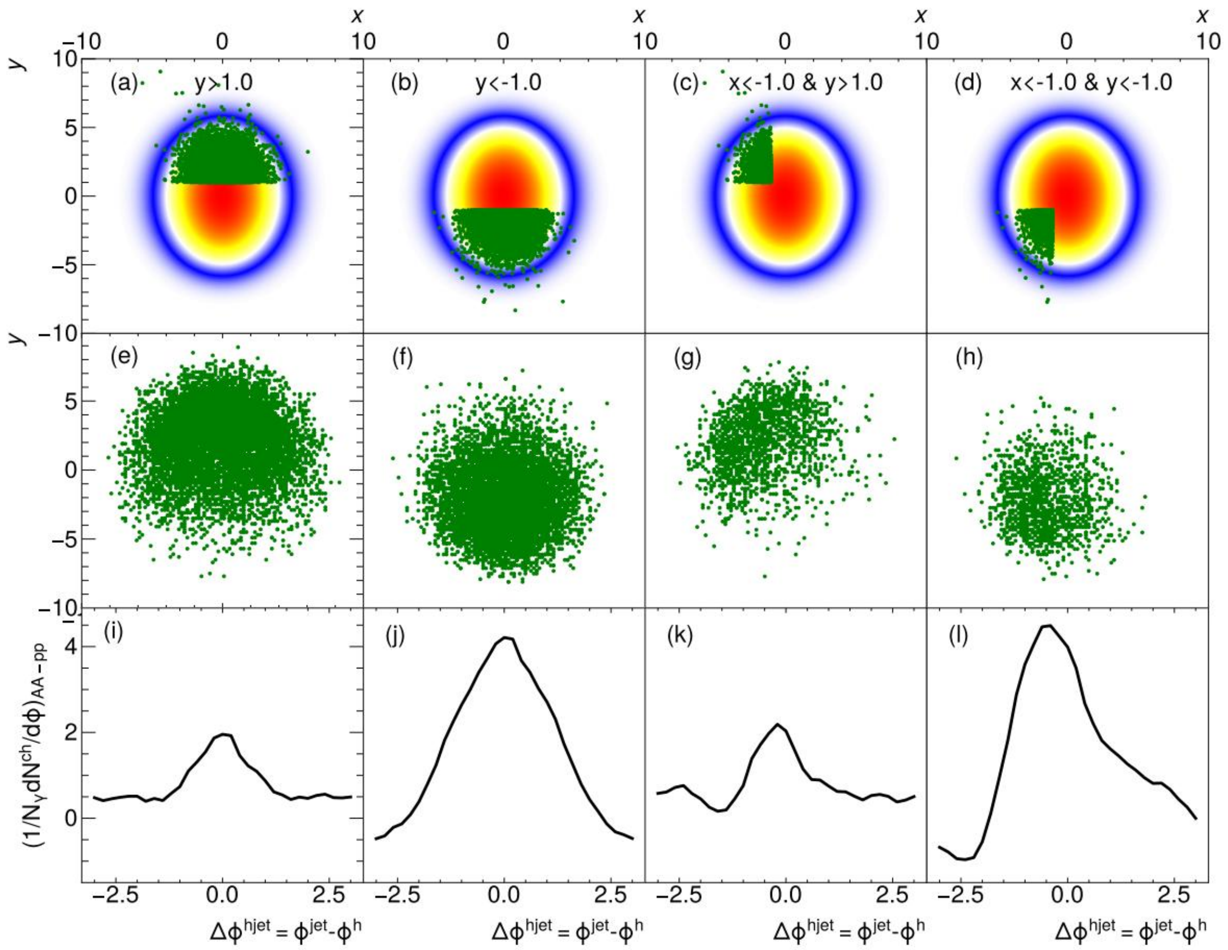
CLVisc:
LG Pang, Q Wang, XN Wang, PRC 86 (2012) 024911
LG Pang, H Petersen, XN Wang, PRC 97 (2018) 6, 064918
XY Wu, GY Qin, LG Pang, XN Wang,PRC 105 (2022) 3, 034909

CoLBT:

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

DL assisted jet tomography

The Jet direction



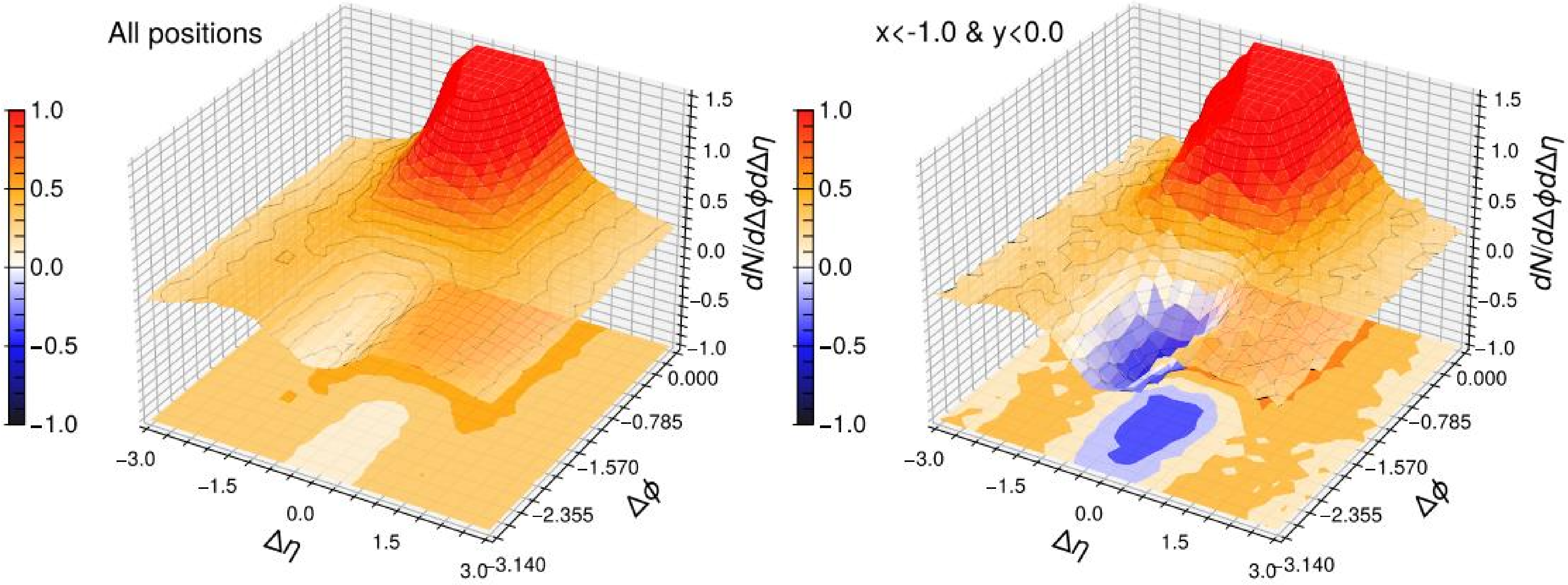
Network predictions

True locations

Jet hadron correlation for selected events whose locations are constrained to specific regions using DL assisted jet tomography

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

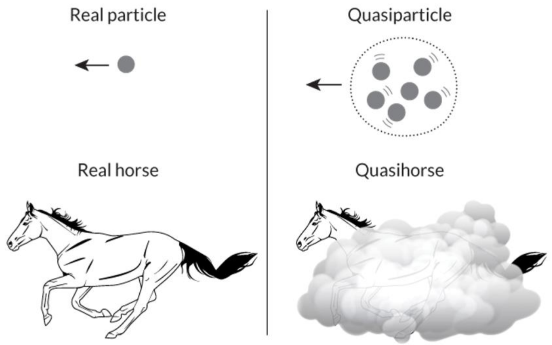
Enhance the Diffusion Wake signal

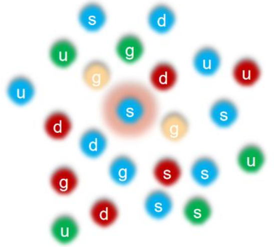


Z Yang, YY He, W Chen, WY Ke, LG Pang, XN Wang, EPJC 83 (2023) 7, 652

Z Yang, T Luo, W Chen, LG Pang, XN Wang, PRL 130 (2023) 5, 052301

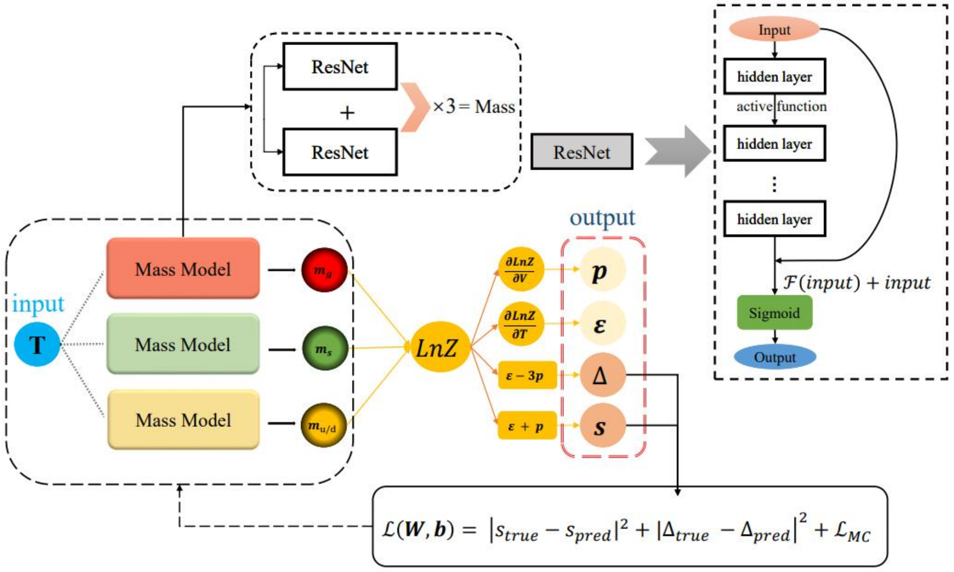
Effective theory: DL For Quasi Particle Mass





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.

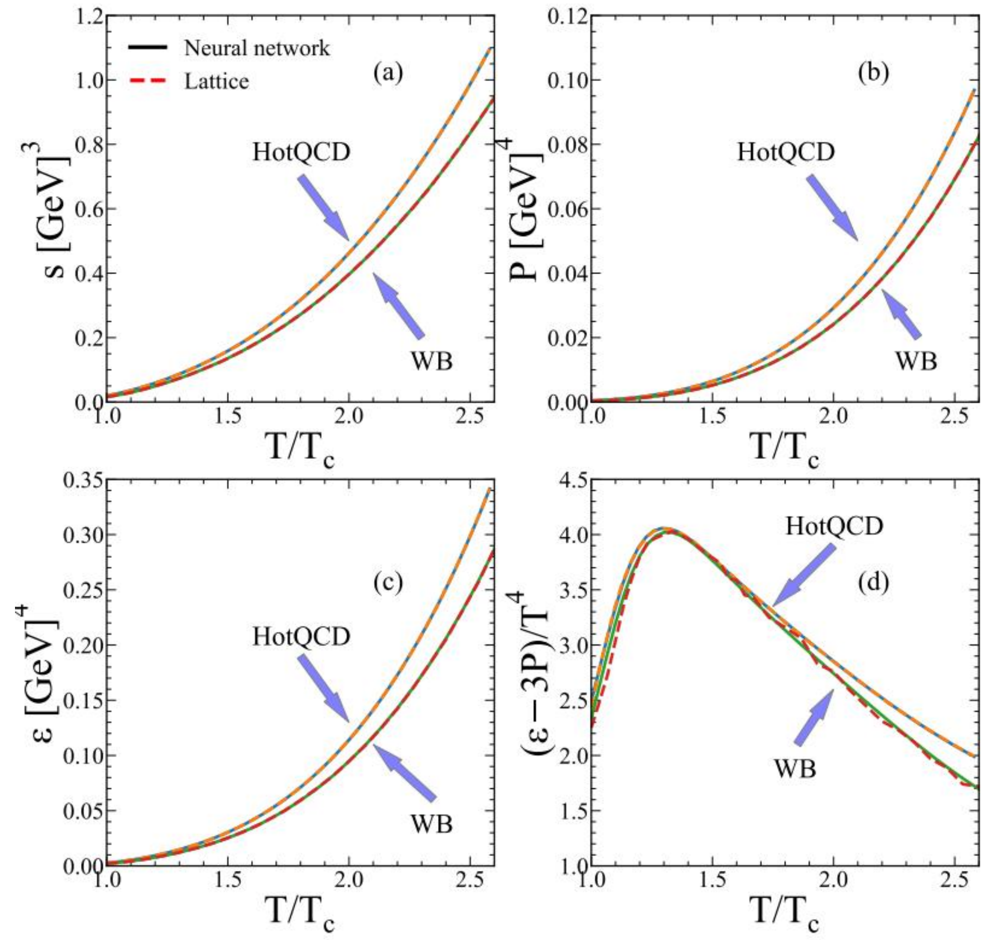
The resulting pressure and energy density are computed using the following statistical formulae,

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

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

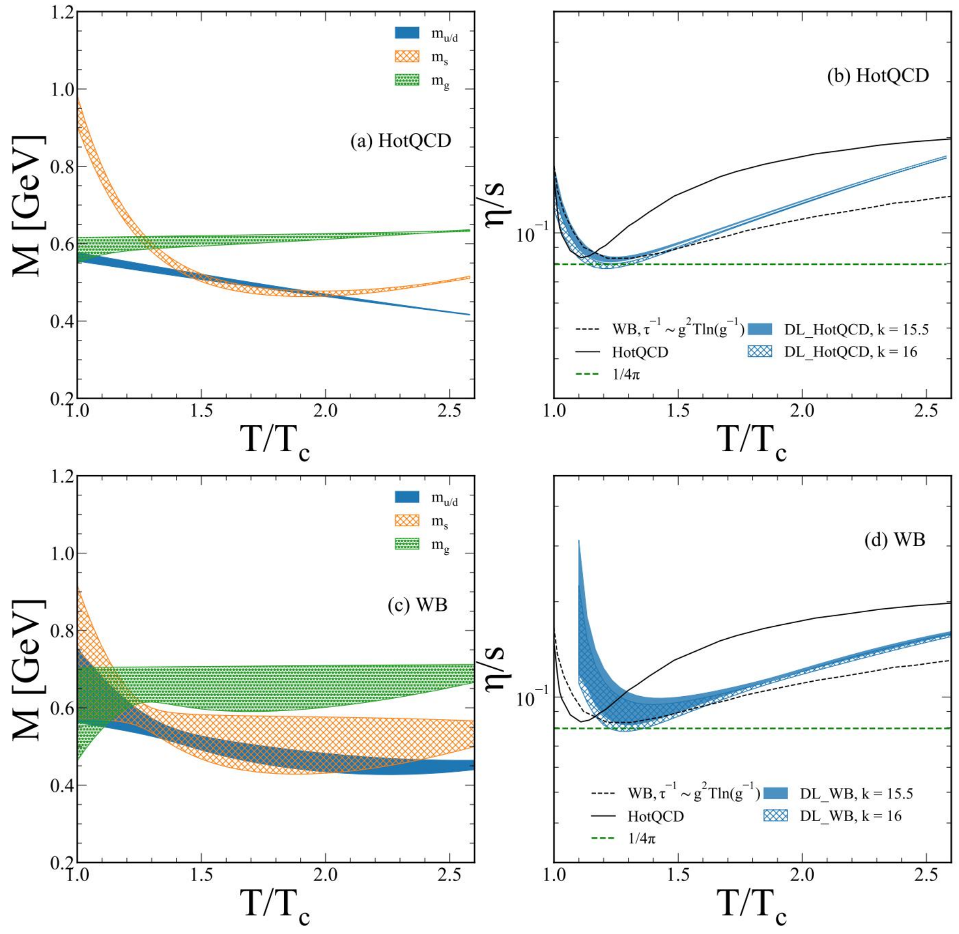
The learned quasi parton mass

EoS vs Lattice QCD



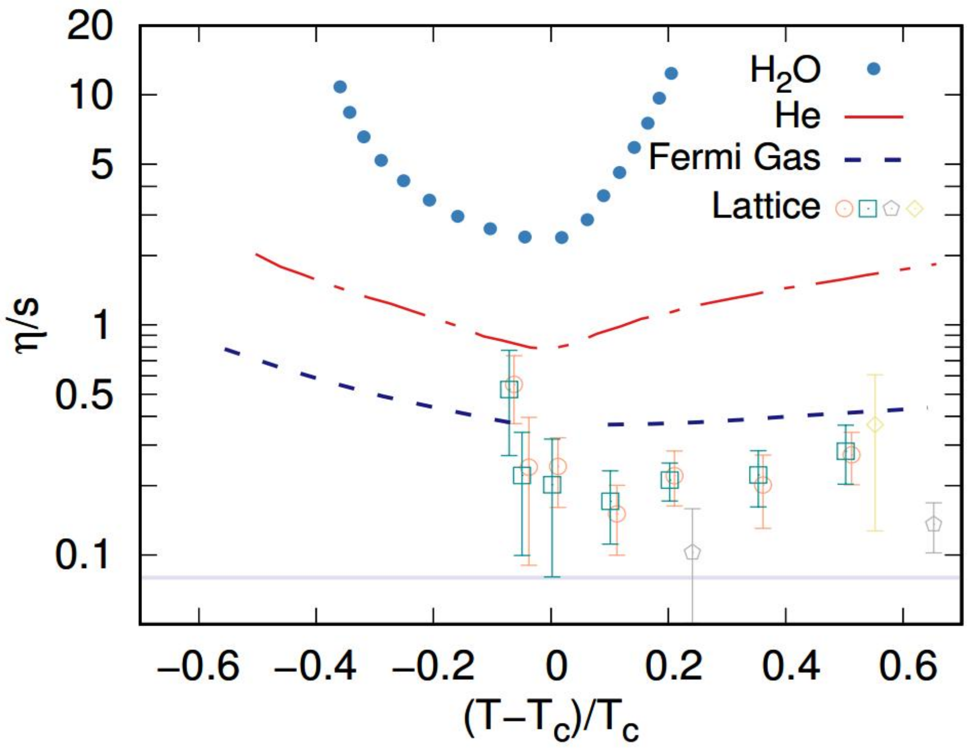
Learned Mass

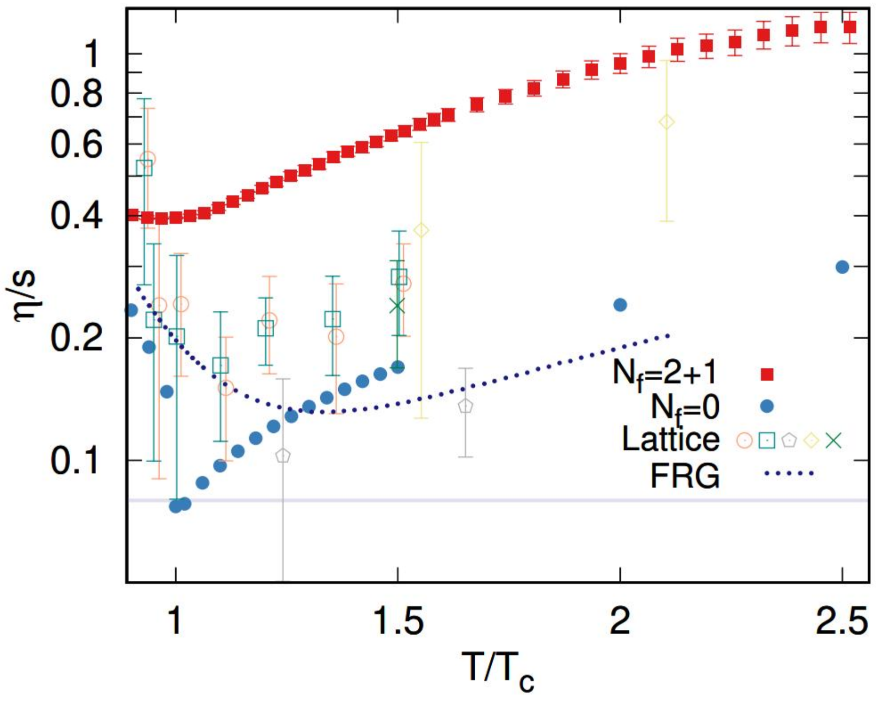
η/s



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

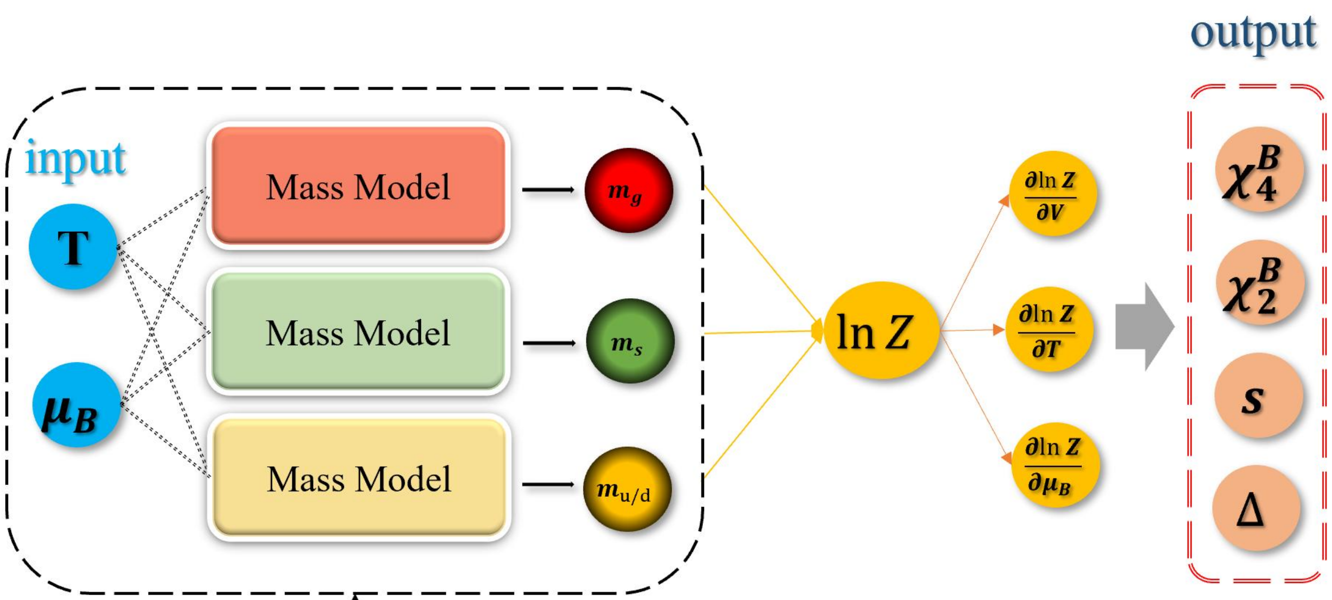
Location of minimum eta/s



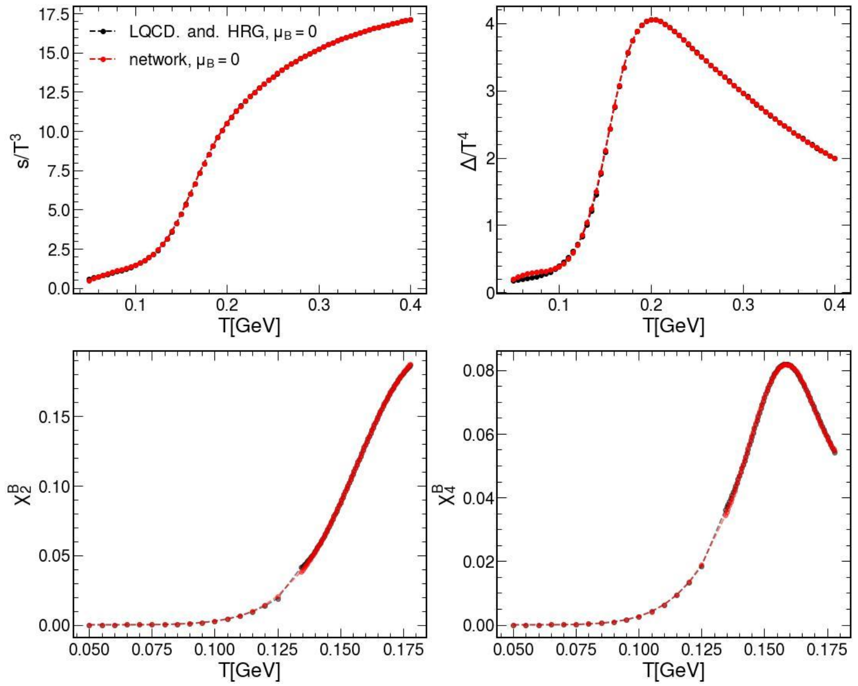


Thesis of Valeriya Mykhaylova, 2023

Extend Quasi Parton Model to finite muB



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

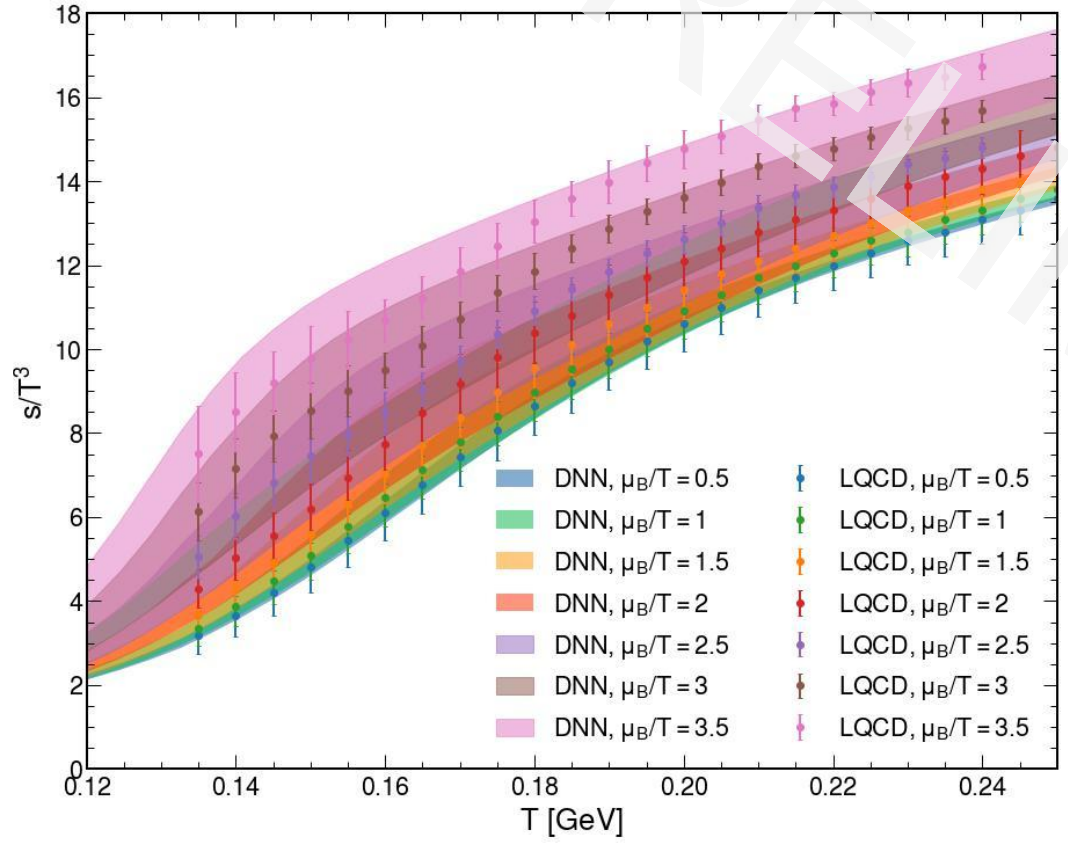


Model:
Deep learning Quasi Parton Model
Effective theory of strongly coupled QGP and nuclear matter at finite baryon density

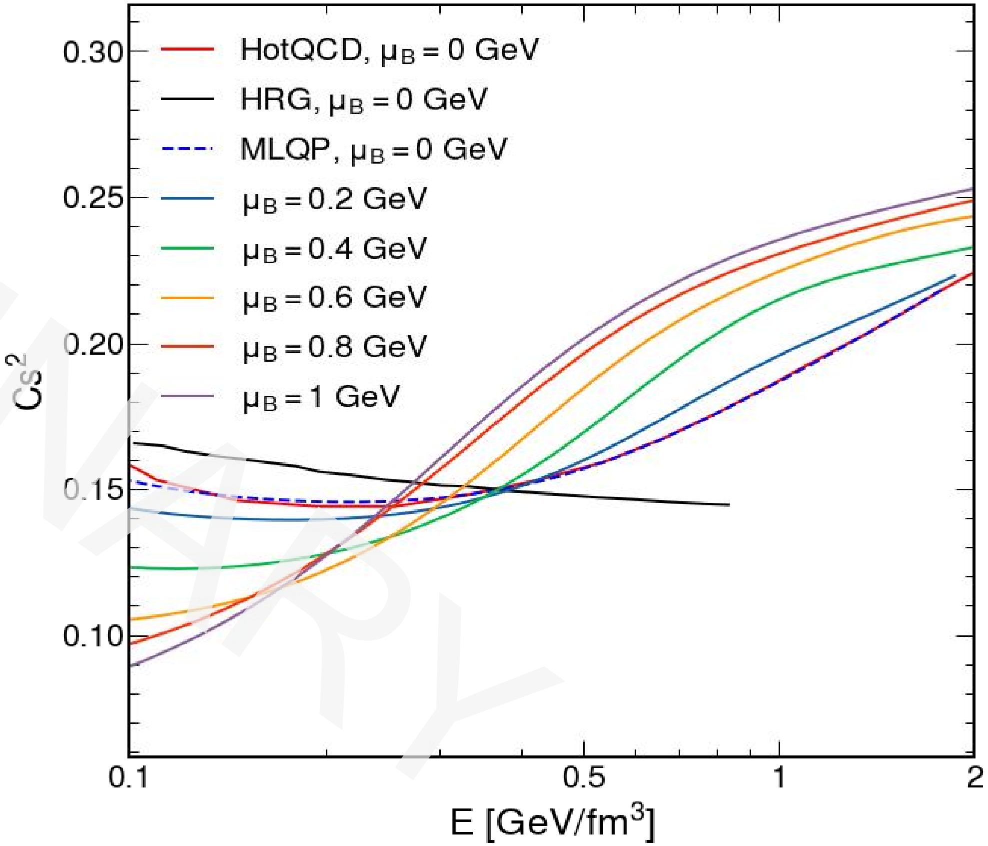
Training data: Lattice QCD + HRG
PRD 95, 054504 (2017)
PRL118, 182301 (2017)
PRD 90, 094503 (2014)

Predictions of DL quasi parton model

Entropy density



Speed of sound



Summary

- We explored 3 approaches to studying QCD EoS using deep learning
- For soft probes, DL serves as an EoS-meter
- For hard probes, DL assisted jet tomography aids in the investigation of QCD EoS through Mach cones
- DL and auto-diff are widely used to represent unknown functions to construct effective theories
- DL quasi parton model are extended to finite muB region