Neural Unfolding of the Chiral Magnetic Effect in Heavy-Ion Collisions

Chinese Physics Letters 42, 110101 (2025)

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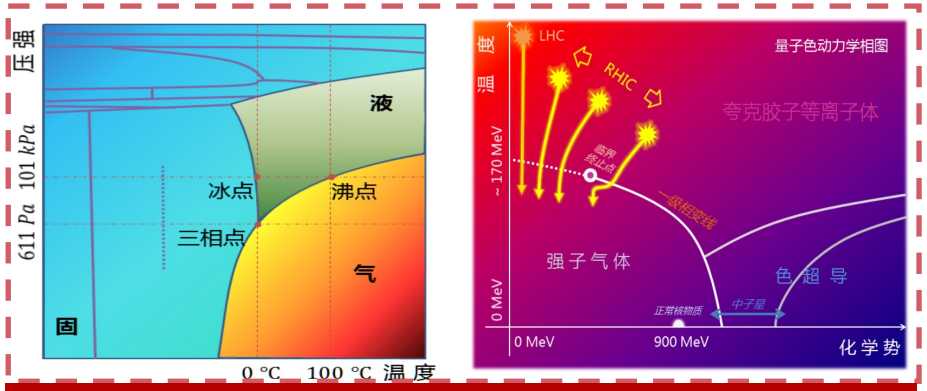
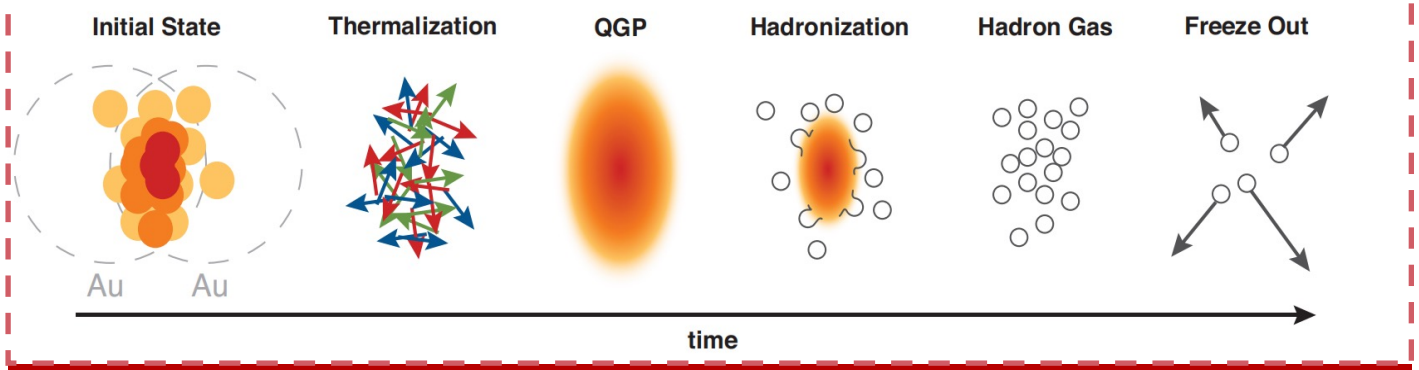
[4]School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen (CUHK-Shenzhen), Guangdong, 518172, China

■ BACKGROUND

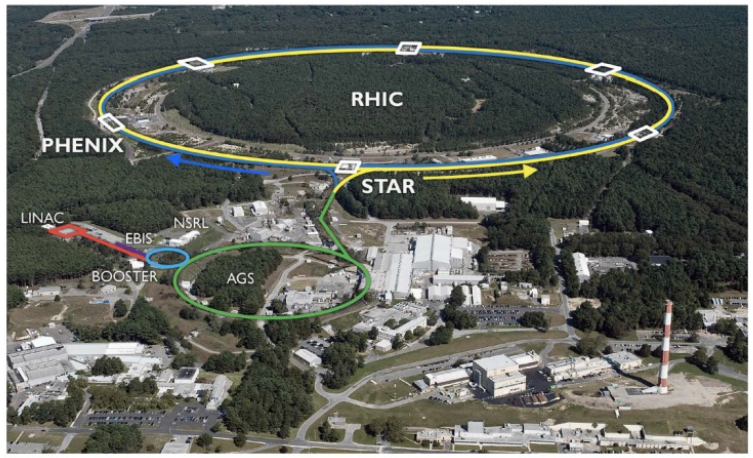


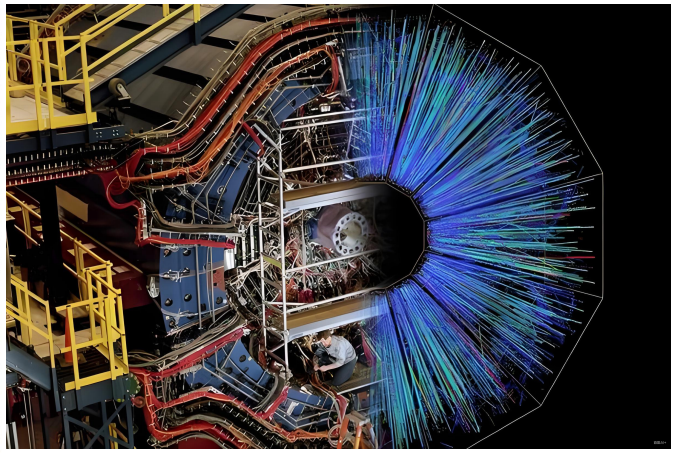
Water, Nuclear Matter Phase Diagram



Relativistic Heavy- ion Collision

Experimental Facility



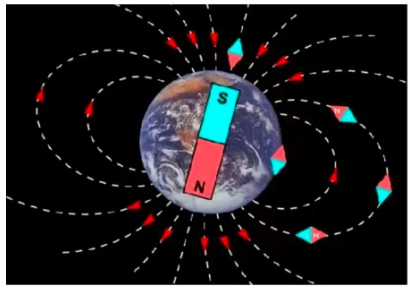


Final hadrons

↓

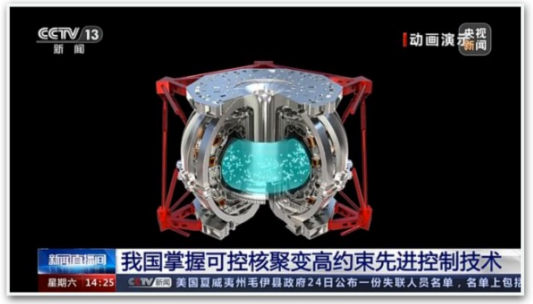
Initial QGP

■ MOTIVATION

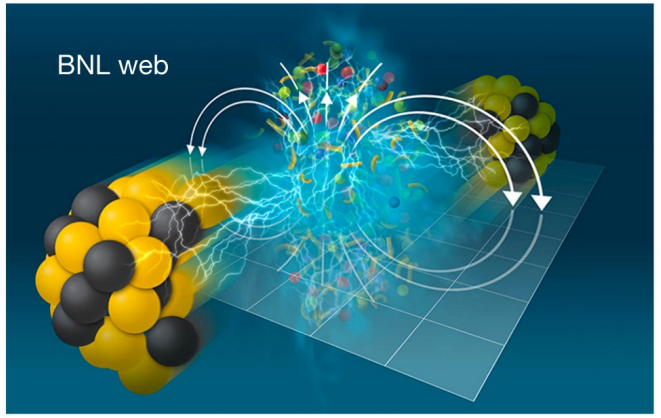


~ 0.5 G

~ 10 thousand G



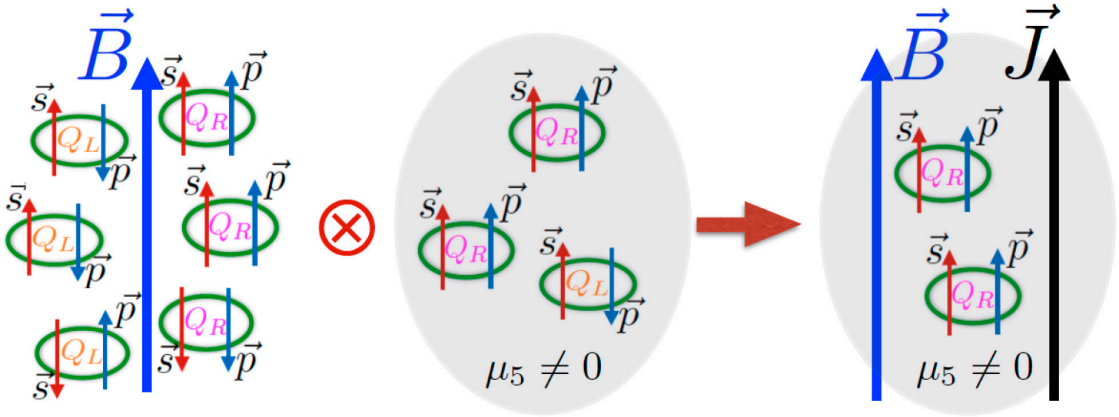
~ 100 thousand G



Strongest Magnetic Field: B ~ 10^{18} G

Xuguang Huang, Quark Gluon Matter in Strong Magnetic and Vortical Fields

Chiral Magnetic Effect (CME):



- The local CP symmetry violation in QCD leads to a chiral imbalance in QGP, generating a chiral chemical potential
- An excess of right or left handed quarks μ_5 leads to a current flow along the magnetic field.

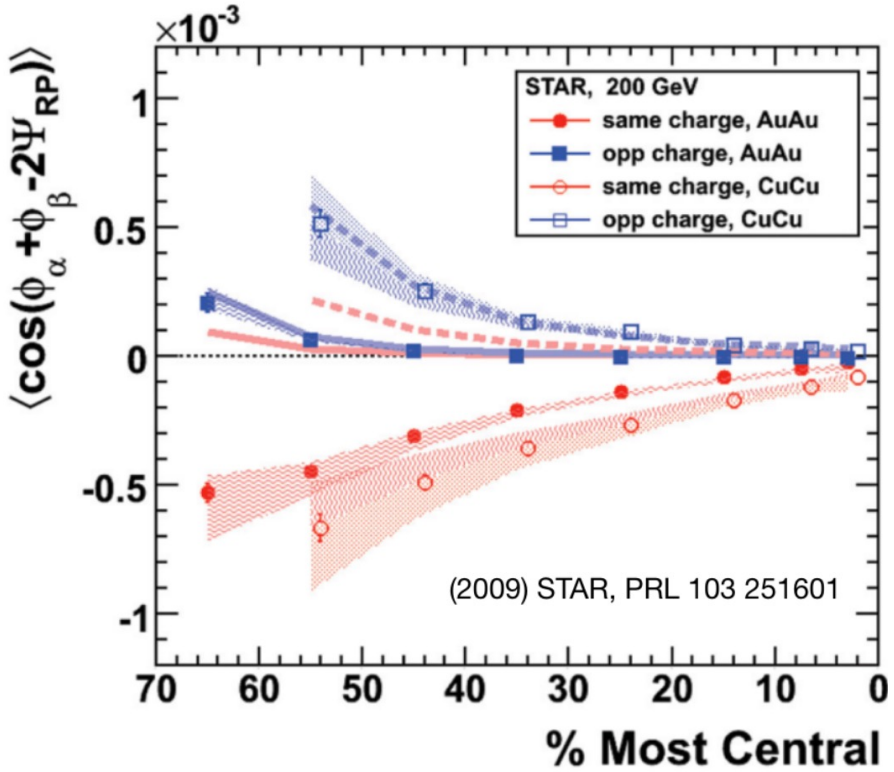
$$J = \frac{Qe}{2\pi^2}\mu_5 B$$

D.E. Kharzeev, J. Liao etal, PROG. PART. NUCL. PHYS. 88, 1(2016)

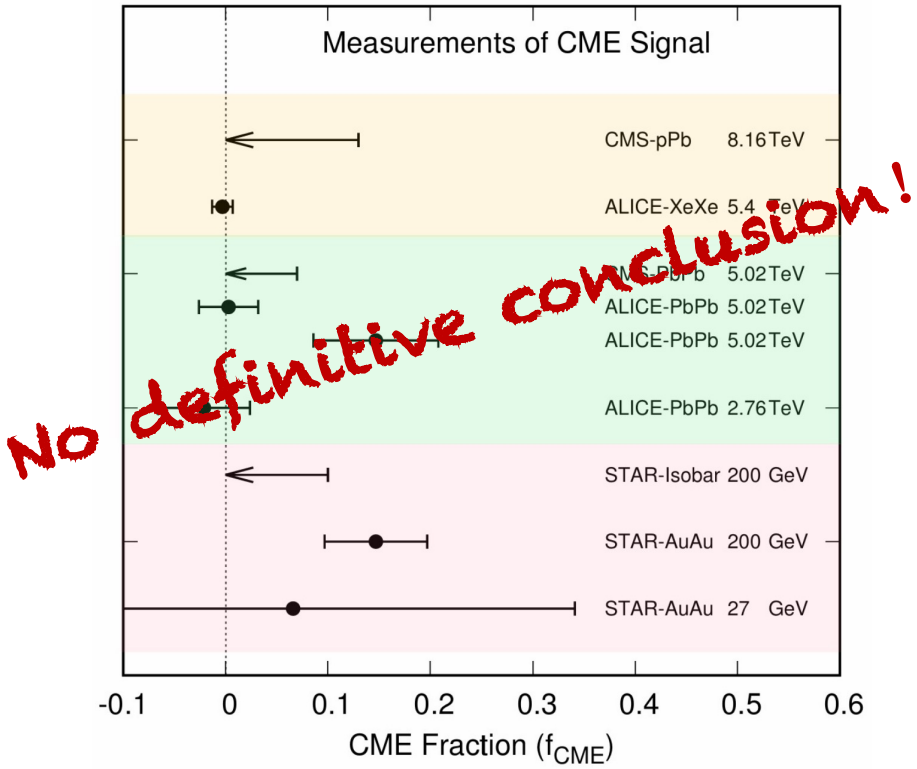
Local CP symmetry violation in QCD ---> **A** chiral imbalance in QGP ---> **A** charge separation along the magnetic field

Relativistic Heavy-ion Collision

Probing CP symmetry in strong interactions.

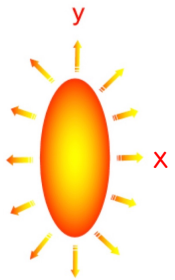


$$\Delta\gamma = < \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) >$$



Chiral magnetic effect in heavy ion collisions: The present and future
Int.J.Mod.Phys.E 33 (2024), 2430007

■ MOTIVATION

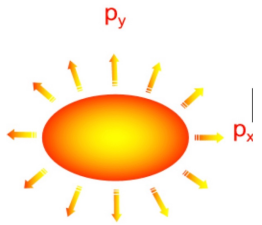


CME
in early stage

Parton interaction

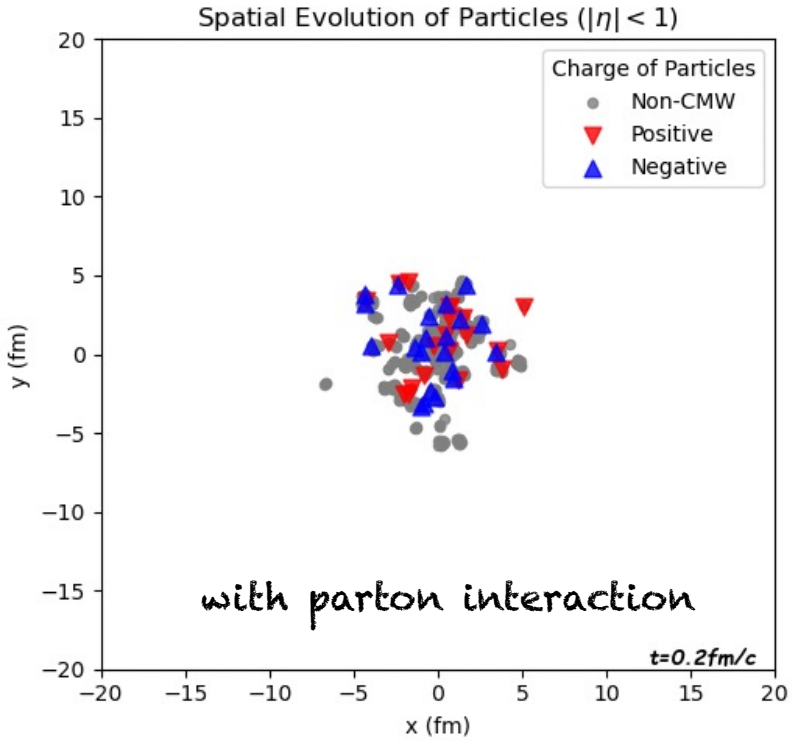
QGP evolution

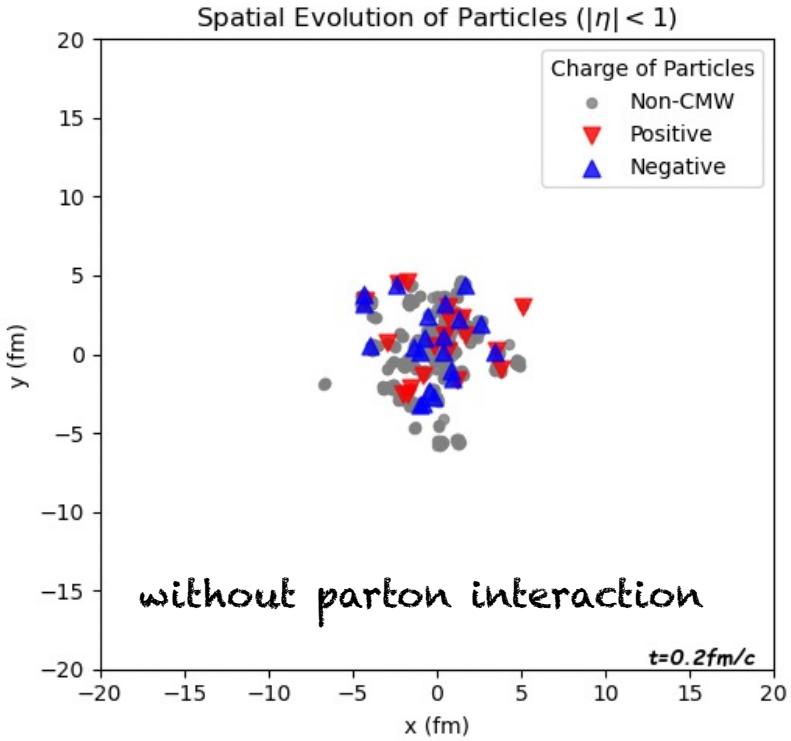
Large background
in final stage



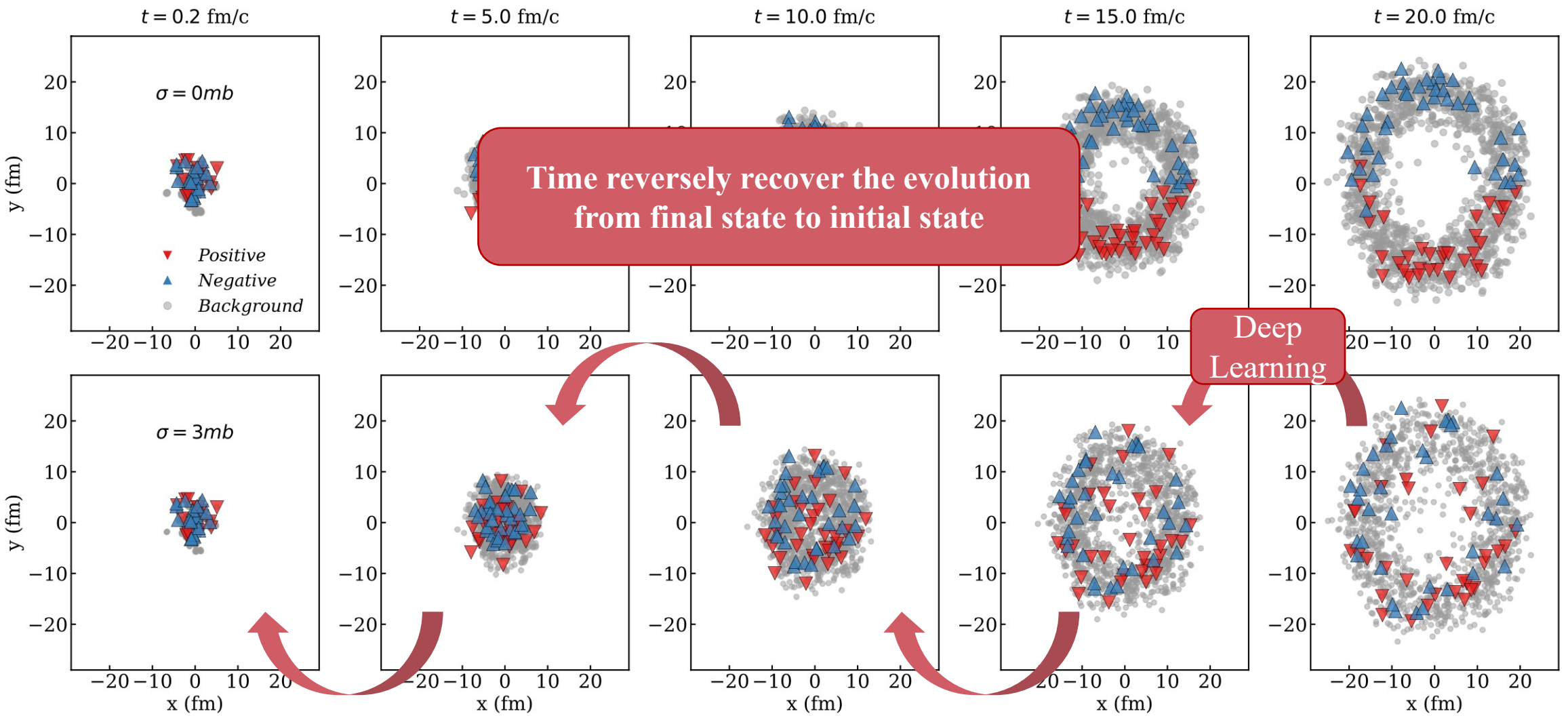
Charge separation of QGP in initial coordinate space

Experimental available of hadron in final momentum space

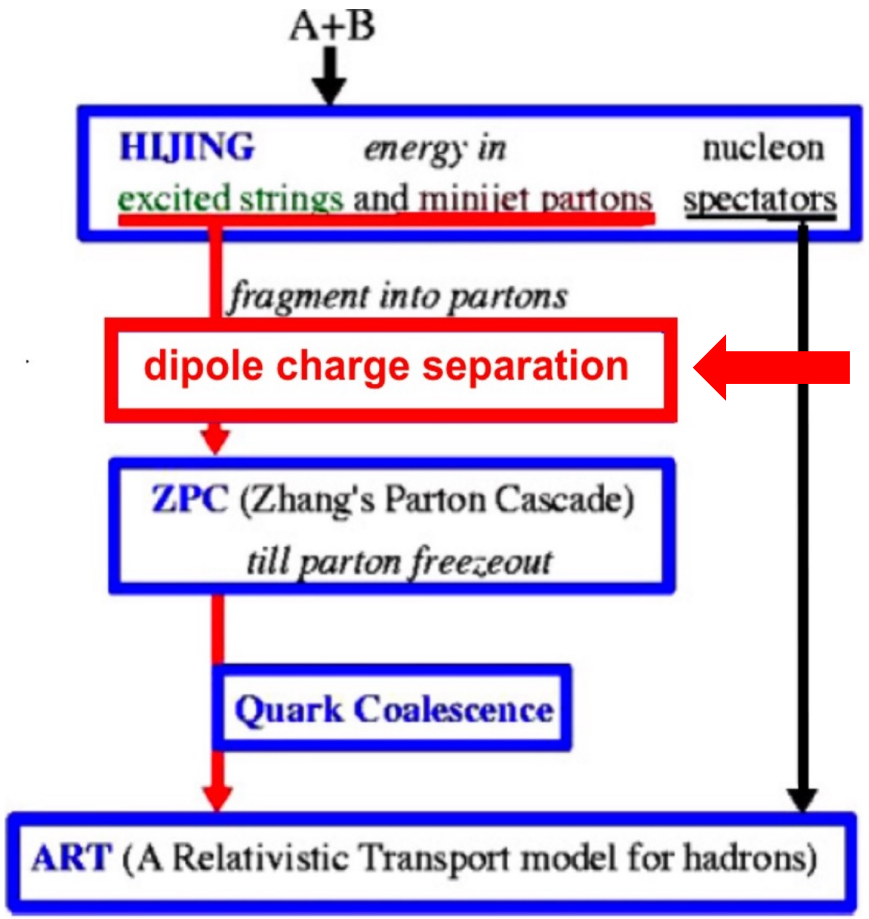




METHOD


t = 0.2 fm/c
t = 5.0 fm/c
t = 10.0 fm/c
t = 15.0 fm/c
t = 20.0 fm/c
σ = 0mb
σ = 3mb
Positive
Negative
Background
Time reversely recover the evolution
from final state to initial state
Deep
Learning
y (fm)
x (fm)

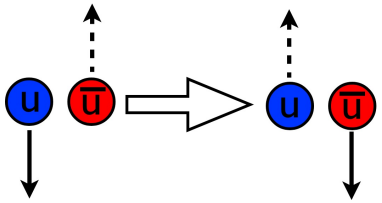
■ MODEL：AMPT

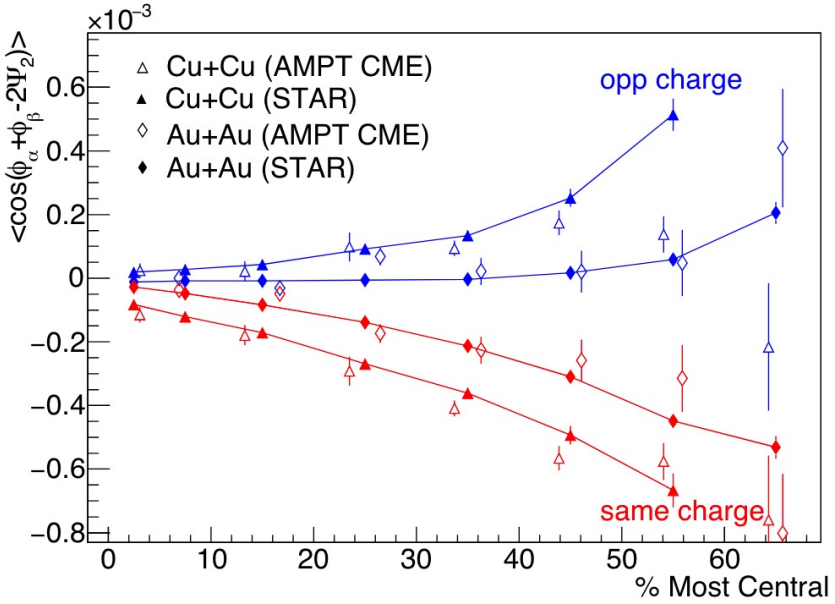


Guo-Liang Ma, Bin Zhang, Phys. Lett. B 700, 39 (2011)

- Include an initial dipole charge separation mechanism into AMPT model.

$$f = \frac{N^{\pm}_{\uparrow(\downarrow)} - N^{\pm}_{\downarrow(\uparrow)}}{N^{\pm}_{\uparrow(\downarrow)} + N^{\pm}_{\downarrow(\uparrow)}}$$



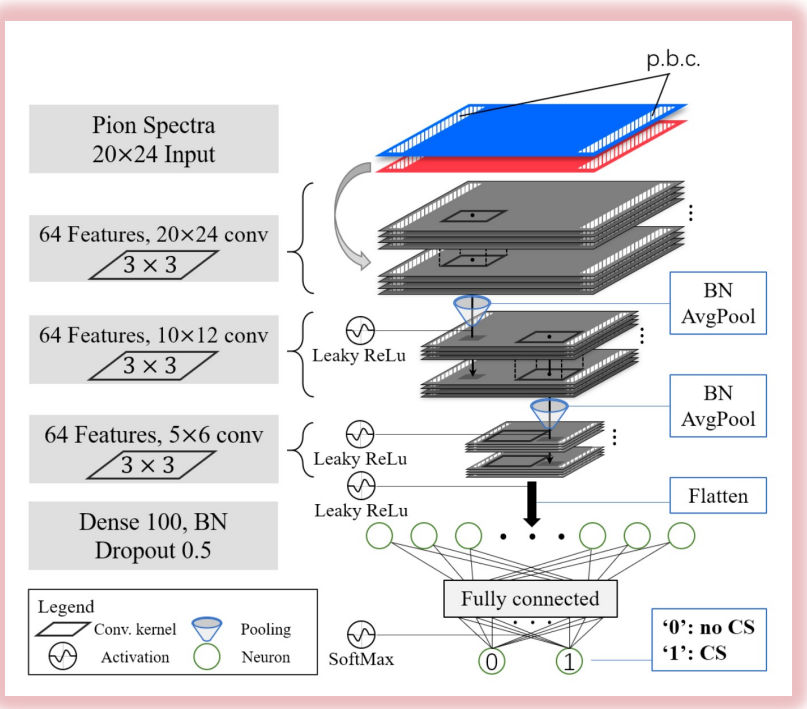


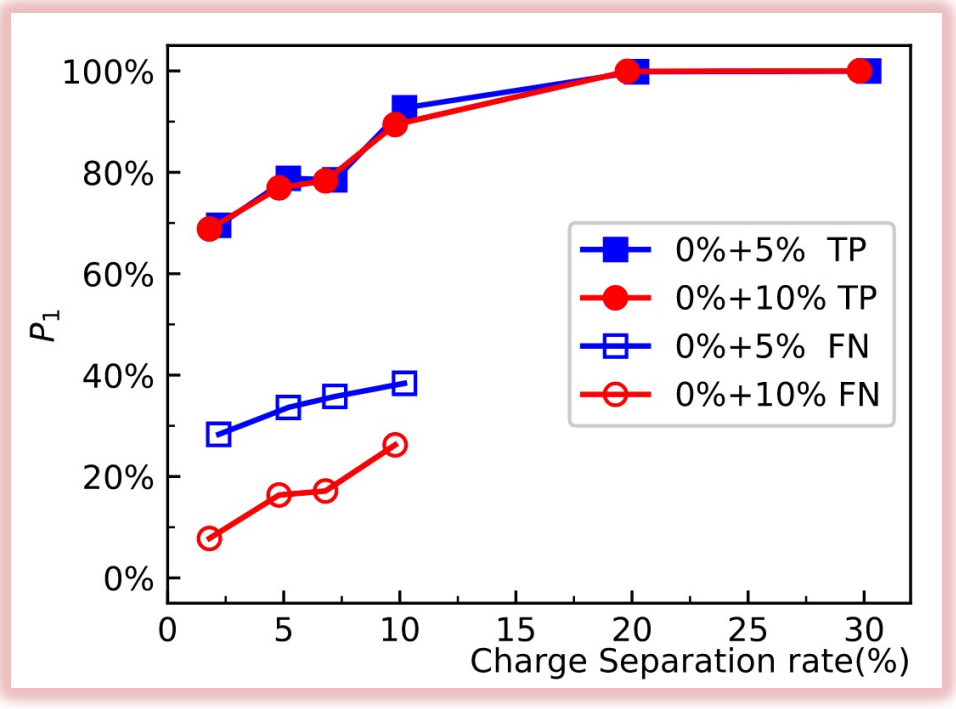
Phys. Rev. C 97, 044901 (2018)

- AMPT can fit experiment data well by setting certain f.

■ MODEL： AMPT

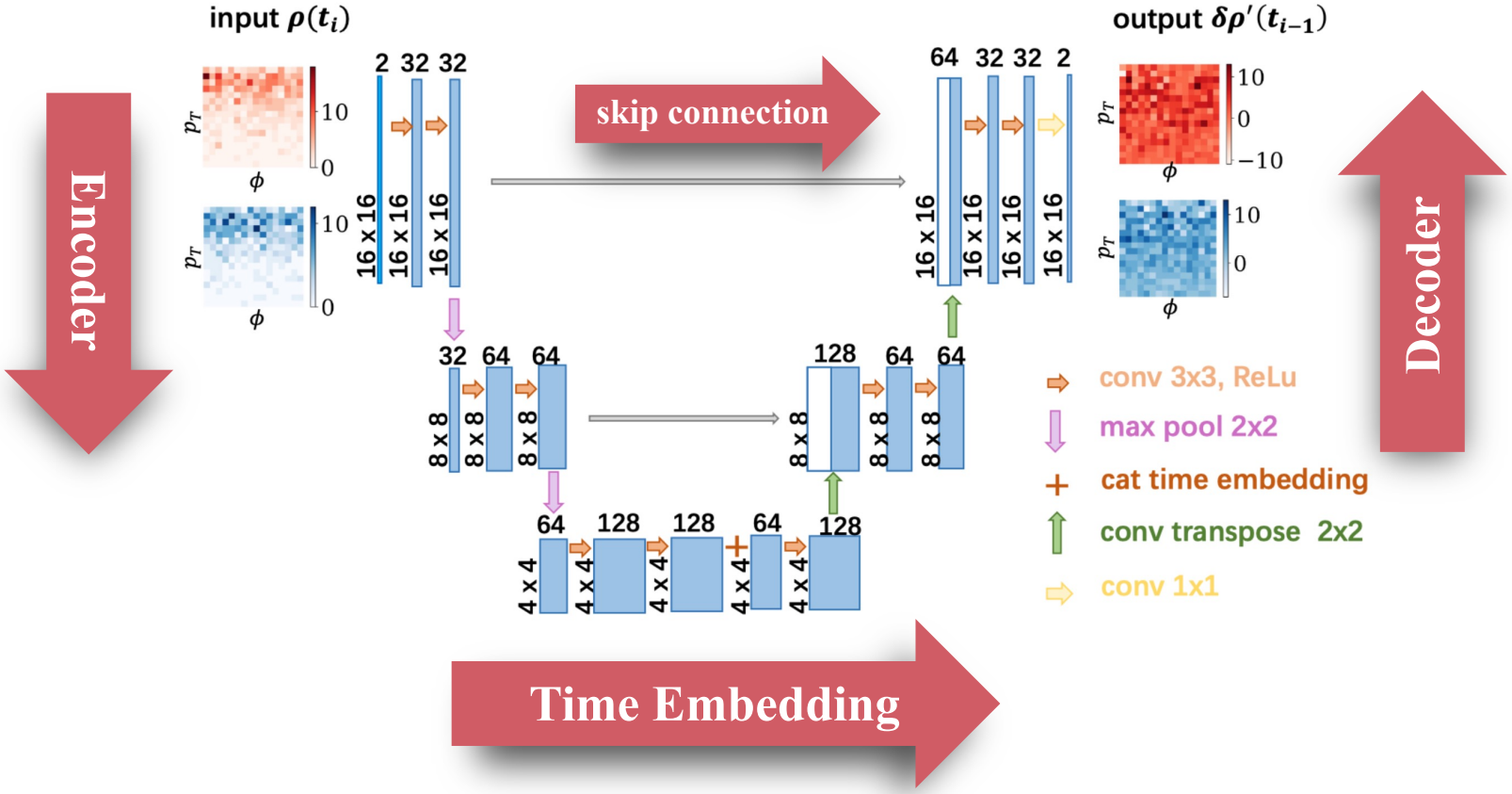
Yuan-Sheng Zhao, Lingxiao Wang, Kai Zhou, and Xu-Guang Huang.
PHYSICAL REVIEW C 106, L051901 (2022)





- CME signal undergoes substantial changes during the dynamical evolution of HICs
- Flow-related backgrounds progressively dominate as the HIC system evolves.

■ METHOD：U-Net



Input：

$\rho(t_i)$

Output:

$\delta\rho'(t_{i-1})$

Target：

$$\delta\rho(t_{i-1}) = \rho(t_{i-1}) - \rho(t_i)$$

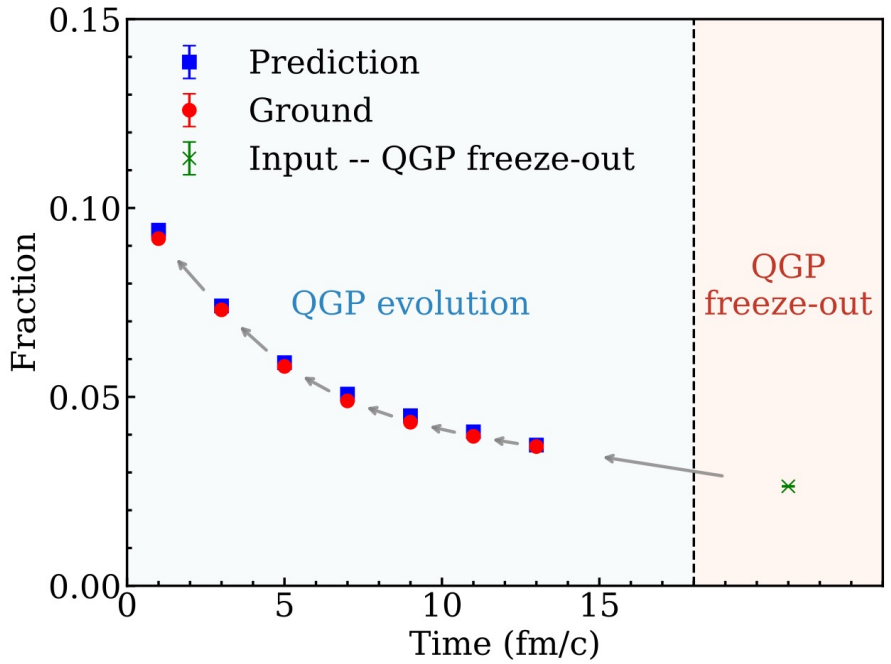
Next input：

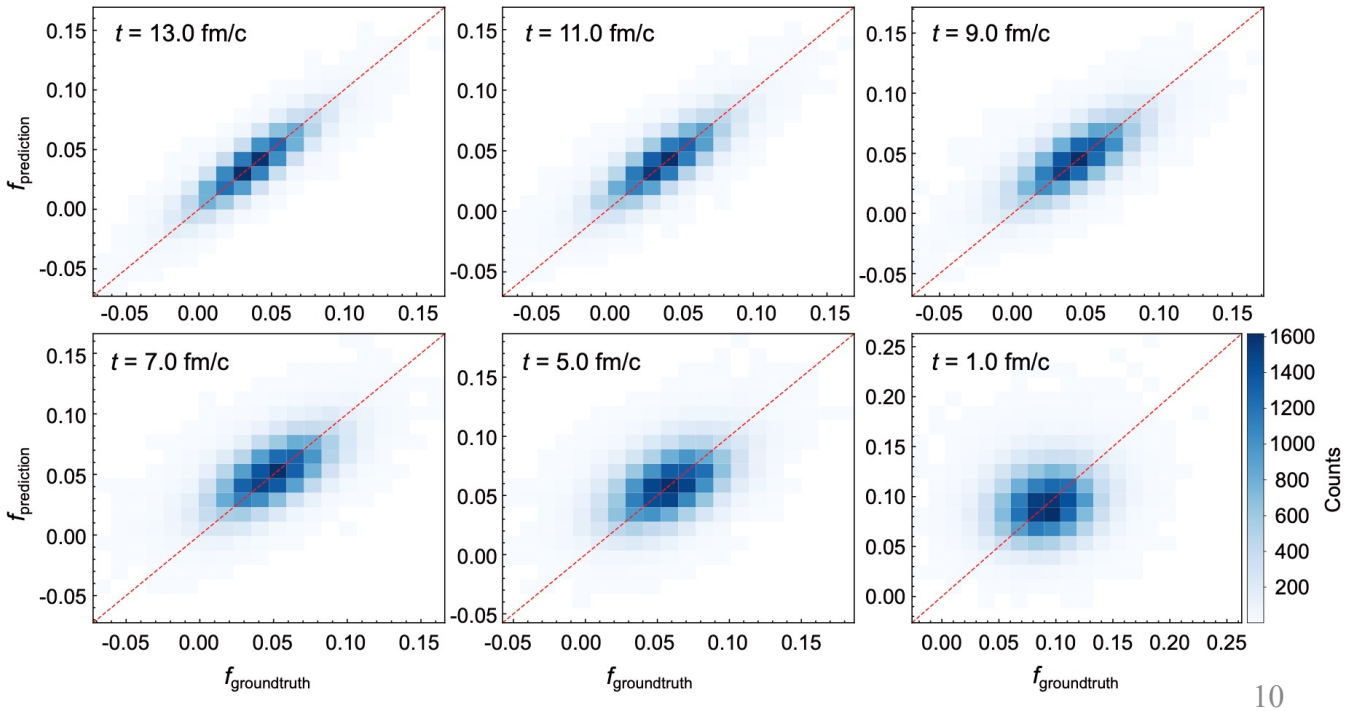
$$\rho'(t_{i-1}) = \delta\rho'(t_{i-1}) + \rho(t_i)$$

- Encoder captures hierarchical spatial features of the input distribution;
- Decoder preserves fine-grained spatial details throughout the reconstruction process;
- Time embeddings provide essential temporal context.

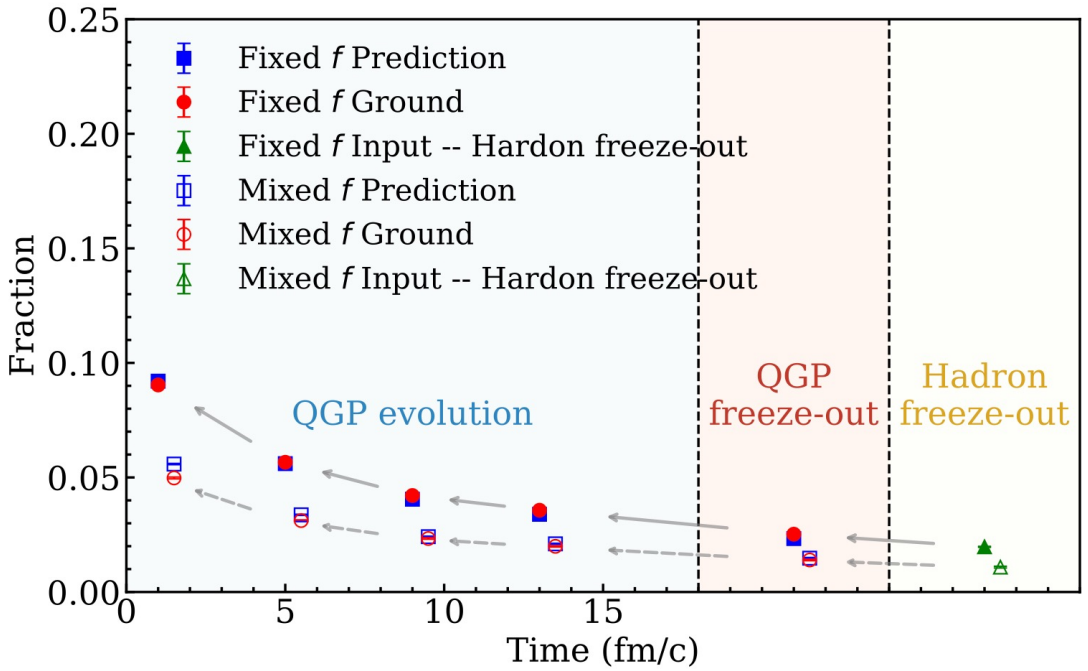
Case	Initial CME Condition	Input to U-Net
Case 1	Fixed $f = 10\%$	p_T distribution of partons at QGP freeze-out
Case 2	Fixed $f = 10\%$	p_T distribution of hadrons at hadron freeze-out
Case 3	Mixed $f = 1\%, 2\%, 3\%, ..., 10\%$	p_T distribution of hadrons at hadron freeze-out

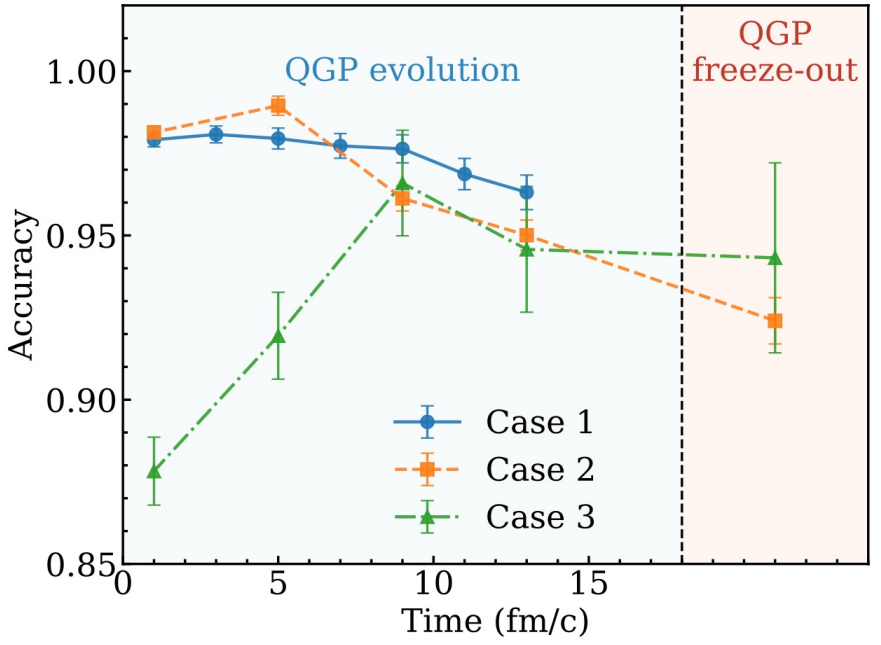
CASE 1





CASE 2 & 3
Input the final hadrons‘ transverse momentum





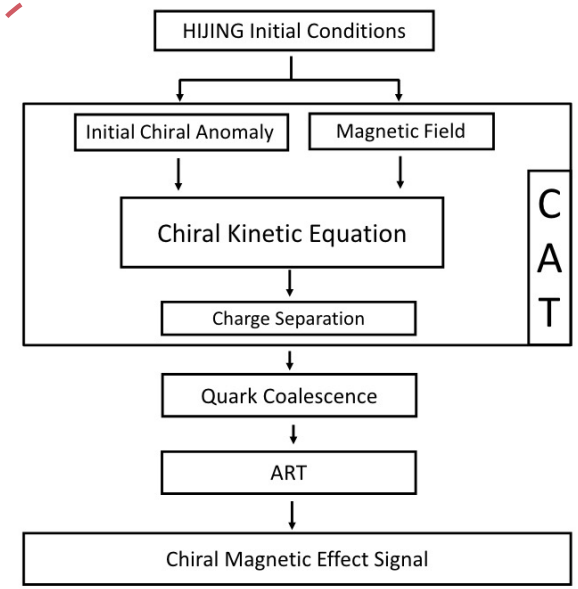
$$Accuracy = 1 - \frac{|f_{\text{prediction}} - f_{\text{ground truth}}|}{f_{\text{ground truth}}}$$

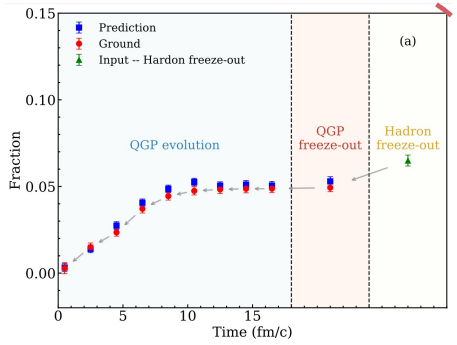
- Successfully captures both the trend and magnitude of charge separation throughout the HICs evolution
- Remains robust with a wide range of initial charge separation strengths

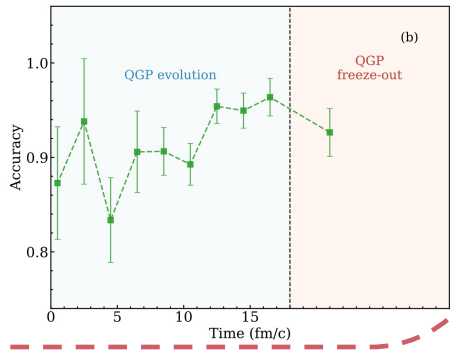
■ SUMMARY and OUTLOOK

- ✓ Successfully captures both the trend and magnitude of charge separation throughout the HICs evolution;
- ✓ Remains robust with a wide range of initial charge separation strengths;
- ✓ Opens a novel perspective for investigating the fundamental properties of the QGP and other related physics in HICs.

1. From simulation model

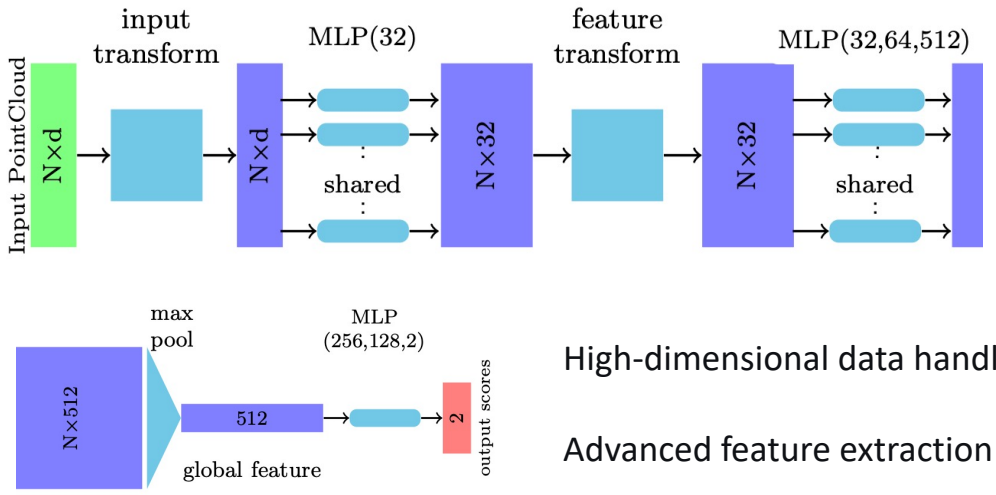






Yuan Z, Huang A, Xie G, Zhou W H, Ma G L, and Huang M 2025 Phys. Rev. C 111 044913

2. From deep learning



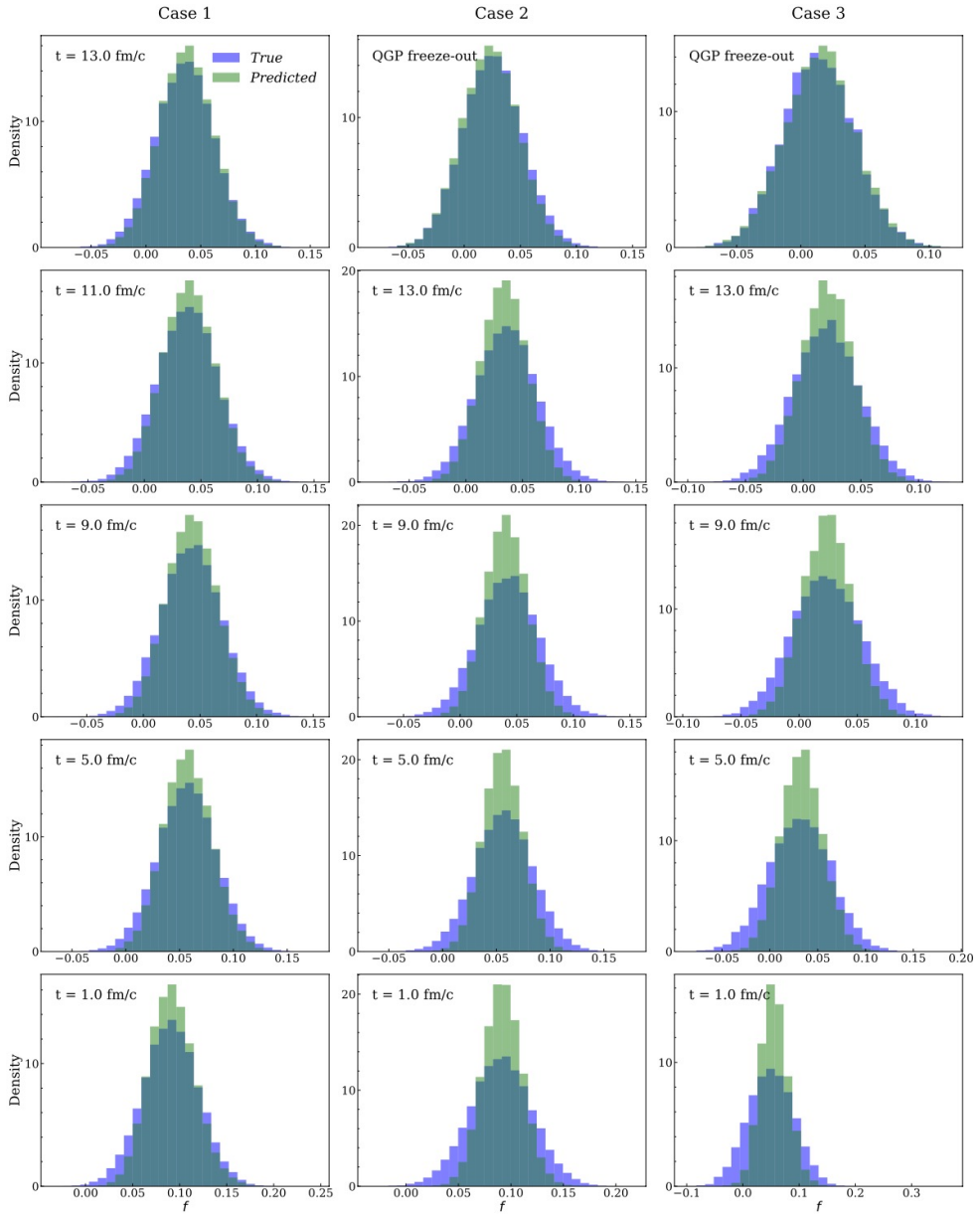
High-dimensional data handling

Advanced feature extraction

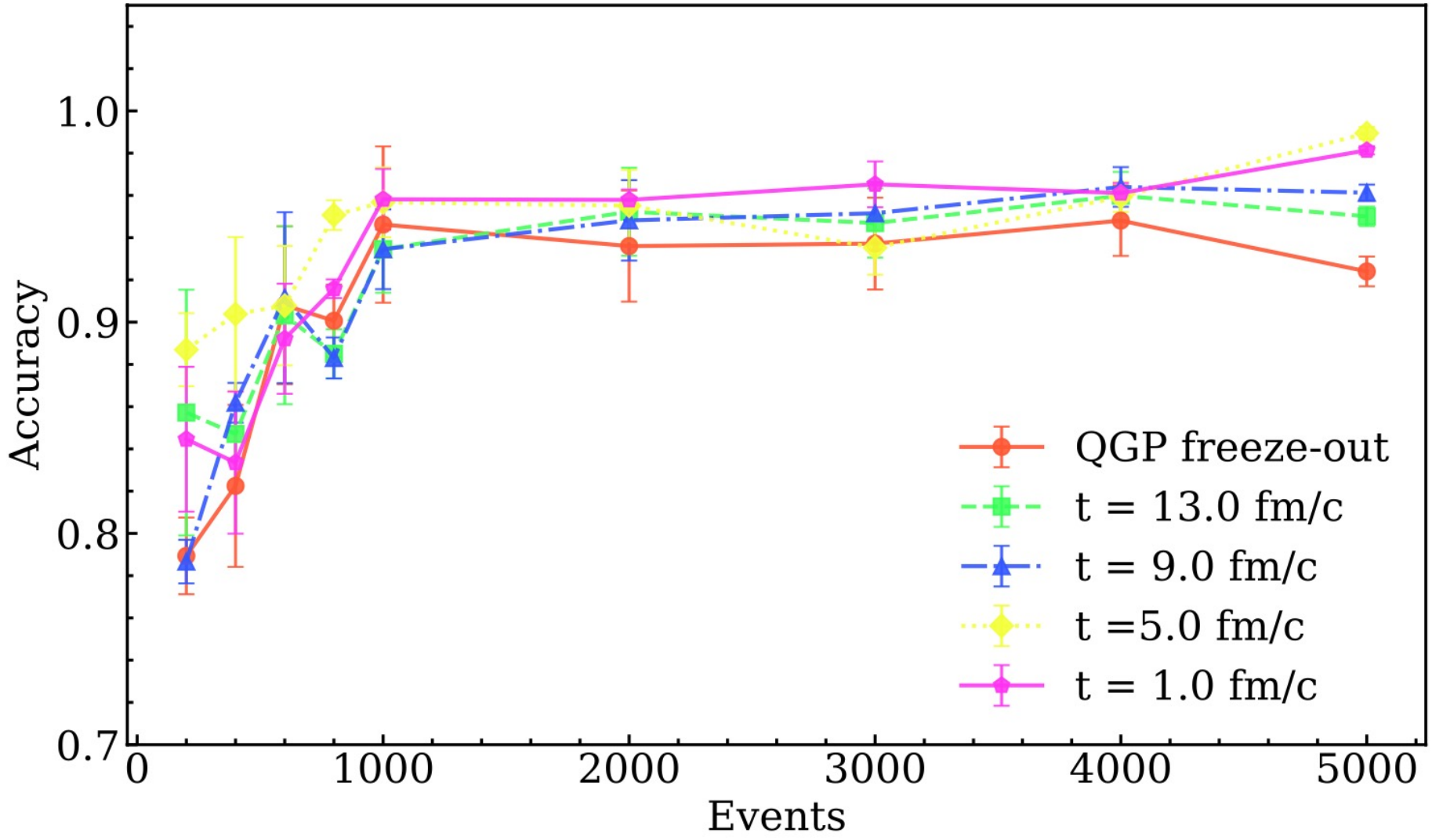
GuoS, Wang H S, Zhou K, and Ma G L 2024 Phys.Rev. C 110 024910

BACK UP

One-dimensional histograms of charge separation (CS) fractions comparing model predictions (green) and ground truth (blue) across three cases.



BACK UP


1.0
0.9
0.8
0.7
Accuracy
0
1000
2000
3000
4000
5000
Events
QGP freeze-out
t = 13.0 fm/c
t = 9.0 fm/c
t =5.0 fm/c
t = 1.0 fm/c