# Nucleon-size Independence of Hadronic Nucleus-Nucleus Cross Sections

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极端核物质前沿研讨会

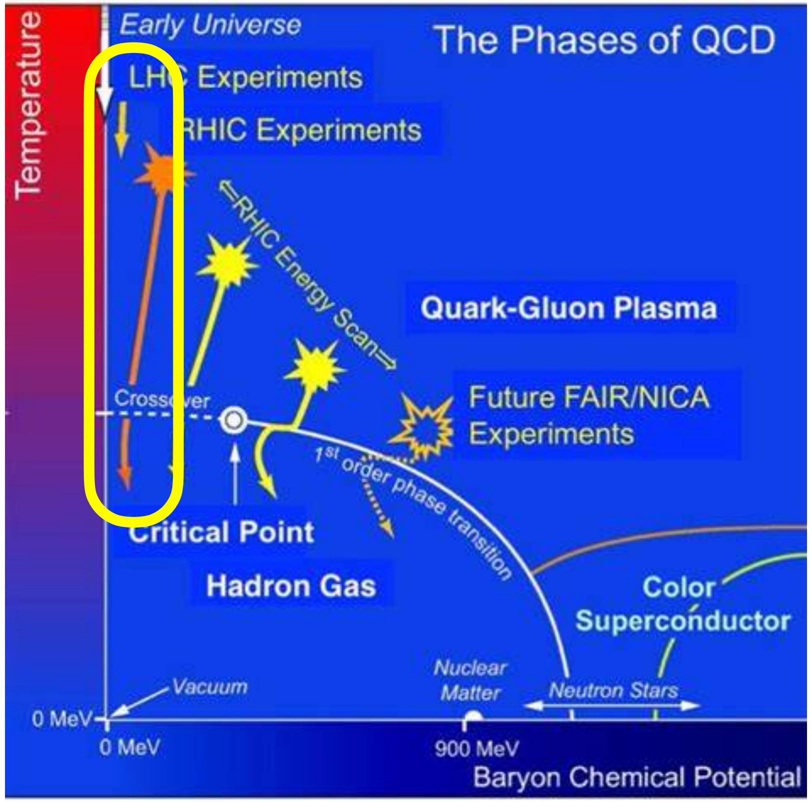
湖北.宜昌，2026年4月24-28日

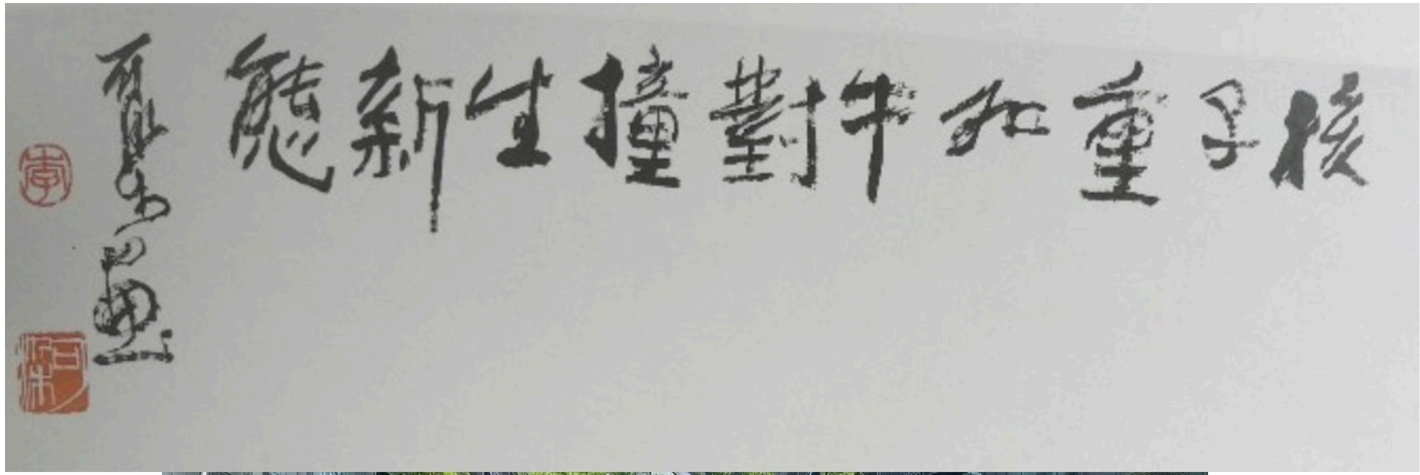
# QCD相图

极端条件：

高温：相对论重离子碰撞，宇宙早期

高密：致密星的内部



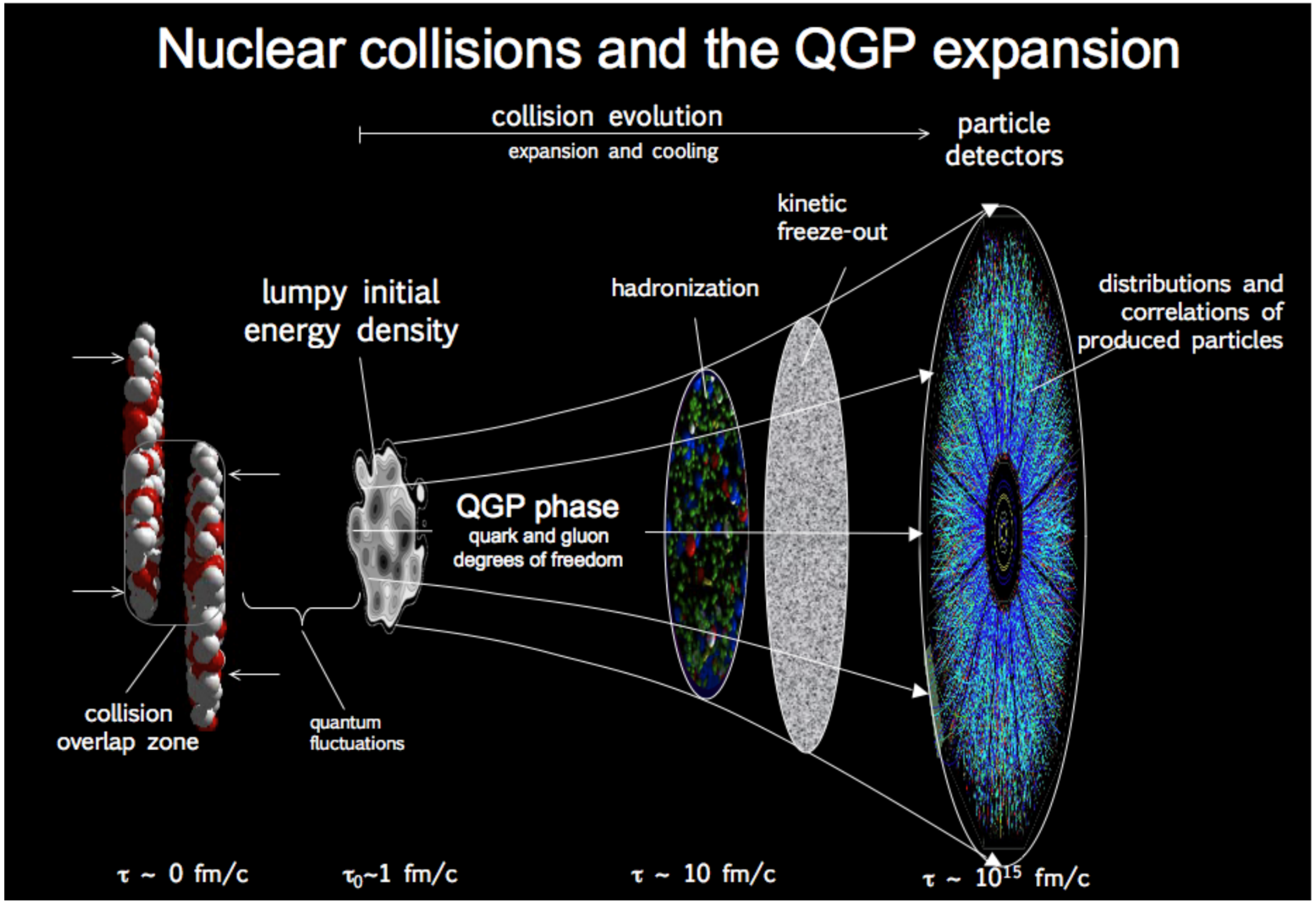



徐浩洁（湖州师范大学）

# 相对论重离子碰撞

RHIC
- $^{197}$Au+$^{197}$Au@$\sqrt{s_{\rm NN}}$ = 200 GeV, BES
- $^{238}$U+$^{238}$U@ $\sqrt{s_{\rm NN}}$ = 193 GeV
- Isobars collisions:
  $^{96}$Ru+$^{96}$Ru & $^{96}$Zr+$^{96}$Zr @ $\sqrt{s_{\rm NN}}$ = 200 GeV
- $^{16}$O+$^{16}$O@ $\sqrt{s_{\rm NN}}$ = 200 GeV
- ……

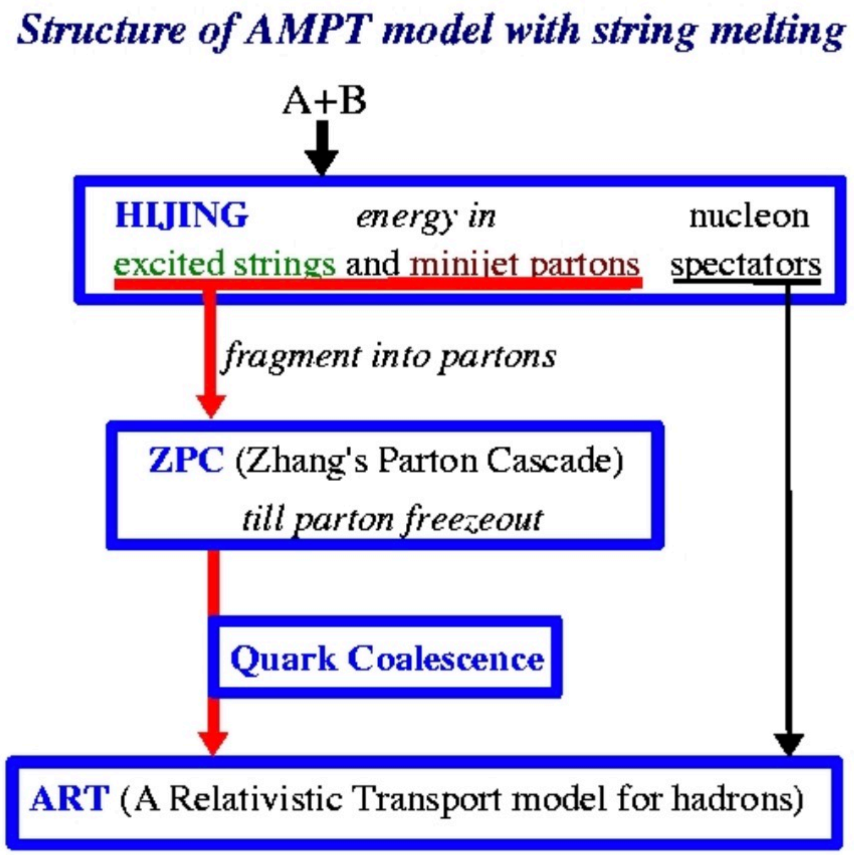
LHC
- $^{208}$Pb+$^{208}$Pb@$\sqrt{s_{\rm NN}}$ = 2.76 TeV & 5.02 TeV
- $^{129}$Xe+$^{129}$Xe@ $\sqrt{s_{\rm NN}}$ = 5.44 TeV
- $^{16}$O+$^{16}$O & $^{20}$Ne+$^{20}$Ne@ $\sqrt{s_{\rm NN}}$ = 5.36 TeV
- ……



# 相对论流体力学

微观：输运模型

Z. Lin, PRC72, 064901(2014)




宏观：流体力学模型 $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = \epsilon U^\mu U^\nu - (\mathcal{P} + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

理想流体力学模型

P. Kolb, J. Sollfrank, U. Heinz, PRC77, 064901(2008)

耗散流体力学模型

$$\pi^{\mu\nu} = \eta^{\langle}\nabla^\mu U^{\nu\rangle} - \tau_\pi \left[ {}^{\langle}D\pi^{\mu\nu\rangle} + \frac{4}{3}\pi^{\mu\nu}\nabla\cdot U \right] - \frac{\lambda_1}{\eta^2}\pi^{\langle\mu}{}_\alpha\pi^{\nu\rangle\alpha} - \frac{\lambda_2}{\eta}\pi^{\langle\mu}{}_\alpha\Omega^{\nu\rangle\alpha} - \lambda_3\Omega^{\langle\mu}{}_\alpha\Omega^{\nu\rangle\alpha},$$

iEBE-VISHNU: (2+1)维耗散流体力学模型

H. Song, U. Heinz, PRC77, 064901(2008)

MUSIC: (3+1)维耗散流体力学模型

B. Schenke, S. Jeon, C.Gale, PRC82, 024911(2012)

CLVis: (3+1)维耗散流体力学模型

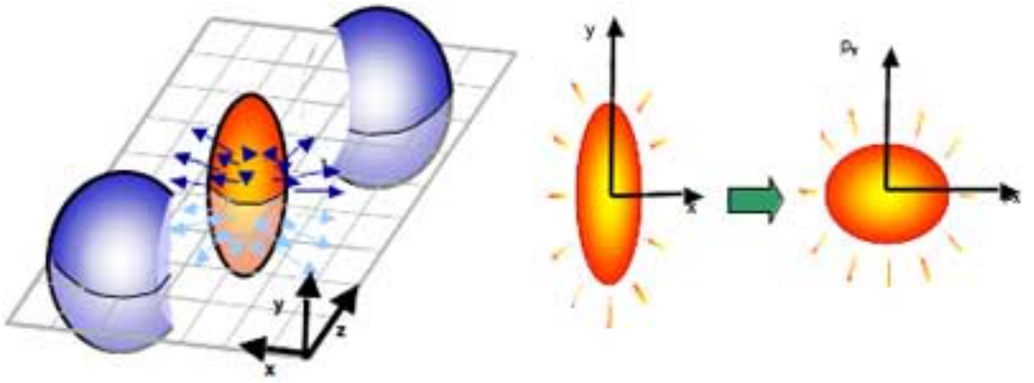
L. Pang, Q. Wang, X. Wang, PRC82, 024911(2012)

# 流体力学响应

碰撞几何的各向异性 $\varepsilon_n = \frac{\int r^n e^{in\phi} \rho(r,\phi)\, d^2r}{\int r^n \rho(r,\phi)\, d^2r}$

流体力学演化　压强梯度的各向异性

动量空间的各向异性 $\frac{dN}{d\phi} \propto 1 + \sum_n v_n \cos n(\phi - \Phi_n)$



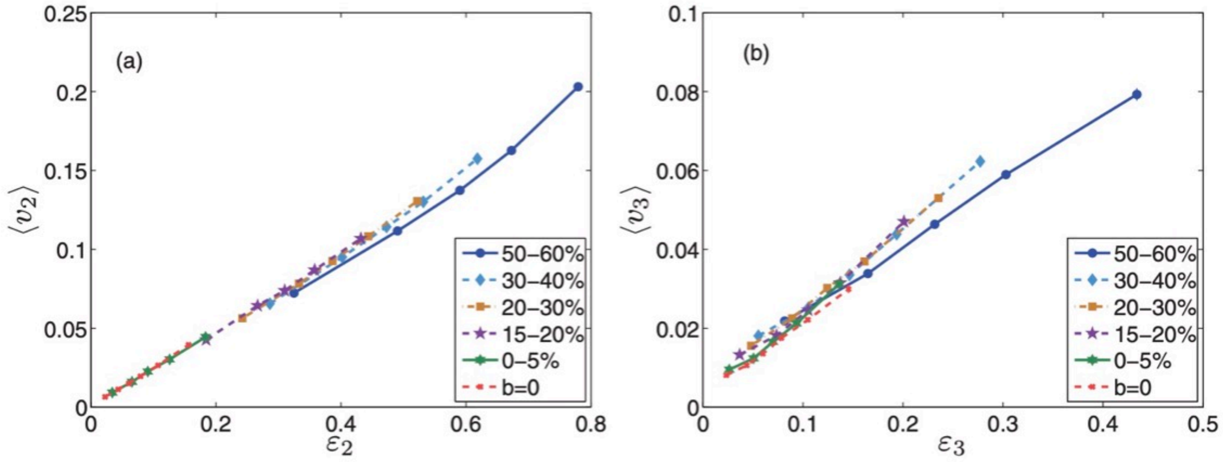
初态几何结构 ⟺ 末态观测量

$$v_n = \kappa \epsilon_n$$

对于$n = 2,3$, 有很好的线性行为，

特别是在极端中心碰撞区域（b=0 或 0-5% 中心度）

Z. Qiu and U. Heinz, PRC84, 024911(2011)



# 普适规律

李可：观测从冷原子到高温QPG的普适各向异性膨胀

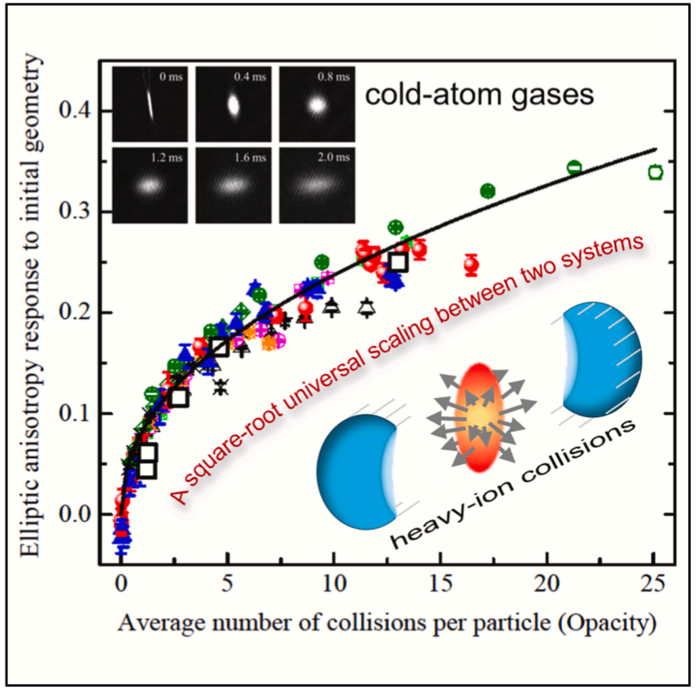
湖州师范大学冷原子物理团队

H. Song, Y. Shen, K. Li, CPB 32, 094205 (2023)

**Newton** K. Li, H. Song, **HJX,** Y. Sun, F. Wang, *Newton*, 1, 100237, 062502 (2025) **Article**

## Observation of universal expansion anisotropy from cold atoms to hot quark-gluon plasma

### Graphical abstract





### Authors

Ke Li, Hong-Fang Song, Hao-Jie Xu, Yu-Liang Sun, Fuqiang Wang

### Correspondence

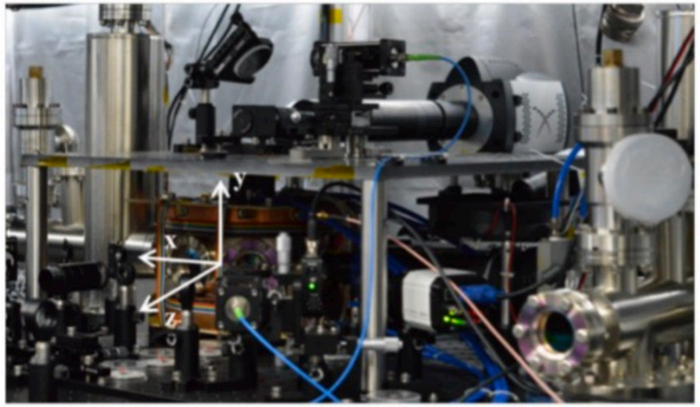
like99@zjhu.edu.cn (K.L.), fqwang@purdue.edu (F.W.)



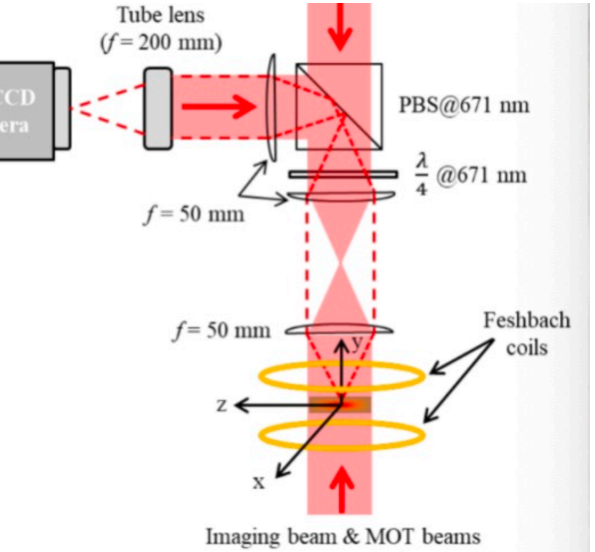
### In brief

As cold-atom experiments are conducted and compared to high-energy nuclear collisions, Li et al. observe a universal scaling in opacity (average number of collisions per particle) of the expansion anisotropy between the two systems, despite their vast differences in scale and physics. The scaling is of an approximate square-root dependence, characteristic of random walks. This finding may alter the hydrodynamic paradigm of expansion dynamics and potentially unifies a variety of physical systems, from dilute gases to dense quark-gluon plasma of the early universe.


### Highlights



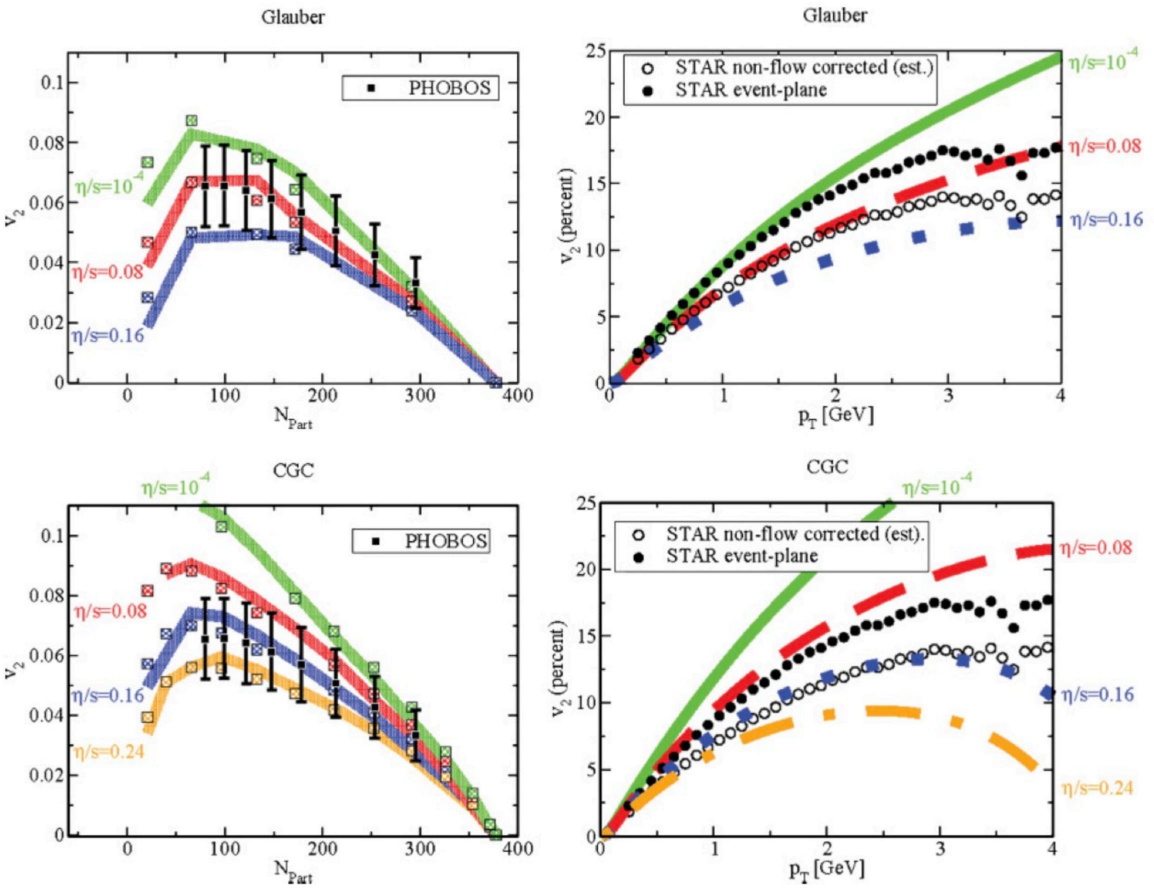

(a)

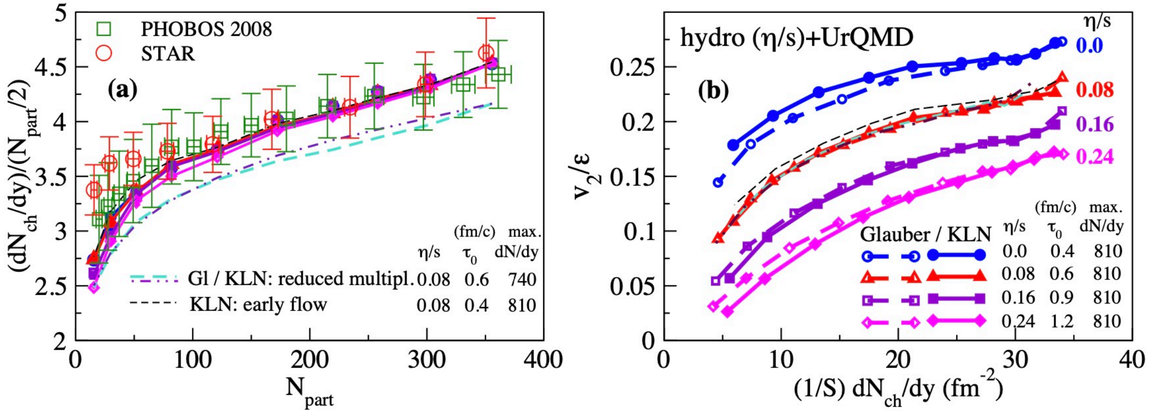


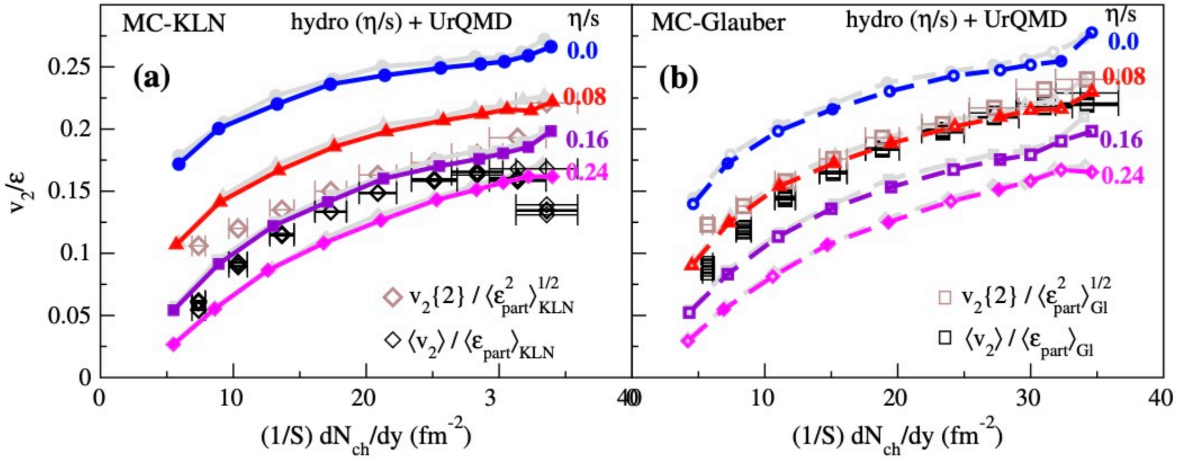

(b)

# 耗散流体力学

$v_2(p_T)$ 更符合实验，$\eta/s$ 接近强耦合极限$1/4\pi$



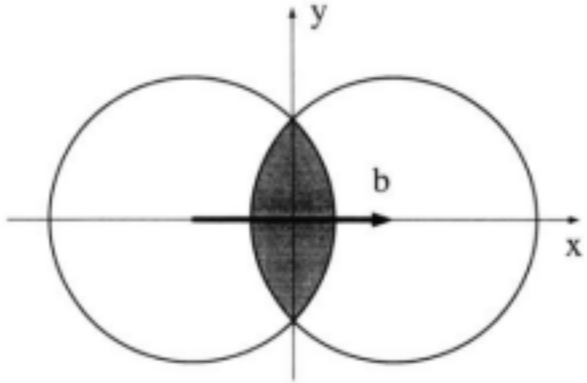



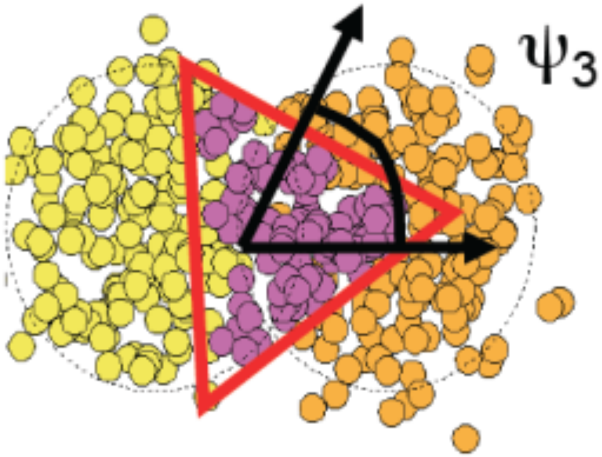

M. Luzum, P. Romatschke, PRC78, 034915 (2007)

H. Song, et.al, PRL106, 192301 (2010)

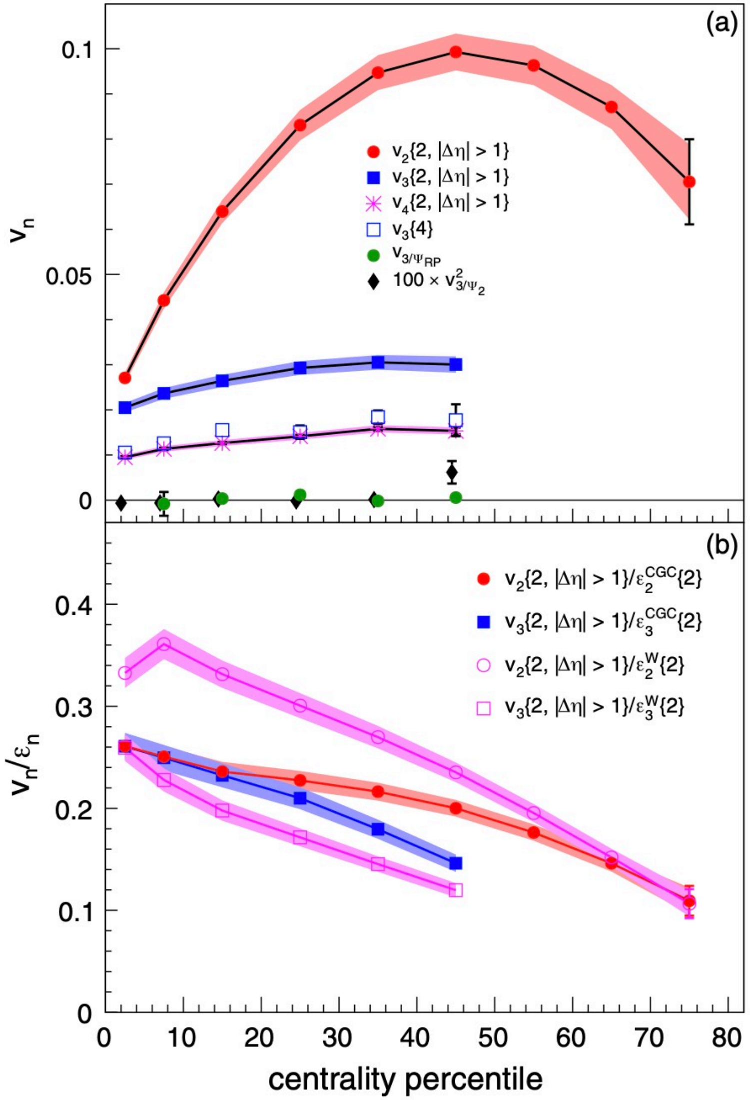
# 初态几何

逐事件初态涨落



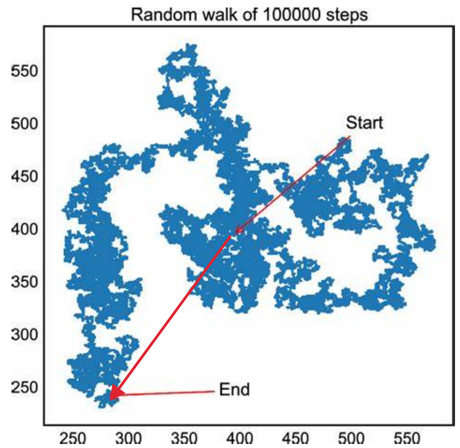

ALICE, PRL107, 032301 (2011)




$$\frac{dN}{d\phi} \propto 1 + \sum_n v_n \cos n(\phi - \Phi_n)$$

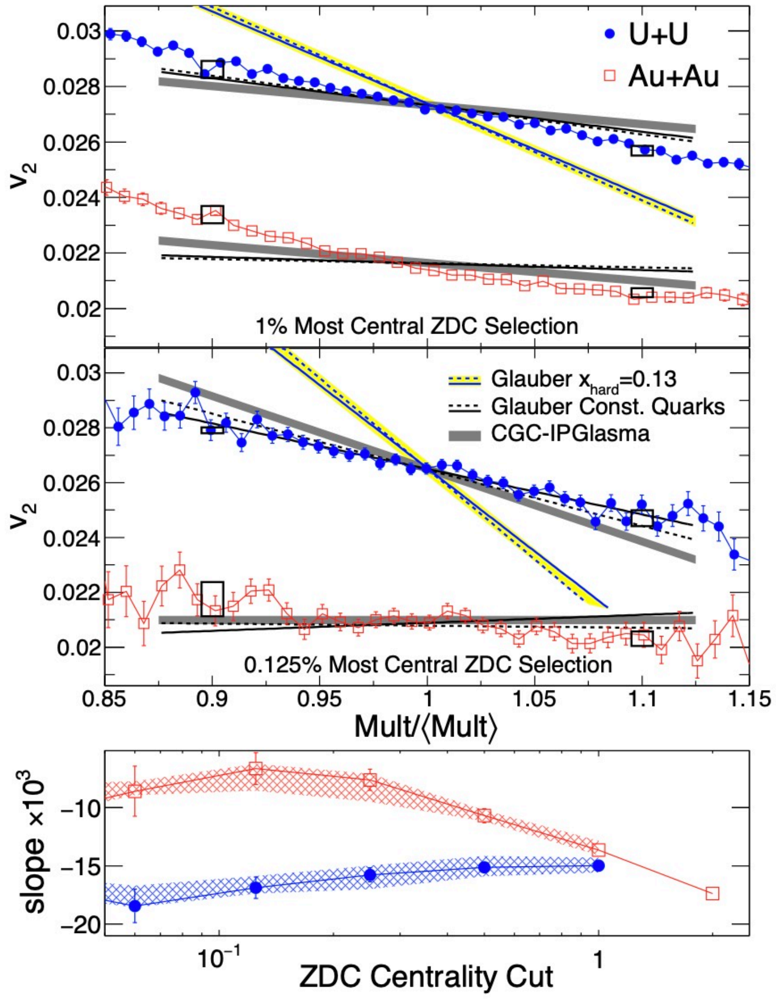
$$v_n\{2\}^2 = \langle \frac{Q_n^2 - M}{M(M-1)} \rangle$$

$$Q_n = \sum_{i=1}^{M} e^{in\varphi_i}$$



# Trento模型

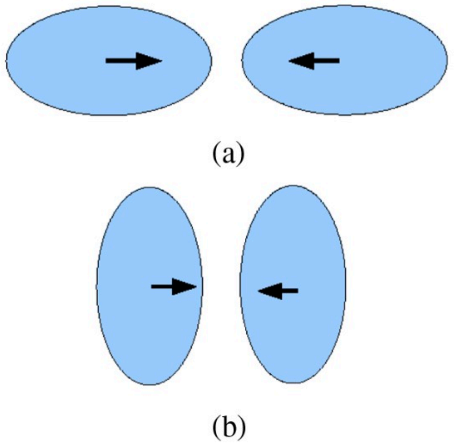
STAR, PRL115, 222301 (2015)




Glauber model:

$$N_{ch} \propto xN_{coll} + (1-x)N_{part}/2$$

$$f \sim (T_A + T_B) + \alpha T_A T_B$$

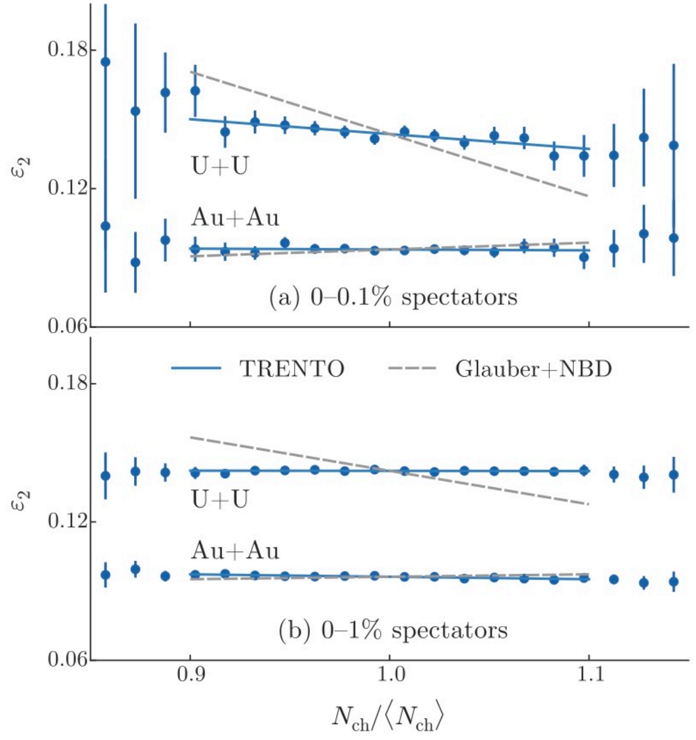



S. Voloshin, PRL95, 122301 (2010)

Trento model:

$$f \sim \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$

J. Moreland, et.al, PRC92, 011901(2015)



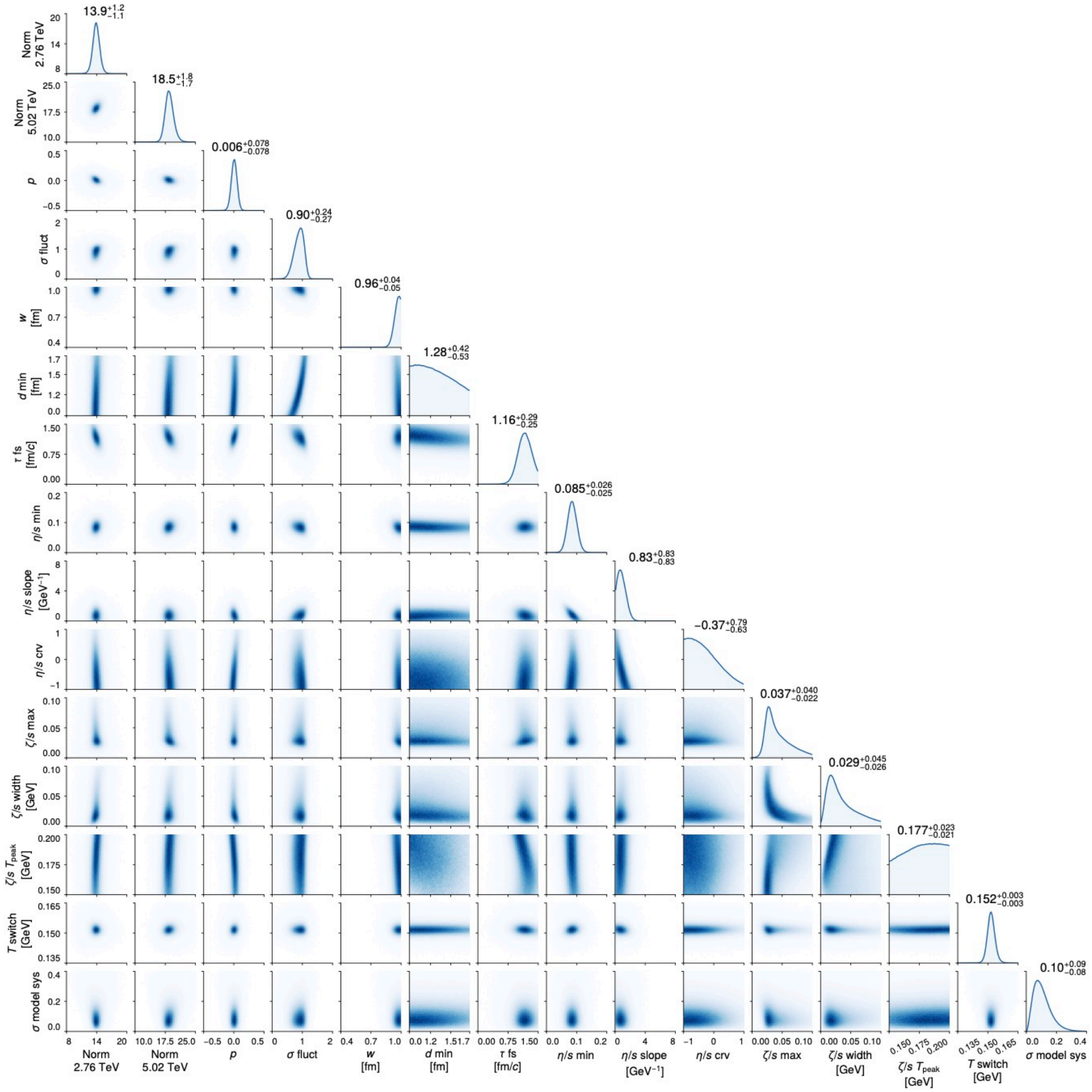
# Bayesian分析

## 多参数的Bayesian拟合

**Supplementary Table 1 | Summary of estimated parameters**

| Parameter | Description | Prior range | Posterior estimate | MAP valu |
|---|---|---|---|---|
| Norm [GeV] | Normalization factor, $\sqrt{s_{NN}}$ = 2.76 TeV | 8–20 | $13.9^{+1.2}_{-1.1}$ | 13.94 |
| Norm [GeV] | Normalization factor, $\sqrt{s_{NN}}$ = 5.02 TeV | 10–25 | $18.5^{+1.8}_{-1.7}$ | 18.38 |
| $p$ | Energy deposition parameter | −1/2 to +1/2 | $0.006^{+0.078}_{-0.078}$ | 0.007 |
| $\sigma_{fluct}$ | Std. dev. of nucleon multiplicity fluctuations | 0–2 | $0.90^{+0.24}_{-0.27}$ | 0.918 |
| $w$ [fm] | Gaussian nucleon width | 0.4–1.0 | $0.96^{+0.04}_{-0.05}$ | 0.956 |
| $d_{min}$ [fm] | Minimum inter-nucleon distance | 0–1.7 | $1.28^{+0.42}_{-0.53}$ | 1.27 |
| $\tau_{fs}$ [fm/$c$] | Free streaming time | 0–1.5 | $1.16^{+0.29}_{-0.25}$ | 1.16 |
| $\eta/s$ min | Minimum value of $\eta/s$ (at $T_c$) | 0–0.2 | $0.085^{+0.026}_{-0.025}$ | 0.081 |
| $\eta/s$ slope [GeV$^{-1}$] | Slope of $\eta/s$ above $T_c$ | 0–8 | $0.83^{+0.83}_{-0.83}$ | 1.11 |
| $\eta/s$ crv | Curvature of $\eta/s$ above $T_c$ | −1 to +1 | $-0.37^{+0.79}_{-0.63}$ | −0.48 |
| $\zeta/s$ max | Maximum value of $\zeta/s$ | 0–0.1 | $0.037^{+0.040}_{-0.022}$ | 0.052 |
| $\zeta/s$ width [GeV] | Width of $\zeta/s$ peak | 0–0.1 | $0.029^{+0.045}_{-0.026}$ | 0.022 |
| $\zeta/s$ $T_{peak}$ [GeV] | Temperature of $\zeta/s$ maximum | 0.150–0.200 | $0.177^{+0.023}_{-0.021}$ | 0.183 |
| $T_{switch}$ [GeV] | Switching / particlization temperature | 0.135–0.165 | $0.152^{+0.003}_{-0.003}$ | 0.151 |

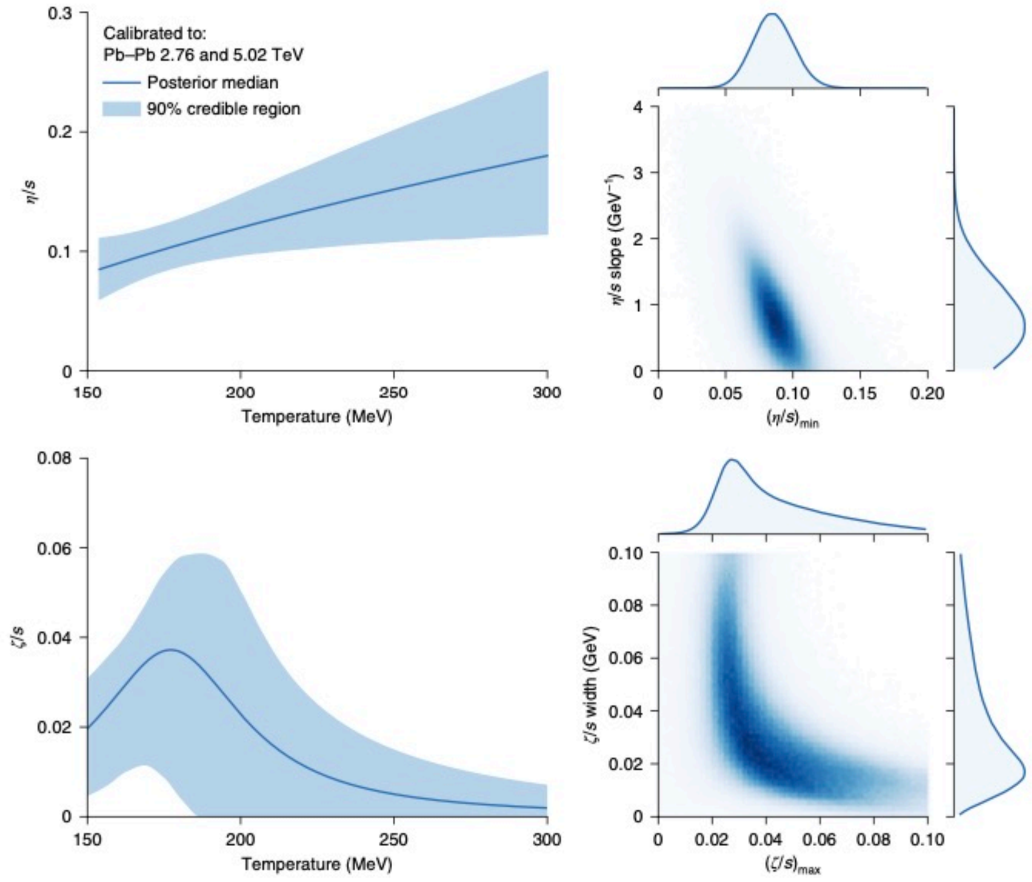
Posterior estimates: The central values are the medians; uncertainties are the 90% highest posterior density (HPD) cre ble intervals. The maximum a posteriori (MAP) values were determined by numerically maximizing the posterior probabi

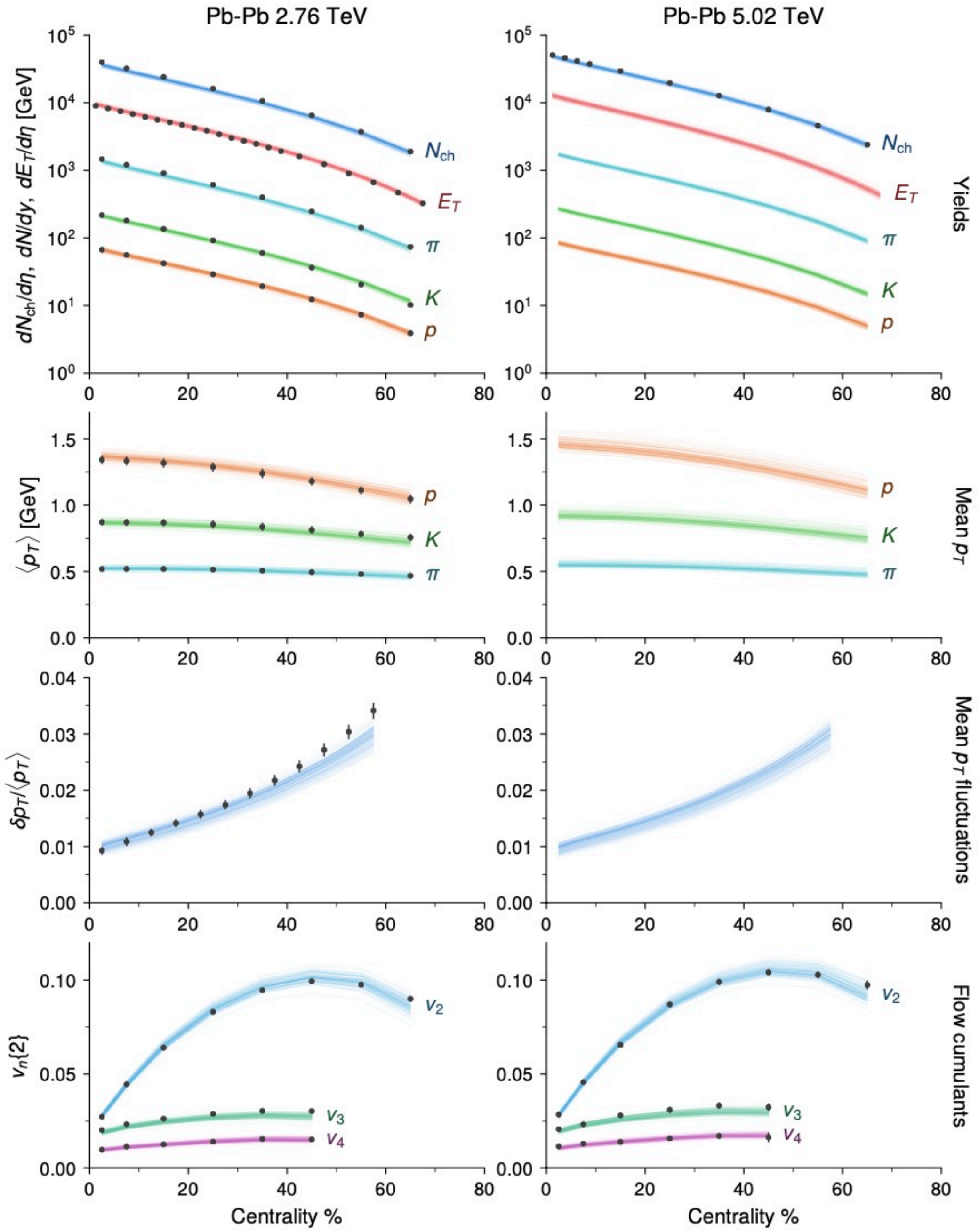



**Supplementary Fig. 2 | Posterior distribution for all parameters.** Diagonal: Marginal distributions (histograms) for each parameter. Annotated are the posterior medians and 90% highest posterior density (HPD) credible intervals. Off-diagonal: Joint distributions (density histograms) showing correlations between pairs of parameters.

# Bayesian分析

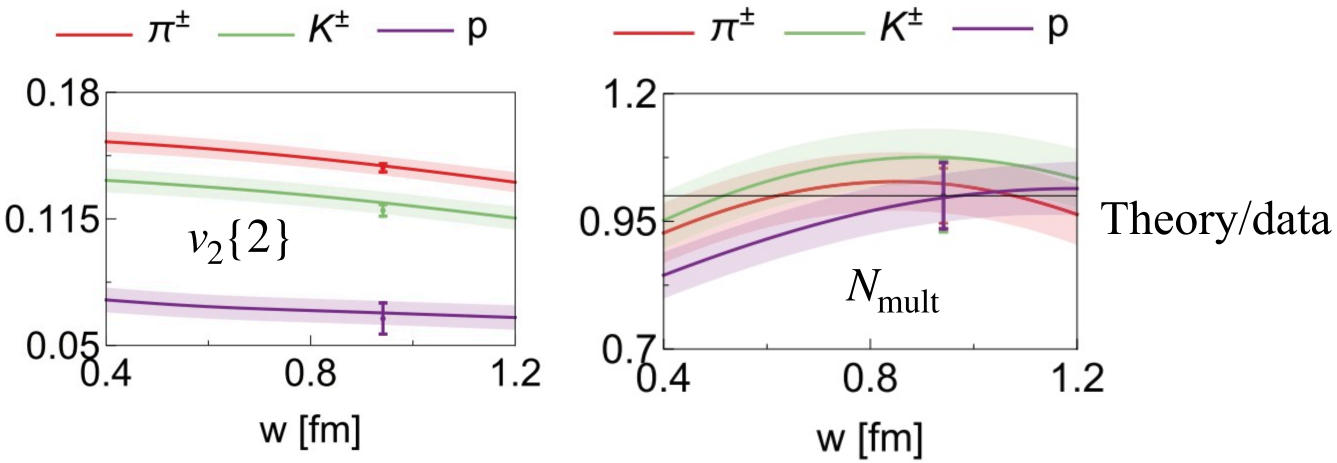
通过实验数据提取QGP的性质



# 核子宽度

G. Nijs, et.al, PRC103, 054909 (2021)




初态模型：假设核子为宽度w的高斯分布

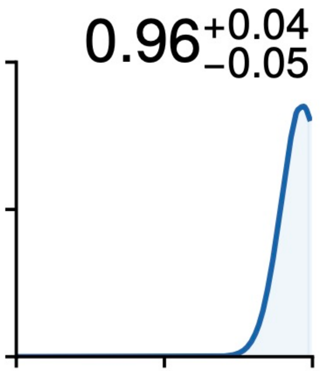
高斯型形状因子

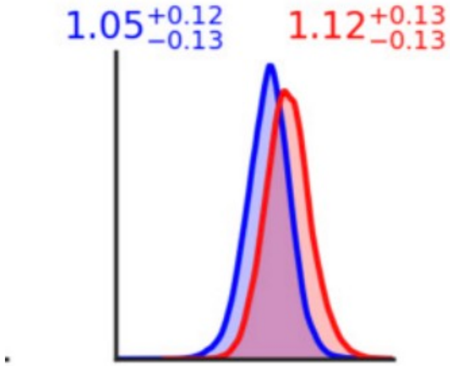
早期尝试：w=0.5 fm -> 核子电荷半径

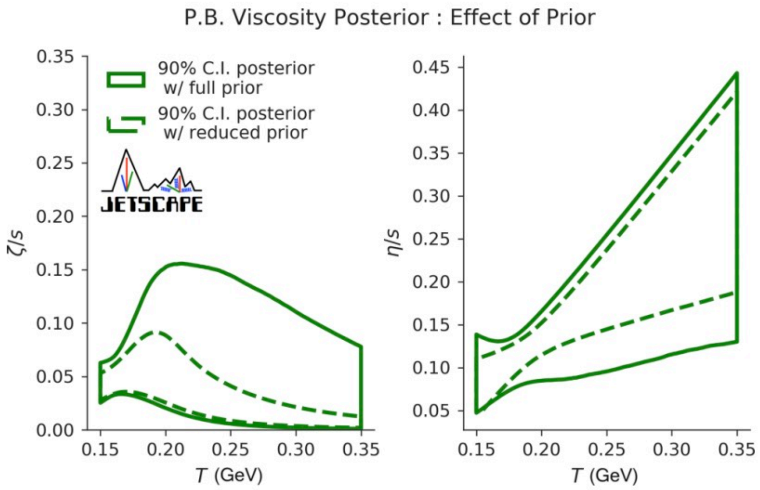
w=0.4 fm -> 核子强相互作用半径

近5-7年：w作为自由参数的贝叶斯分析

**w~1 fm**



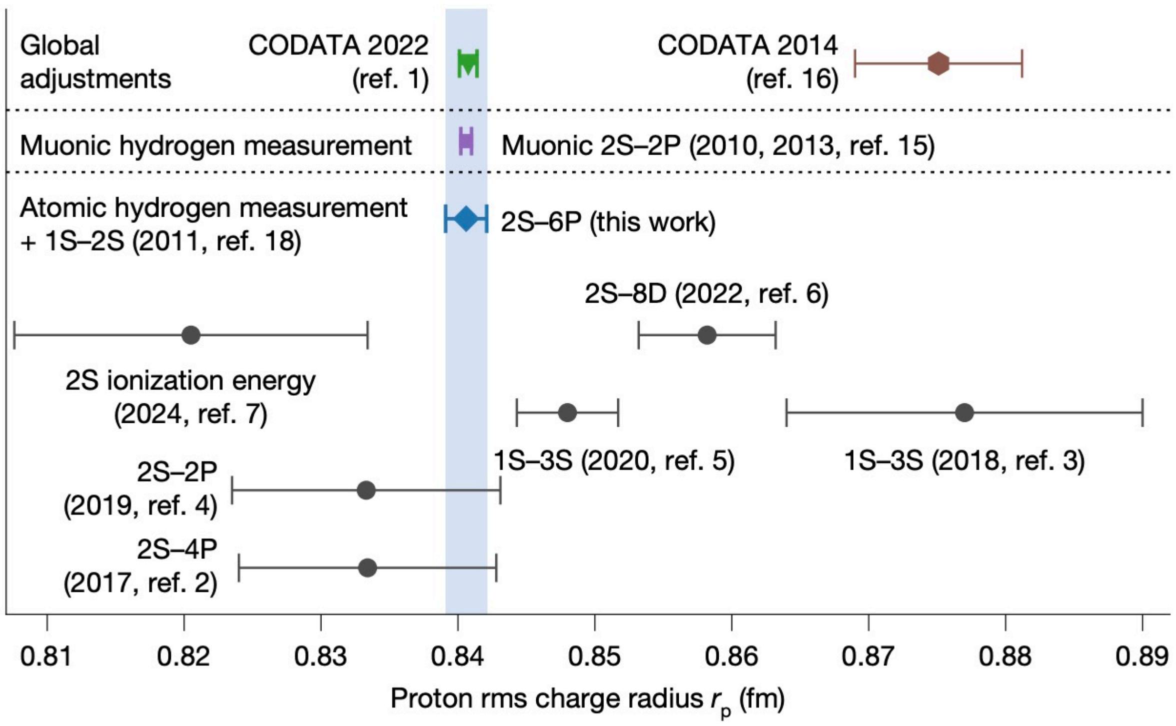




J. Bernhard, et.al, Nature Physics, 15 ,1113-1117 (2019)

JETSCAPE, PRC103, 054904 (2021)

# 核子宽度实验

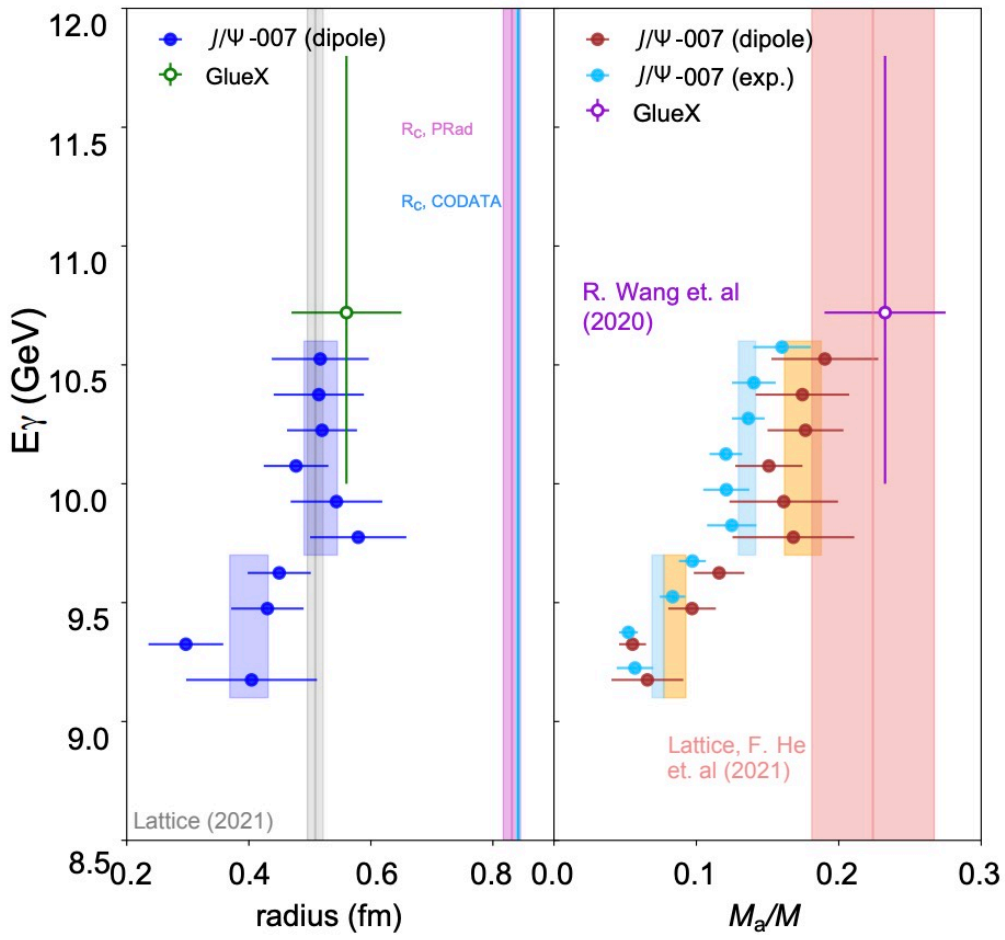
## 电荷宽度




L. Maisenbacher, et.al, Nature, 650, 845-851 (2026)

$$r_{\mathrm{p}} = 0.84 \text{ fm and } w = r_{\mathrm{p}}/\sqrt{3} \sim 0.5 \text{ fm}$$

## 强相互作用宽度




B. Duran, et.al, Nature, 615, 813-816 (2023)

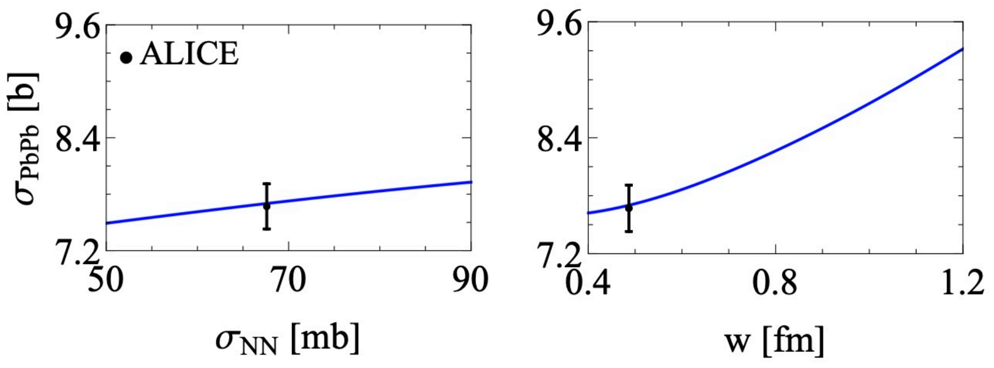
# 非弹截面

通过Pb+Pb的非弹性截面可以约束w~0.4-0.5 fm?

PHYSICAL REVIEW LETTERS **129,** 232301 (2022)

**Hadronic Nucleus-Nucleus Cross Section and the Nucleon Size**

Govert Nijs[1] and Wilke van der Schee[2]
[1]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Theoretical Physics Department, CERN, CH-1211 Genève 23, Switzerland*




非弹截面

$$\sigma_{AA} = \pi b_{max}^2 N_{interact}/N_{total}$$

$N_{interact}$: 碰撞事件数
$N_{total}$: 总事件数
$b_{max} = 20$ fm

**Nucleon Size Independence of Hadronic Nucleus-Nucleus Cross Sections**

Hao-jie Xu[1,2,*]
[1]*School of Science, Huzhou University, Huzhou, Zhejiang 313000, China*
[2]*Strong-Coupling Physics International Research Laboratory (SPiRL), Huzhou University, Huzhou, Zhejiang 313000, China.*

HJX, arXiv:2602.18683

Recent proposals to constrain the nucleon size using hadronic cross sections ($\sigma_{AA}$) conflict with collective flow data. I demonstrate this dependence is an artifact of "geometric inflation," where smearing point-like nucleons unintentionally dilutes the nuclear surface. By implementing a self-consistent framework that preserves the global nuclear density, I show that $\sigma_{AA}$ is essentially insensitive to the nucleon width. This establishes $\sigma_{AA}$ as a robust probe of the nuclear surface rather than the sub-nucleon scale. Utilizing this property, I extract a neutron skin thickness for $^{208}$Pb of $\Delta r_{np} \in [0, 0.21]$ fm, providing an unconventional way to constrain the nuclear symmetry energy using high-energy hadronic observables.

# Glauber/Trento模型中的碰撞截面

## Fitting the cross section

通过独立核子近似处理每个核子核子碰撞！

It is vital that the model reproduce the inelastic nucleon-nucleon cross section $\sigma_{NN}$. This condition may be written

$$\sigma_{NN} = \int d^2b\, P_{\mathrm{coll}}(b),$$

where

$$P_{\mathrm{coll}}(b) = 1 - \exp[-\sigma_{gg} T_{AB}(b)]$$

is the probability of two nucleons colliding at impact parameter $b$.

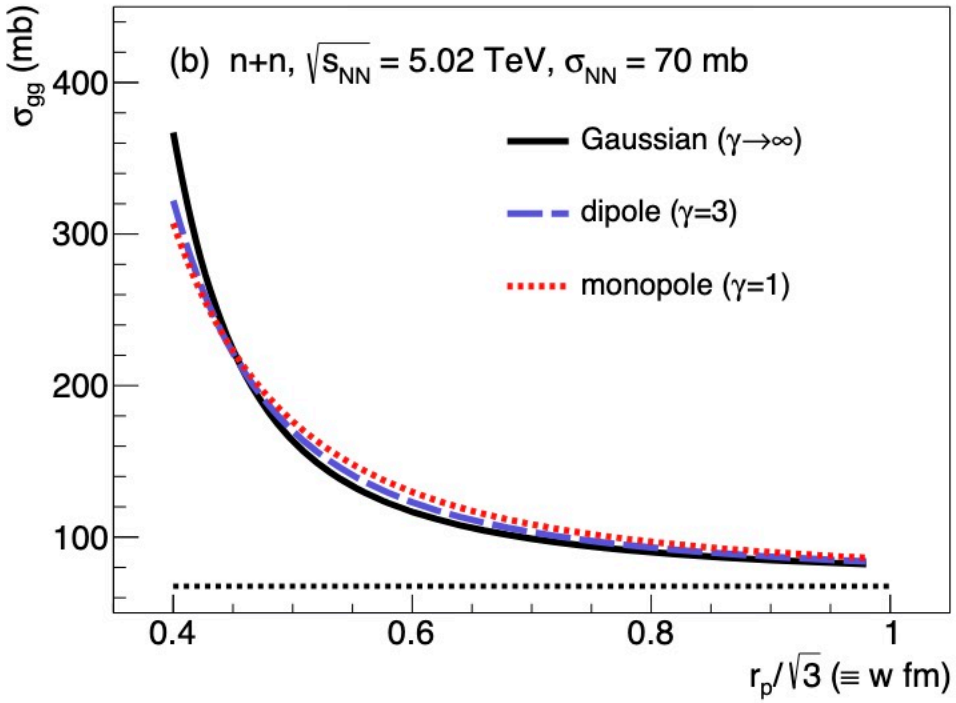
$$\sigma_{NN} = \int_0^{b_{\max}} 2\pi b\, db \left\{1 - \exp\left[-\frac{\sigma_{gg}}{4\pi w^2}\exp\left(-\frac{b^2}{4w^2}\right)\right]\right\},$$

where $b_{\max}$ is the maximum impact parameter for a collision. Let $b_{\max} = Aw$, i.e. some number of nucleon widths (the actual code uses $A = 6$).

After appropriate change of variables, this relation may be written

$$\frac{\sigma_{NN}}{4\pi w^2} = \frac{A^2}{4} + \mathrm{Ei}\left(-e^{-A^2/4}\frac{\sigma_{gg}}{4\pi w^2}\right) - \mathrm{Ei}\left(-\frac{\sigma_{gg}}{4\pi w^2}\right)$$

where Ei is the exponential integral. This is still a transcendental equation but it can be quickly solved numerically for a given cross section and nucleon width.




Glauber 波函数 → C.N. Yang 几何：厚度函数 → Trento 几何：厚度函数

# 形状因子和核子几何

HJX, arXiv:2602.18683

| Case | Thickness function $T_{pp}(b)$ | Form factor $F(q)$ | Nucleon density $\rho(r)$ | RMS radius $r_p$ |
|---|---|---|---|---|
| General $\gamma$ | $\frac{\kappa}{4\pi\zeta^2}\left(\frac{b}{\zeta}\right)^{\gamma}K_\gamma\left(\frac{b}{\zeta}\right)$ | $\frac{1}{(1+q^2\zeta^2)^{\nu}}$ | $\frac{1}{(2\pi)^{3/2}\zeta^3}\frac{2^{1-\nu}}{\Gamma(\nu)}\left(\frac{r}{\zeta}\right)^{\nu-3/2}K_{\nu-3/2}\left(\frac{r}{\zeta}\right)$ | $\sqrt{3(1+\gamma)}\,\zeta$ |
| $\gamma=1$ (monopole) | $\frac{1}{4\pi\zeta^2}\frac{b}{\zeta}K_1\left(\frac{b}{\zeta}\right)$ | $\frac{1}{1+q^2\zeta^2}$ | $\frac{1}{4\pi r\zeta^2}e^{-r/\zeta}$ | $\sqrt{6}\,\zeta$ |
| $\gamma=3$ (dipole) | $\frac{1}{96\pi\zeta^2}\left(\frac{b}{\zeta}\right)^3K_3\left(\frac{b}{\zeta}\right)$ | $\frac{1}{(1+q^2\zeta^2)^2}$ | $\frac{1}{8\pi\zeta^3}e^{-r/\zeta}$ | $2\sqrt{3}\,\zeta$ |
| $\gamma\to\infty$ (Gaussian) | $\frac{1}{4\pi w^2}\exp\left(-\frac{b^2}{4w^2}\right)$ | $\exp\left(-\frac{q^2w^2}{2}\right)$ | $\frac{1}{(2\pi)^{3/2}w^3}\exp\left(-\frac{r^2}{2w^2}\right)$ | $\sqrt{3}\,w$ |

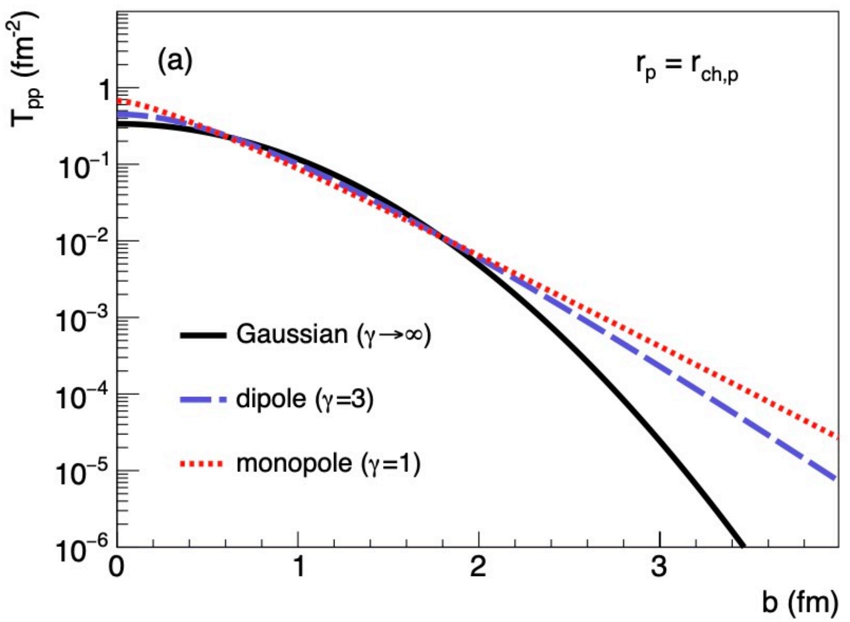
$$\tilde{K}(q;\gamma,\zeta)=2\pi\int_0^\infty b\,db\,J_0(qb)\,T_{pp}(b), \qquad (2)$$

with $J_0$ the Bessel function of the first kind. Using the kernel,

$$\begin{aligned}\tilde{K}(q;\gamma,\zeta)&=2\pi\int_0^\infty b\,db\,J_0(qb)\,\frac{\kappa}{4\pi\zeta^2}\left(\frac{b}{\zeta}\right)^{\gamma}K_\gamma\left(\frac{b}{\zeta}\right)\\&=\frac{\kappa}{2\zeta^2}\int_0^\infty b\,db\,J_0(qb)\left(\frac{b}{\zeta}\right)^{\gamma}K_\gamma\left(\frac{b}{\zeta}\right). \qquad (3)\end{aligned}$$

With $x=b/\zeta$, we have

$$\begin{aligned}\tilde{K}(q;\gamma,\zeta)&=\frac{\kappa}{2\zeta^2}\int_0^\infty \zeta^2x\,dx\,J_0(q\zeta x)\,x^\gamma K_\gamma(x)\\&=\frac{\kappa}{2}\int_0^\infty dx\,x^{1+\gamma}J_0(q\zeta x)K_\gamma(x)\\&=\frac{1}{(1+q^2\zeta^2)^{1+\gamma}}\equiv|F(q;\gamma,\zeta)|^2. \qquad (4)\end{aligned}$$



# 几何膨胀效应

HJX, arXiv:2602.18683

改变w

=>

改变原子核密度分布！！！

$$\rho(\mathbf{r}; w) = \int d^3\xi\, f(\xi)\, \mathbf{K_p}(\mathbf{r}, \xi)$$

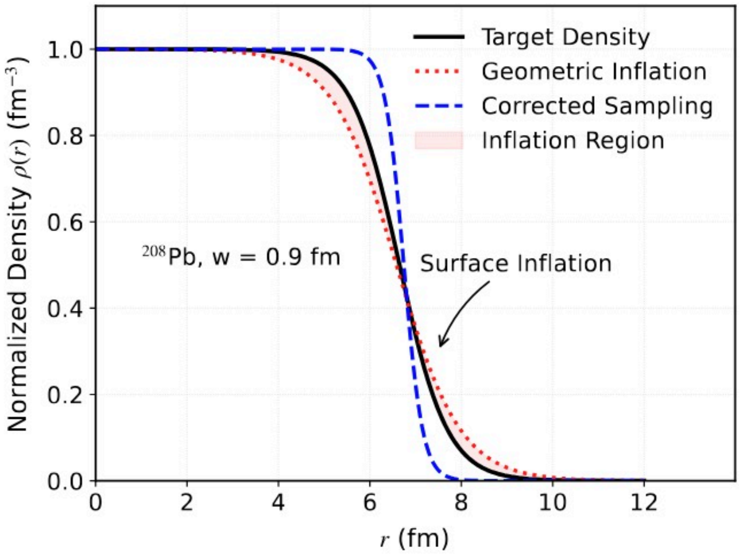
$$\langle \rho(r;w) \rangle = \langle \rho^{\mathrm{WS}}(r) \rangle, \quad (4)$$

$$\langle r\rho(r;w) \rangle = \langle r\rho^{\mathrm{WS}}(r) \rangle, \quad (5)$$

$$\langle r^2\rho(r;w) \rangle = \langle r^2\rho^{\mathrm{WS}}(r) \rangle, \quad (6)$$

$$\tilde{R} \approx R + w^2 \frac{15R}{15R^2 + 7\pi^2 a^2},$$

$$\tilde{a} = \sqrt{a^2 - \frac{\tilde{R}^3 - R^3}{\pi^2 \tilde{R}}}. \quad (7)$$




$^{208}$Pb

电荷分布参数：

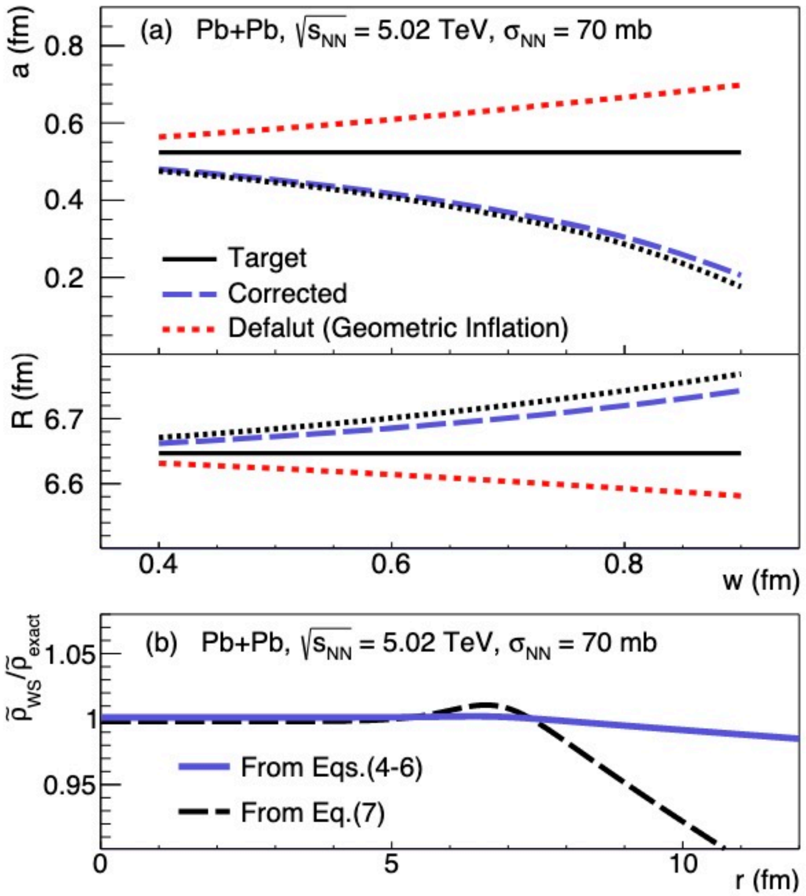
$R = 6.647$ fm

$a = 0.523$ fm

质子中心分布参数：

$R = 6.682$ fm

$a = 0.447$ fm

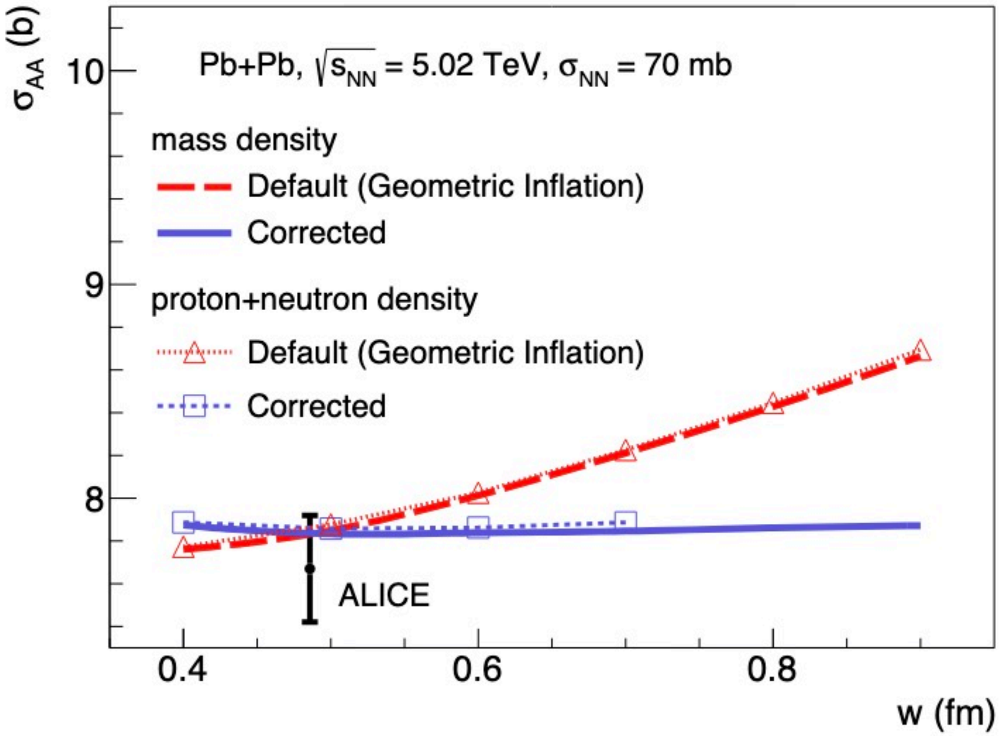


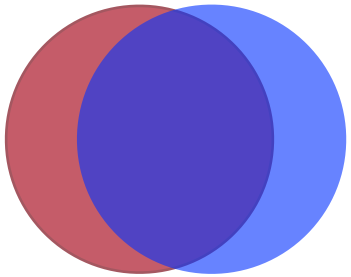
# 核分布依赖 VS 核子分布依赖

HJX, arXiv:2602.18683

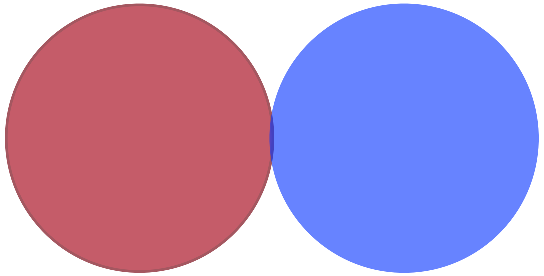
红线：改变w时核密度由于几何膨胀而改变
蓝线：改变$w$时确保核密度分布不变

非弹截面不随$w$的变化而改变！



几乎都会发生碰撞



取决于边缘核子核子是否发生碰撞

核子核子非弹性截面不变 => 核核非弹性截面不变

proton+neutron density: 质子分布和中子分布分别处理

$$\rho(\mathbf{r}; w) = \int d^3\xi \, f(\xi) \, \mathbf{K}_\mathbf{p}(\mathbf{r}, \xi)$$

原则上需要分别反卷积处理两个分布。

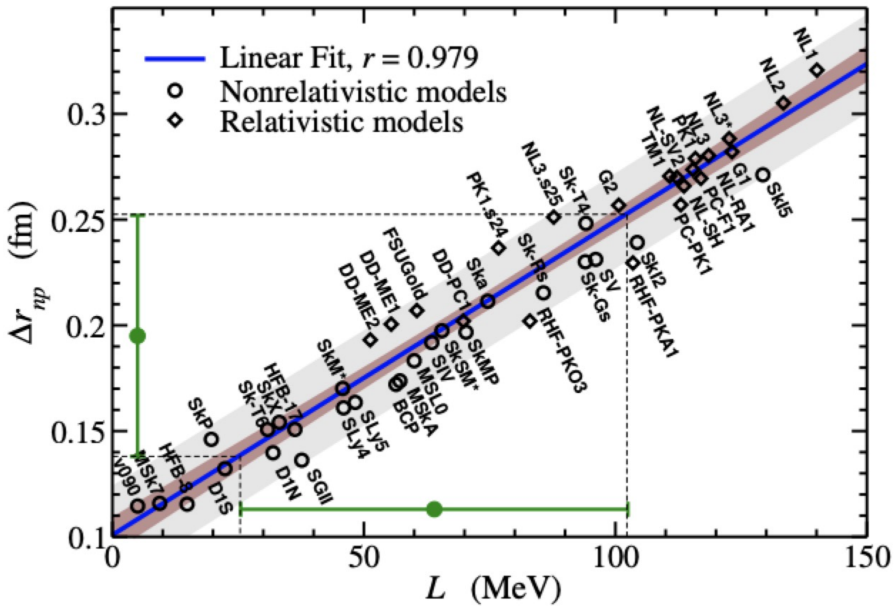
# 中子皮测量

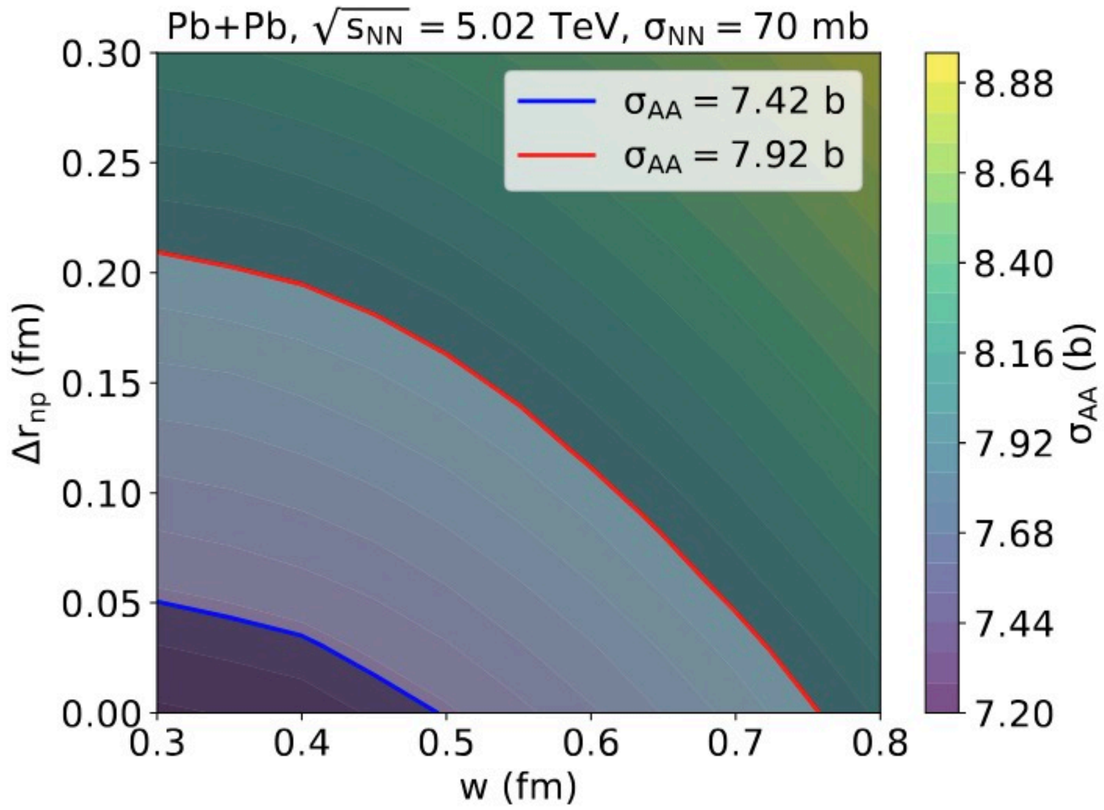
HJX, arXiv:2602.18683

$$L \equiv L(\rho) = 3\rho \left[\frac{dE_{\mathrm{sym}}(\rho)}{d\rho}\right]_{\rho=\rho_0} \text{ saturation density}$$

$$L(\rho_c) = 3\rho_c \left[\frac{dE_{\mathrm{sym}}(\rho)}{d\rho}\right]_{\rho=\rho_c=0.11\rho_0/0.16}$$

$$R_m^2 = R_{\mathrm{p,point}}^2 + 3w^2 + \frac{126}{208}\left(2R_{\mathrm{p,point}}\Delta r_{\mathrm{np}} + \Delta r_{\mathrm{np}}^2\right).$$



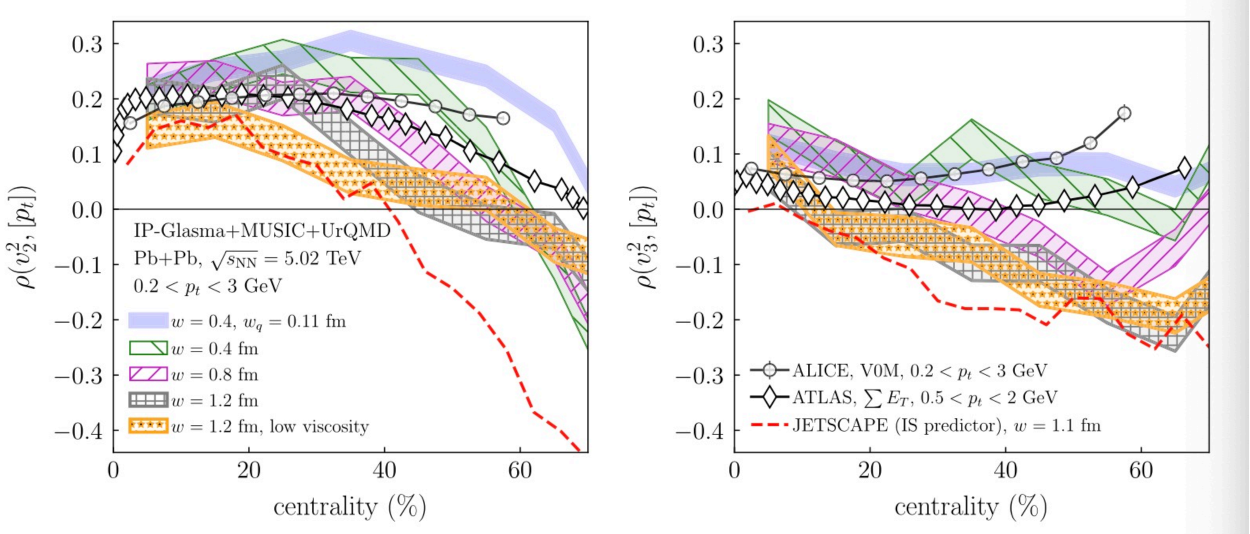
# 集体流观测量

PHYSICAL REVIEW LETTERS **128,** 042301 (2022)

$$\rho_n \equiv \rho(v_n^2, [p_t]) = \frac{\langle \delta v_n^2 \delta[p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta[p_t])^2 \rangle}},$$

## Constraining the Nucleon Size with Relativistic Nuclear Collisions

Giuliano Giacalone,[1] Björn Schenke,[2] and Chun Shen[3,4]
[1]*Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
[2]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[3]*Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201, USA*
[4]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*




PHYSICAL REVIEW LETTERS **125,** 192301 (2020)

## Observable Signatures of Initial State Momentum Anisotropies in Nuclear Collisions

Giuliano Giacalone,[1] Björn Schenke,[2] and Chun Shen[3,4]

PHYSICAL REVIEW LETTERS **128,** 082301 (2022)

## Evidence of the Triaxial Structure of $^{129}$Xe at the Large Hadron Collider

Benjamin Bally,[1] Michael Bender,[2] Giuliano Giacalone,[3] and Vittorio Somà[4]

PHYSICAL REVIEW LETTERS **133,** 192301 (2024)

## Exploring the Nuclear-Shape Phase Transition in Ultrarelativistic $^{129}$Xe + $^{129}$Xe Collisions at the LHC

Shujun Zhao,[1,2,*] Hao-jie Xu,[2,3,†] You Zhou,[4,‡] Yu-Xin Liu,[1,5,6,§] and Huichao Song[1,5,6,∥]
[1]*School of Physics, Peking University, Beijing 100871, China*
[2]*School of Science, Huzhou University, Huzhou, Zhejiang 313000, China*
[3]*Strong-Coupling Physics International Research Laboratory (SPiRL), Huzhou University, Huzhou, Zhejiang 313000, China*
[4]*Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[5]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*
[6]*Center for High Energy Physics, Peking University, Beijing 100871, China*

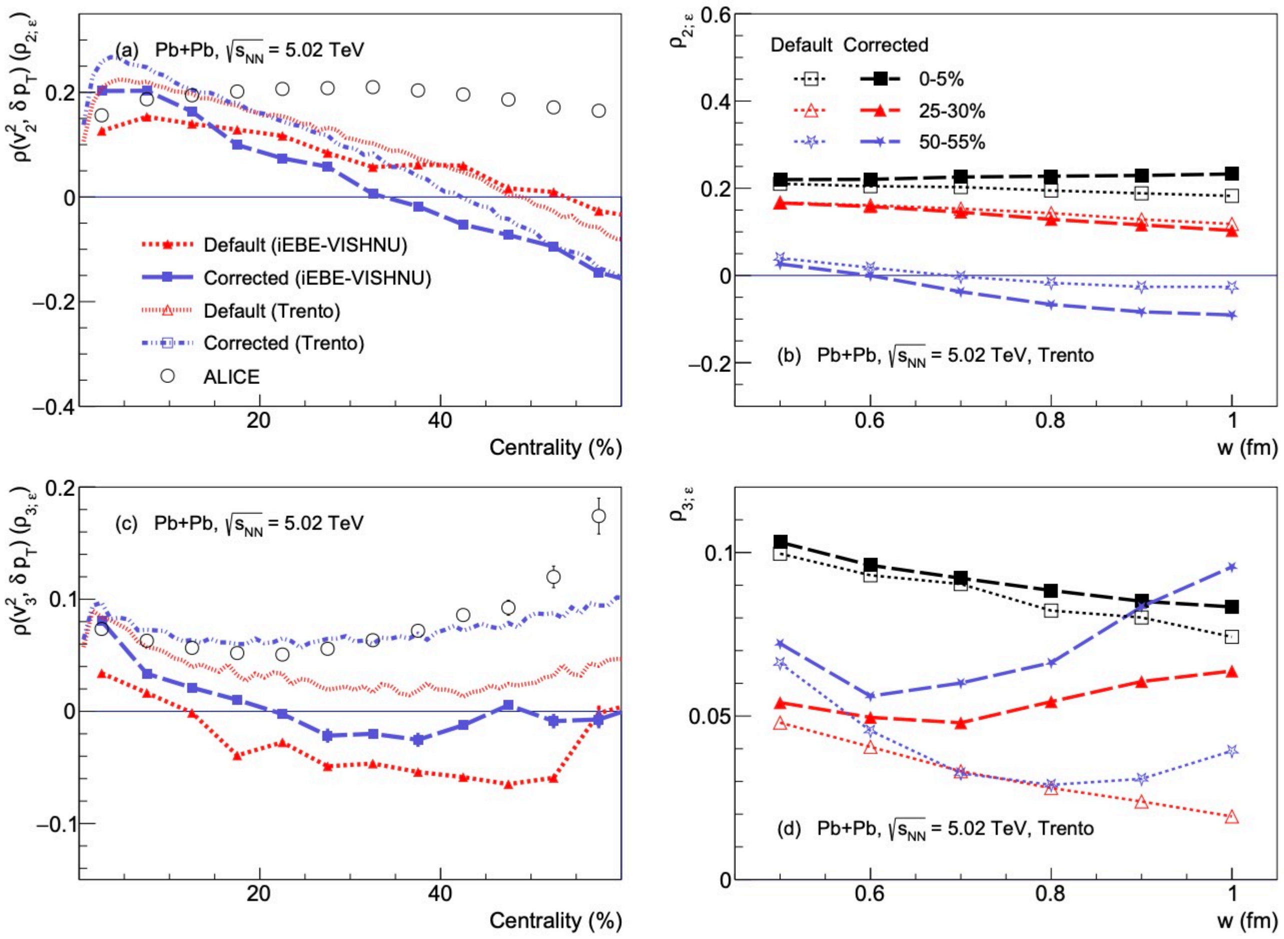
# 修正后的核子分布依赖

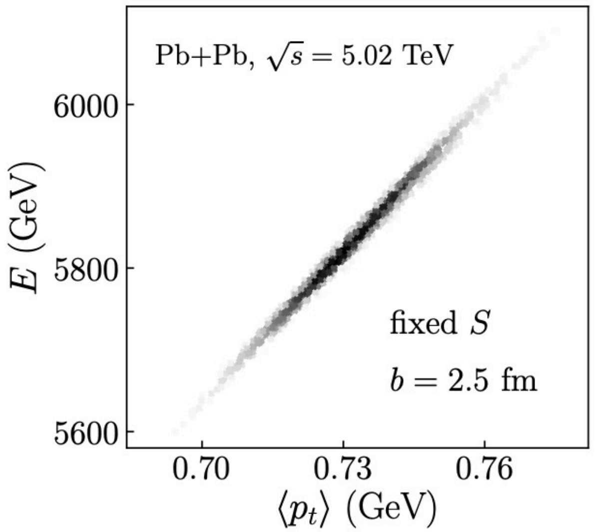
J. Wang, HJX, arXiv:2602.22383

$$\rho(\vec{r}; w) = \frac{1}{(2\pi w^2)^{3/2}} \int d^3\xi\, f(\vec{\xi})\, \exp\left(-\frac{(\vec{r}-\vec{\xi})^2}{2w^2}\right).$$

TABLE I. The corrected Woods-Saxon parameters for sampling nucleon centers ensure that the global nuclear geometry remains invariant under Gaussian smearing with parameter $w$.

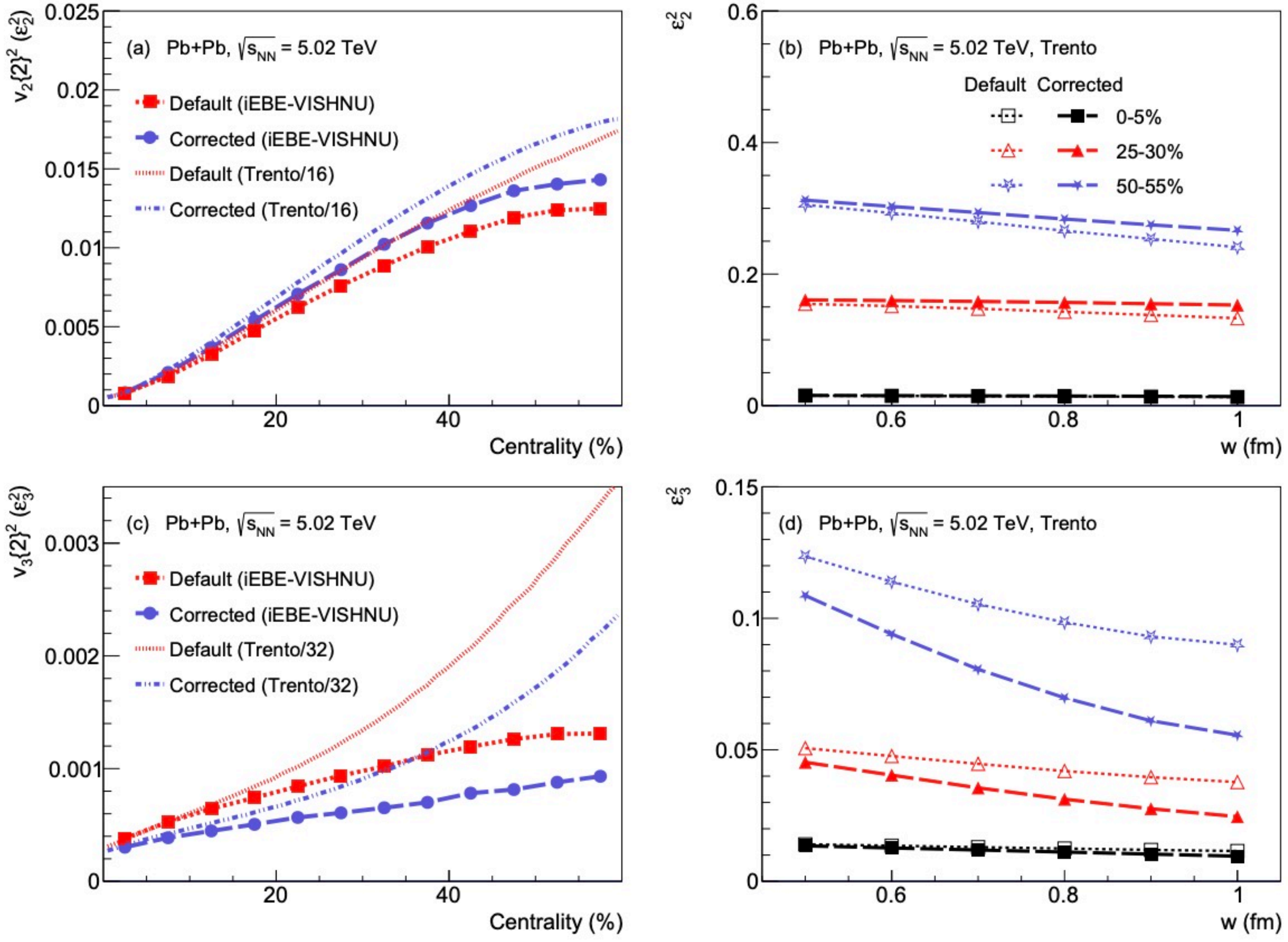
| $w$ (fm) | $^{208}$Pb | | $^{48}$Ca | |
|---|---|---|---|---|
| | $\tilde{R}$ (fm) | $\tilde{a}$ (fm) | $\tilde{R}$ (fm) | $\tilde{a}$ (fm) |
| 0.4 | 6.64 | 0.504 | 3.73 | 0.487 |
| 0.5 | 6.65 | 0.479 | 3.74 | 0.464 |
| 0.6 | 6.66 | 0.445 | 3.74 | 0.435 |
| 0.7 | 6.67 | 0.402 | 3.75 | 0.396 |
| 0.8 | 6.70 | 0.344 | 3.77 | 0.345 |
| 0.9 | 6.71 | 0.262 | 3.80 | 0.271 |
| 1.0 | 6.74 | 0.109 | 3.84 | 0.138 |



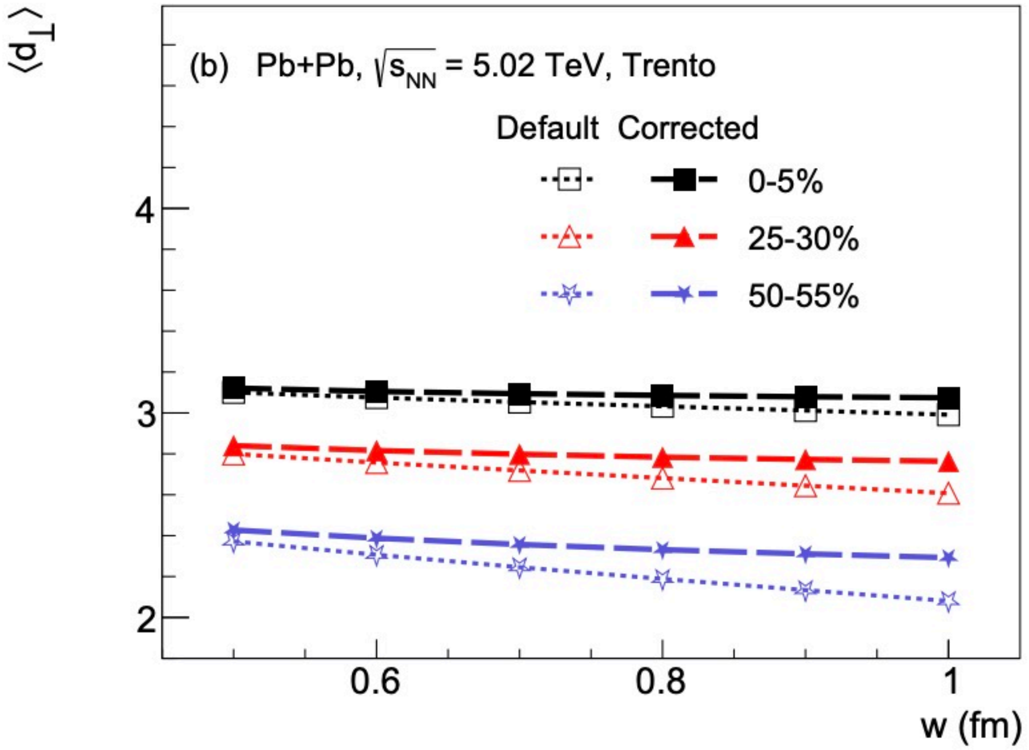



# 修正后的核子分布依赖

J. Wang, HJX, arXiv:2602.22383

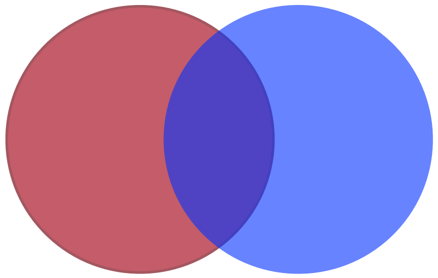



平均横动量极大地和$w$参数解耦！！！



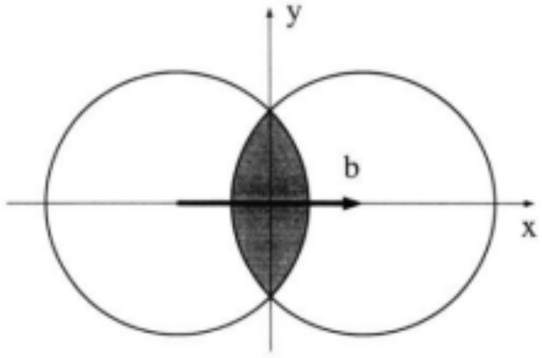
# 碰撞尺寸 VS 能量沉积尺寸

Trento模型框架



抽样单核子

参与者




单核子中心的分布

$\rho_A^C(r)$ $\rho_B^C(r)$

$+\ w$

核密度分布

核子-核子碰撞概率

$$P(b) = 1 - \exp\left(-\sigma_{gg} T_{pp}(\mathbf{b})\right)$$

$$T_{pp}(\mathbf{b}) = \exp(-b^2/4w^2)/(4\pi w^2)$$

核子-核子碰撞概率

$$T_A = \sum_{i=1}^{N_{\text{part}}} w_i \int dz\, \rho_{\text{proton}}(x - x_i, y - y_i, z - z_i),$$

3D

$$\int dz \rho_{\text{proton}} = \frac{1}{2\pi w^2} \exp\left(-\frac{x^2 + y^2}{2w^2}\right)$$

相等

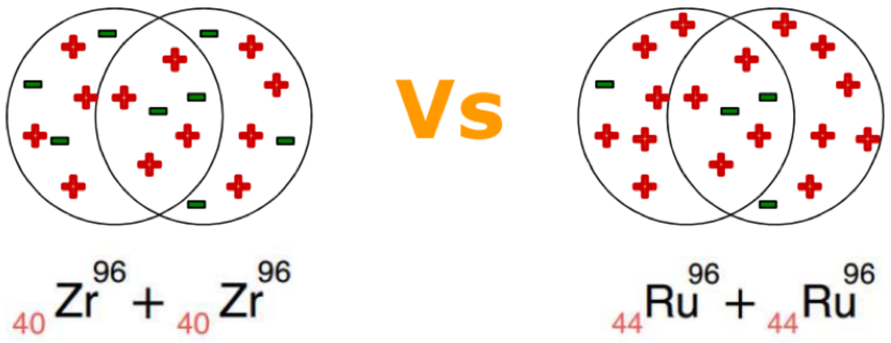
相等？？

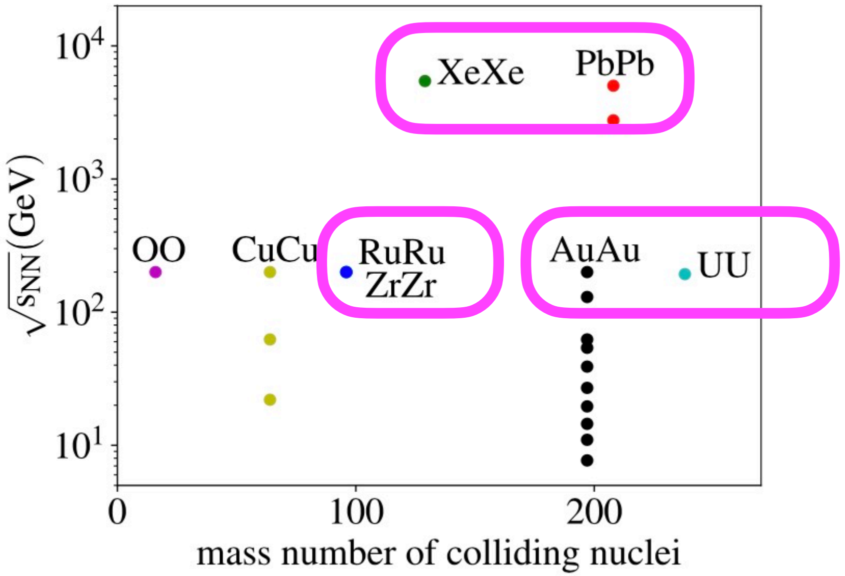
HJX, in progress

# 相对论同量异位素核碰撞

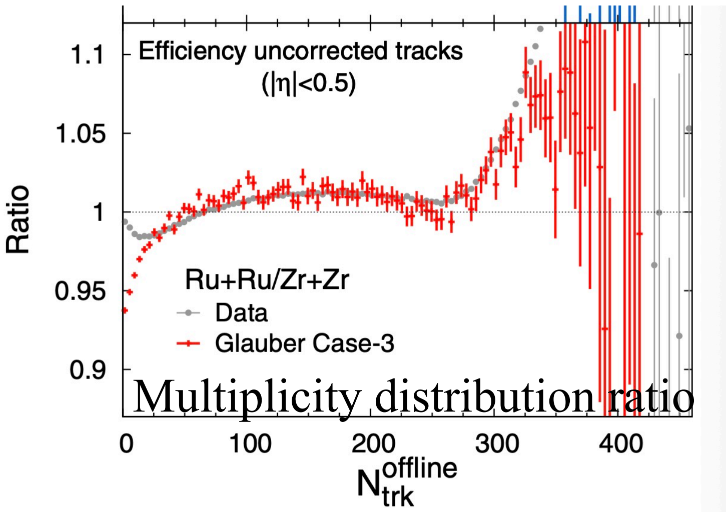
类同量异位素核碰撞

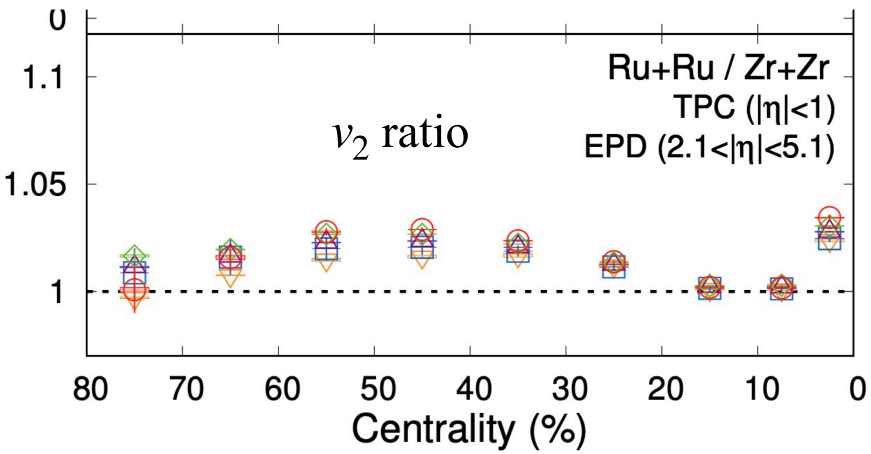
Q. Liu, S. Zhao, HJX, H. Song, PRC109, 034912(2024)



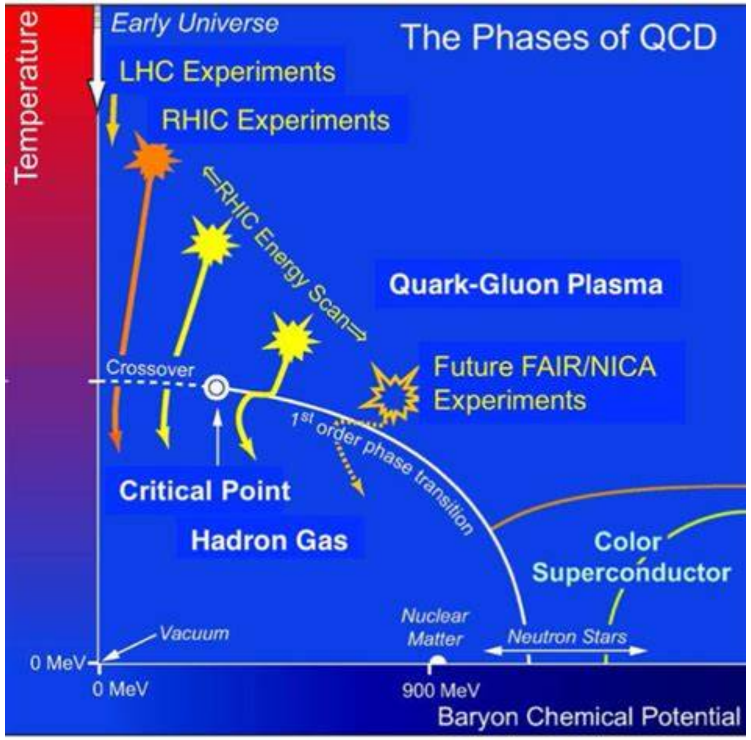

STAR, PRC105, 014901(2022)



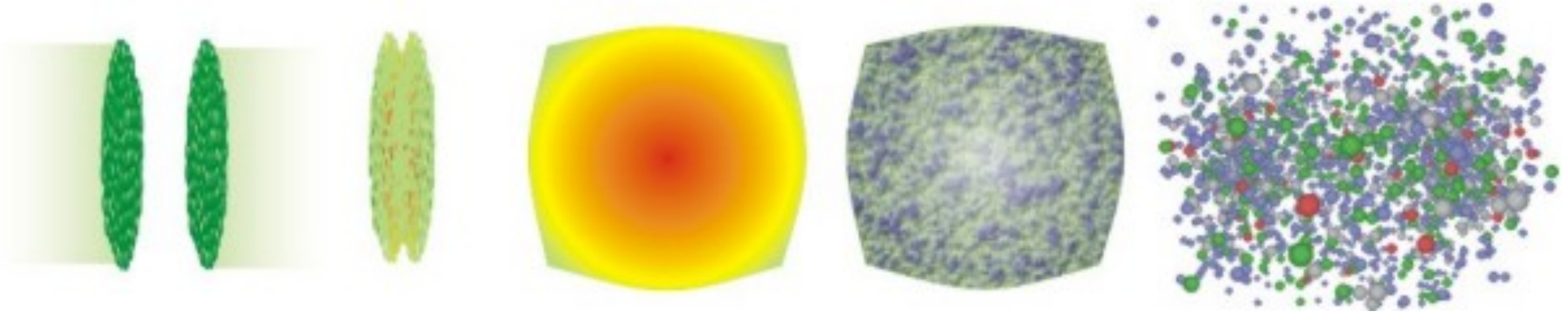




高精度的研究需要更细致的研究！

# 总结



Early Universe
The Phases of QCD
LHC Experiments
RHIC Experiments
Temperature
RHIC Energy Scan
Quark-Gluon Plasma
Future FAIR/NICA Experiments
Crossover
1st order phase transition
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

# Thank you for your attention!

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Huzhou Normal University(湖州师范大学)