湖州欢迎你！

相对论同量异位素核碰撞中的核结构研究

徐浩洁
湖州师范学院

原子核结构与中高能重离子碰撞交叉学科理论讲习班，
湖州，2021年7月9-24日

提纲

I. 相对论重离子碰撞简介

II. 初态几何模型

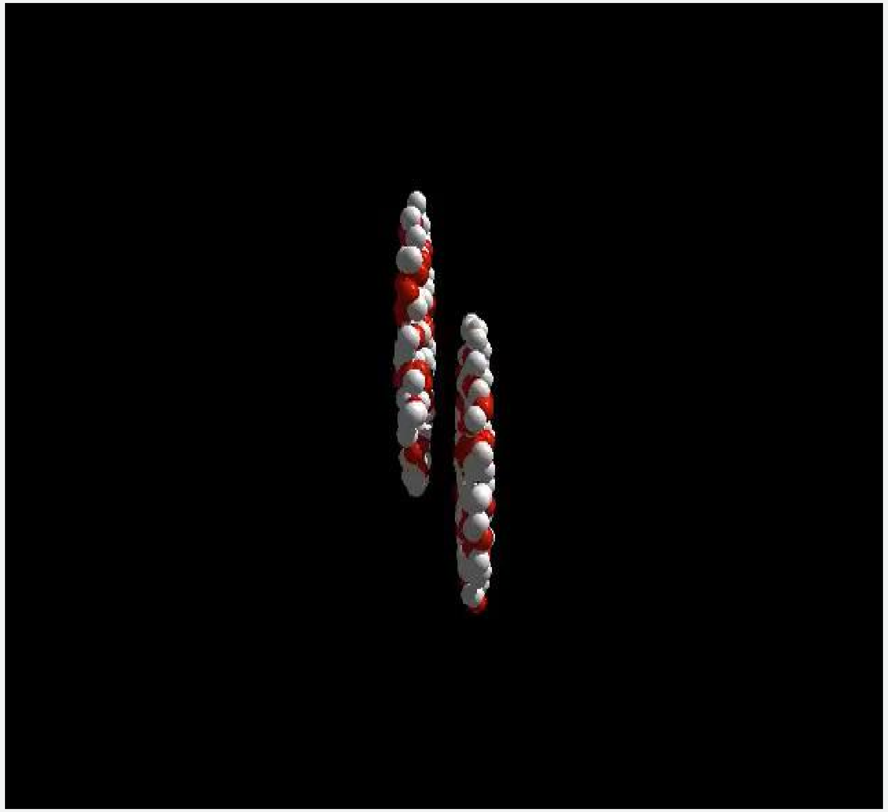
III. 核结构对手征磁效应测量的影响

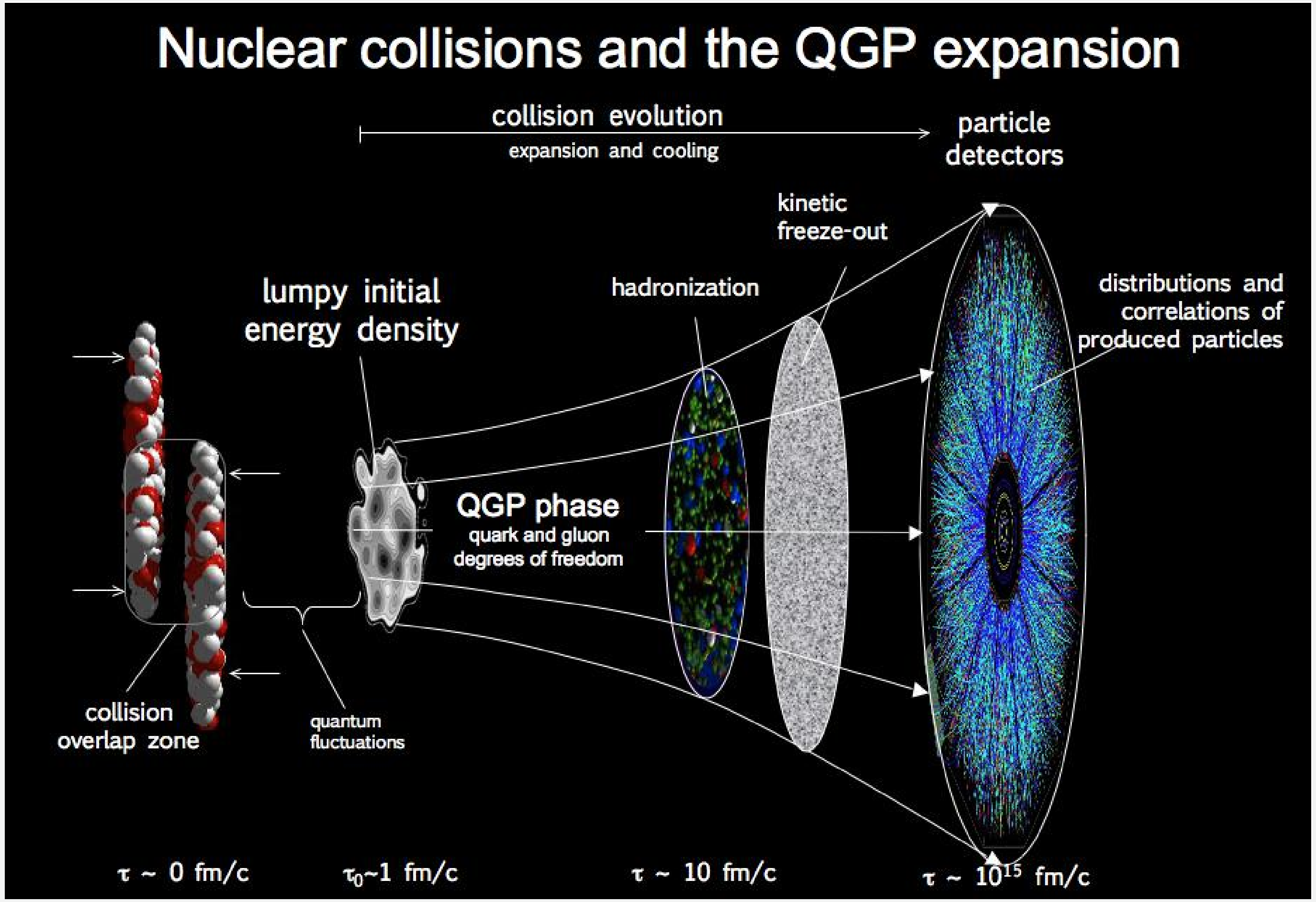
IV. 通过同量异位素核碰撞测量中子皮

V. 总结

I. 相对论重离子碰撞简介

相对论重离子碰撞




Nuclear collisions and the QGP expansion
collision evolution
expansion and cooling
particle detectors
kinetic freeze-out
hadronization
lumpy initial energy density
distributions and correlations of produced particles
QGP phase
quark and gluon degrees of freedom
collision overlap zone
quantum fluctuations
τ ~ 0 fm/c
τ0~1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

相对论重离子碰撞的特点

- 极高的能量（RHIC, v=0.99995c）
- 极短的碰撞时间 fm/c~10^{-23}s
- 低重子数密度
- 极高温度（QGP，夸克胶子等离子体）
- 极强的磁场
- 极大的涡旋

相对论重离子碰撞的观测量

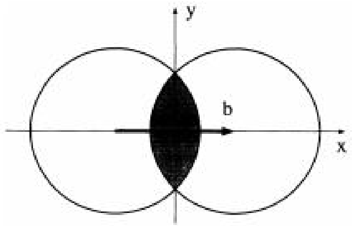
- 粒子产额（统计模型；反物质产生）
- 集体流（各向异性流及其关联；QGP性质）
- 电荷关联（手征磁效应等）
- 高阶矩（QCD相变）
- 电磁探针、重味探针、喷注淬火等等

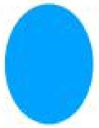
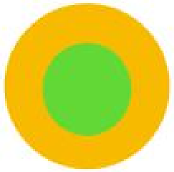
相对论重离子碰撞的常用模型

- 相对论流体力学模型
- AMPT模型
- UrQMD模型
- Hijing模型
- 。。。。。

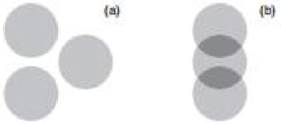
II. 初态几何模型

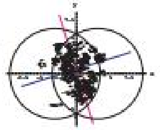
初始几何特性

- 非中心对撞几何不对称性 

- 形变核 
- 中子皮（周边碰撞） 

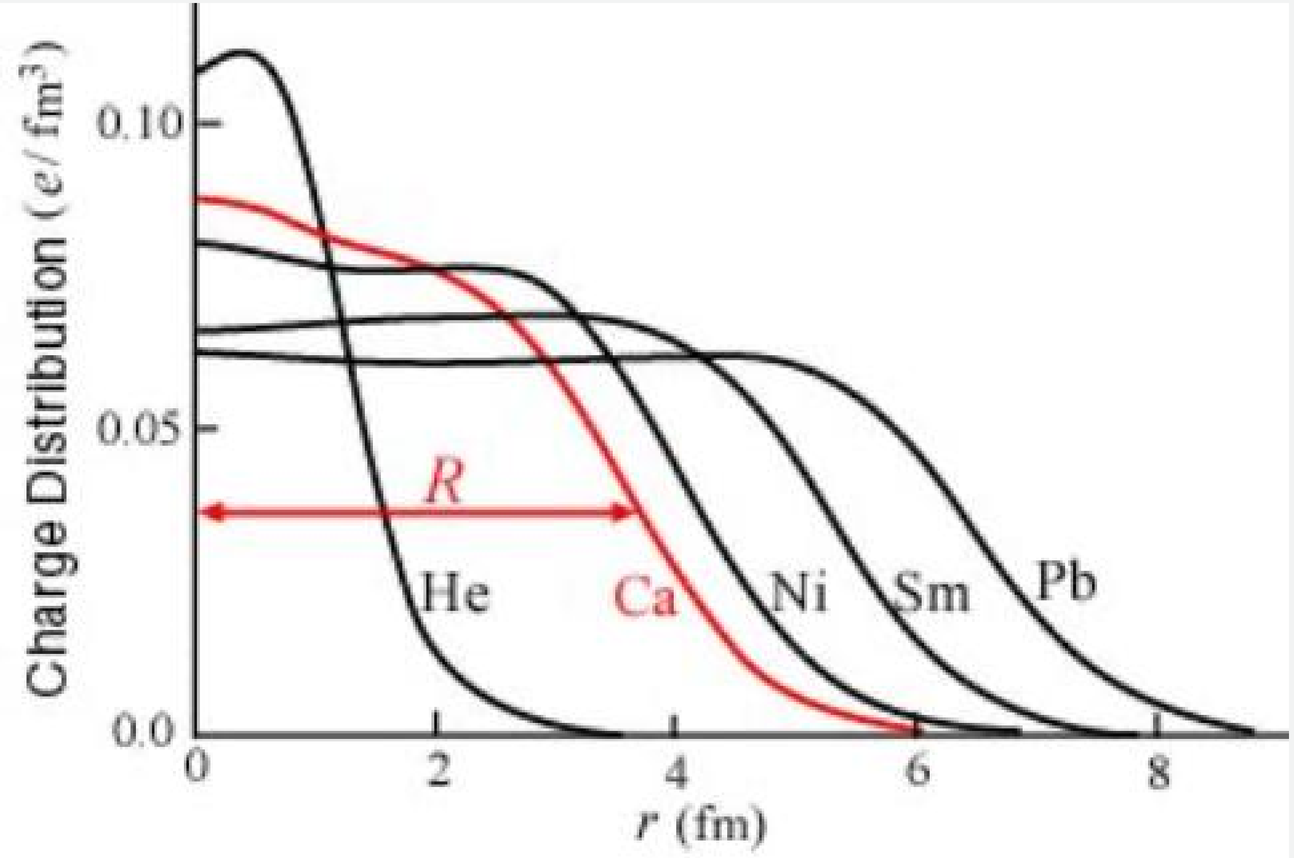
Hao-jie Xu et al., PLB-819(2021)136453,
Hanlin Li et al., PRL-125(2020)222301

- **α-cluster结构** 

- 涨落 

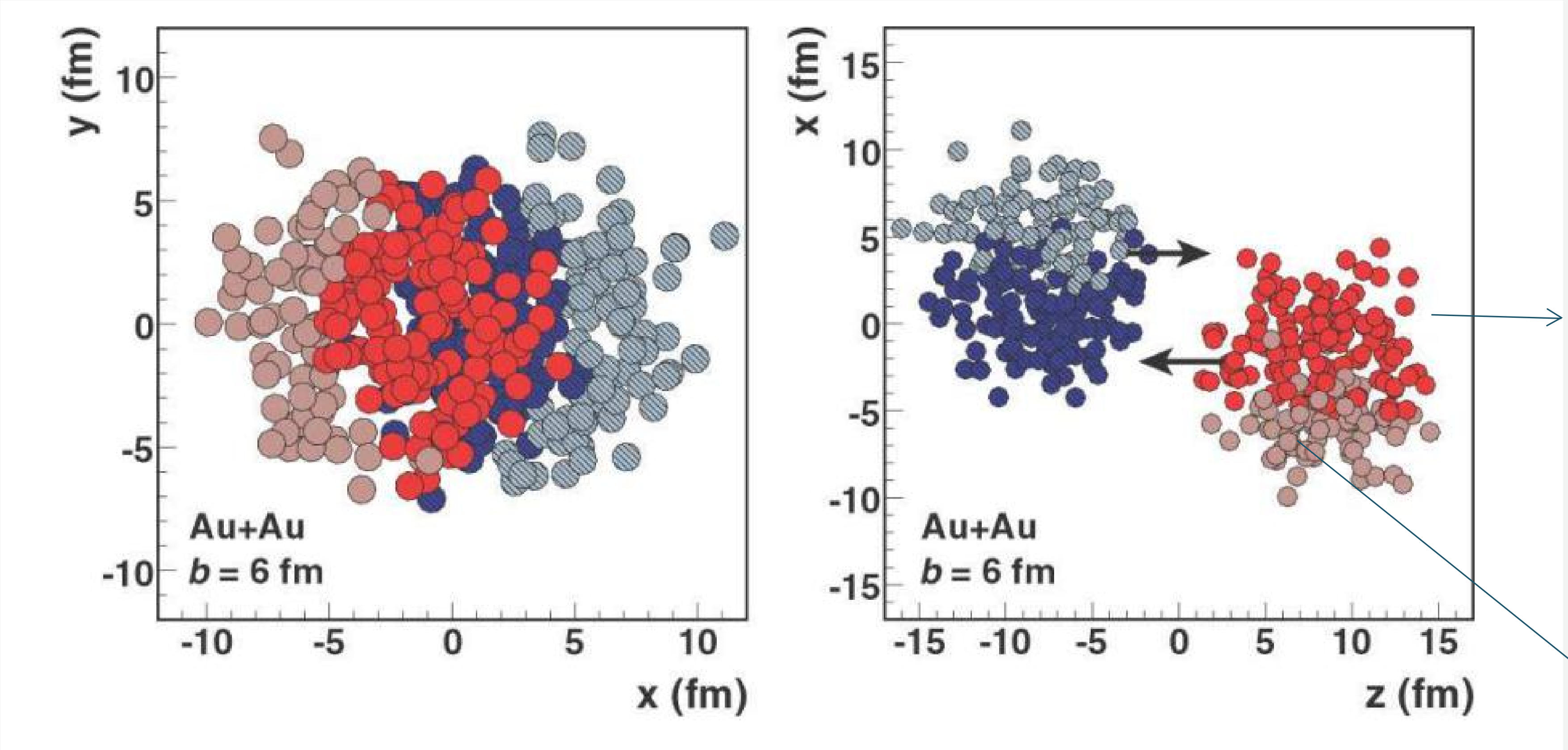
Woods-Saxon分布

$$\rho(r) = \rho_0 \frac{1 + w\left(\frac{r}{R}\right)^2}{1 + e^{(r-R)/a}}$$



Nucleus	R [fm]	a [fm]	w [fm]
^{2}H	0.01	0.5882	0
^{16}O	2.608	0.513	-0.51
^{28}Si	3.34	0.580	-0.233
^{32}S	2.54	2.191	0.16
^{40}Ca	3.766	0.586	-0.161
^{58}Ni	4.309	0.517	-0.1308
^{62}Cu	4.2	0.596	0
^{186}W	6.58	0.480	0
^{197}Au	6.38	0.535	0
^{207}Pb^{a}	6.62	0.546	0
^{238}U	6.81	0.6	0

参与者与旁观者



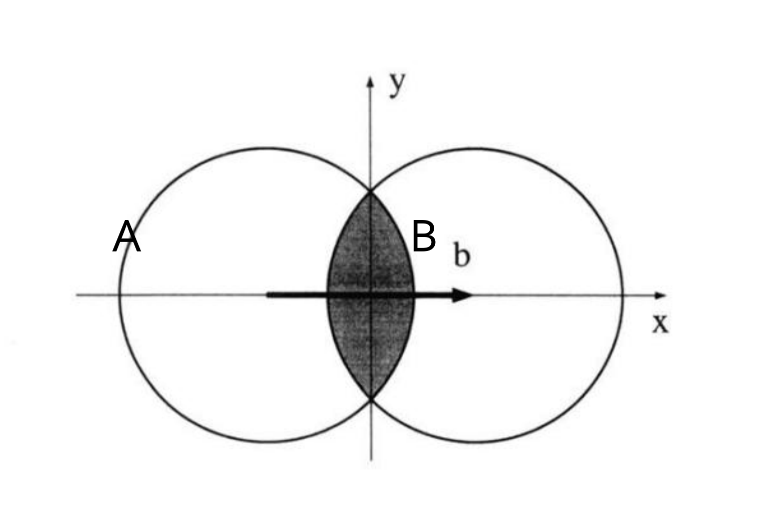
Participant

- Number of binary collisions
- Number of participants

Spectator

Michael L. Miller, Klaus Reygers, Stephen J. Sanders, Peter Steinberg，Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243

Optical Glauber model



- Thickness function

$$T(s_T) = \int_{-\infty}^{\infty} \rho(s_T, z) dz$$

- The probability of a nucleon in A interact with a nucleon in B is

$$p_{AB}(b) = \sigma_{in}^{NN} \frac{\int dxdy\, T_A(x + b/2, y) T_B(x - b/2, y)}{AB}$$

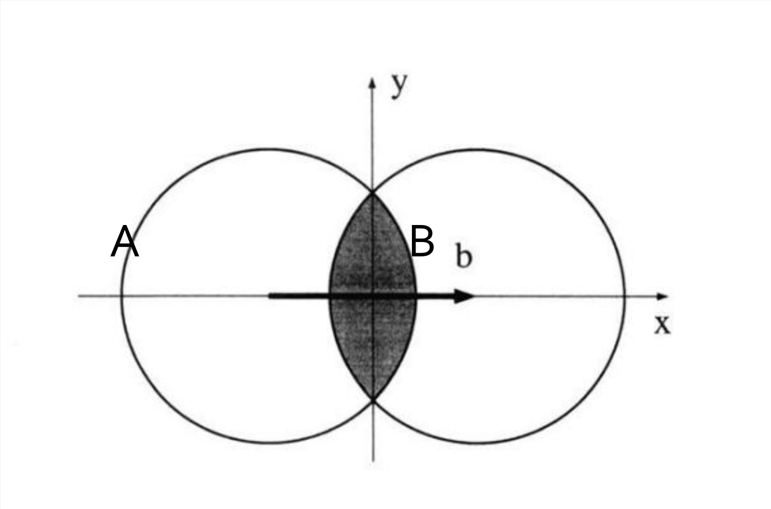
- For a given nucleon in A, it interact with a nucleon in B is

$$p_A(x, y; b) = \sigma_{in}^{NN} \frac{T_B(x - b/2, y)}{B}$$

A+B cross section

- The probability of having n binary collision is

$$P(n) = \binom{AB}{n} p_{AB}^{n} (1 - p_{AB})^{AB-n}$$



- The total cross section of an interaction between A and B is

$$\frac{d^2\sigma_{in}^{A+B}}{db^2} = \sum_{i=1}^{AB} P(n;b) = 1 - (1 - p_{AB})^{AB}$$

$$\approx 1 - e^{-\sigma_{in}^{NN} \int dxdy\, T_A(x+b/2,y) T_B(x-b/2,y)}$$

Number of binary collisons

$$N_{coll}(b) = \sum_{i=1}^{AB} nP(n;b) = \sigma_{in}^{NN} \int dxdy\, T_A(x+b/2,y) T_B(x-b/2,y)$$

Number of participant(wounded nucleons)

$$N_{part}(b) = \int dxdy\, T_A(x+b/2,y) \left\{1 - \left[1 - \sigma_{in}^{NN} \frac{T_B(x-b/2,y)}{B}\right]^B\right\}$$

$$+ \int dxdy\, T_B(x-b/2,y) \left\{1 - \left[1 - \sigma_{in}^{NN} \frac{T_A(x+b/2,y)}{A}\right]^A\right\}$$

PHYSICAL REVIEW C **94**, 054903 (2016)

Cumulants of multiplicity distributions in most-central heavy-ion collisions

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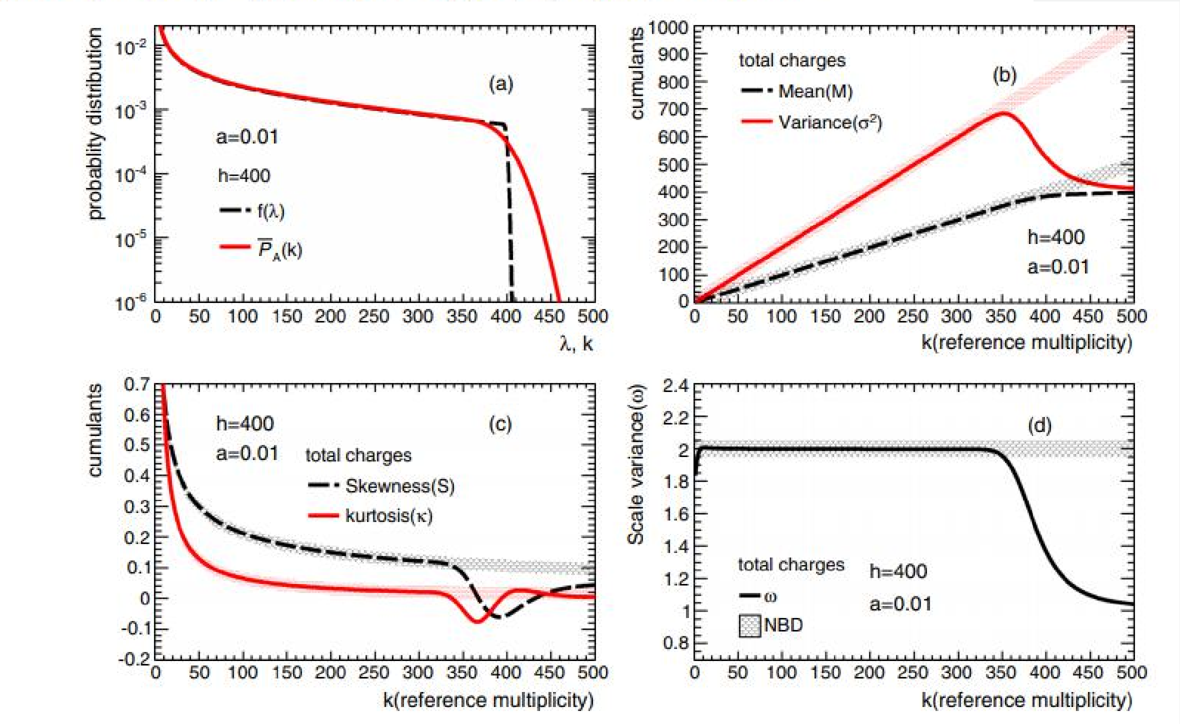
(Received 17 April 2016; revised manuscript received 11 August 2016; published 11 November 2016)

I investigate the volume corrections on cumulants of total charge distributions and net proton distributions. The required volume information is generated by an optical Glauber model. I find that the corrected statistical expectations of multiplicity distributions mimic the negative binomial distributions at noncentral collisions, and they tend to approach the Poisson ones at most-central collis
the volume corrections. However, net proton distributions a
to the external volume fluctuations at most-central collisions,
volume distributions in event-by-event multiplicity fluctuatio



优点：解析公式，不占计算资源

缺点：没有涨落

涨落

Glaber modeling in high energy nuclear collisions #1

Michael L. Miller (MIT, LNS), Klaus Reygers (Munster U.), Stephen J. Sanders (Kansas U.), Peter Steinberg (Brookhaven) (Jan, 2007)

Published in: *Ann.Rev.Nucl.Part.Sci.* 57 (2007) 205-243 • e-Print: nucl-ex/0701025 [nucl-ex]

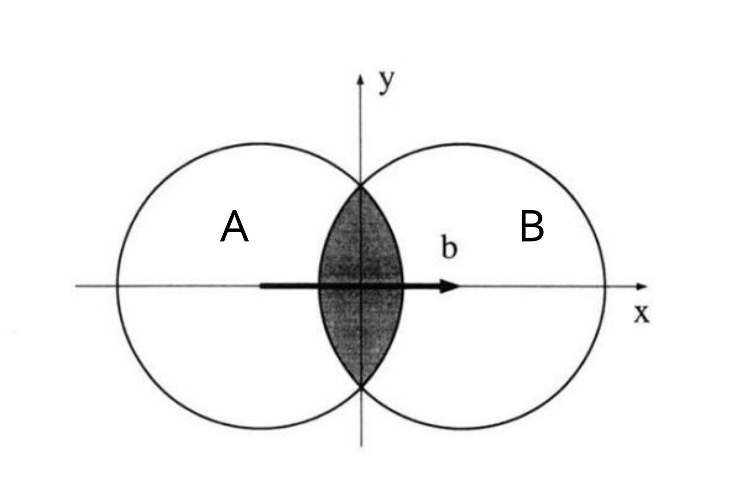
pdf DOI cite 1,467 citations

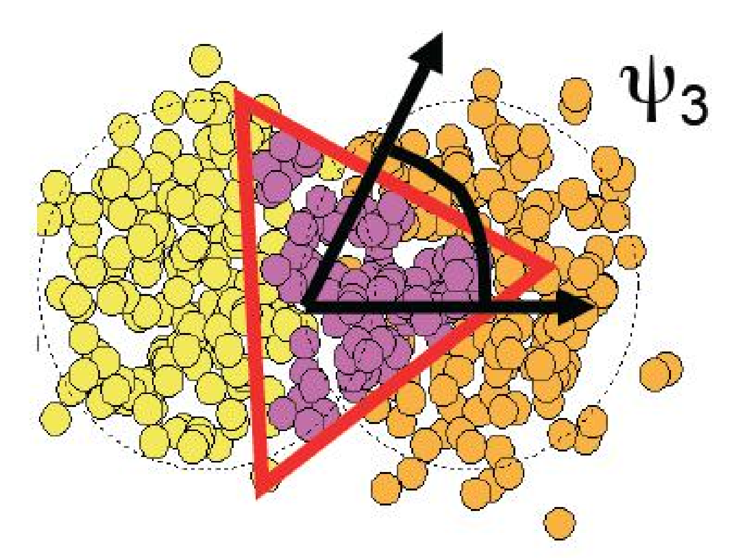
The PHOBOS Glauber Monte Carlo #3

B. Alver (MIT), M. Baker (Brookhaven), C. Loizides (MIT), P. Steinberg (Brookhaven) (May, 2008)

e-Print: 0805.4411 [nucl-ex]

pdf cite





The effect of triangular flow on di-hadron azimuthal correlations in relativistic heavy ion collisions #1

Jun Xu (Texas A-M), Che Ming Ko (Texas A-M, Cyclotron Inst. and Texas A-M) (Nov, 2010)

Published in: *Phys.Rev.C* 83 (2011) 021903 • e-Print: 1011.3750 [nucl-th]

pdf DOI cite 59 citations

Elliptic and triangular flow in event-by-event (3+1)D viscous hydrodynamics #2

Bjorn Schenke (McGill U.), Sangyong Jeon (McGill U.), Charles Gale (McGill U.) (Sep, 2010)

Published in: *Phys.Rev.Lett.* 106 (2011) 042301 • e-Print: 1009.3244 [hep-ph]

pdf DOI cite 611 citations

Triangular flow in event-by-event ideal hydrodynamics in Au+Au collisions at $\sqrt{s_{NN}} = 200A$ GeV #3

Hannah Petersen (Duke U.), Guang-You Qin (Duke U.), Steffen A. Bass (Duke U.), Berndt Muller (Duke U.) (Aug, 2010)

Published in: *Phys.Rev.C* 82 (2010) 041901 • e-Print: 1008.0625 [nucl-th]

pdf DOI cite 202 citations

Triangular flow in hydrodynamics and transport theory #4

Burak Han Alver (MIT, LNS), Clement Gombeaud (Saclay, SPhT), Matthew Luzum (Saclay, SPhT), Jean-Yves Ollitrault (Saclay, SPhT) (Jul, 2010)

Published in: *Phys.Rev.C* 82 (2010) 034913 • e-Print: 1007.5469 [nucl-th]

pdf DOI cite 345 citations

Collision geometry fluctuations and triangular flow in heavy-ion collisions #5

B. Alver (MIT), G. Roland (MIT) (Mar, 2010)

Published in: *Phys.Rev.C* 81 (2010) 054905, *Phys.Rev.C* 82 (2010) 039903 (erratum) • e-Print: 1003.0194 [nucl-th]

pdf DOI cite 807 citations

蒙特卡洛Glauber模型的一些细节

- 如何判断碰撞发生

Step function

$$d \leq \sqrt{\sigma_{\text{inel}}^{\text{NN}}/\pi}$$

Gaussian function

$$p(b) = Ae^{-\pi Ab^2/\sigma_{\text{inel}}}.$$

- Recenter(1)

PHYSICAL REVIEW C **84**, 064913 (2011)

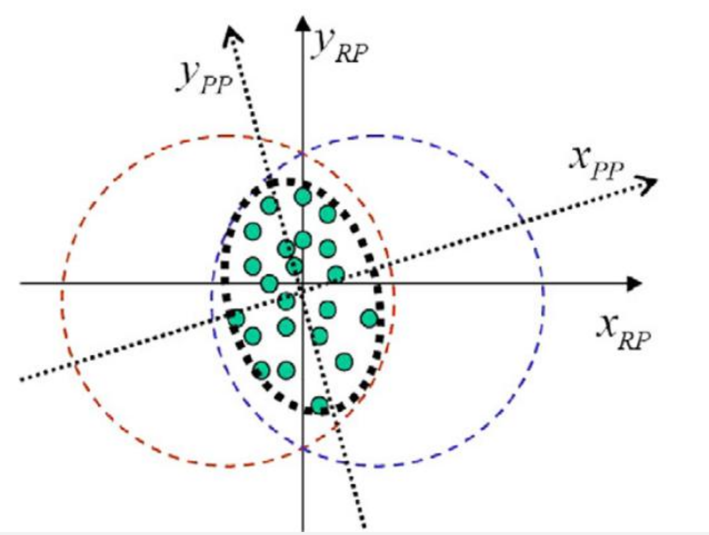
Wounded-nucleon model with realistic nucleon-nucleon collision profile and observables in relativistic heavy-ion collisions

Maciej Rybczyński[1,*] and Wojciech Broniowski[2,1,†]

[1] *Institute of Physics, Jan Kochanowski University, PL-25406 Kielce, Poland*

[2] *The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Kraków, Poland*

(Received 1 September 2011; published 22 December 2011)



Eccentricity (Point-like nucleons)

$$\psi_n\{\text{part}\} = \frac{1}{n}\left[\arctan\frac{\langle r^n \sin(n\varphi)\rangle}{\langle r^n \cos(n\varphi)\rangle} + \pi\right]$$

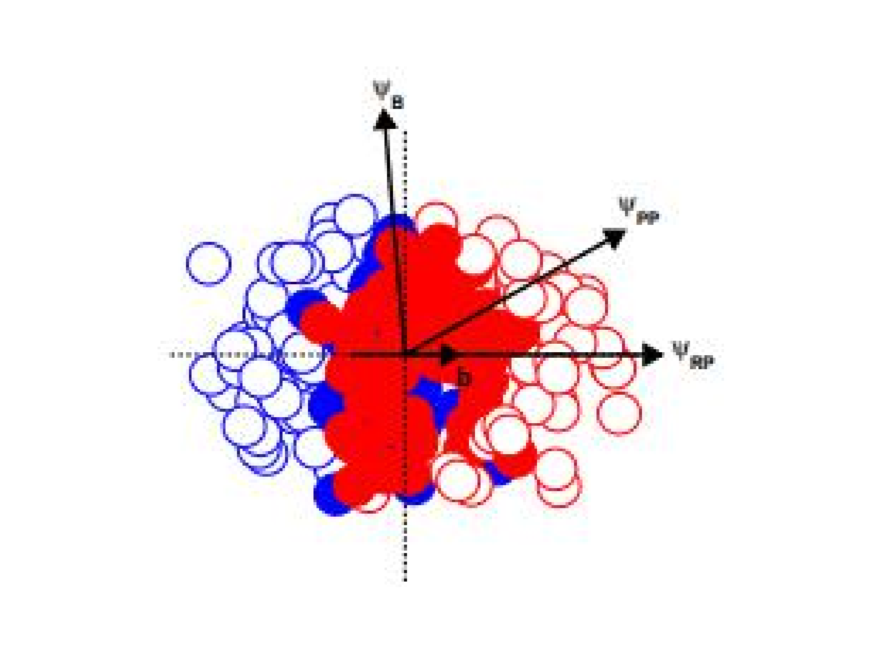
Recenter(2)

$$\varepsilon_n\{\text{part}\} = \frac{\sqrt{\langle r^n \cos(n\varphi)\rangle^2 + \langle r^n \sin(n\varphi)\rangle^2}}{\langle r^n\rangle},$$

$\varepsilon_n(b)$, $\varepsilon_n(N_{part})$

$\varepsilon_n(N_{ch})$,

$N_{ch} = n_{pp}(xN_{coll} + (1-x)N_{part}/2)$



Energy (entropy) density

Two-component Glauber

$$s_0(\boldsymbol{x}_\perp) = \left.\frac{dS}{\tau_0 dx dy d\eta_s}\right|_{\eta_s=0} = \frac{C}{\tau_0}\left(\frac{1-\delta}{2}\frac{dN_{\text{part}}}{d^2 x_\perp} + \delta\frac{dN_{\text{coll}}}{d^2 x_\perp}\right).$$

Color Glass condensate (CGC)

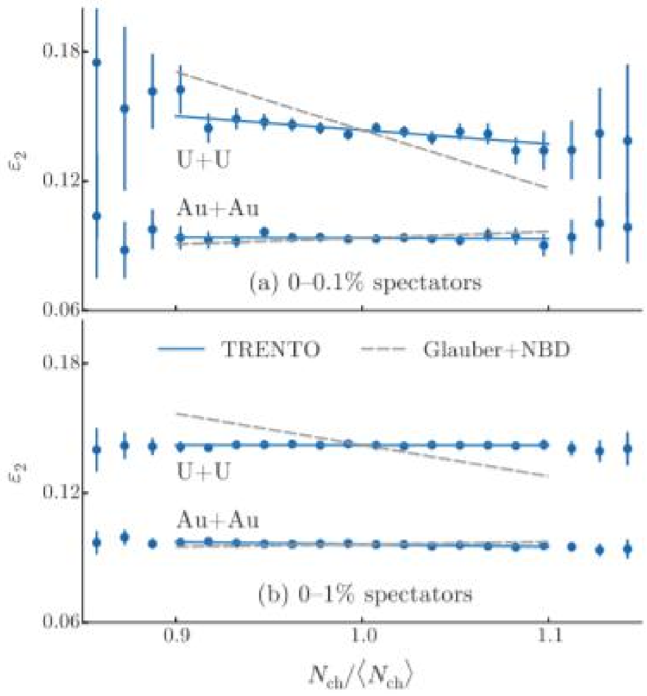
$$\frac{dN_g}{d^2 x_\perp dy} = \frac{2\pi^2}{C_F}\int\frac{d^2 p_T}{p_T^2}\int^{p_T}\frac{d^2 k_T}{4}\alpha_s(Q^2) \times \phi_A(x_1,(\boldsymbol{p}_T+\boldsymbol{k}_T)^2/4;\boldsymbol{x}_\perp) \times \phi_B(x_2,(\boldsymbol{p}_T-\boldsymbol{k}_T)^2/4;\boldsymbol{x}_\perp),$$

$$s_0(\boldsymbol{x}_\perp) = 3.6 n_g = 3.6\left.\frac{dN_g}{\tau_0 d^2 x_\perp d\eta_s}\right|_{y=\eta_s=0}.$$

$$Q^2_{s,A}(x;\boldsymbol{x}_\perp) = Q^2_{s,0}\frac{T_A(\boldsymbol{x}_\perp)}{T_{A,0}}\left(\frac{x_0}{x}\right)^\lambda$$

Energy (entropy) density

Trento model



PHYSICAL REVIEW C **92**, 011901(R) (2015)

Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions

J. Scott Moreland, Jonah E. Bernhard, and Steffen A. Bass
Department of Physics, Duke University, Durham, North Carolina 27708-0305, USA

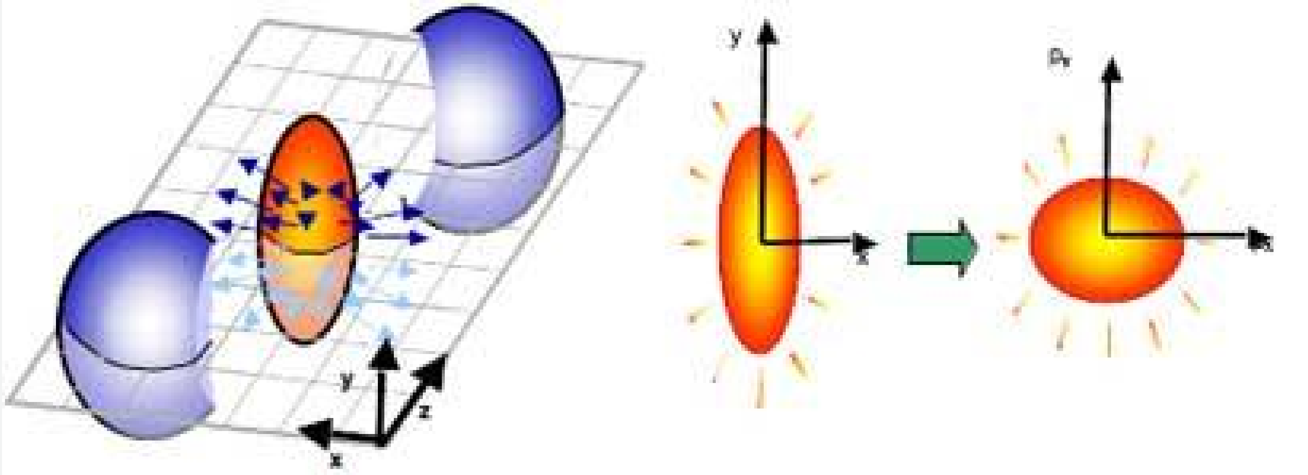
(Received 23 December 2014; revised manuscript received 11 May 2015; published 6 July 2015)

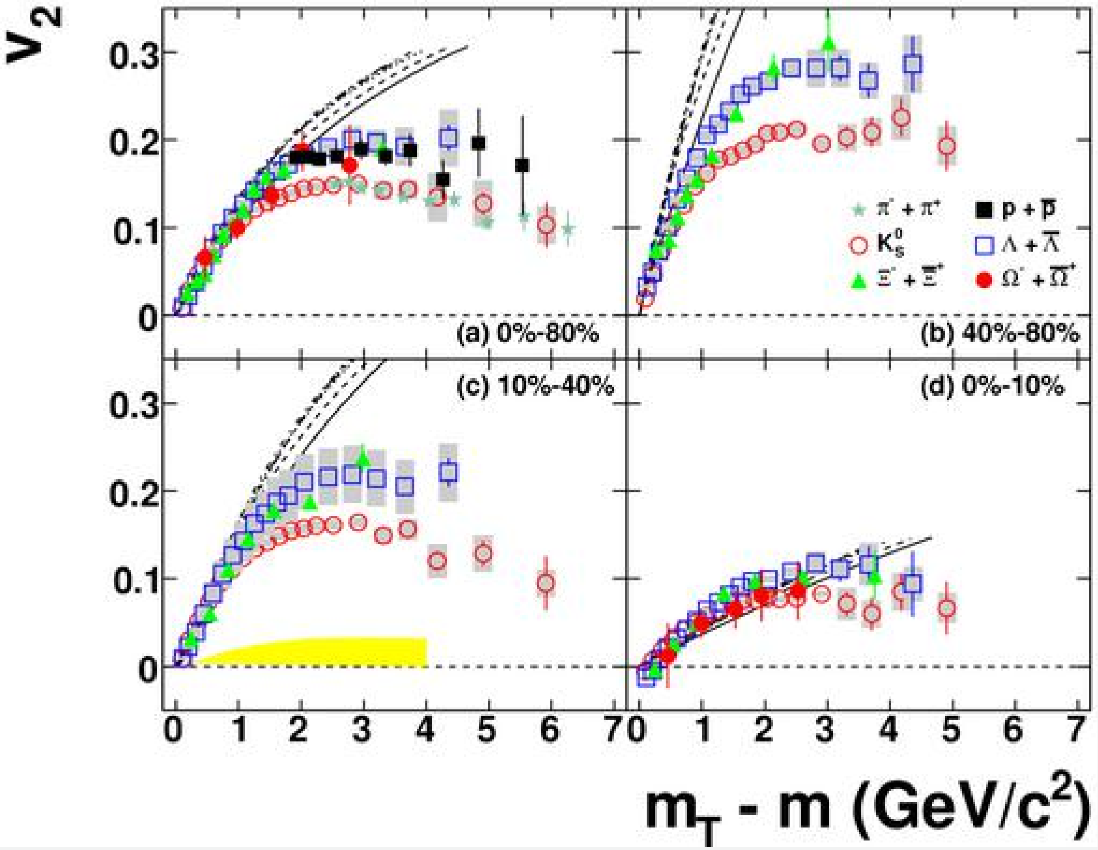
We introduce a new parametric initial-condition model for high-energy nuclear collisions based on eikonal entropy deposition via a "reduced-thickness" function. The model simultaneously describes experimental proton-proton, proton-nucleus, and nucleus-nucleus multiplicity distributions and generates nucleus-nucleus eccentricity harmonics consistent with experimental flow constraints. In addition, the model is compatible with ultracentral uranium-uranium data unlike existing models that include binary collision terms.

$$f = T_R(p;\, T_A, T_B) \equiv \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p},$$

$$T_R = \begin{cases} \max(T_A, T_B), & p \to +\infty \\ (T_A + T_B)/2, & p = +1 \text{ (arithmetic)} \\ \sqrt{T_A T_B}, & p = 0 \text{ (geometric)} \\ 2T_A T_B/(T_A + T_B), & p = -1 \text{ (harmonic)} \\ \min(T_A, T_B), & p \to -\infty. \end{cases}$$

Collision geometry and anisotropic flow





With the WS densities, we have made very successful connections between the final flow observable and the initial collision geometry.

$$\frac{dN}{d\phi} = N(1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]))$$

Prefect fluid - strong coupling QGP (sQGP)

STAR, PRC 77, 054901 (2018)

Q vector

PHYSICAL REVIEW C **83**, 044913 (2011)

Flow analysis with cumulants: Direct calculations

Ante Bilandzic,[1,2] Raimond Snellings,[2] and Sergei Voloshin[3]
[1] *Nikhef, Science Park 105, NL-1098 XG Amsterdam, The Netherlands*
[2] *Utrecht University, P.O. Box 80000, NL-3508 TA Utrecht, The Netherlands*
[3] *Wayne State University, 666 West Hancock Street, Detroit, Michigan 48201, USA*
(Received 6 October 2010; published 26 April 2011)

Anisotropic flow measurements in heavy-ion collisions provide important information on the properties of hot and dense matter. These measurements are based on analysis of azimuthal correlations and might be biased by contributions from correlations that are not related to the initial geometry, so-called nonflow. To improve anisotropic flow measurements, advanced methods based on multiparticle correlations (cumulants) have been developed to suppress nonflow contribution. These multiparticle correlations can be calculated by looping over all possible multiplets, however, this quickly becomes prohibitively CPU intensive. Therefore, the most used technique for cumulant calculations is based on generating functions. This method involves approximations, and has its own biases, which complicates the interpretation of the results. In this paper we present a new exact method for direct calculations of multiparticle cumulants using moments of the flow vectors.

$$Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i},$$

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

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2 \cdot \mathrm{Re}[Q_{2n} Q_n^* Q_n^*]}{M(M-1)(M-2)(M-3)} - 2\frac{2(M-2) \cdot |Q_n|^2 - M(M-3)}{M(M-1)(M-2)(M-3)}.$$

Hydrodynamics and flow

$$\partial_\mu T^{\mu\nu}(x) = 0 \quad \text{and} \quad \partial_\mu j^\mu(x) = 0,$$

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22 March 2001

PHYSICS LETTERS B

Physics Letters B 503 (2001) 58–64

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Radial and elliptic flow at RHIC: further predictions

P. Huovinen [a], P.F. Kolb [b,c], U. Heinz [b], P.V. Ruuskanen [d], S.A. Voloshin [e]

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[b] *Department of Physics, The Ohio State University, 174 West 18th Avenue, Columbus, OH 43210, USA*
[c] *Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*
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[e] *Department of Physics and Astronomy, Wayne State University, 666 W. Hancock Street, Detroit, MI 48202, USA*

Received 12 January 2001; accepted 30 January 2001
Editor: R. Gatto

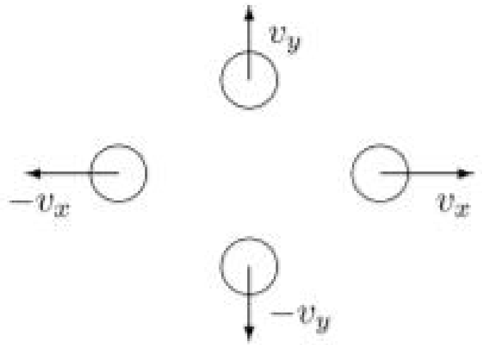


Fig. 6. Simple source of four fireballs.

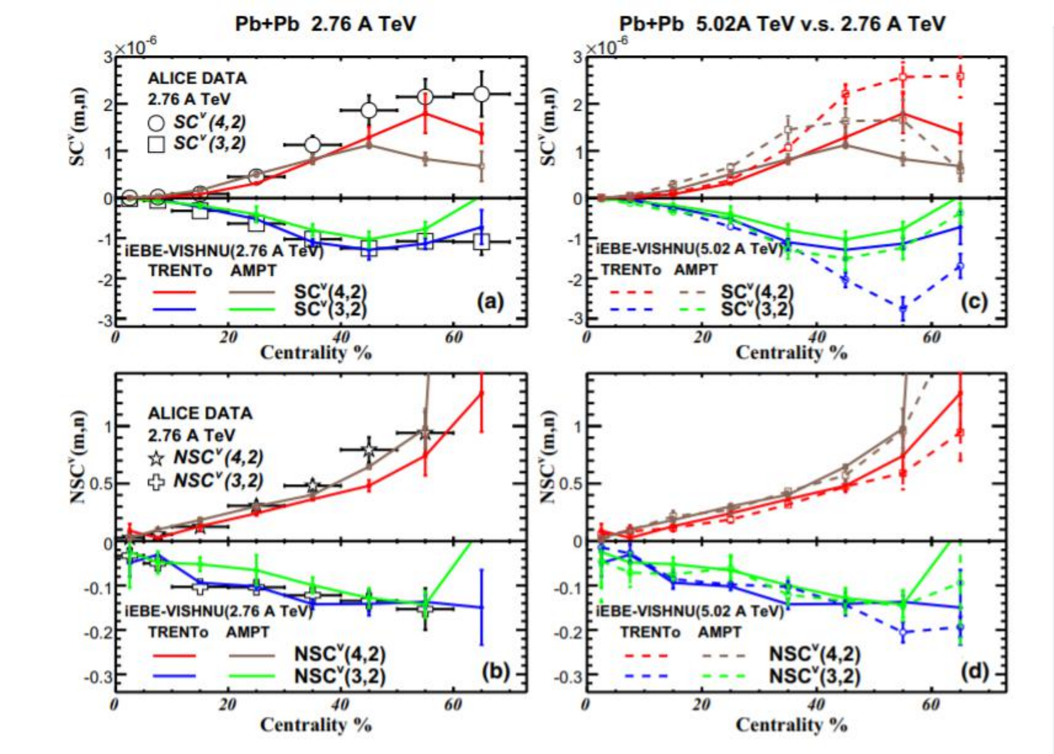
$$v_2(p_t) \approx \tanh\left(\frac{1}{2}\left(\frac{\kappa p_t - \lambda m_t}{T} + \mu\right)\right).$$

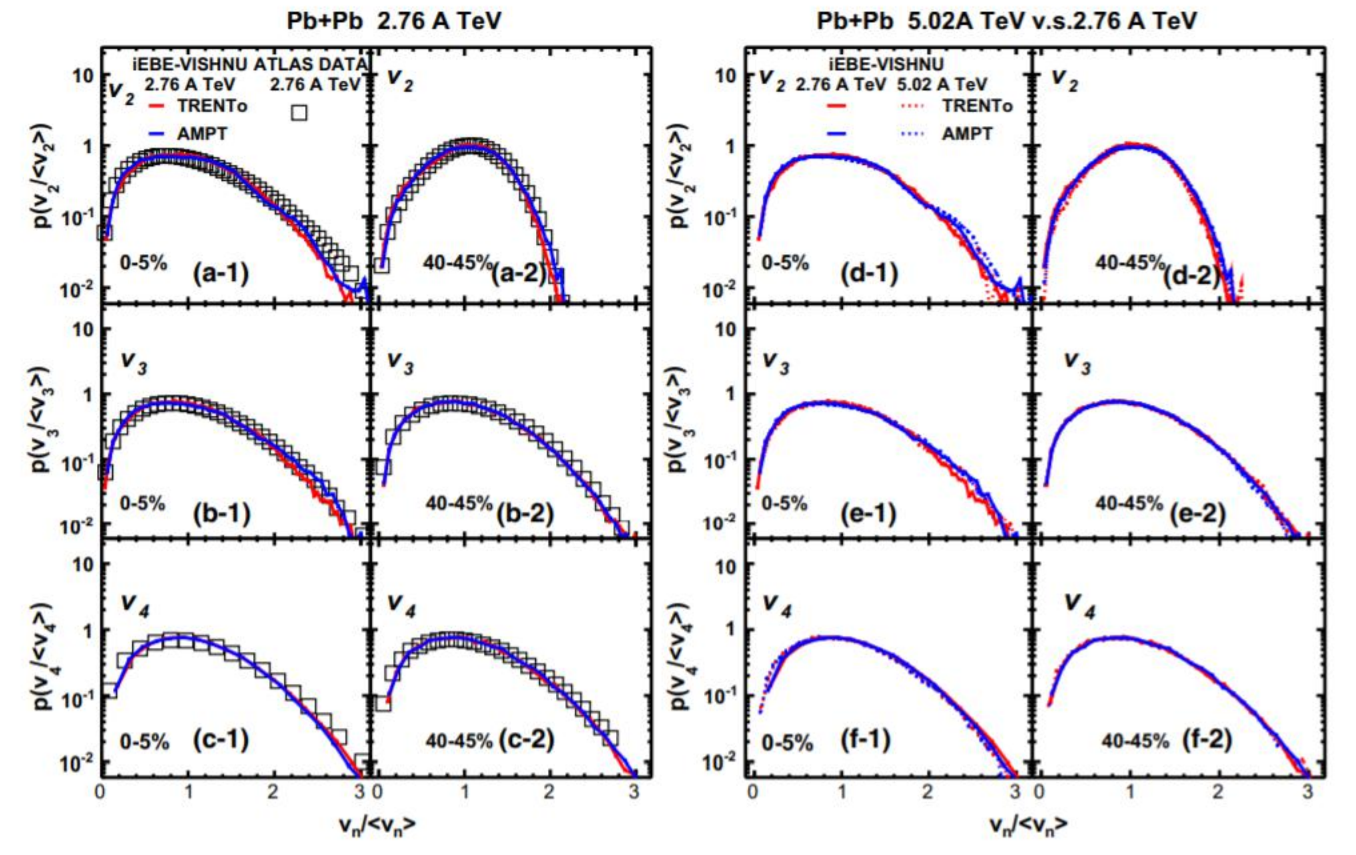
flow fluctuation & correlations

Collective flow in 2.76 A TeV and 5.02 A TeV Pb+Pb collisions #14

Wenbin Zhao (Peking U. and Peking U., SKLNPT), Hao-jie Xu (Peking U. and Peking U., SKLNPT), Huichao Song (CICQM, Beijing and Peking U., CHEP and Peking U., SKLNPT) (Mar 31, 2017)

Published in: *Eur.Phys.J.C* 77 (2017) 9, 645 • e-Print: 1703.10792 [nucl-th]





flow fluctuation in small system

Table 1
Four sets parameters used in iEBE-VISHNU simulations with HIJING initial conditions for pp collisions at 13 TeV.

	σ_R	σ_0	τ_0	η/s	K	T_{sw} (MeV)
Para-I	1.0	0.4	0.1	0.07	1.26	147
Para-II	0.8	0.4	0.2	0.08	1.25	148
Para-III	0.4	0.2	0.6	0.20	1.13	148
Para-IV	0.6	0.4	0.4	0.05	1.28	147

Physics Letters B 780 (2018) 495–500

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Physics Letters B

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Hydrodynamic collectivity in proton–proton collisions at 13 TeV

Wenbin Zhao [a,b], You Zhou [c,*], Hao-jie Xu [d,a], Weitian Deng [e], Huichao Song [a,b,f,*]

g University, Beijing 100871, China

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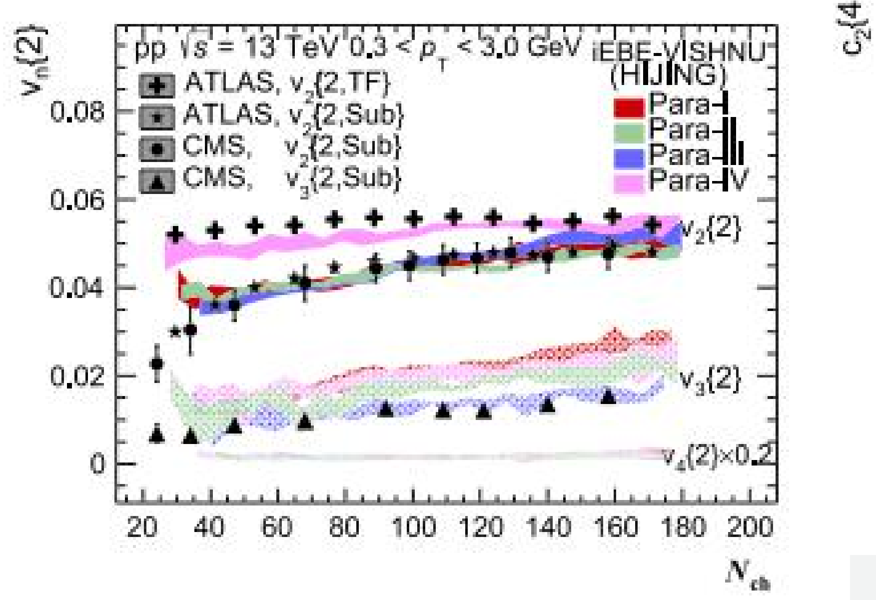
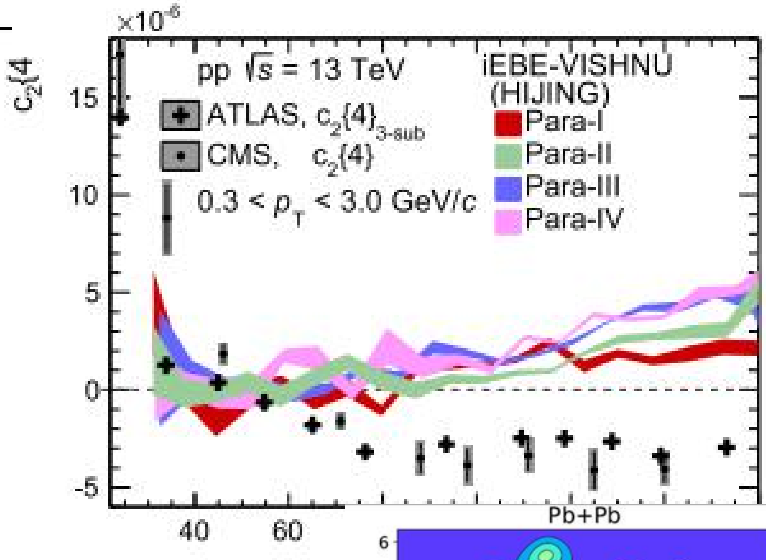
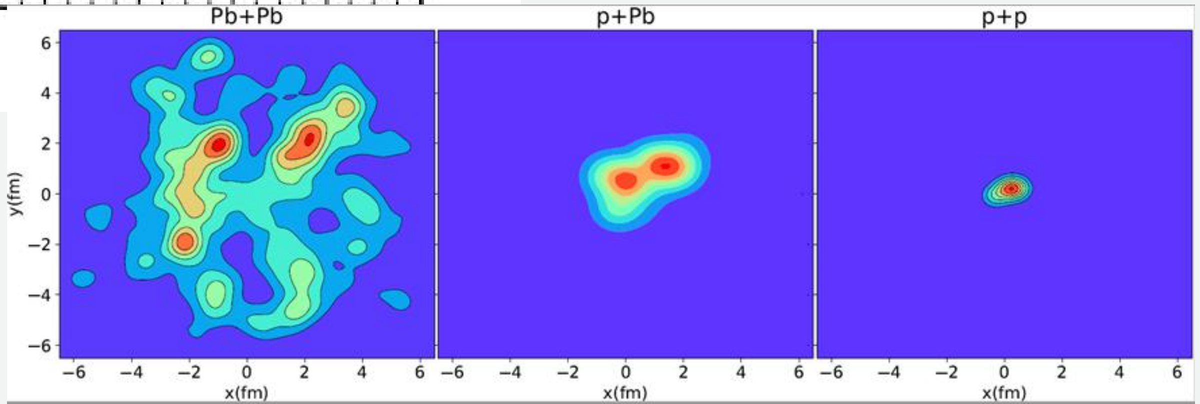




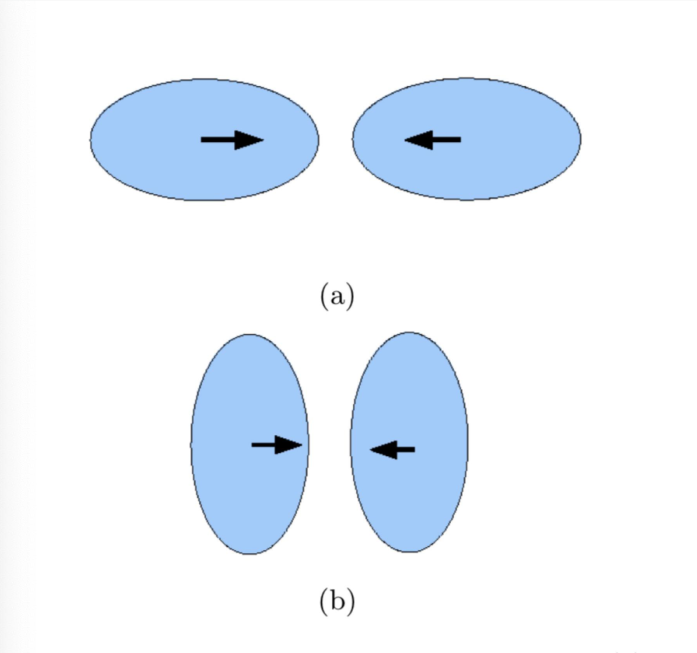


Effect of deformation

$$\rho(r) = \frac{\rho_0}{1 + \exp[\frac{r - R(1 + \beta_2 Y_{20} + \beta_4 Y_{40})}{a}]}$$

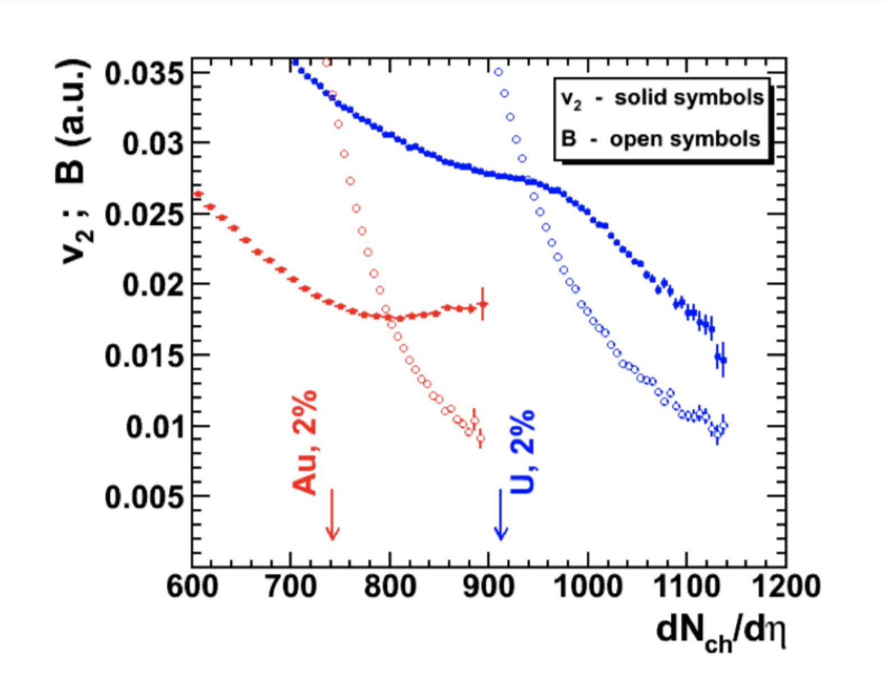
Au: $\beta_2 =- 0.131$; U: $\beta_2 = 0.28$

Knee structure of v2 distributions at most-central U+U collisions



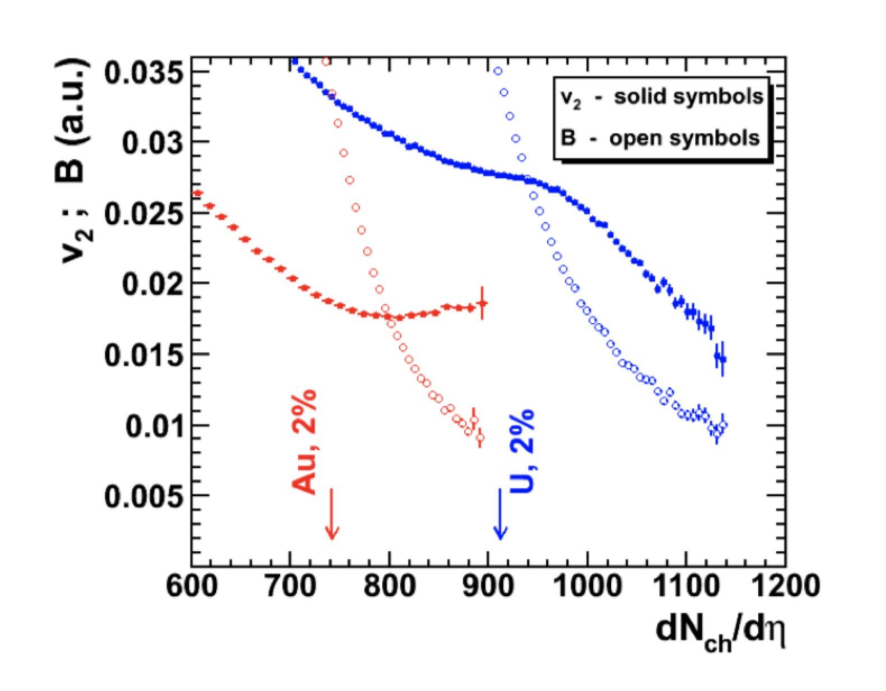
Small v_2

Large v_2

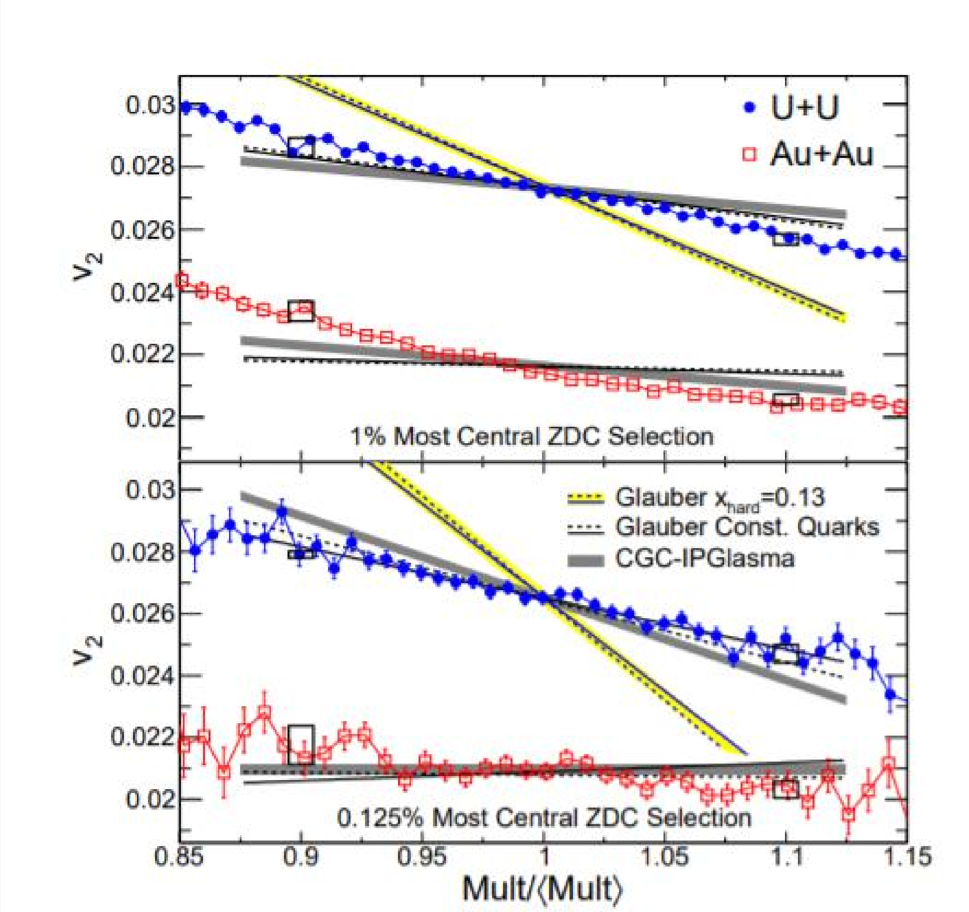


S. Voloshin, PRL105, 172301 (2010)

From Glauber to Trento

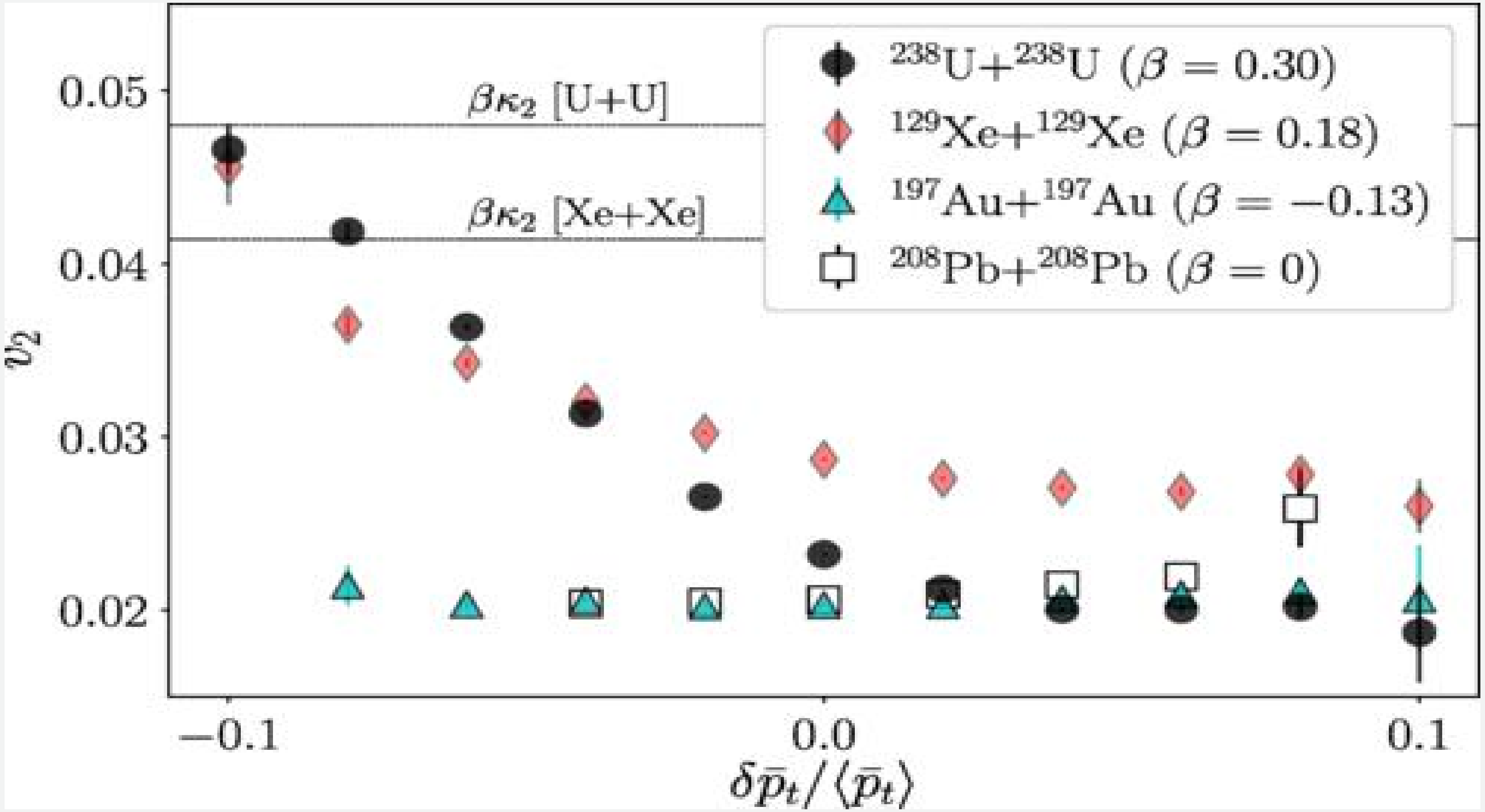


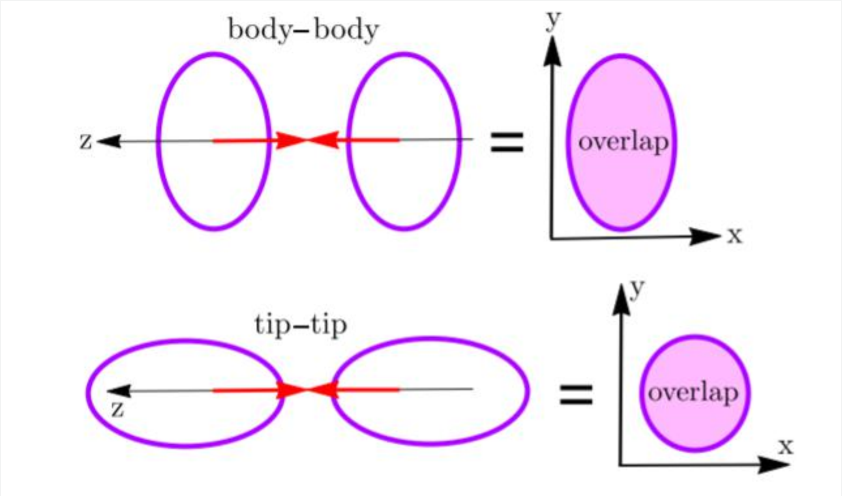
S. Voloshin, PRL105, 172301 (2010)



STAR, PRL115, 222301 (2015)

Prediction with Trento

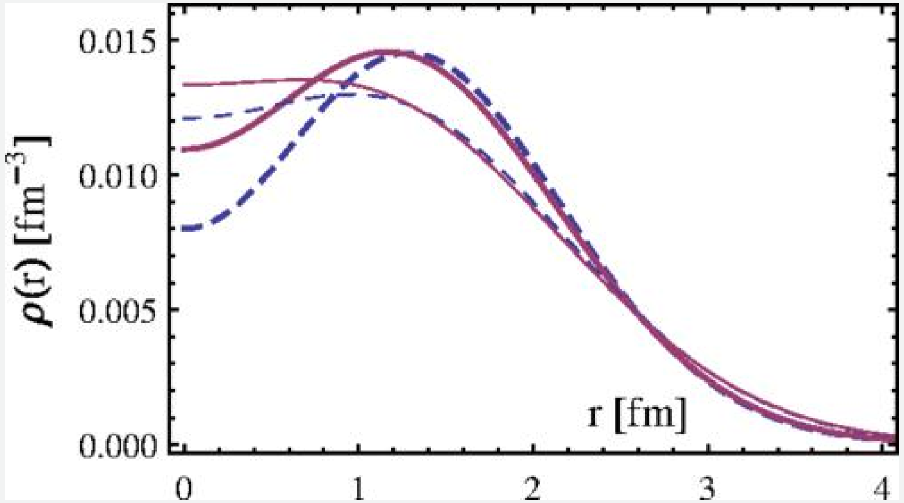


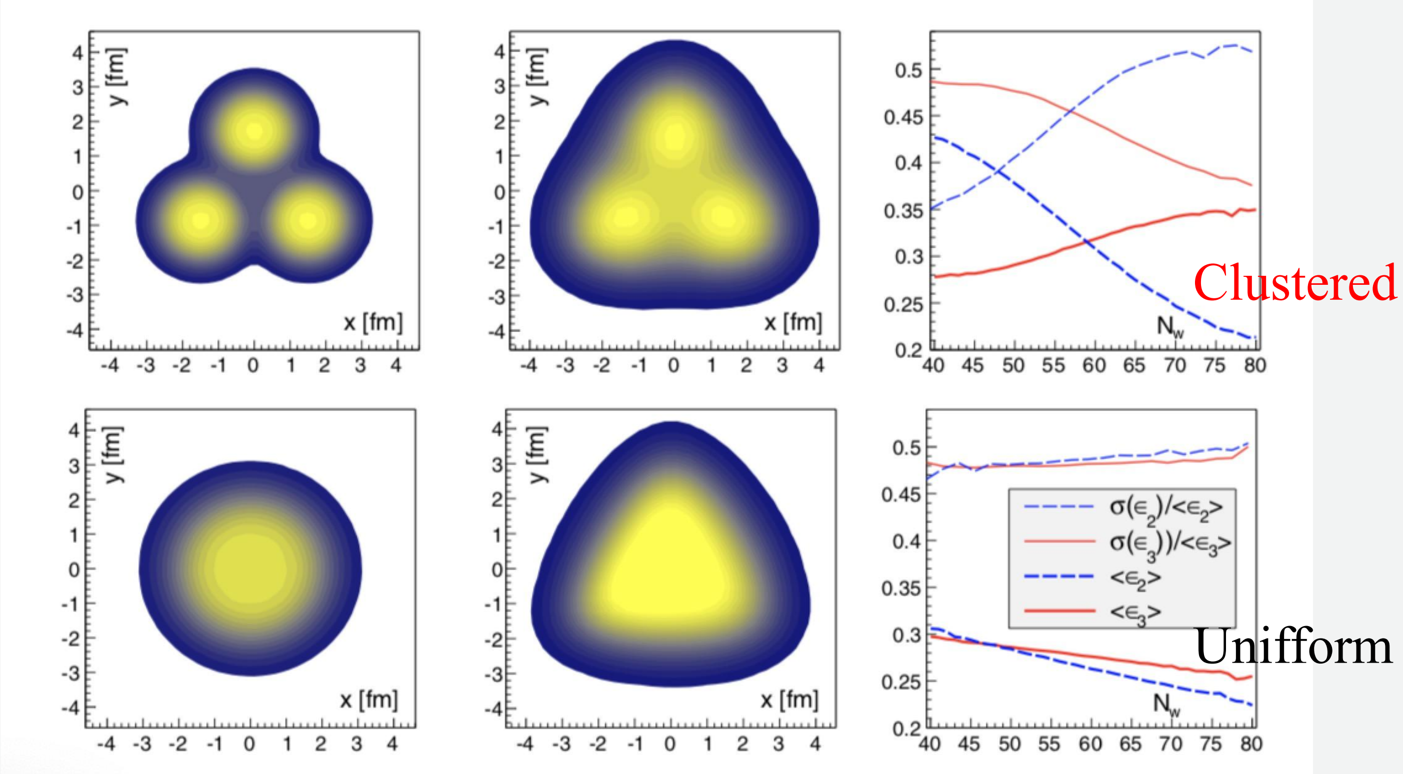


G. Giacalone, PRL124, 202301 (2020)

Effect of cluster correlations

$^{12}_{6}C + ^{208}_{82}Pb$

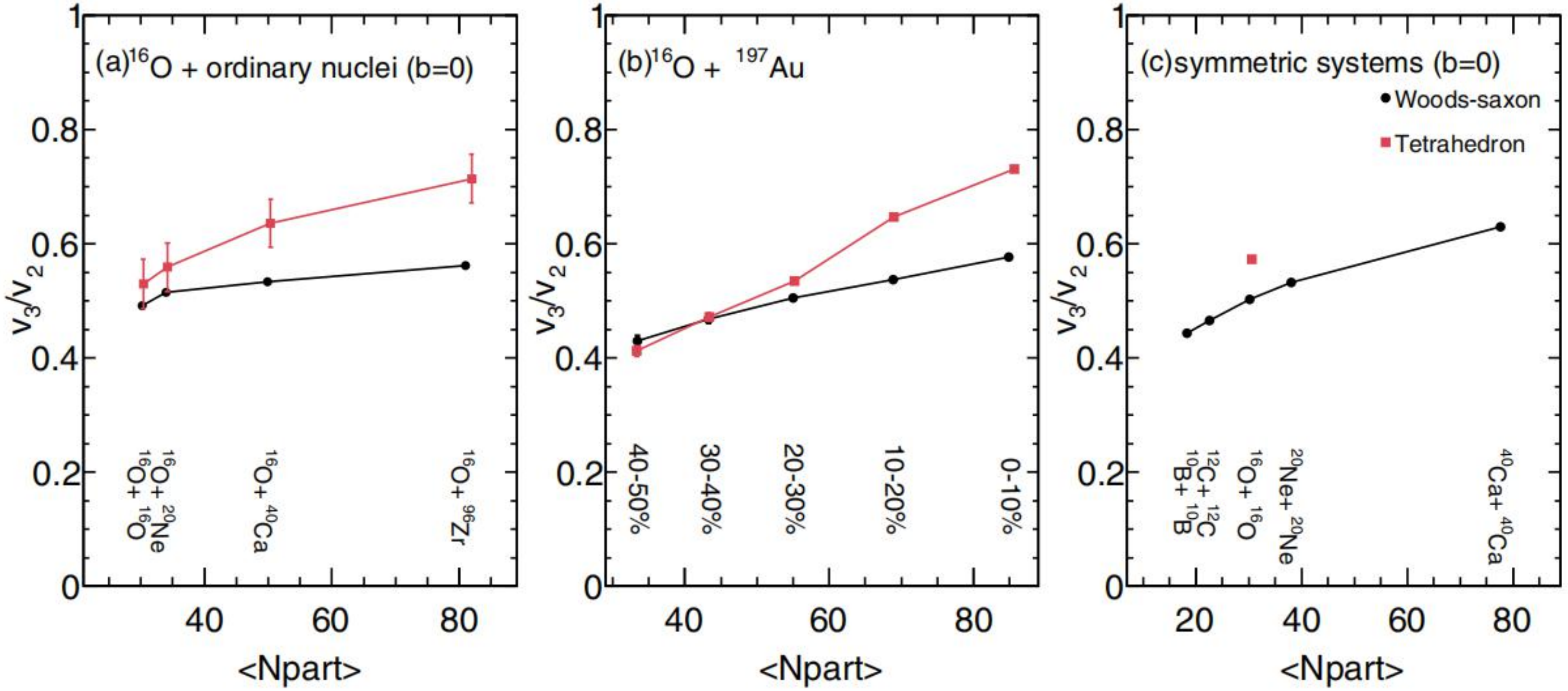




W. Broniowski, E. Arriola, PRL112, 112501 (2014)

The α-clustered and uniform 12C have very different predictions on v3, its event-by-event fluctuations, or the correlations of the v2 and v3

利用系统扫描甄别α-cluster结构



✓非对称系统扫描，v_3/v_2两种构型具有明显的差别，WS构型非常平坦

✓$^{16}O+^{197}Au$中心度依赖，高多重数下v_3/v_2的比，两种构型具有明显的差别

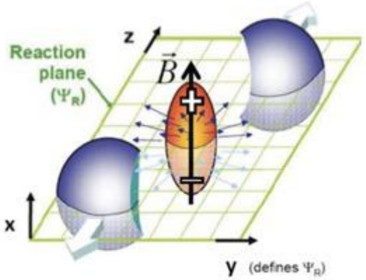
✓对称系统扫描，明显看到四面体构型的$^{16}O+^{16}O$系统系的v_3/v_2偏离系统学

Y.A. Li, S. Zhang, Y.G. Ma, Phys. Rev. C 102, 054907 (2020)

Isobar collisions

STAR

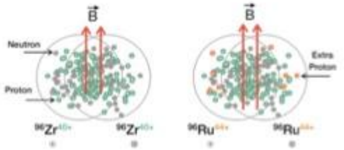
Chiral Magnetic Effect (CME)



- CME: a novel phenomenon predicted in HI collisions
  - Prerequisite: chiral imbalance+ magnetic field
  - Consequence: charge separation along *B* field

- **Experimental search is challenging due to overwhelming background → Isobar**

Isobar Blind Analysis



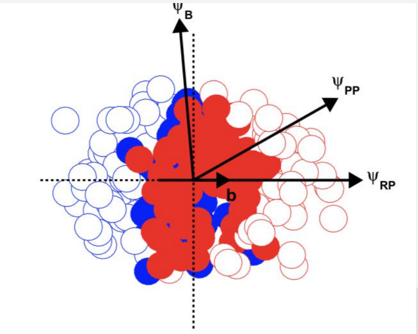
- **Mock data challenge** — Test data structure (27 GeV files)
- **Isobar-Mixed Analysis** — QA, physics & code freezing (One run is Ru+Zr)
- **Isobar-Blind Analysis** — Run-by-run QA, full analysis (One run is Ru/Zr)
- **Isobar-Unblind Analysis** — Full analysis (Ru and Zr separated)

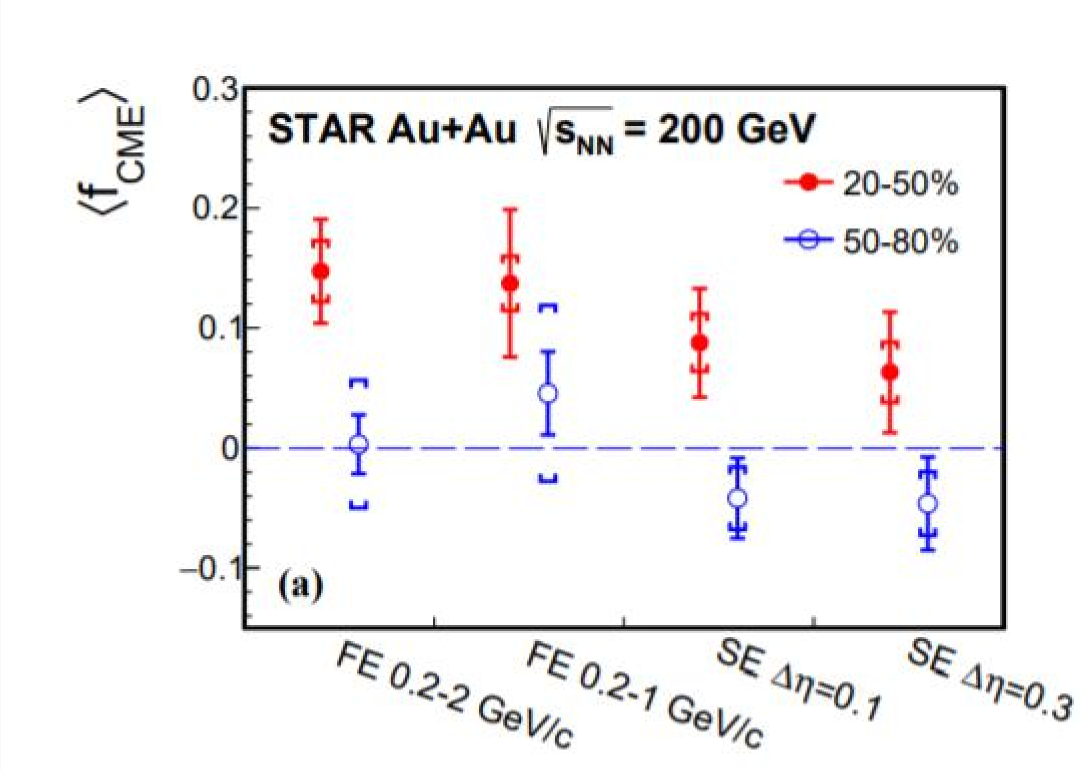
STAR, arXiv:1911.00596
Cartoon: arXiv:2009.01230

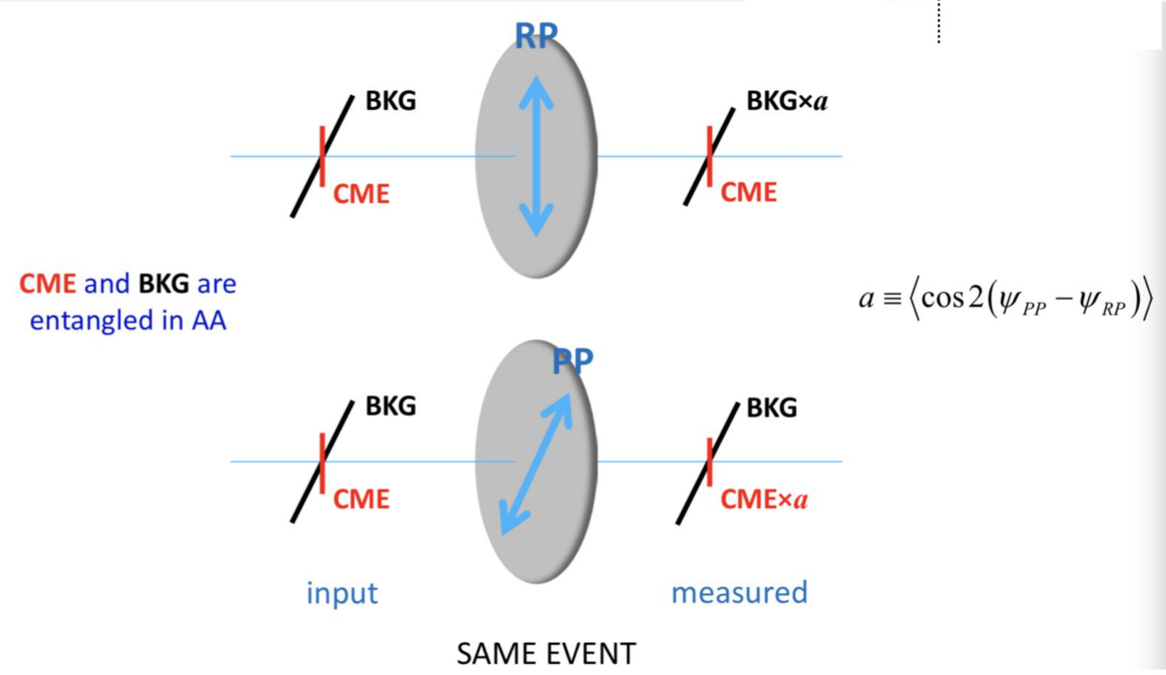
Processing...

05/17/2021 Rongrong Ma, SQM 2021 7

CME measured in Au+Au collisions





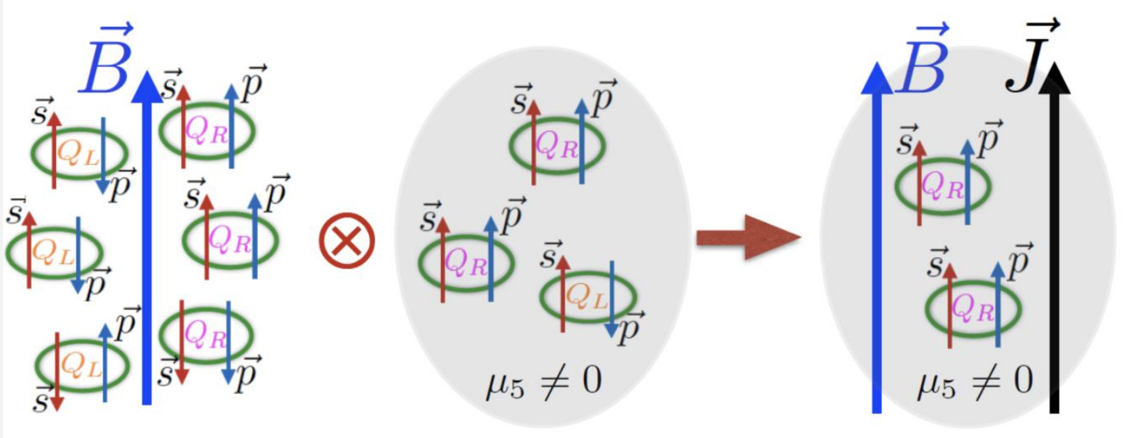


H. Xu, et.al, CPC42, 084103 (2018)

STAR, arXiv:2106.09243

III. 核结构对手征磁效应测量的影响

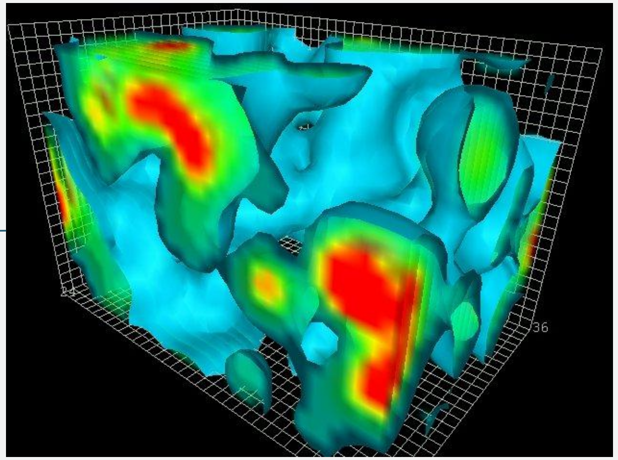
Chiral magnetic effect



Chiral magnetic effect (CME)

$$\mathbf{J}_{\mathbf{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \mathbf{B},$$

D. Kharzeev, PPNP88, 1(2016)

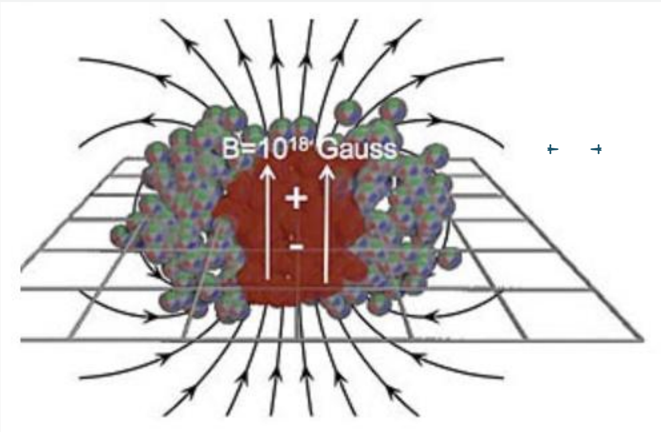


QCD Vacuum: Fluctuations of topological charge

$$Q_\mathrm{w} = \frac{g^2}{32\pi^2} \int \mathrm{d}^4 x\, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

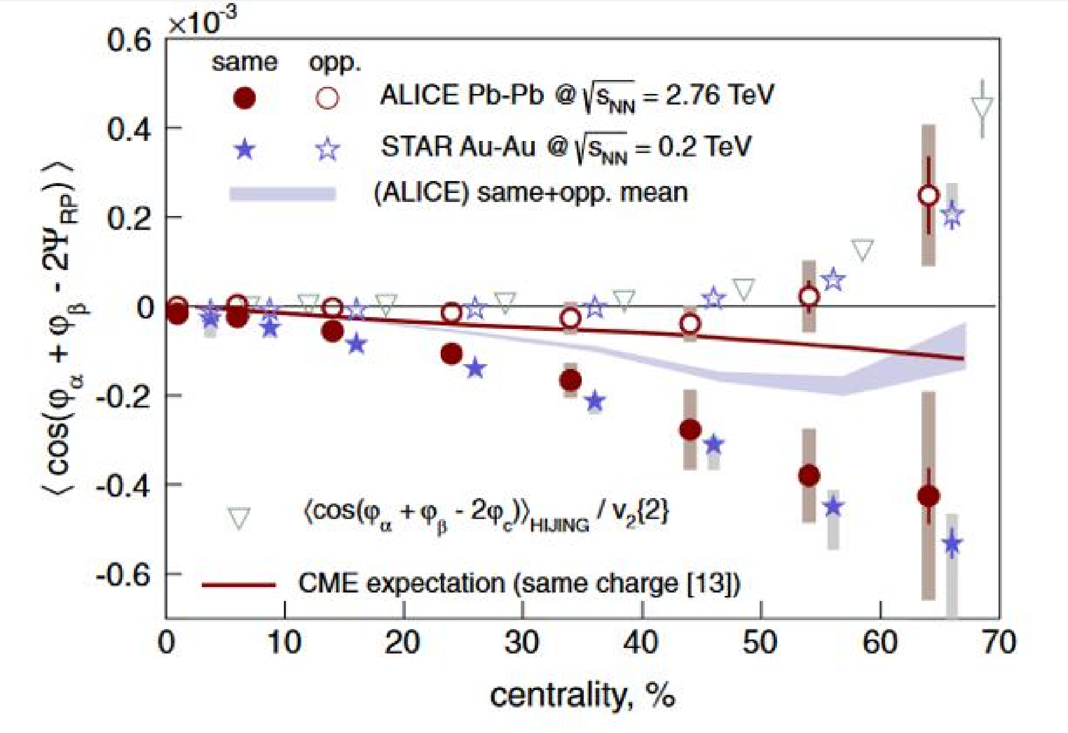
Strong magnetic field

$$eB \sim m_\pi^2 @HIC$$

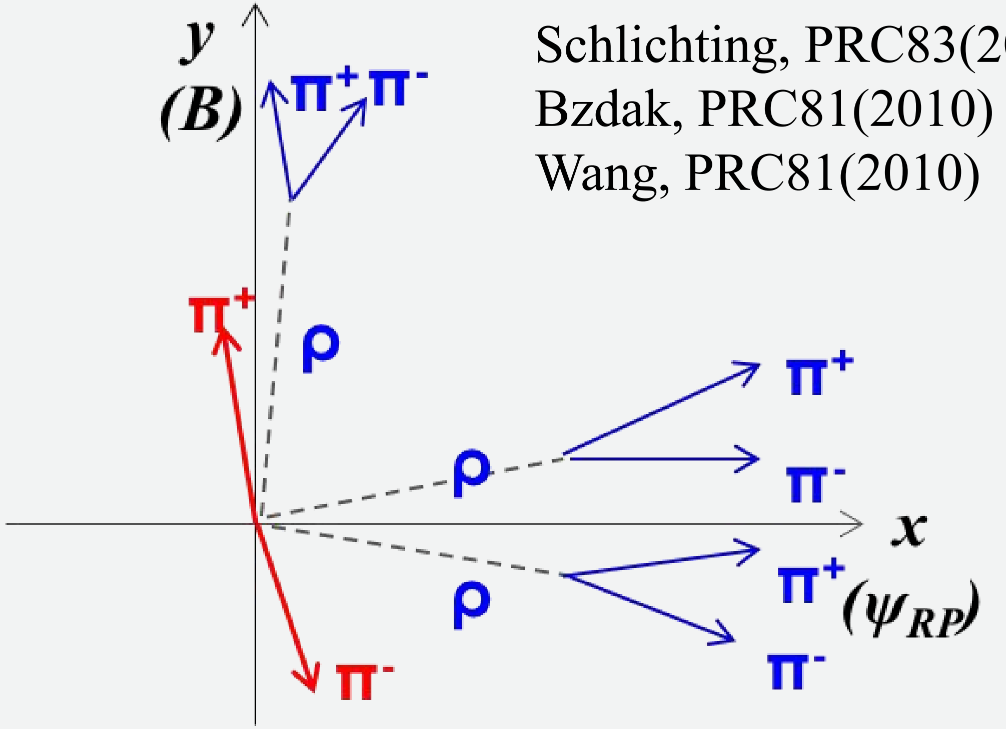


Signal and v_2 background

$$\gamma \equiv \langle \cos\left(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}\right)\rangle$$



STAR, PRL103, 251601 (2009)
ALICE, PRL110, 012301 (2013)



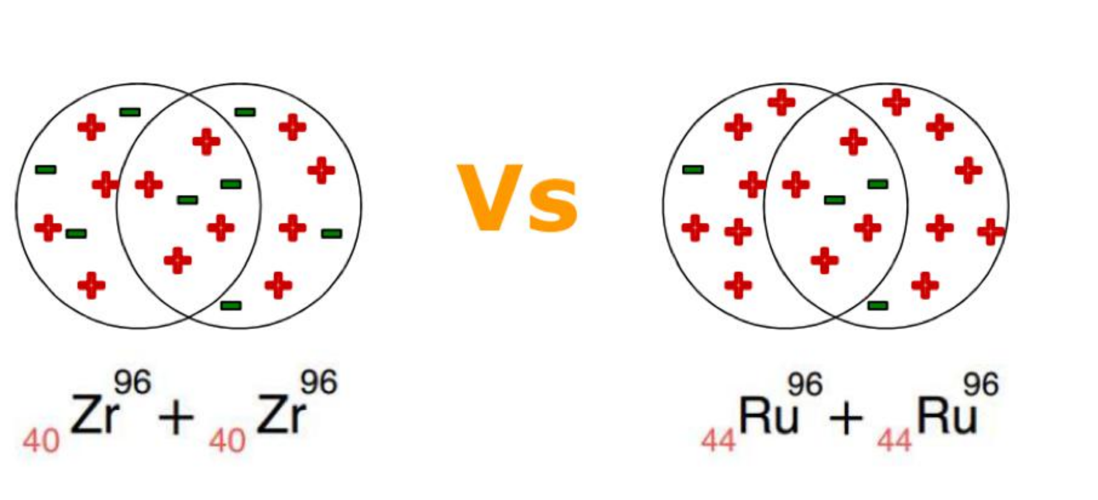
Schlichting, PRC83(2011)
Bzdak, PRC81(2010)
Wang, PRC81(2010)

Cluster decay + elliptic flow(v_2)

$$\begin{aligned}
& \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle \\
\propto\ & \langle\cos(\phi_\alpha + \phi_\beta - 2\phi_\rho + 2\phi_\rho - 2\Psi_{RP})\rangle \\
\simeq\ & \langle\cos(\phi_\alpha + \phi_\beta - 2\phi_\rho)\rangle\langle 2(\phi_\rho - |\Psi_{RP})\rangle \\
=\ & \langle\cos(\phi_\alpha + \phi_\beta - 2\phi_\rho)\rangle v_2^\rho
\end{aligned}$$

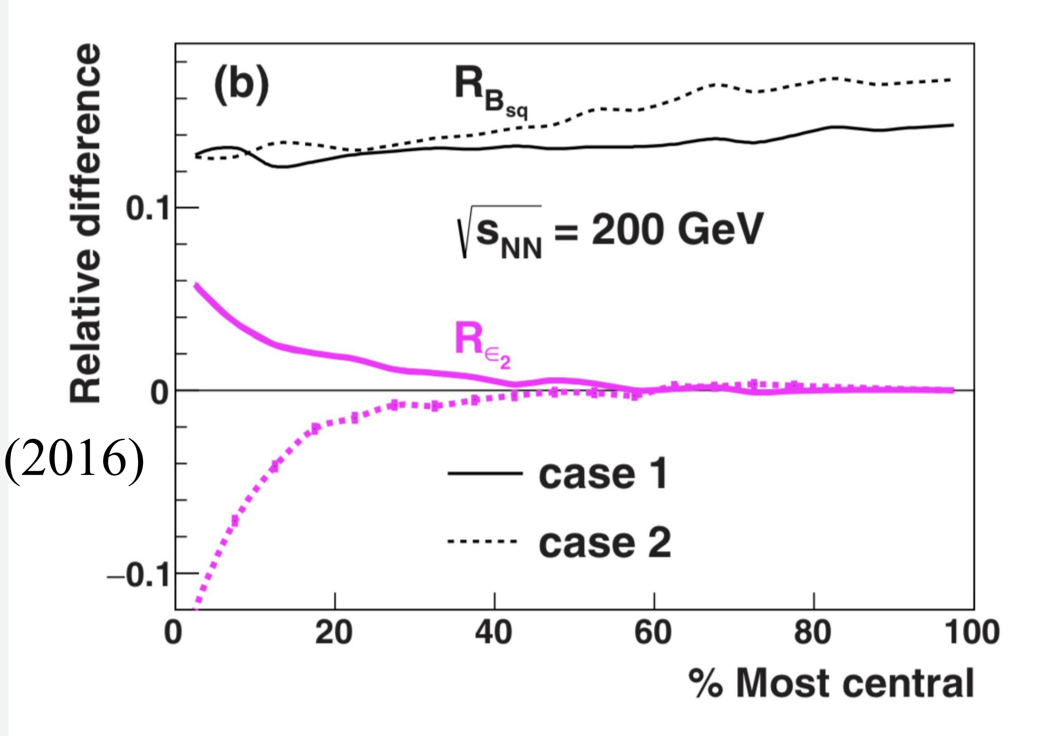
Isobar collisions

The isobar collisions was proposed to measure the chiral magnetic effect.
S. Voloshin, PRL105, 172301 (2010)



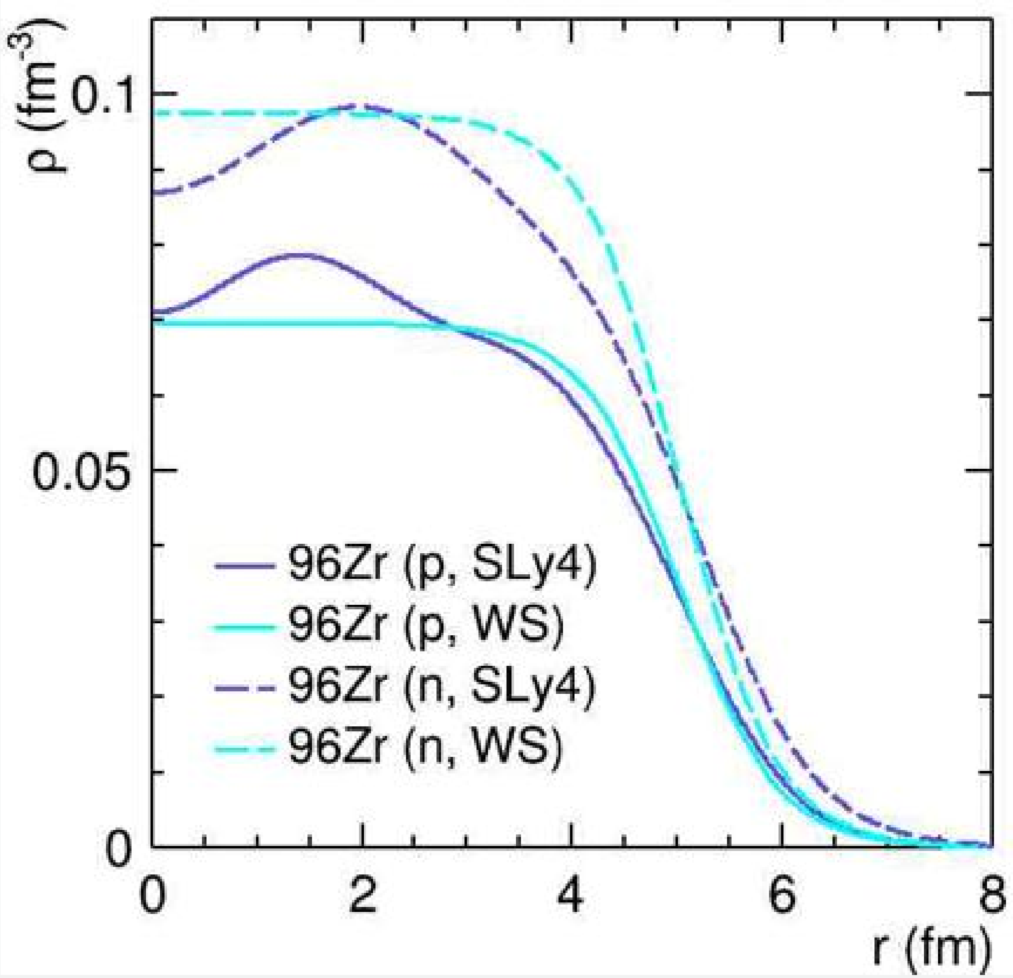
W. Deng, X. Huang, PRC94, 041901(2016)

	R	a	β_2
Zr	5.02	0.46	0.08/0.217
Ru	5.085	0.46	0.158/0.053

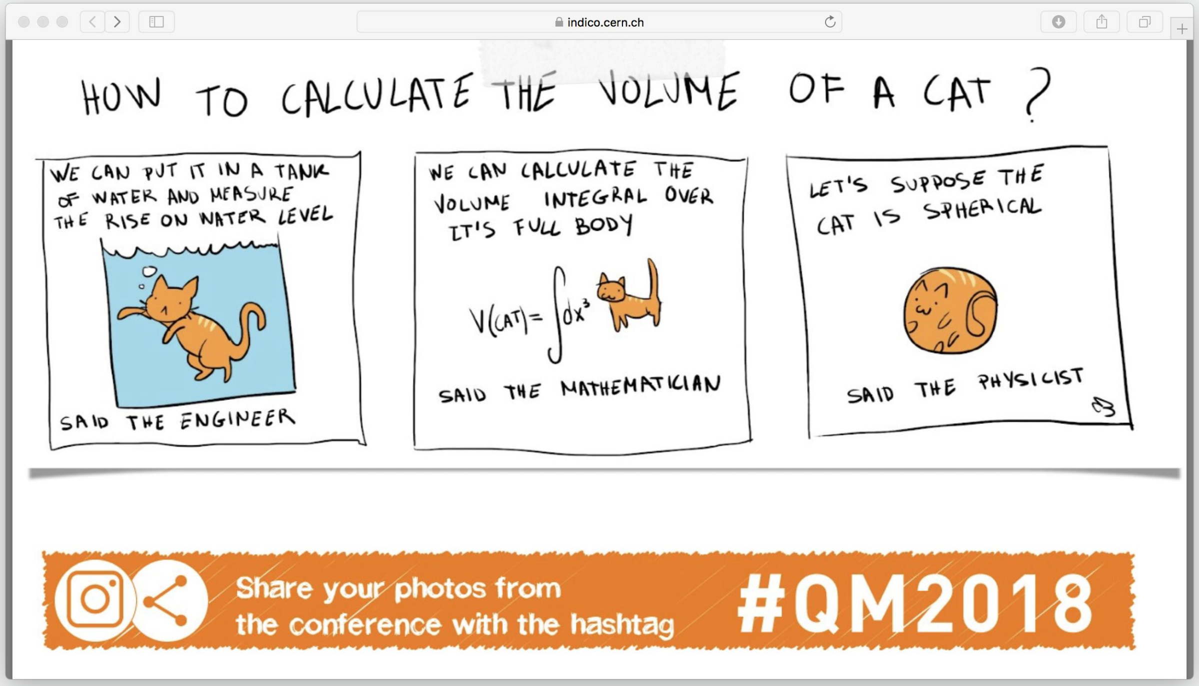


- Same eccentricities => flow background
- Different magnetic field => CME signals

DFT densities VS WS densities

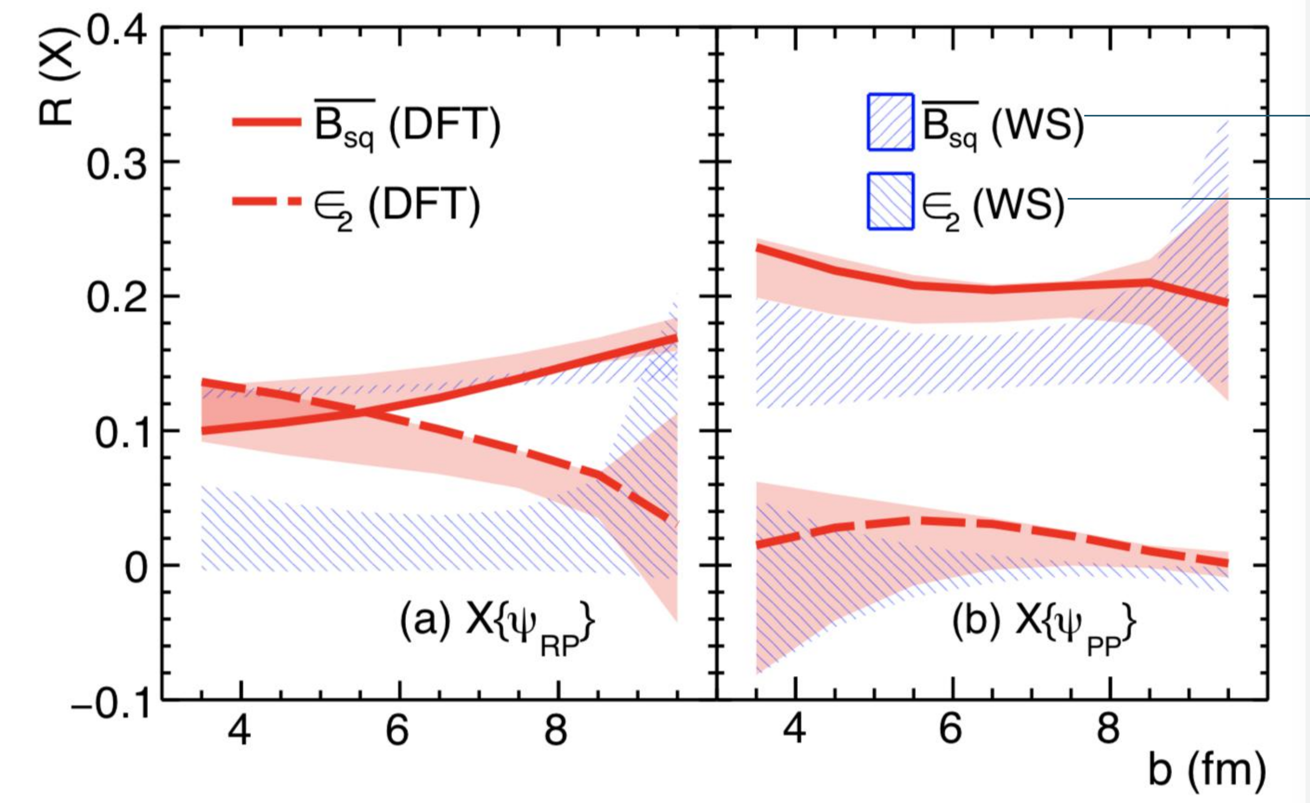


H. Xu, et.al, PRL121, 022301 (2018)



Instead of the WS densities, we use the densities obtained from the **density functional theory (DFT)** with parameter set SLy4.

Static model: Monte Carlo Glauber model



Signal

Background

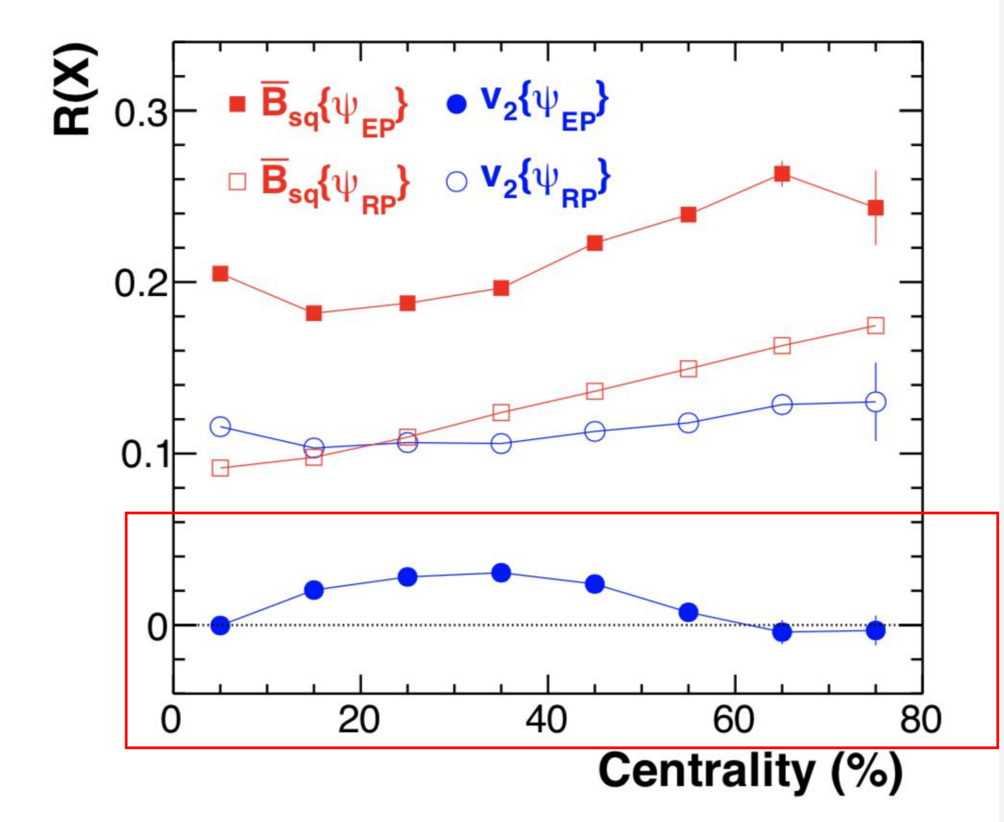
Monte Carlo Glauber Model

$$R(X) \equiv 2(X_{\mathrm{RuRu}} - X_{\mathrm{ZrZr}})/(X_{\mathrm{RuRu}} + X_{\mathrm{ZrZr}}),$$

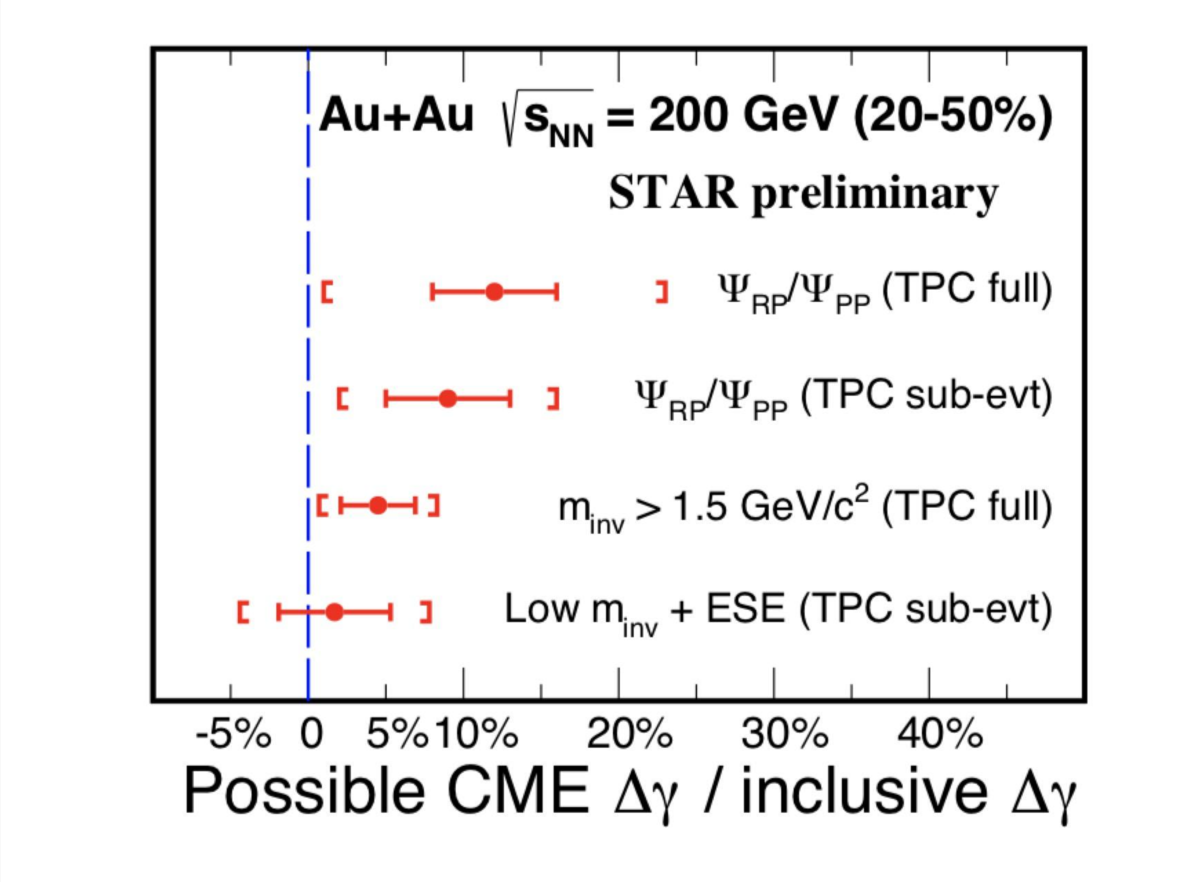
$$\epsilon_2\{\psi\} = \langle\langle \cos 2(\phi - \psi) \rangle\rangle$$

$$\overline{B_{sq}}\{\psi\} = \langle \int N_{part}^2(\mathbf{r})(eB(r,0)/m_\pi^2)^2 \cos 2(\psi_B - \psi) d\mathbf{r} / \int N_{part}^2(\mathbf{r}) d\mathbf{r} \rangle$$

AMPT simulations



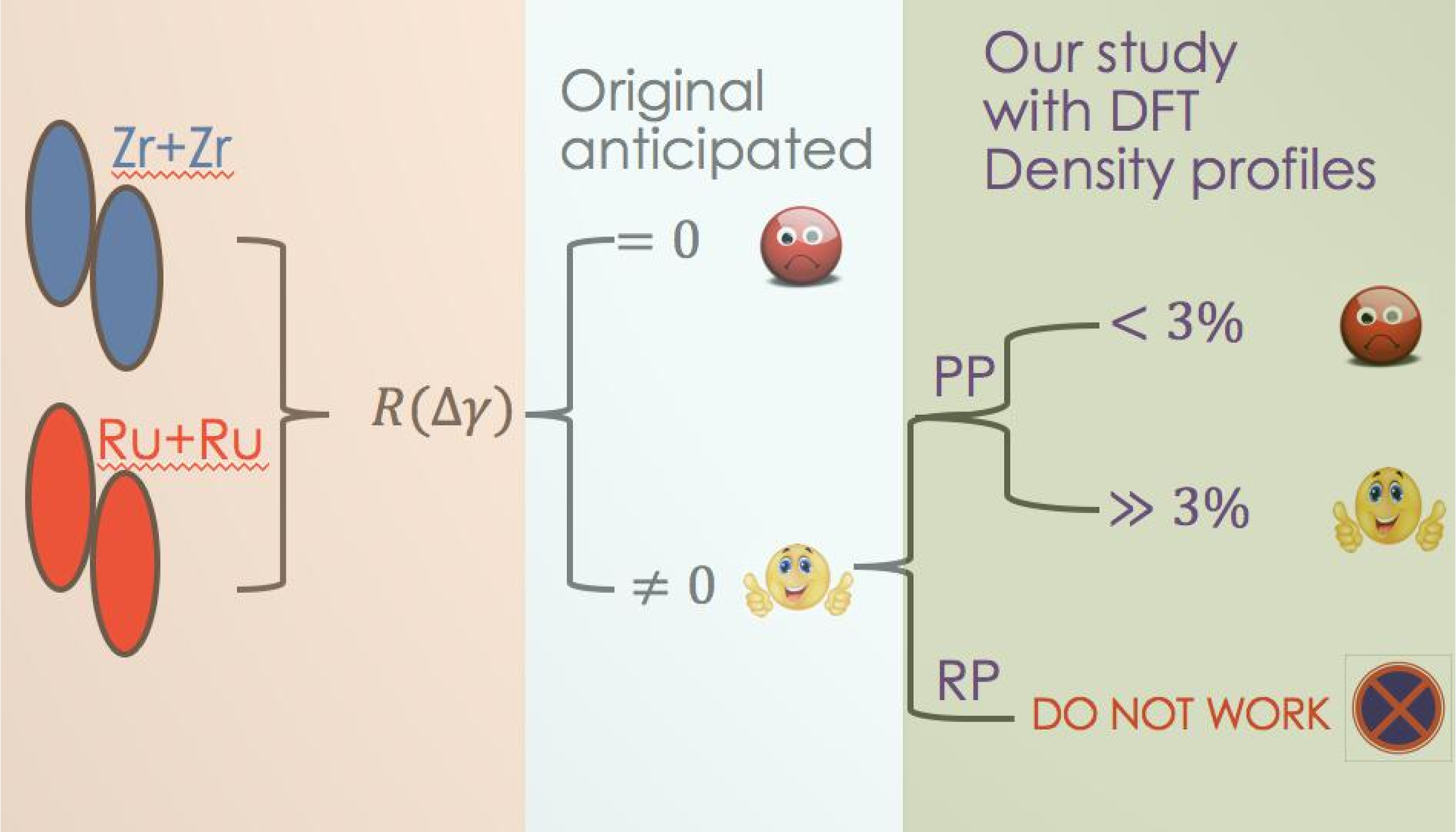
AMPT model



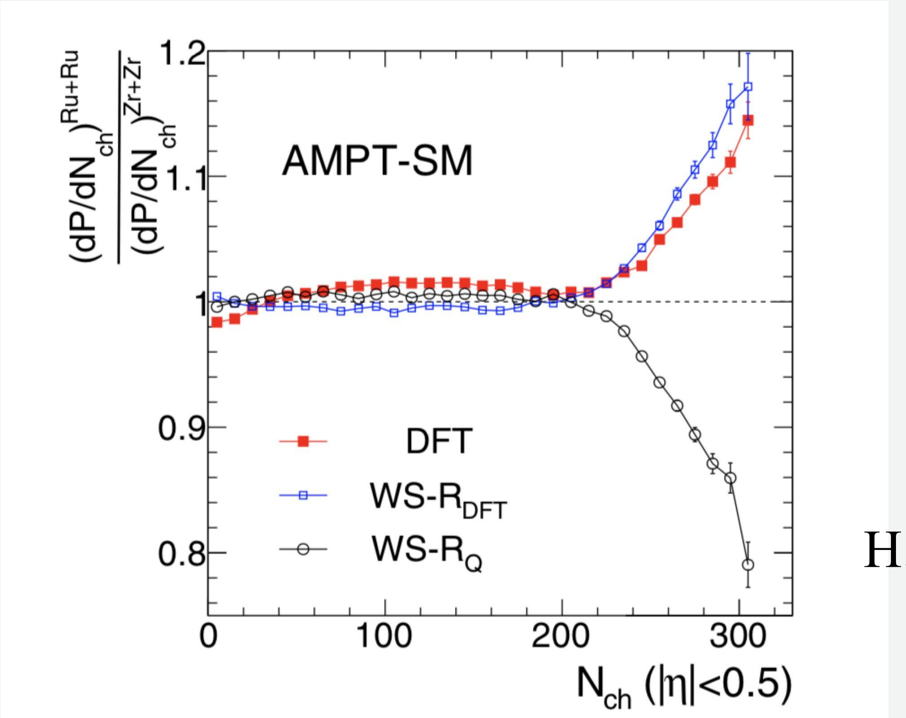
J. Zhao (STAR), NPA982, 535(2019)

Background dominated

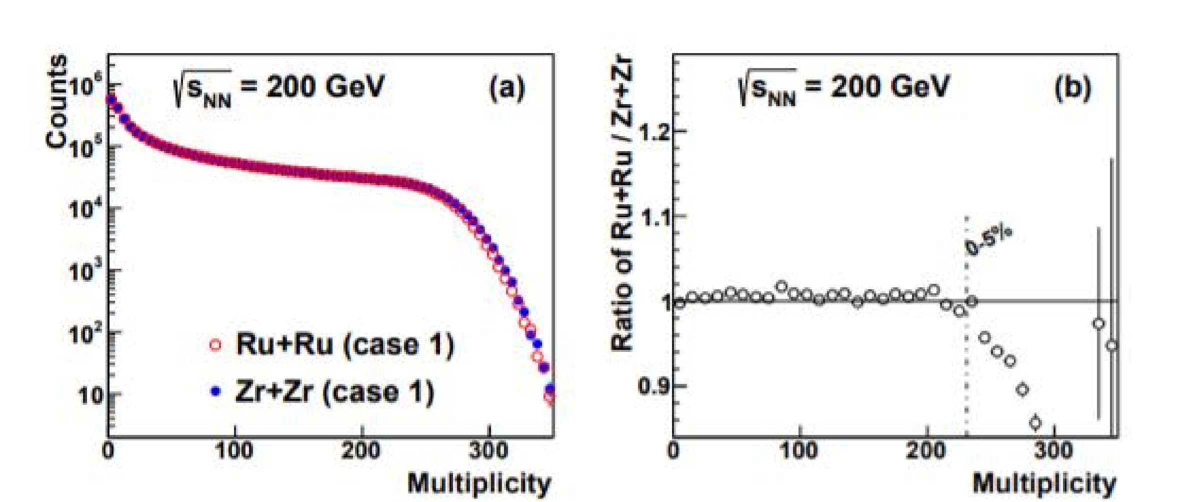
--- The CME signal, if exist, is very small


Zr+Zr
Ru+Ru
$R(\Delta\gamma)$
Original anticipated
= 0
≠ 0
Our study with DFT Density profiles
PP
< 3%
≫ 3%
RP
DO NOT WORK

Multiplicity distributions

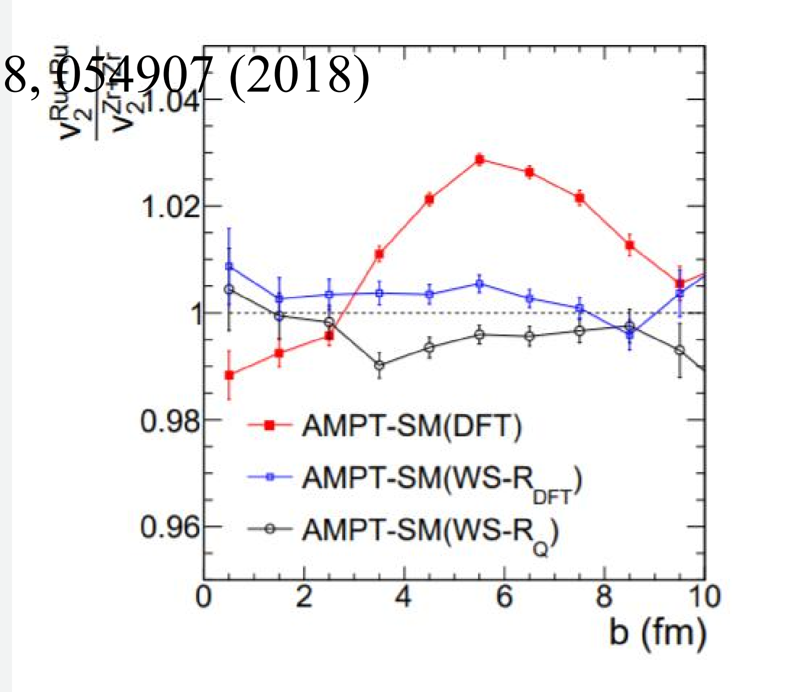


		$^{96}_{44}$Ru		$^{96}_{40}$Zr	
		Charge	mass	Charge	mass
WS-R_Q	R_0	5.085 [5]		5.020 [5]	
	$\sqrt{\langle r^2\rangle}$	4.294		4.248	
DFT	$\sqrt{\langle r^2\rangle}$	4.327	4.343	4.271	4.366
	$R_0 \equiv 1.183\sqrt{\langle r^2\rangle}$	5.119	5.138	5.053	5.165



W. Deng, X. Huang, PRC94, 041901(2016)

H. Li, et.al, PRC98, 054907 (2018)



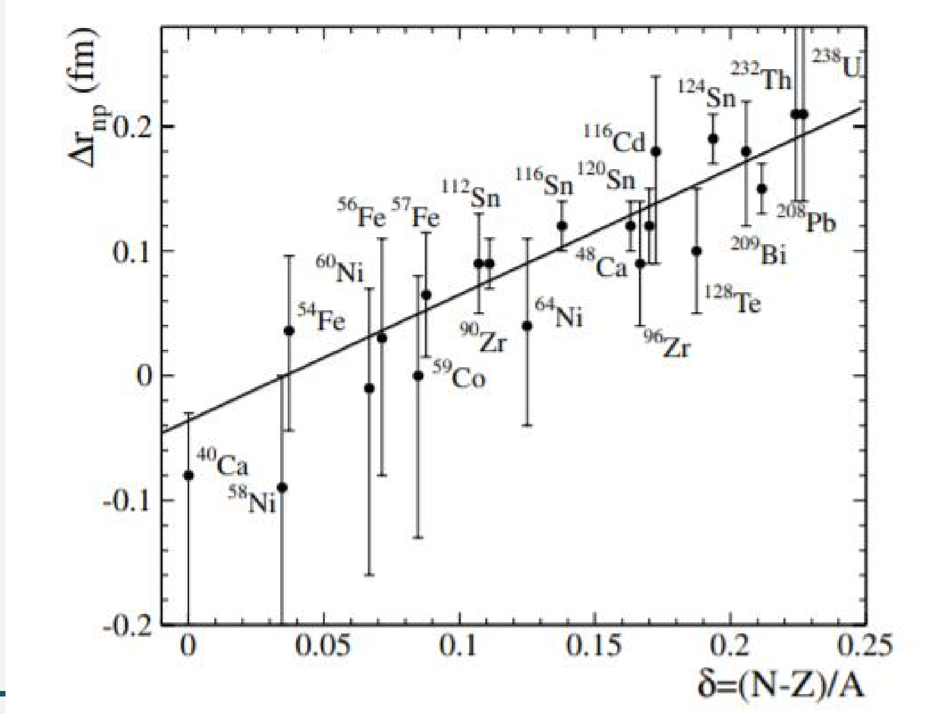
IV. 通过同量异位素核碰撞测量中子皮

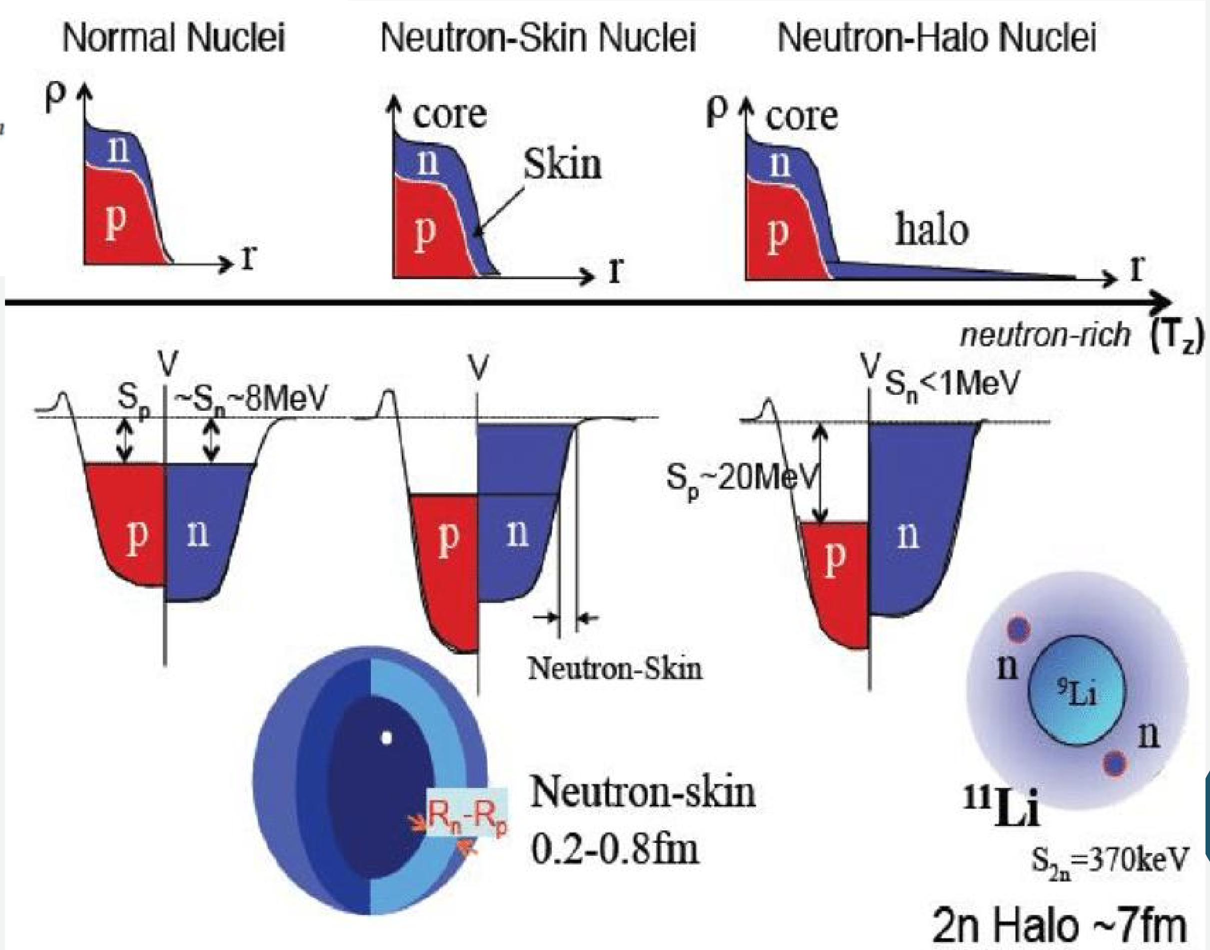
Neutron skin from antiprotonic atoms

VOLUME 87, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 2001

Neutron Density Distributions Deduced from Antiprotonic Atoms

A. Trzcińska, J. Jastrzębski, and P. Lubiński
Heavy Ion Laboratory, Warsaw University, PL-02-093 Warsaw, Poland
F. J. Hartmann, R. Schmidt, and T. von Egidy
Physik-Department, Technische Universität München, D-85747 Garching, Germ
B. Kłos
Katowice, Poland
ust 2001)



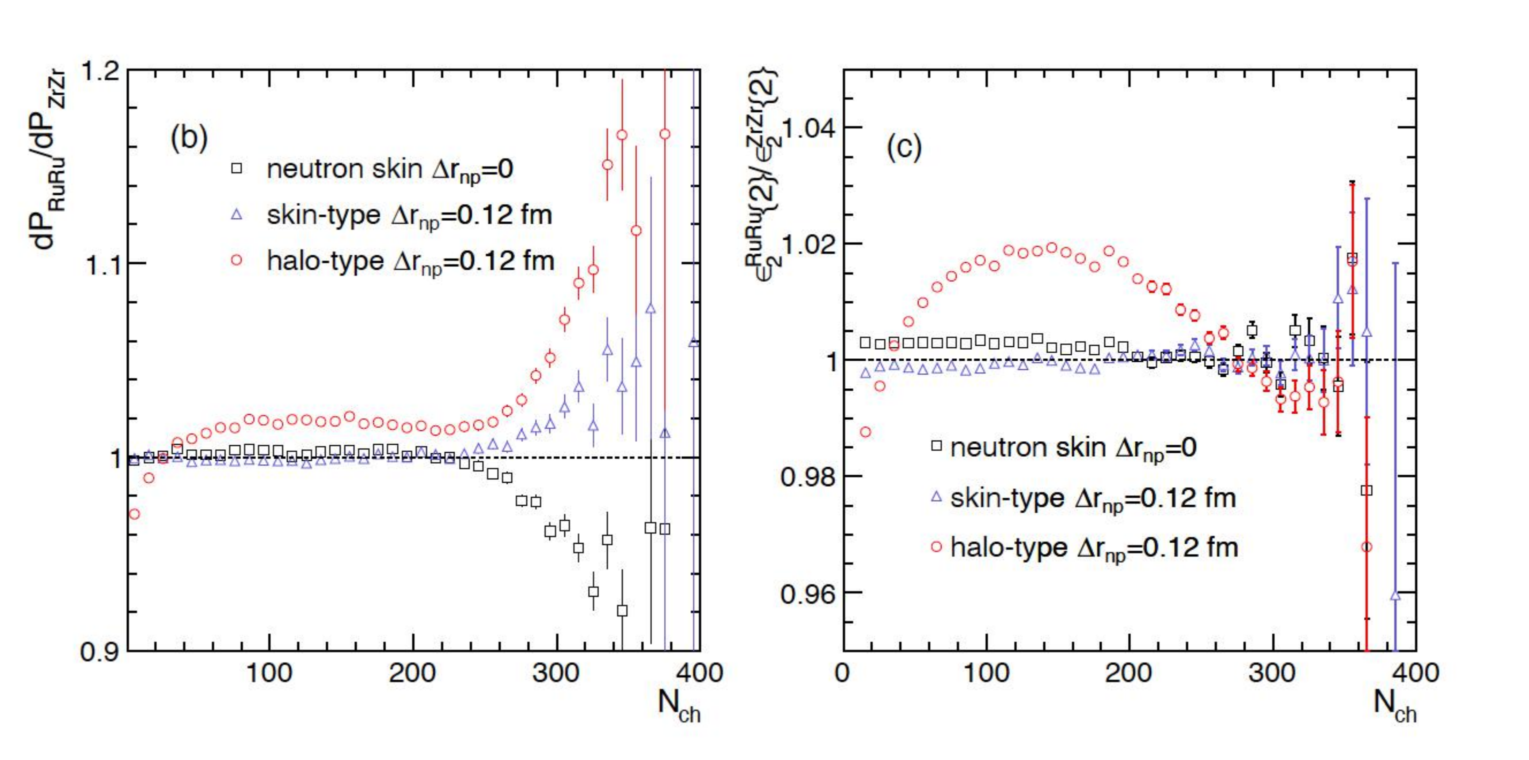


徐浩洁，湖州师范学院

Determine the neutron skin type

H. Xu, H. Li, X. Wang, C. Shen, F. Wang, PLB819, 136453 (2021)

	^{96}Ru		^{96}Zr	
	R	*a*	*R*	*a*
p	5.085	0.523	5.021	0.523
skin-type n	5.085	0.523	5.194	0.523
halo-type n	5.085	0.523	5.021	0.592



Trento Model

- The Nch ratios bends up above unity at large Nch because the larter neutron skin thickness of Zr
- The shapes of the Ru+Ru/Zr+Zr ratios of the Nch distributions and eccentricity in mid-central collisions can further distinguish between skin-type and halo-type neutron densities, both having the same skin thickness.

Nuclear density distributions

SHF: Standard Skyrme-Hartree-Fock (SHF) model
eSHF: Extended SHF model

$$E(\rho,\delta) = E_0(\rho) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

$$\rho = \rho_n + \rho_p; \;\; \delta = \frac{\rho_n - \rho_p}{\rho}; \;\; \rho_c \simeq 0.11 fm^{-3}$$

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

Z. Zhang, PRC94, 064326(2016)

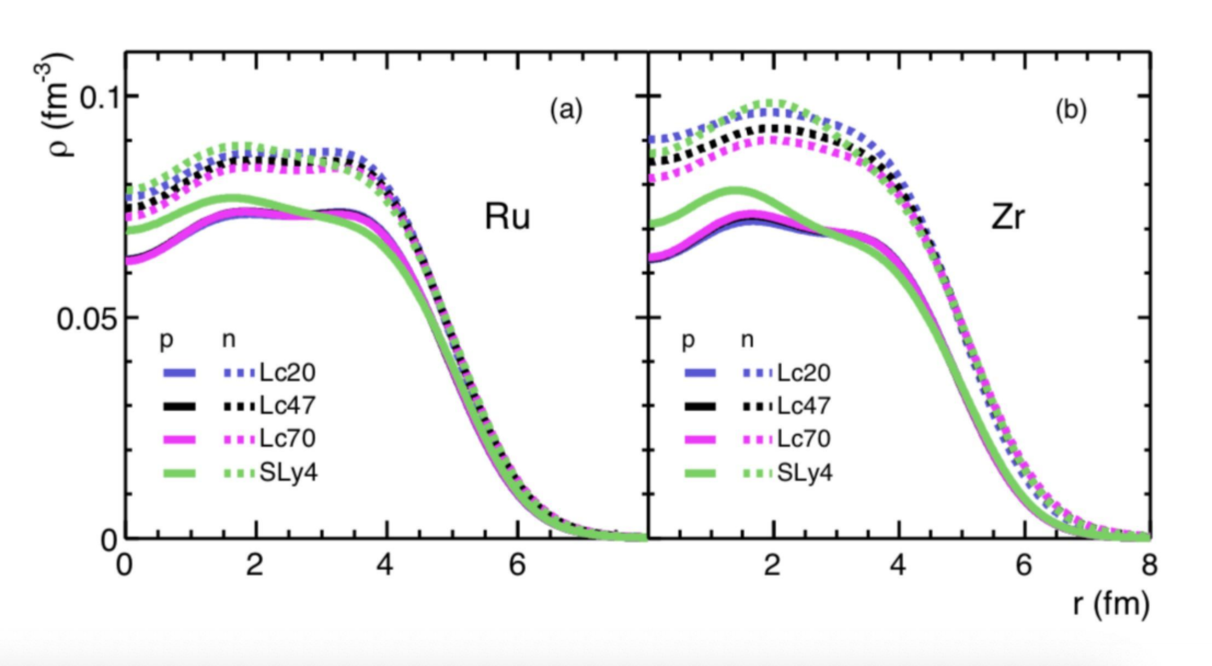
$$\begin{aligned} v_{i,j} = & \; t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}) + \frac{1}{6}t_3(1+x_3P_\sigma)\rho^\alpha(\boldsymbol{R})\delta(\boldsymbol{r}) \\ & + \frac{1}{2}t_1(1+x_1P_\sigma)[K'^2\delta(\boldsymbol{r}) + \delta(\boldsymbol{r})K^2] \\ & + t_2(1+x_2P_\sigma)\boldsymbol{K}'\cdot\delta(\boldsymbol{r})\boldsymbol{K} \\ & + \frac{1}{2}t_4(1+x_4P_\sigma)[K'^2\delta(\boldsymbol{r})\rho(\boldsymbol{R}) + \rho(\boldsymbol{R})\delta(\boldsymbol{r})K^2] \\ & + t_5(1+x_5P_\sigma)\boldsymbol{K}'\cdot\rho(\boldsymbol{R})\delta(\boldsymbol{r})\boldsymbol{K} \\ & + iW_0(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\cdot[\boldsymbol{K}'\times\delta(\boldsymbol{r})\boldsymbol{K}], \end{aligned} \quad (4)$$

Extended

	eSHF			SHF
	Lc20	Lc47	Lc70	SLy4
$L(\rho_c)$(MeV)	20.000	47.300	70.000	42.661
$E_{\rm sym}(\rho_c)$(MeV)	26.650	26.650	26.650	26.450
ρ_0(fm^{-3})	0.15414	0.15267	0.15059	0.15954
t_0(MeV · fm^3)	−2063.0	−2037.3	−1855.3	−2488.9
t_1(MeV · fm^5)	442.48	524.18	576.91	486.82
t_2(MeV · fm^5)	−562.02	−521.60	−76.702	−54.640
t_3(MeV · fm$^{3+3\alpha}$)	14726.	13734.	12367.	13777.
t_4(MeV · fm$^{5+3\beta}$)	−1532.5	−1615.7	−1650.2	-
t_5(MeV · fm$^{5+3\gamma}$)	3037.5	2153.2	−436.51	-
x_0	0.92728	0.29070	−0.26752	0.83400
x_1	1.3163	0.37275	−0.51268	−0.34400
x_2	−0.55463	−0.55121	3.1558	−1.00000
x_3	0.98695	0.13143	−0.83906	1.35400
x_4	1.7600	0.29499	−1.5709	-
x_5	−0.83852	−0.65206	−4.1683	-
α	0.28356	0.27858	0.31853	0.16667
β	1	1	1	-
γ	1	1	1	-
W_0(MeV · fm^5)	92.759	100.14	113.61	123.00

Additional density-dependent two-body forces to effectively simulate the momentum-dependent three-body forces

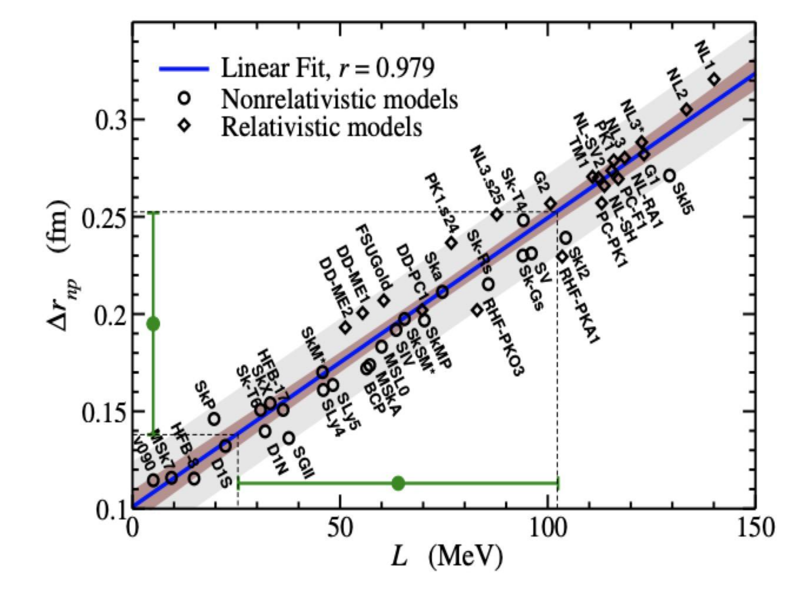
Neutron skin thickness



	$L(\rho_c)$	$L(\rho_0)$	^{96}Zr r_n	r_p	Δr_{np}	^{96}Ru r_n	r_p	Δr_{np}	^{208}Pb Δr_{np}
Lc20	20	13.1	4.386	4.27	0.115	4.327	4.316	0.011	0.109
Lc47	47.3	55.7	4.449	4.267	0.183	4.360	4.319	0.042	0.190
Lc70	70	90.0	4.494	4.262	0.232	4.385	4.32	0.066	0.264
SLy4	42.7	46.0	4.432	4.271	0.161	4.356	4.327	0.030	0.160

$$\sqrt{\langle r^2\rangle} = \sqrt{\int \rho(r) r^4 dr / \int \rho(r) r^2 dr}$$

$$\Delta r_{np} = r_n - r_p$$



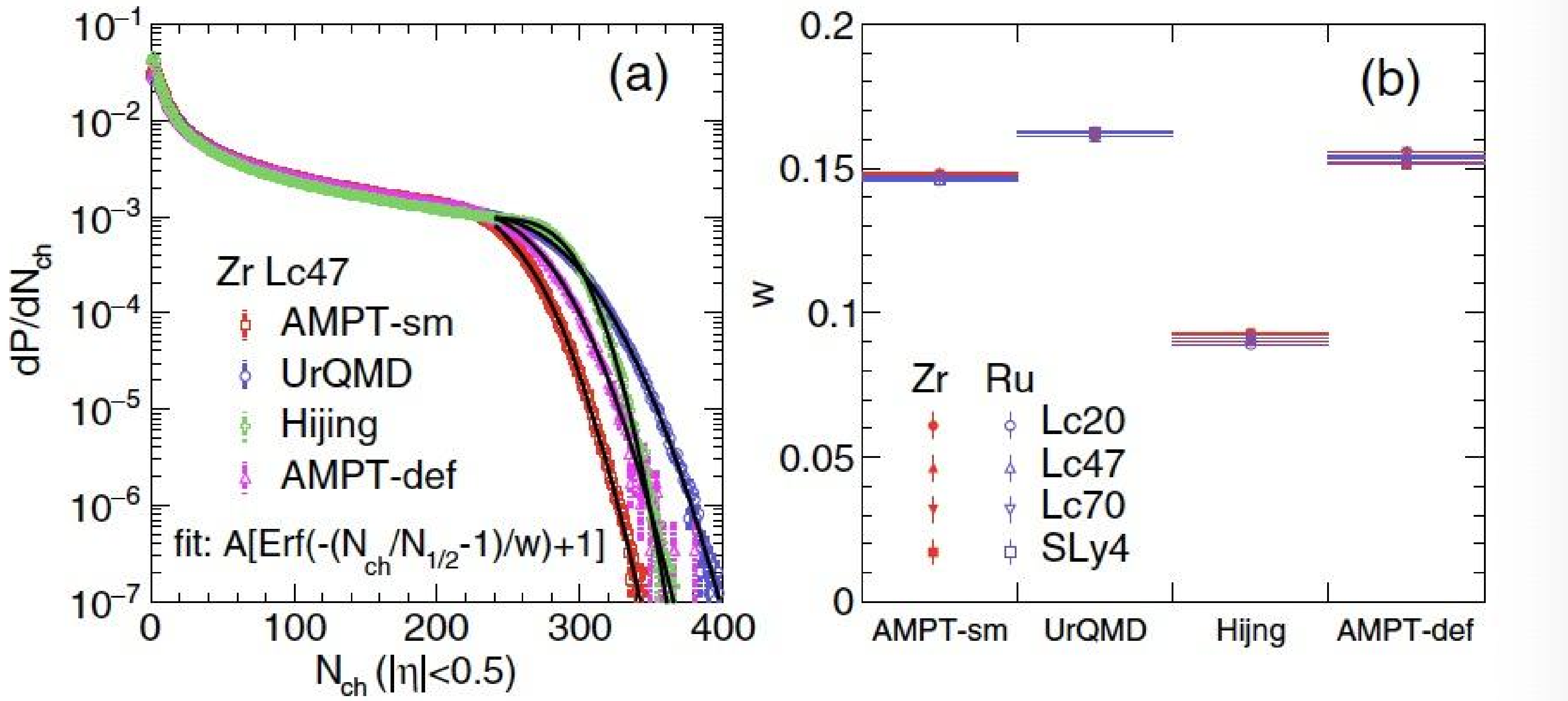
The four interactions give similar proton rms, but the neutron radius increase with $L(\rho_c)$

Roca-Maza, PRL106, 252501 (2011)

Heavy ion event generators

- Heavy ion jet interaction generator (Hijing)
- A Multi-Phase Transport model (AMPT)
  - Default (String fragmentation)
  - String melting
- Ultra relativistic Quantum Molecular Dynamics (UrQMD)

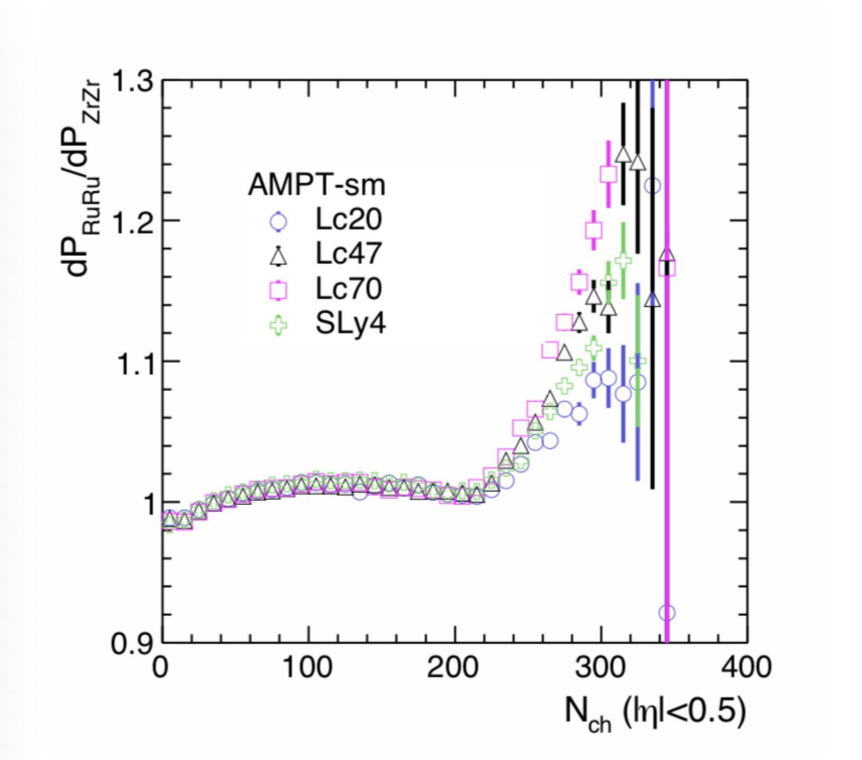
Multiplicity distributions

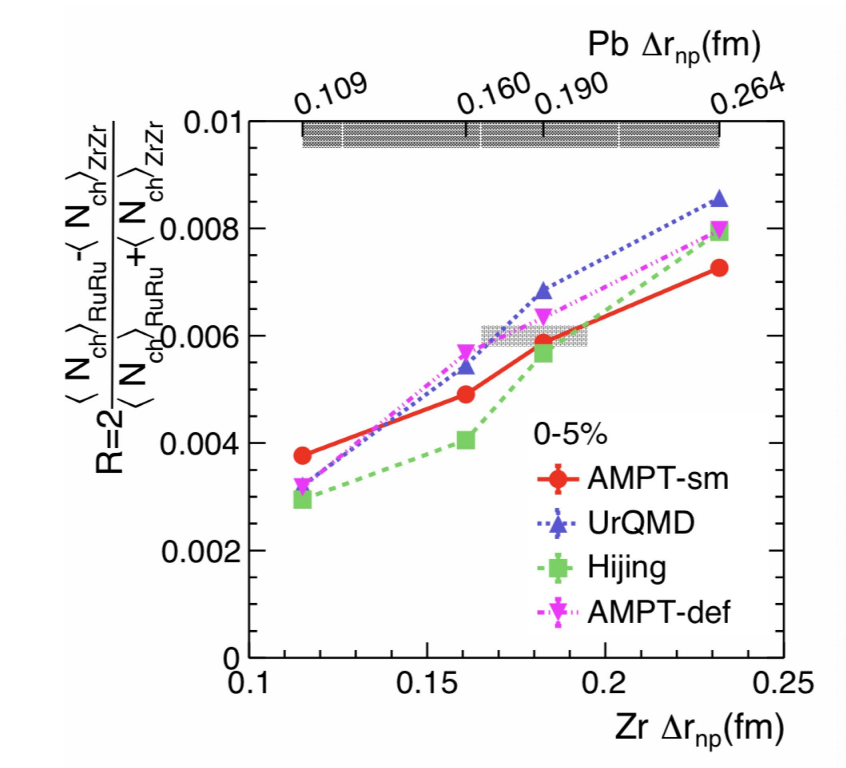


$$dP/dN_{\rm ch} \propto -{\rm Erf}[-(N_{\rm ch}/N_{1/2}-1)/w]+1, \qquad (1)$$

The effect is hardly observable in a plot of the N_{ch} distributions themselves.

Ratios of N_{ch} distributions



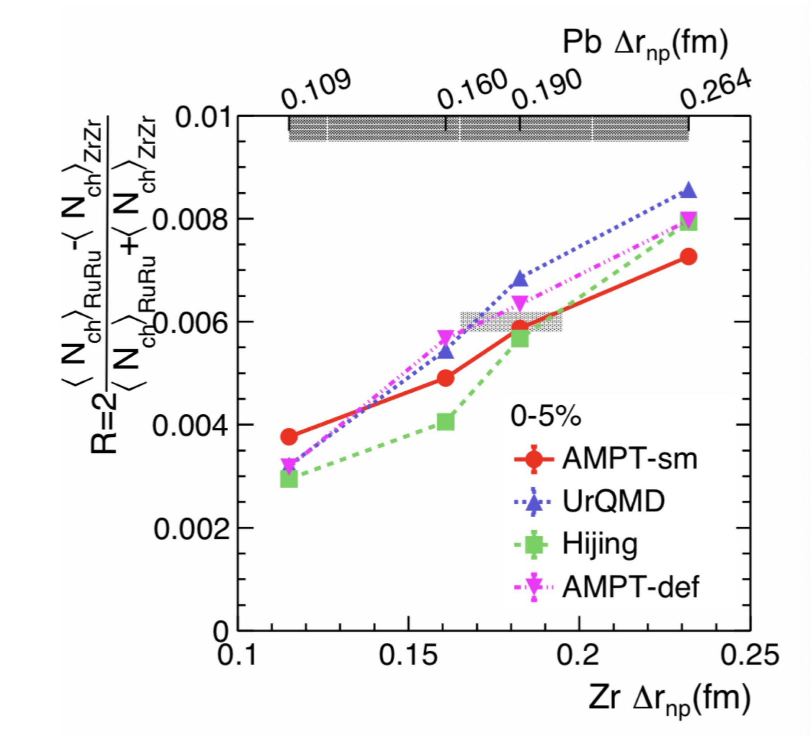


- The ratio of N_{ch} distributions highlight the differences but cumbersome to quantify
- To quantify the differences, we use the R observable of $\langle N_{ch}\rangle$ at top 5% centrality.

The R observable

R is a relative measure, **much of experimental effects cancel:**

1. **Track inefficiency**: We use only 0-5% central collisions , where the tracking efficiency is constant to a good degree
2. **Trigger inefficiency**: the trigger inefficiency can be corrected in experiment. Even without correction, the uncertainty is about 2×10^{-4}, negligible small.



Question: The R observable is actually an isospin insensitive observable, why it have **rather weak model dependence**?

The particle production in relativistic heavy ion collisions **is insensitive to the details of the QCD physics**, which is in contrast to the hadronic observables in low-energy studies.

初态几何模型

- **Glauber model**

$$\frac{dN}{dy} \propto s \propto \frac{(1-x)}{2} n_{part} + x n_{coll}$$

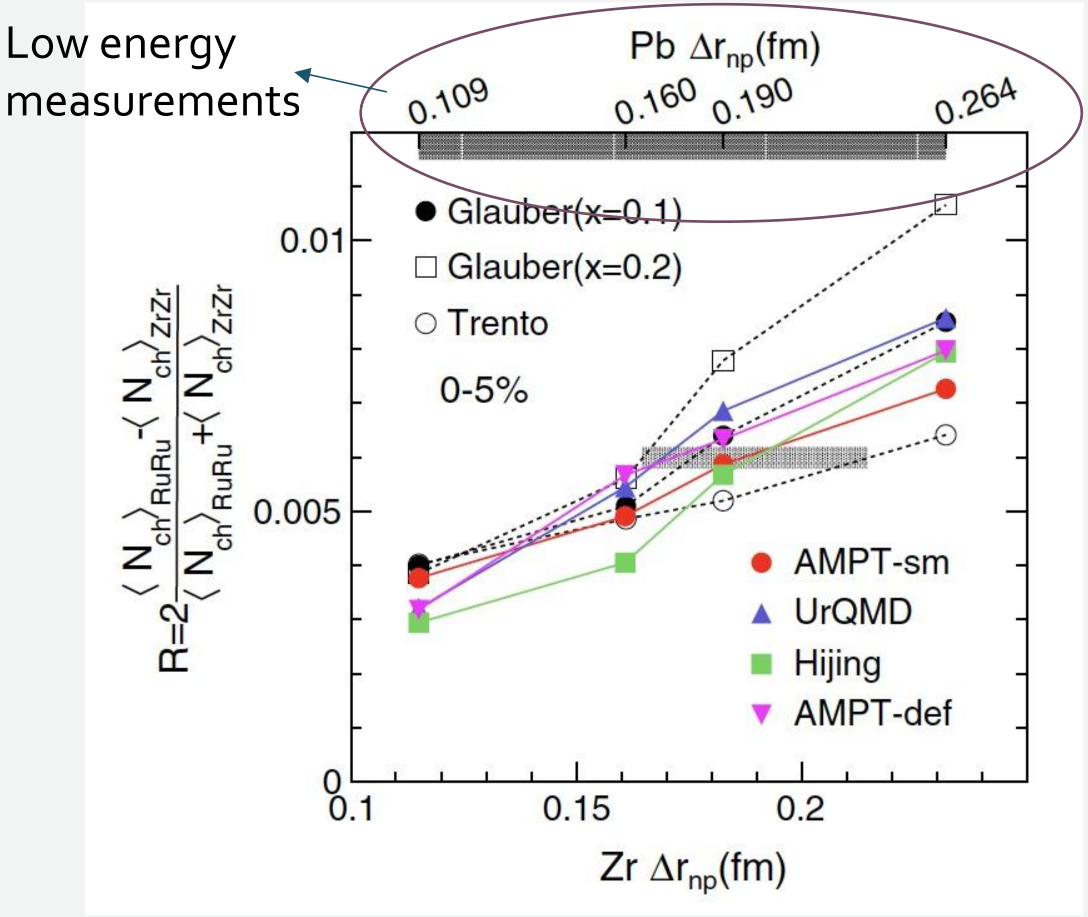
n_{part}: number of participant; n_{coll}: number of binary collisions

$x = 0.1$(default), $x = 0.2$(extreme)

- **Trento model** (J. Moreland, et.al, PRC92, 011901(2015))

$$\frac{dN}{dy} \propto s \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p} ; p = 0 \text{ and } k = 1.4$$

Probe the neutron skin thickness



4 dynamic models + 2 static models

The R observable in isobaric collisions at ultra-relativistic energies provide a novel approach to determine the neutron skin thickness to a precision that may comparable to or even exceed those achieved by traditional low-energy nuclear experiments.

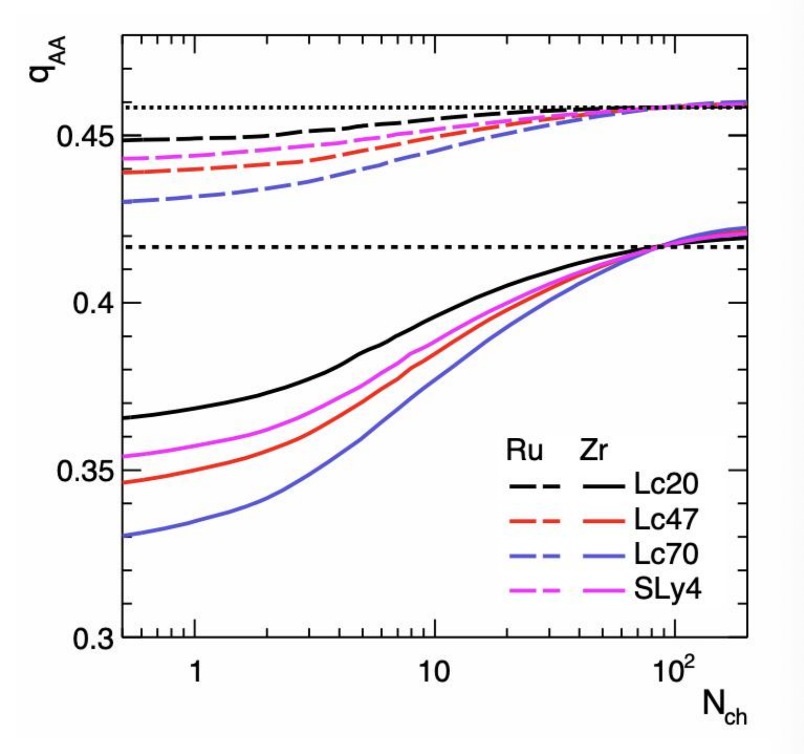
STAR isobar collisions (2018):

- More statistics: 6.3 billion isobar events
- Less systematical uncertainty

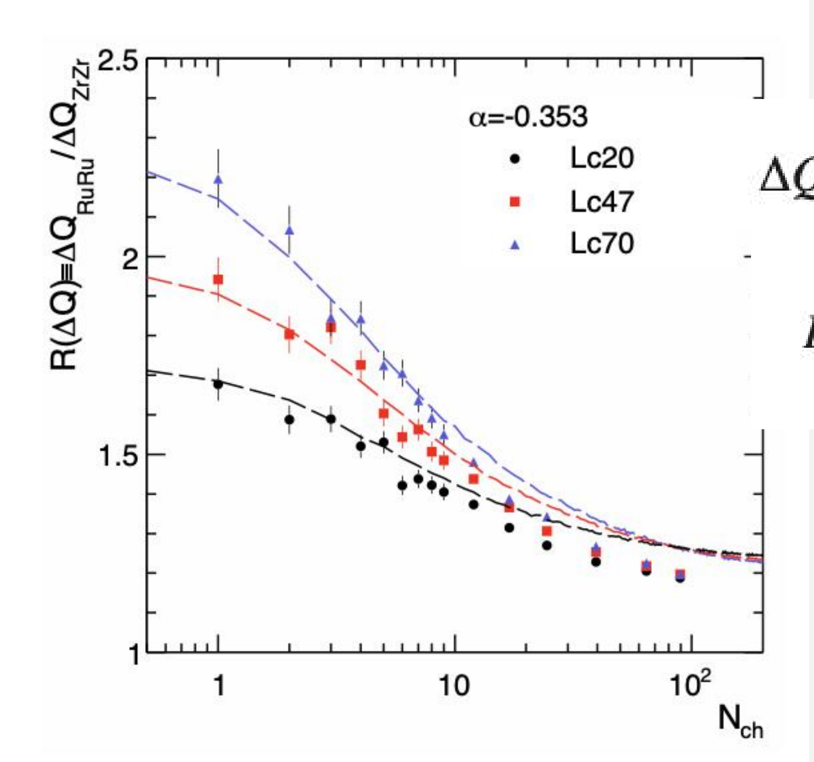
Grazing isobaric collisions

H. Xu, H. Li, Y. Zhou, X. Wang, J. Zhao, L. Chen, F. Wang, arXiv:2105.04052 (2021)

Number of particpnat potons / Number of total participants



Net charge number ratios between Ru+Ru and Zr+Zr



superimposition assumption

$$\Delta Q_{AA} \propto q_{AA} \Delta Q_{pp} + (1 - q_{AA}) \Delta Q_{nn} ,$$

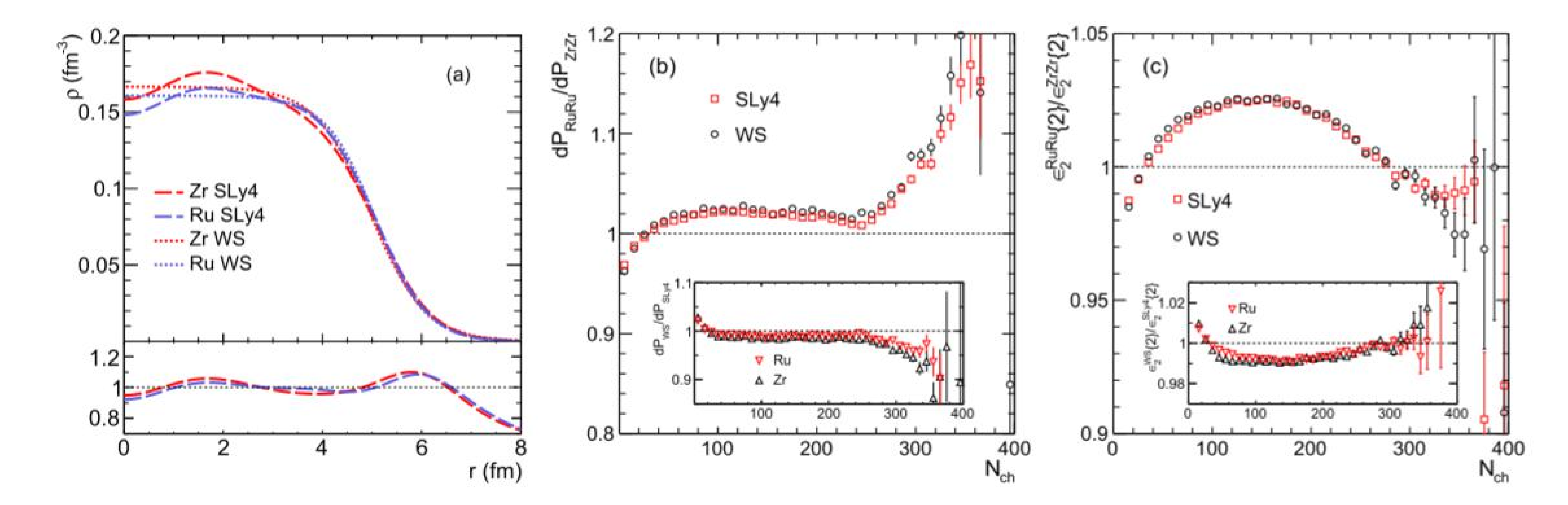
$$R_{\Delta Q} \equiv \frac{\Delta Q_{\mathrm{RuRu}}}{\Delta Q_{\mathrm{ZrZr}}} = \frac{q_{\mathrm{RuRu}} + \alpha/(1-\alpha)}{q_{\mathrm{ZrZr}} + \alpha/(1-\alpha)} ,$$

UrQMD model
Trento model

We propose a direct measurement of the neutron skin by using net-charge multiplicities in ultra-peripheral (grazing) collisions of those isobars.

DFT and WS densities

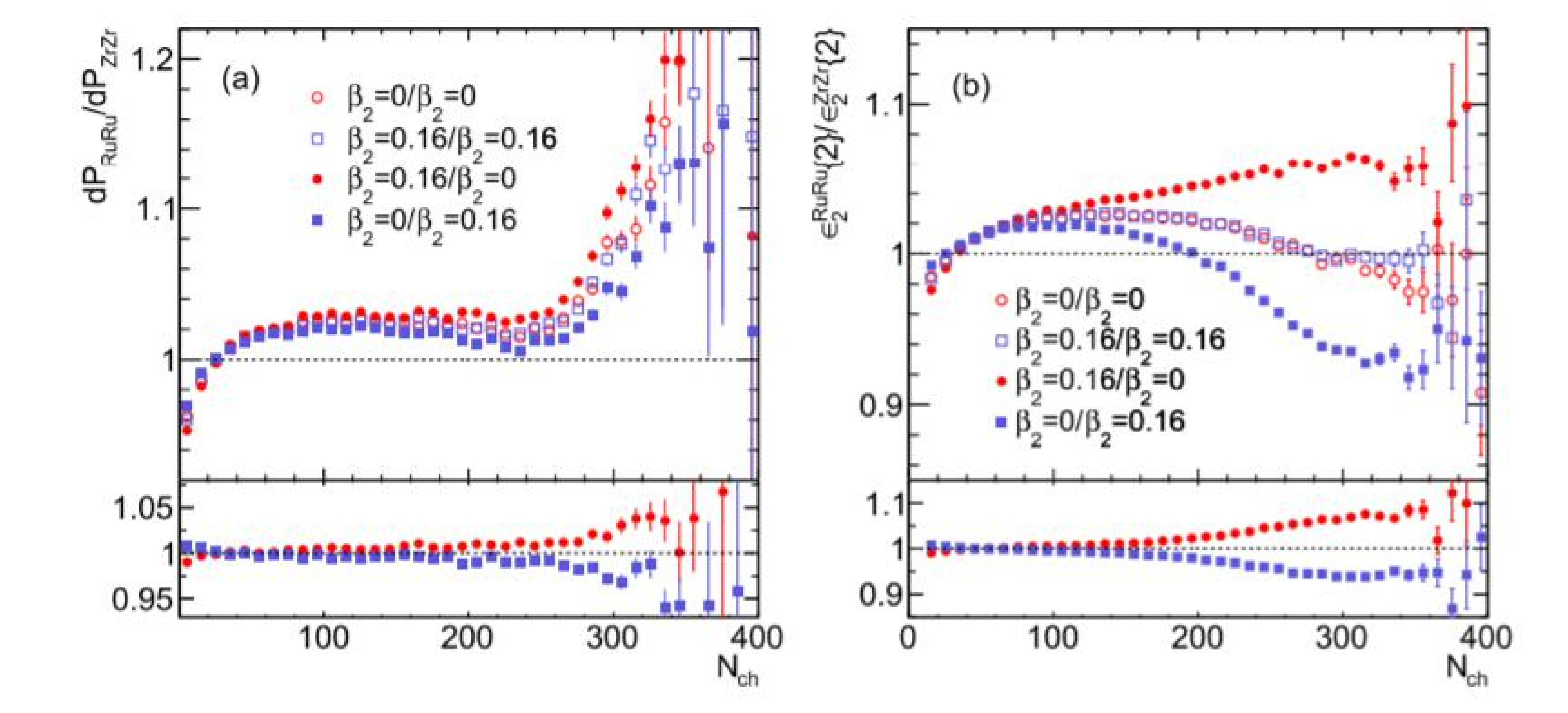
H. Xu, H. Li, X. Wang, C. Shen, F. Wang, PLB819, 136453 (2021)



$$\langle r\rangle_{\mathrm{DFT}} = \langle r\rangle_{\mathrm{WS}}$$
$$\langle r^2\rangle_{DFT} = \langle r^2\rangle_{WS}$$

Effective of nuclei deformation

H. Xu, H. Li, X. Wang, C. Shen, F. Wang, PLB819, 136453 (2021)



Giuliano Giacalone, Jiangyong Jia, Vittorio Soma, arXiv:2102.08158
Giuliano Giacalone, Jiangyong Jia, Chunjian Zhang, arXiv: 2105.01638
Jiangyong Jia, Shenli Huang, Chunjiang Zhang, arXiv:2105.05713
Jiangyong Jia, arXiv:2106.08768

V 总结

PHYSICAL REVIEW LETTERS **125,** 222301 (2020)

arXiv: 1910.06170

Probing the Neutron Skin with Ultrarelativistic Isobaric Collisions

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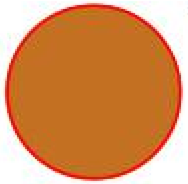
(Received 24 October 2019; accepted 15 October 2020; published 23 November 2020)

Particle production in ultrarelativistic heavy ion collisions depends on the details of the nucleon den distributions in the colliding nuclei. We demonstrate that the charged hadron multiplicity distribution isobaric collisions at ultrarelativistic energies provide a novel approach to determine the poorly kn neutron density distributions and thus the neutron skin thickness in finite nuclei, which can in turn stringent constraints on the nuclear symmetry energy.



DOI: 10.1103/PhysRevLett.125.222301

Physics Letters B 819 (2021) 136453

Contents lists available at ScienceDirect

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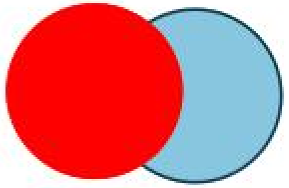

Determine the neutron skin type by relativistic isobaric collisions

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arXiv: 2103.05595

ARTICLE INFO

Article history:
Received 17 March 2021
Received in revised form 3 May 2021
Accepted 14 June 2021
Available online 17 June 2021
Editor: D.F. Geesaman

ABSTRACT

The effects of neutron skin on the multiplicity (N_{ch}) and eccentricity (ϵ_2) in relativistic $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr collisions at $\sqrt{s_{NN}} = 200$ GeV are investigated with the Trento model. It is found that the Ru+Ru/Zr+Zr ratios of the N_{ch} distributions and ϵ_2 in mid-central collisions are exquisitely sensitive to the neutron skin type (skin vs. halo). The state-of-the-art calculations by energy density functional theory (DFT) favor the halo-type neutron skin and can soon be confronted by experimental data. It is demonstrated that the halo-type density can serve as a good surrogate for the DFT density, and thus can be efficiently employed to probe nuclear deformities by using elliptic flow data in central collisions. We provide hereby a proof-of-principle venue to simultaneously determine the neutron skin type, thickness, and nuclear deformity.

Measuring neutron skin by grazing isobaric collisions

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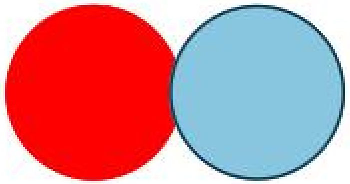
Neutron skin thickness (Δr_{np}) of nuclei and the inferred nuclear symmetry energy are of critical importance to nuclear physics and astrophysics. It is traditionally measured by nuclear processes with significant theoretical uncertainties. We recently proposed an indirect measurement of the Δr_{np} by charged hadron multiplicities in central isobaric collisions at relativistic energies, which are sensitive to nuclear densities. In this paper we propose a direct measurement of the Δr_{np} by using net-charge multiplicities in ultra-peripheral (grazing) collisions of those isobars, under the assumption that they are simple superimposition of nucleon-nucleon interactions. We illustrate this novel approach by the TRENTO and URQMD models.

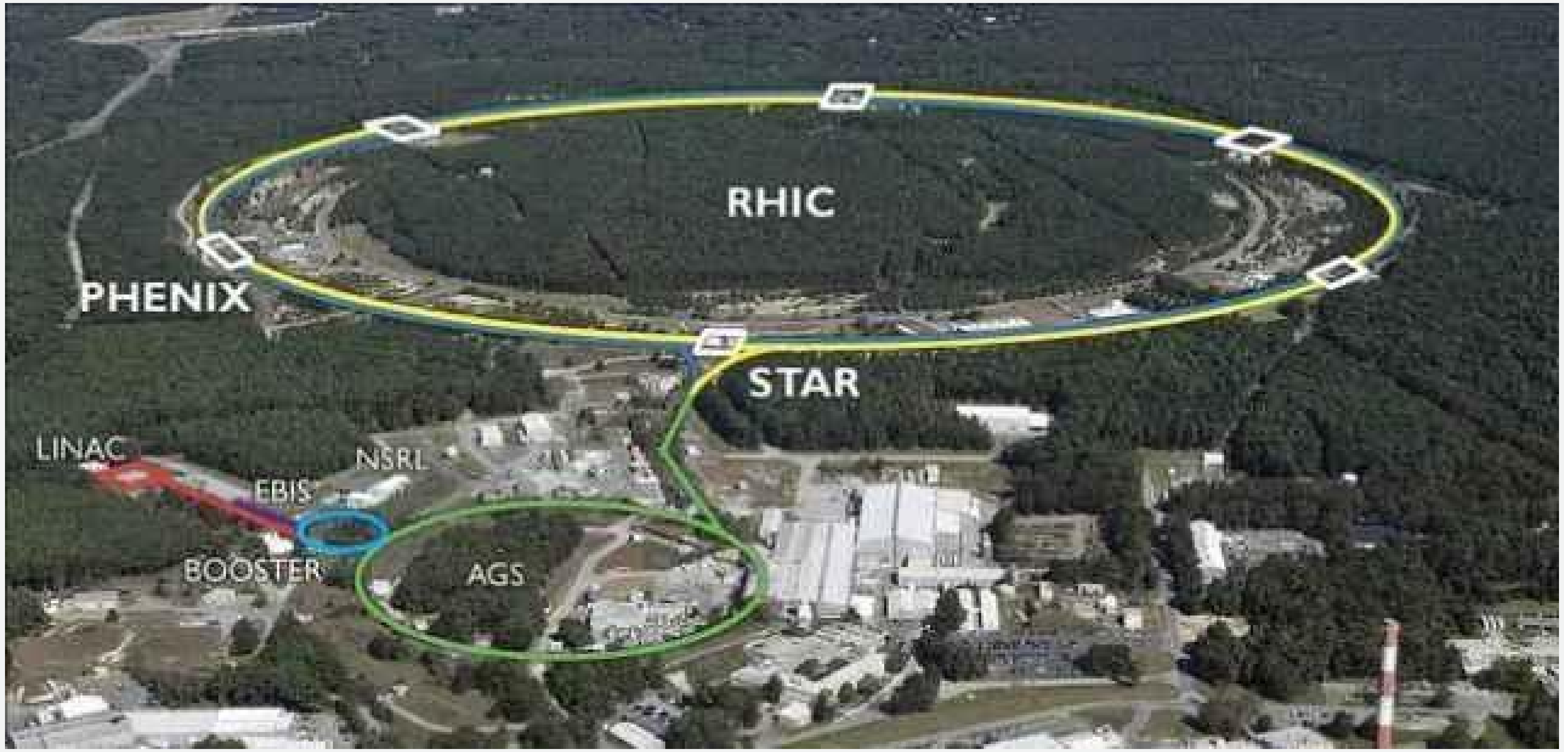
PACS numbers:

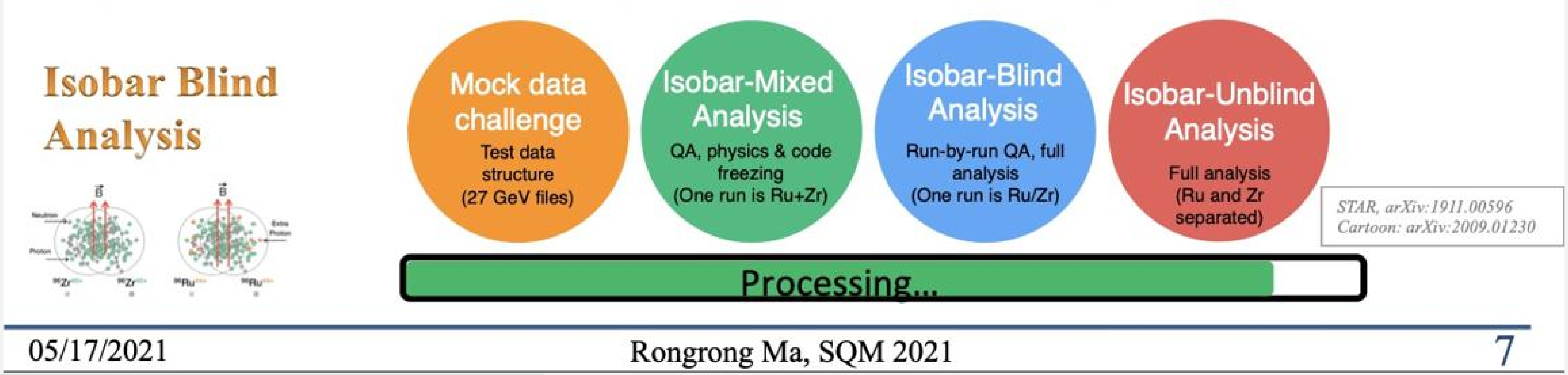
arXiv: 2105.04052



V总结

相对论同量异位素核碰撞是研究核结构绝佳平台！





Thank you for your attention!