INSTITUTE for NUCLEAR THEORY

Intersection of nuclear structure and high-energy nuclear collisions

Isobar Run: Motivation and Outcome

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U.S. DEPARTMENT OF ENERGY

PURDUE UNIVERSITY

OUTLINE

1. Chiral Magnetic Effect (CME)
2. Measuring CME — the background issue
3. Motivation for the isobar run
4. Outcome from the isobar run
5. Byproduct — turn bad into good

OUR UNIVERSE IS REALLY STRANGE!

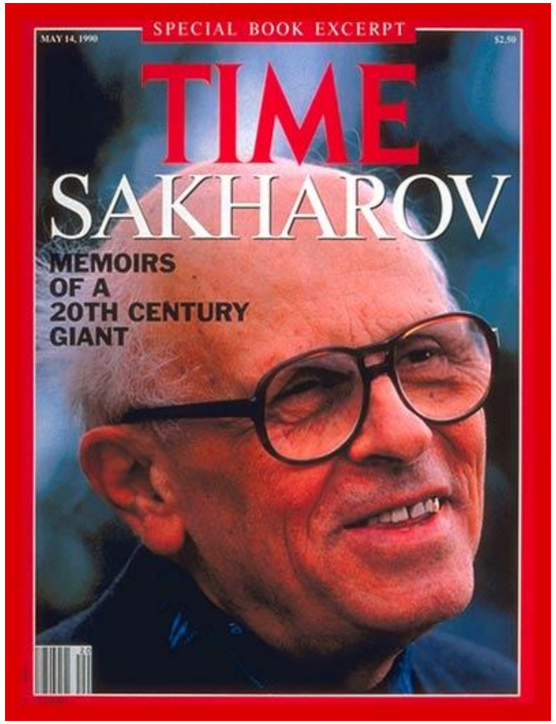
- Started with Big Bang, with equal matter and anti-matter. Today: All are matter, almost no visible anti-matter.

- Only left-handed neutrinos and right-handed antineutrinos; No right-handed neutrinos, no left-handed antineutrinos.

MATTER-ANTIMATTER ASYMMETRY

- Why? How?

- Sakharov's three conditions –JETP Lett. 5 (1967) 24
  - Baryon number violation
  - Non-equilibrium
  - CP violation (physical laws governing matter and antimatter differ)



CP VIOLATION

MATTER ⟷ **C** ⟷ **ANTI-MATTER**

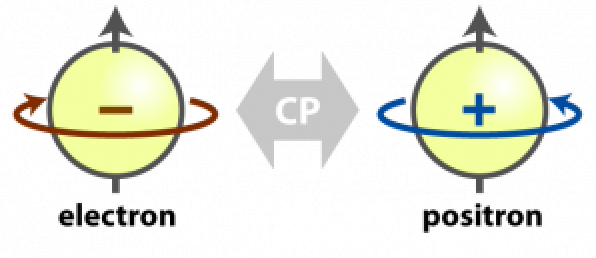
$$\Gamma(p_L^+ \to e_R^+ \gamma_L) \neq \Gamma(p_L^- \to e_R^- \gamma_L)$$
$$\Gamma(p_R^+ \to e_L^+ \gamma_R) \neq \Gamma(p_R^- \to e_L^- \gamma_R)$$

C violation not enough as sum of the left sides (matter) can still equal to sum of the right sides (antimatter). Need additionally **CP violation**.

LEFT-HANDED ⟷ **P** ⟷ **RIGHT-HANDED**

LEFT-HANDED MATTER ⟷ **CP** ⟷ **RIGHT-HANDED ANTIMATTER**

$$\Gamma(p_L^+ \to e_R^+ \gamma_L) \neq \Gamma(p_R^- \to e_L^- \gamma_R)$$
$$\Gamma(p_R^+ \to e_L^+ \gamma_R) \neq \Gamma(p_L^- \to e_R^- \gamma_L)$$



Somehow our universe preferred matter over antimatter, and left over right.
Something must have happened in the early universe that favored matter over anti-matter.
All anti-matter is annihilated with matter, with tiny matter excess ($10^{-9\sim10}$) that makes up today's universe.

THE θ–VACCUM

$$\mathcal{L}_{QCD} = \sum_q \left(\bar{\psi}_{qi} i\gamma^{\mu} \left[\delta_{ij}\partial_{\mu} + ig\left(G_{\mu}^{\alpha} t_{\alpha}\right)_{ij} \right] \psi_{qj} - m_q \bar{\psi}_{qi}\psi_{qi} \right) - \frac{1}{4} G_{\mu\nu}^{\alpha} G_{\alpha}^{\mu\nu}$$

quarks — quark-gluon interactions — quarks

$$= \frac{1}{2}\left(E^2 - B^2\right)$$

gluons

't Hooft vacuum

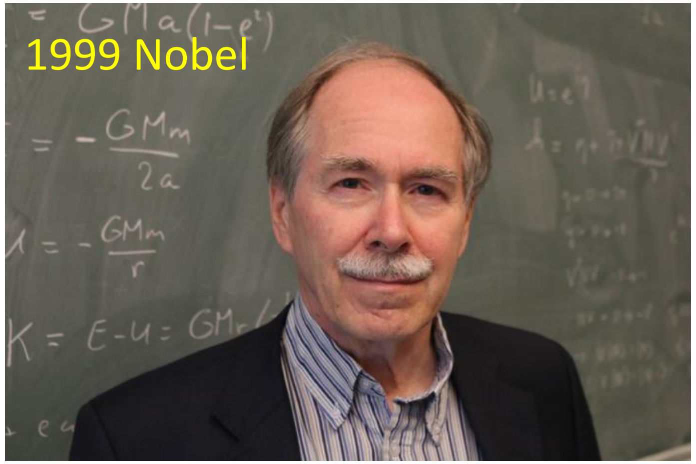
$$+\theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^{\alpha} \tilde{G}_{\alpha}^{\mu\nu}$$

$$= -\theta \frac{\alpha_s}{2\pi} \vec{E}_{\alpha} \cdot \vec{B}_{\alpha}$$

Gluon pseudoscalar density

Explicitly breaks CP symmetry

E: C-odd, P-odd, T-even
B: C-odd, P-even, T-odd



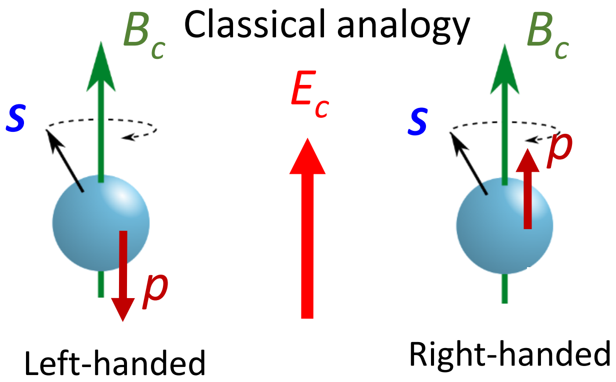
PHYSICAL REVIEW D VOLUME 14, NUMBER 12 15 DECEMBER 1976

Computation of the quantum effects due to a four-dimensional pseudoparticle*

G. 't Hooft†
Physics Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 28 June 1976)

A detailed quantitative calculation is carried out of the tunneling process described by the Belavin-Polyakov-Schwarz-Tyupkin field configuration. A certain chiral symmetry is violated as a consequence of the Adler-Bell-Jackiw anomaly. The collective motions of the pseudoparticle and all contributions from single loops of scalar, spinor, and vector fields are taken into account. The result is an effective interaction Lagrangian for the spinors.

Classical analogy



At ***E·B*** ≠ 0, particle number for a given chirality is not conserved quantum mechanically (Adler-Bell-Jackiw anomaly, 1969)

$$Q_W = \frac{\alpha_s}{8\pi} \int G_{\mu\nu}^{\alpha} \tilde{G}_{\alpha}^{\mu\nu} d\mathbf{r}dt$$

Topological charge Q_W appreciably nonzero at high temperature
Fluctuating vacuum domains in the early universe: $N_R - N_L = Q_W \neq 0$

THE θ–*VACCUM* IS TOPOLOGICAL

'**t Hooft vacuum**

$$+\theta\frac{\alpha_s}{8\pi}G^{\alpha}_{\mu\nu}\tilde{G}^{\mu\nu}_{\alpha}$$

$$=-\theta\frac{\alpha_s}{2\pi}\vec{E}_{\alpha}\cdot\vec{B}_{\alpha}$$

Topological charge (quantum number):

$$Q_W=\frac{\alpha_s}{8\pi}\int G^{\alpha}_{\mu\nu}\tilde{G}^{\mu\nu}_{\alpha}\,d\mathbf{r}dt$$

$$N_R-N_L=Q_W$$

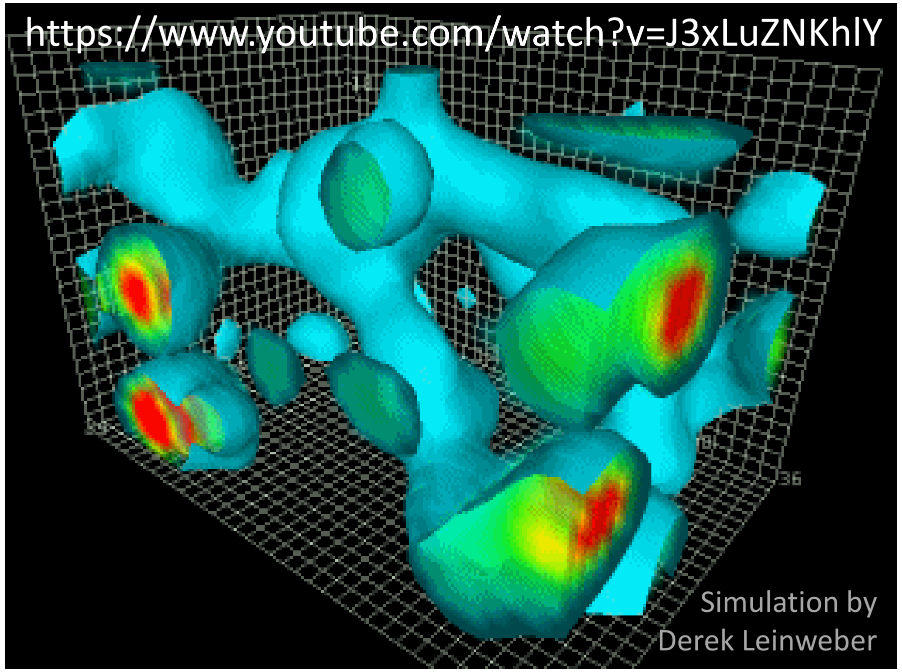
CS winding number: $N_{CS}=\nu=Q_W$

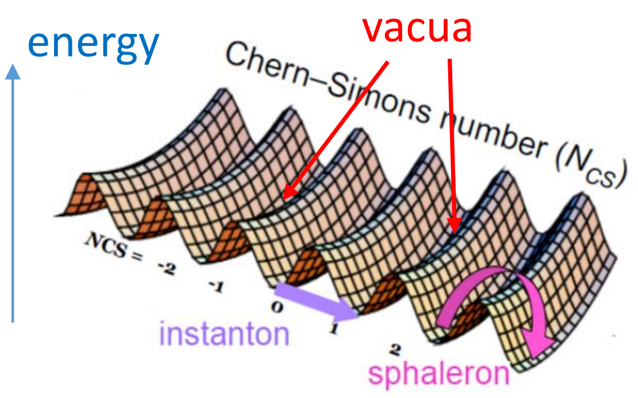
$$A=\sum_{\nu}e^{i\nu\theta}A_{\nu}\qquad \nu=0,\pm1,\pm2,\ldots$$

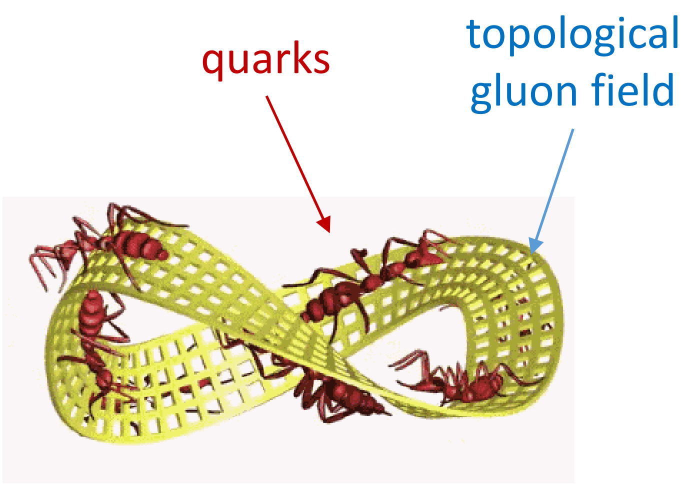
Contributions from $\nu\neq0$ breaks the $U(1)_A$ symmetry

QCD vacuum fluctuation → Chiral anomaly →

Topological gluon field → Chirality imbalance



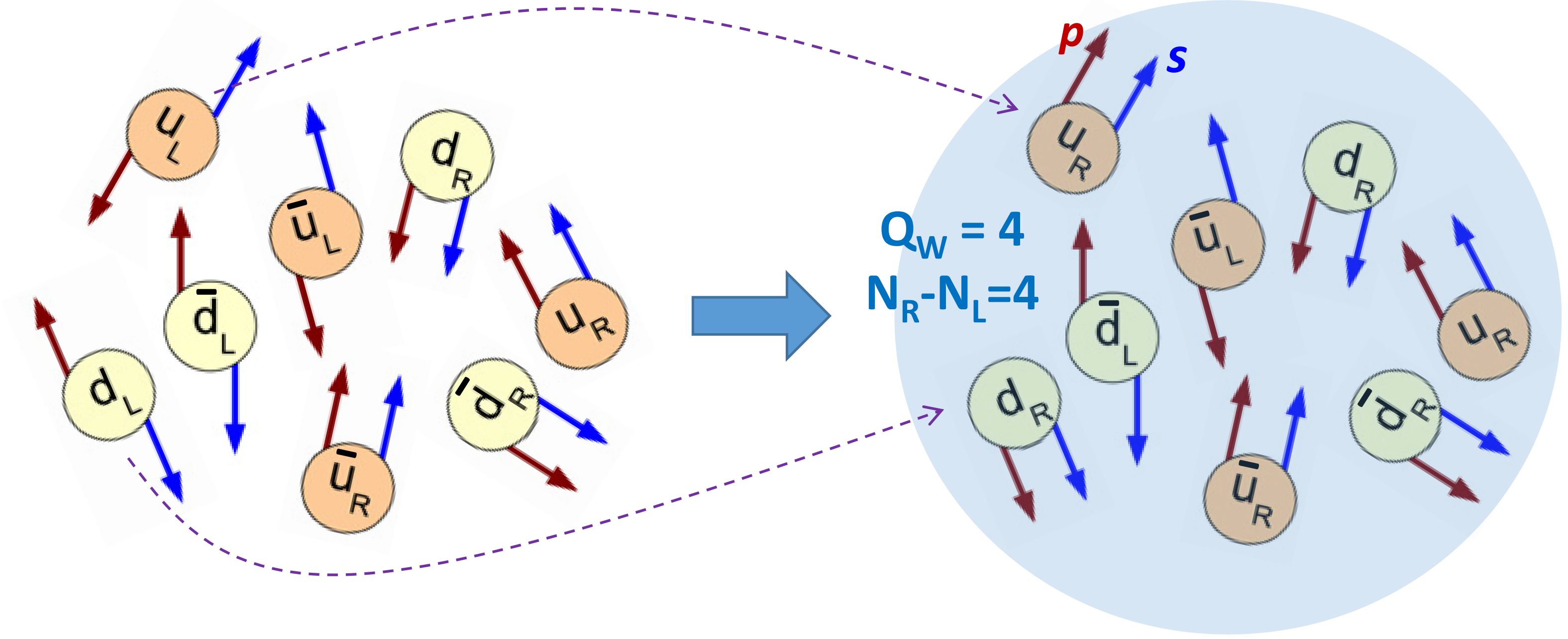




CHIRAL MAGNETIC EFFECT

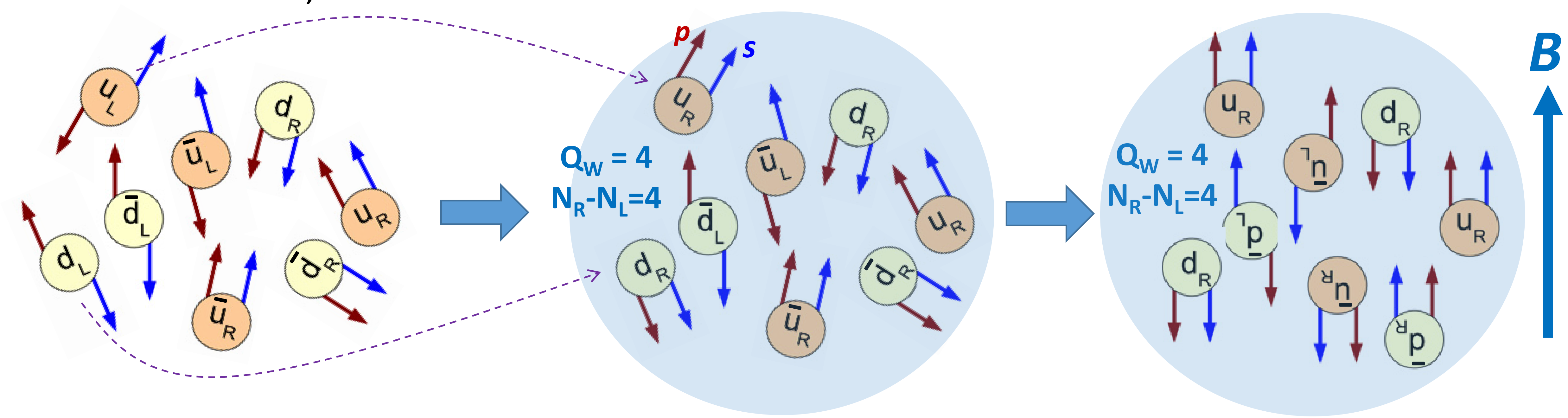
L-R balanced, chaotic

L-R imbalanced, chaotic



CHIRAL MAGNETIC EFFECT

L-R balanced, chaotic | L-R imbalanced, chaotic | L-R imbalanced, aligned



How strong is the needed magnetic field?

$E = -\boldsymbol{\mu} \cdot \mathbf{B}$

Charge Separation

Want the Landau energy gap >> thermal momentum ~1 GeV

$$\hat{H} = \frac{1}{2m}\left[\hat{p}_x^2 + (\hat{p}_y - qB\hat{x})^2 + \hat{p}_z^2\right]$$

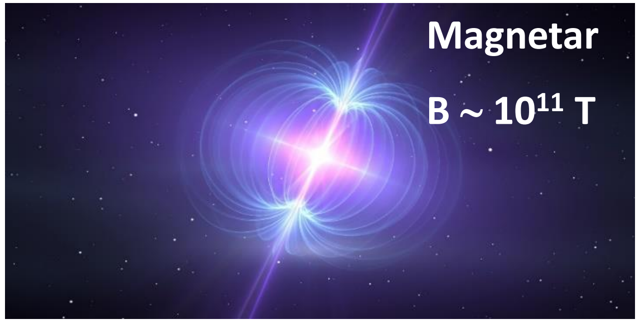
$$E_n = (n + 1/2)\hbar\omega_c \quad (\text{where } \omega_c = qB/m)$$

$$eB \sim 2mE/\hbar \sim 2\times 5\text{MeV} \times 1\text{GeV} \sim 10^4\,\text{MeV}^2 = 0.5 m_\pi^2 \sim 10^{13}\text{T}$$

$$p[\text{GeV}] = 0.3Br[\text{Tm}] \Rightarrow 1\text{T} = \frac{1\text{GeV}}{0.3\text{m}} = \frac{1\text{GeV}}{0.3\times 10^{15}\,\text{fm}} \sim \frac{1\text{GeV}\cdot\text{MeV}}{1.5\times 10^{12}} \sim 7\times 10^{-10}\,\text{MeV}^2$$

STRONG MAGNETIC FIELD & CME

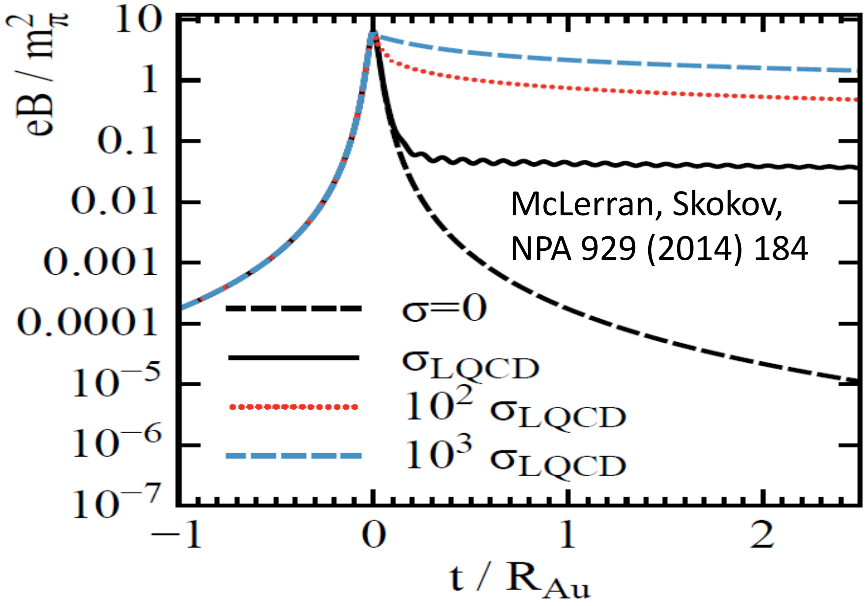
$$B=\frac{\mu_0}{4\pi}\cdot\frac{qv}{r^2}\cdot\gamma\cdot 2=10^{-7}\,\frac{50\cdot 1.6\times 10^{-19}\cdot 3\times 10^{8}}{(7\times 10^{-15})^2}\cdot 100\cdot 2=10^{15}\ \mathrm{T}\approx 40m_\pi^2$$



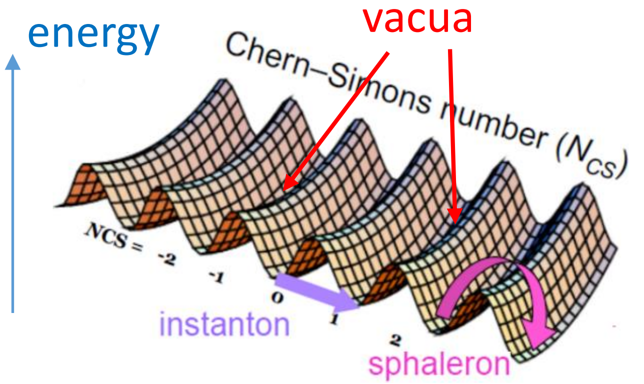
Shi et al., Annals Phys 394 (2018) 50

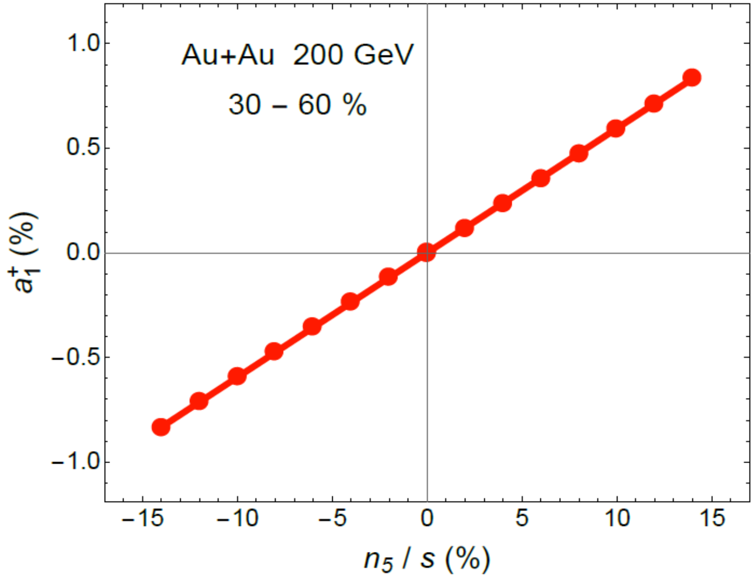
$$\sqrt{\langle n_5^2\rangle}\simeq\frac{Q_s^4\,(\pi\rho_{tube}^2\tau_0)\,\sqrt{N_{coll.}}}{16\pi^2\,A_{overlap}}$$

$$n_5=n_R-n_L\ ,\ \ n_5/s\sim 10\%$$



How large should the CME be
→ matter-antimatter asymmetry?

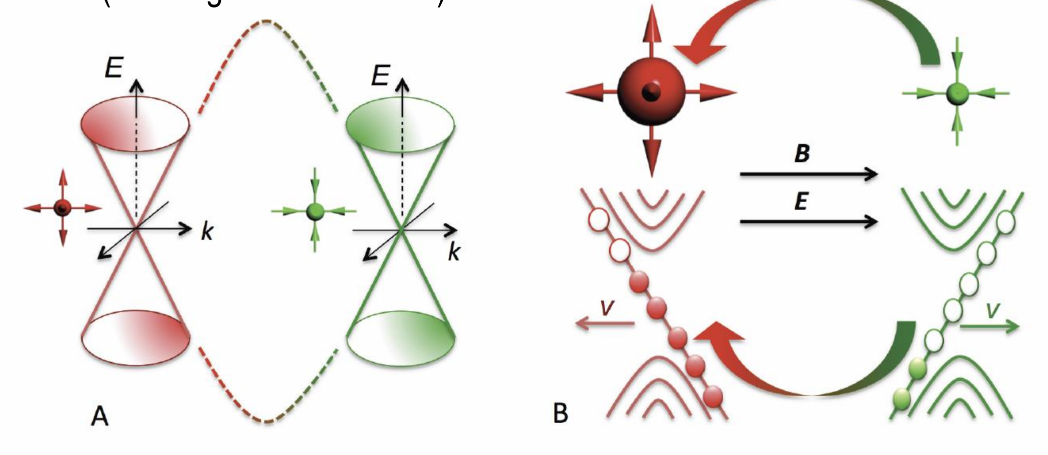


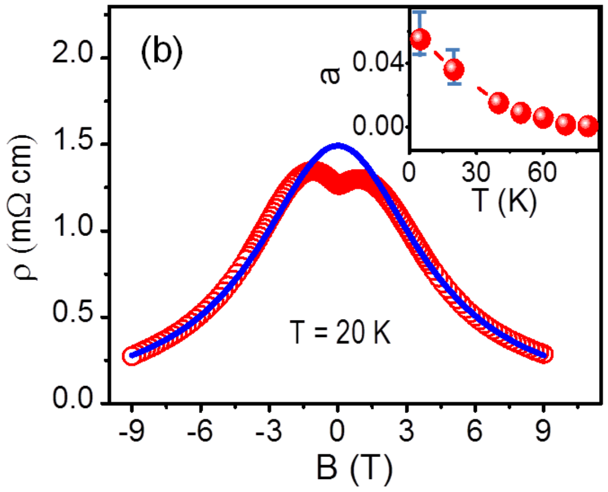


CME IN CONDENSED MATTER

S.Y. Xu, et al., Science 349 (2015) 613–617
B.Q. Lv, et al., Phys. Rev. X 5 (2015) 031013
X. Huang, et al., Phys. Rev. X 5 (2015) 031023
Qiang Li et al., Nat. Phys. 12 (2016) 550

Weyl semimetal
(non-degenerated bands)





Small cusps at very low field are due to the weak anti-localization

Non-zero chiral chemical potential:

$$\mu \equiv \mu_L - \mu_R \propto \vec{E} \cdot \vec{B}$$

CME current: $$\vec{J}_{CME} = \frac{e^2}{2\pi^2} \mu \vec{B} \propto B^2$$

Quadratic field dependence of the magneto-conductance at *B//I* is a clear indication of the CME

Man-made chiral asymmetry + Magnetic field (and magnetic moment) → CME must result

CHIRAL MAGNETIC EFFECT (CME)

The strong interaction

$$\mathcal{L}_{QCD} = \sum_q \left(\underbrace{\bar{\psi}_{qi} i\gamma^\mu \left[\delta_{ij}\partial_\mu}_{\text{quarks}} + \underbrace{ig\left(G^\alpha_\mu t_\alpha\right)_{ij}}_{\text{quark-gluon interactions}} \right]\psi_{qj} \underbrace{- m_q \bar{\psi}_{qi}\psi_{qi}}_{\text{quarks}} \right) \underbrace{- \frac{1}{4} G^\alpha_{\mu\nu} G^{\mu\nu}_\alpha}_{\text{gluons}}$$

$$= \frac{1}{2}\left(E^2_\alpha - B^2_\alpha\right)$$

't Hooft vacuum

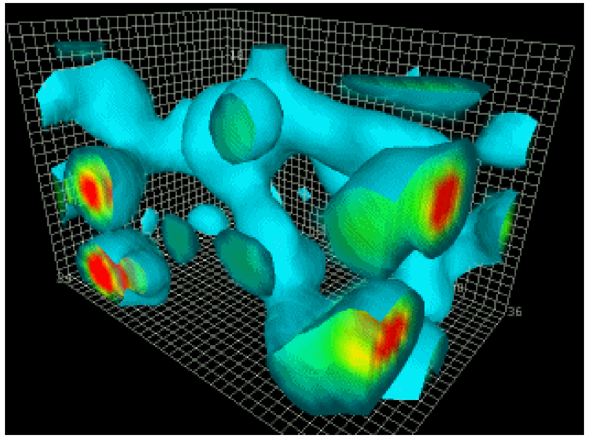
$$+\theta \frac{\alpha_s}{8\pi} G^\alpha_{\mu\nu} \tilde{G}^{\mu\nu}_\alpha = -\theta \frac{\alpha_s}{2\pi} \vec{E}_\alpha \cdot \vec{B}_\alpha$$

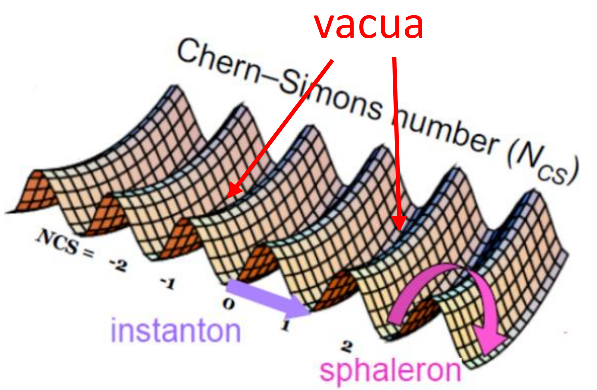
to solve the $U(1)_A$ problem (1976)

E: C-odd, P-odd, T-even
B: C-odd, P-even, T-odd

Explicitly breaks CP

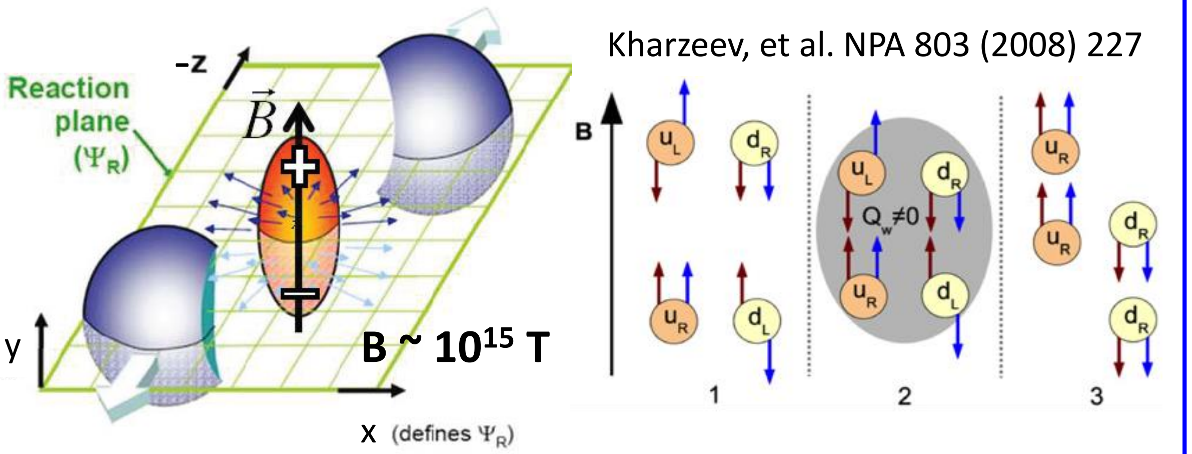
Early universe ultraviolet $\theta \approx 1$?? >> current infrared $\theta \approx 0$





Kharzeev,Pisarski,Tytgat,PRL81(1998)512

QCD vacuum fluctuation, chiral anomaly, topological gluon field



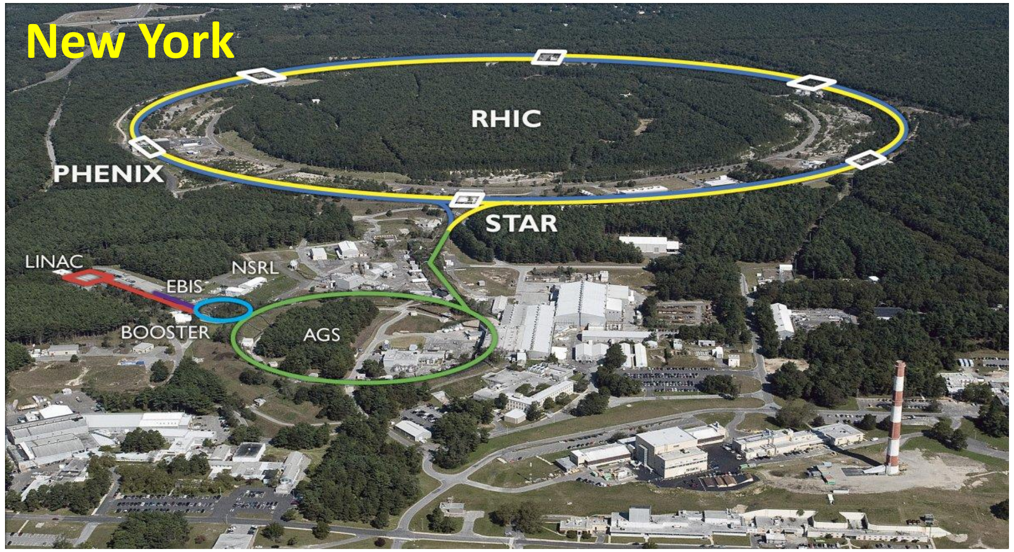
Kharzeev, et al. NPA 803 (2008) 227

Chiral Magnetic Effect (CME)

Discovery of the CME would imply: Chiral symmetry restoration (current-quark DOF & deconfinement); UA(1) chiral anomaly; Local P/CP violation that may solve the strong CP problem (matter-antimatter asymmetry)

2

MEASURING CME – the background issue

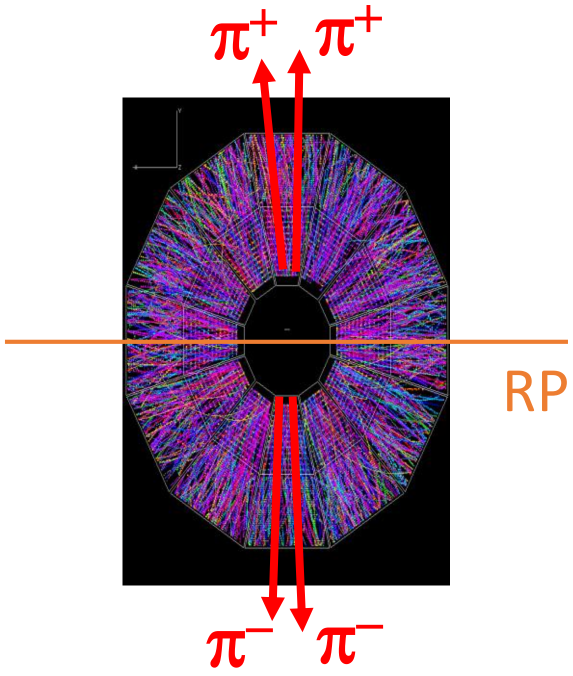


High energy machines to collide heavy ions

to recreate the early universe

THE $\Delta\gamma$ CORRELATOR

Look for charge separation



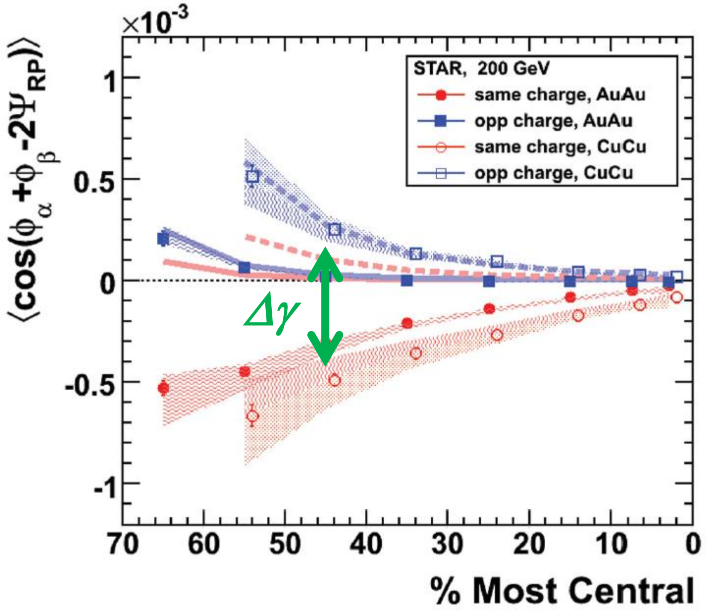
Voloshin, PRC 2004

$$\gamma_{\alpha\beta} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{RP}) \right\rangle$$

$$\gamma_{+-,-+} > 0, \quad \gamma_{++,--} < 0$$

$$\Delta\gamma = \gamma_{\text{opposite-sign}} - \gamma_{\text{same-sign}} > 0$$

STAR, PRL 2009, PRC 2010



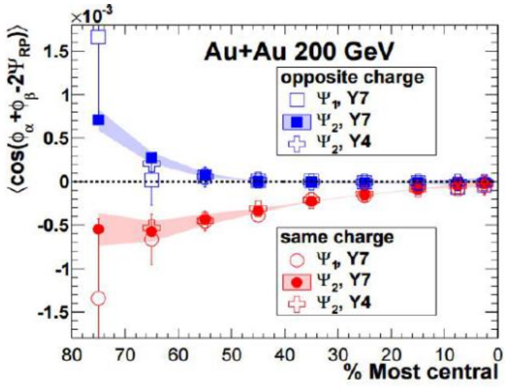
Significant signal

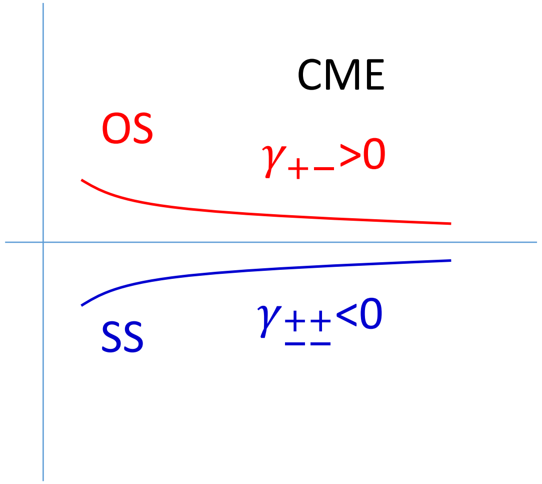
$\Delta\gamma \sim 5 \times 10^{-4}$

BACKGROUNDS IN γ CORRELATORS

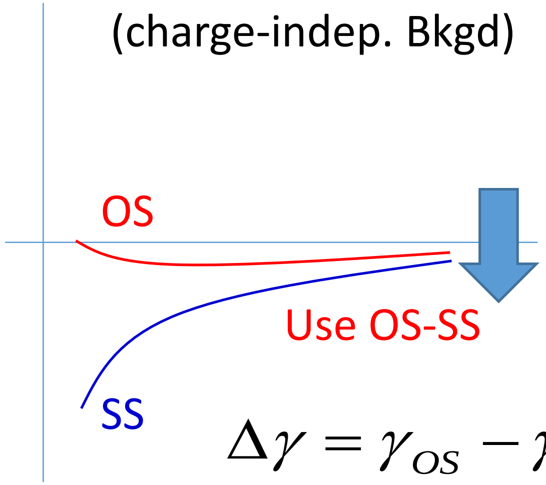
Voloshin 2004; FW 2009; Bzdak, Koch, Liao 2010; Pratt, Schlichting 2010; …

$$\gamma_{\alpha\beta} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$



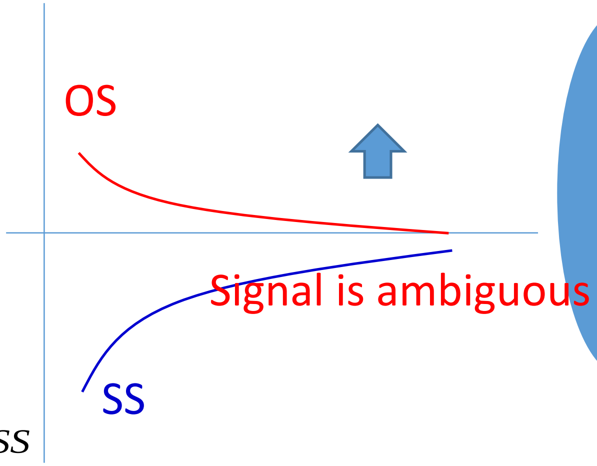


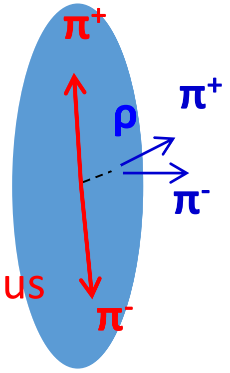
CME
+ mom. conserv.
(charge-indep. Bkgd)



$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

CME
+ mom. conserv. (charge-indep.)
+ charge conserv. (charge-dep.)





$$dN_\pm / d\varphi \propto 1 + 2v_1 \cos\varphi_\pm + 2a_\pm \cdot \sin\varphi_\pm + 2v_2 \cos 2\varphi_\pm + \dots$$

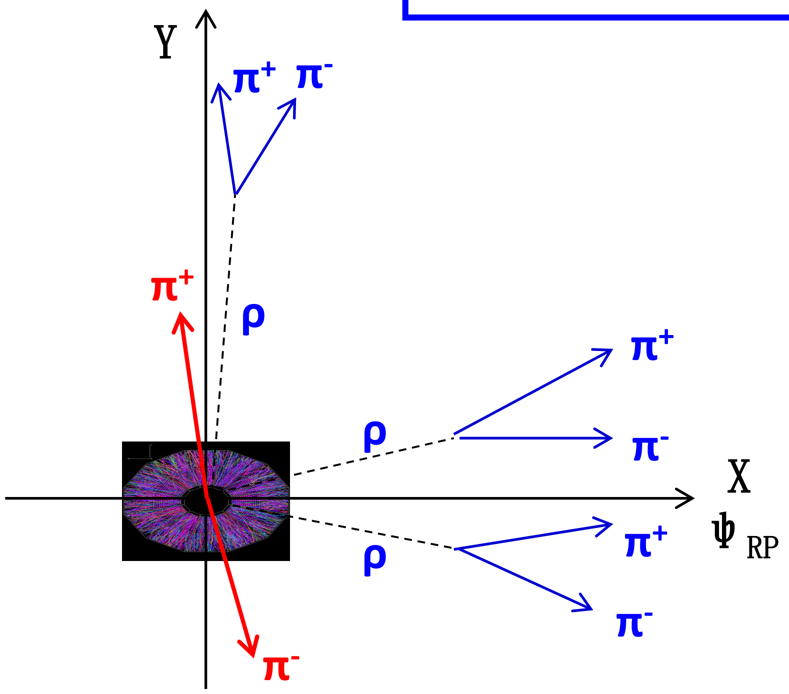
$$\gamma_{\alpha\beta} = \left[\underbrace{\left\langle \cos(\varphi_\alpha - \psi_{RP}) \cos(\varphi_\beta - \psi_{RP}) \right\rangle}_{\langle v_{1,\alpha} v_{1,\beta} \rangle \approx 0} - \underbrace{\left\langle \sin(\varphi_\alpha - \psi_{RP}) \sin(\varphi_\beta - \psi_{RP}) \right\rangle}_{\text{CME: } \langle a_\alpha a_\beta \rangle} \right] + \underbrace{\left[\frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\varphi_{RP}) \right\rangle \right]}_{\text{charge-indep. + charge-dep.}}$$

BACKGROUND IN Δγ CORRELATOR

Voloshin 2004; FW 2009; Bzdak, Koch, Liao 2010; Pratt, Schlichting 2010; …

$$\gamma_{\alpha\beta} = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$



$$dN_\pm / d\varphi \propto 1 + 2v_1 \cos\varphi^\pm + 2a_\pm \cdot \sin\varphi^\pm + 2v_2 \cos 2\varphi^\pm + \ldots$$

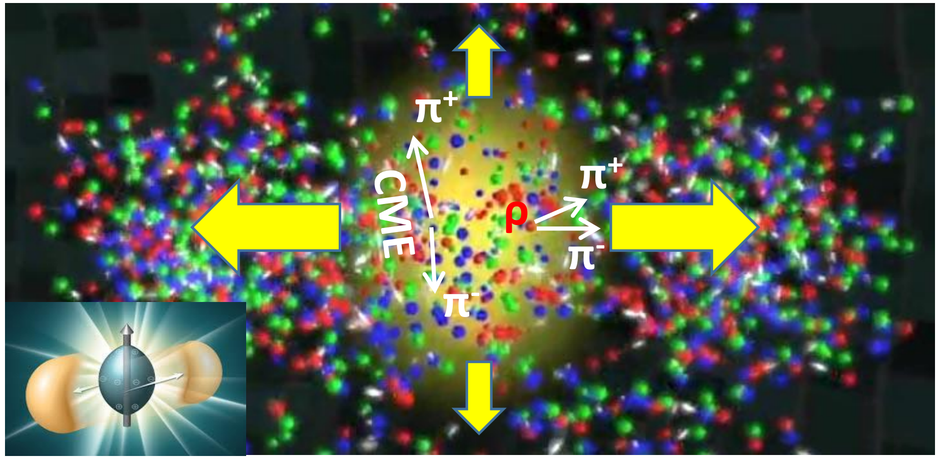
$$\gamma_{\alpha\beta} = \left[\left\langle \cos(\varphi_\alpha - \psi_{RP}) \cos(\varphi_\beta - \psi_{RP}) \right\rangle - \left\langle \sin(\varphi_\alpha - \psi_{RP}) \sin(\varphi_\beta - \psi_{RP}) \right\rangle \right]$$
$$+ \left[\frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \cos(2\varphi_{cluster} - 2\varphi_{RP}) \right\rangle \right]$$
$$= \left[\left\langle v_{1,\alpha} v_{1,\beta} \right\rangle - \left\langle a_\alpha a_\beta \right\rangle \right] + \frac{N_{cluster}}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{cluster}) \right\rangle v_{2,cluster}$$

$$\Delta\gamma = 2\left\langle a_1^2 \right\rangle + \frac{N_\rho}{N_\alpha N_\beta} \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \right\rangle v_{2,\rho}$$

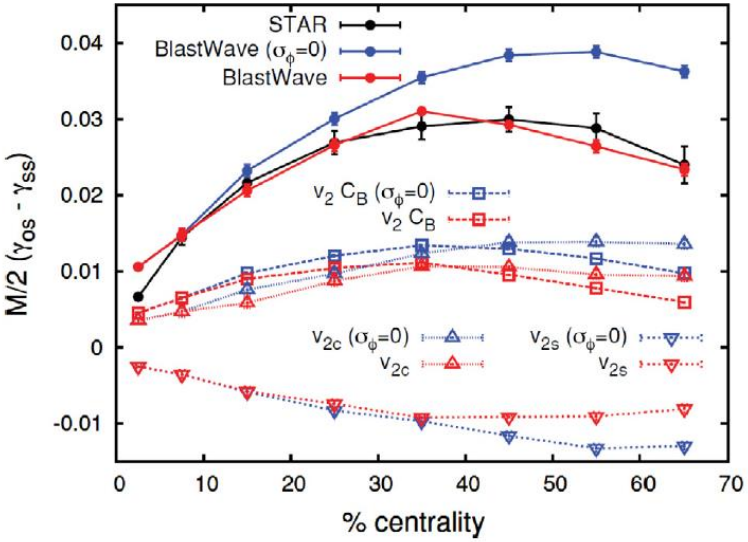
Flow-induced charge-dependent background:
nonflow coupled with flow

$$\Delta\gamma_{\mathrm{Bkg}} \propto v_2 / N$$

BACKGROUND IS LARGE



Schlichting, Pratt, PRC 83 (2011) 014913



PHYSICAL REVIEW C **81**, 064902 (2010)

Effects of cluster particle correlations on local parity violation observables

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(Received 20 November 2009; revised manuscript received 15 April 2010; published 7 June 2010)

We investigate effects of cluster particle correlations on two- and three-particle azimuth correlator observables sensitive to local strong parity violation. We use two-particle angular correlation measurements as inputs and estimate the magnitudes of the effects with straightforward assumptions. We found that the measurements of the azimuth correlator observables in the STAR experiment can be entirely accounted for by cluster particle correlations together with a reasonable range of cluster anisotropy in nonperipheral collisions. Our result suggests that new physics, such as local strong parity violation, may not be required to explain the correlator data.

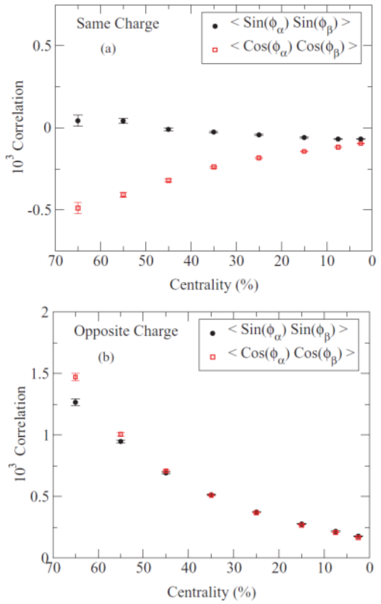
DOI: 10.1103/PhysRevC.81.064902 PACS number(s): 25.75.Gz, 25.75.Ld

Bzdak, Koch, Liao, PRC 81 (2010) 031901(R)

$$\Delta\gamma_{\rm Bkg} = \frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho)\right\rangle v_{2,\rho}$$

$20/100^2 \times 0.65 \times 0.1$

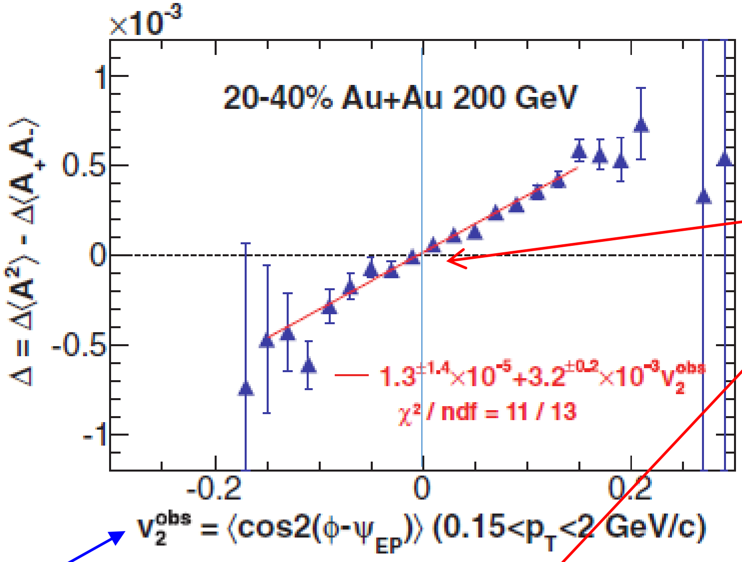
$\sim 10^{-4}$



STATISITICAL EVENT-SHAPE-ENGINEERING

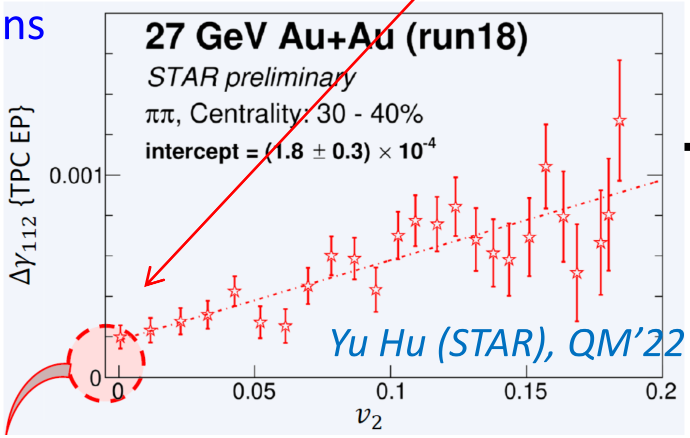
STAR, PRC 89 (2014) 044908

Here Δ is similar to cos(α+β−2ψ) correlator



Primarily stat. fluctuations

Event-by-event v_2 technique

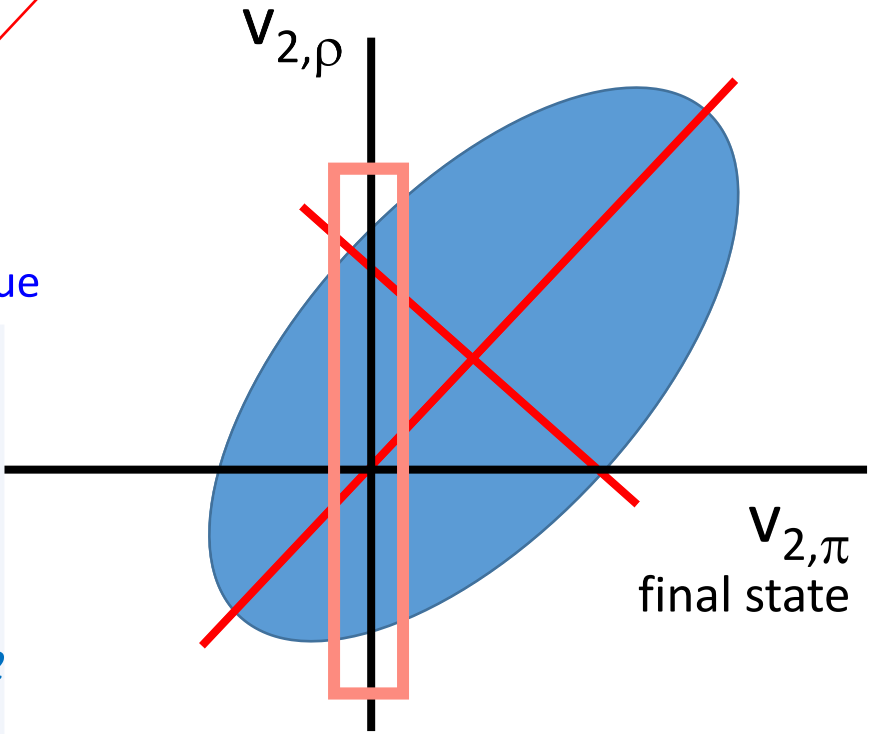


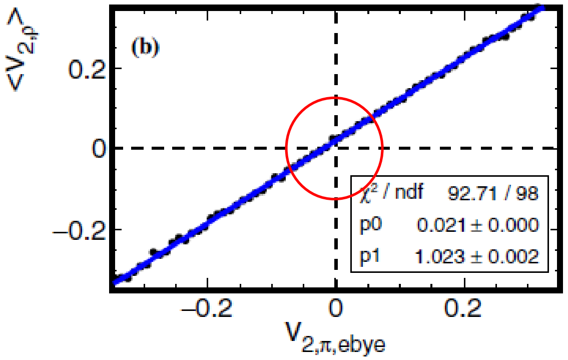
Yu Hu (STAR), QM'22

$$\Delta\gamma = 2\left\langle a_1^2 \right\rangle \frac{v_{2,c\perp B}}{v_{2,c}^*} + \frac{C_{2p}N_{2p}}{N^2}\frac{v_{2,2p}v_{2,c}}{v_{2,c}^*} + \frac{C_{3p}N_{3p}}{2N^3 v_{2,c}^*}$$

Still has residual background, because background ~ $v_{2,\rho}$ not $v_{2,\pi}$

FW, Jie Zhao, PRC 95 (2017) 051901(R)





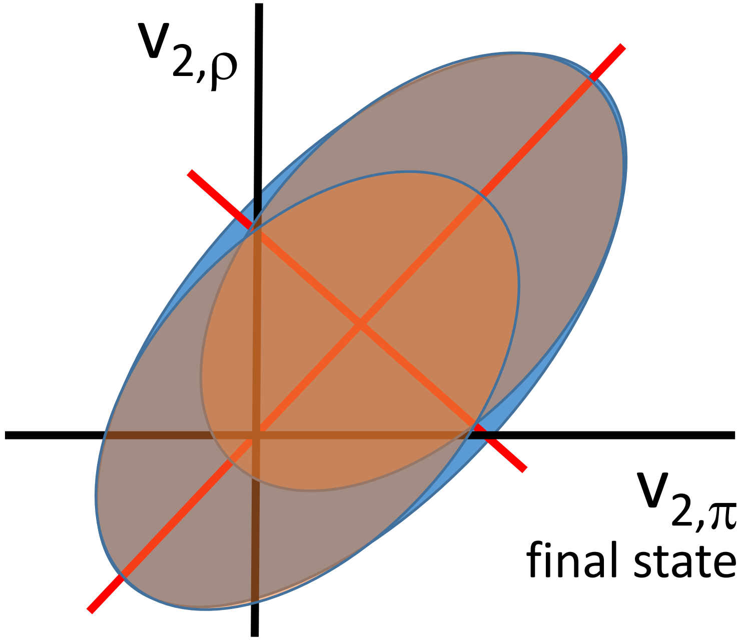
- Engineering on stat. fluctuations
- Background suppressed, but not totally eliminated
- LHC does not have this issue as v_2 selection in different phase space

DYNAMICAL EVENT-SHAPE-ENGINEERING

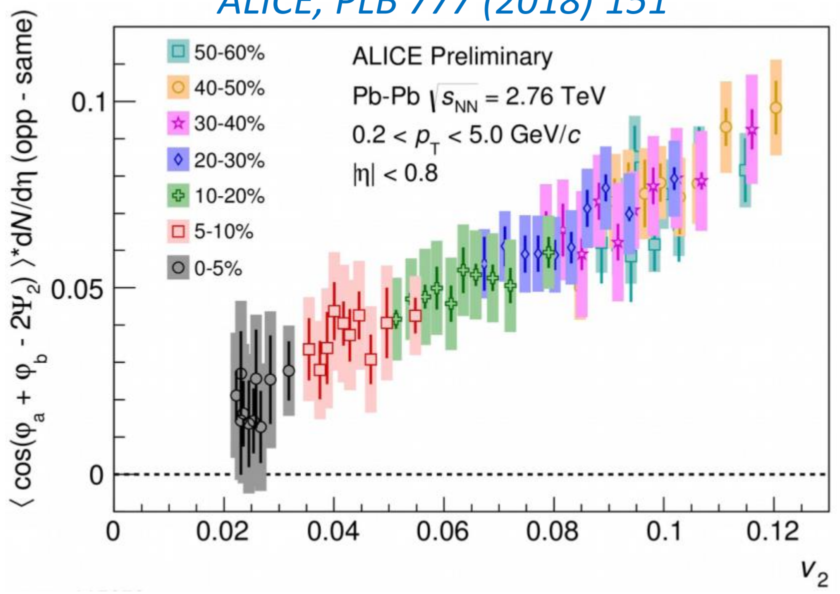
Schukraft, Timmins, Voloshin, PLB 719 (2013) 394

$$\Delta\gamma = 2\langle a_1^2\rangle \frac{v_{2,c\perp B}}{v_{2,c}^*} + \frac{C_{2p}N_{2p}}{N^2}\frac{v_{2,2p}v_{2,c}}{v_{2,c}^*} + \frac{C_{3p}N_{3p}}{2N^3 v_{2,c}^*}$$

ESE displaced from
α, β phase space



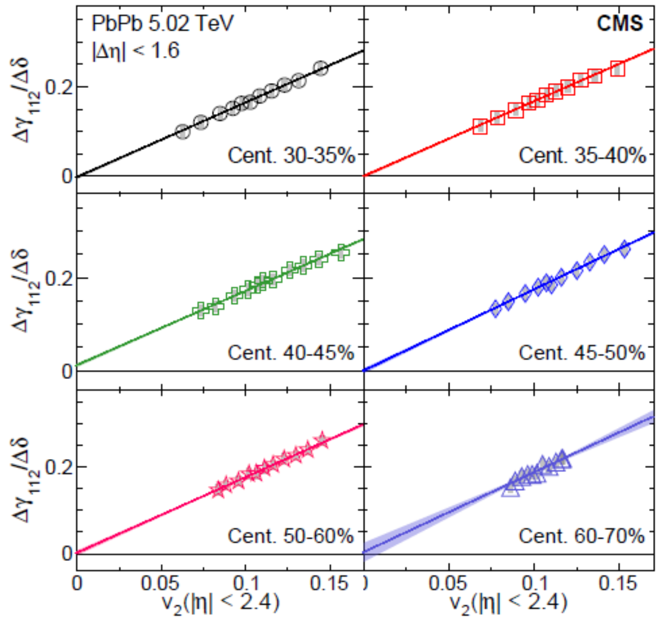
ALICE, PLB 777 (2018) 151



More sophisticated (model-dep.) assumption of B dependence on v2 within a given centrality

Upper limit 26%

CMS, PRC 97 (2018) 044912



Assume CME does not depend on v_2 within a given centrality

Upper limit 7%

Promising way to extract possible CME signal. Will need to assess nonflow effects

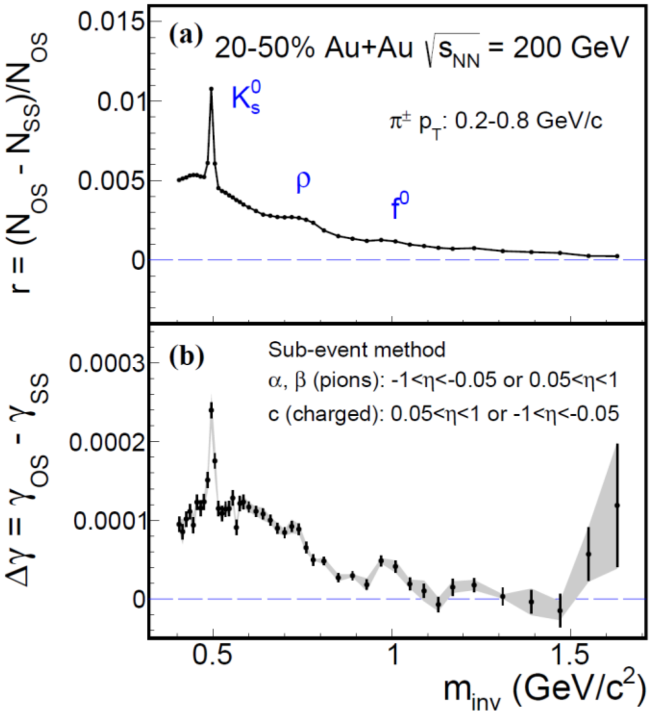
THE INVARIANT MASS DEPENDENCE

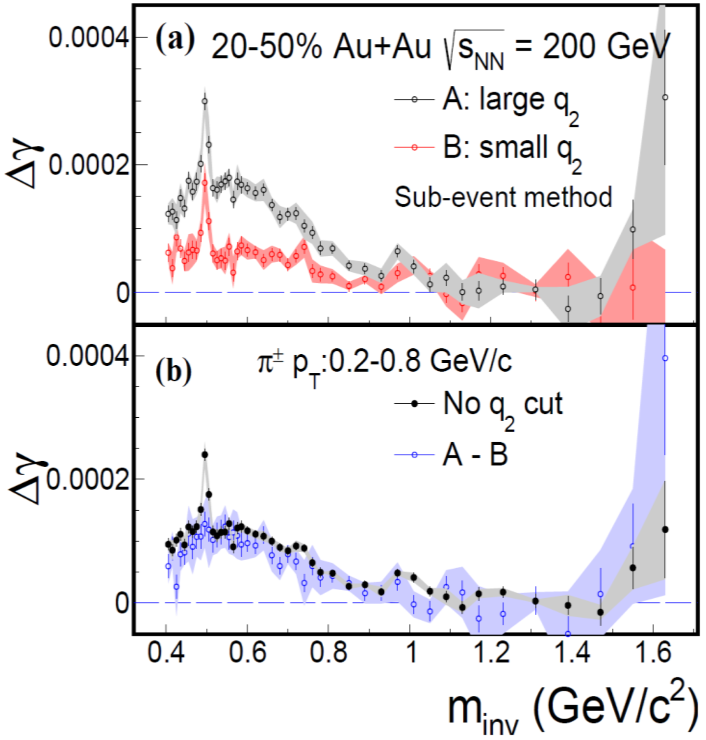
Zhao, Li, Wang, Eur.Phys.J.C 79 (2019) 168

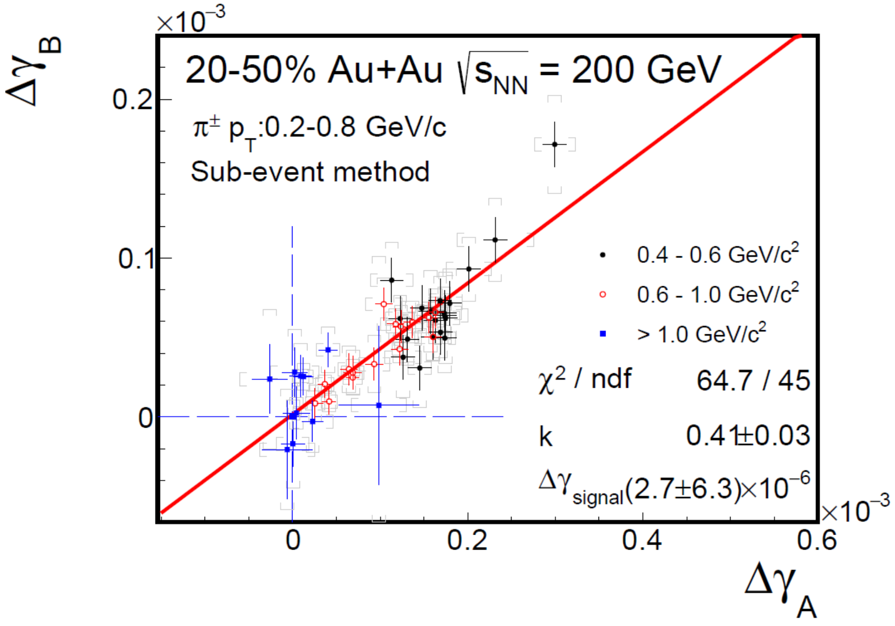
STAR, PRC 106 (2022) 034908, arXiv:2006.05035

$$\Delta\gamma = 2\left\langle a_1^2 \right\rangle \frac{v_{2,c\perp B}}{v_{2,c}^{*}} + \frac{C_{2p}N_{2p}}{N^2}\frac{v_{2,2p}v_{2,c}}{v_{2,c}^{*}} + \frac{C_{3p}N_{3p}}{2N^3 v_{2,c}^{*}}$$

$$\Delta\gamma_B = k\Delta\gamma_A + (1-k)\Delta\gamma_{sig}$$





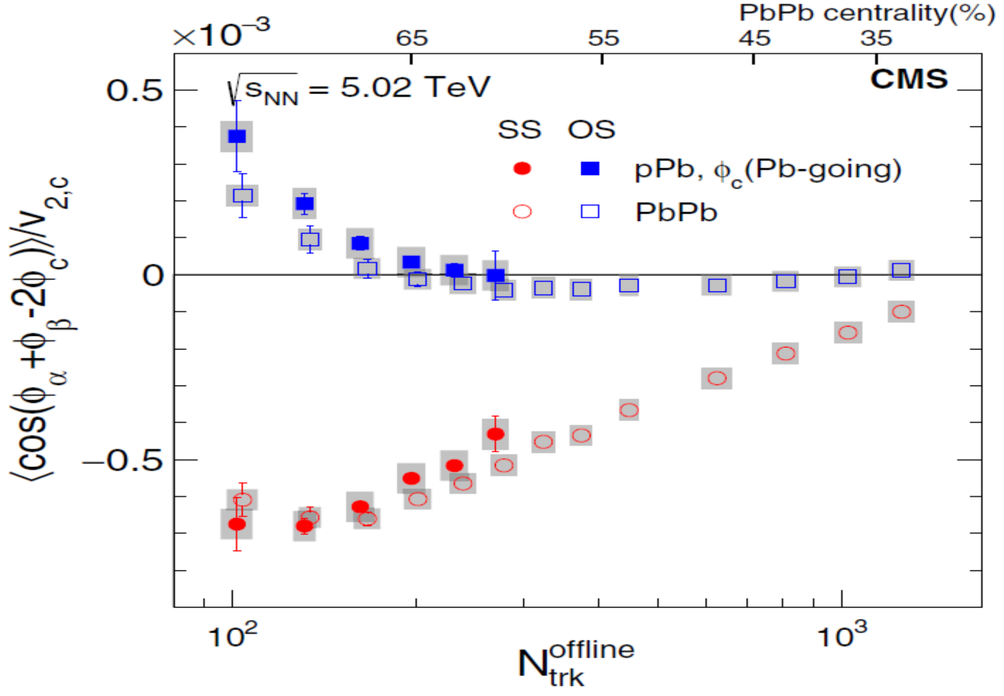


CME fraction = $(2 \pm 4 \pm 5)\%$

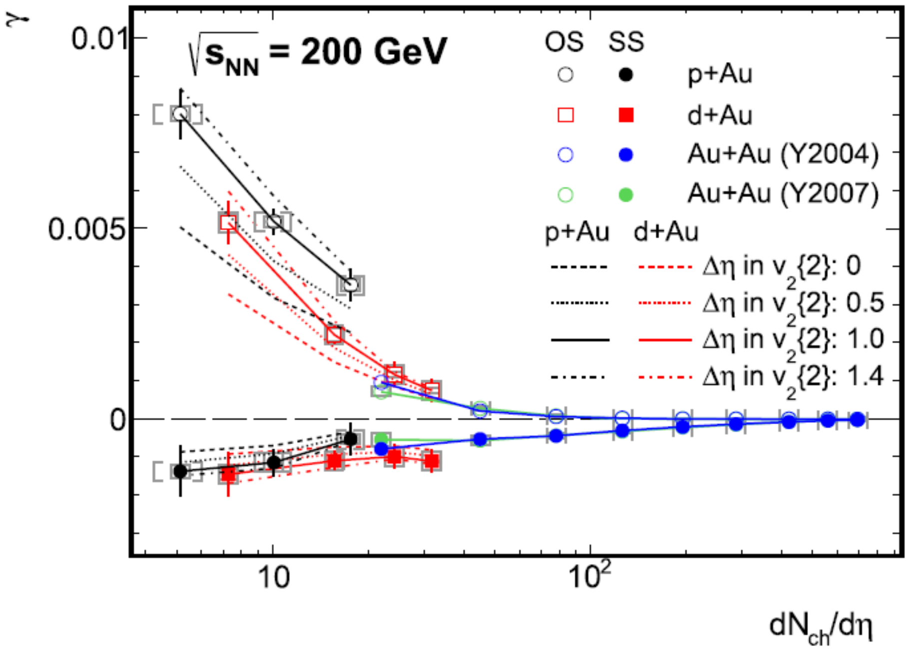
CME upper limit 15% at 95% CL

LARGE SIGNALS ALSO IN SMALL SYSTEMS

CMS, PRL 118 (2017) 122301



STAR, PLB 798 (2019) 134975

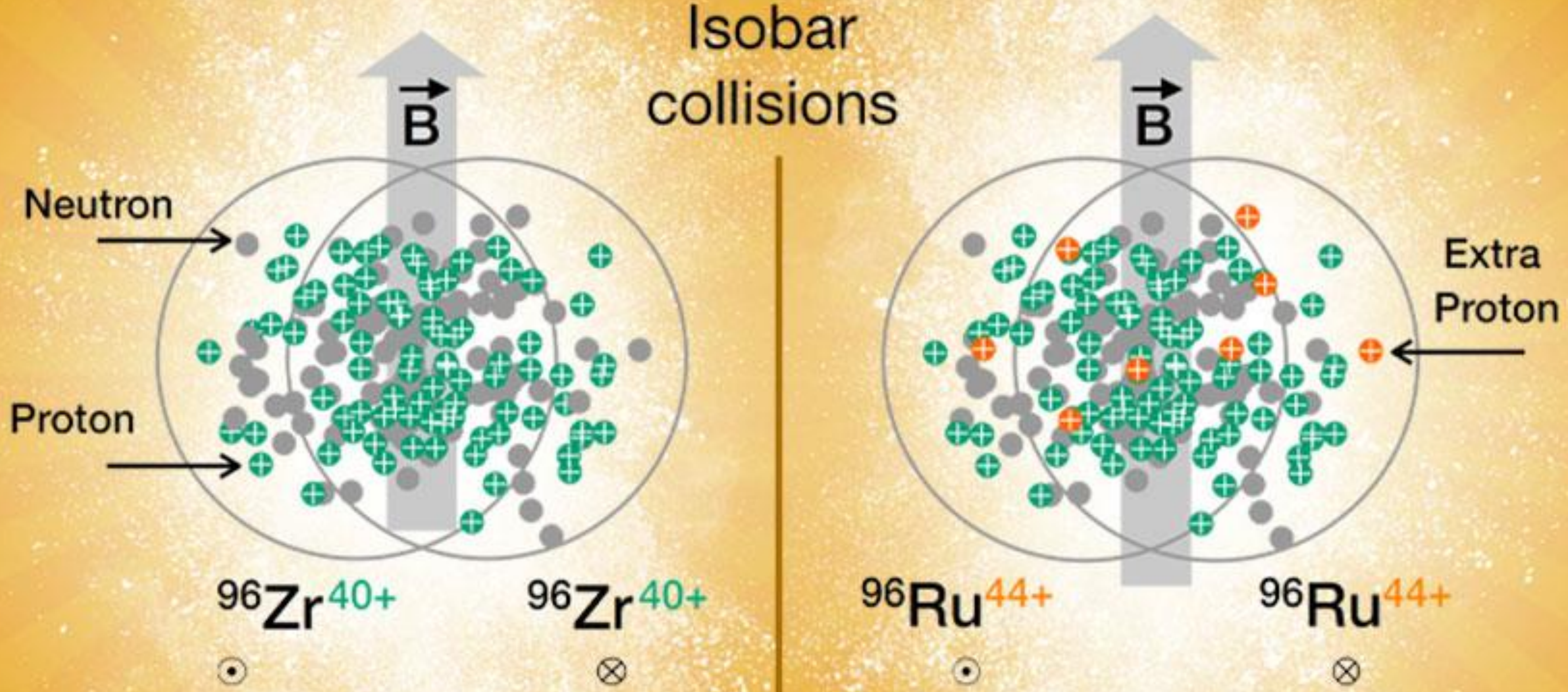


When background is large, comparative measurements are often the best and the most robust.

- Spectator Plane (SP) vs. Participant Plane (PP)
  - Pro: within the same event, physics guaranteed to be identical
  - Con: SP measured by ZDC, with poor EP resolution

- Ru+Ru vs. Zr+Zr
  - Pro: both measured by TPC, with good EP resolution
  - Con: collision systems are not identical

MOTIVATION for Isobar Run



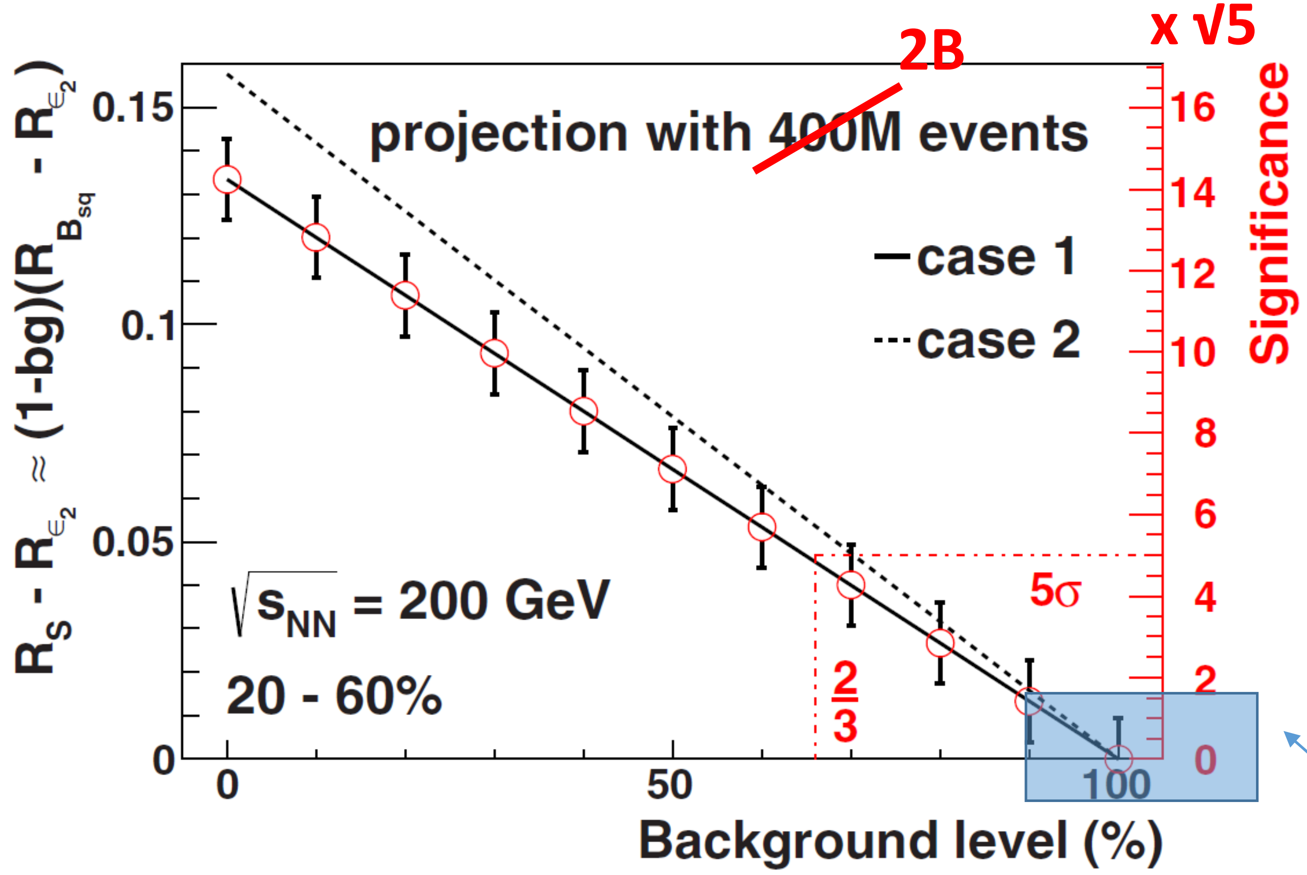
Same A → Same background

Different Z → Different signal

Voloshin, PRL 105 (2010) 172301

ISOBAR S/B ESTIMATES

Deng et al. PHYSICAL REVIEW C **94**, 041901(R) (2016)



Back-of-envelop:

$$\delta(\Delta\gamma) \approx \frac{2/\sqrt{12}}{\sqrt{(N_{POI}/2)^2}} \cdot \sqrt{2} \cdot \frac{1}{\sqrt{N_{evt}}} \cdot \frac{1}{R_{EP}} \approx 0.8\times10^{-6}$$

$N_{POI} \approx 160$ $\Delta\gamma$ $N_{evt} \approx 0.7$B (20-50%) $R_{EP} \approx 0.5$

Precision on Ru/Zr: $$\frac{\delta(\Delta\gamma)}{\Delta\gamma \approx 3\times10^{-4}} \cdot \sqrt{2} \approx 0.4\%$$

Statistical uncertainty = 0.4%

If isobar f_{CME}=10%, then signal = 15%*10% = 1.5%

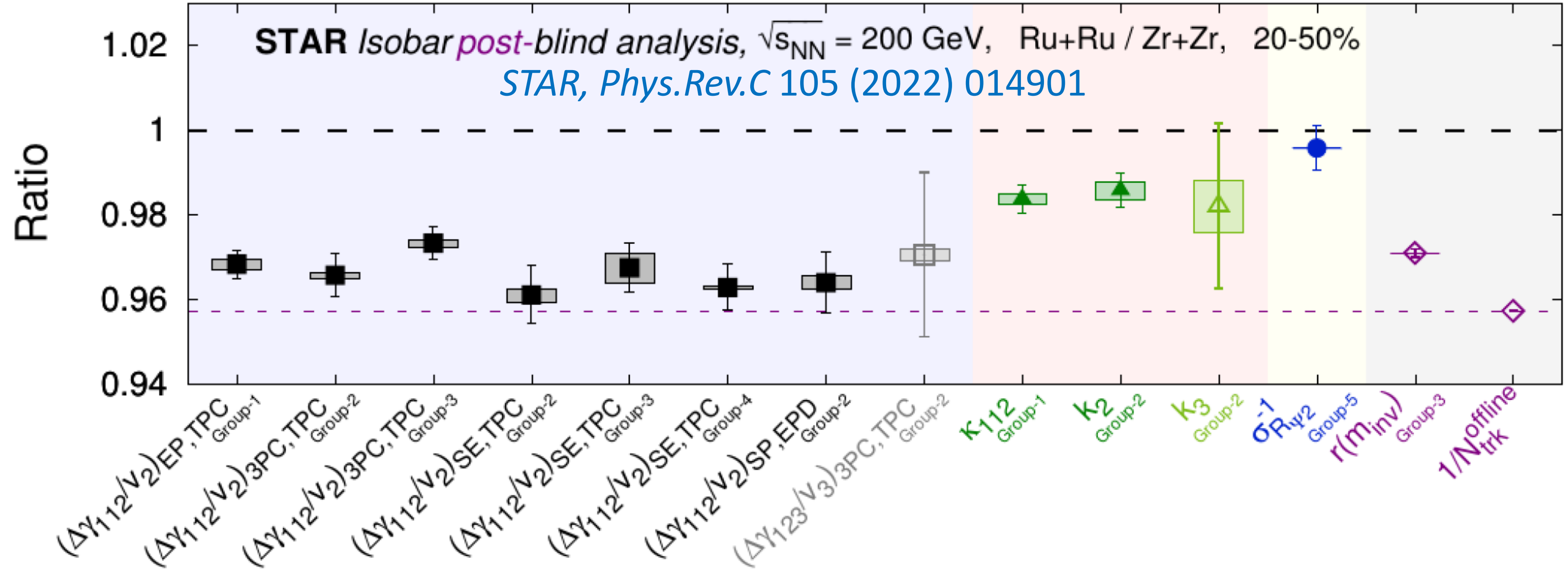
Ru/Zr = 1.015 ± 0.004 → 4σ effect

ISOBAR Run Outcome

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC, arXiv:2109.00131, *Phys. Rev. C* 105 (2022) 014901

Press release: https://www.bnl.gov/newsroom/news.php?a=119062

$\Delta\gamma/v_2$



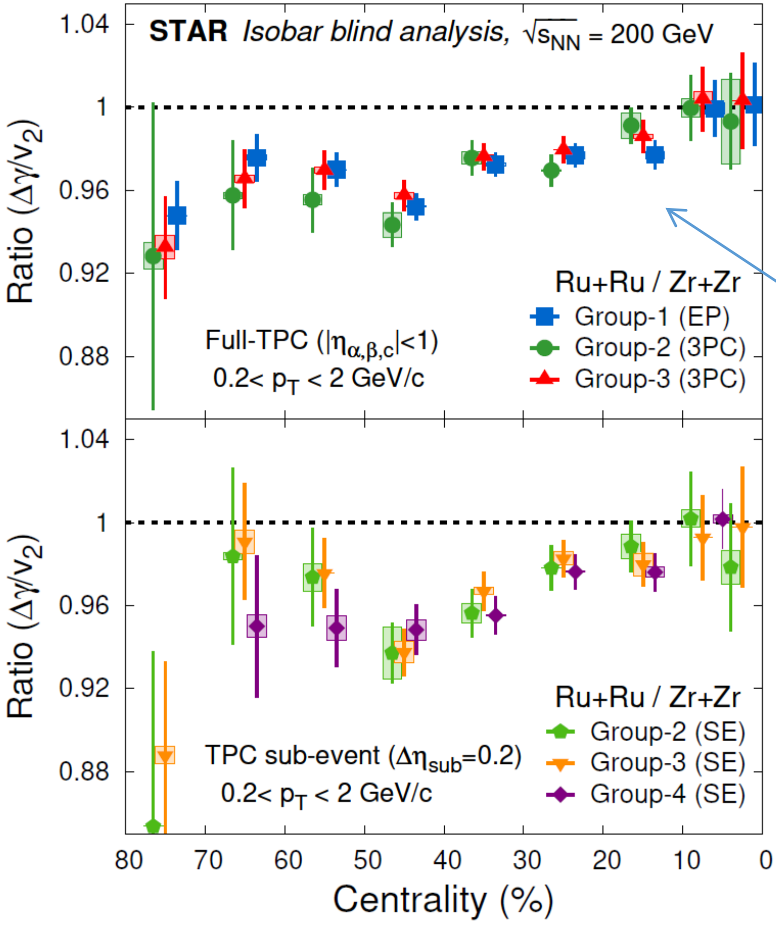
Precision of 0.4% is indeed achieved!

ISOBAR DATA $\Delta\gamma/v_2$

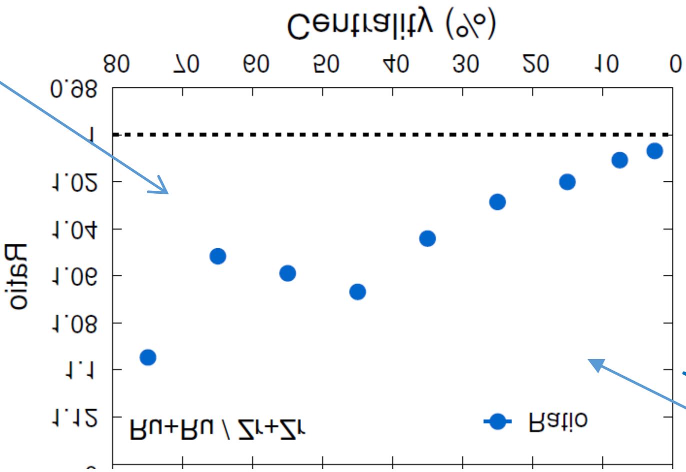
STAR, Phys.Rev.C 105 (2022) 014901, arXiv: 2109.00131

But results all below unity: trivial multiplicity dilution effect

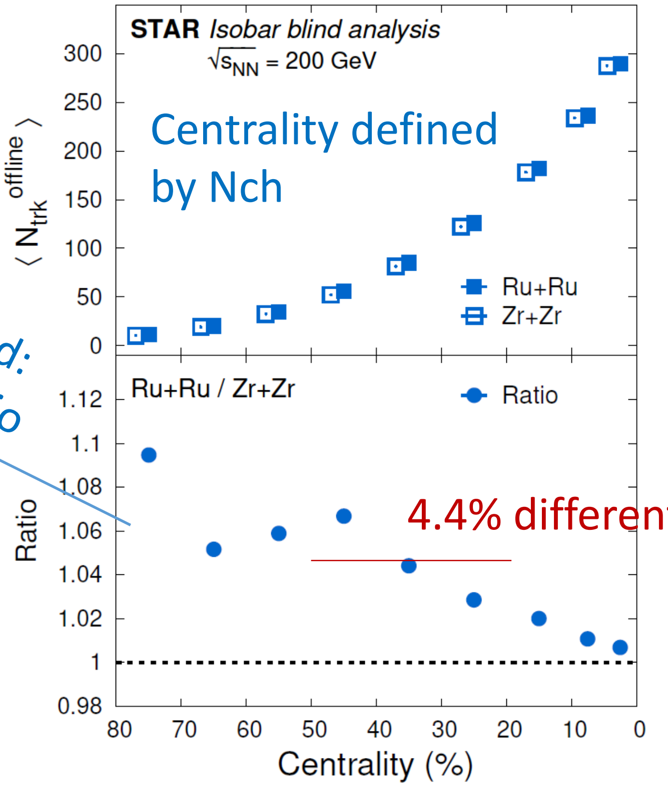
$$\Delta\gamma_{\rm bkgd} = \frac{4N_{\rm 2p}}{N^2}\langle\cos(\phi_\alpha+\phi_\beta-2\phi_{\rm 2p})\rangle v_{2,\rm 2p}$$



Indeed 0.4% precision!



Flipped: 1/N ratio



$\Delta\gamma/v_2$ follows closely with N_{ch}

$N\Delta\gamma/v_2$ would be better

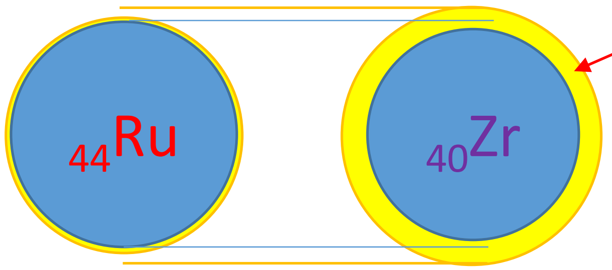
ISOBARS ARE NOT IDENTICAL

Multiplicities differ by 4.4%!

Predicted by DFT: *Haojie Xu et al. PRL **121** (2018) 022301*
*Hanlin Li et al. PRC **98** (2018) 054907*

Halo-type

$$\rho \propto \left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}$$



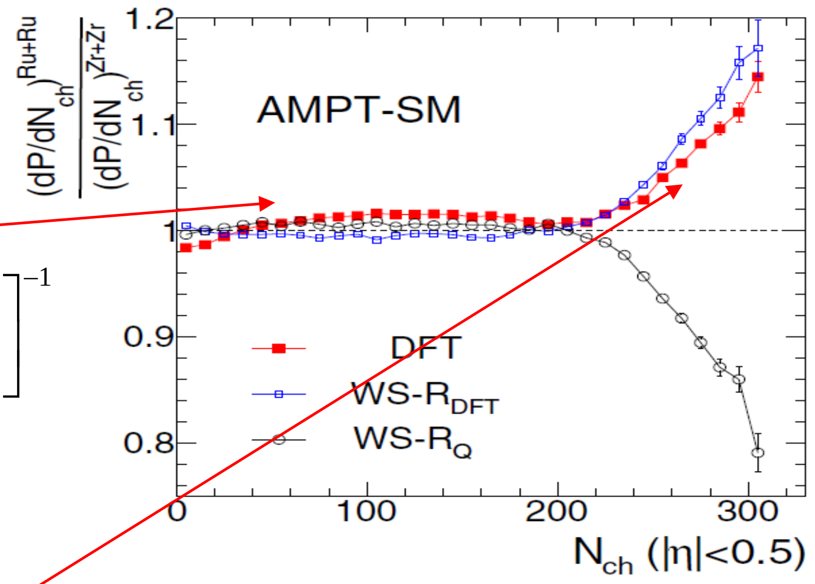
Larger charge radius
Little neutron skin

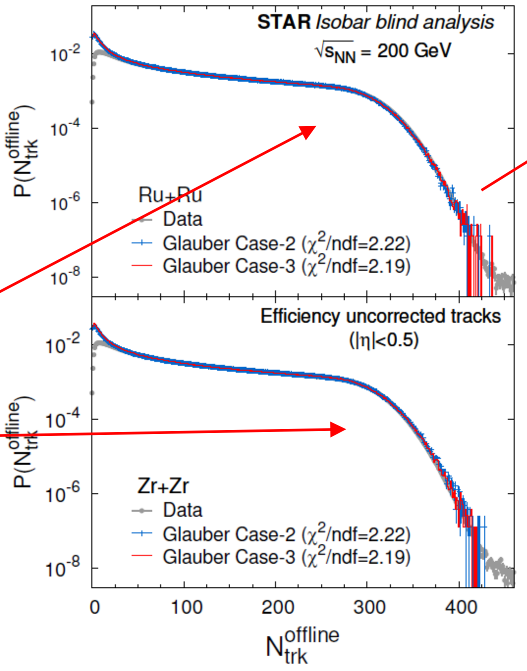
Smaller charge radius
Thicker neutron skin

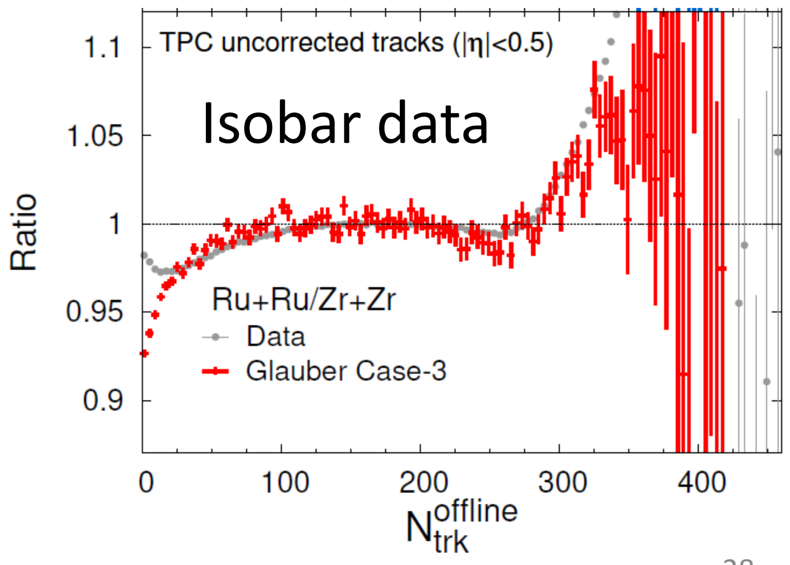
Overall size: Ru < Zr

→ Larger energy density in Ru > Zr

→ Larger multiplicity in Ru > Zr



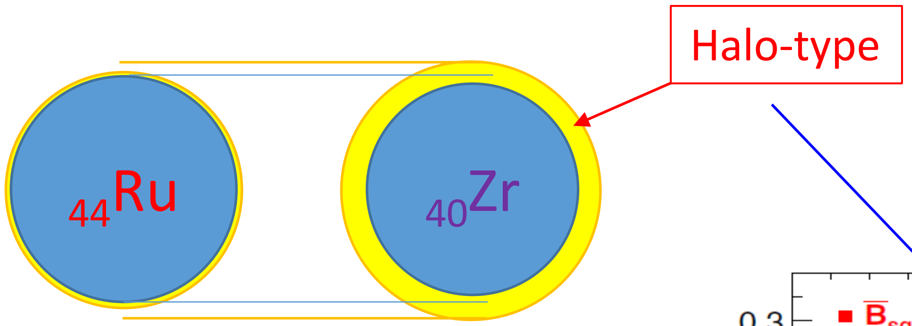




ISOBARS ARE NOT IDENTICAL

v_2 differ by 2-3%!

Predicted by DFT: *Haojie Xu et al. PRL **121** (2018) 022301*
*Hanlin Li et al. PRC **98** (2018) 054907*

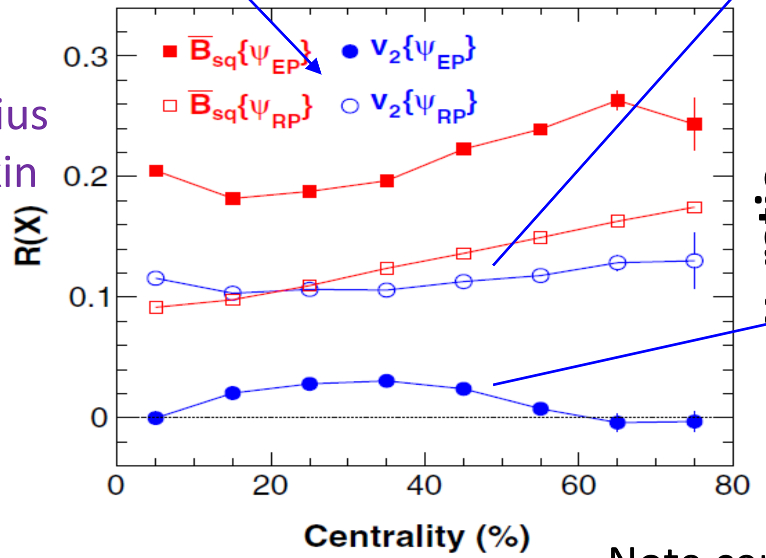


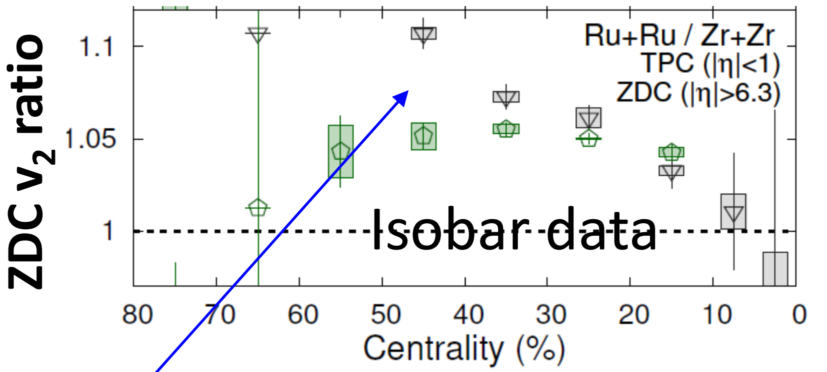
Larger charge radius
Little neutron skin

Smaller charge radius
Thicker neutron skin

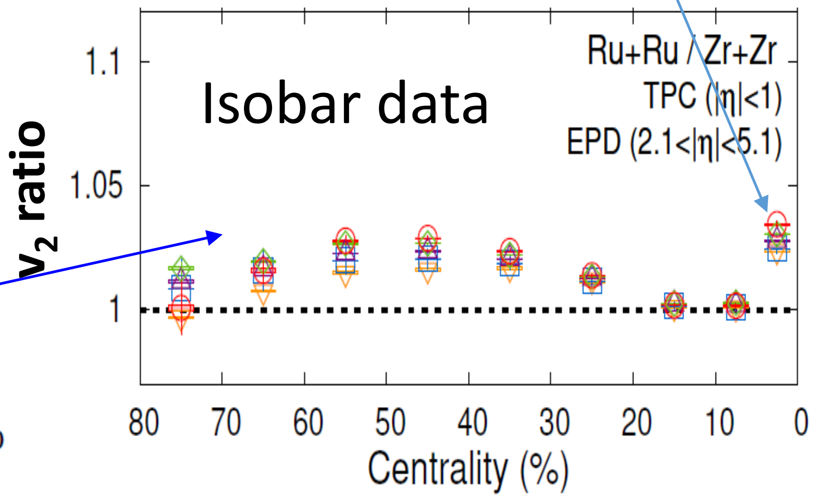
$$\Delta\gamma_{\rm bkgd} = \frac{4N_{\rm 2p}}{N^2}\langle\cos(\phi_\alpha+\phi_\beta-2\phi_{\rm 2p})\rangle v_{2,{\rm 2p}}$$

Normalize by v_2 and N → $N\Delta\gamma/v_2$



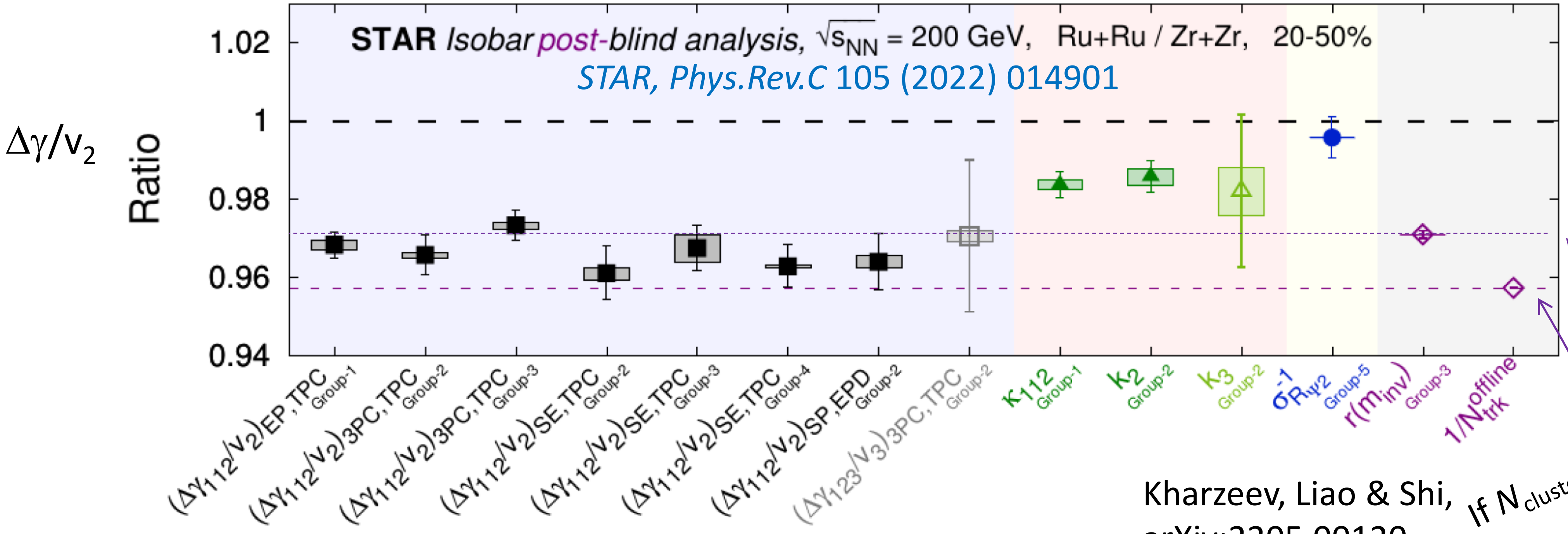


Nuclear deformity:
Deng et al. PRC 94 (2016) 041901(R)
Zhang & Jia, PRL 128 (2022) 022301



Note centrality axis flip

ISOBAR RESULTS



$r = \frac{N_{OS} - N_{SS}}{N_{OS}}$

Kharzeev, Liao & Shi, arXiv:2205.00120

If $N_{cluster} \propto N$

$\Delta\gamma_{bkg} \propto N_{cluster} / N^2$

- $\Delta\gamma/v_2$ isobar ratio smaller than unity
- Primary reason is mult. difference

REMAINING NONFLOW EFFECTS

FENG Yicheng (STAR): QM’2022, SQM’2022

Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

$$C_3 = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p} v_2 + \frac{C_{3p}N_{3p}}{2N^3}; \quad C_{2p} \equiv \langle \cos(\alpha+\beta-2\phi_{2p}) \rangle \quad C_{3p} \equiv \langle \cos(\alpha+\beta-2c) \rangle_{3p}$$

$$\varepsilon_2 \equiv \frac{C_{2p}N_{2p}}{N} \cdot \frac{v_{2,2p}}{v_2} \qquad \varepsilon_3 \equiv \frac{C_{3p}N_{3p}}{2N}$$

$$v_2^{*2} = v_2^2 + v_{2,\mathrm{nf}}^2 \qquad \varepsilon_{\mathrm{nf}} \equiv v_{2,\mathrm{nf}}^2 / v_2^2$$

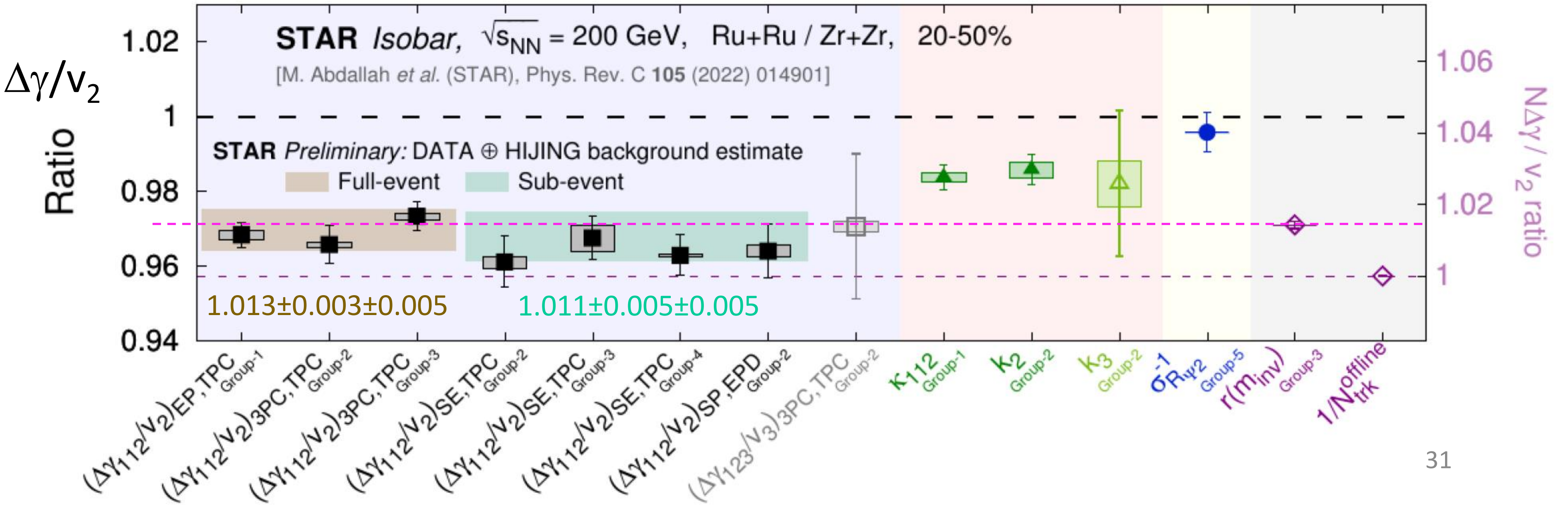
$$N \approx N_+ \approx N_- \qquad \Delta X \equiv X^{\mathrm{Ru}} - X^{\mathrm{Zr}}$$

$$\frac{(N\Delta\gamma/v_2^*)^{\mathrm{Ru}}}{(N\Delta\gamma/v_2^*)^{\mathrm{Zr}}} \equiv \frac{(NC_3/v_2^{*2})^{\mathrm{Ru}}}{(NC_3/v_2^{*2})^{\mathrm{Zr}}} \approx \frac{\varepsilon_2^{\mathrm{Ru}}}{\varepsilon_2^{\mathrm{Zr}}} \cdot \frac{(1+\varepsilon_{\mathrm{nf}})^{\mathrm{Zr}}}{(1+\varepsilon_{\mathrm{nf}})^{\mathrm{Ru}}} \cdot \frac{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Ru}}}{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Zr}}} \approx \frac{\varepsilon_2^{\mathrm{Ru}}}{\varepsilon_2^{\mathrm{Zr}}} - \frac{\Delta\varepsilon_{\mathrm{nf}}}{1+\varepsilon_{\mathrm{nf}}} + \frac{\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}}{1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}} \left(\frac{\Delta\varepsilon_3}{\varepsilon_3} - \frac{\Delta\varepsilon_2}{\varepsilon_2} - \frac{\Delta N}{N} - \frac{\Delta v_2^2}{v_2^2} \right)$$

Current total uncertainty:
0.4%⊕0.3%⊕0.5% = 0.7%

Assuming 15% B^2 diff:
δf_{CME} = 0.7%/15% = 5%

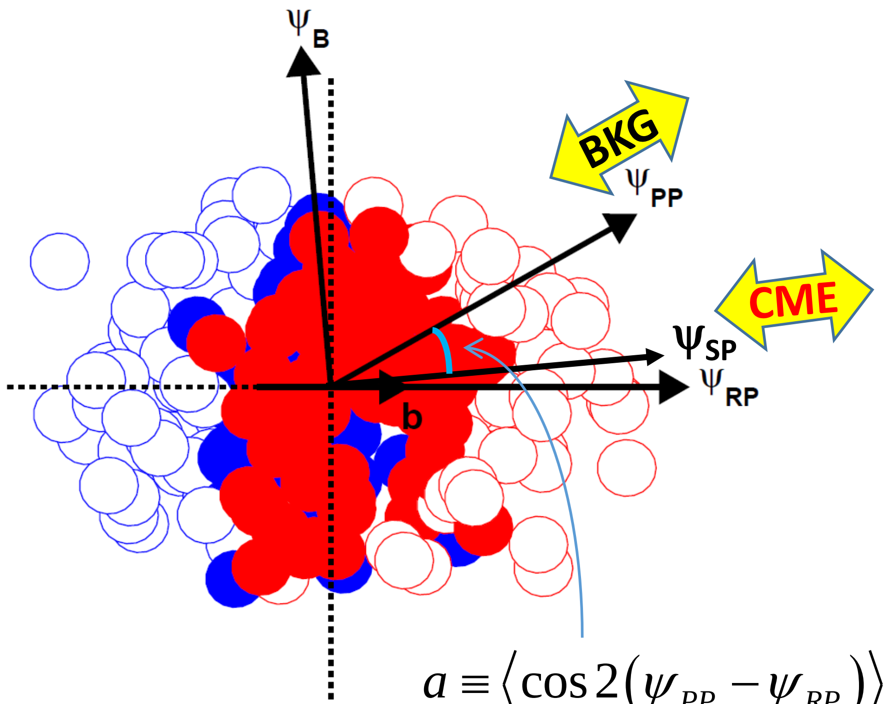
My conservative estimate:
f_{CME} < 10% at 98% CL



SPECTATOR & PARTICIPANT PLANES

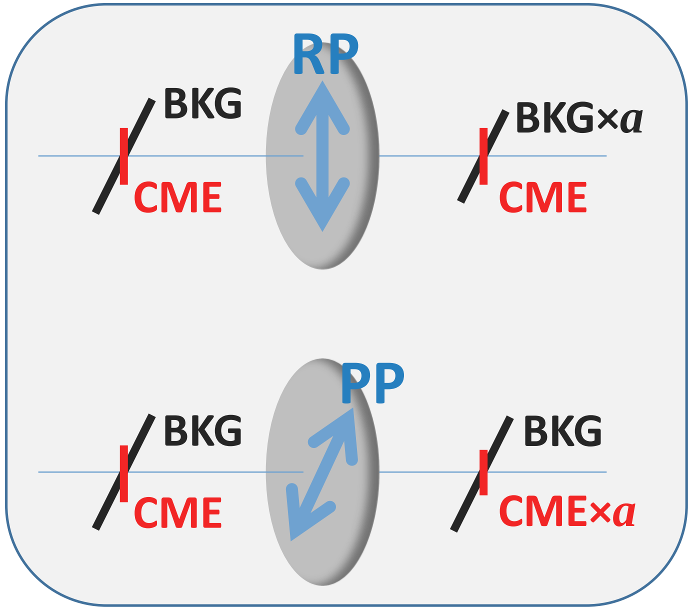
H.-j. Xu, FW, et al., CPC 42 (2018) 084103, arXiv:1710.07265

$$\Delta\gamma = 2\left\langle a_1^2 \right\rangle \frac{v_{2,c\perp B}}{v_{2,c}^*} + \frac{C_{2p}N_{2p}}{N^2}\frac{v_{2,2p}v_{2,c}}{v_{2,c}^*} + \frac{C_{3p}N_{3p}}{2N^3 v_{2,c}^*}$$



$$a \equiv \left\langle \cos 2\left(\psi_{PP} - \psi_{RP}\right)\right\rangle$$

INTRA-EVENT "CME-v_2 FILTER"



IN THE SAME EVENT

$$\Delta\gamma\{\mathrm{SP}\} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{PP}\}}{a} + a\Delta\gamma_{\mathrm{Bkg}}\{\mathrm{PP}\}$$

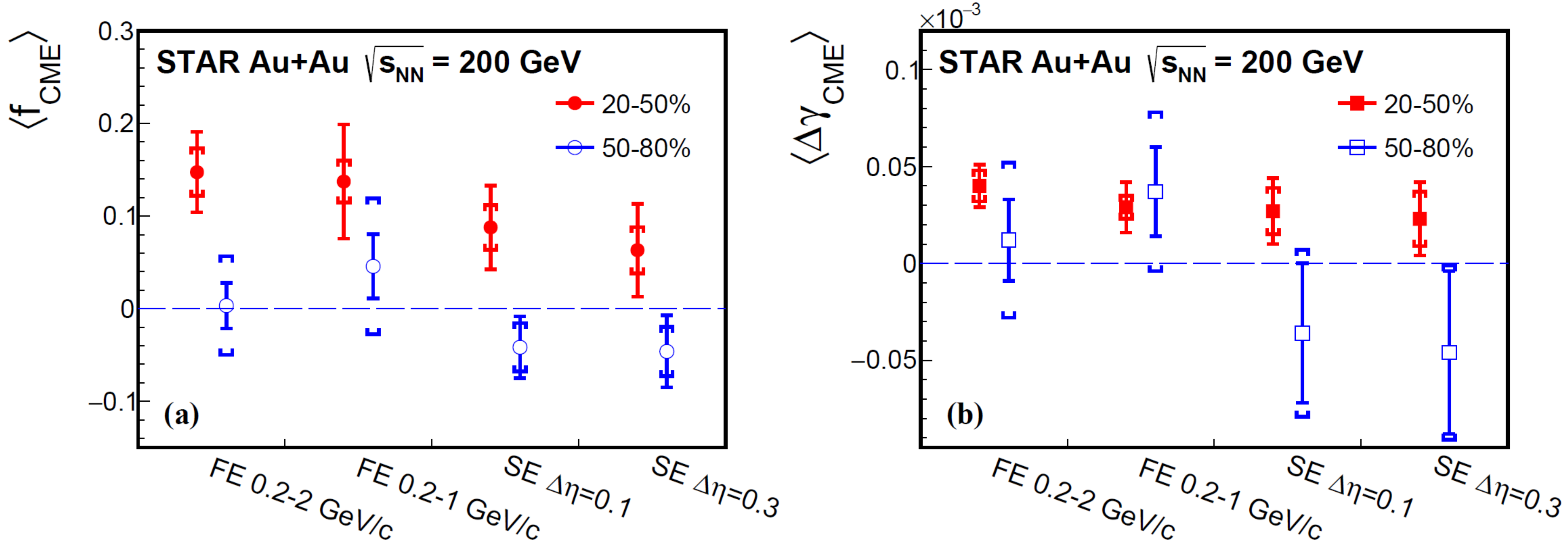
$$\Delta\gamma\{\mathrm{PP}\} = \Delta\gamma_{\mathrm{CME}}\{\mathrm{PP}\} + \Delta\gamma_{\mathrm{Bkg}}\{\mathrm{PP}\}$$

$$f_{\mathrm{CME}} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{PP}\}}{\Delta\gamma\{\mathrm{PP}\}} = \frac{A/a-1}{1/a^2-1}$$

$$A = \Delta\gamma\{\mathrm{SP}\}/\Delta\gamma\{\mathrm{PP}\},\ a = v_2\{\mathrm{SP}\}/v_2\{\mathrm{PP}\}$$

Au+Au Collisions at 200 GeV (2.4B MB)

STAR, PRL 128 (2022) 092301, arXiv:2106.09243



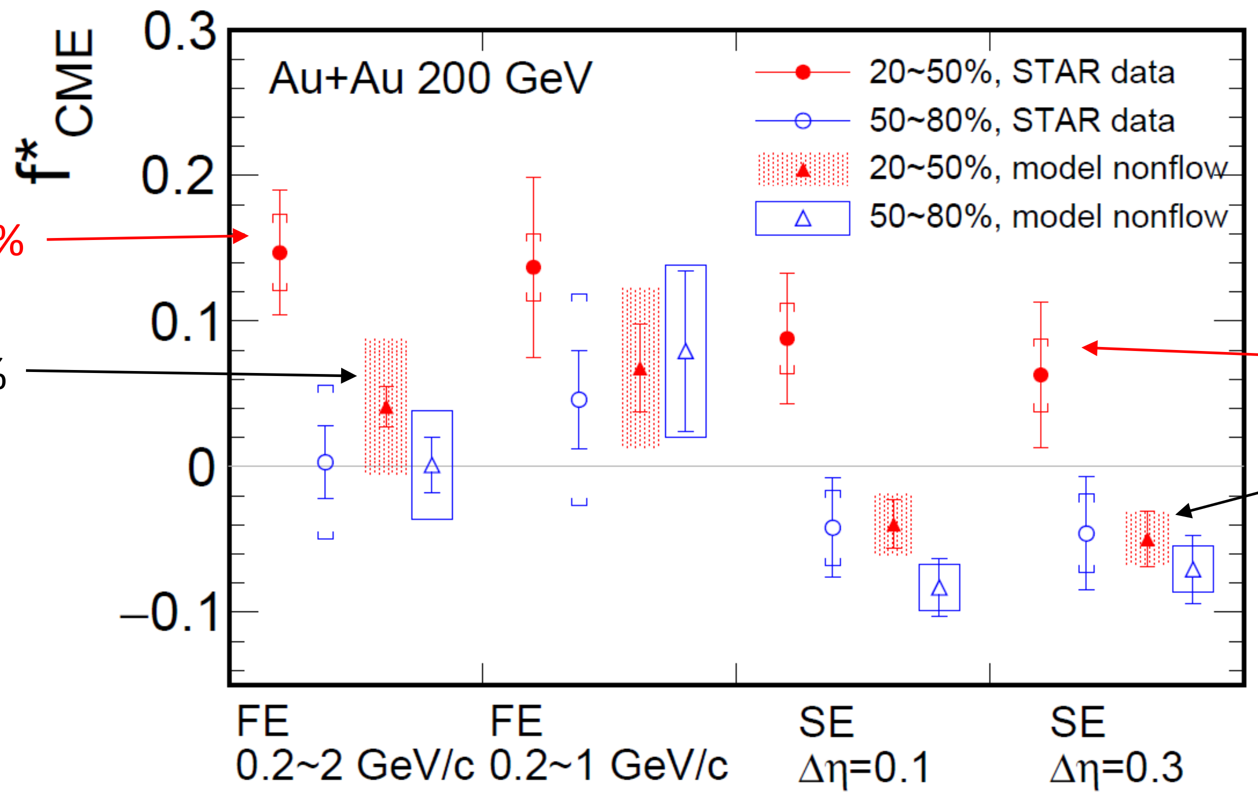
- Peripheral 50-80% collisions: consistent-with-zero signal with relatively large errors
- Mid-central 20-50% collisions: indication of finite CME signal with 1-3σ significance
- How much is there remaining nonflow contamination?

IMPLICATIONS TO Au+Au DATA

STAR, PRL 128 (2022) 092301, arXiv:2106.09243
Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

(14.7 ± 5.0)%

(4.1 ± 4.8)%



(6.3 ± 5.6)%

(–5.0 ± 2.6)%

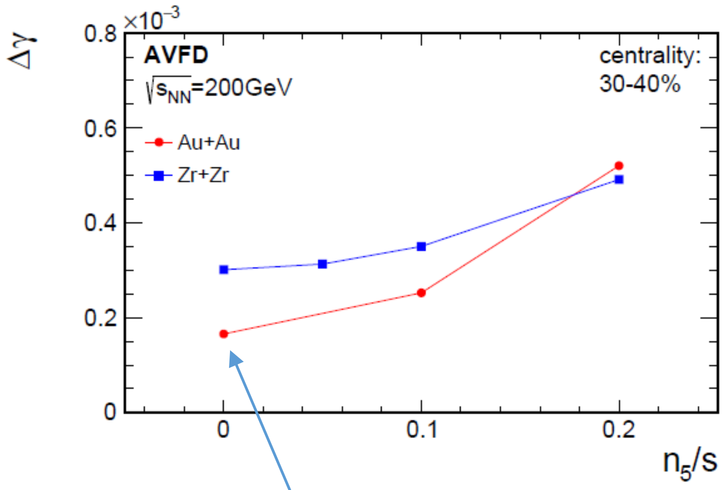
Net nonflow effect could be negative

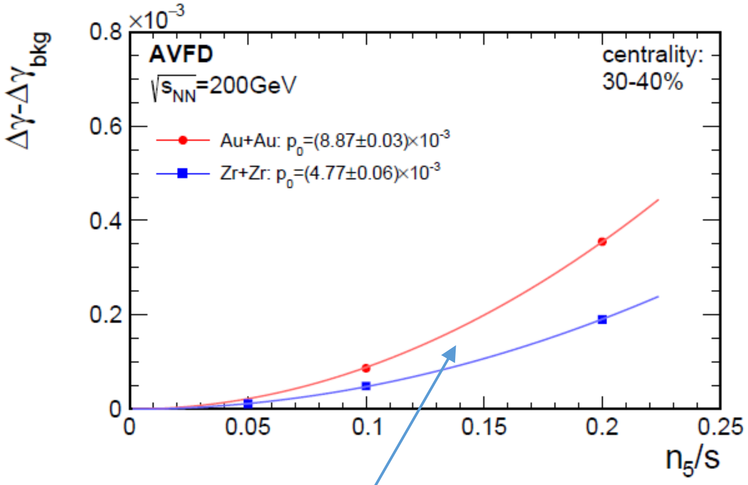
There may indeed be hint of CME in the Au+Au data

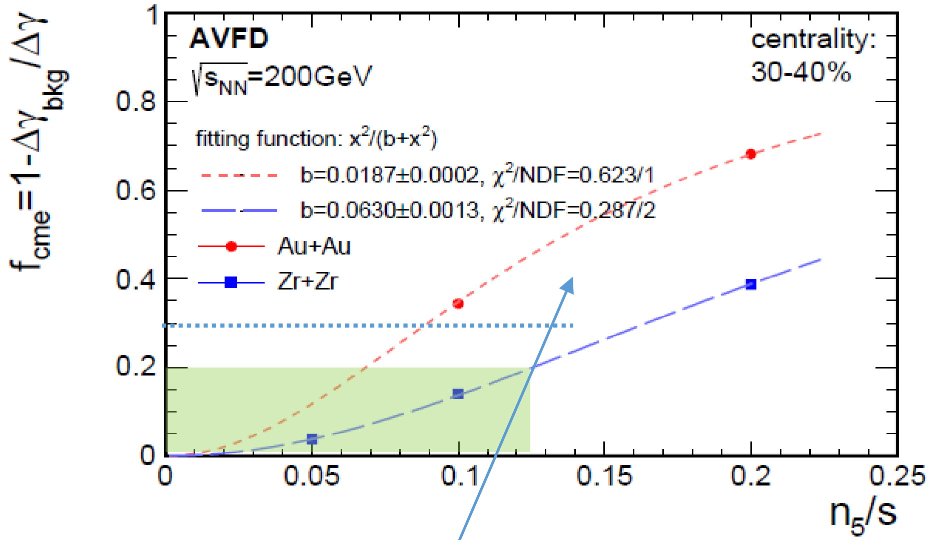
ISOBAR SIGNAL MAY BE EXPECTED SMALL

Feng, Lin, Zhao & FW, PLB 820 (2021) 136549, arXiv:2103.10378

AVFD simulations in preparation for isobar blind analysis







Background $\propto$ 1/N
isobar/AuAu ~ 2

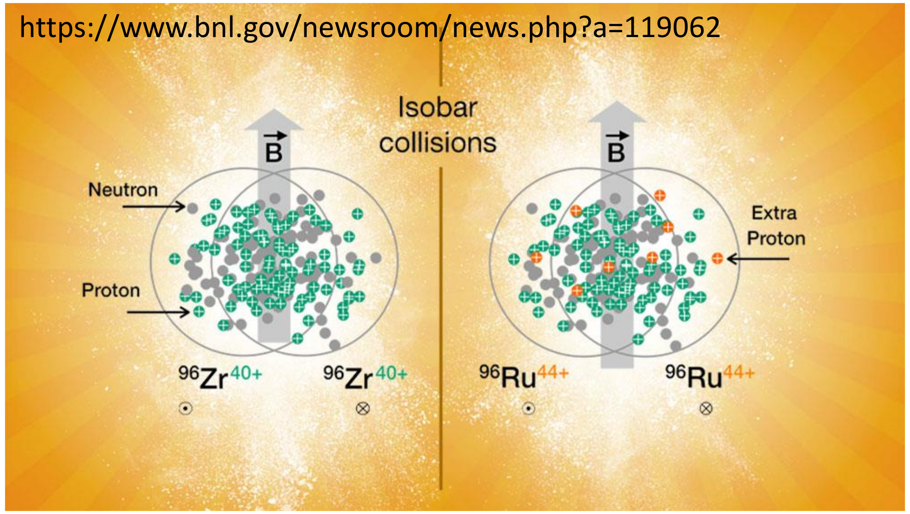
Mag. field B ~ A/A$^{2/3}$ ~ A$^{1/3}$
$\Delta\gamma_{CME}$ ~ B^2 ~ A$^{2/3}$
Signal: AuAu/isobar ~ 1.5

Could be x3 reduction in f_{CME} at the same n_5/s
If AuAu f_{CME}=10%, then isobar 3% (1σ effect)
Ru/Zr = 1 + 15%*3% = 1.005 (±0.004)

Caveats: Axial charge densities and sphaleron transition probabilities could be different between Au+Au and isobar, e.g. AVFD-glasma μ_5/s: isobar/AuAu ~ 1.5

ISOBAR S/B ESTIMATES

Voloshin, PRL 105 (2010) 172301



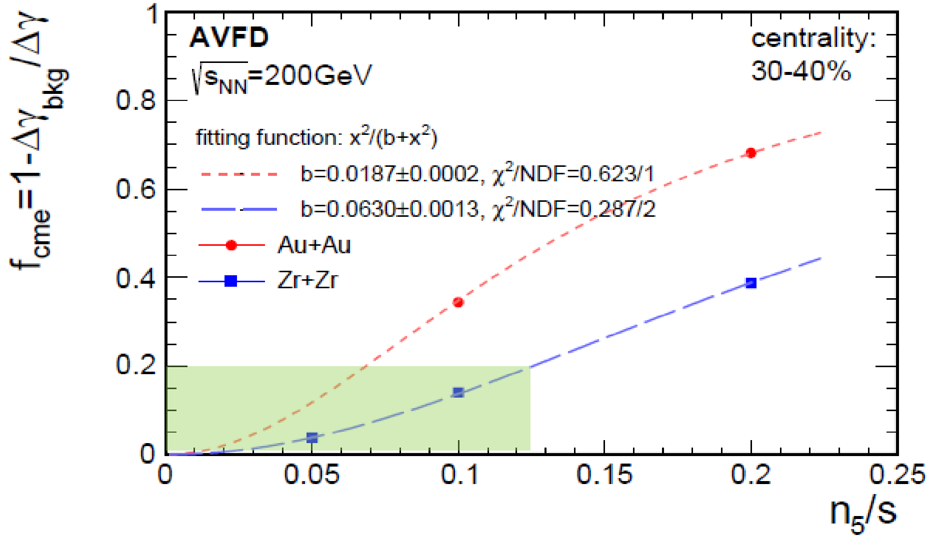
$\Delta\gamma \propto B^2$, differ by 15% between isobars

If CME signal in isobar ~ Au+Au ~ 10%,

then $\Delta\gamma^{Ru}/\Delta\gamma^{Zr}$ - 1 ~ 1.5%.

With 0.4% uncertainty, ~4σ effect

Feng, Lin, Zhao & FW, PLB 820 (2021) 136549, arXiv:2103.10378



If CME signal in isobar is x3 small

than in Au+Au, then ~1σ effect

5

BYPRODUCTS – Turn bad into good

- Use isobar collisions to probe nuclear structure

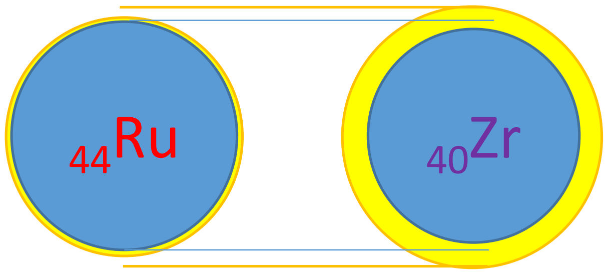
ISOBAR BYPRODUCT – SYMMETRY ENERGY

- Nearly identical nuclei
- Exquisitely matched running conditions, frequently alternating beam species
- Well controlled systematics, largely canceled

$$E(\rho,\delta) = E_0(\rho) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4); \quad \rho = \rho_n + \rho_p; \quad \delta = \frac{\rho_n - \rho_p}{\rho};$$

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

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



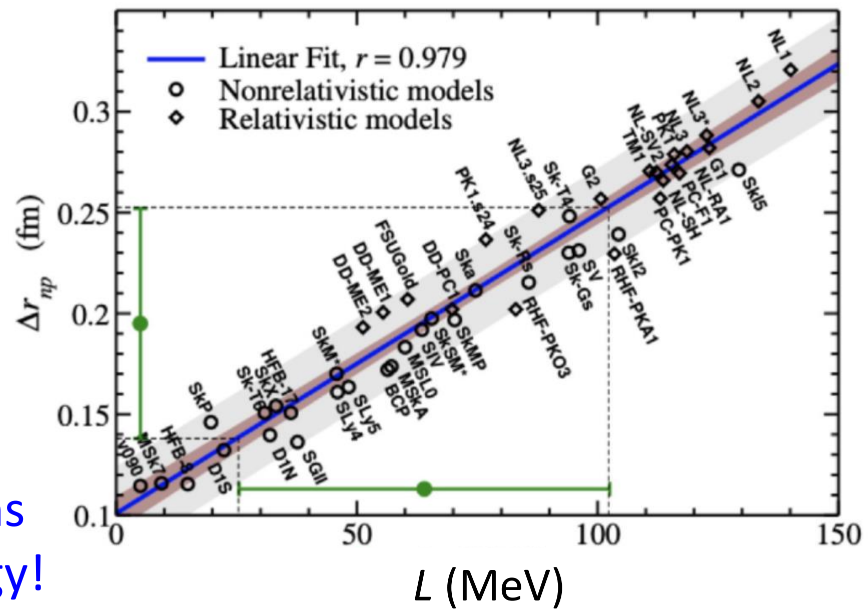
Larger charge radius
Little neutron skin

Smaller charge radius
Thicker neutron skin

Overall size: Ru < Zr
→ Larger energy density in Ru > Zr
→ Larger multiplicity in Ru > Zr

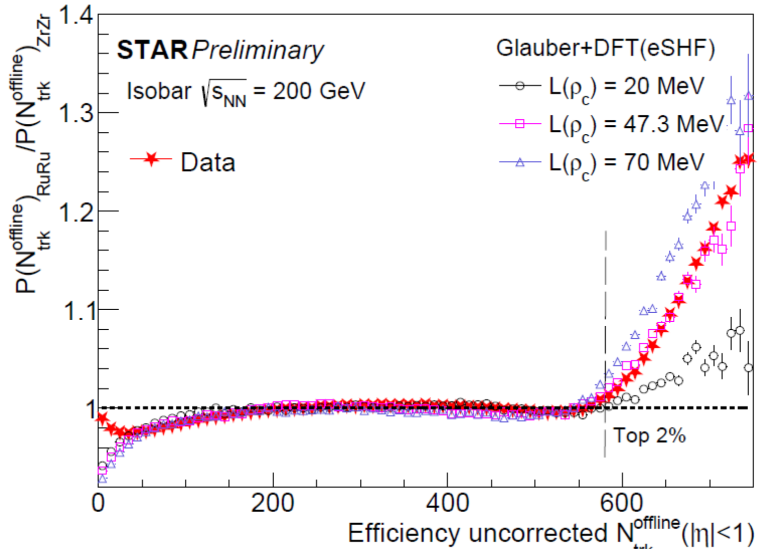
Larger L, harder EOS
⇕
Smaller δ to lower E
⇕
Smaller ρ_n, larger Δr_{np}

Brown, PRC 85, 5296 (2000)
Furnstahl, NPA 706, 85 (2002)
Roca-Maza et al., PRL 106, 252501 (2011)



Relativistic heavy-ion collisions can probe the symmetry energy!

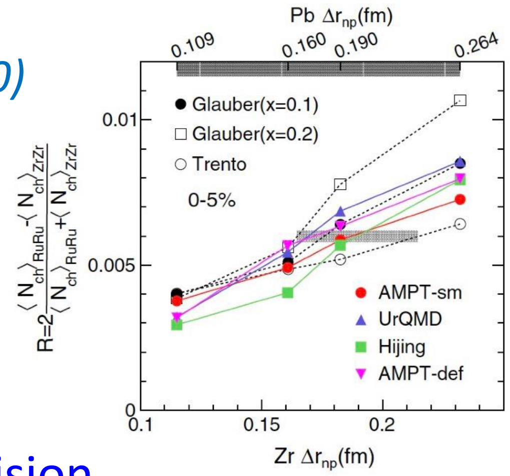
ISOBAR BYPRODUCT – SYMMETRY ENERGY



Hanlin Li, Haojie Xu, et al., PRL 125, 222301 (2020)

Haojie Xu, QM 2022, arXiv:2208.06149

Zhang & Chen, PRC 94, 064326 (2016)



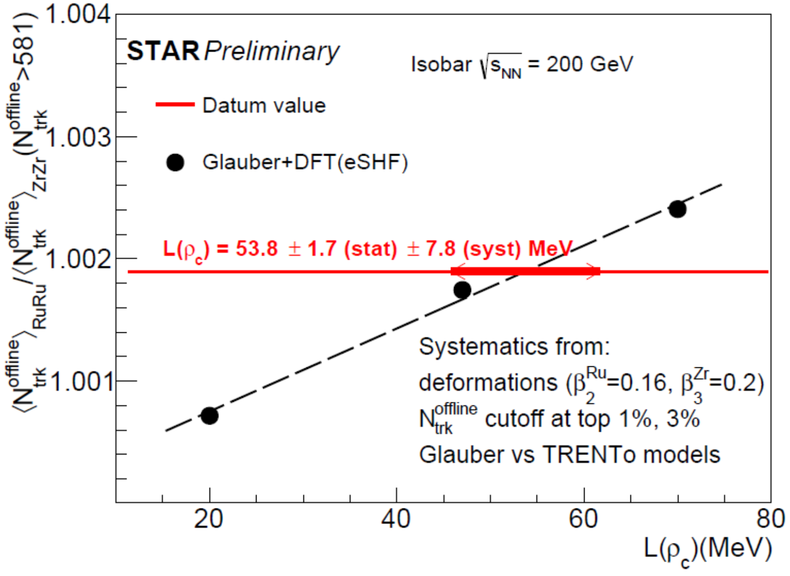
$\Delta r_{np,Zr} = 0.195 \pm 0.019$ fm

$\Delta r_{np,Ru} = 0.051 \pm 0.009$ fm

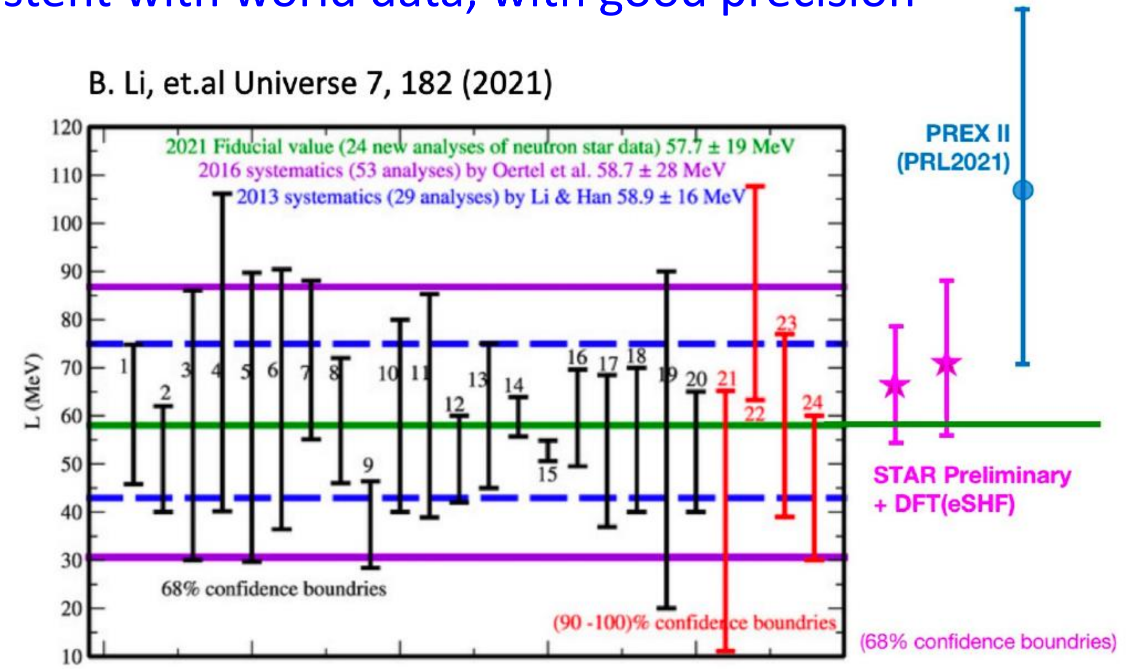
$L(\rho_c) = 53.8 \pm 1.7 \pm 7.8$ MeV

$L(\rho) = 65.4 \pm 2.1 \pm 12.1$ MeV

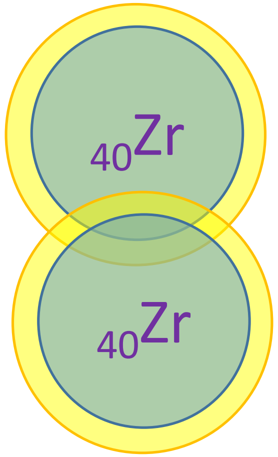
Consistent with world data, with good precision



B. Li, et.al Universe 7, 182 (2021)



NET-CHARGE IN GRAZING ISOBAR COLLISIONS



Larger neutron skin of colliding nuclei
More nn collisions in grazing impact
Fewer participant charges
Smaller net-charge at mid-rapidity

Haojie Xu et al., PRC 105, L011901 (2022)

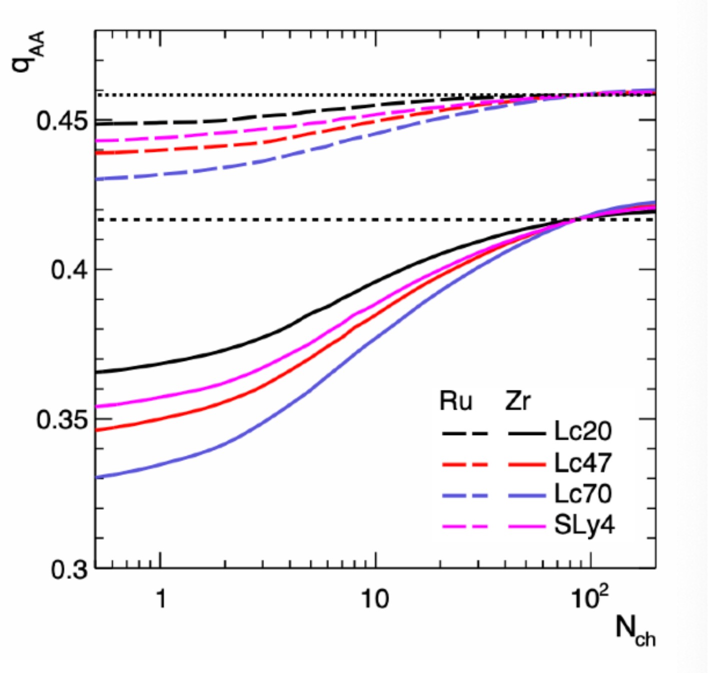
Superimposition assumption:

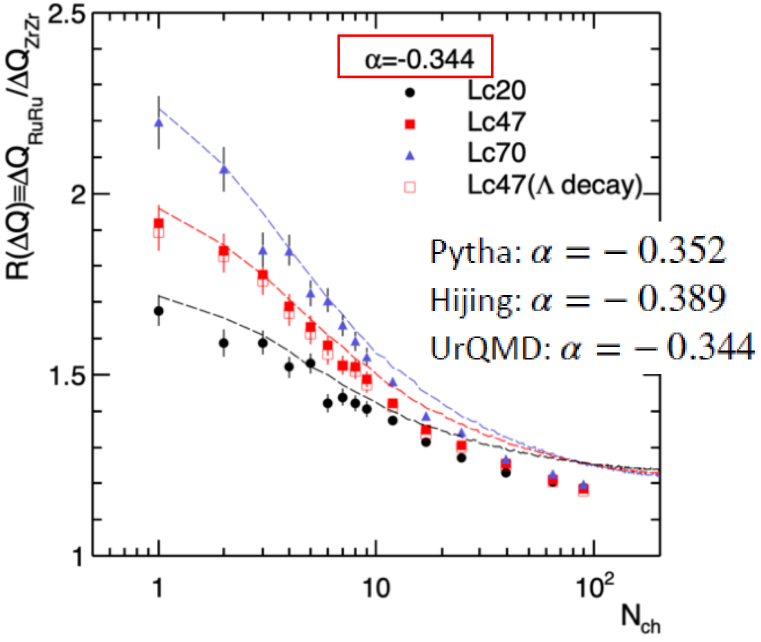
$$R(\Delta Q) = \frac{q_{RuRu} + \alpha/(1-\alpha)}{q_{ZrZr} + \alpha/(1-\alpha)}$$

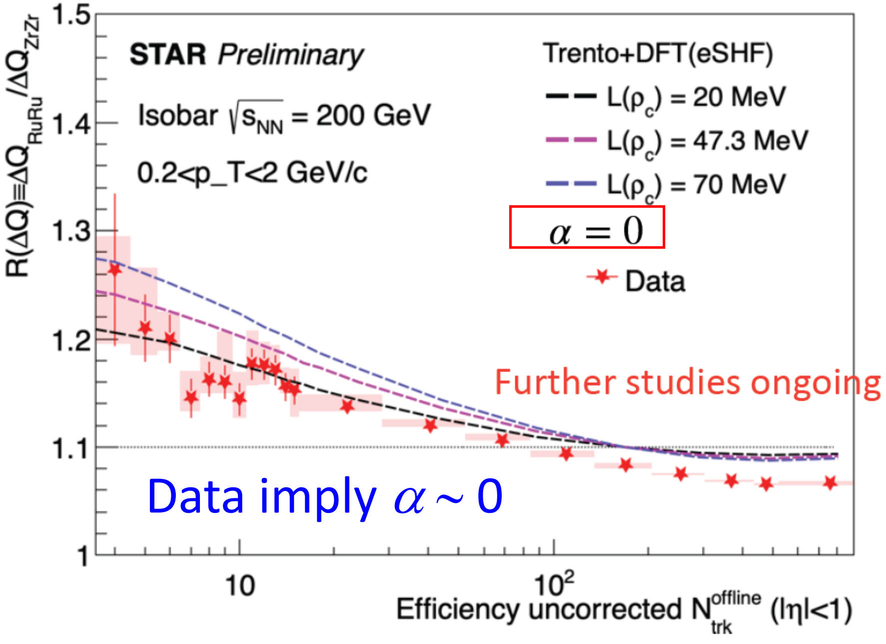
q_{AA}: participant p/(p+n)

$\alpha = \Delta Q_{nn} / \Delta Q_{pp}$

Haoiie Xu, QM 2022, arXiv:2208.06149







SUMMARY

- CME is a fundamental physics in QCD and the Standard Model; may be pertinent to left/right, matter/antimatter asymmetry

- Isobar collisions have been a powerful tool, but background is too large that statistics aren't enough to make a decisive conclusion. Not a contradiction to Au+Au where a $\sim 2\sigma$ effect is observed.

- Somewhat unexpected but pleasant byproduct: high sensitivity to nuclear structure