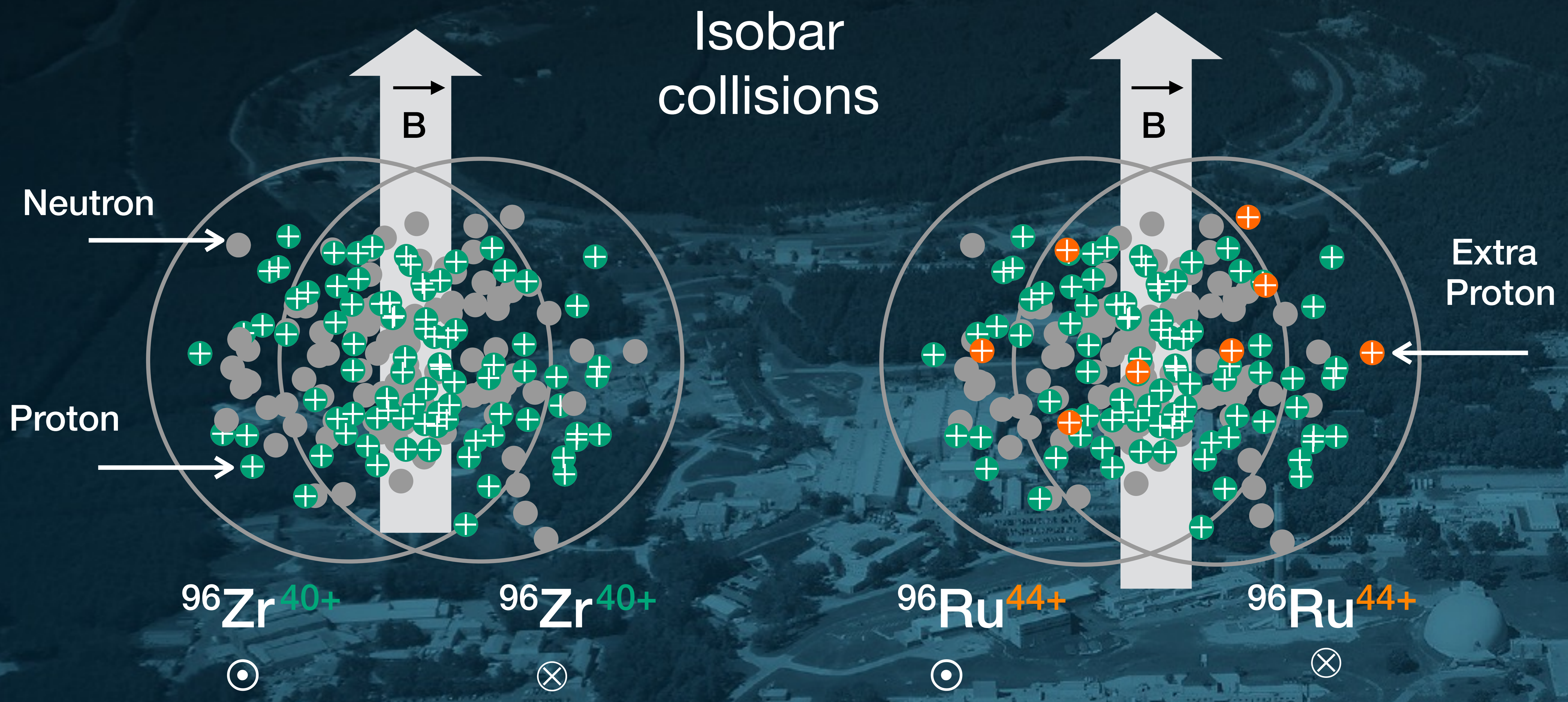


Brookhaven™ National Laboratory

U.S. DEPARTMENT OF ENERGY

Search for the chiral magnetic effect with isobar collisions

Based on: https://arxiv.org/abs/2109.00131 Phys. Rev. C 105, 014901 (2022)

Prithwish Tribedy
(Brookhaven National Laboratory)
ptribedy@bnl.gov

EMMI

New vistas in Photon Physics in Heavy-Ion Collisions, Sep 19 – 22, 2022
Institute of Nuclear Physics Polish Academy of Sciences & AGH University of Science and Technology

Isobar program at RHIC: journey since 2018

Brookhaven National Laboratory

Relativistic Heavy Ion Collider Begins 18th Year of Experiments

First smashups with 'isobar' ions and low-energy gold-gold collisions will test earlier hints of exciting discoveries as accelerator physicists tune up technologies to enable future science

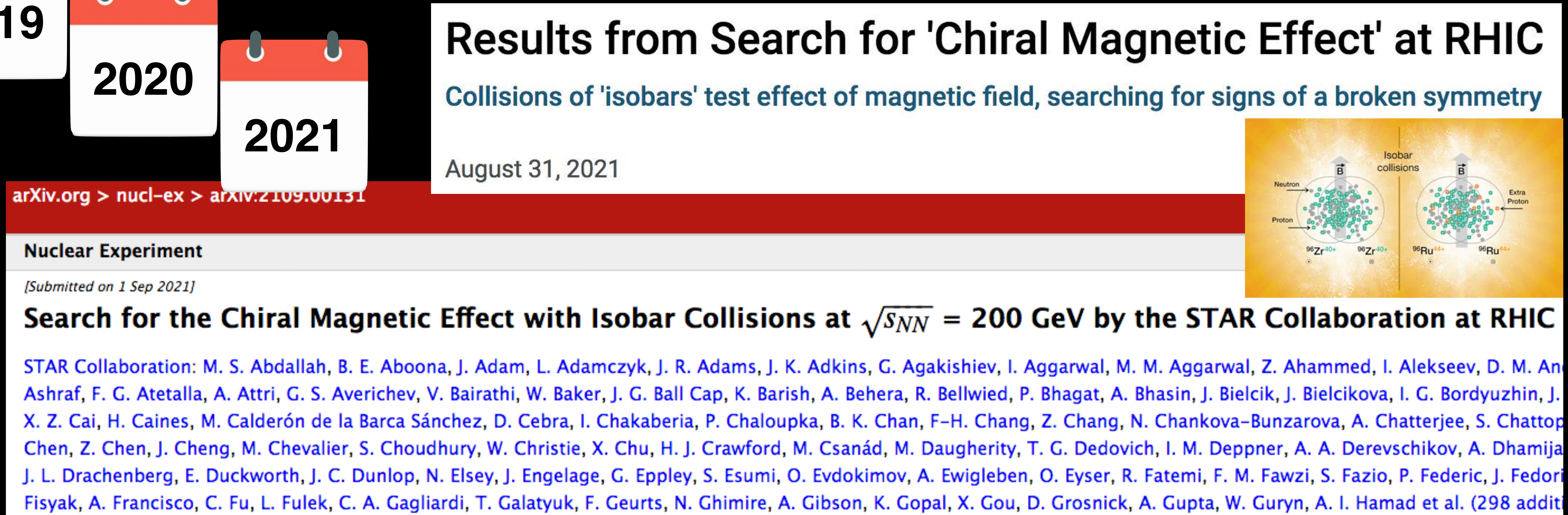
March 21, 2018

2018

2019

2020

2021



Results from Search for 'Chiral Magnetic Effect' at RHIC

Collisions of 'isobars' test effect of magnetic field, searching for signs of a broken symmetry

August 31, 2021

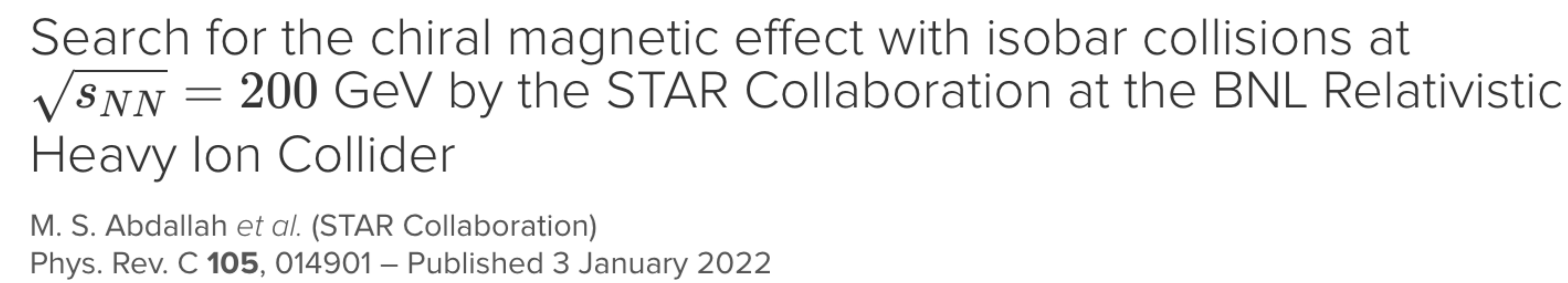
arXiv.org > nucl-ex > arXiv:2109.00131

Nuclear Experiment

[Submitted on 1 Sep 2021]

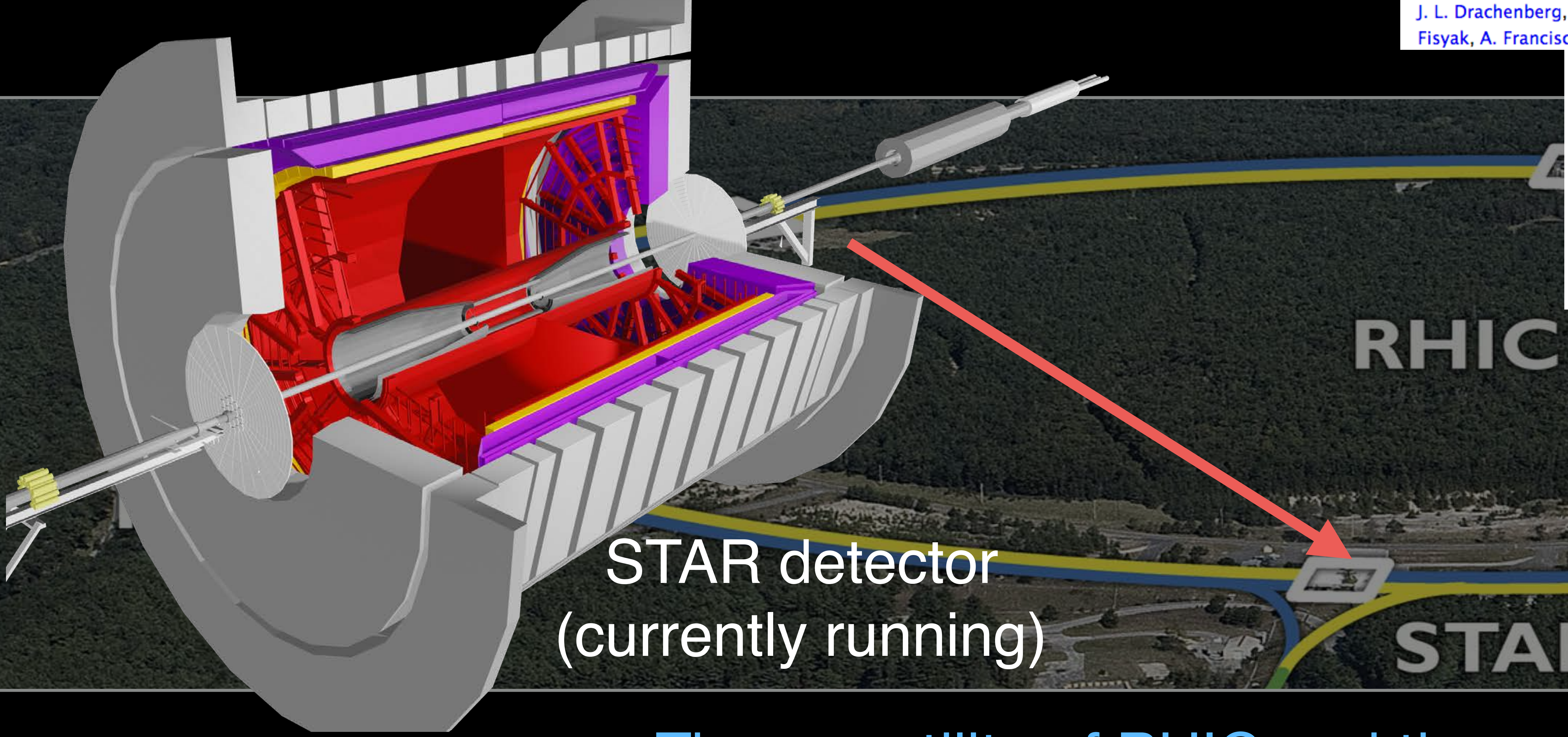
Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC

STAR Collaboration: M. S. Abdallah, B. E. Aboona, J. Adam, L. Adamczyk, J. R. Adams, J. K. Adkins, G. Agakishiev, I. Aggarwal, M. M. Aggarwal, Z. Ahammed, I. Alekseev, D. M. An
Ashraf, F. G. Atetalla, A. Attri, G. S. Averichev, V. Bairathi, W. Baker, J. G. Ball Cap, K. Barish, A. Behera, R. Bellwied, P. Bhagat, A. Bhasin, J. Bielcik, J. Bielcikova, I. G. Bordyuzhin, J.
X. Z. Cai, H. Caines, M. Calderón de la Barca Sánchez, D. Cebra, I. Chakaberia, P. Chaloupka, B. K. Chan, F-H. Chang, Z. Chang, N. Chankova-Bunzarova, A. Chatterjee, S. Chattop
Chen, Z. Chen, J. Cheng, M. Chevalier, S. Choudhury, W. Christie, X. Chu, H. J. Crawford, M. Csanád, M. Daugherity, T. G. Dedovich, I. M. Deppner, A. A. Derevschikov, A. Dhamija
J. L. Drachenberg, E. Duckworth, J. C. Dunlop, N. Elsey, J. Engelage, G. Eppley, S. Esumi, O. Evdokimov, A. Ewigleben, O. Eyser, R. Fatemi, F. M. Fawzi, S. Fazio, P. Federic, J. Fedori
Fisyak, A. Francisco, C. Fu, L. Fulek, C. A. Gagliardi, T. Galatyuk, F. Geurts, N. Ghimire, A. Gibson, K. Gopal, X. Gou, D. Grosnick, A. Gupta, W. Guryn, A. I. Hamad et al. (298 additi



Search for the chiral magnetic effect with isobar collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider

M. S. Abdallah *et al.* (STAR Collaboration)
Phys. Rev. C **105**, 014901 – Published 3 January 2022



STAR detector
(currently running)

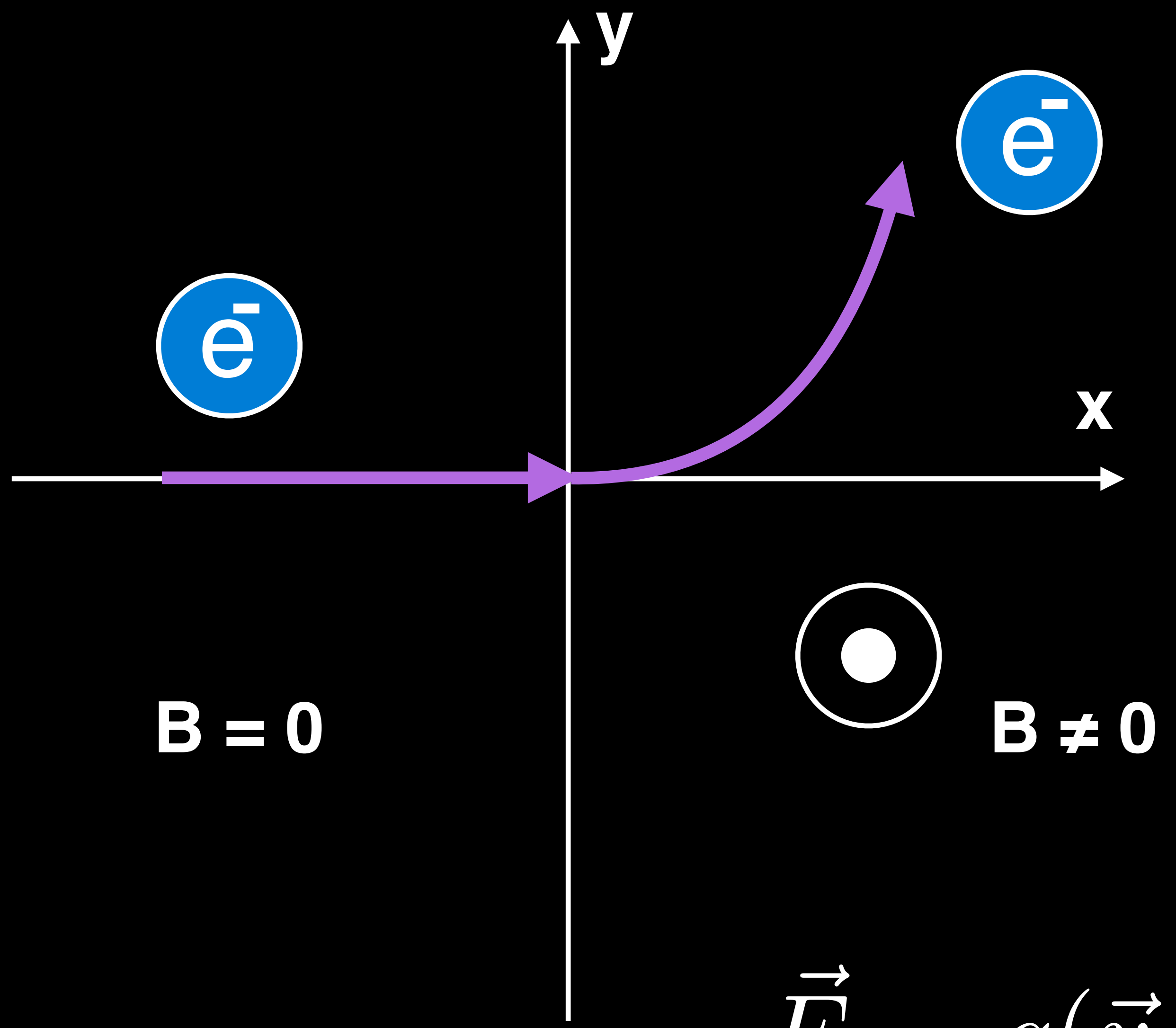
RHIC: known for species (U, Au, Ru, Zr, Cu, Al..) and energy (γ~100-3.85) maneuver capability

STAR: known for precision measurement capability of hadrons over wide acceptance

The versatility of RHIC and the unique capabilities of the STAR detector were crucial to the success of our program

Chiral Magnetic Effect : why unique?

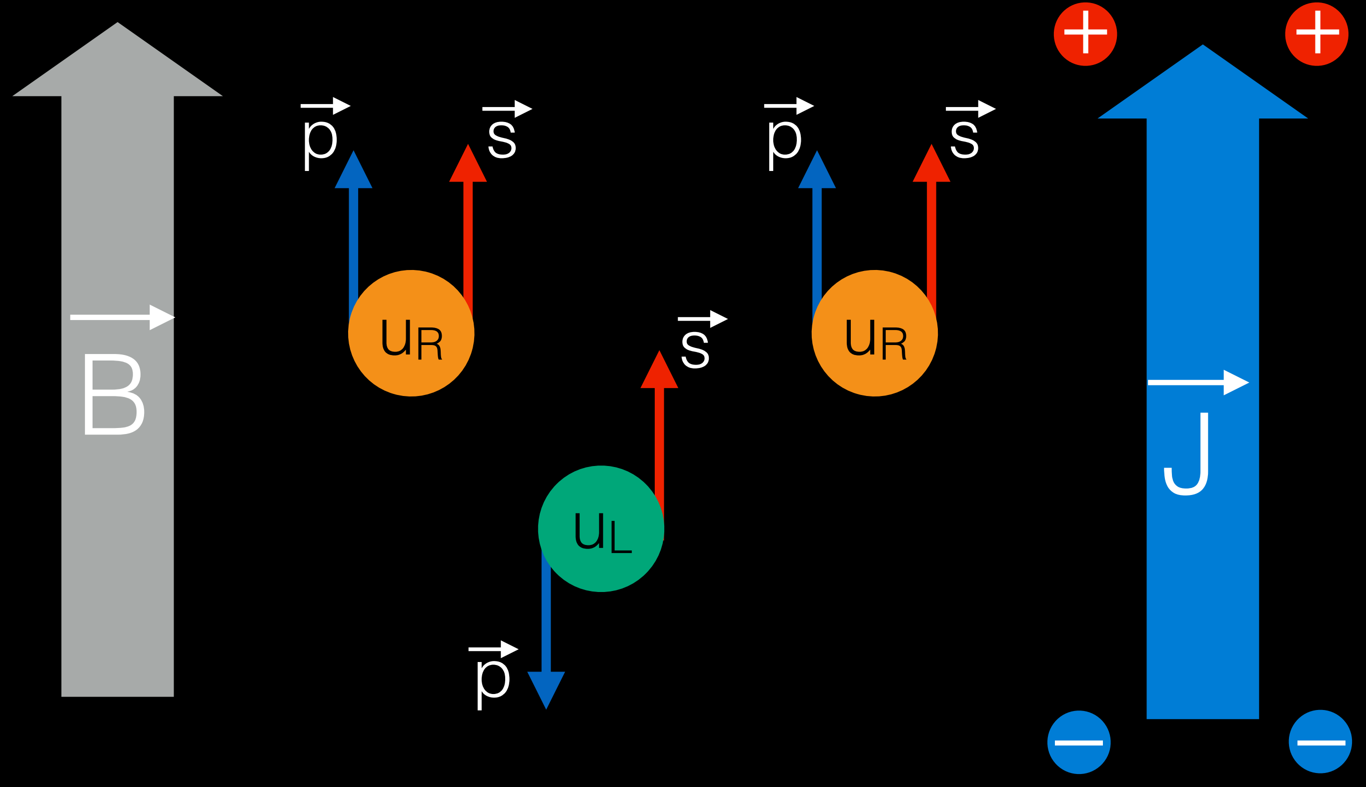
A phenomenon different from everyday motions of charge in EM-field



Motion of charge in EM-field

$$\vec{F} = q(\vec{v} \times \vec{B})$$

Chiral Magnetic Effect



CME: Generation of current along B-field due to chirality imbalance

$$\vec{J} = \sigma_{\mathrm{CME}} \vec{B}$$

Parity-odd
T-odd

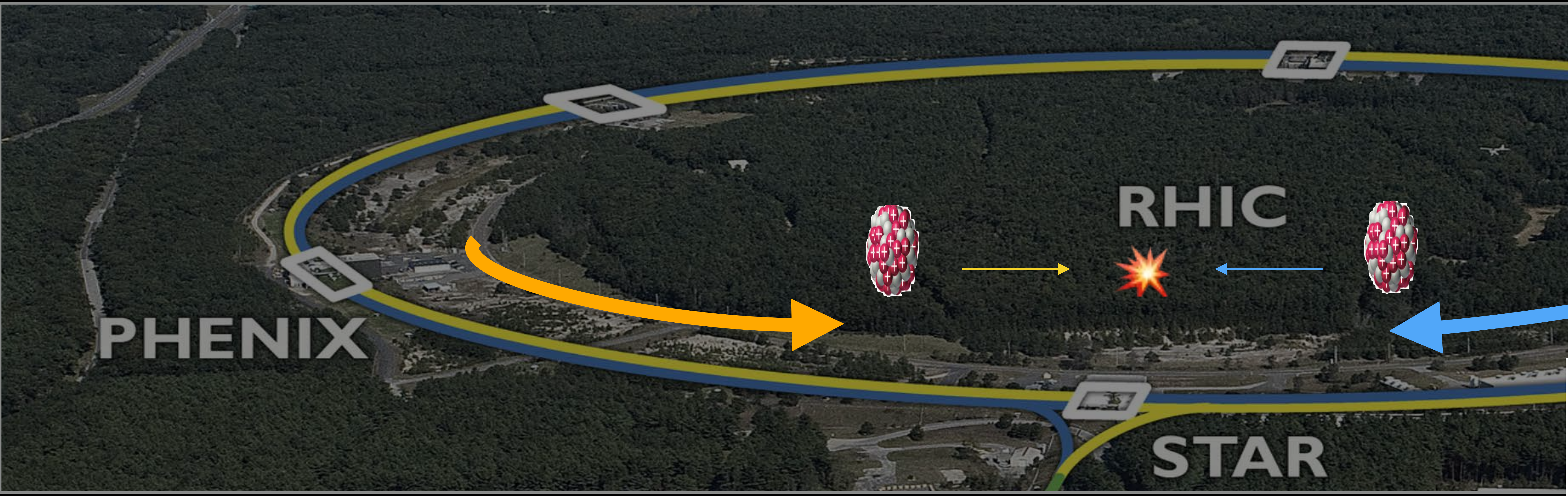
Parity-odd
T-even

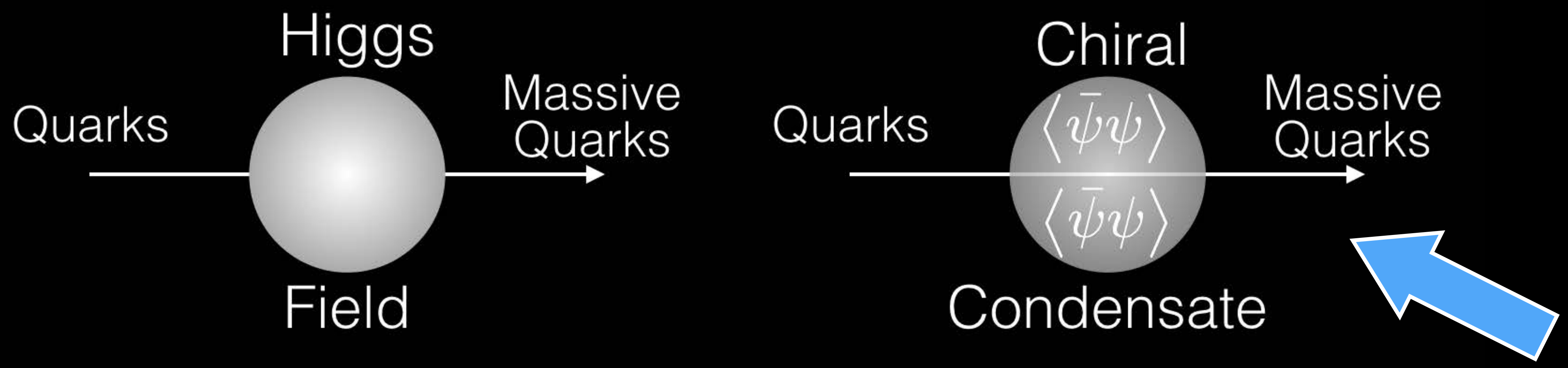
Parity-even
T-odd

CME is related to local parity violation in strong interactions

Earliest Reference :
"Equilibrium Parity Violating Current In A Magnetic Field", A. Vilenkin,

RHIC: A machine to play with the vacuum





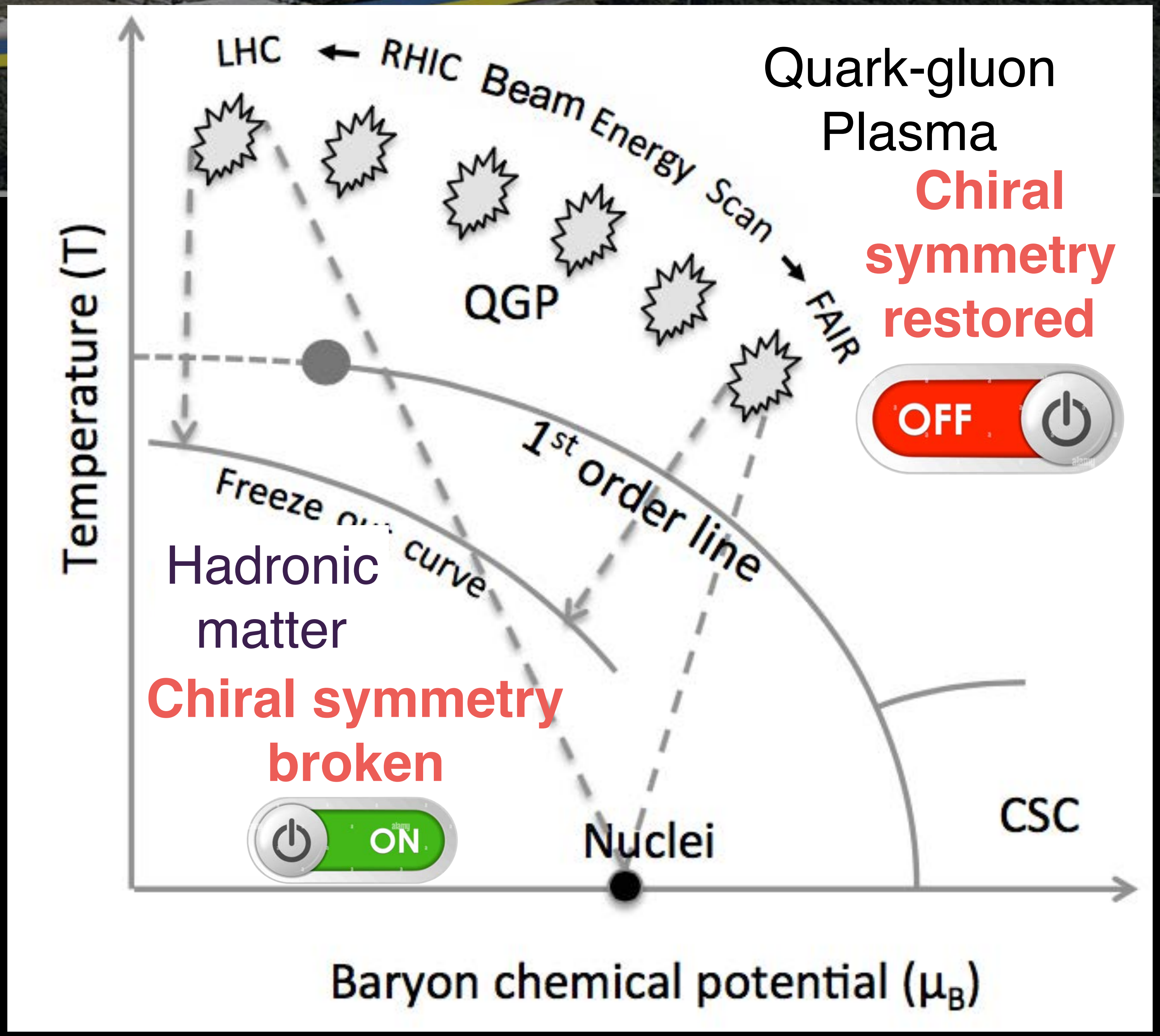
Higgs
Quarks
Massive Quarks
Field

Chiral
Quarks
Massive Quarks
$\langle\bar{\psi}\psi\rangle$
Condensate

Turn this OFF

$$\mathcal{L}_{QCD} = \bar{\psi}_a \left(i(\gamma^\mu D_\mu)_{ab}\right)\psi_b - \cancel{m\delta_{ab}\bar{\psi}_a\psi_b} - \frac{1}{4}G^c_{\mu\nu}G^{\mu\nu}_c$$

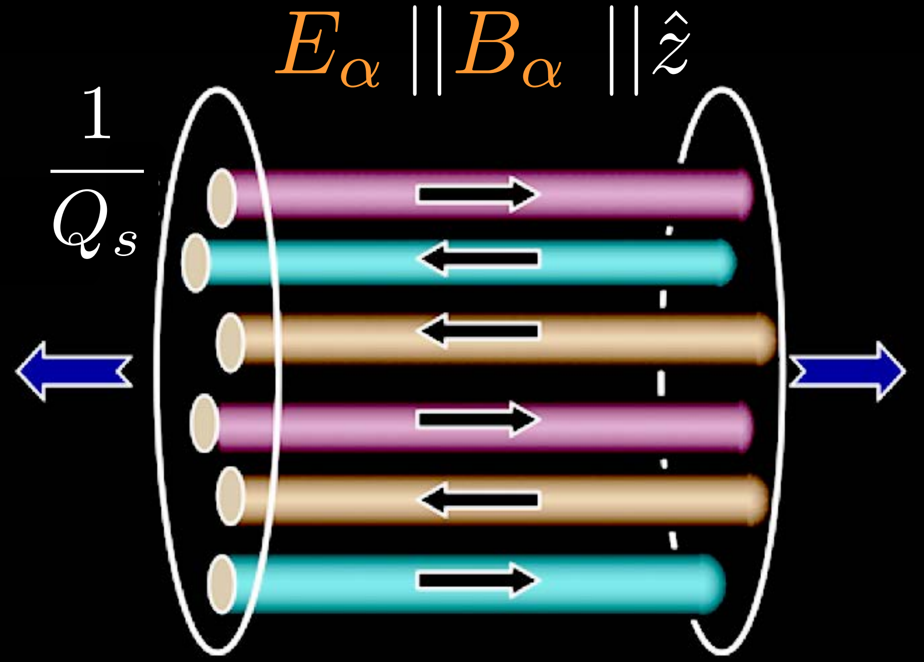
Collisions aim to produce a medium of de-confined gluons and nearly massless quarks (chiral symmetry restored)



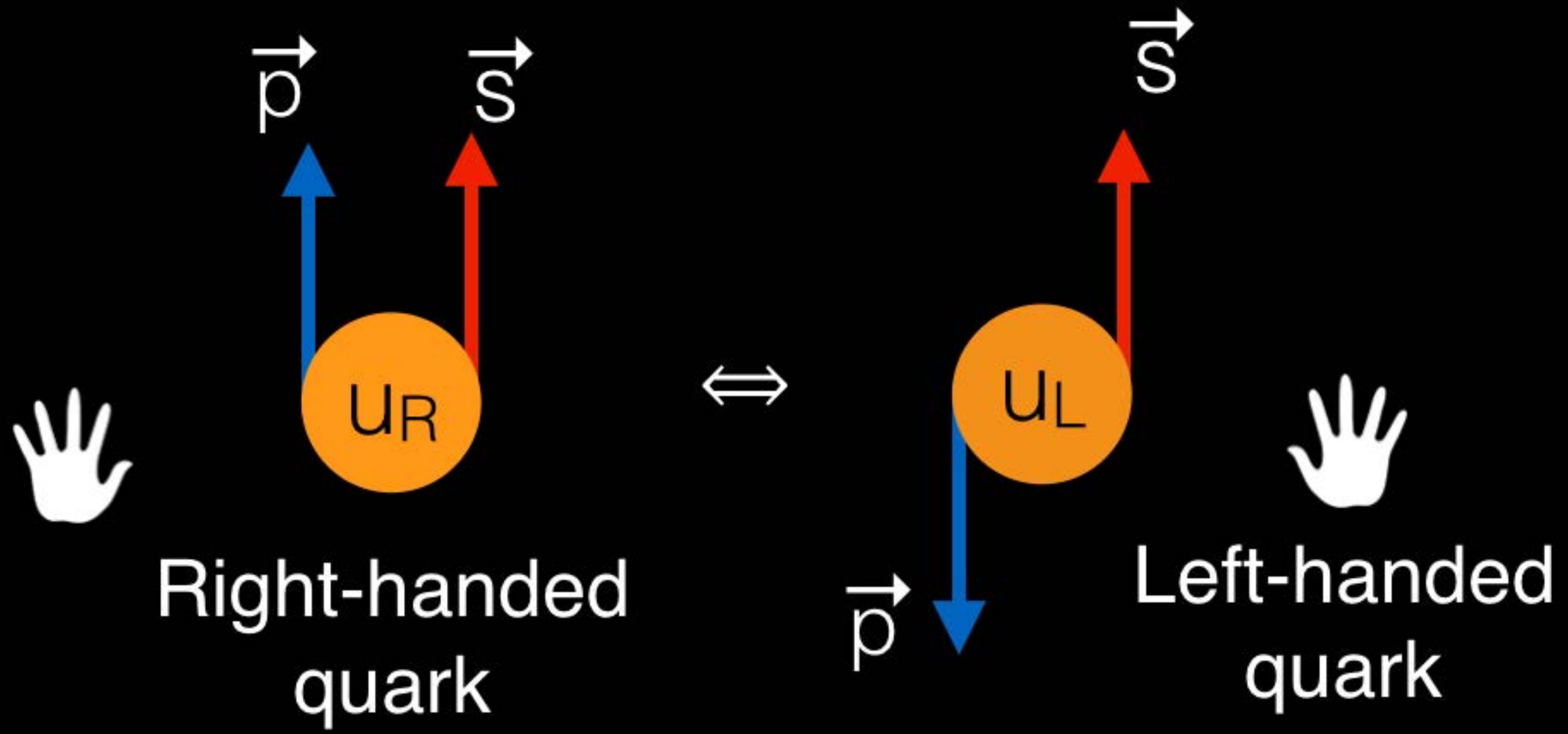
Phase diagram of QCD

Local violation of the CP symmetry of QCD

$$\mathcal{L}_{QCD} = \bar{\psi}_a \left(i(\gamma^\mu D_\mu)_{ab}\right) \psi_b - \cancel{m\delta_{ab}\bar{\psi}_a\psi_b} - \frac{1}{4}G^c_{\mu\nu}G^{\mu\nu}_c \boxed{-\frac{\theta}{32\pi^2}g^2 F^{\mu\nu}_\alpha \tilde{F}_{\alpha\mu\nu} = -\frac{\theta}{8\pi^2}g^2 \vec{E}_\alpha.\vec{B}_\alpha}$$

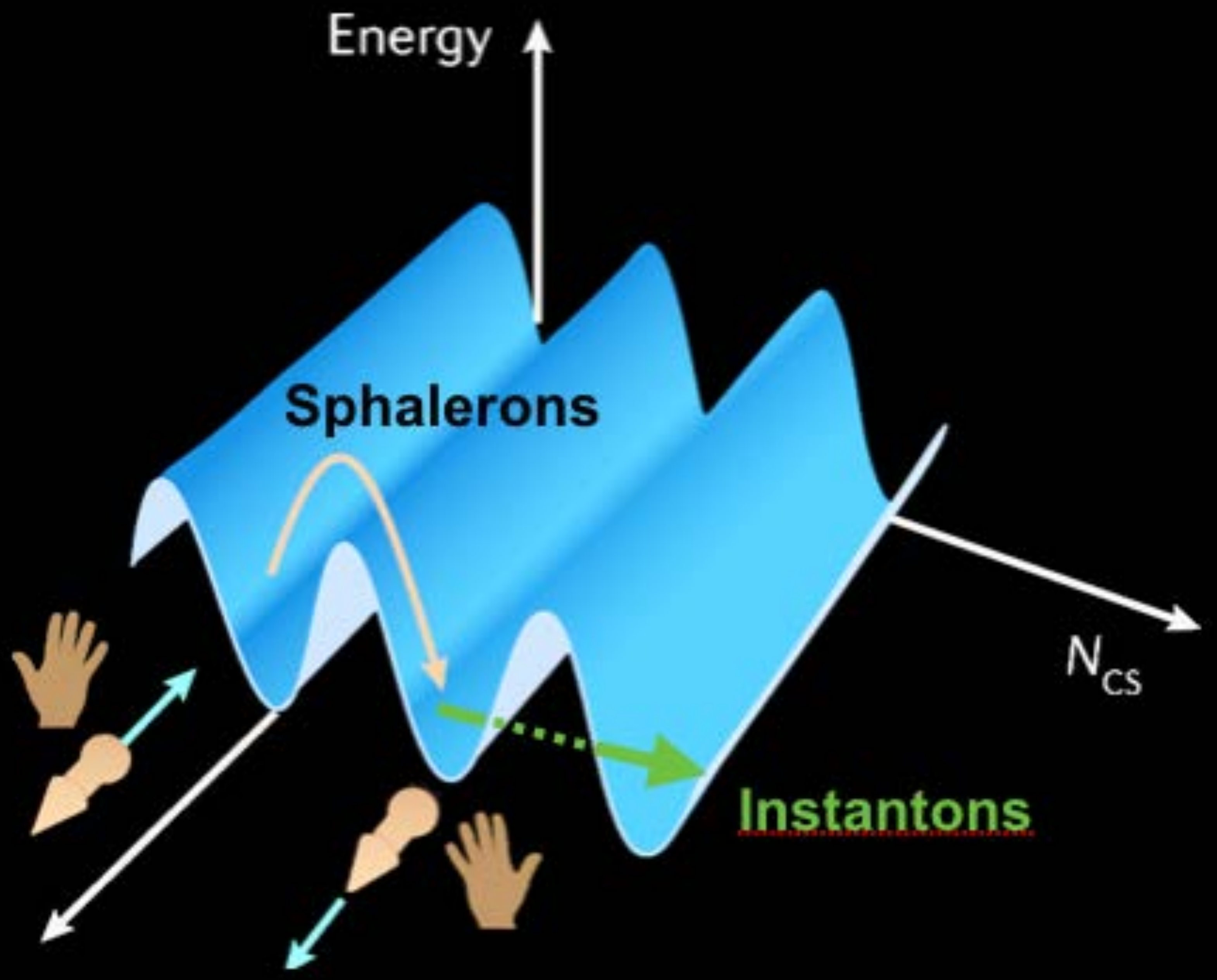


Massless QCD does not distinguish between R.H. & L.H.



$$\frac{dN_{CS}}{dt} = \frac{g^2}{8\pi^2}\int d^3x\, \vec{E}_\alpha.\vec{B}_\alpha$$

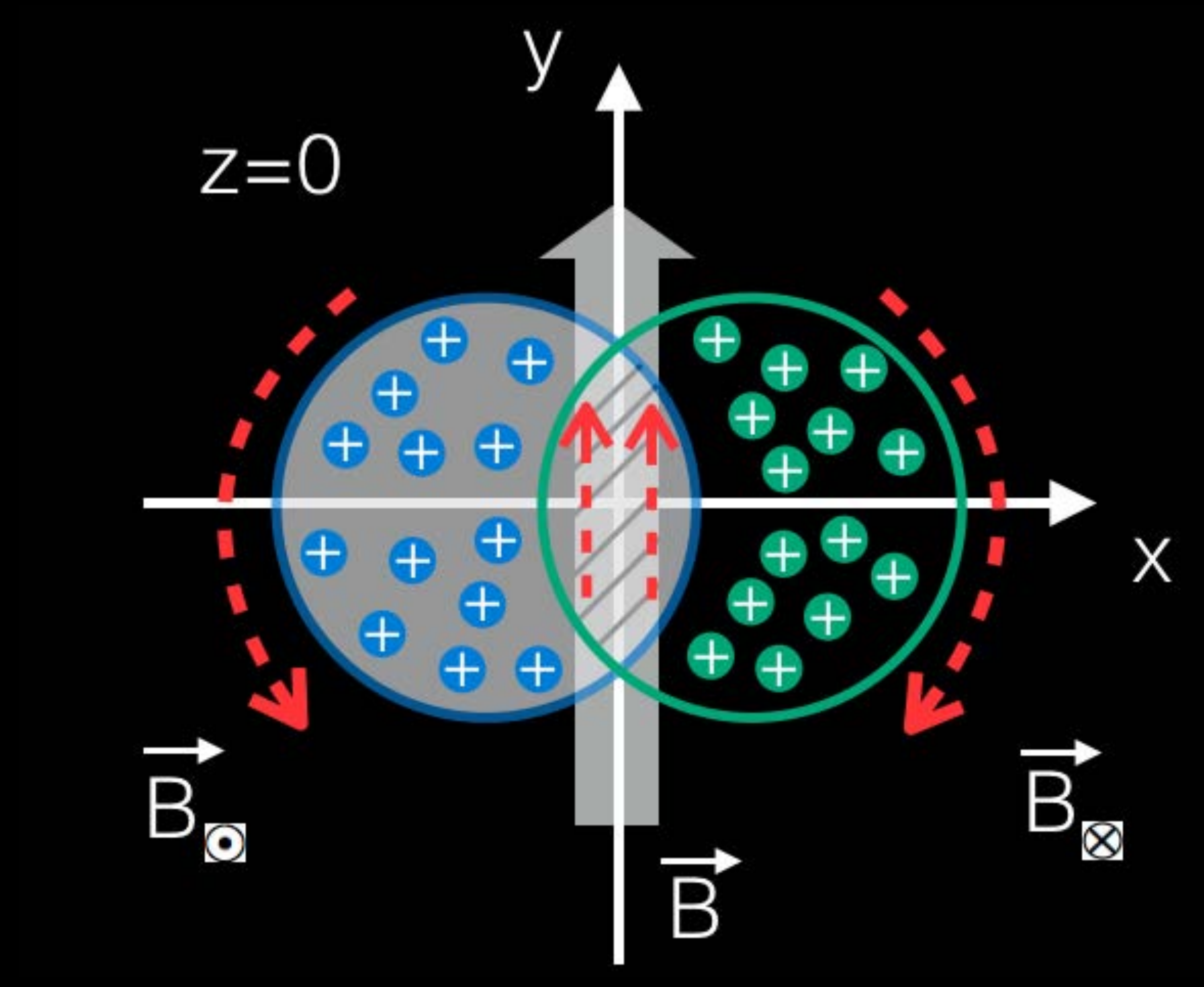
Quantum anomaly: $U_A(1)$ symmetry breaking: chirality imbalance

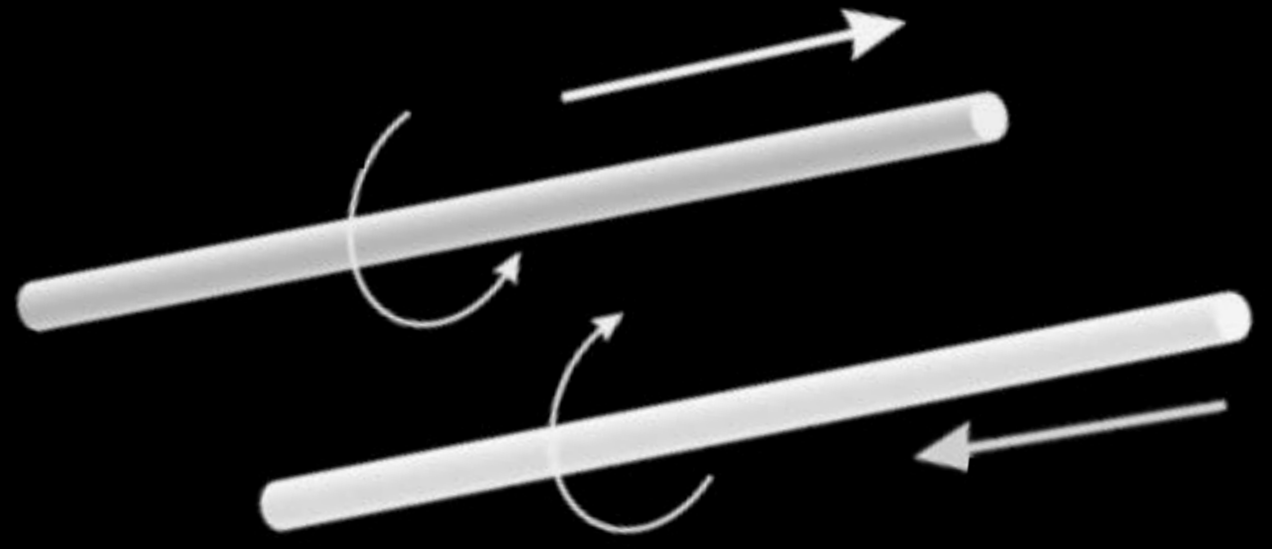


Quantum fluctuations break P & CP symmetry locally and create chirality imbalance → chirality-genesis

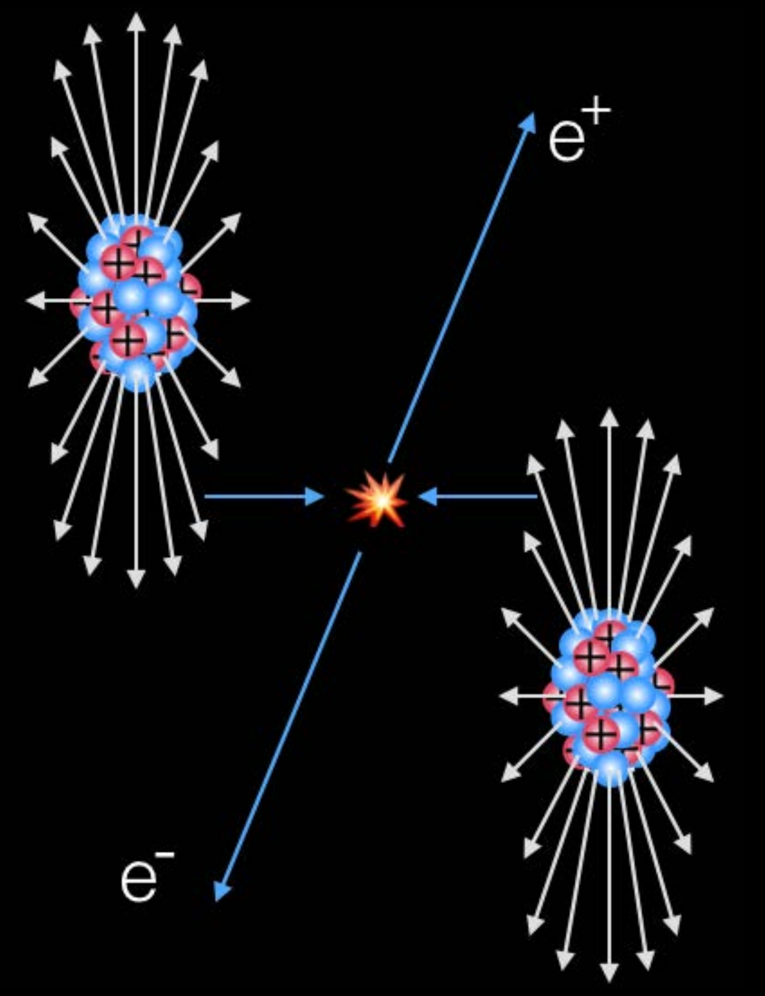
Creation of strong electro-magnetic fields

Strongest EM field in the nature: $B \sim 10^{18}$ Gauss (~ pion-mass^2)



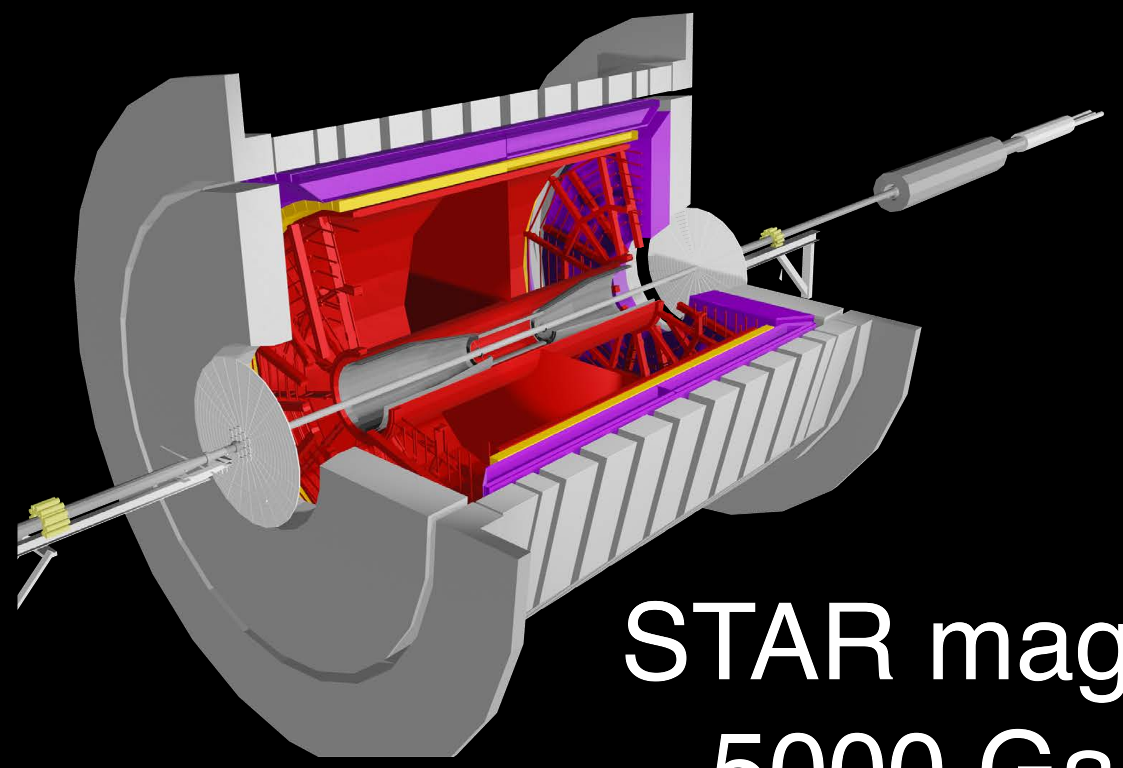


Kharzeev et al 0711.0950, Skokov et al 0907.1396 McLerran, Skokov, 1305.0774

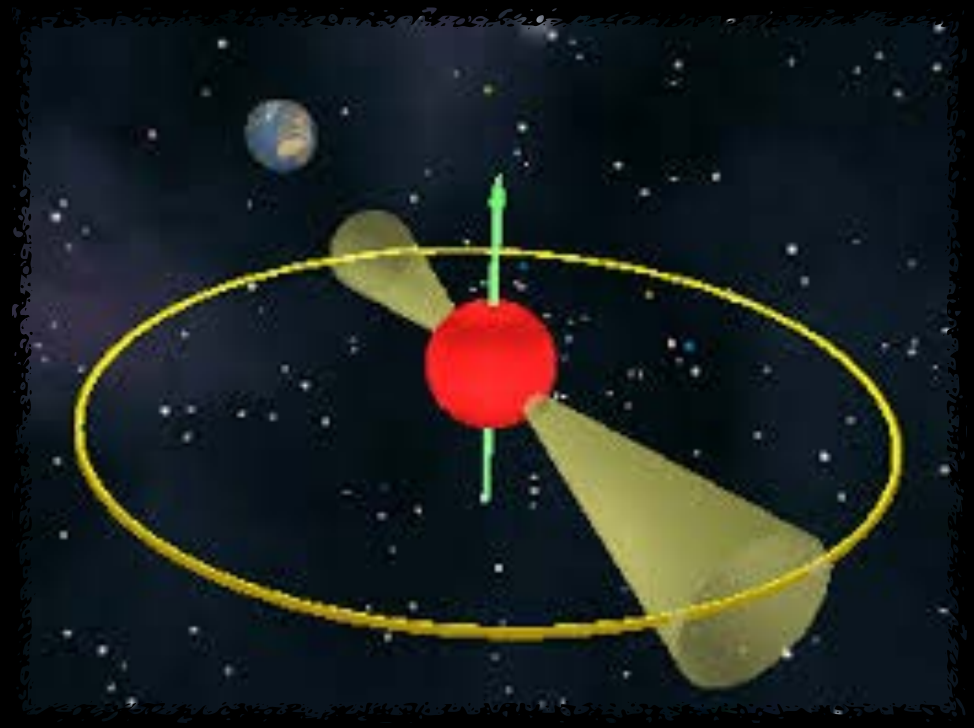


$eB > eB_C \approx m_e^2$ $\sim 10^{12}$ Gauss

Earth
~0.5 Gauss



STAR magnet
~ 5000 Gauss

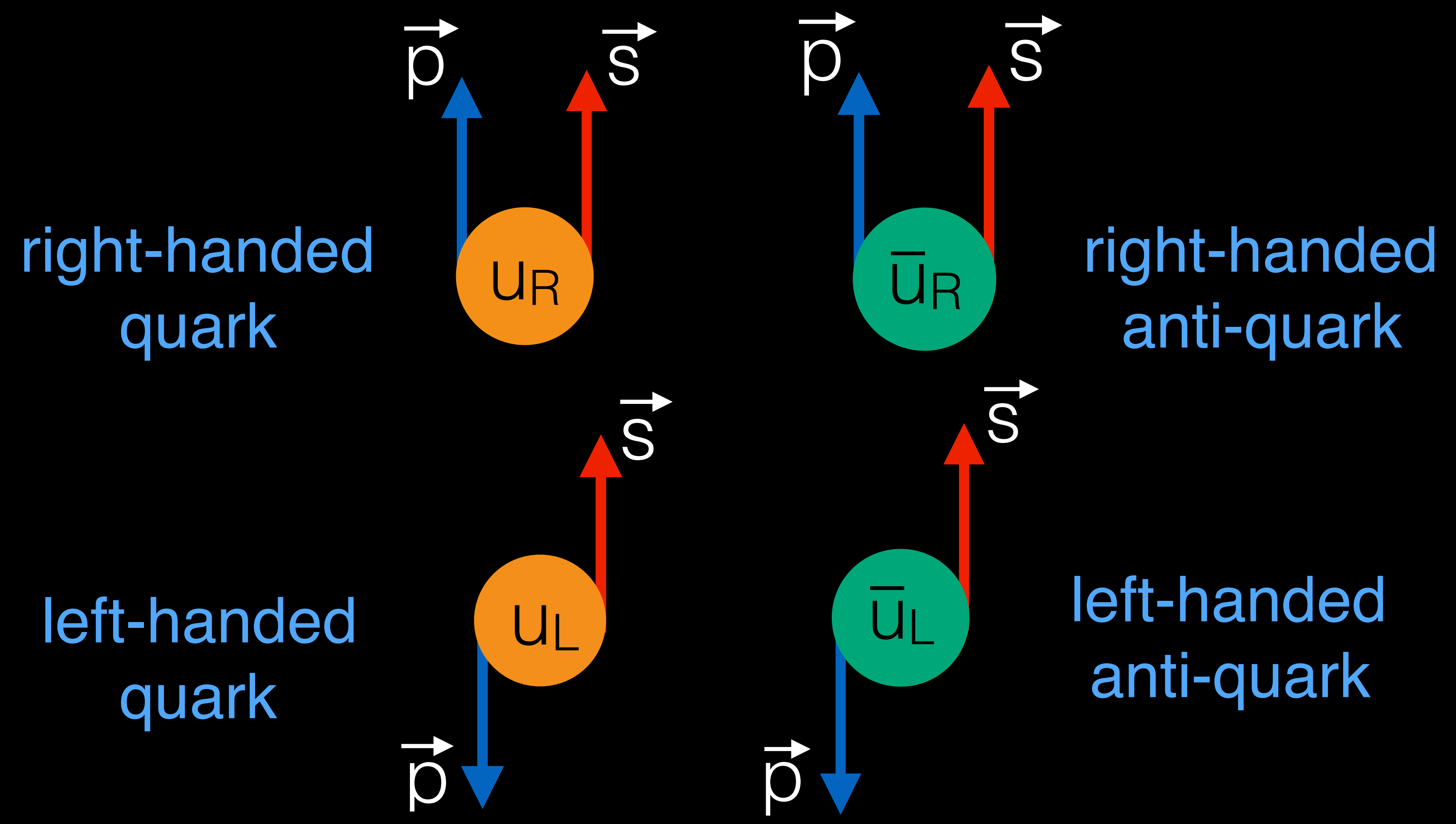


Neutron Star
~ 10^{15} Gauss

The chiral magnetic effect (CME) in four steps

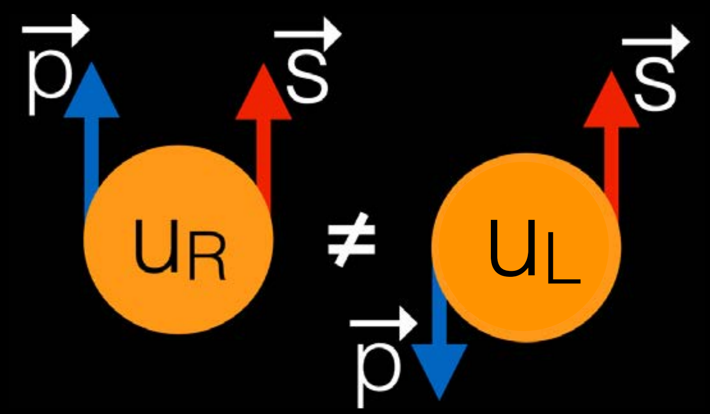
Brookhaven National Laboratory

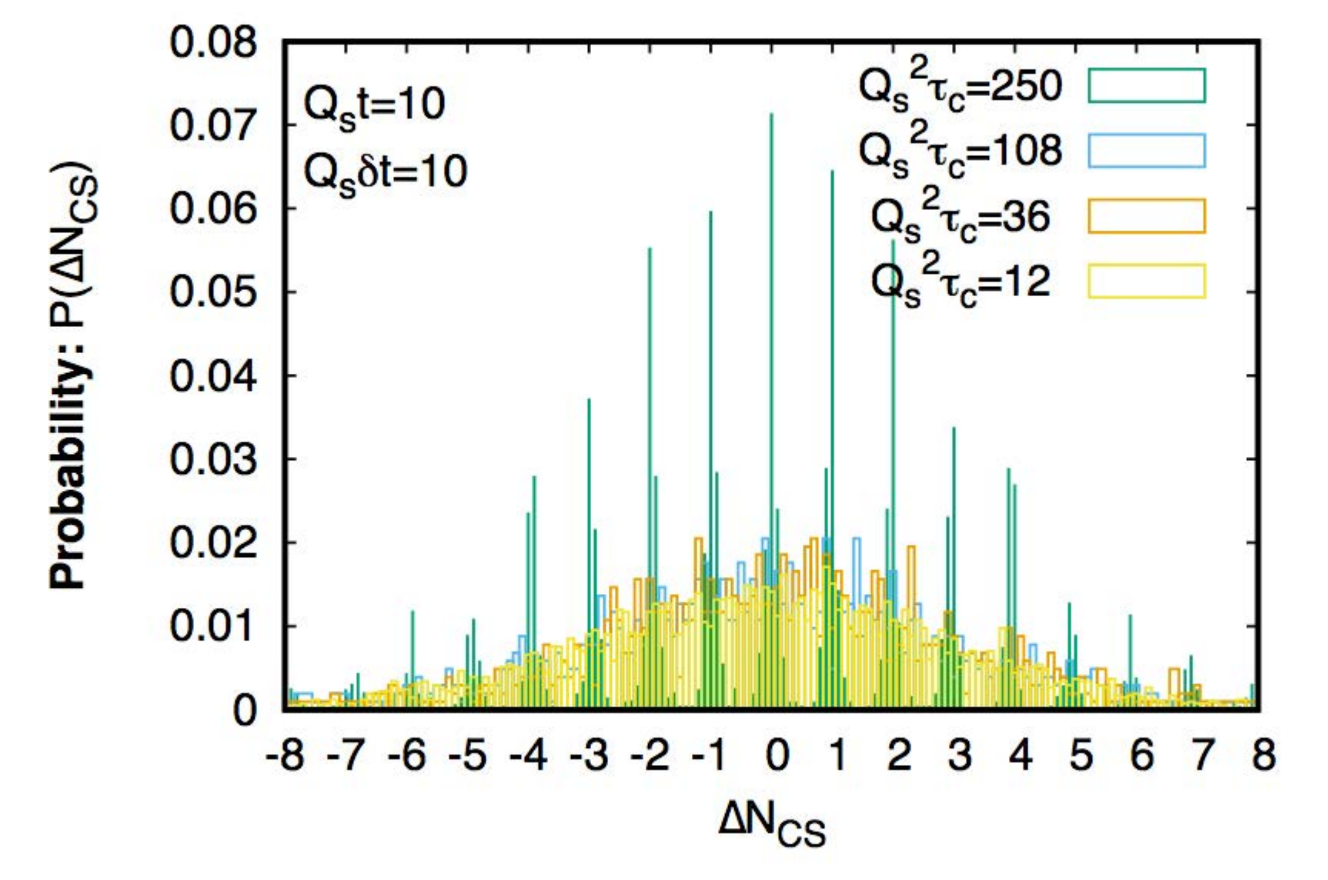
① Deconfined medium of massless quark (chiral symmetry restored)



Kharzeev, McLerran,Warringa 0711.0950

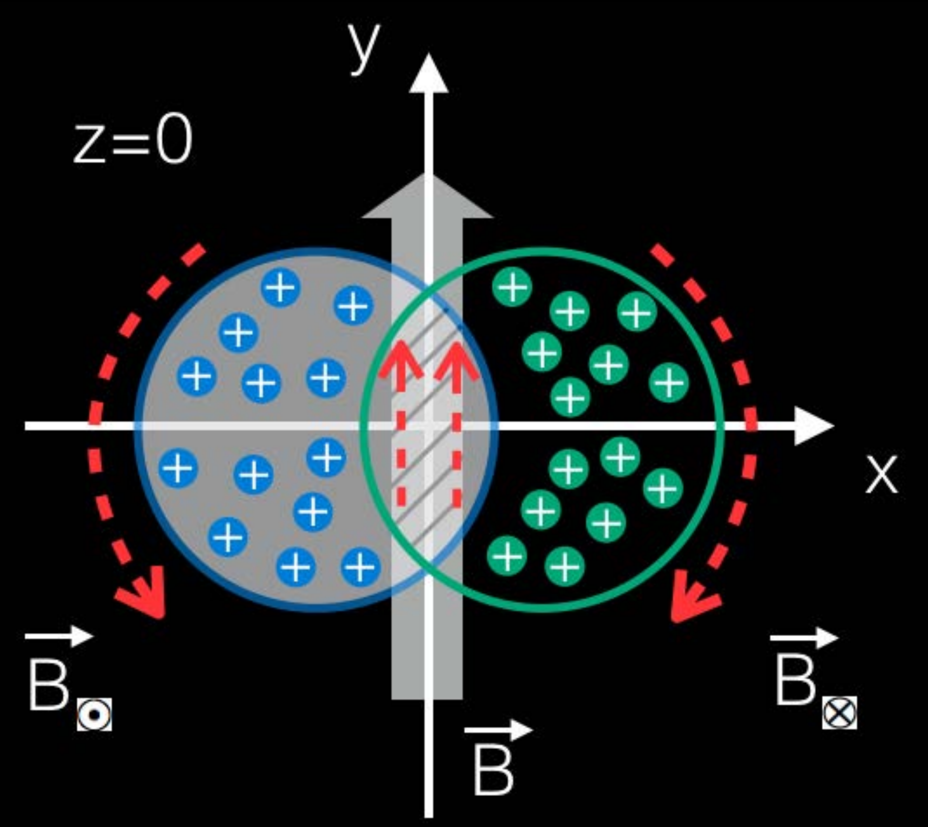
② Mechanism to create imbalance of left & right handed quarks

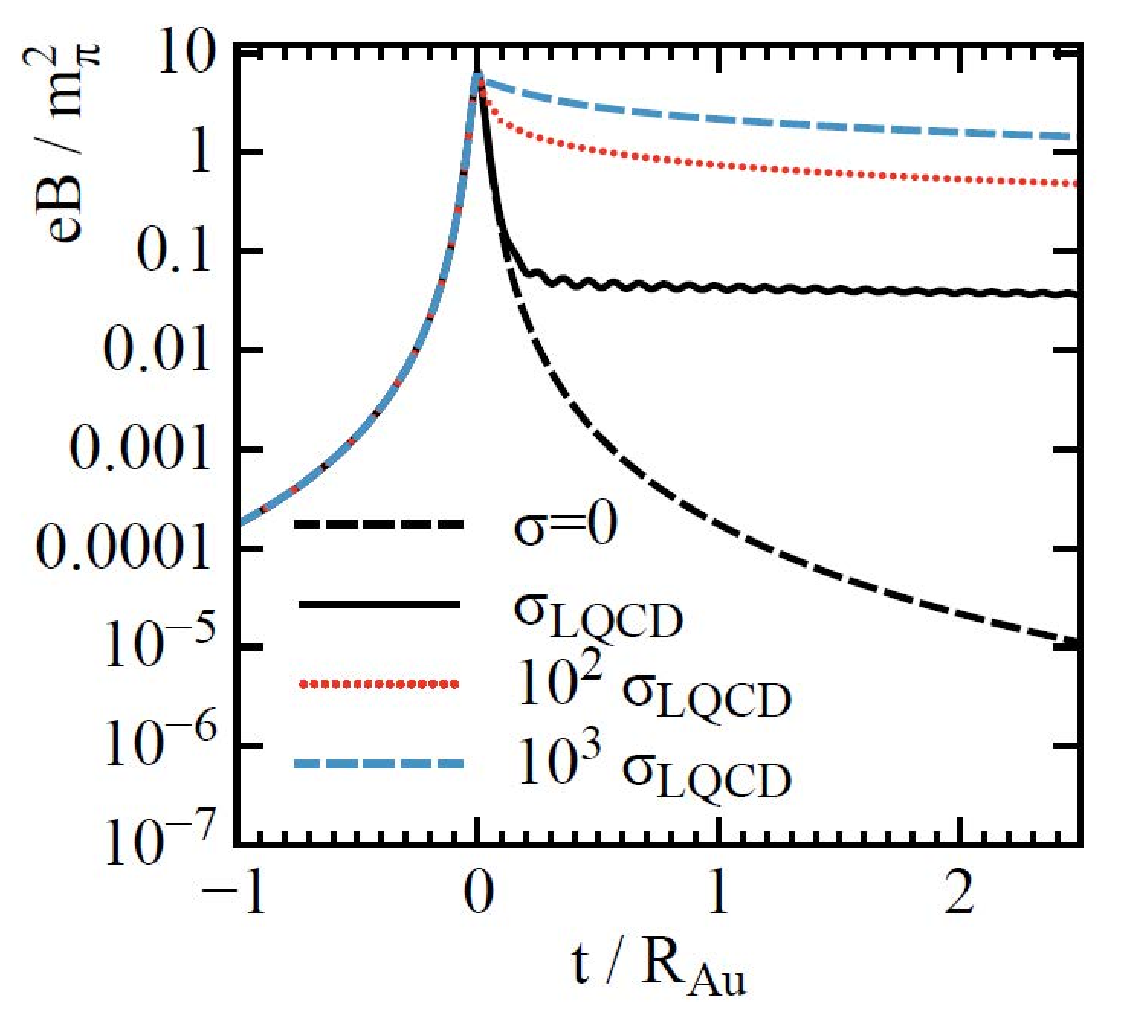




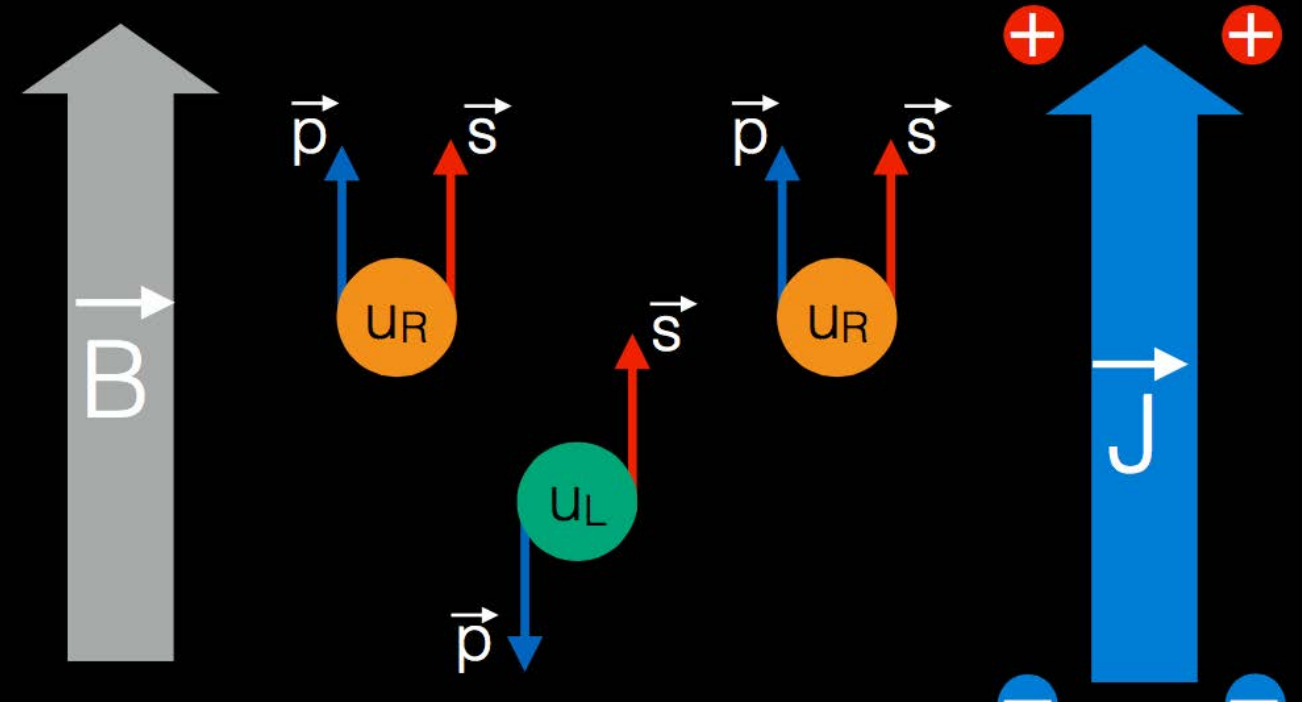
Kharzeev et al, hep-ph/0109253, Mace et al, 1601.07342, Muller et. al.1606.00342, Lappi et al,1708.08625

③ Strong B-field



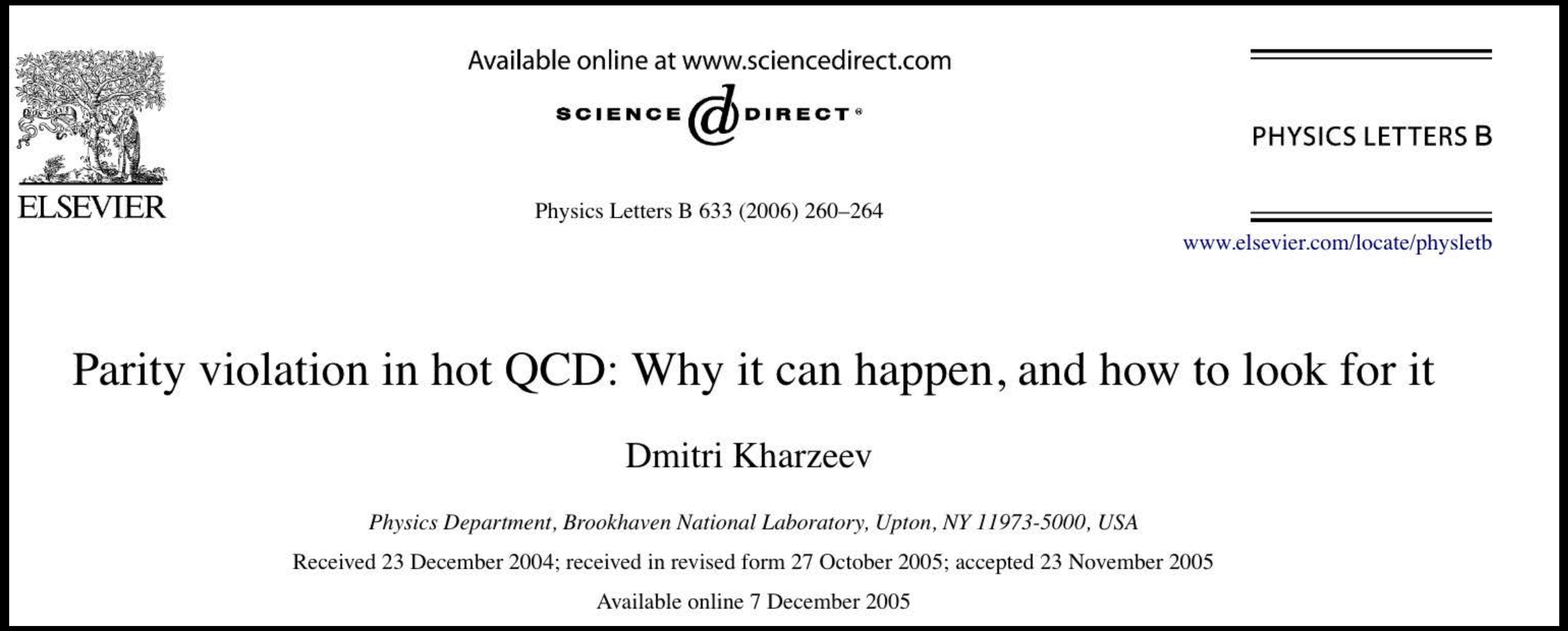


④ The Chiral Magnetic Effect (J || B)



Kharzeev, arXiv:hep-ph/0406125

Parity Violation in Hot QCD: Chiral Magnetic Effect



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Physics Letters B 633 (2006) 260–264
PHYSICS LETTERS B
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Parity violation in hot QCD: Why it can happen, and how to look for it

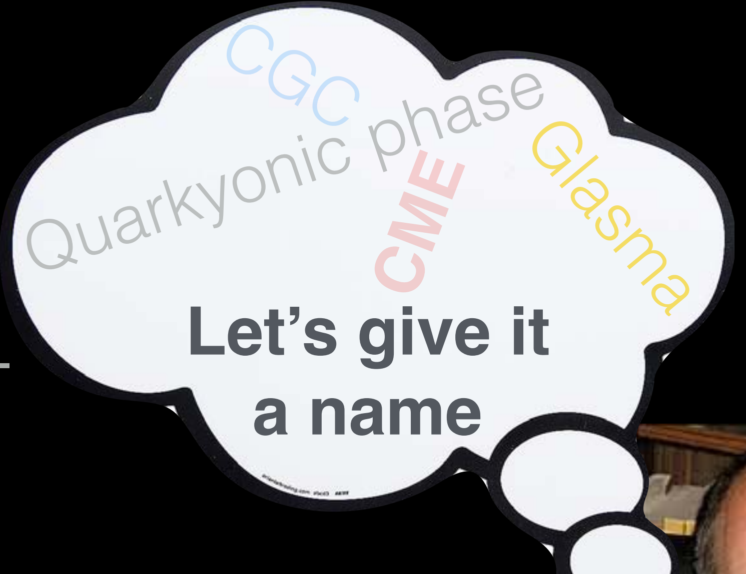
Dmitri Kharzeev

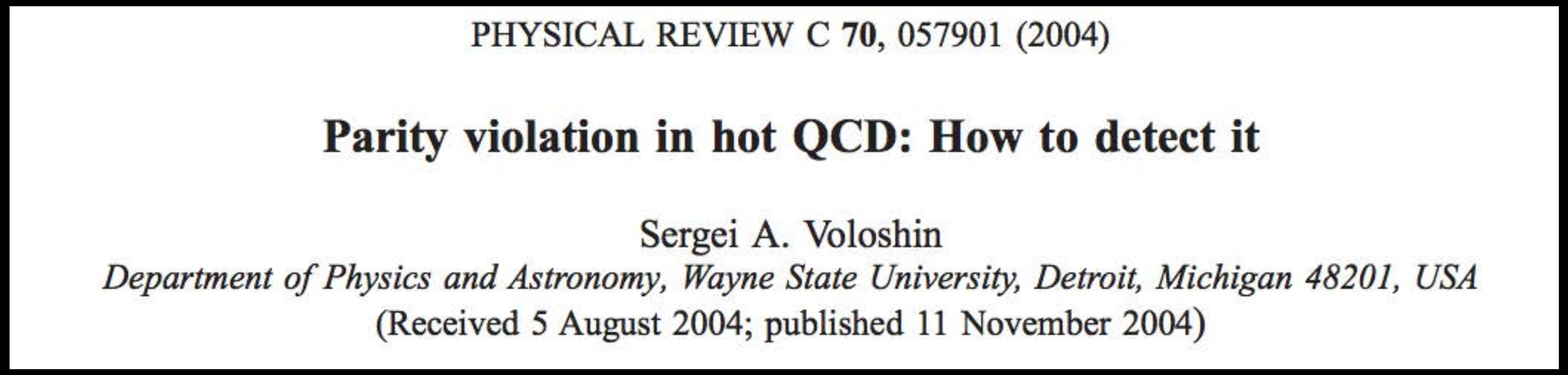
Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
Received 23 December 2004; received in revised form 27 October 2005; accepted 23 November 2005
Available online 7 December 2005

Early theory paper

Kharzeev, hep-ph/0406125

Also see : Kharzeev et al, hep-ph/9906401, Kharzeev et al, hep-ph/9804221





PHYSICAL REVIEW C **70**, 057901 (2004)

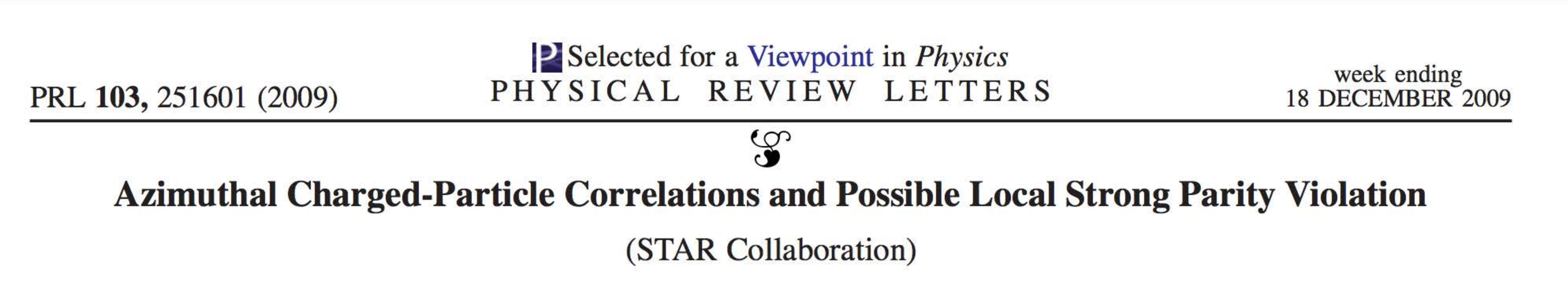
Parity violation in hot QCD: How to detect it

Sergei A. Voloshin
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201, USA
(Received 5 August 2004; published 11 November 2004)

First method paper

Voloshin, hep-ph/0406311

Also: Finch et al Phys.Rev.C 65 (2002) 014908



PRL **103,** 251601 (2009)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 18 DECEMBER 2009

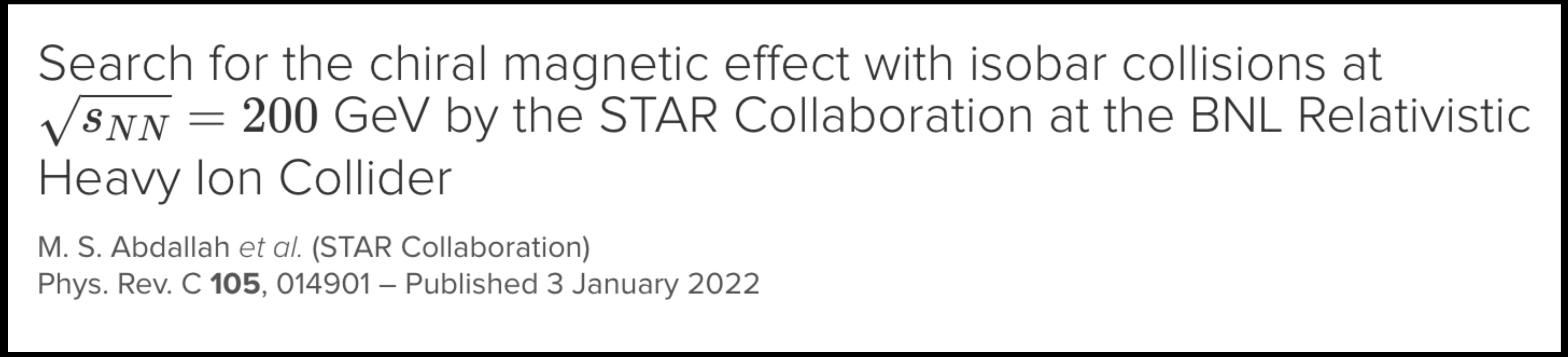
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)

First experimental paper

STAR collaboration, arXiv:0909.1739

~12 years



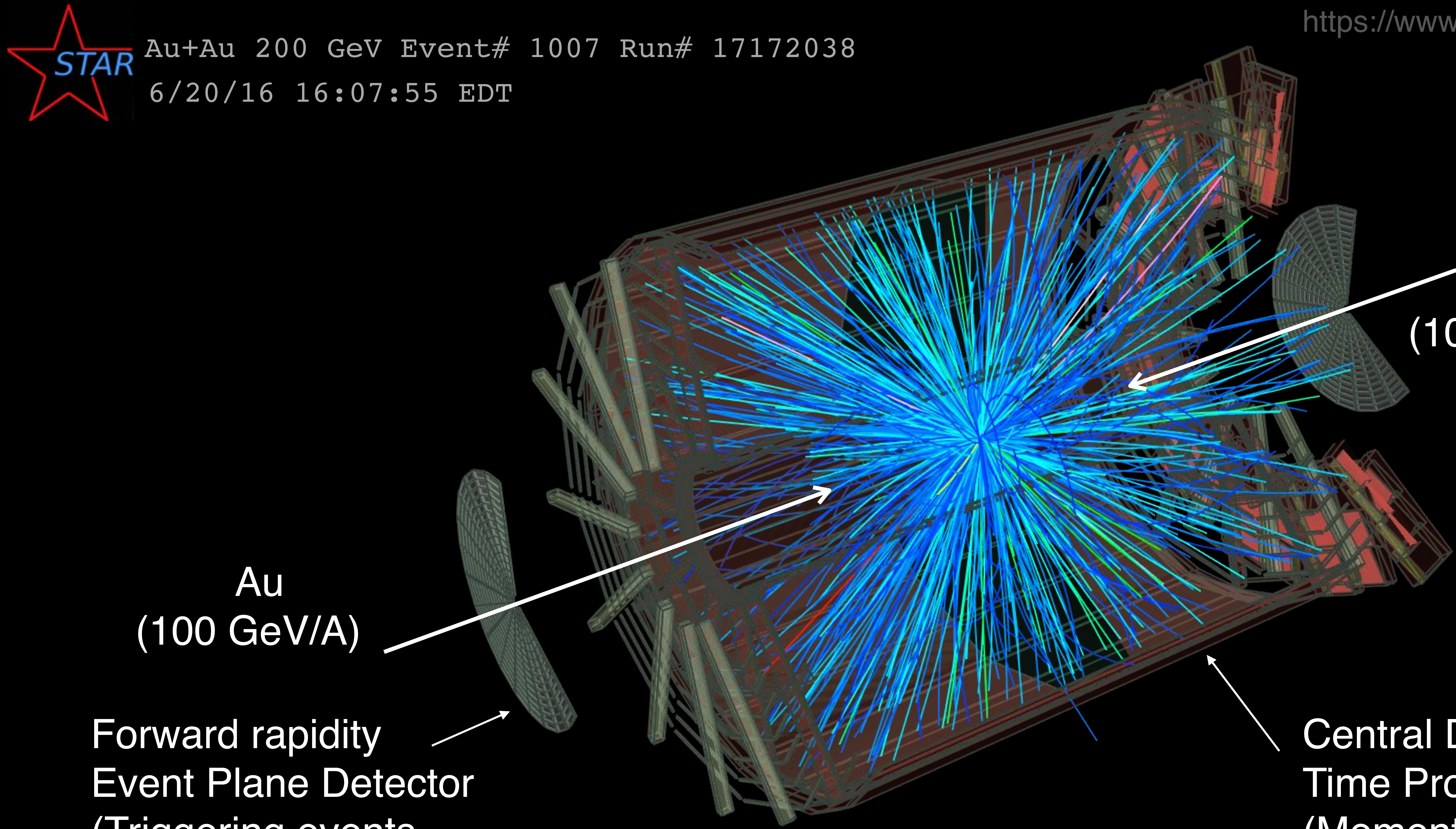
Search for the chiral magnetic effect with isobar collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider

M. S. Abdallah *et al.* (STAR Collaboration)
Phys. Rev. C **105**, 014901 – Published 3 January 2022

Blind analysis of the Isobar data

STAR collaboration, arXiv:2109.00131

A gold-gold collision @ STAR detector



https://www.star.bnl.gov/~dmitry/edisplay/

Au
(100 GeV/A)

Au
(100 GeV/A)

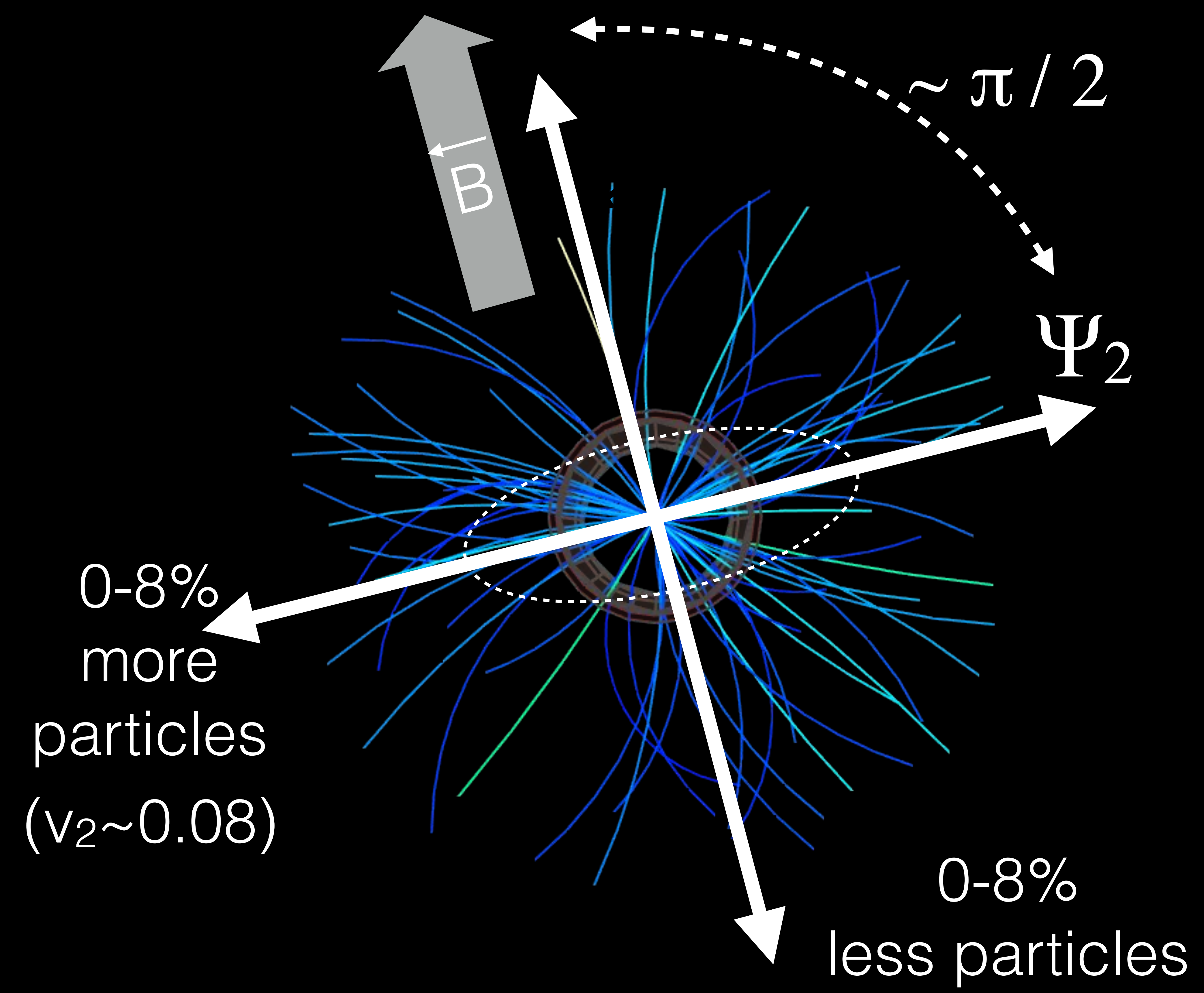
Forward rapidity
Event Plane Detector
(Triggering events,
plane of collisions)

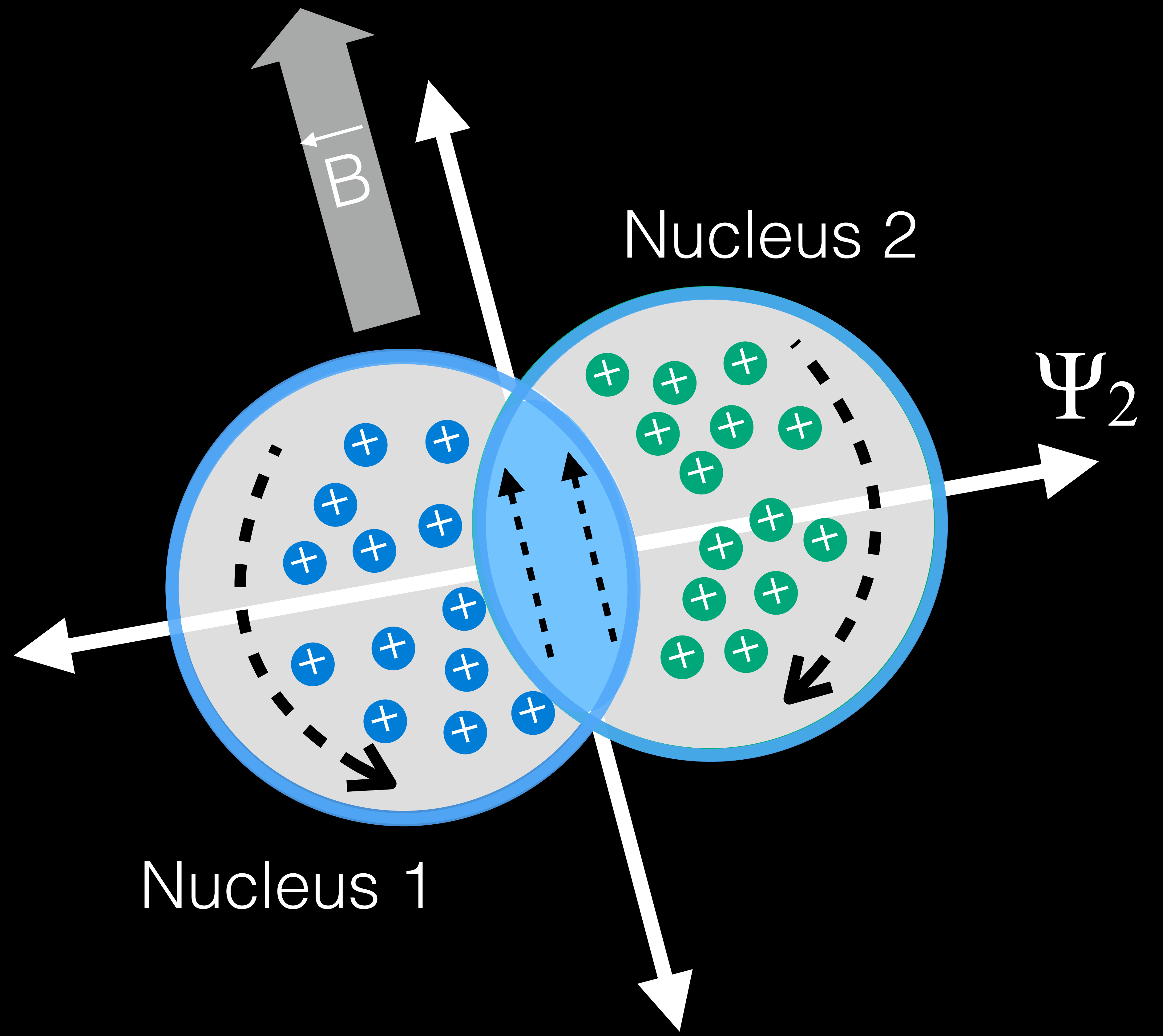
Central Detector (mid-rapidity)
Time Projection Chamber
(Momentum, charge state,
particle identification)

Elliptic anisotropy and B-field direction

Elliptic anisotropy is measured by correlation between two particles

$$v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle \qquad v_2\{2\}^2 = \langle \cos(2\phi_1 - 2\phi_2) \rangle$$



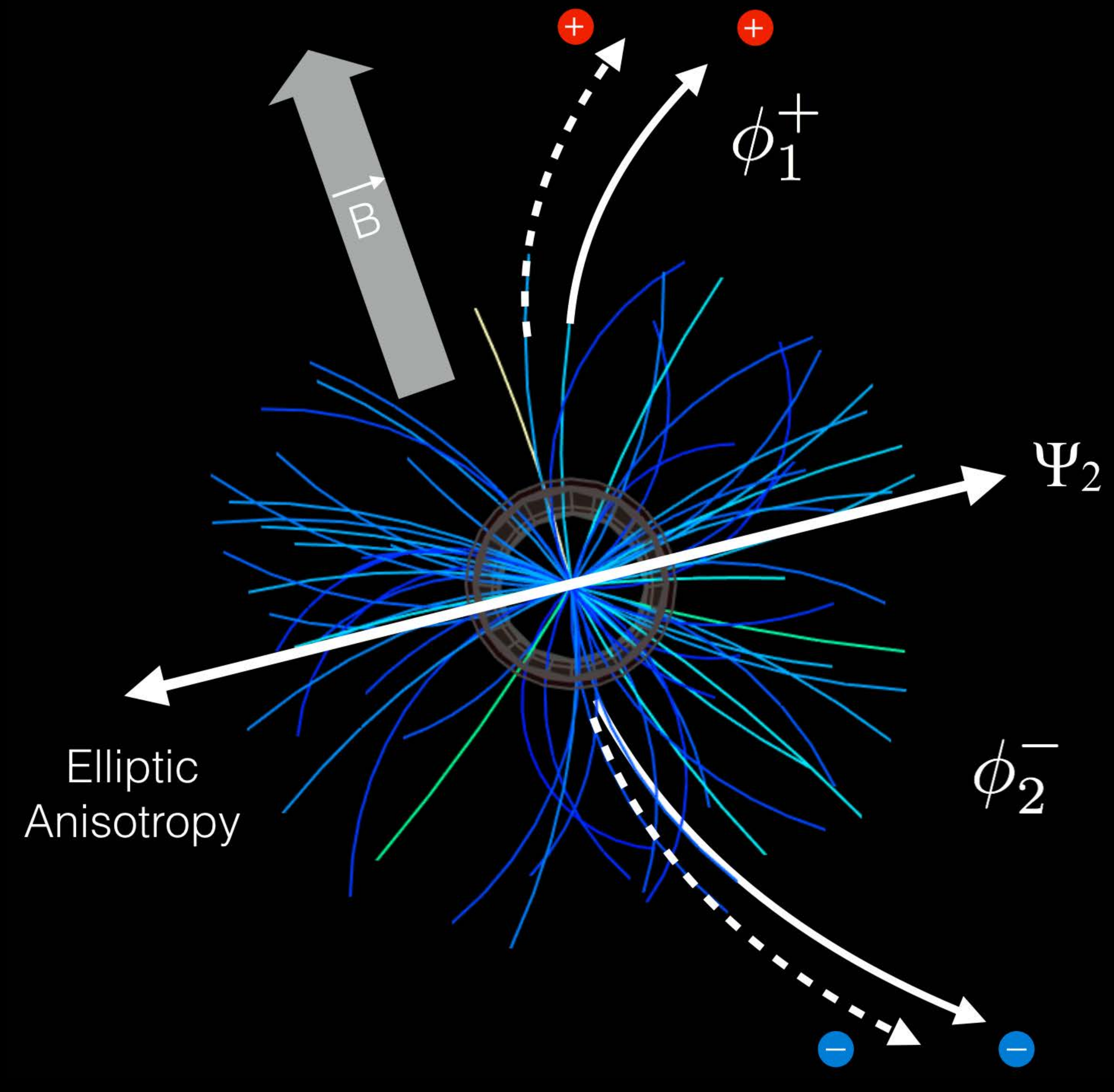


Distributions of particles look elliptic in every event: major axis is elliptic anisotropy plane Ψ_2

The plane of elliptic anisotropy Ψ_2 is correlated to B-field direction

How to measure charge separation due to CME ?

Measure charge separation across Ψ_2 using the correlator:



$$\gamma^{\alpha,\beta} = \langle \cos(\phi_1^{\alpha} + \phi_2^{\beta} - 2\Psi_2) \rangle$$

CME case : $\gamma^{ss} \neq \gamma^{os}$

$$\gamma^{+-} = \cos(\pi/2 - \pi/2 + 0) = 1$$
$$\gamma^{++,--} = \cos(\pi/2 + \pi/2 + 0) = -1$$

Voloshin,

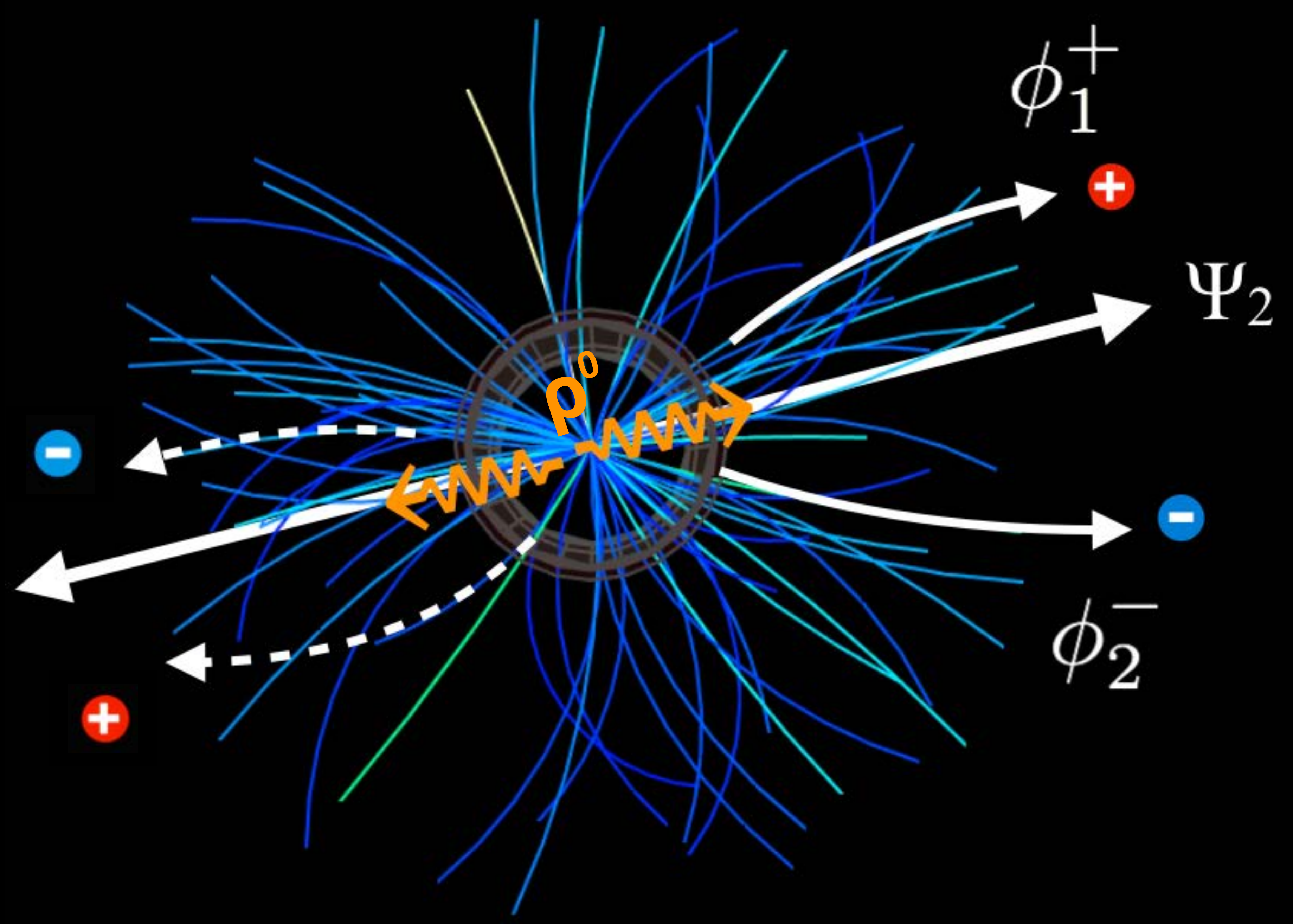
Quantity of interest:

$$\Rightarrow \Delta\gamma^{CME} = \gamma^{os} - \gamma^{ss} > 0$$

CME causes difference in opposite-sign & same-sign correlation

Major source of background: decay of neutral clusters

Measure charge separation across Ψ_2 using the correlator:



$$\gamma^{\alpha,\beta} = \langle\cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_2)\rangle$$

Flowing resonance decay: $\gamma^{ss} \neq \gamma^{os}$

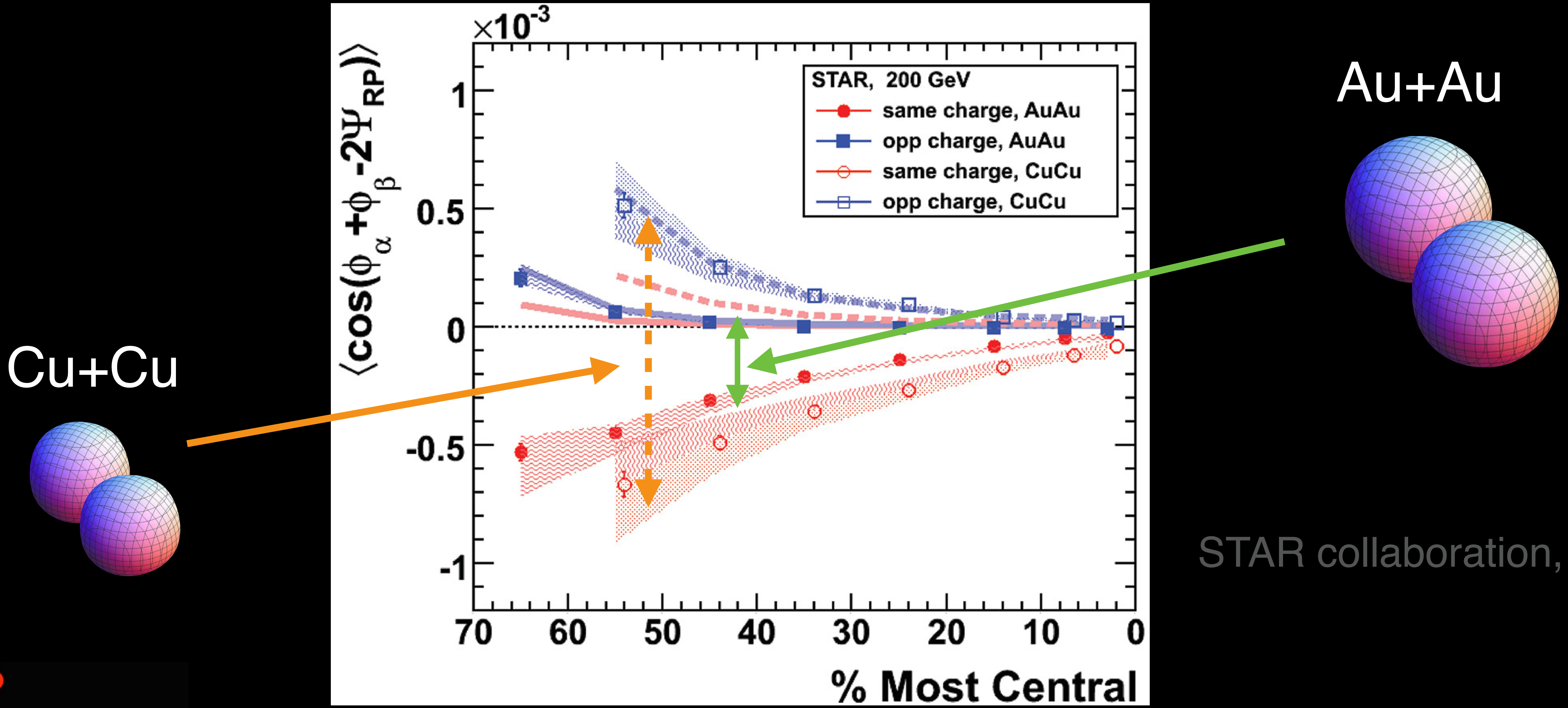
$$\gamma^{+-} = \cos(0+0+0) = 1$$
$$\gamma^{++,--} = \cos(0+\pi+0) = -1$$

Voloshin,

Non-CME effect such as flowing resonance decay can lead to difference

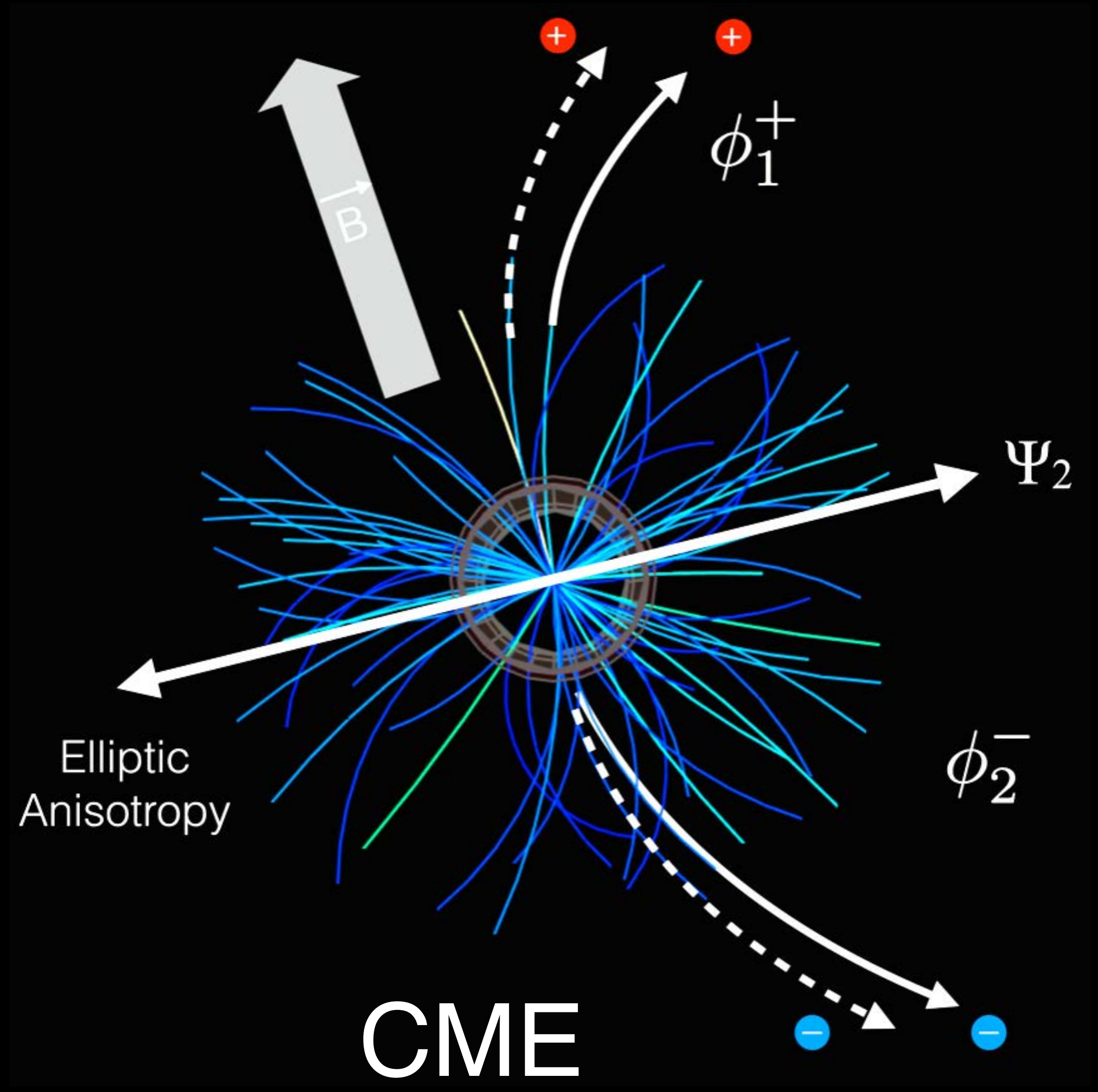
$$\Rightarrow \Delta\gamma^{reso} = \gamma^{os} - \gamma^{ss} \propto \frac{v_2^{reso}}{N}$$

The first measurements at RHIC



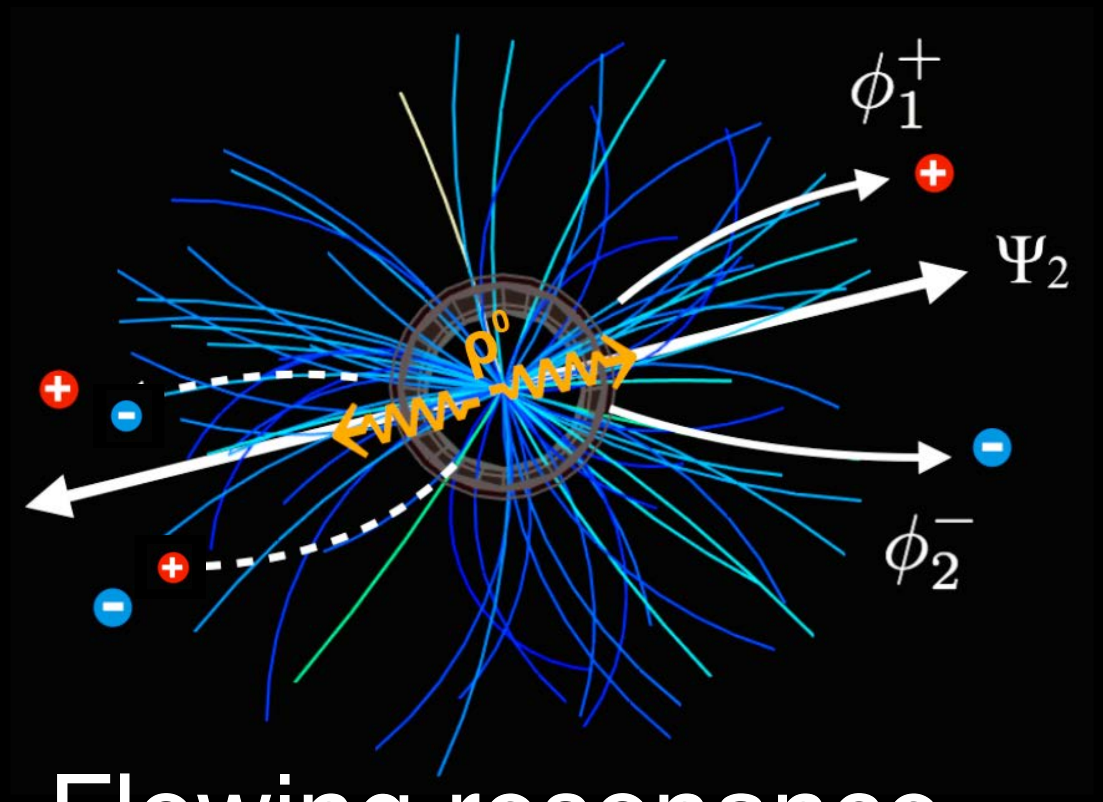
STAR collaboration, PRL 103, 251601 (2009

Three possible sources of charge separation



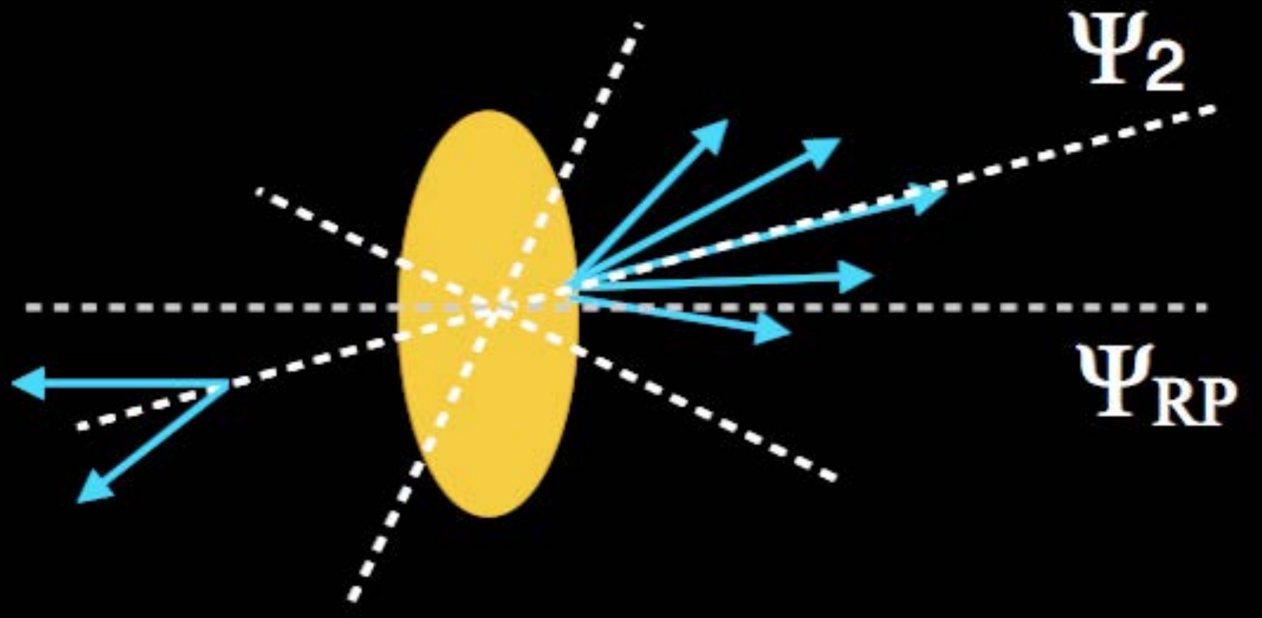
CME

\+



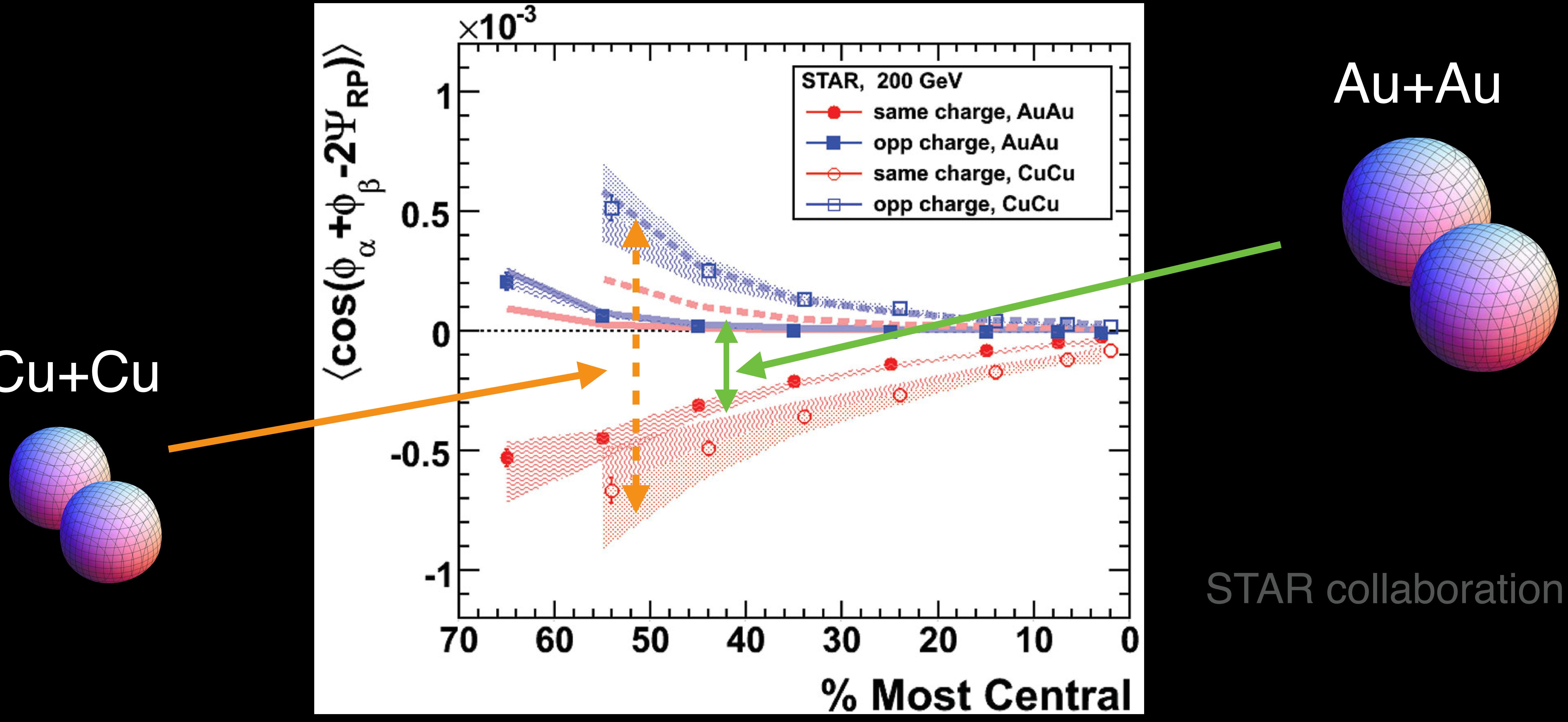
Flowing resonance

\+



Di-jets (non-flow)

The first measurements at RHIC



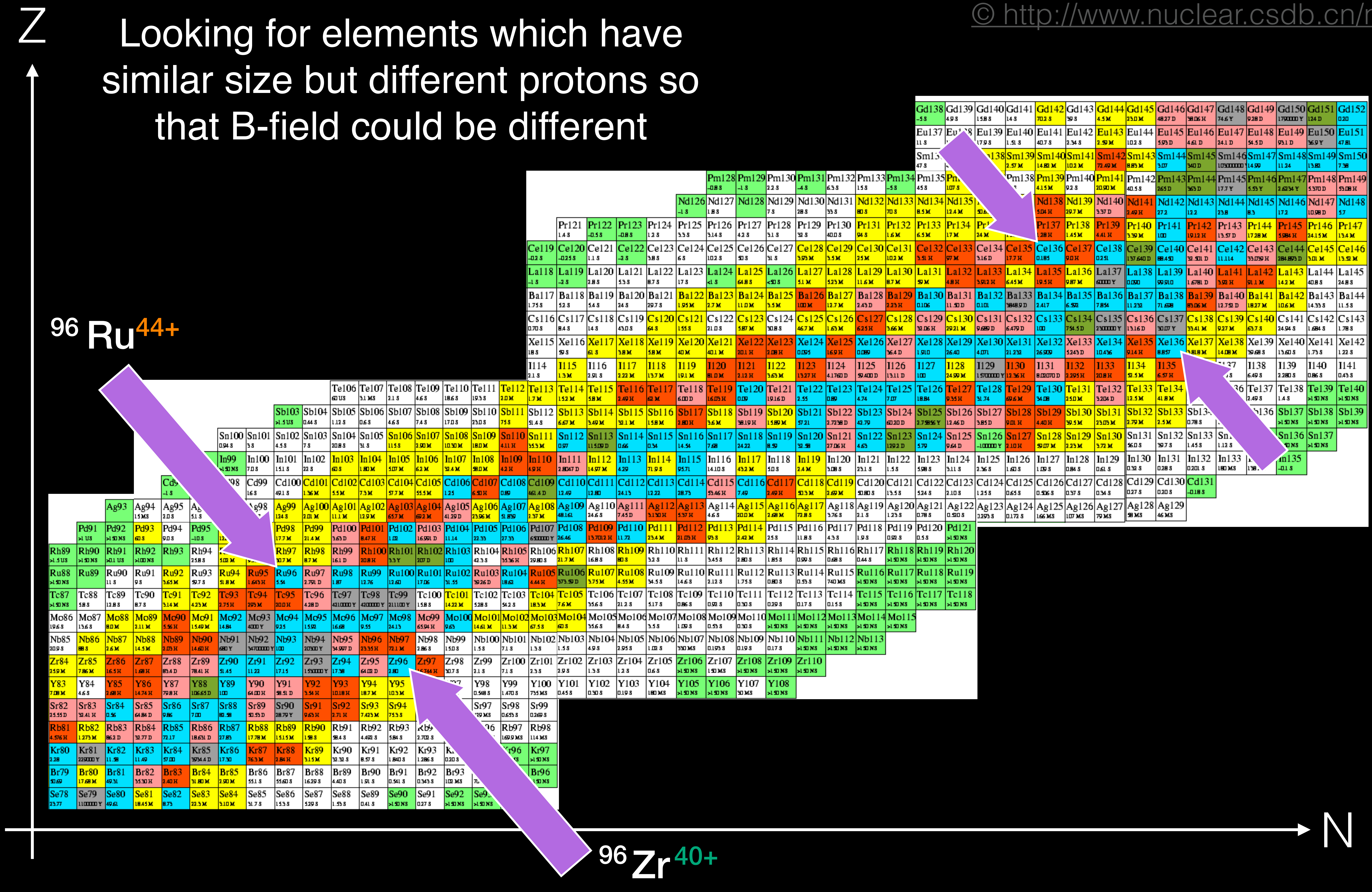
STAR collaboration, PRL 103, 251601 (2009

Significant charge separation observed, consistent with CME+ Background

$$\underbrace{\Delta\gamma}_{\text{Measurement}} = \underbrace{\Delta\gamma^{CME}}_{\text{Signal}} + \underbrace{k \times \frac{v_2}{N}}_{\text{Background-1}} + \underbrace{\Delta\gamma^{non-flow}}_{\text{Background-2}}$$

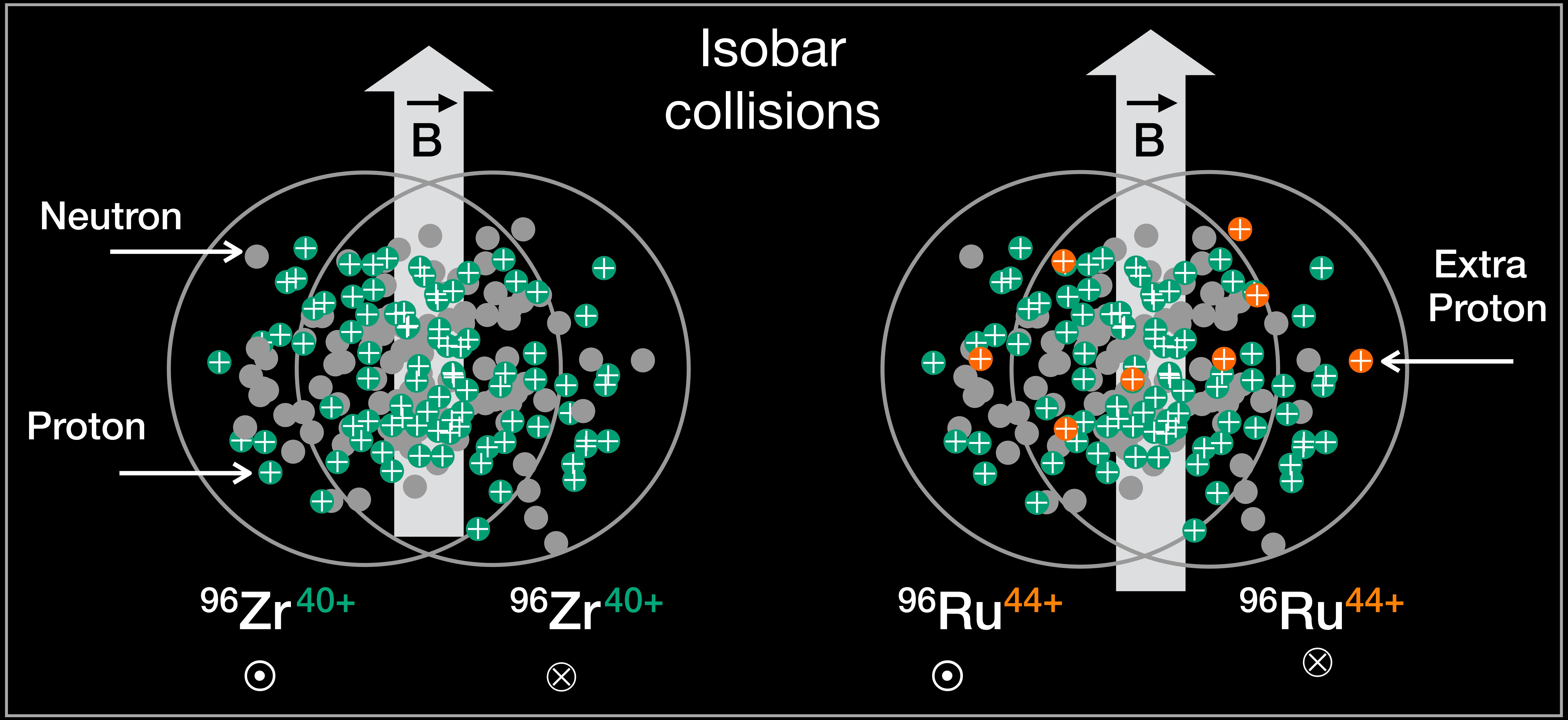
Isobar in the chart of nuclides

Looking for elements which have similar size but different protons so that B-field could be different



© http://www.nuclear.csdb.cn/nuclear/chart9.asp

Isobar collisions



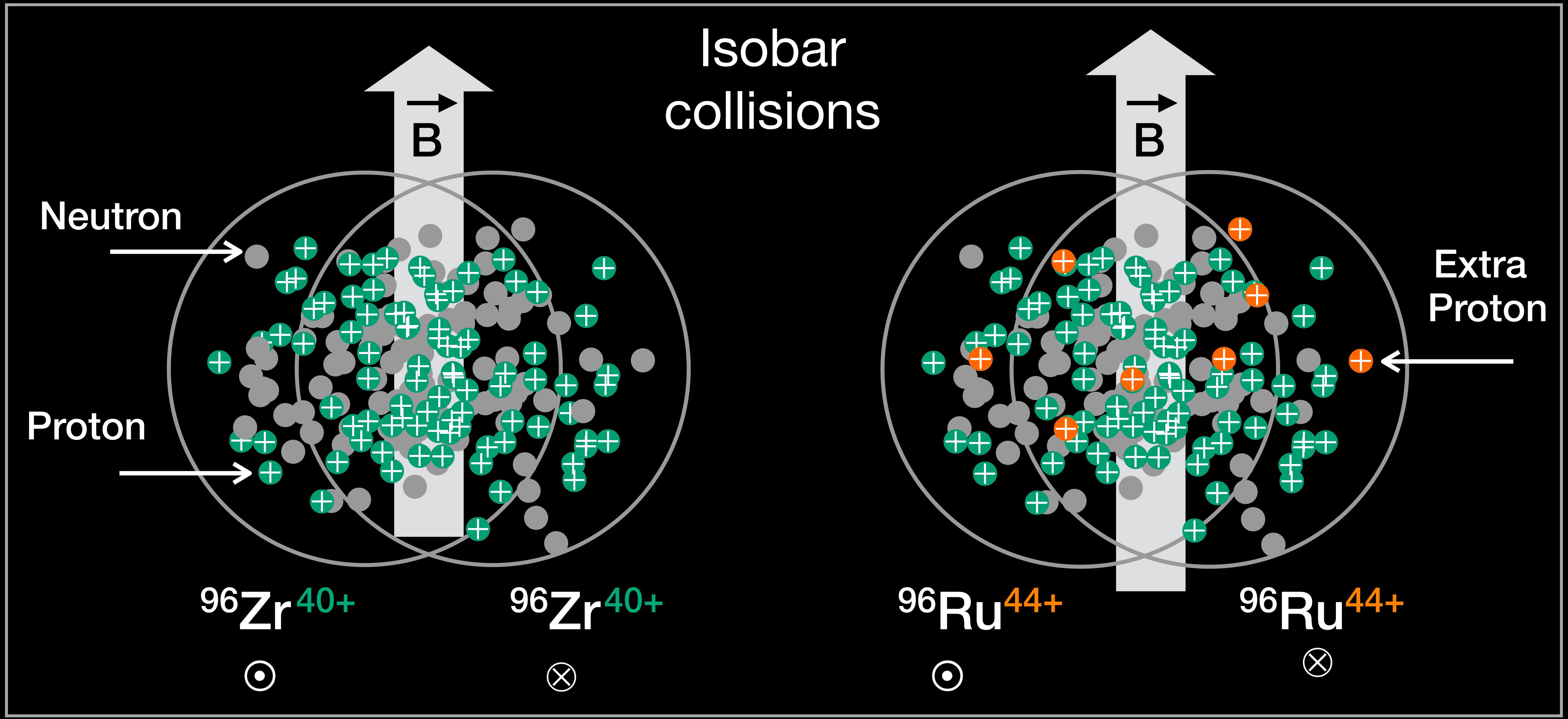
Voloshin,

B-field square is 10-18% larger in Ru+Ru

$$\begin{array}{ccccc}
\Delta\gamma \overset{\text{Ru+Ru}}{=} & \Delta\gamma^{CME} & + k \times & \dfrac{v_2}{N} & + \Delta\gamma^{non-flow} \\
?? & \nparallel & & \wr\wr & \| \\
\Delta\gamma \overset{\text{Zr+Zr}}{=} & \Delta\gamma^{CME} & + k \times & \dfrac{v_2}{N} & + \Delta\gamma^{non-flow}
\end{array}$$

Isobar collisions provide the best possible control of signal and background compared to all previous experiments

Isobar collisions



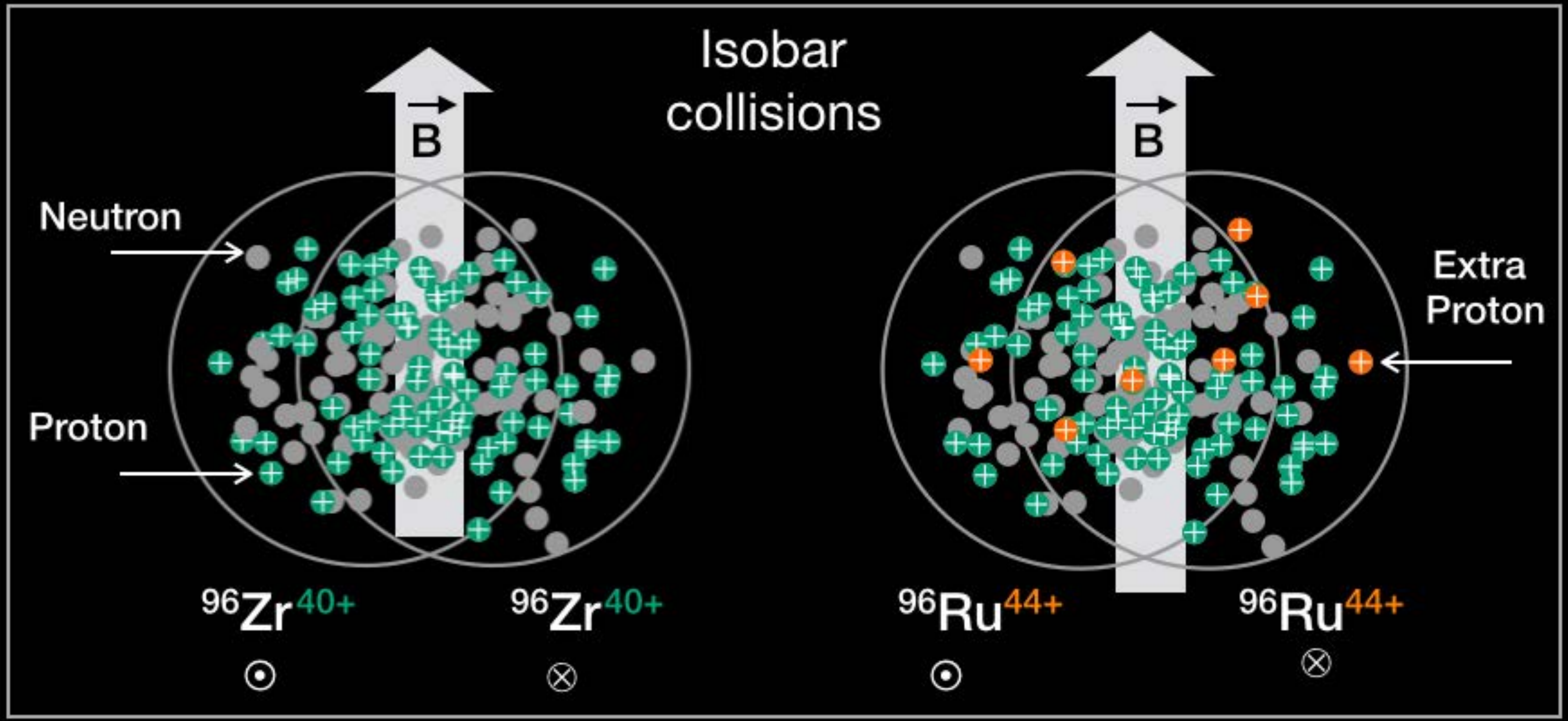
Voloshin,

B-field square is 10-18% larger in Ru+Ru

$$\begin{array}{ccccc}
\Delta\gamma^{\text{Ru+Ru}} & = & \Delta\gamma^{CME} & + k \times & \dfrac{v_2}{N} \\
?? & & \rotatebox{90}{$\neq$} & & \rotatebox{90}{$\approx$} \\
\Delta\gamma^{\text{Zr+Zr}} & = & \Delta\gamma^{CME} & + k \times & \dfrac{v_2}{N}
\end{array}$$

Isobar collisions provide the best possible control of signal and background compared to all previous experiments

Isobar collisions



Voloshin,

B-field square is 10-18% larger in Ru+Ru

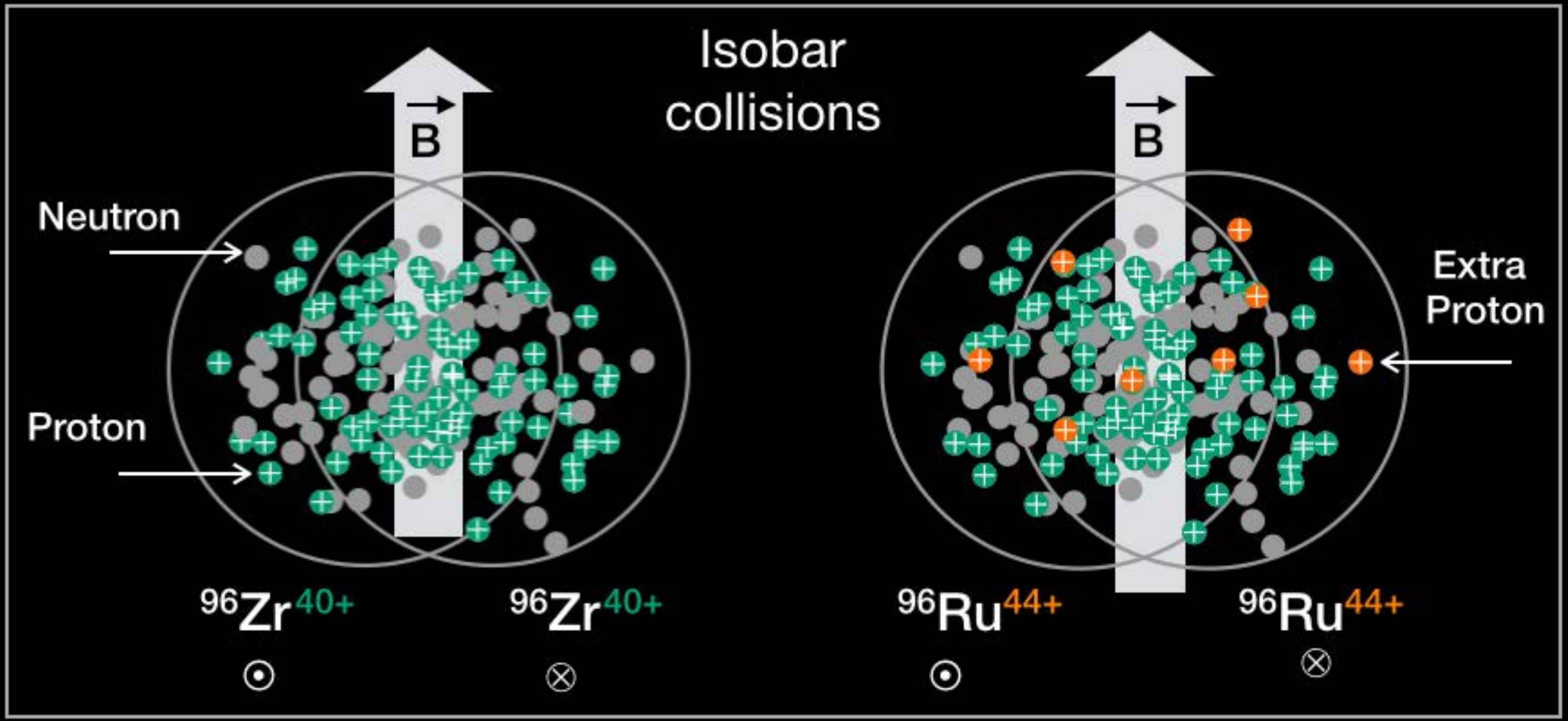
$$\begin{array}{ccccc} \Delta\gamma^{\text{Ru+Ru}} & = & \Delta\gamma^{CME} & + \, k \times & \frac{v_2}{N} \\ ?? & & \nparallel & & \wr \\ \Delta\gamma^{\text{Zr+Zr}} & = & \Delta\gamma^{CME} & + \, k \times & \frac{v_2}{N} \end{array}$$

Isobar collisions provide the best possible control of signal and background compared to all previous experiments

If multiplicity (N) is same in two isobars:

$$\frac{(\Delta\gamma/v_2)_{\text{Ru+Ru}}}{(\Delta\gamma/v_2)_{\text{Zr+Zr}}} \approx 1 + f^{\text{Zr+Zr}}_{\underset{\underset{\text{Unknown}}{\uparrow}}{\text{CME}}}[\underbrace{(B_{\text{Ru+Ru}}/B_{\text{Zr+Zr}})^2 - 1}_{0.18}] > 1 \ (\text{for CME})$$

Isobar collisions



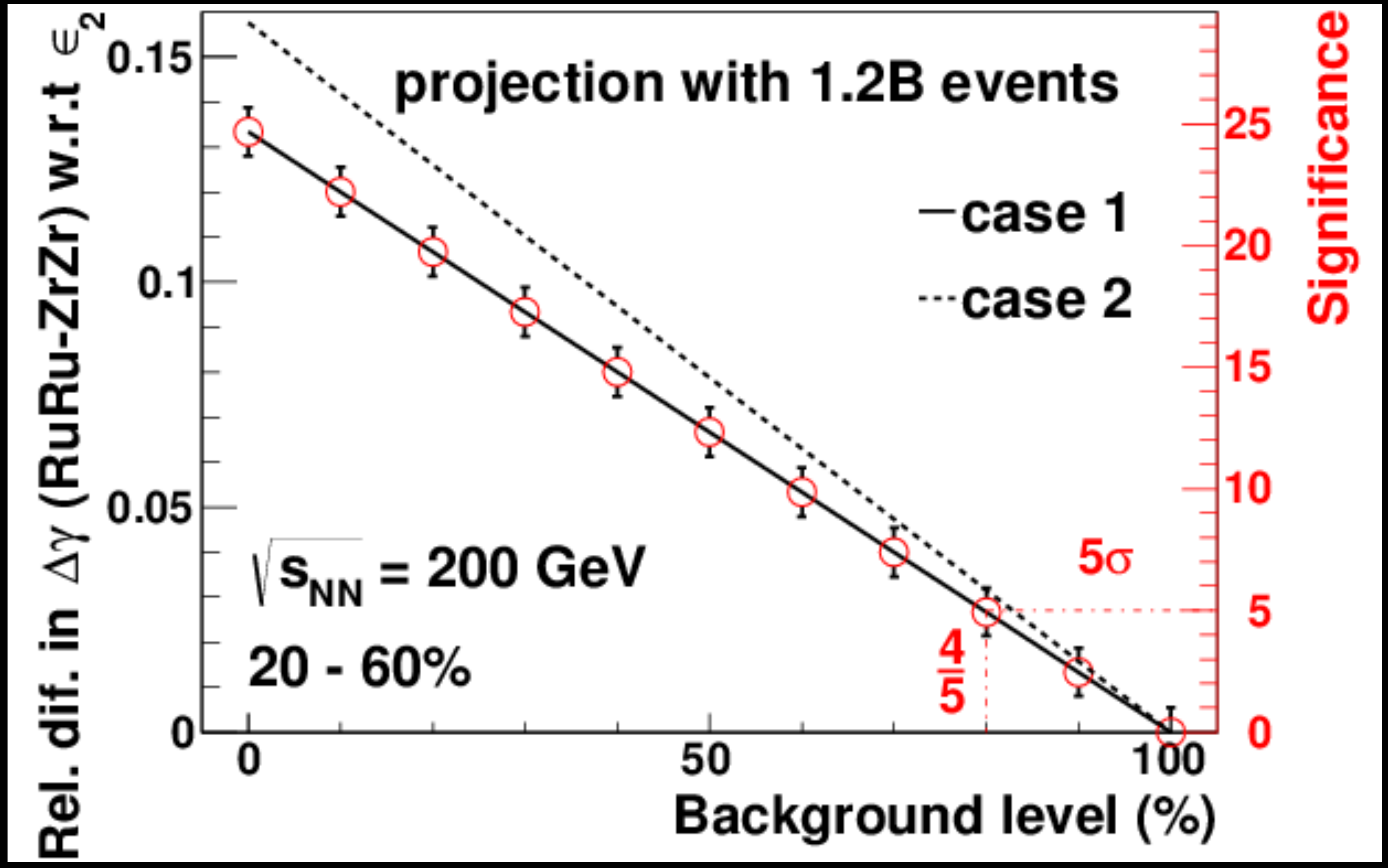
Voloshin,

B-field square is 10-18% larger in Ru+Ru

https://drupal.star.bnl.gov/STAR/system/files/STAR_BUR_Run1718_v22_0.pdf

$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + \underset{\substack{\uparrow \\ \text{Unknown}}}{f^{\mathrm{Zr+Zr}}_{\mathrm{CME}}}\underbrace{[(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1]}_{0.18}$$

$$\boxed{> 1 \ (\text{for CME})}$$



1.2 B collision events for each species can give 5σ significance for 20% signal level ($f_{\mathrm{CME}} \sim 0.2$)

$$(1 - f_{\mathrm{CME}}) \times 100\%$$

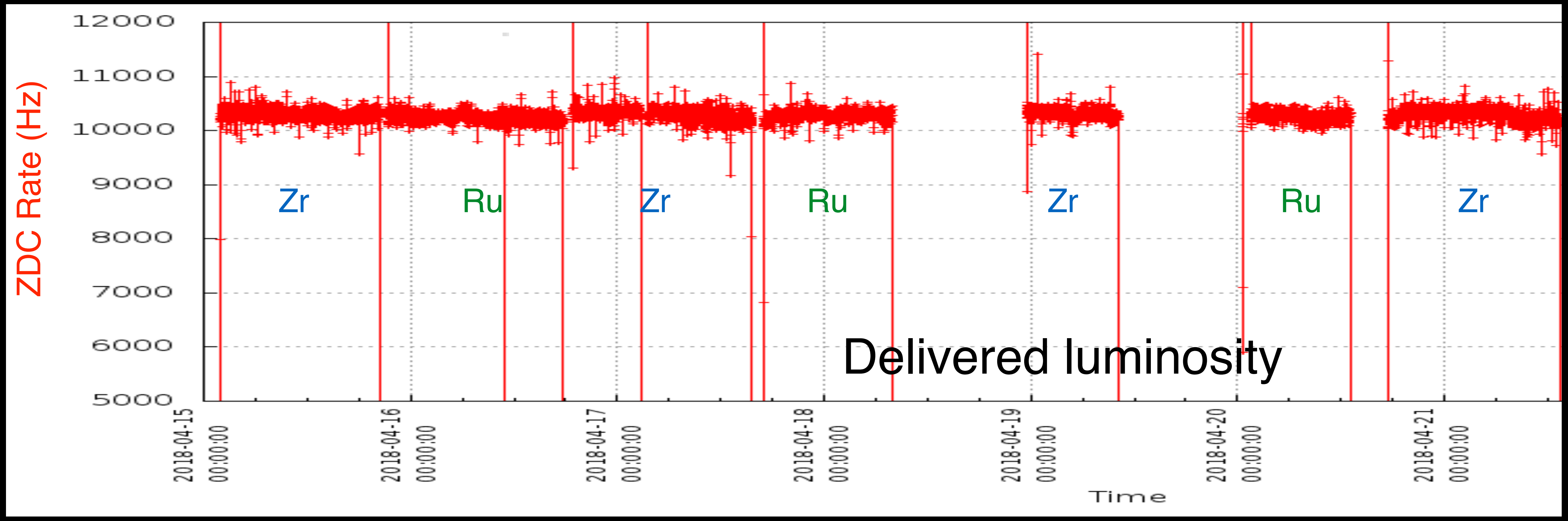
(A precision of 0.5% is needed !!)

Details Of The Data Taking Of The Isobar Run

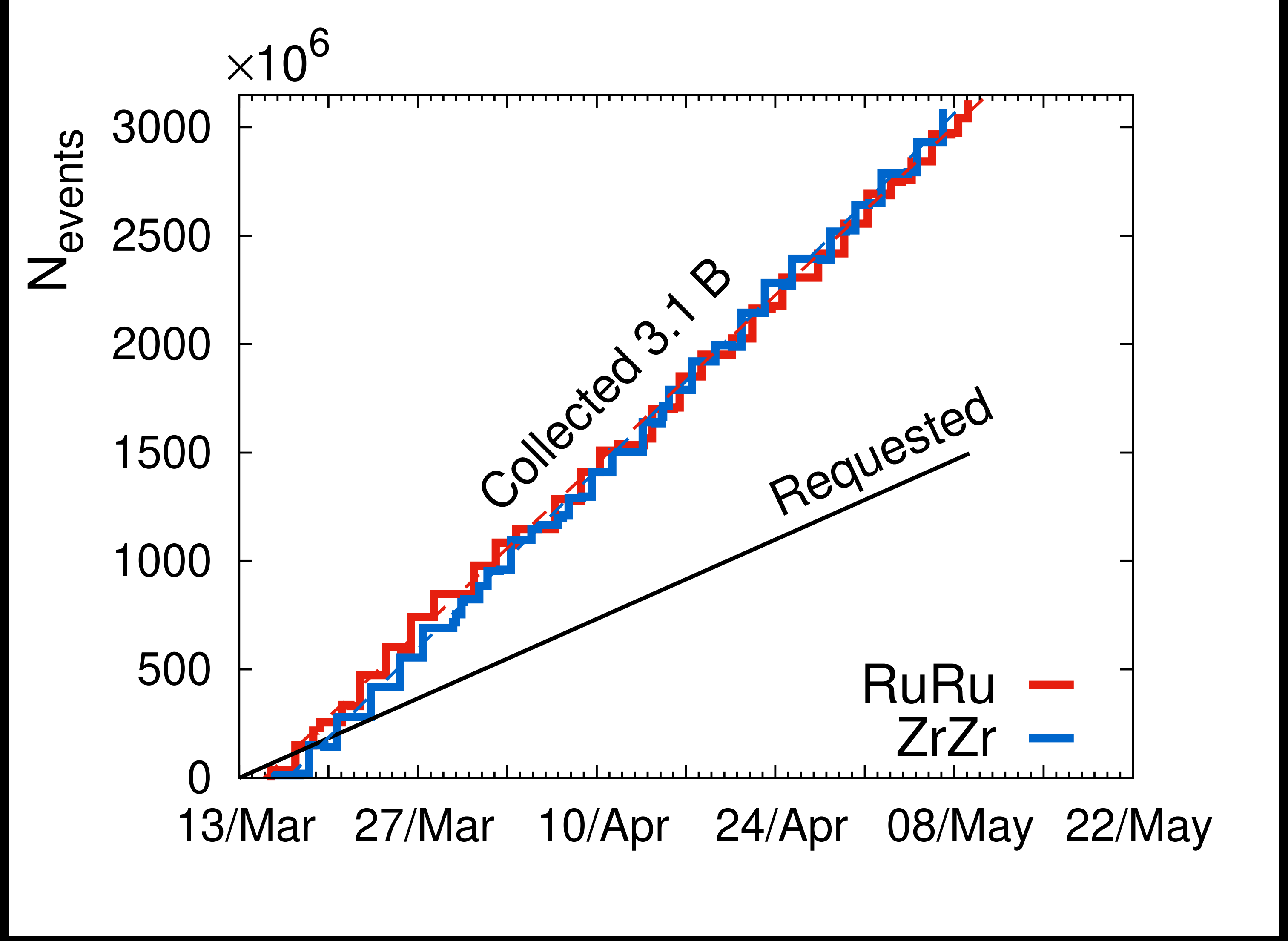
G. Marr et al., in 10th International Particle Accelerator Conference (2019) pp. 28–32.

Goal: minimize the systematics in observable ratios, similar run conditions for both species

Two important steps:
1) Fill-by-fill switching
2) Level luminosity

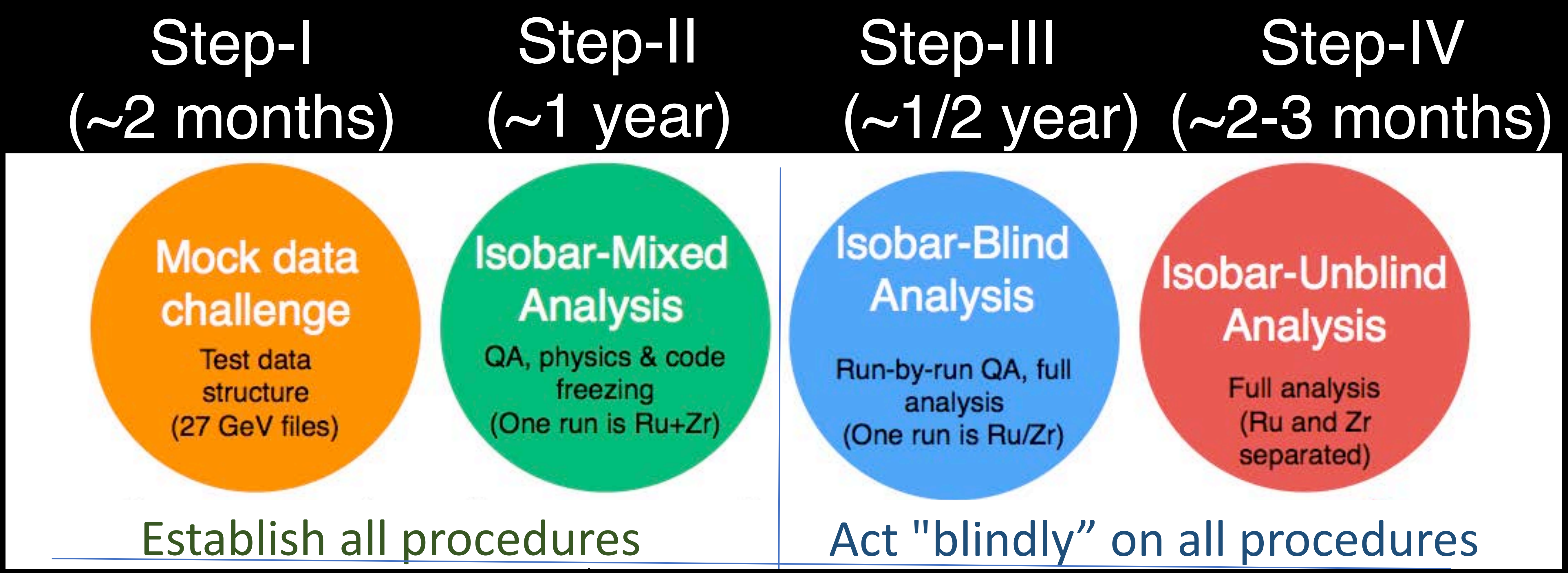


Delivered luminosity



Blind analysis of the isobar data

Steps of Isobar blind analysis



Step-I (~2 months)

Step-II (~1 year)

Step-III (~1/2 year)

Step-IV (~2-3 months)

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)

Establish all procedures

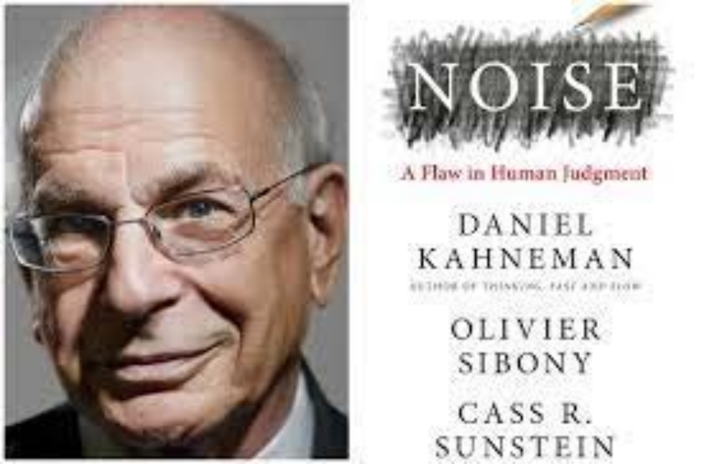
Act "blindly" on all procedures

STAR Collaboration
Nucl.Sci.Tech. 32 (2021) 5, 48
arXiv:1911.00596 [nucl-ex]

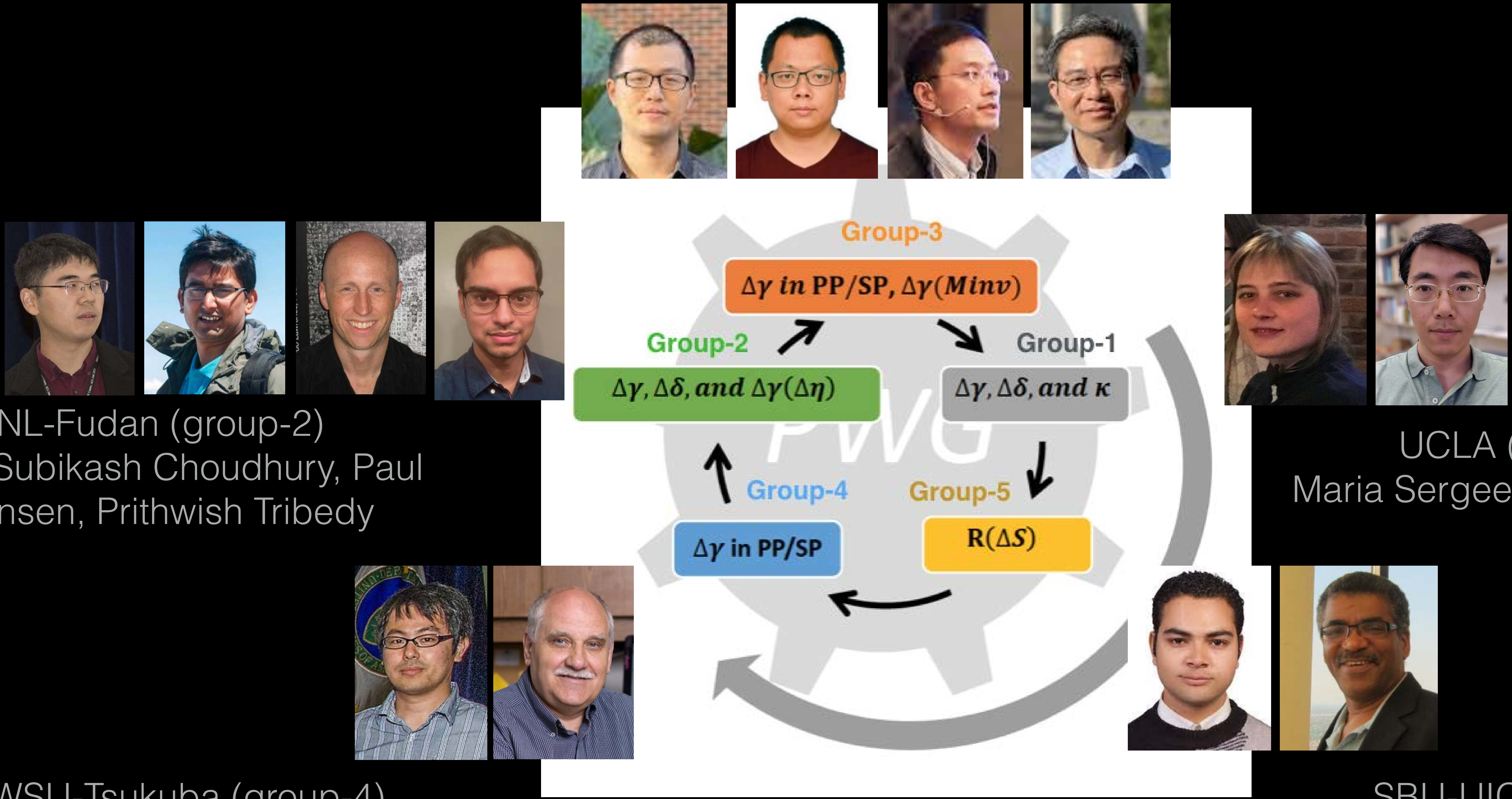
- NPP PAC recommended a blind analysis of isobar data Blinding
- No access to species-specific information before last step
- Everything documented (not written → not allowed)
- Case for CME & interpretation must be pre-defined

Quality assurance is done by pattern recognition algorithms to remove bias & noise

~~Huristics~~ → Algorithms



Five independent groups did isobar blind analysis



Purdue-Huzhou (group-3)
Yicheng Feng, Haojie Xu, Jie Zhao, Fuqiang Wang

BNL-Fudan (group-2)
Yu Hu, Subikash Choudhury, Paul Sorensen, Prithwish Tribedy

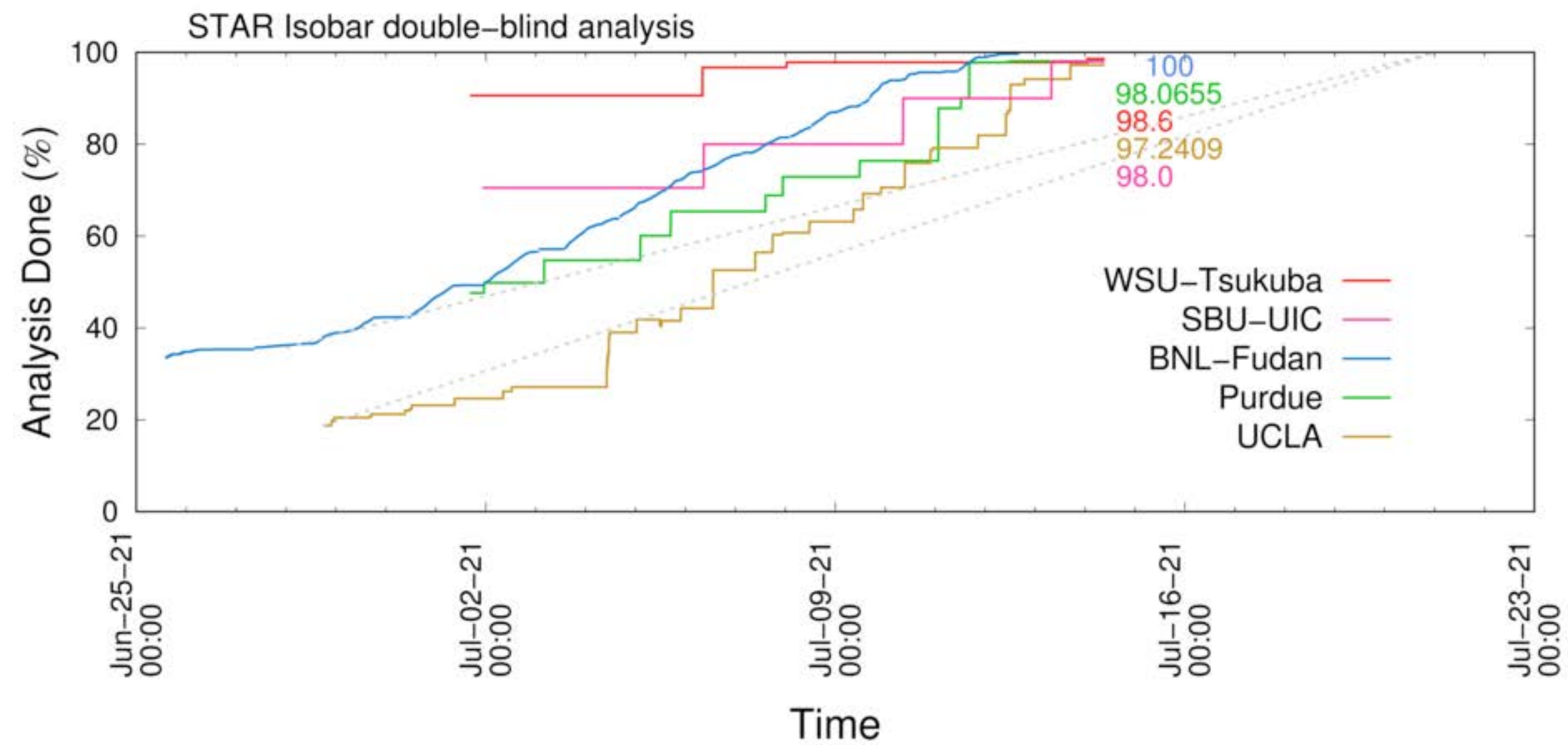
UCLA (group-1)
Maria Sergeeva, Gang Wang

WSU-Tsukuba (group-4)
Takafumi Niida, Sergei Voloshin

SBU-UIC (group-5)
Niseem Magdy, Roy Lacey

Five independent groups will perform analysis, all codes must be frozen and run by another person, results have to directly sent for publication

How the isobar blind analysis was done

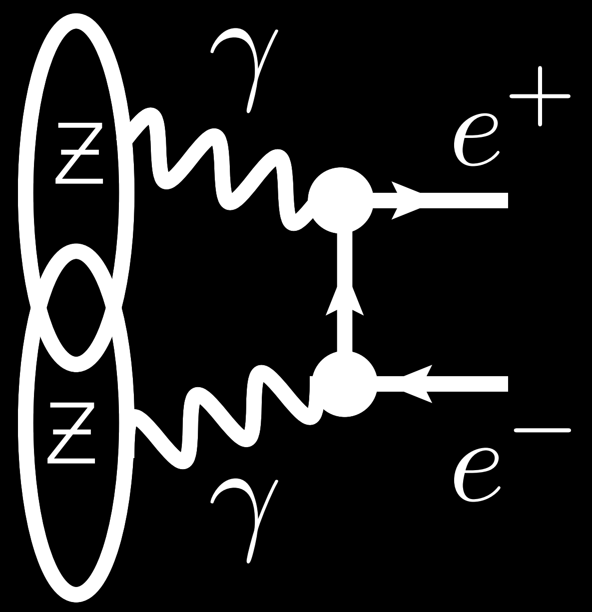


Different people run frozen codes

→ Analyzers open box → Directly publish the result

(Took all nodes of RHIC comp. facility for a month)

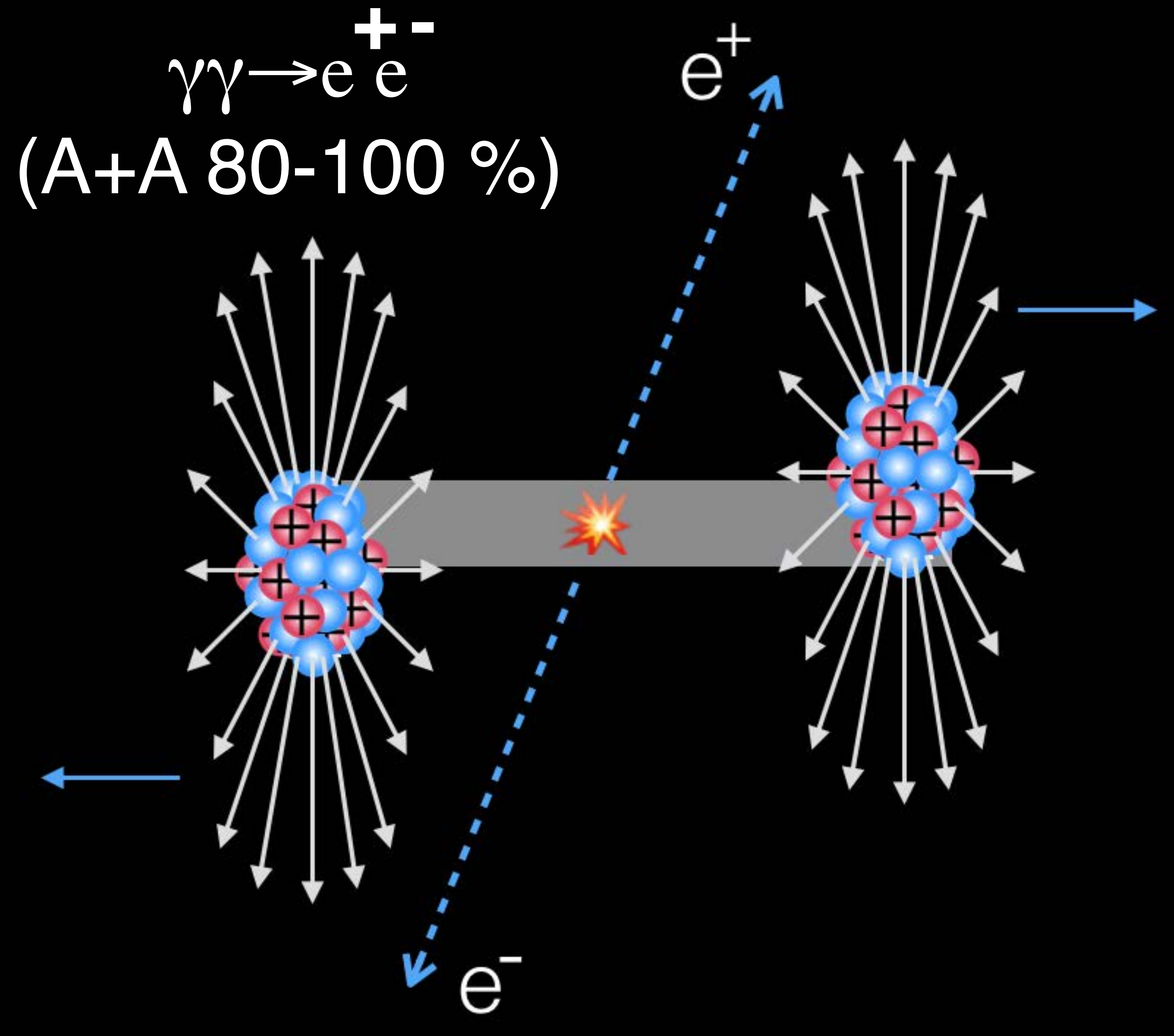
Independent test of B-field difference in isobars



Low p_T di-electron (Breit-Wheeler)

$$\sigma(\gamma\gamma \to e^+e^-) \sim \mathcal{Z}^4$$

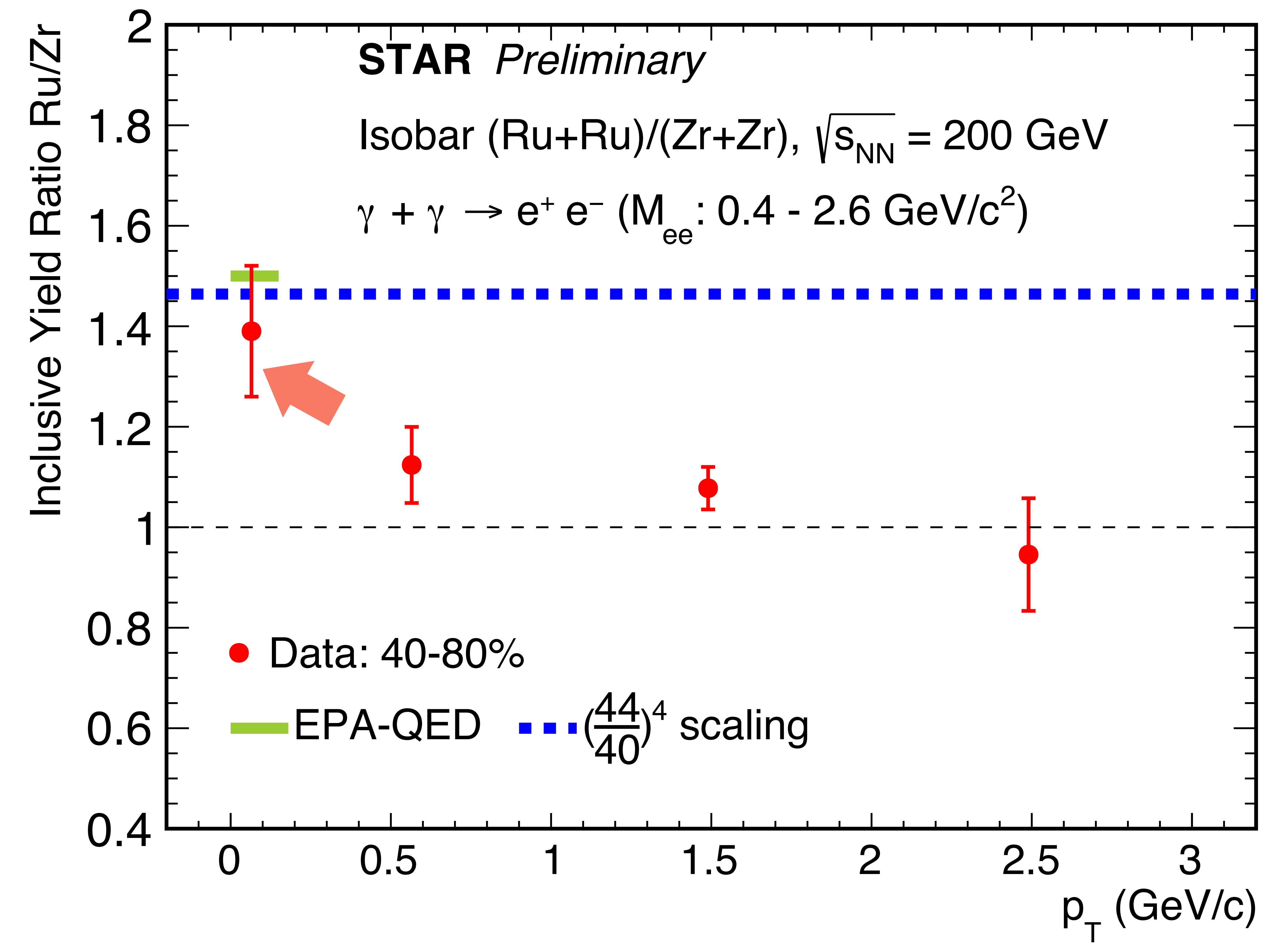
$$\frac{\sigma_{\mathrm{Ru+Ru}}(\gamma\gamma \to e^+e^-)}{\sigma_{\mathrm{Zr+Zr}}(\gamma\gamma \to e^+e^-)} \sim \left(\frac{44}{40}\right)^4$$



$$eB > eB_C \approx m_e^2$$

~10^{12} Gauss

Ru+Ru indeed produces larger B-field than Zr+Zr

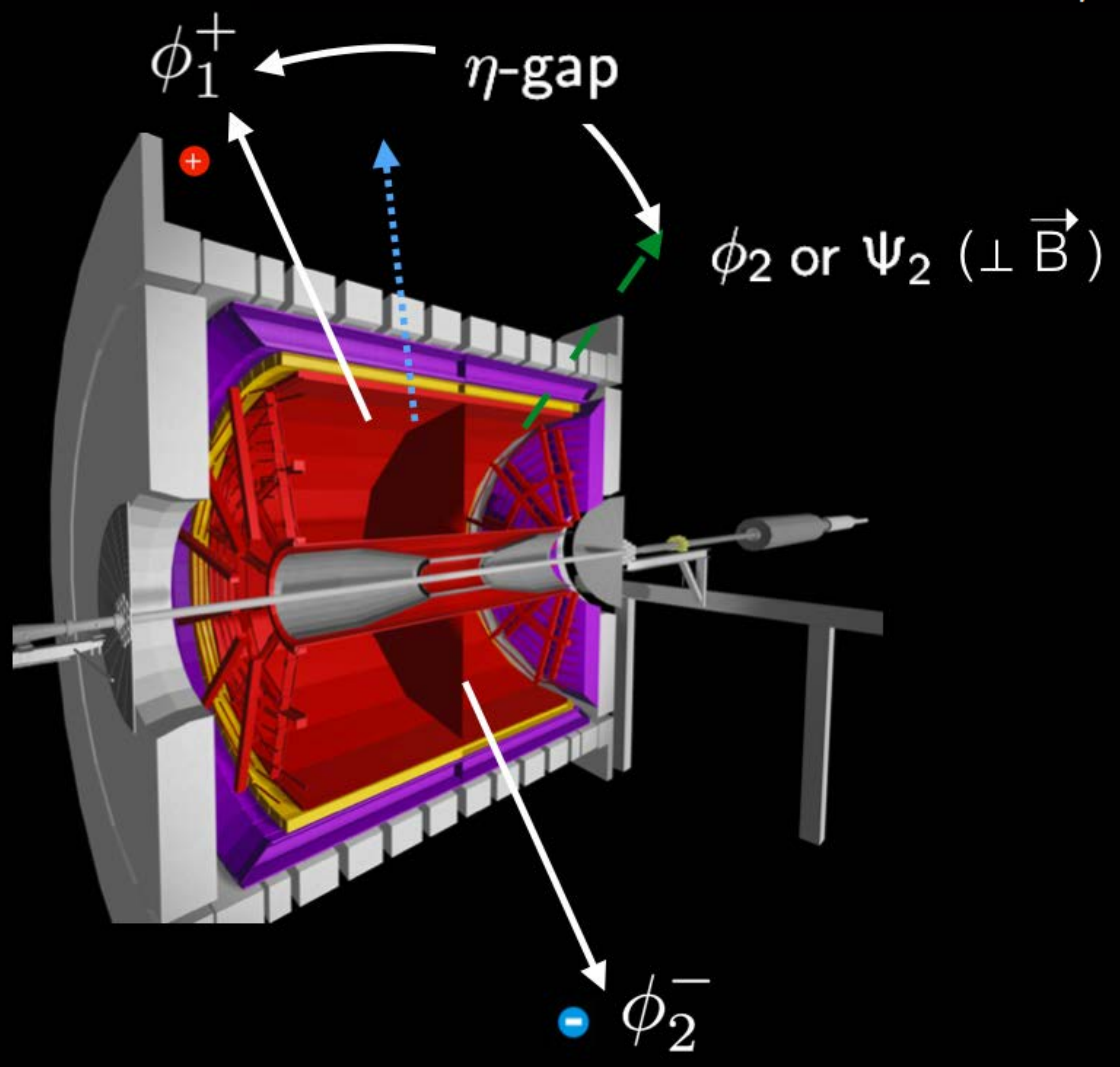


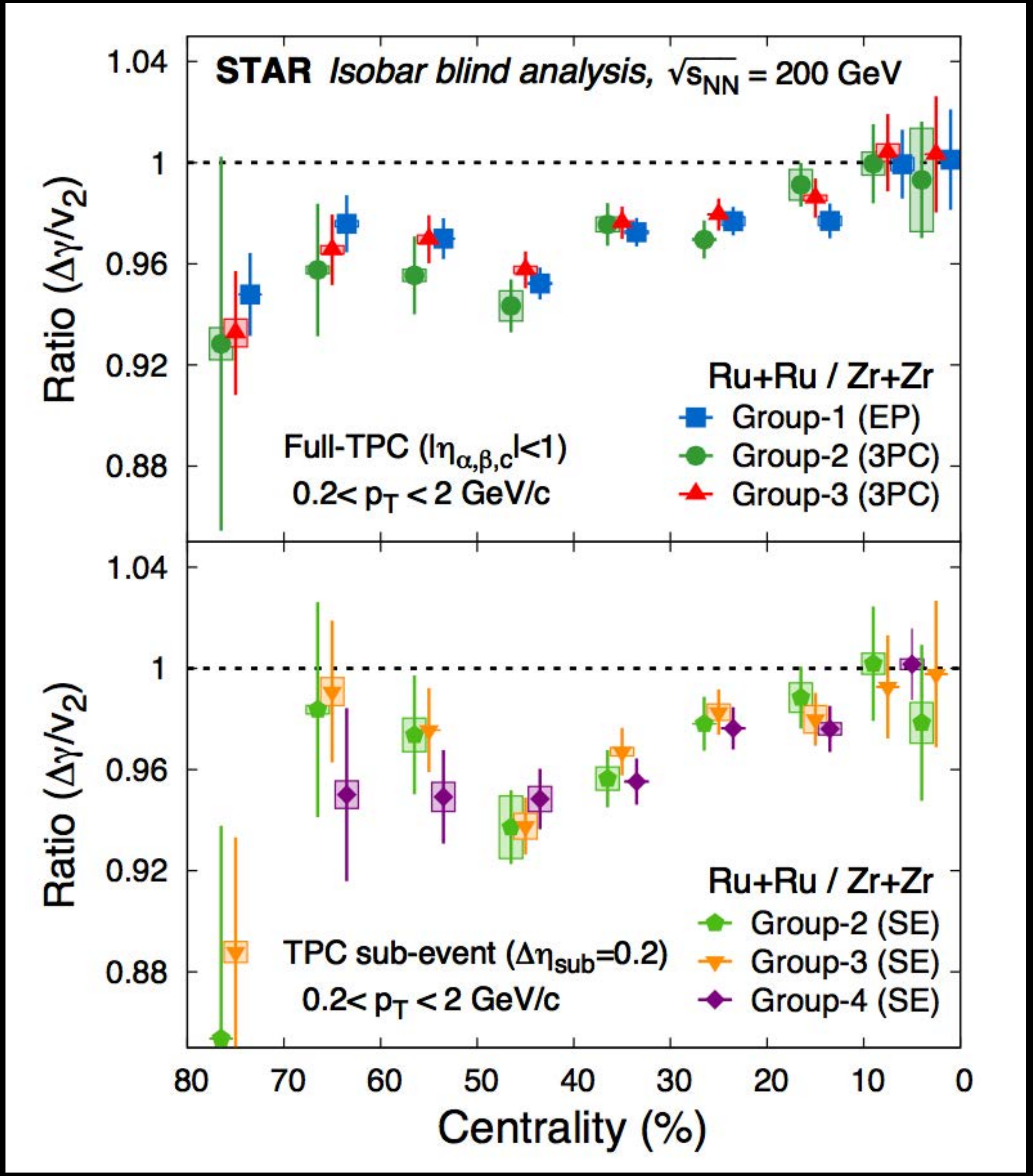
Data suggest low p_T photon induced processes follow “Z” scaling of EM-fields for isobars

CME sensitive observables

Charge separation scaled by elliptic flow

$$\gamma_{112}\{\mathrm{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\mathrm{TPC}})\rangle$$





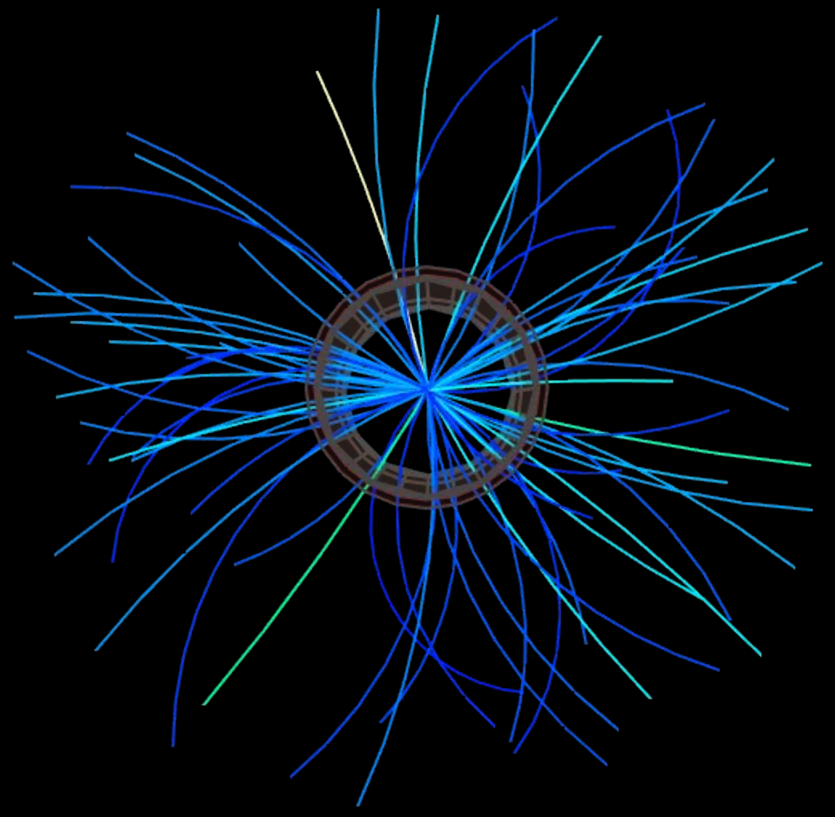
$$\boxed{\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + \underset{\substack{\uparrow\\ \text{Unknown}}}{f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}}\underbrace{[(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1]}_{0.18}}$$

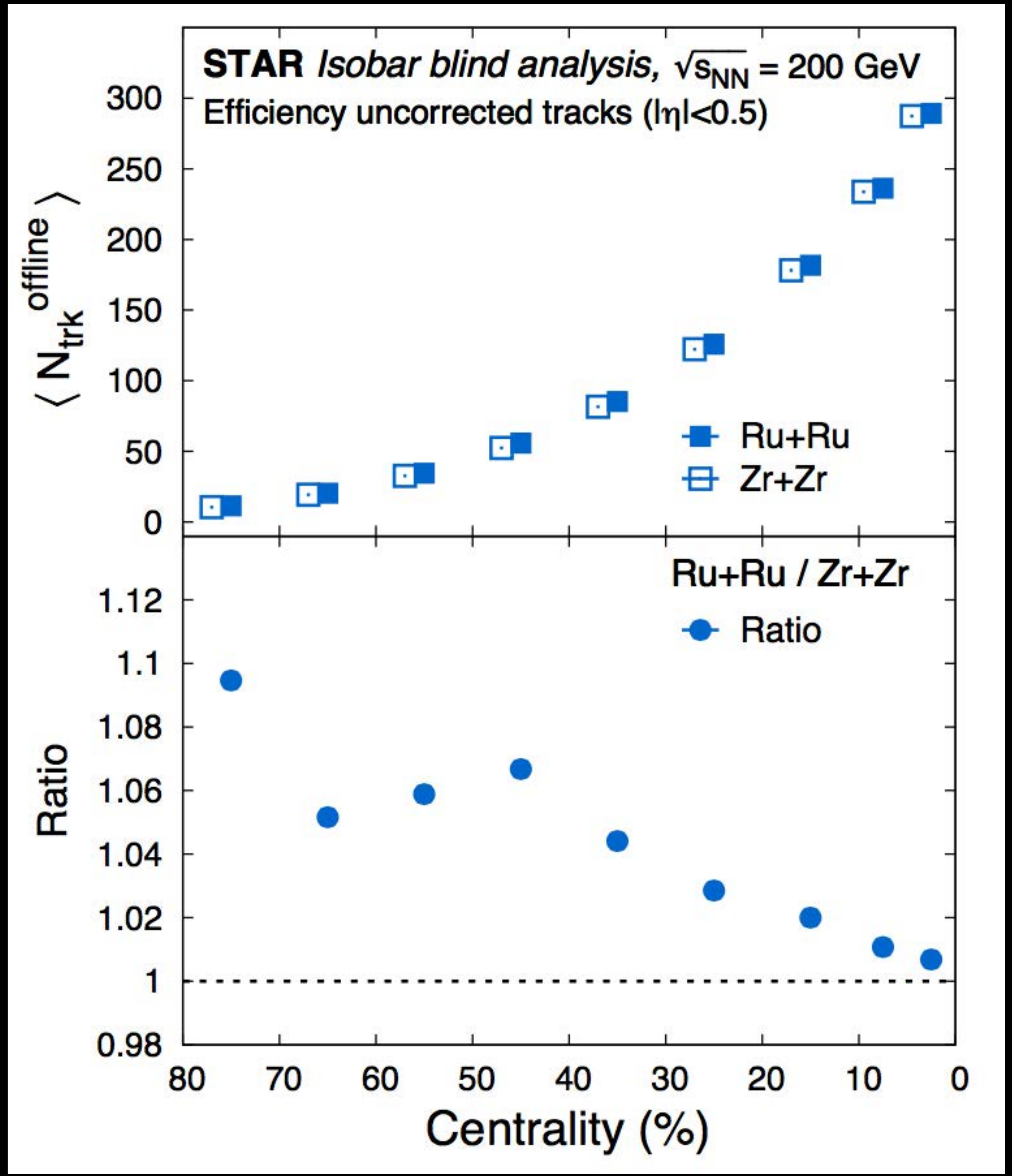
Pre-defined criteria for CME

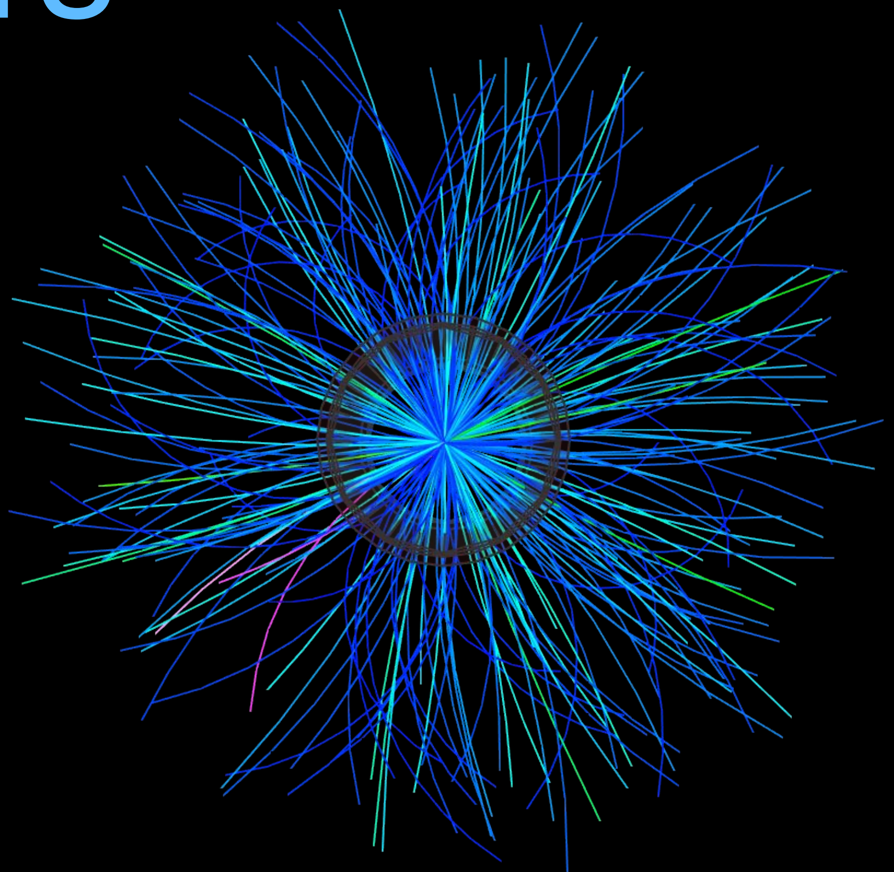
$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$$

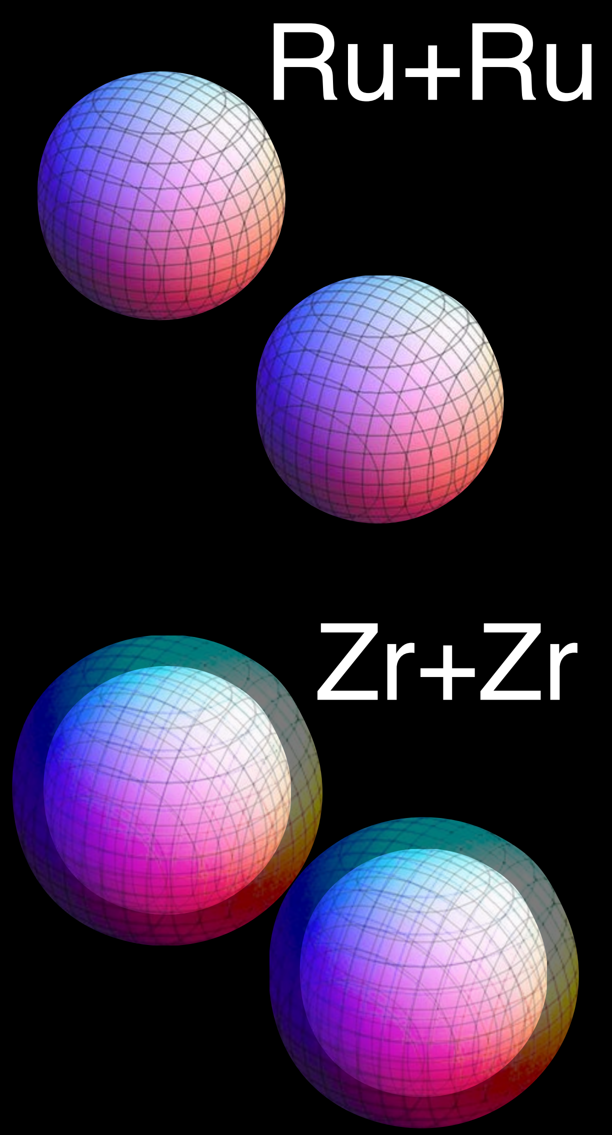
NOT seen!!

Multiplicity difference between the isobars









Neutron skin:
$\Delta r_{np}(Zr) > \Delta r_{np}(Ru)$

Mean efficiency uncorrected multiplicity density is larger in Ru than in Zr in a matching centrality, this can affects signal and background difference between isobars

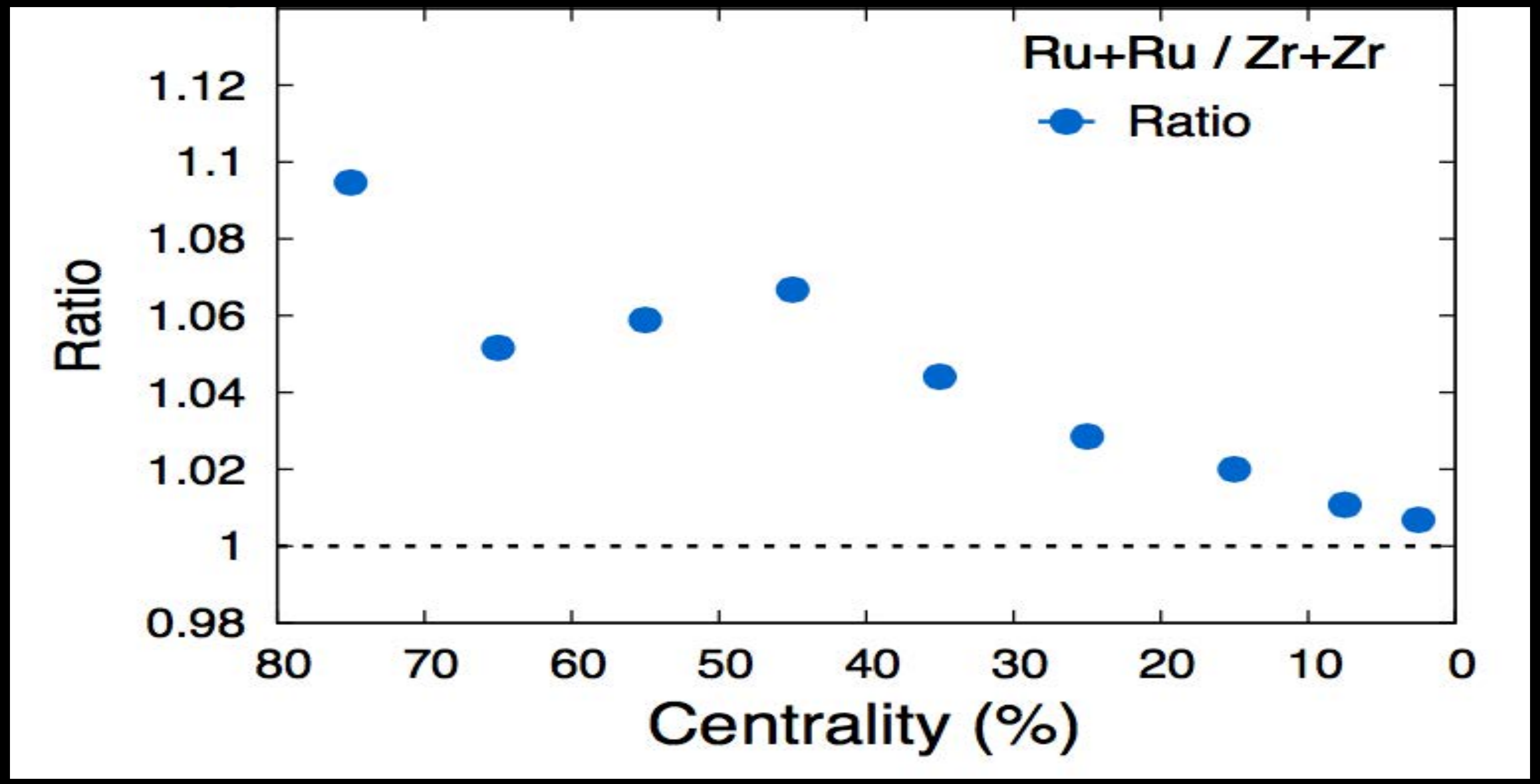
Quite unexpected result!! Points to larger neutron skin of Zr

Limited Post-blind analysis: modified CME baseline

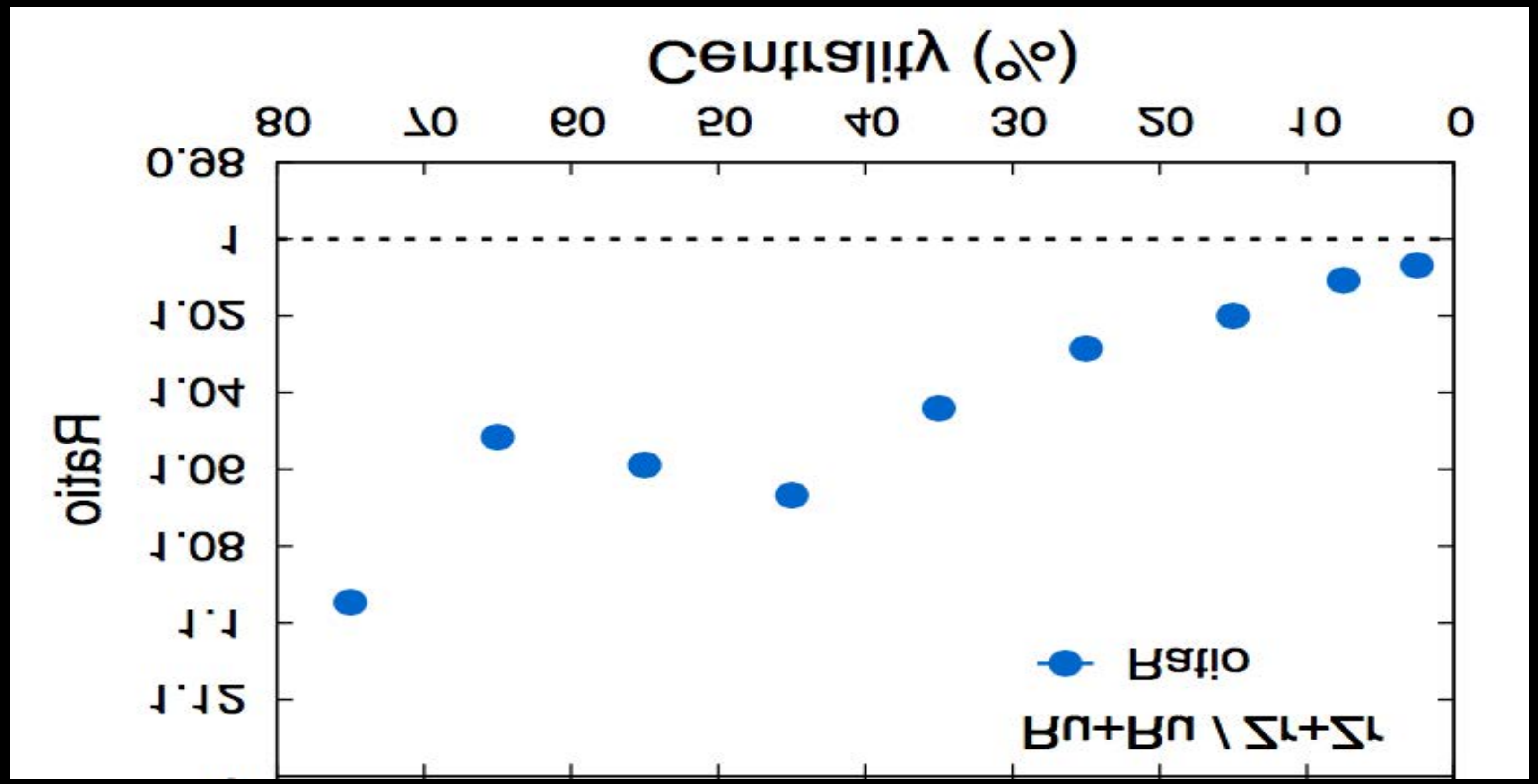
Voloshin for STAR, DNP 2021

$$\frac{(N_{\rm ch})_{\rm RuRu}}{(N_{\rm ch})_{\rm ZrZr}}$$

Multiplicity is larger in Ru+Ru



Flip



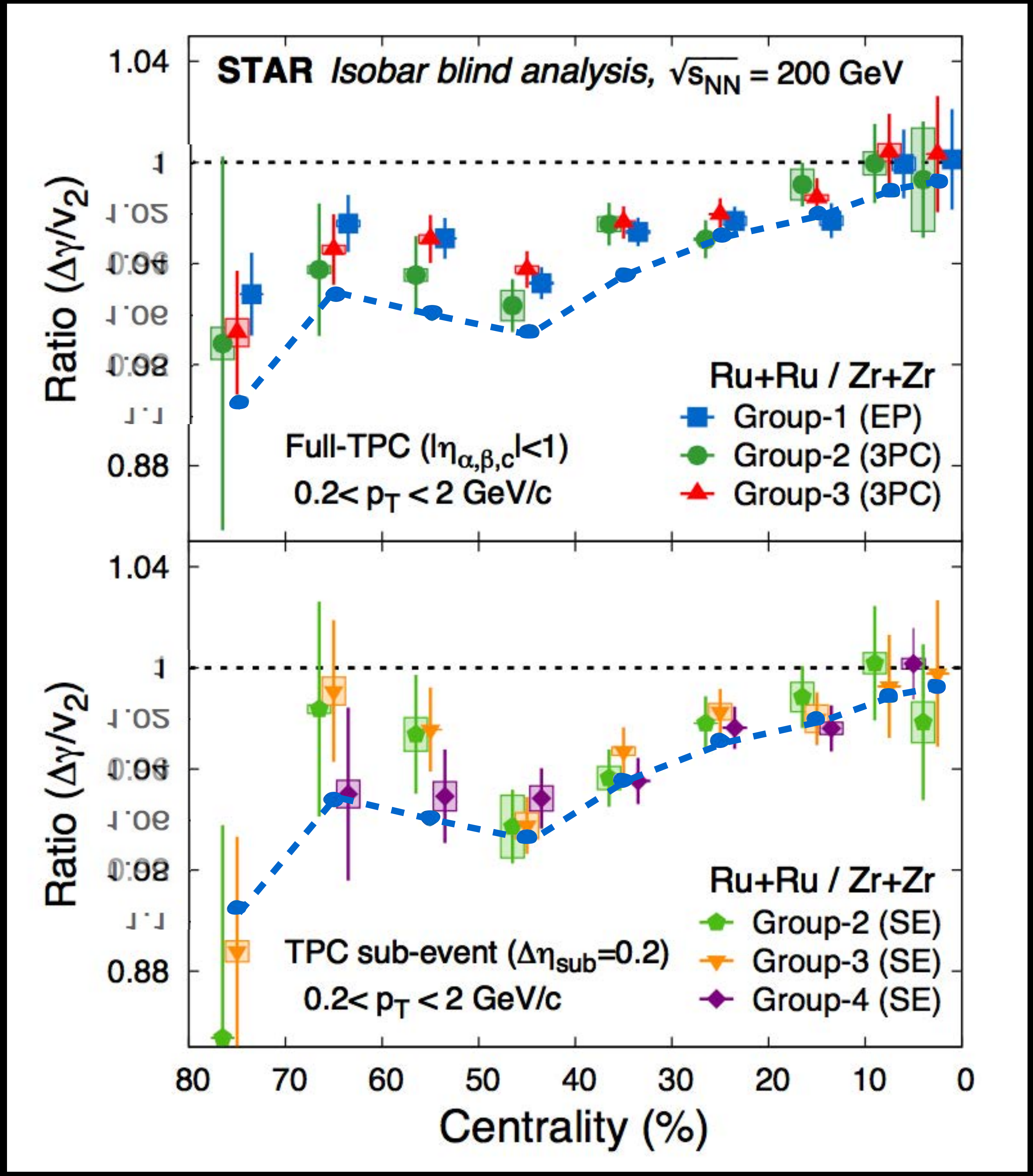
Dilution ~ 1/multiplicity is more in Ru+Ru

$$\frac{(1/N_{\rm ch})_{\rm RuRu}}{(1/N_{\rm ch})_{\rm ZrZr}}$$

overlay

Change of baseline from “1” to 1/multiplicity

$$\frac{(\Delta\gamma/v_2)_{\rm Ru+Ru}}{(\Delta\gamma/v_2)_{\rm Zr+Zr}} \leftrightarrow \frac{N_{\rm Zr+Zr}}{N_{\rm Ru+Ru}}$$



Inverse of multiplicity ratio explain the qualitative trend

Limited Post-blind analysis: modified CME baseline

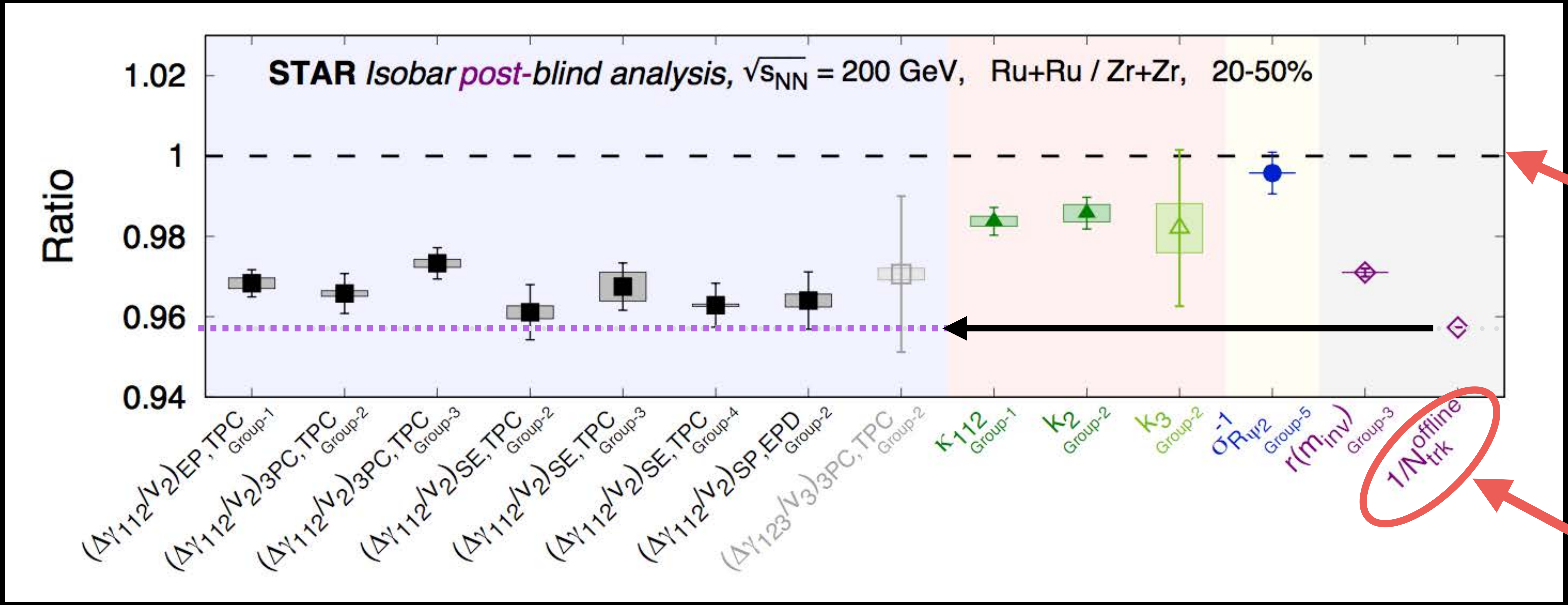
Challenge: Multiplicity turned out to be different for the two isobar, was not know before blind analysis, dilution of signal & background ~ 1/multiplicity, this effect is different for two species

Blind analysis criterion for CME: $\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > 1$

$$\begin{array}{ccc} \Delta\gamma^{\text{Ru+Ru}} = & \Delta\gamma^{CME} & + k \times \frac{v_2}{N} \\ ?? & \nparallel & \wr \\ \Delta\gamma^{\text{Zr+Zr}} = & \Delta\gamma^{CME} & + k \times \frac{v_2}{N} \end{array}$$

Post-blinding criterion for CME:

$$\frac{(\Delta\gamma/v_2)_{\mathrm{RuRu}}}{(\Delta\gamma/v_2)_{\mathrm{ZrZr}}} > \frac{(1/N_{\mathrm{ch}})_{\mathrm{RuRu}}}{(1/N_{\mathrm{ch}})_{\mathrm{ZrZr}}}$$



Blind analysis baseline

Post-blinding modified baseline

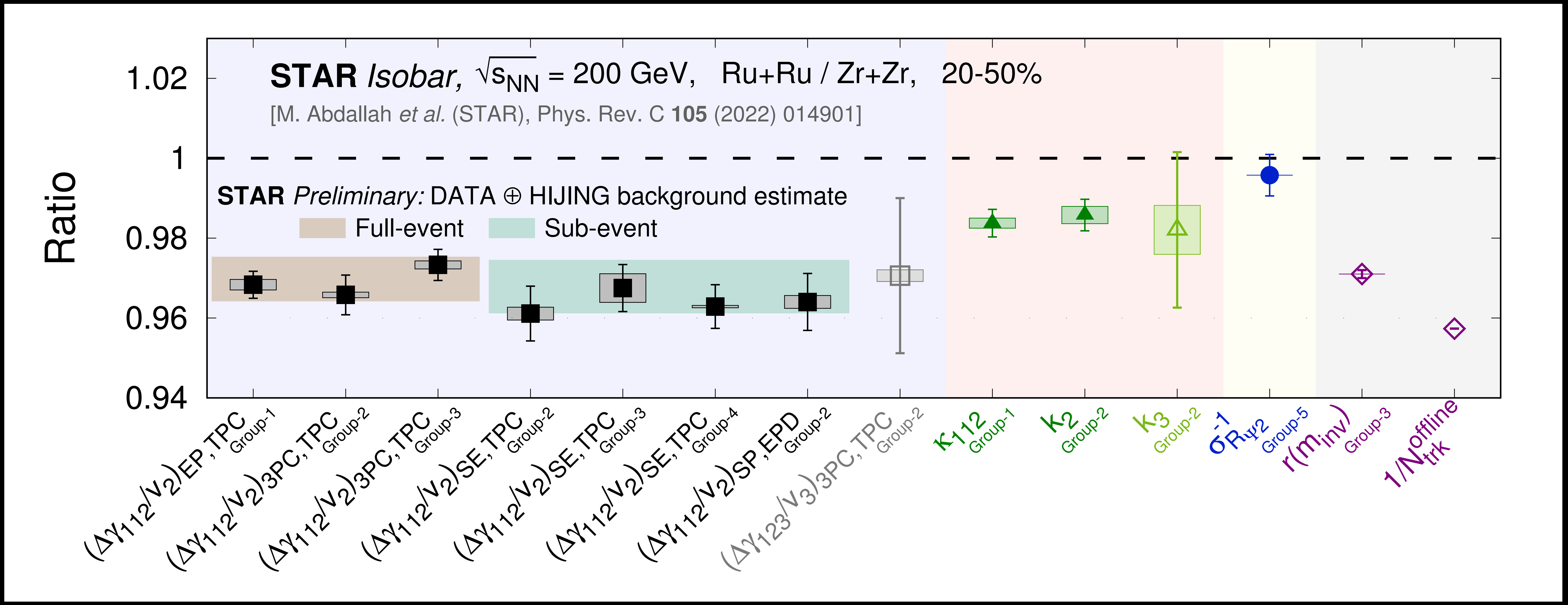
Compilation of results

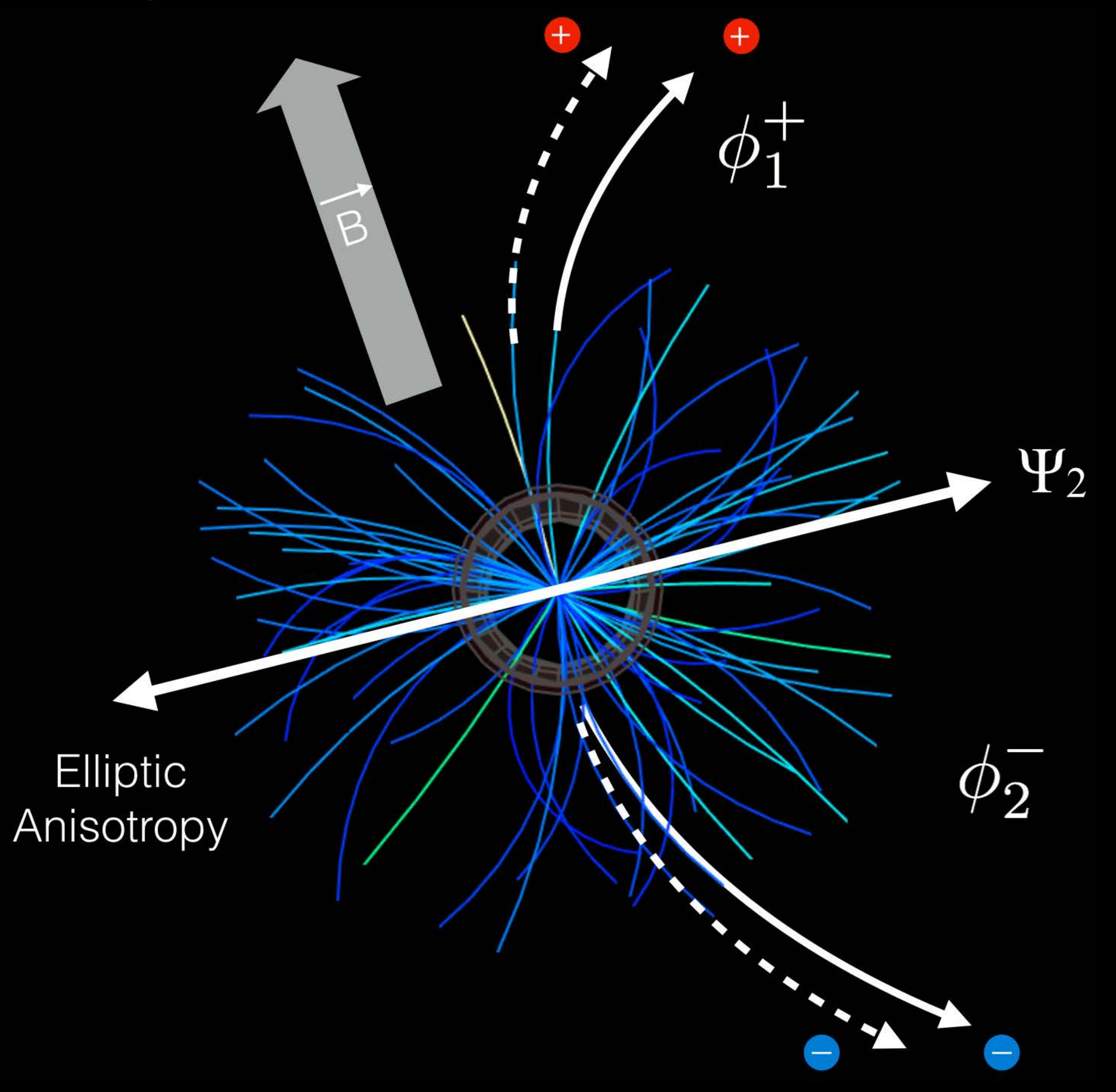
M. Abdallah et al. (STAR Collaboration), Phys. Rev. C 105 (2022) 1, 014901

Blind analysis performed with pre-defined criteria for primary CME sensitive observable:

$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + \underset{\overset{\uparrow}{\text{Unknown}}}{f^{\mathrm{Zr+Zr}}_{\mathrm{CME}}}[\underbrace{(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1}_{0.1\text{-}0.15}] > 1 \text{ (for CME)}$$

Precision of 0.4% achieved





Yicheng Feng (STAR Collaboration), QM 2022

No pre-defined signature of CME is observed in isobar collisions, possible residual signal due to change of baseline & non-flow effects are under study

Remaining signal estimates

1. STAR isobar blind analysis (most precision measurement):

M. Abdallah et al. (STAR Collaboration), Phys. Rev. C 105 (2022) 1, 014901

$$\boxed{R = \frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} = 0.9683 \pm 0.0034 \pm 0.0013}$$

$$\frac{(1/N_{\mathrm{ch}})_{\mathrm{Ru+Ru}}}{(1/N_{\mathrm{ch}})_{\mathrm{Zr+Zr}}} = 0.957337 \pm 0.000017$$

2. STAR background estimate including non-flow:

Yicheng Feng, STAR collaboration, QM 2022

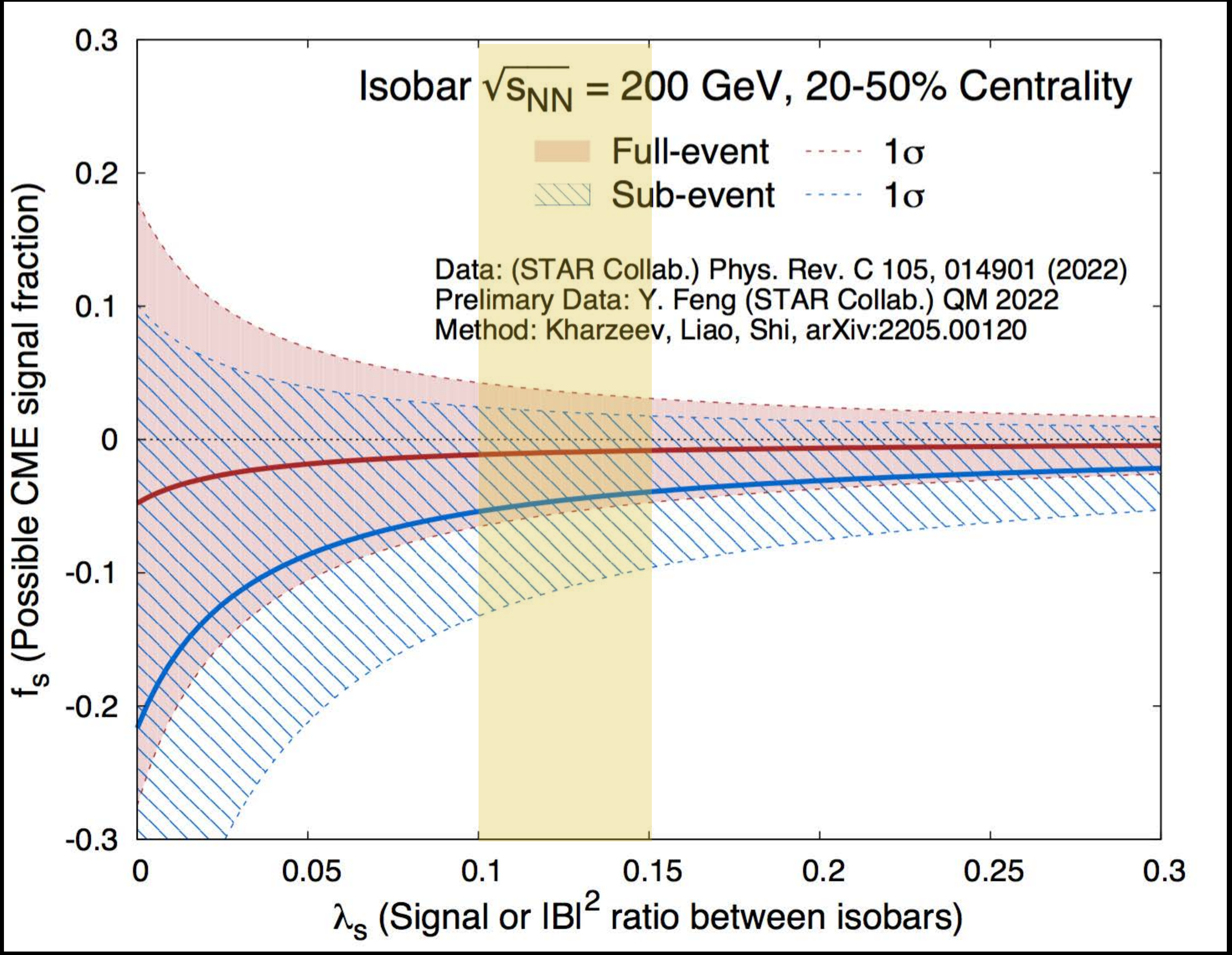
$$\frac{(N_{\mathrm{ch}}\,\Delta\gamma/v_2)^{\mathrm{bkg}}_{\mathrm{Ru+Ru}}}{(N_{\mathrm{ch}}\,\Delta\gamma/v_2)^{\mathrm{bkg}}_{\mathrm{Zr+Zr}}} = 1.013 \pm 0.003 \pm 0.005$$

$$\boxed{R^{\mathrm{bkg}} = \frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} = 0.9698 \pm 0.003 \pm 0.005}$$

3. Estimates of Possible CME signal:

Kharzeev, Liao, Shi, 2205.00120 [nucl-th]

$$f_s = \frac{1/R^{\mathrm{bkg}} - 1/R}{\lambda_s + 1/R^{\mathrm{bkg}} - 1}$$

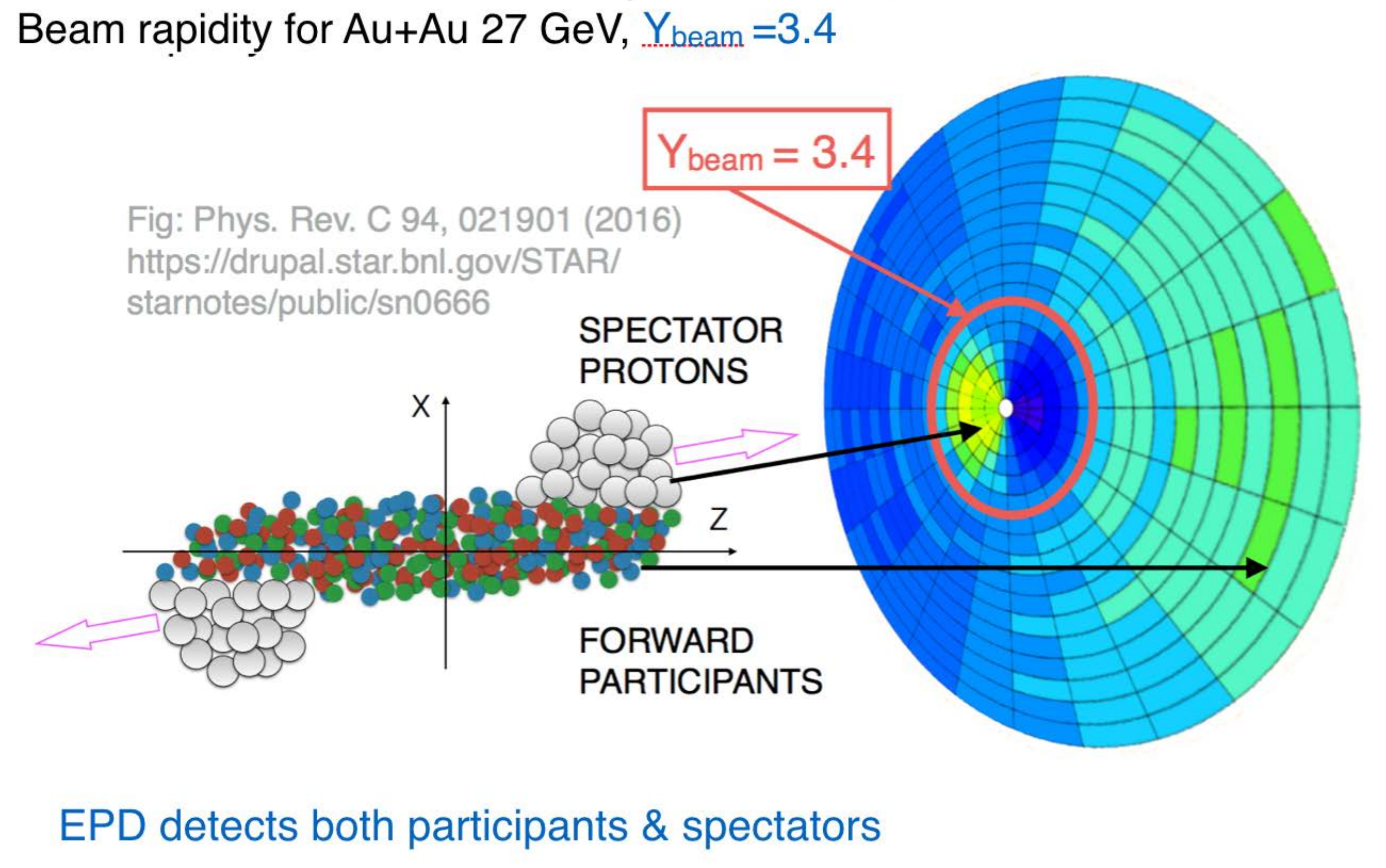


Data: (STAR Collab.) Phys. Rev. C 105, 014901 (2022)
Prelimary Data: Y. Feng (STAR Collab.) QM 2022
Method: Kharzeev, Liao, Shi, arXiv:2205.00120

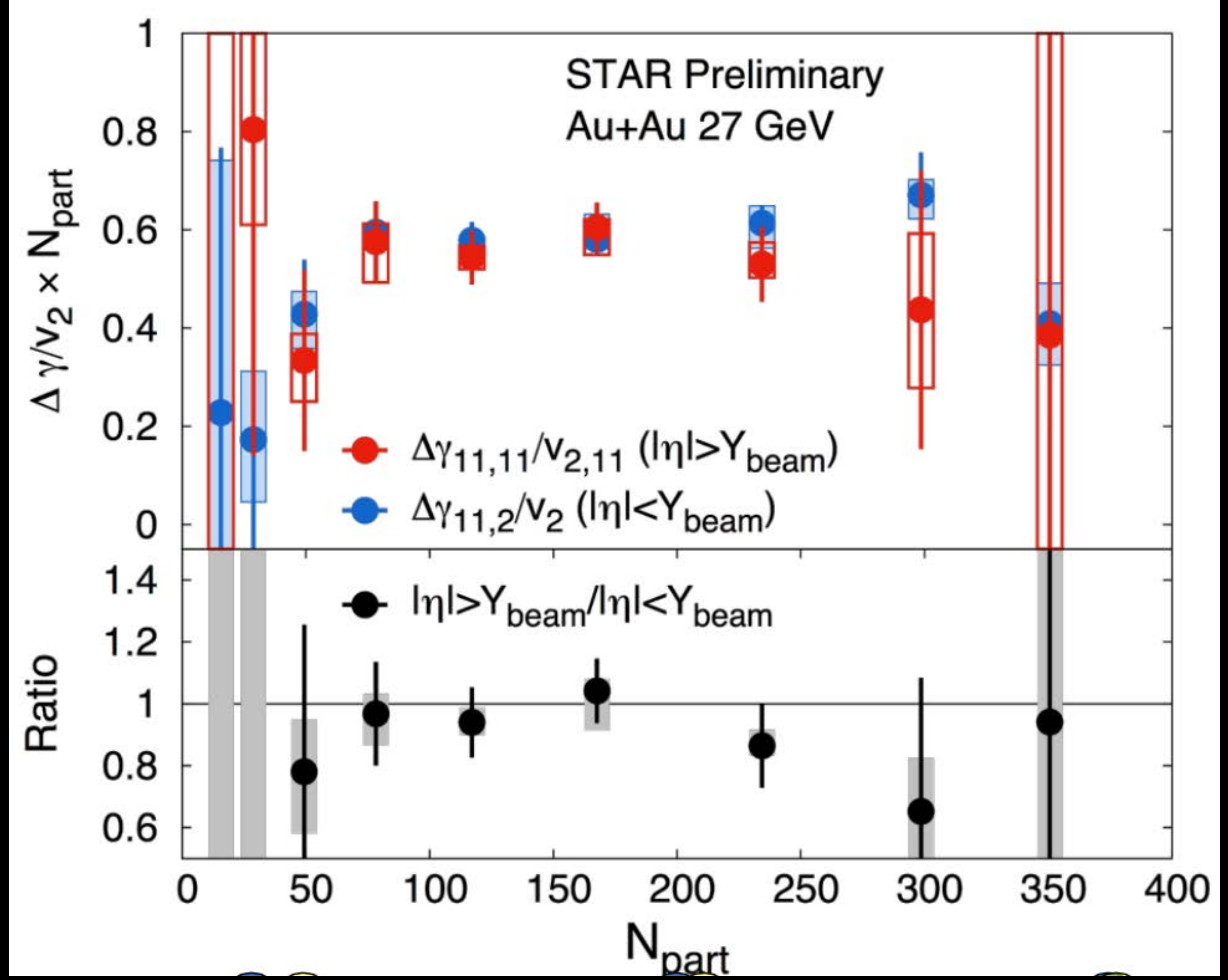
More work from STAR collaboration is underway

What is the future of CME search?

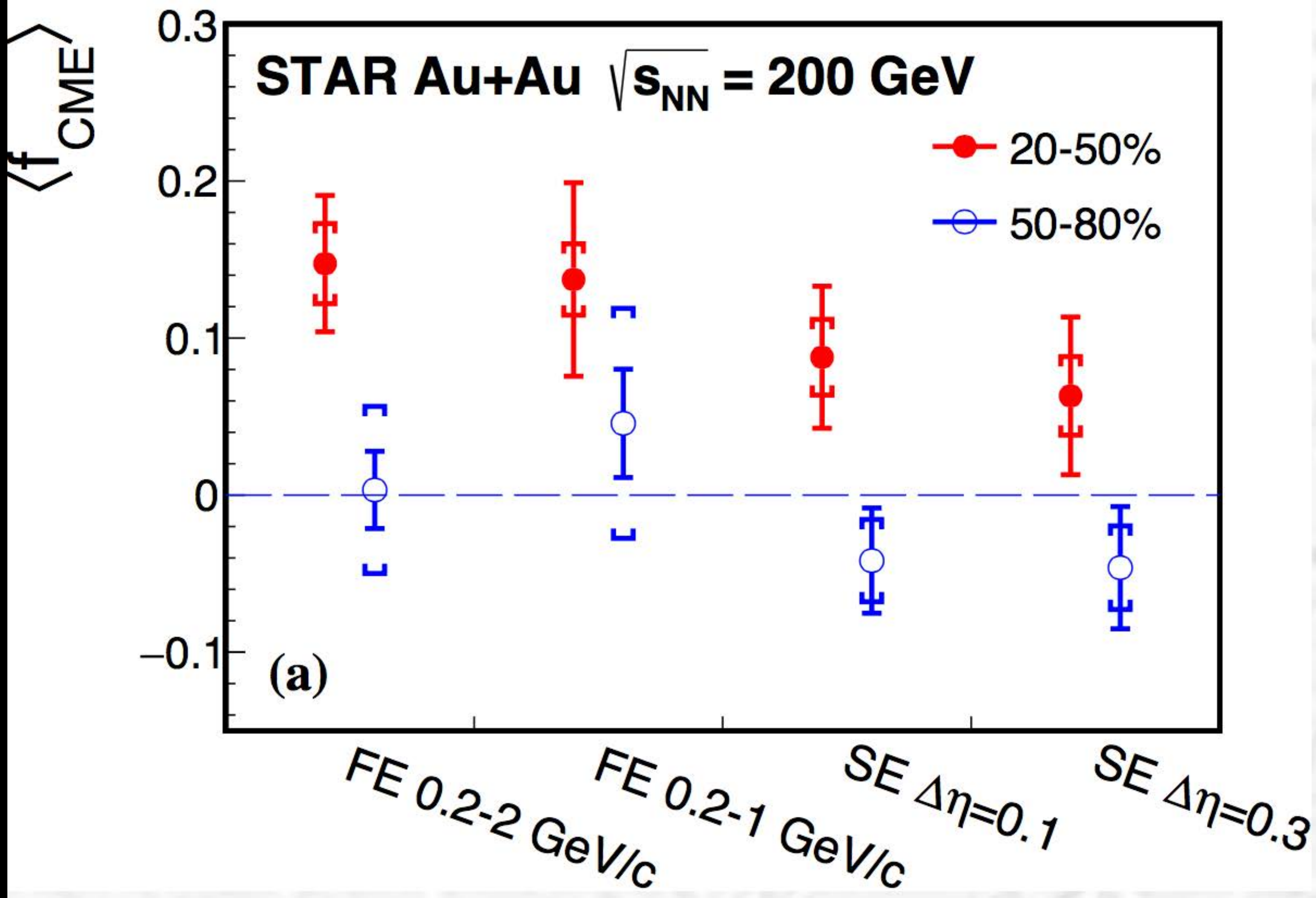
STAR EPD: better handle on B-field direction (1912.05243)



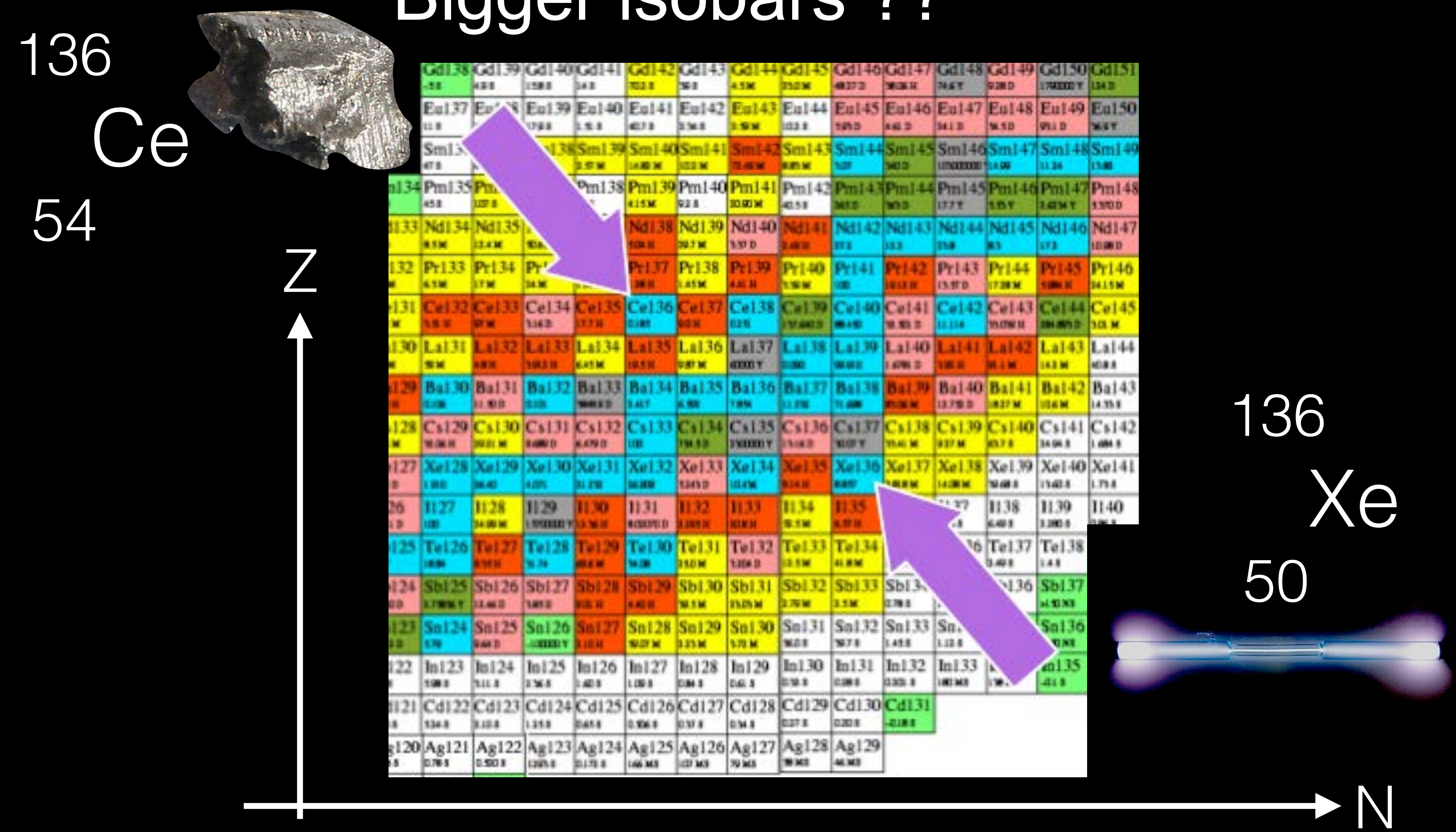
CME @ BES-II data arXiv:2110.15937
Criticality & CME 2012.02926



High statistics RHIC 2023 run
CME in Au+Au (2106.09243)



Bigger isobars ??



CME search with AIML
(2105.13761)

DeepDream

Summary

Experimental test of CME in isobar collisions performed using a blind analysis

A precision down to 0.4% achieved but no pre-defined signature of CME is observed

Primary CME observable $\Delta\gamma/v_2$ baseline is affected by the multiplicity difference (4% in 20-50%), post-blind analysis is needed to search for residual CME signal

Possible residual signal due to change of baseline & non-flow effects are under study