

# Search for the chiral magnetic effect with isobar collisions

Based on: https://arxiv.org/abs

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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

# Brookhaven<sup>®</sup> National Laboratory



Phys. Rev. C 105, 014901 (2022)

Extra

Proton

## Isobar program at RHIC: journey since 2018

#### Relativistic Heavy Ion Collider Begins 18th Year of Experiments

March 21, 2018

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

2018

### **STAR detector** (currently running)

# detector were crucial to the success of our program

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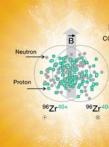


#### **Results from Search for 'Chiral Magnetic Effect' at RHIC**

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

August 31, 2021





#### 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. A 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, 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. Chatto 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. Dhamij 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. Fedor 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 addit

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

RHIC RHIC: known for species (U, Au, Ru, Zr, Cu, Al..) and energy ( $\gamma \sim 100-3.85$ ) maneuver capability

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

The versatility of RHIC and the unique capabilities of the STAR

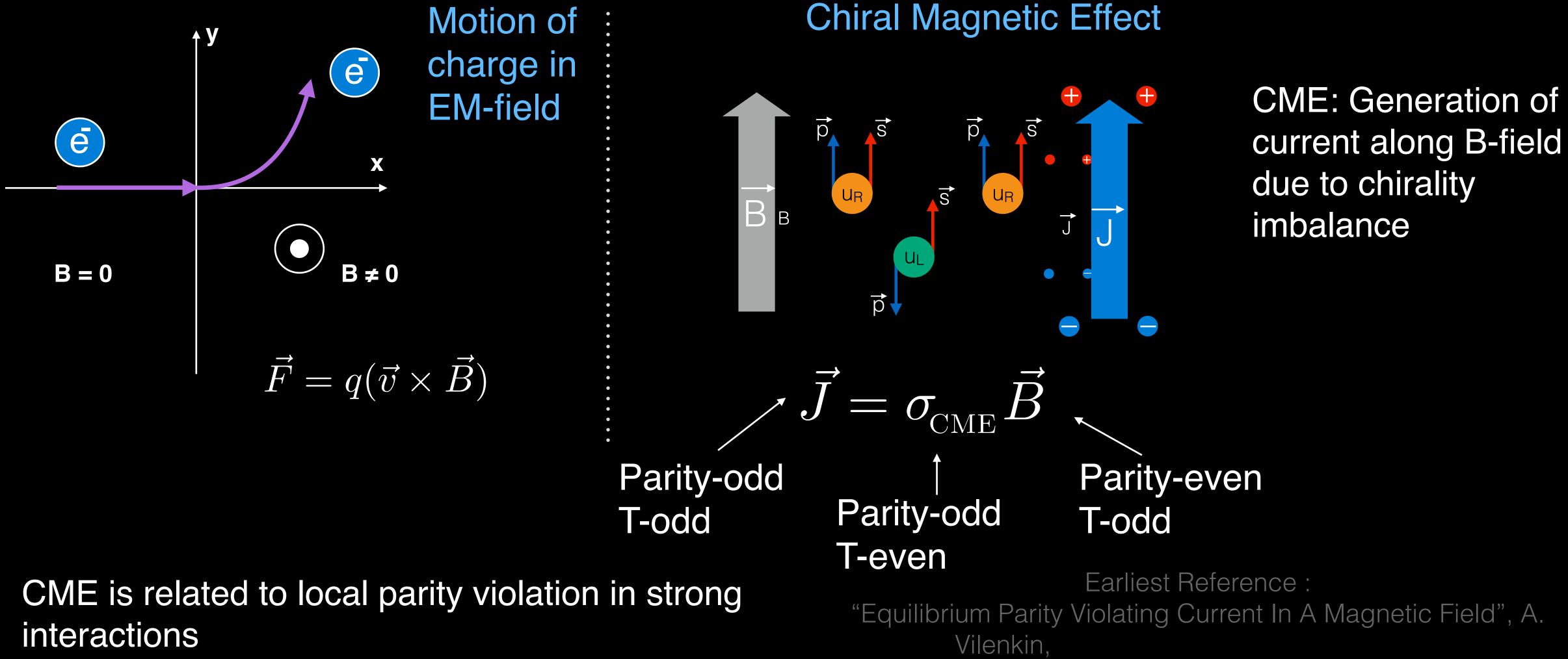






## Chiral Magnetic Effect : why unique?

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

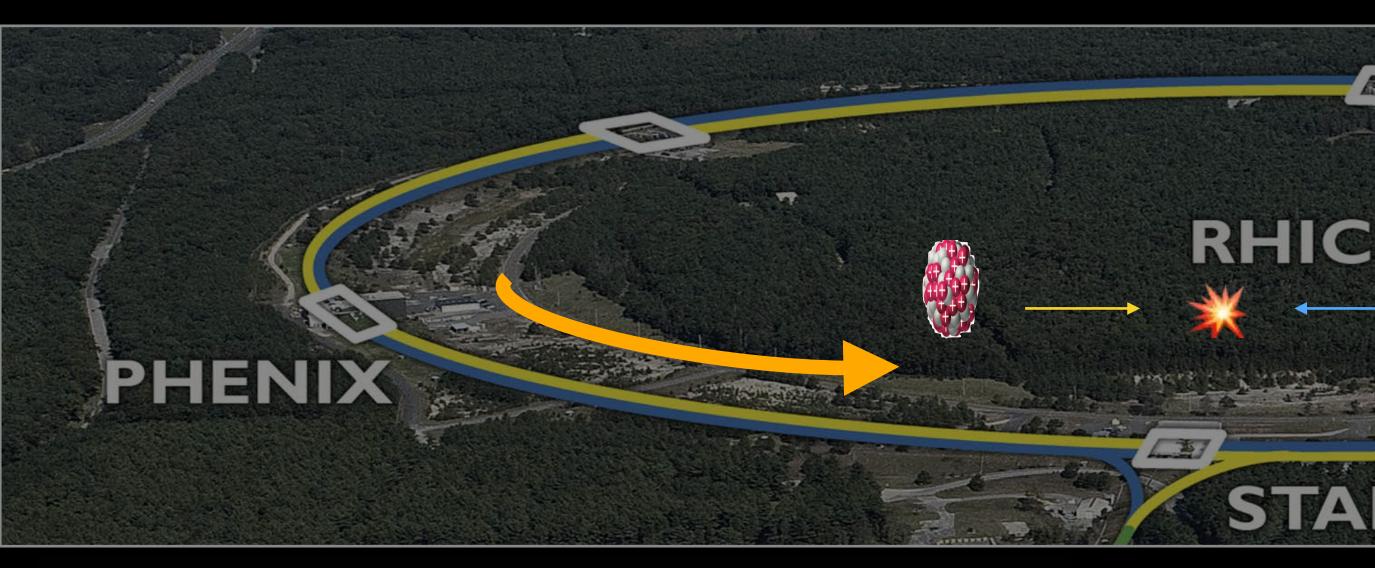


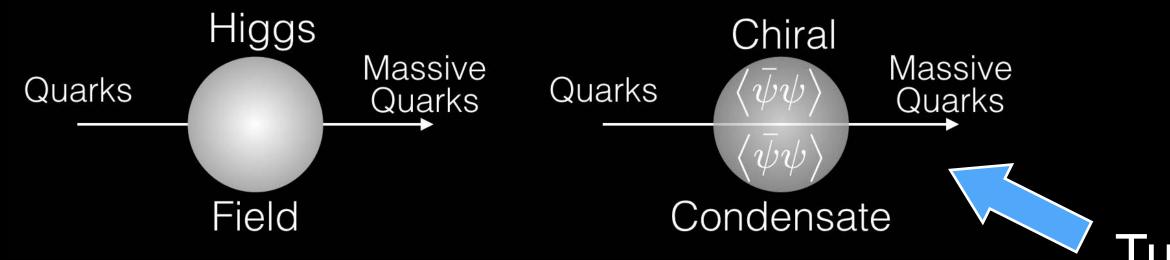
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## RHIC: A machine to play with the vacuum





 $\mathcal{L}_{QCD} = \bar{\psi}_a \left( i(\gamma^\mu D_\mu)_{ab} \right) \psi_b - m \delta_{ab}$ 

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

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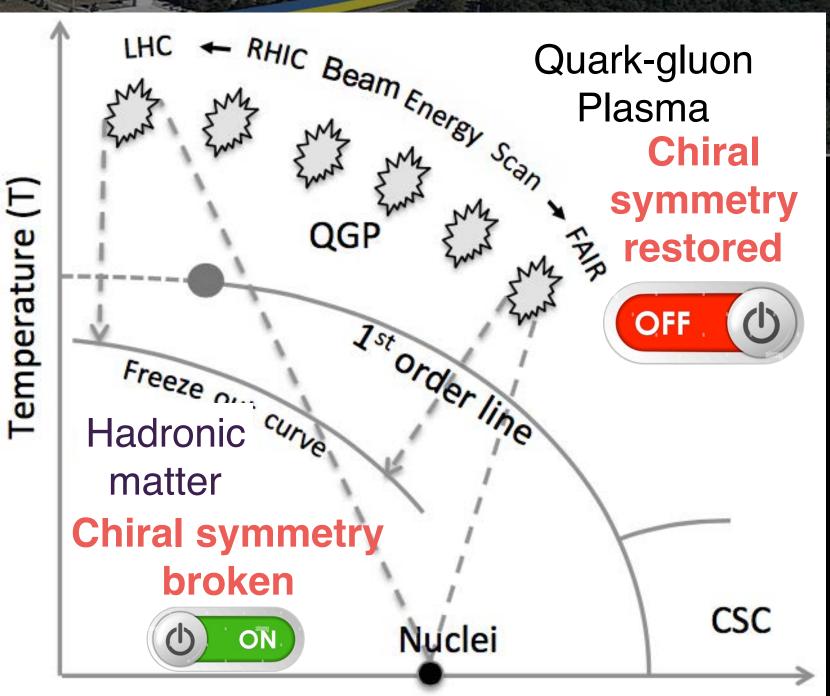
15 Al



## Turn this OFF

STAR

$$-\frac{1}{4}G^c_{\mu\nu}G^{\mu\nu}_c$$

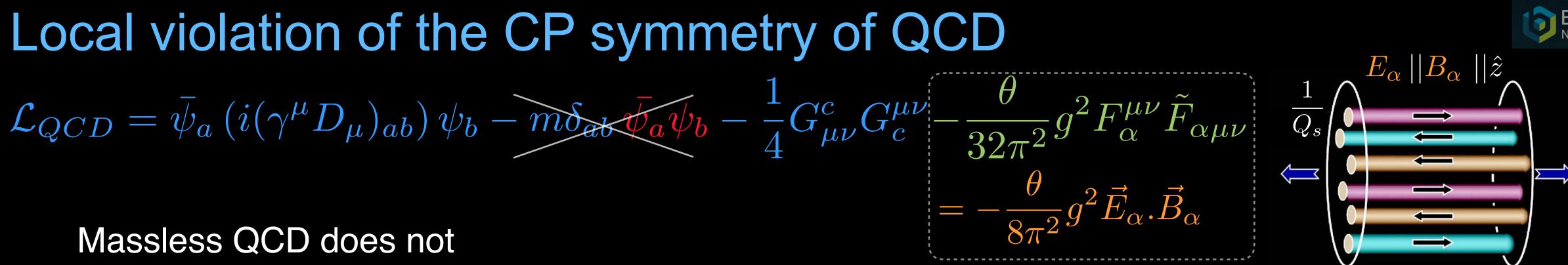


Baryon chemical potential ( $\mu_{\rm B}$ )

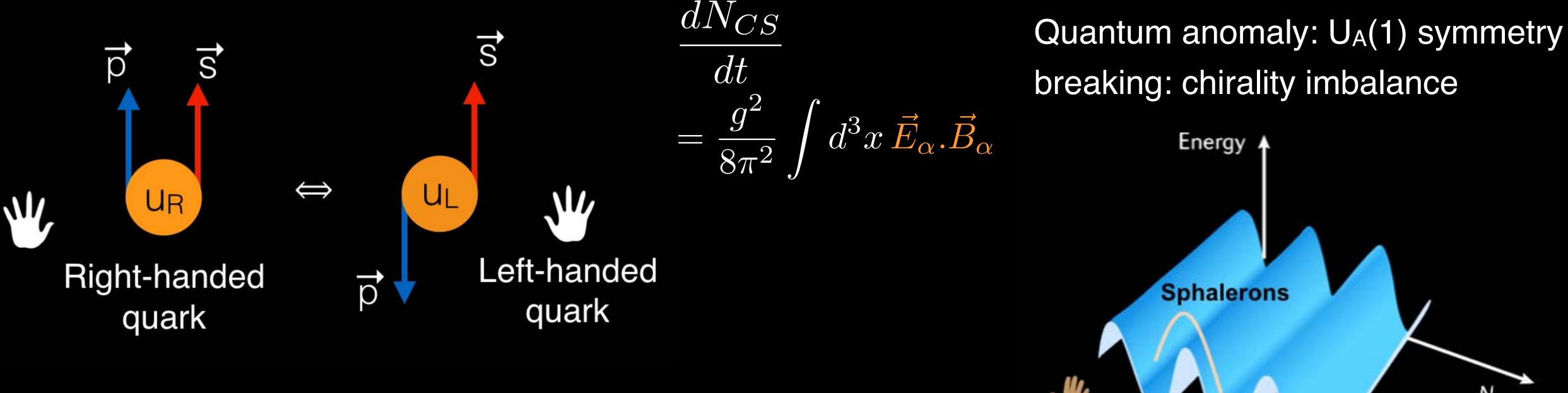
Phase diagram of QCD

#### Brookhaven National Laboratory





# distinguish between R.H. & L.H.



Quantum fluctuations break P & CP symmetry locally and create chirality imbalance  $\rightarrow$  chirality-genesis

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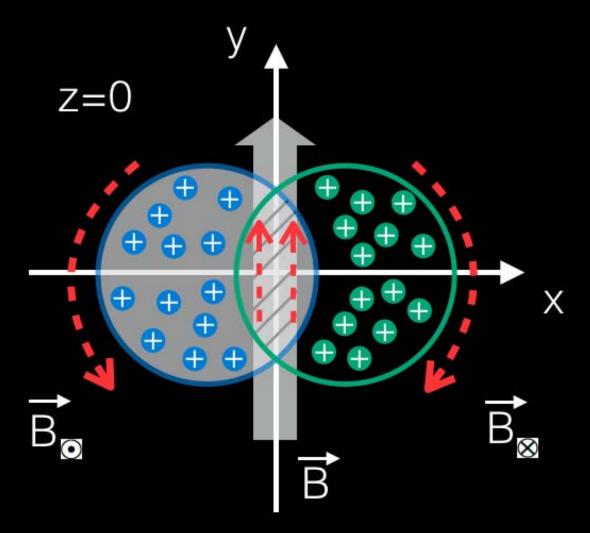
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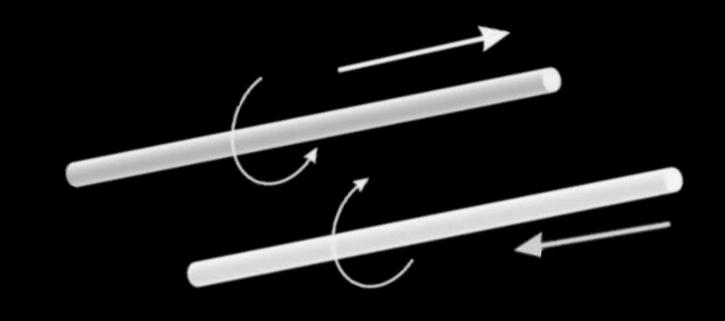
Instantons



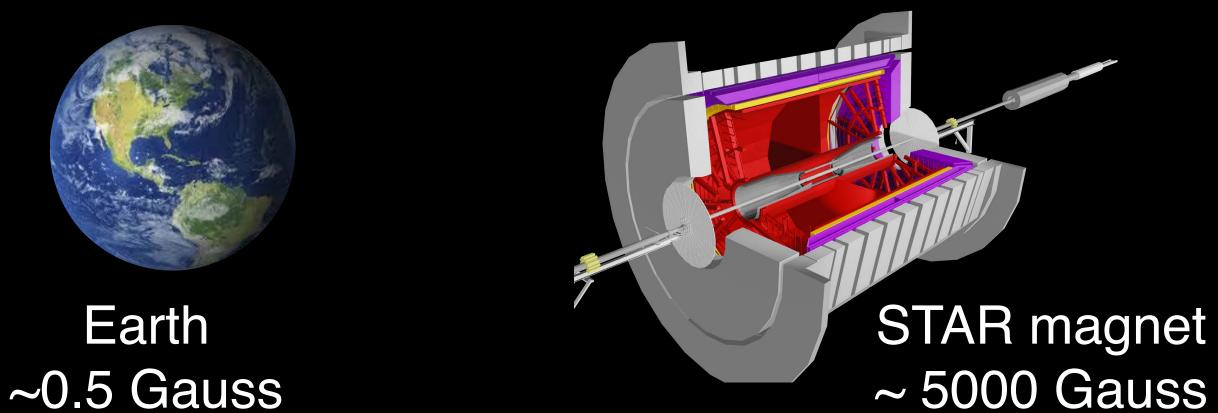
## Creation of strong electro-magnetic fields

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



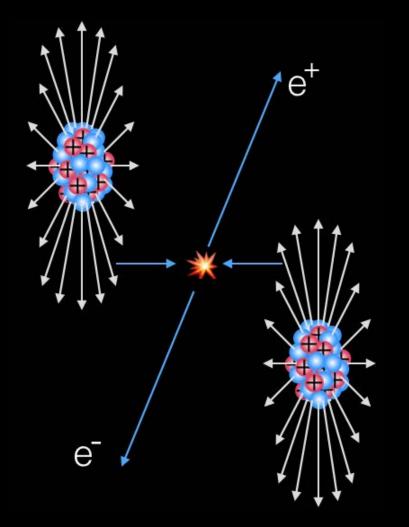


Kharzeev et al 0711.0950, Skokov et al 0907.1396 McLerran, Skokov, 1305.0774

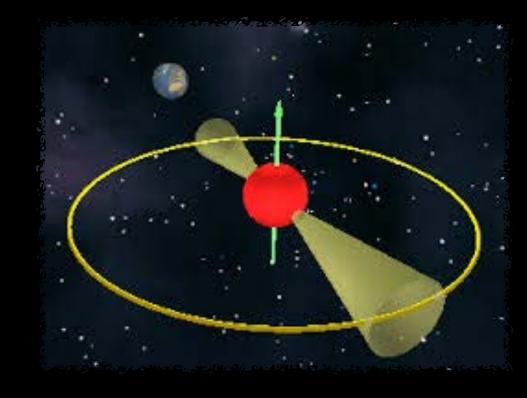


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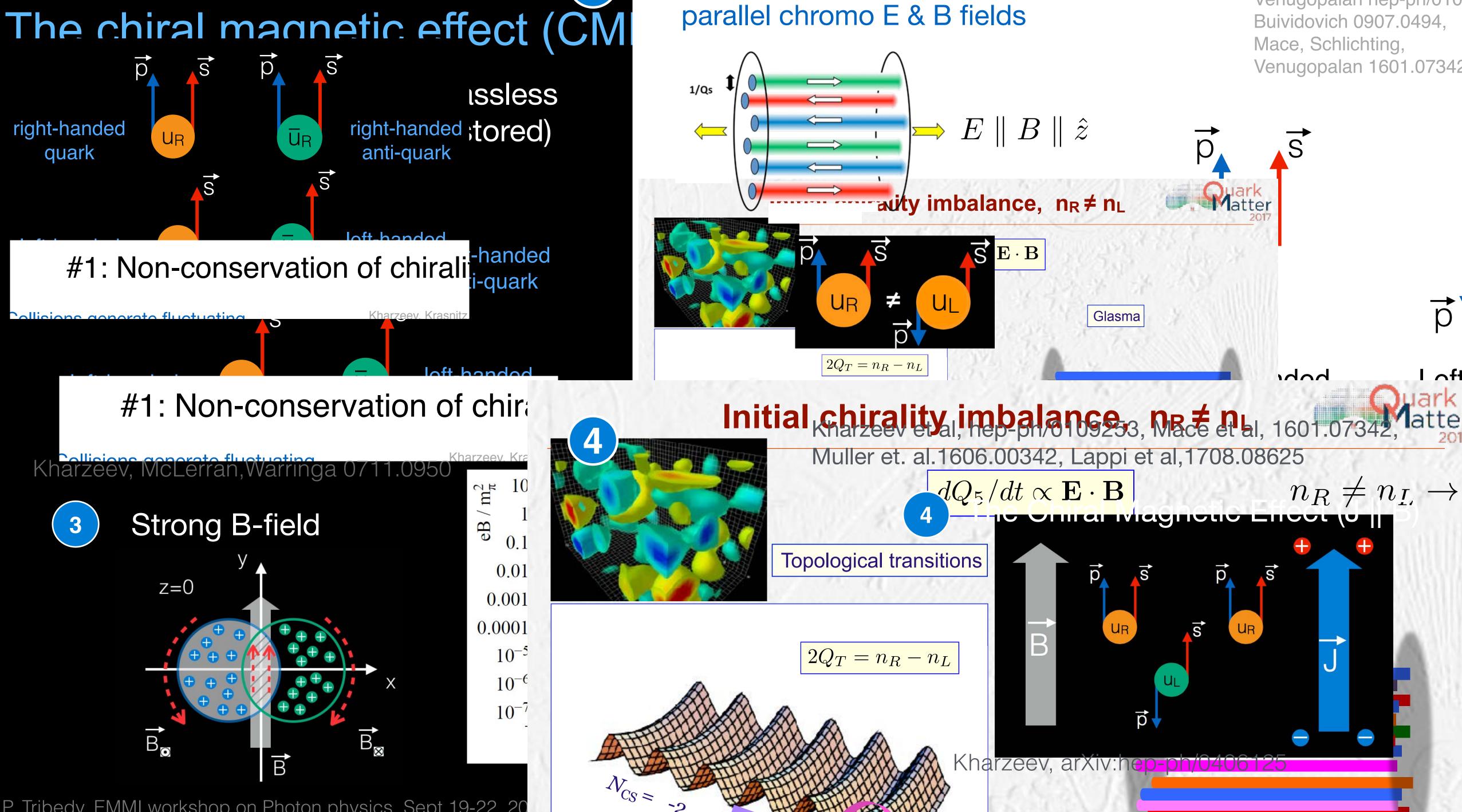




### $eB > eB_C \approx m_e^2 \sim 10^{12}$ Gauss



Neutron Star ~ 10<sup>15</sup> Gauss



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## Parity Violation in Hot QCD: Chiral Magnetic Effect





Available online at www.sciencedirect.com



Physics Letters B 633 (2006) 260-264

#### 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

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)

PRL 103, 251601 (2009)

Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS

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**Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation** 

(STAR Collaboration)



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

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PHYSICS LETTERS B

vww.elsevier.com/locate/physletb

#### Early theory paper

Kharzeev, hep-ph/0406125 Also see : Kharzeev et al, hepph/9906401, Kharzeev et al,

hep-ph/9804221

Let's give it a name

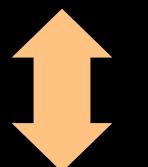
### First method paper

Voloshin. hep-ph/0406311 Also: Finch et al Phys.Rev.C 65 (2002) 014908

week ending **18 DECEMBER 2009** 

#### First experimental paper

STAR collaboration, arXiv:0909.1739



~12 years

#### Blind analysis of the Isobar data STAR collaboration, arXiv:2109.00131







## A gold-gold collision @ STAR detector

Au+Au 200 GeV Event# 1007 Run# 17172038 STAR 6/20/16 16:07:55 EDT

#### Au (100 GeV/A)

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

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



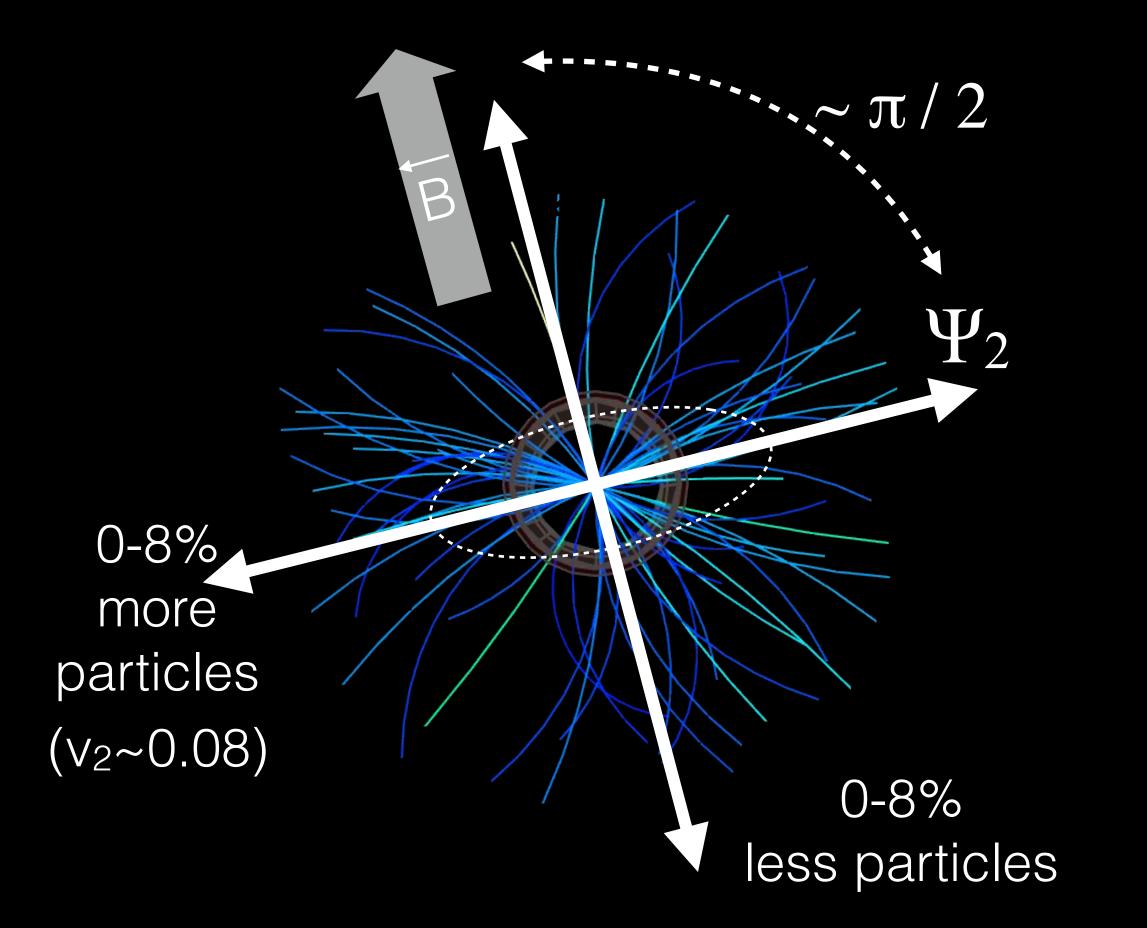
Central Detector (mid-rapidity) **Time Projection Chamber** (Momentum, charge state, particle identification)







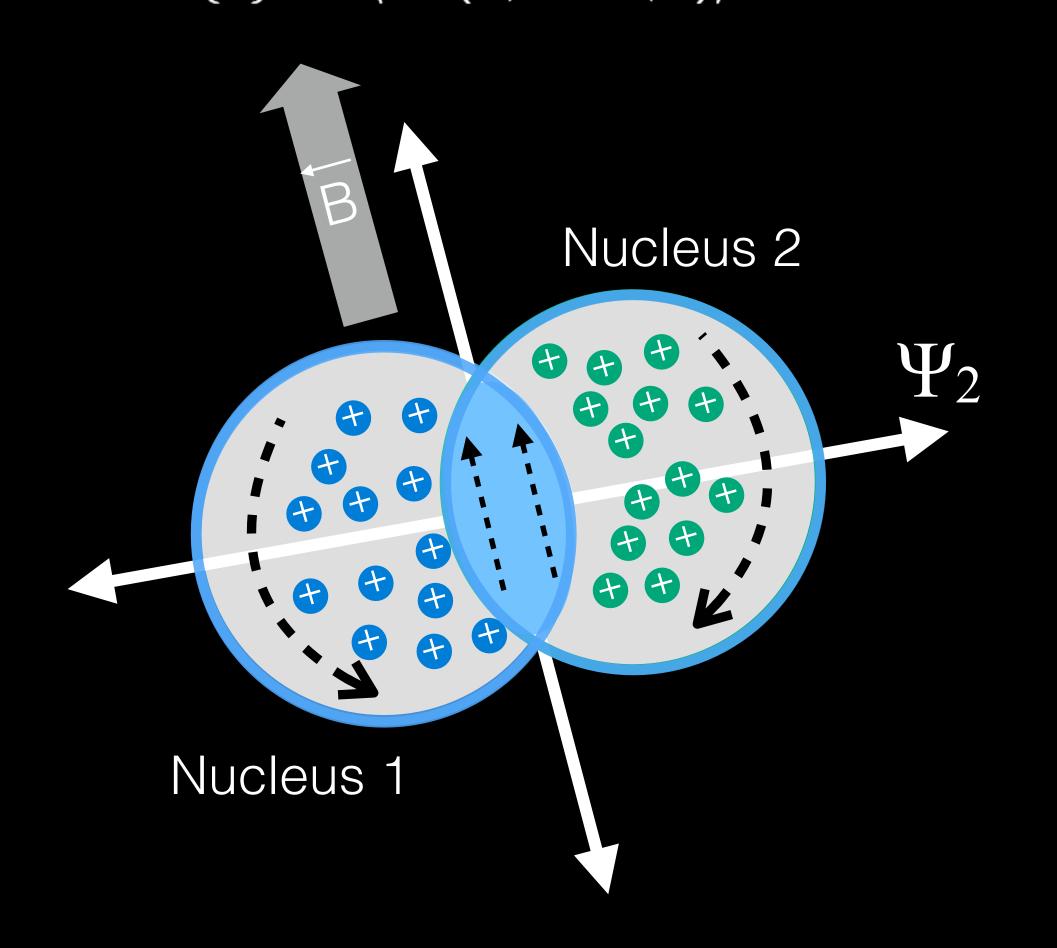
### Elliptic anisotropy and B-field direction Elliptic anisotropy is measured by correlation between two particles $v_2\{EP\} = \langle \cos(2\phi_1 - 2\Psi_2) \rangle \quad v_2\{2\}^2 = \langle \cos(2\phi_1 - 2\phi_2) \rangle$



# Distributions of particles look elliptic in every event: major axis is elliptic anisotropy plane $\Psi_2$

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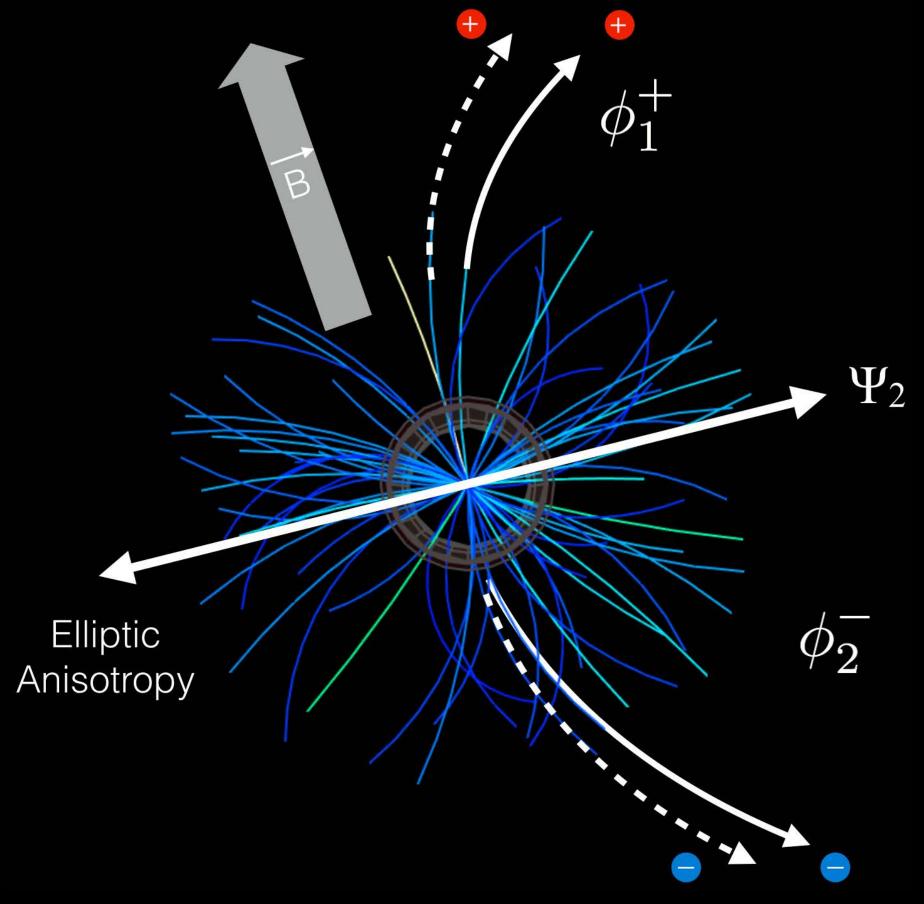




The plane of elliptic anisotropy  $\Psi_2$  is correlated to B-field direction



## How to measure charge separation due to CME ?



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Measure charge separation across  $\Psi_2$  using the correlator:

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

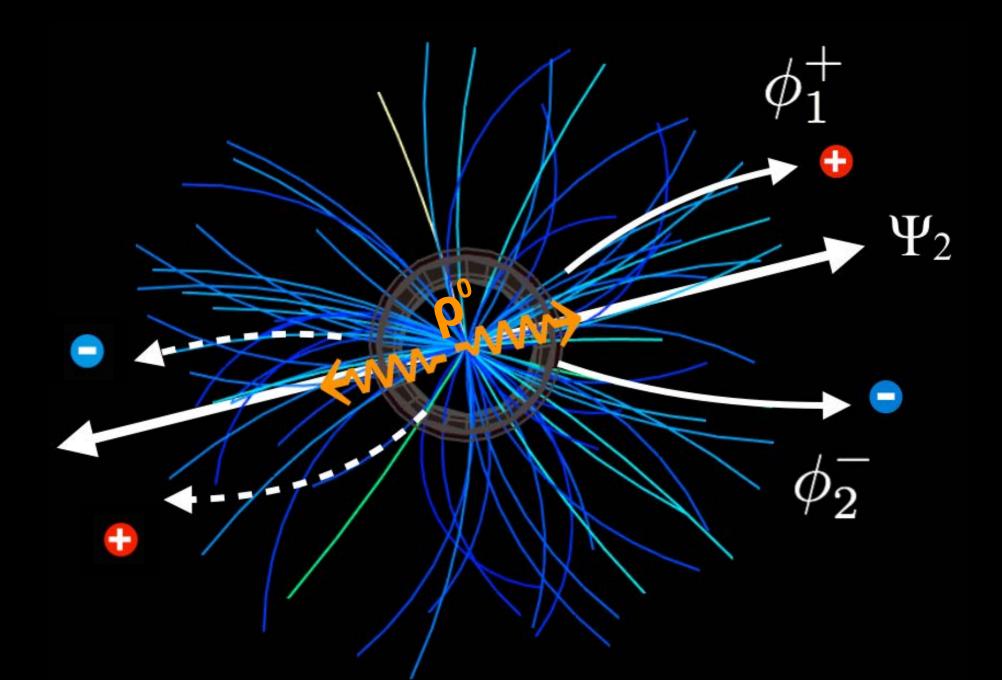
CME case : 
$$\gamma^{SS} \neq \gamma^{OS}$$
  
 $\gamma^{+-} = \cos(\pi/2 - \pi/2 + 0) = 1$   
 $\gamma^{++,--} = \cos(\pi/2 + \pi/2 + 0) = -1$ 

Quantity of interest:  $\gamma^{CME} = \gamma^{OS} - \gamma^{SS} > 0$  $\Delta \gamma$ 

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



## Major source of background: decay of neutral clusters



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

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Measure charge separation across  $\Psi_2$  using the correlator:

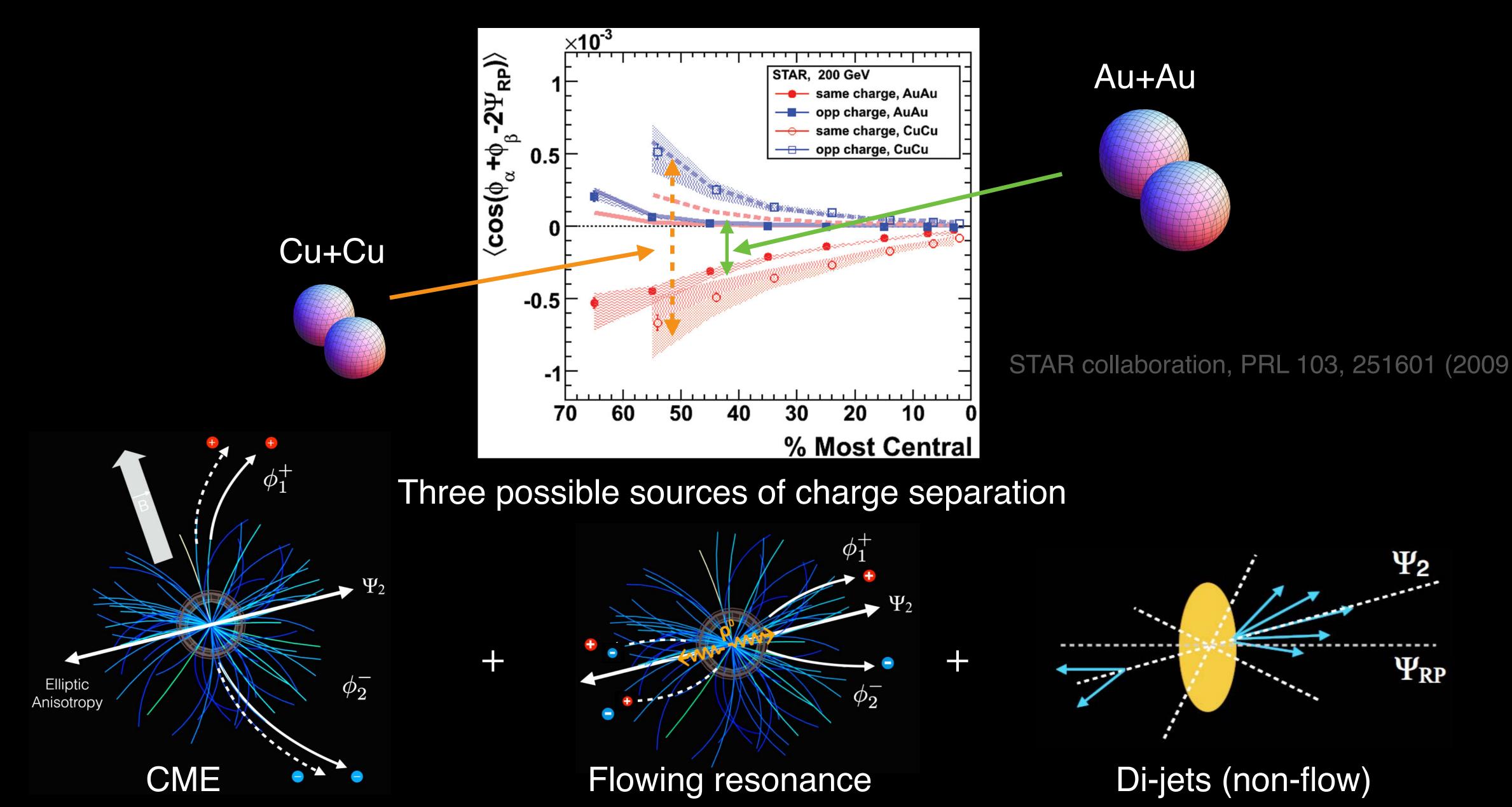
$$\gamma^{\alpha,\beta} = \langle \cos(\phi_1^{\alpha} + \phi_2^{\beta} - 2\Psi_2) \rangle$$

Flowing  $\neq \gamma^{os}$ SSresonance decay:  $\gamma$ 

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

$$\Rightarrow \Delta \gamma^{reso} = \gamma^{OS} - \gamma^{SS} \propto \frac{v_2^{reso}}{N}$$

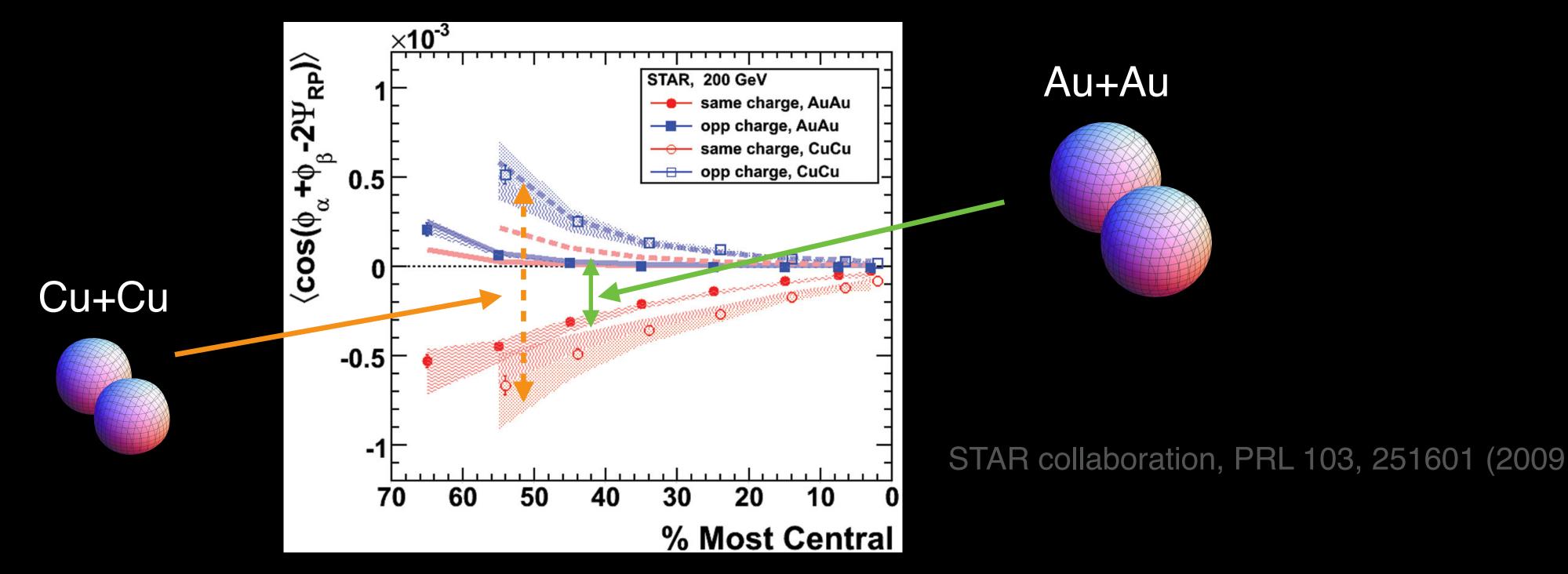
## The first measurements at RHIC

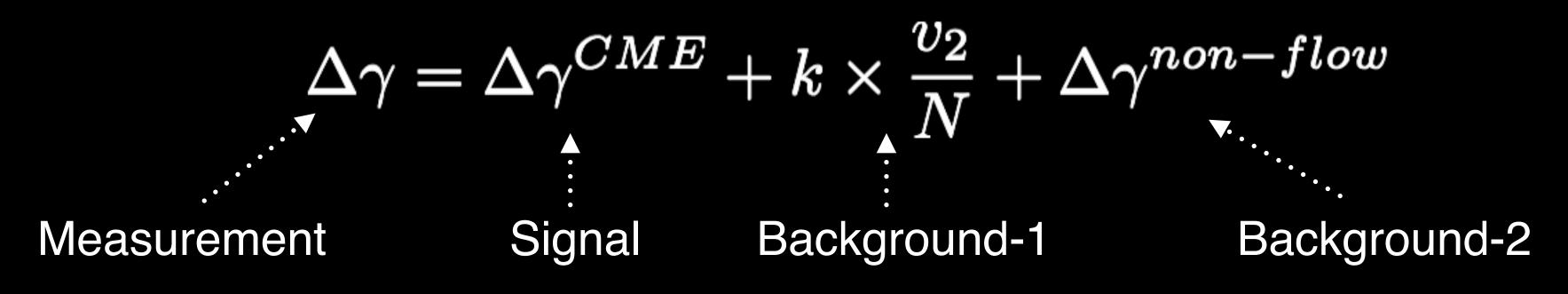


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## The first measurements at RHIC





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### Significant charge separation observed, consistent with CME+ Background

## Isobar in the chart of nuclides

Ζ

Looking for elements which have similar size but different protons so

Similar Size but umerent protons so	
that D field aculd ha different	Gd138 Gd139 Gd140 Gd141 Gd142 Gd143 Gd144 Gd145 Gd145 Gd146 Gd147 Gd148 Gd149 Gd150 Gd151 Gd152
that B-field could be different	Eu137 Ev <sup>3</sup> 8 Eu139 Eu140 Eu141 Eu142 Eu143 Eu144 Eu145 Eu146 Eu147 Eu148 Eu149 Eu150 Eu151
	Sm15 478 138 Sm139 Sm140 Sm141 Sm142 Sm143 Sm144 Sm145 Sm146 Sm147 Sm148 Sm149 Sm150 1482 M 1482 M 102 M 1249 M 885 M 307 340 D 1030000 1459 11 24 1382 738
Pm128 Pm129 Pm130 Pm131 Pm132 Pm133 -088 -18 228 -48 638 158	3 Pm134 Pm135 Pn Pm138 Pm139 Pm140 Pm141 Pm142 Pm143 Pm144 Pm145 Pm146 Pm146 Pm147 Pm148 Pm149
Nd126 Nd127 Nd128 Nd129 Nd130 Nd131 Nd132	2 Nd133 Nd134 Nd135 Nd138 Nd139 Nd140 Nd141 Nd142 Nd143 Nd144 Nd145 Nd146 Nd147 Nd148
Pr121       Pr122       Pr123       Pr124       Pr125       Pr126       Pr127       Pr128       Pr129       Pr130       Pr131         148       -0.58       -0.58       -0.58       -0.58       -0.58       33.5       31.45       42.5       31.5       32.5       40.0.5       94.5	Pr132 Pr133 Pr134 Pr1 15M 55M 17M 24M 12 Pr137 Pr138 Pr139 Pr140 Pr141 Pr142 Pr143 Pr143 Pr144 Pr145 Pr146 Pr147 15M 1357D 1728M 5584H 2415M 134M
Ce119 Ce120 Ce121 Ce122 Ce123 Ce124 Ce125 Ce126 Ce127 Ce128 Ce129 Ce129 Ce130	Се131 Се132 Се133 Се134 Се135 Се136 Се137 Се138 Се139 Се140 Се141 Се142 Се143 Се144 Се144 Се145 Се146
La118 La119 La120 La121 La122 La123 La124 La125 La126 La127 La128 La129	
	Bal29 Bal30 Bal31 Bal32 Bal33 Bal34 Bal35 Bal35 Bal36 Bal37 Bal38 Bal39 Bal40 Bal41 Bal42 Bal43 Bal44 223 H DID6 11.5D DID6 11.5D DID6 100 98489 DI 2417 6.57 7854 11.232 71.678 Bal58 Bal39 Bal40 Bal41 Bal42 Bal43 Bal44 11.55
	Cs128         Cs129         Cs130         Cs131         Cs132         Cs133         Cs134         Cs135         Cs136         Cs137         Cs138         Cs139         Cs140         Cs141         Cs142         Cs143         Cs143         Cs143         Cs144         Cs144 <th< th=""></th<>
Xe115 Xe116 Xe117 Xe118 Xe119 Xe120 Xe121 Xe122 Xe123 Xe124 Xe125 Xe126	Xe127 Xe128 Xe129 Xe130 Xe131 Xe132 Xe133 Xe134 Xe135 Xe136 Xe137 Xe138 Xe138 Xe139 Xe140 Xe141 Xe142
1114 1115 1116 1117 1118 1119 1120 1121 1122 1123 1124 1125	1126 1127 1128 1129 1130 1131 1132 1133 1134 1135
Tel06       Tel07       Tel08       Tel09       Tel10       Tel111       Tel12       Tel13       Tel14       Tel15       Tel16       Tel19       Tel20       Tel21       Tel22       Tel23       Tel24       Tel24       Tel23       Tel24       Tel24       Tel23       Tel24       Tel24       Tel23       Tel24       Tel23       Tel24       Tel23       Tel23       Tel24       Tel24       Tel23       Tel23       Tel24       Tel24       Tel23       Tel23       Tel24       Tel24       Tel23       Tel23       Tel24       Tel24       Tel23       Tel24       Tel24       Tel23       Tel24       Tel24       Tel24       Tel23       Tel24       Tel24       Tel24       Tel23       Tel24       Tel24 <t< th=""><th></th></t<>	
Sb103 Sb104 Sb105 Sb106 Sb107 Sb108 Sb109 Sb110 Sb111 Sb112 Sb113 Sb114 Sb115 Sb116 Sb117 Sb118 Sb119 Sb120 Sb121 Sb122 Sb123	Sb124 Sb125 Sb126 Sb127 Sb128 Sb129 Sb130 Sb131 Sb132 Sb133 Sb135 5136 Sb137 Sb138 Sb139
Sn100 Sn101 Sn102 Sn103 Sn104 Sn105 Sn106 Sn107 Sn108 Sn109 Sn110 Sn111 Sn112 Sn113 Sn114 Sn115 Sn116 Sn117 Sn118 Sn119 Sn120 Sn121 Sn122	Sn123 Sn124 Sn125 Sn126 Sn127 Sn128 Sn129 Sn130 Sn131 Sn132 Sn133 Sn. Sn136 Sn137
1094       38       4.55       78       2083       31.8       1158       250M       1030M       160M       411H       553M       0.97       1150p       0.66       0.34       14.54       7.68       24.22       8.50       32.99       27.06 H       4.55         1099       10100       10101       10102       10103       10105       10106       10107       10108       10109       10110       10111       10112       10113       10114       10115       10110       10110       10112       10113       10114       10115       10116       10117       10112       10112       10113       10114       10115       10116       10117       10112       10112       10113       10114       10115       10116       10117       10112       10112       10113       10114       10115       10116       10117       10112       10112       10113       10114       10115       10116       10117       10112       10112       10113       10114       10115       10116       10117       10112       10112       10113       10114       10115       10116       10117       10112       10112       10113       10114       10115       10116       10112	In122 In123 In124 In125 In126 In127 In128 In129 In130 In131 In132 In133 In135
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-18 163 491 8 1.36M 5.5M 7.3M 7.3M 7.7M 55.5M 125 6.50H 0.89 461.4D 12.49 128D 2413 1222 28.73 53.46H 7.49 2.49H 51.3M 2.49M 51.3D 2.69M 51.60 5 2.60	13.58         524.8         210.8         125.8         0.55.8         0.37.8         0.34.8         0.27.8         0.20.8         -0.18.8           0         Ag120         Ag121         Ag122         Ag123         Ag124         Ag125         Ag126         Ag127         Ag128         Ag129
ISMS       2DS       51 S       IZ4 S       2DI M       IL1 M       IZ9 M       657 M       692 M       41 29 D       2396 M       51 BS       2.37 M       4816L       24 ES       745 D       3180 H       537 H       4 ES       2DD M       248 M       72 BS       376 S       21 S         Pd91       Pd92       Pd93       Pd94       Pd95       Pd98       Pd99       Pd100       Pd101       Pd102       Pd103       Pd104       Pd105       Pd106       Pd106       Pd107       Pd108       Pd109       Pd111       Pd112       Pd113       Pd116       Pd117       Pd118         10 US       10 S       10 S       12 A       12 A       365 D       B47 H       102       1659 D       11 H       12 A       12 A       11 H       12 B       13 B       13 B       21 B       13 B       43 S       19 S       13 B       14 B       13 B       43 S       19 S	
Rh89 Rh90 Rh91 Rh92 Rh93 Rh94 K Rh97 Rh98 Rh99 Rh100 Rh101 Rh102 Rh103 Rh104 Rh105 Rh106 Rh107 Rh108 Rh109 Rh110 Rh111 Rh112 Rh113 Rh114 Rh115 Rh116 Rh116 Rh117	
Ru88 Ru89 Ru90 Ru91 Ru92 Ru93 Ru93 Ru94 Ru95 Ru96 Ru97 Ru98 Ru99 Ru90 Ru100 Ru101 Ru102 Ru103 Ru104 Ru105 Ru106 Ru107 Ru108 Ru109 Ru110 Ru111 Ru112 Ru113 Ru114 Ru115 Ru116	
Te87 Te88 Te89 Te90 Te91 Te92 Te93 Te94 Te95 Te96 Te95 Te96 Te97 Te98 Te99 Te100 Te101 Te102 Te103 Te104 Te105 Te106 Te107 Te108 Te109 Te110 Te111 Te112 Te113 Te114 Te115	
Mo86 Mo87 Mo88 Mo89 Mo90 Mo91 Mo91 Mo92 Mo91 Mo92 Mo93 Mo94 Mo93 Mo94 Mo95 Mo96 Mo97 Mo96 Mo97 Mo98 Mo99 Mo90 Mo90 Mo90 Mo10 Mo102 Mo103 Mo104 Mo105 Mo105 Mo106 Mo107 Mo108 Mo109 Mo110 Mo111 Mo112 Mo113 Mo114	Mol15
Nb85 Nb86 Nb87 Nb88 Nb89 Nb90 Nb90 Nb91 Nb92 Nb92 Nb92 Nb92 Nb92 Nb92 Nb92 Nb93 Nb94 Nb95 Nb96 Nb95 Nb96 Nb97 Nb98 Nb98 Nb99 Nb98 Nb99 Nb100 Nb102 Nb102 Nb103 Nb104 Nb105 Nb106 Nb107 Nb108 Nb108 Nb109 Nb108 Nb109 Nb110 Nb112 Nb112 Nb113 Nb112 Nb113 Nb112 Nb113 Nb112 Nb113 Nb114 Nb112 Nb113 Nb114 Nb112 Nb113 Nb104 Nb105 Nb106 Nb107 Nb108 Nb108 Nb109 Nb110 Nb111 Nb112 Nb113 Nb112 Nb113 Nb114 Nb112 Nb113 Nb114 Nb1	
Zr84       Zr85       Zr86       Zr87       Zr88       Zr88       Zr89       Zr90       Zr91       Zr92       Zr93       Zr93       Zr95       Zr95       Zr90       Zr90       Zr93       Zr93       Zr95       Zr95       Zr90       Zr90       Zr93       Zr93       Zr95       Zr95       Zr90       Zr100       Zr102       Zr103       Zr104       Zr105       Zr106       Zr107       Zr108       Zr109       Zr100       Zr100       Zr101       Zr103       Zr104       Zr105       Zr106       Zr107       Zr108       Zr109       Zr100       Zr100       Zr101       Zr100	
Y83       Y84       Y85       Y86       Y87       Y88       Y89       Y90       Y91       Y92       Y93       Y94       Y95       Y98       Y99       Y100       Y101       Y102       Y103       Y104       Y105       Y106       Y107       Y108         708 M       46 S       268 H       1474 H       798 H       106650       100       55.9 H       101.8 H       187.0 H       103.0 H       187.0 H       735.0 H       0.50 S       0.45 S       0.30 S       0.19 S       140.0 S       150.0 S       30.0 S	
Sr82       Sr83       Sr84       Sr85       Sr85       Sr87       Sr87       Sr88       Sr89       Sr90       Sr91       Sr92       Sr92       Sr93       Sr94       Sr97       Sr98       Sr99         25.550       32.41 H       0.56       Sr85       700       Sr90       Sr91       Sr92       Sr92       Sr93       Sr94       75.38       Sr97       Sr98       Sr99         25.550       32.41 H       0.56       Sr90       50.50       Sr90       Sr92       75.38       Sr97       Sr98       Sr99         25.550       Sr91       Sr92       71.14       7.423 M       75.38       Sr97       Sr98       Sr99       0.269 S	
Rb81       Rb82       Rb83       Rb84       Rb85       Rb86       Rb87       Rb88       Rb87       Rb88       Rb89       Rb91       Rb92       Rb93       Kb9       C       Rb93       Kb93       Rb93       Rb93 <th< th=""><th></th></th<>	
Kr80       Kr81       Kr82       Kr83       Kr84       Kr85       Kr86       Kr87       Kr88       Kr89       Kr90       Kr91       Kr92       Kr93       K         228       229000 Y       11.59       11.49       57.00       56.00       76.3 M       2.84 H       3.15 M       52.32 S       8.57 S       1.840 S       1.286 S       0.20 S       75       Kr97       1.90	
Br79       Br80       Br81       Br82       Br83       Br84       Br85       Br86       Br87       Br88       Br89       Br90       Br91       Br92       Br93         50.69       17.69 M       49.31       33.50 H       2.40 H       31.80 M       2.50 M       55.1 s       55.60 s       162.9 s       4.40 s       1.91 s       0.541 s       0.343 s       1.12 MS       7.1       1.50 NS	
Se78       Se79       Se80       Se81       Se82       Se83       Se84       Se85       Se85       Se86       Se87       Se88       Se89       Se90       Se91       Se92       Se92         23.77       110000 y       49561       1845 x       87.3       31.7 s       153 s       529 s       1.53 s       529 s <th></th>	

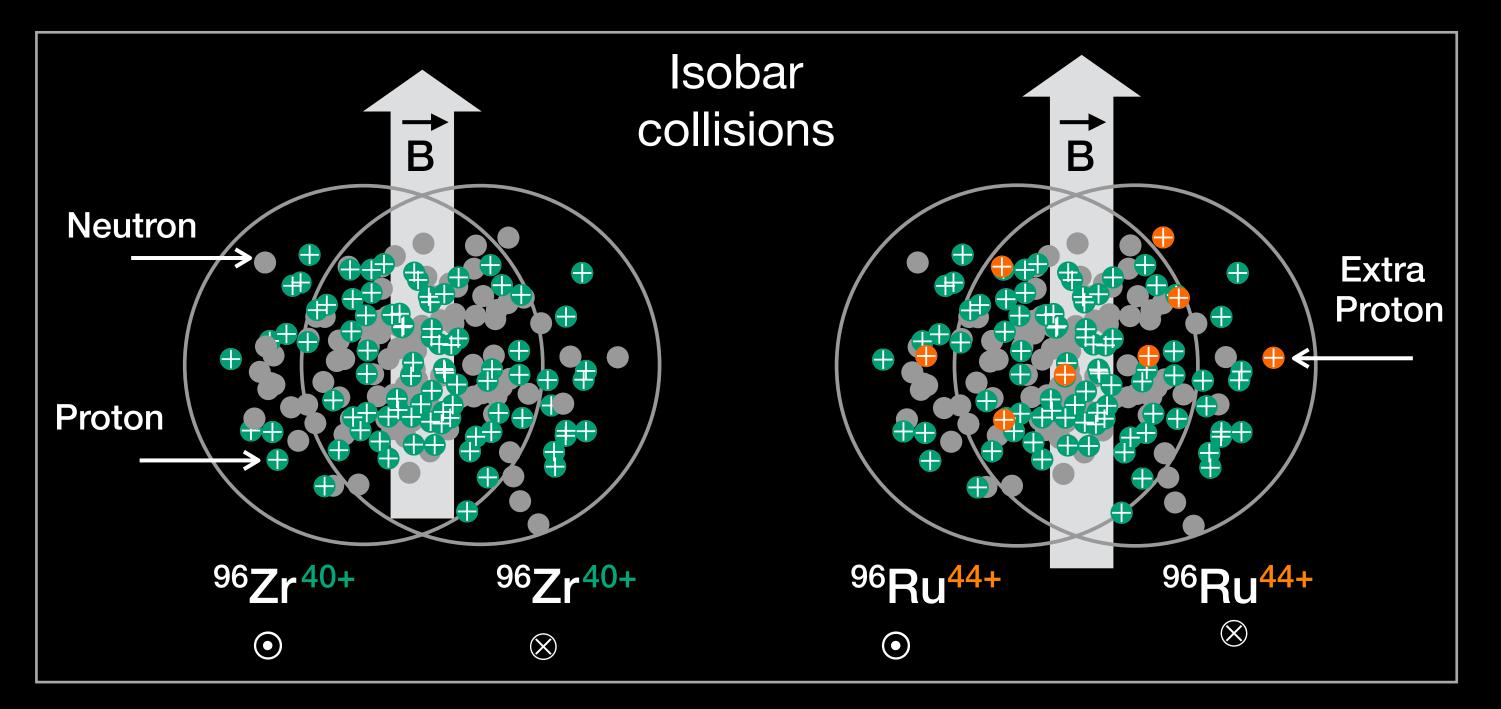
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#### © http://www.nuclear.csdb.cn/nuclear/chart9.asp







$$\begin{array}{l} \Delta \stackrel{\text{Ru+Ru}}{\gamma} = \Delta \gamma^{CME} + k \times \frac{v_2}{N} + \Delta \gamma^{non-flow} \\ \stackrel{??}{\approx} & \parallel \\ \Delta \stackrel{\text{Zr+Zr}}{\gamma} = \Delta \gamma^{CME} + k \times \frac{v_2}{N} + \Delta \gamma^{non-flow} \end{array}$$

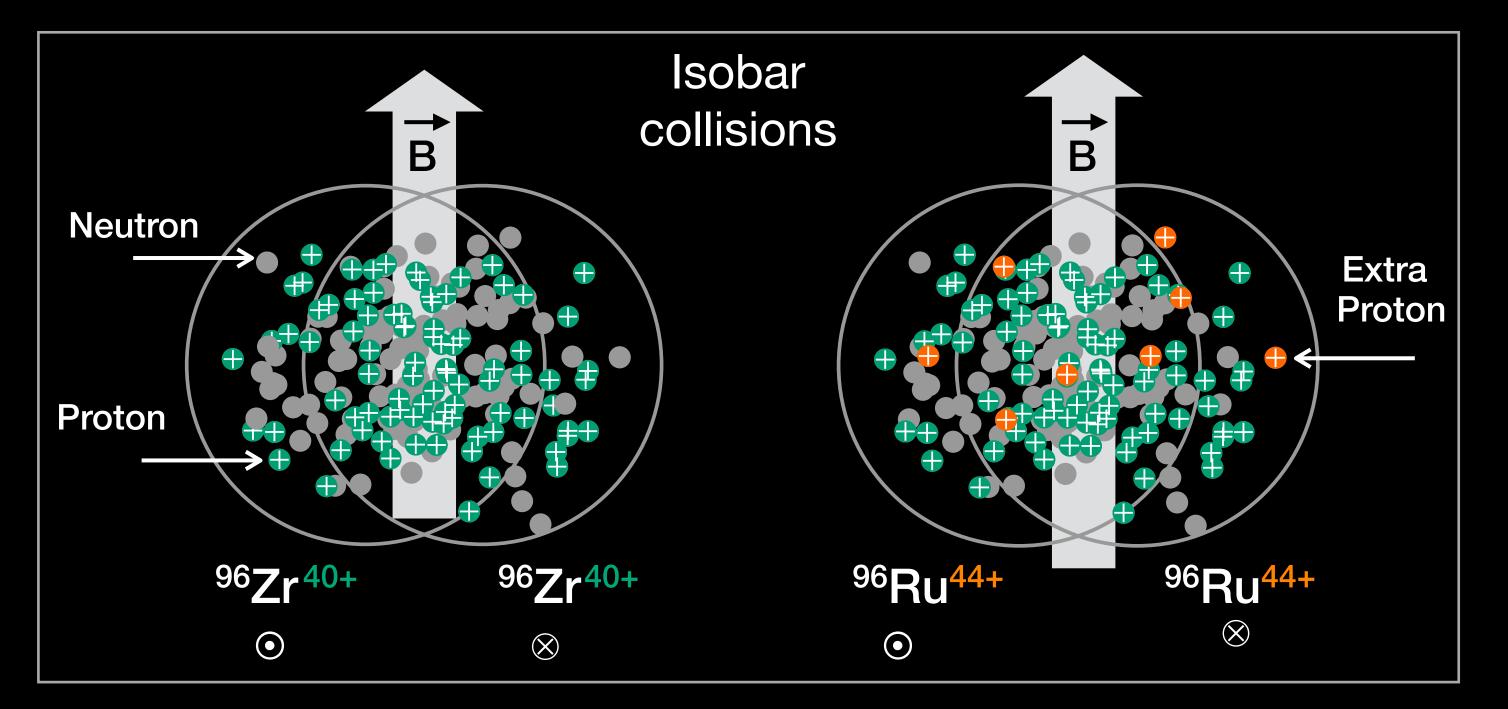


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Voloshin,

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

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



P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022

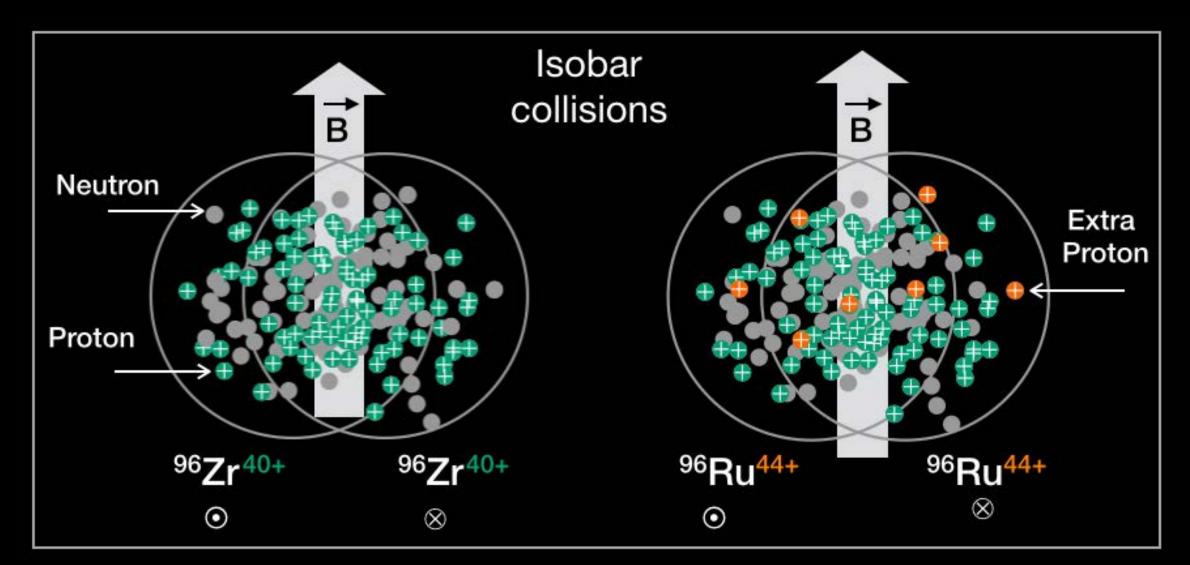


17

Voloshin,

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

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



If multiplicity (N) is same in two isobars:

$$\frac{(\Delta \gamma / v_2)_{\rm Ru+Ru}}{(\Delta \gamma / v_2)_{\rm Zr+Zr}} \approx 1 + f_{\rm CME}^{\rm Zr+Zr} [(B_{\rm Ru+Ru} / B_{\rm Zr+Zr})]$$

P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022



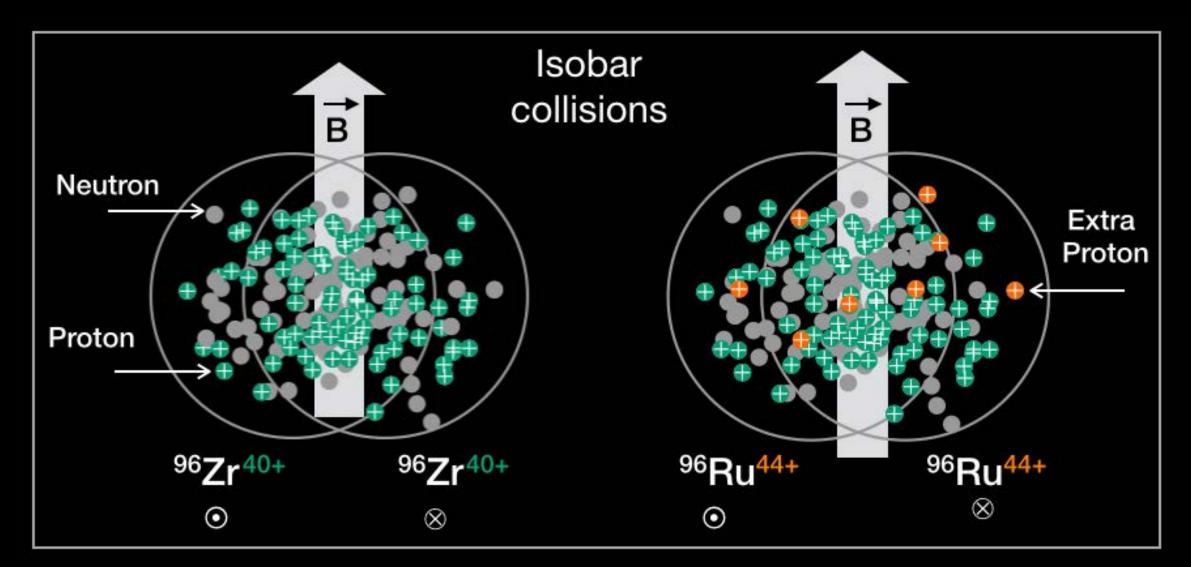
18

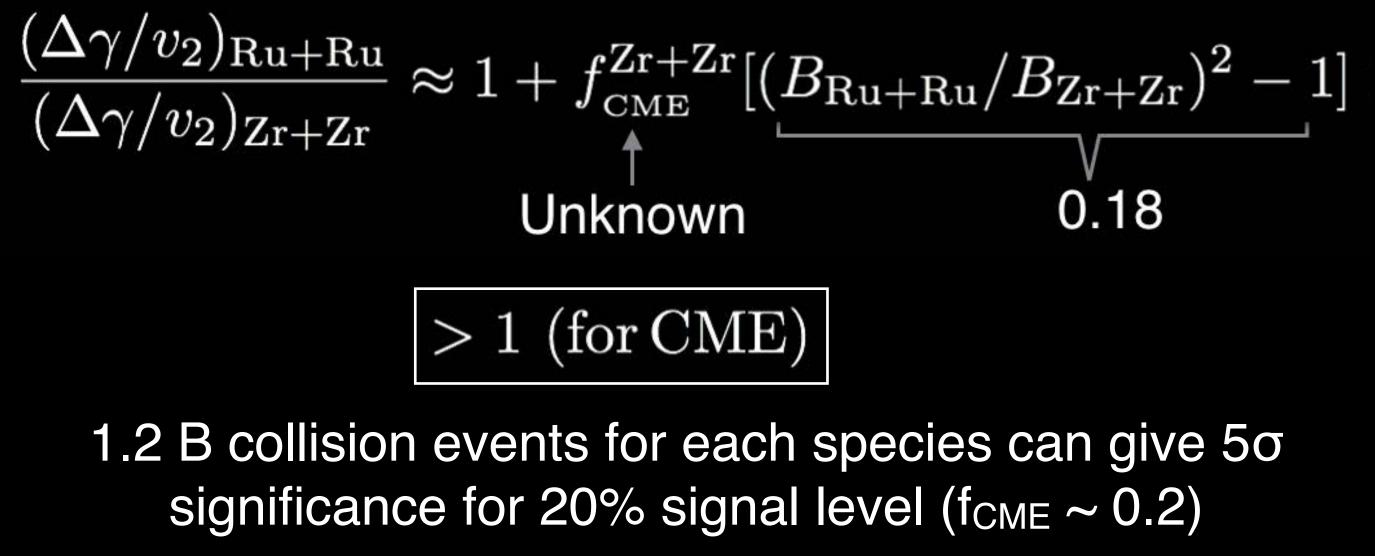
Voloshin,

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

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

 $)^2 - 1] > 1 \text{ (for CME)}$ 





(A precision of 0.5% is needed !!)

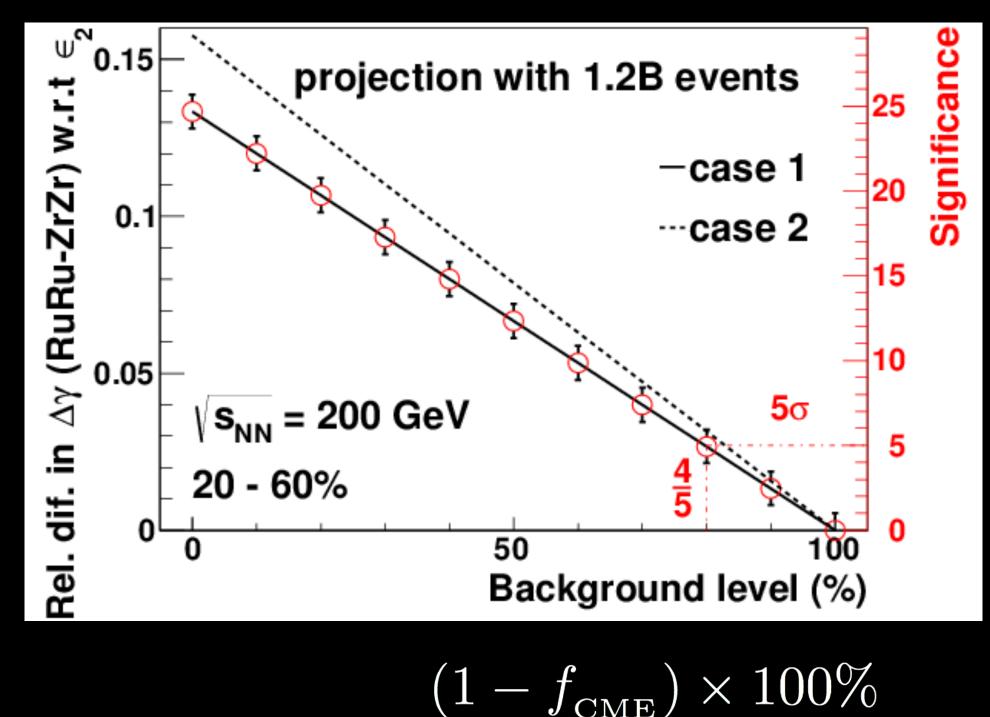
P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022



Voloshin,

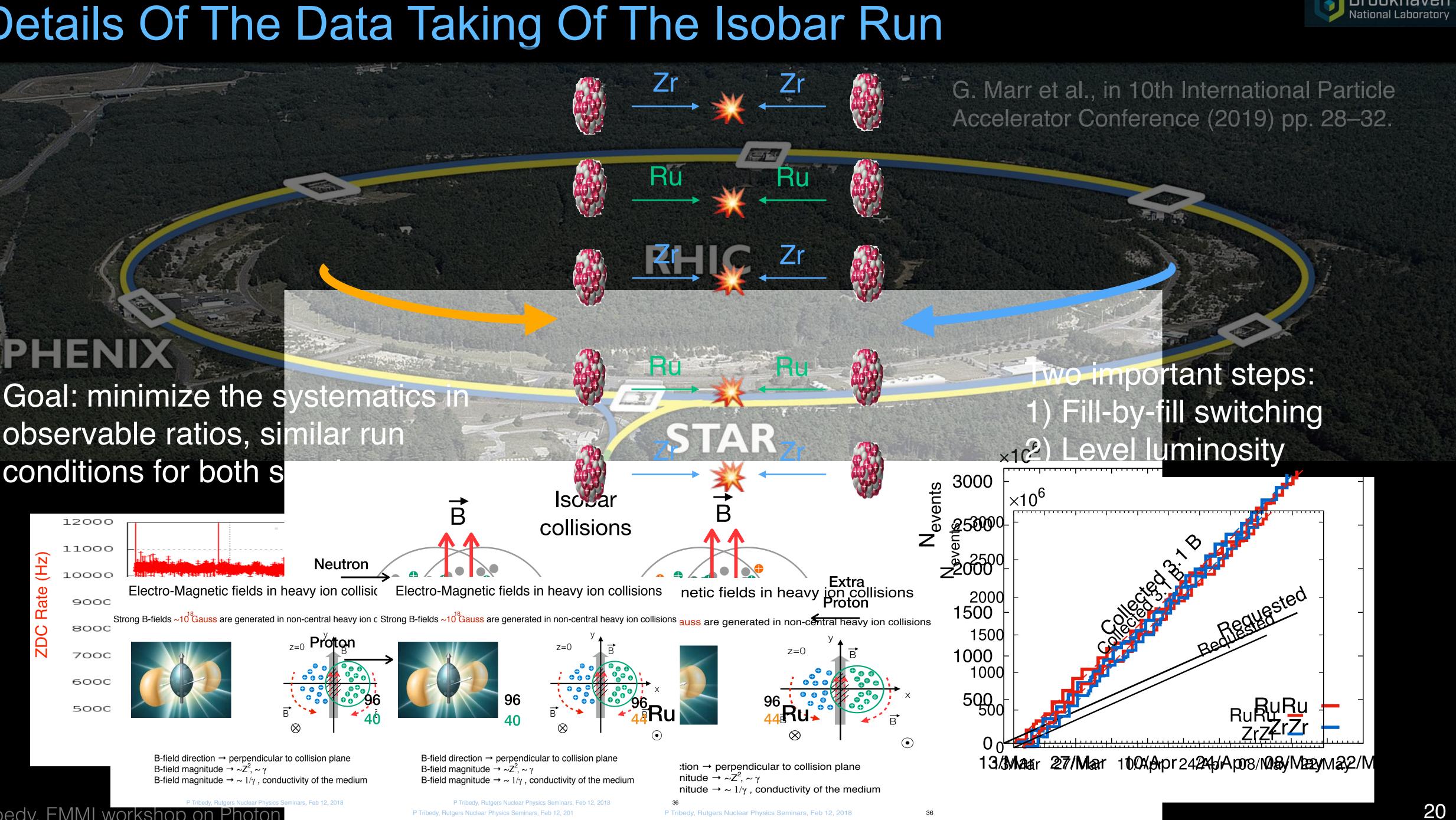
### B-field square is 10-18% larger in Ru+Ru

#### https://drupal.star.bnl.gov/STAR/system/files/ STAR BUR Run1718 v22 0.pdf



## Details Of The Data Taking Of The Isobar Run

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



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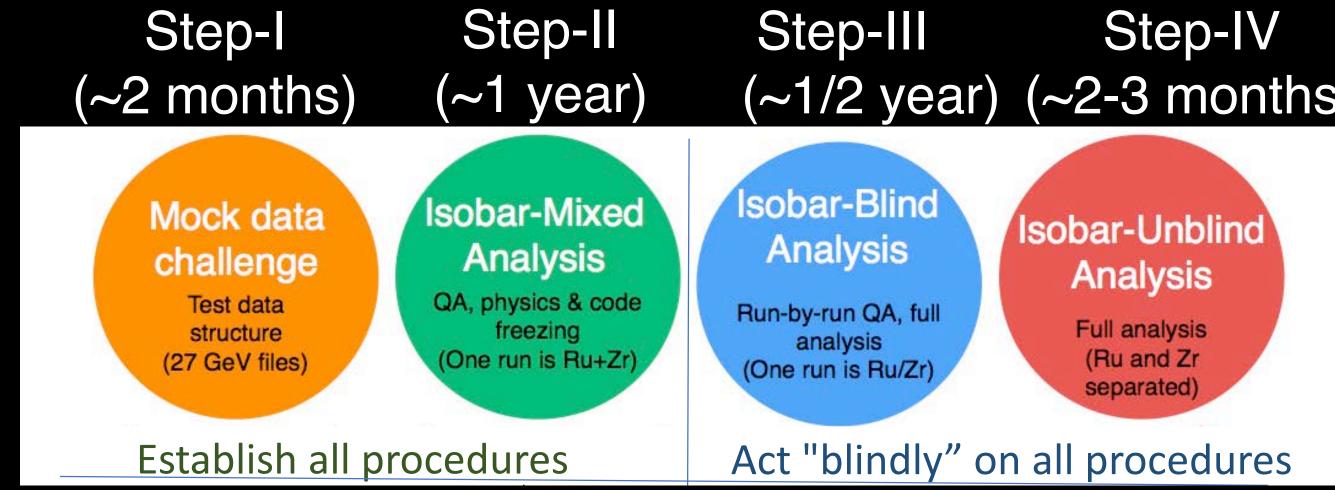
## Blind analysis of the isobar data



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## Steps of Isobar blind analysis



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

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



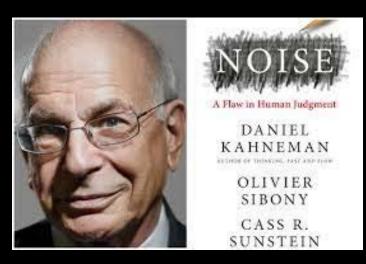
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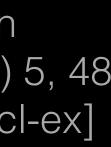


# (~2-3 months)

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





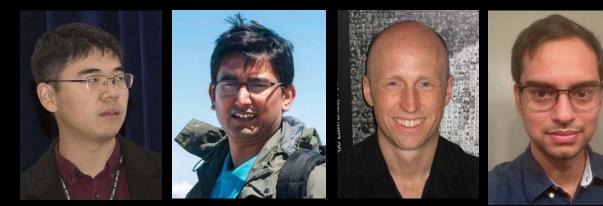




## Five independent groups did isobar blind analysis

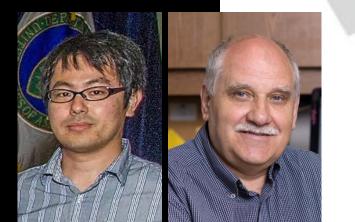
Purdue-Huzhou (group-3) Yicheng Feng, Haojie Xu, Jie Zhao, Fuqiang Wang





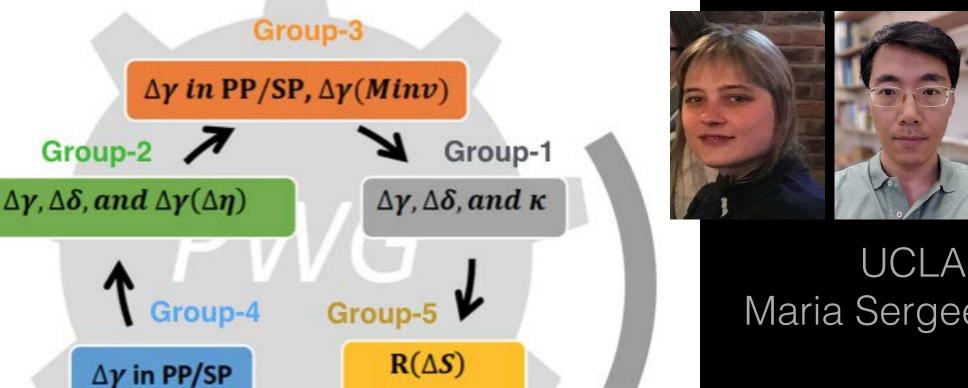
BNL-Fudan (group-2) Yu Hu, Subikash Choudhury, Paul Sorensen, Prithwish Tribedy

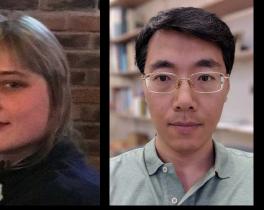
Group-2



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

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#### UCLA (group-1) Maria Sergeeva, Gang Wang



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

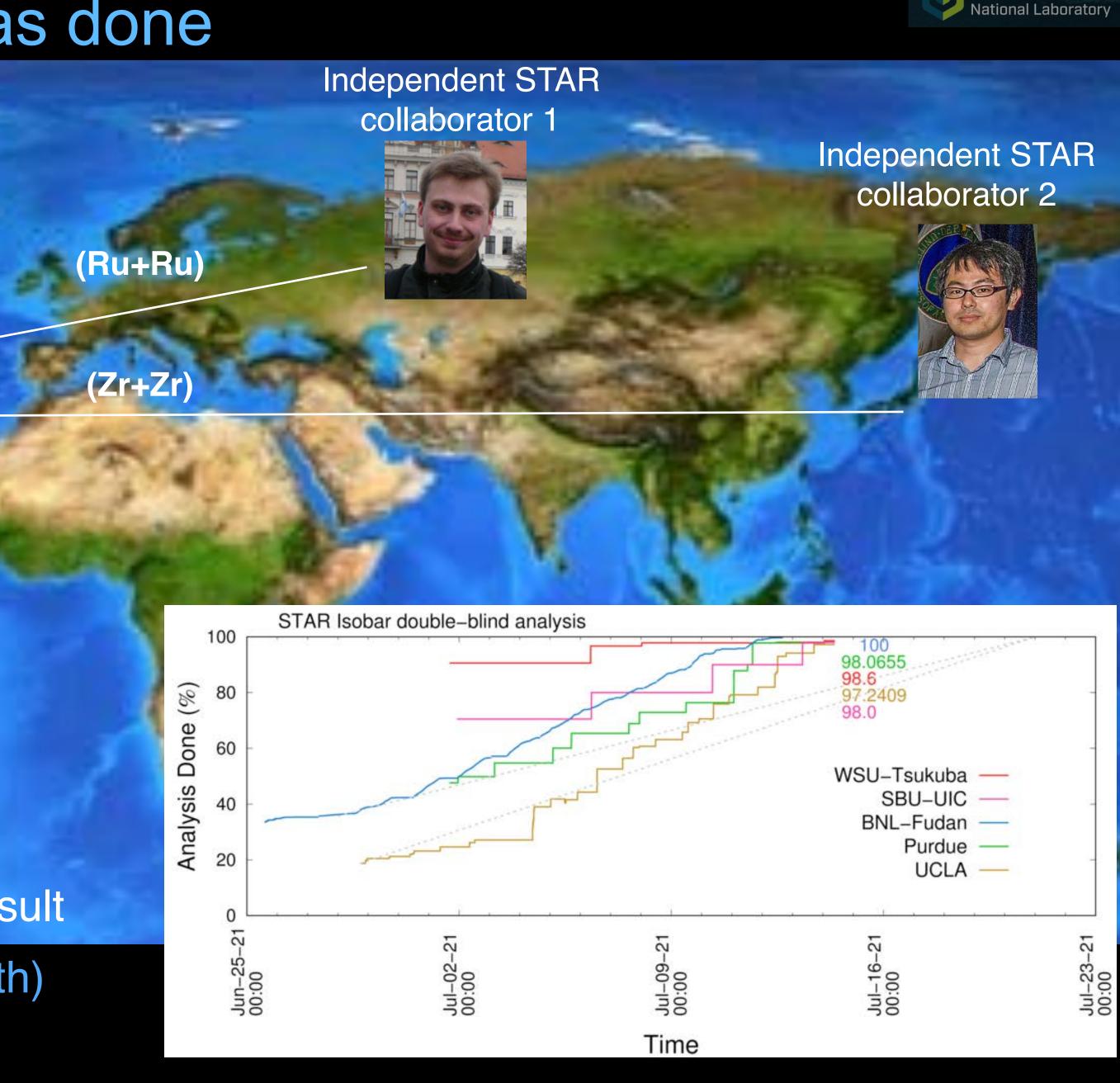


Group-2 (BNL-Fudan)

Different people run frozen codes
→ Analyzers open box → Directly publish the result
(Took all nodes of RHIC comp. facility for a month)

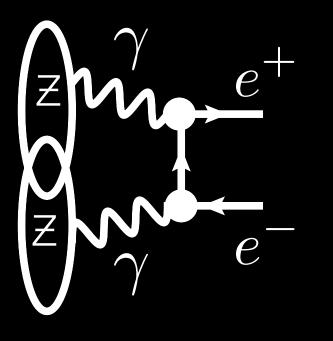
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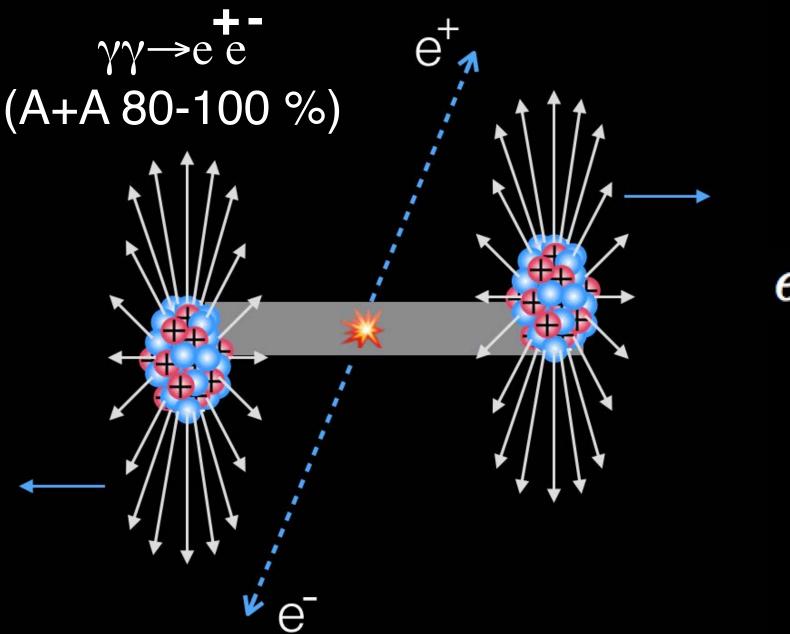


### Independent test of B-field difference in isobars



Low p\_di-electron (Breit-Wheeler)

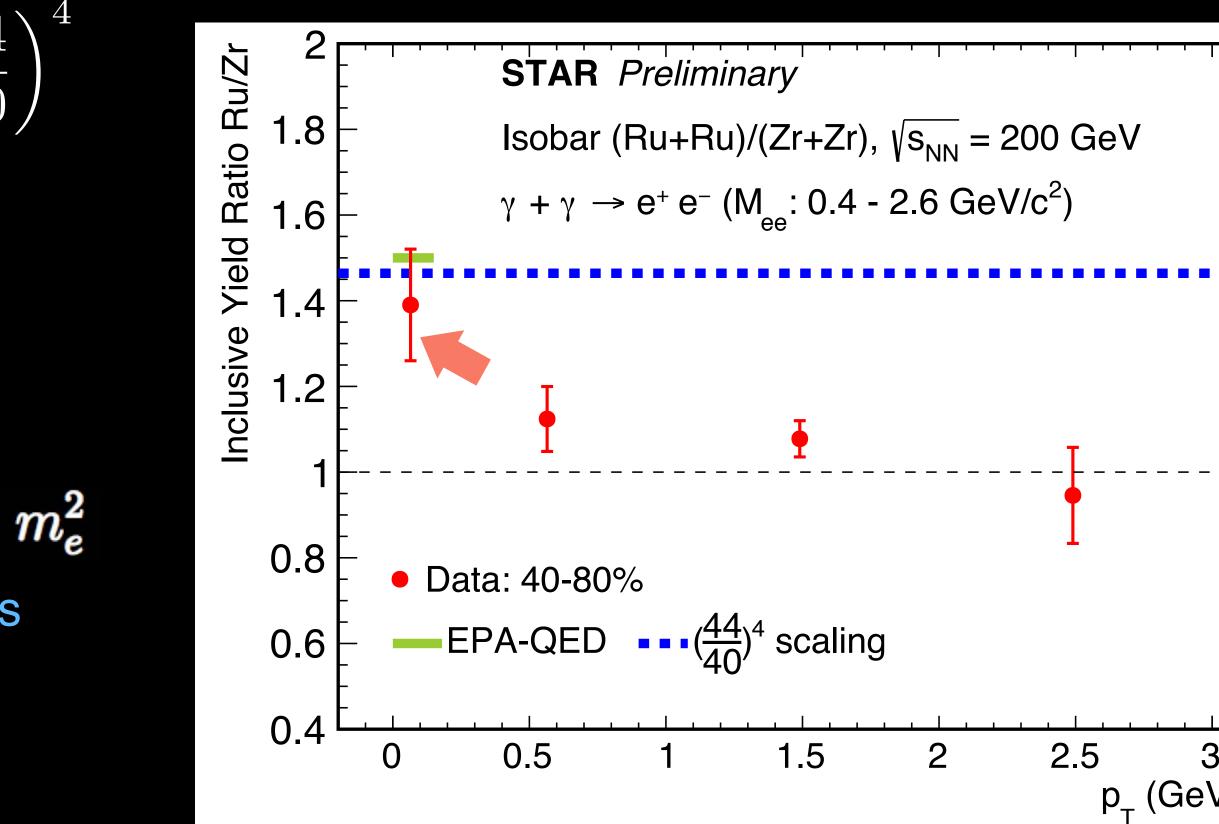
 $\sigma(\gamma\gamma \to e^+e^-) \sim \mathcal{Z}^4$  $\frac{\sigma_{\rm Ru+Ru}(\gamma\gamma \to e^+e^-)}{\sigma_{\rm Zr+Zr}(\gamma\gamma \to e^+e^-)} \sim \left(\frac{44}{40}\right)^4$ 



 $eB > eB_C \approx m_e^2$ ~10<sup>12</sup> Gauss

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#### 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

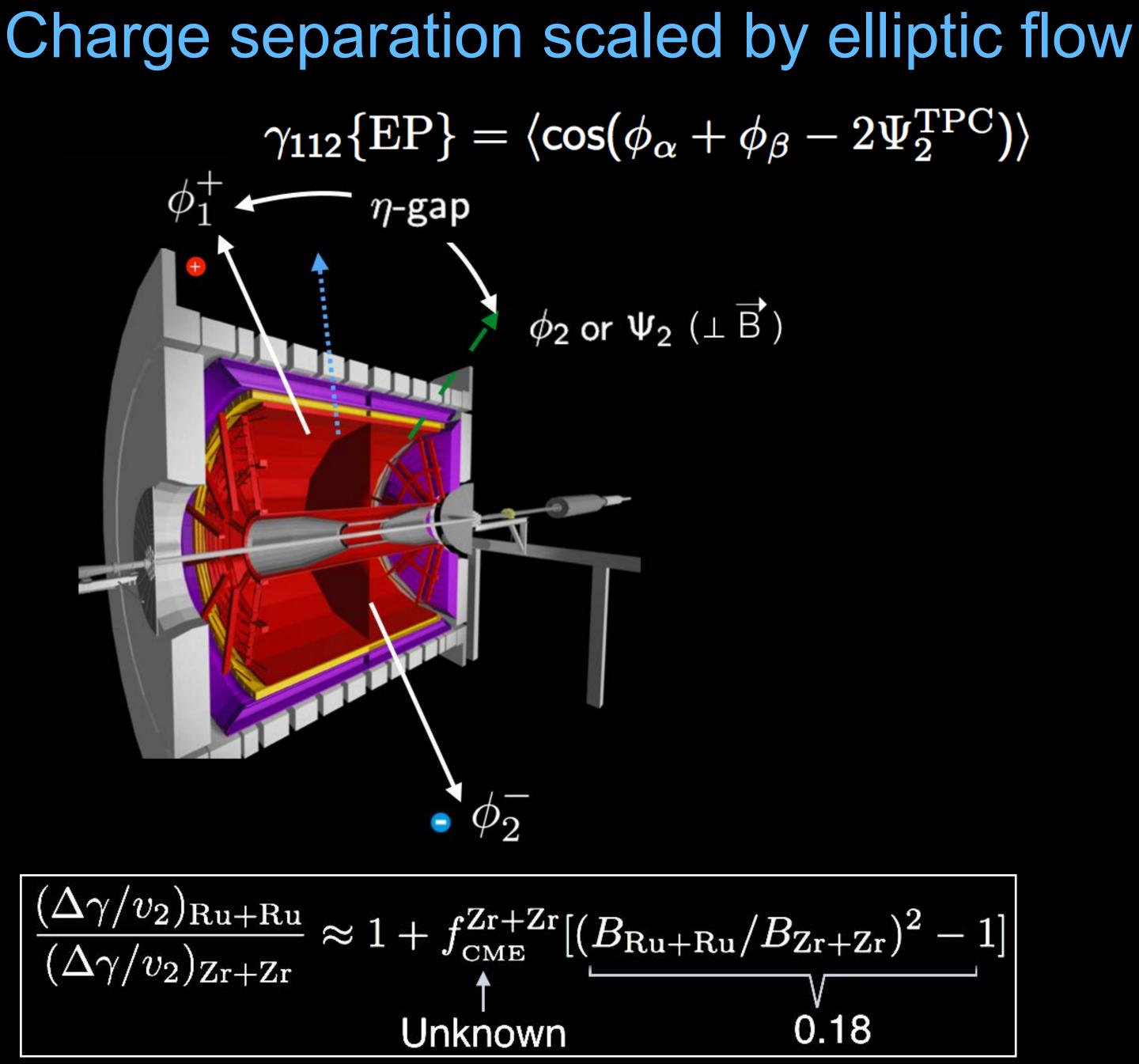


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### CME sensitive observables

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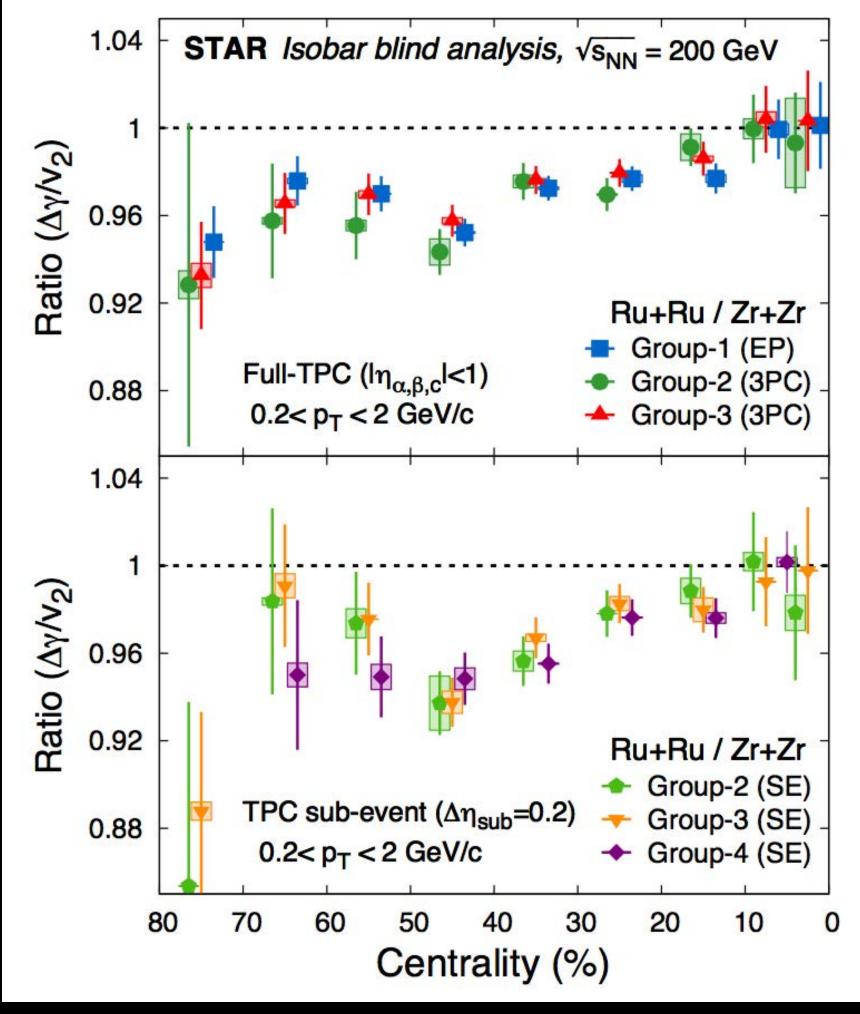




P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022

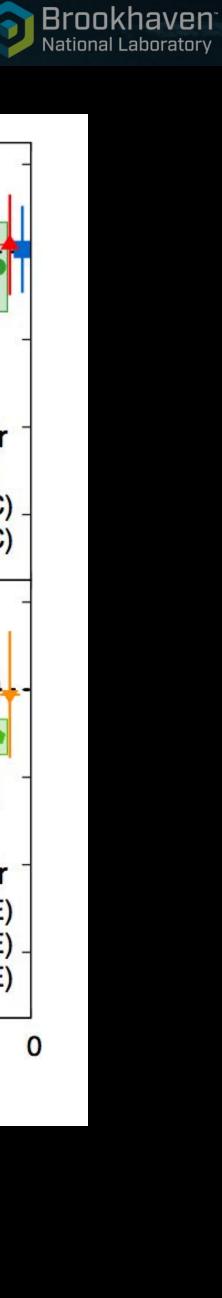
1]

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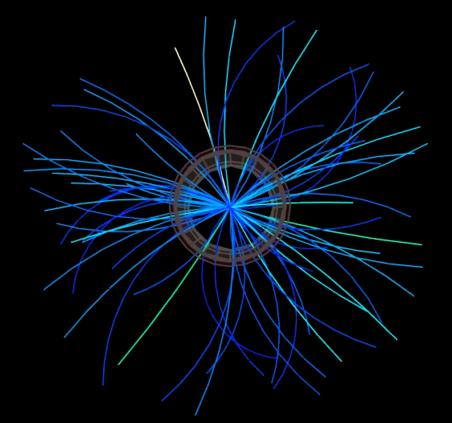
**Pre-defined criteria for CME**  $(\Delta \gamma / v_2)_{
m RuRu}$ NOT seen!!  $(\Delta \gamma / v_2)_{\rm ZrZr}$ 

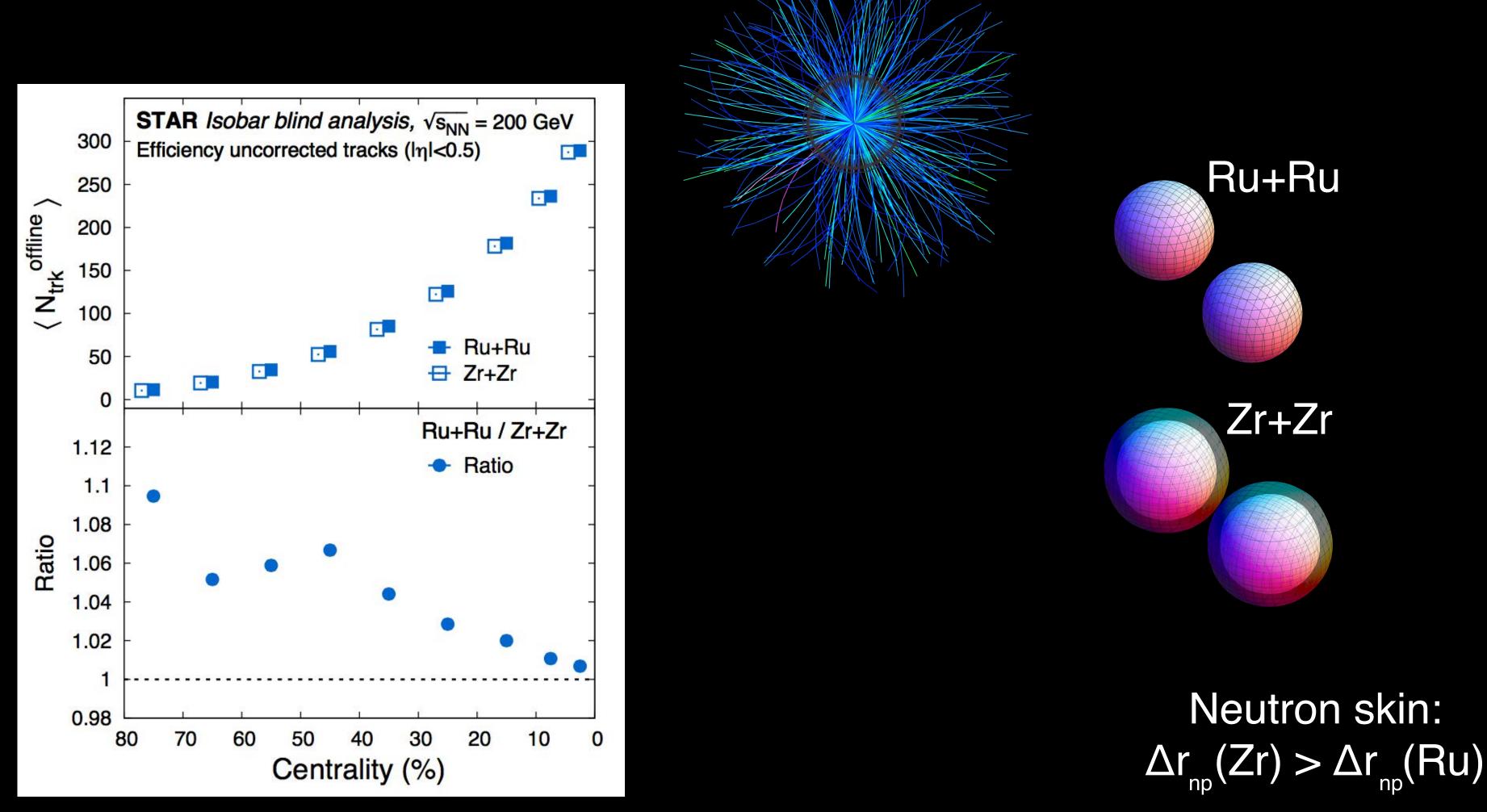






## Multiplicity difference between the isobars





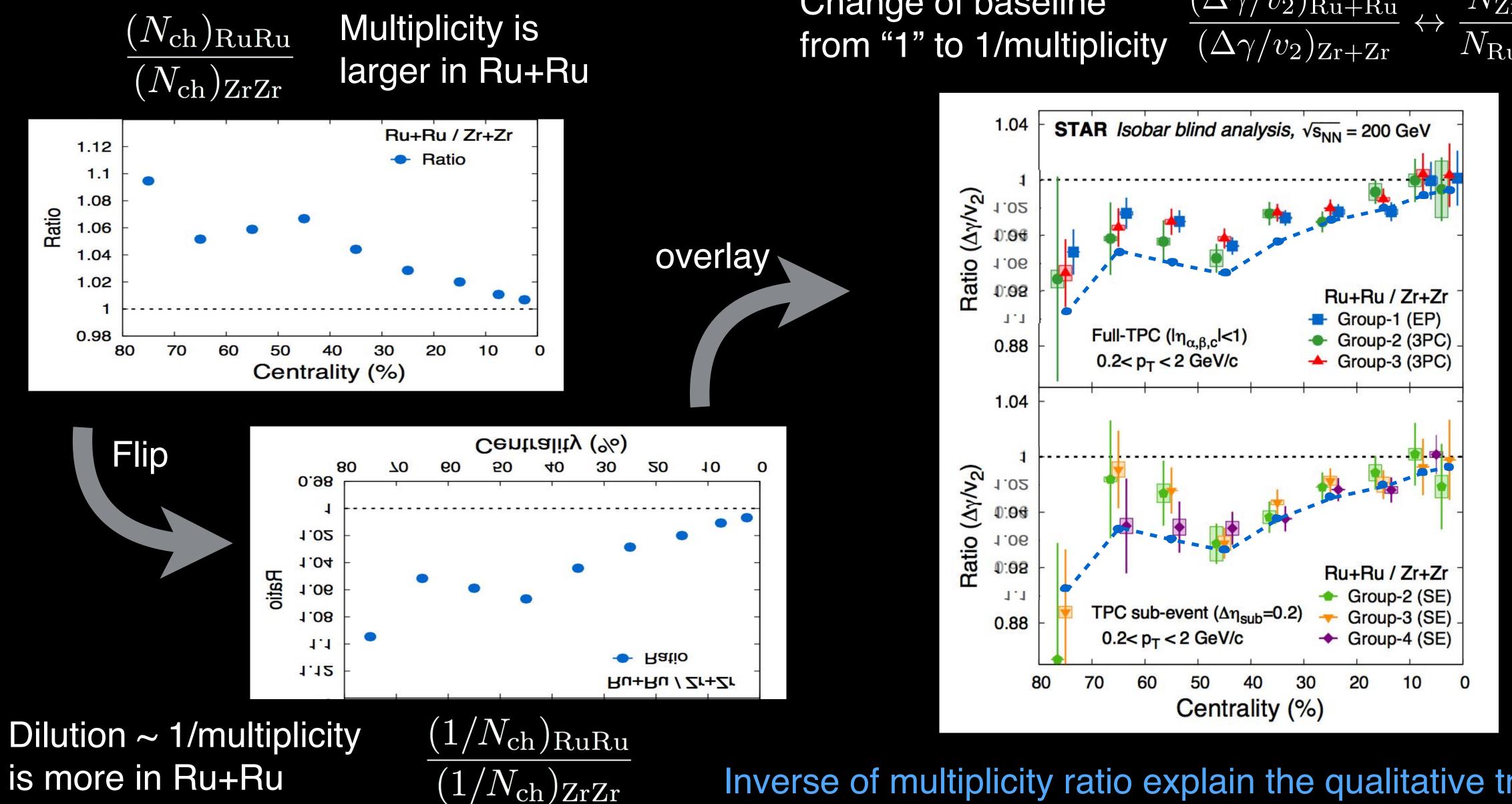
Mean efficiency uncorrected multiplicity density is larger in Ru than in Zr in a matching centrality, this can affects signal and background difference between isobars

P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022



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

## Limited Post-blind analysis: modified CME baseline

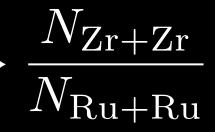


P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022

Voloshin for STAR, DNP 2021

Change of baseline

 $(\Delta \gamma / v_2)_{\mathrm{Ru+Ru}}$ 



Inverse of multiplicity ratio explain the qualitative trend

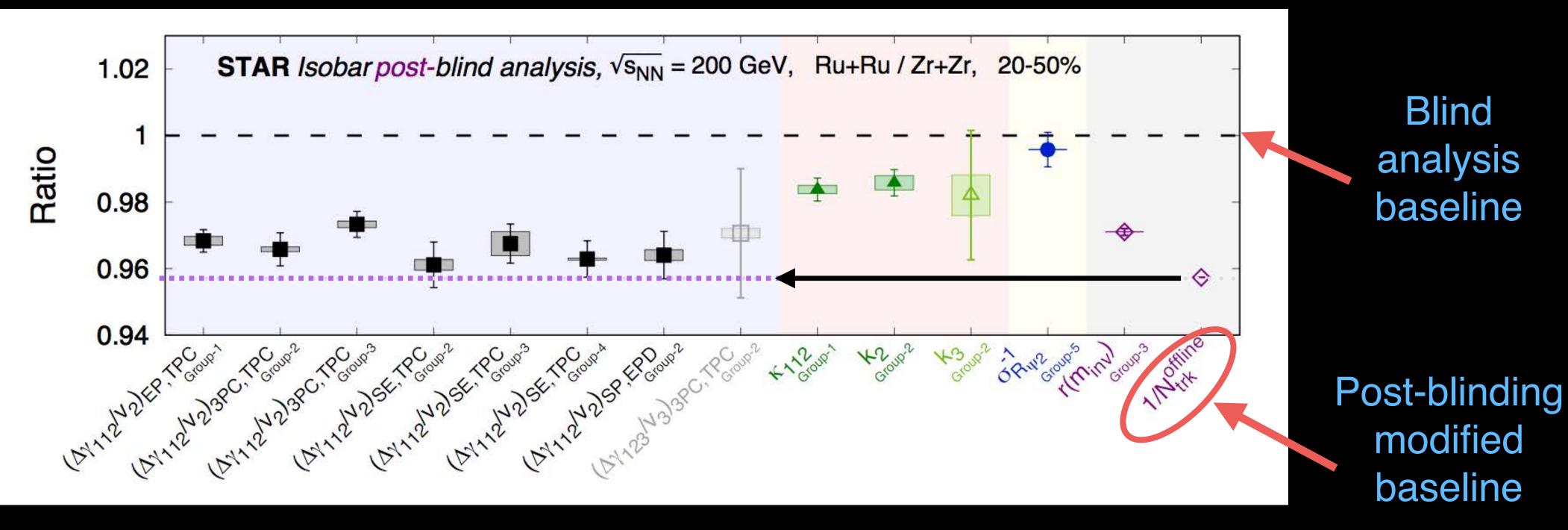




## Limited Post-blind analysis: modified CME baseline

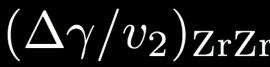
Challenge: Multiplicity turned out to be different for the two isobar, was not know before blind analysis, dilution of signal & background  $\sim 1$ /multiplicity, this effect is different for two species

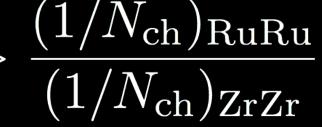
Blind analysis criterion for CME:  $\frac{(\Delta \gamma / v_2)_{\text{RuRu}}}{(\Delta \gamma / v_2)_{\text{ZrZr}}} > 1$ 



P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022

Post-blinding criterion for CME:  $\frac{(\Delta \gamma / v_2)_{\rm RuRu}}{(\Delta \gamma / v_2)_{\rm ZrZr}} >$  $(1/N_{\rm ch})_{
m RuRu}$ 

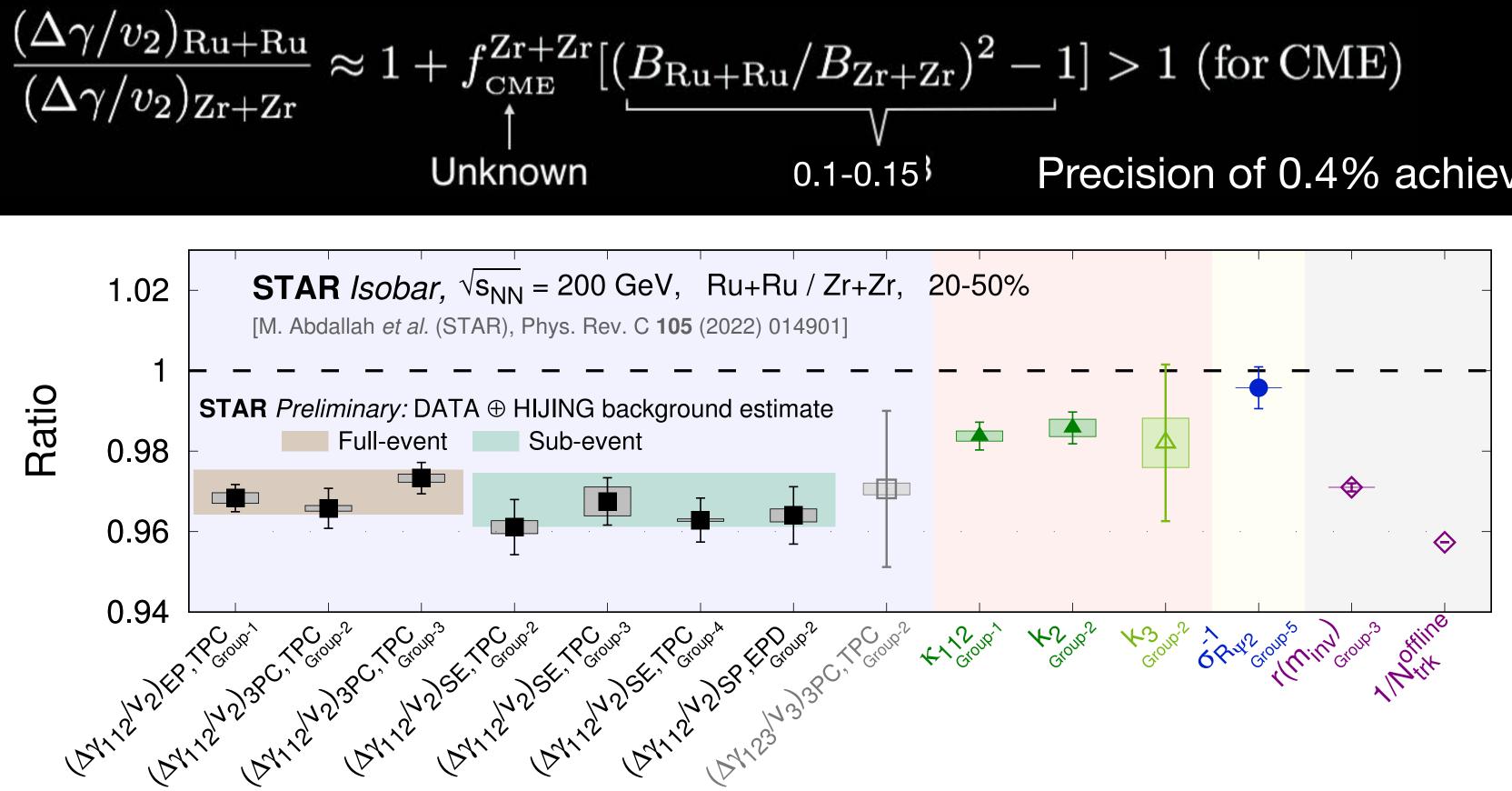






### Compilation of results

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

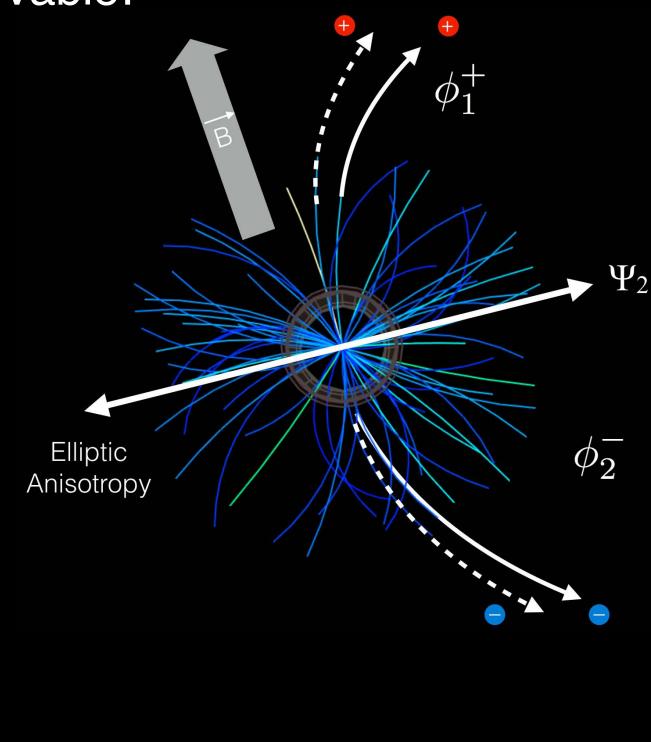


No pre-defined signature of CME is observed in isobar collisions, possible residual signal due to change of baseline & non-flow effects are under study

P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022

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

Precision of 0.4% achieved



Yicheng Feng (STAR Collaboration), QM 2022





## Remaining signal estimates

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

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

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

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

#### 2. STAR background estimate including non-flow:

Yicheng Feng, STAR collaboration, QM 2022

$$\frac{\left(N_{\rm ch}\,\Delta\gamma/v_2\right)_{\rm Ru+Ru}^{\rm bkg}}{\left(N_{\rm ch}\,\Delta\gamma/v_2\right)_{\rm Zr+Zr}^{\rm bkg}} = 1.013\pm0.003\pm0.005$$

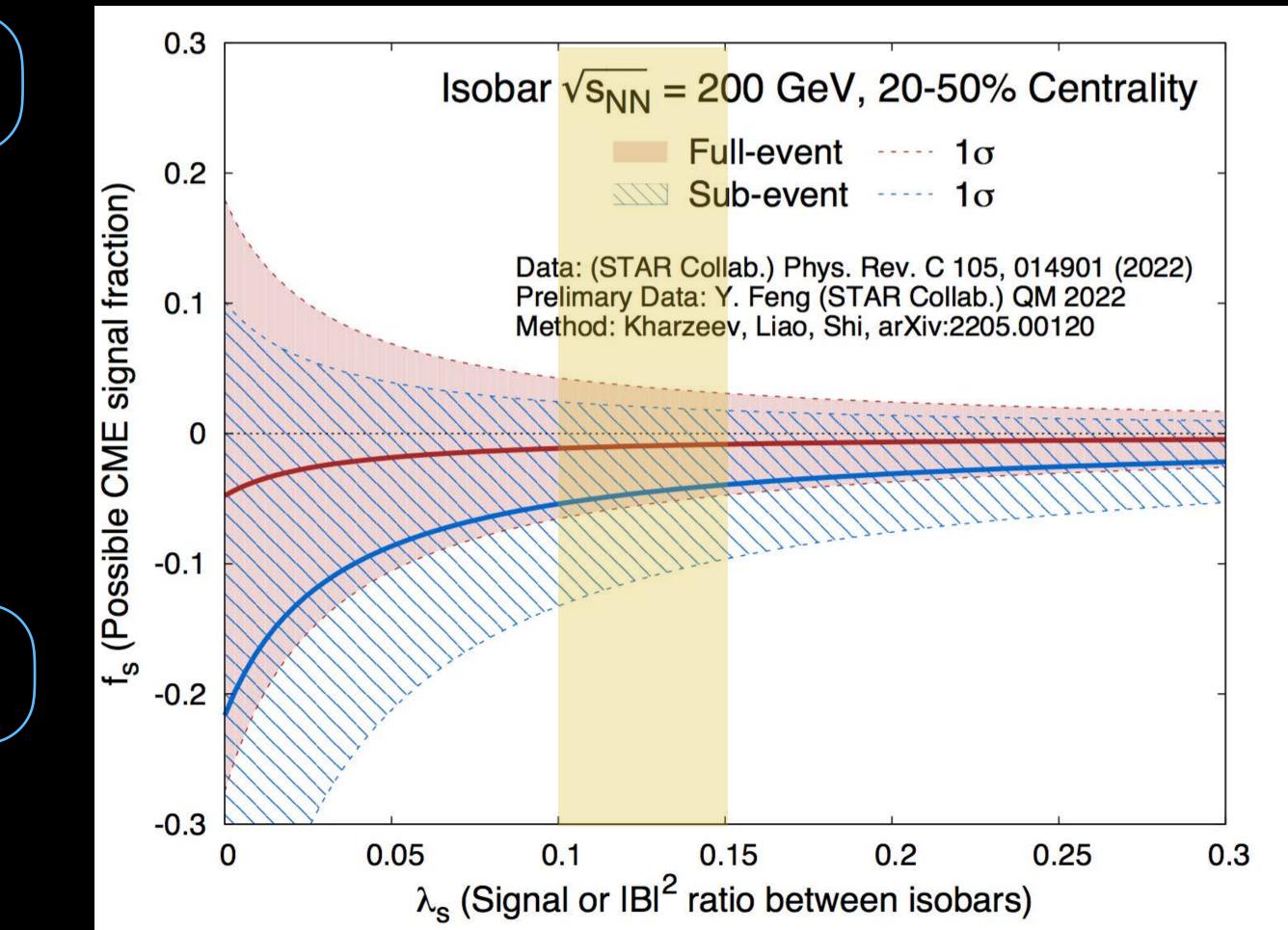
 $\Delta\gamma/v_2)_{
m Ru+Ru}$  $R^{\mathrm{bkg}}$  $= 0.9698 \pm 0.003 \pm 0.005$  $(\Delta \gamma / v_2)_{
m Zr+Zr}$ 

3. Estimates of Possible CME signal:

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

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

P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022



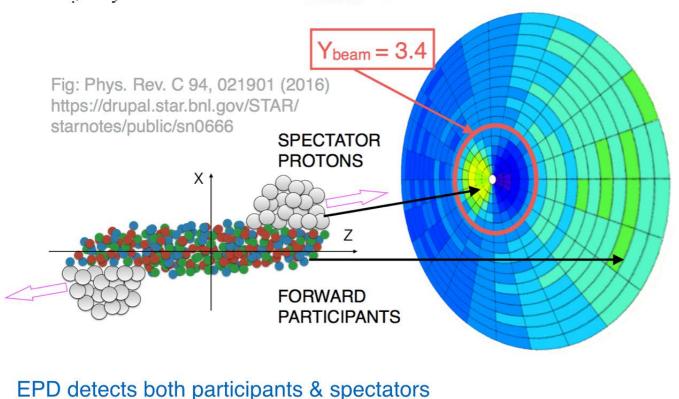
More work from STAR collaboration is underway

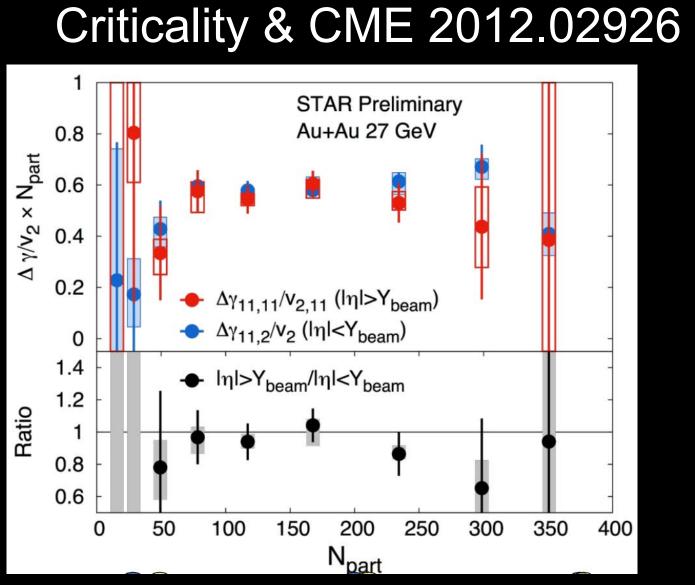


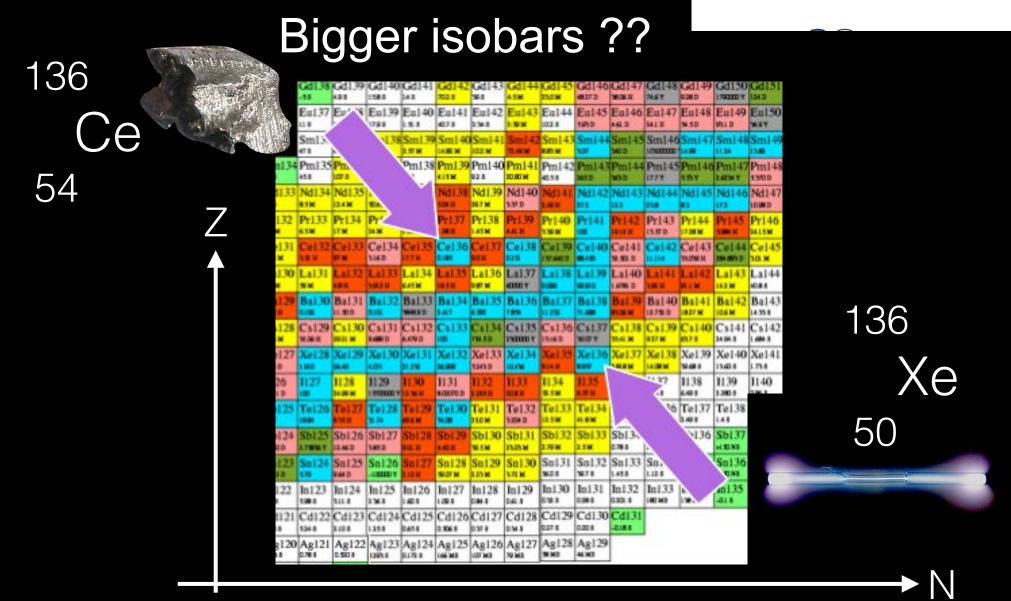
## What is the future of CME search?

#### STAR EPD: better handle on B-field direction (1912.05243) CME @ BES-II data arXiv:2110.15937

STAR Event Plane detector acceptance:  $2.1 < |\eta| < 5.1$ Beam rapidity for Au+Au 27 GeV, Y<sub>beam</sub> = 3.4

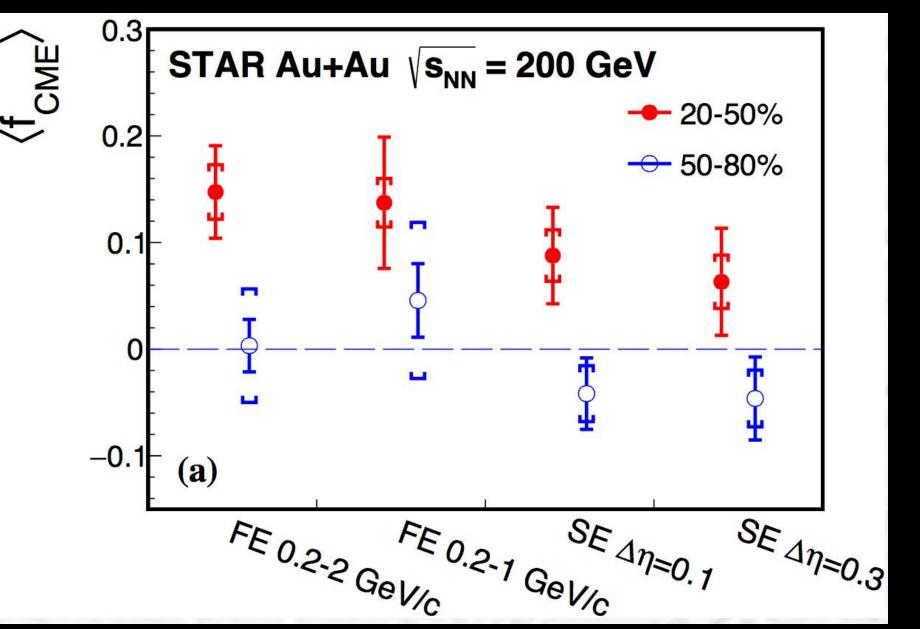






P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022

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



# CME search with AIML (2105.13761)





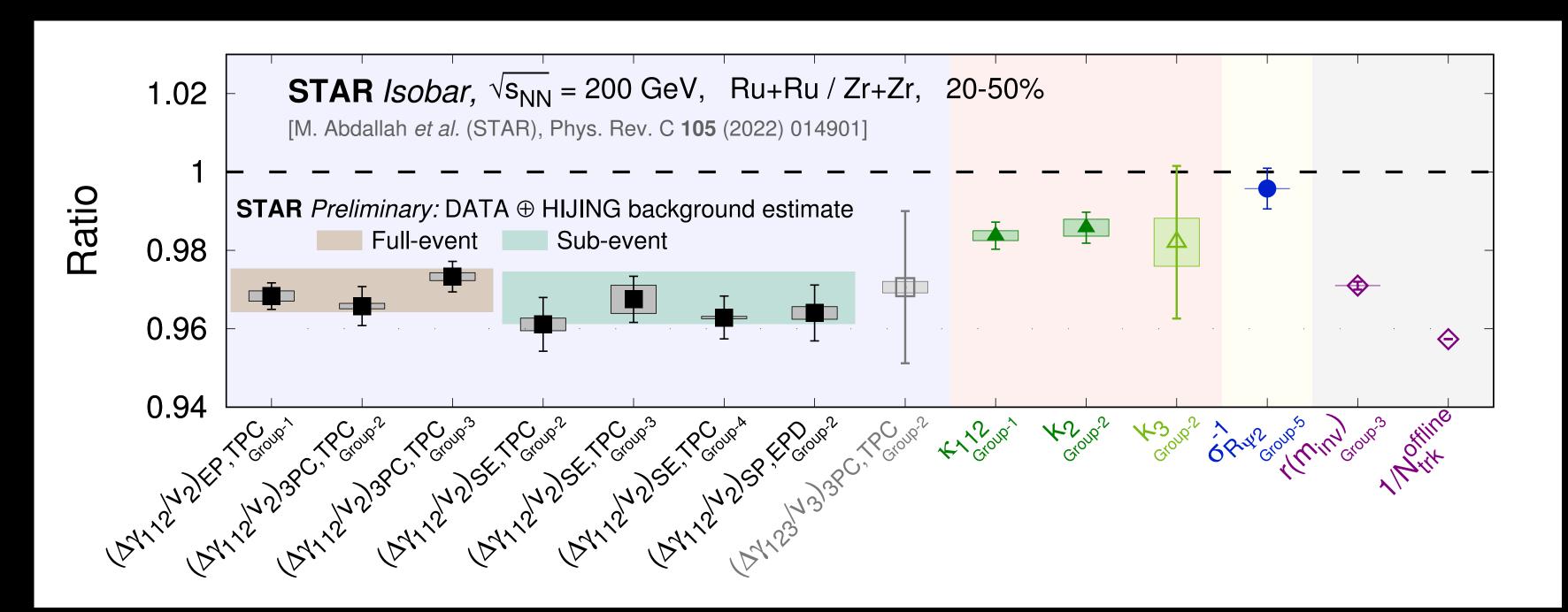
## Summary

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

blind analysis is needed to search for residual CME signal

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



P. Tribedy, EMMI workshop on Photon physics, Sept 19-22, 2022

- Primary CME observable  $\Delta \gamma / v_2$  baseline is affected by the multiplicity difference (4% in 20-50%), post-



