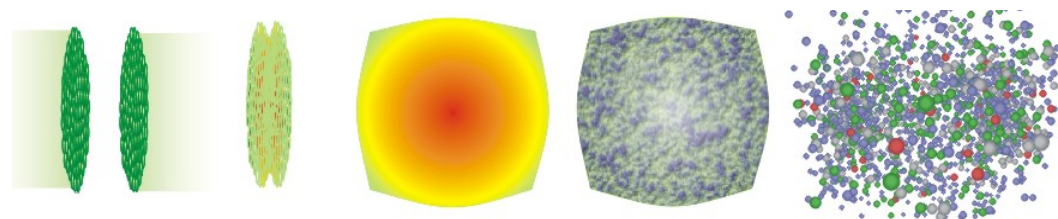


Symposium on Nuclear Physics Frontiers and Interactions

相对论重离子碰撞中手征磁效应的实验

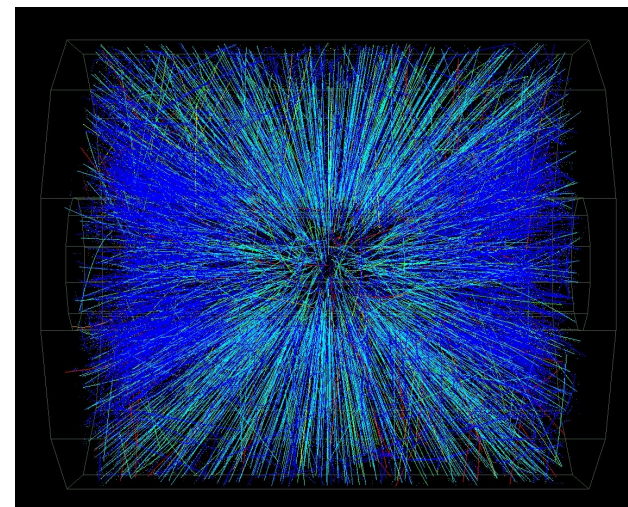
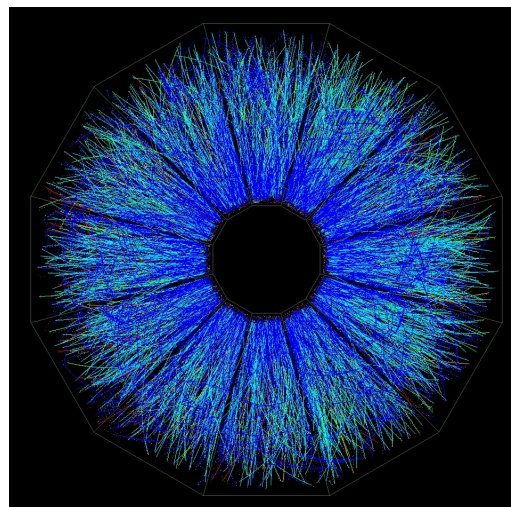
研究进展



陈金辉

复旦大学

2022-8-27



提纲



简介



重要实验结果点评

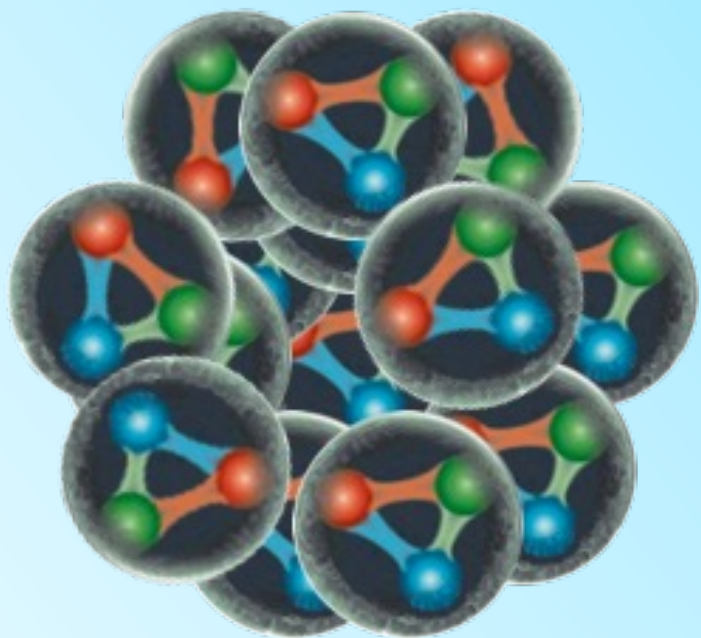


总结与展望

高能重离子对撞生新态？

研究思路：

色禁闭

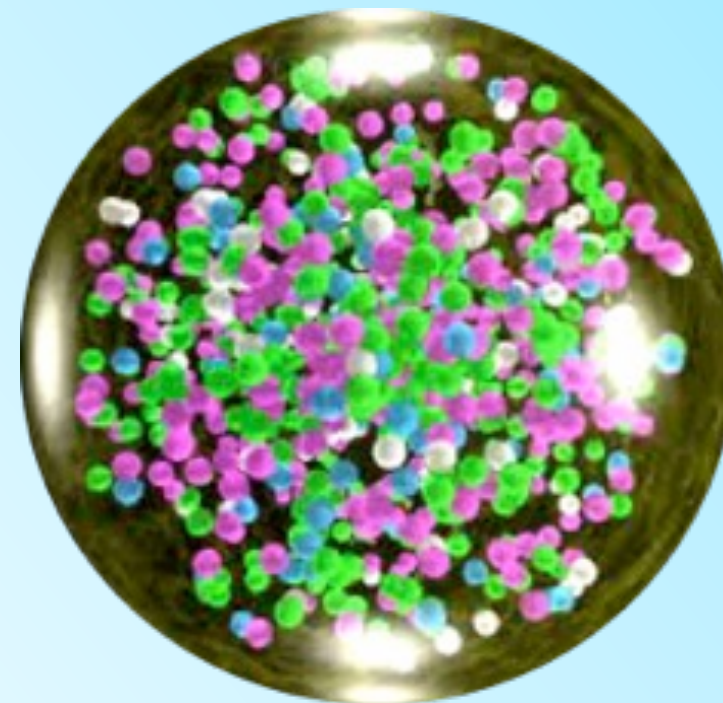


原子核

相对论重离子对撞

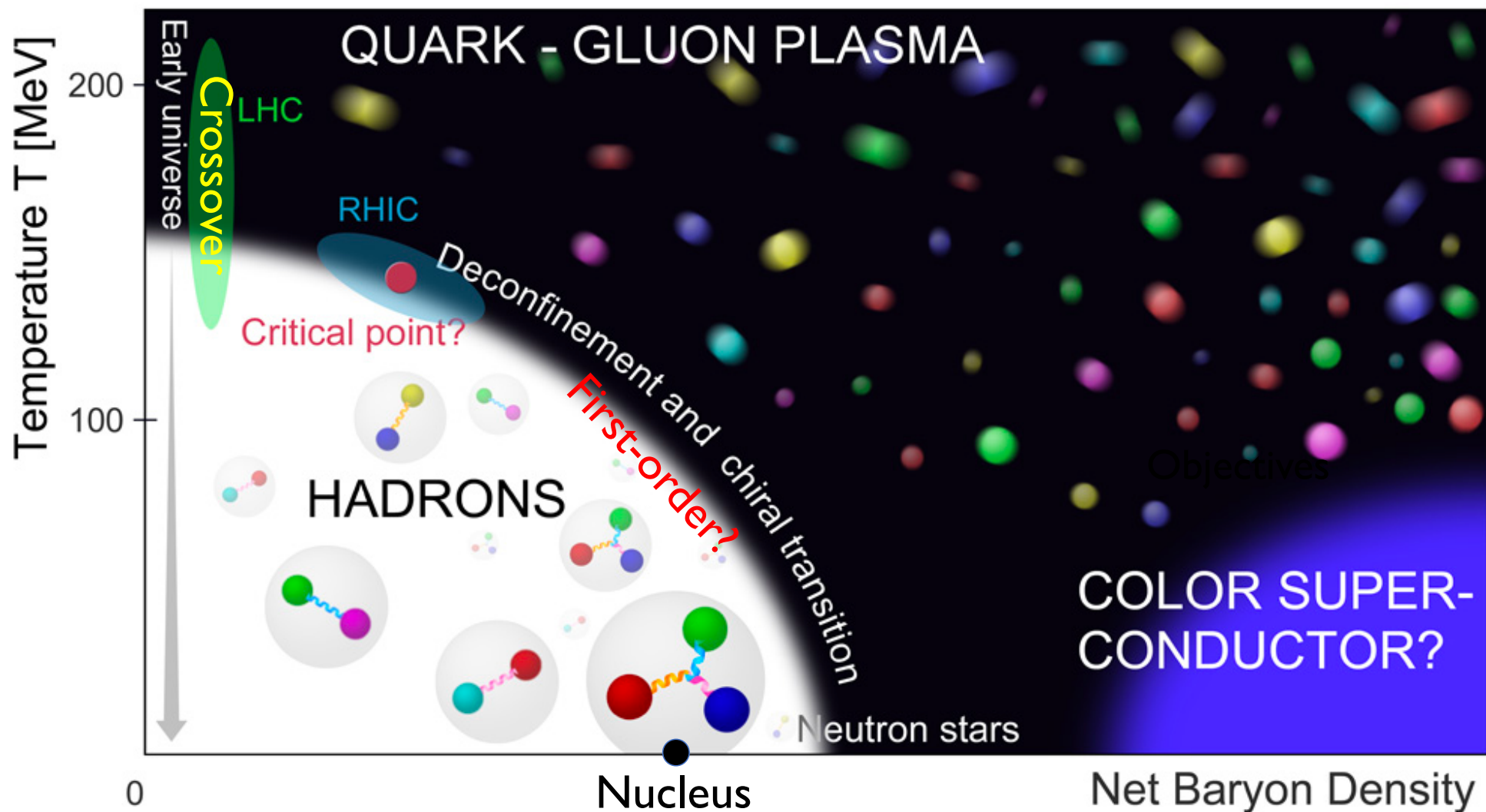


解禁闭



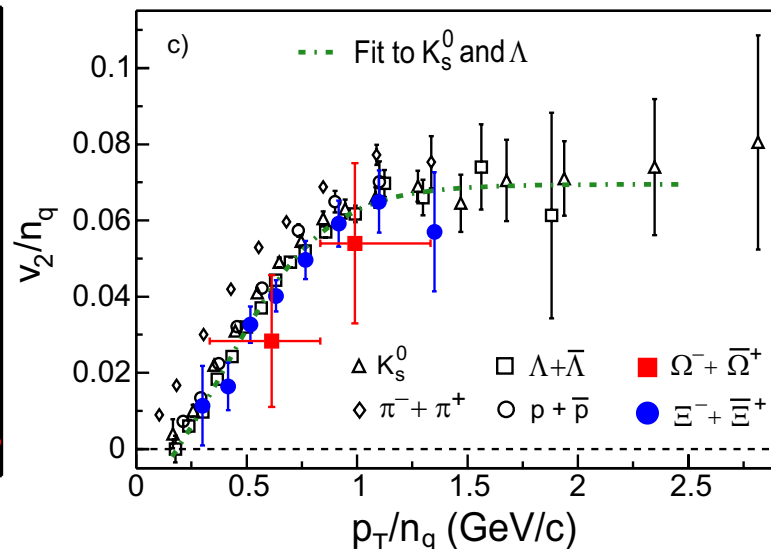
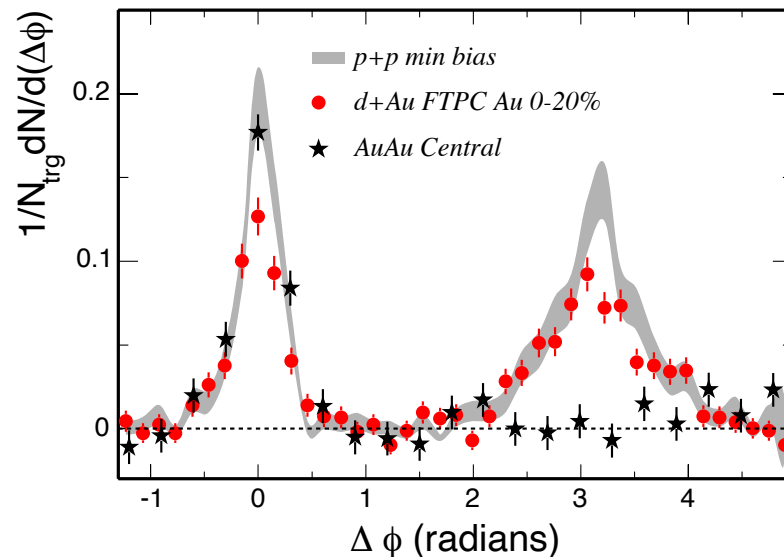
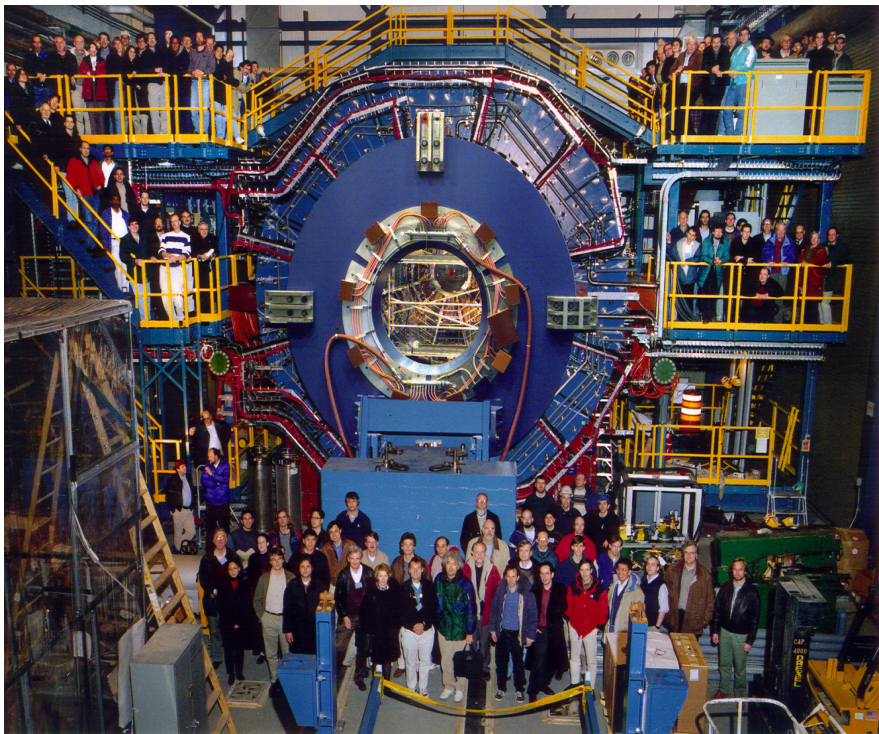
夸克胶子等离子体

QCD多体系统物理



- 实验上寻找解禁闭夸克胶子等离子体信号，并研究其性质
- 研究QCD相结构及寻找相变信号

相对论重离子对撞机的物理目标



- RHIC早期主要科学发现：喷注淬火、强的集体流及其组分夸克数标度行为...

Strong evidences pointing to a “dense, opaque, low-viscous, pre-hadronic liquid state of matter not anticipated before RHIC”

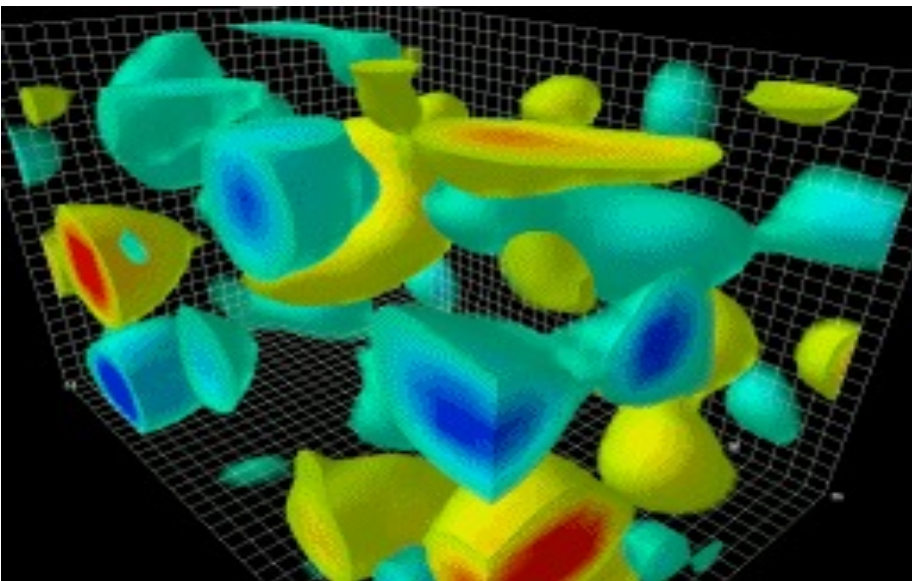
Nucl. Phys. A 757 (2005)

- RHIC近期的研究焦点：夸克物质整体/局域极化、相结构和临界点、QCD反常输运现象...

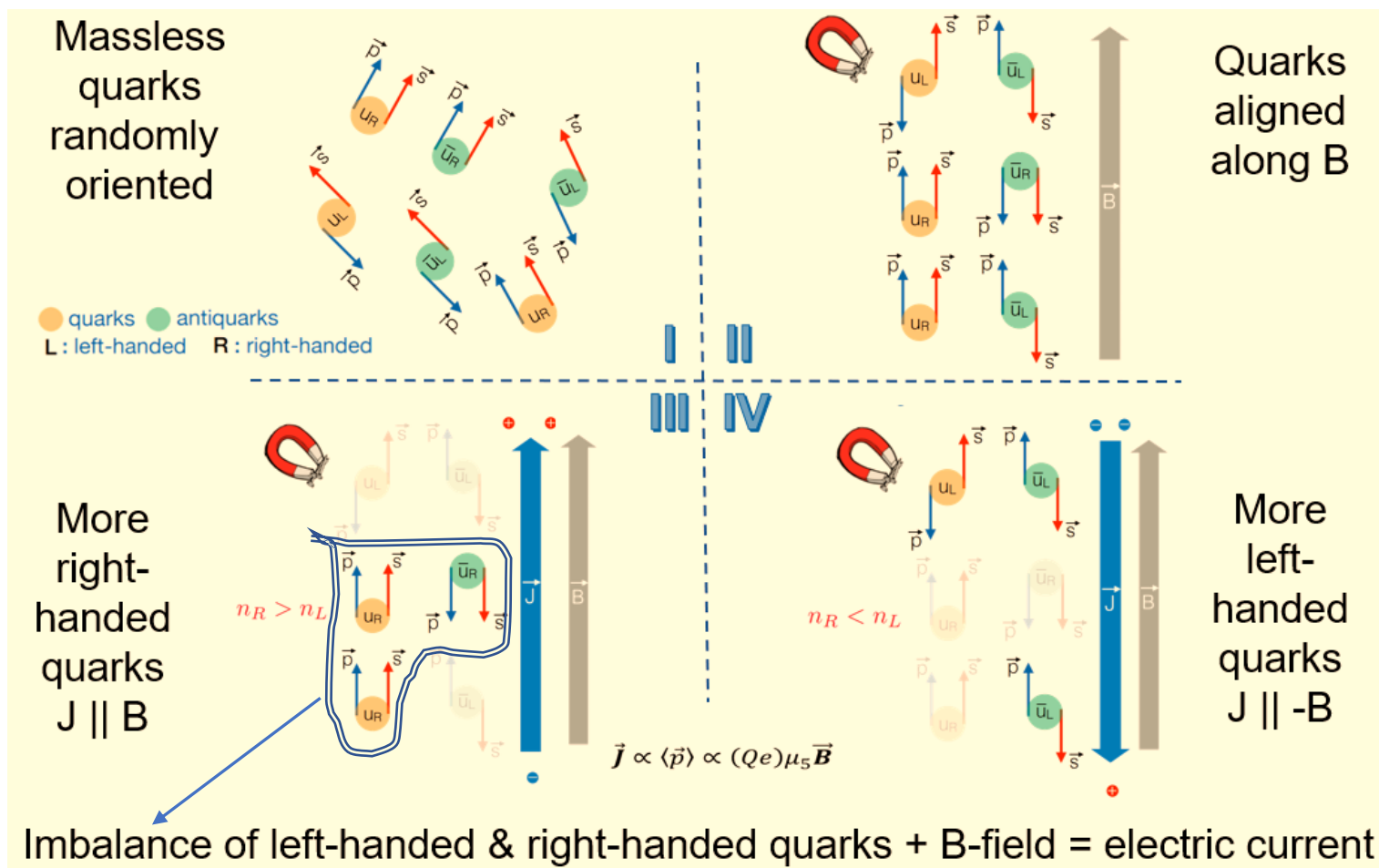
聚焦手征磁效应

QCD 规范场拓扑涨落

- **手征磁效应 (CME) :**
QCD真空拓扑涨落导致强相互作用中局域宇称破缺 + 强磁场



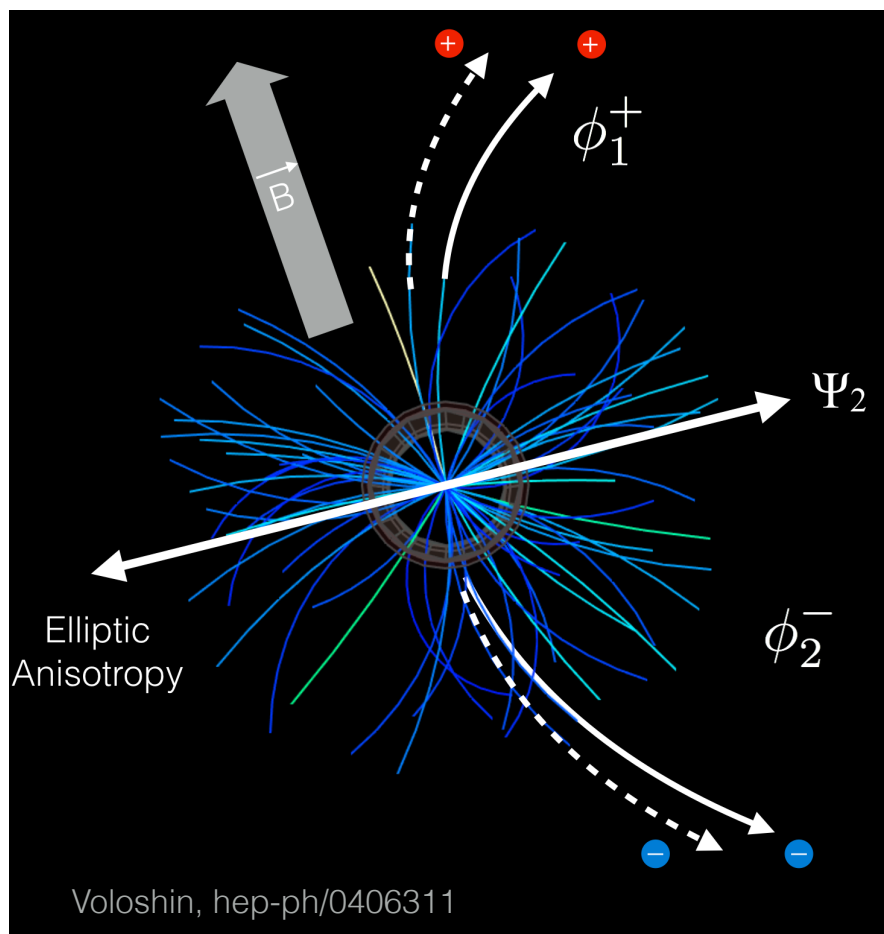
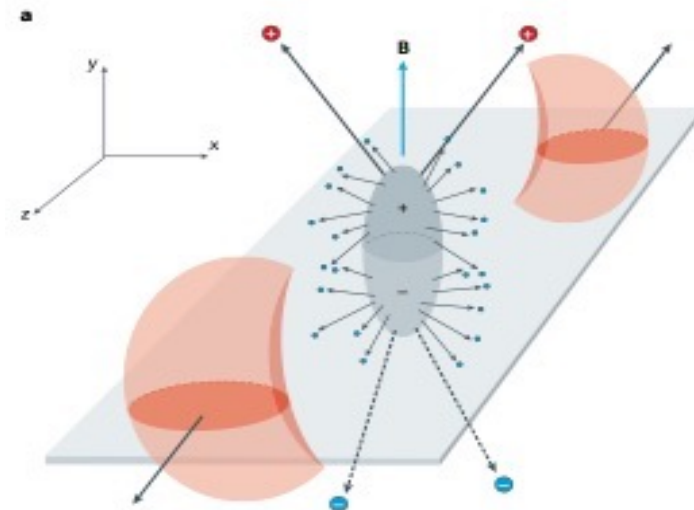
Kharzeev, McLerran, Warringa, Fukushima 2007



实验测量手段

实验上怎么探测：找到磁场方向，带电粒子和磁场关联

$$\gamma_{\alpha\beta} = \cos(\phi_\alpha + \phi_\beta - 2\Psi)$$



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

$$= \langle \cos(\phi_\alpha - \Psi_2) \cos(\phi_\beta - \Psi_2) - \sin(\phi_\alpha - \Psi_2) \sin(\phi_\beta - \Psi_2) \rangle$$

手征磁效应信号：

$$\gamma^{ss} \neq \gamma^{os}$$

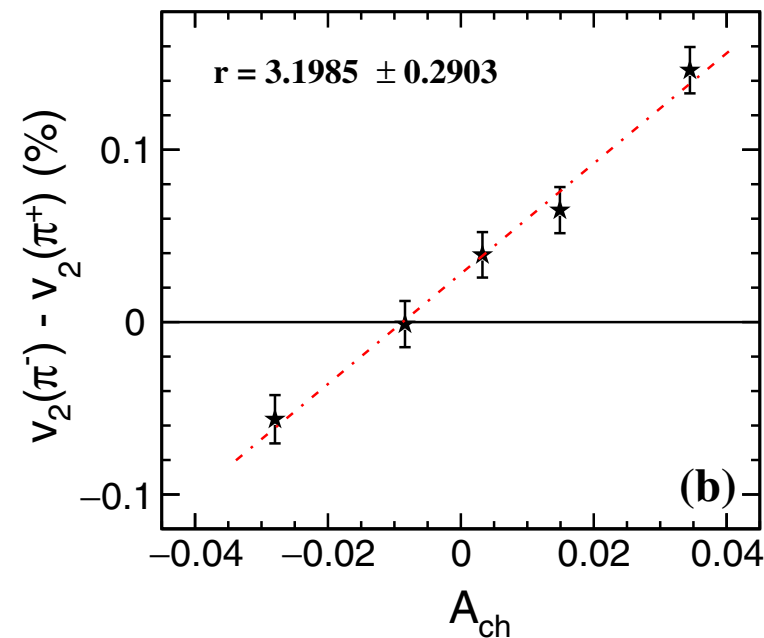
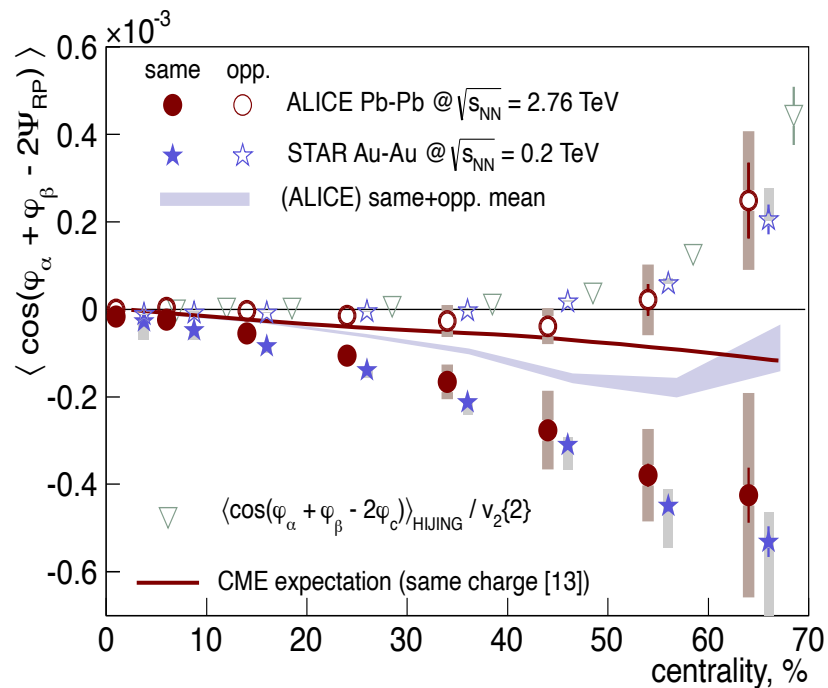
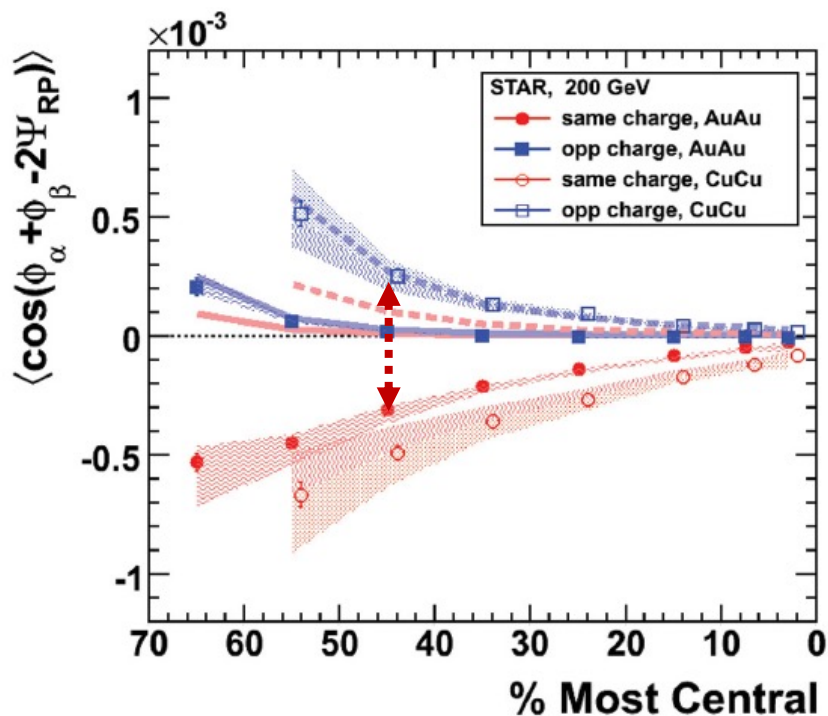
$$\begin{aligned} \gamma^{+-} &= \cos(\pi/2 - \pi/2 + 0) = 1 \\ \gamma^{++,--} &= \cos(\pi/2 + \pi/2 + 0) = -1 \end{aligned}$$

实验测量手征磁效应 (1)

高能重离子碰撞中观测到的可能的电荷分离和手征磁波的信号?

$$\gamma_{\alpha\beta} = \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi)$$

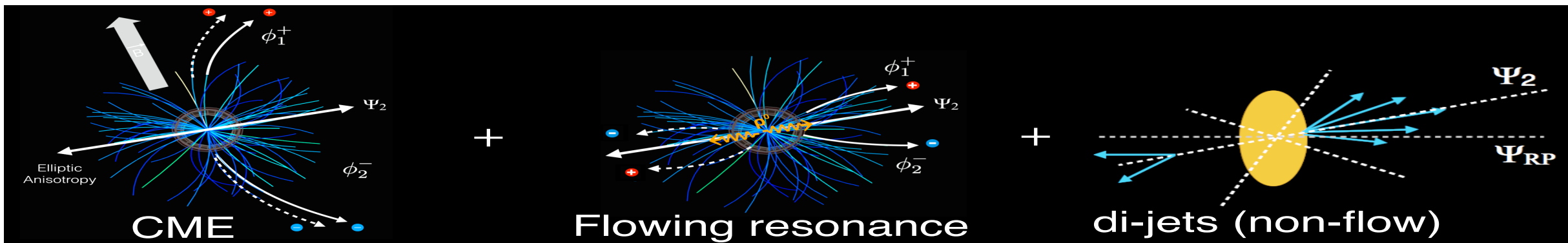
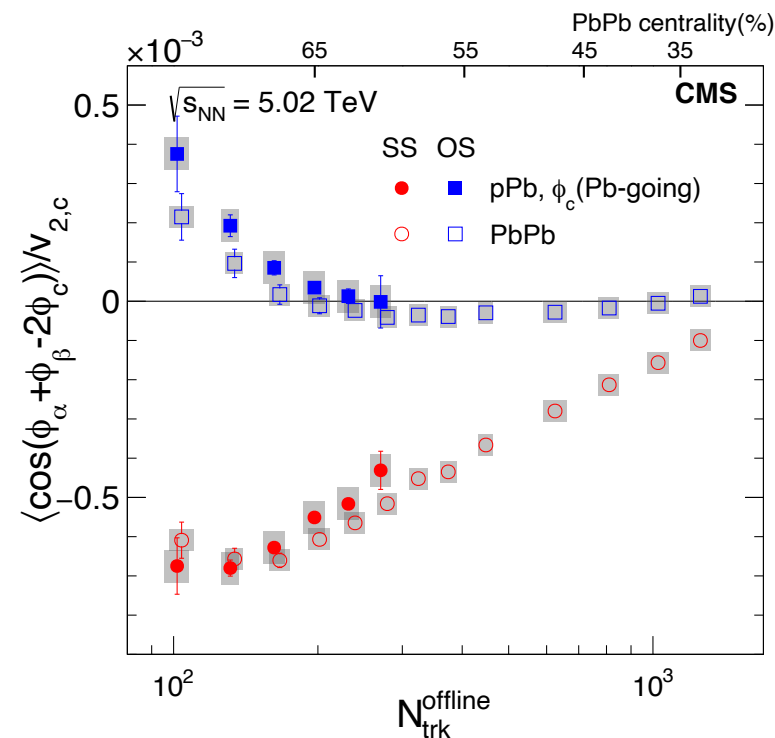
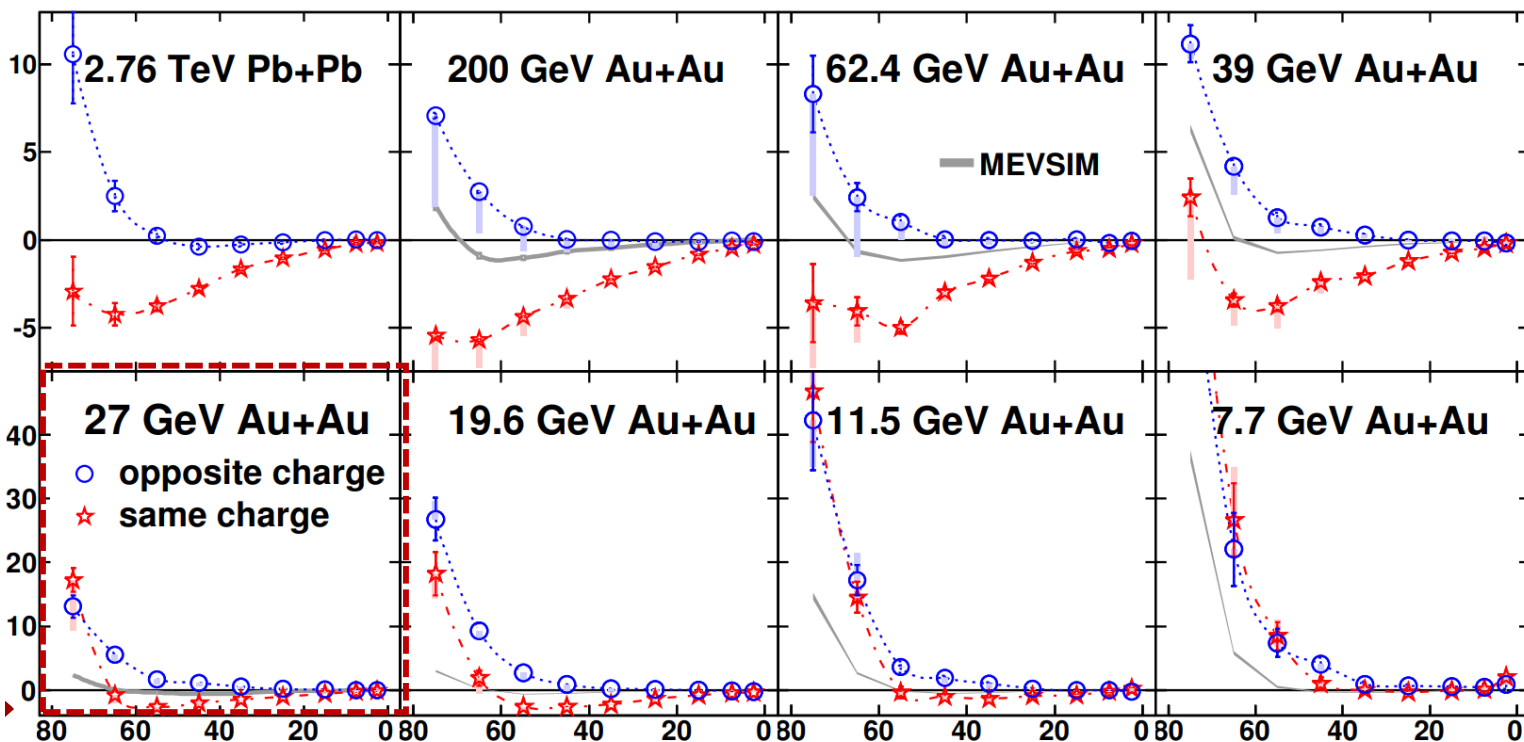
STAR Col. *PRL* **103** (2009) 251601 (编辑推荐) *PRL* **114** (2015) 252302 (编辑推荐) ALICE Col. *PRL* **110** (2013) 012301 ...



实验测量手征磁效应 (2)

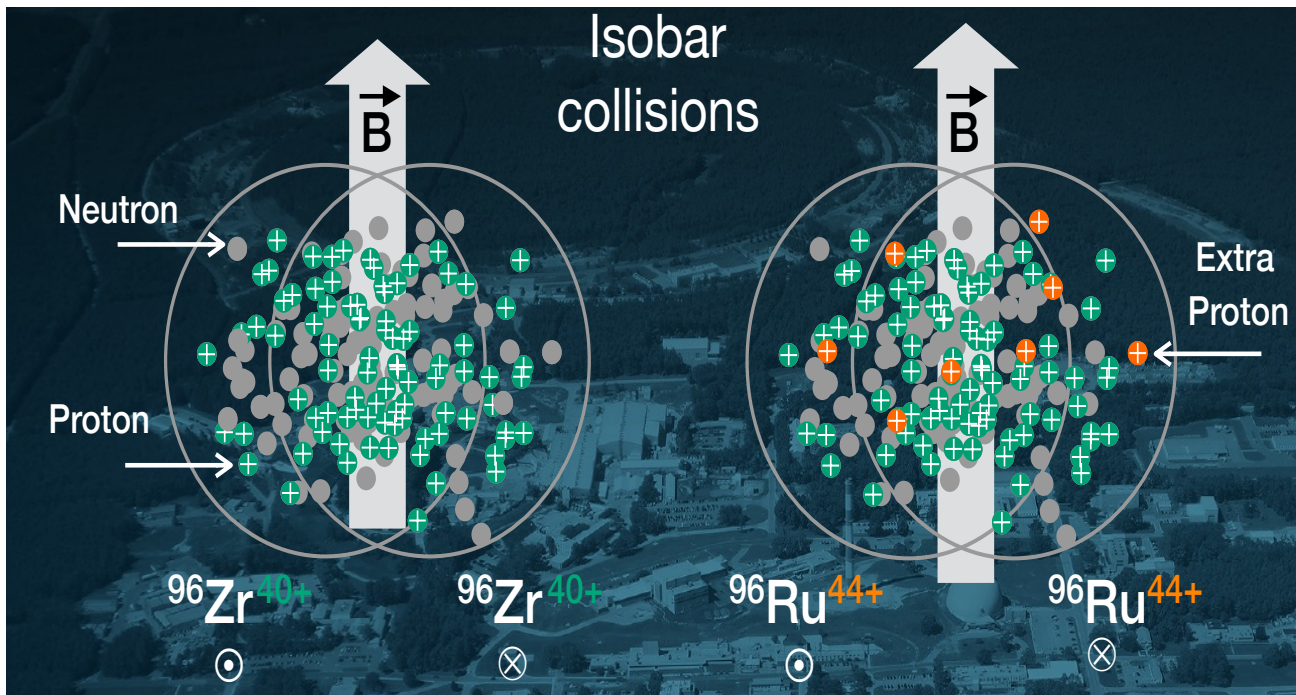
- CME信号的束流能量依赖和碰撞系统依赖

STAR Col. *PRL* **113**, 052302 (2014); CMS Col. *PRL* **118**, 122301 (2017)

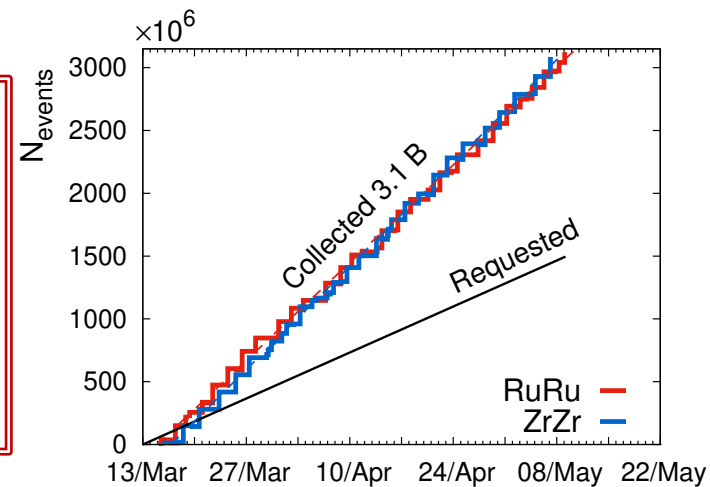


同量素实验

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



- 2018开始同量素实验
- 2021完成数据分析

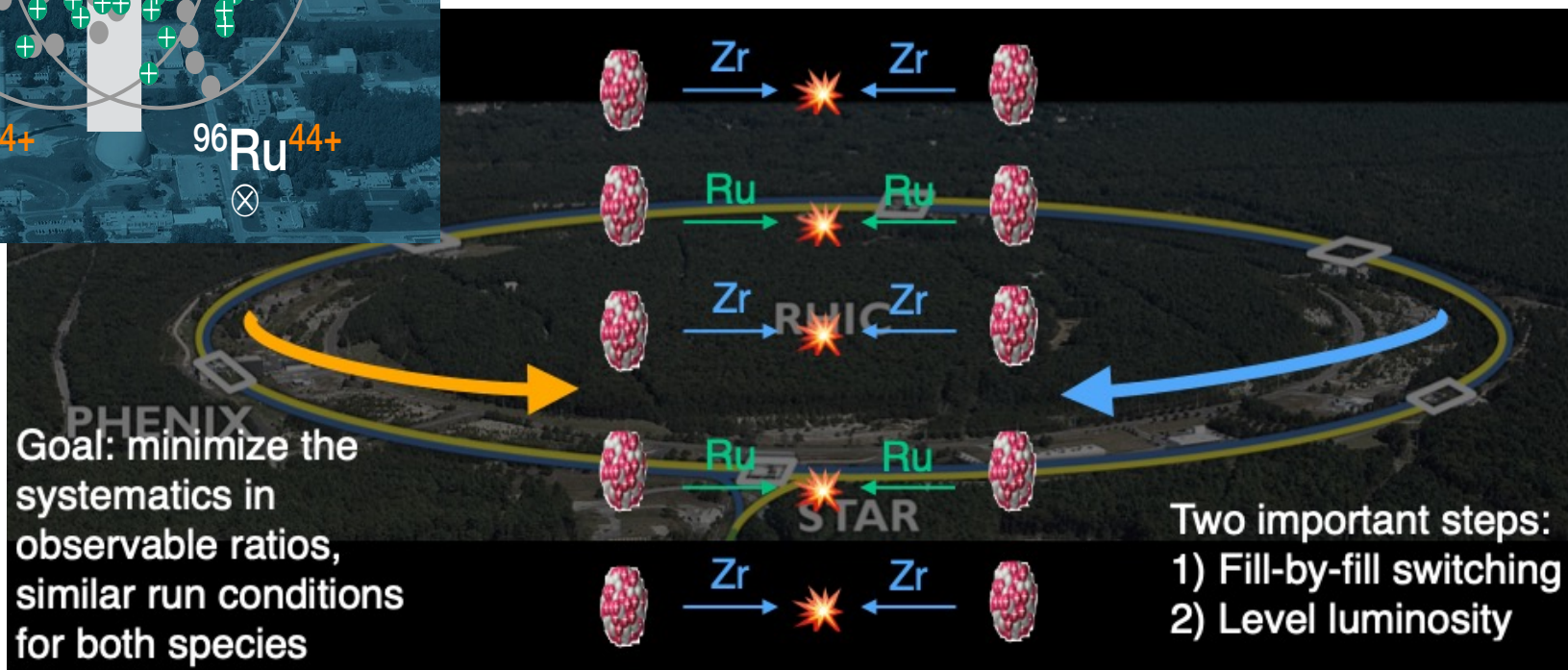


$$\Delta\gamma = \Delta\gamma^{\text{CME}} + k \frac{v_2}{N} + \Delta\gamma^{\text{non-flow}}$$

$$\Delta\gamma^{\text{Ru+Ru}} = \Delta\gamma^{\text{CME}} + k \frac{v_2}{N} + \Delta\gamma^{\text{non-flow}}$$

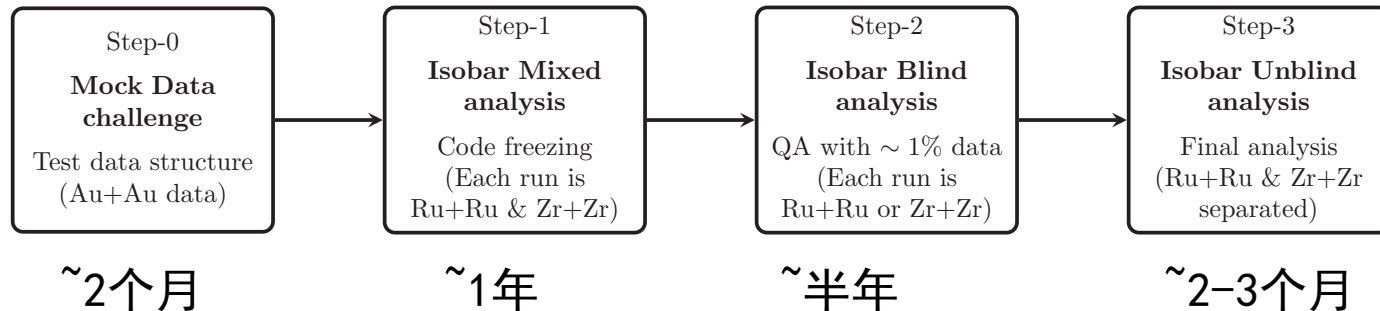
$$\Delta\gamma^{\text{Zr+Zr}} = \Delta\gamma^{\text{CME}} + k \frac{v_2}{N} + \Delta\gamma^{\text{non-flow}}$$

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



同量素实验 (2)

同量素实验新测量



Pre-defined CME criteria:

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

$$\frac{(\Delta\gamma_{112}/v_2)^{Ru+Ru}}{(\Delta\gamma_{112}/v_2)^{Zr+Zr}} > 1$$

$$\frac{(\Delta\gamma_{112}/v_2)^{Ru+Ru}}{(\Delta\gamma_{112}/v_2)^{Zr+Zr}} > \frac{(\Delta\gamma_{123}/v_3)^{Ru+Ru}}{(\Delta\gamma_{123}/v_3)^{Zr+Zr}}$$

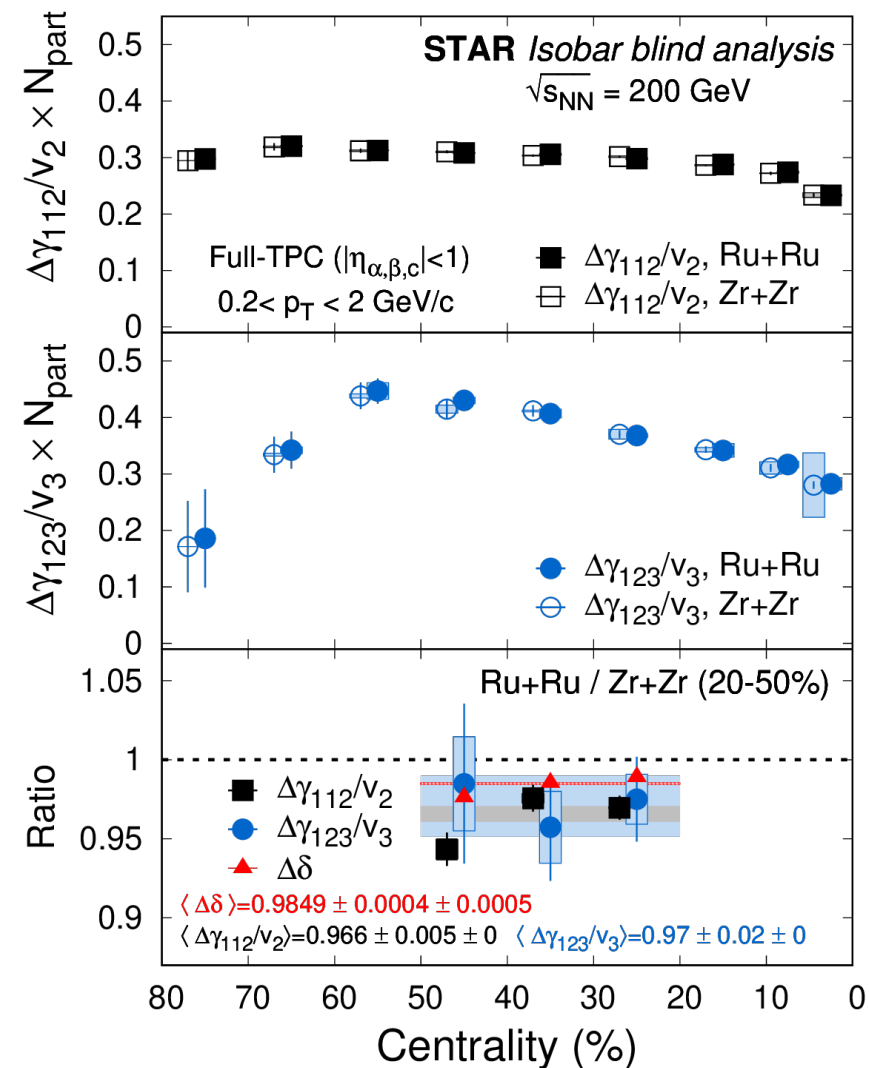
$$\frac{(\Delta\gamma_{112}/v_2)^{Ru+Ru}}{(\Delta\gamma_{112}/v_2)^{Zr+Zr}} > \frac{(\Delta\delta)^{Ru+Ru}}{(\Delta\delta)^{Zr+Zr}}$$

$$\gamma_{112} \equiv \left\langle \cos(\phi_1(\eta_1) + \phi_2(\eta_2) - 2\psi_2^{|\eta|<1}) \right\rangle$$

$$\gamma_{123} \equiv \left\langle \cos(\phi_1(\eta_1) + 2\phi_2(\eta_2) - 3\psi_3^{|\eta|<1}) \right\rangle$$

$$\delta = \langle \cos(\phi_1 - \phi_2) \rangle$$

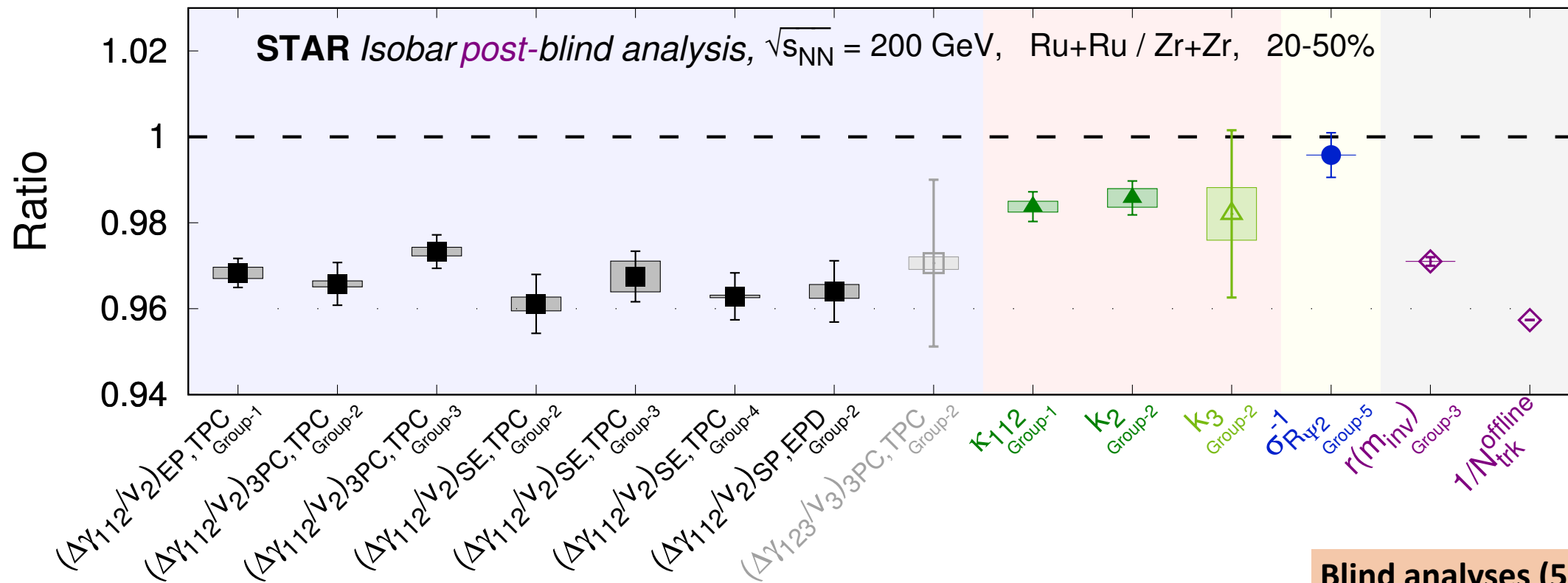
STAR Col. *PRC* 105, 014901 (2022)



Data not compatible with pre-defined CME criteria

同量素实验 (3)

STAR Col. *PRC 105*, 014901 (2022)



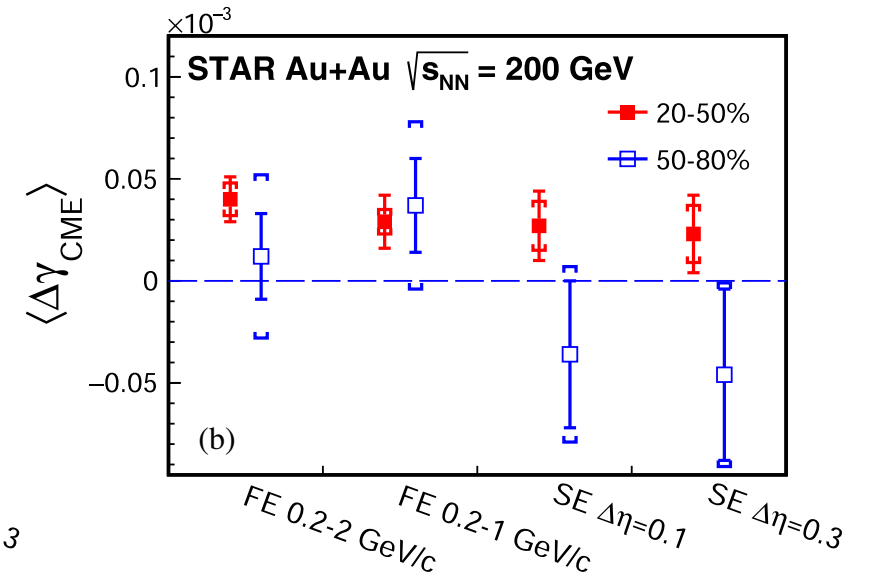
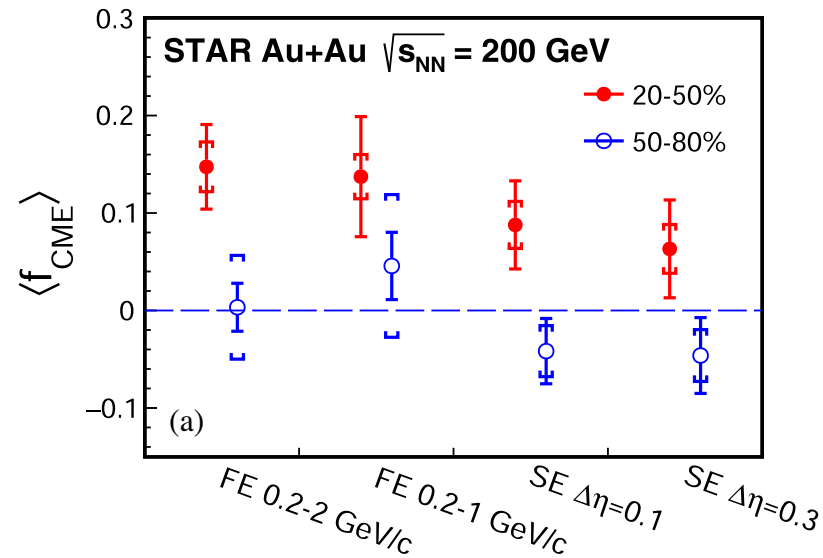
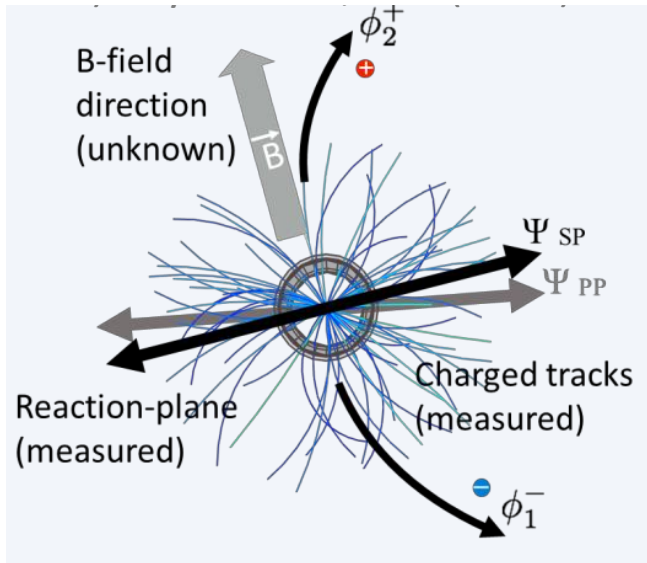
- 多个研究小组，双盲分析
 - ✓ 钨/铅对撞系统中没有观测到显著差异
 - ✓ 0.4%的数据精度指出在目前定义的CME观测量中，没有观测到信号
- 一系列的后续研究持续进行中

Blind analyses (5 groups):

- ❖ $\Delta\gamma, \Delta\delta$ and κ
- ❖ $\Delta\gamma, \Delta\delta, \Delta\gamma(\Delta\eta)$
- ❖ $\Delta\gamma$ in PP/SP, $\Delta\gamma(M_{inv})$
- ❖ $\Delta\gamma$ in PP/SP
- ❖ $R(\Delta S)$ Correlator.

新的思路和实验计划

STAR Col. *PRL* **128**, 092301 (2022)



$$\Delta\gamma(\Psi_{\text{TPC}}) = \Delta\gamma^{BG}(\Psi_{\text{TPC}}) + \Delta\gamma^{CME}(\Psi_{\text{TPC}})$$

$$\Delta\gamma(\Psi_{\text{ZDC}}) = \Delta\gamma^{BG}(\Psi_{\text{ZDC}}) + \Delta\gamma^{CME}(\Psi_{\text{ZDC}})$$

$$\frac{\Delta\gamma^{BG}(\Psi_{\text{TPC}})}{\Delta\gamma^{BG}(\Psi_{\text{ZDC}})} = \frac{v_2(\Psi_{\text{TPC}})}{v_2(\Psi_{\text{ZDC}})}$$

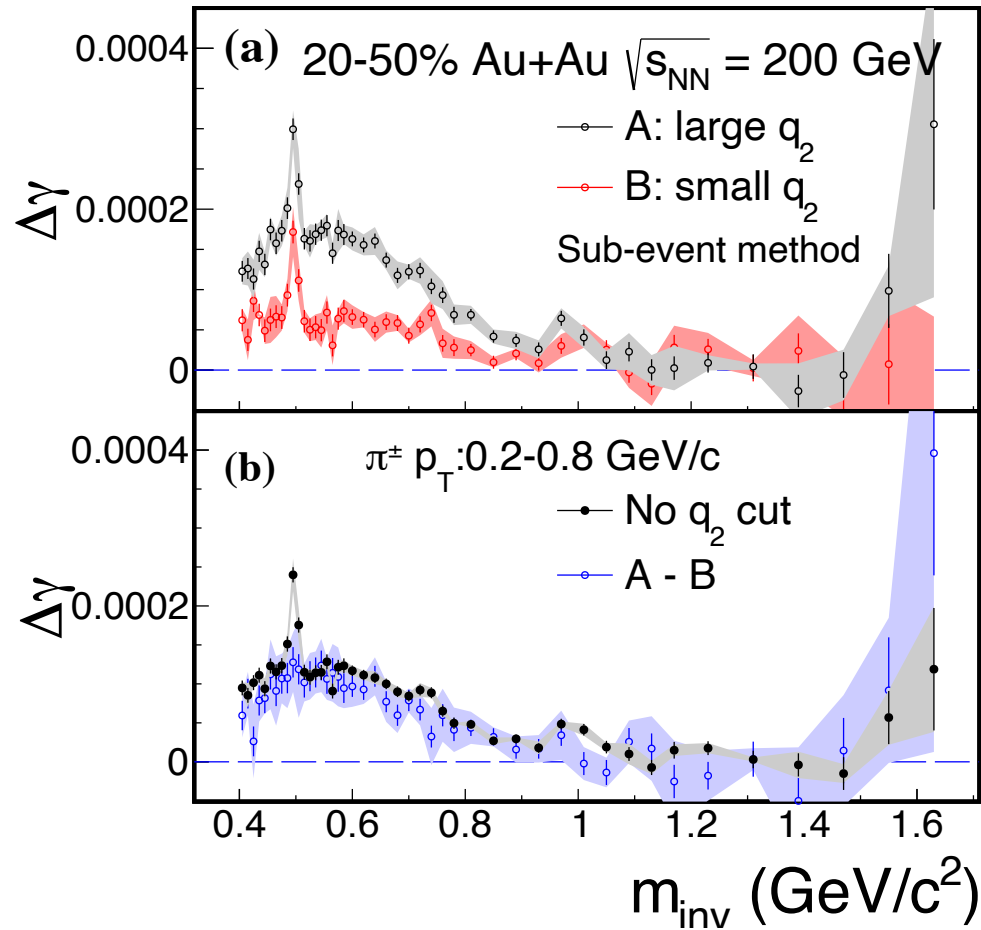
$$\frac{\Delta\gamma^{CME}(\Psi_{\text{TPC}})}{\Delta\gamma^{CME}(\Psi_{\text{ZDC}})} = \frac{v_2(\Psi_{\text{ZDC}})}{v_2(\Psi_{\text{TPC}})}$$

$$f_{\text{CME}} = \frac{\Delta\gamma^{CME}(\Psi_{\text{TPC}})}{\Delta\gamma(\Psi_{\text{TPC}})}$$

- STAR 2011/2014/2016金核数据 (2. 4b)
- 集体流物理背景扣除后, 在20%-50%半中心系统可能还有信号, 而50-80%周边碰撞信号很弱
- 非集体流效应因素效应正在研究中
- BES II (27GeV等, 升级的事件平面探测器)

物理背景分析

STAR Col. arXiv:2006.05035 (accepted by PRC)



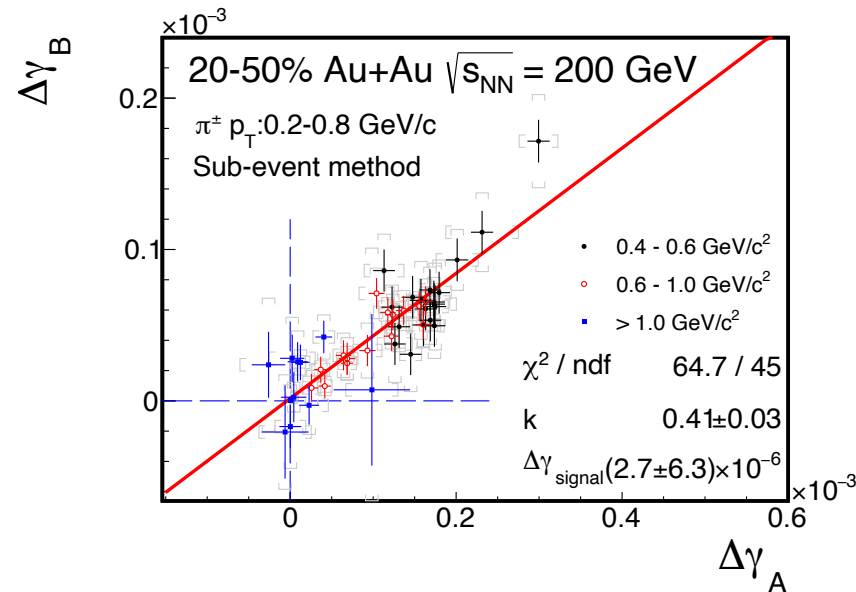
$$\Delta\gamma(m) = r(m) \cdot \cos(\alpha + \beta - 2\phi_{\text{reso.}}) \cdot v_{2,\text{reso.}} + \text{CME}$$

- 使用事件形状工程ESE分析背景分布

✓ 挑选不同 v_2 事件(q_2)

✓ 背景分布 $\Delta\gamma_A - \Delta\gamma_B$

✓ 拟合 $\Delta\gamma = k \cdot (\Delta\gamma_A - \Delta\gamma_B) + \text{CME}$



- $\Delta\gamma$ 信号比前面的测量小一个数量级

总结与展望

重离子碰撞提供了研究宇宙早期新物质形态的理想场所，CME在一系列科学问题处于显著位置。

- ✓ STAR早先电荷分离测量支持CME信号
- ✓ STAR新的同量素实验测量指出，对于目前采用的通用观测量，没有探测到CME信号
- ✓ 实验数据精度和严格物理背景分析是关键要素
 - ✓ 金核数据中多探测器联合分析(PP/SP)给出 $1-3\sigma$ 信号
 - ✓ 2023–2025高统计量金核对撞实验将显著提高测量精度

感谢STAR合作组！
感谢聆听，请批评指正！

简单介绍复旦ALICE计划

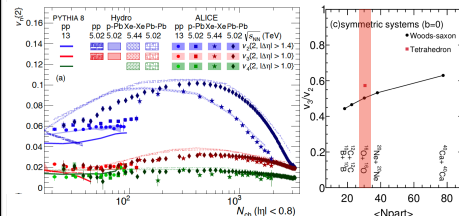
ALICE实验小系统计划

O+O, p+O
~1week 2024



Flow proposal: v_n

ALICE, PRL123, 142301 (2019)

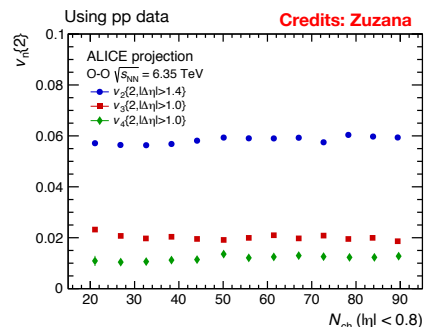


❖ v_n from 2- and multi-particle correlations in O-O runs, and comparisons to results in pp, p-Pb, Xe-Xe and Pb-Pb collisions

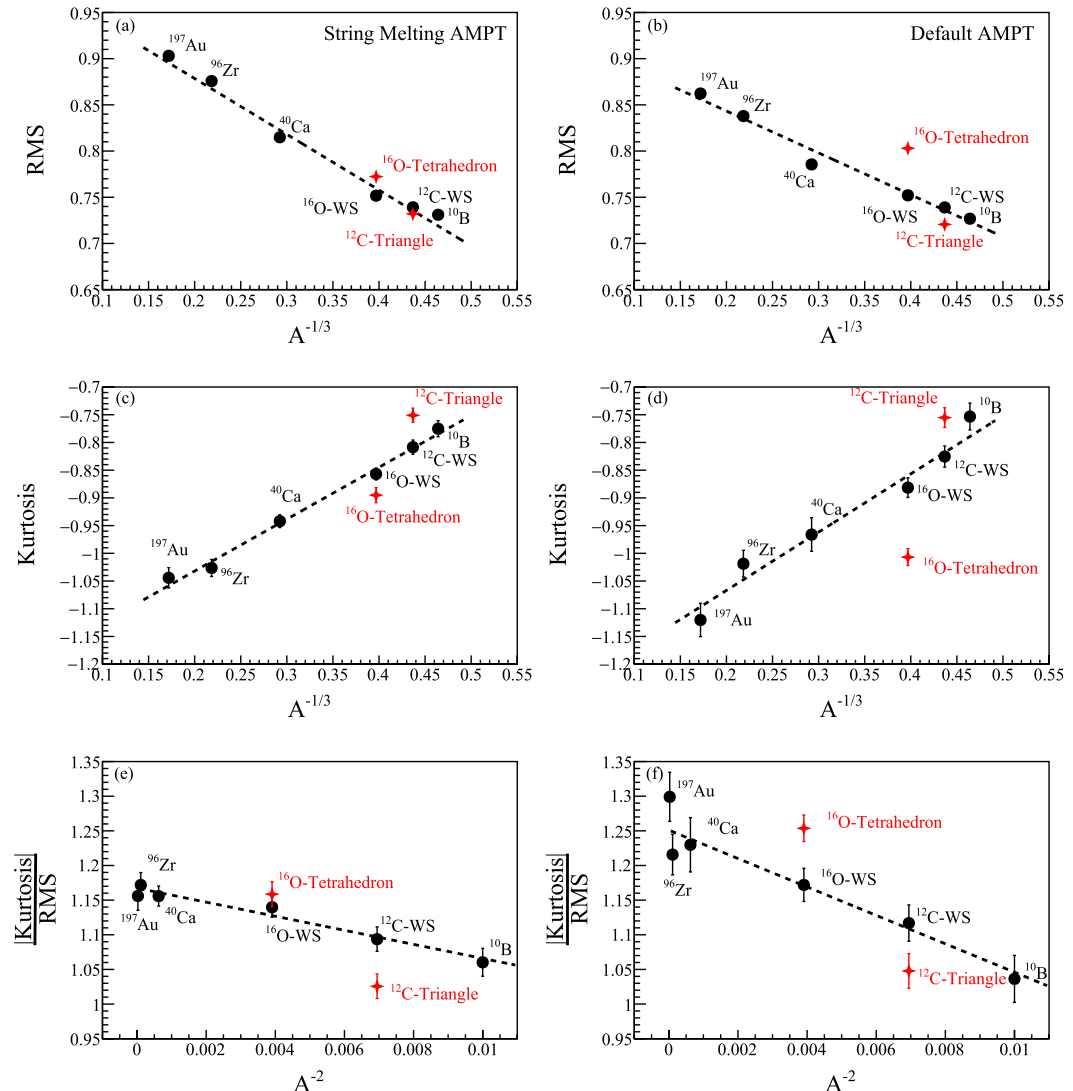
- standard cumulants and v_n
- $v_2 > v_3 > v_4$ observed in all systems (at low N_{ch})
- Neither hydro nor PYTHIA describes the data for such low N_{ch} region

❖ Different initial conditions

- Pb-Pb & Xe-Xe $\rightarrow$ geometry
- p-Pb & pp $\rightarrow$ fluctuations
- O-O $\rightarrow$ geometry
 - Large overlap with p-Pb & pp at low N_{ch} (flu-dominant)
 - Large overlap with Pb-Pb at high N_{ch} (geo-dominant)
 - v_3/v_2 ratio is sensitive to the nuclear structure of ^{16}O
 - Woods-saxon vs Tetrahedron



Y.-Z. Wang, S. Zhang and Y.-G. Ma, *Phys. Lett. B* **831** (2022) 137198



ALICE, the projections for the O+O RUN,
<https://indico.cern.ch/event/995891/>