



相对论重离子碰撞中的手征磁效应实验研究进展

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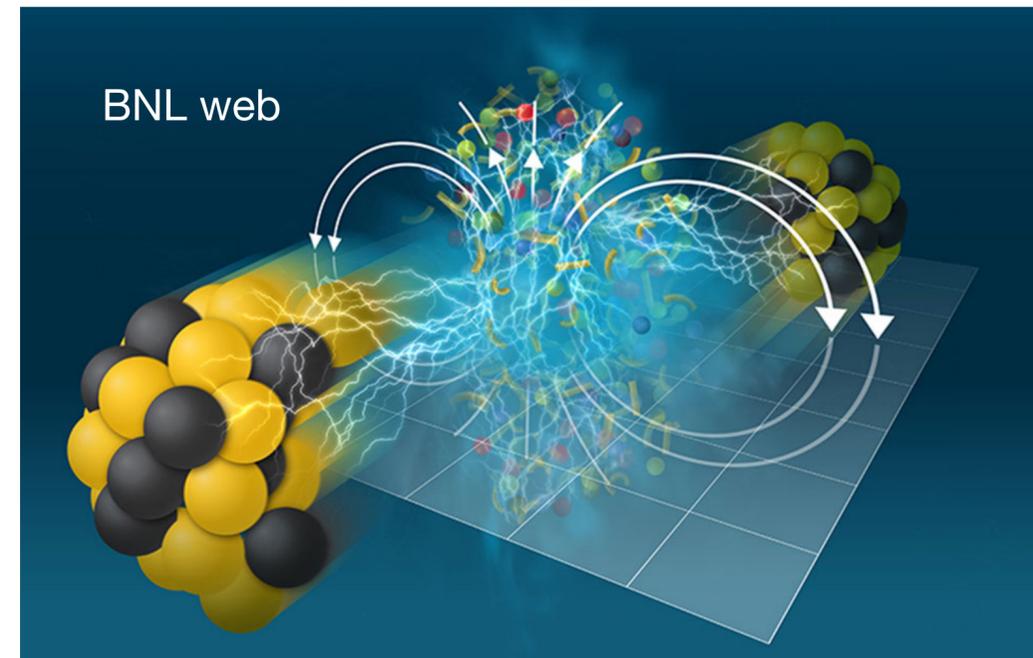
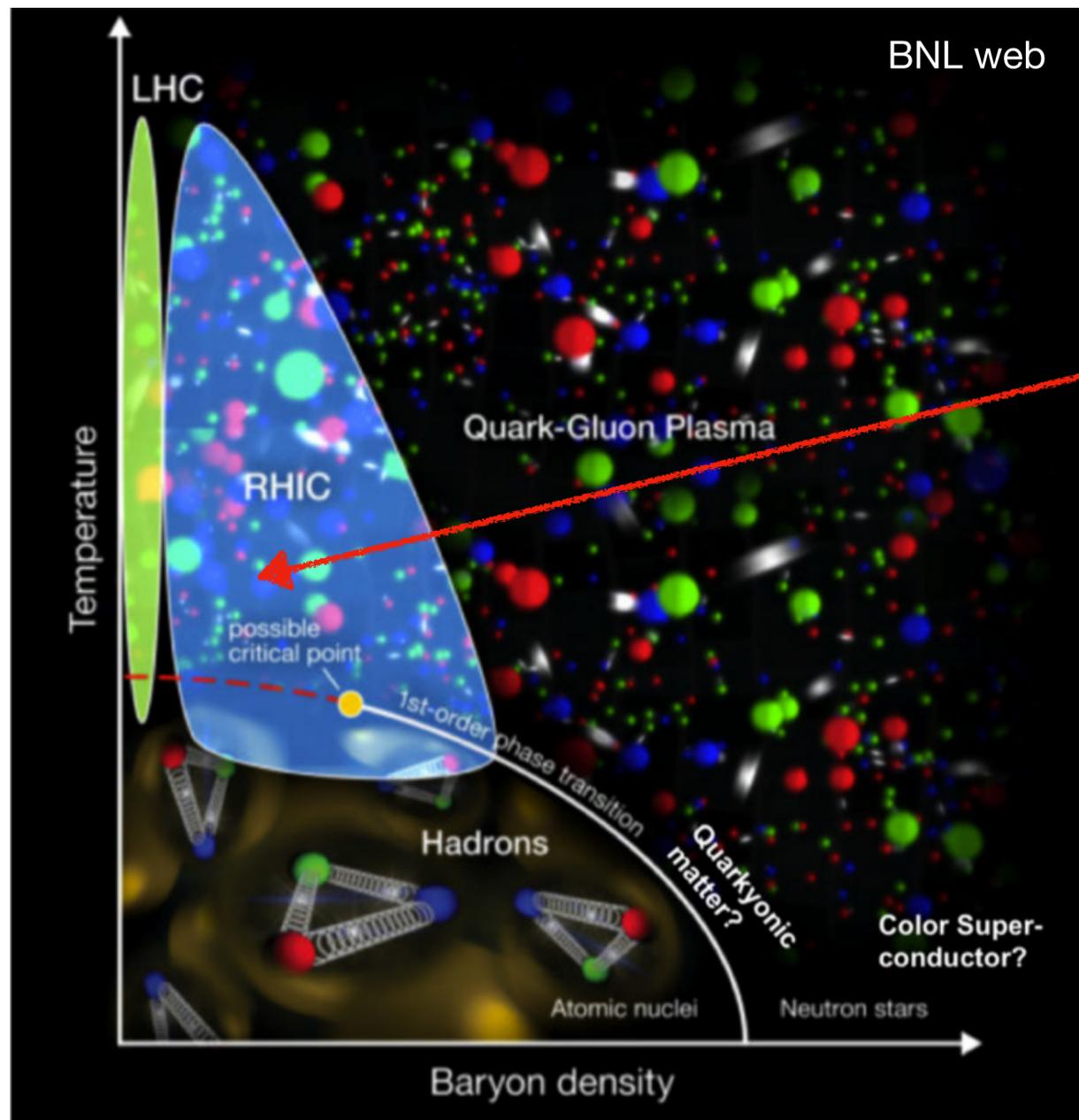
01 手征磁效应介绍

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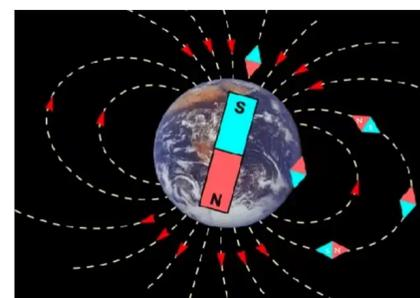
03 总结与展望



相对论重离子对撞与手征磁效应 (CME)



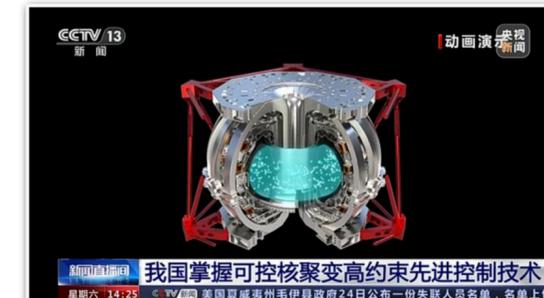
$B \sim 10^{18}$ 高斯



~0.5 高斯



~1 万高斯



~10 万高斯

相对论重离子对撞机产生夸克胶子等离子体:

- 手征对称性恢复
- 强磁场

相对论重离子对撞与手征磁效应 (续)

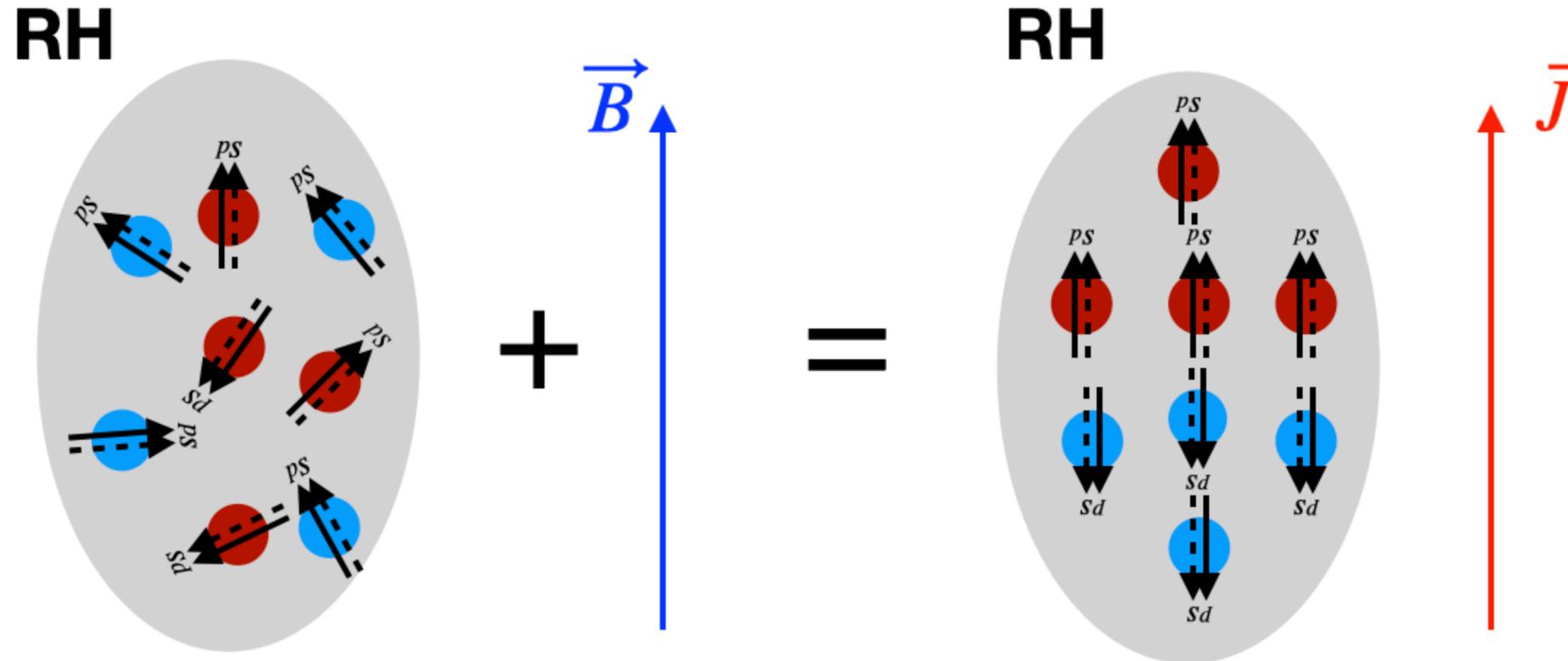
Possibility of Spontaneous Parity Violation in Hot QCD

Dmitri Kharzeev,¹ Robert D. Pisarski,² and Michel H. G. Tytgat^{2,3}

¹RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000

²Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000

D.E. Kharzeev, J. Liao, Nat. Rev. Phys. 3 (2021) 55–63



Dmitri Kharzeev

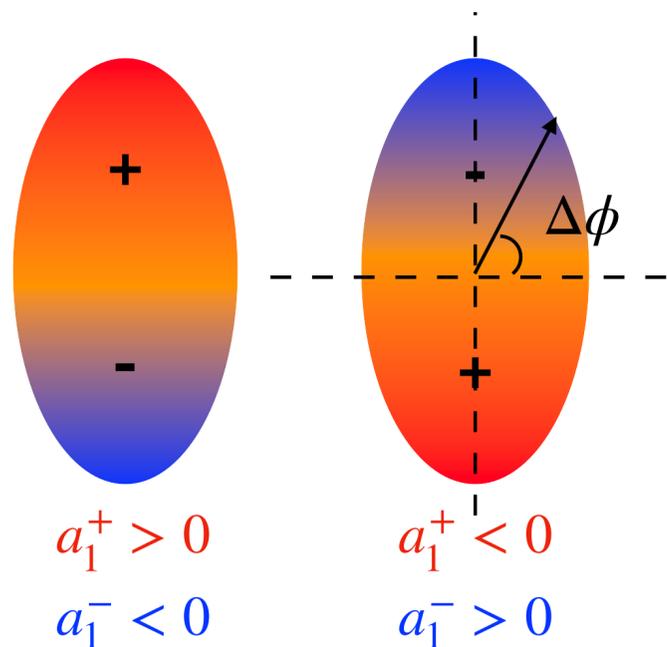
98年提出 (35岁)

QCD中的局域CP对称性破坏导致QGP手征不平衡（比如更多右手夸克）。

在外磁场下表现为沿着磁场方向的电荷分离效应。

研究意义：实验上检验强相互作用中的CP对称性。

如何在重离子实验中测量CME?



$$f(\Delta\phi^+) = 2a_1^+ \sin(\Delta\phi^+) + \sum 2v_n \cos(n\Delta\phi^+)$$

两大特点:

- ① 手征反常的涨落特性 $\langle a_1^\pm \rangle = 0$.
- ② 自旋磁矩的电荷依赖性 $a_1^+ = -a_1^-$.



Sergei A. Voloshin

PHYSICAL REVIEW C 70, 057901 (2004)

Parity violation in hot QCD: How to detect it

Sergei A. Voloshin

2004年第一个实验方法提出:

$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos \Delta\phi_\alpha \cos \Delta\phi_\beta \rangle - \langle \sin \Delta\phi_\alpha \sin \Delta\phi_\beta \rangle = v_1^\alpha v_1^\beta - a_1^\alpha a_1^\beta$$

$$\gamma_{112}^{+-} = v_1^2 + a_1^2$$

$$\gamma_{112}^{++/--} = v_1^2 - a_1^2$$

Other observables:

N. Magdy, Phys. Rev. C 97 (2018) 061901

A. H. Tang, Chin. Phys. C 44 054101 (2020)

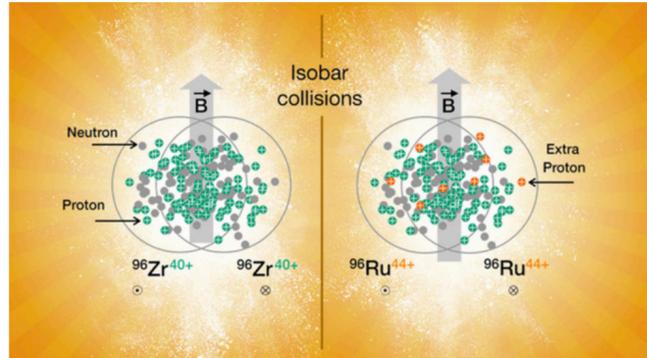
Subikash Choudhury, CPC 46 014101 (2022)

实验结果大事记

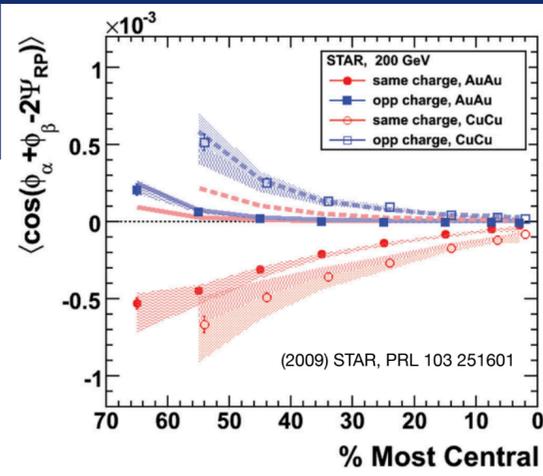
提出理论

1998

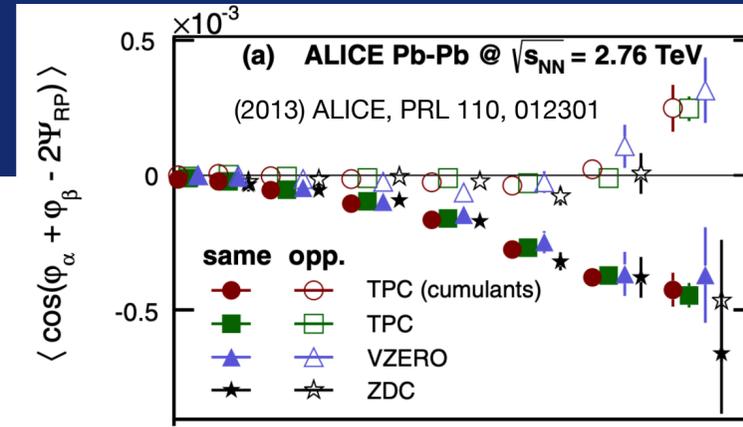
2004提出实验方法



(2023) STAR, PLB 839 137779

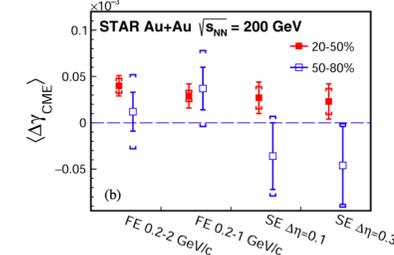


2009 STAR发现“信号”



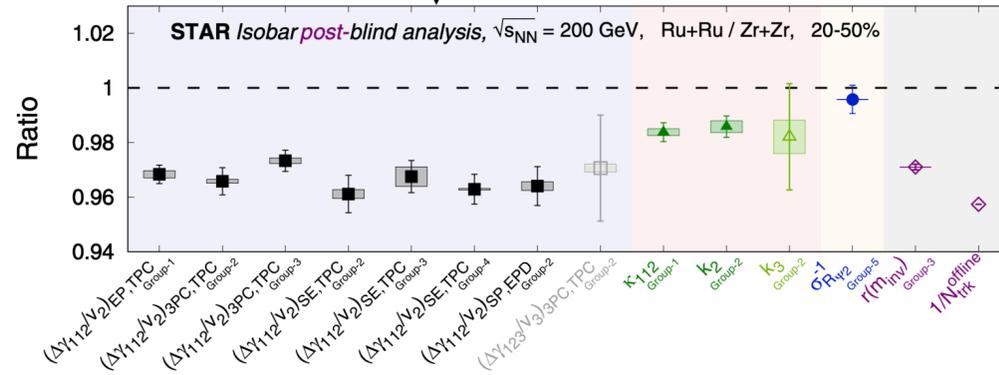
2013 ALICE得到类似结果
信号或背景?

(2013) STAR, PRC 88, 064911

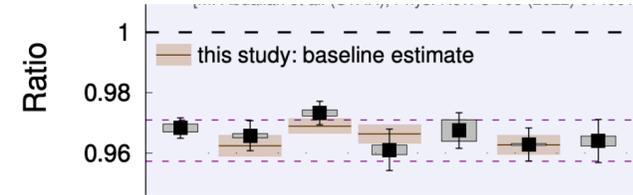


(2022) STAR, PRL 128, 0921301

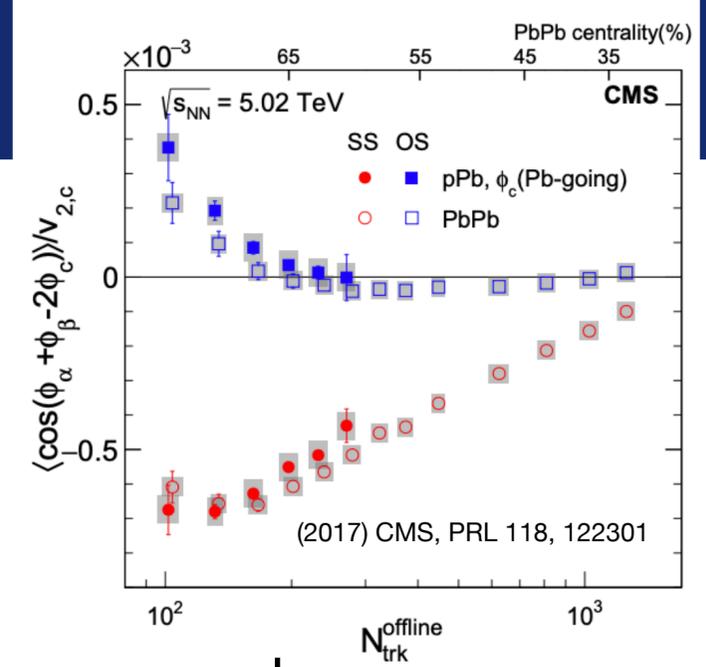
(2022) STAR, PRC 106, 034908



(2024) STAR, PRR, 6 032005



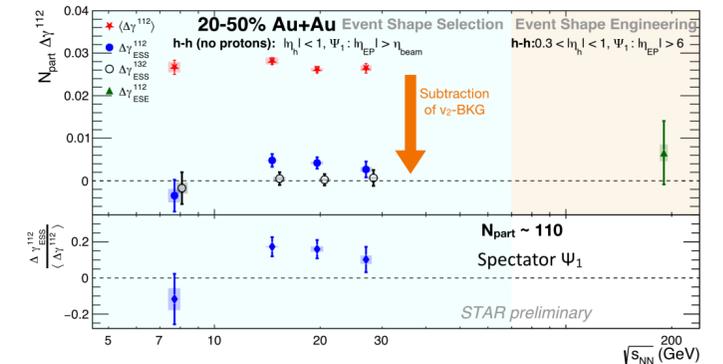
(2024) STAR, PRC, 110 014905



2017 CMS在p+Pb中得到类似结果
背景主导

(2018) ALICE, PLB 777 151

(2018) CMS, PRC 97, 044912



2024 ALICE Phys. Lett. B 856 138862

BESII 新结果 (准备中)

2025

实验研究的主要困难是什么？

$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos \Delta\phi_\alpha \cos \Delta\phi_\beta \rangle - \langle \sin \Delta\phi_\alpha \sin \Delta\phi_\beta \rangle = v_1^\alpha v_1^\beta - a_1^\alpha a_1^\beta$$

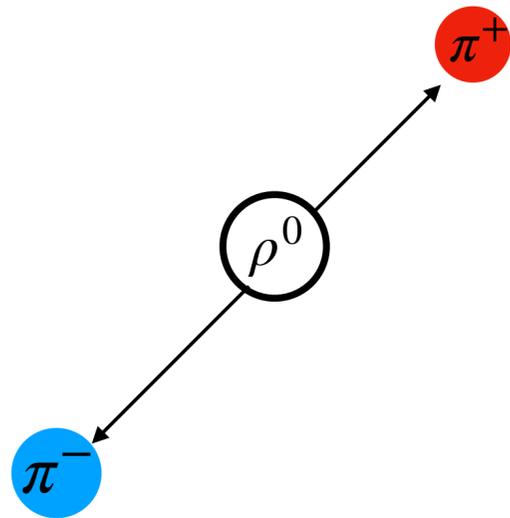
↑
假设产生的粒子统计独立

实验研究的主要困难是什么？

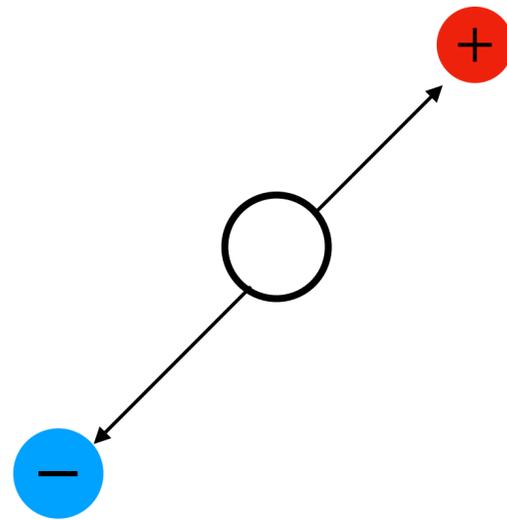
$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos \Delta\phi_\alpha \cos \Delta\phi_\beta \rangle - \langle \sin \Delta\phi_\alpha \sin \Delta\phi_\beta \rangle = v_1^\alpha v_1^\beta - a_1^\alpha a_1^\beta$$

假设产生的粒子统计独立 **✘**

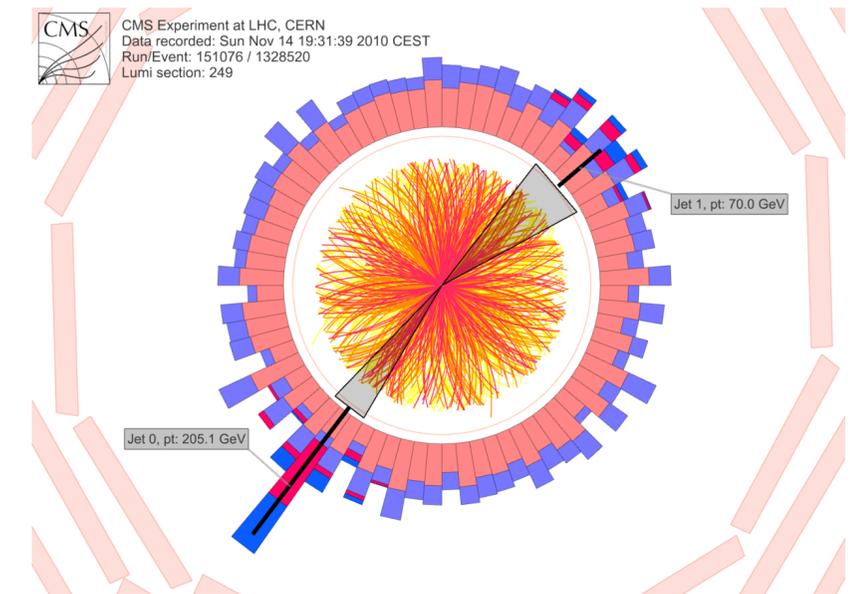
共振态衰变



局域电荷守恒



喷注、动量守恒。。。



实验研究的主要困难是什么？

$$\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos \Delta\phi_\alpha \cos \Delta\phi_\beta \rangle - \langle \sin \Delta\phi_\alpha \sin \Delta\phi_\beta \rangle = v_1^\alpha v_1^\beta - a_1^\alpha a_1^\beta$$

Key: 假设产生的粒子统计独立 **×**

$$\begin{aligned} \gamma_{112} &= \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos \Delta\phi_\alpha \cos \Delta\phi_\beta \rangle - \langle \sin \Delta\phi_\alpha \sin \Delta\phi_\beta \rangle \\ &= \langle \cos \Delta\phi_\alpha \rangle \langle \cos \Delta\phi_\beta \rangle + \underbrace{\text{Cov}(\cos \Delta\phi_\alpha, \cos \Delta\phi_\beta)}_{\mathbf{B}_{in}} - \langle \sin \Delta\phi_+ \rangle \langle \sin \Delta\phi_- \rangle - \underbrace{\text{Cov}(\sin \Delta\phi_+, \sin \Delta\phi_-)}_{\mathbf{B}_{out}} \\ &= v_1^\alpha v_1^\beta - a_1^\alpha a_1^\beta + \mathbf{B}_{in} - \mathbf{B}_{out} \end{aligned}$$

实验研究的主要困难是什么？

理想情况

$$\gamma_{112}^{+-} = v_1^2 + a_1^2$$

$$\gamma_{112}^{++/--} = v_1^2 - a_1^2$$

两个方程两个未知数

实际情况

$$\gamma_{112}^{+-} = a_1^2 + v_1^2 + \overset{b}{\boxed{B_{\text{in}}^{+-} - B_{\text{out}}^{+-}}}$$

$$\gamma_{112}^{++/--} = -a_1^2 + \boxed{v_1^2 + B_{\text{in}}^{++/--} - B_{\text{out}}^{++/--}} \underset{c}{}$$

两个方程三个未知数！

解决方案：

- ① 令 $B = 0$
- ② 令 $B_{\text{in}} = B_{\text{out}}$
- ③ 令 $B^{+-} = B^{++/--}$
- ④ 再加一个方程

鲜有研究

Event shape engineering / selection

鲜有研究

Isobar / spectator plane vs. participant plane

实验研究进展——Event shape engineering

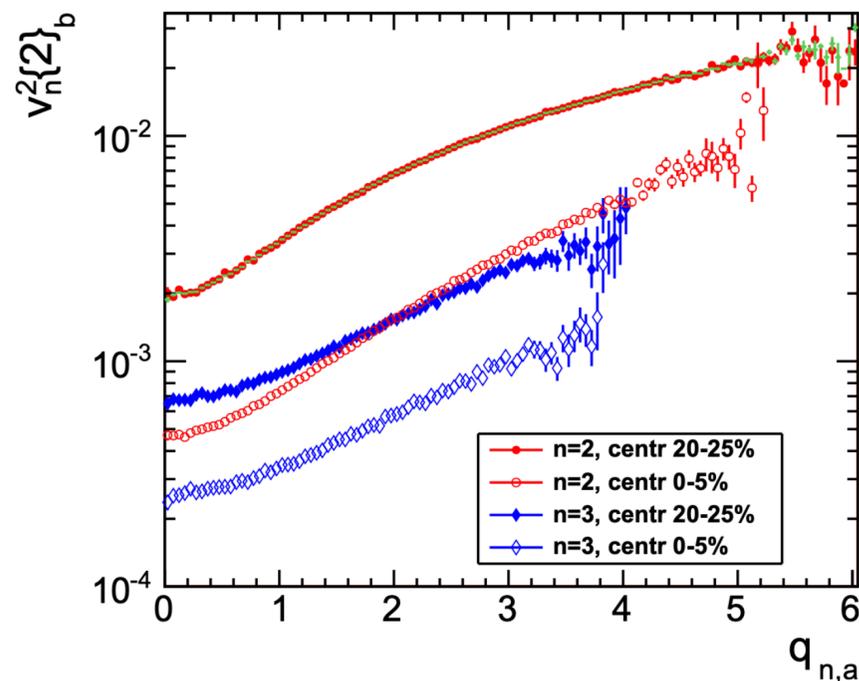
$$\Delta\gamma = \gamma^{+-} - \gamma^{++/--} = 2a_1^2 + B_{in} - B_{out}$$

$$B_{in} - B_{out} \propto v_2$$

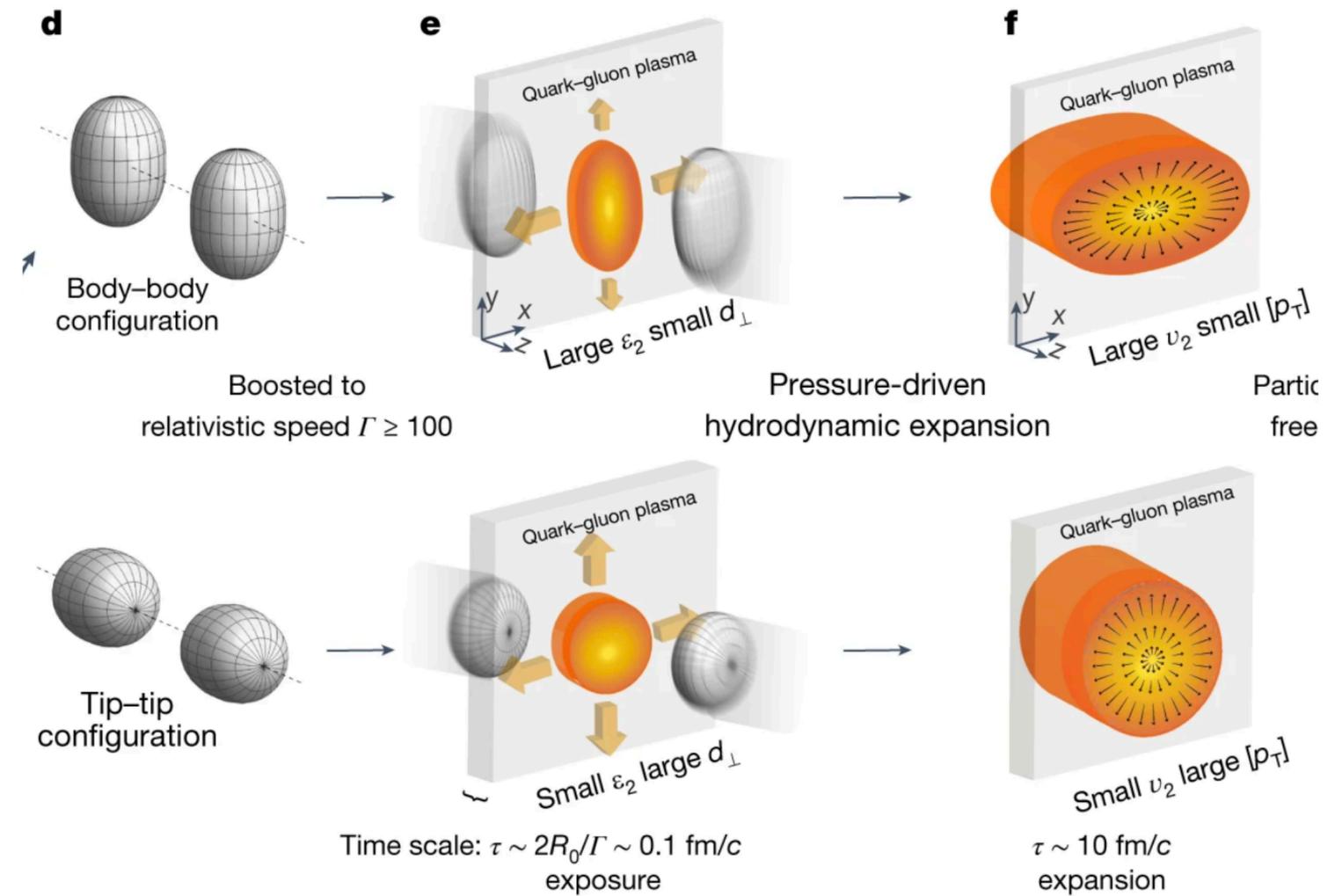
事件选择:

- ① 相同中心度: 相同磁场
- ② 不同事件形状: 不同 v_2

$$q_2 = \frac{|Q_2|}{\sqrt{M}}, \quad \vec{Q}_2 = \left(\sum \cos 2\phi_i, \sum \sin 2\phi_i \right)$$



Jurgen Schukraft et al., PLB 719 394-398



STAR, Nature 635 67-72 (2024)

PRL 105, 172301 (2010)

PHYSICAL REVIEW LETTERS

week ending
22 OCTOBER 2010

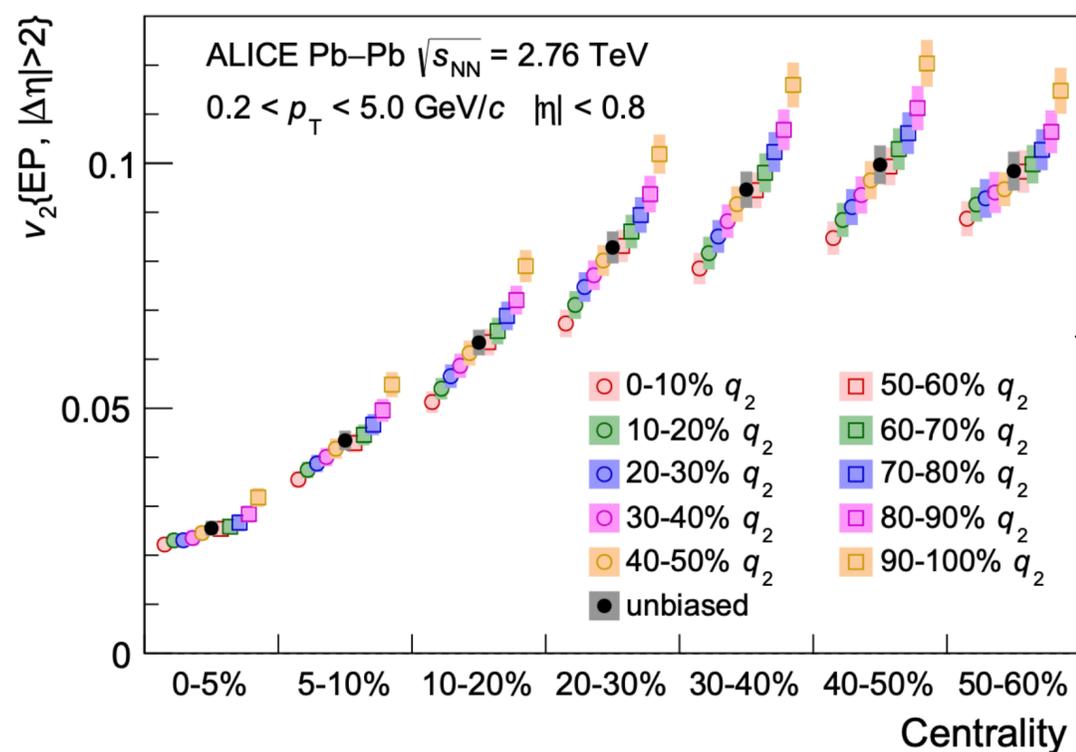
Testing the Chiral Magnetic Effect with Central $U + U$ Collisions

Sergei A. Voloshin

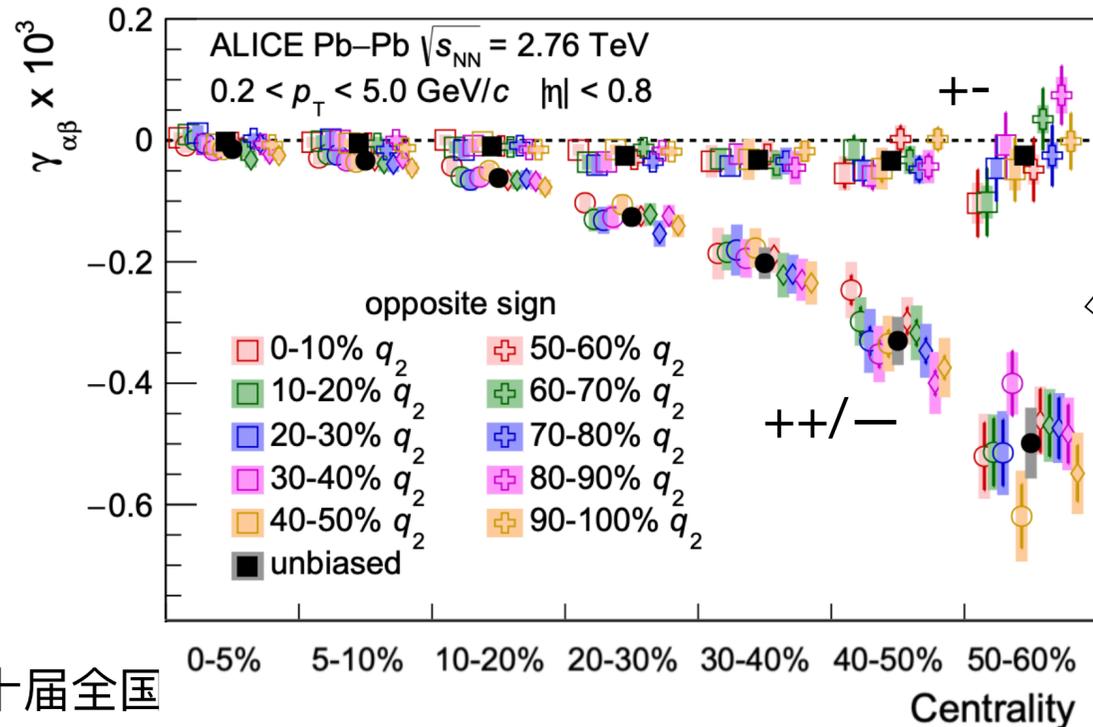
Wayne State University, Detroit, Michigan 48201, USA
(Received 22 June 2010; published 19 October 2010)

实验研究进展——Event shape engineering

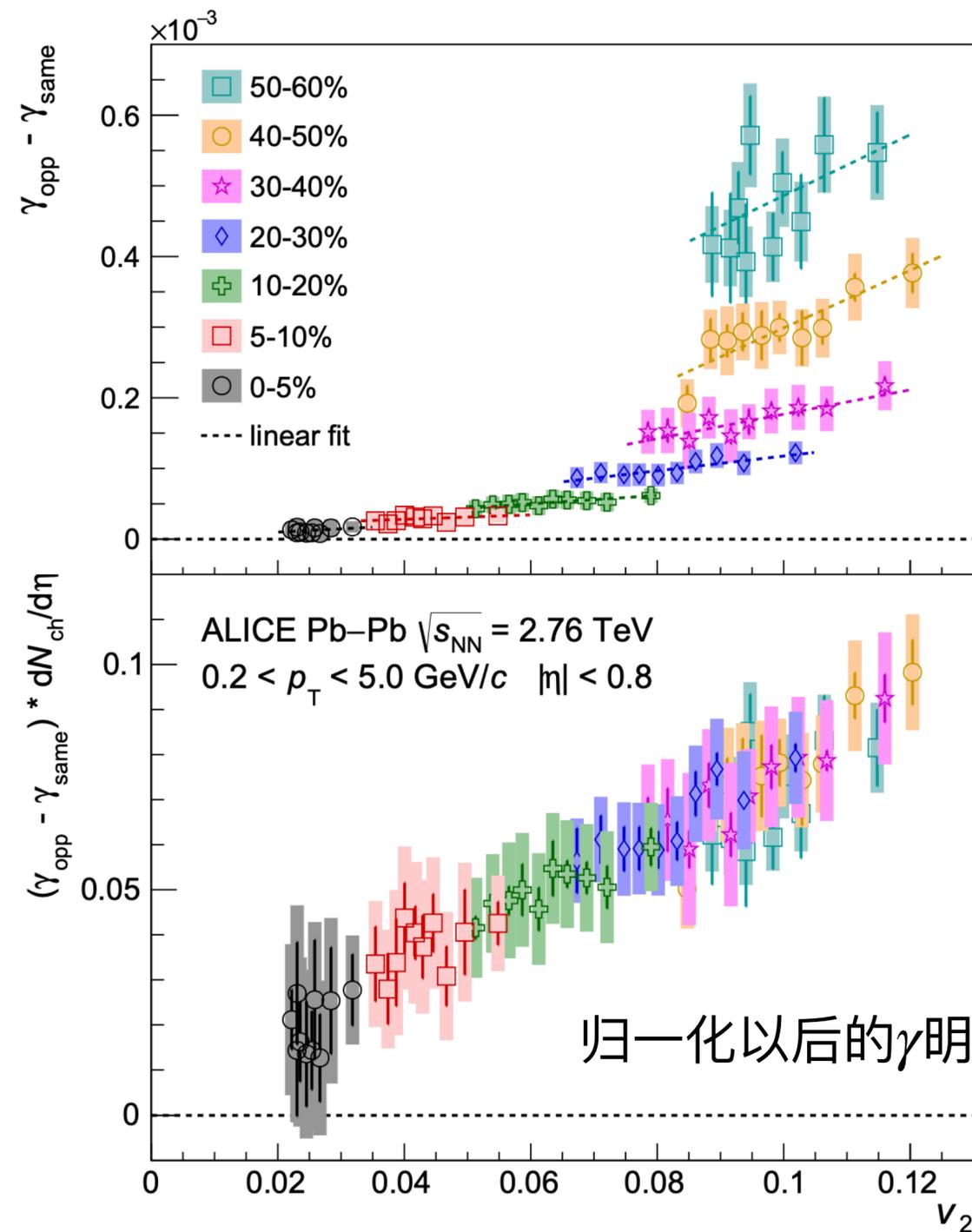
ALICE, Phys. Lett. B 777 151-162



不同的 q_2 有不同的 v_2



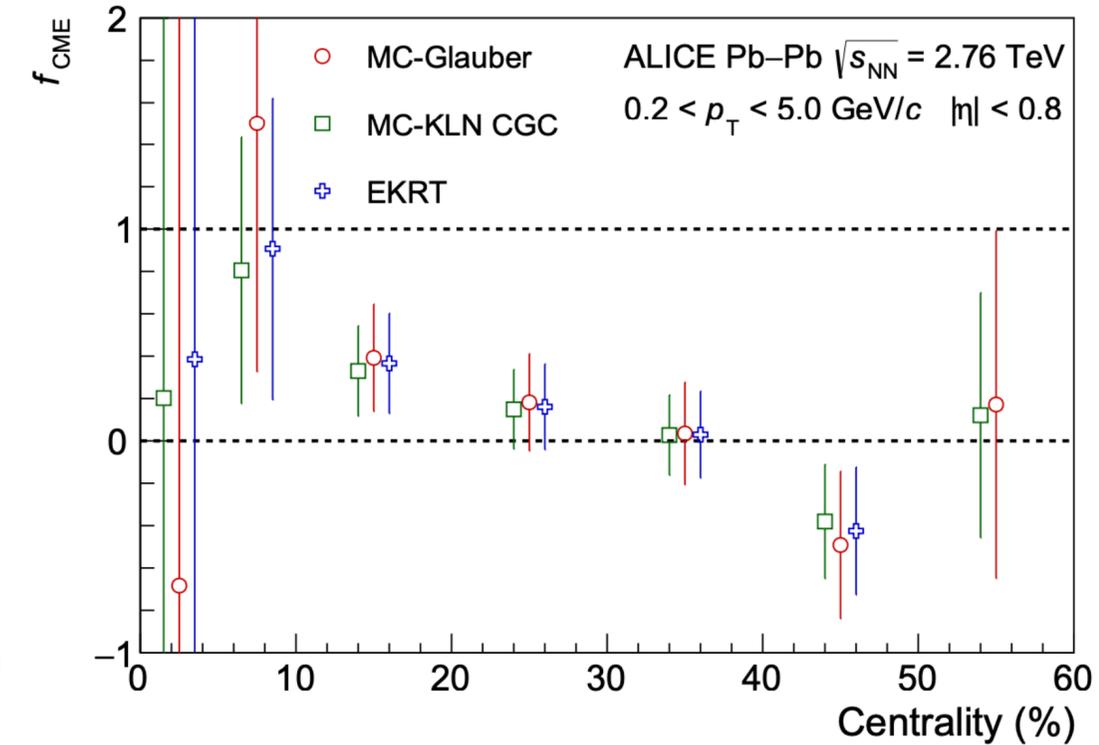
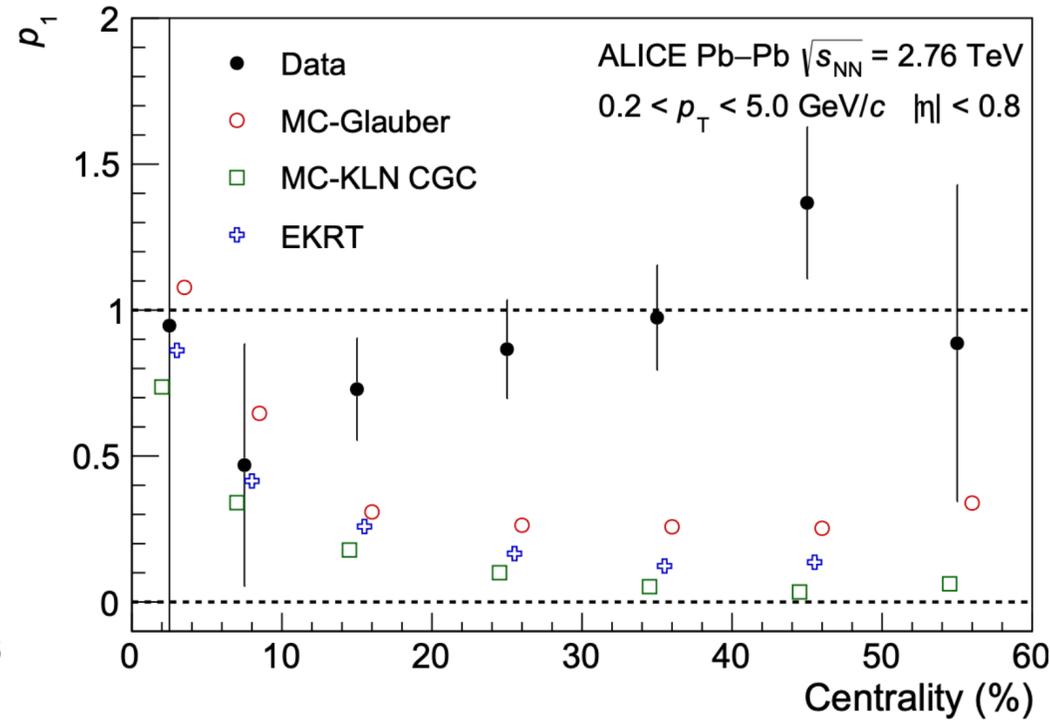
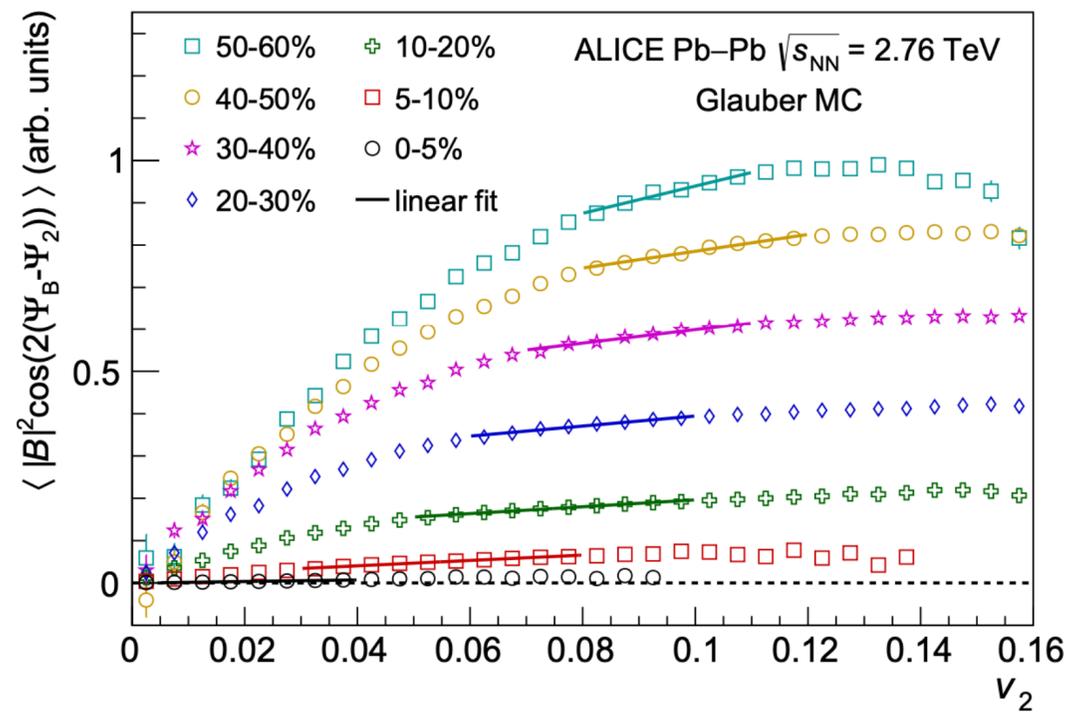
不同的 q_2 有不同的 γ



实验研究进展——Event shape engineering

CME随 v_2 的变化?

ALICE, Phys. Lett. B 777 151-162



$$F_1(v_2) = p_0(1 + p_1(v_2 - \langle v_2 \rangle) / \langle v_2 \rangle),$$

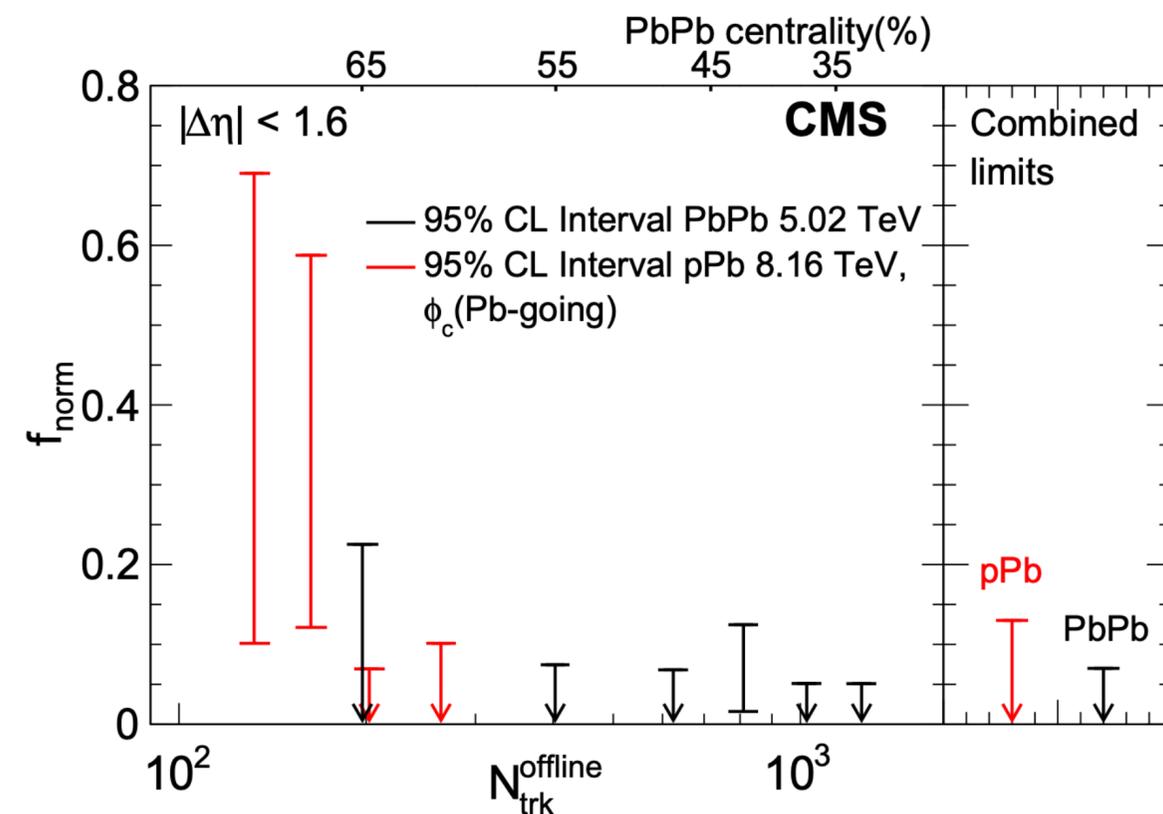
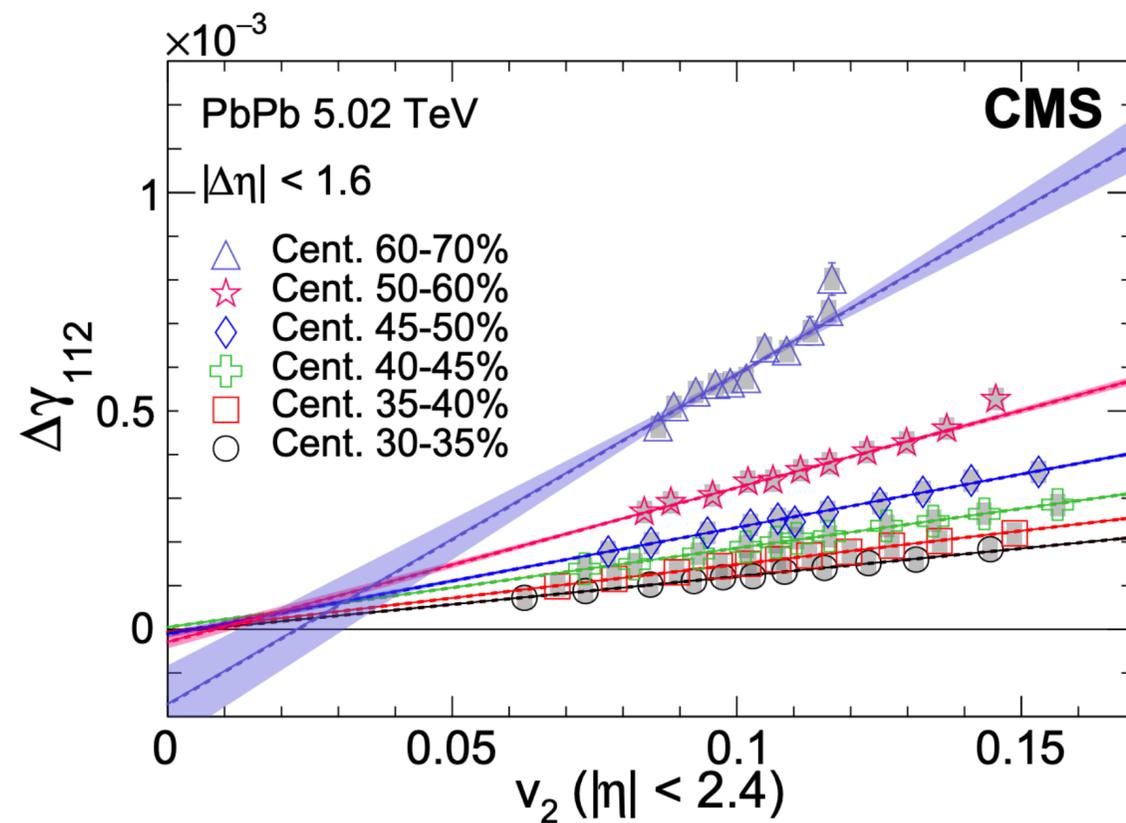
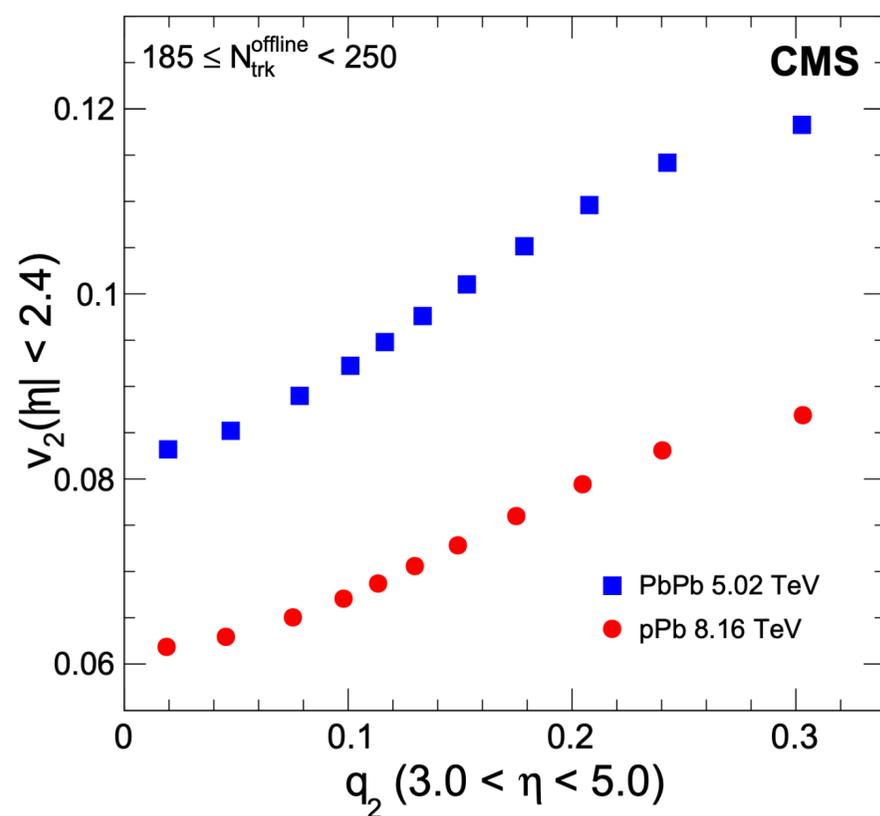
$$f_{CME} \times p_{1,MC} + (1 - f_{CME}) \times 1 = p_{1,data},$$

$$f_{CME} = \frac{(\gamma_{opp} - \gamma_{same})^{CME}}{(\gamma_{opp} - \gamma_{same})^{CME} + (\gamma_{opp} - \gamma_{same})^{Bkg}}.$$

由于统计不足，没有CME信号。

实验研究进展——Event shape engineering

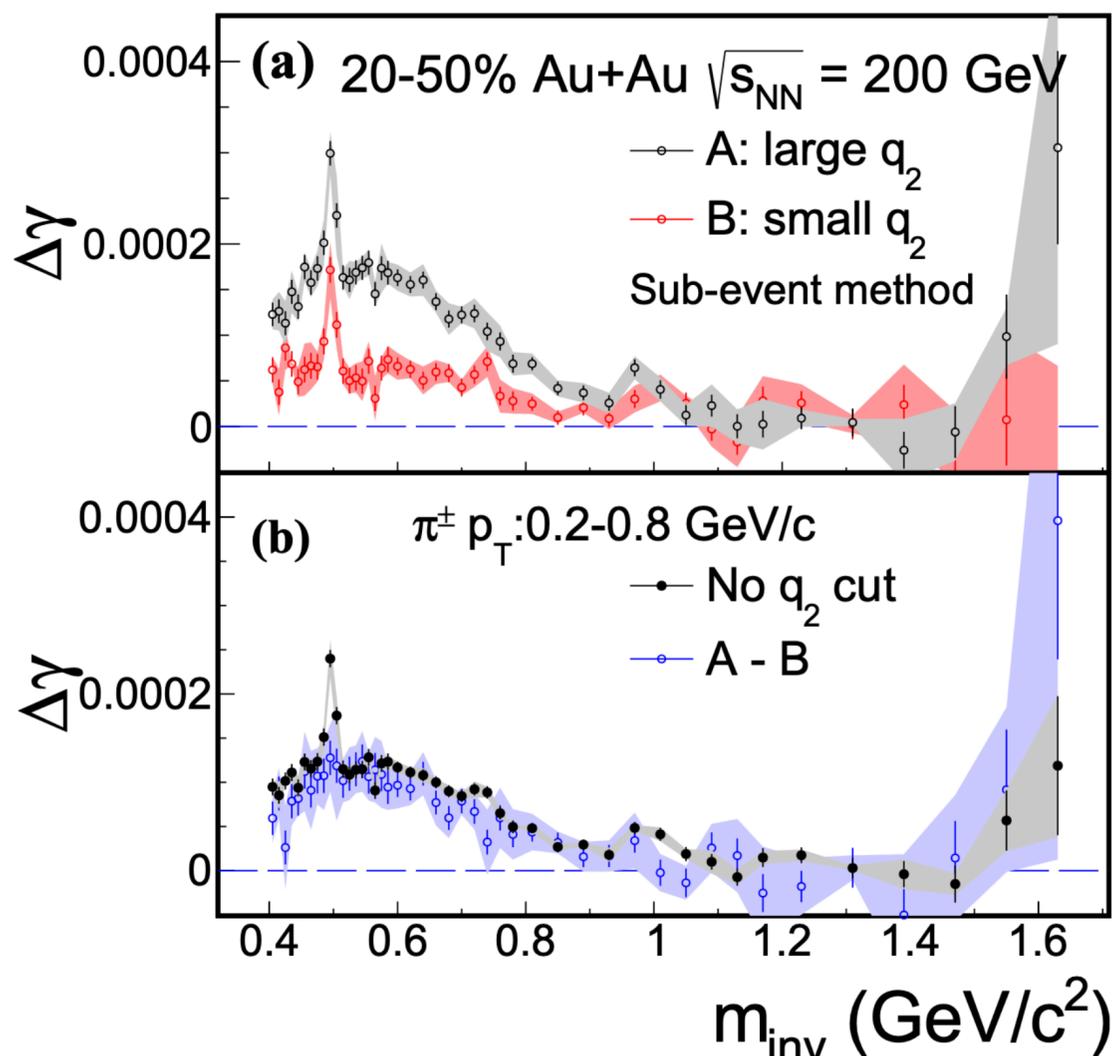
CMS, Phys. Rev. C 97 044912



CMS的测量结果显示在5TeV铅-铅对撞中 CME占比 < 8%。

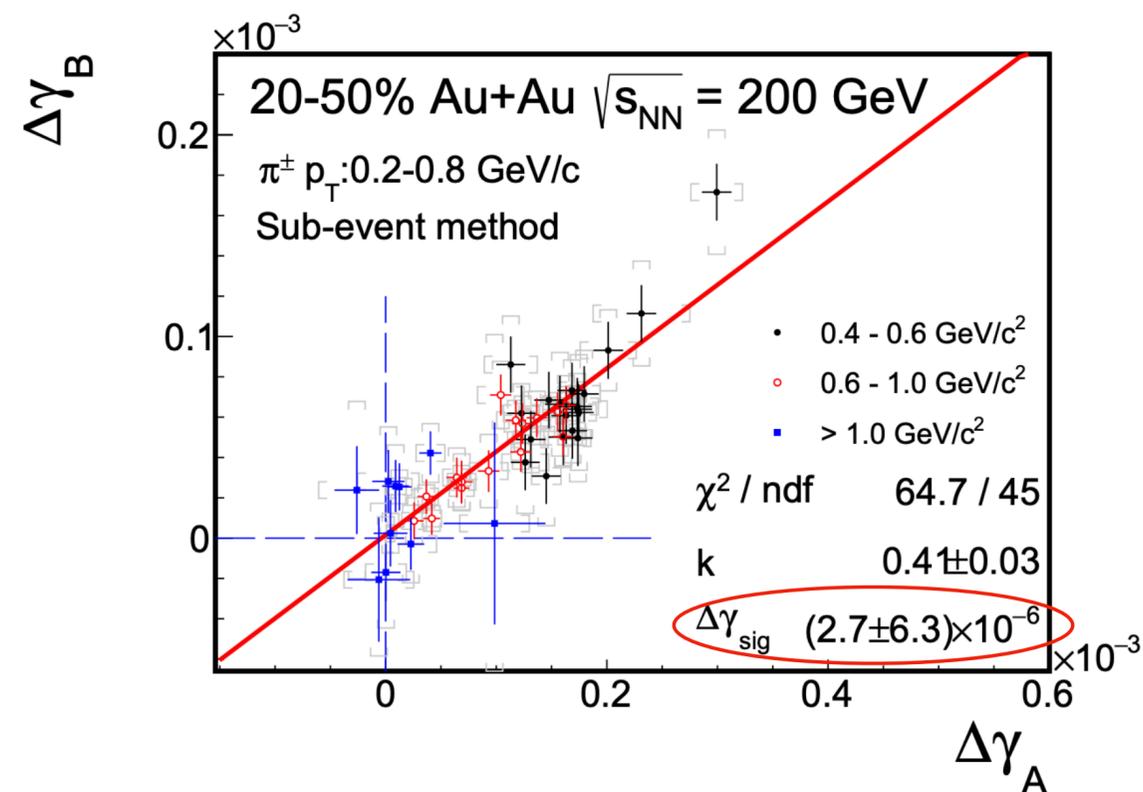
实验研究进展——Event shape engineering

ESE+不变质量谱



STAR, Phys. Rev. C 106 034908

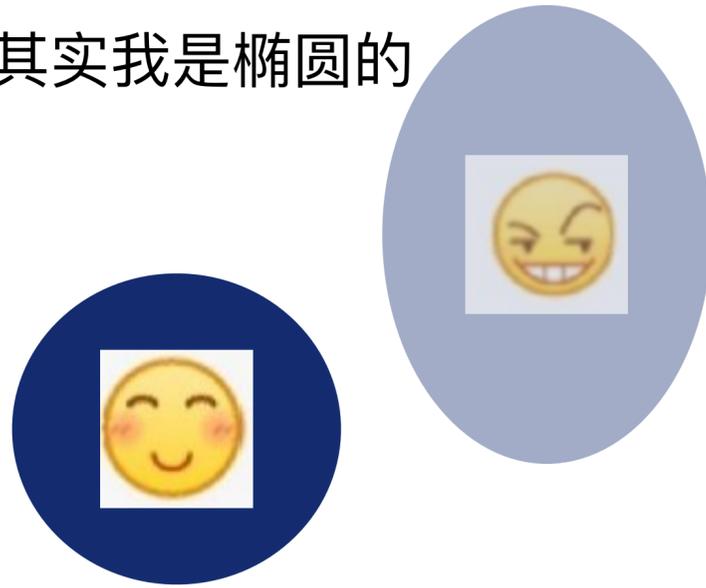
- ① CME不随两粒子不变质量变化。
- ② 不同的 q_2 事件CME大小一样。
- ③ 不同的 q_2 事件背景的不变质量分布一样，大小不同。



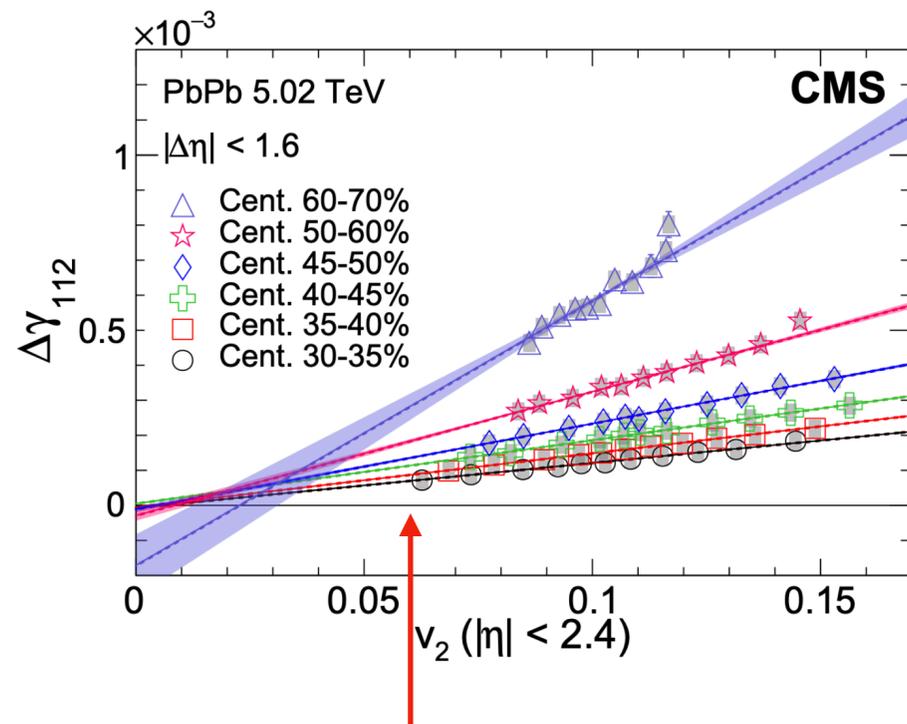
$$\Delta\gamma_B = k\Delta\gamma_A + (1 - k)\Delta\gamma_{\text{sig}},$$

实验研究进展——Event Shape Selection

$|\eta| < 1$: 其实我是椭圆的

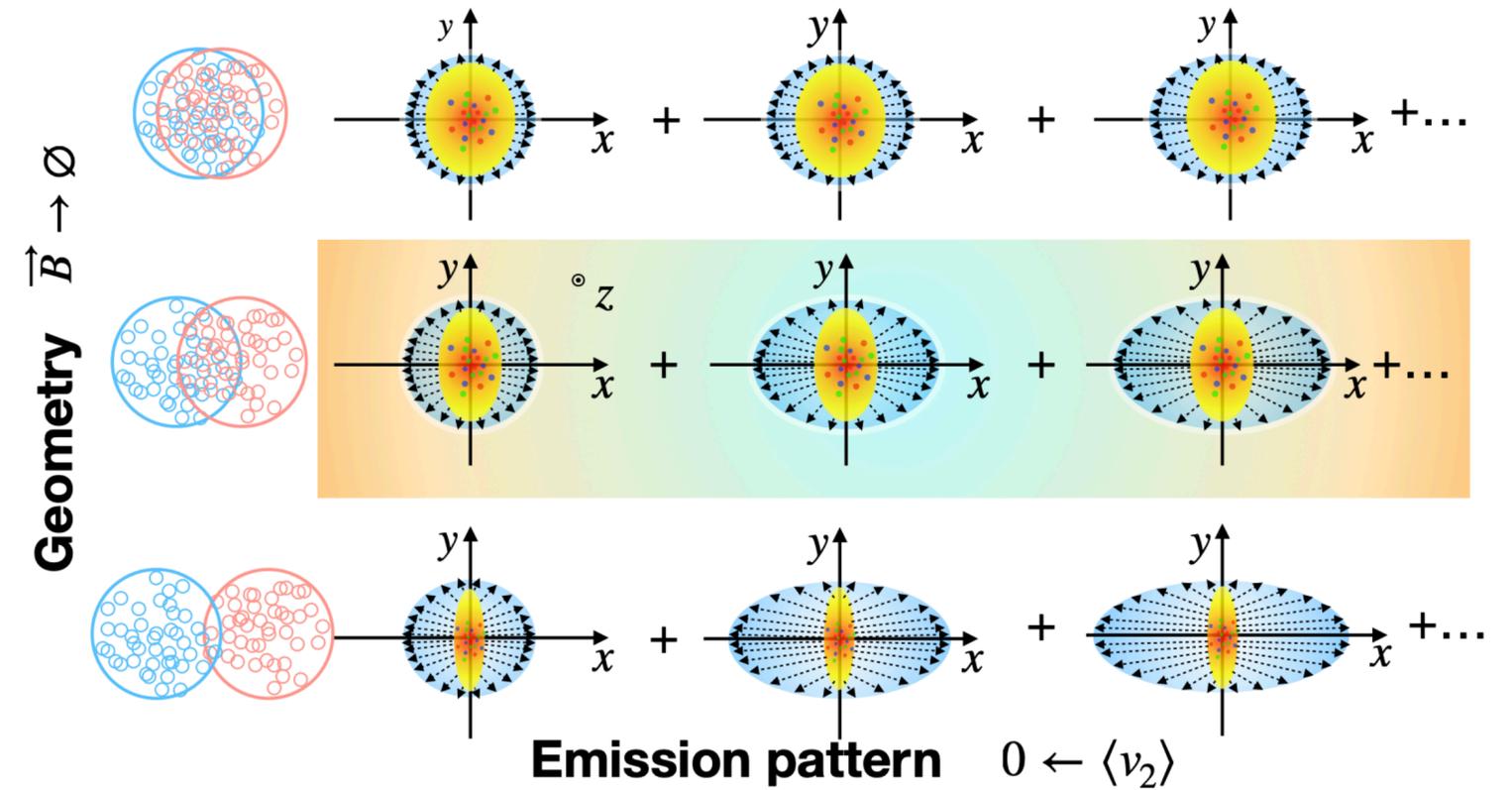


$|\eta| > 1$: 我是圆的



Flow decorrelation 导致 v_2 离 0 太远, 截距误差大

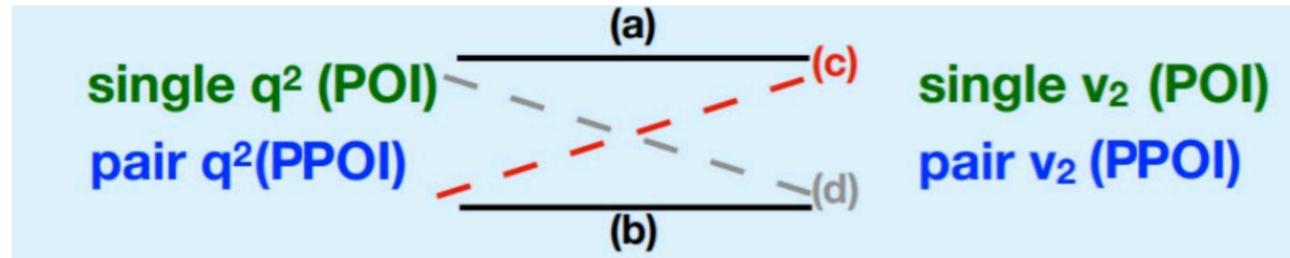
Z. Xu et al, PLB 848 138367 (2024)



使用中快度的粒子来计算 q_2 、 v_2 → 同时选择初态几何与末态出射分布

实验研究进展——Event Shape Selection

四种组合：

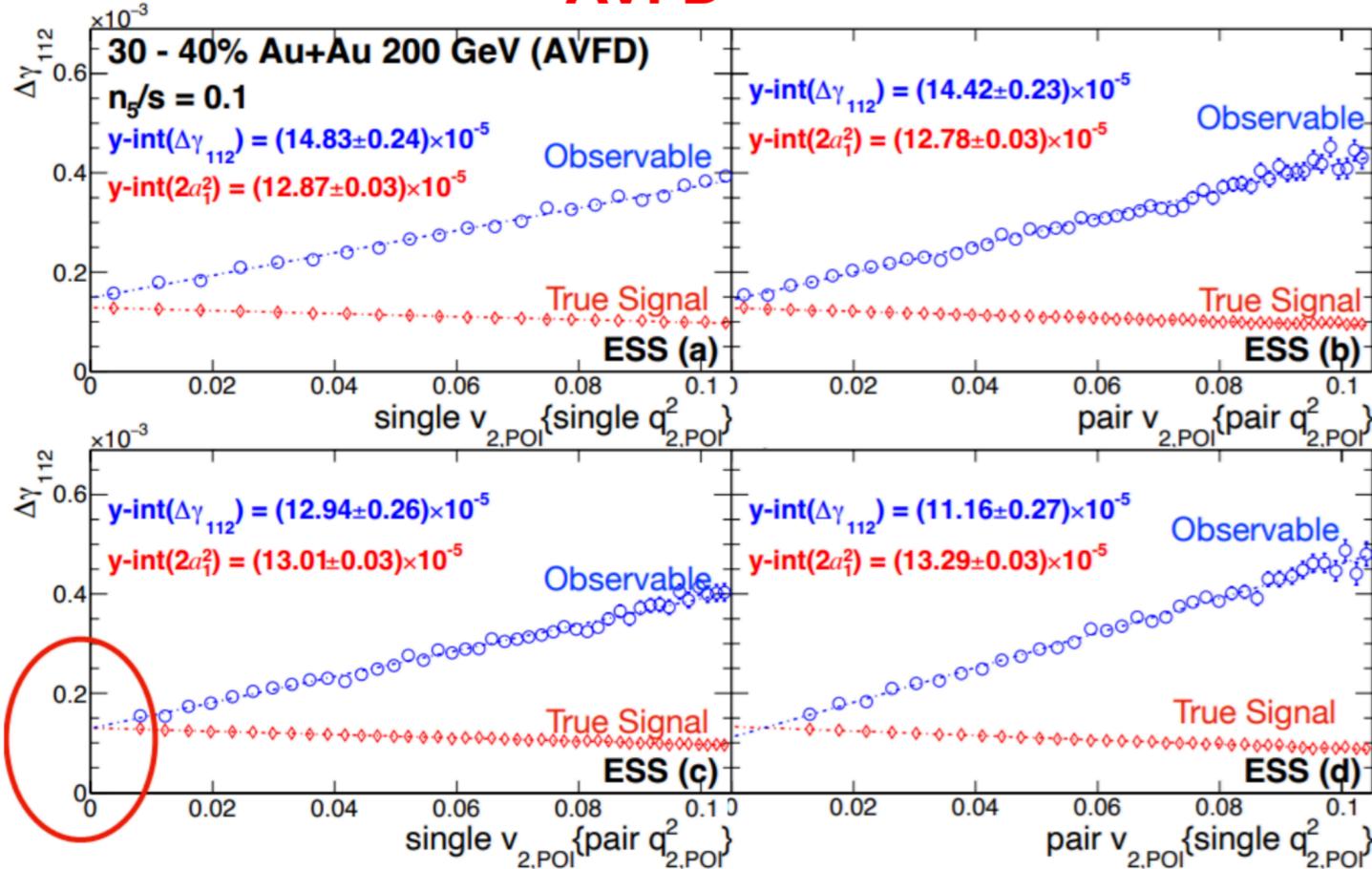


Z. Xu et al, PLB 848 138367 (2024)

$$v_{2,\text{pair}} = \langle \cos(2\varphi^{\text{P}} - 2\Psi_{\text{RP}}) \rangle,$$

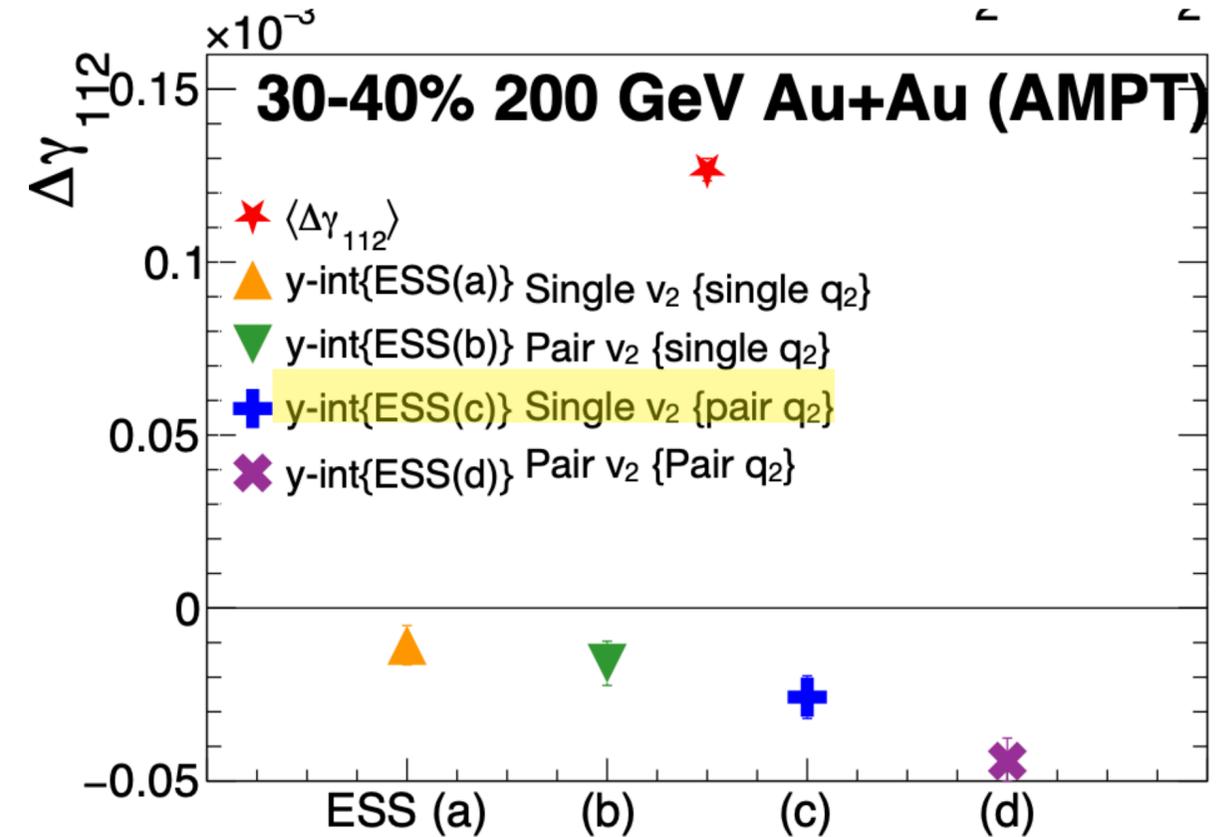
$$q_{2,\text{pair}}^2 = \frac{(\sum_{i=1}^{N_{\text{pair}}} \sin 2\varphi_i^{\text{P}})^2 + (\sum_{i=1}^{N_{\text{pair}}} \cos 2\varphi_i^{\text{P}})^2}{N_{\text{pair}}(1 + N_{\text{pair}}v_{2,\text{pair}}^2)}$$

AVFD



AVFD中组合c可以很好还原CME信号

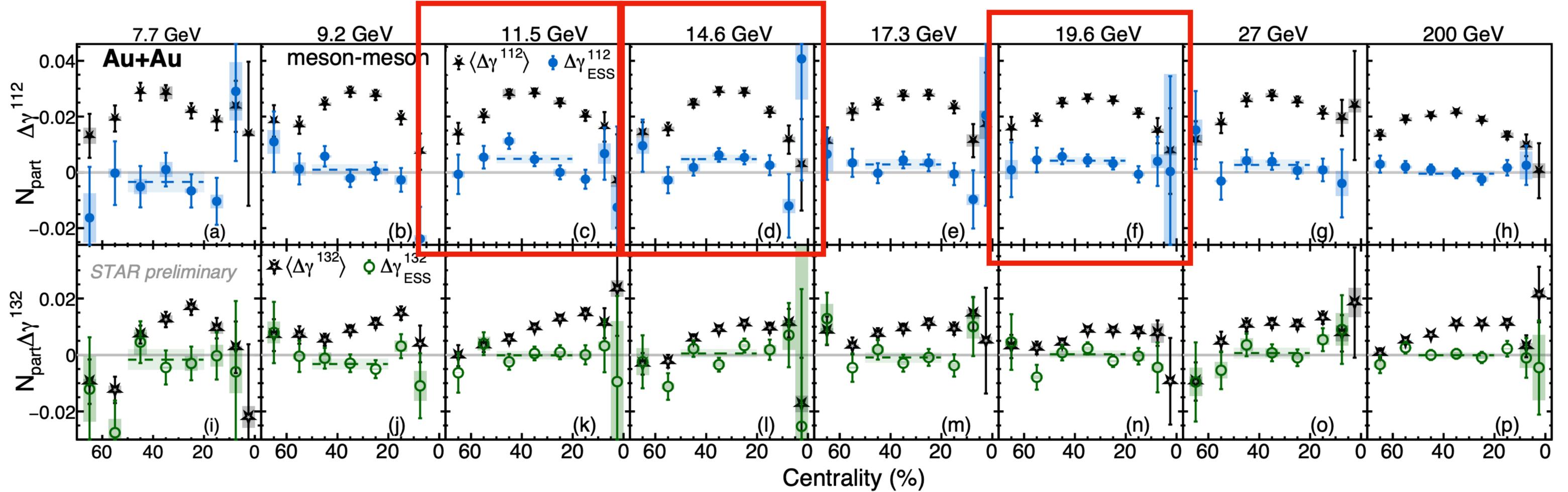
AMPT



AMPT模型中所有组合都过减背景

实验研究进展——Event Shape Selection

Zhiwan Xu @ QM 2025



$$\gamma^{112} = \langle \cos(\varphi_1 + \varphi_2 - 2\Psi_{RP}) \rangle$$

$$\gamma^{132} = \langle \cos(\varphi_1 - 3\varphi_2 + 2\Psi_{RP}) \rangle$$

$$\Delta\gamma^{112} = \Delta\gamma^{\text{CME}} + \cancel{k \frac{v_2}{N}} + \Delta\gamma^{\text{nonflow}}$$

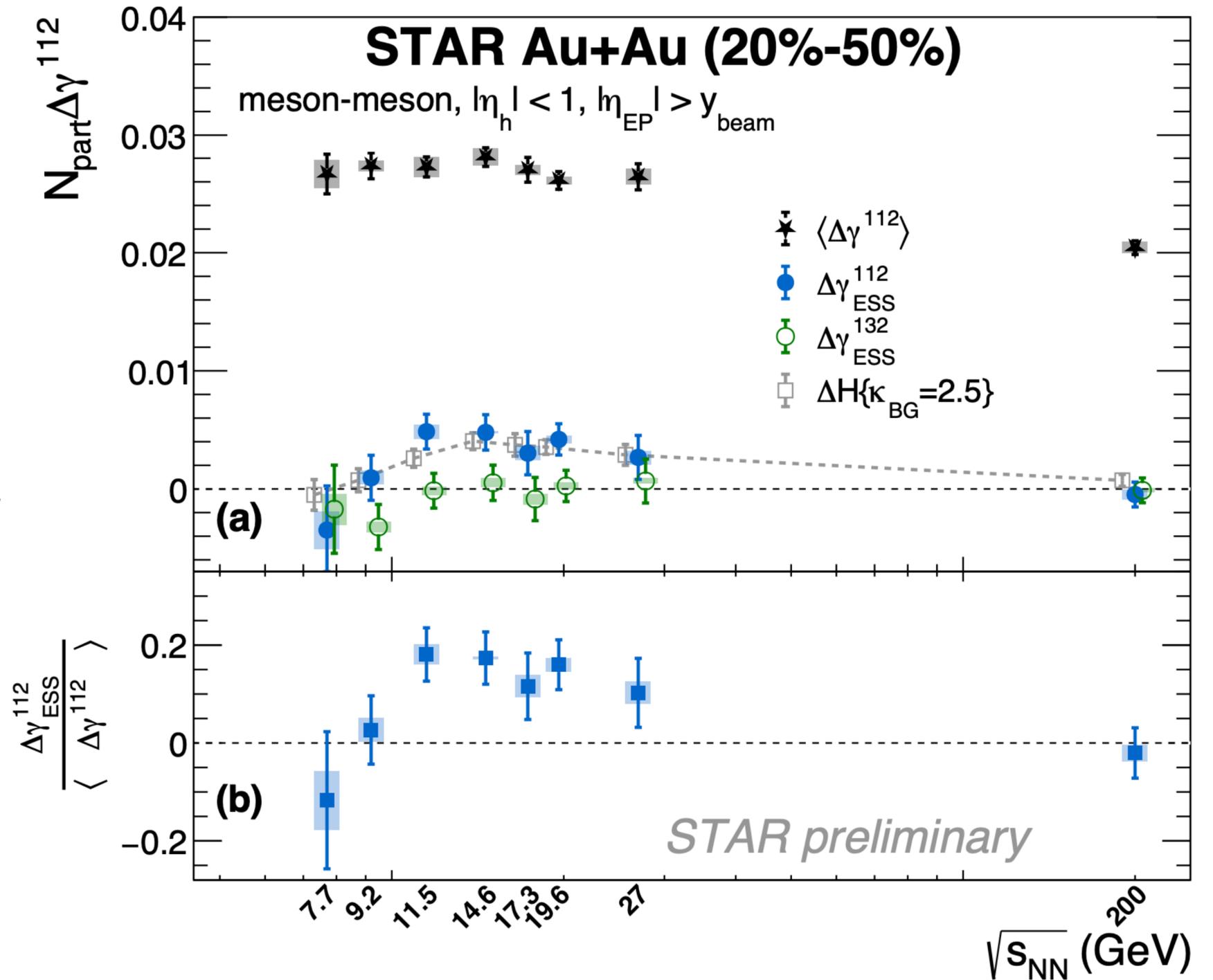
ESS Spectator Plane Ψ_1

金-金 11.5、14.6、19.6 GeV中统计显著度 $> 3\sigma$

减去了 v_2 背景之后:

- $\Delta\gamma^{132}$ 在所有能量下为零
- $\Delta\gamma^{112}$ 随着能量降低增大再减小
- 11.5, 14.6, 19.6 GeV三个能量加起来超过 5σ

7.7 GeV: 统计误差? 手征相变?



实验研究进展——Spectator plane vs Participant plane

Sergei, Phys. Rev. C 98 054911 (2018)

$$\Delta\gamma = \Delta\gamma^{\text{BG}} + \Delta\gamma^{\text{CME}},$$

$$\Delta\gamma^{\text{BG}} = bv_2$$

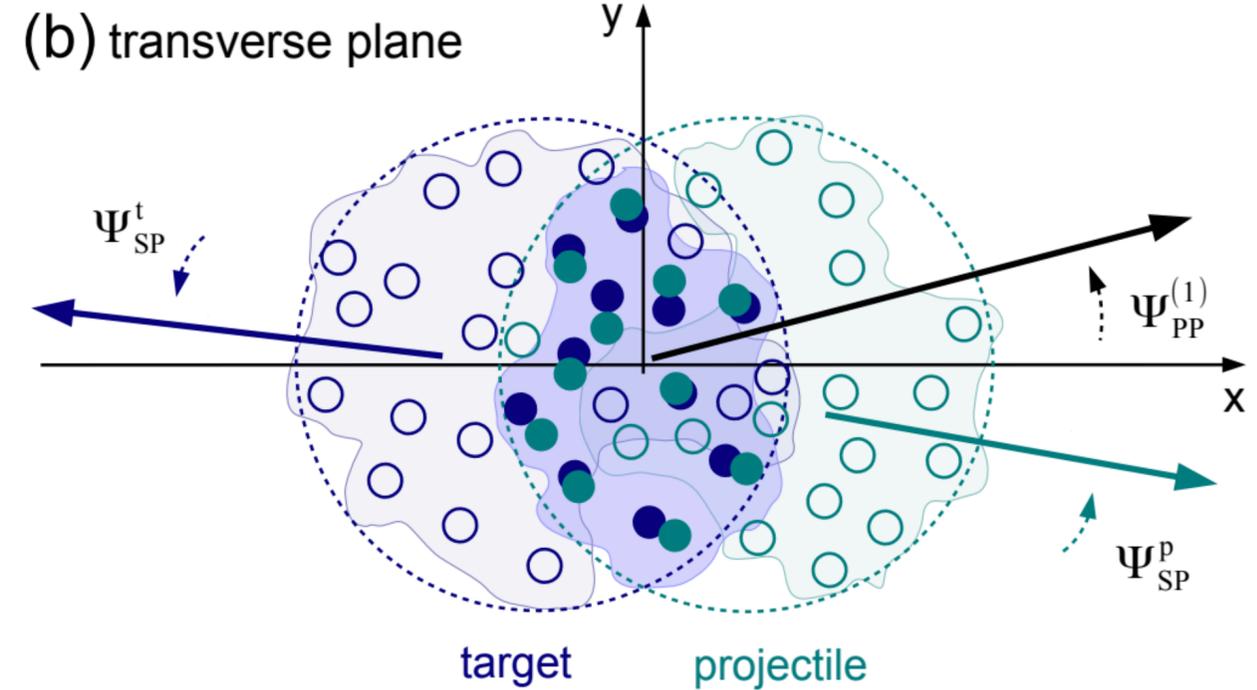
$$\frac{\Delta\gamma^{\text{BG}}}{v_2} = b \longrightarrow \text{参数 } b \text{ 对任何的事件平面不变}$$

若 $\frac{\Delta\gamma}{v_2}(\Psi_{\text{sp}}) = \frac{\Delta\gamma}{v_2}(\Psi_{\text{pp}})$, 则全是背景,

否则存在CME。

$$\text{若进一步认为 } \frac{\Delta\gamma_{\text{SP}}^{\text{CME}}}{\Delta\gamma_{\text{PP}}^{\text{CME}}} = \frac{v_{2,\text{PP}}}{v_{2,\text{SP}}} = \frac{1}{a}, \text{ 则 } f_{\text{CME}} = \frac{\Delta\gamma_{\text{PP}}^{\text{CME}}}{\Delta\gamma_{\text{PP}}} = \frac{A/a - 1}{1/a^2 - 1}, \quad A = \frac{\Delta\gamma_{\text{SP}}}{\Delta\gamma_{\text{P}}}$$

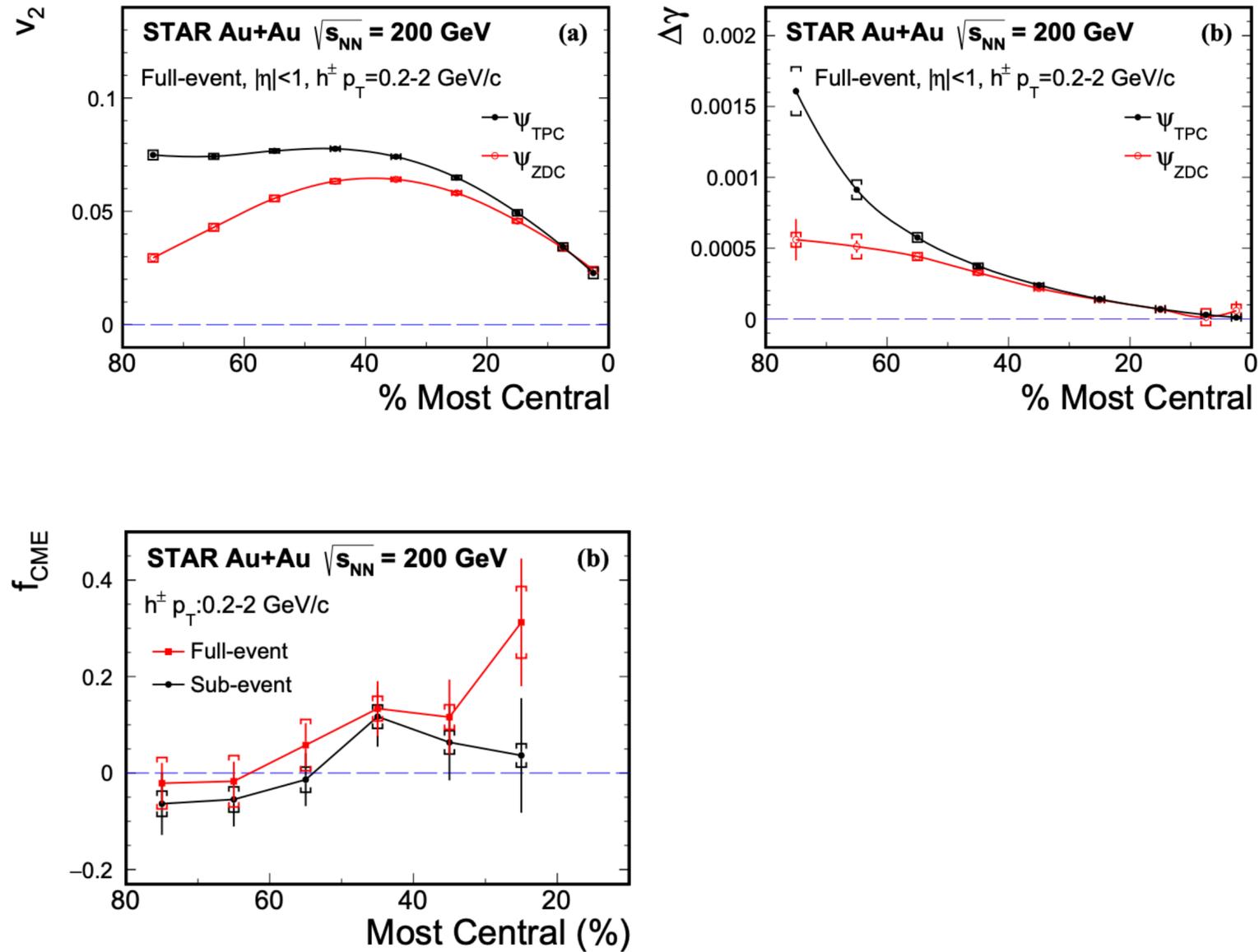
ALICE, Phys. Rev. Lett. 111 232302 (directed flow paper)



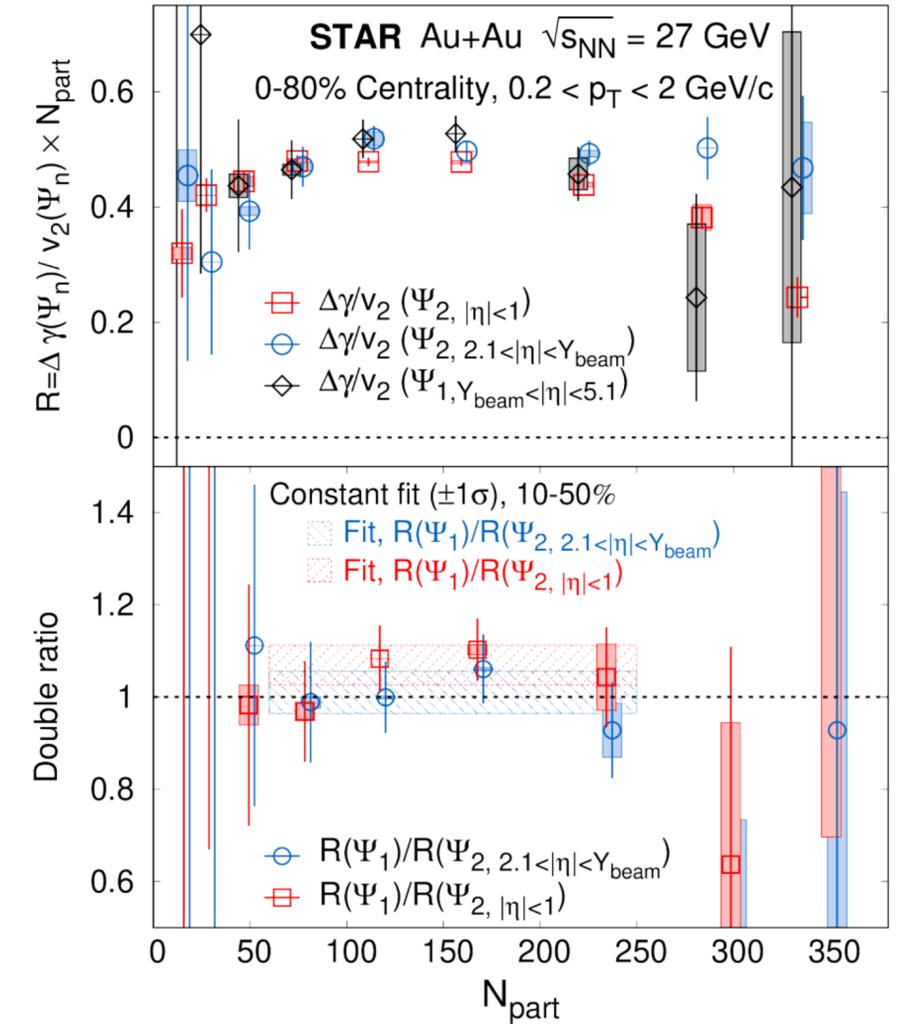
实验研究进展——Spectator plane vs Participant plane

STAR, Phys. Rev. Lett. 128 092301

Au+Au 200 GeV

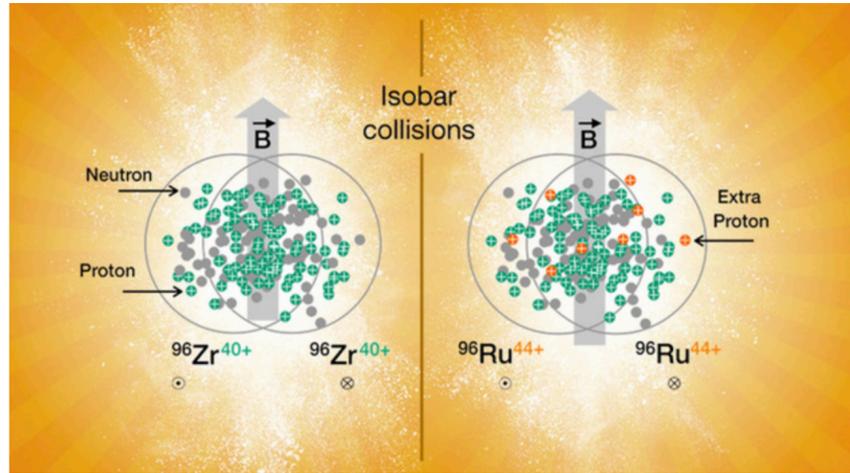


Au+Au 27 GeV



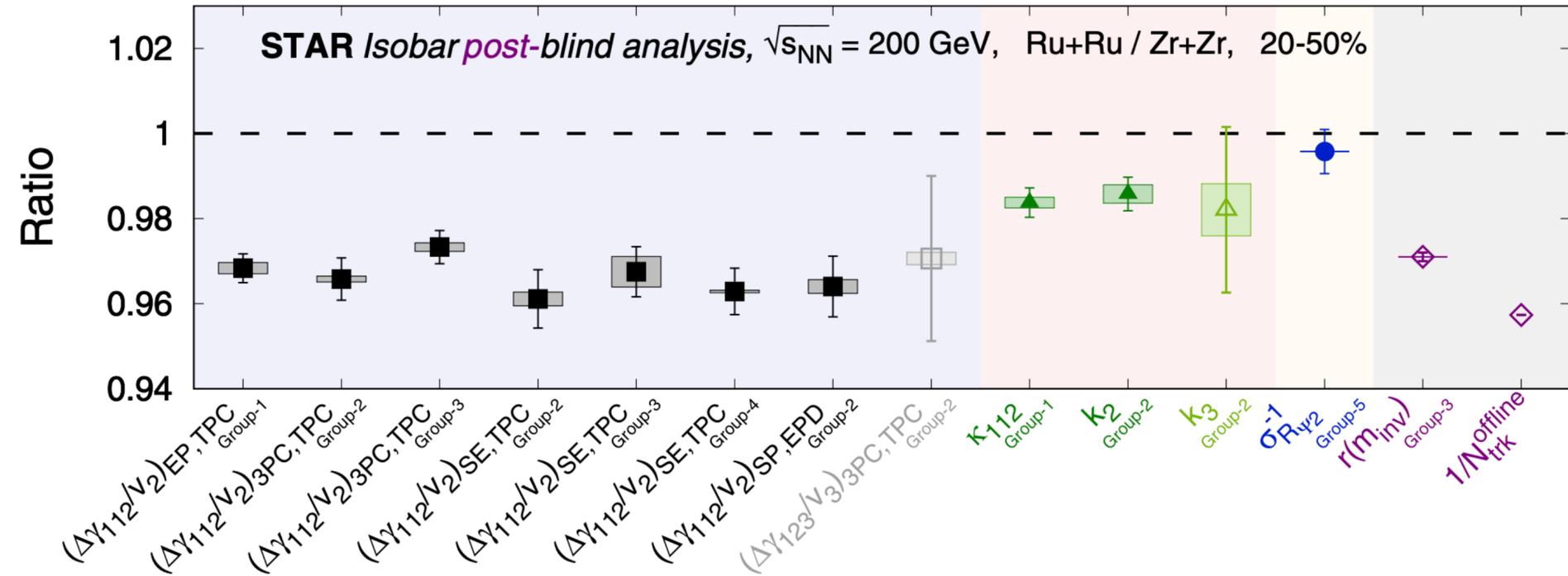
误差范围内200GeV、27GeV没看到CME信号

实验研究进展——Isobar post-blind analysis



$$\text{CME: } \frac{\Delta\gamma^{\text{Ru}}}{\Delta\gamma^{\text{Zr}}} > 1$$

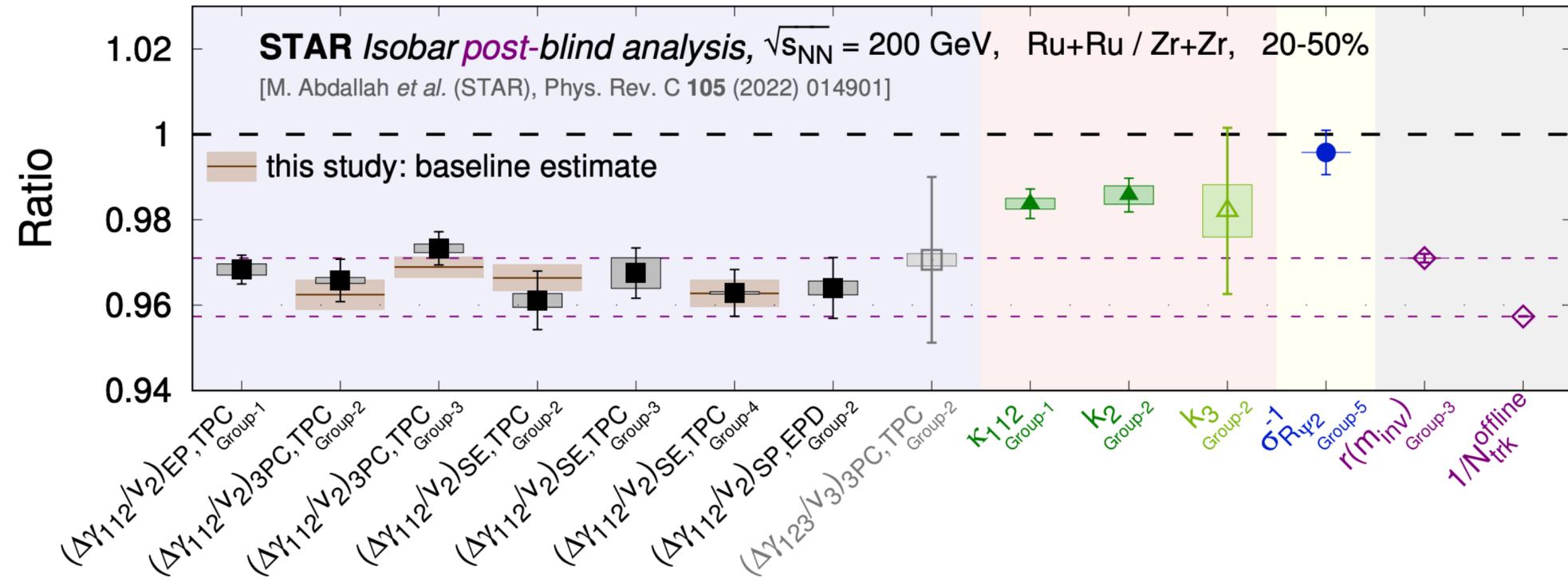
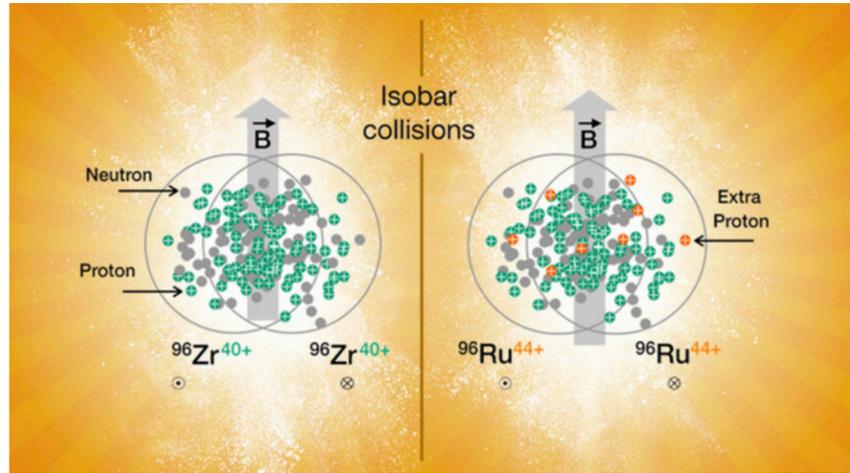
$$\text{BKG: } \frac{\Delta\gamma^{\text{Ru}}}{\Delta\gamma^{\text{Zr}}} = 1$$



Blind analysis的结果显示Ru+Ru与Zr+Zr的背景不一致

实验研究进展——Isobar post-blind analysis

STAR, Phys. Rev. R 6, L032005



$$\text{CME: } \frac{\Delta\gamma^{\text{Ru}}}{\Delta\gamma^{\text{Zr}}} > 1$$

$$\text{BKG: } \frac{\Delta\gamma^{\text{Ru}}}{\Delta\gamma^{\text{Zr}}} = 1$$

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{\text{RP}}) \rangle \quad (1)$$

$$\Delta\gamma = \gamma_{\text{os}} - \gamma_{\text{ss}},$$

$$\frac{\Delta\gamma_{\text{bkgd}}}{v_2^*} = \frac{C_{2p}}{N} \frac{v_2^2}{v_2^{*2}} + \frac{C_{3p}}{N} \frac{1}{N_c v_2^{*2}} = \frac{C_{2p}}{N} \frac{1 + \frac{C_{3p}/C_{2p}}{N v_2^2}}{1 + \epsilon_{\text{nf}}}, \quad (2)$$

$$\frac{C_{2p}}{N} = \frac{N_{2p}}{N_{\text{os}}} \left(C_{2p,\text{os}} \frac{v_{2,2p}}{v_2} - \frac{\gamma_{\text{ss}}}{v_2} \right), \quad (3)$$

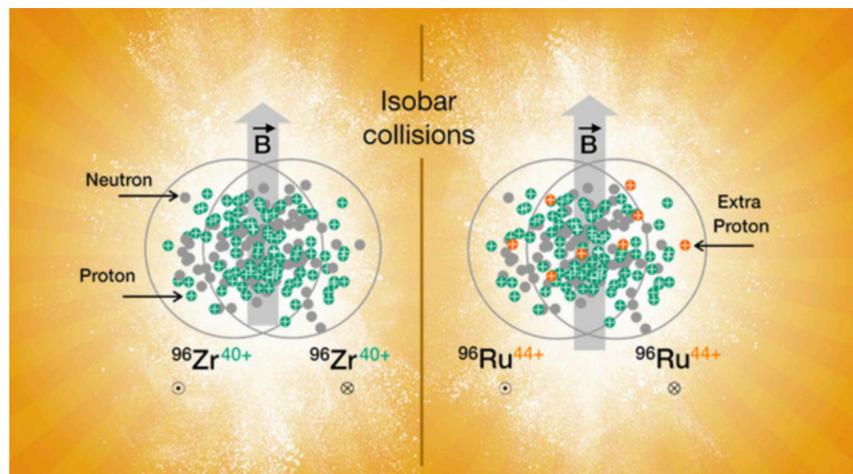
$$\frac{C_{3p}}{N} = \frac{N_{3p,\text{os}}}{N_{\text{os}}} C_{3p,\text{os}} - \frac{N_{3p,\text{ss}}}{N_{\text{ss}}} C_{3p,\text{ss}}. \quad (4)$$

$$\epsilon_{\text{nf}} = (v_2^*/v_2)^2 - 1, \quad (5)$$

$$Y_{\text{bkgd}} \equiv \frac{(\Delta\gamma_{\text{bkgd}}/v_2^*)^{\text{Ru}}}{(\Delta\gamma_{\text{bkgd}}/v_2^*)^{\text{Zr}}} \approx 1 + \frac{\delta(C_{2p}/N)}{C_{2p}/N} - \frac{\delta\epsilon_{\text{nf}}}{1 + \epsilon_{\text{nf}}} + \frac{1}{1 + \frac{N v_2^2}{C_{3p}/C_{2p}}} \left(\frac{\delta C_{3p}}{C_{3p}} - \frac{\delta C_{2p}}{C_{2p}} - \frac{\delta N}{N} - \frac{\delta v_2^2}{v_2^2} \right), \quad (6)$$

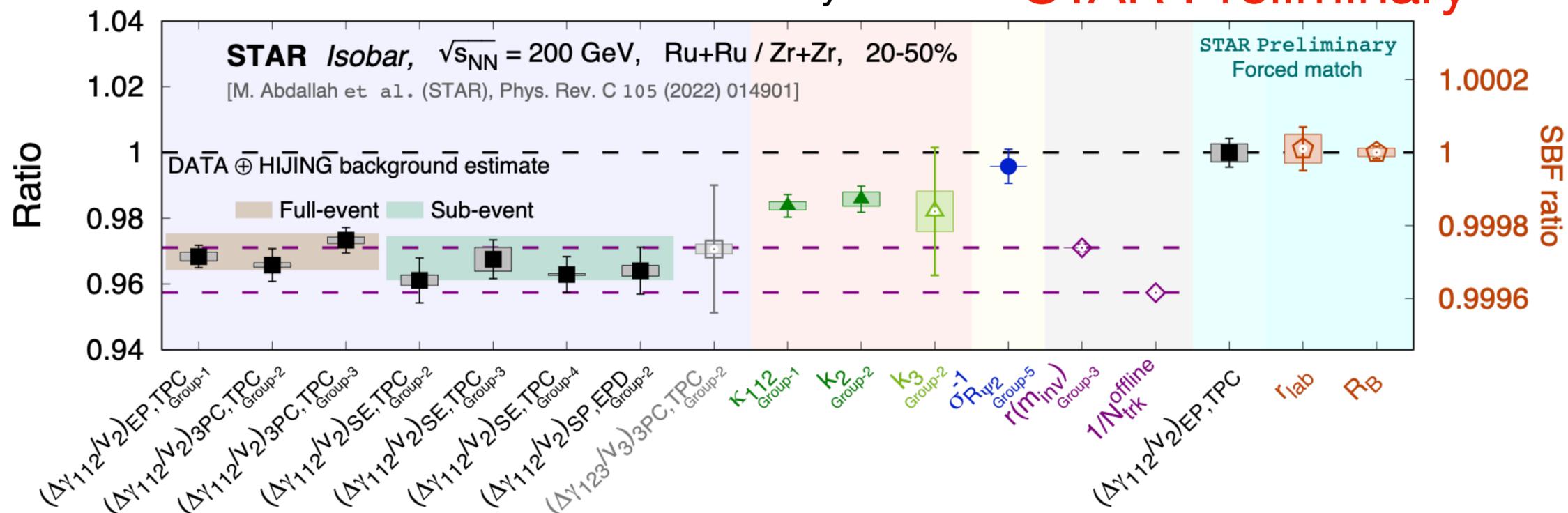
新的基线与测量结果一致

实验研究进展——Isobar post-blind analysis



Yufu Lin @ Chirality 2023

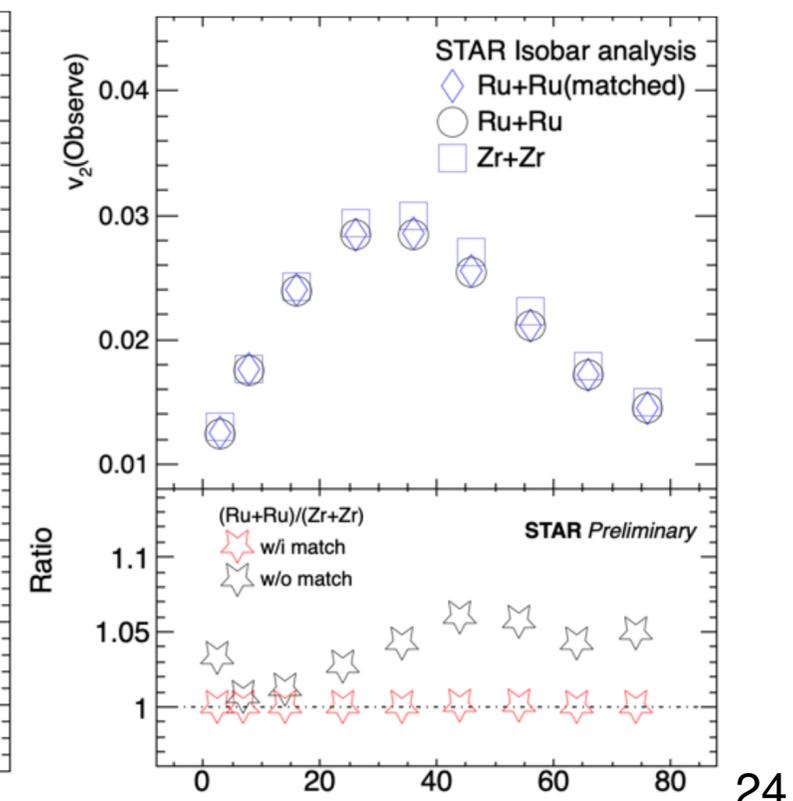
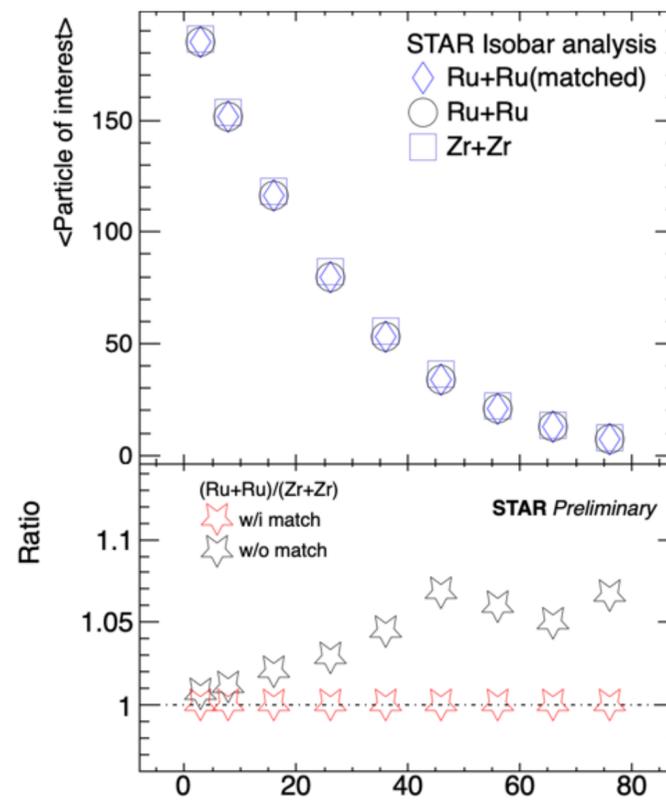
STAR Preliminary



$$\text{CME: } \frac{\Delta\gamma^{\text{Ru}}}{\Delta\gamma^{\text{Zr}}} > 1$$

$$\text{BKG: } \frac{\Delta\gamma^{\text{Ru}}}{\Delta\gamma^{\text{Zr}}} = 1$$

将两个系统的差异通过引入权重抹去，得到的新结果与1一致

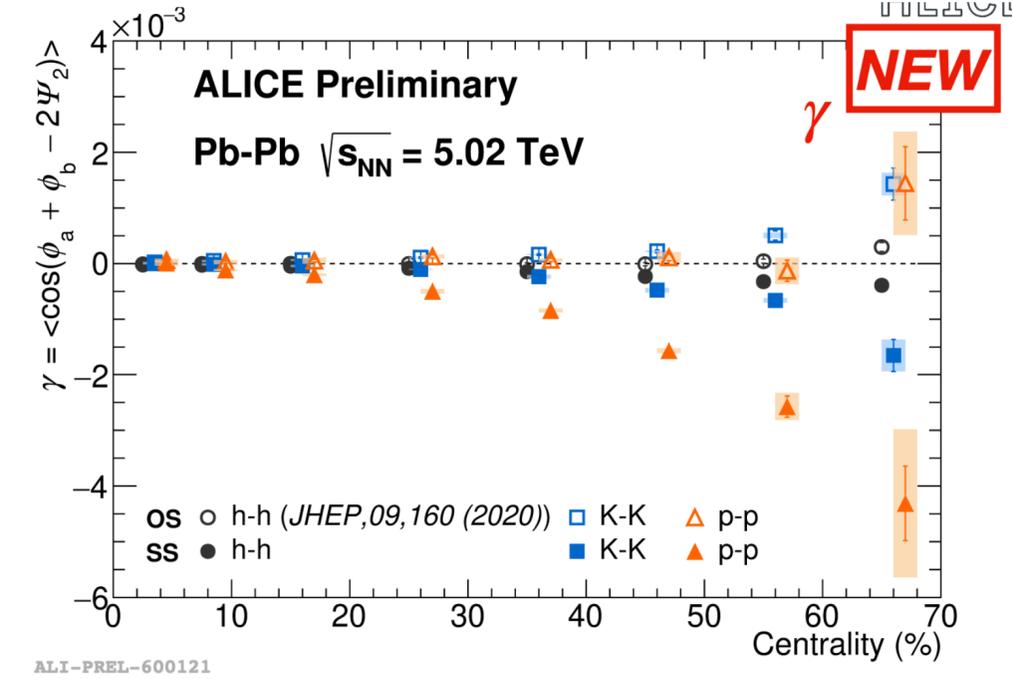
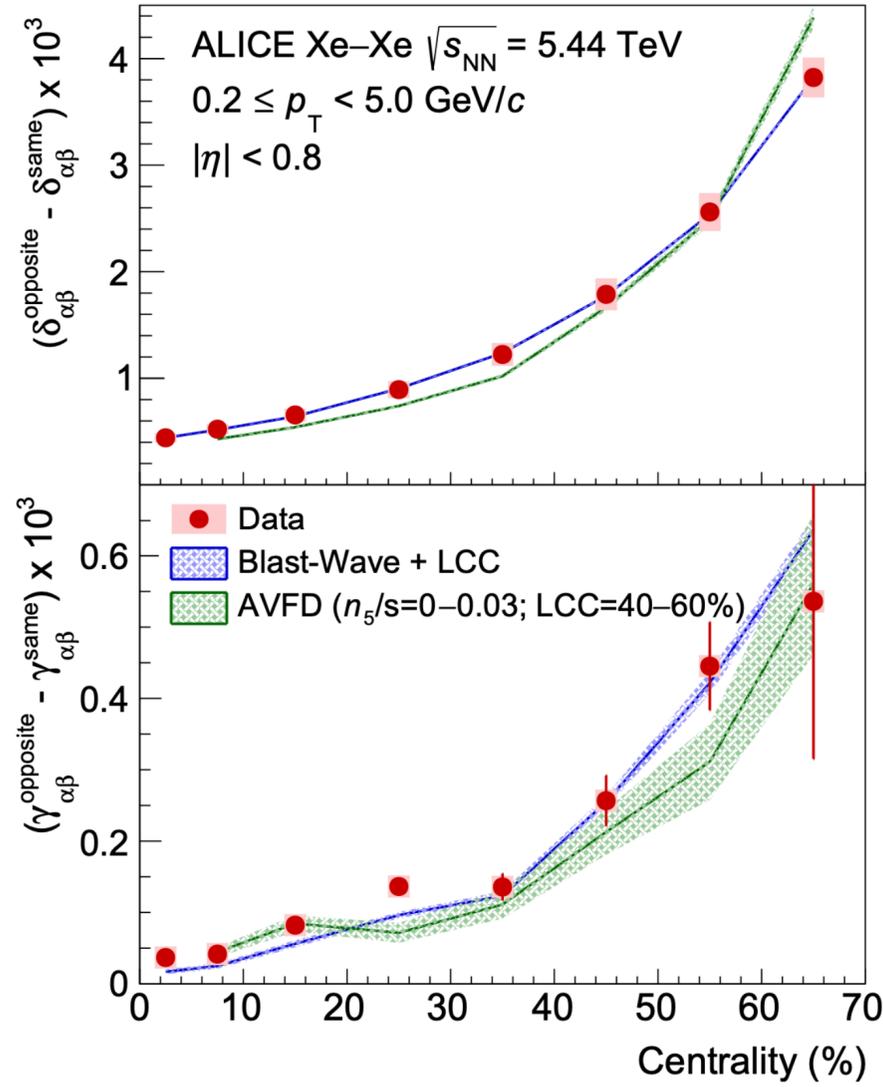
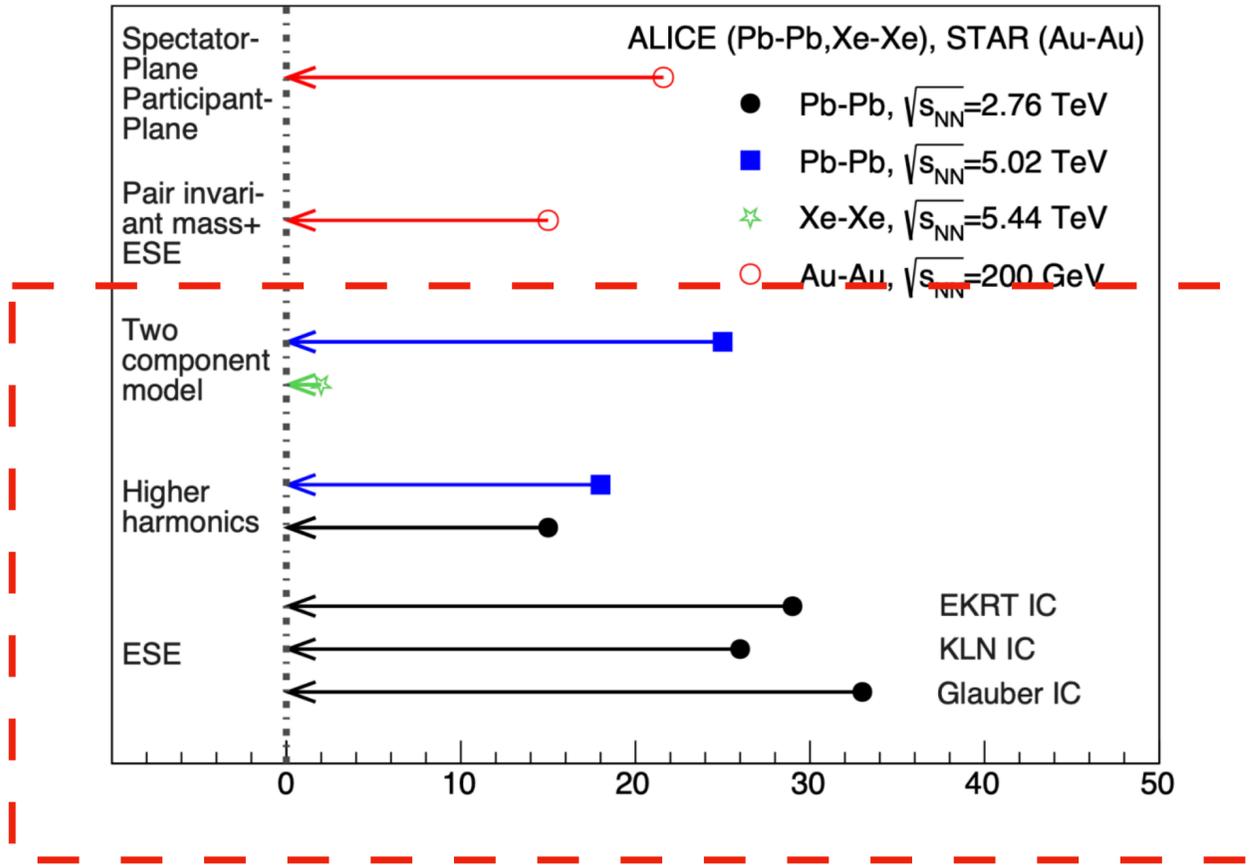


实验研究进展——LHC 能量

S. Qiu, EPJ Web Conf. 274, 05001

ALICE, Phys. Lett. B 856 138862

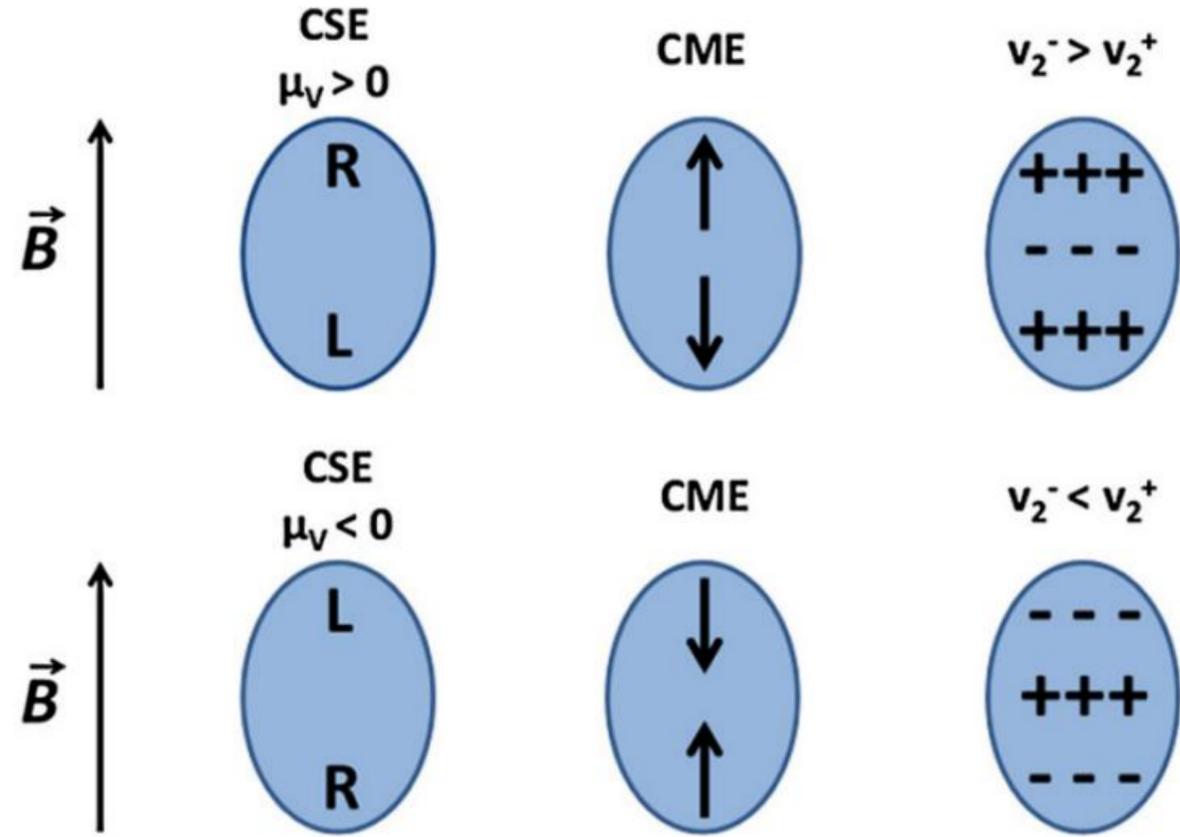
Zhengqing Wang @ QM 2025



- Xe-Xe 5.44 TeV结果显示CME的比例<3%
- ALICE利用不同的强子对研究CME背景

实验研究进展——CMW

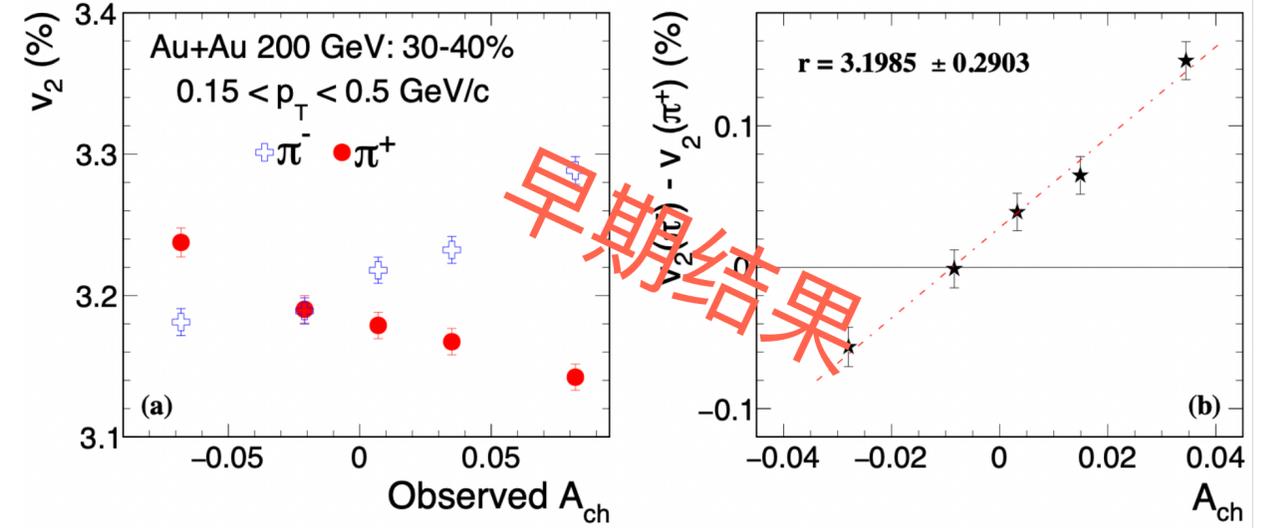
Y. Burnier Phys. Rev. Lett. 107 052303



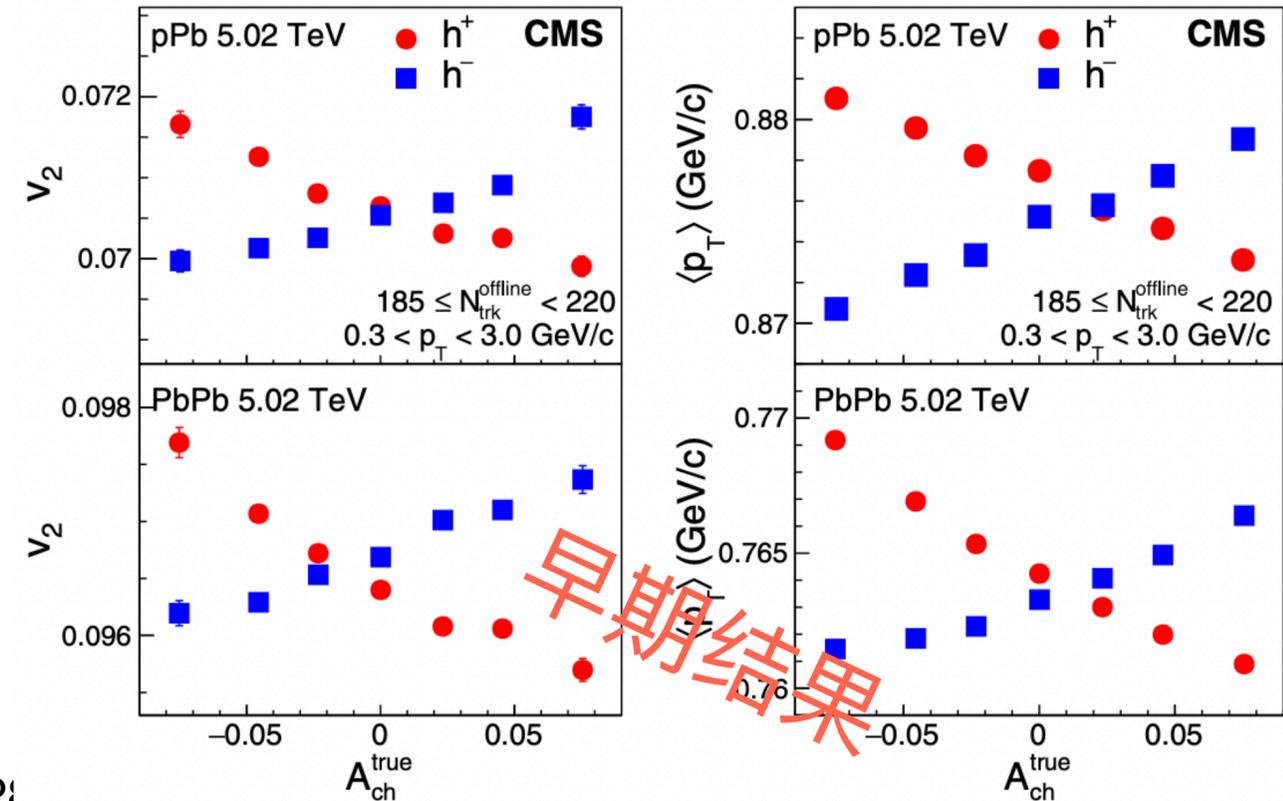
$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$$

$$\Delta v_2 = v_2^+ - v_2^- = r A_{ch}$$

STAR, Phys. Rev. Lett. 114 252302

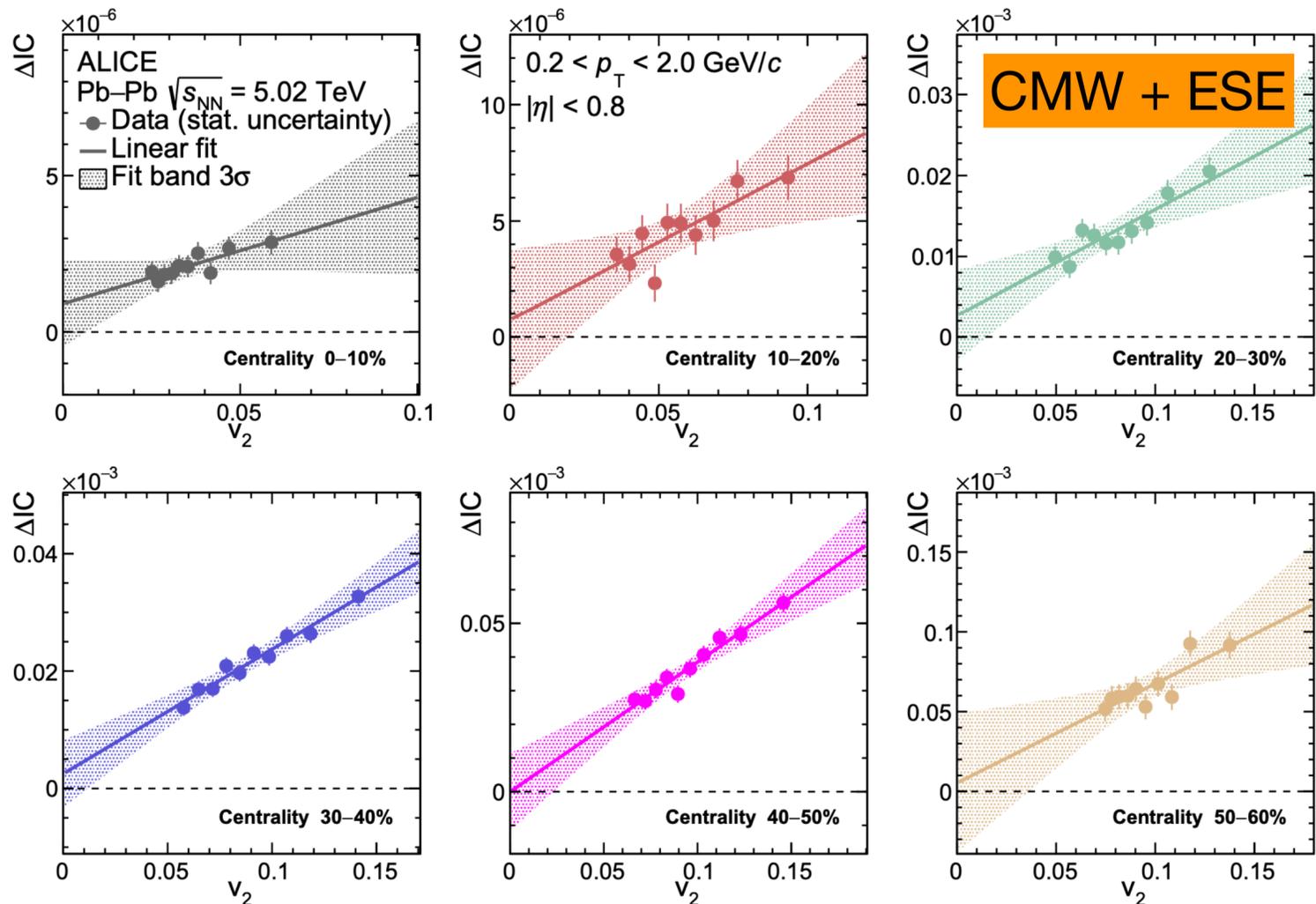


CMS, Phys. Rev. C 100 064908



实验研究进展——CMW

ALICE, JHEP 12 067 (2023)

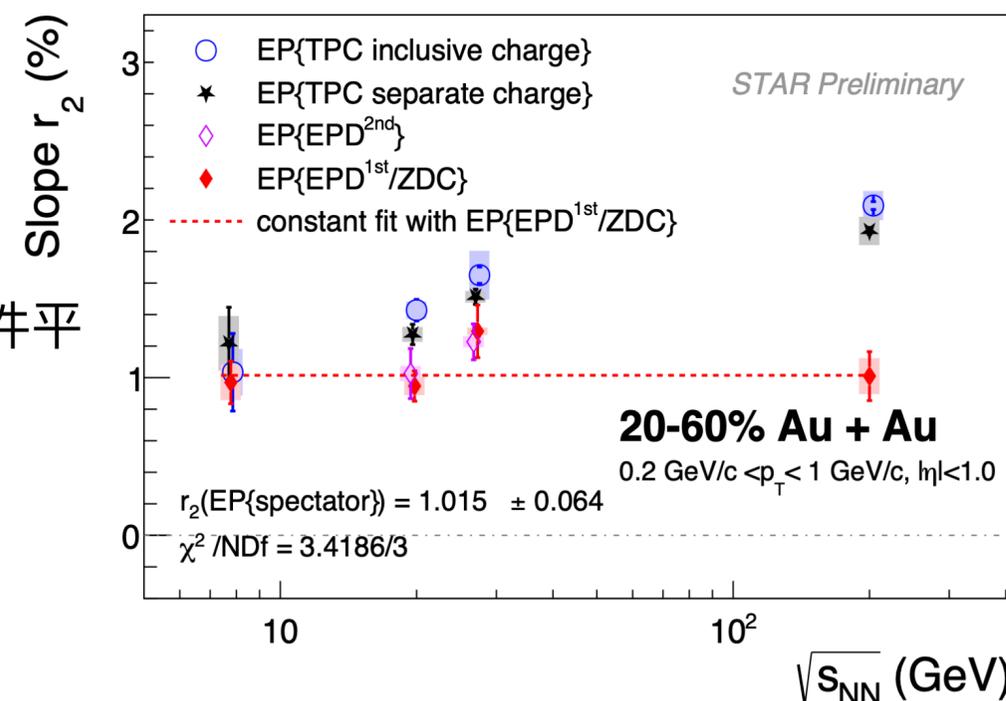
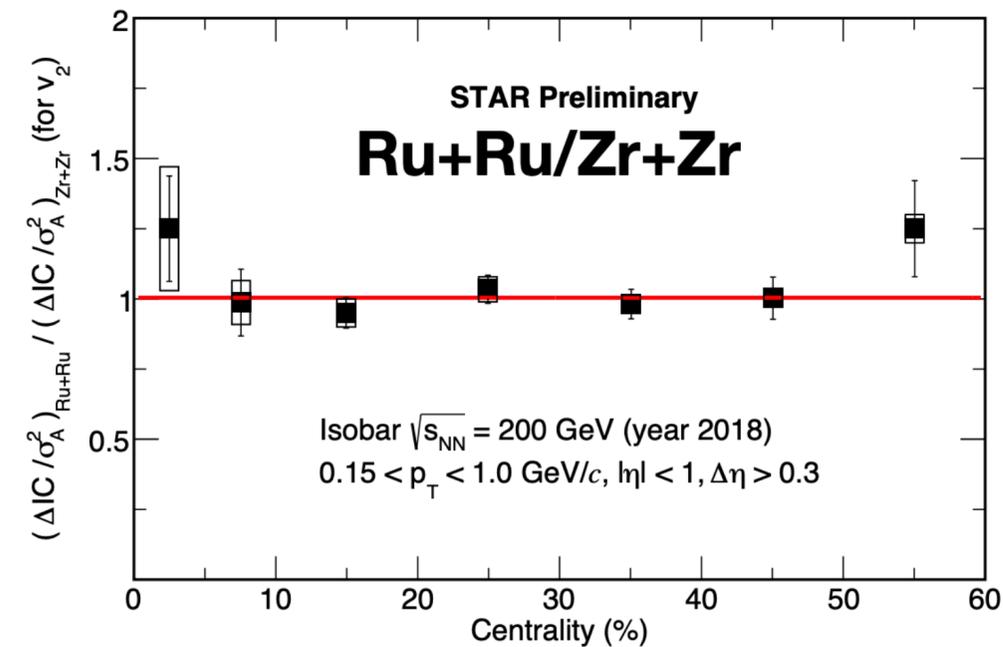


$$\Delta IC = \left(\langle v_2^- A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^- \rangle \right) - \left(\langle v_2^+ A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^+ \rangle \right),$$

利用ESE扣除背景以后, Pb-Pb 5.02 TeV没有CMW信号

Antika @ QM 2025

Isobar比值为1, 没有发现CMW



BESII能量下, 一阶事件平面 r_2 不随能量变化?

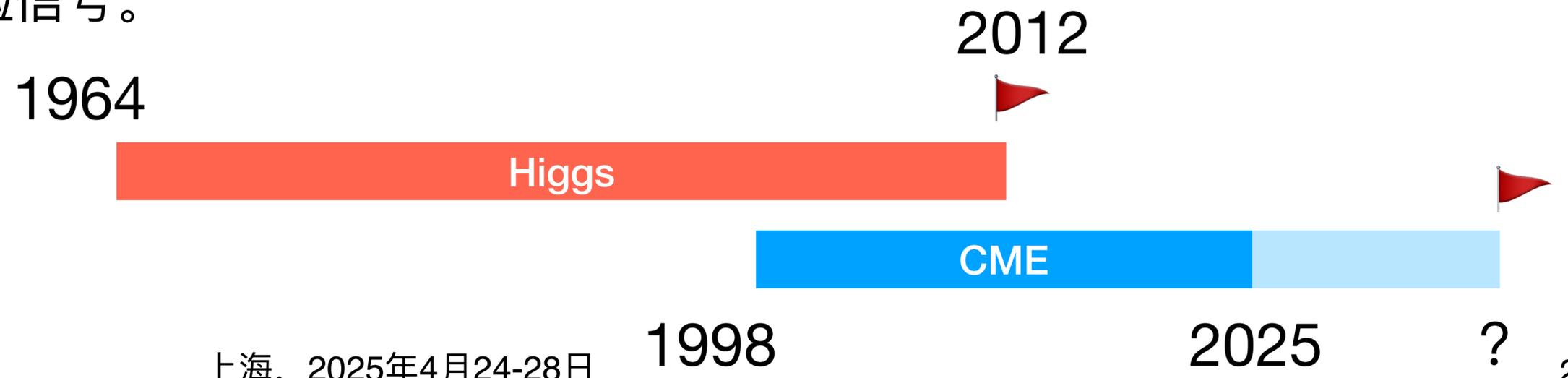
总结和展望

手征磁效应来自于**强相互作用中的CP破坏**

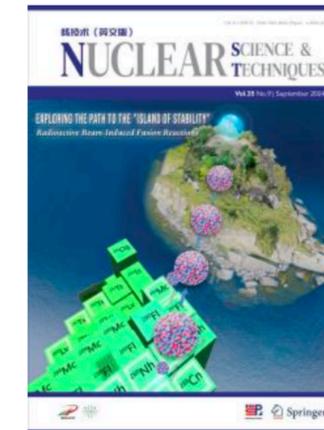
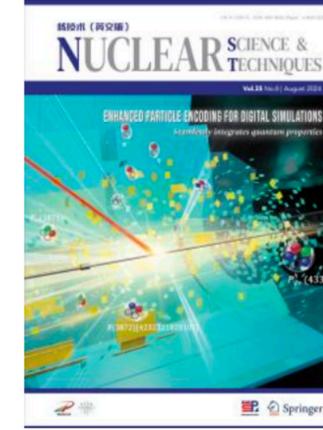
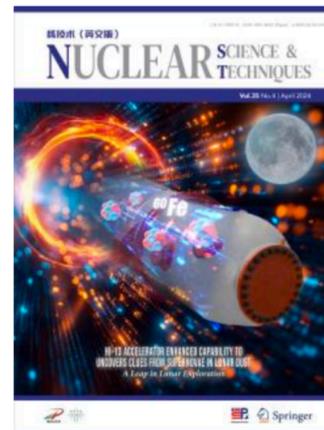
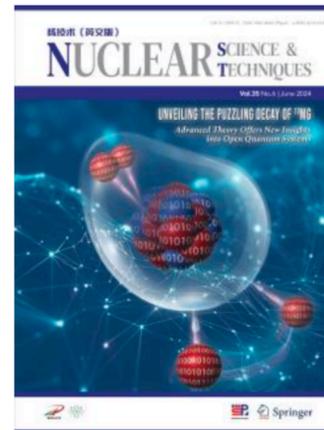
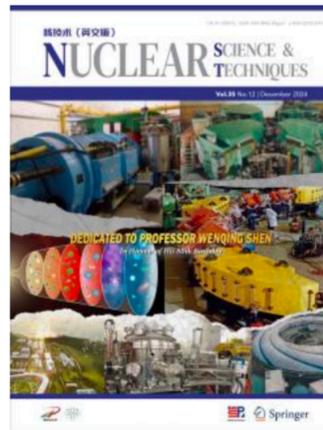
- 在LHC能量下没有发现CME信号。
- 在200GeV的Au+Au对撞中，使用SP/PP的结果没有统计显著的CME信号。
- 在200GeV的isobar对撞中，后双盲实验结果没有显示出CME信号。
- **11.5、14.6、19.6GeV的Au+Au对撞中，在使用ESS方法的最新结果显示，在减去了flow引起的背景之后依然存在 $> 3\sigma$ 的 $\Delta\gamma$ 。**
- 7.7 GeV 信号消失？ -> 需要更多理论解释

手征磁波来自于CME + CSE，也可用于检验强作用中的CP对称性

- 目前没有发现CMW的实验信号。



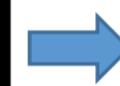
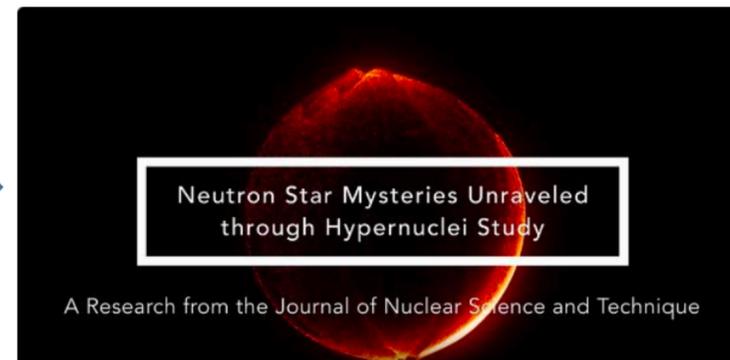
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 - Synchrotron radiation applications, beamline technology
 - Accelerator, ray technology and applications
 - Nuclear electronics and instrumentation
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Yu-Gang Ma



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