

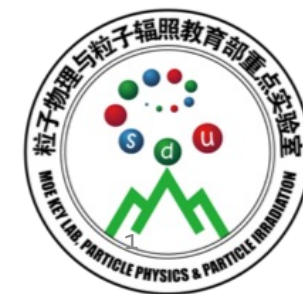


通过高能核-核碰撞中的 光生过程研究原子核结构

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目录

- 相对论重离子碰撞中的光生过程
- 超周边碰撞
- 极化光子-光子相互作用
- 极化光子-原子核相互作用
- 总结

相对论重离子碰撞中的光生过程

V. Weizsäcker, E.J. Williams:

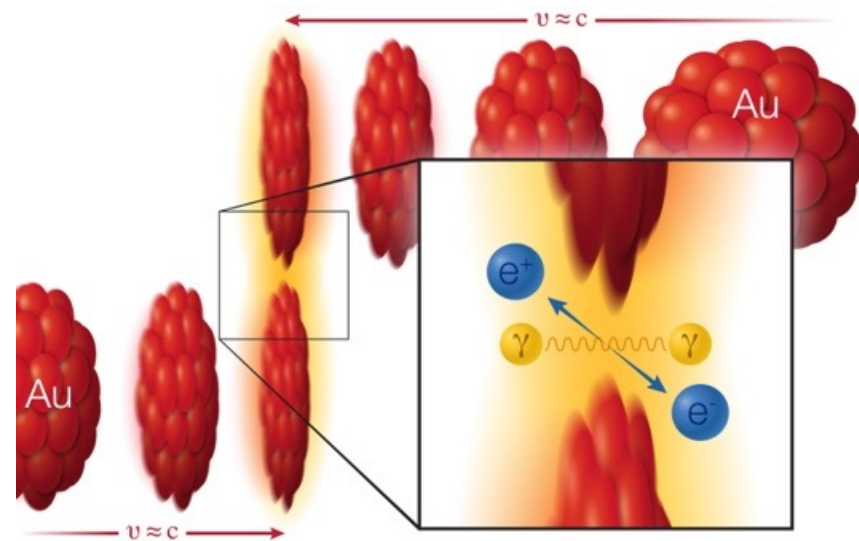
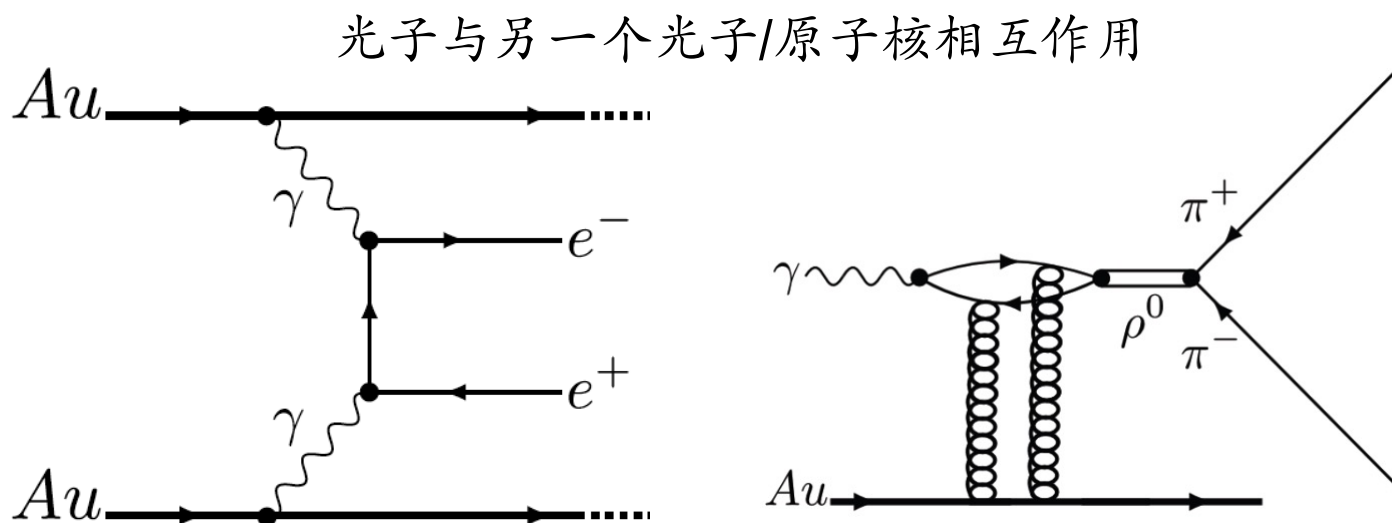
Weizsäcker, C. F. v. Zeitschrift für Physik 88, 612 (1934)

等效光子近似 (EPA)

接近光速运动的重离子

高度洛伦兹压缩的电磁场

“准实光子”

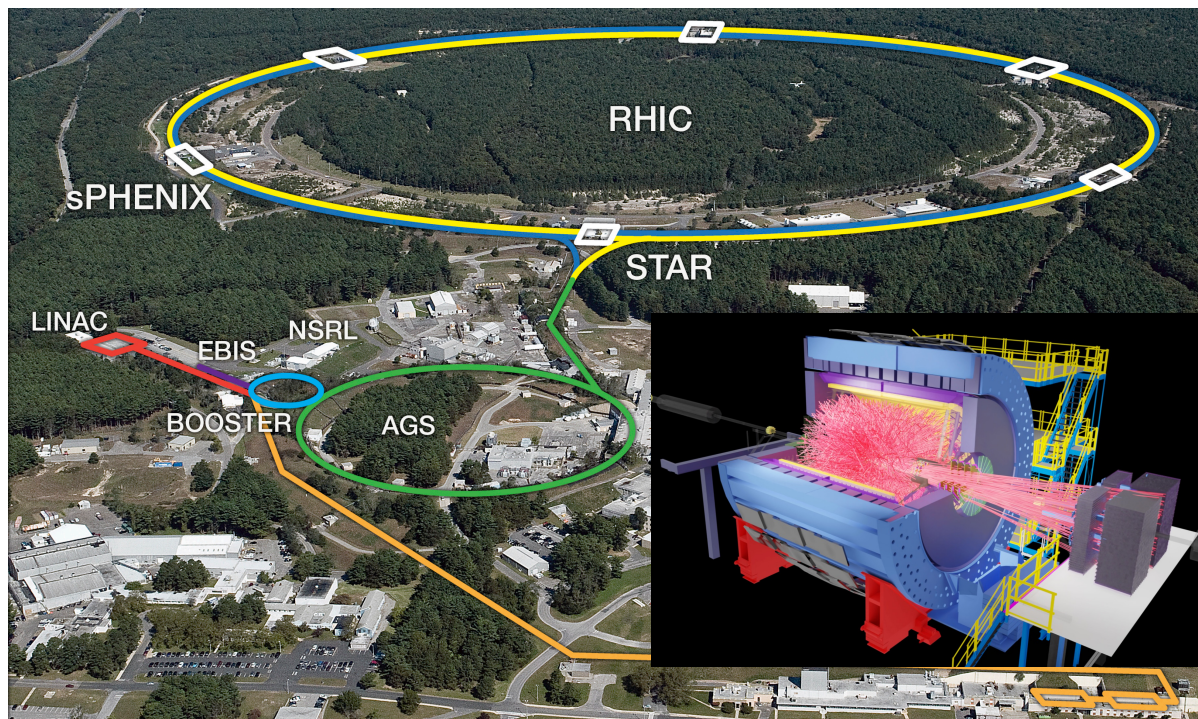


$$\gamma\gamma \rightarrow l^+l^- (h\bar{h})$$

$$\gamma A \rightarrow VM \rightarrow l^+l^- (h\bar{h})$$

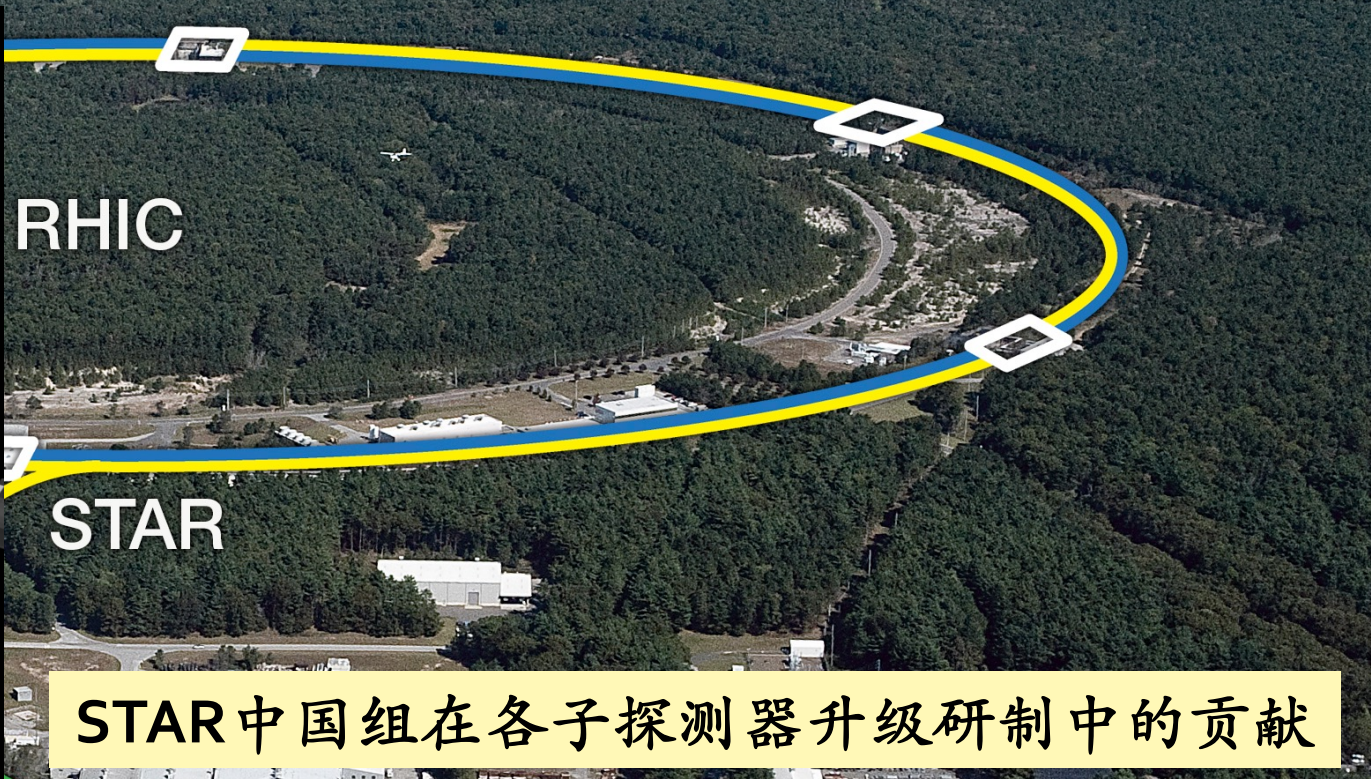
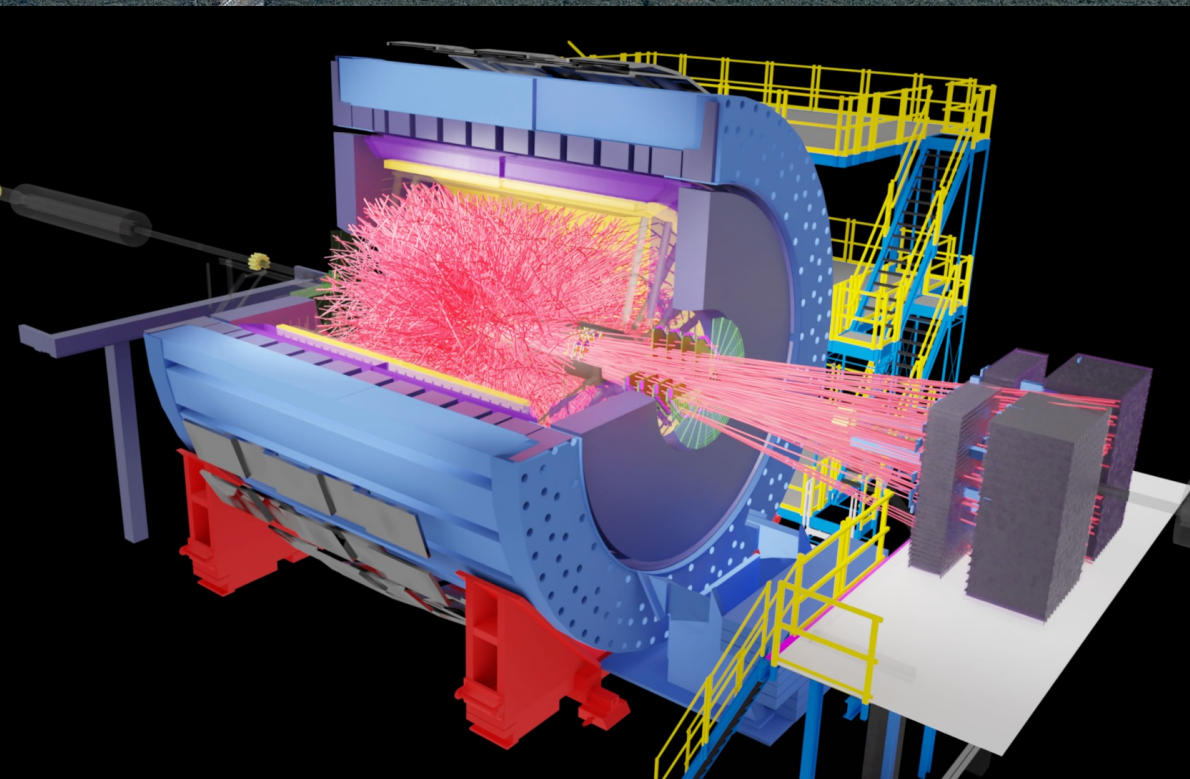
实验装置

相对论重离子对撞机
Relativistic Heavy Ion Collider (RHIC)



大型强子对撞机
Large Hadron Collider (LHC)





RHIC

STAR

STAR中国组在各子探测器升级研制中的贡献



BOOST

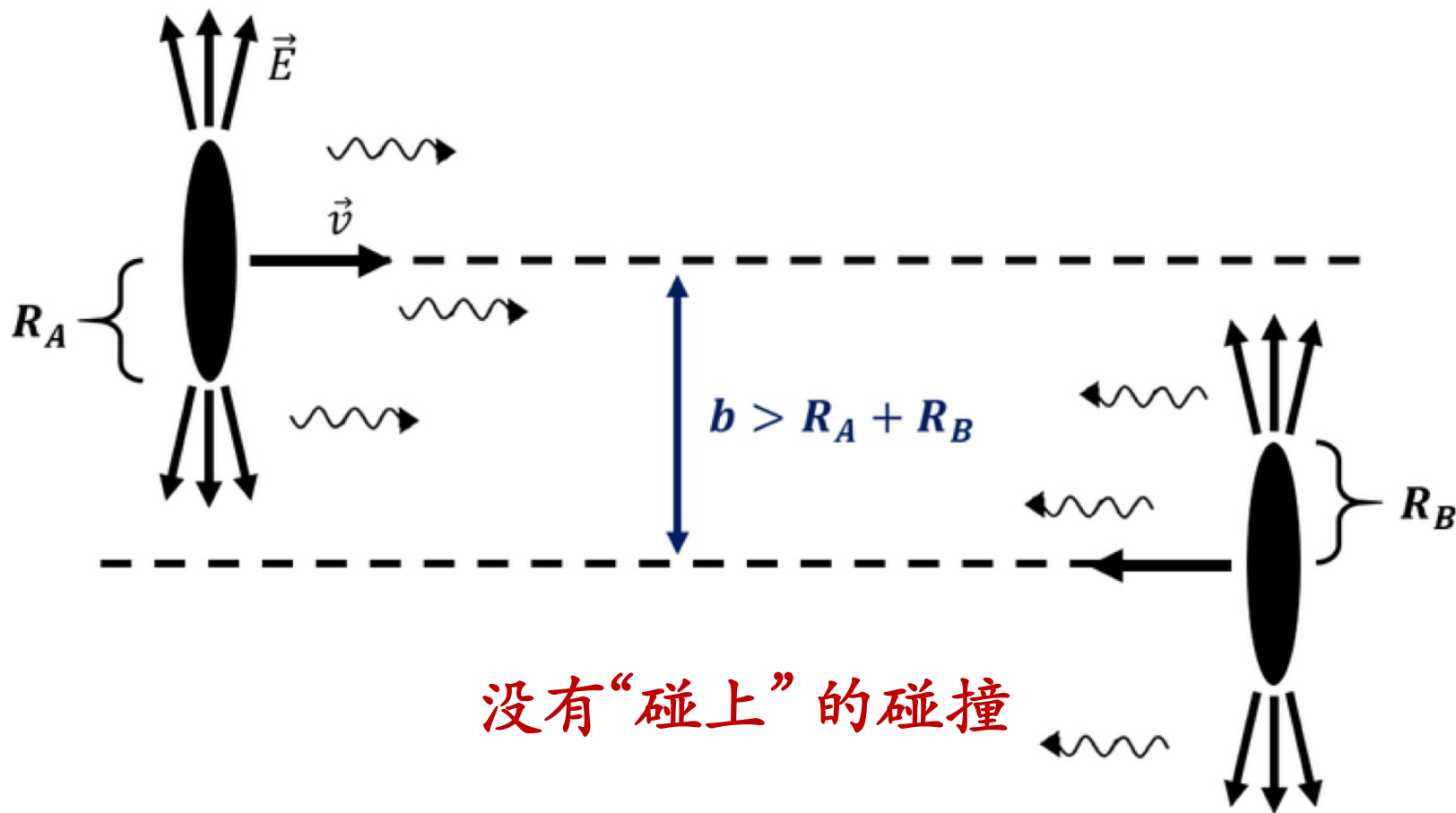
	STAR	TOF	MTD	HFT	iTPC	eTOF	EPD	FST	FTT	FCS
CCNU				✓		✓	✓			
FDU	✓			✓	✓		✓			✓
IMP				✓			✓	✓		
SDU					✓			✓	✓	✓
THU	✓	✓				✓				
USTC	✓	✓	✓		✓	✓	✓		✓	



ANDERMS

超周边碰撞

Ultra-Peripheral Collisions (UPCs)



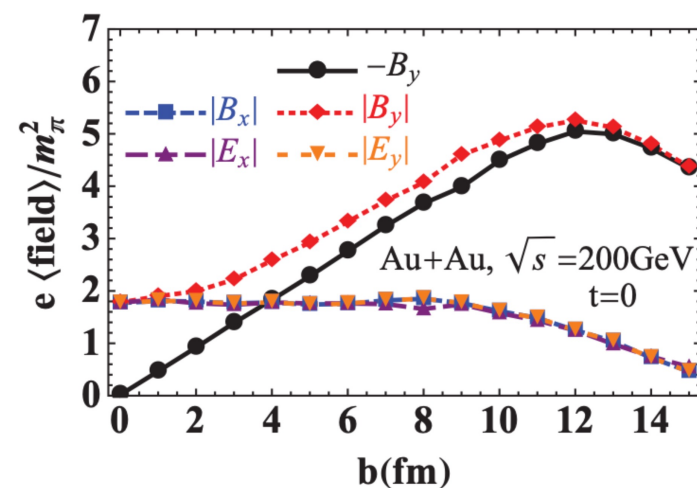
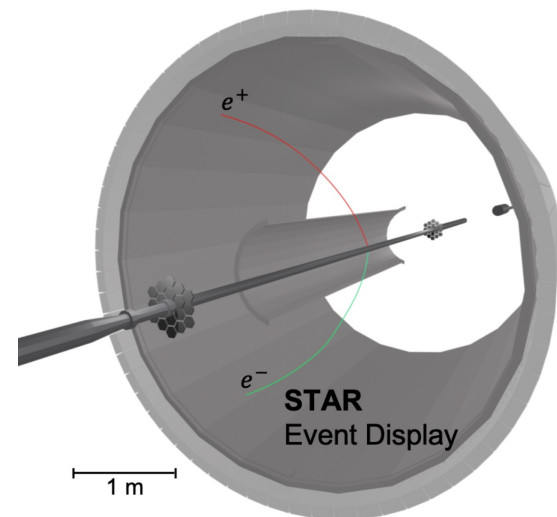
超周边碰撞

- 干净的**遍举**测量
- 高度洛伦兹压缩的电磁场: **准实光子**
- 光子**能量高**: $Q \sim 1/R \quad \sim 30 \text{ MeV @ LHC/RHIC}$
 $E_{\text{max}} \approx \gamma \hbar c / R \quad \sim 80 \text{ GeV @ LHC}, \sim 3 \text{ GeV @ RHIC}$
- 光子**密度高**: $\propto Z^2$ (来自单个重离子的通量)
- **低虚度**: $Q^2 \lesssim (\hbar/R_A)^2$ in UPCs $\Rightarrow$ 接近实光子

Ann.Rev.Nucl.Part.Sci. 55, 271-310 (2005)

- **对原子核结构敏感**: 初始的强电磁场和胶子分布
- 与非超周边碰撞比较: 研究介质的电磁特性

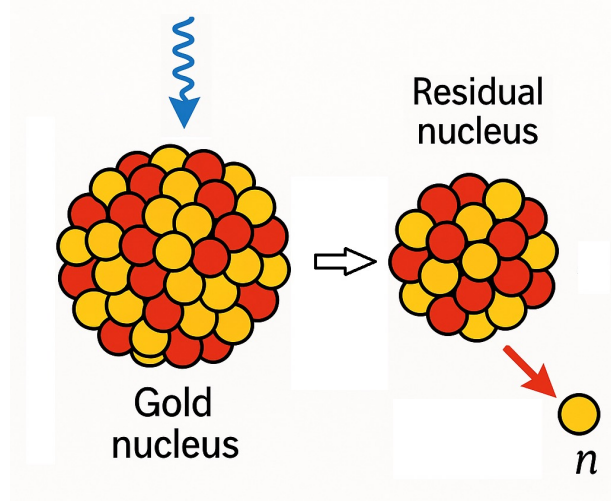
报告仅包含与核结构相关的部分内容, 未包含真空
激发测量、胶子饱和探索、奇特态寻找等重要工作



WT Deng, XG Huang, Phys. Rev. C, 85, 044907 (2012)

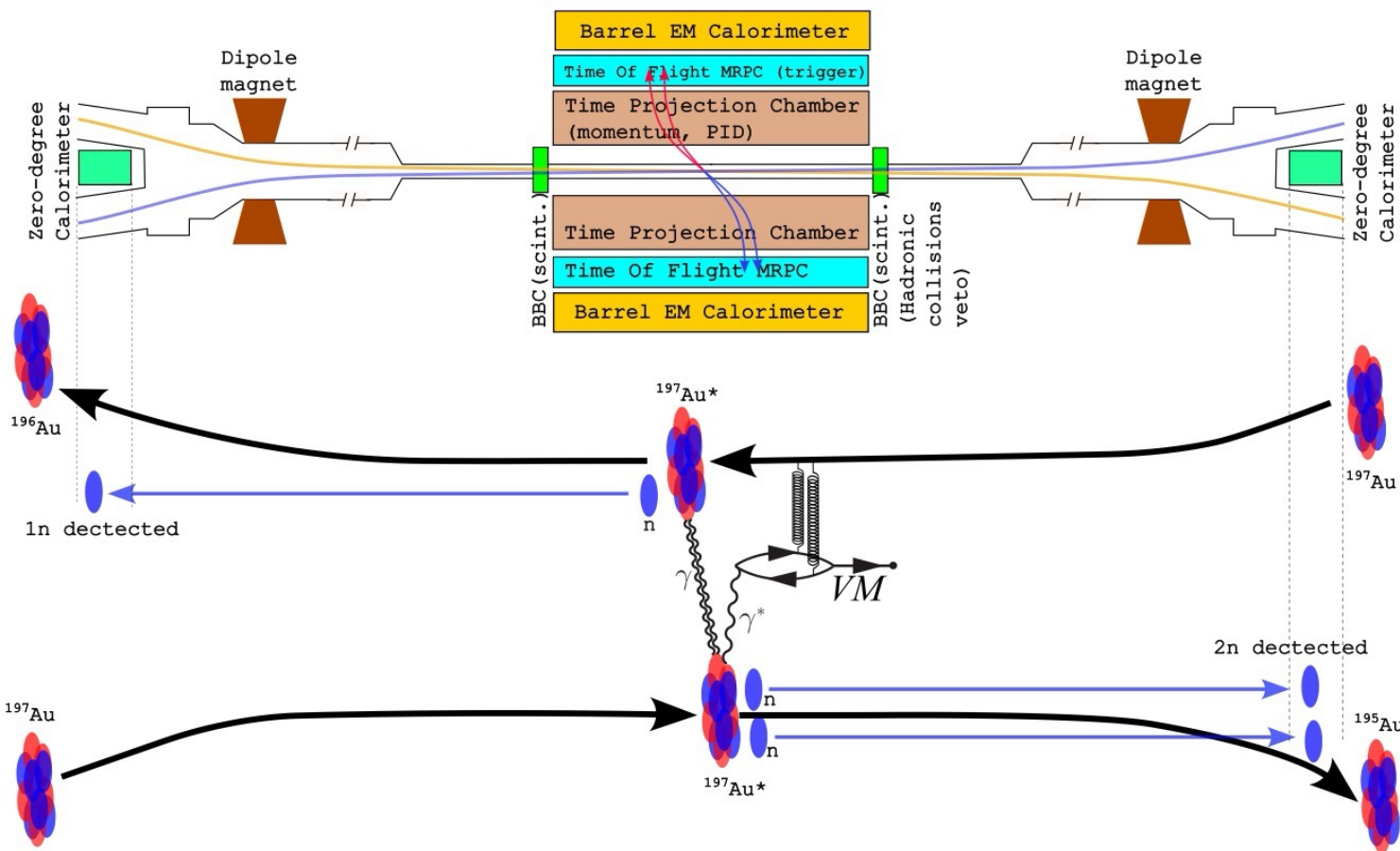
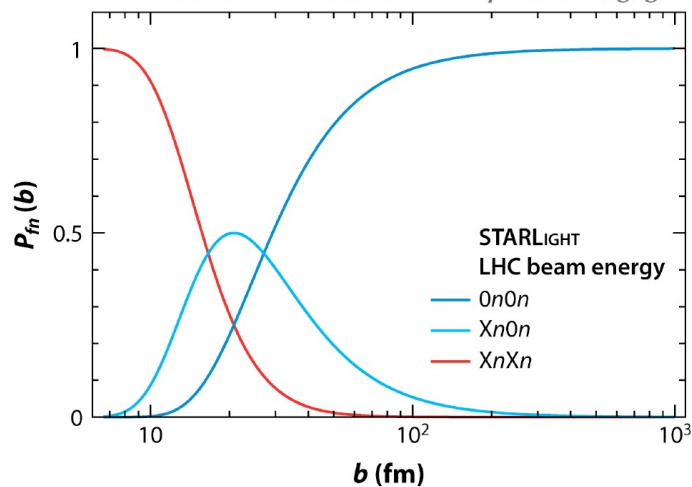
超周边碰撞中的中子标记

库伦解离产生的中子：用于UPC触发



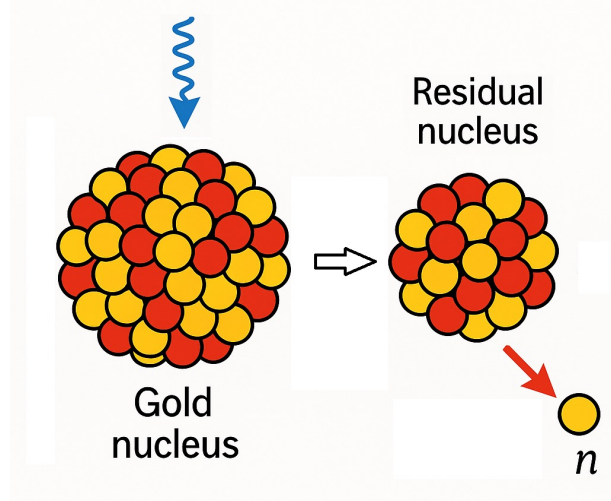
碰撞参数与中子发射的关系

[Ann.Rev.Nucl.Part.Sci. 70 \(2020\) 323](#)



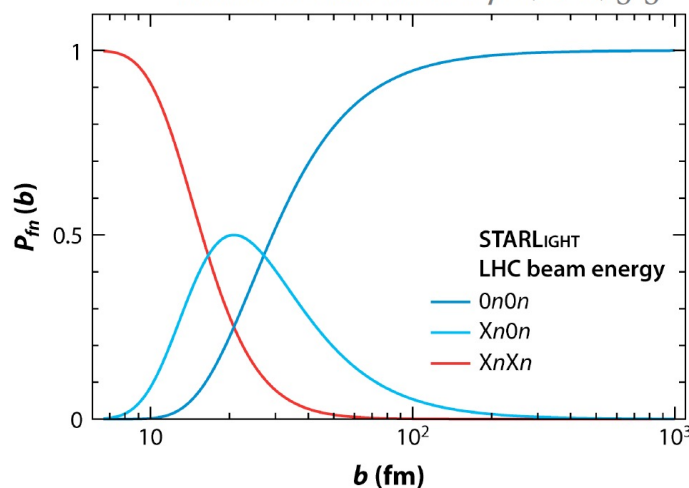
超周边碰撞中的中子标记

库伦解离产生的中子：用于UPC触发

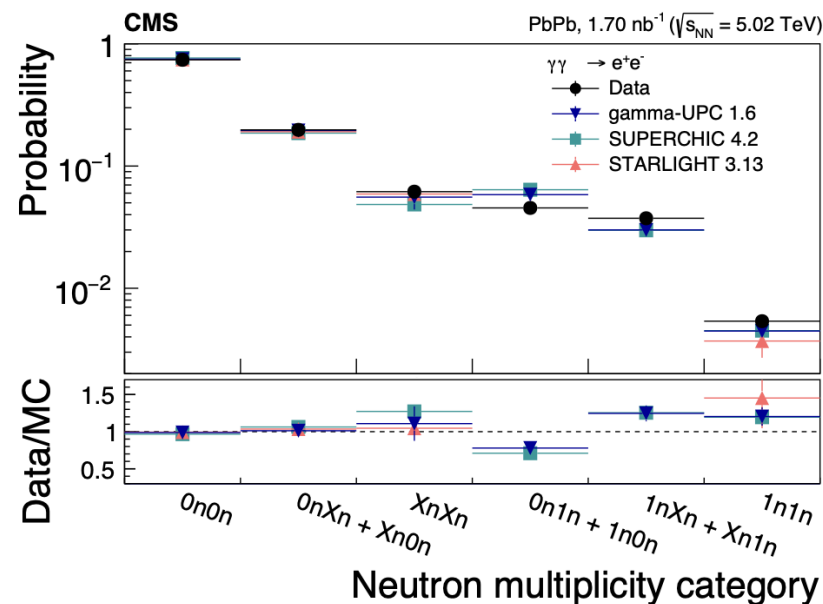
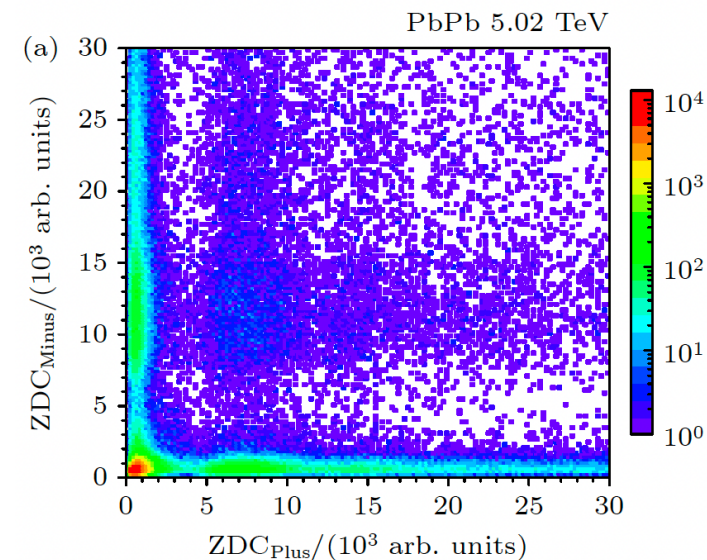
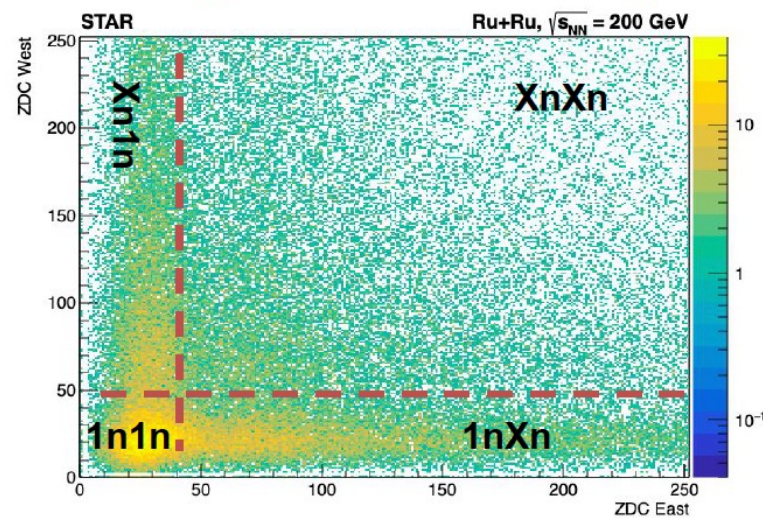


碰撞参数与中子发射的关系

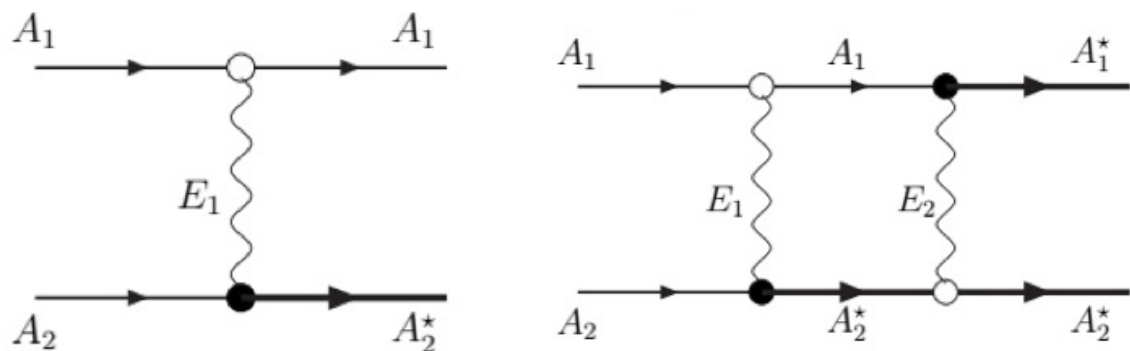
[Ann.Rev.Nucl.Part.Sci. 70 \(2020\) 323](#)



Neutron-tagged events are selected using the ZDC



同质异位素对撞中的库伦解离测量

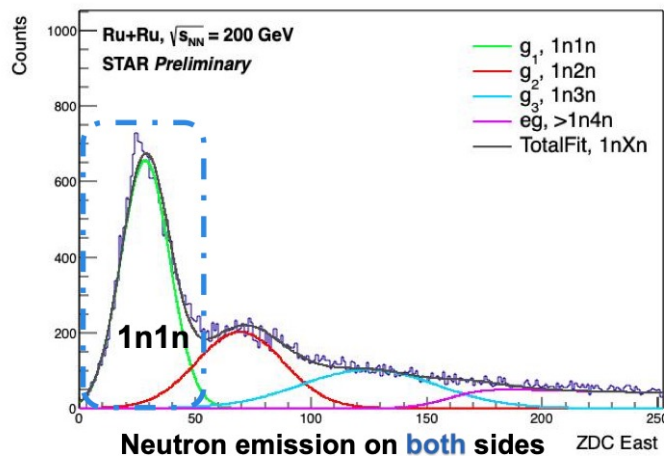


同质异位素:

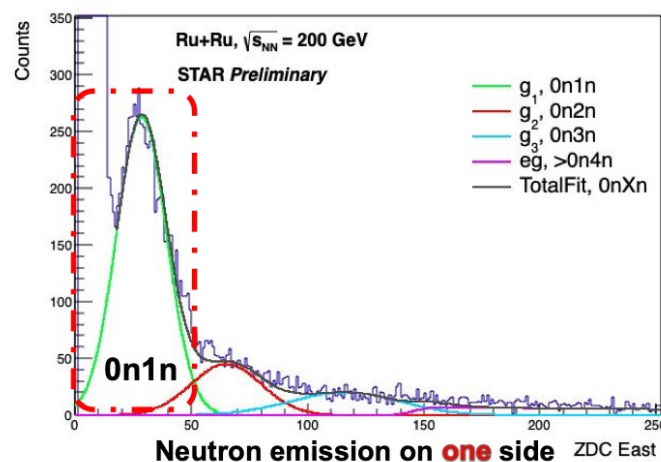
钌 ($^{96}_{44}\text{Ru}$) 锆 ($^{96}_{40}\text{Zr}$)

- 相同的核子数
- 不同的电荷数
- 核结构“不同”

b). Single Coulomb dissociation (SCD)



c). Mutual Coulomb dissociation (MCD)



$$\frac{Z_{\text{Ru}}^2}{Z_{\text{Zr}}^2} \approx 1.21$$

Neutron	Ratio (Ru/Zr)		
1n1n	2.18	± 0.02	± 0.21
1nXn	1.43	± 0.05	± 0.12
XnXn	0.88	± 0.02	± 0.09

Neutron	Ratio (Ru/Zr)		
0n1n	1.60	± 0.02	± 0.04
0nXn	1.03	± 0.06	± 0.02
0nXn+Xn0n	1.03	± 0.06	± 0.02

on1n (onXn) SCD 和 1n1n (XnXn) 的产额比偏离 Z^2

不同的电荷分布和/或GDR区域不同的光生截面?

$$\gamma\gamma \rightarrow l^+ l^-$$

布雷特-惠勒过程

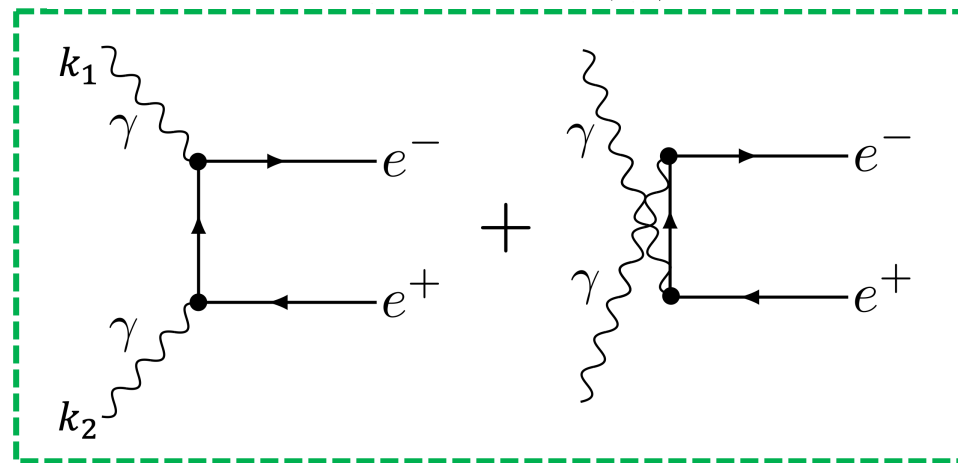
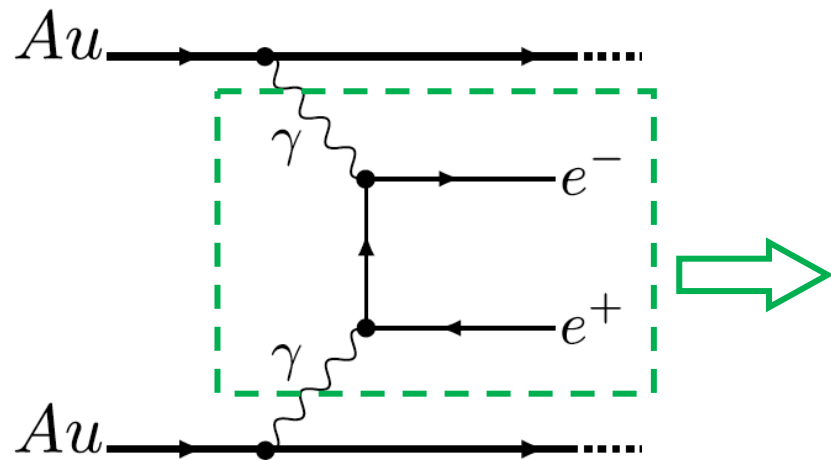
DECEMBER 15, 1934

PHYSICAL REVIEW

VOLUME 46

Collision of Two Light Quanta

G. BREIT* AND JOHN A. WHEELER,** *Department of Physics, New York University*
(Received October 23, 1934)



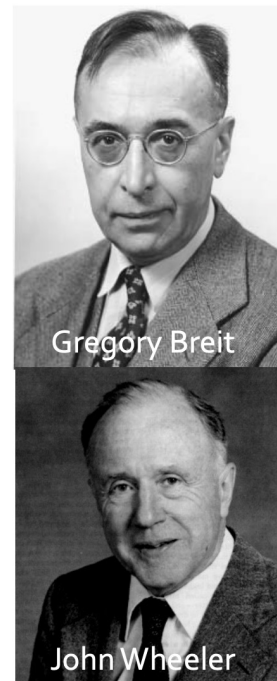
The Breit-Wheeler Process $\gamma\gamma \rightarrow e^+e^-$

- 光与物质相互作用的基本过程之一
- 高能天体物理、强场QED研究中的一个重要过程

他们指出，将原子核场量子化可能有帮助

E. J. Williams Phys. Rev. 45, 729 (1934)

K. F. Weizsacker, Z. Physik, 612 (1934)



Gregory Breit

John Wheeler

Converting photons into e^+e^-

G. Breit, J. A. Wheeler, Phys. Rev. 46, 1087 (1934)

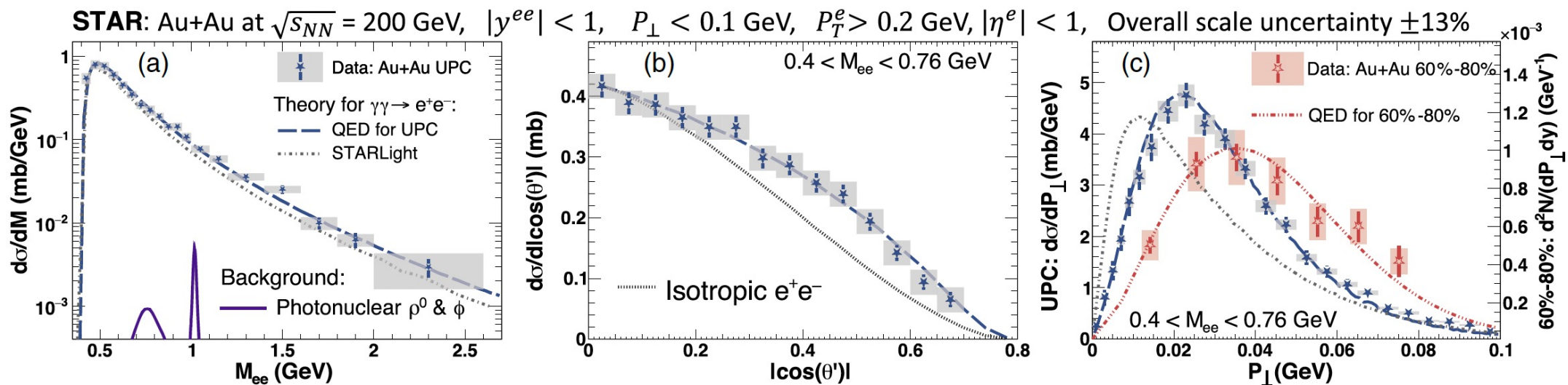
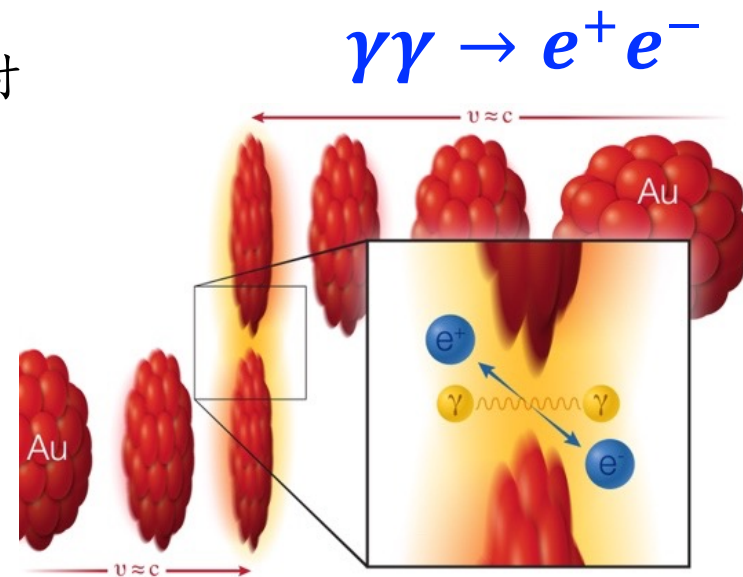
of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number of nucleii available in unit volume of ordinary materials, increases the effect to observable amounts. Analyzing the field of the nucleus into quanta by a procedure similar to that of v. Weizsäcker,⁴ he finds that if one quantum $h\nu$

布雷特-惠勒对产生的研究

STAR实验测量到BW过程

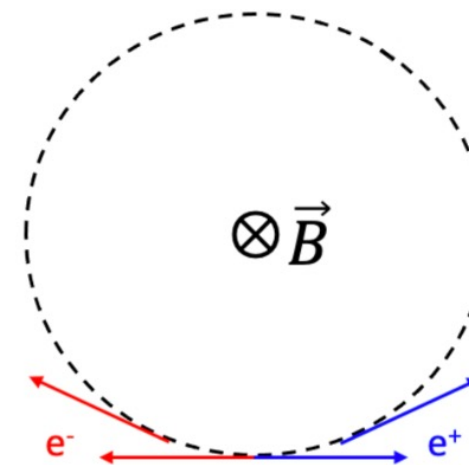
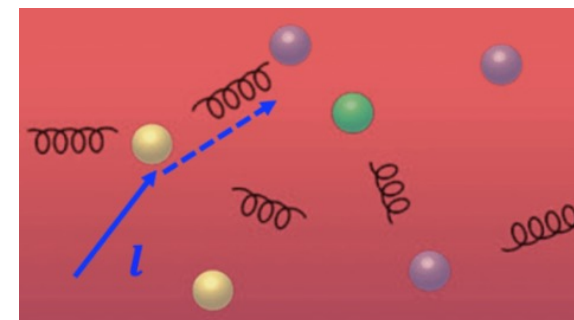
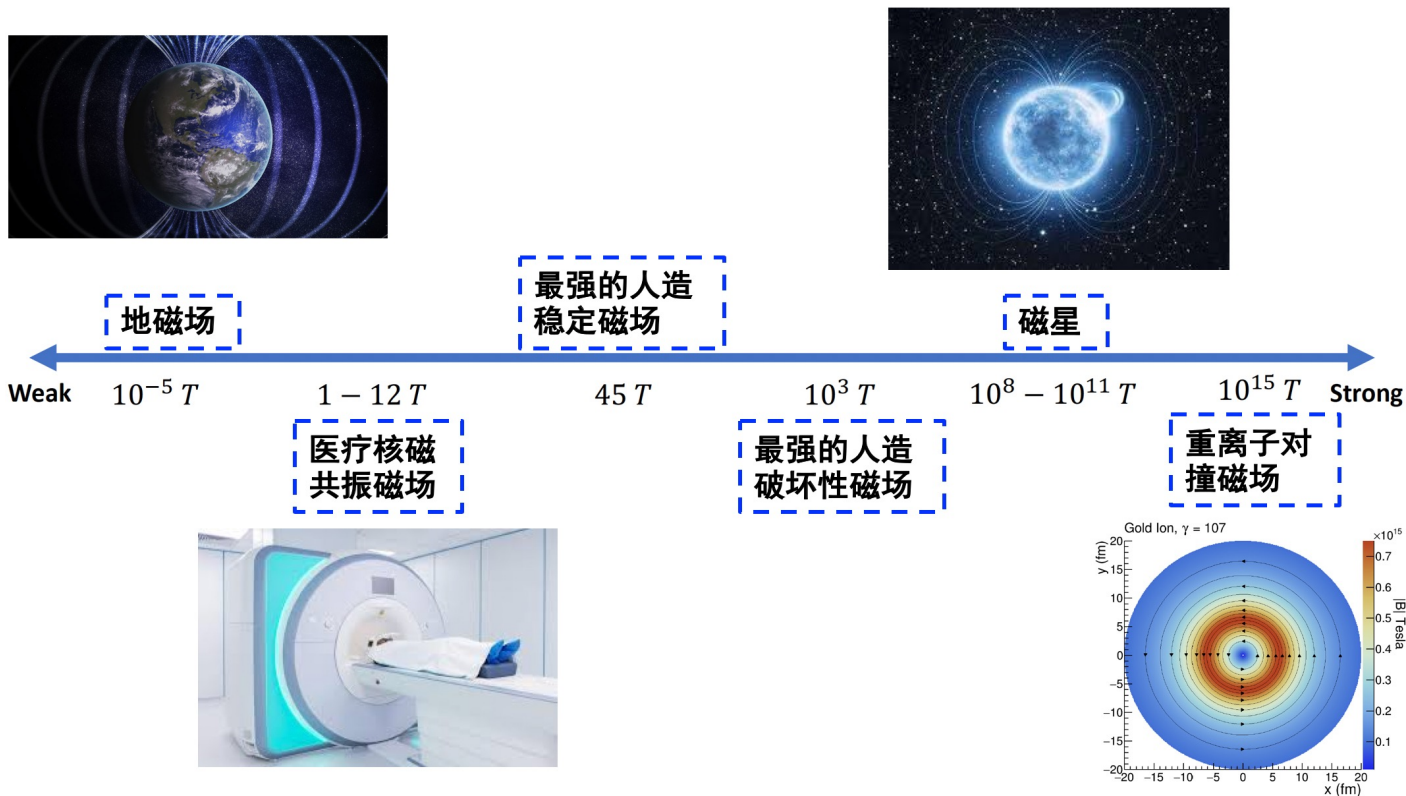
- UPC中6085 对遍举起来正负电子对
- 未观测到矢量介子贡献
- 低横动量下的显著信号
- 与QED预期符合的多物理量测量

Quantity	Measured	SL	GEPA	QED
$\sigma(\mu\text{b})$	$261 \pm 4 \pm 13 \pm 34$	220	260	260



强磁场 + 夸克胶子等离子体

强磁场时间短，但是磁刚度可达MeV量级，产生可观测的效应



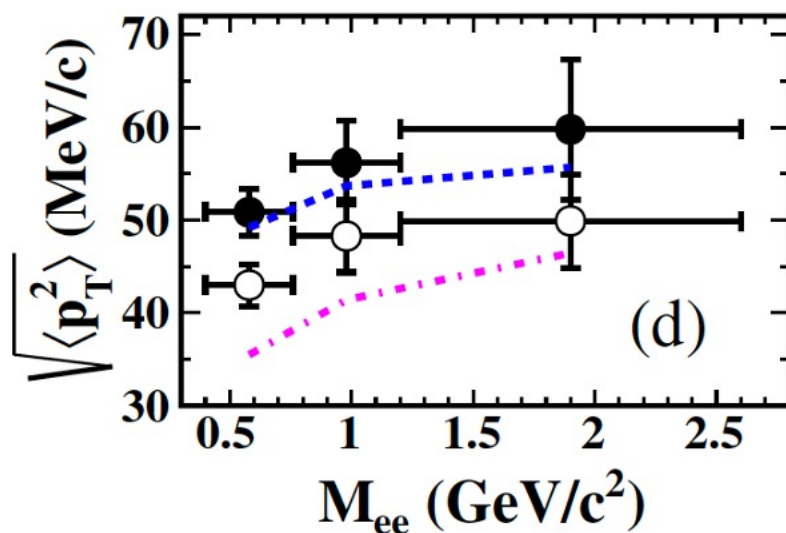
“末态效应”?

QGP中禁錮的磁场或库伦散射可能导致横动量展宽

强磁场 + 夸克胶子等离子体

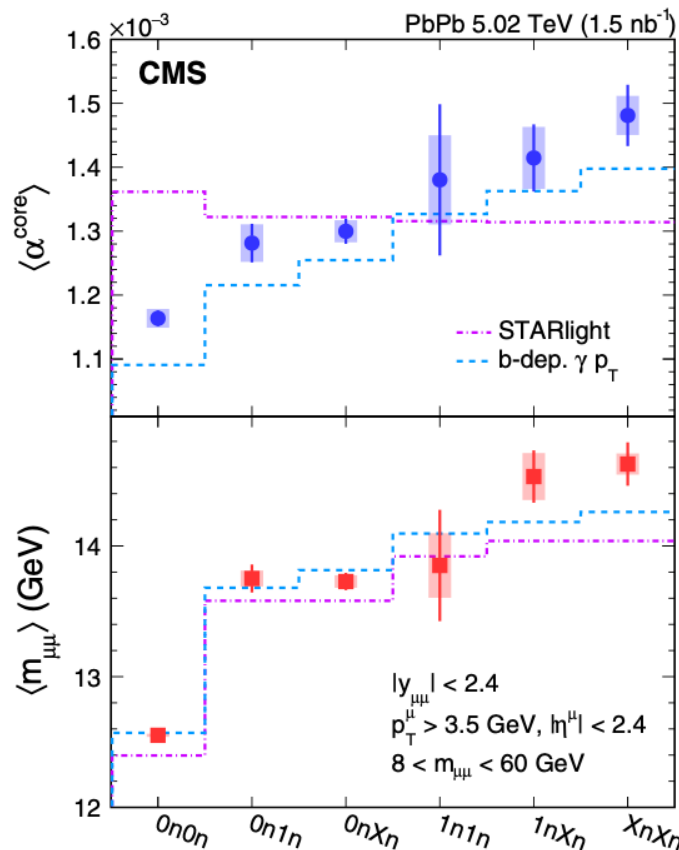
观测到可能的末态效应? -> 应考虑碰撞参数的依赖 -> 中心度和能量扫描

$$\gamma\gamma \rightarrow e^+e^-$$



STAR, PRL 121, 132301 (2018)

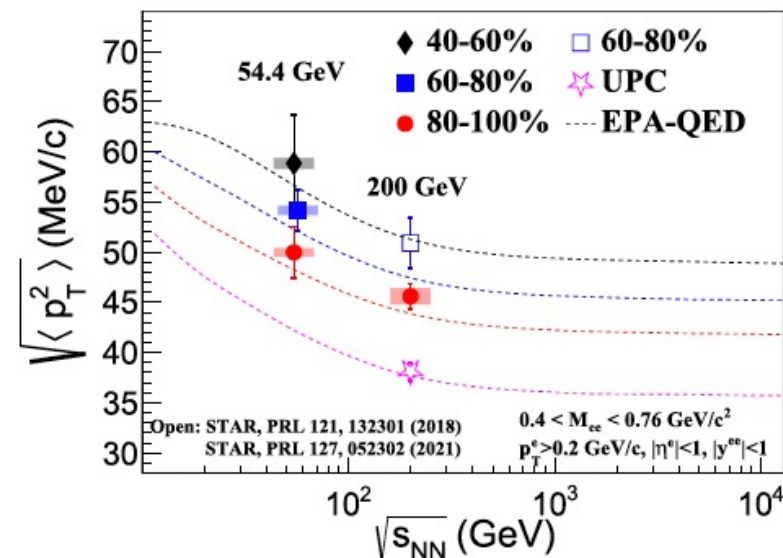
$$\gamma\gamma \rightarrow \mu^+\mu^-$$



CMS, PRL 127, 122001 (2021)

W. Zha, et al. PLB 800, 135089 (2020)

$$\gamma\gamma \rightarrow e^+e^-$$

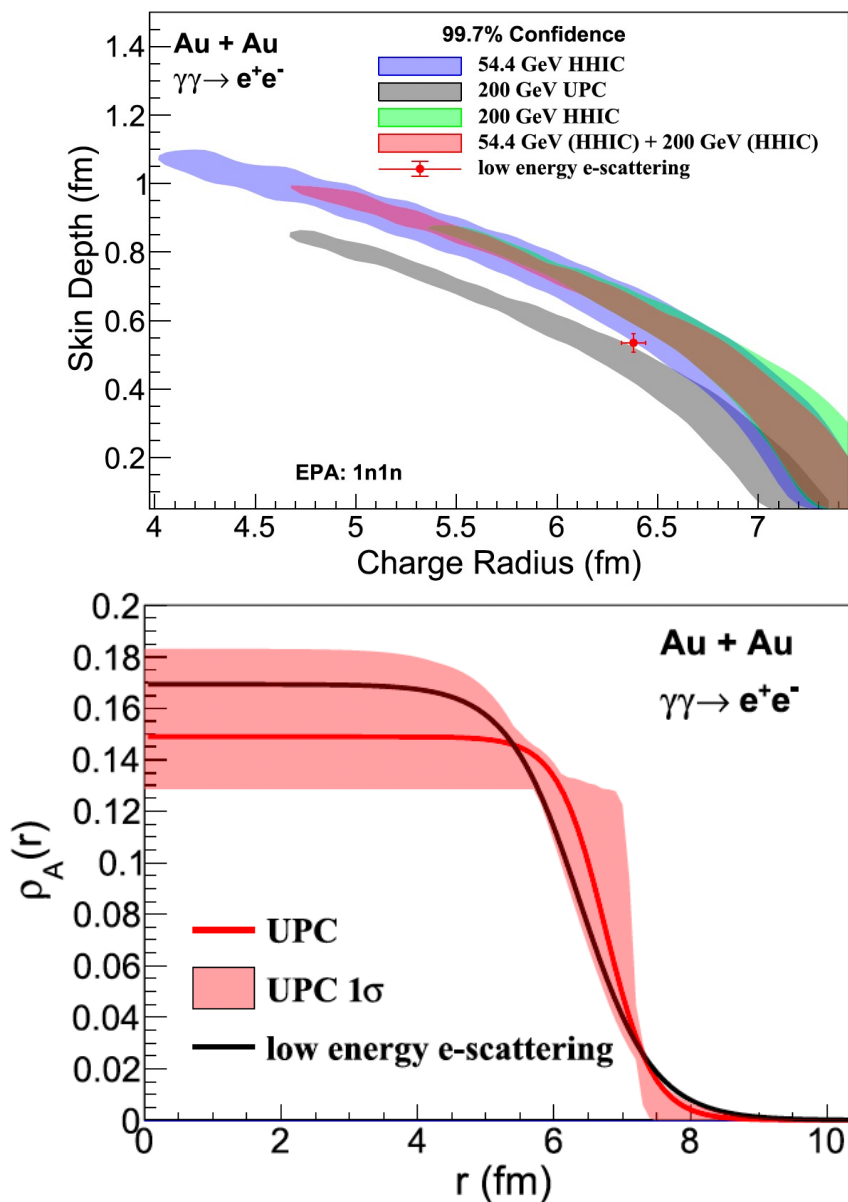


- $\sqrt{\langle p_T^2 \rangle}$ (不同中心度和UPC中测量)
碰撞参数依赖
- $\sqrt{\langle p_T^2 \rangle}$ (能量扫描测量)
4.3 σ (能量依赖+ 可能的末态效应)

STAR, PRC 111, 014909 (2025)

研究原子核电电荷分布

QED计算 vs 实验测量：约束原子核电电荷分布



- 与QED理论计算比较，约束理论计算中的电荷分布输入 (Wood-Saxon distribution)
$$\rho_A(r) = \frac{\rho_0}{1 + \exp[(r - R)/d]}$$
- 存在QGP和无QGP的结果有区别 (末态效应?)
- 可能的末态效应将导致更大的电荷分布半径
- UPC中的结果与低能电子散射实验结果符合
- 未来更精确的实验测量将给出更好的约束

STAR, PRC 111, 014909 (2025)

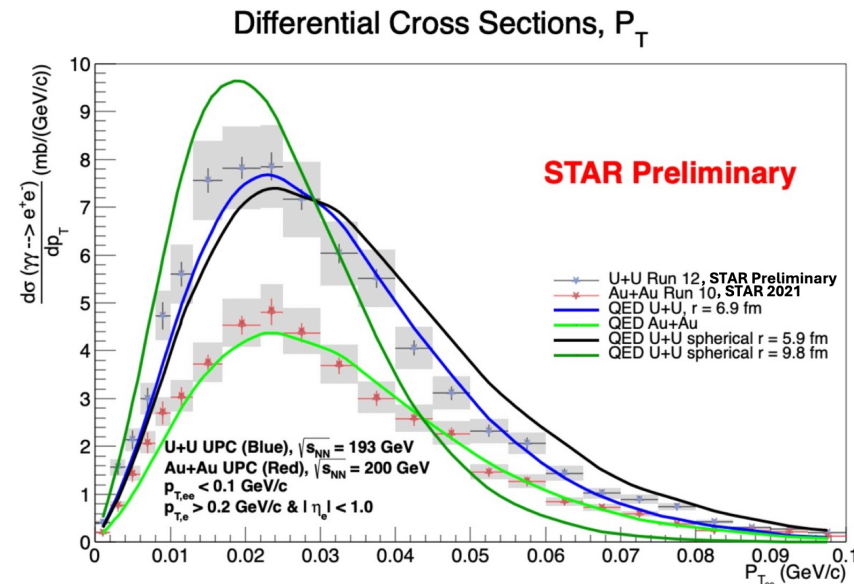
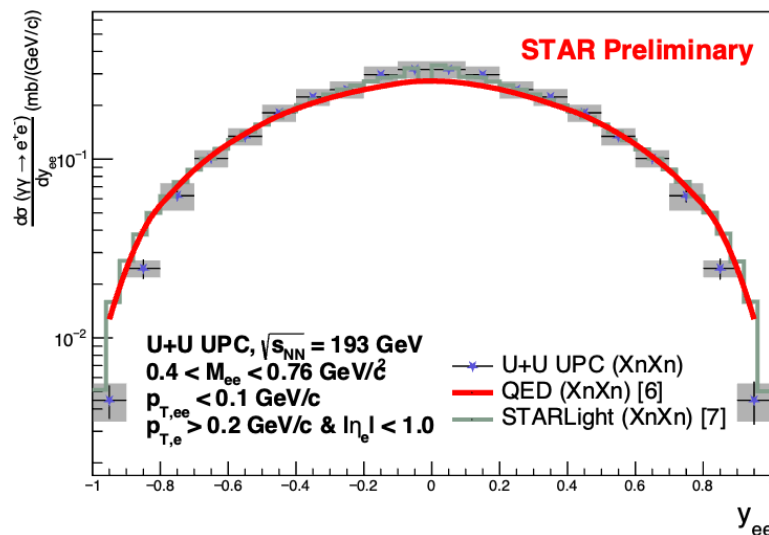
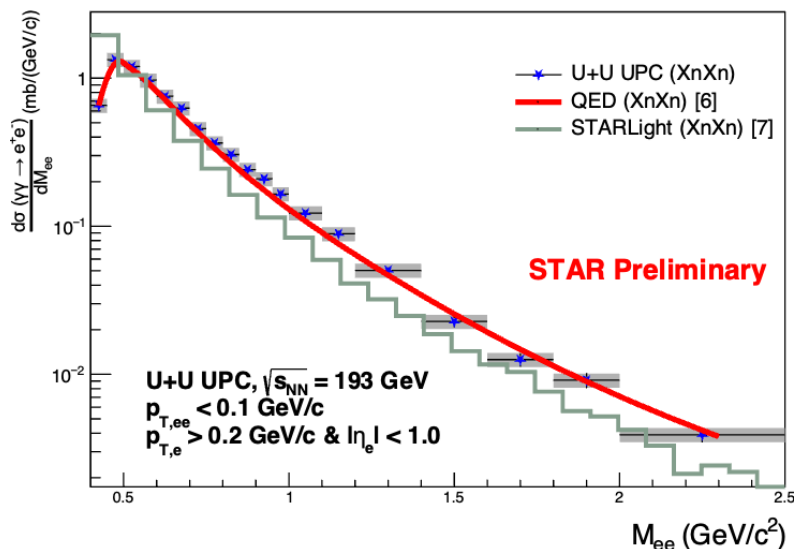
X. Wang, J. Brandenburg, L. Ruan, F. Shao, Z. Xu, CY, W. Zha, PRC 107, 044906 (2023)

X. Wang, CY, NPA 1060, 123136 (2025)

研究原子核电电荷分布

$$\gamma\gamma \rightarrow e^+e^-$$

铀原子核: 相较于金原子核更不规则

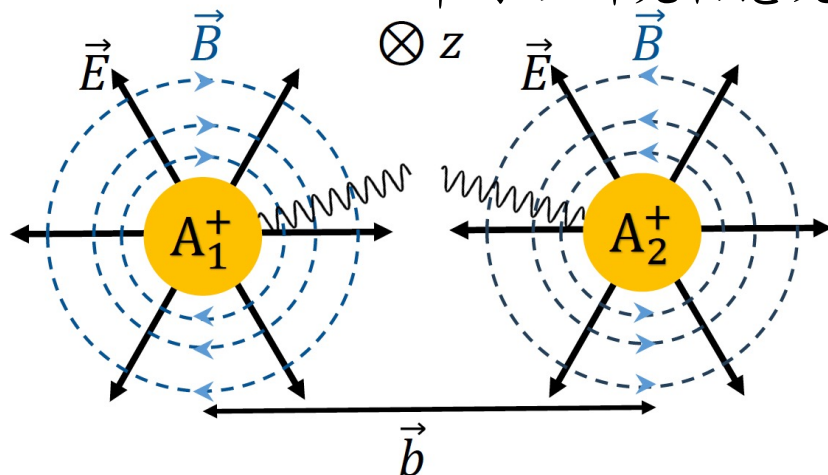


- QED理论预期可以描述铀-铀碰撞中BW过程的质量和快度分布, 但是不能很好描述横动量谱
- 多维度的联合约束?

布雷特-惠勒过程中自旋诱导的末态角分布效应

重离子碰撞自旋物理理论引导实验测量

UPC中可以研究初态光子自旋导致的末态轨道角动量效应



QCD:

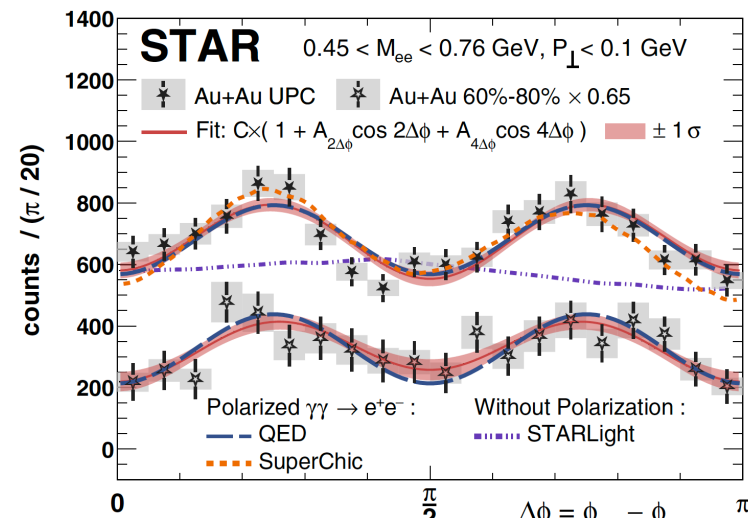
$$gg \rightarrow q\bar{q}$$
$$\Delta\phi = \phi^{q\bar{q}} - \phi^q$$

QED:

$$\gamma\gamma \rightarrow l^+l^-$$
$$\Delta\phi = \phi^l - \phi^l$$

- By direct analogy, in extreme QED fields, the linear photon polarization distribution can be measured via $\cos(2\Delta\phi)$ and $\cos(4\Delta\phi)$ modulations

- 证实初态准实光子的线偏振特性
- 测量到末态方位角四阶余弦振荡
- QED理论计算高精度描述实验测量
- 可能为原子核形状研究提供更多约束



	Ultraperipheral				Peripheral	
	Measured	QED	SC	SL	Measured	QED
$ A_{4\Delta\phi} $ (%)	16.8 ± 2.5	16.5	19	0	27 ± 6	34.5
$ A_{2\Delta\phi} $ (%)	2.0 ± 2.4	0	5	5	6 ± 6	0
$\sqrt{\langle P_{\perp}^2 \rangle}$ (MeV)	38.1 ± 0.9	37.6	35.4	35.9	50.9 ± 2.5	48.5

STAR, PRL 127, 052302 (2021)

C. Li, J. Zhou, Y.-J. Zhou, PLB 795, 576 (2019)

C. Li, J. Zhou, Y.-J. Zhou, PRD 101, 034015 (2020)

E. J. Williams Phys. Rev. 45, 729 (1934)

K. F. Weizsacker, Z. Physik, 612 (1934)

$$\gamma A \rightarrow VM$$

通过高能光子“看”原子核

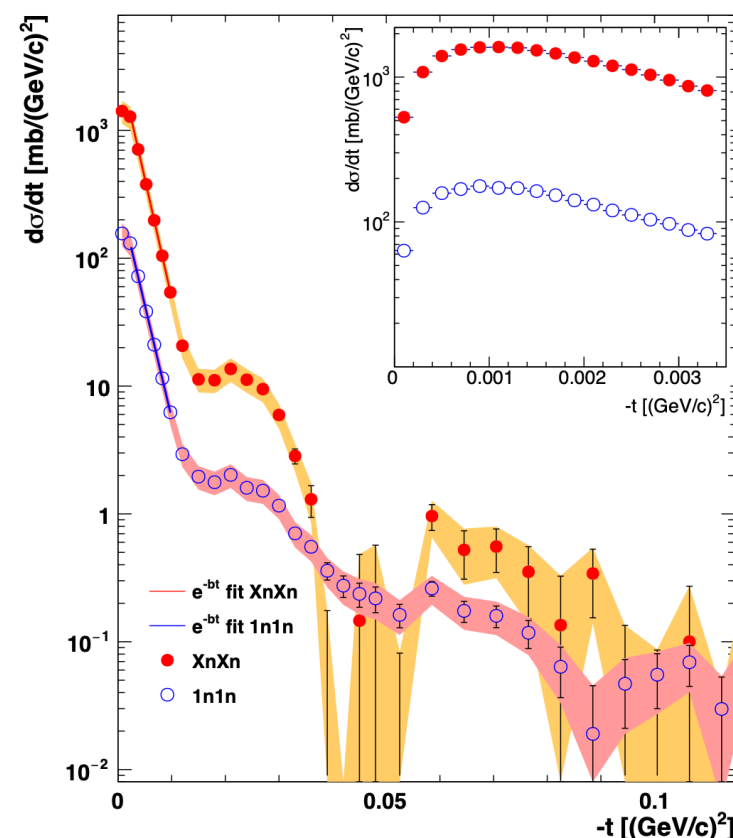
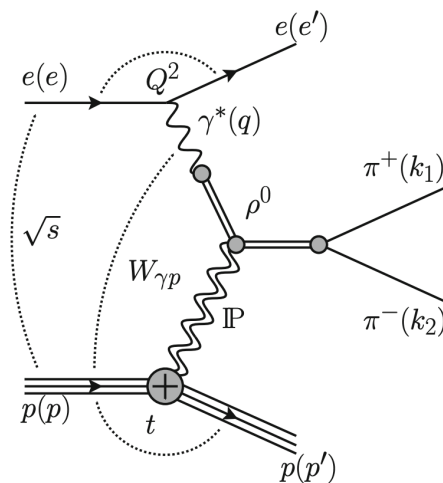
矢量介子的光生过程：长期的研究，QCD物质的良好探针

- 用光“照亮”原子核与胶子
- 一直存在测量的原子核半径偏大的问题

线性极化光子-原子核相互作用

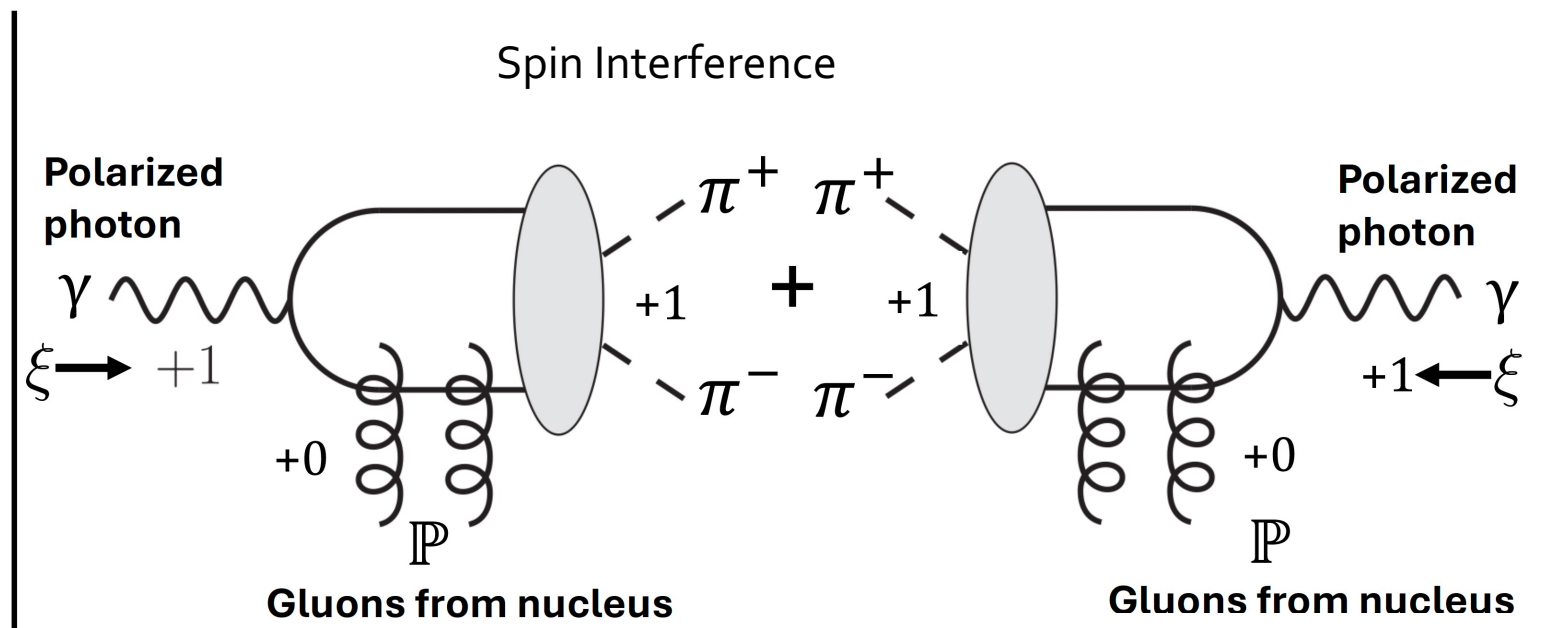
- 通过相干衍射相互作用探测核结构
- 横动量关联于核密度分布的傅里叶变换

$$\sigma(\gamma p \rightarrow Vp) = \frac{d\sigma}{dt} \bigg|_{t=0} \int_{t_{\min}}^{\infty} |F(t)|^2 dt$$



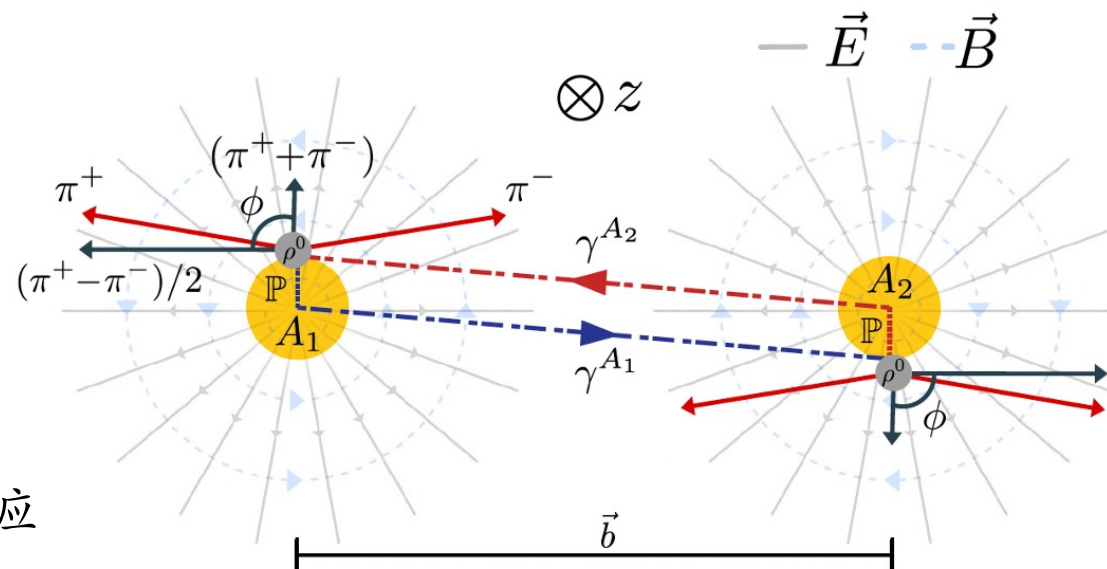
STAR, Phys. Rev. C 96, 054904 (2017)
STAR, Phys. Rev. C 85, 14910 (2012)
STAR, Phys. Rev. C 77, 34910 (2008)
H1, Eur. Phys. J. C 80, 1189 (2020)
H1, J. High Energy. Phys. 2010, 32 (2010)
ZEUS, Eur. Phys. J. C 2, 247–267 (1998)

自旋干涉

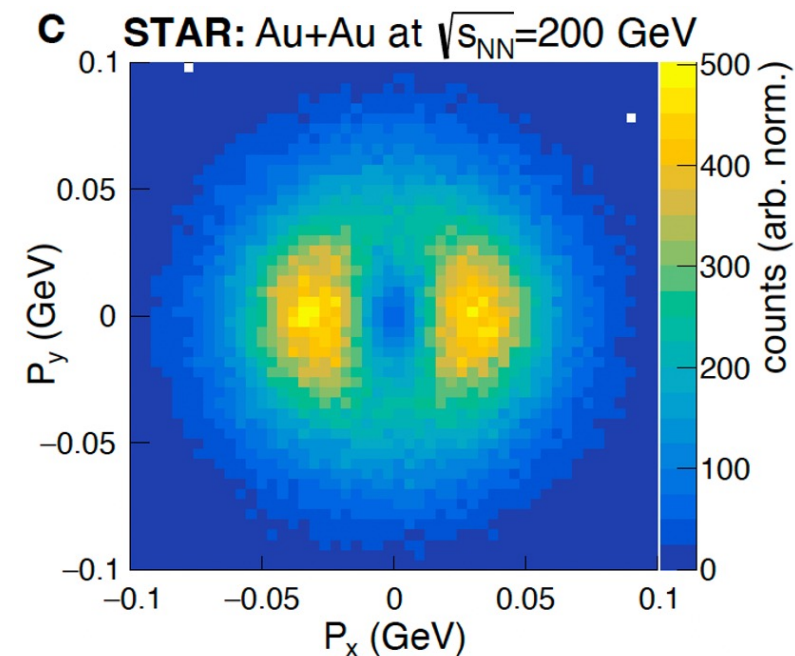
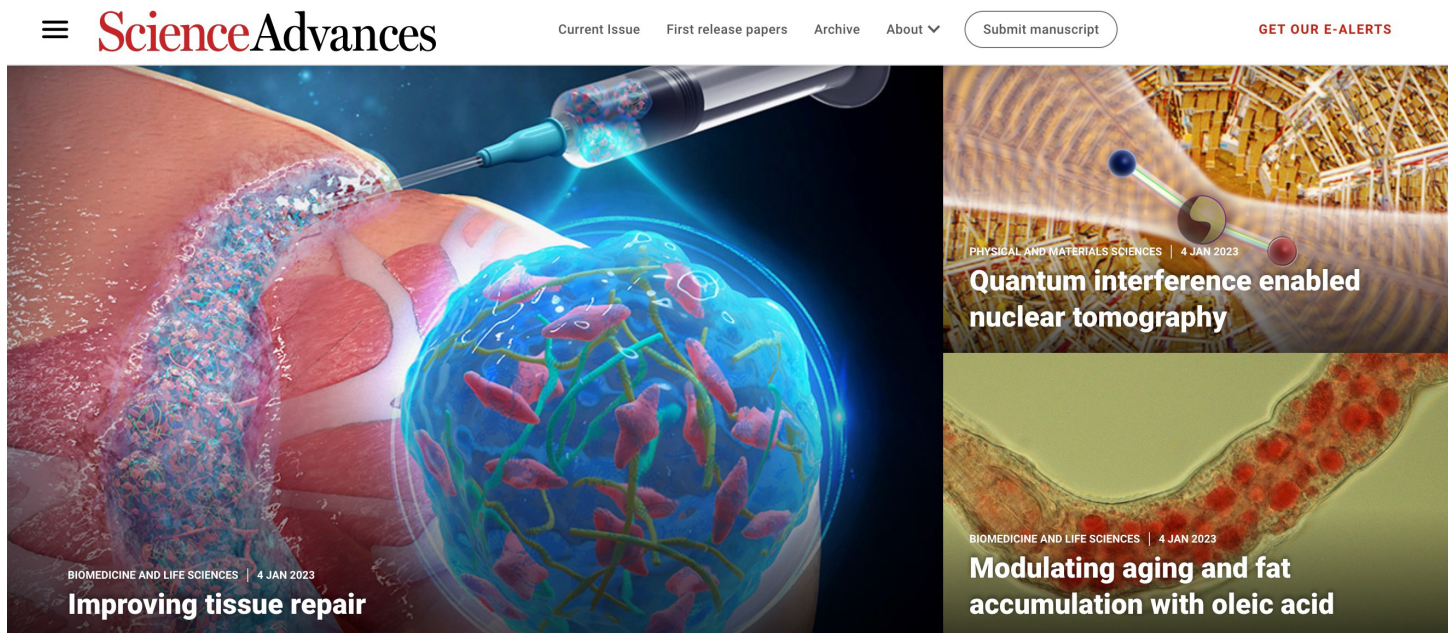


量子干涉效应敏感于:

- 原子核的几何尺寸(胶子分布)
- 碰撞参数(空间分布)
- 与布雷特-惠勒过程类似的末态方位角调制效应



通过量子干涉研究原子核结构



- 动量空间- $\rightarrow$ 极化空间

- 沿着极化方向看干涉最大，垂直于极化方向上看干涉最小

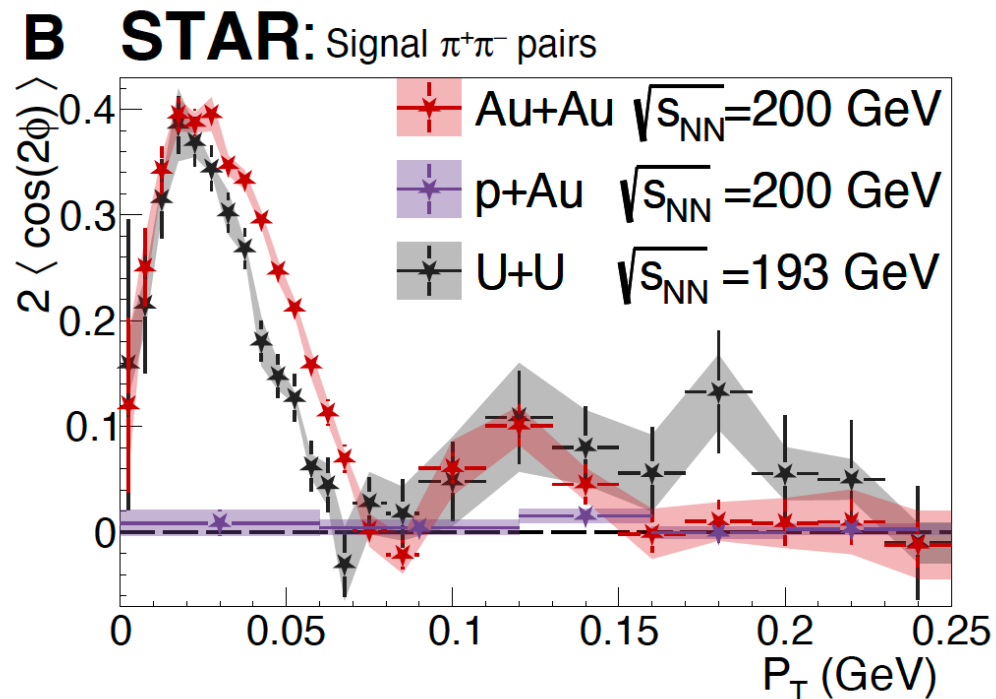
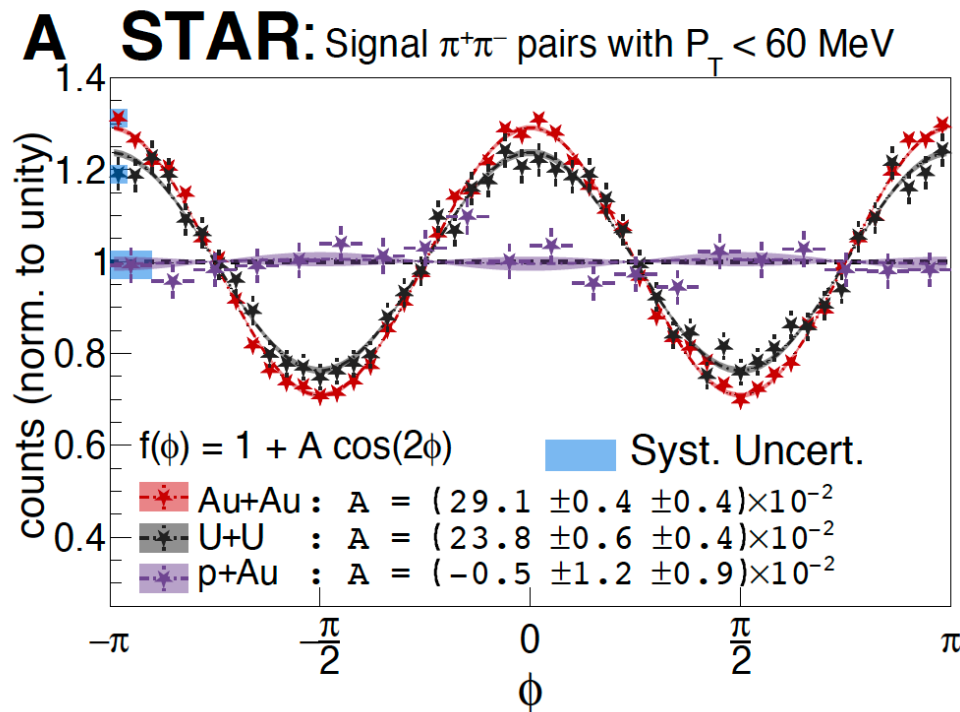
- 干涉+衍射图像

$$P_x = p_T \times \cos \phi$$

$$P_y = p_T \times \sin \phi$$

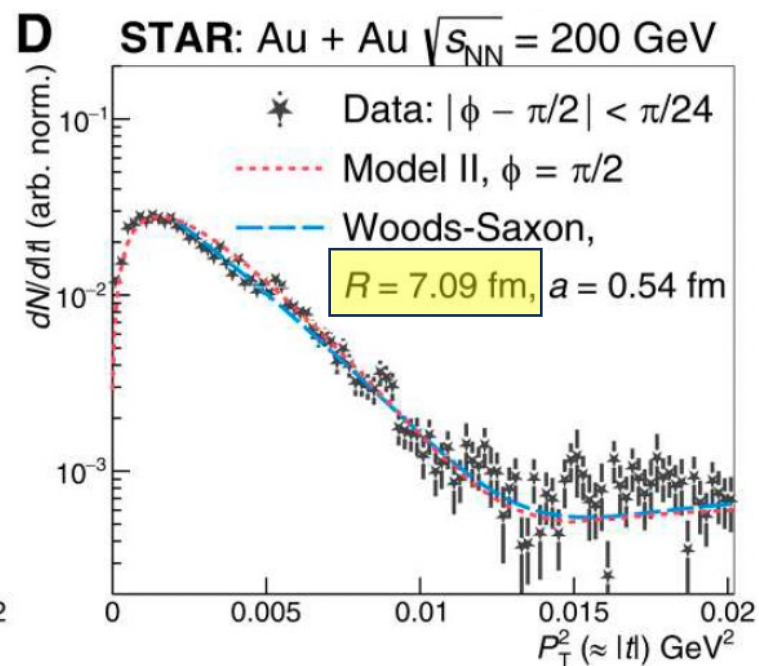
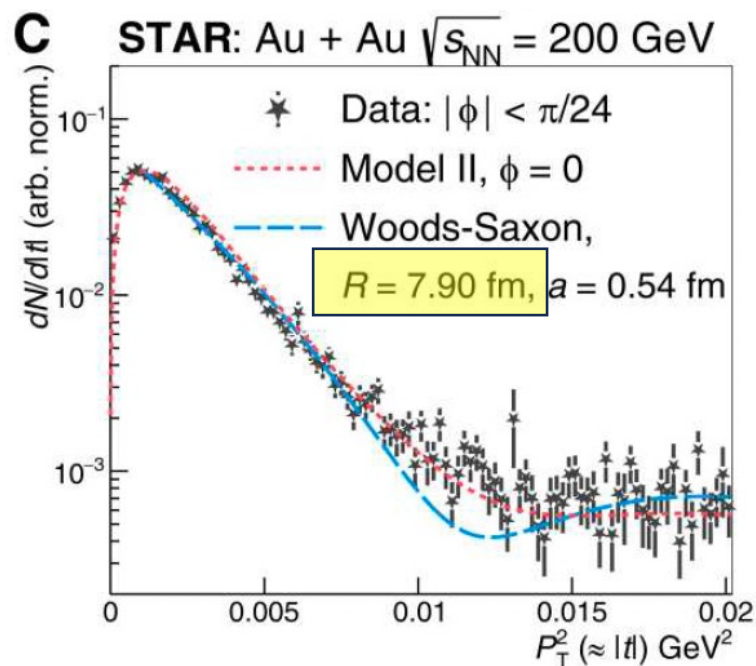
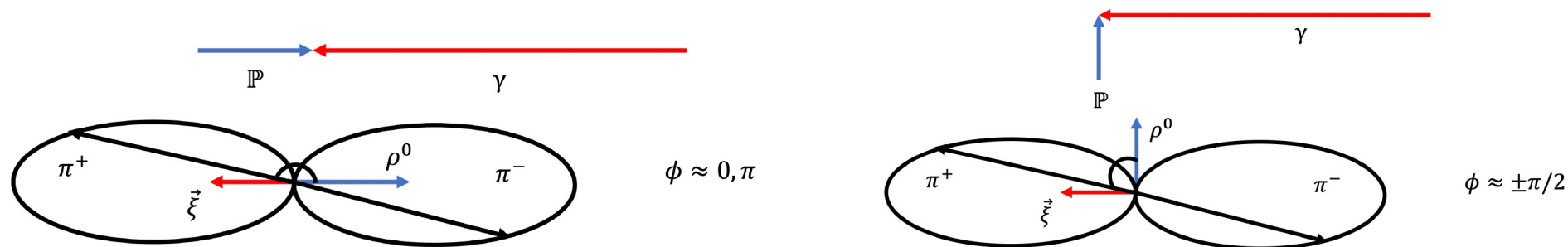
P_x : ρ^0 横动量在 π 横动量方向的投影

末态方位角二阶余弦振荡



- 观测到末态方位角二阶余弦振荡
- 干涉条纹随原子核半径变化而变化
- Au+Au与U+U的幅度不同, 4.3σ (7.6σ)
- p+Au中没有观测到干涉现象

极化方向依赖的强相互作用半径测量



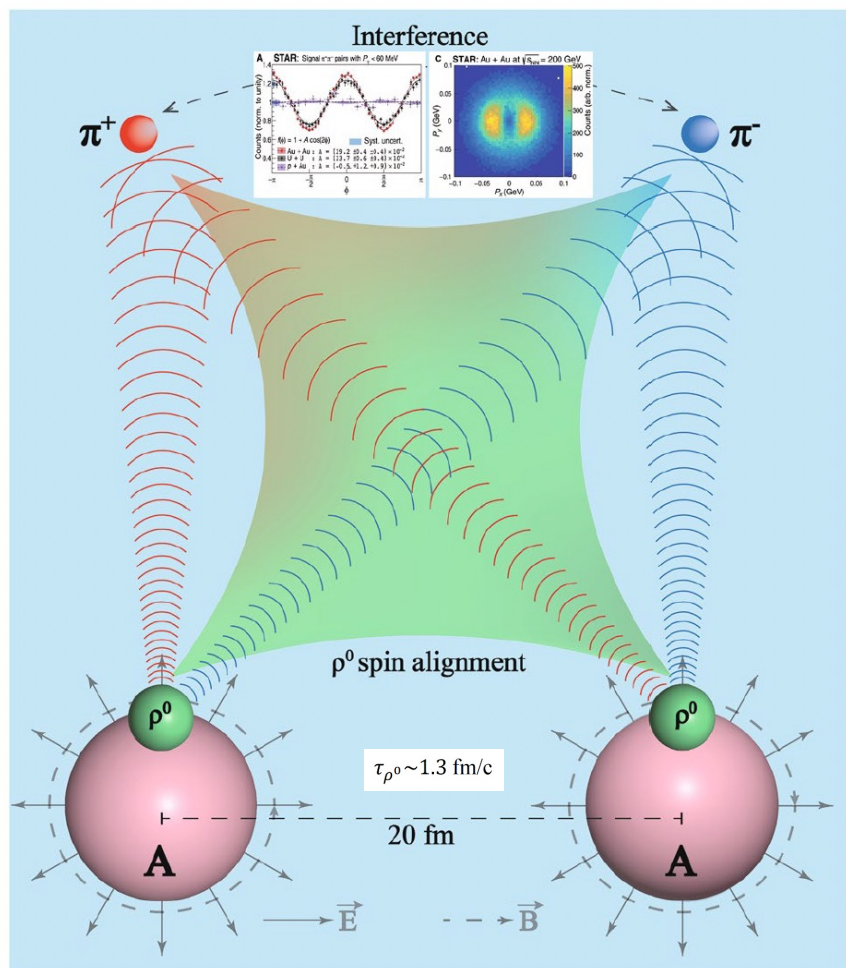
不同方向下测量，差别可达0.8fm

W. Zha, et al. PRC 99, 061901 (2019)

H. Xing, et al. JHEP 10, 064 (2020)

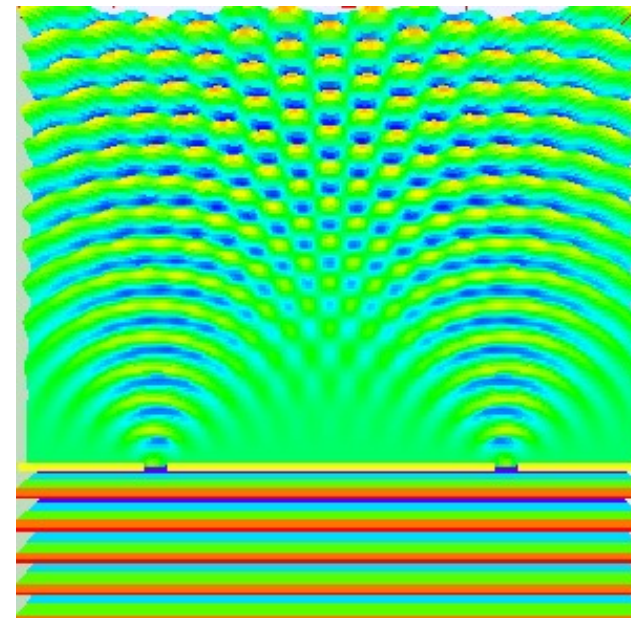
基于纠缠的自旋干涉

费米尺度的双缝干涉



Y.-G. Ma, NST 34, 16 (2023)

W. - M. Zha, et al., PRD 103, 033007 (2021)

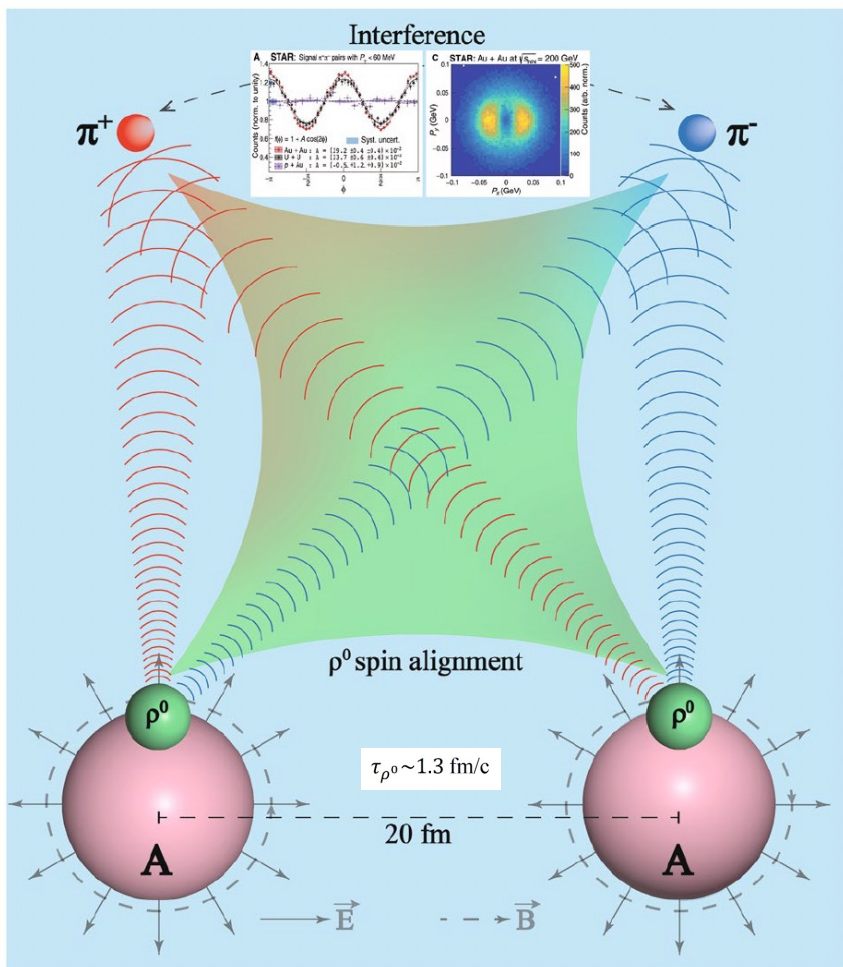


Entanglement Enabled Spin Interference (EESI)

- “缝”间距 $\gg \rho^0$ 介子寿命，干涉现象由 π^+ 和 π^- 协同产生
- 测量的 π^+ 和 π^- 来自同一个 ρ^0 ，但d+Au中无干涉
- “超时空”协同完成干涉，体现量子纠缠

原子核质量半径

费米尺度的双缝干涉

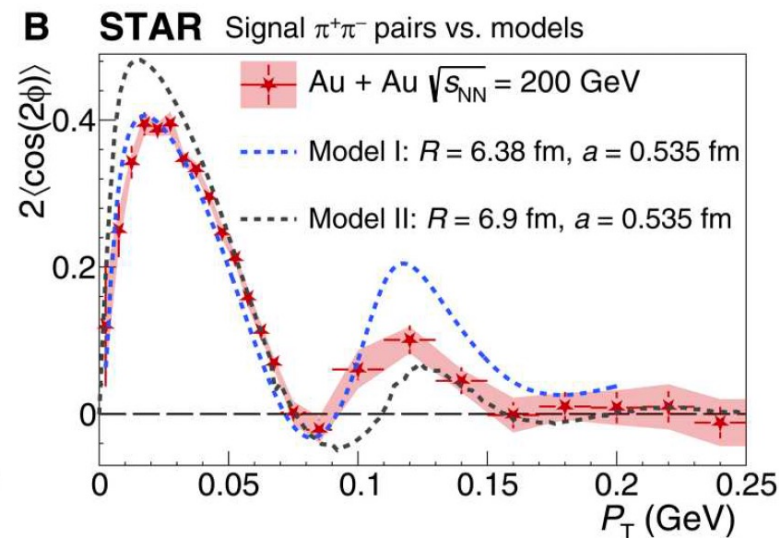
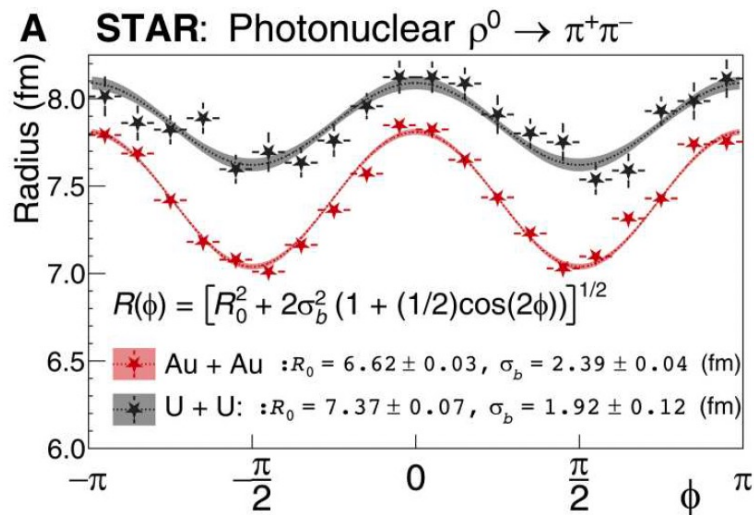


Y.-G. Ma, NST 34, 16 (2023)

W. - M. Zha, et al., PRD 103, 033007 (2021)

	^{197}Au	^{238}U
STAR R (fm)	$6.53 \pm 0.03 \pm 0.05$	$7.29 \pm 0.06 \pm 0.05$
STAR $\langle \cos 2\phi \rangle$ (%)	29.2 ± 0.4 (statistical) ± 0.4 (systematic)	23.7 ± 0.6 (statistical) ± 0.4 (systematic)
R_p (fm)	6.38	6.87

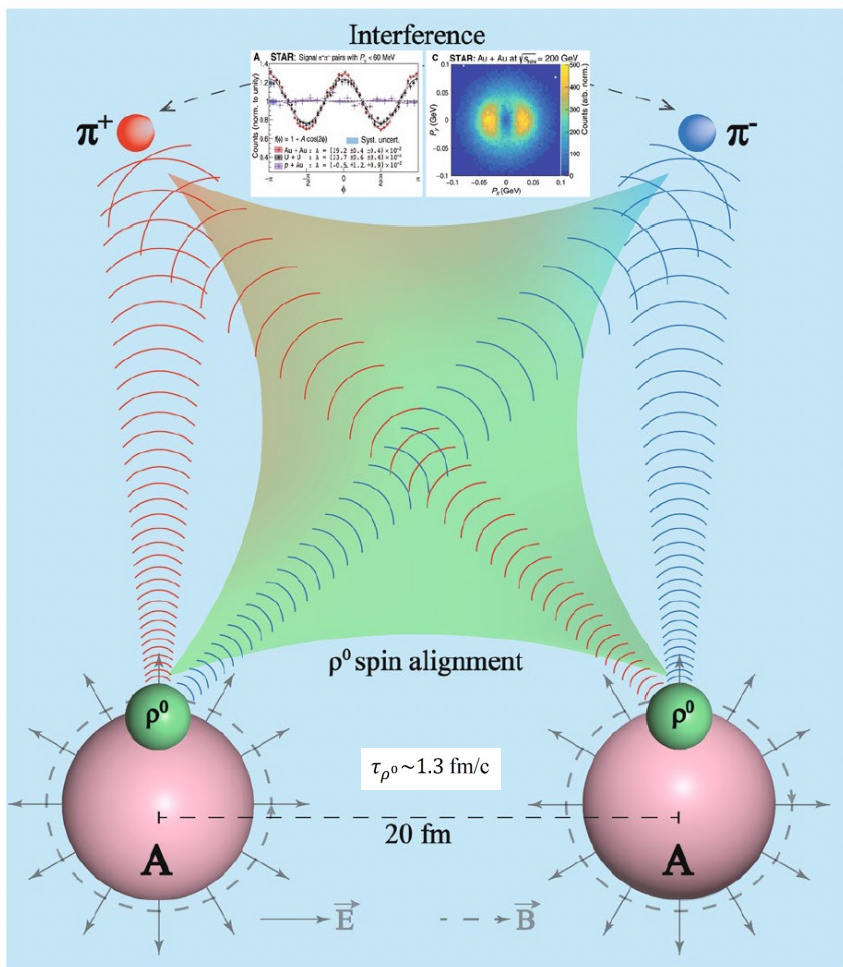
考虑EESI效应，获得“真实”的原子核质量半径



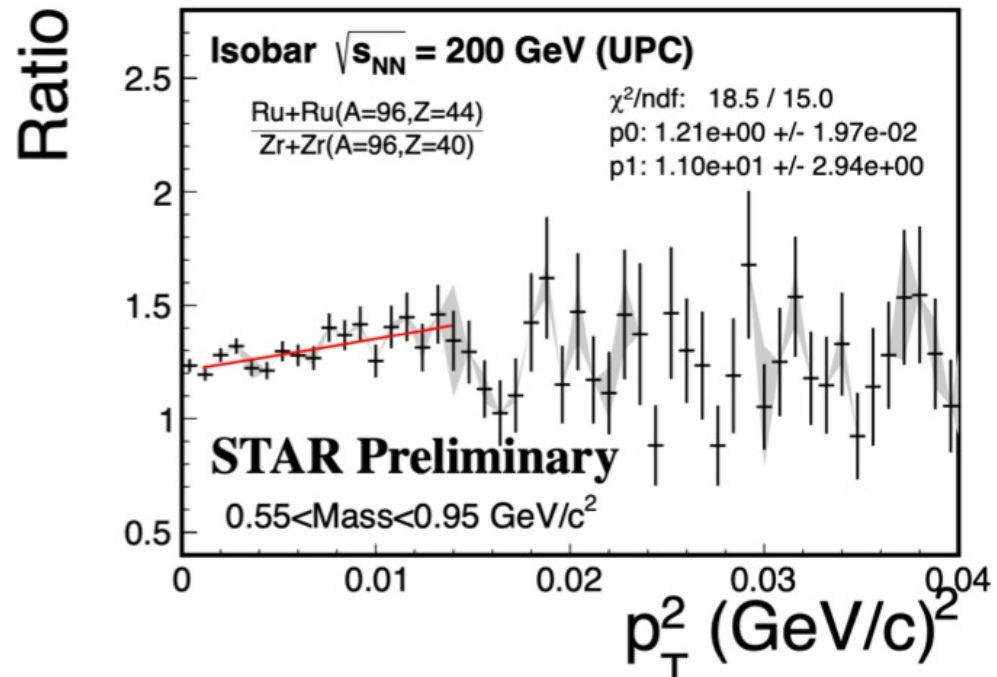
STAR, Sci. Adv. 9, eabq3903 (2023)

原子核质量半径

费米尺度的双缝干涉



同质异位素碰撞中 ρ^0 光生过程的dN/dt比较



dN/dt的斜率比值偏离1 ($\sim 3\sigma$) : 锆核更大的尺寸?

Y.- G. Ma, NST 34, 16 (2023)

W. - M. Zha, et al., PRD 103, 033007 (2021)

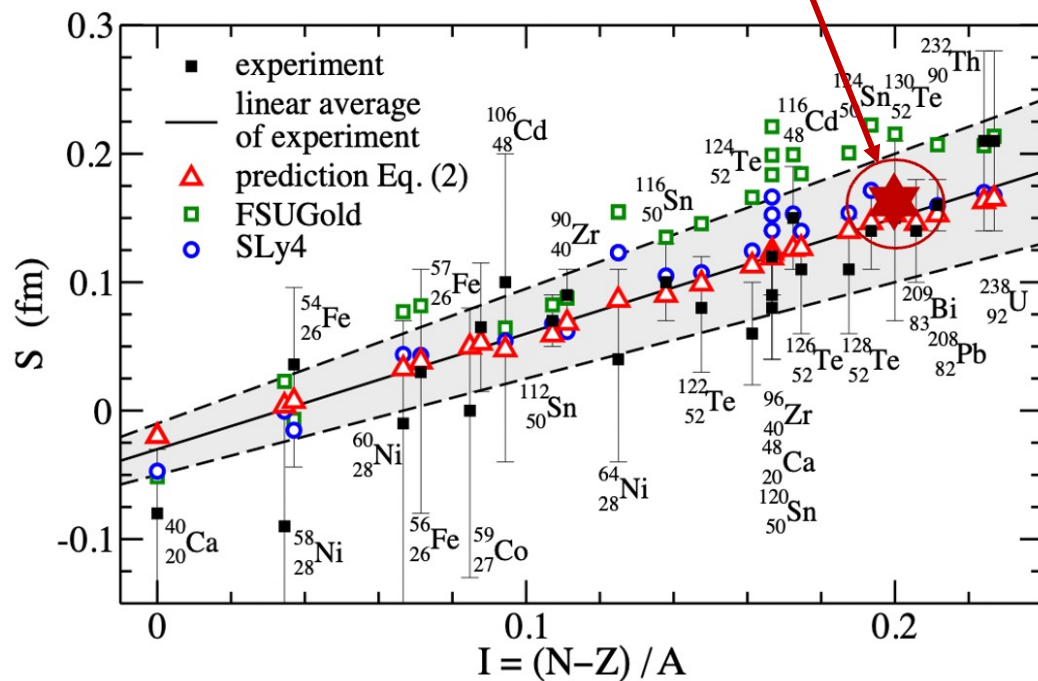
中子皮测算

$$S_{^{238}\text{U}} = 0.44 \pm 0.05 \pm 0.08 \text{ fm}$$

$$S_{^{197}\text{Au}} = 0.17 \pm 0.03 \pm 0.08 \text{ fm}$$



- 假设强相互作用半径是质子半径（电荷半径）与中子半径的加权平均
- 电荷半径->中子半径->中子皮

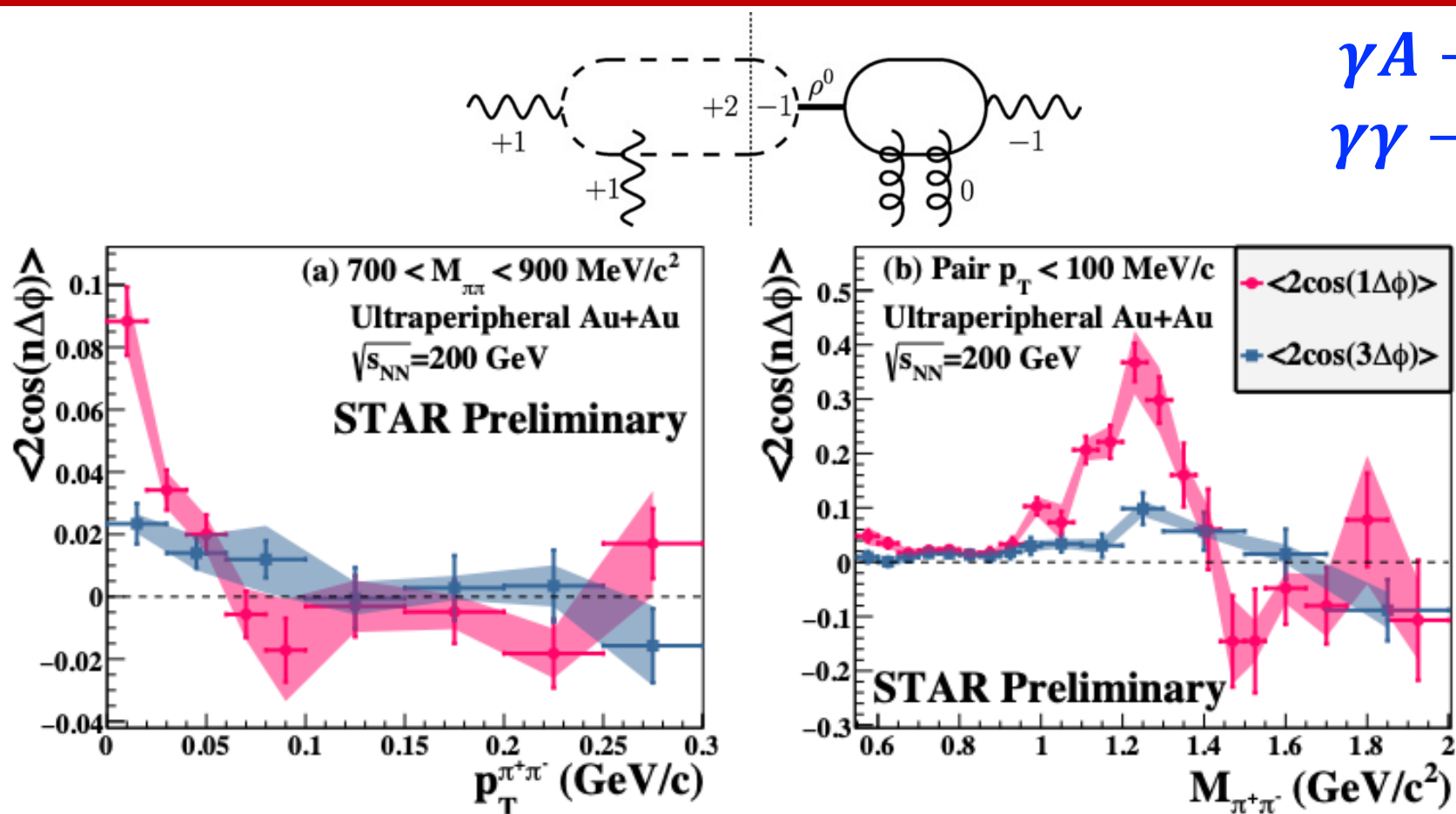


铀原子核具有“更厚的中子皮”：来自核形变的影响？

	¹⁹⁷ Au	²³⁸ U
STAR R (fm)	$6.53 \pm 0.03 \pm 0.05$	$7.29 \pm 0.06 \pm 0.05$
STAR $\langle \cos 2\phi \rangle$ (%)	29.2 ± 0.4 (statistical) ± 0.4 (systematic)	23.7 ± 0.6 (statistical) ± 0.4 (systematic)
R_p (fm)	6.38	6.87

M. Centelles, et al., PRL 102, 122502 (2009)
 Q. Shou, et al., Phys. Lett. B 2015
 H. De Vries, et al., At. Data Nucl. Data Tables 1987

超周边碰撞中 $\pi^+\pi^-$ 末态的自旋干涉



$$\gamma A \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$$
$$\gamma\gamma \rightarrow \pi^+ \pi^-$$

- 在 ρ^0 区间观测到非零的奇数阶余弦振荡，来自光核过程和光光过程的 $\pi^+\pi^-$ 之间的自旋干涉
- 观测到可能来自于 $f_2(1270)$ 的贡献：寻找新粒子/态的可能手段

总结

- 高能核-核碰撞中的光致产生过程测量，为研究原子核结构提供了有效方法

光光过程：约束原子核中电荷分布

光核过程：约束原子核中胶子分布

- 光生过程中自旋干涉效应等奇特现象的研究具有良好物理应用潜力，丰富了重离子碰撞自旋物理

