

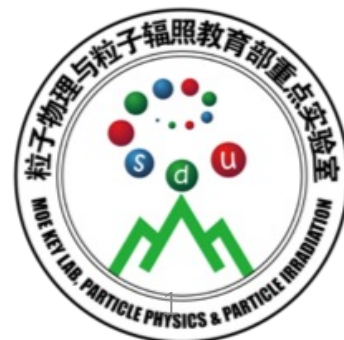


通过RHIC上的光生过程 研究原子核结构

杨 驰
山东大学



原子核结构与相对论重离子碰撞前沿交叉研讨会，大连，2023年8月



光与物质的基本相互作用

光电效应
1887

韧致辐射
1895

康普顿散射
1906

正负电子湮灭
1930

Bethe-Heitler过程
1932

单光子湮灭
1933

Second Series

November 15, 1930

Vol. 36, No. 10

THE PHYSICAL REVIEW

SCATTERING OF HARD γ -RAYS

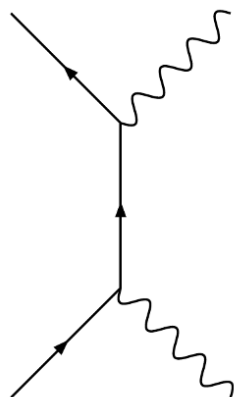
By C. Y. CHAO*

NORMAN BRIDGE LABORATORY OF PHYSICS, CALIFORNIA
INSTITUTE OF TECHNOLOGY

(Received October 13, 1930)



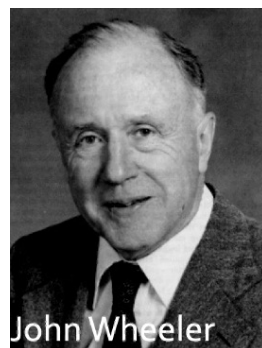
赵忠尧先生1930年
首次观察到正负电
子对的湮灭辐射



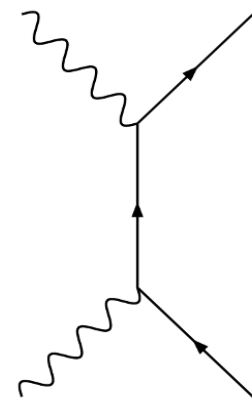
布雷特-惠勒光生过程
1934年预言



Gregory Breit



John Wheeler



布雷特与惠勒：
 $\gamma\gamma \rightarrow e^+e^-$

Phys. Rev. 46, 1087 (1934)

布雷特-惠勒光生过程

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)

As has been reported at the Washington meeting, pair production due to collisions of cosmic rays with the temperature radiation of interstellar space is much too small to be of any interest. We do not give the explicit calculations, since the result is due to the orders of magnitude rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ -rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams,

“hopeless to try”

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 $h\nu$

他们认为在实验室测量基本无望，但同时也提出了可以通过重离子产生的电磁场寻找

相对论重离子碰撞中的光生过程

V. Weizsäcker, E.J. Williams:

等效光子近似 (EPA)

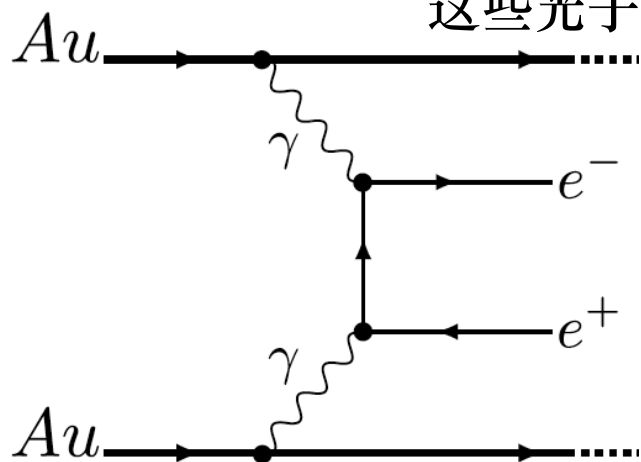
相对论速度下的重离子

高度洛伦兹压缩的电磁场

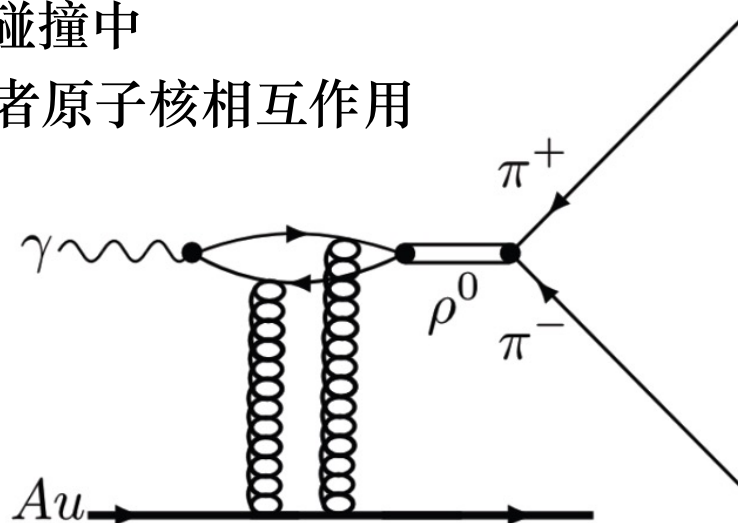
“准实光子”

相对论重离子碰撞中

这些光子与另一个光子或者原子核相互作用



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



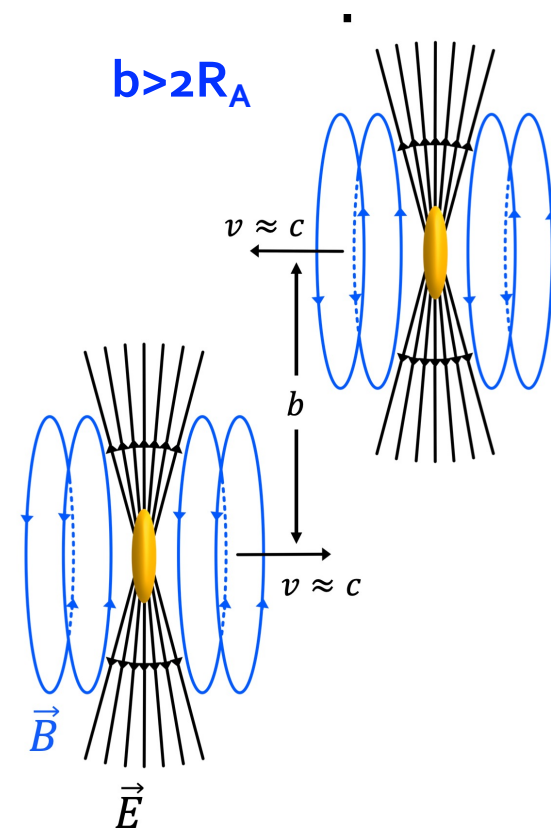
$$\gamma\mathbb{P} \rightarrow J/\psi(\rho^0) \rightarrow l^+l^-(\pi^+\pi^-)$$

超边缘碰撞提供研究条件

Breit-Wheeler过程主要测量难点：
峰位、能量阈、亮度

超边缘碰撞 (UPC) 可以解决这些核心难点：

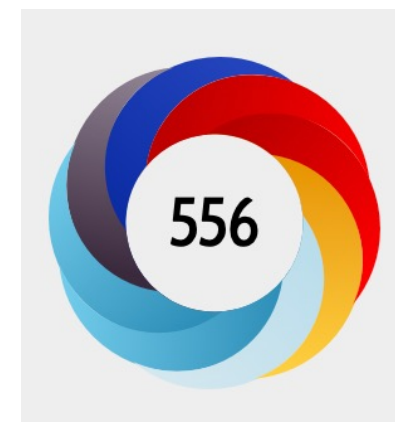
- 高度洛伦兹压缩的电磁场, 等效为准实光子
- $|\mathbf{B}| \sim 10^{14-16} \text{T}$
- 高亮度: $Z\alpha \sim 1$
- $Z^4 \sim$ 四千万倍的光通量 (金金与单电荷粒子对撞相比)
- “干净”的测量



在RHIC-STAR探索布雷特-惠勒光生过程

Phys. Rev. Lett. 127, 052302 (2021)

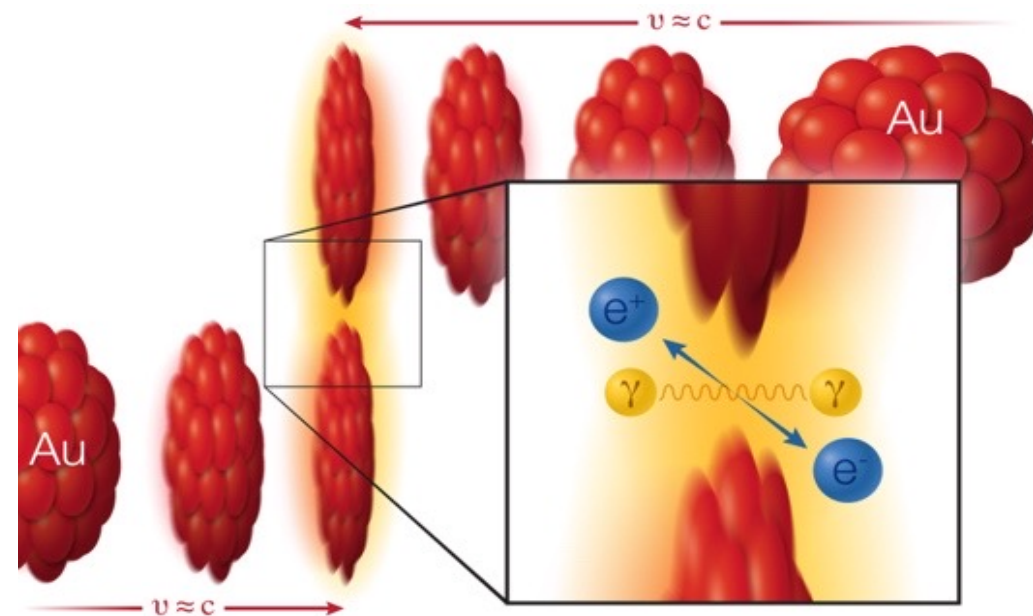
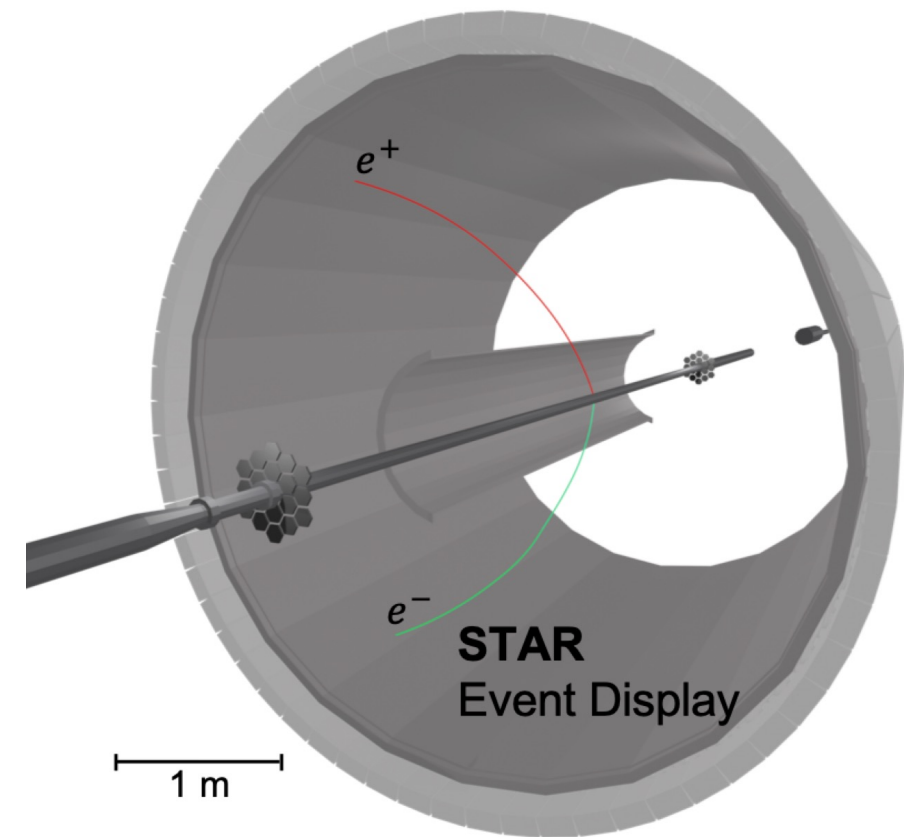
1. 测量到6085对遍举正负电子对



2. 矢量介子光生过程的贡献不可见

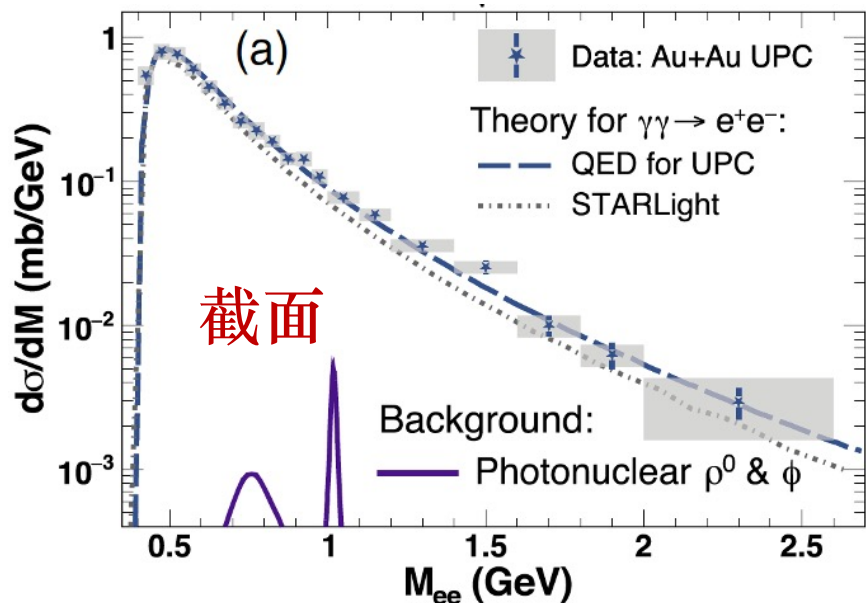
3. 能谱测量

4. 方位角、极角、横动量分布测量



截面、横动量和极角分布

STAR: Au+Au at $\sqrt{s_{NN}} = 200$ GeV, $|y^{ee}| < 1$, $P_{\perp} < 0.1$ GeV, $P_T^e > 0.2$ GeV, $|\eta^e| < 1$.



截面

$\sigma(\gamma\gamma \rightarrow e^+e^-)$ in STAR Acceptance:

$0.261 \pm 0.004(\text{stat.}) \pm 0.013(\text{sys.}) \pm 0.034(\text{scale})$ mb

理论计算: STARLight: 0.22mb

Generalized EPA: 0.26mb

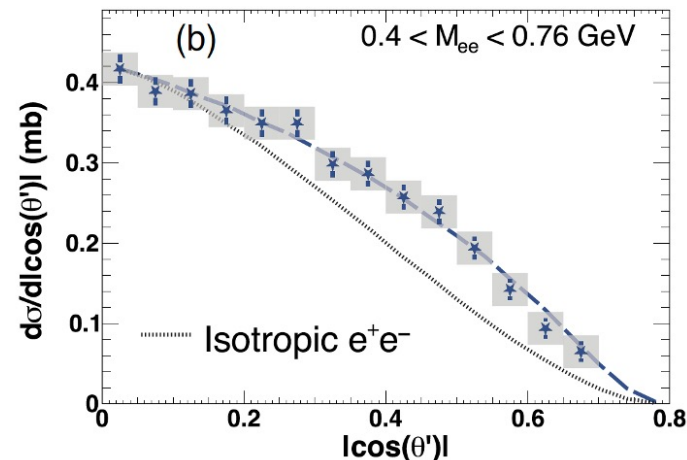
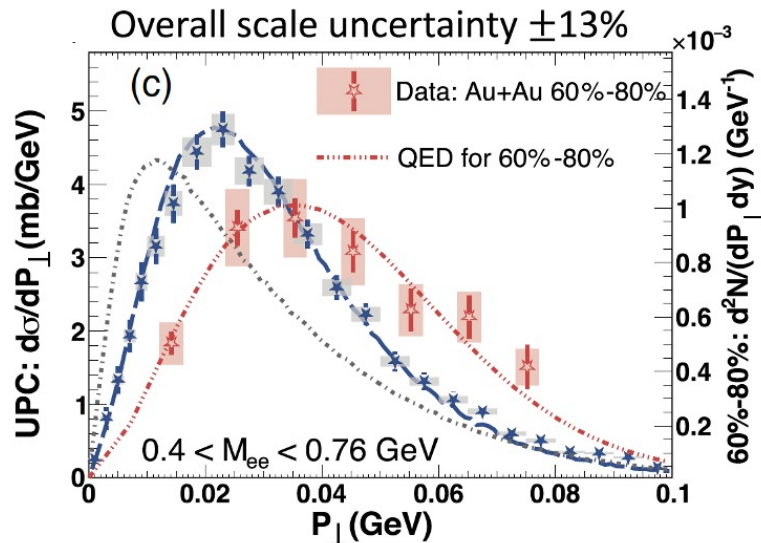
QED: 0.26mb

S.R. Klein, et.al, *Compt.Phys. Commun.* 212, 258 (2017)

W.Zha, et.al, *Phys.Lett.B* 800, 135089 (2020)

C.Li, et.al, *Phys.Rev. D* 101, 034015 (2020)

Phys. Rev. Lett. 127, 052302 (2021)



- 与多个理论计算相符
- 极低横动量下产生
- 碰撞参数依赖
- 极角非均匀分布

为什么要研究QED基本过程？

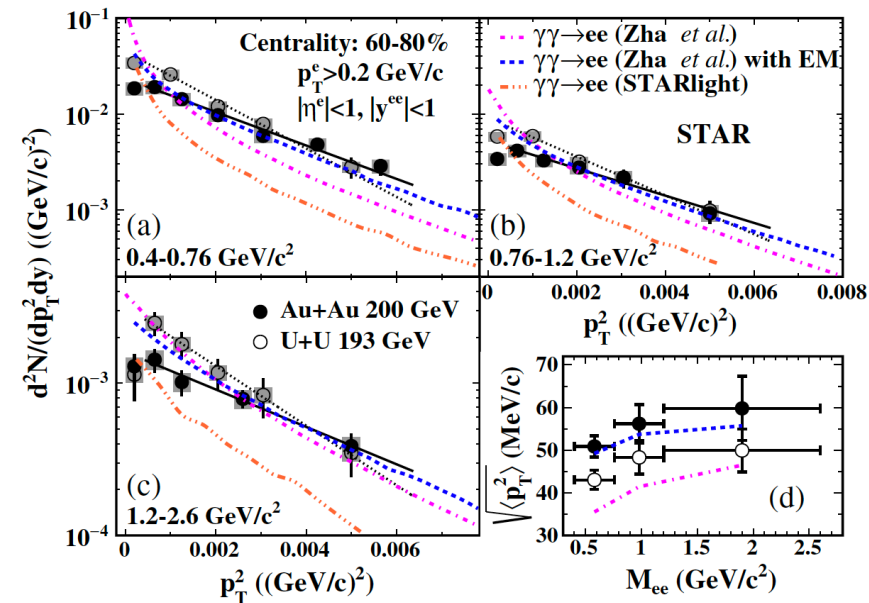
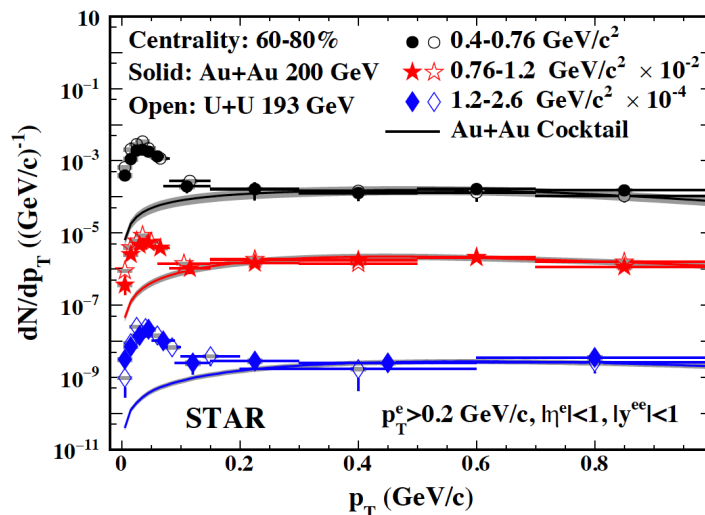
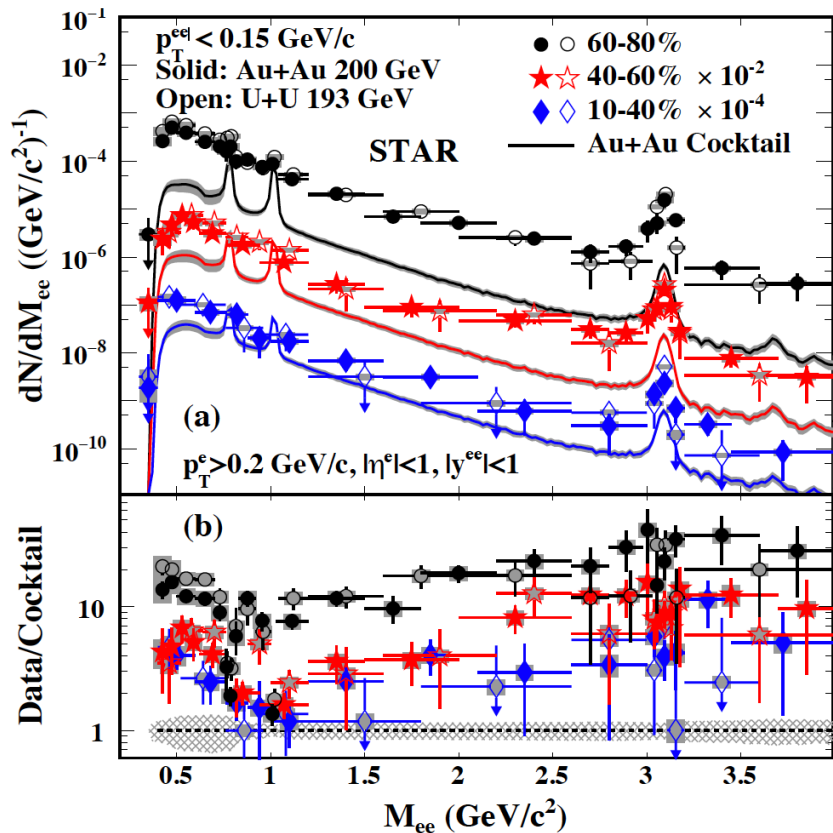
与高温高密核物质研究有什么联系？

与原子核结构研究有什么联系？

偏心碰撞中的光子-光子相互作用

Phys. Rev. Lett. 121, 132301 (2018)

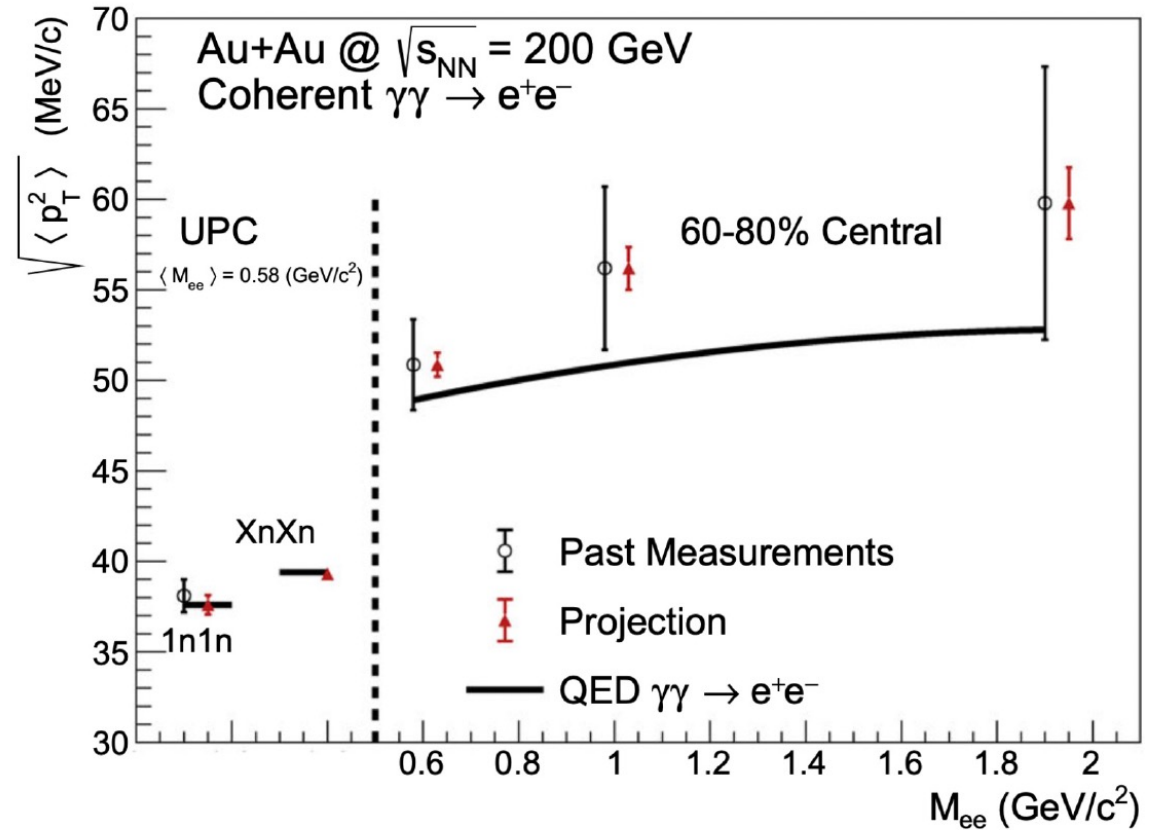
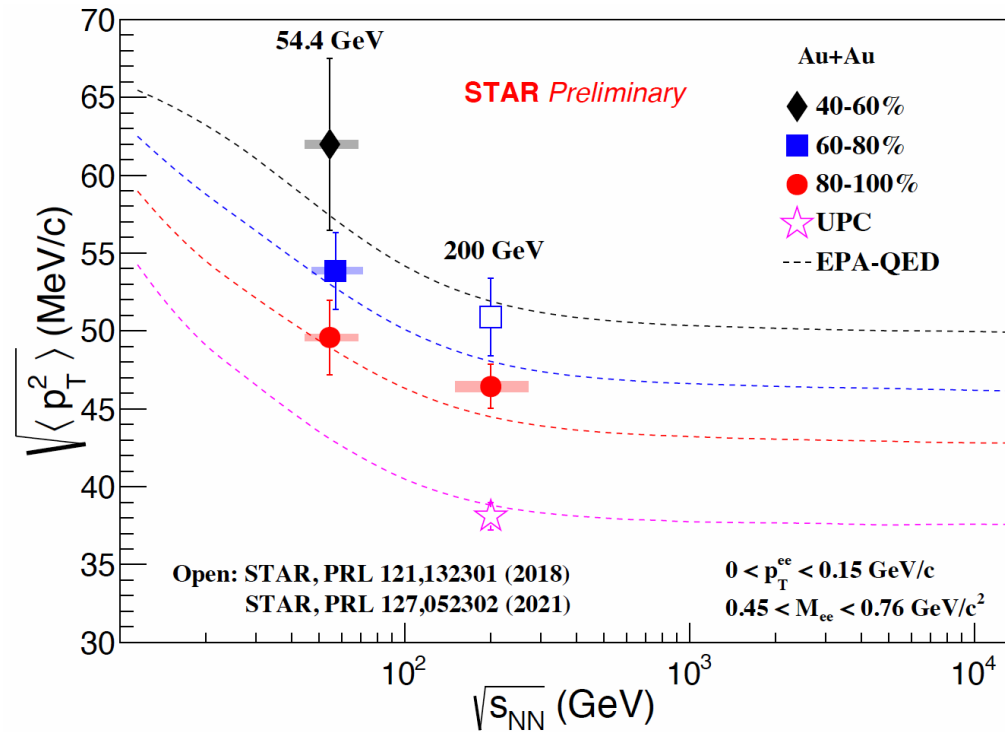
$$\gamma\gamma \rightarrow e^+e^-$$



横动量谱受到强磁场影响?

- 极低横动量下的超常产生 $p_T \approx 0.15 \text{ GeV}/c$
- 偏心碰撞中双轻子相干光致产生

$\sqrt{\langle p_T^2 \rangle}$ 的能量与中心度依赖



- $\langle p_T^2 \rangle$ 对 p_T 展宽效应敏感
- 中心度依赖
- 能量依赖 (3.7σ compared to 200 GeV QED)

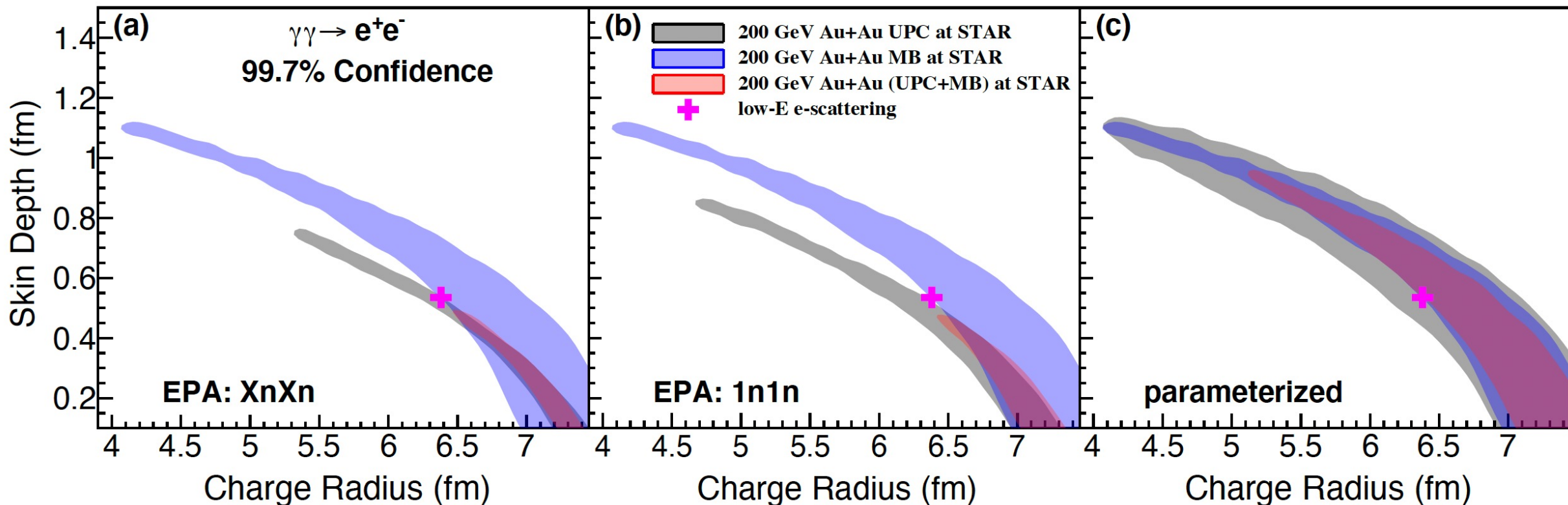
初态效应: 碰撞参数依赖

末态效应: 受到磁场影响 (1.8σ)?

更精确的结论: RHIC run23-25

约束原子核电荷半径

X.Wang, et.al, Phys. Rev. C 107, 044906 (2023)



- Woods-Saxon 分布作为QED计算的输入
- 不同输入参数的LO QED理论计算拟合实验测量

- **UPC 的结果与电子散射的测量结果相符**
- **偏心对撞的结果偏高**

QGP的磁场效应?
能量依赖?

光子的线性极化

Idea generated from a local discussion at SDU between experiment group and theory group.

Phys.Lett. B 795, 576 (2019)

Phys.Rev. D 101, 034015 (2020)



周剑



周雅瑾



李聪

Metz & 周剑, 2011

Glucos are highly linearly polarized.

CGC is highly linearly polarized state.

QCD:

$$gg \rightarrow q\bar{q}$$

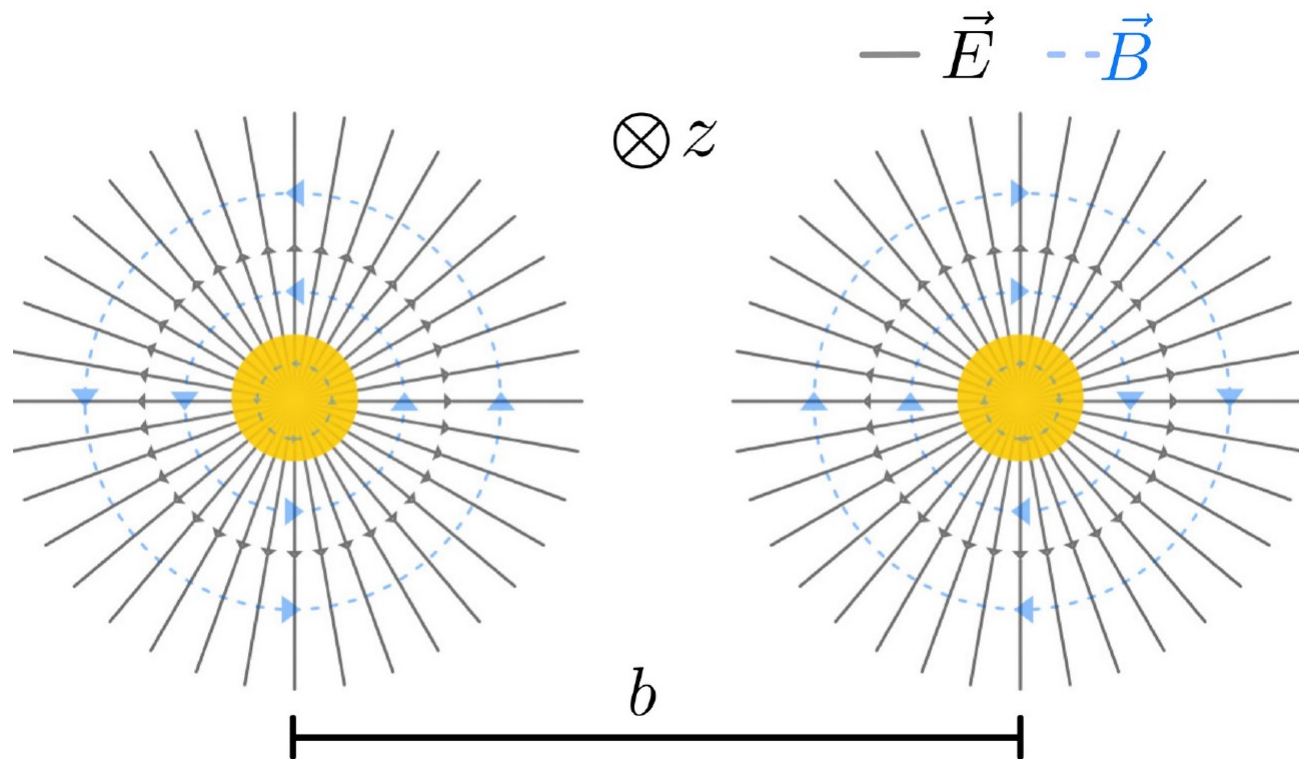
$$\Delta\phi = \phi^{q\bar{q}} - \phi^q$$

QED:

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

$$\Delta\phi = \phi^{ll} - \phi^l$$

准实光子在横平面内线性极化



布雷特-惠勒过程末态方位角的四阶余弦振荡

Idea generated from a local discussion at SDU between experiment group and theory group.

Phys.Lett. B 795, 576 (2019)

Phys.Rev. D 101, 034015 (2020)



周剑



周雅瑾



李聪

Metz & 周剑, 2011

Glucos are highly linearly polarized.

CGC is highly linearly polarized state.

QCD:

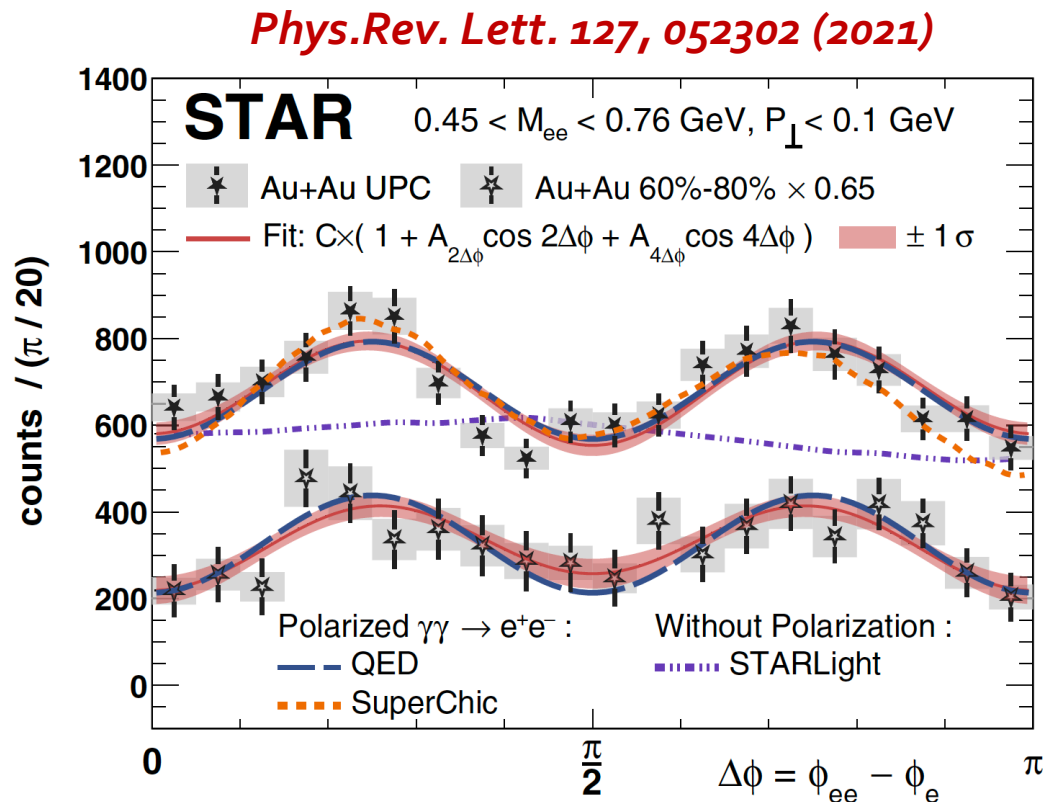
$$gg \rightarrow q\bar{q}$$

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

QED:

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

$$\Delta\phi = \phi^{ll} - \phi^l$$



	Ultraperipheral				Peripheral	
	Measured	QED	SC	SL	Measured	QED
A _{4Δφ} (%)	16.8 ± 2.5	16.5	19	0	27 ± 6	34.5
A _{2Δφ} (%)	2.0 ± 2.4	0	5	5	6 ± 6	0

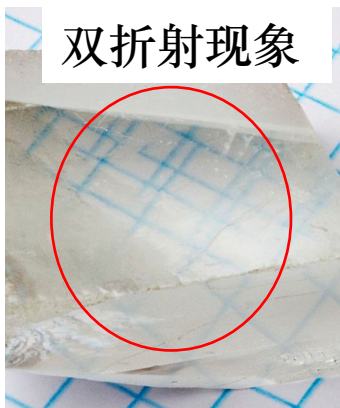
**STAR的测量高精度“重现”他们的理论预言
证实了对撞光子是高度线偏振的**

与真空双折射效应的联系

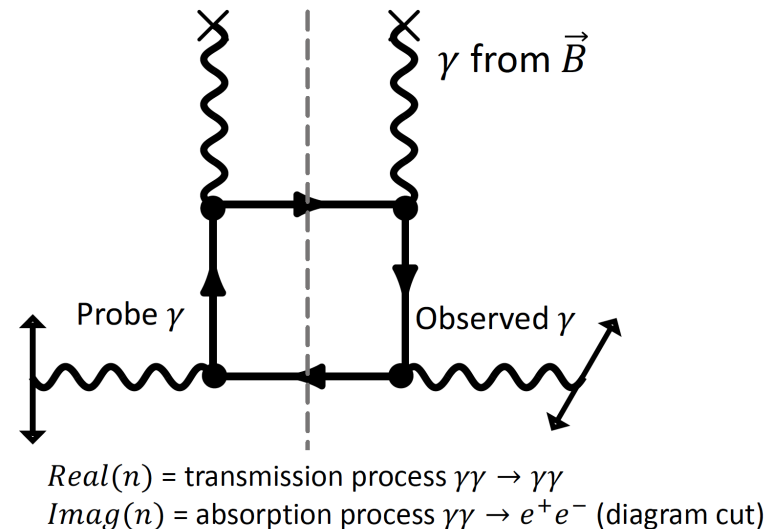
真空双折射 Vacuum birefringence

1936年海森堡与欧拉提出：电磁场可以使真空极化

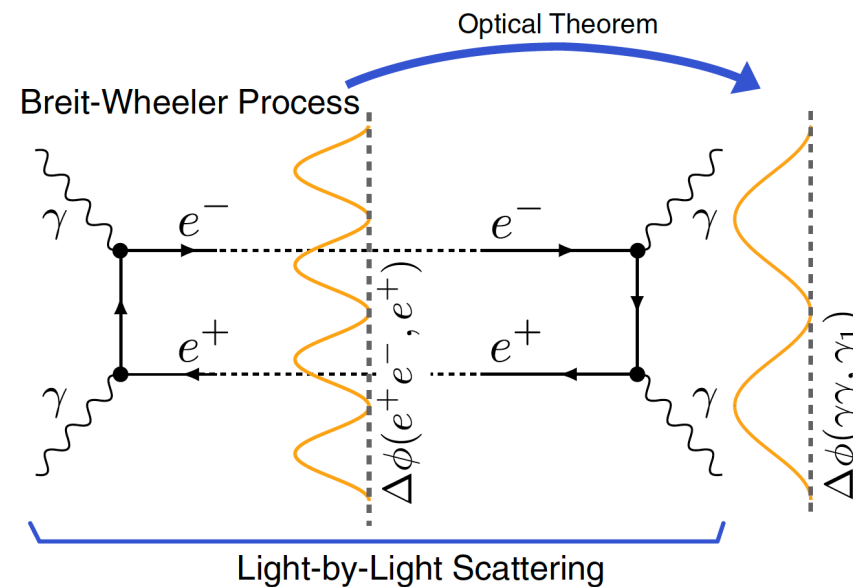
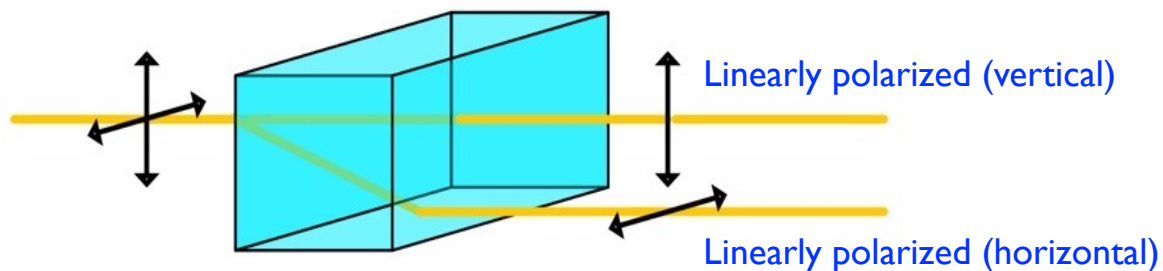
W. Heisenberg and H. Euler, Z. Phys. 98, 714 (1936)



Feynman Diagram for Vacuum Birefringence



QED vacuum + Extreme Magnetic field



Maybe more closely related to the vacuum dichroism?

K. Hattori, H. Taya, and S. Yoshida, JHEP 01,93 (2021)

通过高能光子“看”原子核

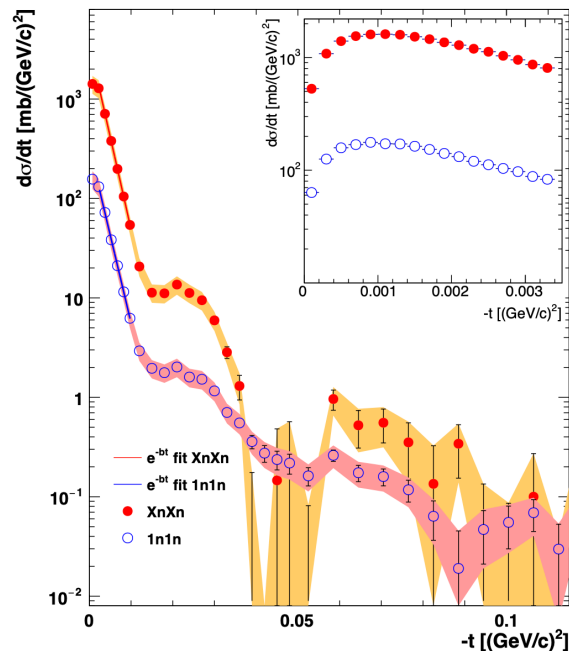
矢量介子的光生过程

- 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

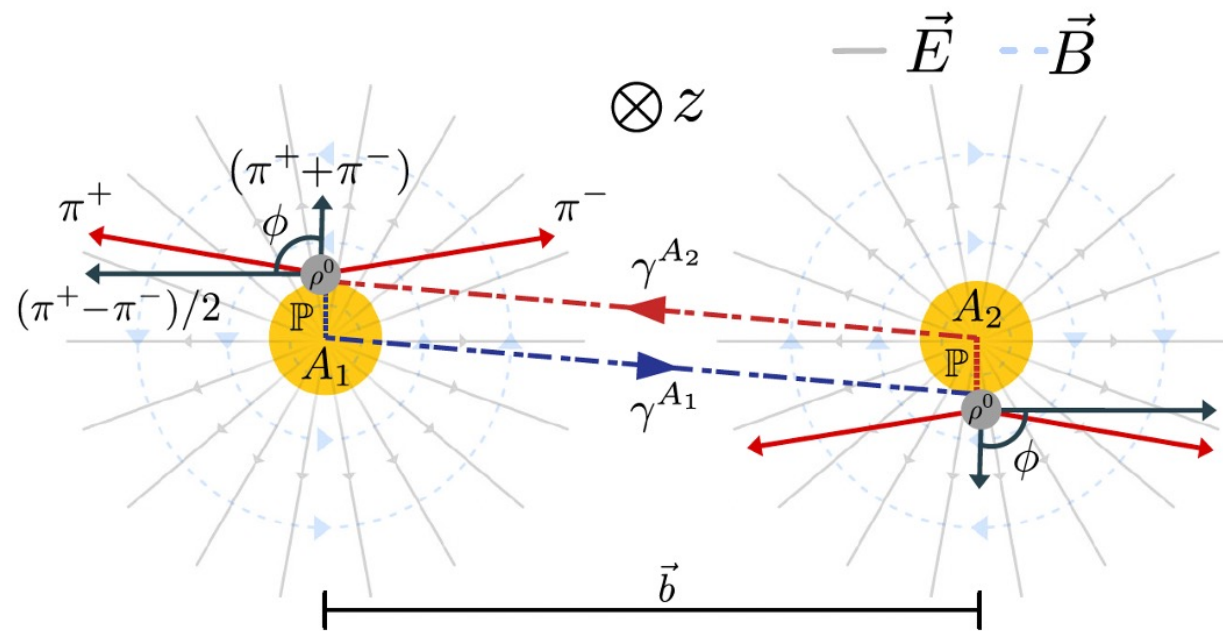
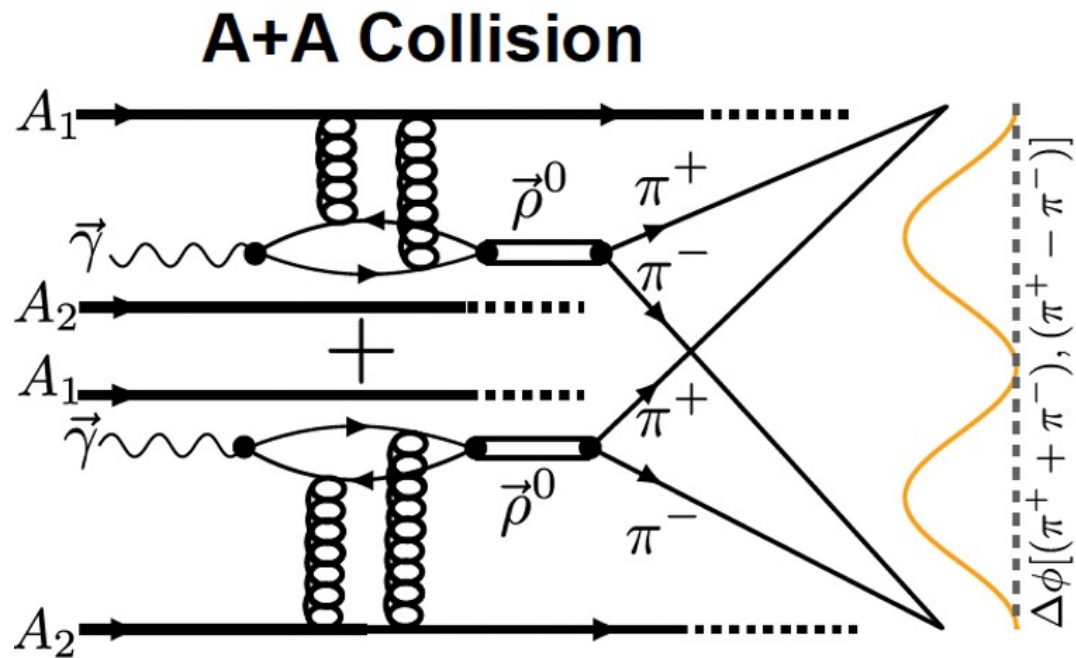
理论预言量子干涉效应敏感于:

- 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



STAR, Phys. Rev. C 96, 054904 (2017)
STAR, Phys. Rev. C 85, 14910 (2012)
STAR, Phys. Rev. C 77, 34910 (2008)

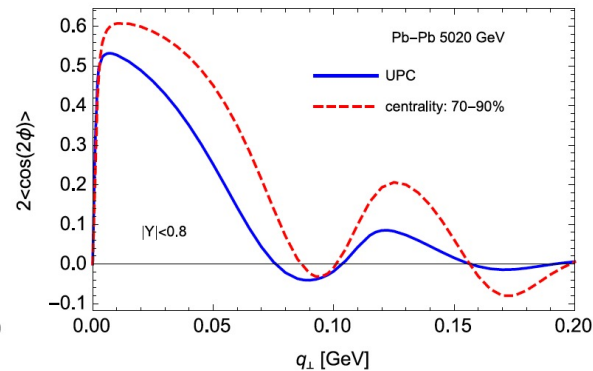
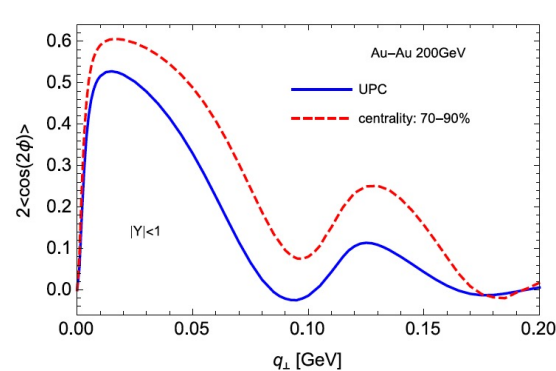
线性极化光子-胶子对撞



Sci.Adv. 9, eabq3903 (2023)

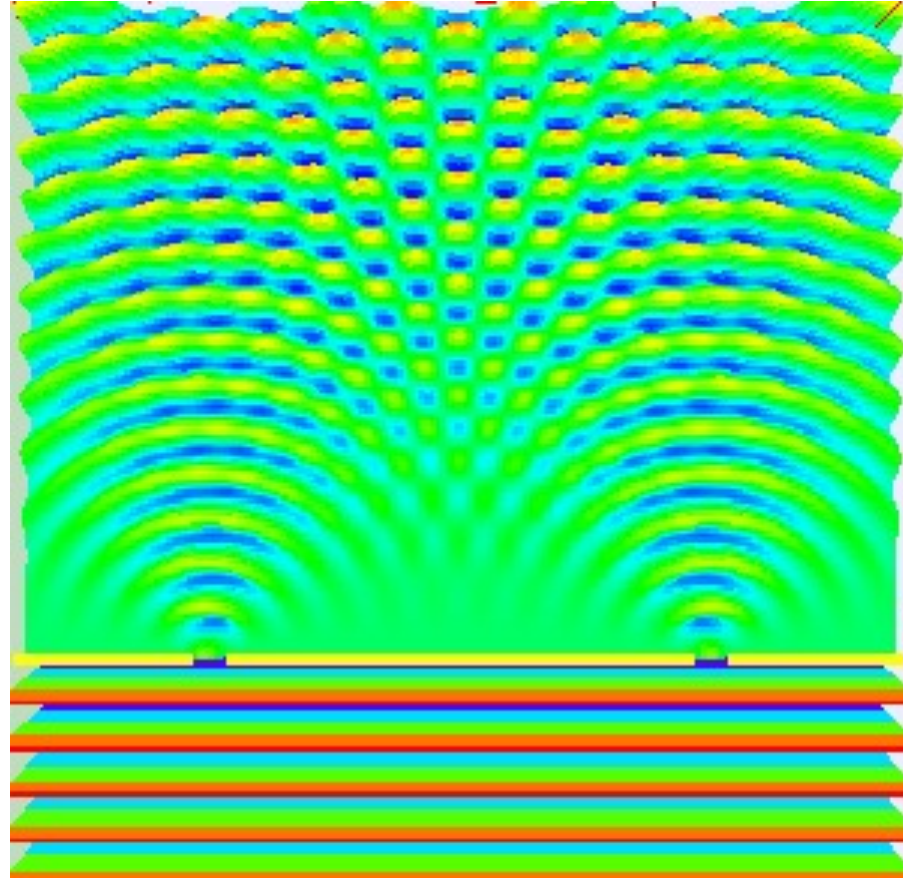
振幅之间的量子干涉引起末态 $\cos(2\Delta\phi)$ 的角分布调制

邢宏喜、周剑、周雅瑾等 *J. High Energy Phys.* 10, 64 (2020)



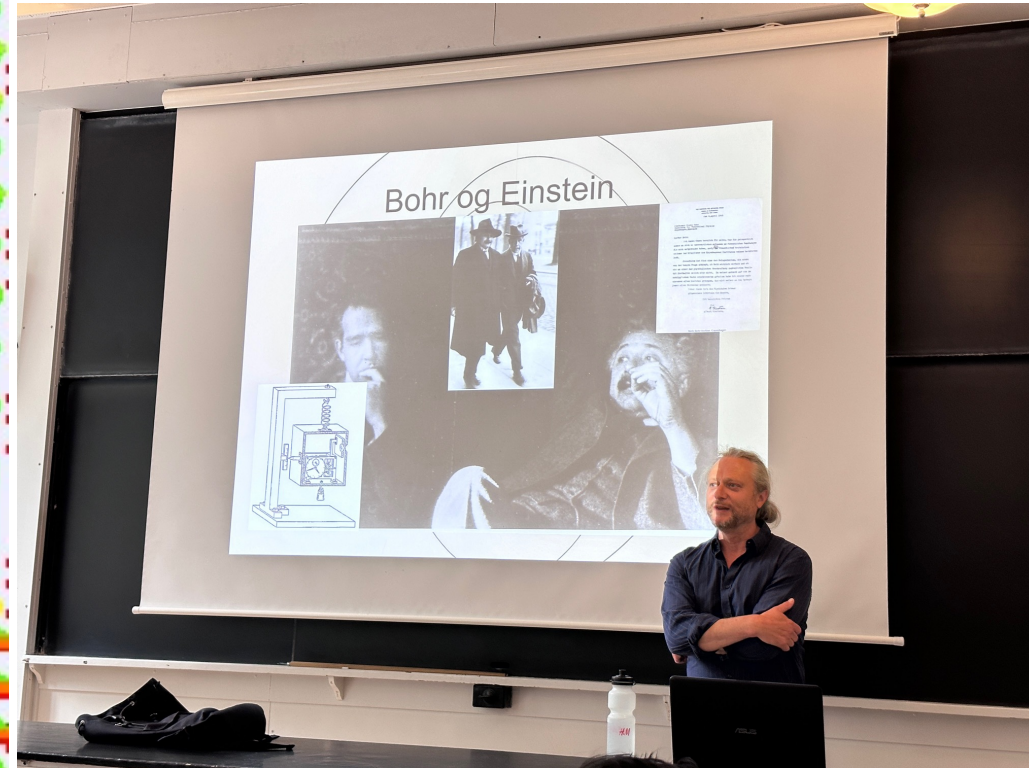
费米尺度的双缝干涉

双缝干涉，经典的物理实验

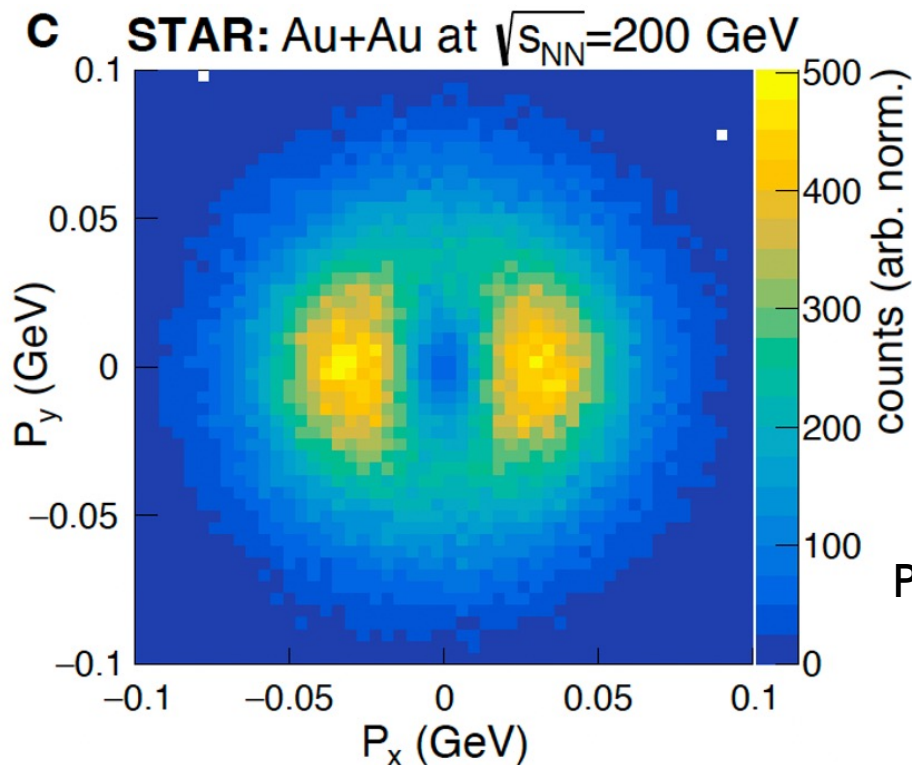
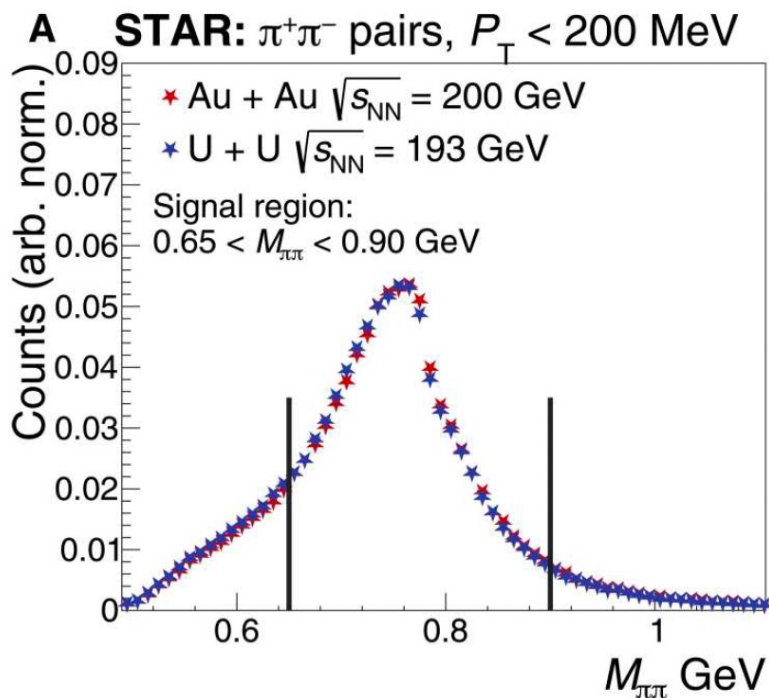


Simplest way:
“一个洞” + “一张纸”

粒子性与波动性的互补原理



动量空间的干涉条纹



Sci. Adv. 9, eabq3903 (2023)

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

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

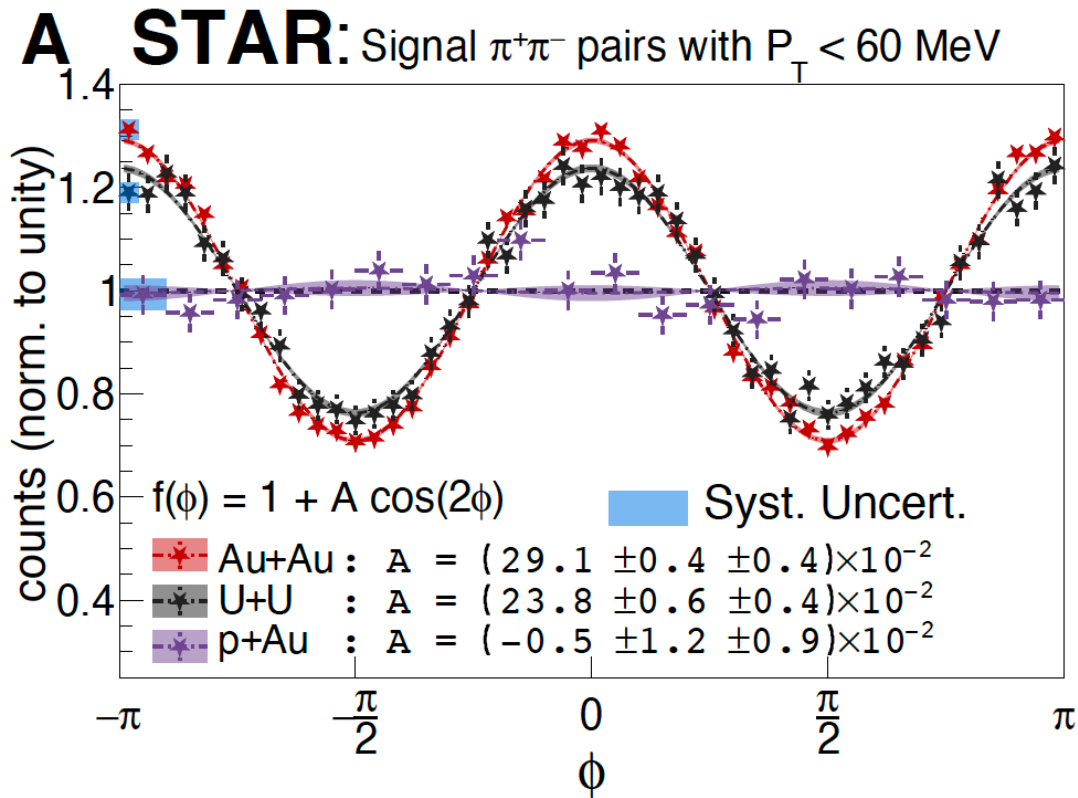
P_x : ρ^0 横动量在 π 横动量方向的投影

- ρ^0 沿着碰撞参数方向的自旋排列
- 量子干涉的方位角依赖

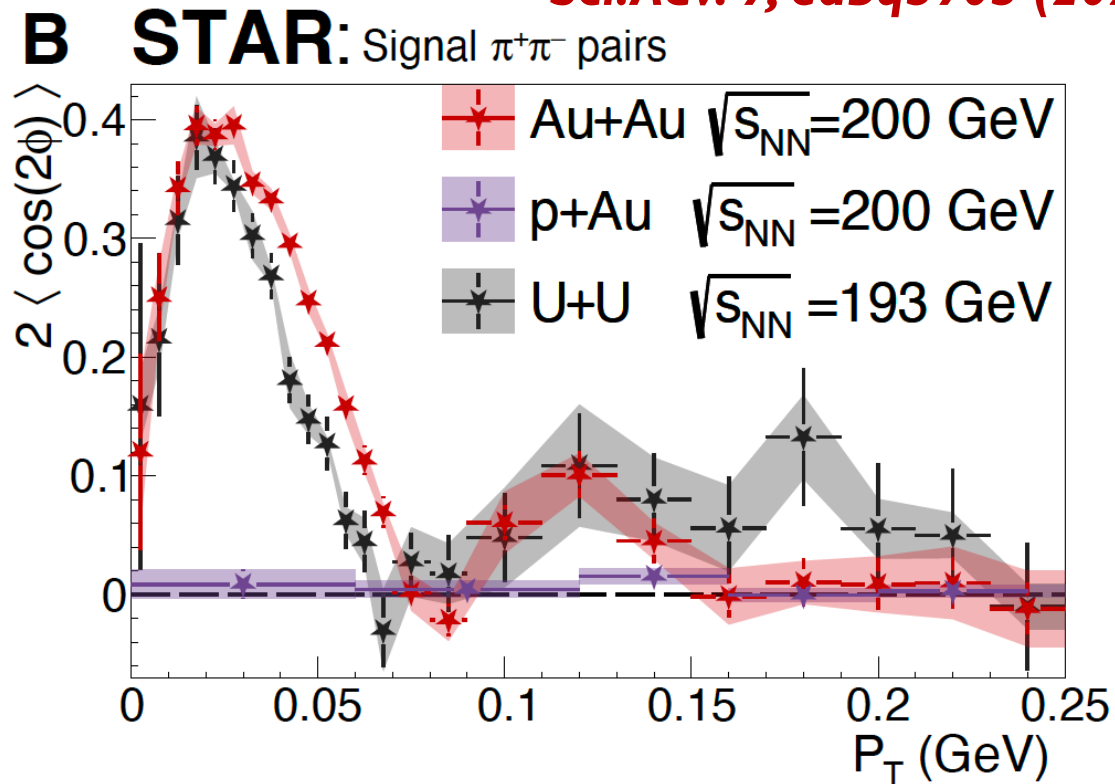
碰撞参数和 ρ^0 横动量不是一个共轭量，
可以同时精确的测量二个量

方位角调制效应、极化空间的干涉条纹

Sci. Adv. 9, eabq3903 (2023)



Au+Au与U+U的幅度不同, 4.3σ (7.6σ)

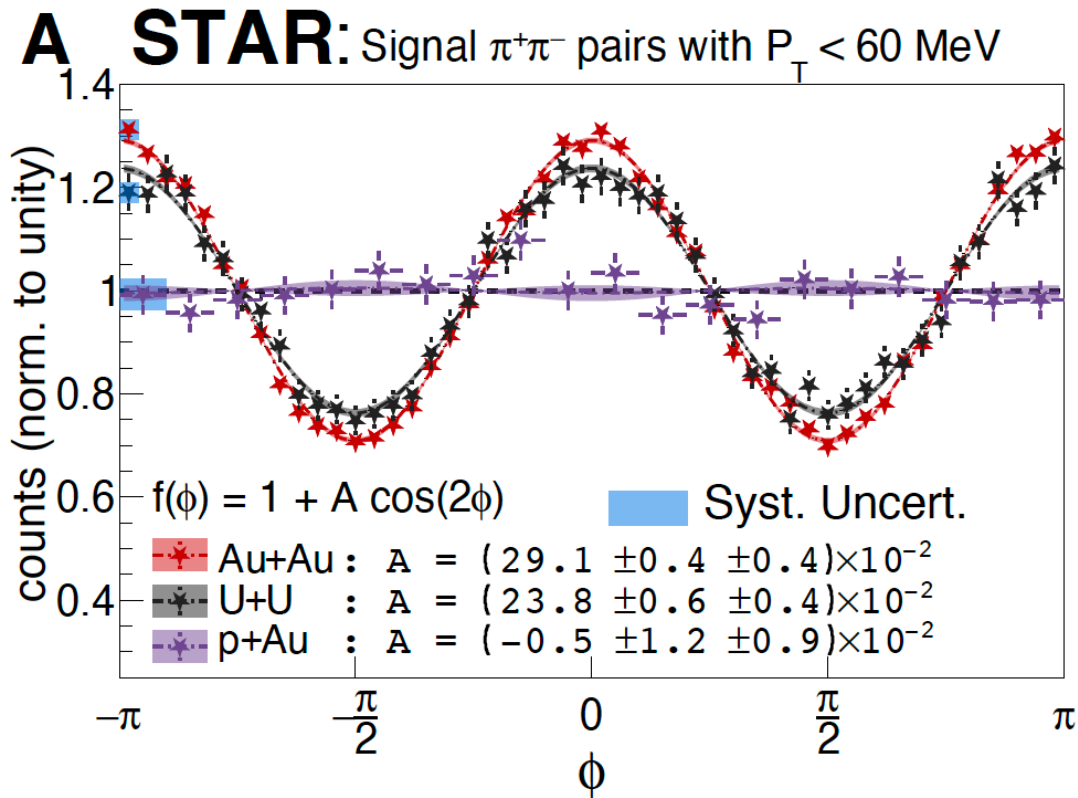


干涉条纹随原子核半径变化而变化

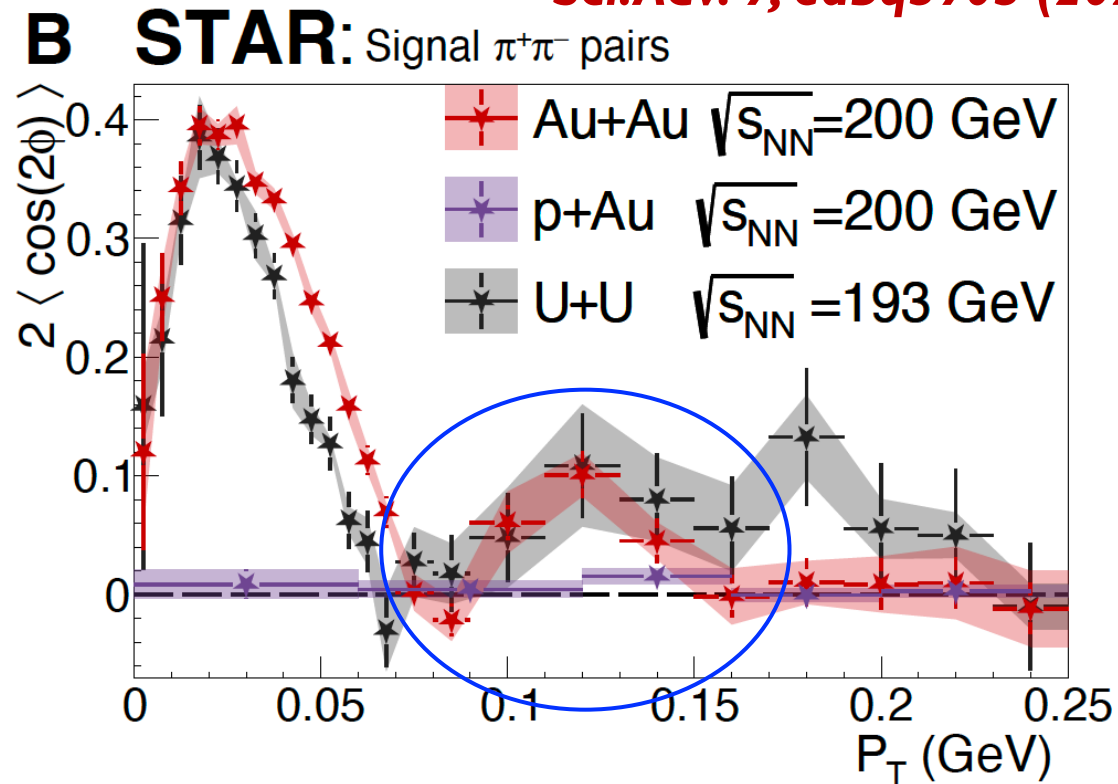
- p+Au中没有干涉现象
- 精度足够, 可以用来研究原子核结构

方位角调制效应、极化空间的干涉条纹

Sci. Adv. 9, eabq3903 (2023)



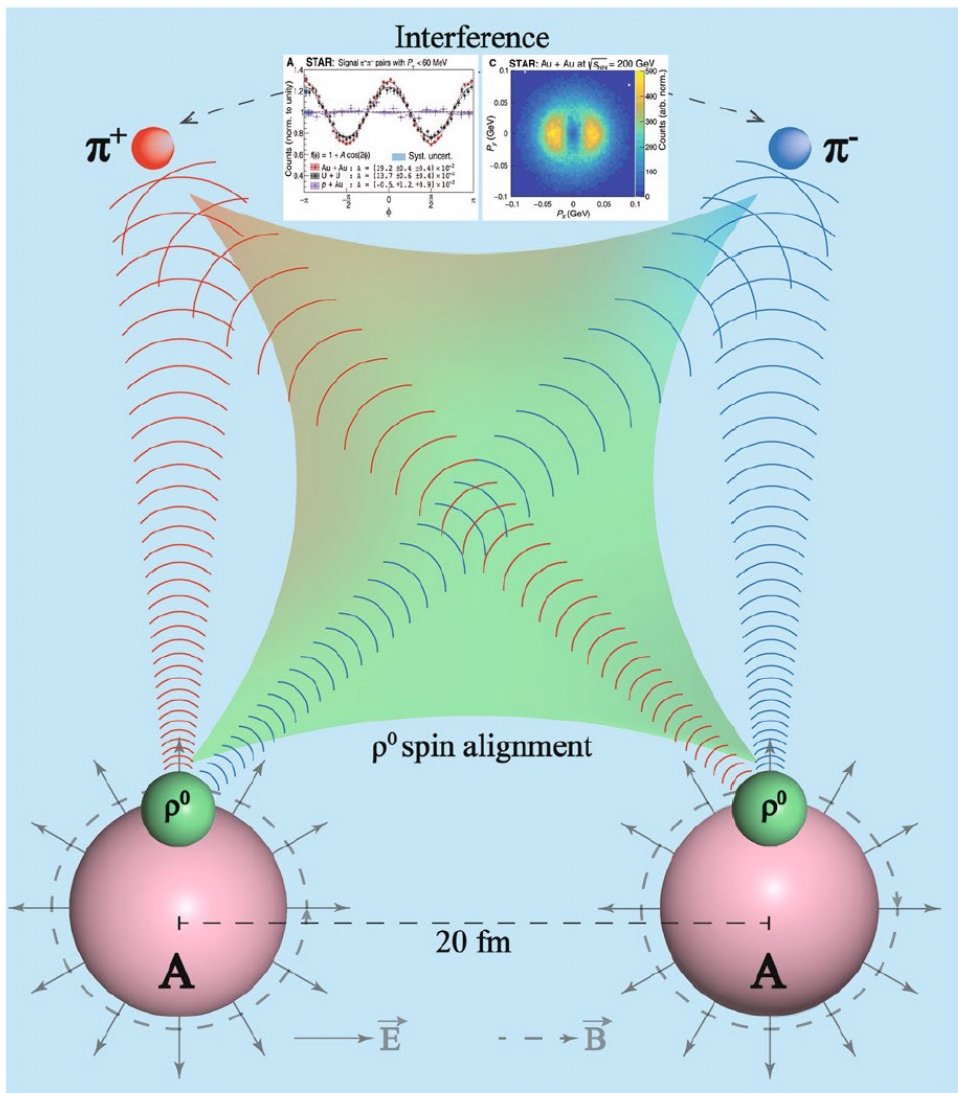
Au+Au与U+U的幅度不同, 4.3σ (7.6σ)



干涉条纹随原子核半径变化而变化

- p+Au中没有干涉现象
- 精度足够, 可以用来研究原子核结构

费米尺度的双缝干涉



- “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

量子纠缠：

怎么理解“可区分”？

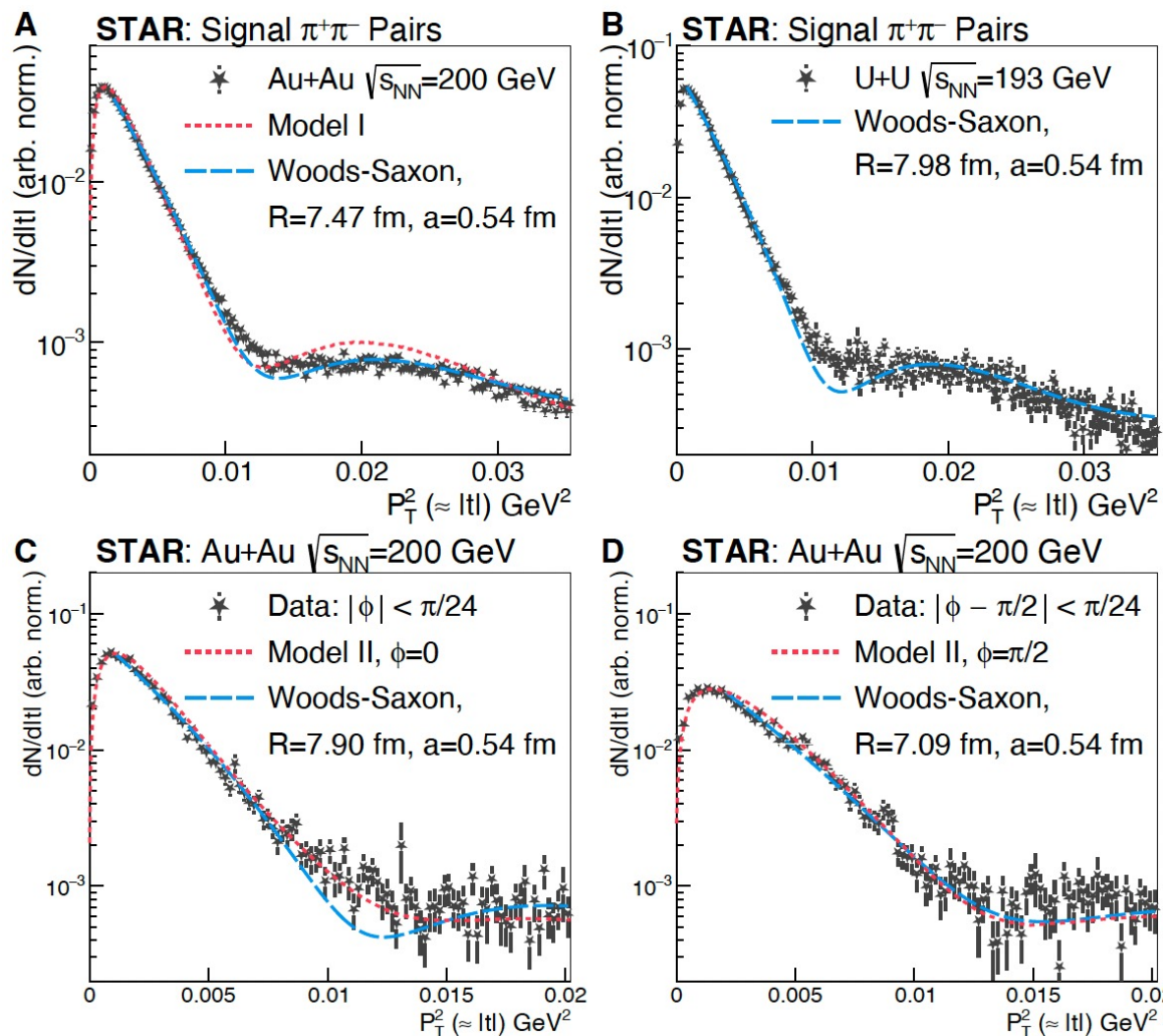
- ✓ 全同粒子之间
- ✓ 不同波长的光子之间
- ✓ 不同电荷的粒子之间

观察者效应（路径测量）

改变对撞核的电荷调制路径

不同极化方向下的|t|分布

Sci.Adv. 9, eabq3903 (2023)



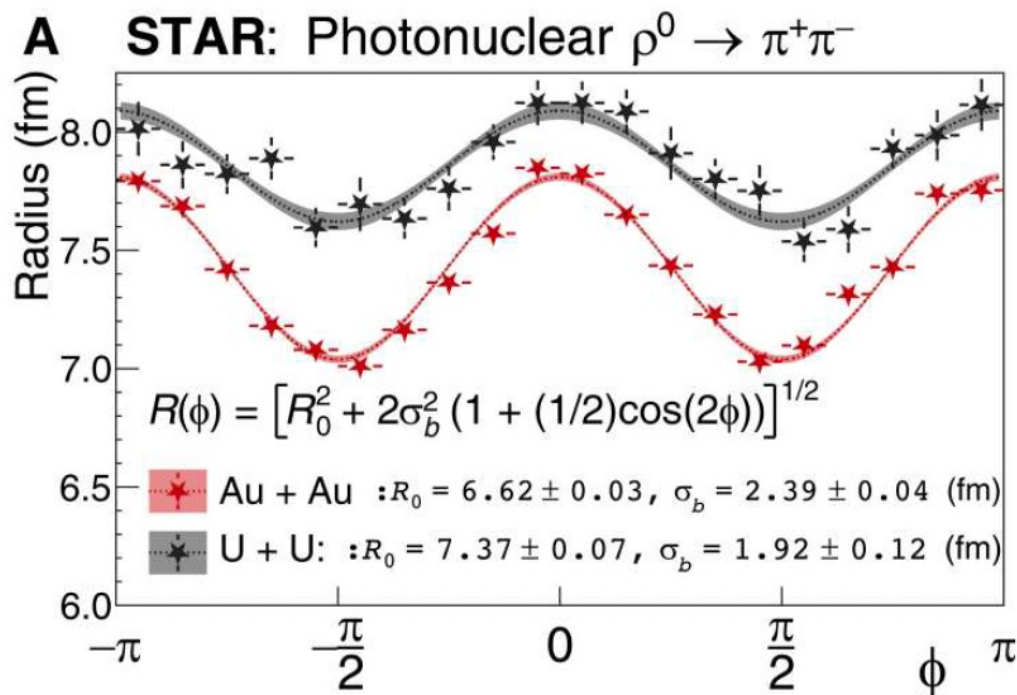
$\phi = 0, R = 7.90$ fm

$\phi = \pi/2, R = 7.09$ fm

不同角度下测量差可达0.8fm

通过费米尺度双缝干涉测量原子核半径

Sci. Adv. 9, eabq3903 (2023)



影响因素:

- Linearly polarized photon
- Spin-induced OAM effect
- photon finite k_T
- Interference along b

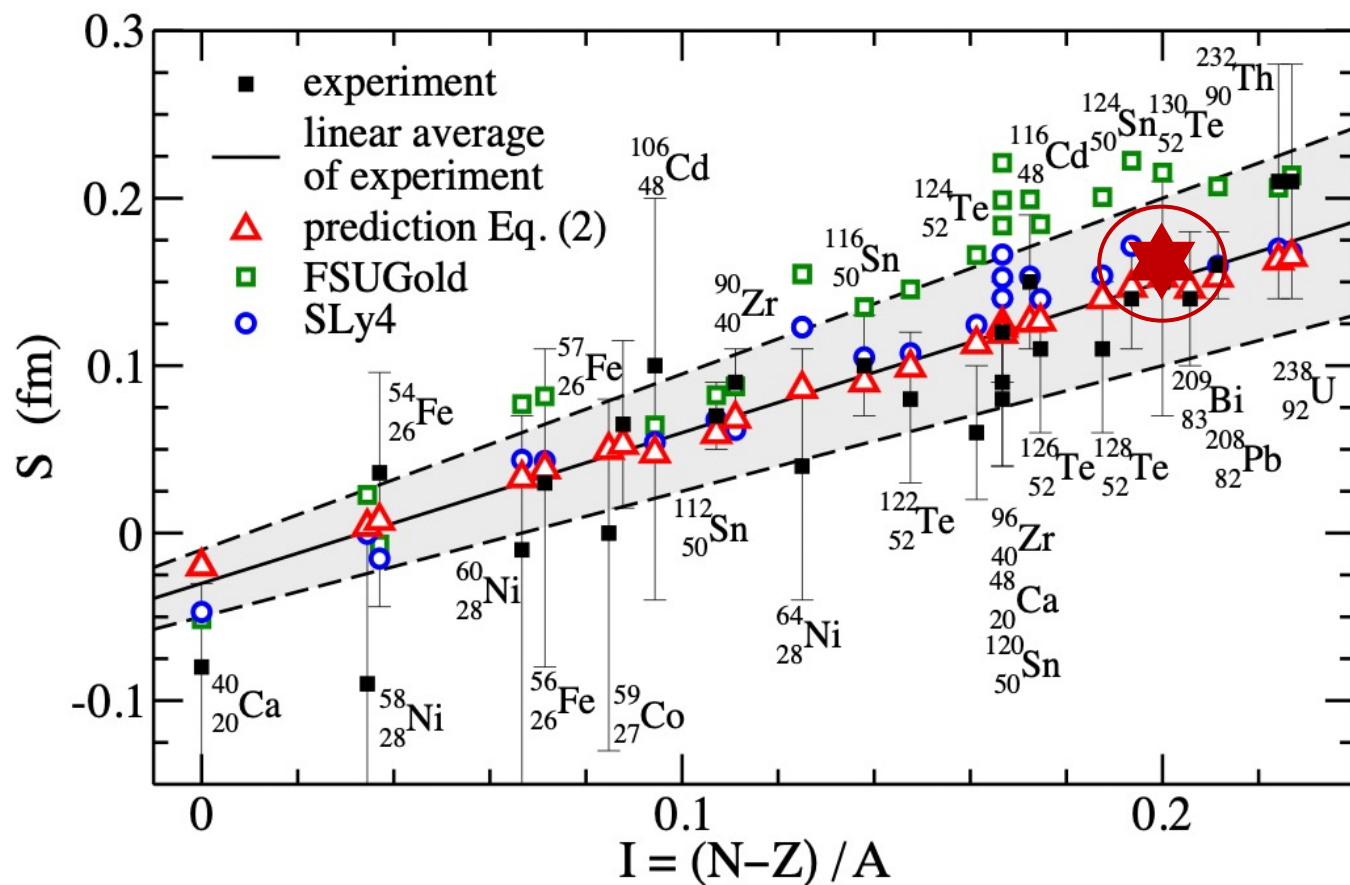
角度分布依赖的测量可以“消除”
这些因素对原子核半径测量的影响

	^{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)

测量中子皮



M. Centelles, et al., Phys. Rev. Lett. 102, 122502 (2009)



假设原子核强相互作用半径是其
中子半径和电荷半径的加权平均

STAR:

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

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

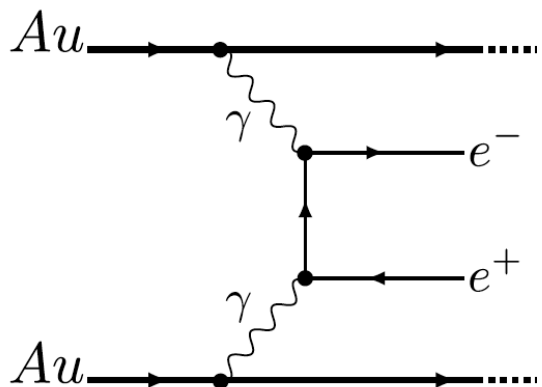
Rp:

Q.Y. Shou, et al., Phys. Lett. B 749, 215 (2015)

H. De Vries, et al., At. Data Nucl. Data Tables 36, 495 (1987)

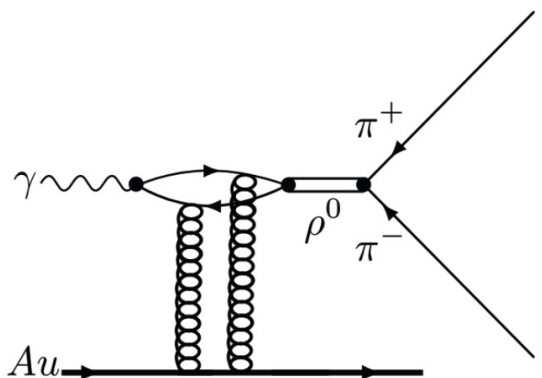
总结

极化光子-光子对撞

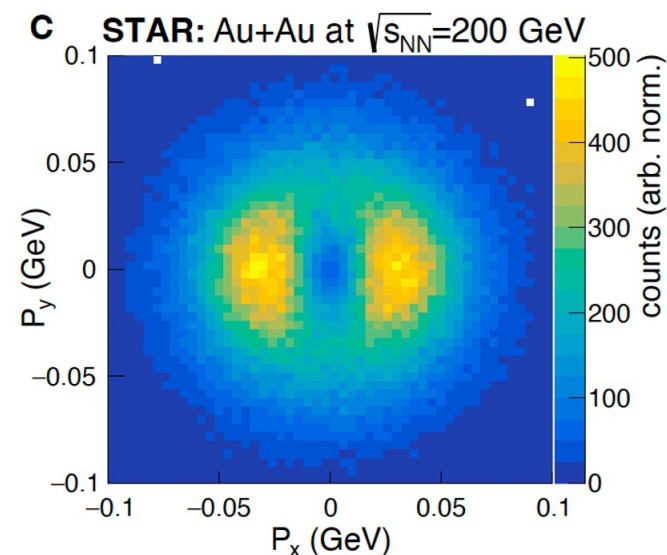
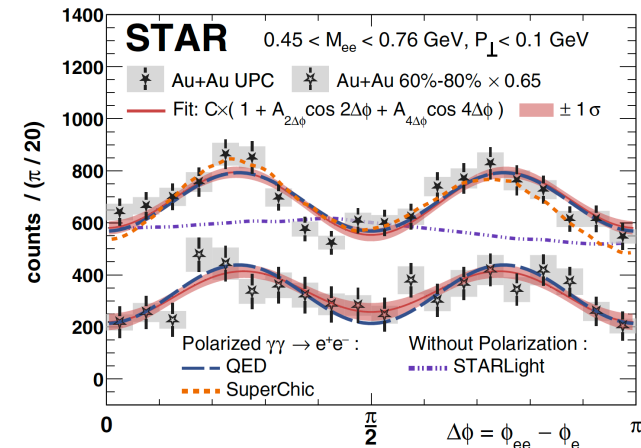


- ✓ 检验极端环境下QED基本过程
- ✓ 末态角分布四阶余弦振荡
- ✓ 证实对撞光子高度线性极化
- ✓ 约束原子核电荷半径

极化光子-胶子对撞



- ✓ 费米尺度的双缝干涉实验
- ✓ 极化方向依赖的费米尺度“断层扫描技术”
- ✓ 约束原子核强相互作用半径和胶子分布等
- ✓ 不同电荷粒子之间的量子干涉与纠缠



感谢您的关注与指导! 25