



N S F C
National Natural Science
Foundation of China



费米尺度下的双缝干涉实验： 高能重离子碰撞中的相干光致产生

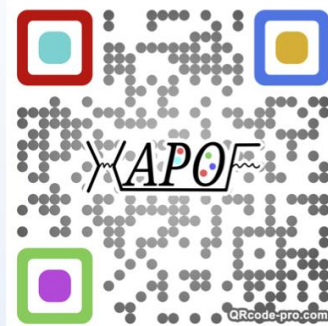
查王妹

中国科学技术大学



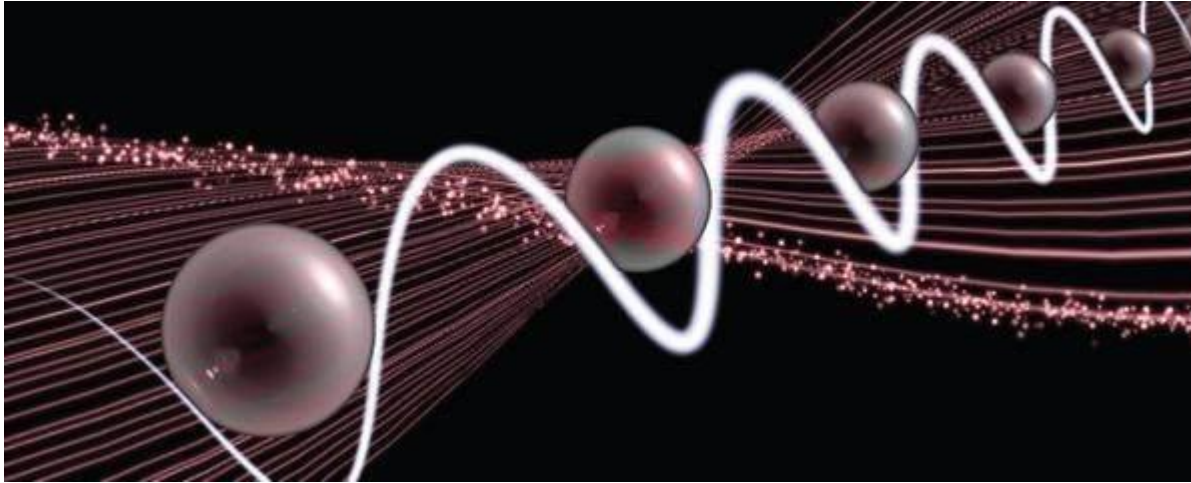
Hadron Physics Online Forum (HAPOF)
<https://indico.itp.ac.cn/category/5/>

强子物理在线论坛
中科大粒子物理
学科联合Seminar



STAR: Sci. Adv. **9** (2023) eabq3903, PRL**127** (2021) 052302, PRL **123** (2019) 132302

量子力学的基石 - 波粒二象性



An experiment can show the particle-like properties of matter, or the wave-like properties; in some experiments both of these complementary viewpoints must be invoked to explain the results.



互补性原理

“Opposites are complementary”

Niels Bohr
(1885-1962)



双缝干涉思想实验

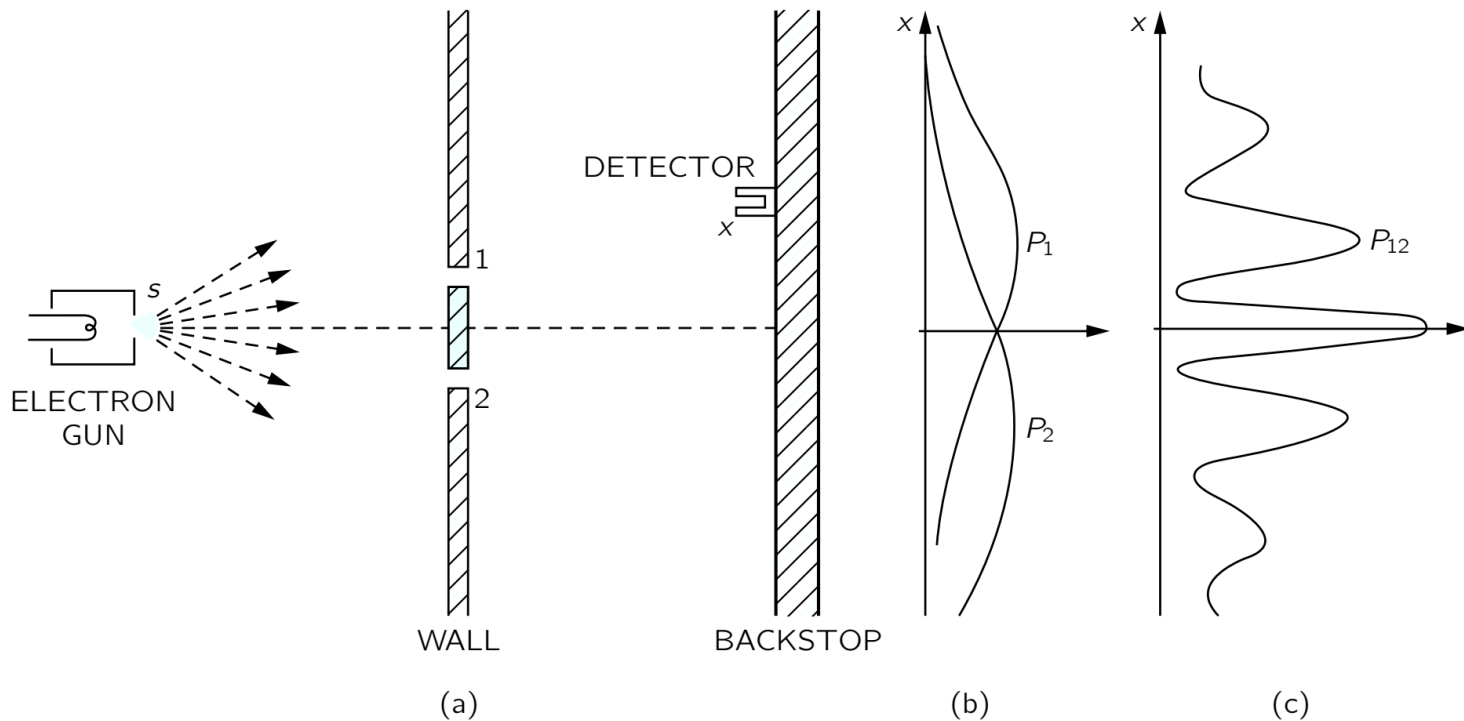
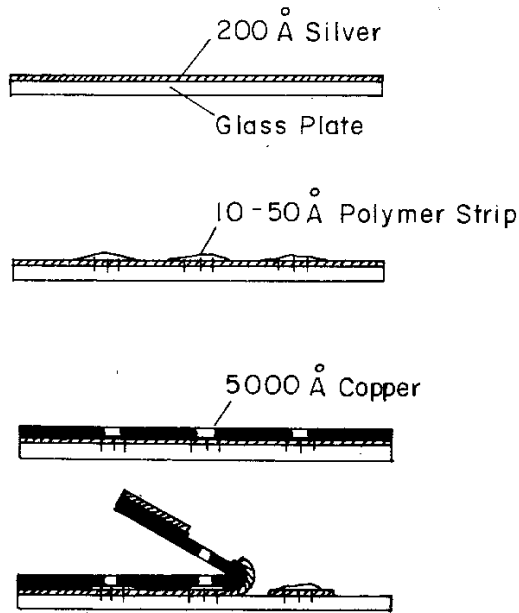


Fig. 3-1. Interference experiment with electrons.

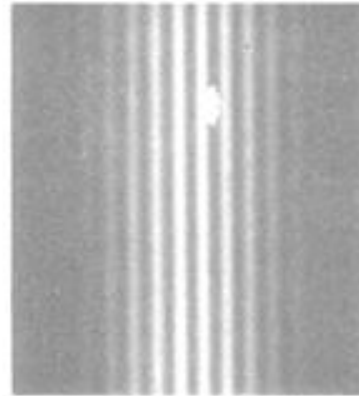
费曼物理学讲义第三卷

We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery. --- **Richard Feynman**

波粒二象性的典型 - 双缝干涉实验



双缝照片



The most beautiful experiment in physics!
Voted by readers of Physics World in 2002

V. C. Jönsson, *Z. Phys.*, **161**(1961) 454

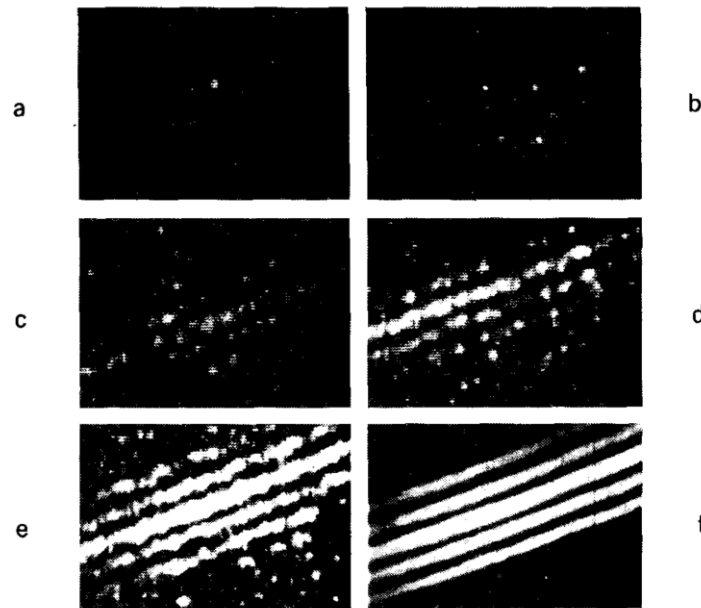
实验对象：电子，中子，原子，分子（C60），生物大分子，玻色-爱因斯坦凝聚态…

尺度：宏观尺度（~毫米） 到 原子尺度

其他的粒子（不稳定）？
更小的尺度？

O. Carnal and J. Mlynek, *Phys. Rev. Lett.* **66** (1991) 2689
; M. Arndt *et al.*, *Nature* **401** (1999) 680 ; M. R. Andrews *et al.*, *Nature* **275** (1997) 637; L. Hackermuller *et al.*, *Phys. Rev. Lett.* **91** (2003) 090408; X. J. Liu *et al.*, *Nature Photonics* **9** (2015) 120

波粒二象性的典型 - 双缝干涉实验



**The most beautiful
experiment in physics!**
Voted by readers of Physics
World in 2002

P. G. Merli et al., Am. J.
Phys. **44** (1976) 306

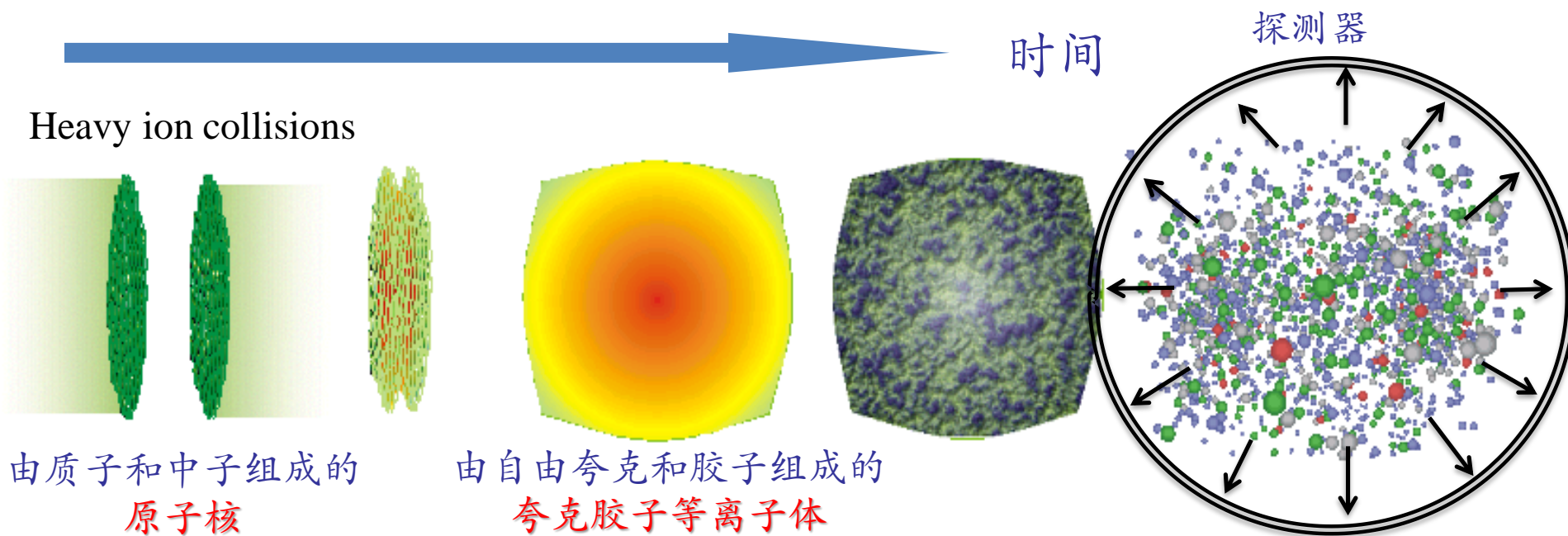
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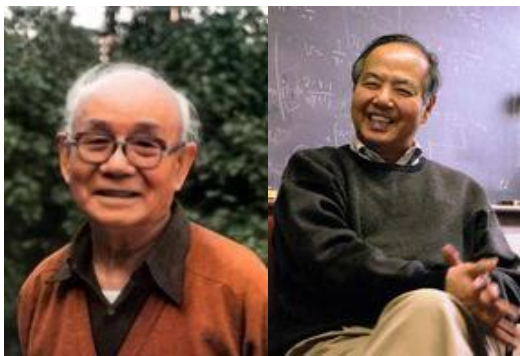
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高能重离子碰撞简介

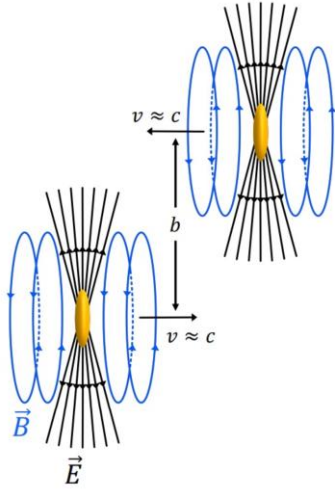


实验室中能量密度、温度最高的“小爆炸”



- ✓ 寻找和研究夸克胶子等离子体QGP
- ✓ 强相互作用 (QCD) 相结构

高能重离子碰撞中的“准实光子”



等效光子近似

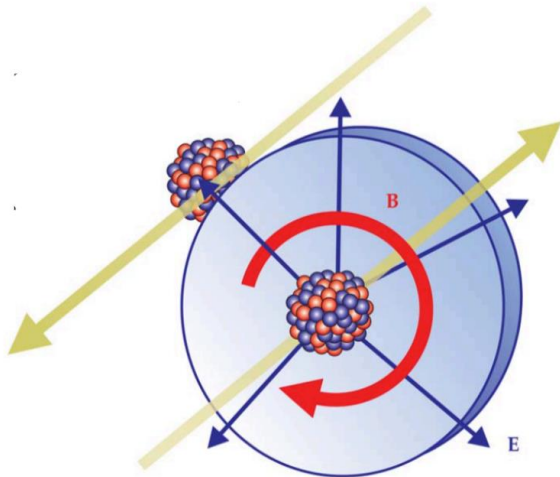
$$\frac{d^3 N_\gamma(\omega_\gamma, \vec{x}_\perp)}{d\omega_\gamma d\vec{x}_\perp} = \frac{4Z^2\alpha}{\omega_\gamma} \left| \int \frac{d^2 \vec{k}_{\gamma\perp}}{(2\pi)^2} \vec{k}_{\gamma\perp} \frac{F_\gamma(\vec{k}_\gamma)}{|\vec{k}_\gamma|^2} e^{i\vec{x}_\perp \cdot \vec{k}_{\gamma\perp}} \right|^2$$

光子四动量: $q^u = (\omega, \vec{q}_T, \omega/v)$

$$Q^2 = \frac{\omega^2}{\gamma^2} + q_T^2 \sim 0 \quad (\text{准实光子})$$

$$\omega \leq \omega_{max} \sim \frac{\gamma}{R}$$

Progress in Particle and Nuclear Physics **39**, 503 (1997)



□ “准实光子”也是核的部分子

□ 更大的分布半径

✓ 核物质密度分布半径 $R_{\text{Nuc}} \sim 6.3 \text{ fm}$ (金核)

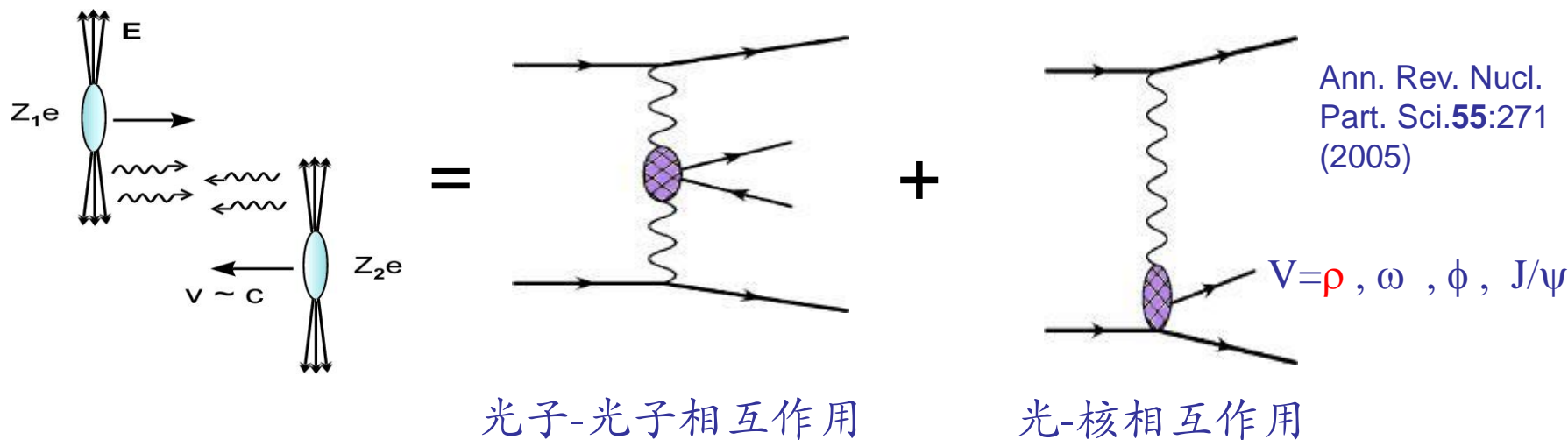
$R_{\text{photons}} \gg R_{\text{Nuc}}$

✓ 核不碰上，依然有强烈的相互作用

Physics Today **70**(10) (2017) 40

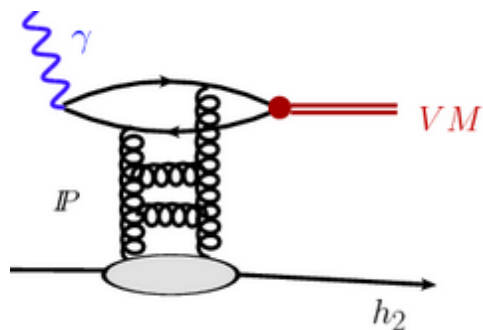
超周边碰撞 (Ultra-peripheral collisions)

高能重离子碰撞中的光致产生



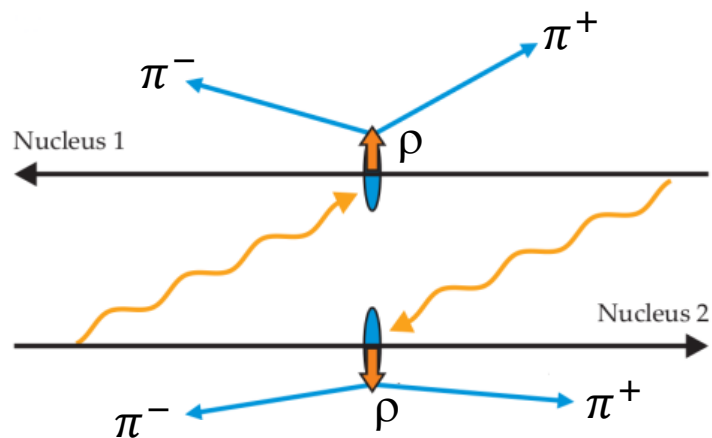
强子对撞机也是光-核（光）对撞机

- ✓ 光-核相互作用：矢量介子产生，核激发…
- ✓ 光子-光子相互作用：光子散射，粒子-反粒子对产生…



坡密子 (Pomeron) 交换

费米尺度的双缝干涉设想

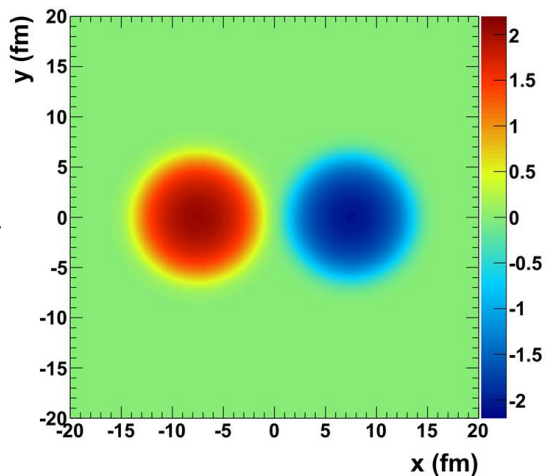


不可区分的两个过程：

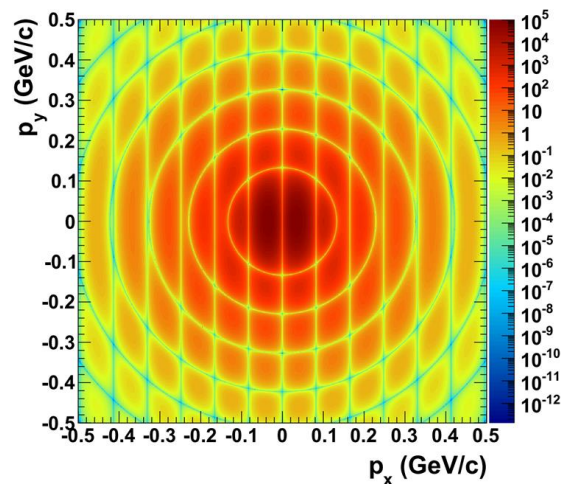
- ✓ 哪个核是光子发射核
- ✓ 哪个核是靶核

双缝干涉！

碰撞参数：15fm



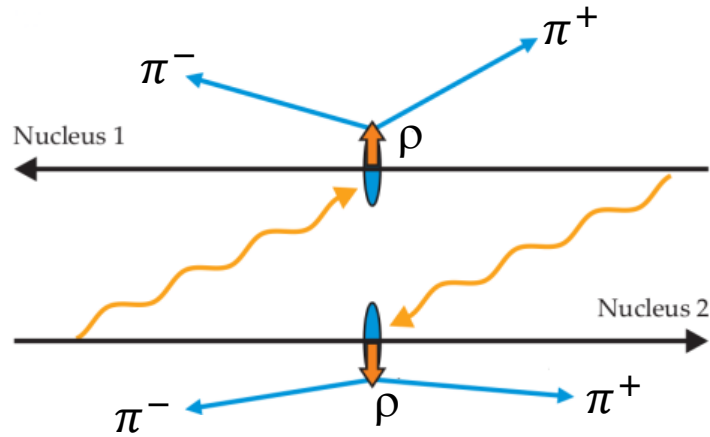
相位差 π
矢量介子的
宇称



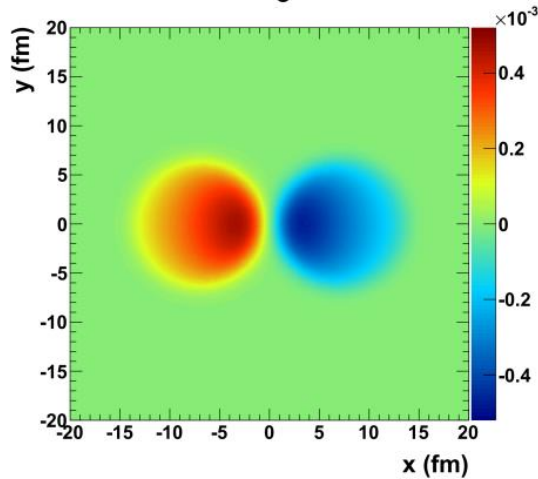
金核-金核200GeV碰撞

W. Zha *et al.*, Phys. Rev. C99 (2019), 061901

费米尺度的双缝干涉设想



碰撞参数: 15fm
c



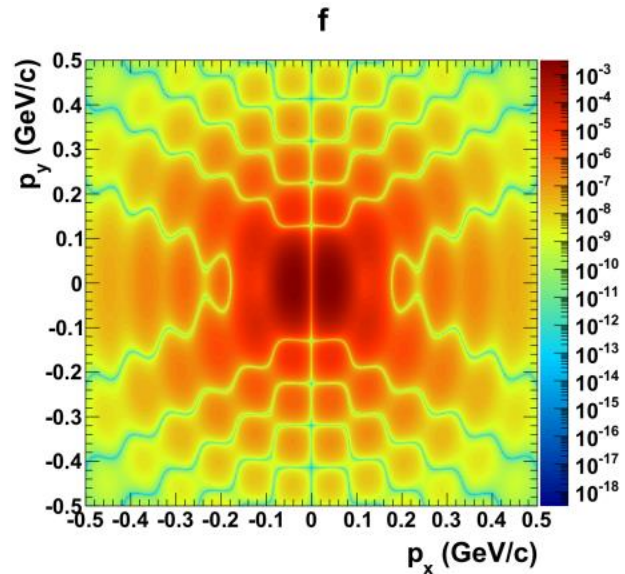
相位差 π
矢量介子
宇称

金核-金核200GeV碰撞

不可区分的两个过程:

- ✓ 哪个核是光子发射核
- ✓ 哪个核是靶核

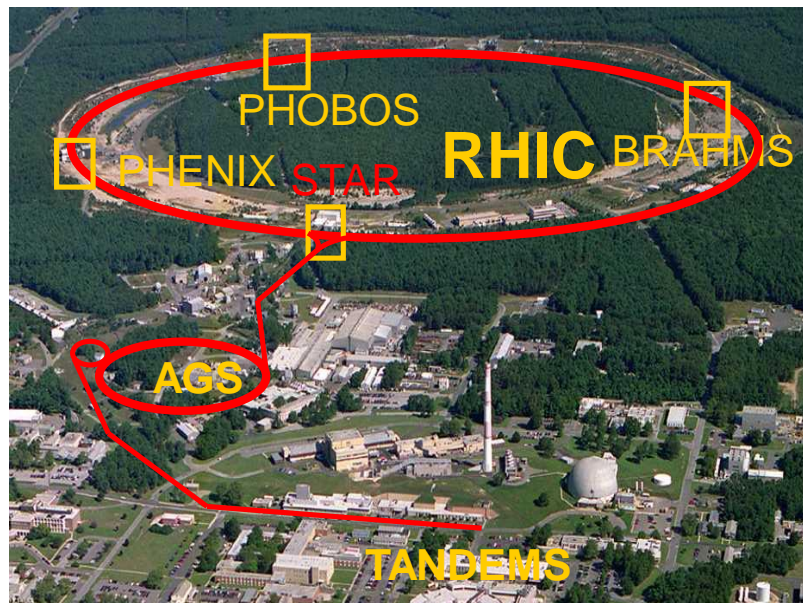
双缝干涉!



W. Zha *et al.*, Phys. Rev. C99 (2019), 061901

高能重离子碰撞实验装置

相对论重离子对撞机(RHIC)



- ✓ 世界上**第一台**重离子对撞机
- ✓ 目前世界上最先进的重离子加速器之一

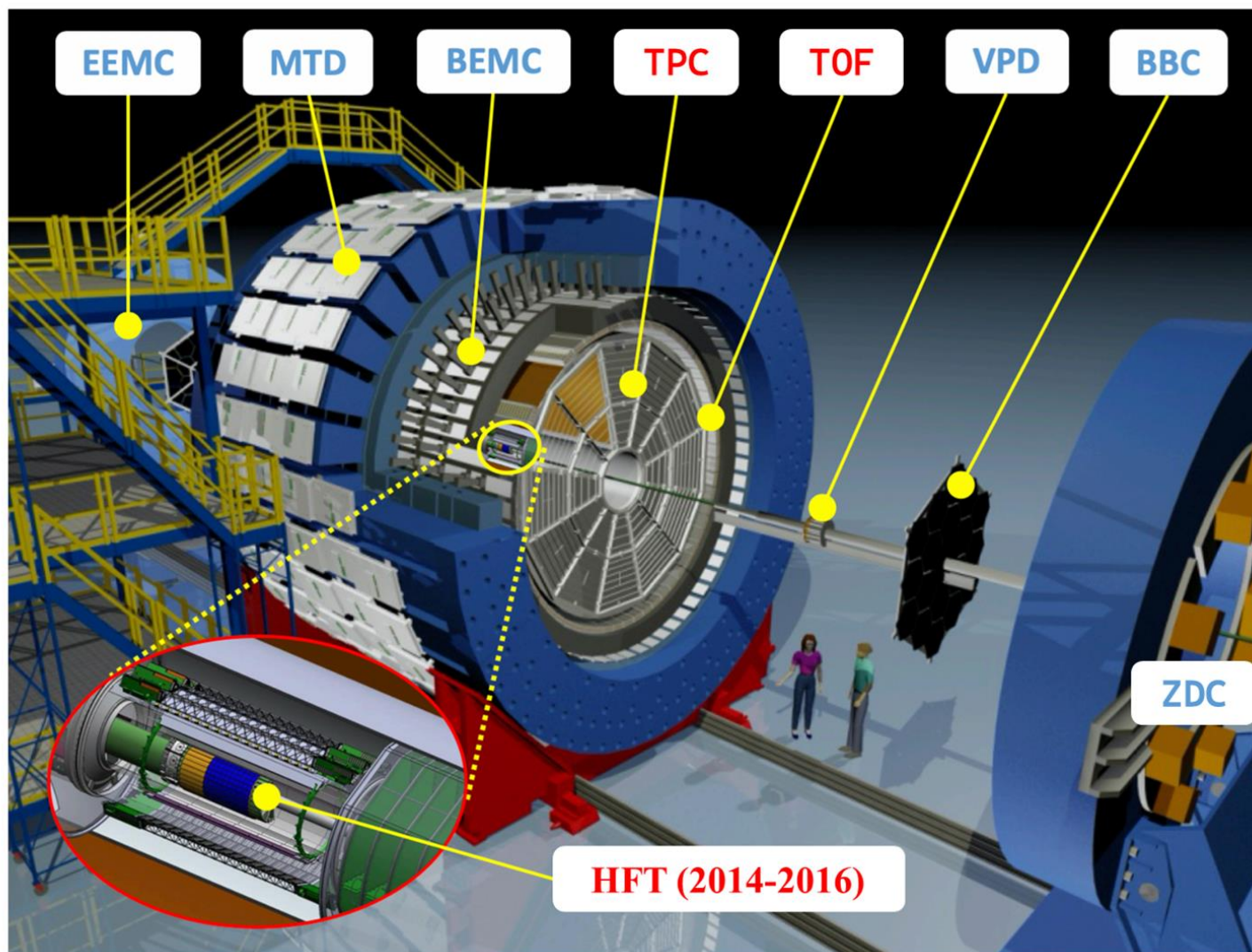
STAR合作组

STAR合作组：15个国家72个单位的**735名**科研人员组成

- ✓ 2002年，科大高能组正式加入STAR国际合作组
- ✓ 2006 - 2009，为STAR批量生产时间飞行谱仪（TOF）模块并顺利安装运行
- ✓ 2009 - 2014，为STAR研制并安装运行缪子探测器（MTD）
- ✓ 2014 - 至今，参与STAR前向升级计划

其他大型实验装置：LHC，NICA，**HIAF（中国惠州）**，FAIR…

STAR探测器系统

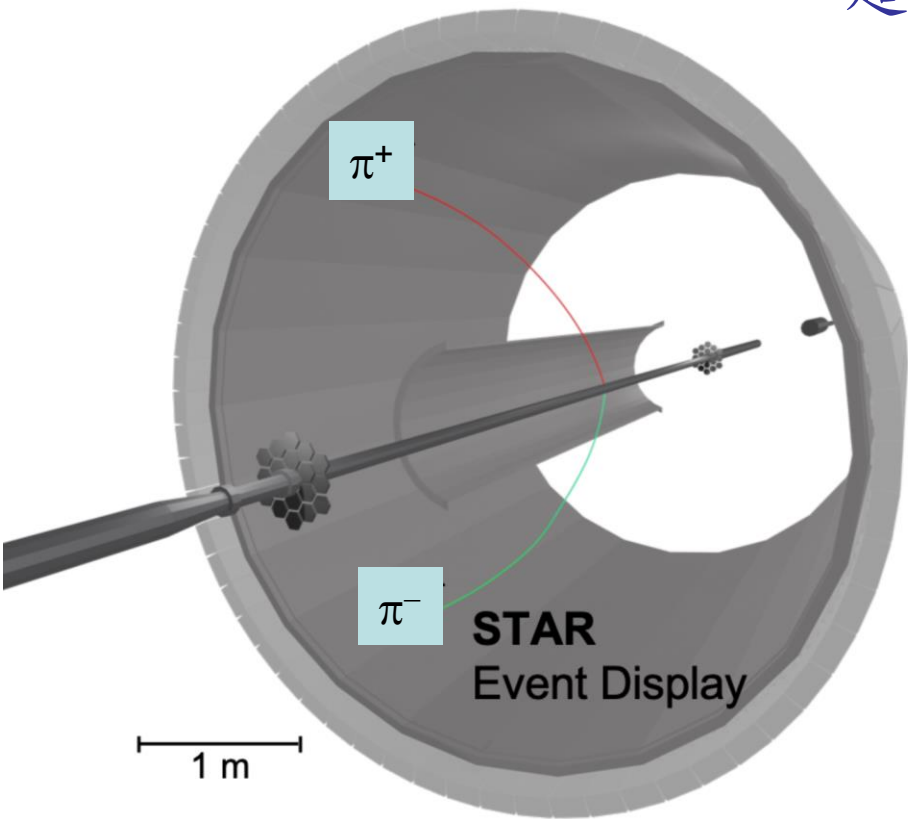
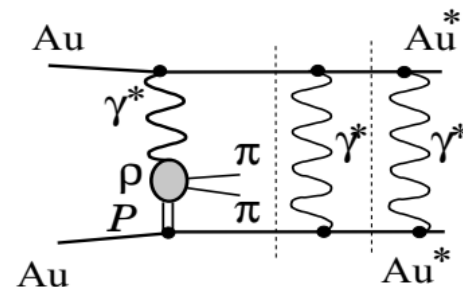


光致产生事例的选取

超周边碰撞 (Ultra-peripheral collisions)

$$b > 2R_A$$

中子触发

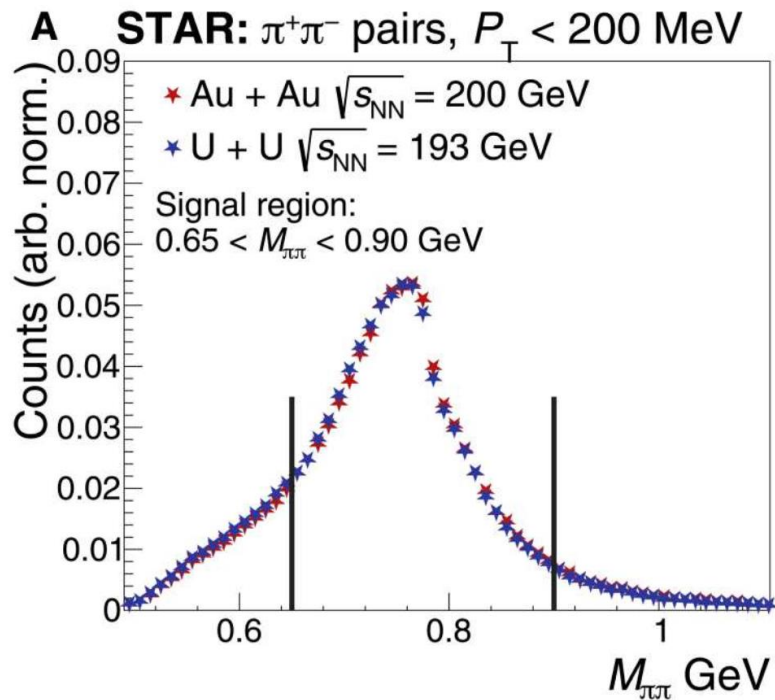


collider		RHIC	RHIC	LHC
species		Au+Au	U+U	Pb+Pb
$\sqrt{s_{NN}}$	GeV	200	192.8	5520
BFPP	b	117	329	272
single EMD	b	94.15	150.1	215
<i>mutual EMD</i>	b	3.79	7.59	6.2
nuclear	b	7.31	8.2	7.9
total	b	218.46	487.3	494.9

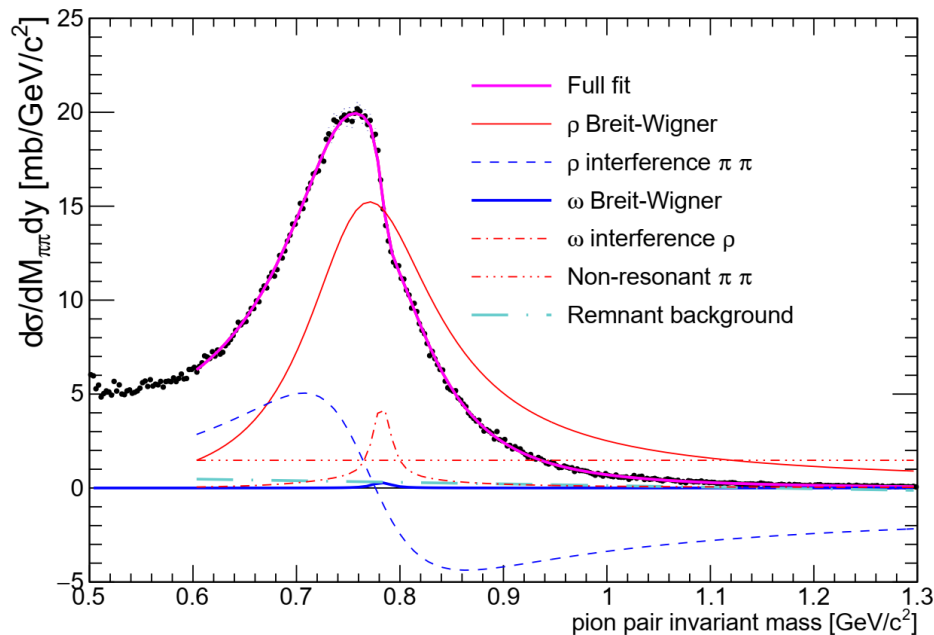
PRC 89 (2014) 014906

事件多重度 (Event activity) 等于2

矢量介子 ρ^0 的信号



PRC96 (2017) 054904

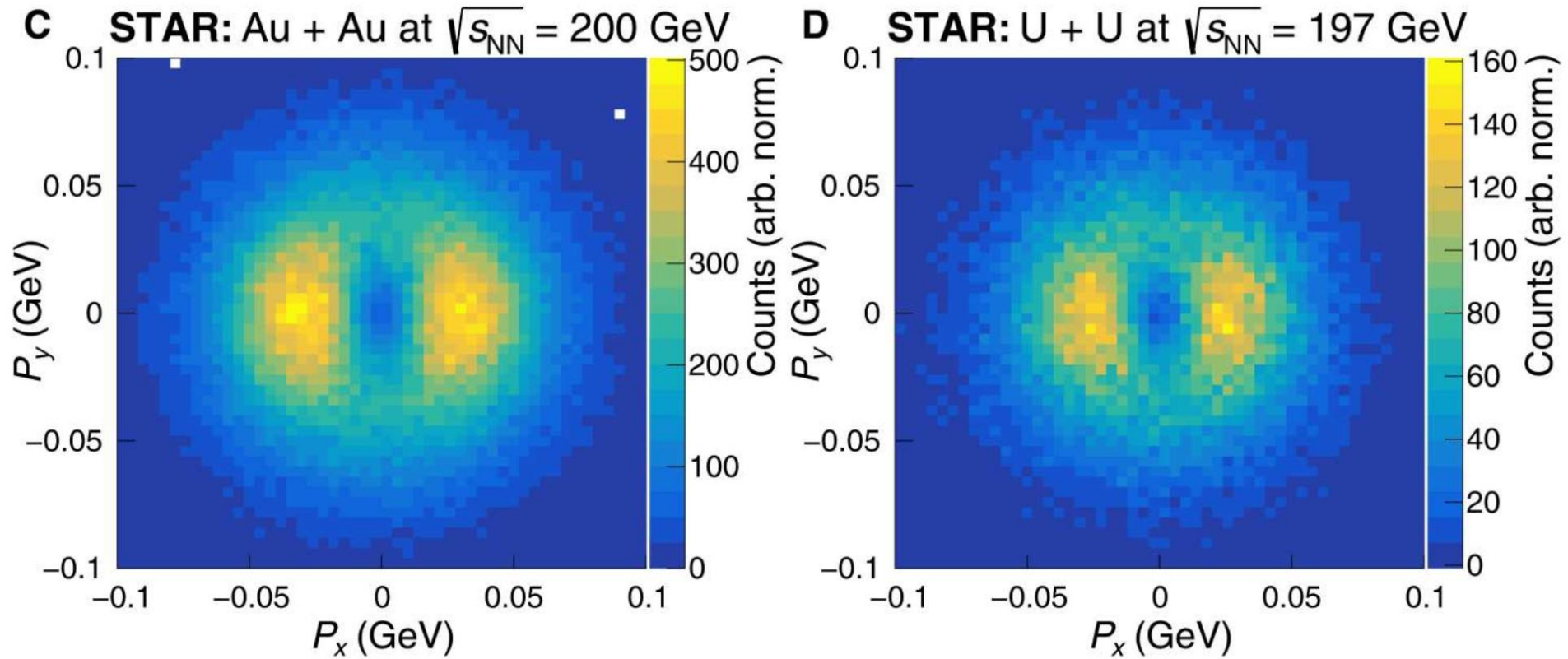


$$\frac{d\sigma}{dM_{\pi^+\pi^-}} \propto \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + B_{\pi\pi} + C_\omega e^{i\phi_\omega} \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_{\omega \rightarrow \pi\pi}}}{M_{\pi\pi}^2 - M_\omega^2 + i M_\omega \Gamma_\omega} \right|^2 + f_p$$

矢量介子不变质量谱中的干涉现象!

矢量介子 ρ^0 的二维横动量分布

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

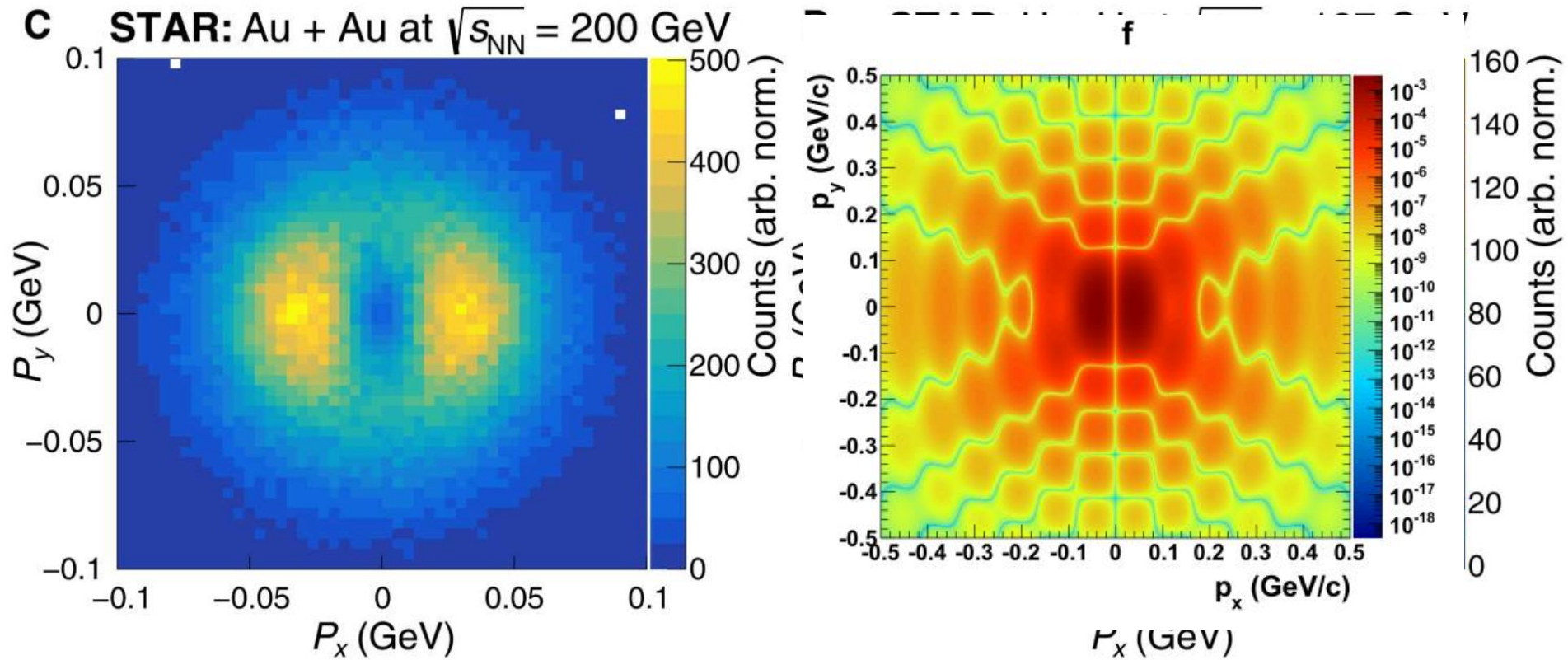


清晰的干涉+衍射图样!

怎么样确定一个固定的方向?

矢量介子 ρ^0 的二维横动量分布

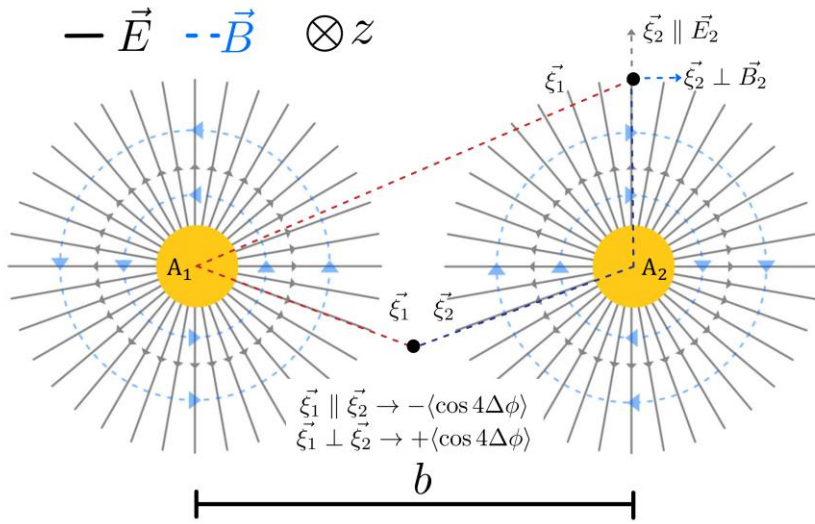
STAR Collaboration, Sci. Adv. **9** (2023) eabq3903



清晰的干涉+衍射图样!

怎么样确定一个固定的方向?

准实光子的线性极化



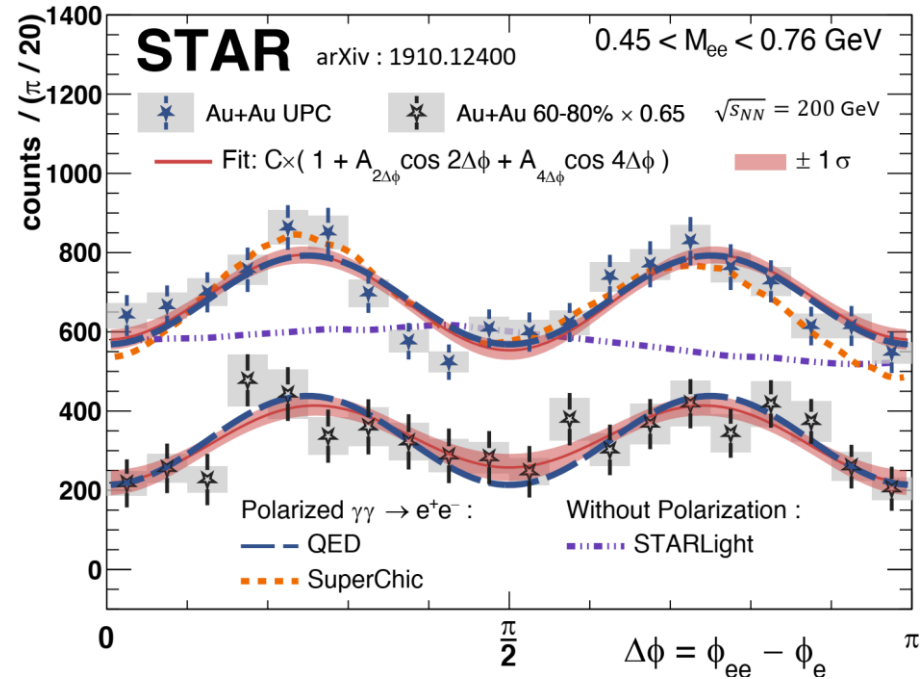
线性极化的光子



布雷特-惠勒过程产生的电子发射角的四阶余弦震荡

PLB 795 (2019) 576

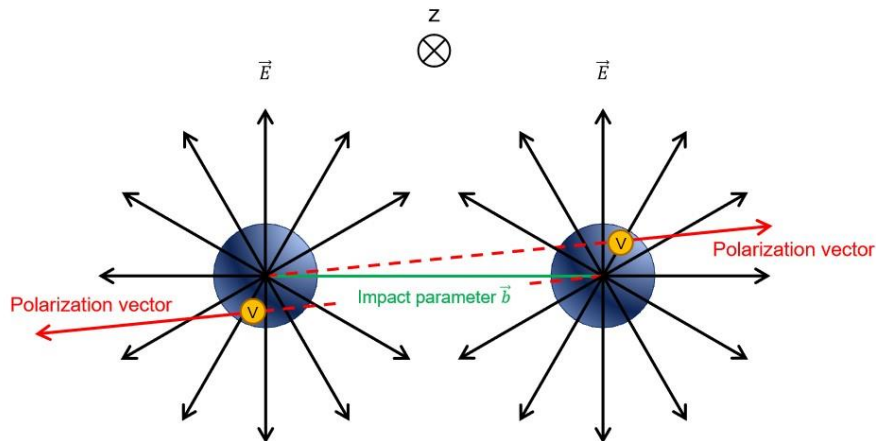
布雷特-惠勒过程角分布



STAR Collaboration, PRL127 (2021) 052302

在实验上证实了光致产生过程的线性极化!

准实光子的线性极化



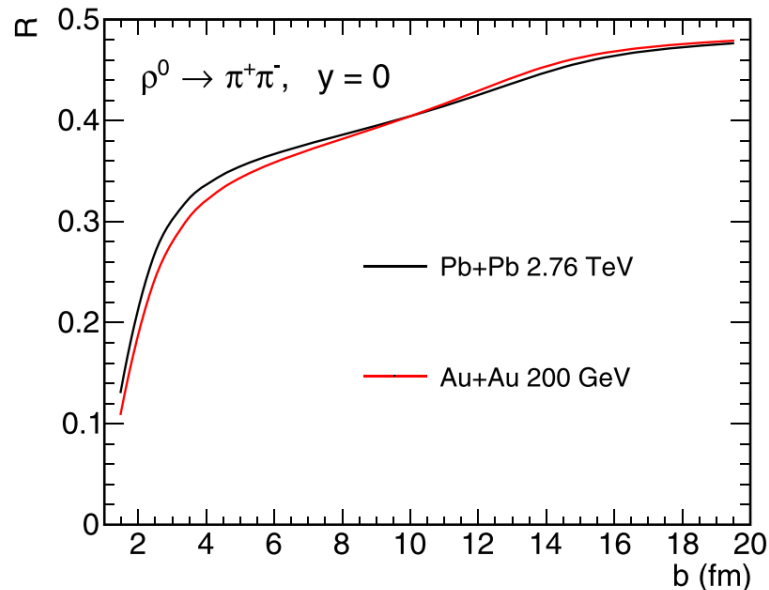
极化方向沿着碰撞参数方向

衰变产物沿着极化方向

$$\frac{d^2 N}{d \cos \theta d \phi} = \frac{3}{8\pi} \sin^2 \theta [1 + \cos 2(\phi - \Phi)]$$

一种新的确定反应平面的方法!

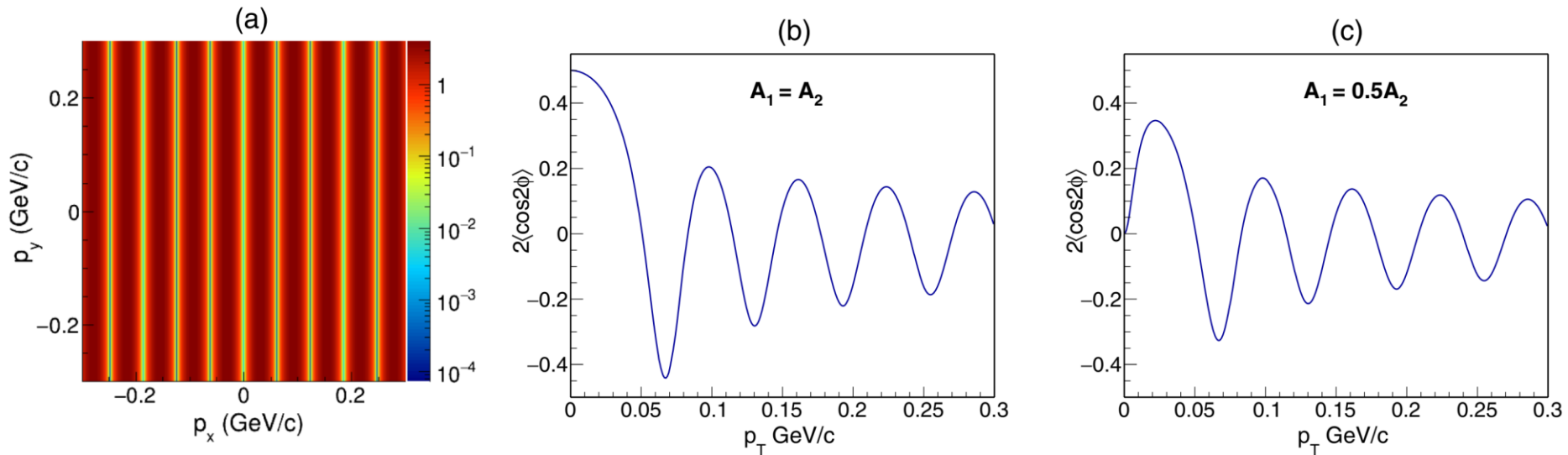
超周边碰撞中分辨率接近0.5



X. Wu et al., PRR 4 (2022) L042048

极化空间的干涉现象

W. Zha *et al.*, PRD103 (2021) 033007



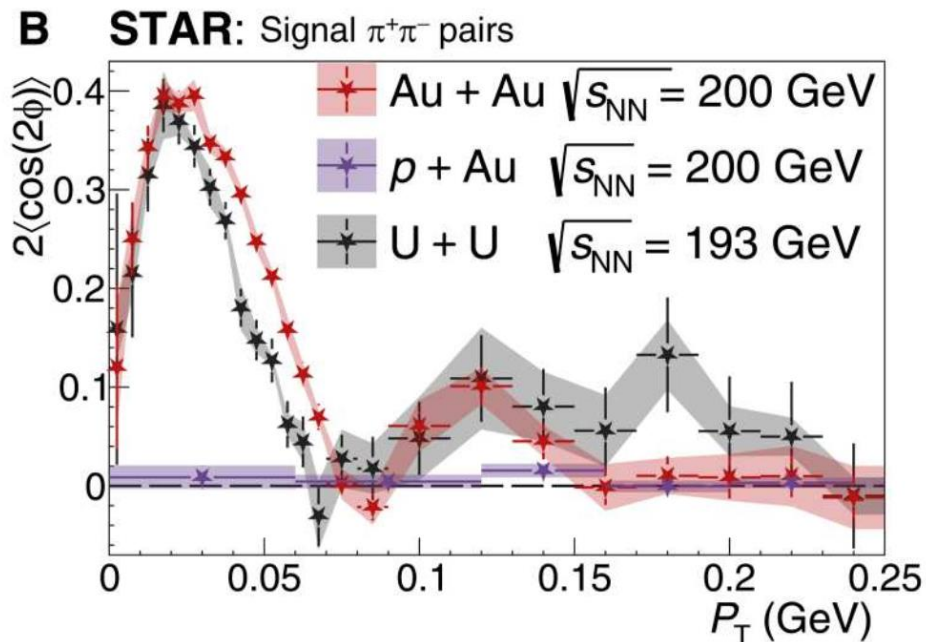
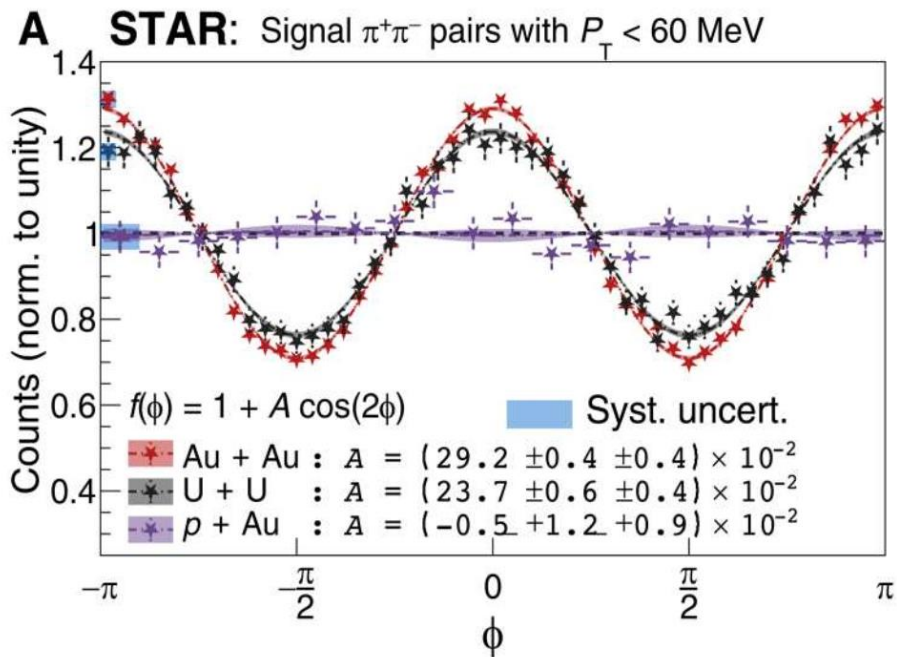
动量空间的干涉

+

矢量介子的线性极化

衰变角二阶余弦调制的周期性变化

极化空间的干涉现象



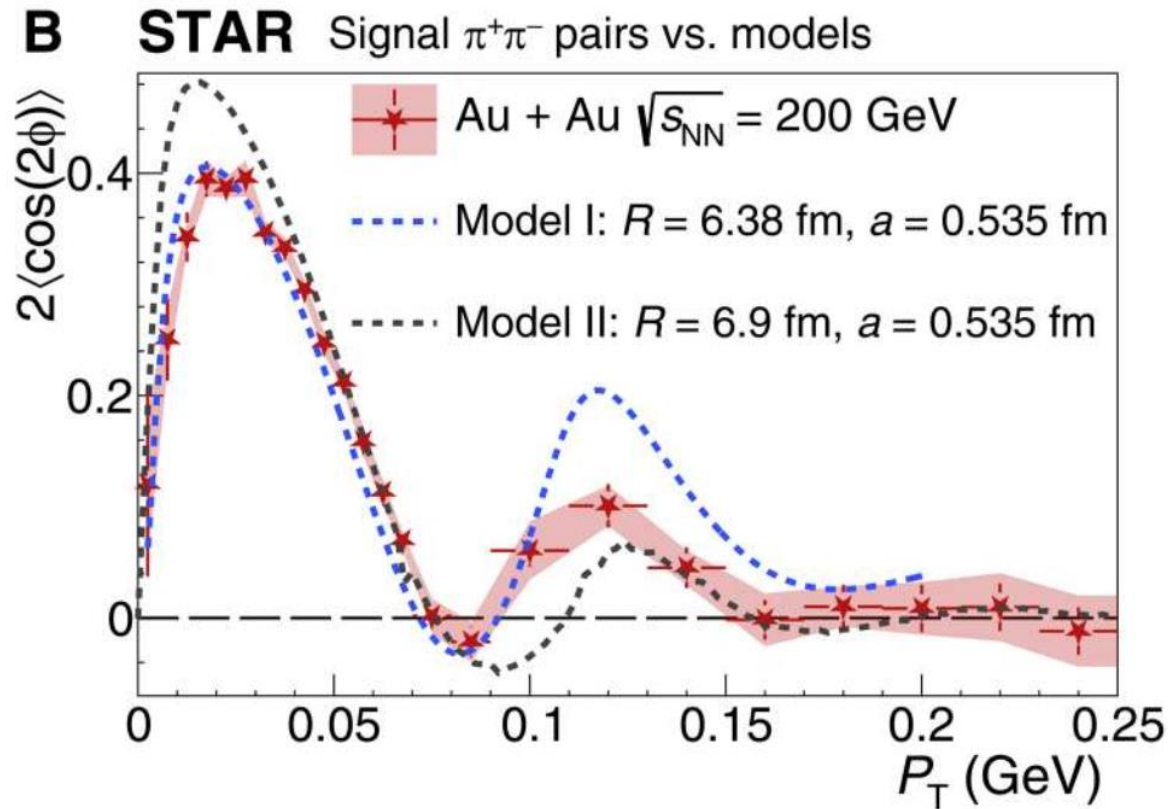
矢量介子光致产生的线性极化

极化空间的干涉现象

p+Au: 无双缝干涉现象

未区分相干、非相干成分

极化空间的干涉现象

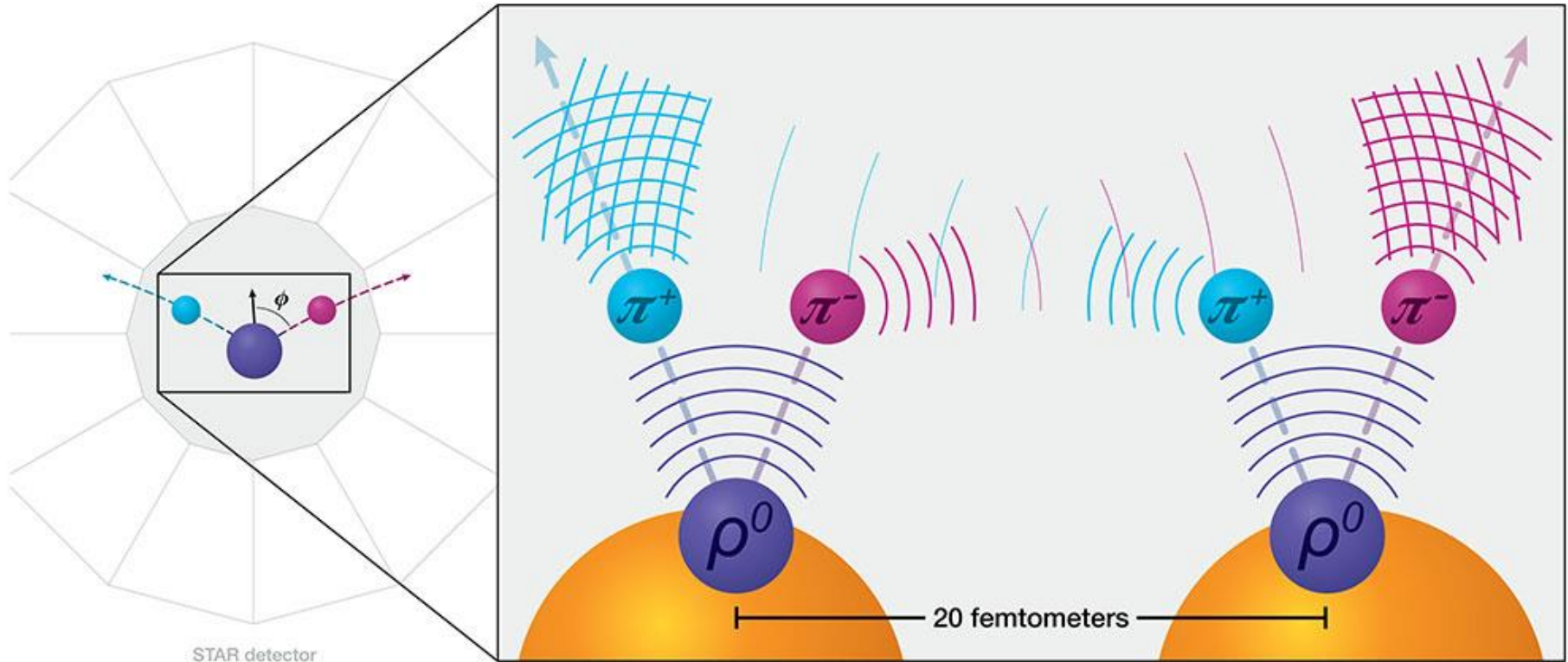


可以定性被模型描述

模型1: 偶极子模型 JHEP10 (2020) 064

模型2: 矢量介子主导模型 PRD103 (2021) 033007

一些特点



单粒子

ρ 的寿命： $\sim 1.3\text{fm}/c$

干涉由衰变产物完成

碰撞的平均的距离： $\sim 40\text{fm}$

量子纠缠？

观察者效应

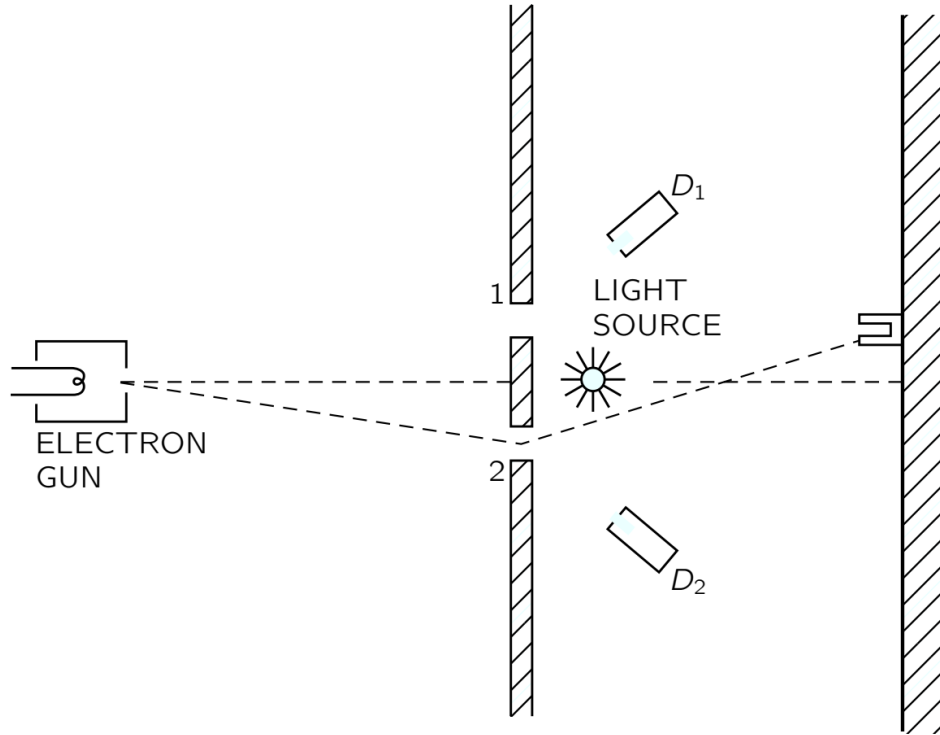
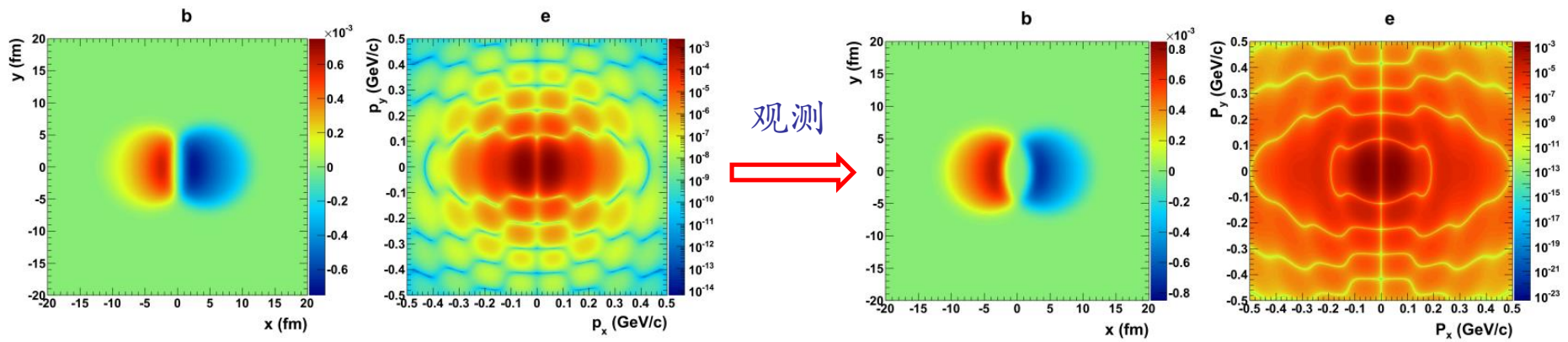
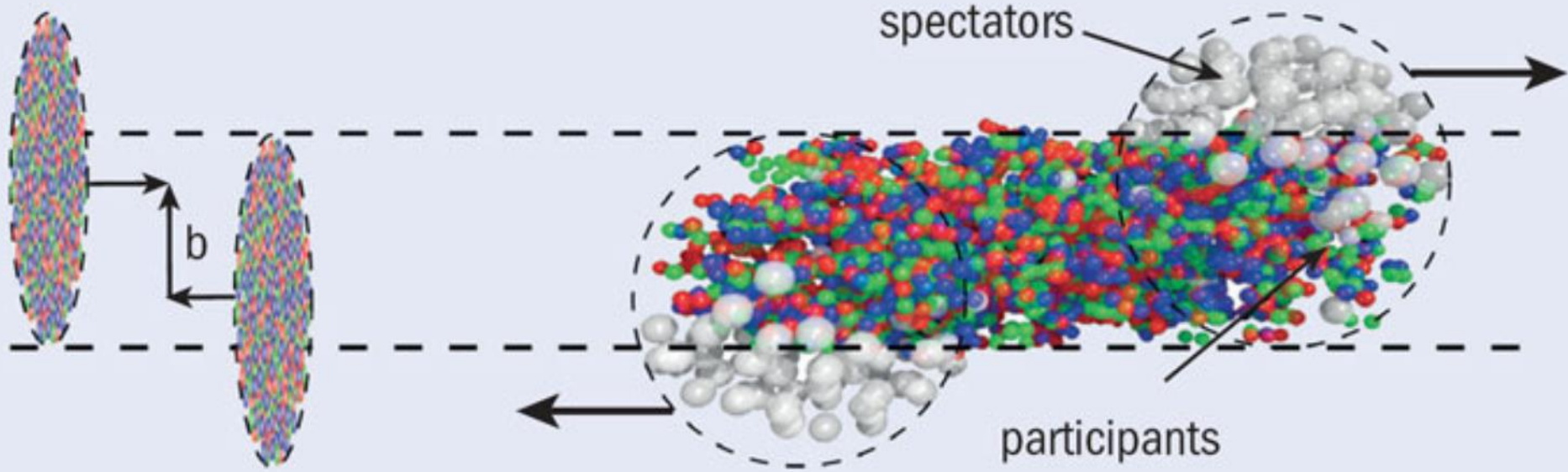


Fig. 3-3. An experiment to determine which hole the electron goes through.

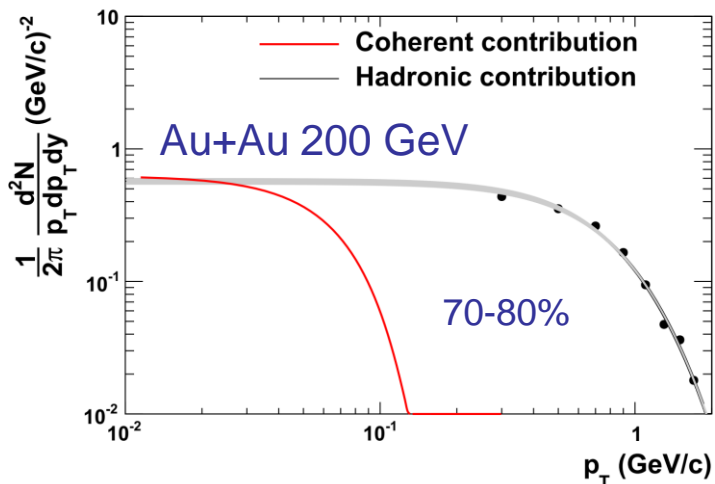
费曼物理学讲义第三卷

测量破坏干涉效应

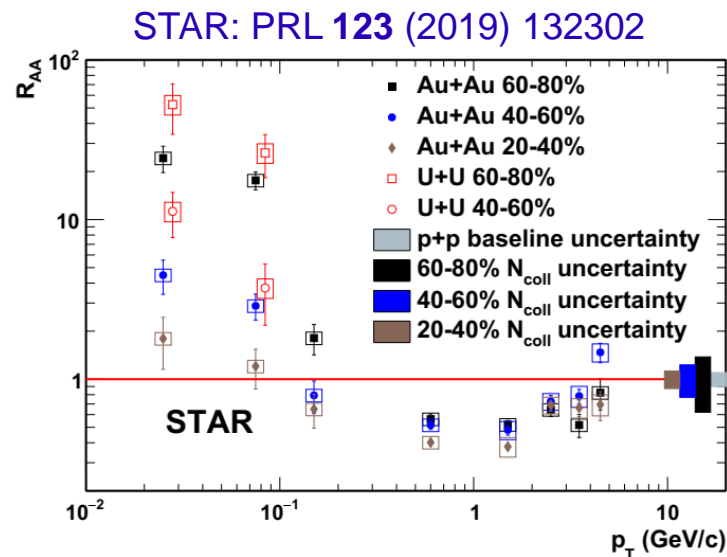
核重叠区域的“观测”



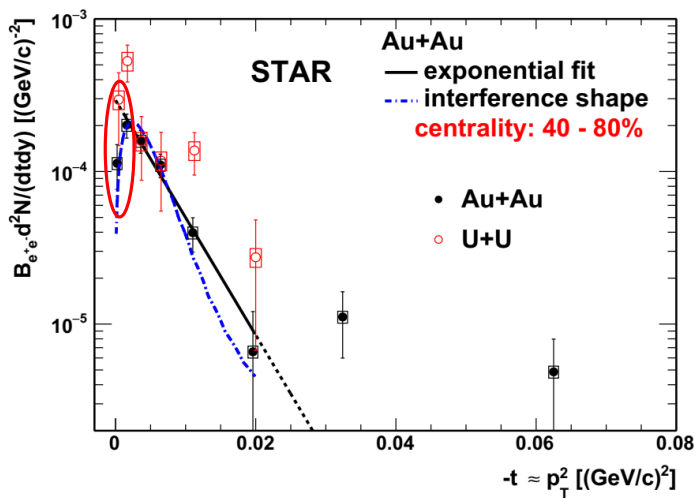
核重叠下的相干光致产生



ρ^0 的信号会被背景淹没



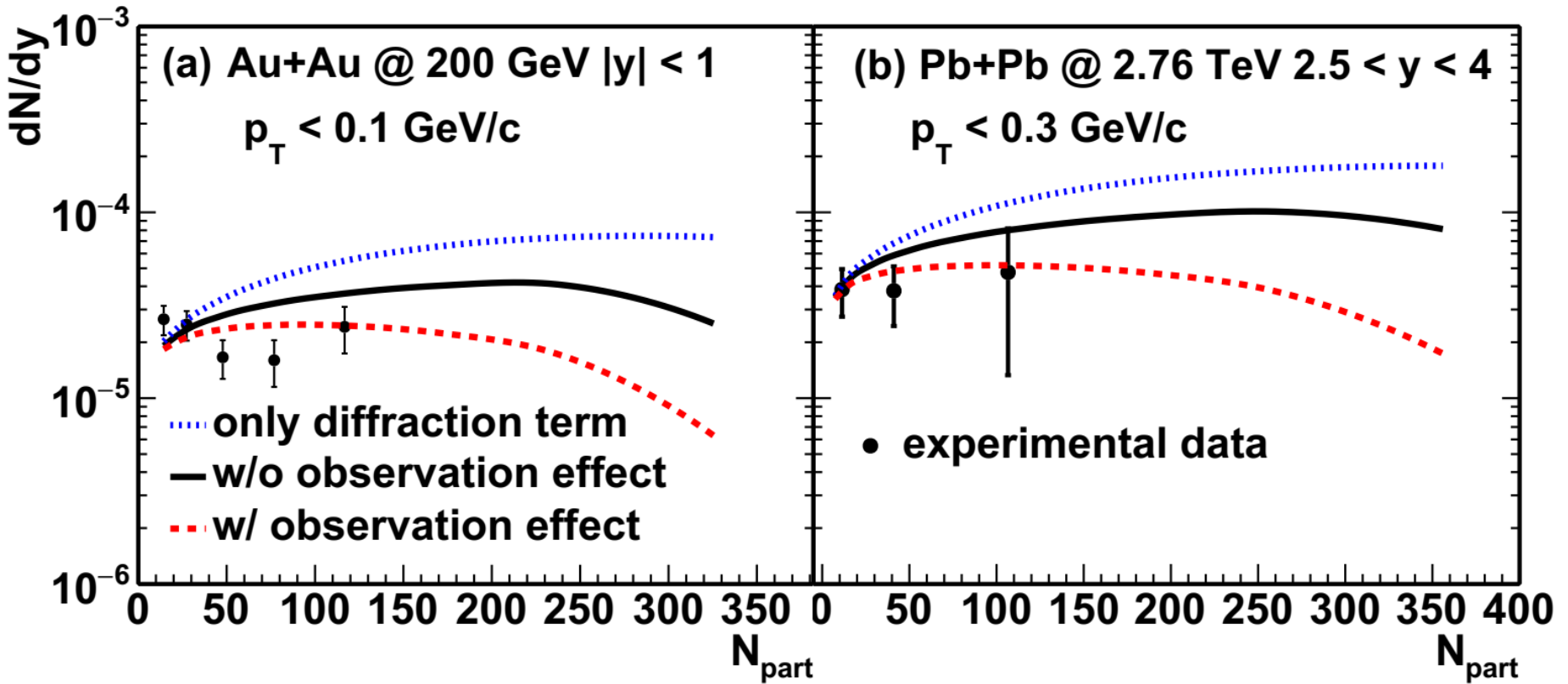
J/ψ信号非常显著



显著的干涉效应

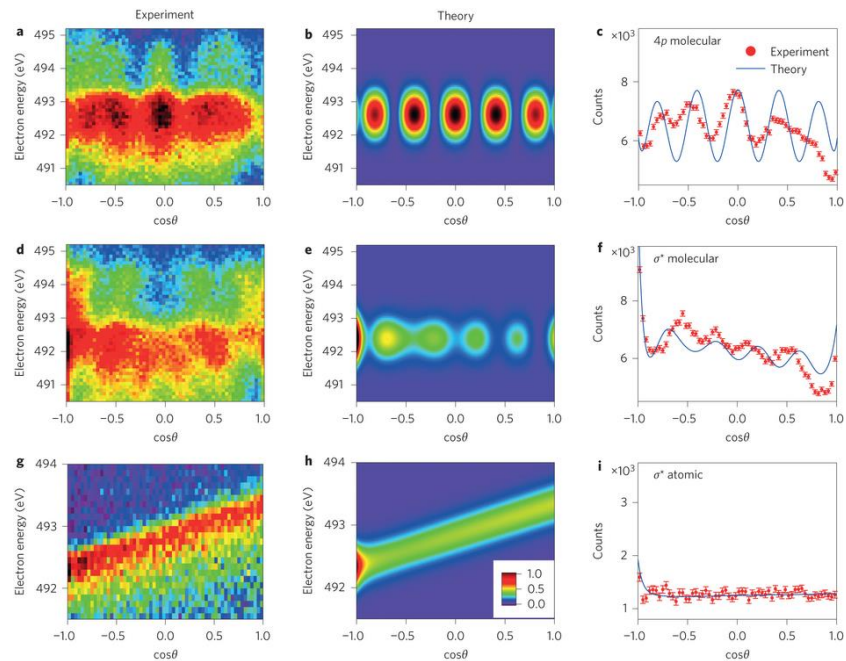
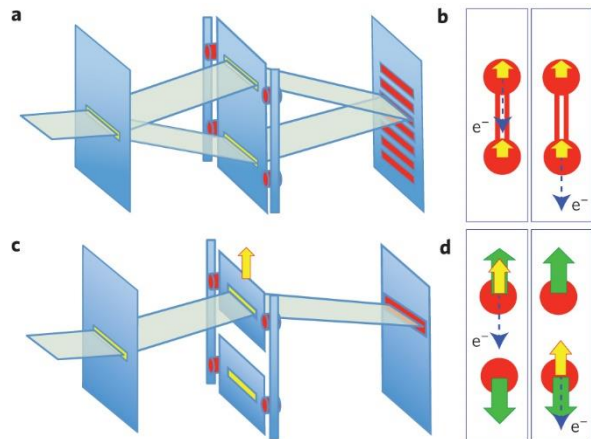
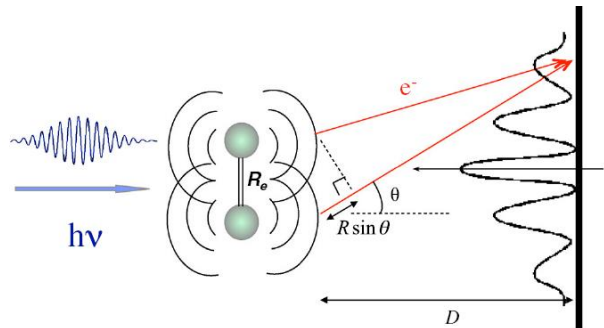
观测者效应?

核重叠下的相干光致产生



观测者效应减少了光致产生的产额!

爱因斯坦-玻尔的回弹缝

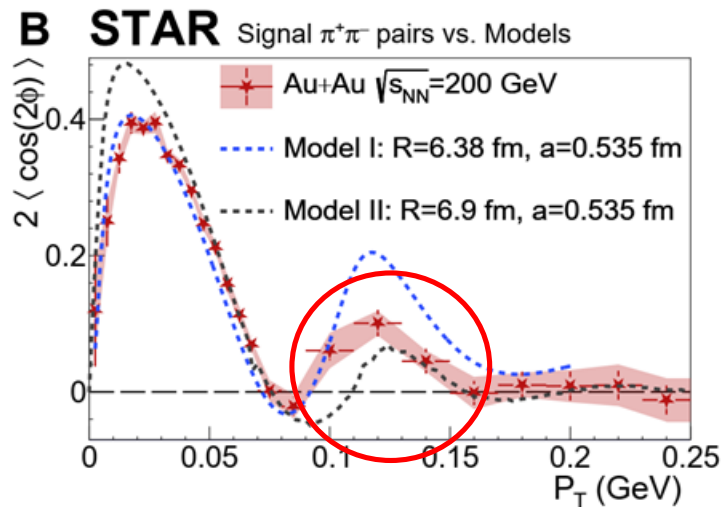
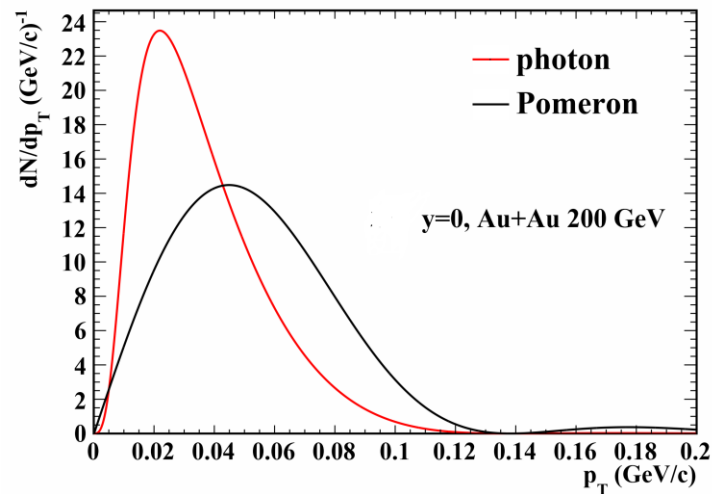
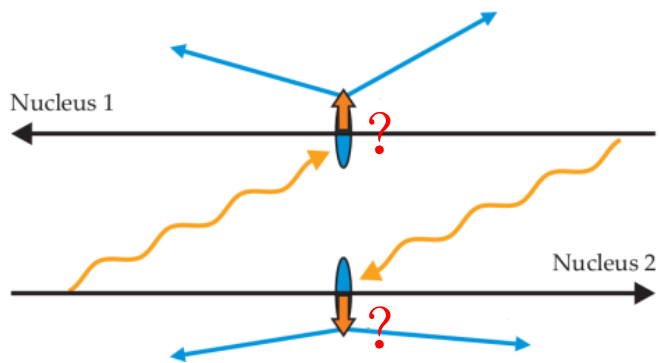


分子尺度的爱因斯坦-玻尔的回弹缝

Nature Photonics 9 (2015) 120

爱因斯坦-玻尔的回弹缝

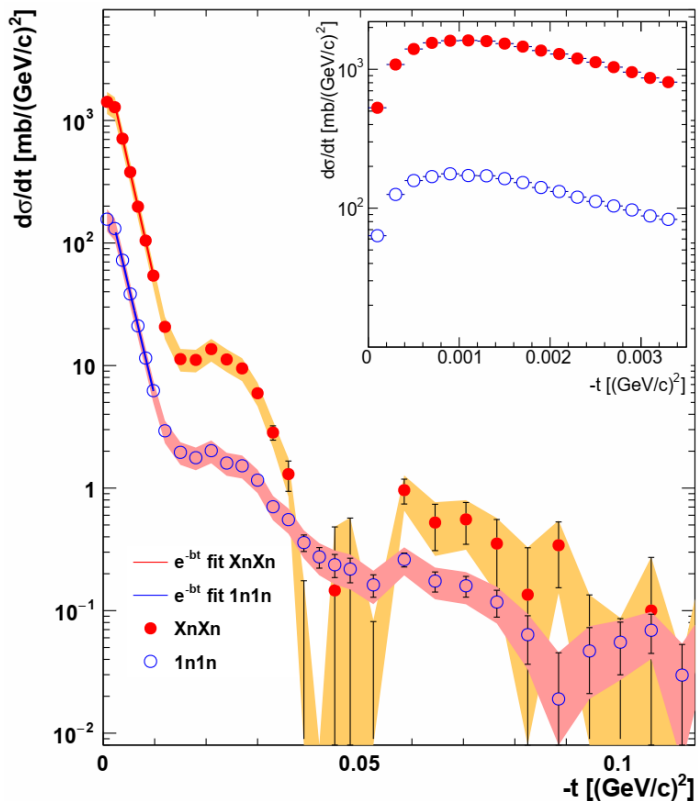
完全不可区分?
 ✓ 回弹的“缝”



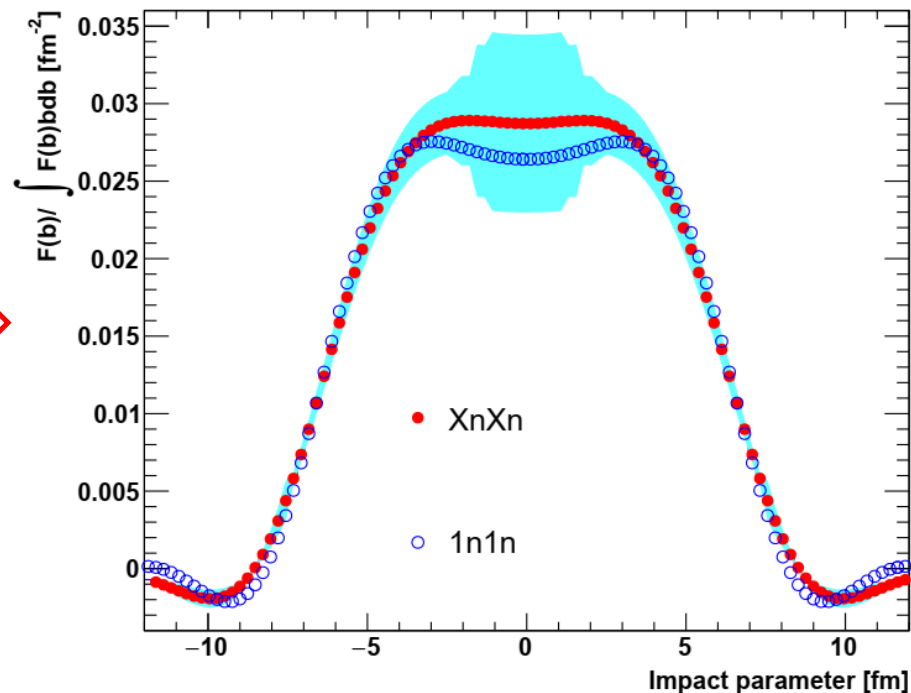
完全不可区分

完全可区分

应用：核物质成像



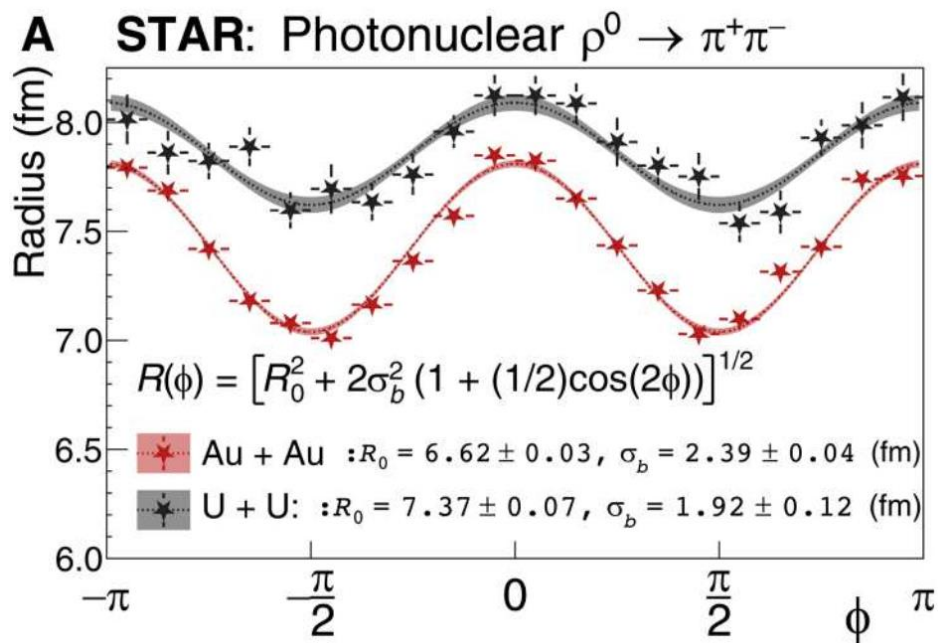
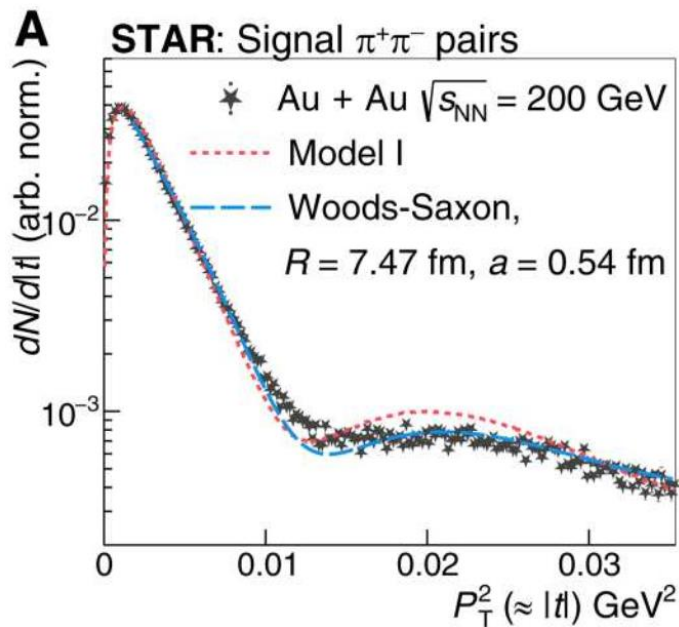
PRC96 (2017) 054904



对作用空间位置分布进行成像

光子动量的影响？ 动量分辨率？

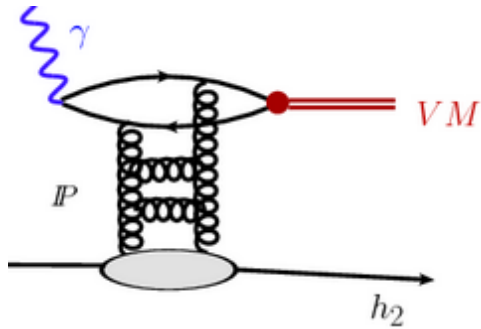
应用：核物质成像



二维成像

核中胶子空间分布？

应用：胶子分布函数

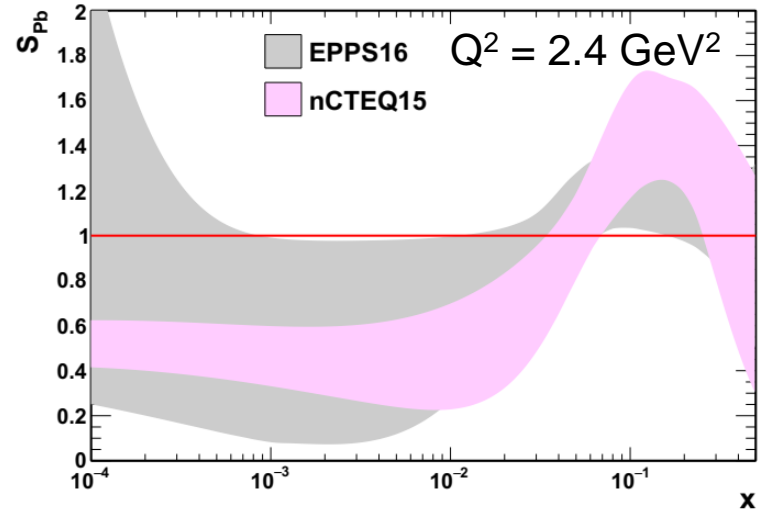


对胶子的分布函数敏感

重味矢量介子

$$\left. \frac{d\sigma(\gamma A \rightarrow VA)}{dt} \right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xG_A(x, Q^2)]^2$$

$$x = \frac{M_V e^{\pm y}}{\sqrt{s}} \quad Q^2 = M_V^2/4$$

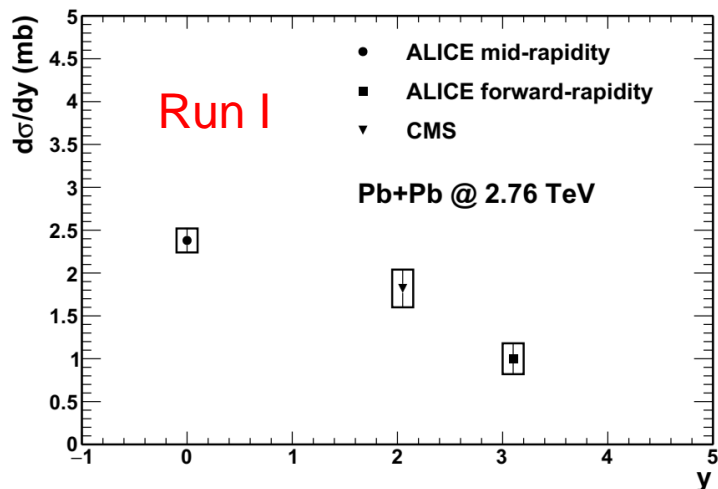


EPPS16: EPJC **77** (2017) 163

nCTEQ15: PRD **93** (2016) 085037

胶子的分布函数存在
非常大的不确定性!

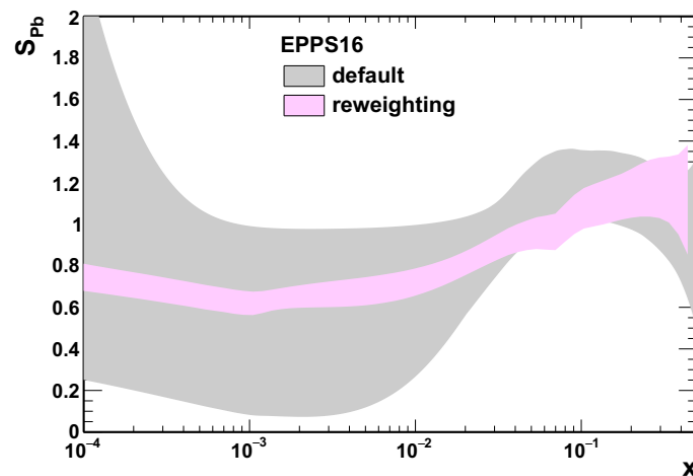
应用：胶子分布函数



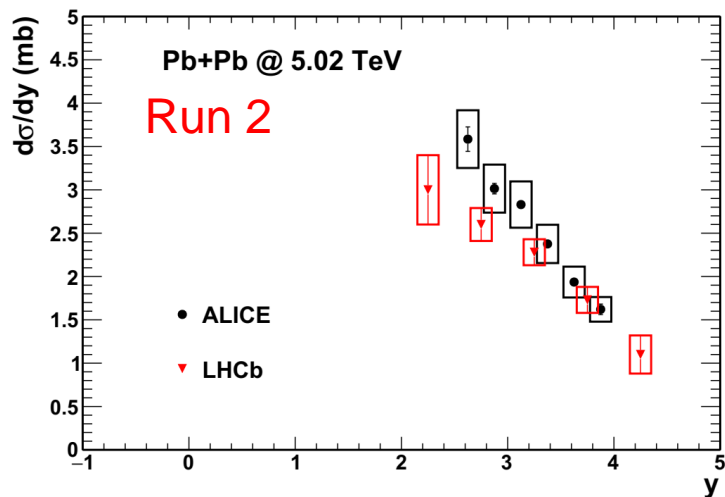
ALICE:
EPJC **73**
(2013) 2617

ALICE: PLB
718 (2013)
1273

CMS: PLB
772 (2017)
489

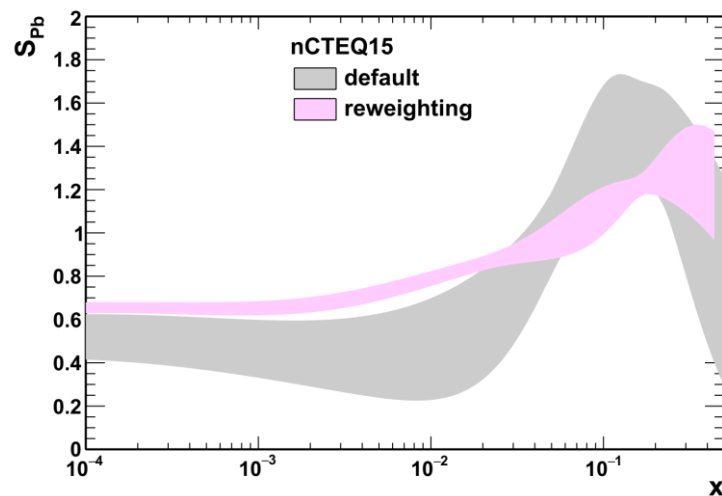


+

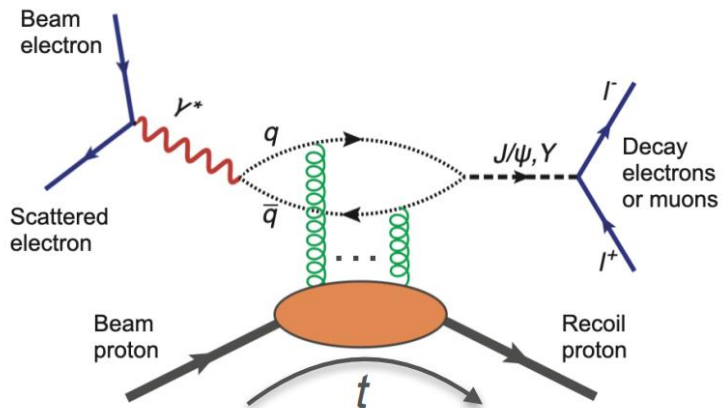


ALICE: PLB
798 (2019)
134926

LHCb: LHCb-
CONF-2018-
003

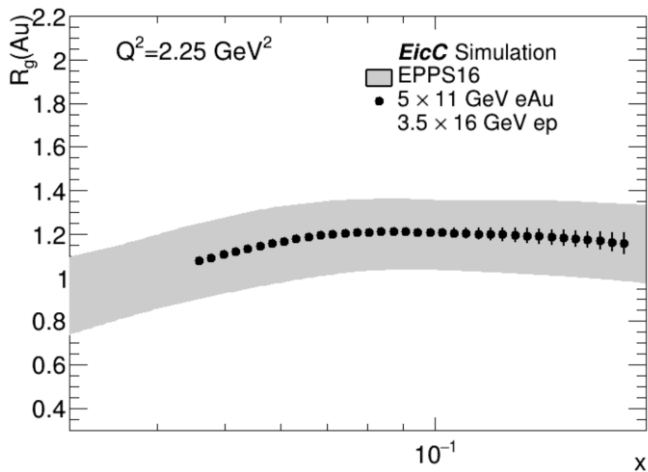


应用：胶子分布函数

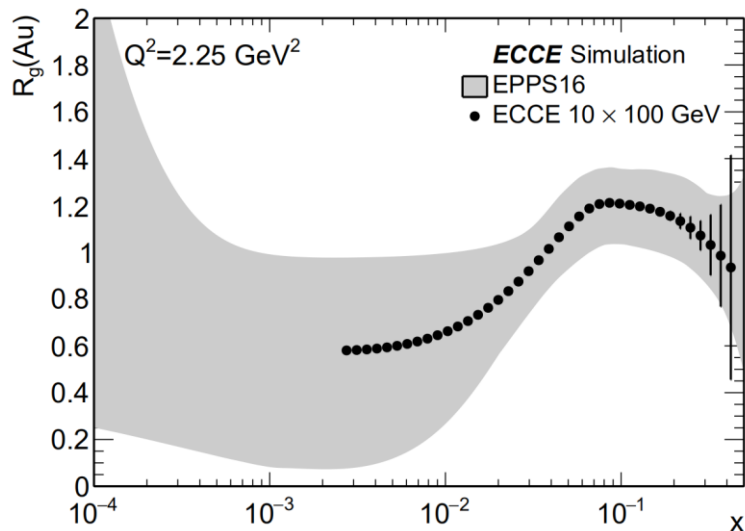


X. Li et al. NIMA **1048** (2023) 167956

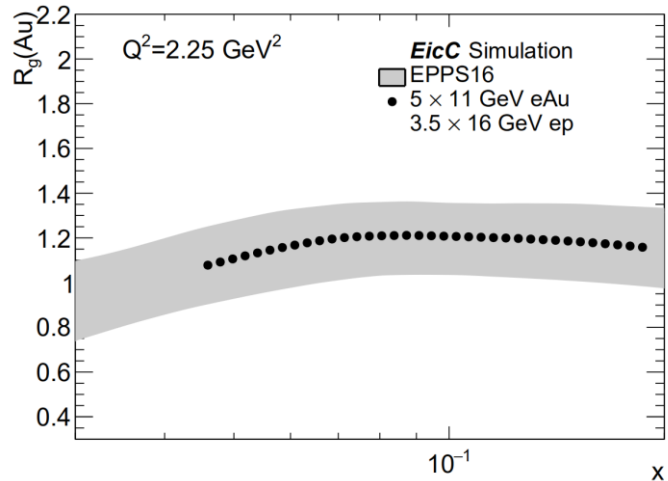
$L_{\text{int}}=50 \text{ fb}^{-1} \text{ ep}; 50/197 \text{ fb}^{-1} \text{ eAu}$



$L_{\text{int}}=100 \text{ fb}^{-1} \text{ ep}; 10/197 \text{ fb}^{-1} \text{ eAu}$

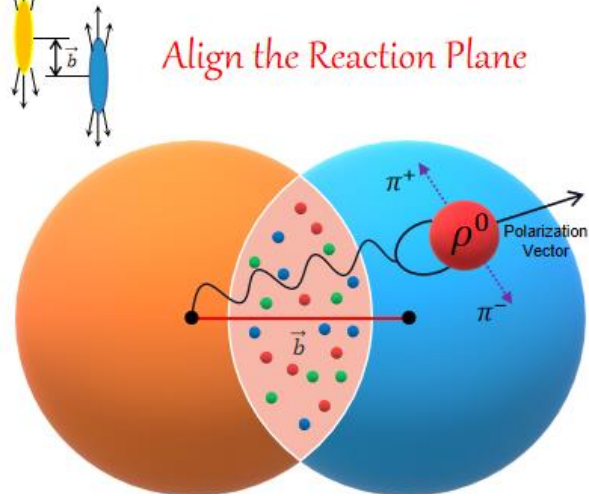


$L_{\text{int}}=20 \text{ fb}^{-1} \text{ eAu}$

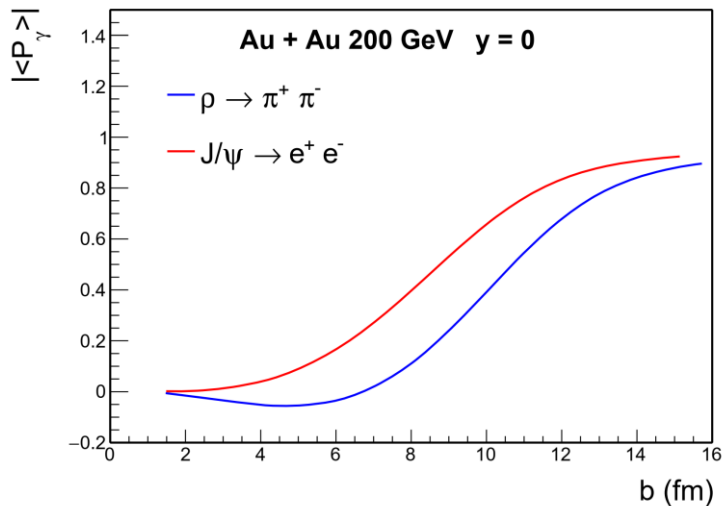
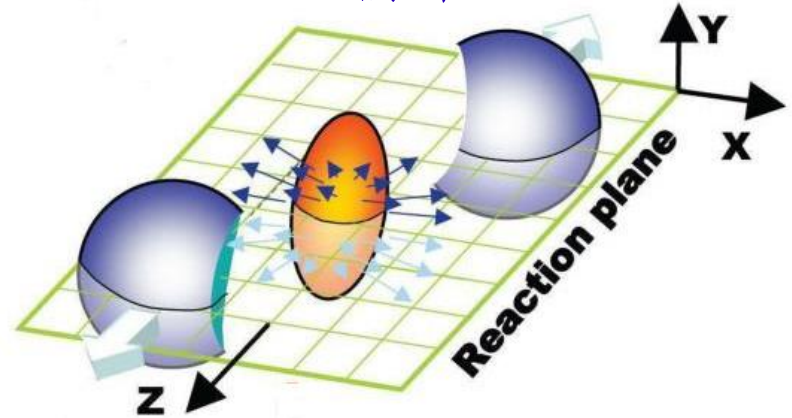


应用：反应平面的确定

X. Wu et al., PRR 4 (2022) L042048

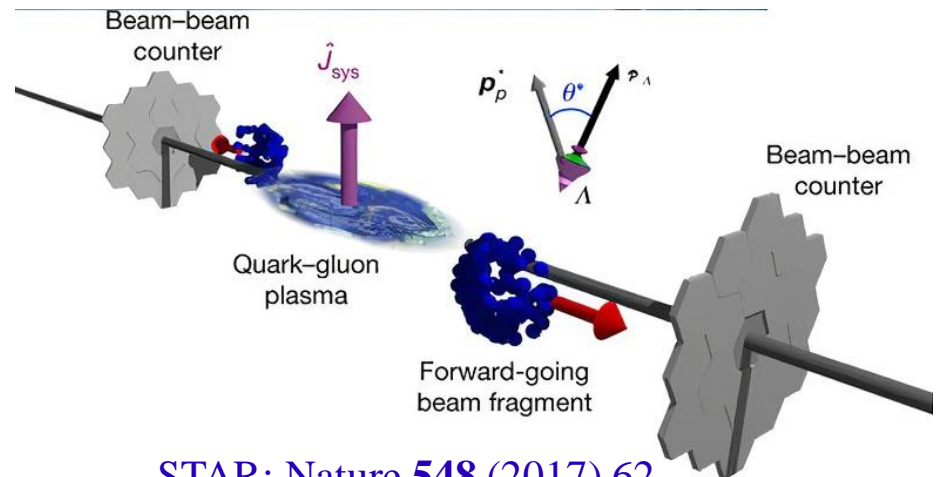


椭圆流



直接联系到反应平面

整体极化

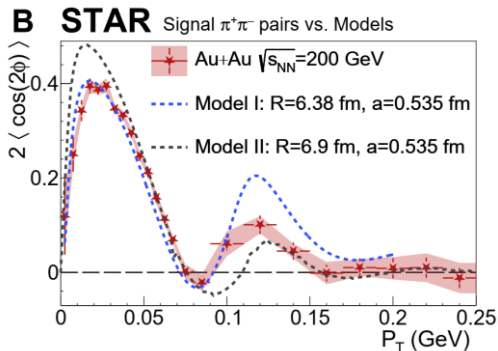
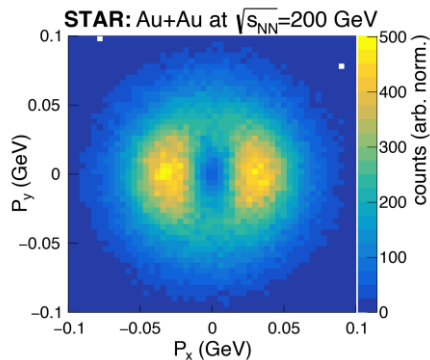


STAR: Nature 548 (2017) 62

总结与展望

□ 在**高能重离子碰撞中实现了费米尺度的双缝干涉实验**

✓ 动量空间和极化空间



□ 路径选择与量子纠缠?

□ 相关应用

✓ 核物质分布成像

✓ 胶子分布函数

✓ 确定初始几何

谢谢各位老师!