



Selected JLab Experiments on QCD

张振宇 武汉大学

量子色动力学的未来：机遇与挑战

北京，北京大学

2019. 11. 10



武汉大学

WUHAN UNIVERSITY



主要内容

- 杰斐逊实验室简介
- A、B、C、D实验大厅QCD相关物理
 - 核结构
 - 核媒质
 - 谱学
- 总结与展望

托马斯·杰斐逊国家加速器装置 (杰斐逊实验室Jefferson Lab)



连续电子束流加速器
(CEBAF)

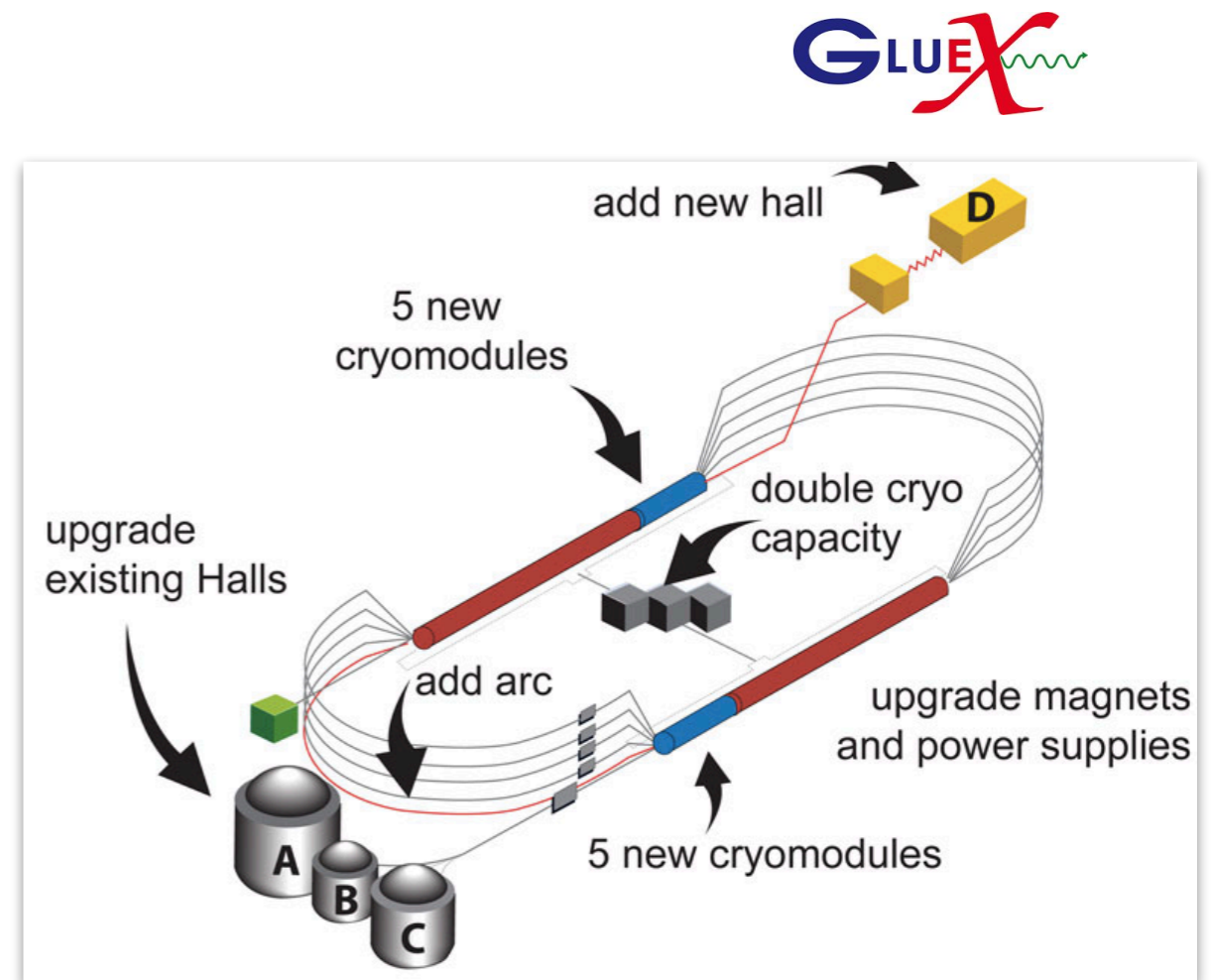


Thomas Jefferson
(1743–1826)

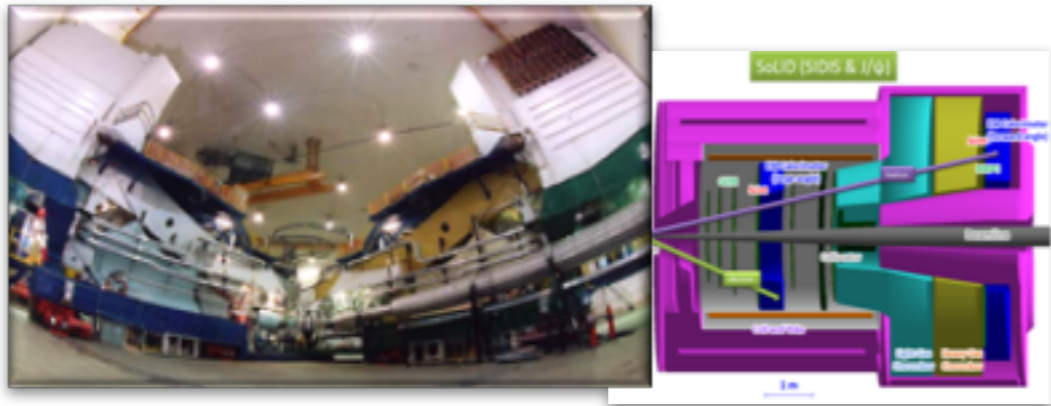
托马斯·杰斐逊国家加速器装置
(杰斐逊实验室Jefferson Lab)

杰斐逊实验室12 GeV升级

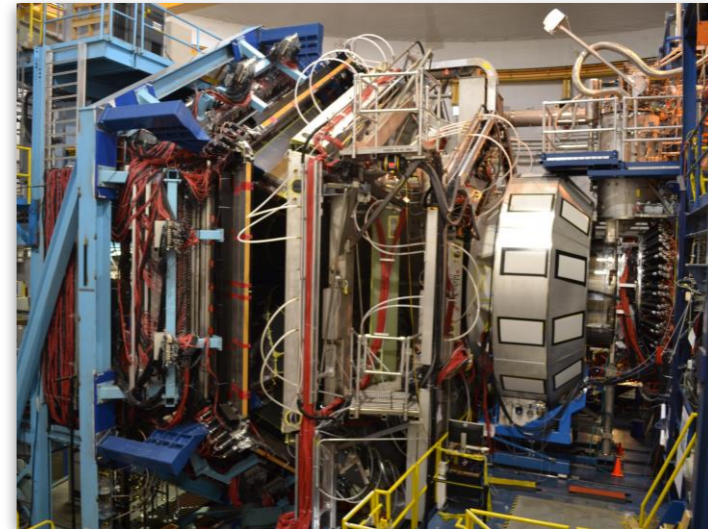
- 2016年2月完成12 GeV升级计划
- 加速器：2.2 GeV/pass
- Halls A, B, C: 1-5 圈加速 <11 GeV
- Hall D: 5.5圈加速 12 GeV
- A、D实验大厅16年春开始取数
- B、C实验大厅17年春开始取数



12 GeV升级科学目标



A实验大厅 – 核结构、形状因子、超核谱等 (HRS), 未来的新实验 (**SoLID** & **MOLLER**)



B实验大厅 – 核结构、核媒质、强子谱等, (**CLAS/CLAS12**)



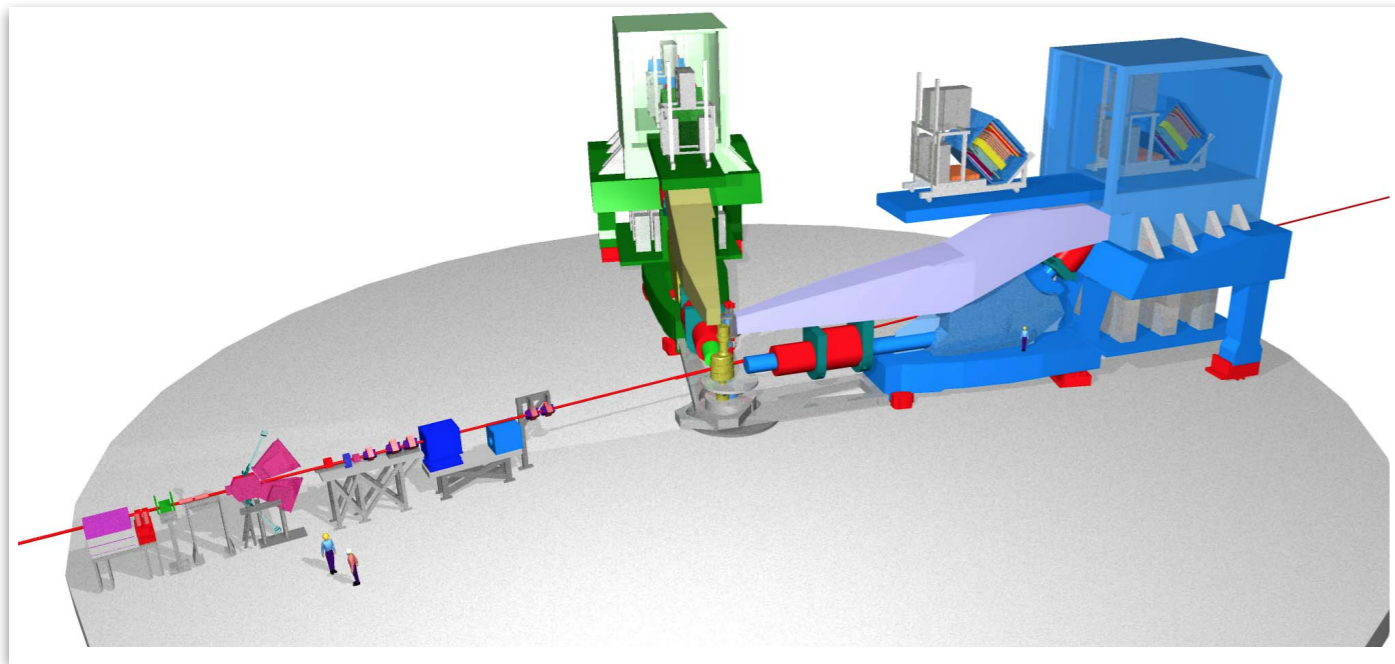
C实验大厅 – 核结构、核媒质 (色透明机制)、粲夸克偶素近阈产生(**J/ψ-007**)等



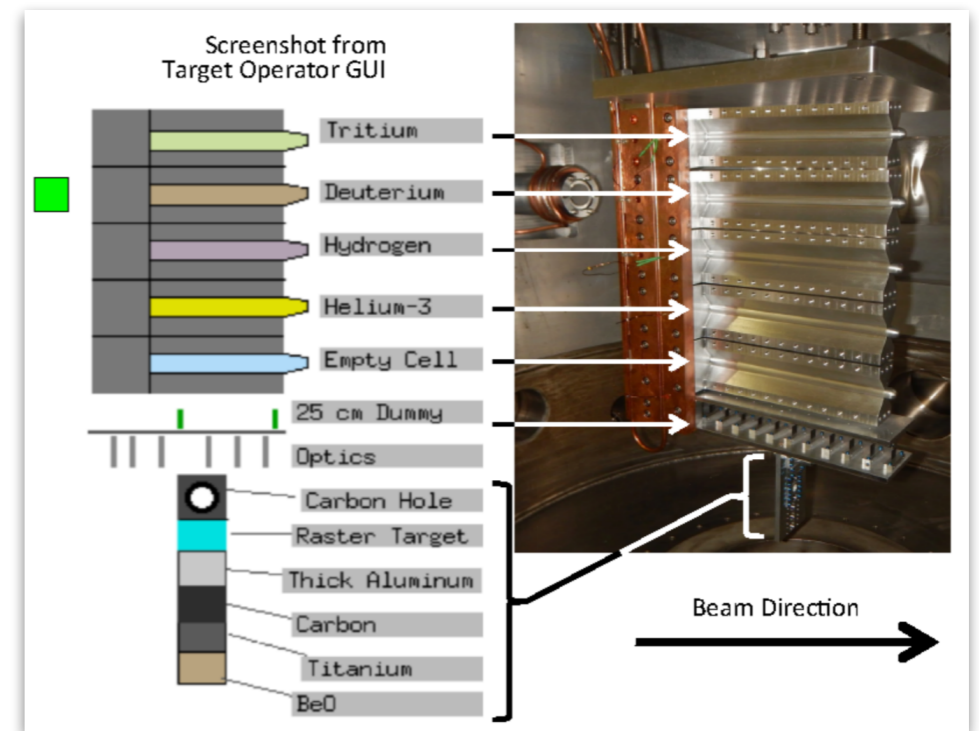
D实验大厅 – 强子谱, 奇特混杂态, 对称性等 (**GlueX**)

核结构、核媒质研究等

Tritium Family & MOLLER & SoLID from Hall A



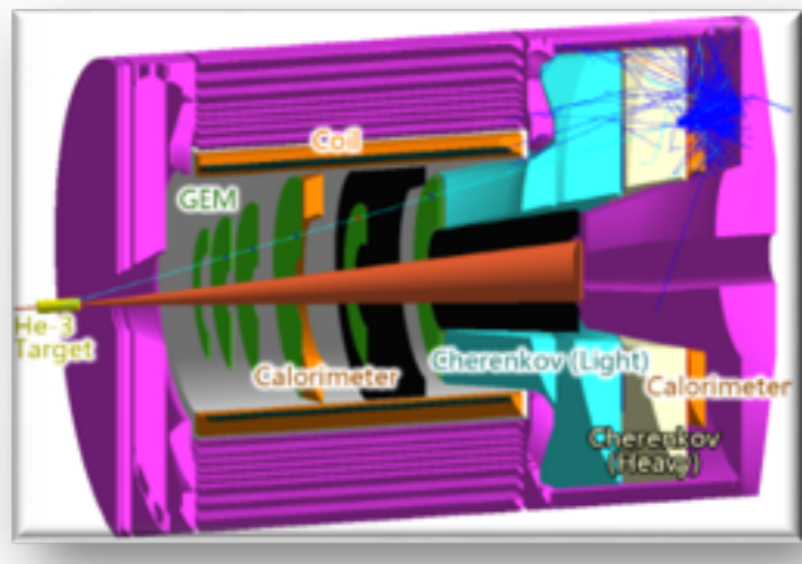
A实验大厅高精度谱仪 (HRS)



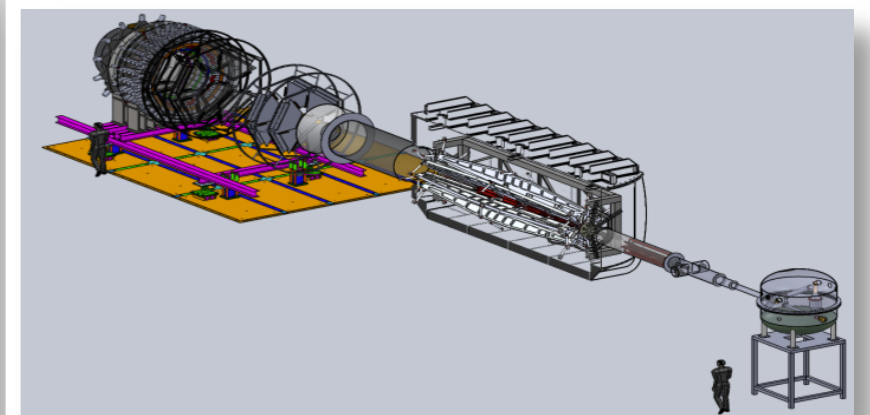
五层靶系统 (Tritium)

- E12-10-103: DIS (MARATHON)
- E12-11-112: Short range correlation
- E12-14-009: Ratio of the electric form factor
- E12-14-011: Proton and Neutron Momentum Distributions
- E12-17-003: Λ -n Interaction

Tritium Family



SoLID

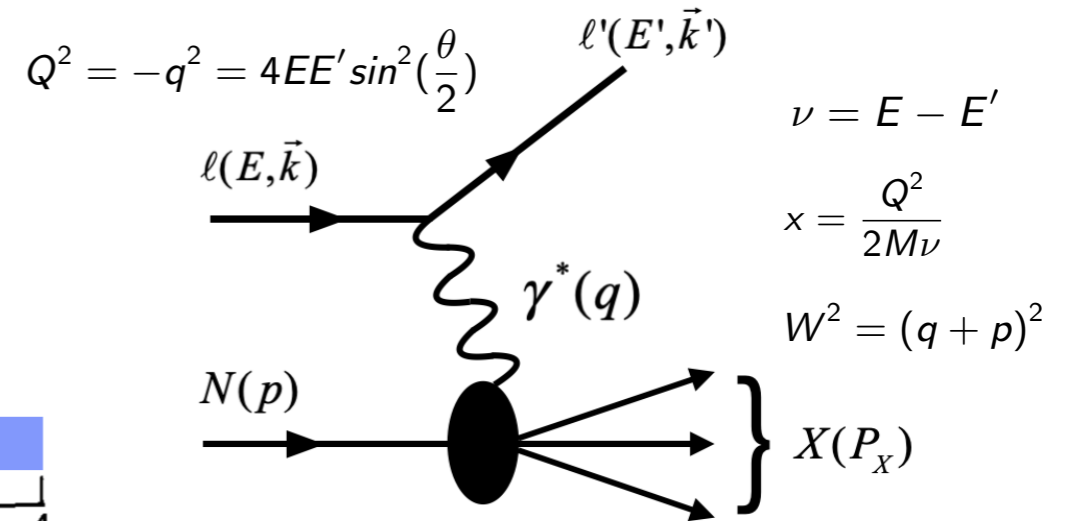
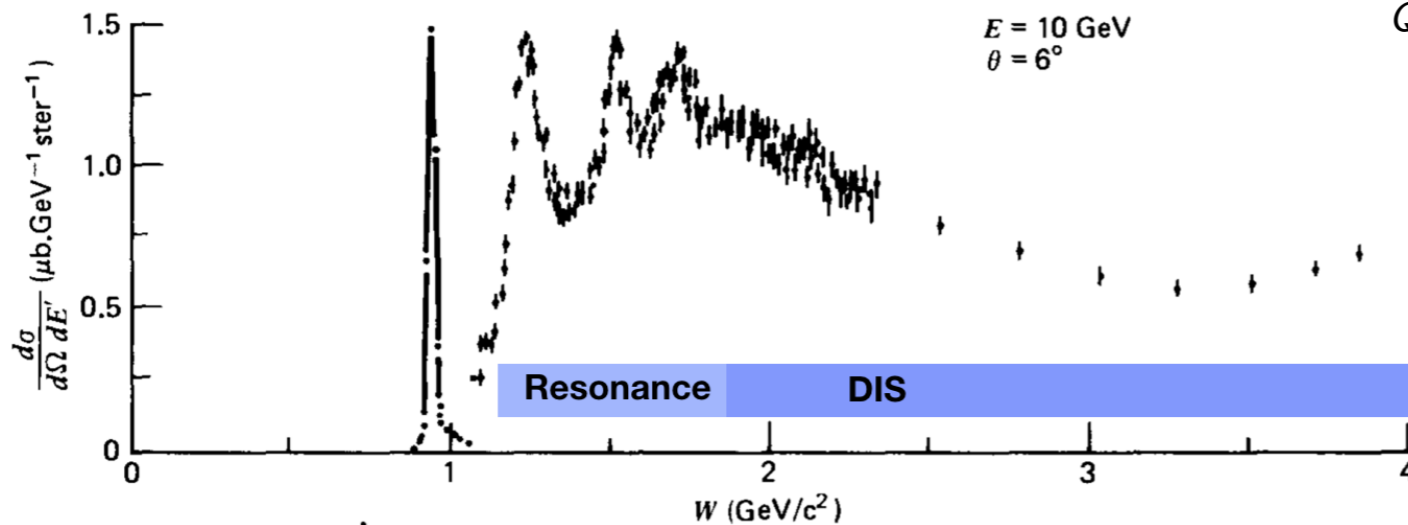
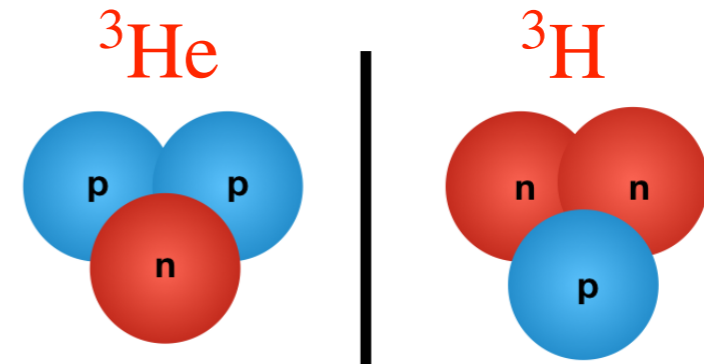


MOLLER

利用镜像靶 ^3H 和 ^3He 探索核子结构

The JLab MARATHON Collaboration from Hall A

- 镜像核在电荷无关的核力下全同
- 研究镜像核性质的差别可以揭示质子和中子的结构信息
- $A=3$ 的镜像核是最简单的镜像系统



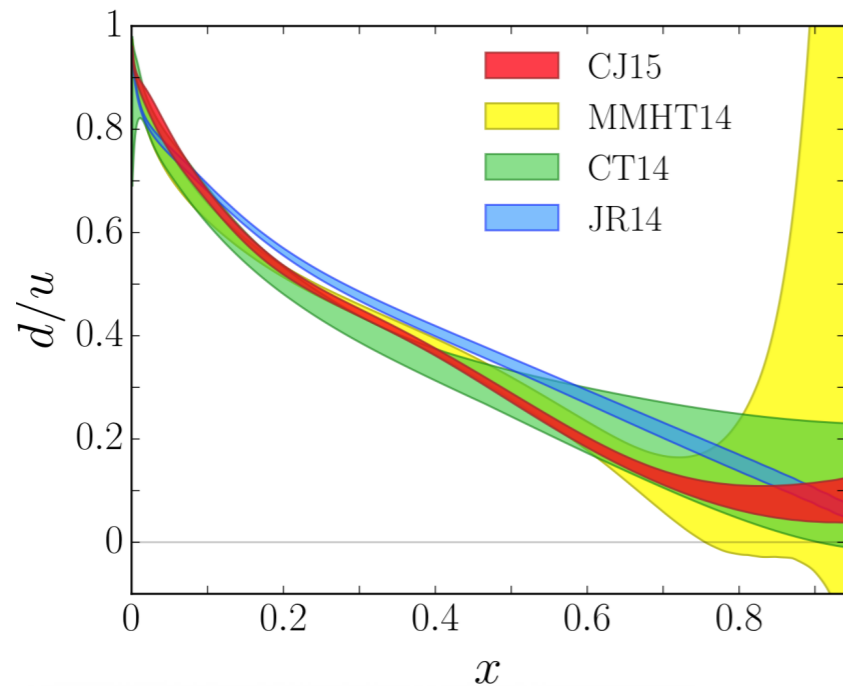
单举深非弹散射过程

- 深非弹：大 W^2 & 大 Q^2
- 单举：仅测量散射电子

Hanjie Liu, MENU 2019, June

利用镜像靶 ^3H 和 ^3He 探索核子结构

The JLab MARATHON Collaboration from Hall A

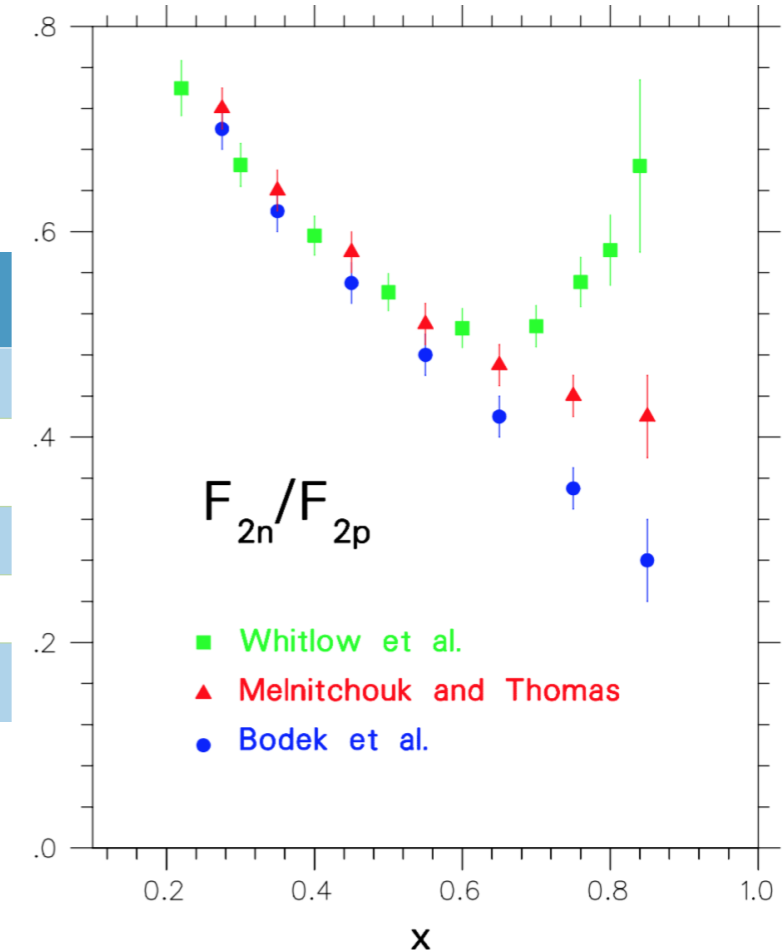


理论上：不同的理论模型给出的核子结构和正反夸克分布比 u/d 的预言不同

实验上：传统通常用氘靶，但氘核的核修正效应模型依赖，不同模型给出的实验测量结果在大 x 下差别较大

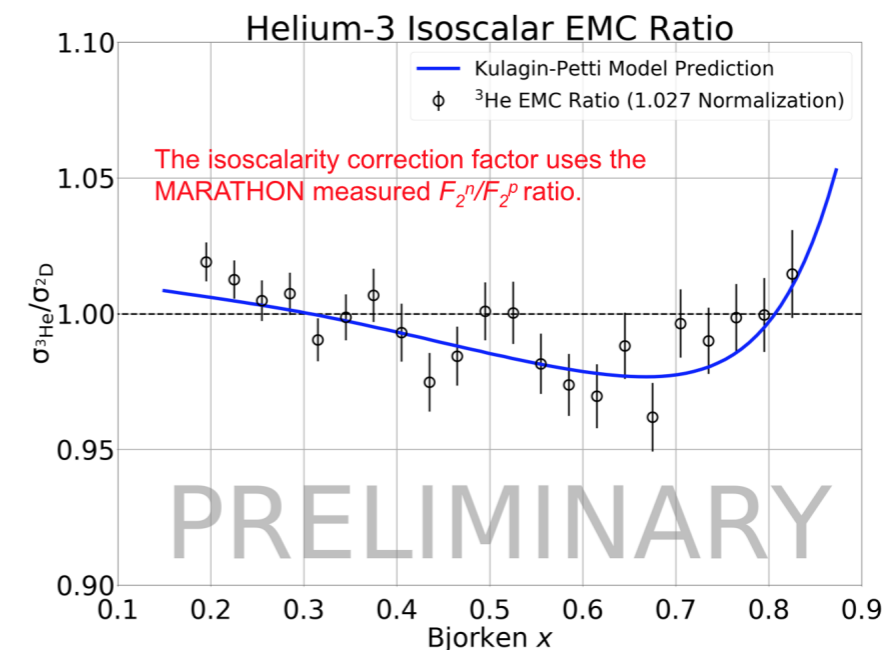
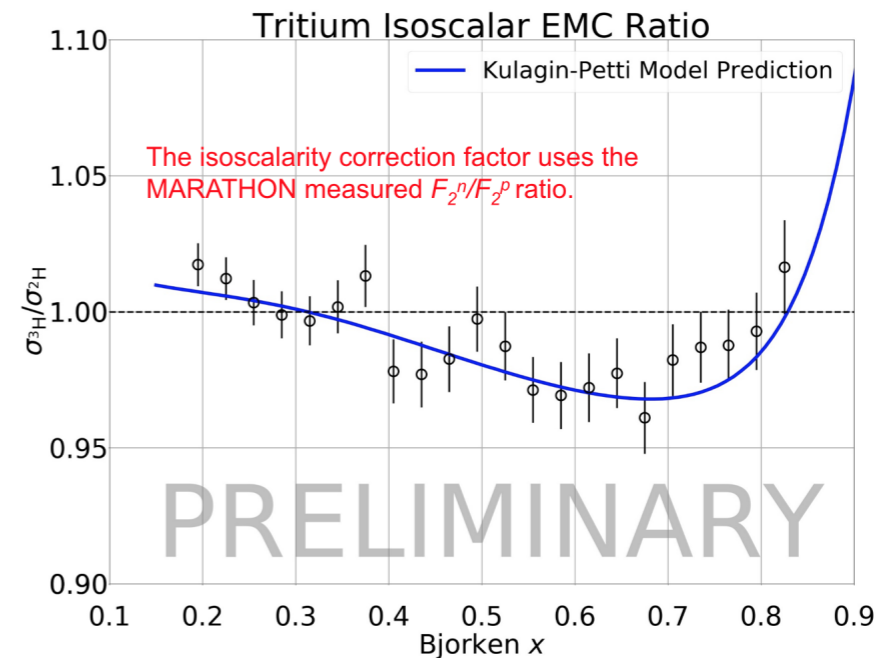
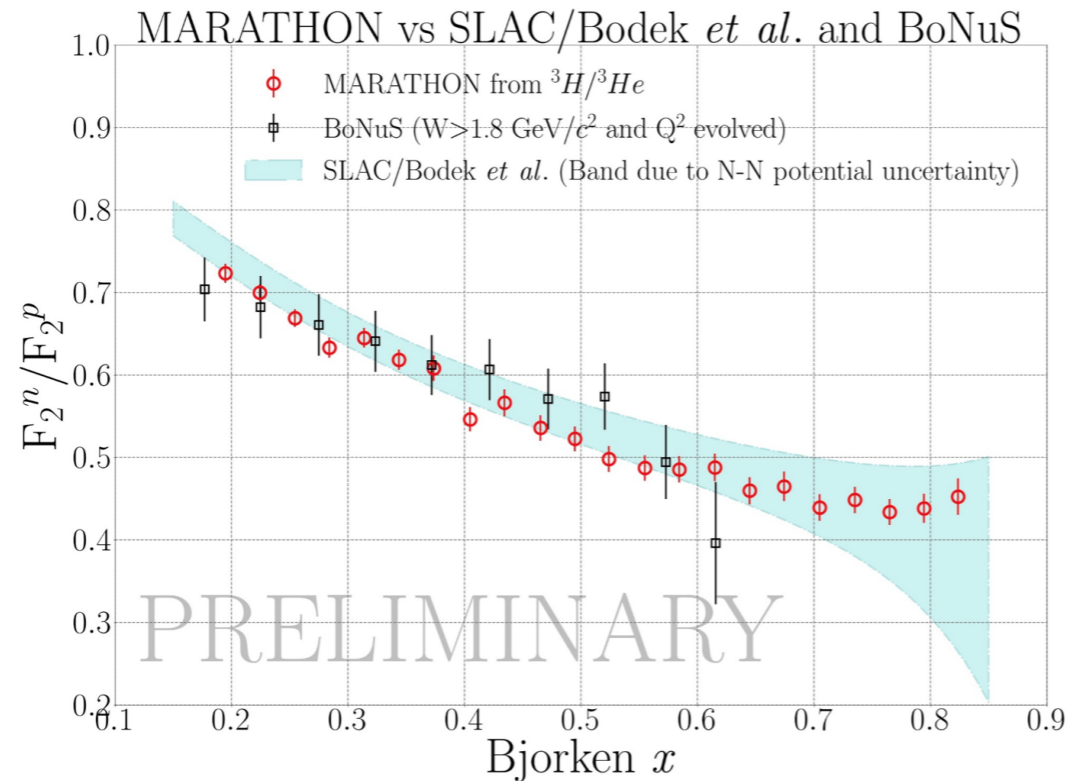
- 测量中子和质子的非弹结构常数 F_2^n/F_2^p
- 测量核子中d夸克和u夸克分布比值 d/u
- 测量 ^3H 与 ^3He 的EMC效应

$x \rightarrow 1$ predictions	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Diquark Model/Feynman	1/4	0
Quark Model/Isgur	1/4	0
Perturbative QCD	3/7	1/5
QCD Counting Rules	3/7	1/5



利用镜像靶 ^3H 和 ^3He 探索核子结构

The JLab MARATHON Collaboration from Hall A



- 给出大 x 下高质量结构常数比值 F_2^n / F_2^p 的测量
- 小 x 下和SLAC数据一致，理论模型依赖的不确定度比SLAC数据小
- 测量了 ^3H 与 ^3He 的EMC效应
- 下一步将移除高扭度贡献，得到d/u结果

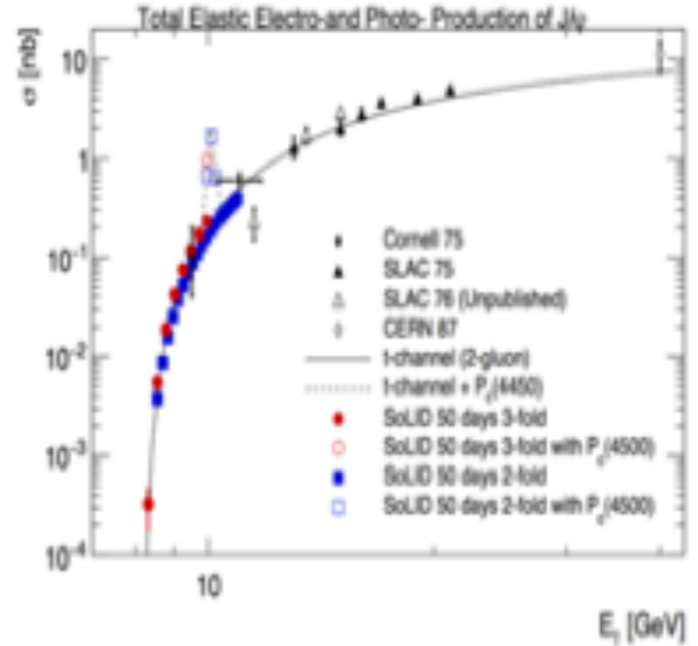
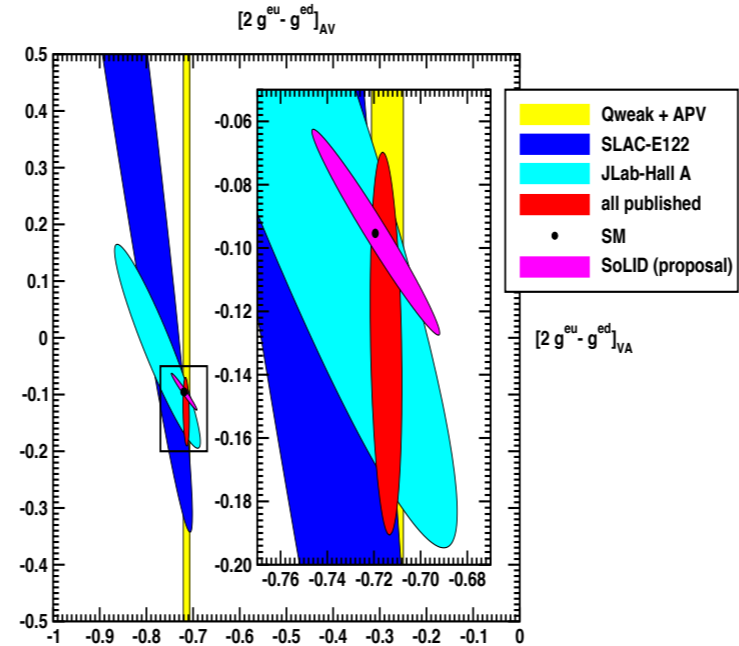
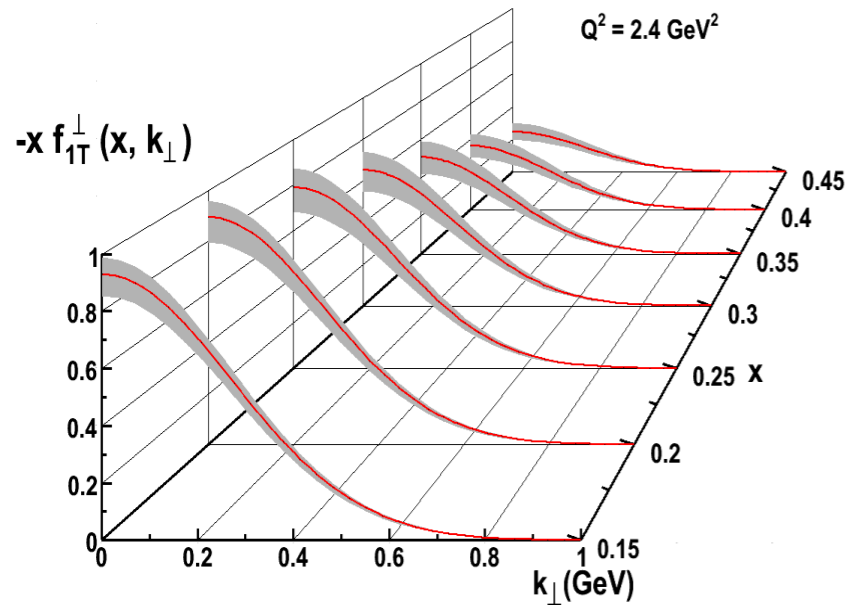
SoLID (Solenoidal Large Intensity Device)

The SoLID Collaboration from Hall A

从双臂到4π

最大程度开发 JLab 12 GeV 升级后的科学目标: **大接收度 & 高亮度** ($10^{37}-10^{39} \text{cm}^{-2}\text{s}^{-1}$)

- 核子三维影像 (中子&质子) : TMD (SIDIS)、GPD 等 (E12-10-006, E12-11-007, E12-10-008)
- PVDIS (氘&氢) : 标准模型检验与强子结构 (E12-10-007)
- J/Psi近阈产生- 探索核子中强色场及其质量起源 (迹反常) (E12-12-006)



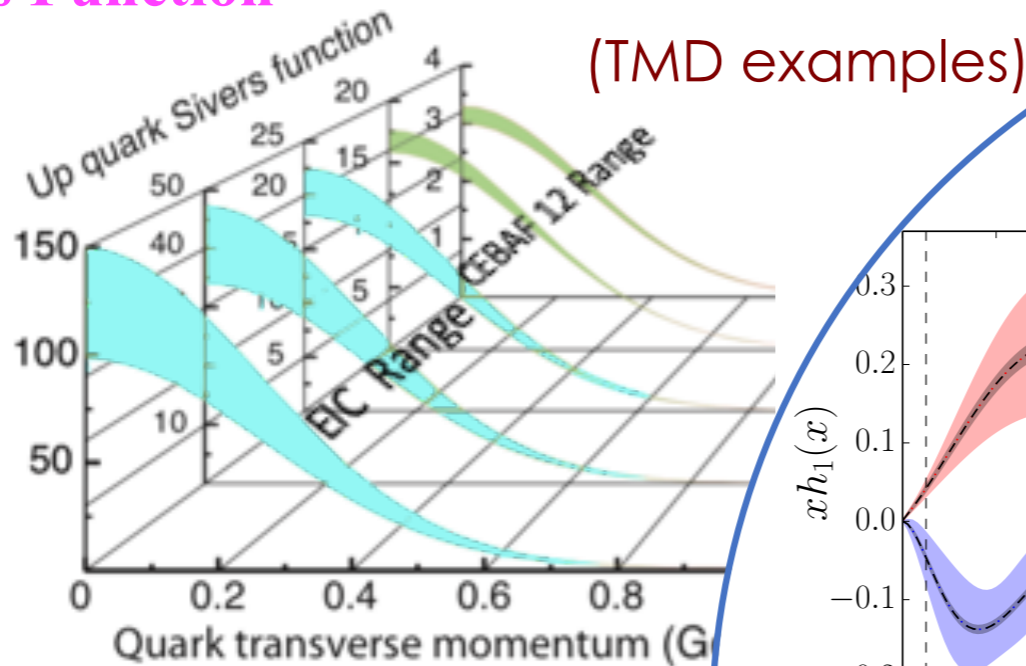
13个国家, 72个单位, 300名合作者 (广泛的国际合作 & 强大的理论支持)

- 2015 LRP recommendation IV
- We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories – **SoLID – mid-scale project**

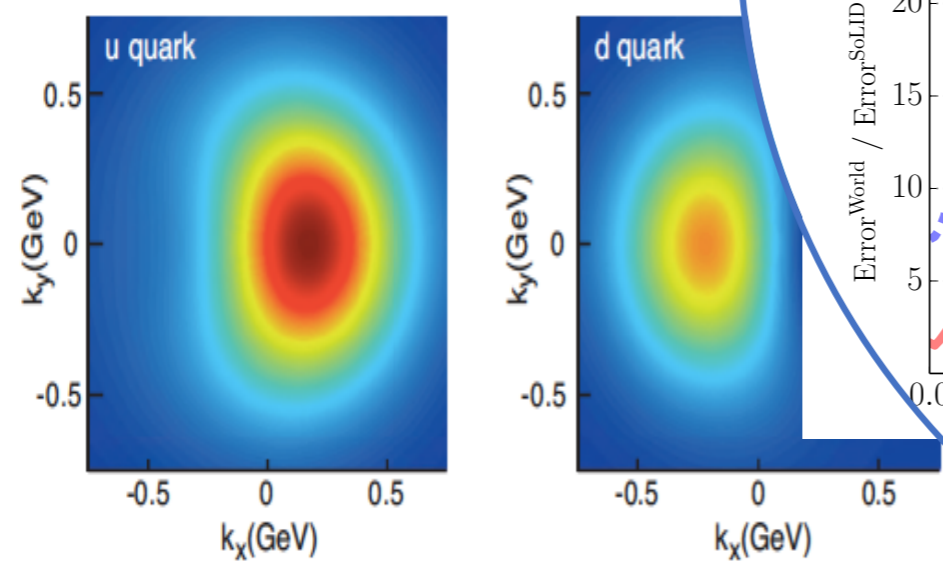
SoLID: 通往EIC的桥梁

SIDIS program of SoLID

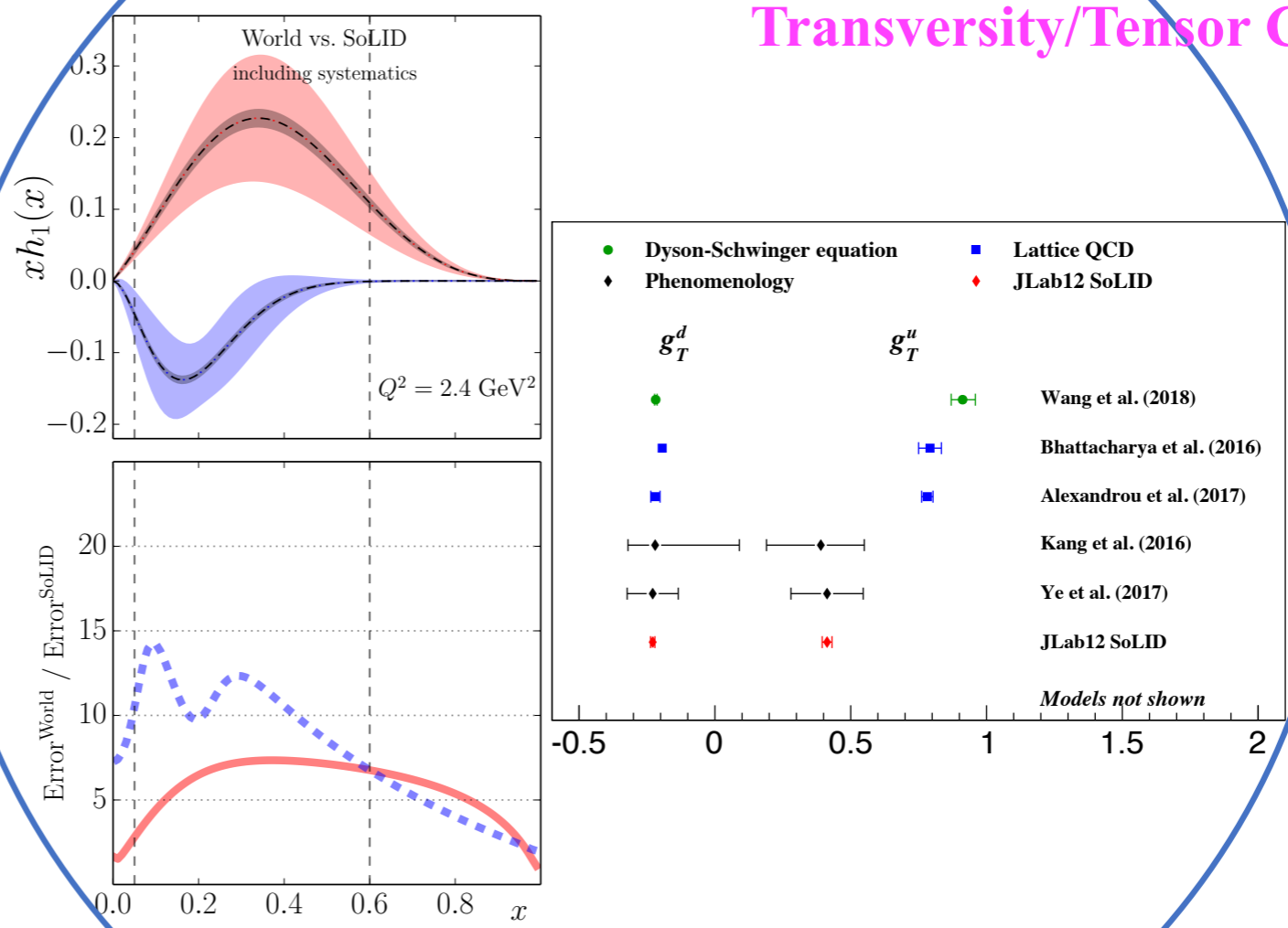
Sivers Function



Polarized Quark 3D Momentum d



Transversity/Tensor Charge

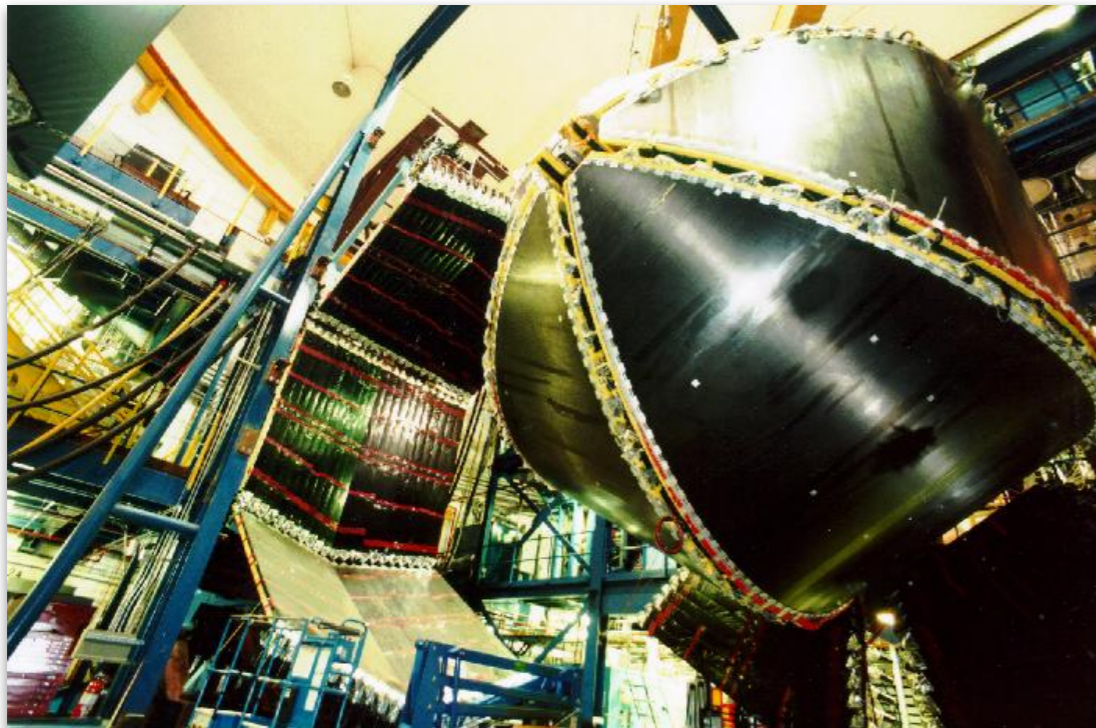


Transversity: valence quark effect

核结构与谱学研究

The CLAS/CLAS12 Collaboration from Hall B

CLAS数据分析结果在发表



- Modified structure of protons and neutrons in correlated pairs, Nature **566**, 354–358 (2019).
EMC模型与短程关联 (SRC)
- First Measurements of the Double-Polarization Observables F , P , and H in ω Photoproduction off Transversely Polarized Protons in the N^* Resonance Region, PRL **123**, 032502 (2019).
- Exploring the Structure of the Bound Proton with Deeply Virtual Compton Scattering, PRL **123**, 032502 (2019).

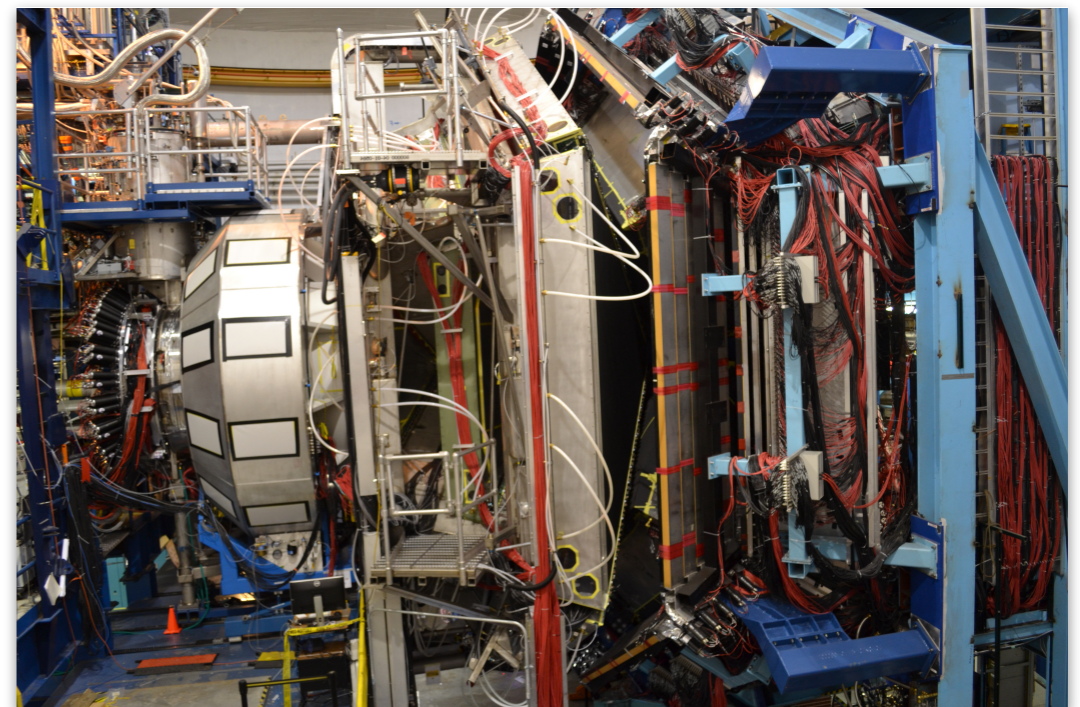
CLAS12数据在采集: Group A、K、B

物理目标

- ◆ 核子的多维结构: 形式因子、PDFs、GPDs 及TMDs
- ◆ 夸克强子化、色透明机制、短程关联等
- ◆ 介子及重子谱研究

其他实验

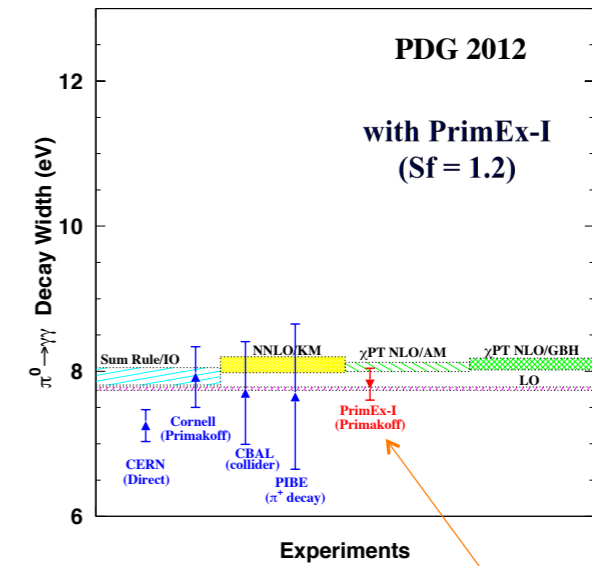
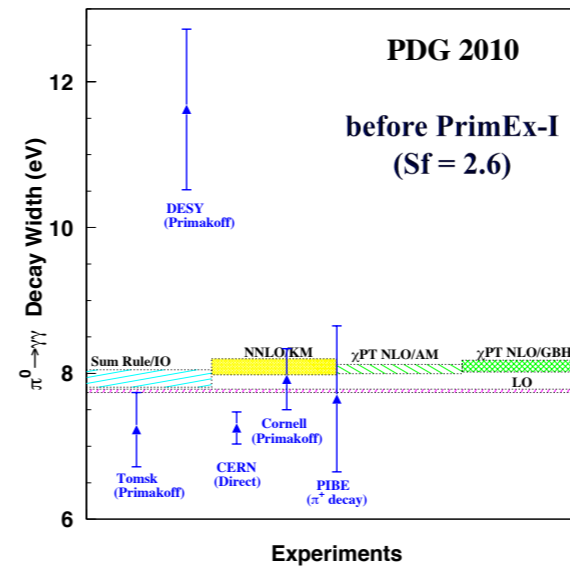
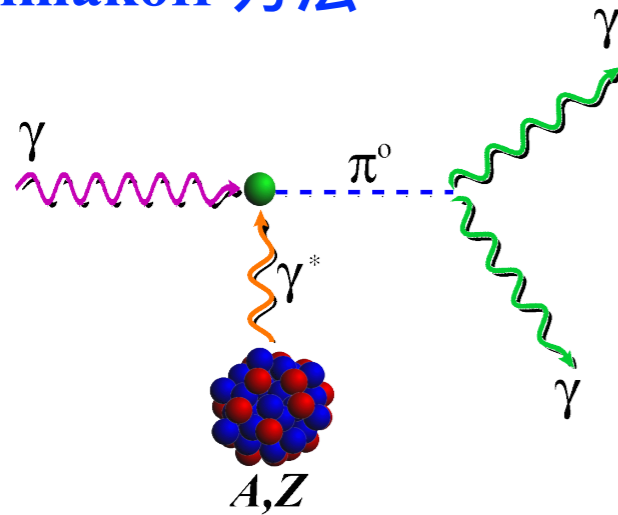
- ◆ Heavy Photon Search (HPS)
- ◆ PrimEx
- ◆ RadPhi
- ◆ g5



低能 QCD 对称性和 π^0 寿命

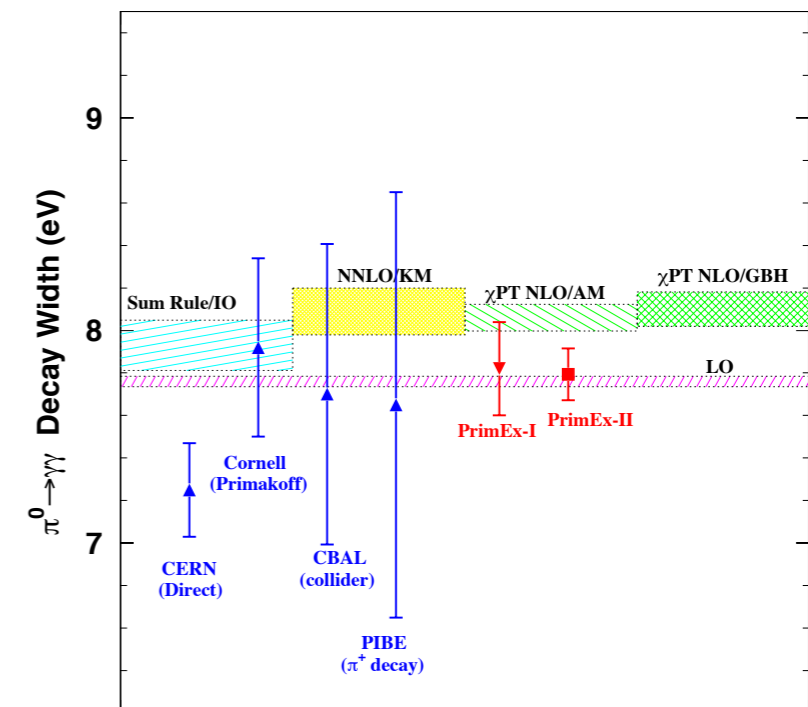
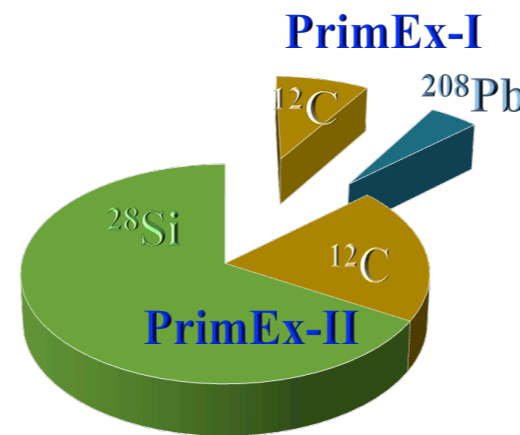
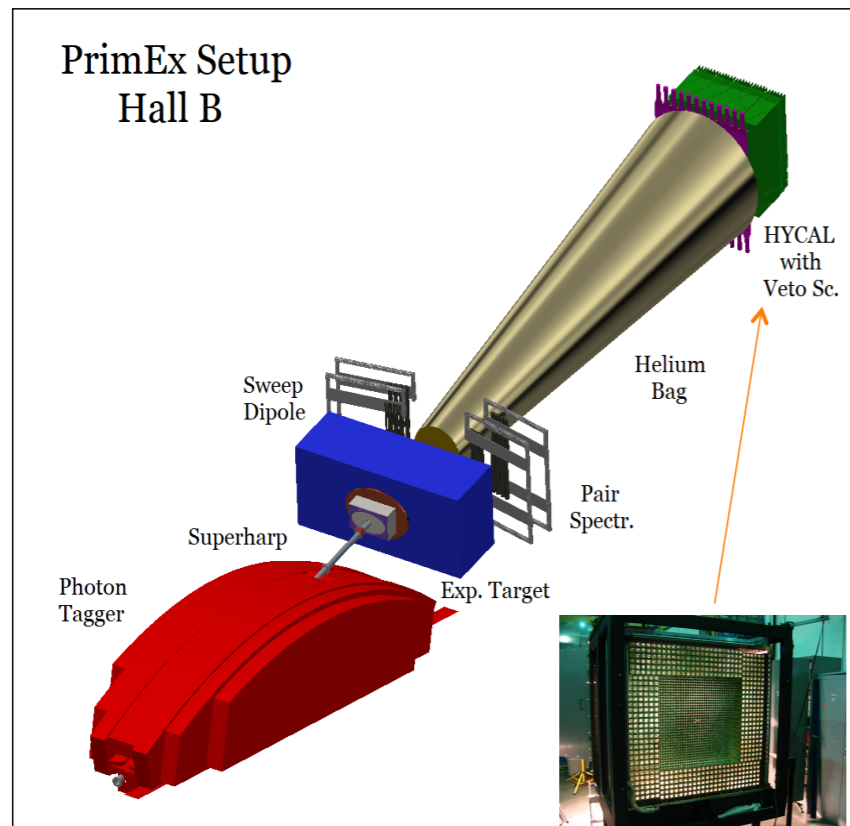
The PrimEx Collaboration from Hall B

Primakoff 方法



$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.82 \pm 0.14(\text{stat}) \pm 0.17(\text{syst}) \text{ eV}$
2.8% total uncertainty

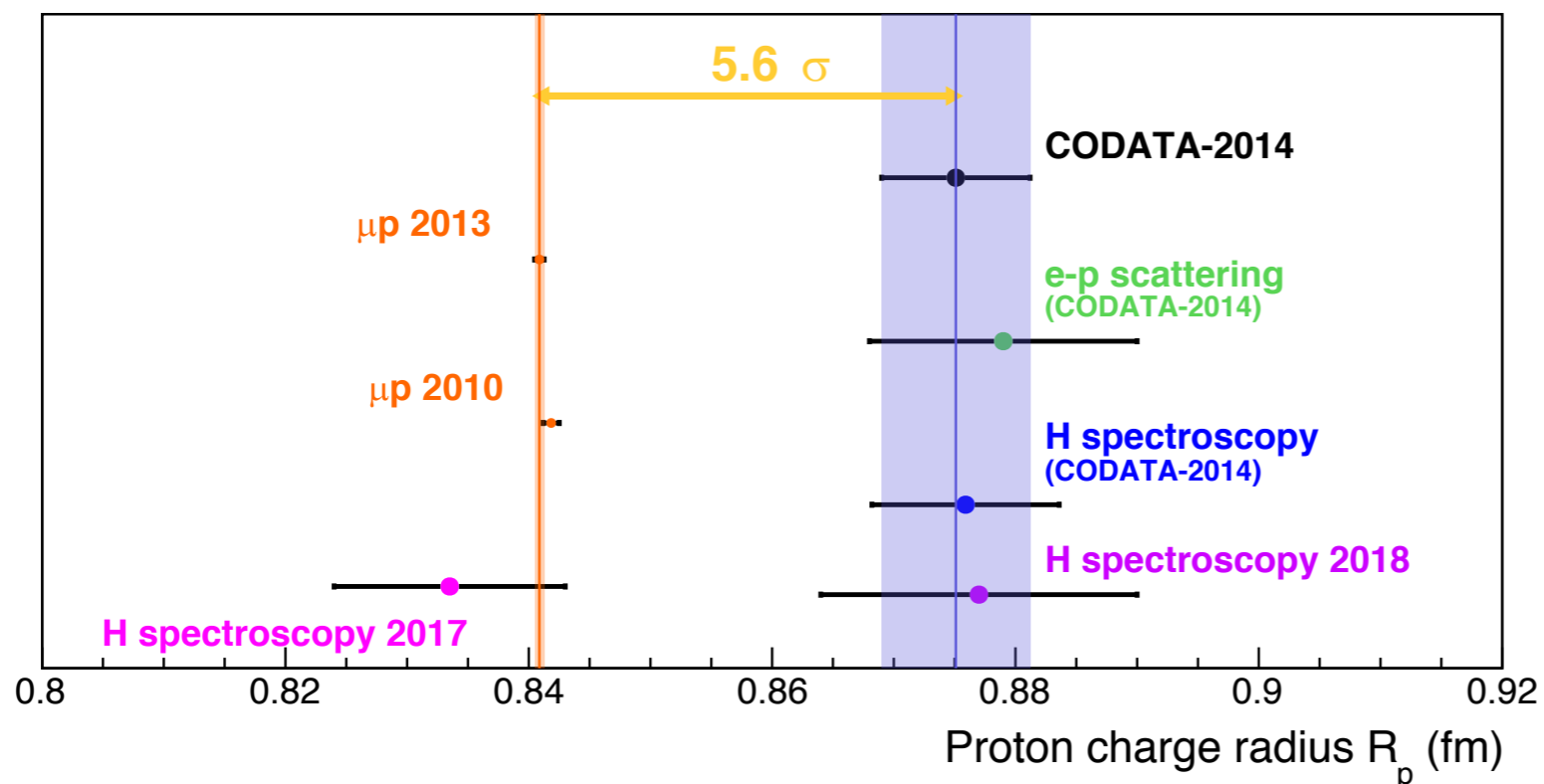
PRL 106, 162303 (2011)



质子电荷半径疑难

The PRad Collaboration from Hall B

● 测量质子的电荷分布



Xiong, W. et al., Nature
575, 147-150 (2019)



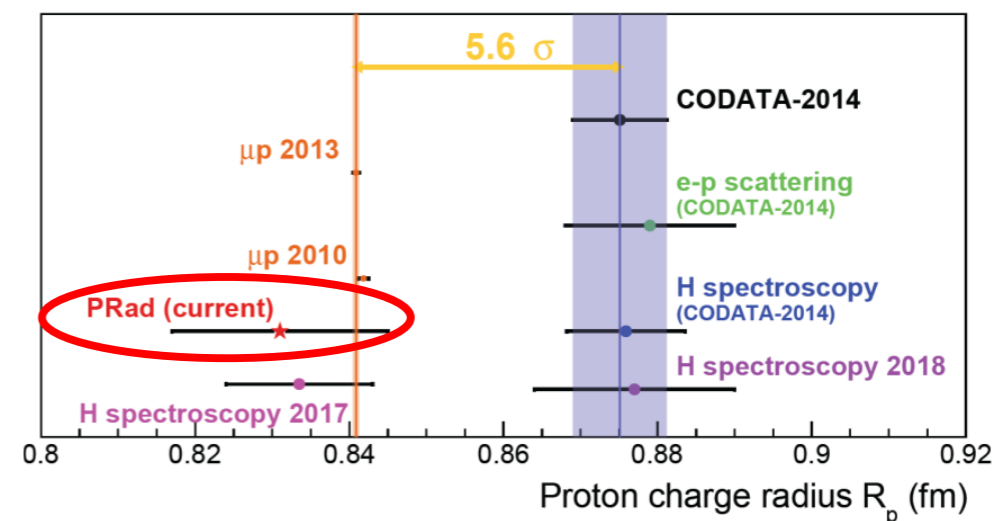
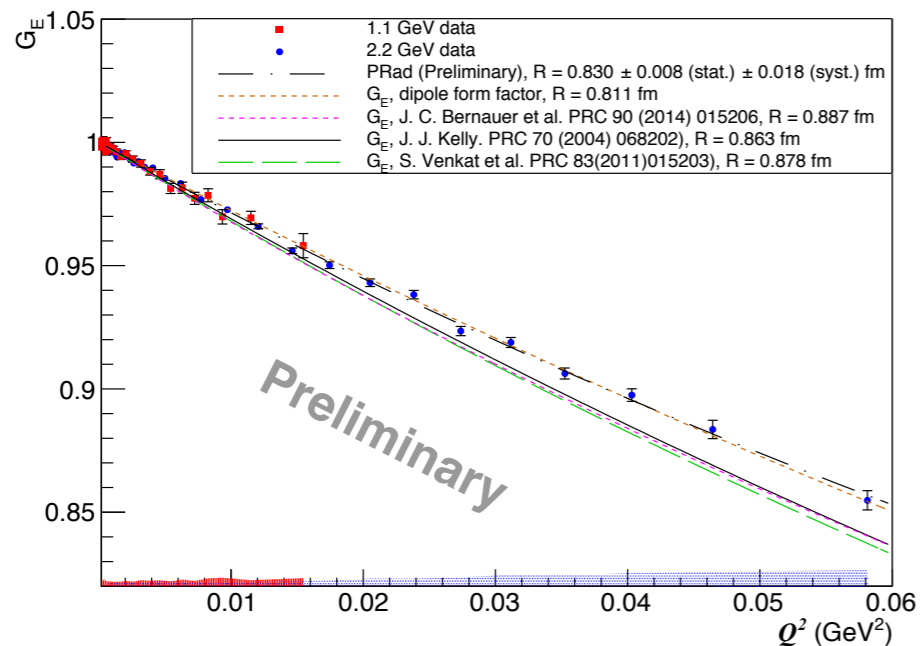
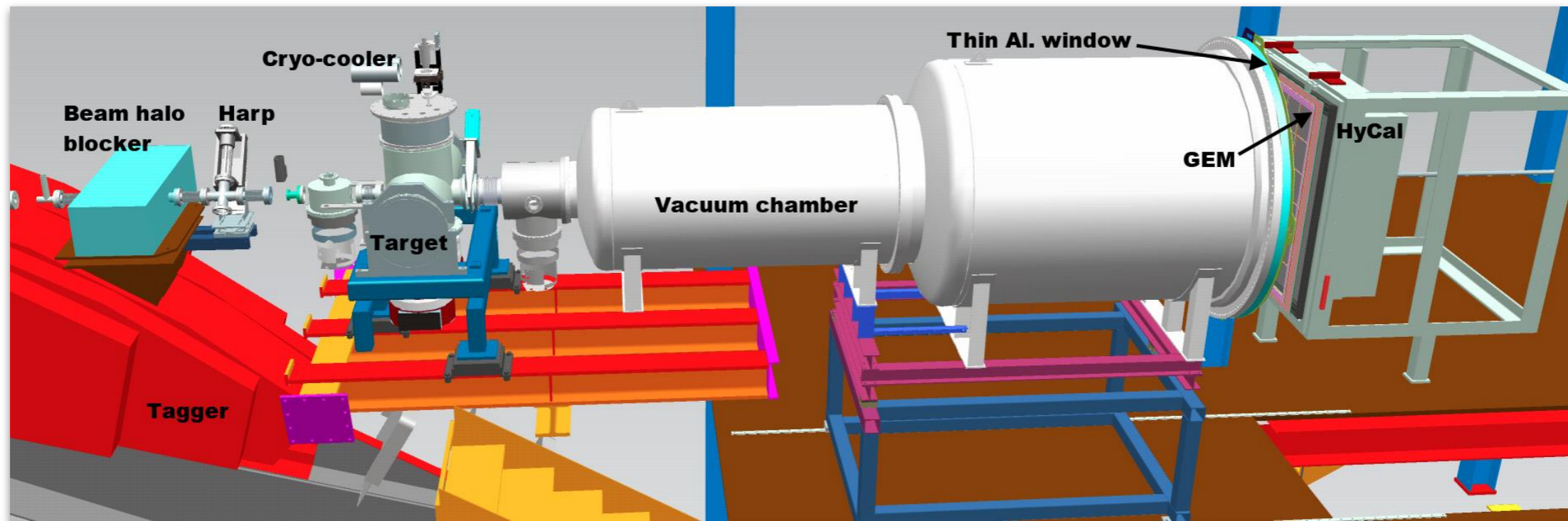
How big is the proton? Particle-size puzzle leaps closer to resolution
Precise measurement affirms that particle's radius is smaller than physicists once thought.

- 电子散射: 0.879 ± 0.011 fm (CODATA 2014)
- μ 子散射: 0.8409 ± 0.0004 fm (CREMA 2010, 2013)
- H谱 (2017) : 0.8335 ± 0.0095 fm (A. Beyer et al. Science 358 6359 (2017))
- H谱 (2018) : 0.877 ± 0.013 fm (H. Fleurbaey et al. PRL 120 183001 (2018))

- 2010年前两种主要测量方法：电子与质子的散射或兰姆位移，基本相符，结果约在0.877fm
- 2010年，新的测量方法，测量了由质子和 μ 子构成的 μ 原子的兰姆位移
- μ 子比电子距离质子更近，使得测量更准确，大约在0.842fm，与之前的结果差别达到5.6 σ
- 近十年间不同实验组不同实验方法多次反复测量质子电荷半径

质子电荷半径疑难

The PRAD Collaboration from Hall B

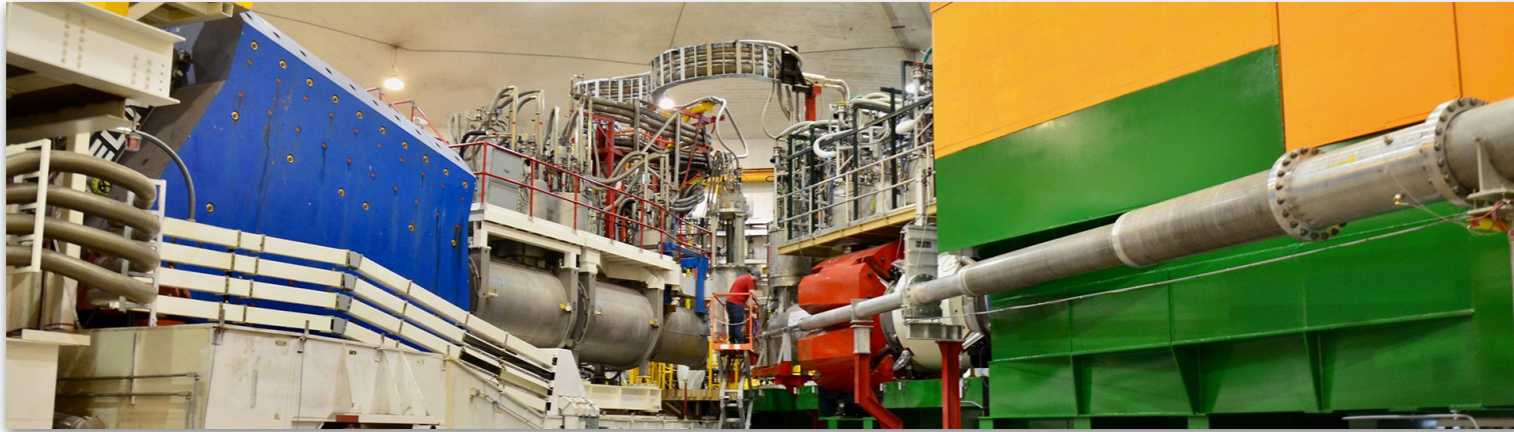


PRad R_p (current) = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

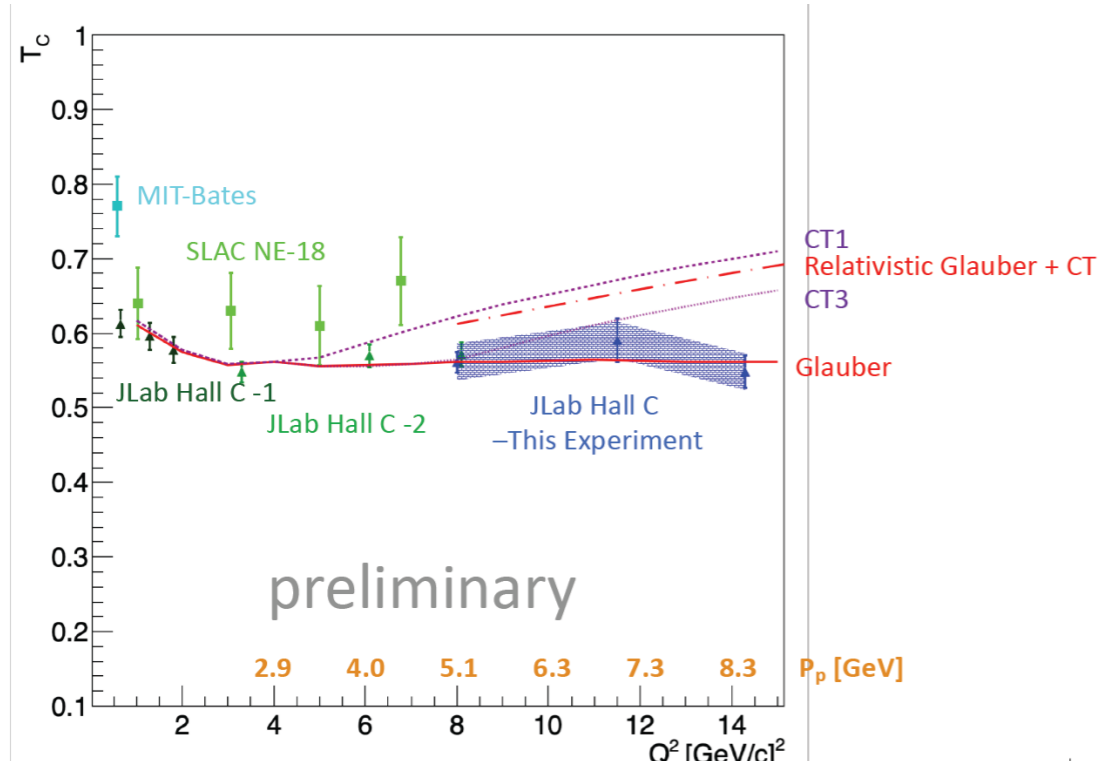
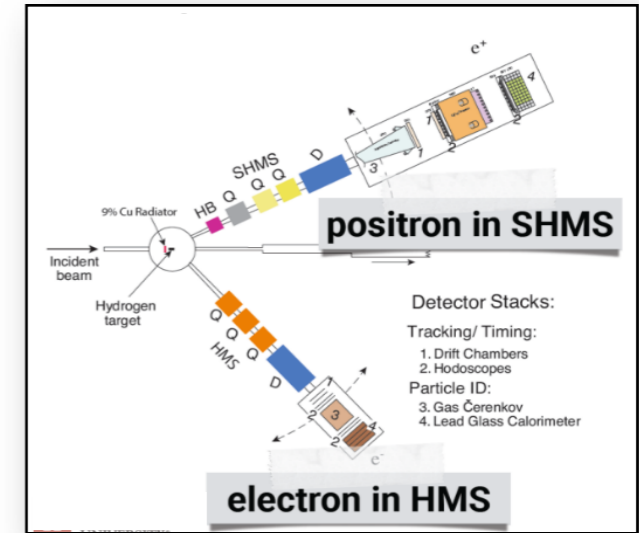
Xiong, W. et al., Nature 575, 147-150 (2019)

粲偶素近阈产生等

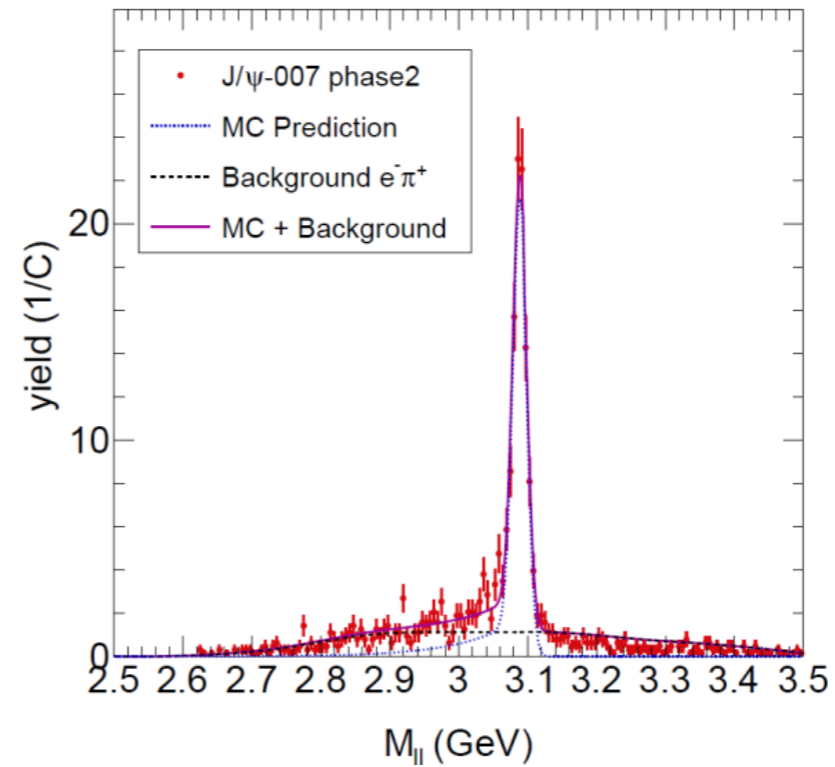
J/ Ψ -007 etc. from Hall C



HMS+SHMS



色透明机制测量

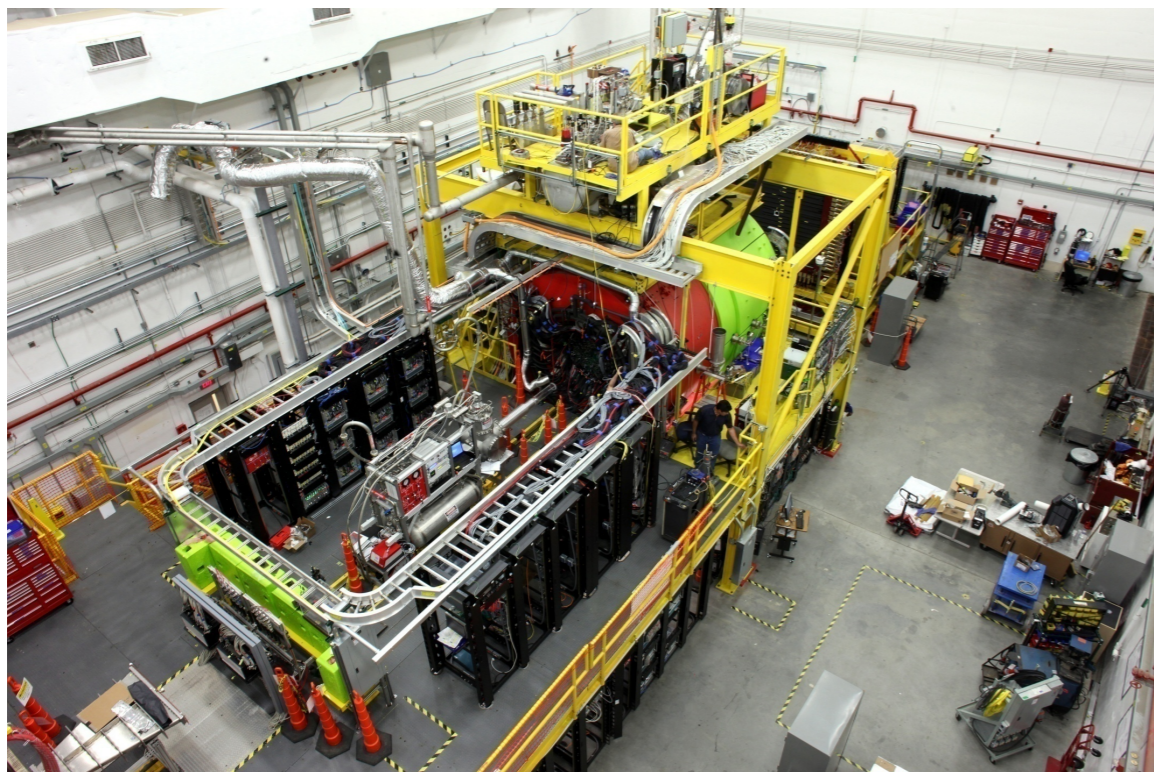


J/ Ψ 近阈产生

S. JOOSTEN, 2019 Hadron-China

强子谱学与奇特混杂态的寻找

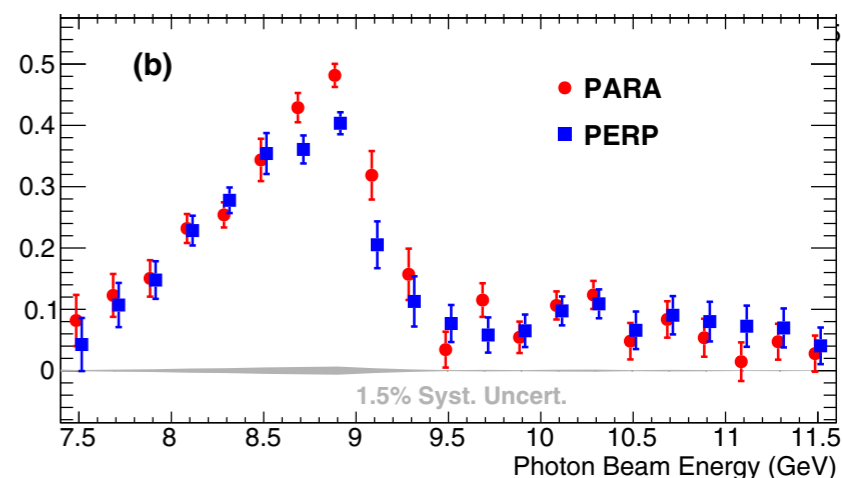
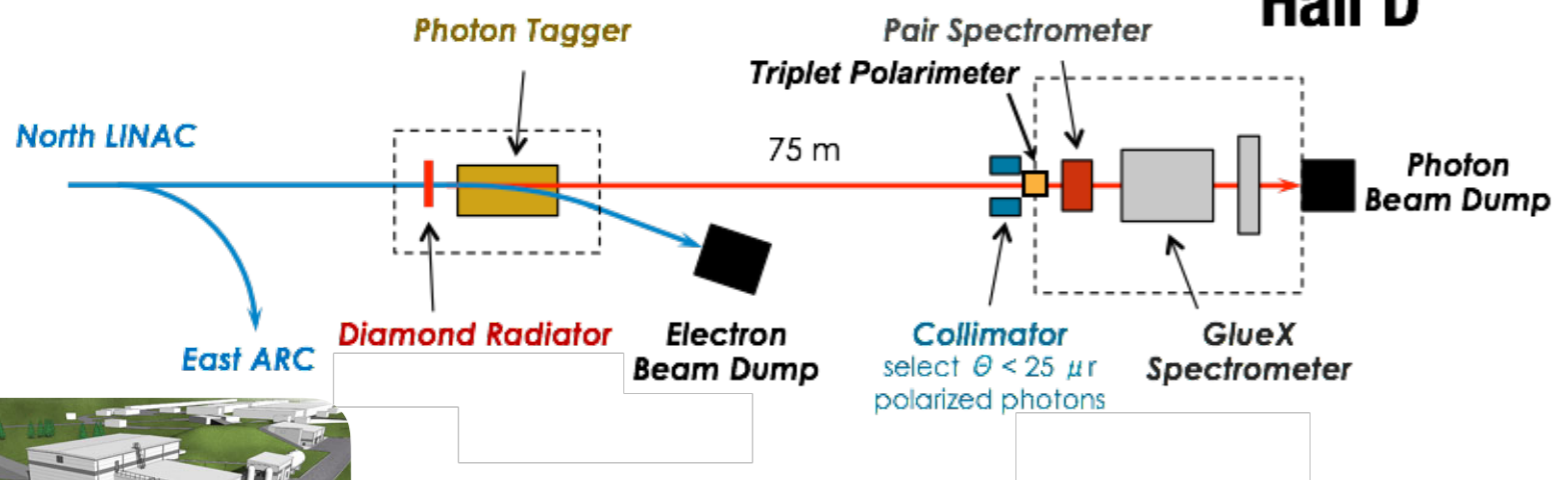
The GlueX Collaboration from Hall D



- 寻找奇特混杂态 (分波分析)
- 轻强子光产生过程及束流不对称度测量
- 自旋密度矩阵元理解产生机制
- 散射截面测量
- 广义部分子分布函数GPD

电子打钻石产生极化 γ 光子
极化 γ 光子轰击液氢靶

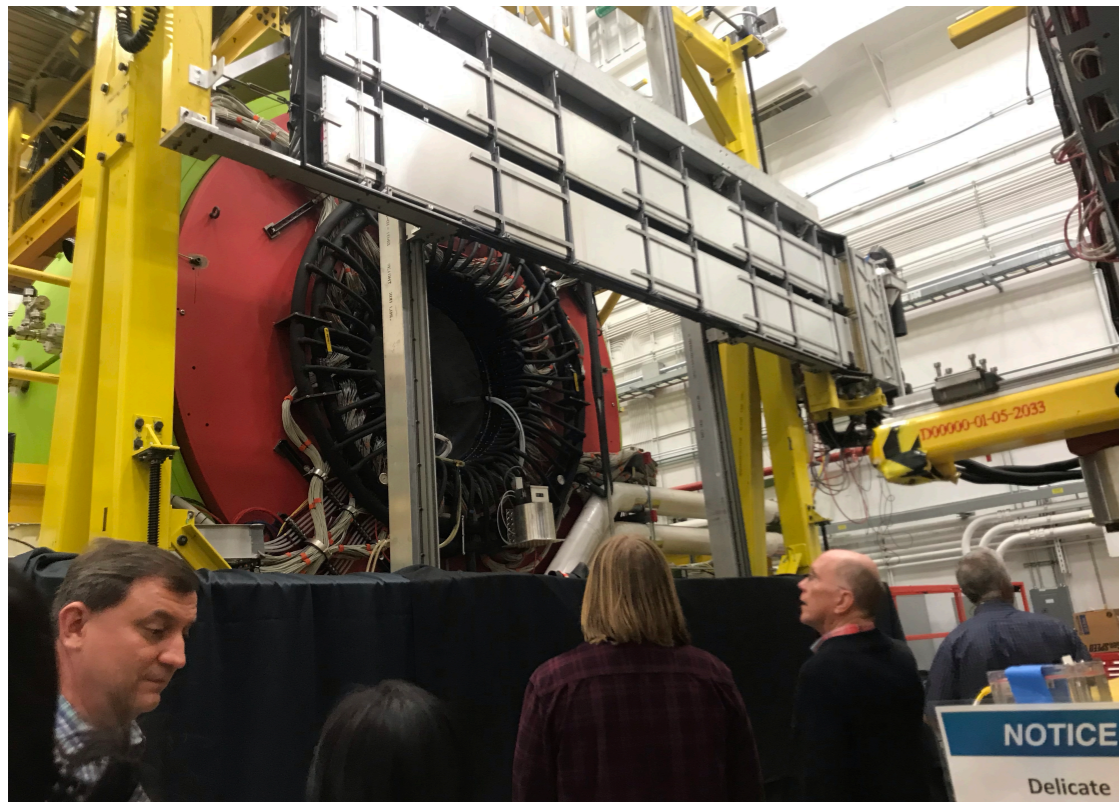
Hall D



PHYS REV C 95, 042201(R) (2017)

Hall D 硬件升级

The GlueX Collaboration from Hall D



DIRC 升级, 提高K/ π 鉴别能力
2 GeV \rightarrow 4 GeV

Proposal for JLab PAC45 [hep-ex] arXiv:1707.05284

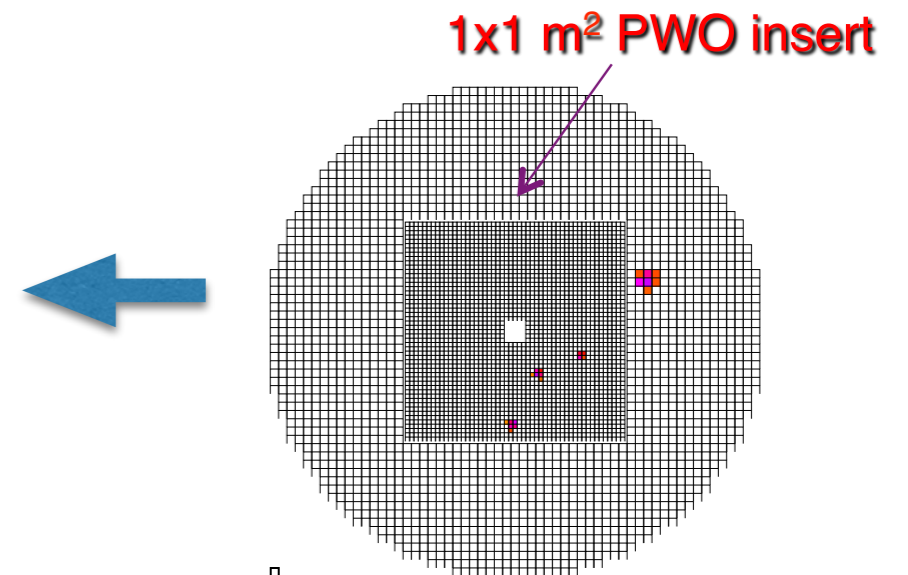
Strange Hadron Spectroscopy with a Secondary K_L Beam at GlueX

前向量能器升级(FCAL-II):

探测 η 衰变中多光子末态

PrimEx- η : η radiative decay width

JEF: Leptophobic B, CVPC, ChPT and the quark mass ratio

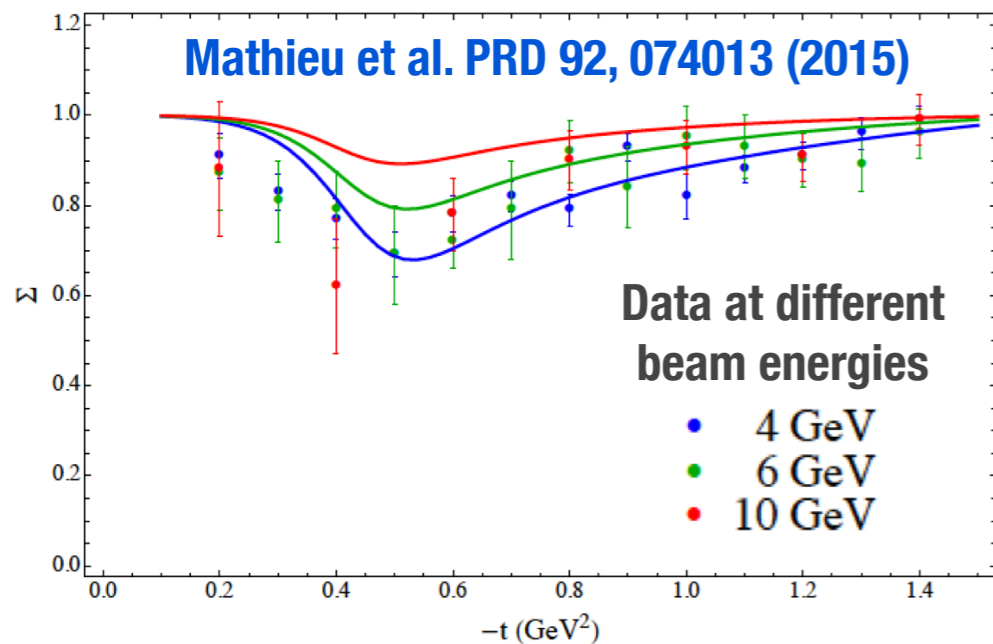
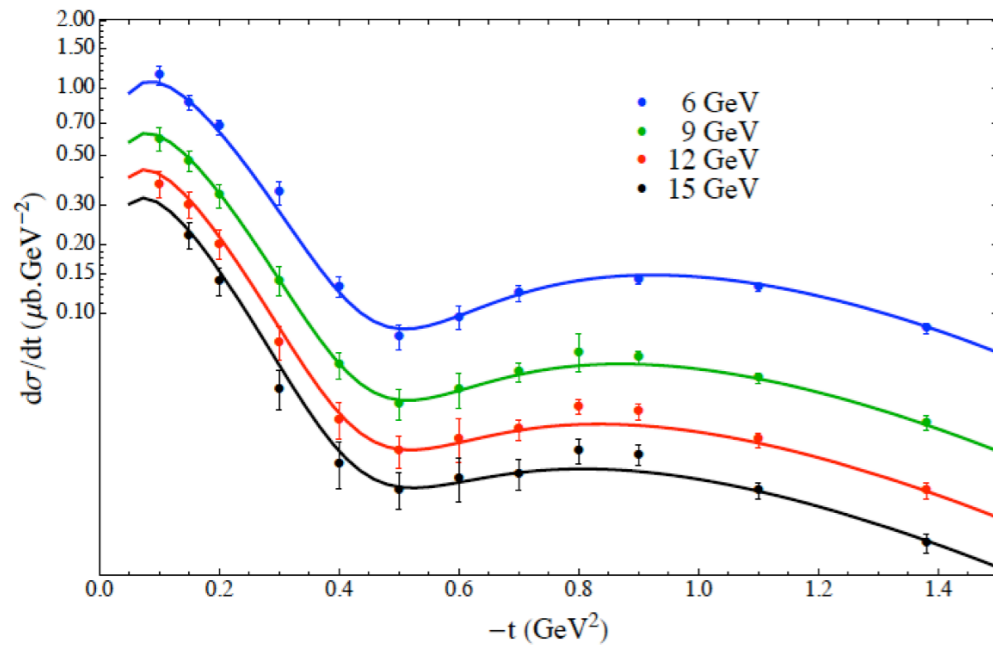


中间插入高精度、高颗粒度PWO晶体

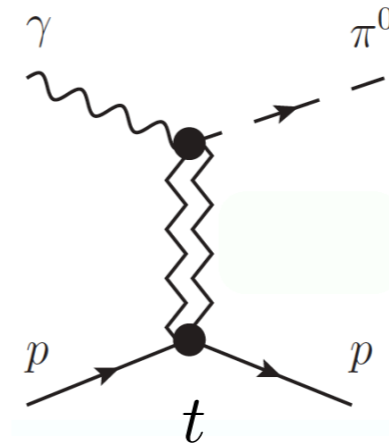
今年已通过上海硅酸盐预定500根PWO 晶体

赝标量介子 π^0/η 光产生

JPAC Regge Model



SLAC: PRD 4, 1937 (1971)



Exchange J^{PC}

$1^{--} : \omega, \rho$

$1^{+-} : b, h$

$$\frac{d\sigma}{dt} = \sigma_{\perp} + \sigma_{\parallel} = |\rho + \omega|^2 + |b + h|^2$$

$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$

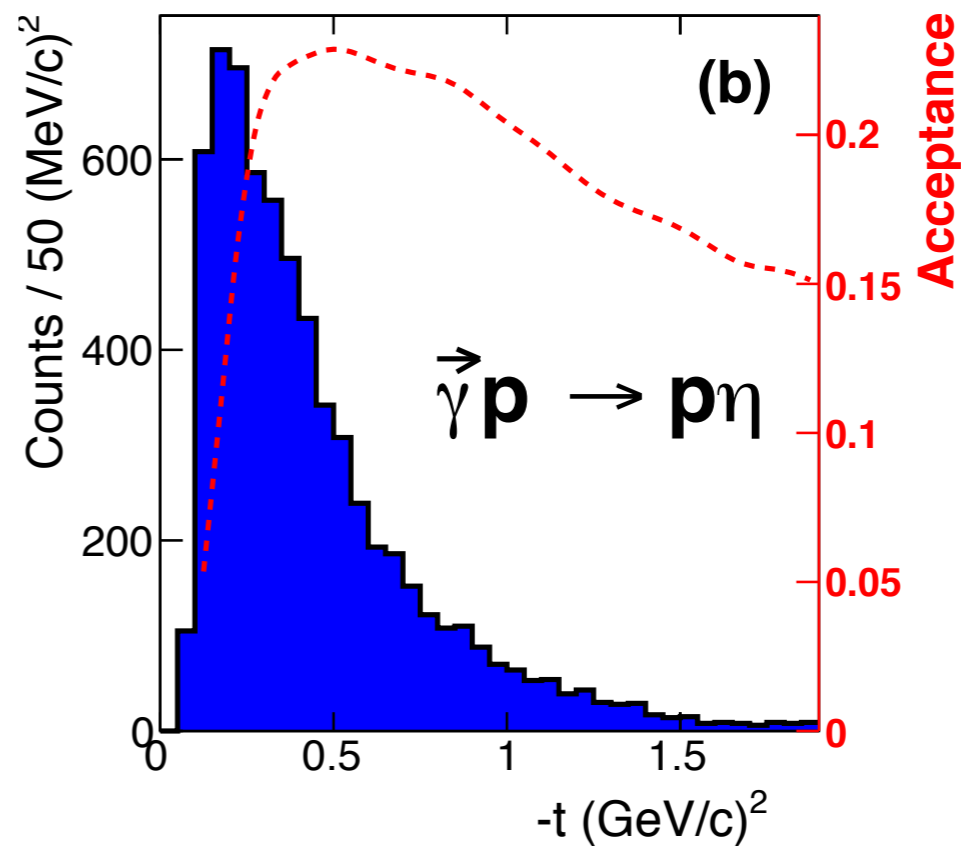
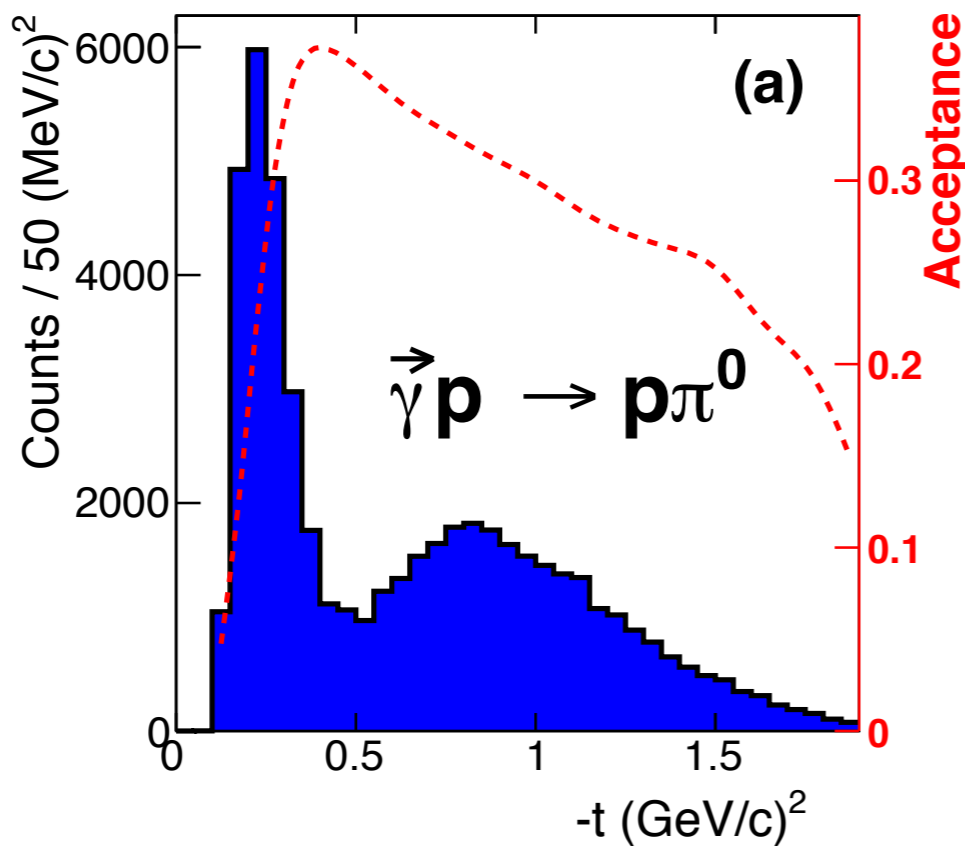
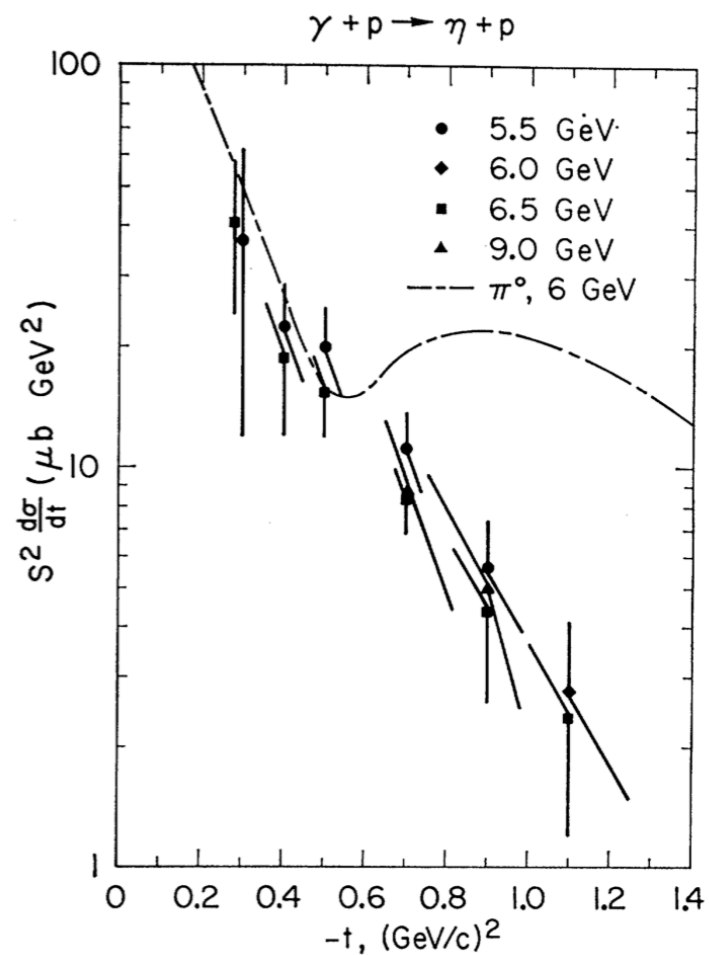
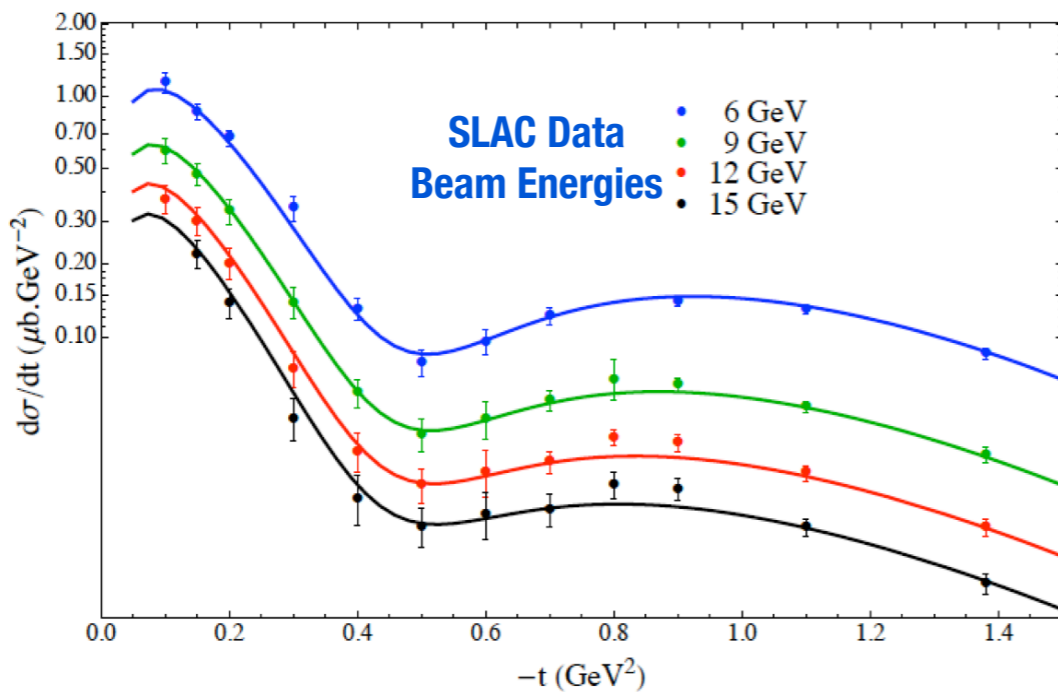
GlueX/Hall D 的线性极化光子束流
将为Regge模型提供新的约束

在光子能量大于3 GeV能区尚没有关于
 $\gamma p \rightarrow \eta p$ 过程的束流不对称度 Σ 的测量

-t 分布

SLAC: PRD 1, 27 (1970)

V. Mathieu (JPAC): PRD 92, 074013

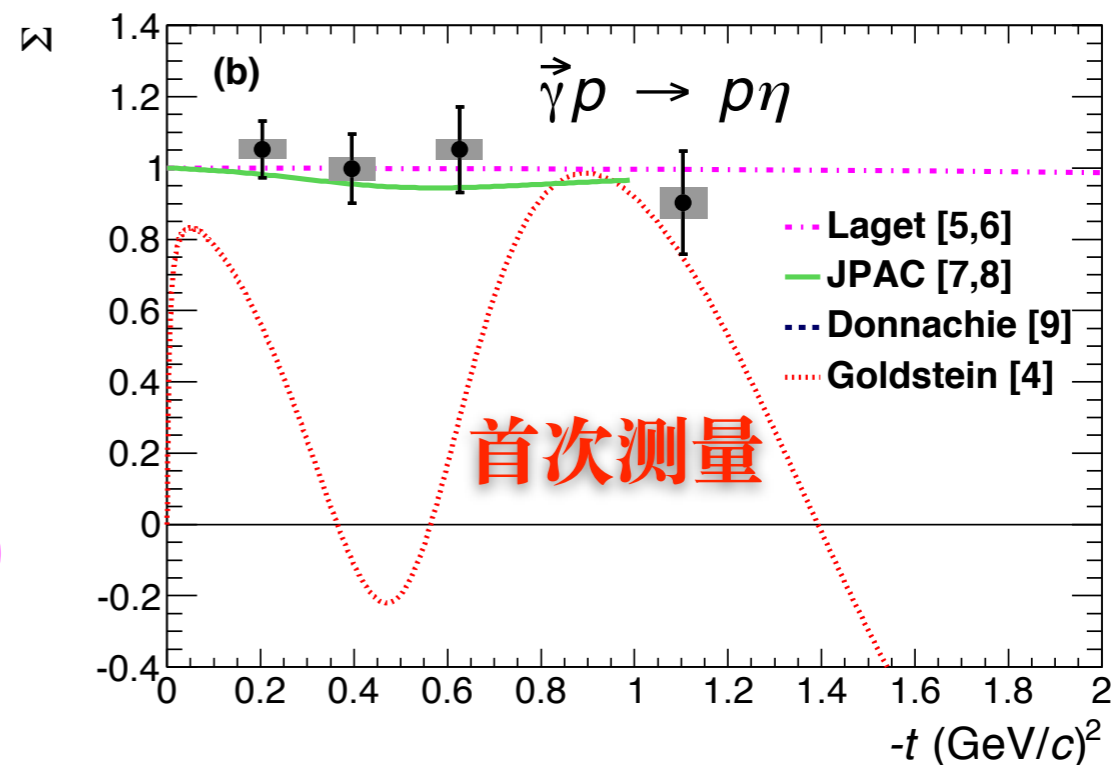
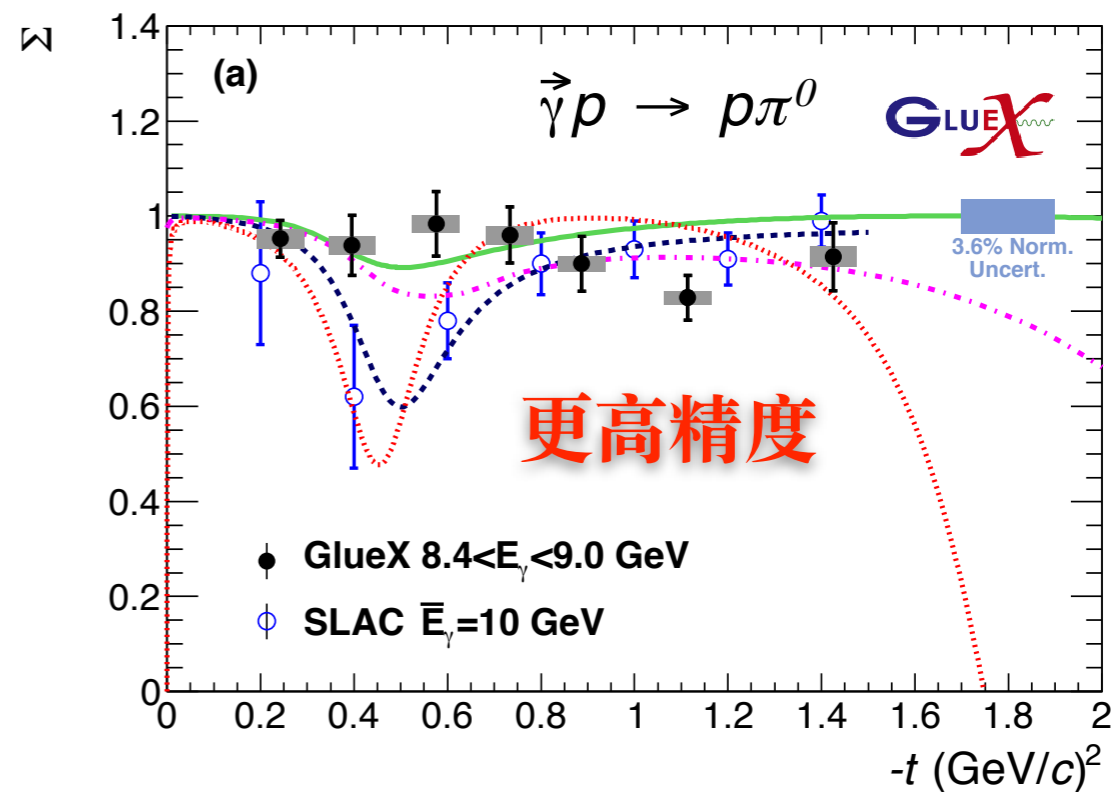


束流不对称度：测量结果

JLab 12GeV升级后的首篇论文

- 测量结果与 SLAC 数据相符
- 不对称度 Σ 接近于1, 对 $-t$ 依赖很小, 支持在此能区赝标介子光产生过程以矢量交换为主
- 在 $-t = 0.5 (\text{GeV}/c)^2$ 处没有观察到部分理论预言的显著下降

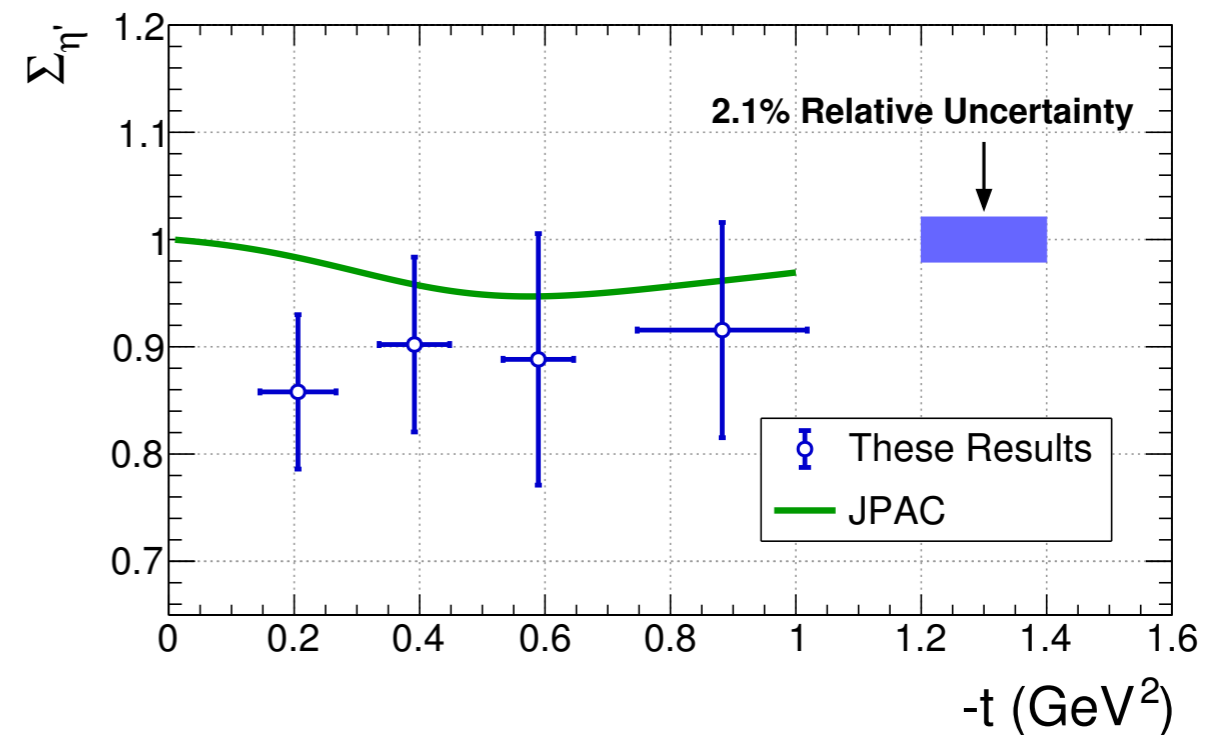
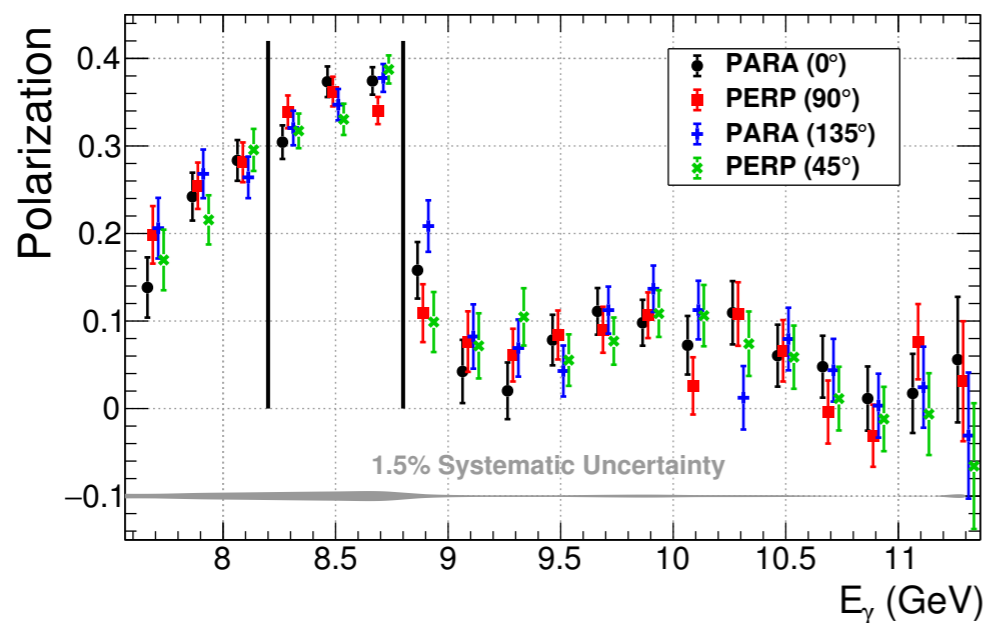
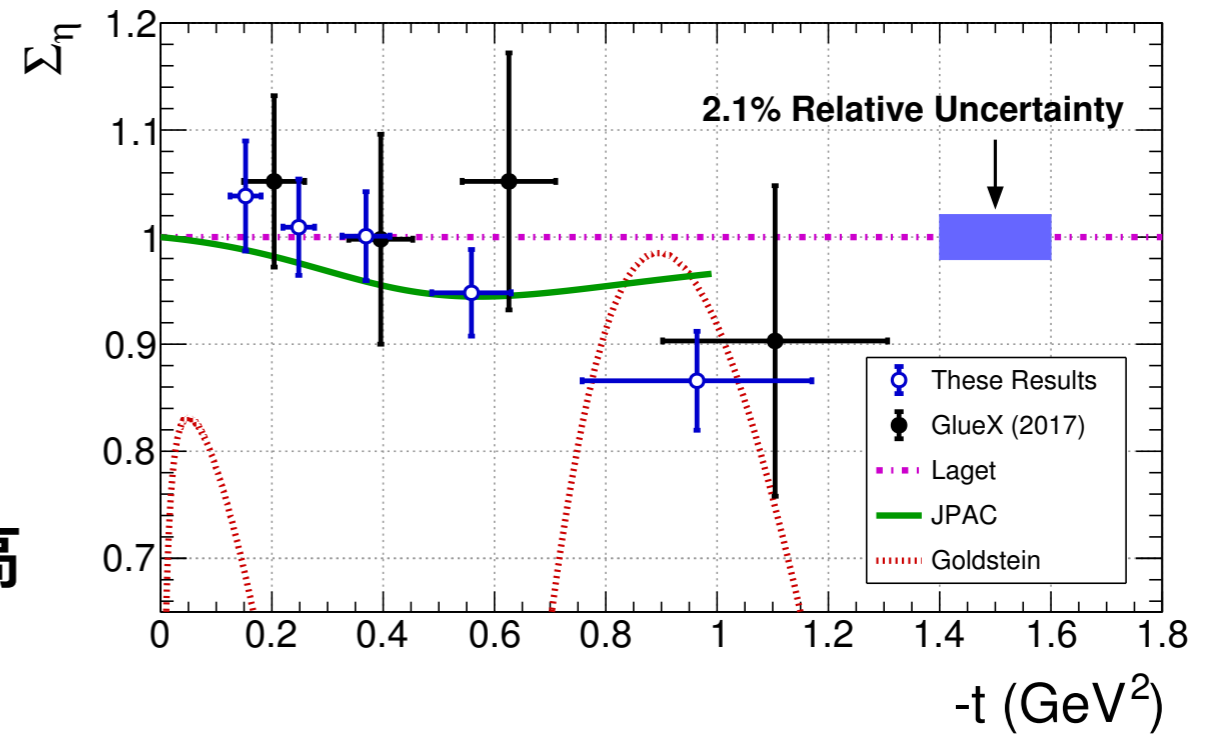
PHYS REV C 95, 042201(R) (2017)



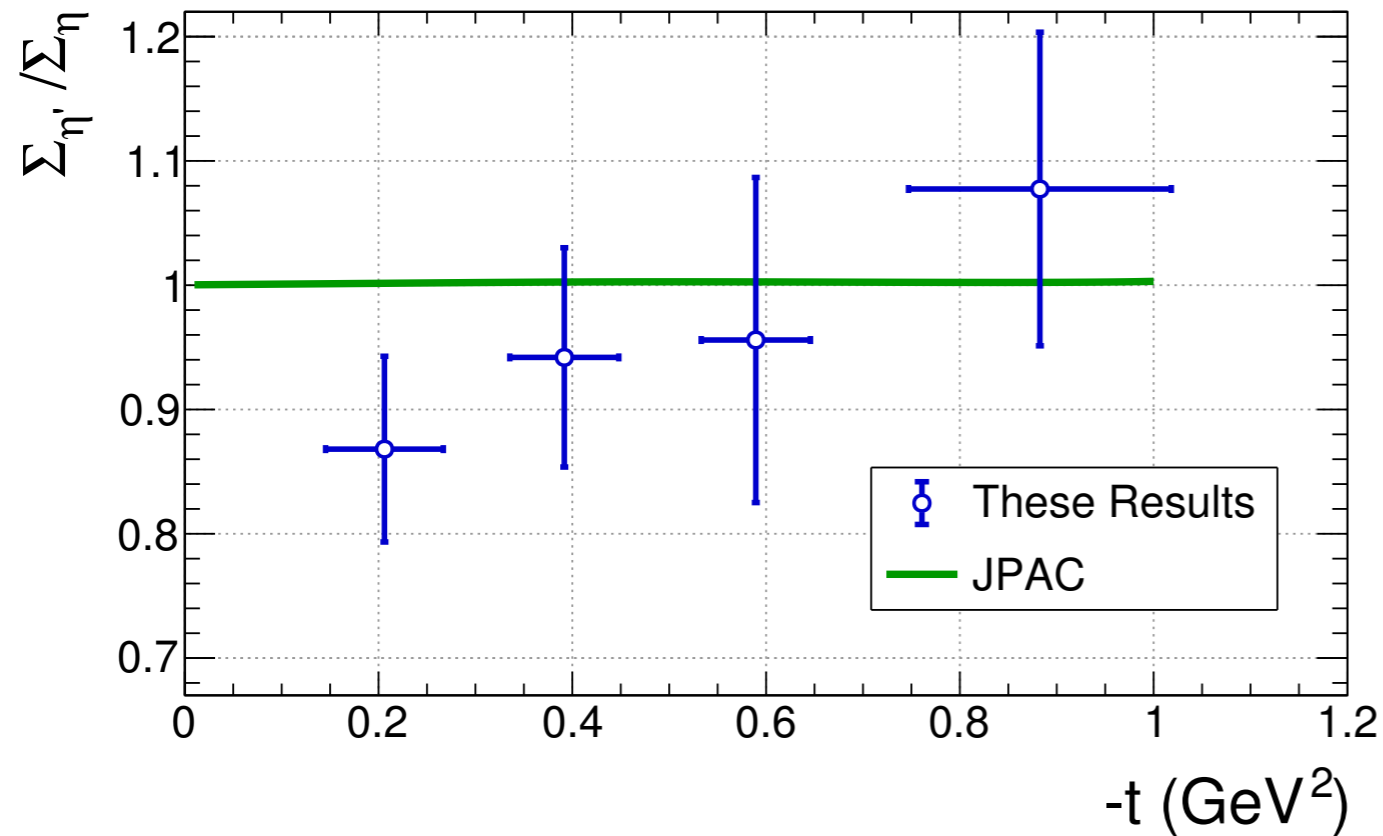
赝标量介子 η/η' 光产生

arXiv:1908.05563 [nucl-ex]

- 利用两组独立的极化光子束流
- η 通过 2γ 道重建
- η' 通过 $\pi^+\pi^-\eta$ 道重建
- η 与17年的数据结果相符，精度更高
- 给出了 η' 首次测量



赝标量介子 η/η' 光产生



矢量介子交换为主导

η/η' 束流不对称度相等暗示
没有含隐藏的奇异数的介子
交换 (如 ϕ 和 h' 介子)

JPAC References:

Phys. Rev. D92, 074013 (2015). Phys. Lett B774, 362 (2017).

[arXiv:1908.05563 \[nucl-ex\]](https://arxiv.org/abs/1908.05563)

双赭标量介子光产生

奇特态1⁻⁺

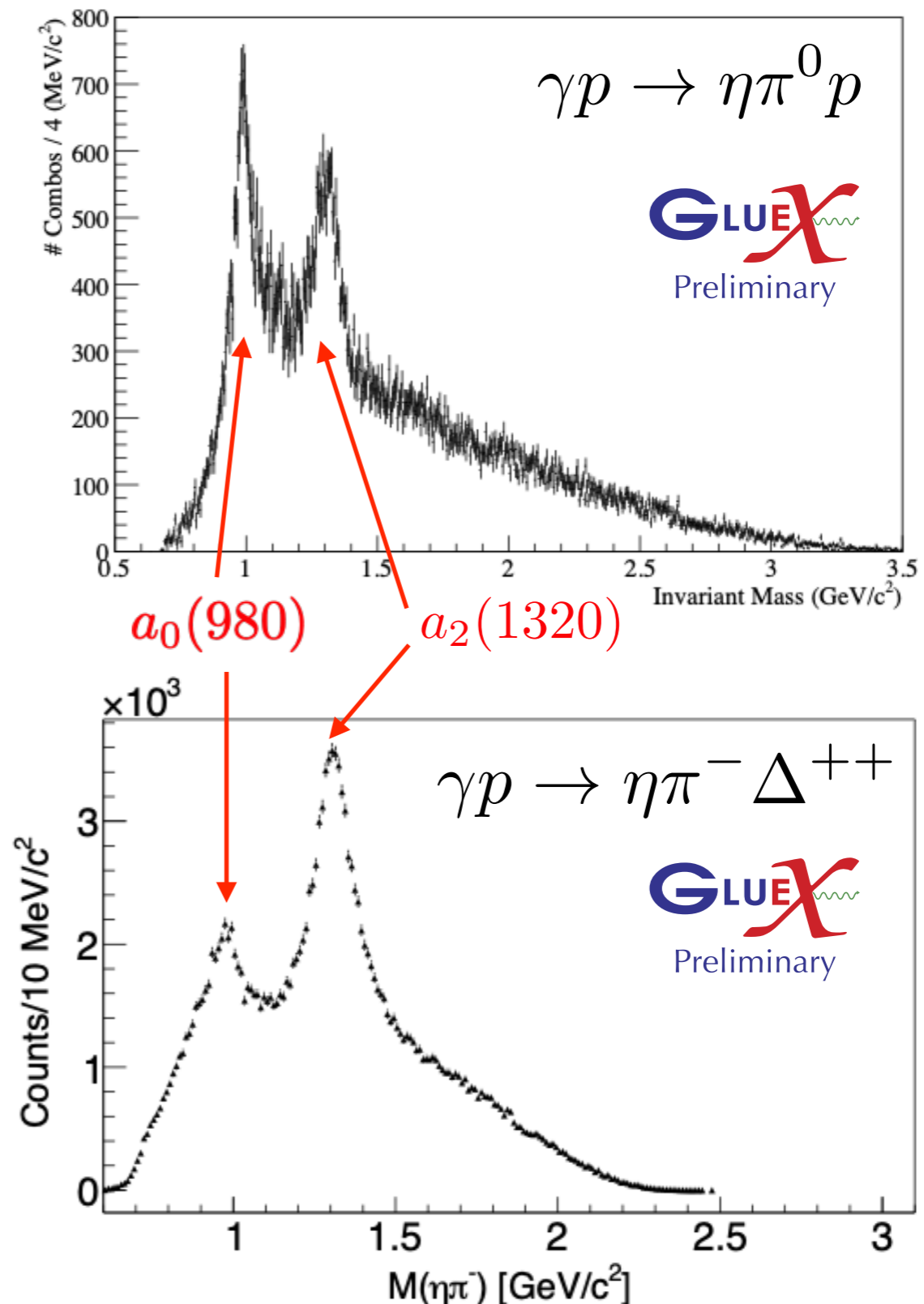
分析工作正在进展中

目前仅用到20%的GlueX
Phase-1的数据

预计GlueX Phase-1
的数据量将达到
COMPASS的两倍

研究双赭标量谱

向着混杂态寻找目标迈进



粲偶素J/ψ近阈光产生过程

测量J/ψ光产生过程散射截面： $8.2 \text{ GeV} < E_\gamma < 11.8 \text{ GeV}$

GlueX 能量范围

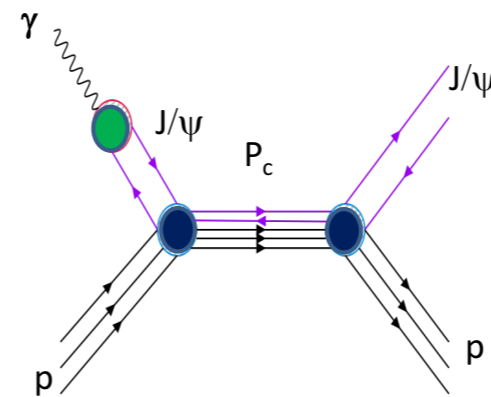
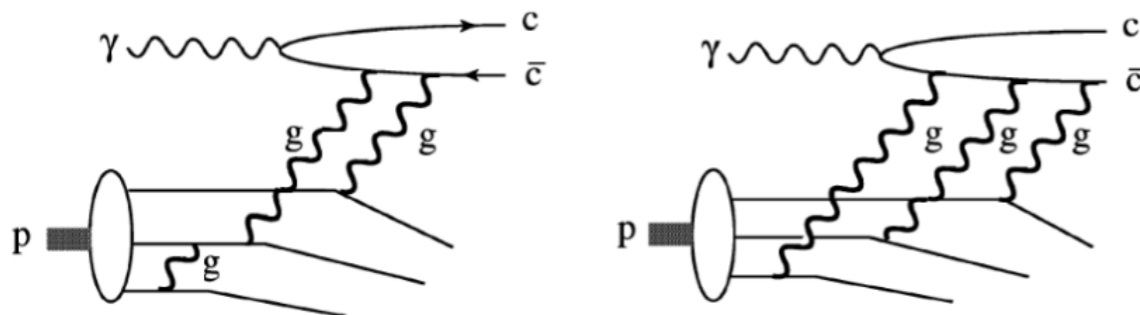
之前的实验近阈能区数据少（非遍举过程）

GlueX实验恰好能在近阈能区提供实验数据

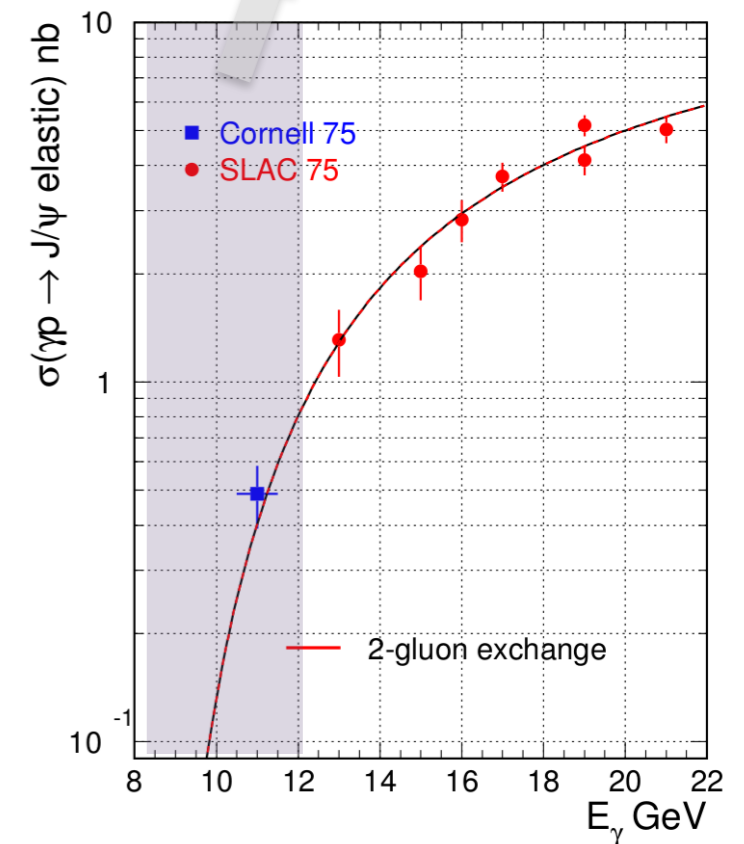
对核子质量的胶子贡献非常重要 [Eur. Phys. C 9 \(1999\)](#)

散射截面对核子中高x下胶子交换敏感 [PLB 498 \(2001\)](#)

寻找LHCb五夸克候选者Pc态



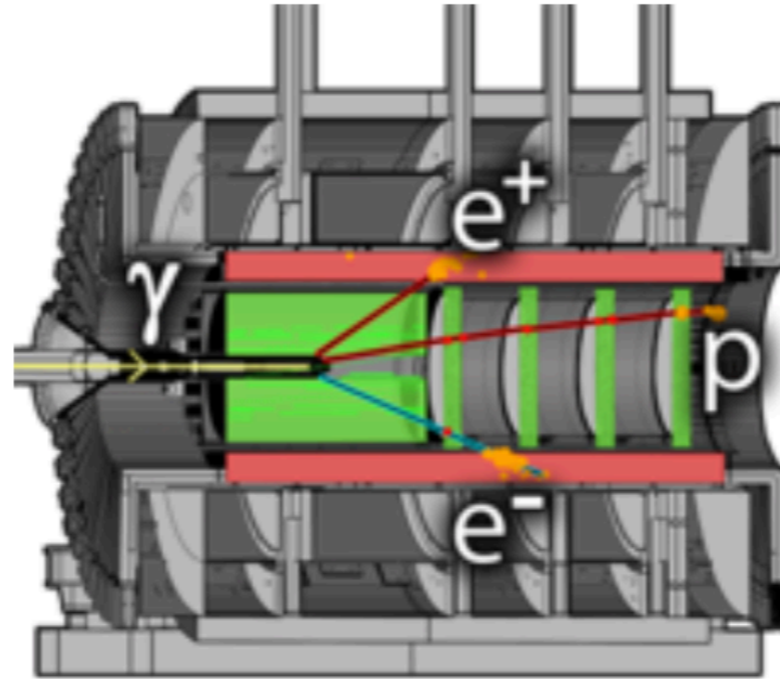
[Brodsky et al. PLB 498, 23 \(2001\)](#)



First Measurement of Near-Threshold J/ψ Exclusive Photoproduction off the Proton

A. Ali *et al.* (GlueX Collaboration)

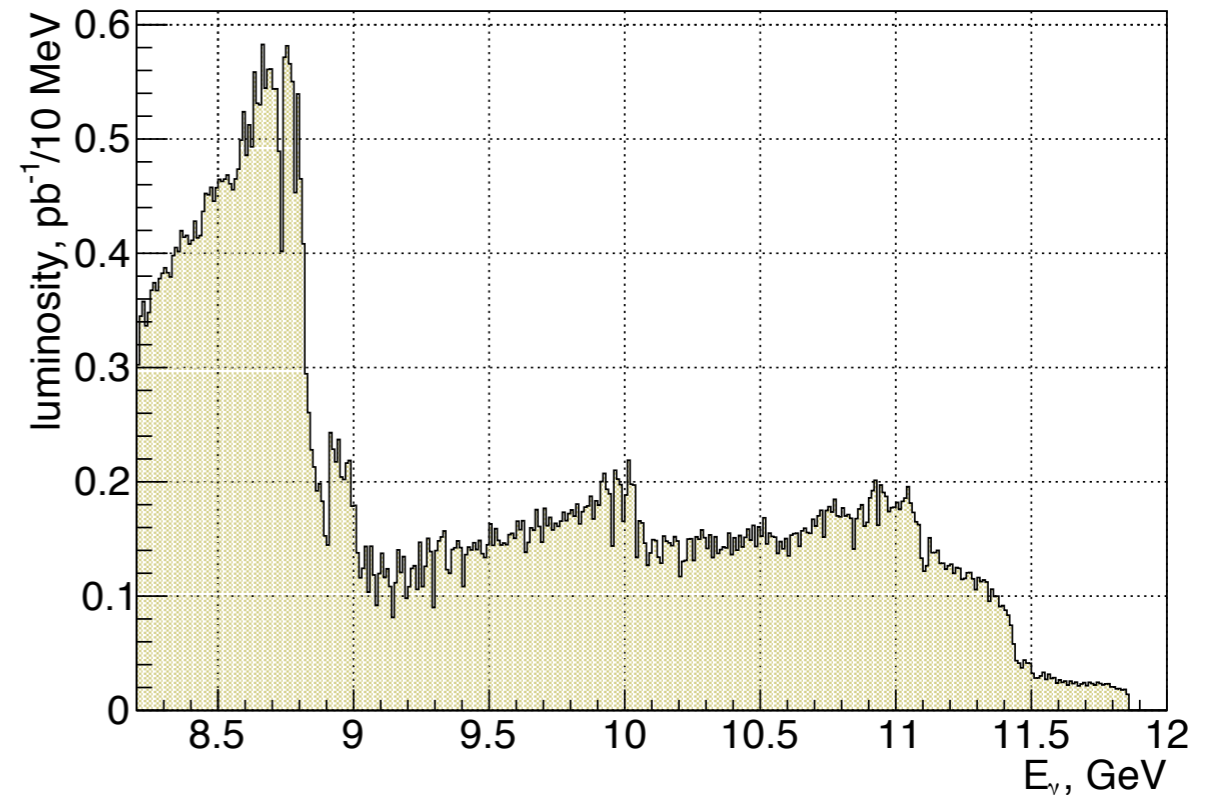
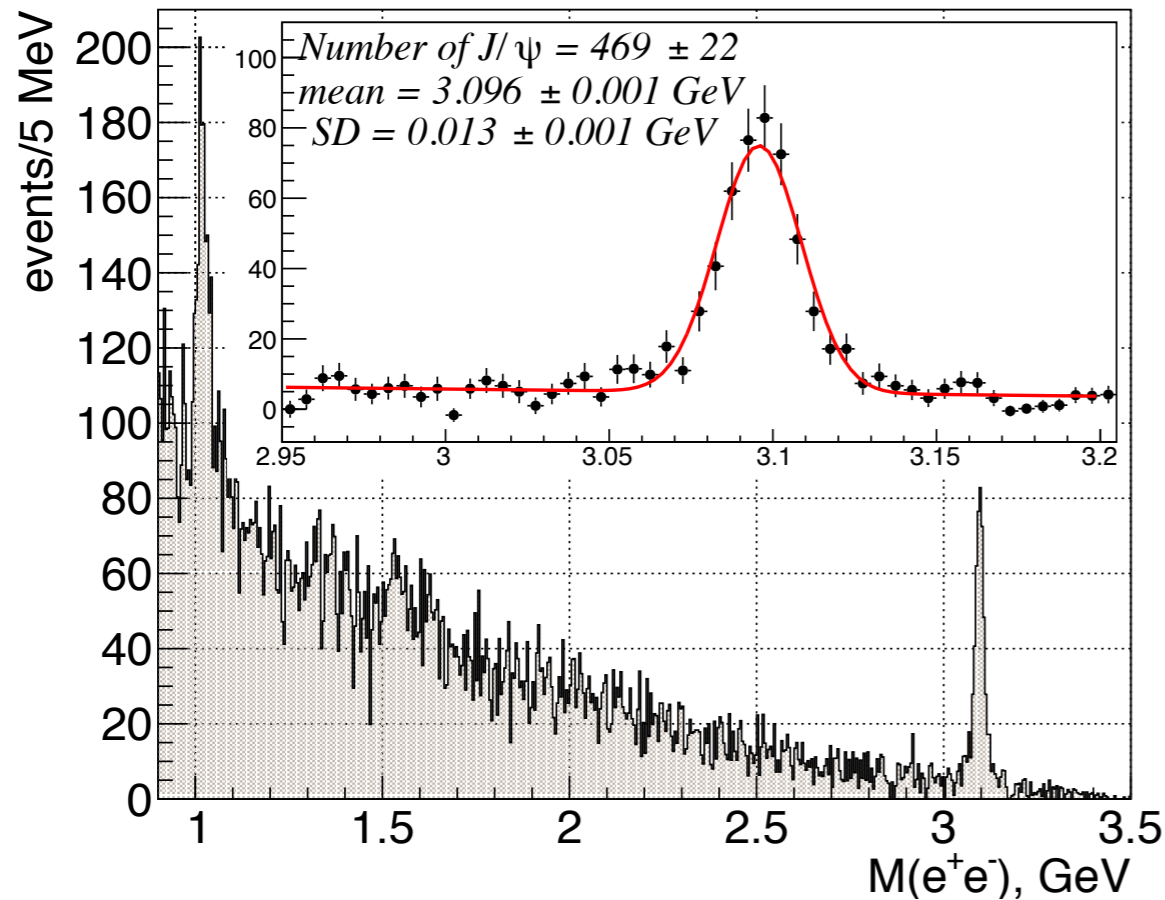
Phys. Rev. Lett. **123**, 072001 (2019) – Published 13 August 2019



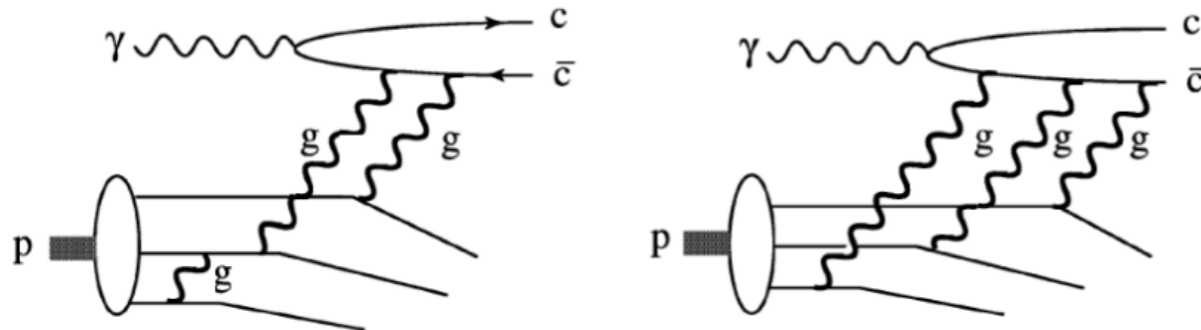
New results from the GlueX collaboration probe the gluonic structure of the proton.

We report on the measurement of the $\gamma p \rightarrow J/\psi p$ cross section from $E_\gamma = 11.8$ GeV down to the threshold at 8.2 GeV using a tagged photon beam with the GlueX experiment. We find that the total cross section falls toward the threshold less steeply than expected from two-gluon exchange models. The differential cross section $d\sigma/dt$ has an exponential slope of 1.67 ± 0.39 GeV⁻² at 10.7 GeV average energy. The LHCb pentaquark candidates P_c^+ can be produced in the s channel of this reaction. We see no evidence for them and set model-dependent upper limits on their branching fractions $\mathcal{B}(P_c^+ \rightarrow J/\psi p)$ and cross sections $\sigma(\gamma p \rightarrow P_c^+) \times \mathcal{B}(P_c^+ \rightarrow J/\psi p)$.

粲偶素 J/ψ 近阈光产生过程

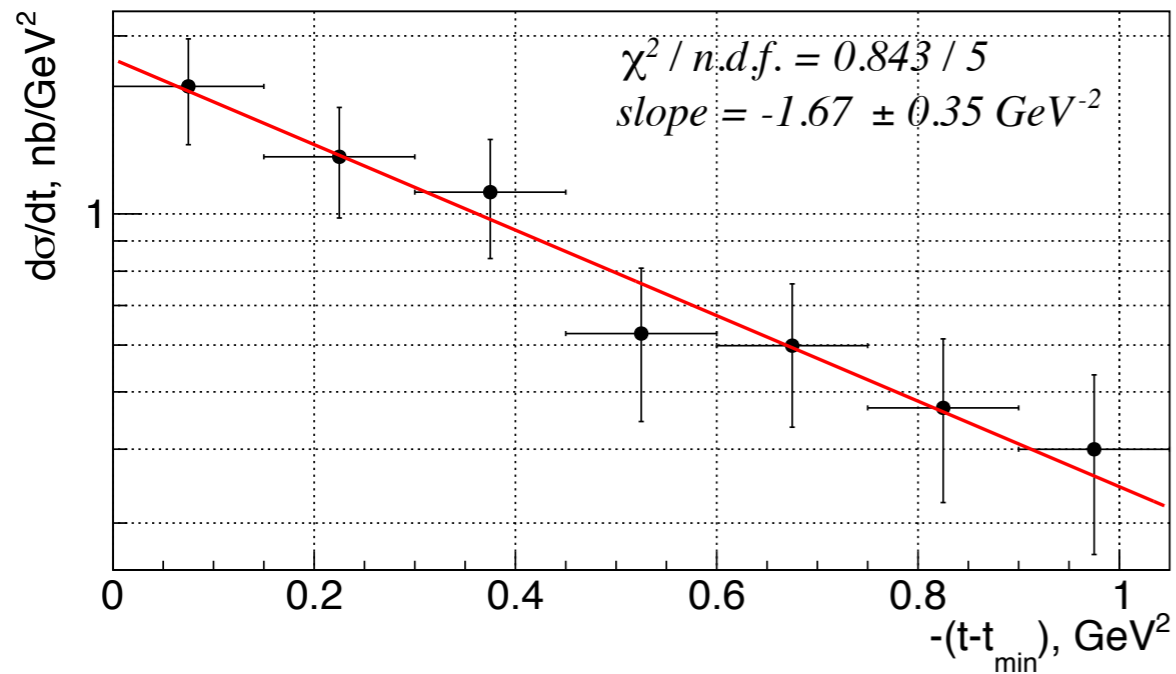


PRL 123, 072001 (2019)

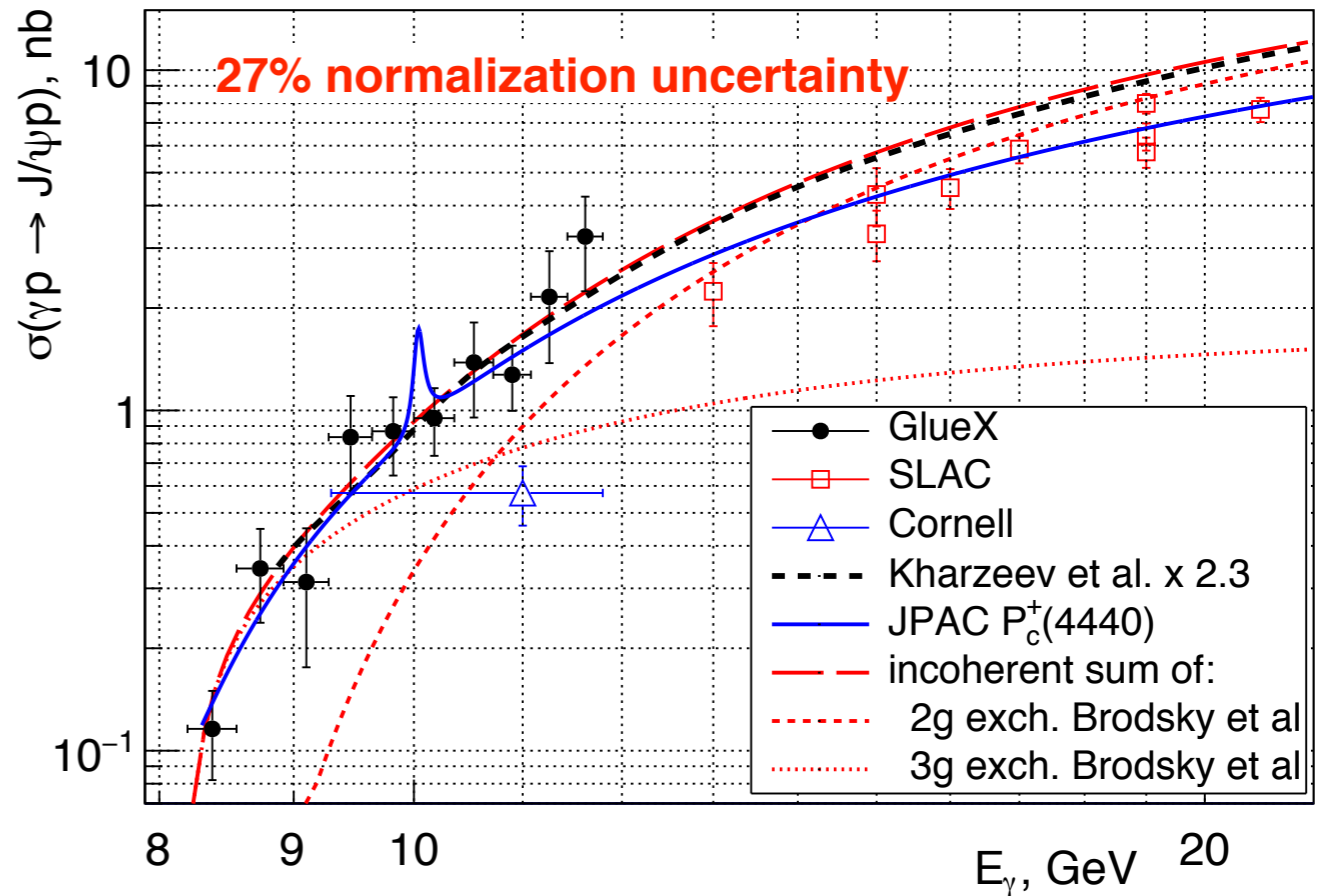


目前结果使用2016+2017数据
大约是GlueX Phase-1 全部数据的25%

粲偶素J/ψ近阈光产生过程



PRL 123, 072001 (2019)



Cornell: PRL **35**, 1616 (1975); SLAC: PRL **35**, 483 (1975);

理论预言: PLB **498**, 23 (2001); NPA **661**, 568 (1999)

JPAC 模型: PRD **94**, 034002 (2016);

近阈能区3胶子交换为主导

目前精度下未看到五夸克态

设定模型依赖分支比上限为百分之几

不久后能将精度提高4倍

目前结果使用2016+2017数据

大约是GlueX Phase-1 全部数据的25%

JLab粲偶素J/ψ近阈产生

四个实验大厅共同关注!

夸克偶素提供了研究核子中胶子场的重要工具

近阈产生能为迹反常、夸克偶素-核子束缚、LHCb五夸克候选者及质子质量起源等问题提供信息

12 GeV能量升级后的JLab为研究这些问题的理想场所!

GlueX
Hall D

HMS+SHMS
Hall C

CLAS 12
Hall B

SoLID
Hall A

~400

~2100

45/天

1627/天, 光产生
86/天, 电子产生

25% GlueX I (4200 with muons)

完成

完成

进行中

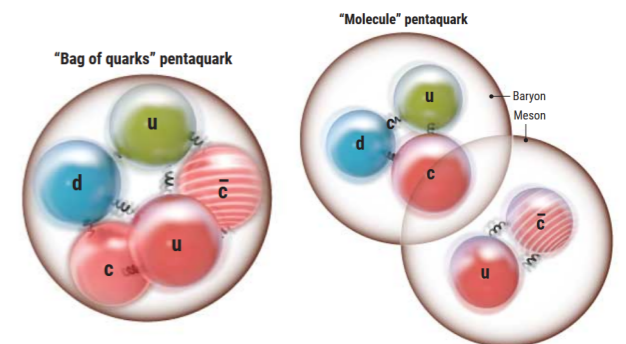
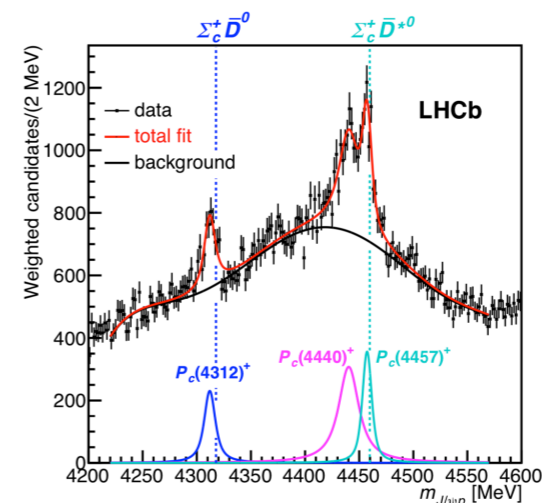
~10年?

2015年LHCb发现五夸克态候选者Pc(4450)等。

PRL 115, 072001(2015)

2019年发现一个新的五夸克态候选者Pc(4312), 并观测到Pc(4450)实际上是由两个质量相近的共振态Pc(4440)和Pc(4457)叠加而成。

PRL 122, 222001(2019)



总结与展望

- 杰斐逊实验室12GeV升级计划完成，四个实验大厅都已在新能量下顺利运行
- 与QCD相关的一系列实验都在进展中，包括通过强子谱学、核结构、核媒质等方法研究QCD禁闭、寻找QCD奇特态等
- 未来设备研制及升级在进行中，如：A厅MOLLER、SoLID计划、D厅DIRC、FCAL-II升级计划等
- JLab的EIC计划预研究也在持续进行中

祝贺赵光达老师八十大寿生日快乐，身体健康！

