惠州强子谱仪 (HHaS)

仇浩

重离子科学与技术全国重点实验室

中国科学院近代物理所

目录

- HIAF高能终端可能研究的物理
- 概念设计
- 各探测器
- 预期性能
- 部分模拟结果
- 国际竞争

强流重离子加速器装置(HIAF)

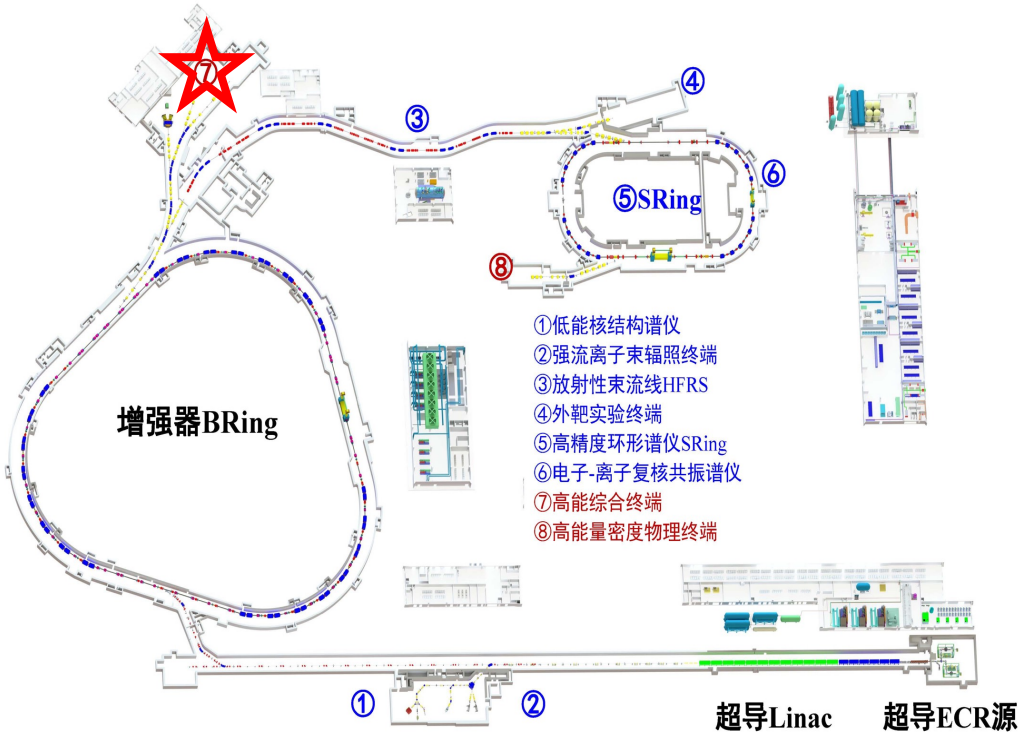


- 国家重大科技基础设施
- 广东，惠州



- 2025.10.28成功出束，一天全线贯通
- 氧束、铋束流强破世界纪录

HIAF及HIAF-U

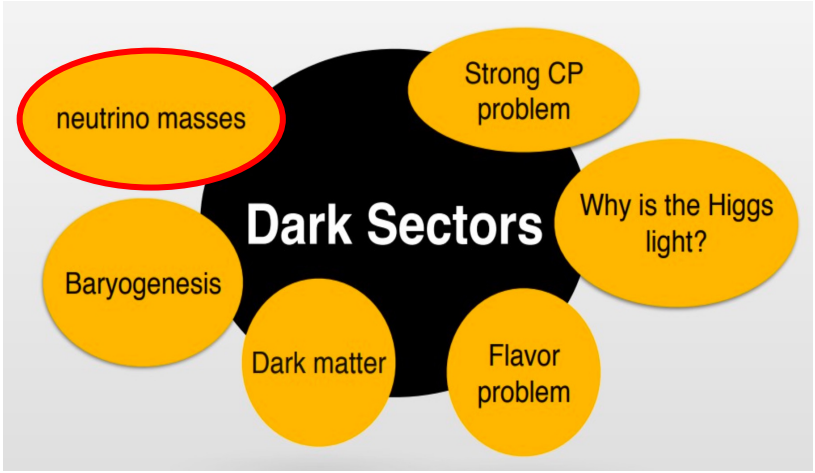


	E_k (GeV/u)	$\sqrt{s_{NN}}$ (GeV)
HIAF p束	<9.3	<4.58
HIAF U束	<2.45	<2.85
HIAF-U U束	<9.1	<4.54

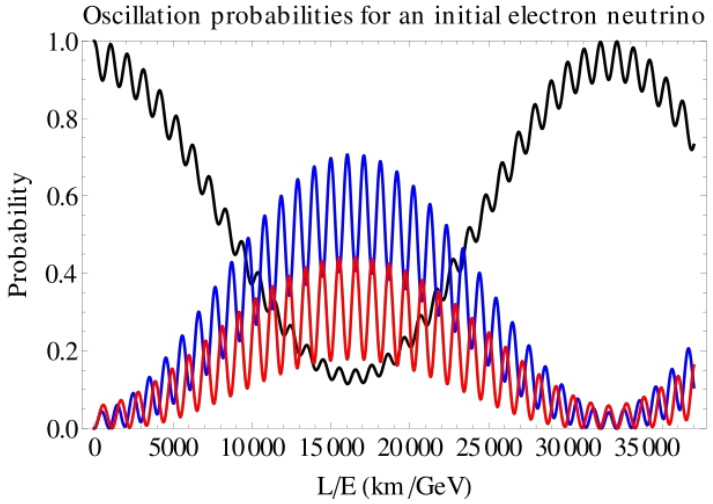
惠州强子谱仪(Huizhou Hadron Spectrometer)

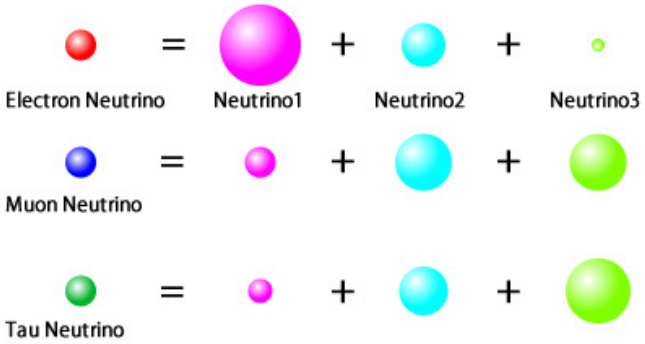
- 质子束流 + 可能产生的K/π次级束流：η介子物理、轻强子物理
- 重离子束流：超核、核物质相结构、状态方程

η介子物理



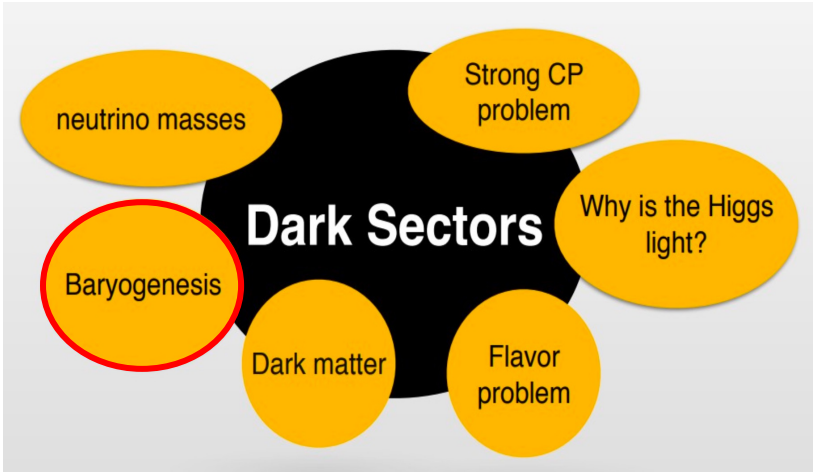
C. Gatto



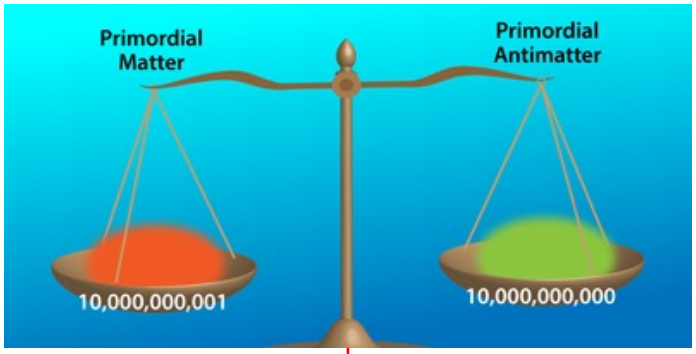


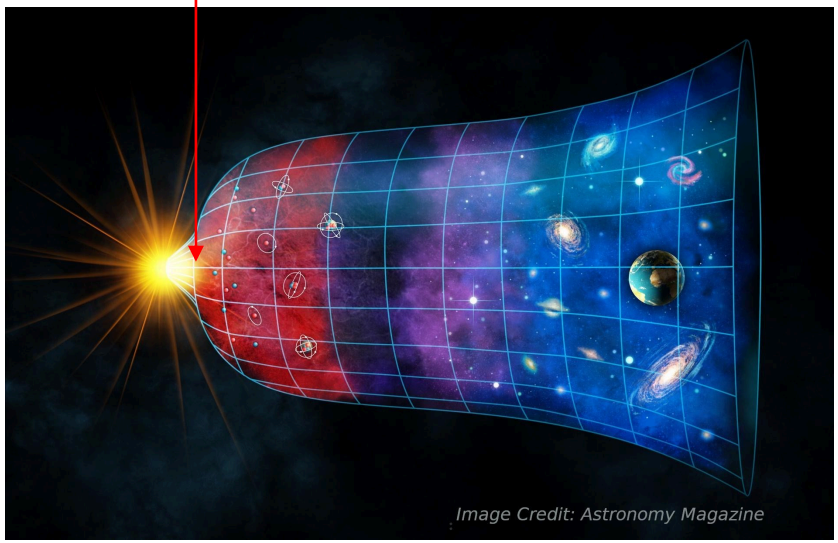
- 粒子物理标准模型面临一些难题，需要超出当前标准模型的新物理
- e.g.中微子有质量

η介子物理



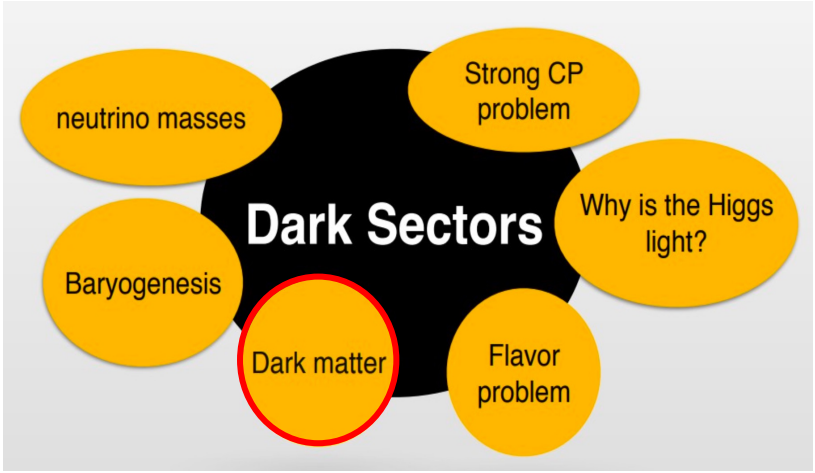
C. Gatto



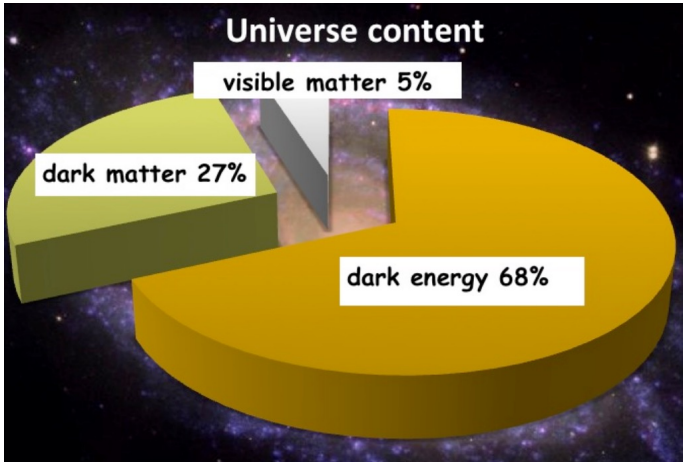


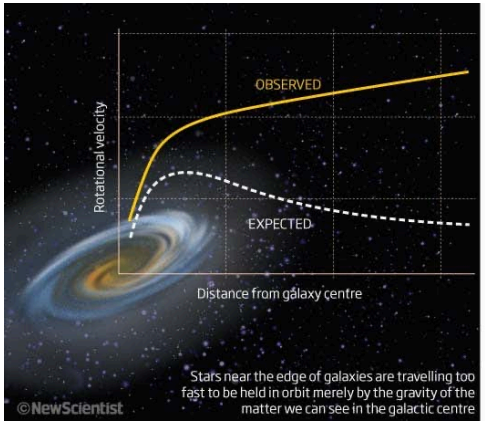
- 粒子物理标准模型面临一些难题，需要超出当前标准模型的新物理
- e.g.宇宙正反物质不对称

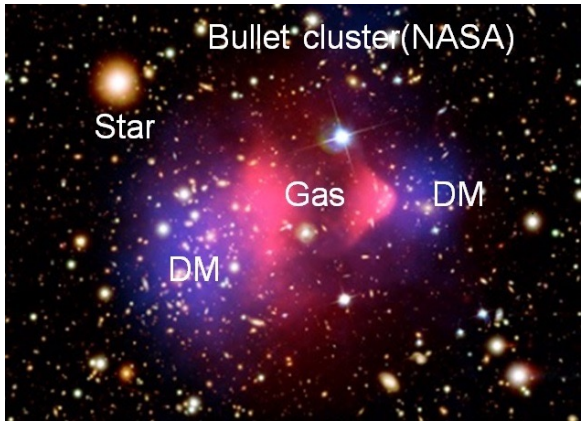
η介子物理



C. Gatto



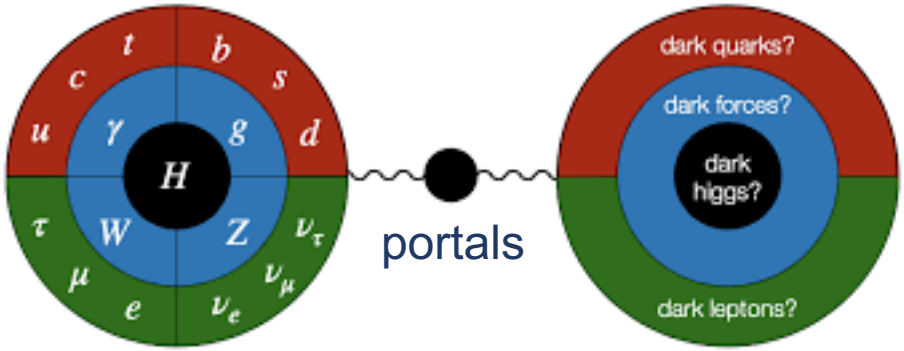




- 粒子物理标准模型面临一些难题，需要超出当前标准模型的新物理
- e.g.暗物质

η介子物理





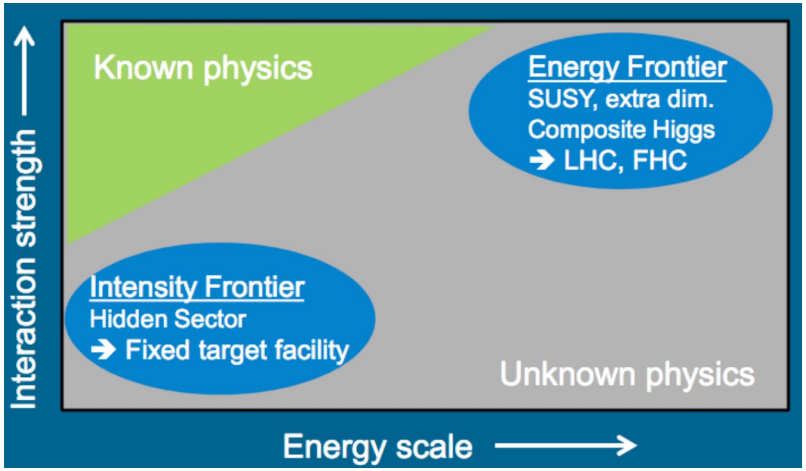
C. Gatto

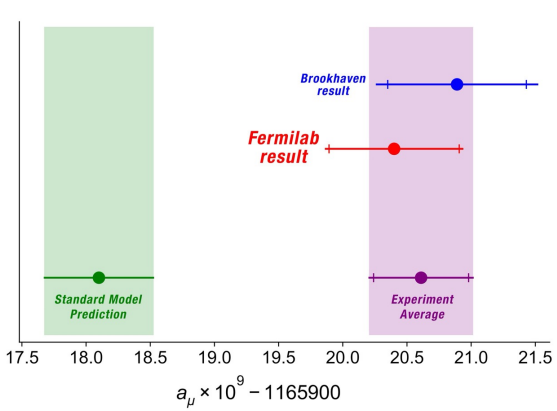
- 粒子物理标准模型面临一些难题，需要超出当前标准模型的新物理
- 可能存在一组（sector）暗物质粒子，通过“门户”（portal）粒子与标准模型粒子有很微弱的联系

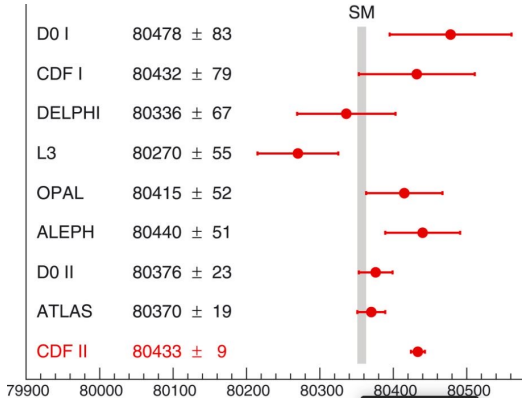
η介子物理



C. Gatto

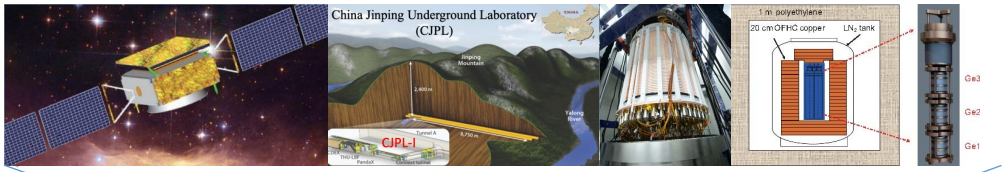


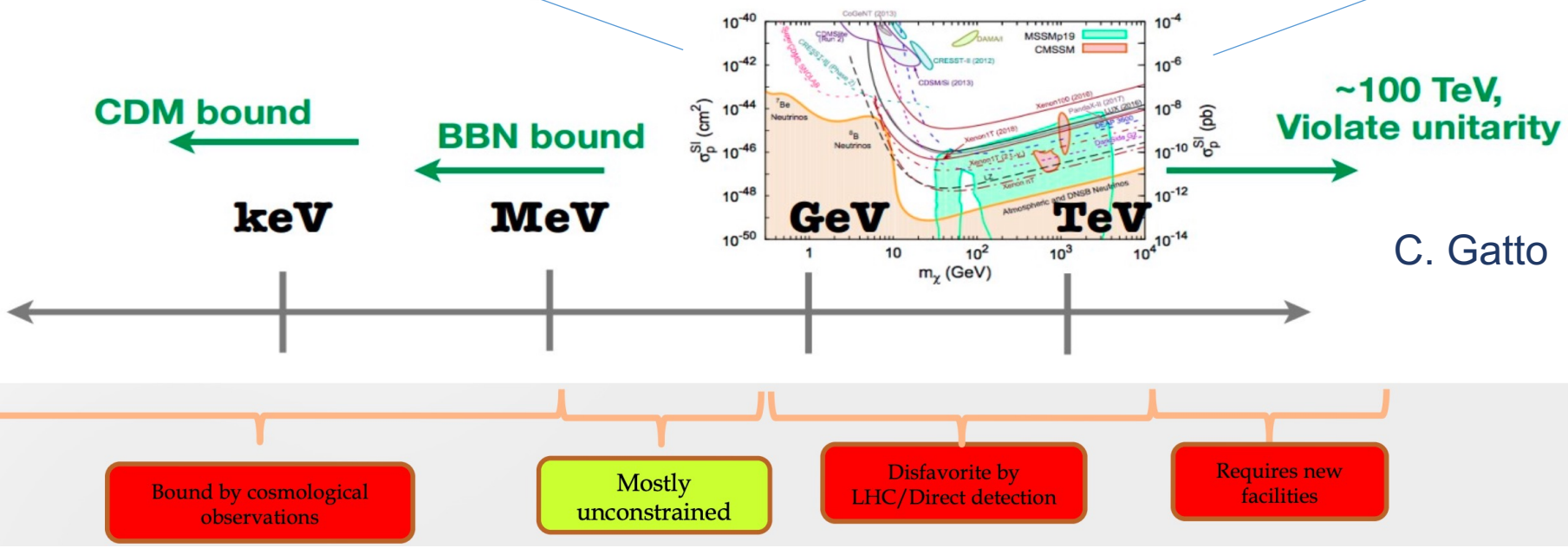




- 粒子物理标准模型面临一些难题，需要超出当前标准模型的新物理
- 除了标准模型预言的Higgs粒子，LHC的高能量前沿实验没有发现其它新粒子/新物理
- 高精度前沿测量，也是发现新物理的重要手段，如μ子反常磁矩g-2、W质量

η介子物理 – 暗物质





Bound by cosmological observations

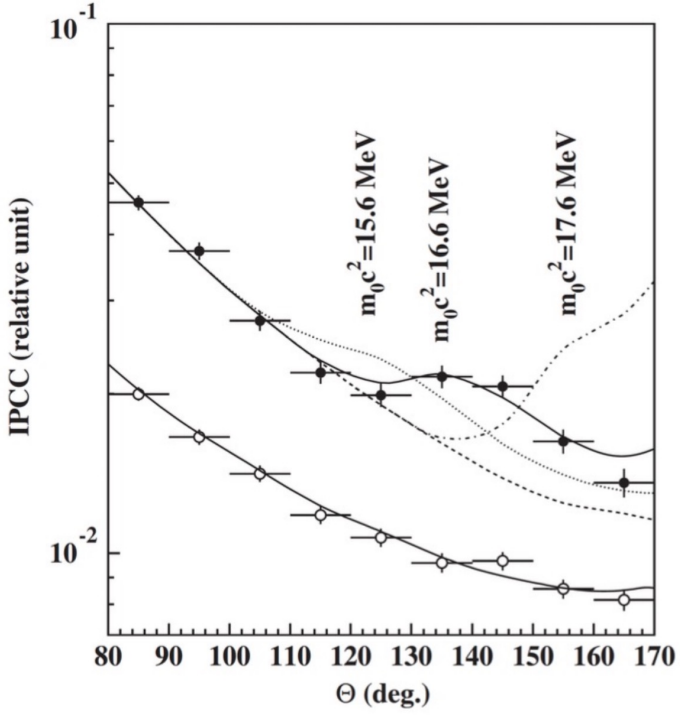
Mostly unconstrained

Disfavorite by LHC/Direct detection

Requires new facilities

- 在暗物质粒子寻找中，传统的大质量弱相互作用粒子(WIMP, GeV~100TeV)可能存在的参数空间不断被实验排除
- 轻暗物质粒子(MeV~GeV)当前实验限制较少，是重要的实验寻找方向
- 强流加速器装置是寻找轻暗物质粒子的有力工具

η介子物理 – X17

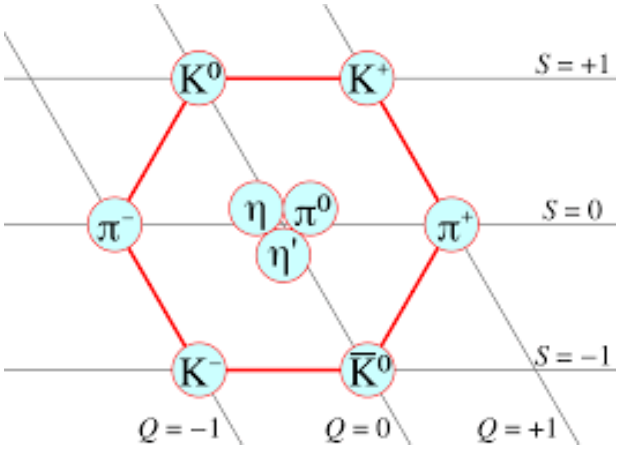


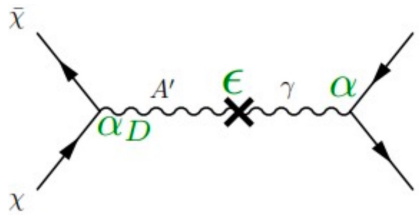
Phys. Rev. Lett. 116 (2016) 042501

- ATOMKI 实验 - ^{7}Li (p, e^+ e^-) ^{8}Be
- 1.03 MeV质子束，18.15 MeV 1^+ ^{8}Be激发态
- e^+ e^- 夹角 ~140° 处异常信号，显著度6.8σ
- 物理解释之一：~17 MeV质量的新玻色子？ Phys. Rev. Lett. 117 (2016) 071803
- 后续有实验观测到类似现象，也有实验没发现类似现象

η介子物理

- η 、 η’具有全零量子数——与Higgs类似
  - Q = I = J = S = B = L = 0
- ⇒ 标准模型衰变被压低
- ⇒ 新物理的分支比更大
- η / η’ 衰变可以用来寻找多种连接暗物质世界的门户(portal)粒子

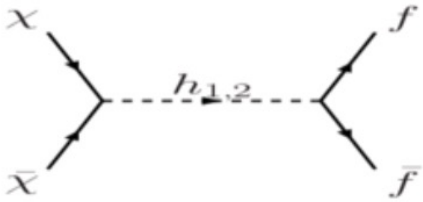




暗光子

$\eta \to \gamma A'$

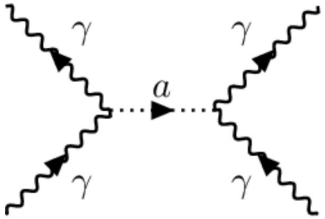
$A' \to \mu^+\mu^- / e^+e^-$



暗Higgs粒子

$\eta \to \pi^0 H$

$H \to \pi^+\pi^- / \mu^+\mu^- / e^+e^-$

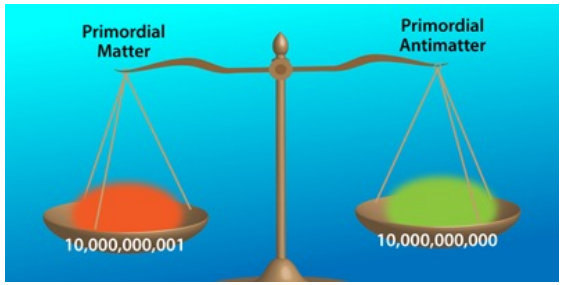


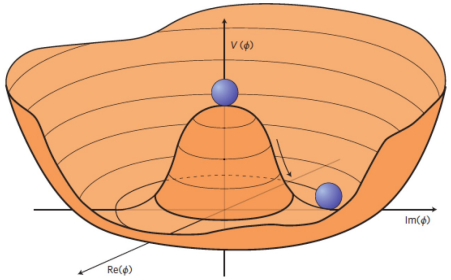
类轴子

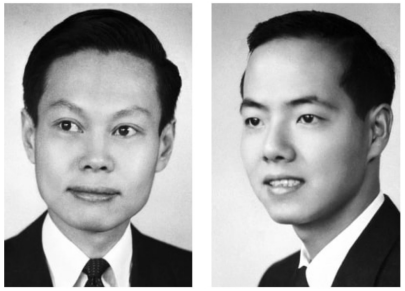
$\eta \to \pi\pi a$

$a \to \gamma\gamma / \mu^+\mu^- / e^+e^-$

η介子物理







杨振宁、李政道

~~P~~: 1957

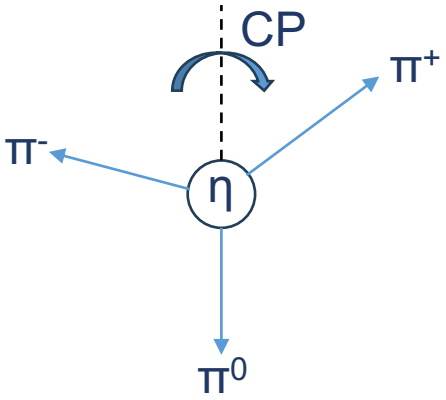




James W. Cronin & Val L. Fitch

~~CP~~: 1980



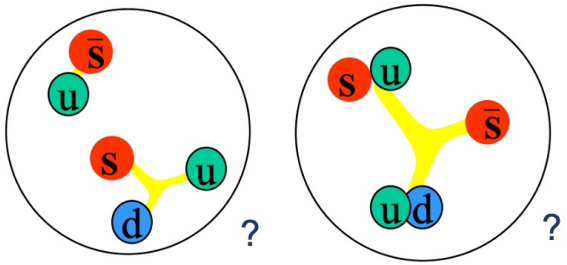


- 基本对称性是物理学中的重要问题
- η 衰变可以寻找新的基本对称性破缺

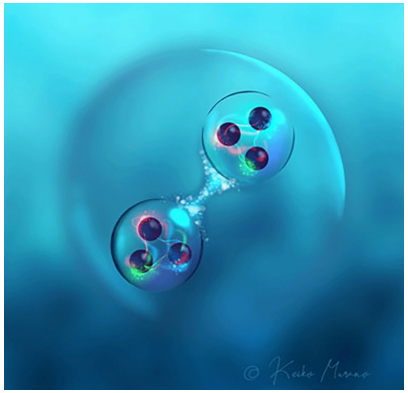
轻强子物理

Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	ΣK	$N\rho$	$\Delta\eta$
$\Delta(1232)$	$3/2^+$	****	****	****				
$\Delta(1600)$	$3/2^+$	****	****	***	****			
$\Delta(1620)$	$1/2^-$	****	****	****	****			
$\Delta(1700)$	$3/2^-$	****	****	****	****	*	*	
$\Delta(1750)$	$1/2^+$	*	*	*		*		
$\Delta(1900)$	$1/2^-$	***	***	***	*	**	*	
$\Delta(1905)$	$5/2^+$	****	****	****	**	*	*	**
$\Delta(1910)$	$1/2^+$	****	***	****	**	**		*
$\Delta(1920)$	$3/2^+$	***	***	***	***	**		**
$\Delta(1930)$	$5/2^-$	***	*	***	*	*		
$\Delta(1940)$	$3/2^-$	**	*	**	*			*
$\Delta(1950)$	$7/2^+$	****	****	****	**	***		
$\Delta(2000)$	$5/2^+$	**	*	**	*		*	
$\Delta(2150)$	$1/2^-$	*		*				
$\Delta(2200)$	$7/2^-$	***	***	**	***	**		
$\Delta(2300)$	$9/2^+$	**		**				
$\Delta(2350)$	$5/2^-$	*		*				
$\Delta(2390)$	$7/2^+$	*		*				
$\Delta(2400)$	$9/2^-$	**	**	**				
$\Delta(2420)$	$11/2^+$	****	*	****				
$\Delta(2750)$	$13/2^-$	**		**				
$\Delta(2950)$	$15/2^+$	**		**				

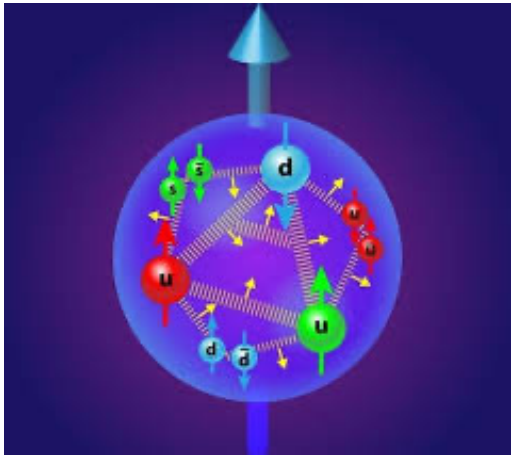
重子谱



轻味五夸克态

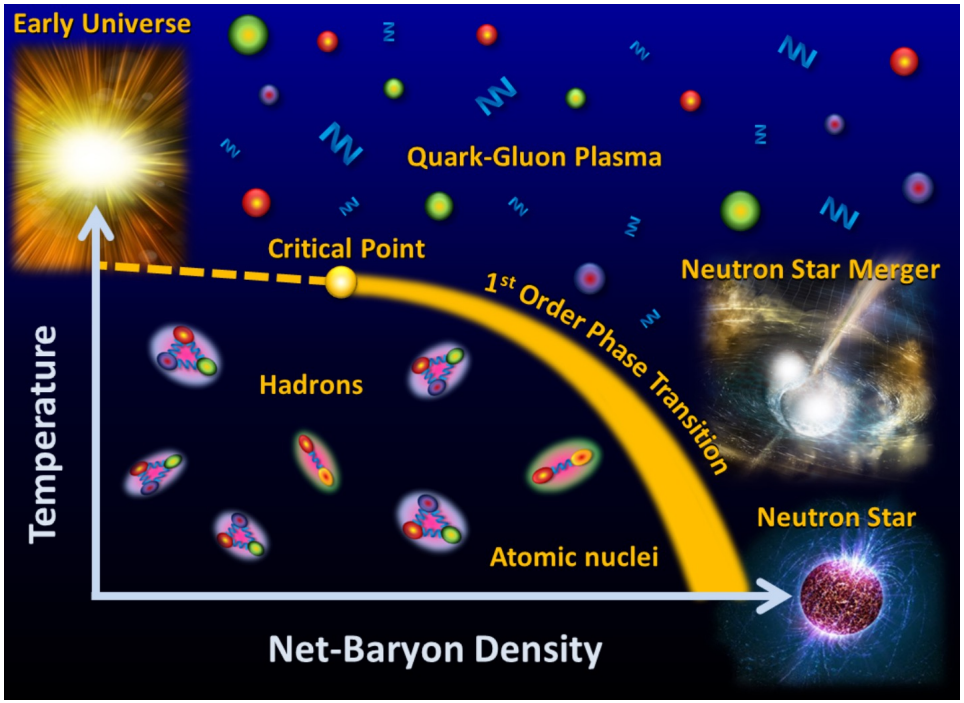


双重子态



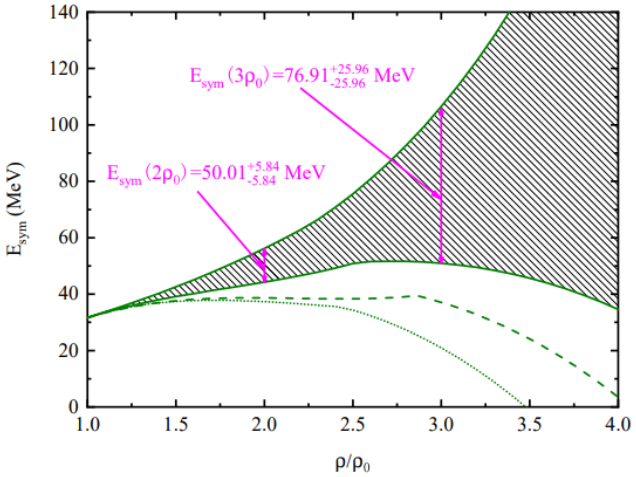
质子、超子等的内部（自旋）结构

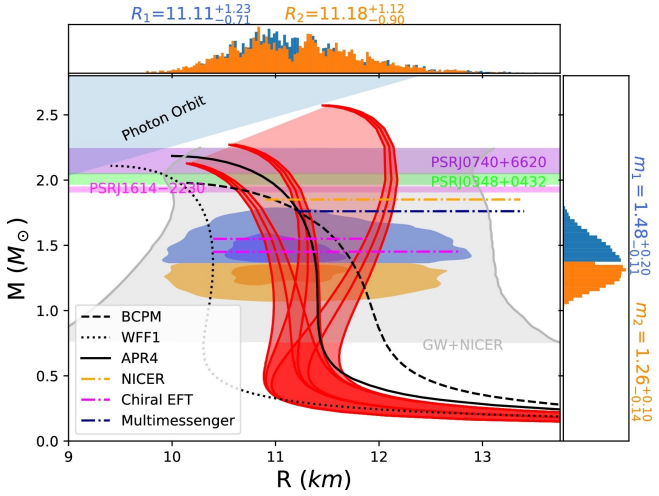
核物质相结构

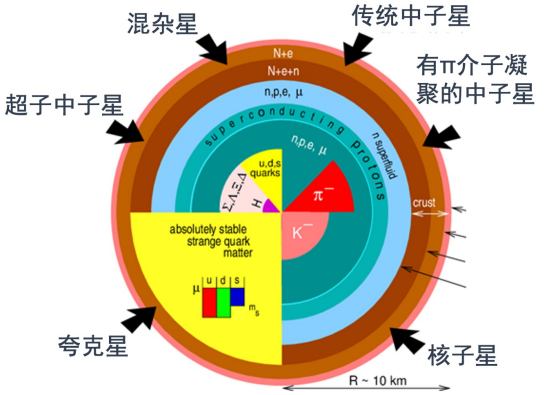


- 通过不同能量的重离子碰撞，能扫描核物质相图上的不同区域
- 寻找理论预言的一级相变和临界点

核物质状态方程

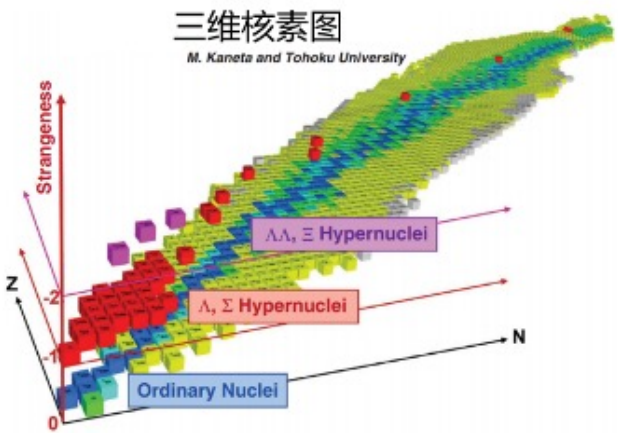


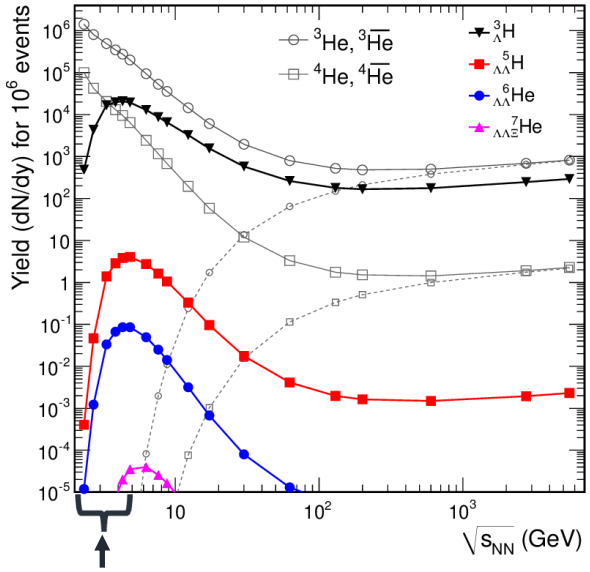




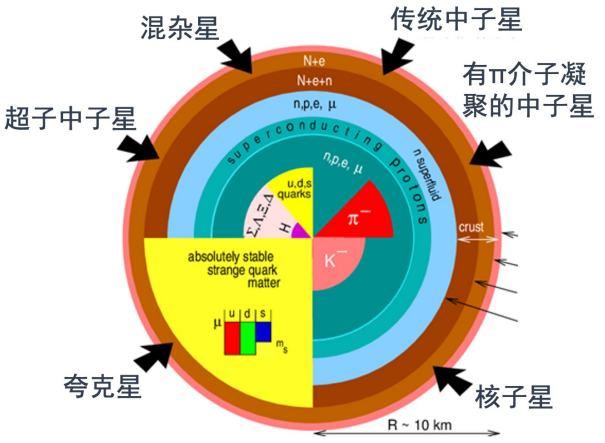
- 高密核物质状态方程
- ⇒ 中子星结构和性质

超核





HIAF & HIAF-U

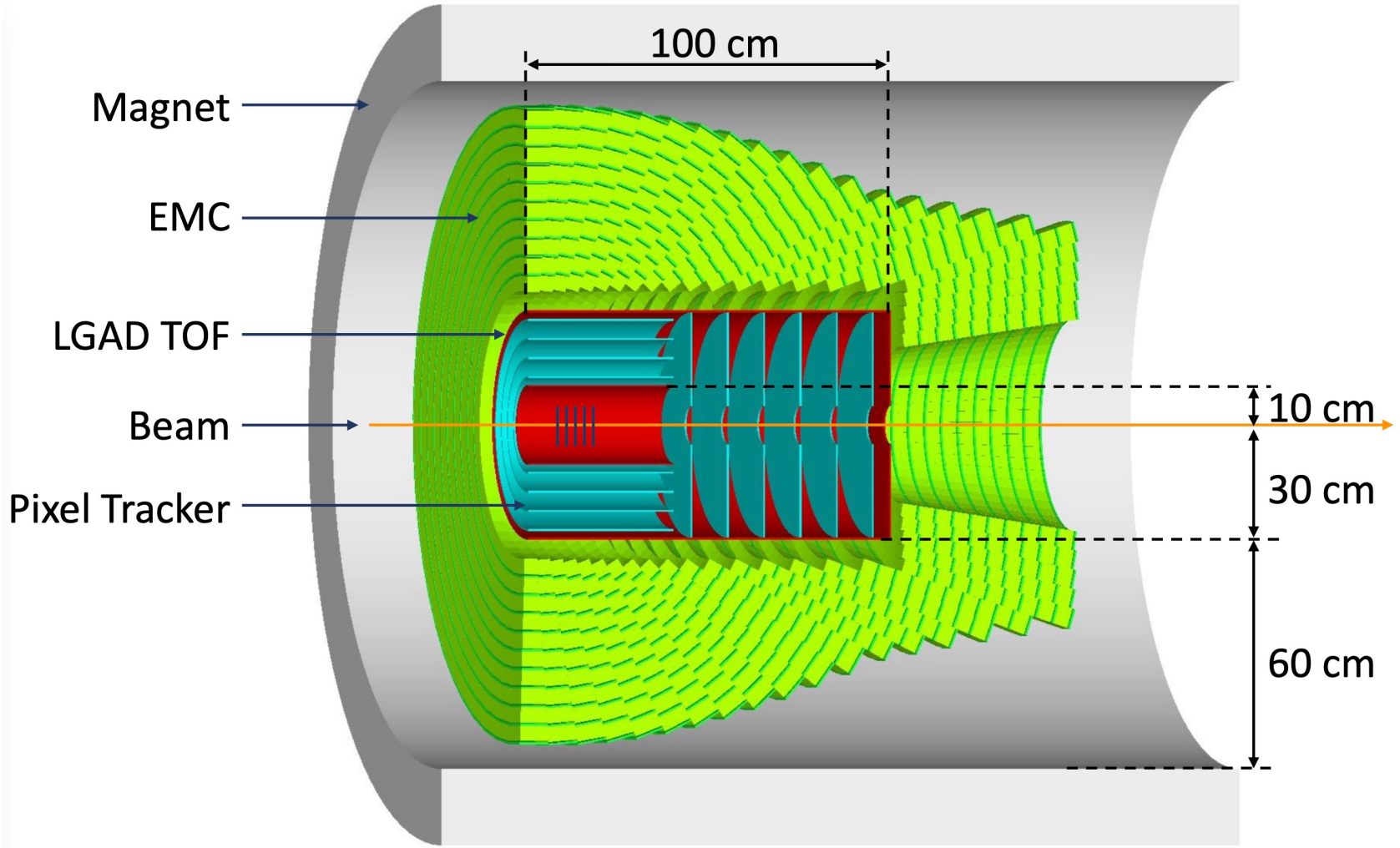


- 超核性质、（多奇异）超核的发现
- ⇒ 超子-核子、超子-超子相互作用
- ⇒ 中子星结构和性质

目录

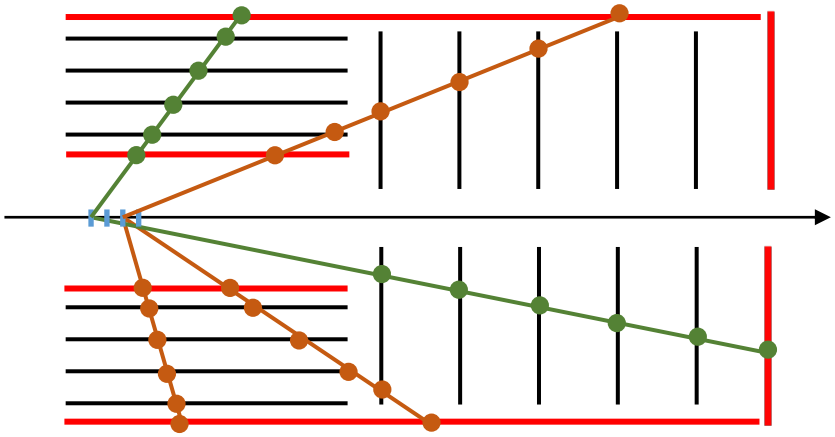
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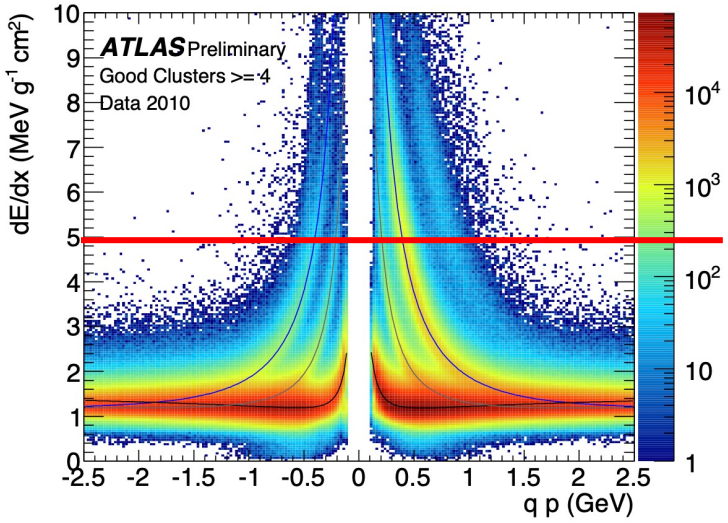
惠州强子谱仪(HHaS)概念设计



arXiv:2511.22864

5维硅像素径迹探测器

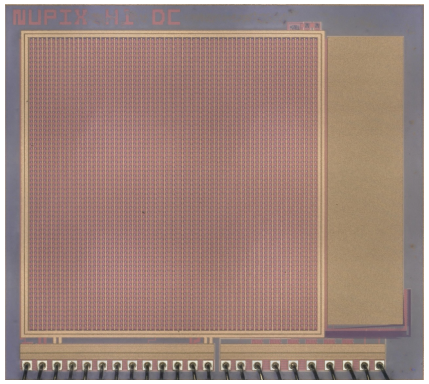


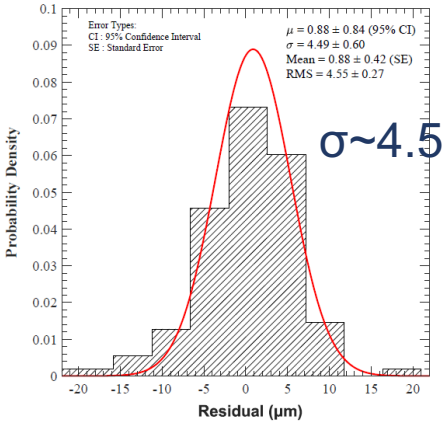


- 5维径迹探测：3维位置 + 时间 + 能量损失
  - 时间用于区分不同碰撞事例：Δt ~10ns (1/100MHz)
    - ⇒ 寻找稀有事例（如超出标准模型）、高精度测量所必需
  - 能量损失(dE/dx)用于区分不同轻核电荷Z（d, ^{4}He, ^{6}Li…）
    - ⇒ 超核等测量所必需
- 像素尺寸~<100μm ⇒ Δx ~<30μm
- X/X_0 ~ 0.3%
- 单pixel死时间~10μs ⇒ 控制高事例率时的占有度

5维硅像素径迹探测器

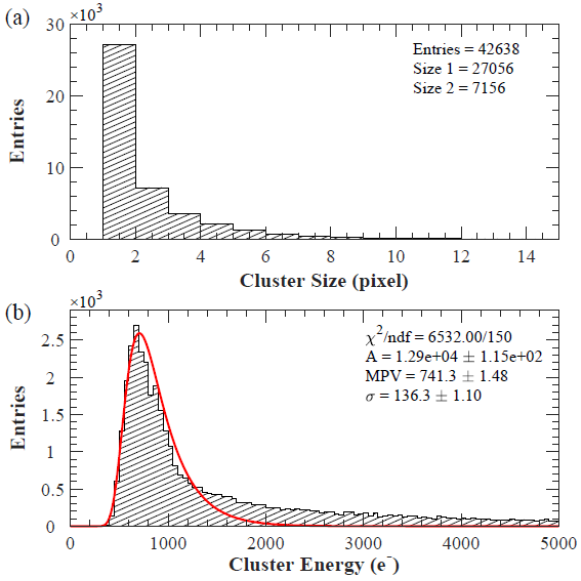
4维硅像素芯片Nupix-H1



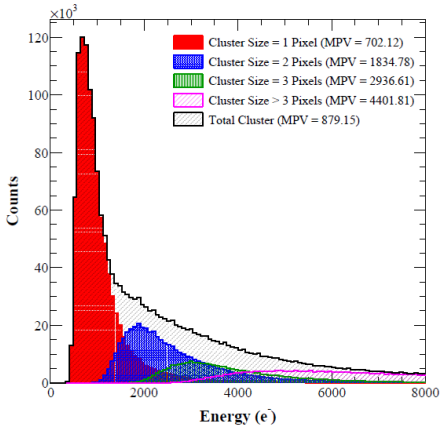


σ~4.5μm

激光测试位置分辨



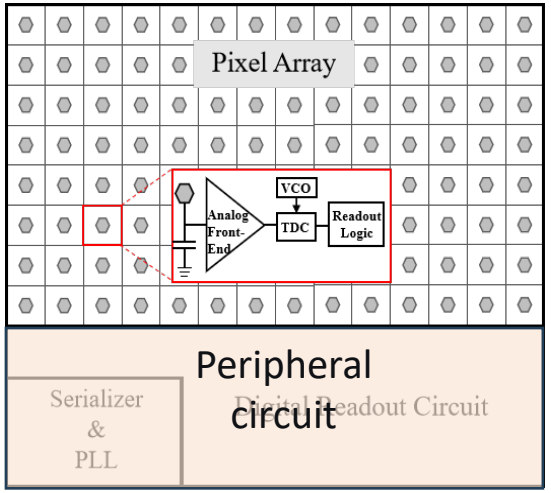
β源测试结果



质子束流测试能谱

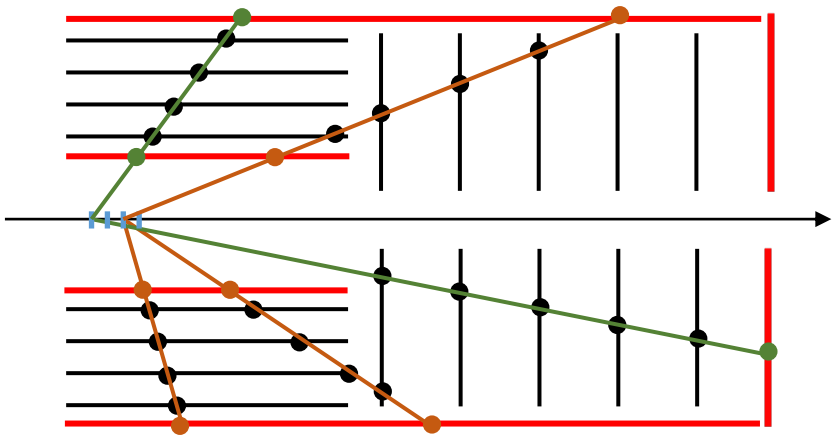
5维硅像素芯片

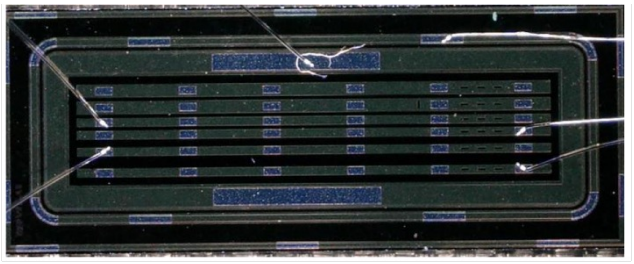
Nupix-H4设计

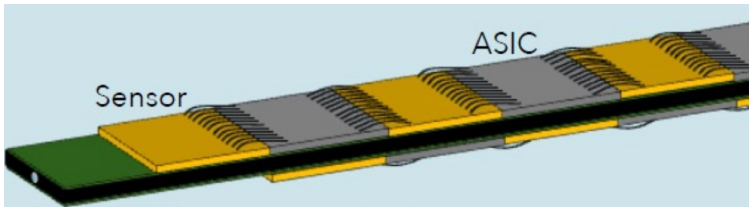


- 计划2026年中流片

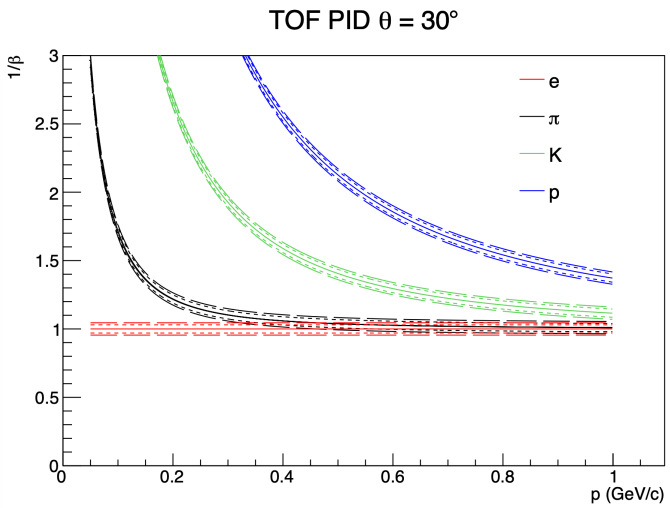
LGAD飞行时间探测器



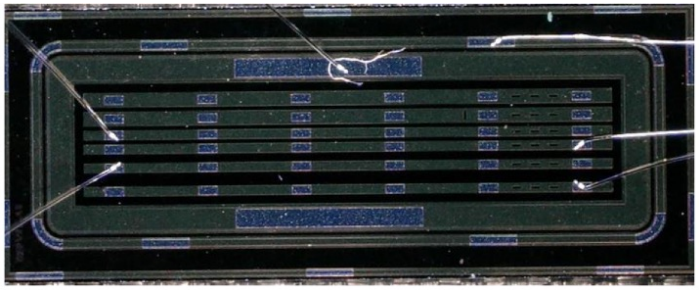


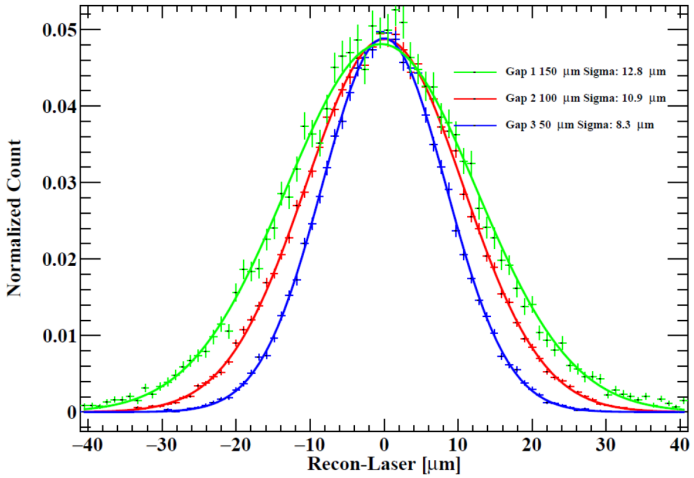


- 最内层测量起始时间，外层、端盖测量到达时间
- 带电粒子鉴别 + 进一步区分不同事例的径迹
- Δt~30ps
- 拟采用条状电极AC LGAD
  - $\Delta x_{r\varphi}$~<30μm ⇒ 同时用于径迹拟合
  - 片内无死区
- X/X_0 ~< 3%



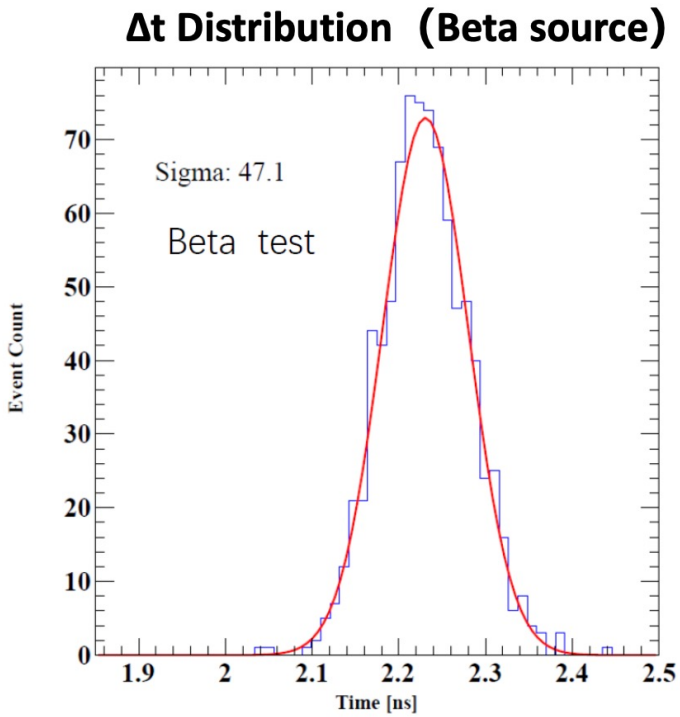
LGAD飞行时间探测器





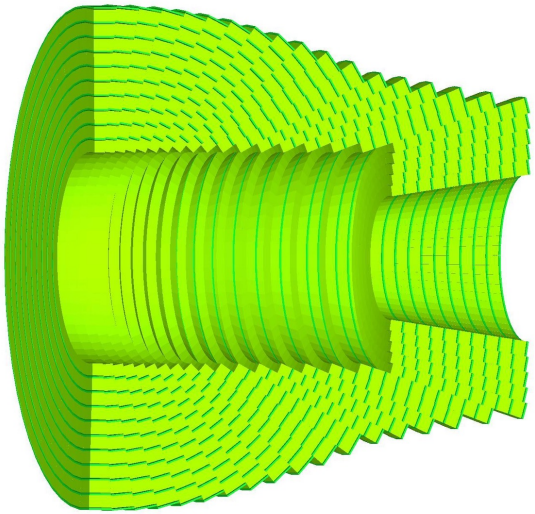
激光测试位置分辨

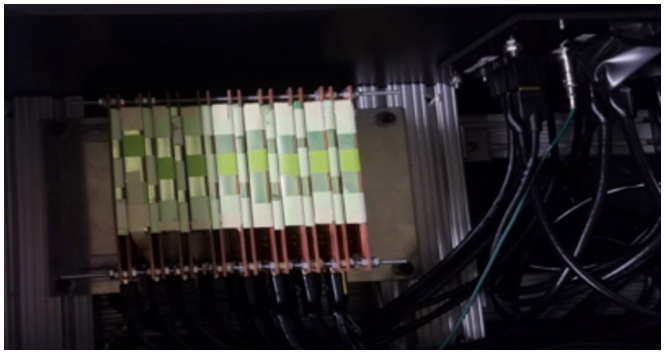
- 8.3 μm (150 μm pitch)
- 10.9 μm (200 μm pitch)
- 12.8 μm (250 μm pitch)

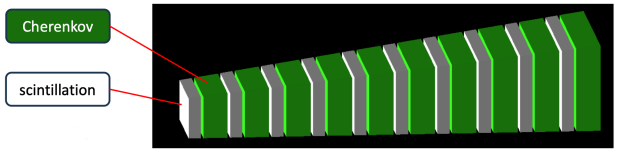


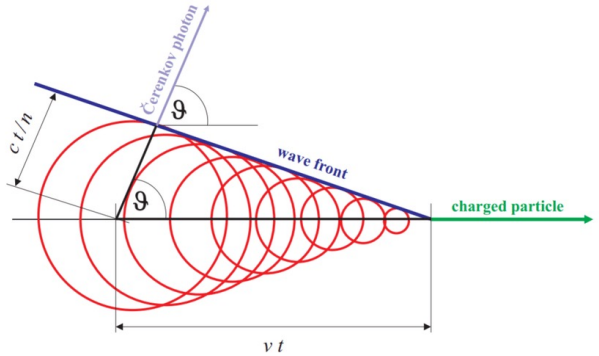
β源测试时间分辨：σ_t = 37.5 ps

双读出电磁量能器



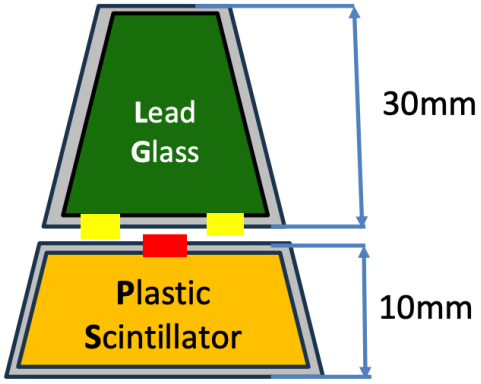


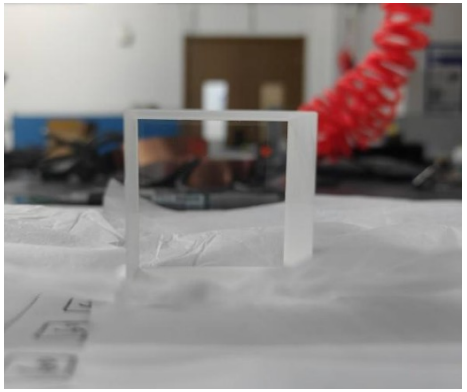


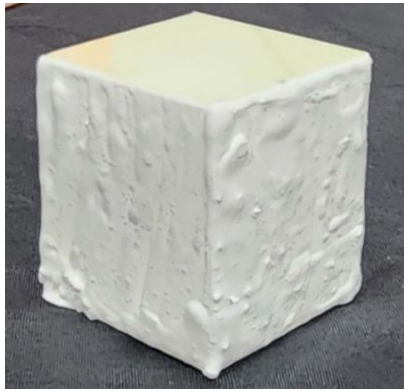


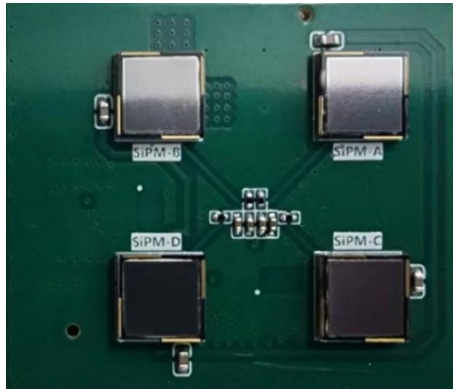
- REDTOP实验组研发的ADRIANO2式电磁量能器
- 铅玻璃+闪烁体双读出 ⇒ 很好的 e^{+-} vs. π^{+-} 、γ vs. n 鉴别能力
  - 铅玻璃：切伦科夫光，仅对电磁簇射敏感
  - 闪烁体：对电磁和强子簇射同时敏感
- ΔE/E ~ 3% @ 1GeV
- Δt ~ 200 ps，用于区分不同事例的信号
- 成型时间（模块死时间）~ μs，控制高事例率时的占有度

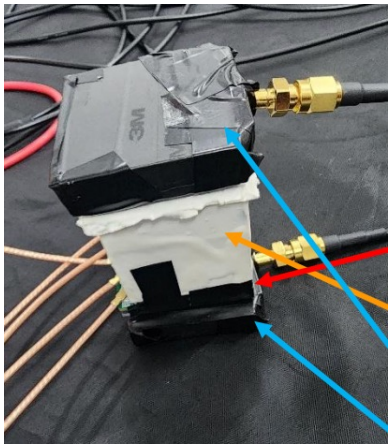
双读出电磁量能器

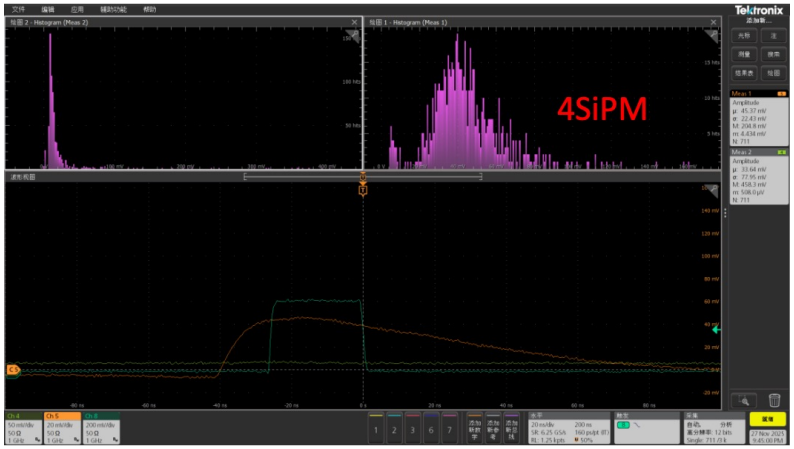


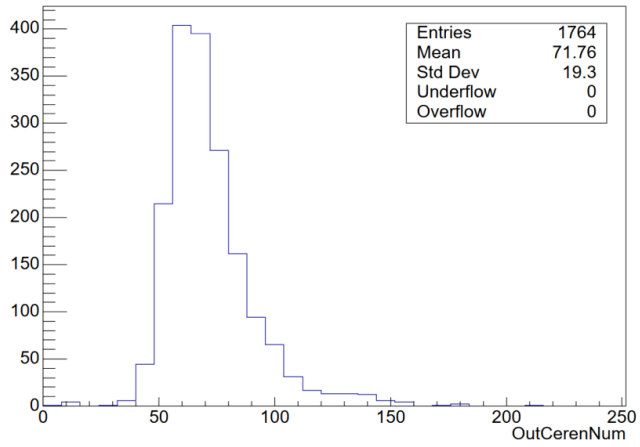




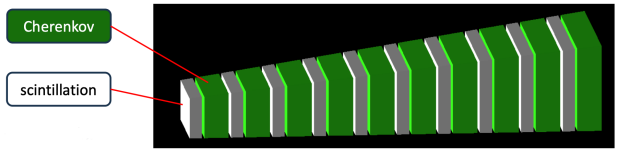








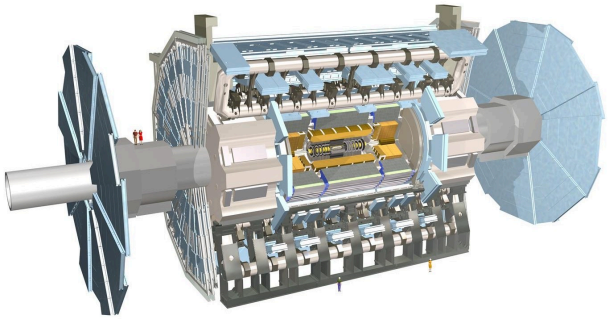
- 利用宇宙线研究了单块铅玻璃的切伦科夫光探测
  - 实测平均95光子，模拟平均71光子，比较接近
- 下一步将组装完整模块



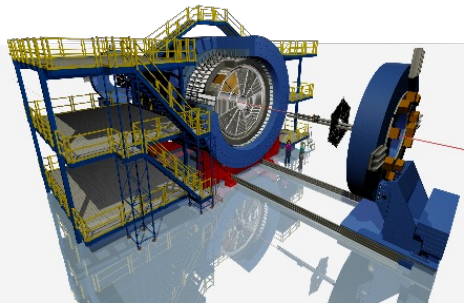
目录

- HIAF高能终端可能研究的物理
- 概念设计
- 各探测器
- 预期性能
- 部分模拟结果
- 国际竞争

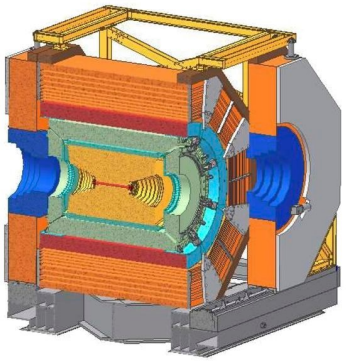
超高事例率



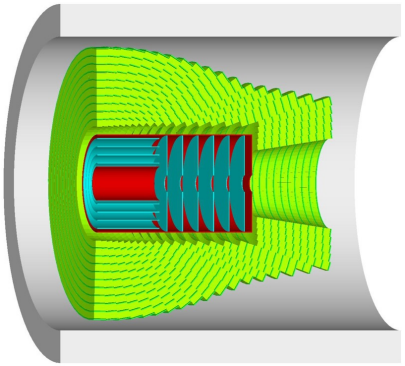
ATLAS: 100 kHz



STAR: 1 kHz

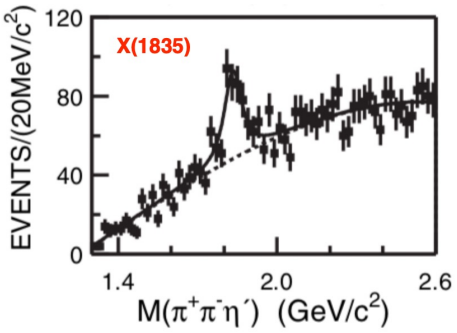


BESIII: 4 kHz



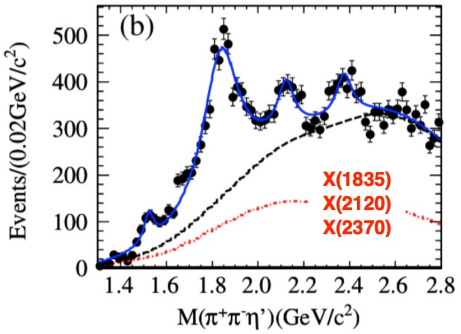
HHaS: 100 MHz

BESII PRL95 (2005) 262001



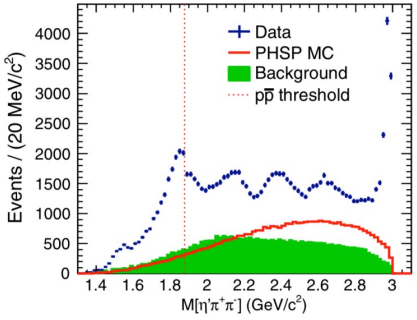
5800万J/ψ

BESIII PRL106 (2011) 072002



2.3亿J/ψ

BESIII PRL117 (2016) 042002



10亿J/ψ

BESIII PRL 132 (2024) 181901

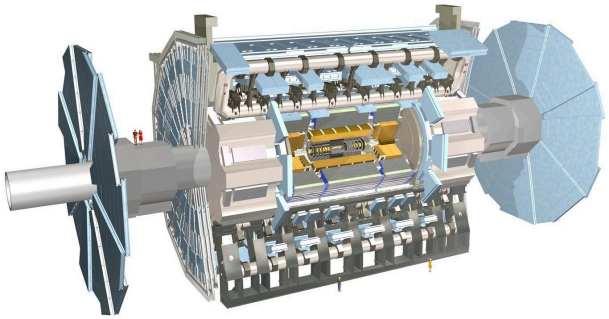
X(2370) $J^{PC} = 0^{-+}$

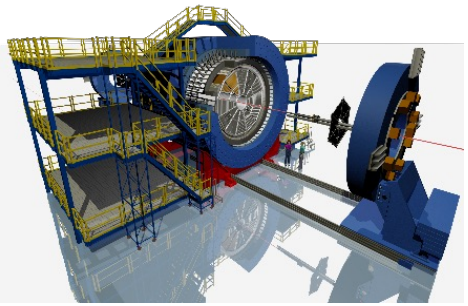
类胶球粒子

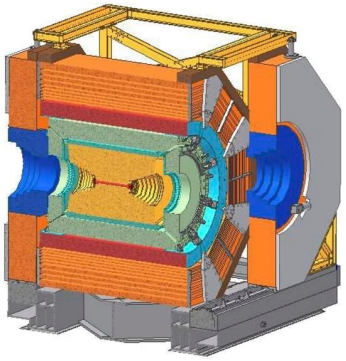
100亿J/ψ

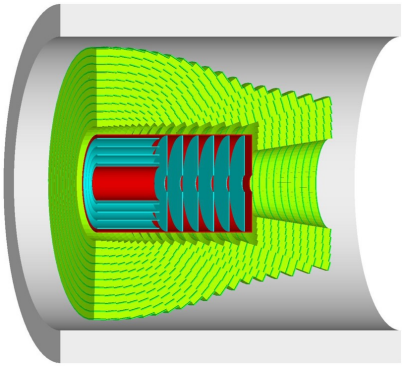
- HHaS事例率比当前主流实验高3-5个量级，大幅领先
- 高统计、高精度导致新发现

超高事例率



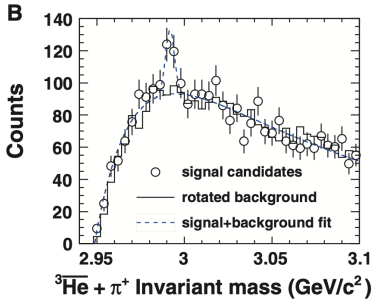




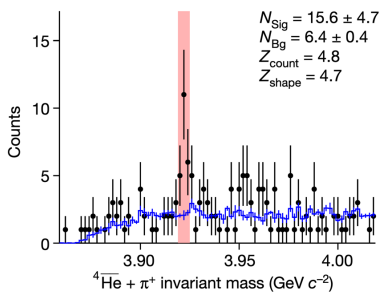


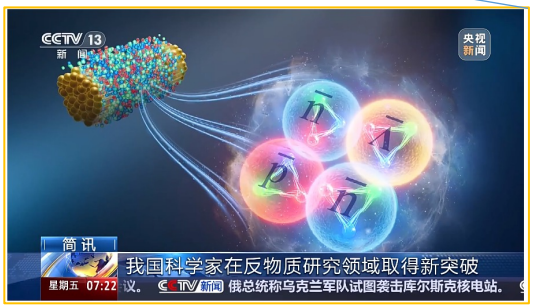
ATLAS: 100 kHz　　STAR: 1 kHz　　BESIII: 4 kHz　　HHaS: 100 MHz

STAR, Science 328 (2010) 58



STAR, Nature 632 (2024) 1026





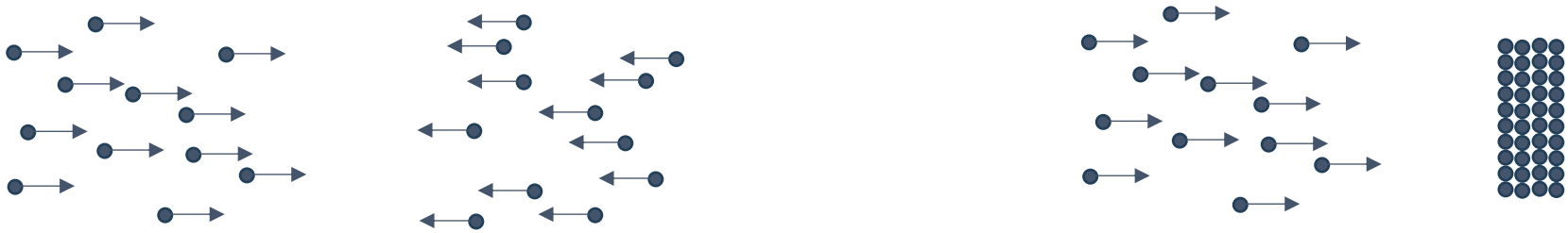
1分钟

首个反物质超核——反超氚　　实验观测到的最重反物质超核——反超氢-4

1.1亿事例　　2010年积累至今的60亿事例

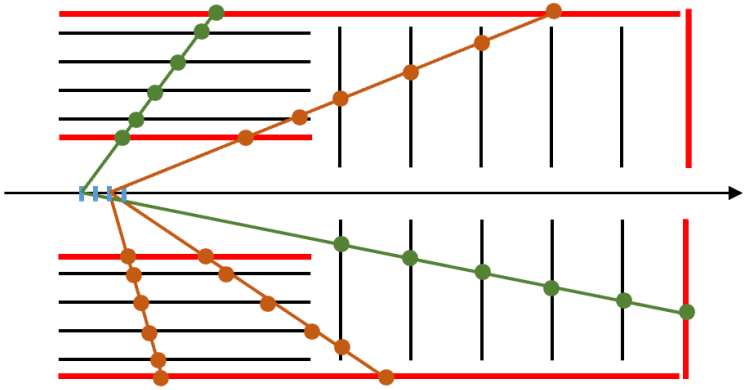
- HHaS事例率比当前主流实验高3-5个量级，大幅领先
- 高统计、高精度导致新发现

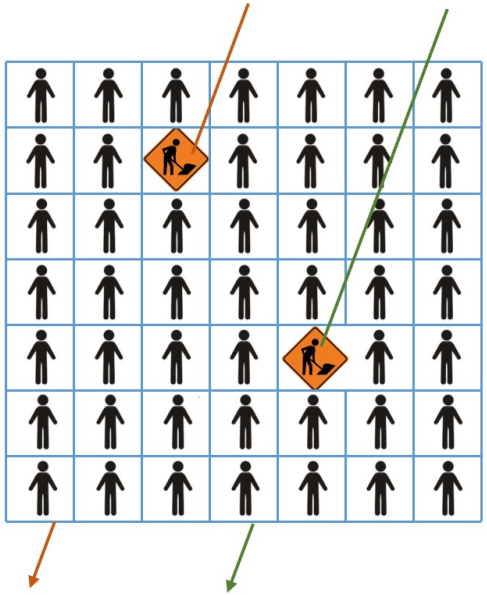
超高事例率



- 与对撞机相比，固定靶实验更容易达到高亮度
- 强流重离子加速器装置 (HIAF)
  - 0.3 秒内产生 2×10^{12} 个质子 ⇒ 最大碰撞事例率 ~10 GHz，远超当前实验探测器的能力
- 要充分利用 HIAF 的高流强，谱仪必须具备超高事例率
  - 近代物理所是最需要5维硅像素探测器的

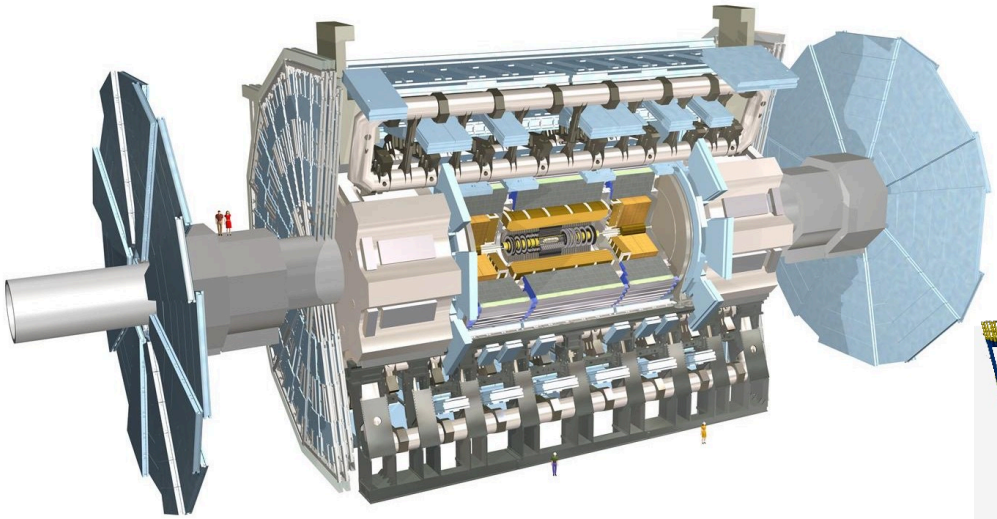
超高事例率



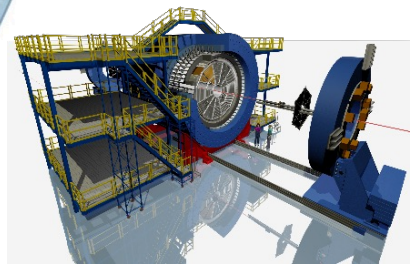


- 每个像素（读出条/量能器单元）记录击中的时间信息
  - 用于区分来自不同碰撞事例的信号
- 像素（读出条/量能器单元）并行工作，记录来自不同碰撞的信号
  - 类似于 GPU：大量像素 ⇒ 超高事件速率
  - 最内层像素超过 20M ⇒ 事件速率为 100 MHz 时占有度仅为 ~0.02%

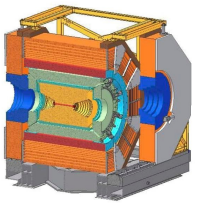
结构紧凑



ATLAS



STAR



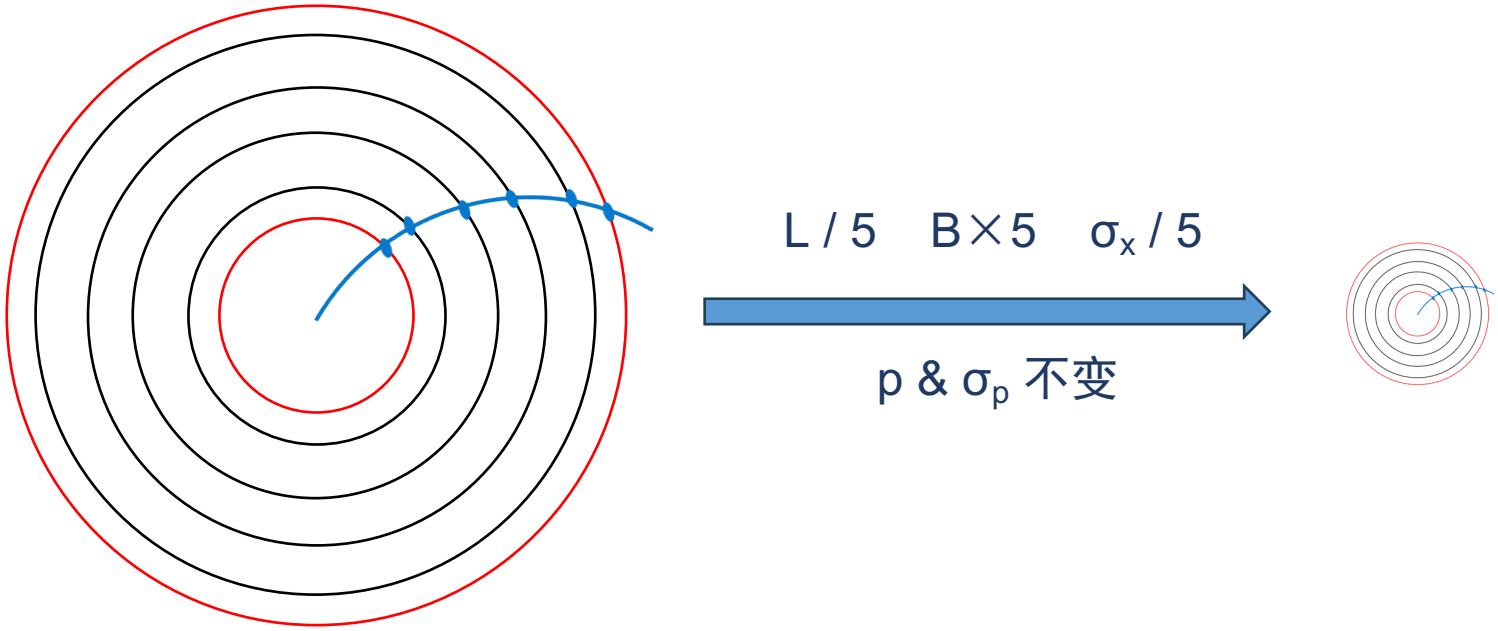
BESIII



HHaS

- 成本可控：~2亿元

结构紧凑

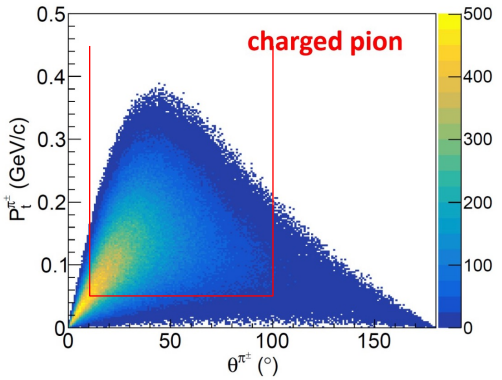


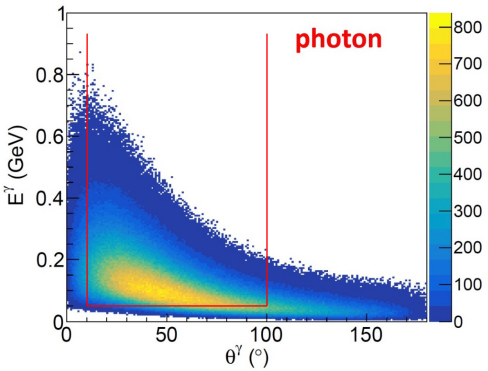
- 传统气体径迹探测器 σ_x ~ mm
- 像素 σ_x ~ 几十μm
- ⇒ R_{out} = 30 cm的HHaS像素径迹探测器具有与米量级气体探测器相似的 σ_p

性能预期

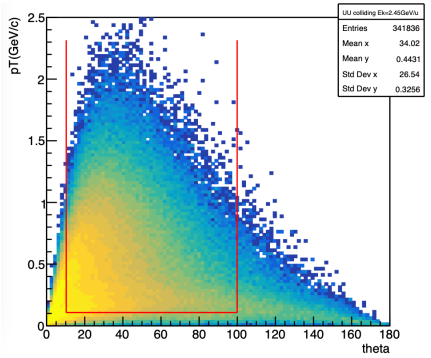
charged particles

$\eta \to \pi^+\pi^-\pi^0(\gamma\gamma)$

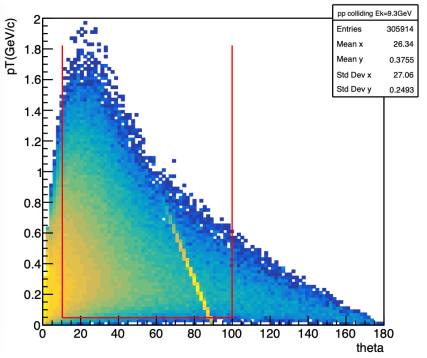




2.45GeV/u U+U



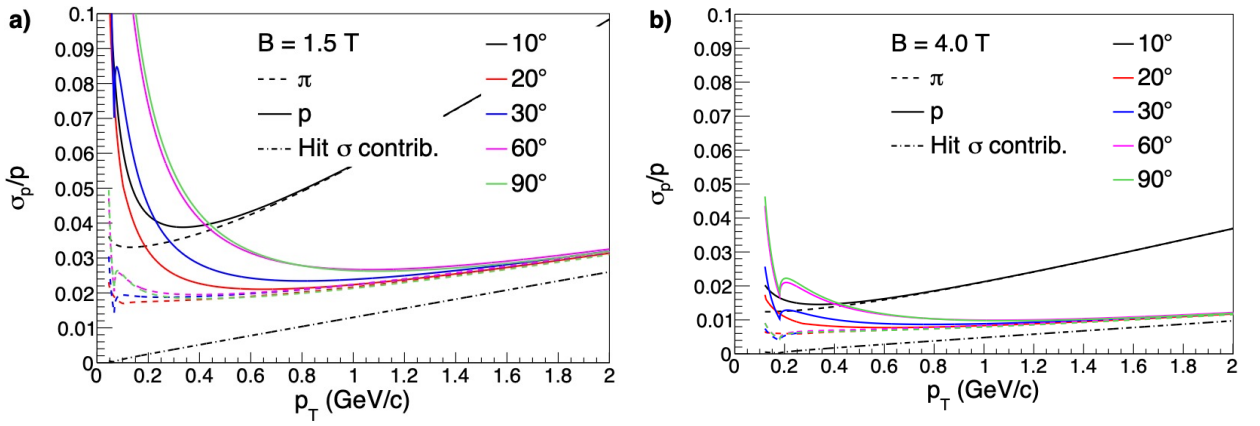
9.3GeV p+p



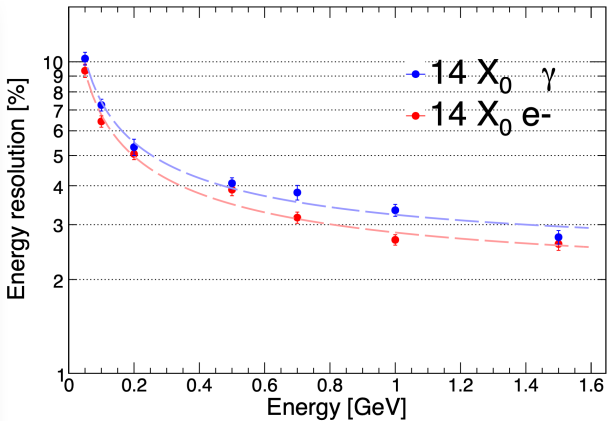
方位角、能动量覆盖

事例率	~100 MHz (p束流), ~1 MHz (重离子束流)
方位角覆盖	θ: 10˚~100˚; φ: 0~2π
带电粒子动量测量范围	p_T > 50 MeV (1.5 T磁场)
γ能量测量范围	E > 50 MeV
典型动量分辨	~1% (4 T磁场); ~3% (1.5 T磁场)
EM能量分辨	~3% @ 1GeV
典型径迹位置分辨	~0.9 mm (p @ 500 MeV/c)
鉴别粒子	e^{+-}, γ, π^{+-}, K^{+-}, p, d, t, ^{3}He, ^{4}He

性能预期



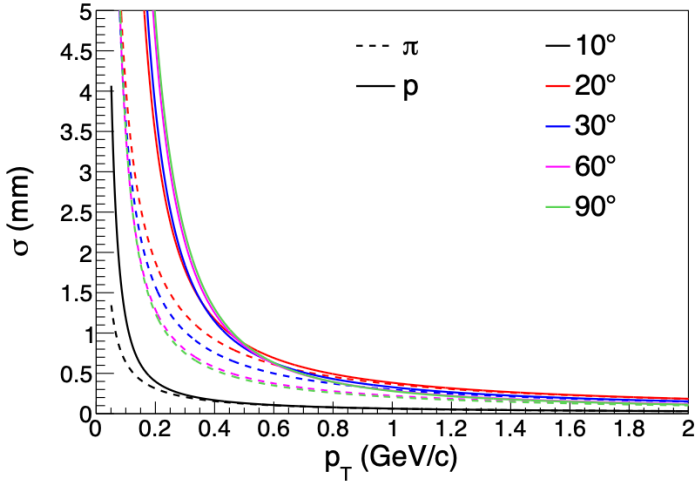
动量分辨



EM能量分辨

事例率	~100 MHz (p束流), ~1 MHz (重离子束流)
方位角覆盖	θ: 10˚~100˚; φ: 0~2π
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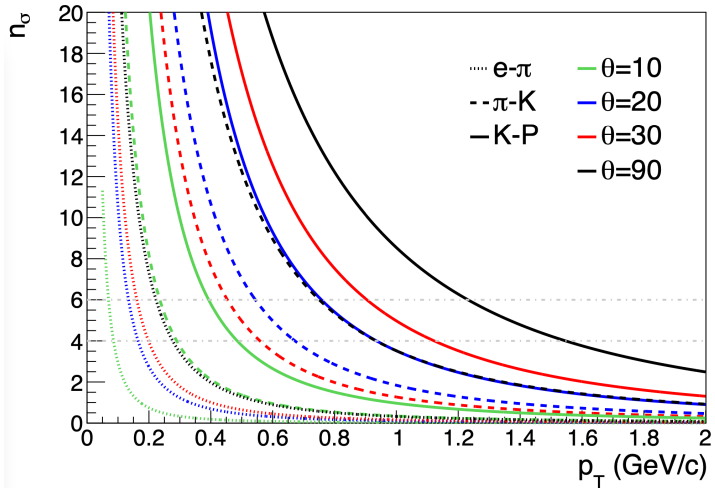
性能预期



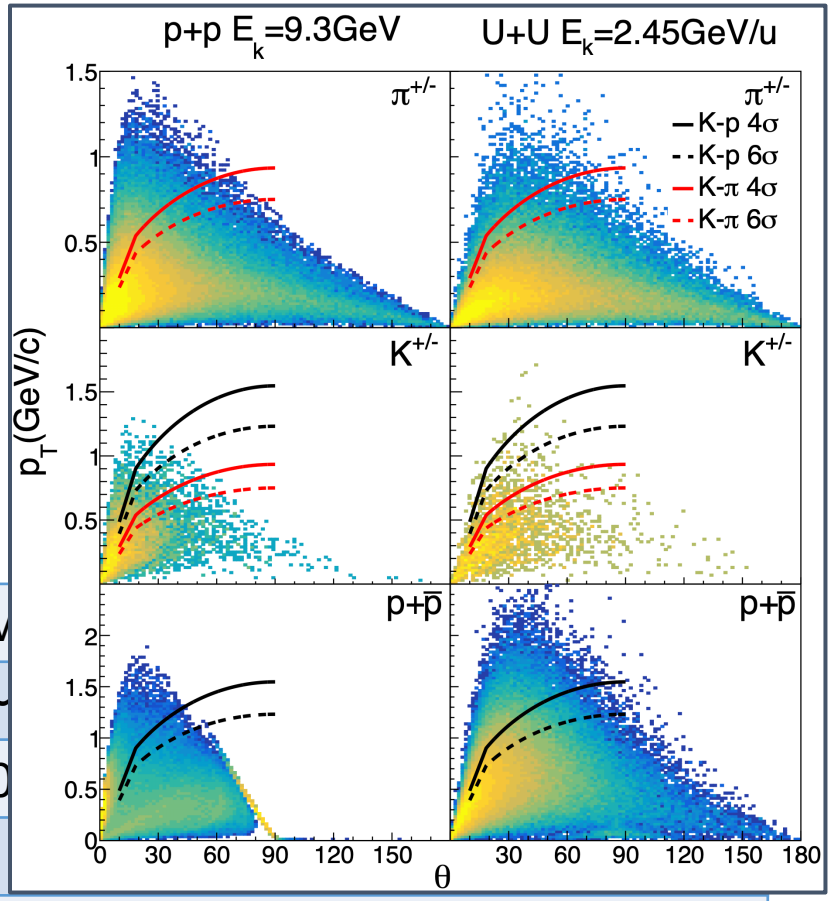
径迹指向位置分辨

事例率	~100 MHz (p束流), ~1 MHz (重离子束流)
方位角覆盖	θ: 10˚~100˚; φ: 0~2π
带电粒子动量测量范围	p_T > 50 MeV (1.5 T磁场)
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性能预期

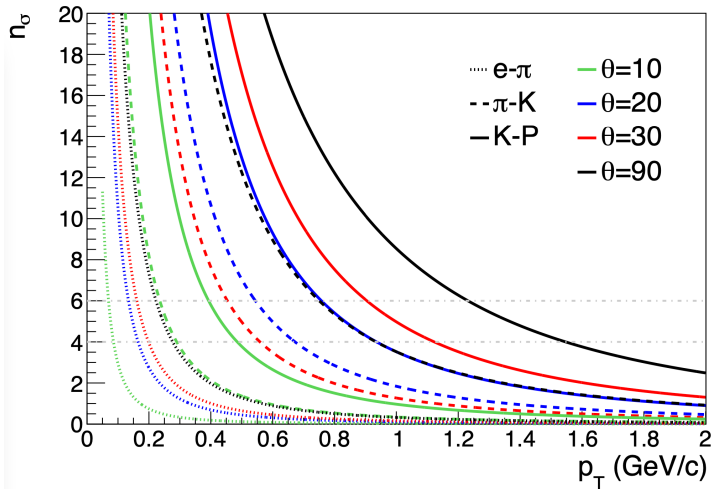


TOF粒子鉴别能力



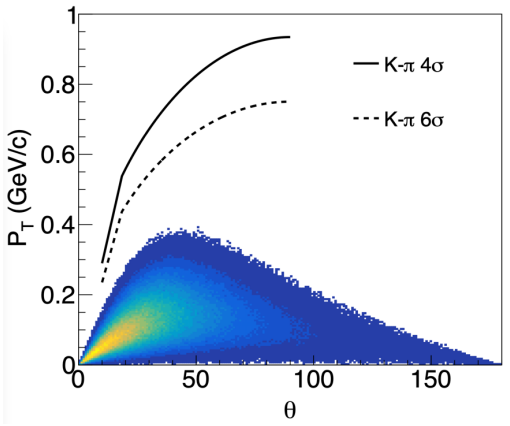
事例率	~100 M
方位角覆盖	θ: 10°~
带电粒子动量测量范围	p_T > 50
γ能量测量范围	E > 50
典型动量分辨	~1% (4 T磁场); ~3% (1.5 T磁场)
EM能量分辨	~3% @ 1GeV
典型径迹位置分辨	~0.9 mm (p @ 500 MeV/c)
鉴别粒子	e^{+-}, γ, π^{+-}, K^{+-}, p, d, t, ^{3}He, ^{4}He

性能预期



TOF粒子鉴别能力

$\eta \to \pi^+\pi^-\pi^0(\gamma\gamma)$

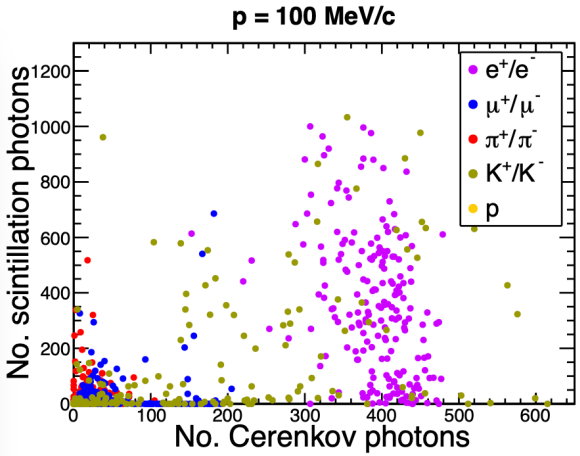


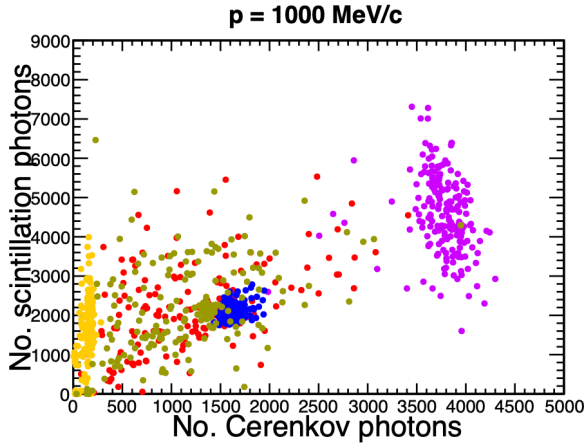
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带电粒子动量测量范围	p_T > 50 MeV (1.5 T磁场)
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鉴别粒子	e^{+-}, γ, π^{+-}, K^{+-}, p, d, t, ^{3}He, ^{4}He

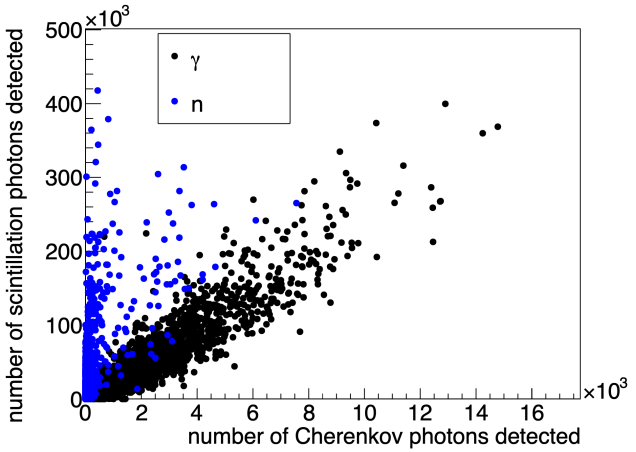
性能预期

双读出量能器EM vs. 强子簇射鉴别









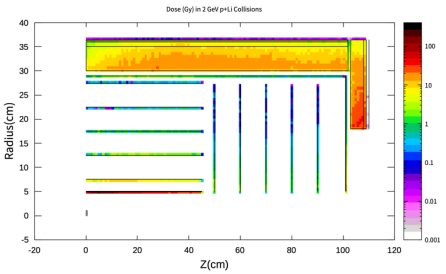
事例率	~100 MHz (p束流), ~1 MHz (重离子束流)
方位角覆盖	θ: 10˚~100˚; φ: 0~2π
带电粒子动量测量范围	p_T > 50 MeV (1.5 T磁场)
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鉴别粒子	e^{+-}, γ, π^{+-}, K^{+-}, p, d, t, ^{3}He, ^{4}He

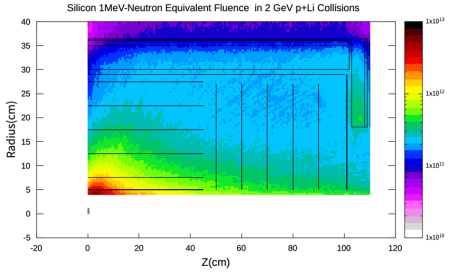
数据率估计

- pixel:
  - 100 MHz * 4 track / event * 4 hits / track * 2 pixel / hit * 8 Byte / pixel = 26 GB/s
- LGAD TOF:
  - 100 MHz * 4 track / event * 2 hits / track * 2 strip / hit * 6 Byte / strip = 10 GB/s
- EMC:
  - 100 MHz * 0.4 γ / event * 9 towers / γ * 8 Byte / tower = 3 GB/s
- 总共 39 GB/s
- 作为参考，CEE设计数据率 5 GB/s

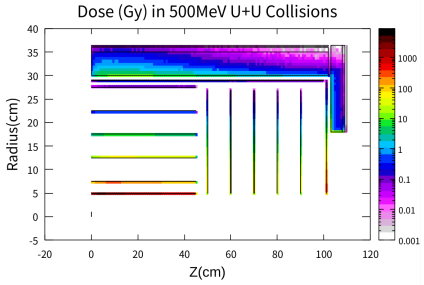
辐射剂量模拟

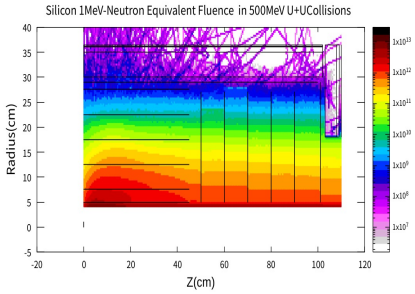
2 GeV p+Li，100MHz，1个月





500 MeV U+U，1MHz，1个月

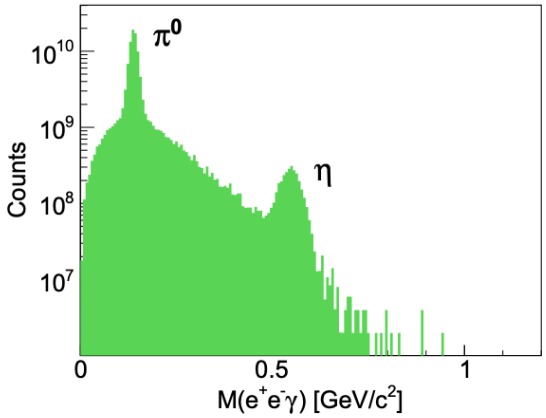


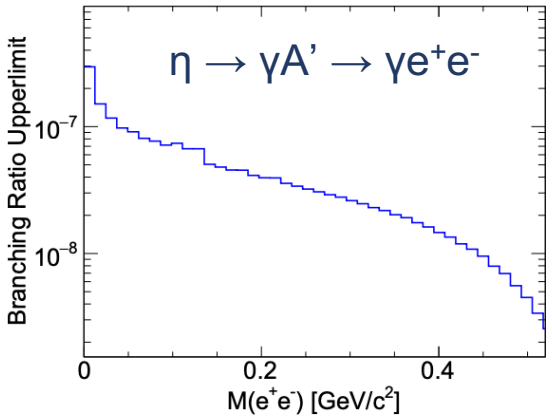


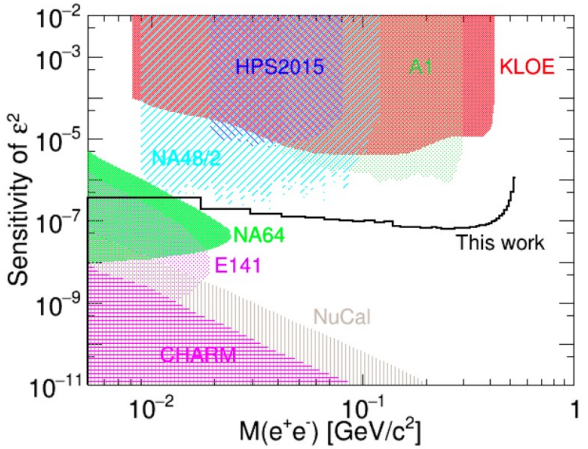
	FLUKA模拟结果		参考抗辐照性能		
	辐射剂量 (Gy)	Si1MeV等效中子通量(n_{eq}/cm^2)	探测器/材料	辐射剂量 (Gy)	Si1MeV等效中子通量 (n_{eq}/cm^2)
最内层硅	3000	3×10^{12}	pixel	2×10^{4}	1.7×10^{13}
			LGAD		1×10^{15}
最内层EMC	50	3×10^{11}	铅玻璃	20	
			SiPM		1×10^{14}

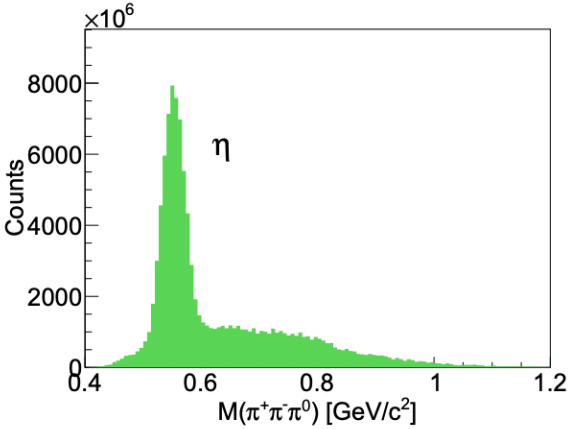
- 大部分探测器部件、材料可以满足抗辐照要求
- 铅玻璃收到的辐射剂量接近其极限，需要选择测试

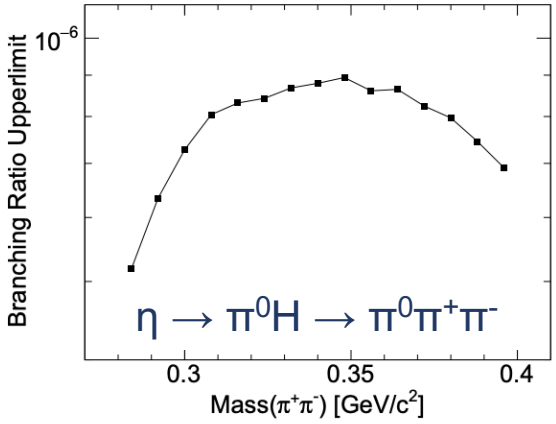
η介子物理模拟-暗光子、暗Higgs

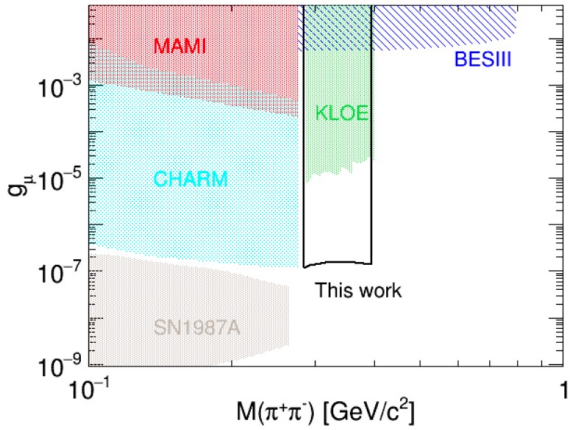












- 1.8 GeV p + ^{7}Li

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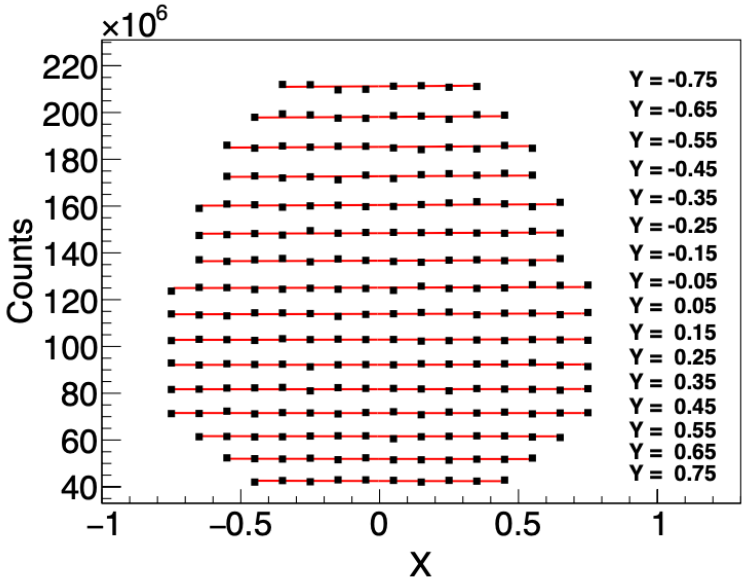
- 100MHz事例率，一个月，平均流强/峰值流强 = 30%
- 共产生6 × 10^{11} 个η

η介子物理模拟- C&CP对称性

$$u \equiv (p_{\pi^+} + p_{\pi^0})^2$$
$$t \equiv (p_{\pi^-} + p_{\pi^0})^2$$
$$s \equiv (p_{\pi^+} + p_{\pi^-})^2$$

$$X \equiv \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{Q_\eta} = \frac{\sqrt{3}}{2m_\eta Q_\eta}(u-t),$$
$$Y \equiv \frac{3T_{\pi^0}}{Q_\eta} - 1 = \frac{3}{2m_\eta Q_\eta}[(m_\eta - m_{\pi^0})^2 - s] - 1,$$

$$N(X,Y) = N_0(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + ...),$$



- 1.8 GeV p + ^{7}Li

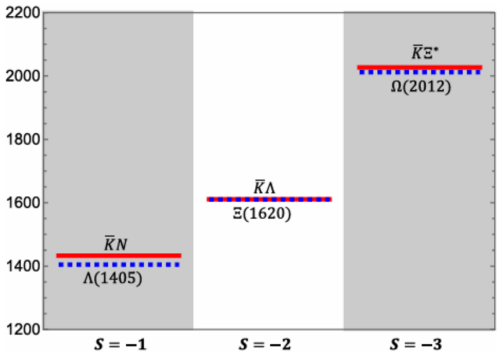
Nuclear Science and Techniques (2025) 36:137

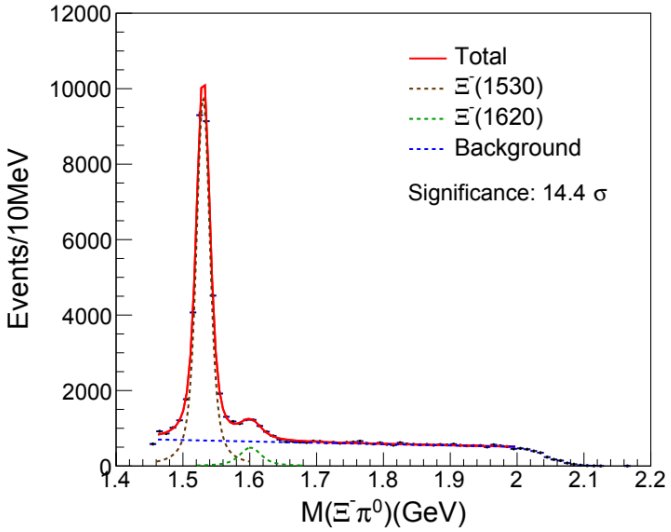
- 100MHz事例率，一个月，平均流强/峰值流强 = 30%
- Δc ~ 5 × 10^{-5}
  - 比COSY和KLOE-II现有结果精确~2个量级

Ξ(1620)⁻模拟

$$K^- p \rightarrow \Xi(1620)^- K^+ \rightarrow \Xi^- \pi^0 K^+$$

$$\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^- \qquad \pi^0 \rightarrow \gamma\gamma$$





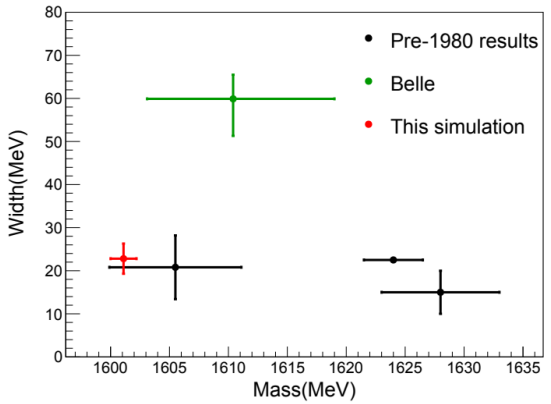
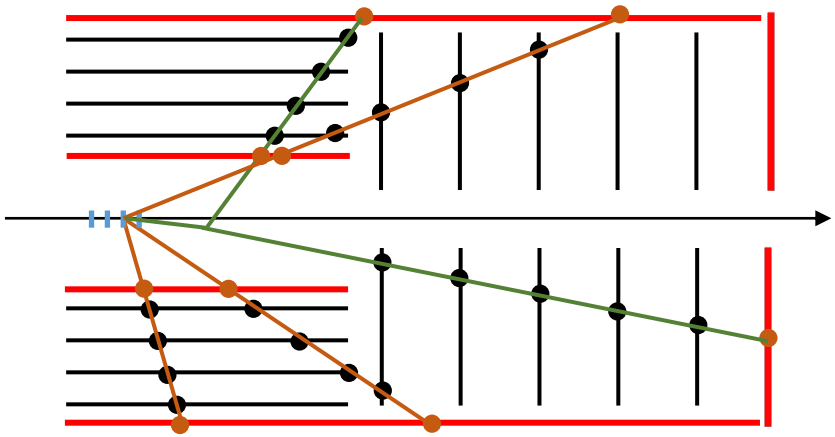
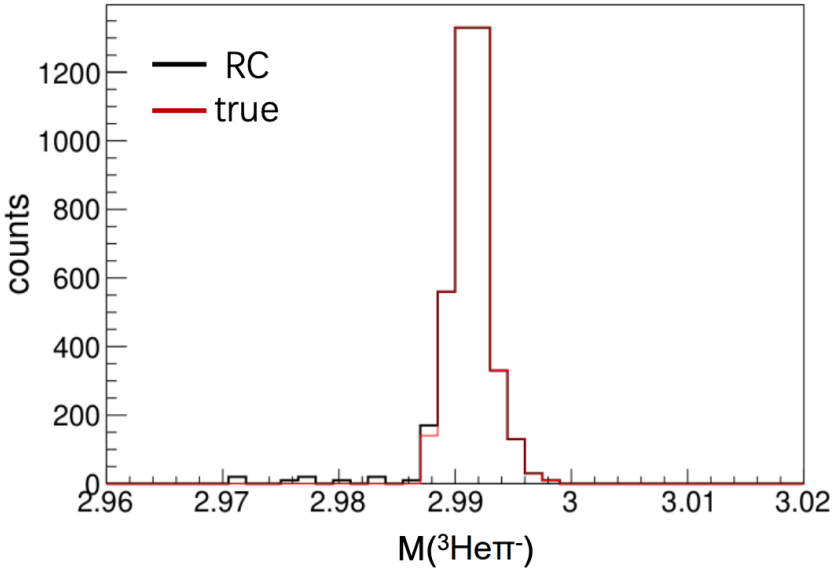


Fig. 7 Width versus mass of the $\Xi(1620)^-$ resonance from this simulation work comparing with previous experimental measurements of $\Xi(1620)^0$ [13-16].

- Ξ(1620)是超子五夸克态候选者，Ξ(1620)⁰已发现
- 使用一个月数据，预期能以~14σ显著度发现Ξ(1620)⁻
- 能动量分辨足以区分Ξ(1620)⁻与旁边的Ξ(1530)⁻

超核重建模拟





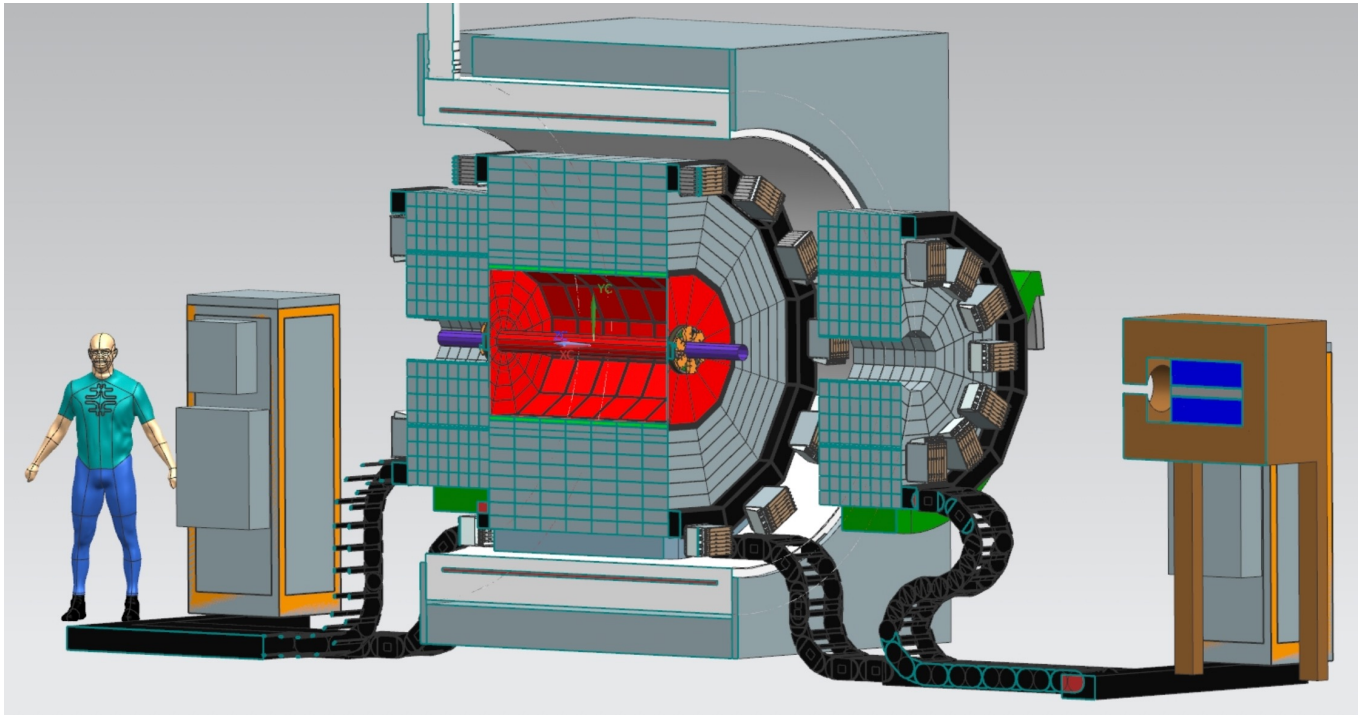
- ~1mm的位置分辨能力

  ⇒ 几乎无本底的超核等弱衰变粒子重建

目录

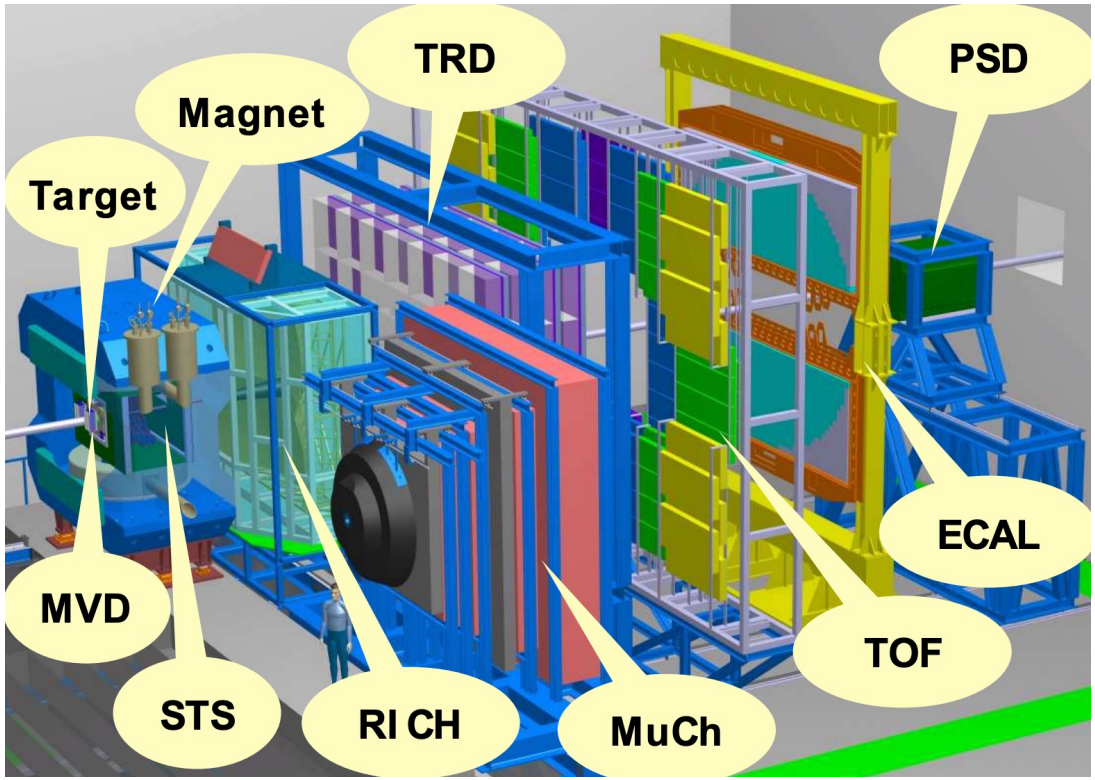
- HIAF高能终端可能研究的物理
- 概念设计
- 各探测器
- 预期性能
- 部分模拟结果
- 国际竞争

国际竞争 - REDTOP



- 82-152 M USD，5.6 – 10亿元
- 处于争取加速器实验室、经费支持阶段
- 无dE/dx测量，无法满足相结构、超核研究需求
- 电磁+强子量能器

国际竞争 - CBM



- 55M欧元，4亿元
- 计划2028年建成
- 事例率<10MHz，无更高的质子打靶事例率
- 低能区方位角覆盖不足

合作组



- 十几家单位，几十位合作者
- 欢迎加入

Huizhou Hadron Spectrometer - a Proposed High-rate Experimental Setup at the High Intensity Heavy-ion Accelerator Facility*

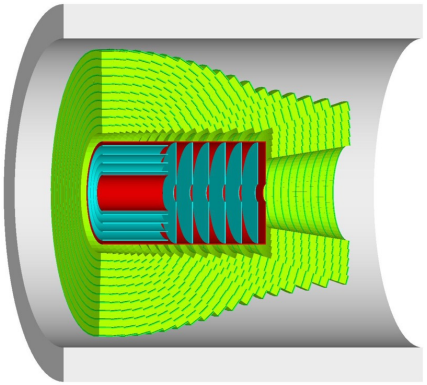
Xurong Chen,[1,2,3] Yunyun Fan,[4,5] Shuangshi Fang,[4,5,6] Zhaoqing Feng,[7,1] Fengkun Guo,[8,5,3] Weijia Han,[1] Jun He,[9] Qinghua He,[10] Xionghong He,[1,2] Hongxia Huang,[9] Xiaolin Kang,[11] Hongli Ma,[12] Weihu Ma,[13] Yongliang Ma,[14] Norihito Muramatsu,[1] Zaiba Mushtaq,[1,2] Xiaoyang Niu,[1,2] Jialun Ping,[9] Hao Qiu,[1,2] Jun Shi,[15,16] Ye Tian,[1] Qian Wang,[15,16] Rong Wang,[1,2] Shuaichun Wang,[13] Xiaoyun Wang,[17] Jiajun Wu,[5,3] Chuwen Xiao,[18] Jujun Xie,[1,2,3] Haibo Yang,[1,2] Xieyang Yu,[1,2] Honglin Zhang,[1] Shenghui Zhang,[12] Chengxin Zhao,[1] Kuangta Chao,[19] Qiang Zhao,[4] and Bingsong Zou[20]

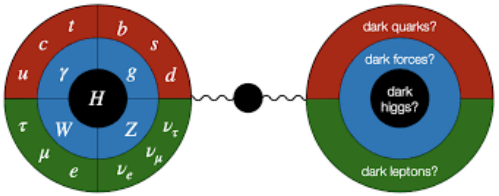
[1]*State Key Laboratory of Heavy Ion Science and Technology, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2]*School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*Southern Center for Nuclear-Science Theory (SCNT), Institute of Modern Physics, Chinese Academy of Sciences, Huizhou 516000, China*
[4]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[5]*School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
[6]*Center for High Energy Physics, Henan Academy of Sciences, Zhengzhou 450046, China*
[7]*School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China*
[8]*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*
[9]*Department of Physics, Nanjing Normal University, Nanjing 210023, China*
[10]*Department of Nuclear Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[11]*School of Mathematics and Physics, China University of Geosciences, Wuhan 430074, China*
[12]*Department of Physics, Chongqing Key Laboratory for Strongly Coupled Physics, Chongqing University, Chongqing 401331, China*
[13]*Institute of Modern Physics, Fudan University, Shanghai 200433, China*
[14]*School of Frontier Sciences, Nanjing University, Suzhou, 215163, China*
[15]*State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China*
[16]*Guangdong Basic Research Center of Excellence for Structure and Fundamental Interactions of Matter, Guangdong Provincial Key Laboratory of Nuclear Science, Guangzhou 510006, China*
[17]*Department of Physics, Lanzhou University of Technology, Lanzhou 730050, China*
[18]*Department of Physics, Guangxi Normal University, Guilin 541004, China*
[19]*School of Physics and Center for High Energy Physics, Peking University, Beijing 100871, China*
[20]*Department of Physics and Center for High Energy Physics, Tsinghua University, Beijing 100084, China*

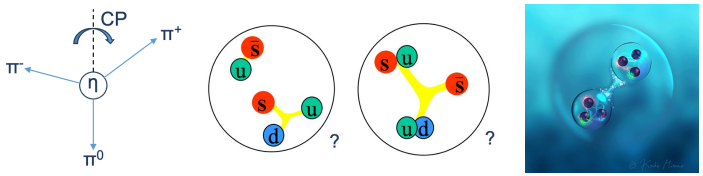
arXiv:2511.22864

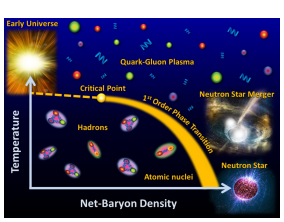
小结

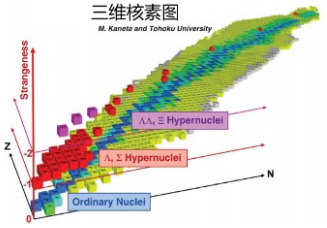
- 惠州强子谱仪(HHaS)
  - 先进的探测器技术
    - 5维硅像素径迹探测器
    - LGAD飞行时间探测器
    - 切伦科夫-闪烁光双读出电磁量能器
  - 优异的性能
    - 超高事例率：~1亿事例/秒 (质子束流)
    - 大接受度
    - 全面的粒子鉴别：
      - e^{+-}, γ, π^{+-}, K^{+-}, p, d, t, ^{3}He, ^{4}He
  - 紧凑尺寸 ⇒ 造价可控 ~2亿
  - 具有与CBM+REDTOP相当的性能和潜力
  - 可以研究广泛的物理
    - 暗物质门户粒子、轻味五夸克态。。。











谢谢 欢迎加入☺

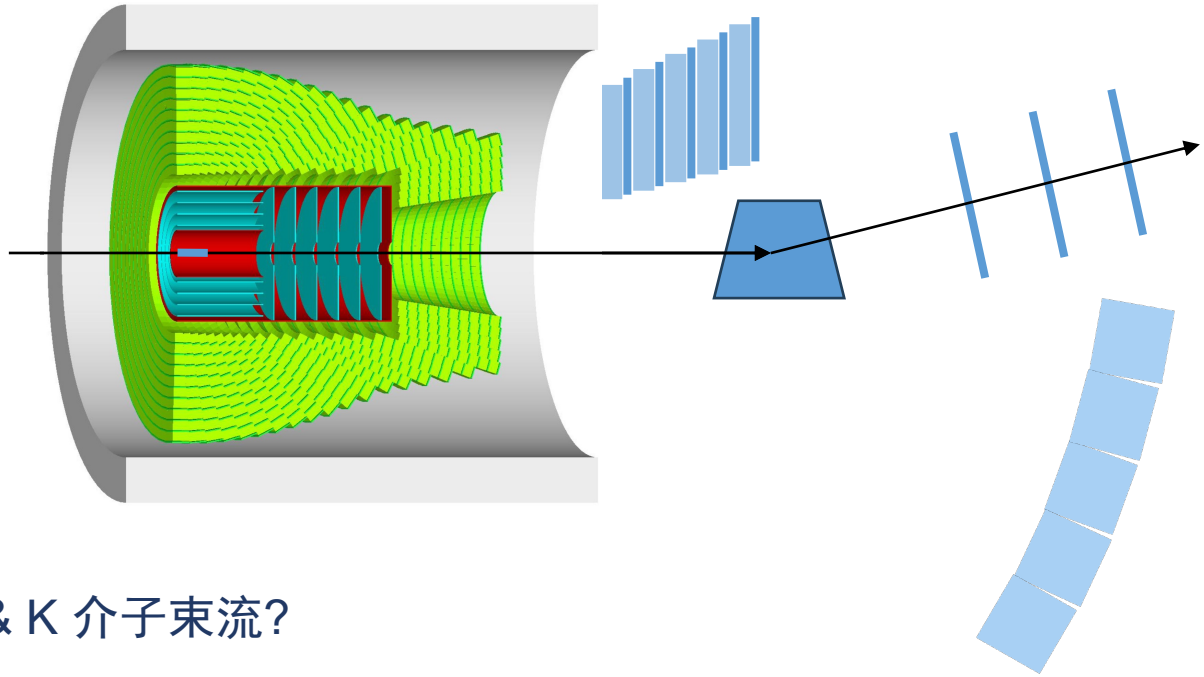
未来的未来

极化束流、靶?

- 自旋物理

缪子探测器：塑料 + MRPC?

- η介子物理增加>2倍衰变道



类弹粒子探测器?

- 类弹超核
- 短程关联

π & K 介子束流?

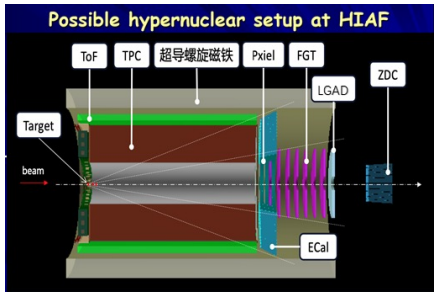
- η介子物理研究更干净
- 轻强子& 超核

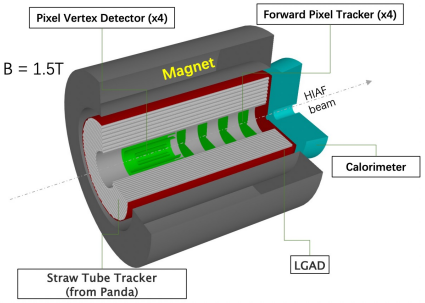
中子墙：液闪?

- 轻强子物理
- 短程关联

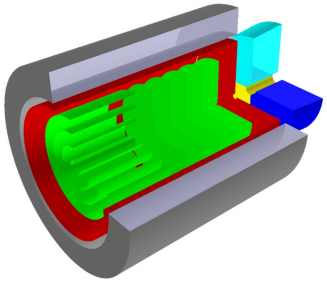
- 欢迎新想法+贡献

Back-up

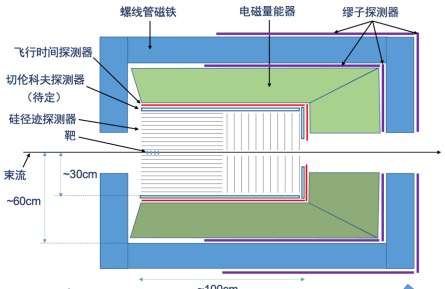




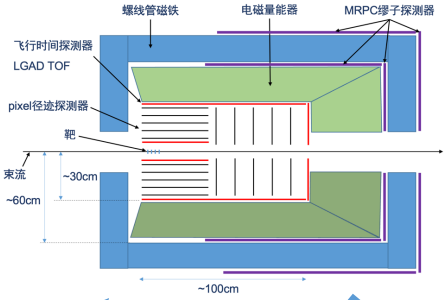
2024.8



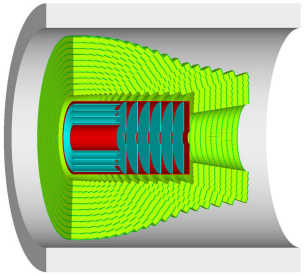
现在



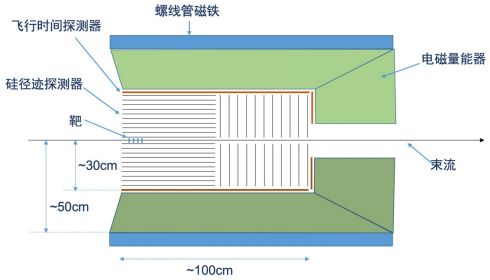
2022.9



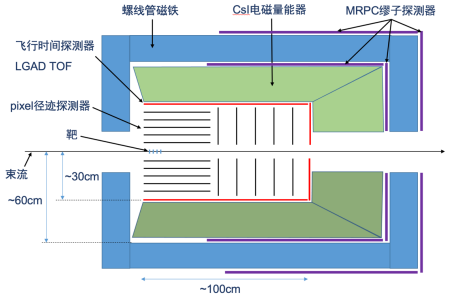
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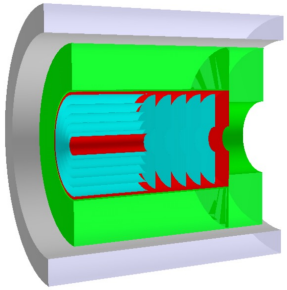
现在



2022.8



2022.12



2024.8

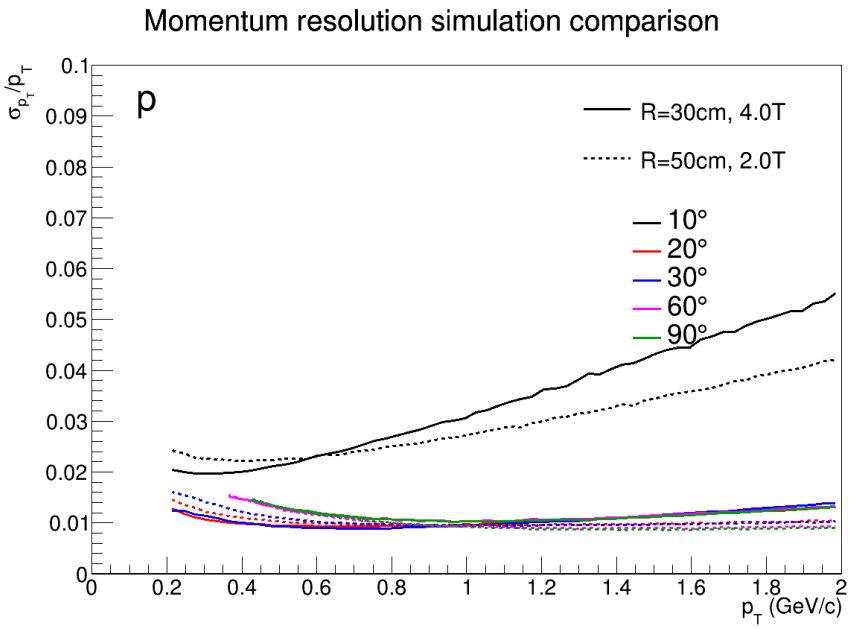
与中国超（子）核（子）谱仪的共识和关键分歧

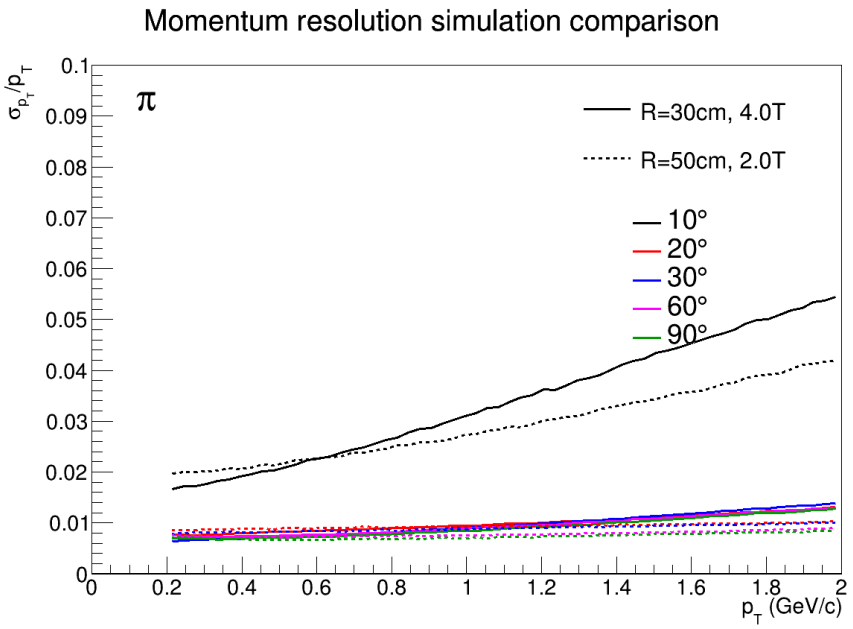
- 共识
  - 螺线管磁铁 + 硅像素径迹探测器 + LGAD飞行时间探测器 + 量能器
- 关键分歧
  - 硅像素探测器技术方案：5维硅像素径迹探测器 vs. 3维硅像素探测器
  - 径迹探测器 + LGAD飞行时间探测器大小：R ~ 30 cm vs. 50 cm
  - 量能器方案：ADRIANO-II vs. 多种选择待定，小覆盖角
  - 物理目标：广泛的物理目标 vs. Λ和质子极化
  - 名称：待定（对应广泛的物理目标）⇒ 惠州强子谱仪

    vs.

    中国超核谱仪 ⇒ 超核谱仪 ⇒ 超子核谱仪 ⇒ 超子-核子谱仪

结构紧凑





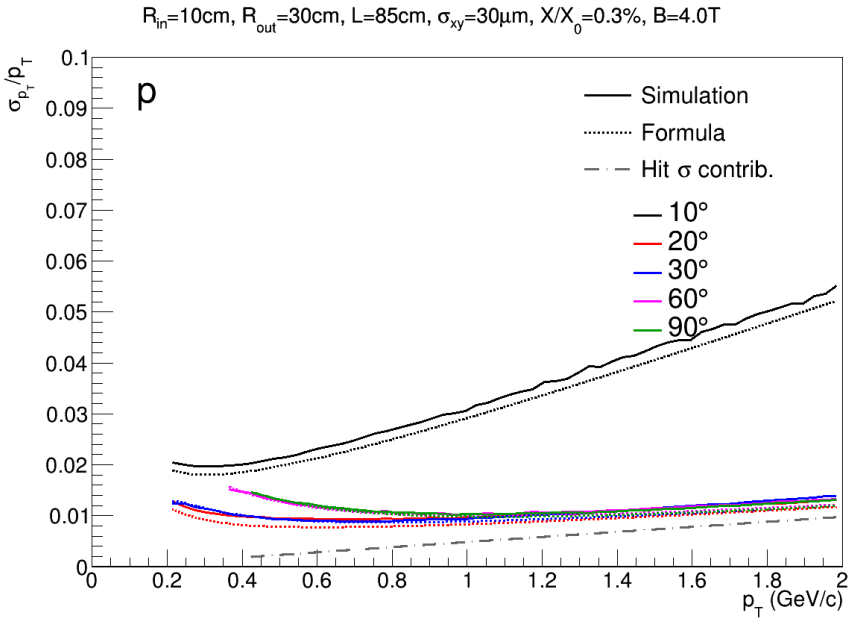
- 通过提高外磁场强度，小一些的硅像素径迹探测器可以取得与更大尺寸的探测器相似的动量分辨率

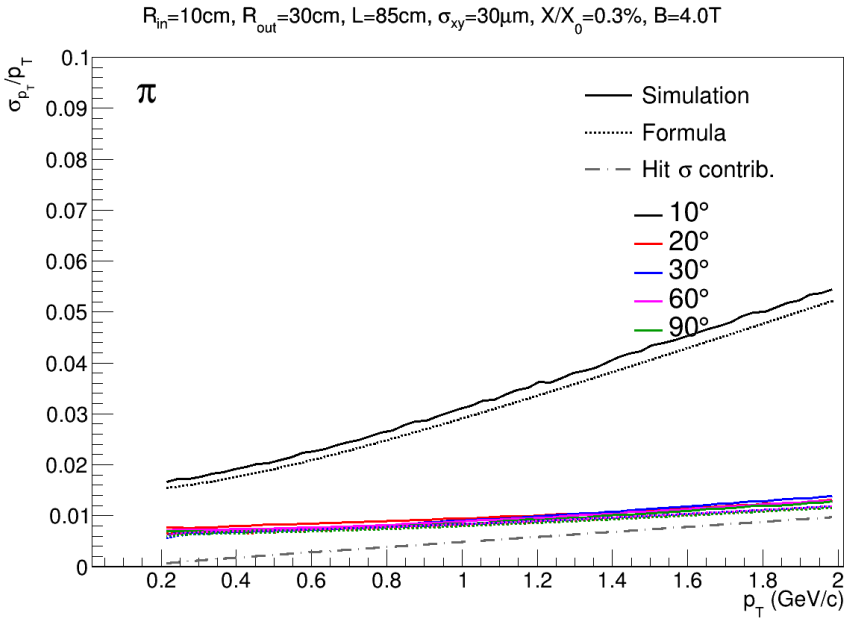
造价估计

子系统	预研预算 （万元）	建造预算 （万元）
靶	-	50
硅像素径迹探测器	830	4870
LGAD飞行时间探测器	600	5500
电磁量能器	580	7160
螺线管磁铁	120	2400
技术支持系统	-	100
数据获取系统	-	2400
合计	2130	22480

- 结构紧凑 ⇒ 成本可控
- 总建造预算约2亿

径迹探测器动量分辨率





- 4T磁场
- $\beta > 0.4$，$p_T > 0.18$ GeV/c，穿过外层LGAD

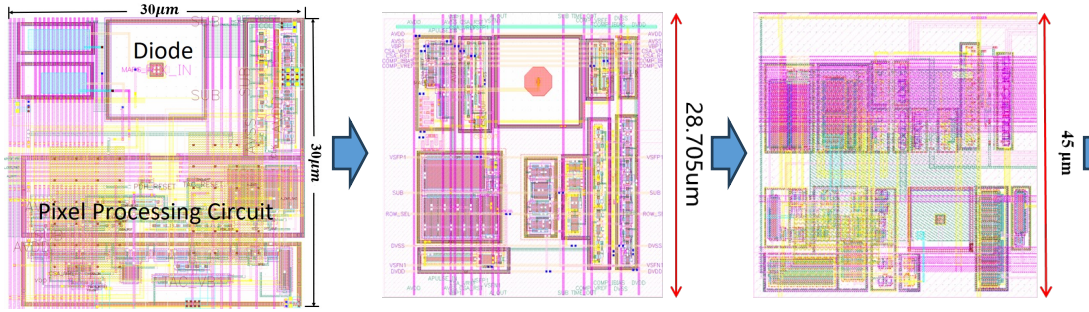
5维硅像素径迹探测器

Nupix-H1
完成

Nupix-H2
完成

Nupix-H3
流片中

Nupix-H4
设计中



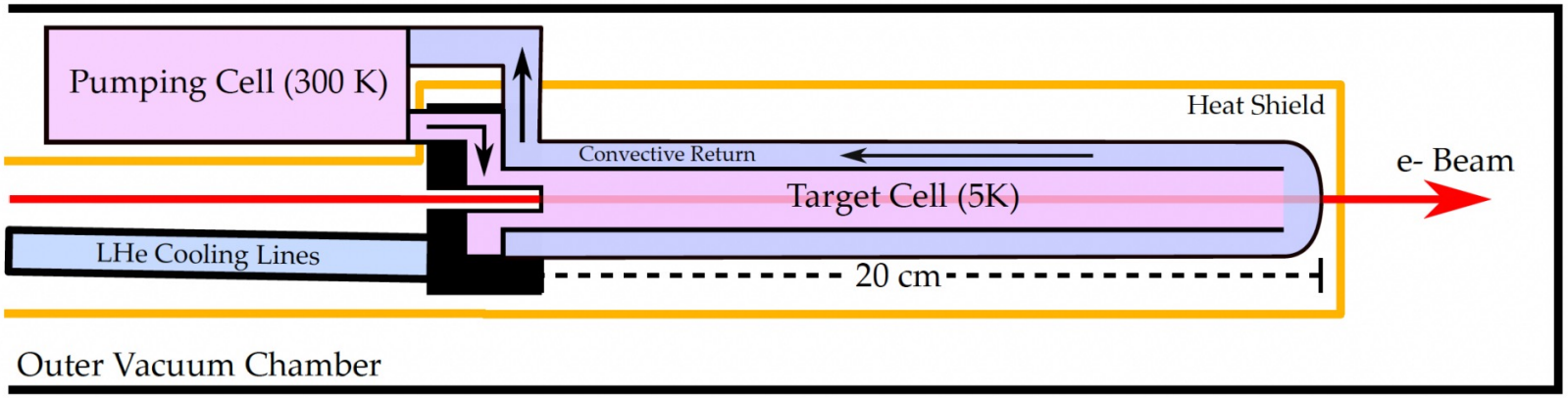
全面瞄准
HHaS需求

设计指标：

像素尺寸	30 μm	30 μm	45 μm	~100 μm
能量测量范围	6 MIPs (~5 ke$^-$)	12 MIPs (~10 ke$^-$)	16 MIPs (~15 ke$^-$)	16 MIPs (~15 ke$^-$)
能量测量噪声	< 1/5 MIPs (150 e$^-$)	< 1/5 MIPs (150 e$^-$)	< 1/5 MIPs (150 e$^-$)	< 1/5 MIPs (150 e$^-$)
时间测量精度	百ns级	~25 ns	~10 ns	~10 ns
功耗	-	-	≤ 600 mW/cm^2	~200 mW/cm2
死时间	-	-	102.4 us	~10 μs

- 已完成两代Nupix-H芯片设计、流片、测试，Nupix-H3流片中
- 逐步接近HHaS需求指标

未来的未来



- ^{3}He极化靶概念图

未来的未来

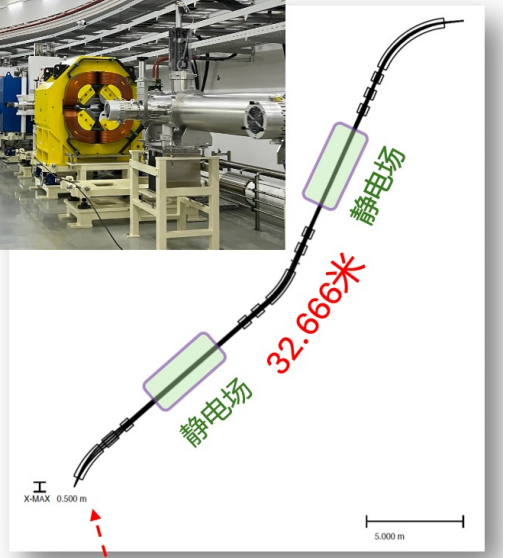
带电次级束流线设计

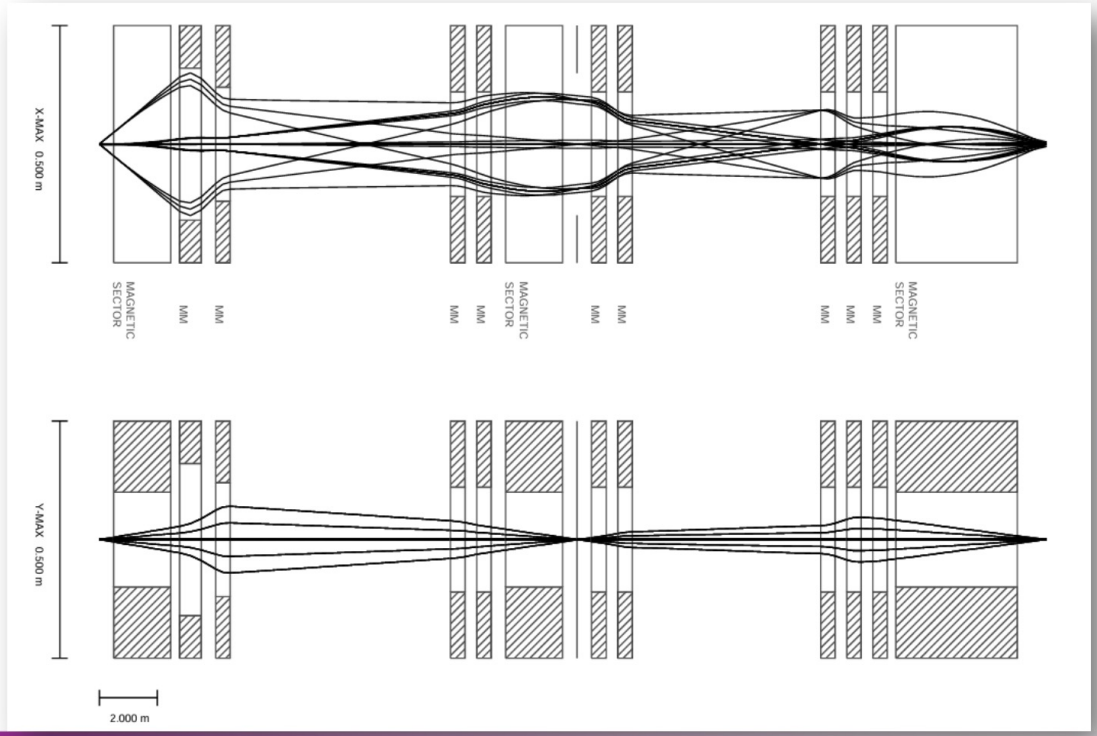
清華大學 Tsinghua University

- 带电粒子束流的分离和甄别

- **总长32.67米：**3个二级磁铁，9个四级磁铁，2个静电场，若干多极磁铁
- **预估造价**：磁铁 100 万+电源50万+真空设备+束流诊断系统 ~ 300万+其他？

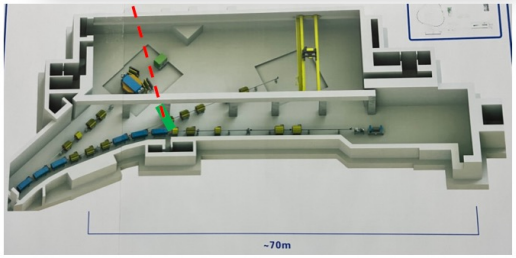






x–z平面

y–z平面

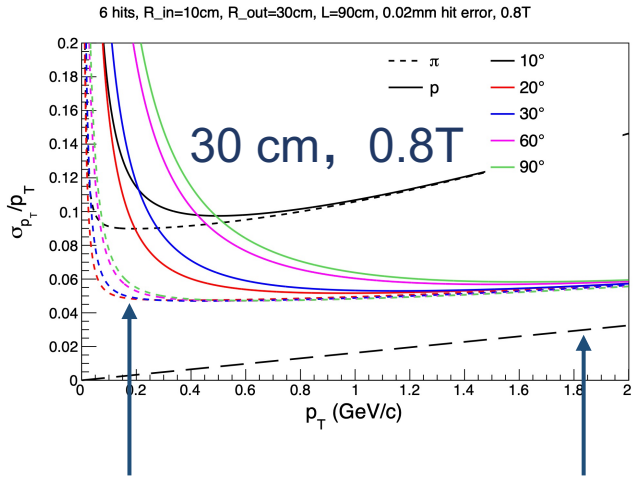


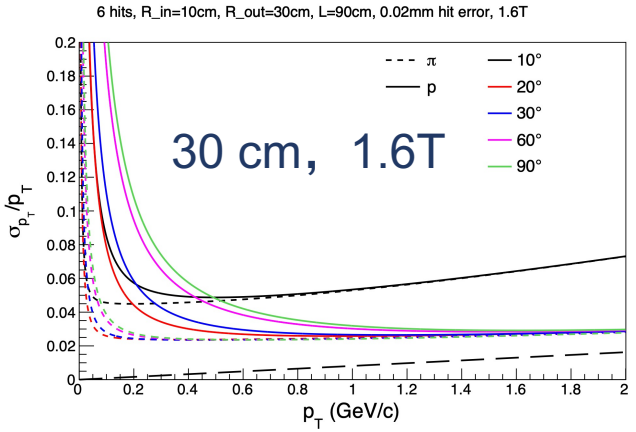
- π & K 介子束流设计模拟
- 叶志鸿、王科、申国栋、冒立军

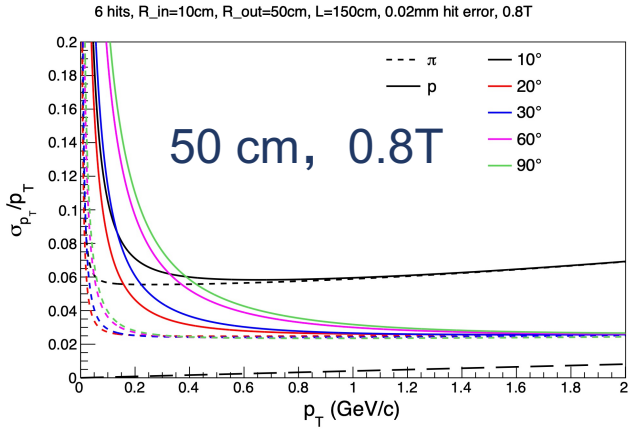
径迹探测器+飞行时间探测器尺寸

R ~ 30 cm vs. 50 cm

动量分辨率问题







多次库伦散射贡献

$\propto \sqrt{(X/X_0)} / (B\ L)$

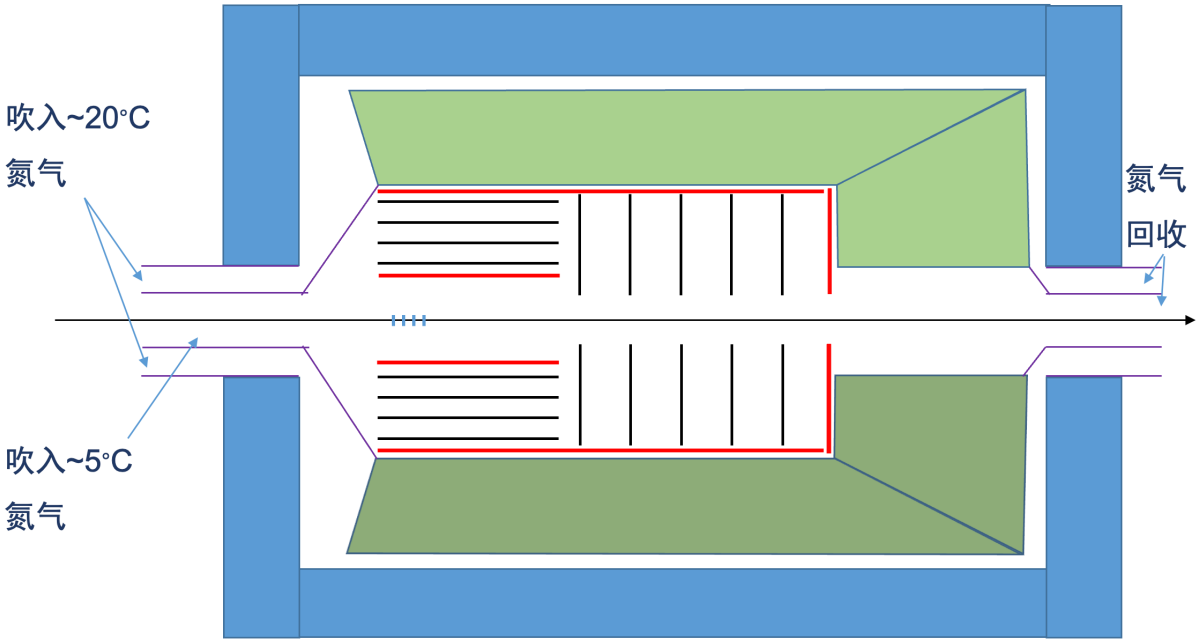
hit误差贡献

$\propto \sigma / (B\ L^2\ \sqrt{N})$

- hit误差贡献不重要 ⇒ 从 σ = 20μm 进一步提高pixel位置精度，几乎没有意义
- 提高磁场强度，增大探测器半径，都可以提高动量分辨

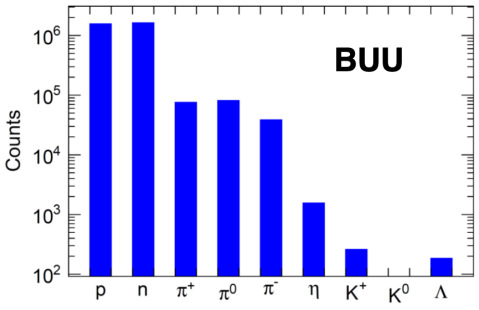
径迹探测器+飞行时间探测器尺寸

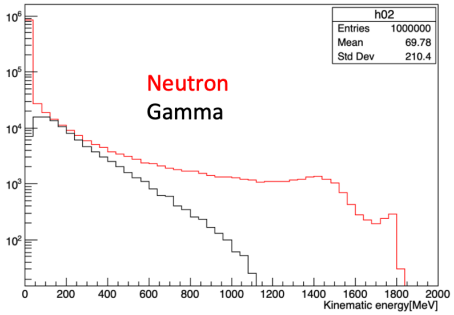
机械布置和散热问题



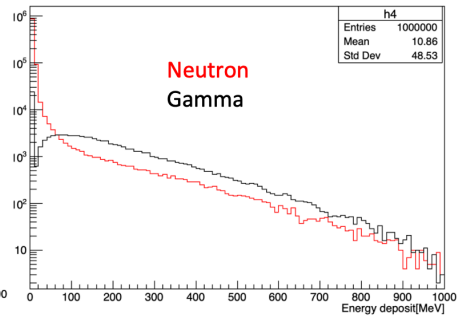
- 最外层LGAD可以用水冷
- 预冷气冷却可以大幅提升散热效果
  - STAR pixel的冷却气体进出温差只有1.5度
  - 如果吹入氮气温度~5°C，回收氮气温度~15 °C ，则同通风量散热量可以增大7倍
  - 额外的好处：更低的芯片工作温度，更小噪声
  - 外围吹常温氮气，防止水汽凝结

量能器方案

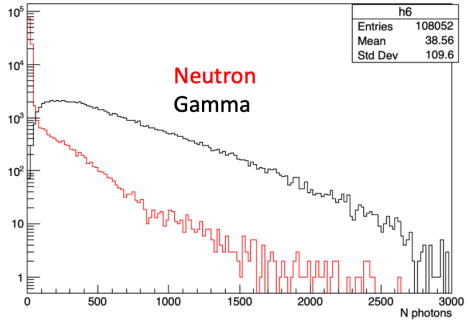




粒子动能分布

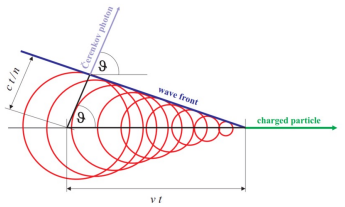


铅玻璃中沉积能量分布



切伦科夫光产额分布

∝ 闪烁体量能器光产额



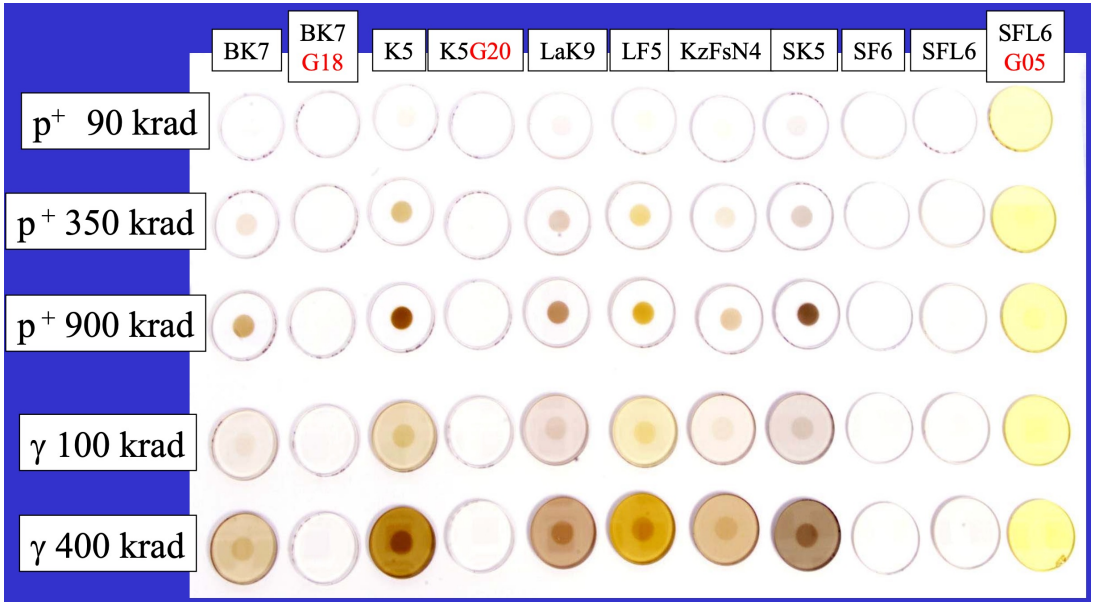
- π^{+-}/e^{+-}~100, n/γ~8 ⇒ 为鉴别 e^{+-} 、γ，需大幅压低π^{+-}、n本底
- 无论使用何种闪烁体探测器，闪烁光产额 ∝ 沉积能量， γ将混入很多的中子本底
- 而强子簇射产生的切伦科夫光远少于电磁簇射，测量切伦科夫光，强子簇射本底被压低

量能器方案

	FLUKA模拟结果		参考抗辐照性能		
	辐射剂量 (Gy)	Si1MeV等效中子通量(n_{eq}/cm^2)	探测器/材料	辐射剂量 (Gy)	Si1MeV等效中子通量 (n_{eq}/cm^2)
最内层硅	3000	3×10^{12}	pixel	2×10^{4}	1.7×10^{13}
			LGAD		1×10^{15}
最内层EMC	50	3×10^{11}	铅玻璃	20	
			SiPM		1×10^{14}

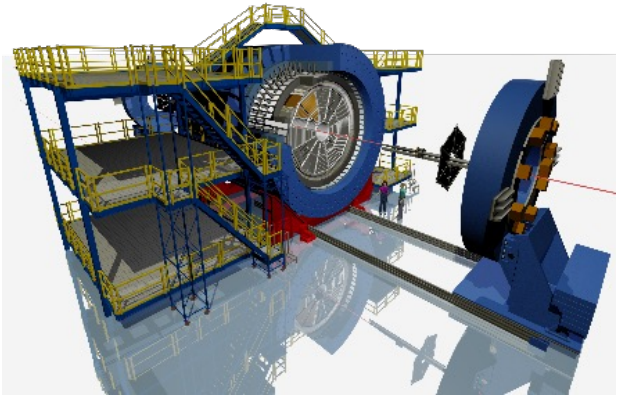
- 表中铅玻璃收到的辐射剂量(50Gy)接近其极限，但铅玻璃有很多不同型号、配方
- 表中：TF101，接收20Gy辐照后光传输率降低1%
  - https://doi.org/10.1016/0168-9002(94)90990-3 ——80年代文献
- 国产铅玻璃ZF2（即ADRIANO2 使用的型号），抗辐射性能无相关资料，待测试
- 德国SCHOTT公司SF6型号铅玻璃，4000Gy辐射剂量照射后，目测透光性良好
- 其它措施：PbF_2晶体替代 / 紫外光或高温恢复

量能器方案



- 表中铅玻璃收到的辐射剂量(50Gy)接近其极限，但铅玻璃有很多不同型号、配方
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- 其它措施：PbF_2晶体替代 / 紫外光或高温恢复

物理目标



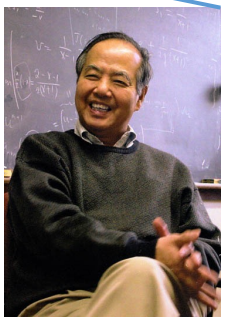
- STAR – 闪耀25年

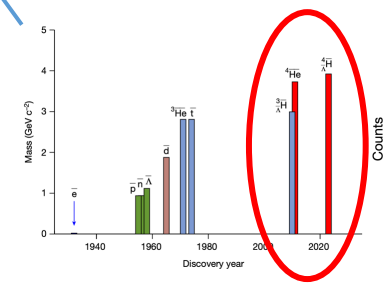
+ 顶点探测器

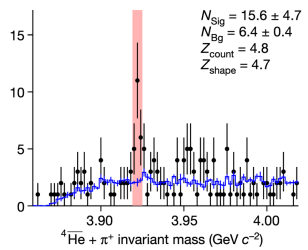
大接收度径迹探测 + 电磁量能器 + 飞行时间探测器 + 缪子探测器 + 内层 TPC 升级 + 前向径迹探测器+量能器

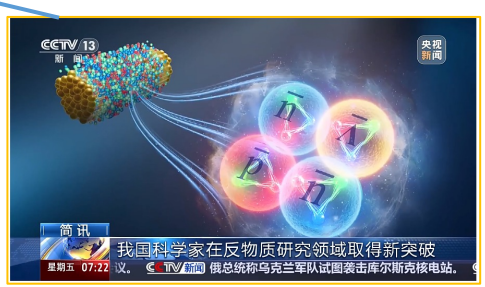
QGP的发现和性质 + 质子自旋 + 反物质 + 相变&临界点 + 超边缘碰撞（光生物质） + 原子核形状











物理目标

Frontiers of Physics
https://doi.org/10.1007/s11467-021-1062-0
Front. Phys.
16(6), 64701 (2021)

REVIEW ARTICLE

Electron-ion collider in China

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- 有成功的单一物理目标的专门实验，也有成功的多物理目标实验

Back-up

物理目标	过程	后续衰变	测量末态粒子	束流种类	质心系能量	束流能量	靶	极化	测量方法、测量量等信息
双重子态	p p → π+ d	-	π+ d	p	~2.6 GeV (扫描附近)	~ 3 GeV	p	更好	微分截面
双重子态	p p → d π+ π0	π0 → γ γ	d π+ γ γ	p	> 2.7 GeV (固定)	> 3 GeV	p		d π0不变质量
双重子态	p p → D30 π- π-	D30 → p p π+ π+	p p π+ π+ π- π-	p	> 2.7 GeV (固定)	> 3 GeV	p		p p π+ π+不变质量谱
重子内的五夸克成分									
隐奇异核子共振态	p p → p p ϕ	ϕ → K+ K-		p	~ 3.2 GeV?	~ 4.6 GeV?	p	更好	p phi不变质量
重子内的五夸克成分	p n → d ϕ	ϕ → K+ K-		p	~ 3.2 GeV?	~ 4.6 GeV?	d? He3?	更好	截面 vs. 束流能量？ 先不管
重子内的五夸克成分	p p → p p η’	η’ → π+ π- η η → π+ π- π0 π0 → γ γ	p p π+ π- π+ π- γ γ	p	~ 3.2 GeV?	~ 4.6 GeV?	p	更好	截面 vs. 束流能量？ 先不管
隐奇异核子共振态	p p → p K+ Λ(1405)	Λ(1405) → Σ0 π0 Σ0 → Λ γ Λ → p π- ; Λ(1405) → Σ+ π- Σ+ → p π0 ; π0 → γ γ	p K+ p π- γ γ γ p K+ p γ γ π-	p	~ 3.2 GeV?	~ 4.6 GeV?	p	更好	Λ(1405)的不变质量谱
隐奇异核子共振态	p p → p K+ Λ(1520)	Λ(1520) → p K-	p K+ p K-	p	~ 3.2 GeV?	~ 4.6 GeV?	p	更好	Λ(1520)的不变质量谱
“失踪”重子共振态	p p → p n π+	-	p π+ (n)	p	~ 3.5 GeV?	~ 5.6 GeV?	p	更好	p π+不变质量
“失踪”重子共振态	p p → p K+ Λ	Λ → p π-	p K+ p π-	p	~ 3.5 GeV?	~ 5.6 GeV?	p	更好	K+ Λ不变质量
“失踪”重子共振态	p p → p K+ Σ0	Σ0 → Λ γ Λ → p π-	p π- γ	p	~ 3.5 GeV?	~ 5.6 GeV?	p	更好	K+ Σ0不变质量
Λ内部结构	p p → p K+ Λ	Λ → p π-	p K+ p π-	p	~ 3.5 GeV?	~ 5.6 GeV?	p	不需	Λ衰变常数（衰变p动量方向跟Λ方向夹角）
ckm矩阵元Vus	p p → p K+ Λ	Λ → p e ν	p K+ p e	p	~ 3.5 GeV?	~ 5.6 GeV?	p	不需	Λ半轻衰变(10^8个Lambda) BR, transition form factor

标准模型相关诺奖

- 1995
- 2012
- 1990
- 1988
- 1984
- 1980
- 1979
- 1976
- 1969
- 1965
- 1957

数据处理能力需求

- 径迹重建CPU时间
  - 0.0012 s / hit
  - 7 hits / track
  - 4 track / event
  - 1.e8 event / s
  - 平均流强/最高流强 ~ 0.3
  - 1个月取数，12个月处理
  - 总的需要CPU核数：0.0012*7*4*1.e8*0.3/12 = 1.e5
- CPU机群预算：10万元/100CPU核 * 1.e5 核 = 1亿元
- 使用GPU代替CPU ~ 1/3
- 未来计算机发展 ~1/2
- 量能器重建能量>50MeV触发/在线选择
- ⇒数据处理机群预算在千万元量级

缪子探测器

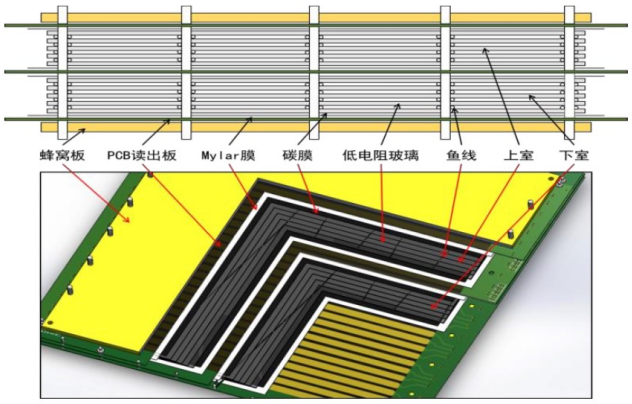
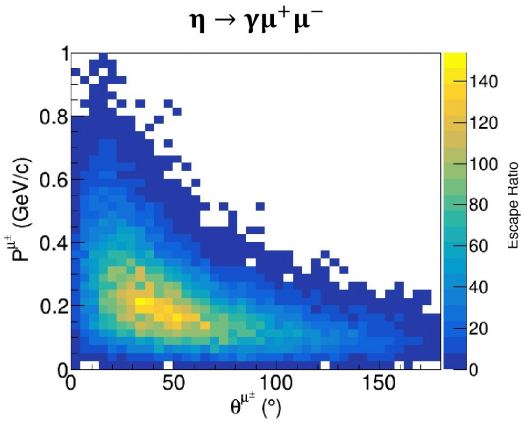
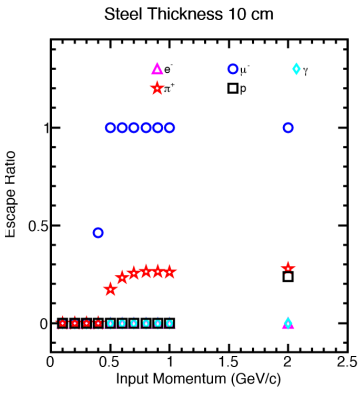
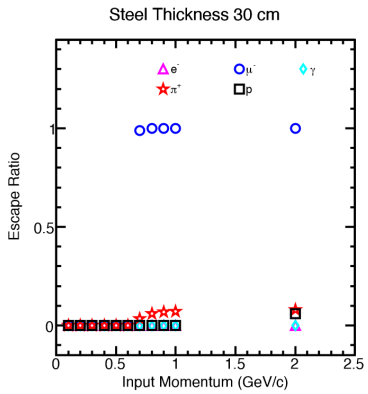


图 10　eTOF MRPC 结构示意图。







- MRPC，类似CEE ETOF
- 阻挡物质越少， μ^{+-}动量可以越低，但π^{+-}压低系数变小
  - 石墨作为阻挡材料？更高效的μ^{+-} / π^{+-}鉴别技术？
- 时间分辨：几十ps
- 位置分辨：几cm　　读出条pitch、双端读出时间差， 与径迹4维配对
- 因为大角度区没有高动量μ^{+-}，仅布置于前角
- 面积~11 m^2　　造价~500万

王荣、孙旭

慢引出束流时间结构

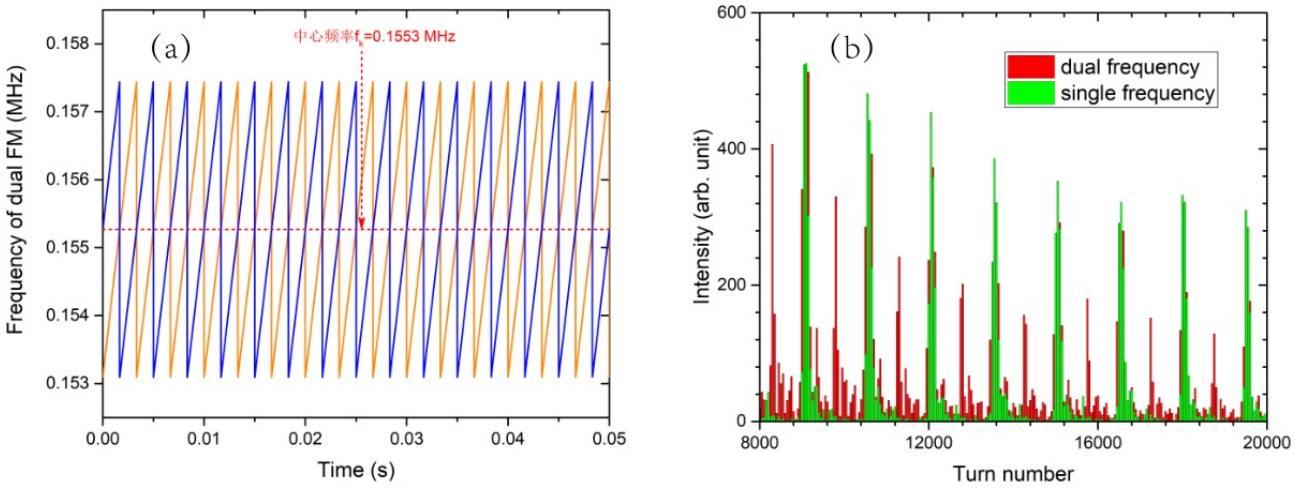


图 5.13 （a）RKO双频调制时频率随时间变化，（b）RKO双频调制对spill时间结构的影响

Figure 5.13 (a) the frequency variation with time in the dual FM process of RKO, (b) the influence of dual frequency modulation of RKO on the spill structure

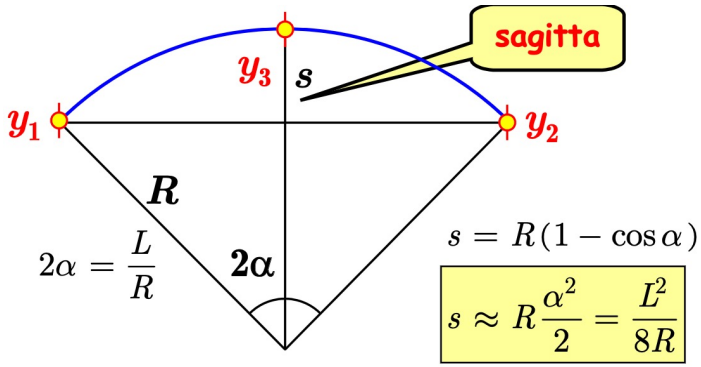
- BRing出来的spill的时间结构
- 红色是双频扫描的，1个峰和1个峰的重复频率在10~30kHz之间，峰与峰之间的束流较少
- BRing引出平台一个周期大约2us，按照3s的引出平顶，总共1.5e6圈，1e11ppp的流强，平均一圈才6.7e4个离子，估计涨落会比较大，也会有时间结构，需要模拟

径迹探测器动量分辨率

- hit误差部分贡献：

$$\frac{\delta p}{p^2} = \frac{\sigma}{0.3BL^2}\sqrt{4C_N}$$

$$C_N = \frac{180N^3}{(N-1)(N+1)(N+2)(N+3)}$$



$$s = R(1-\cos\alpha)$$

$$s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}$$

$$R = \frac{p}{0.3B}$$

An Introduction to Charged Particles Tracking – Francesco Ragusa

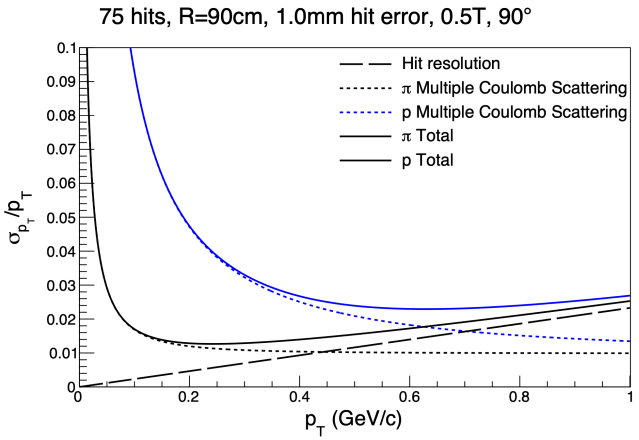
- 多次库伦散射MCS部分贡献：

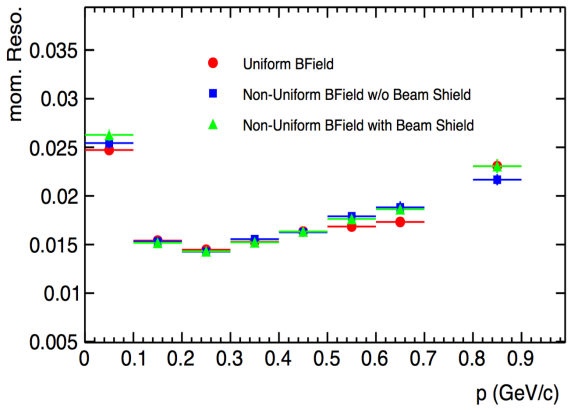
$$\theta_0 = \frac{13.6}{\beta cp} z\sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$$

  - 先计算长度l/2的径迹的散射角度θ_0
  - 再计算长度l/2的径迹两端θ_0的角度对应的曲率$1/R = \theta_0/(l/2)$
  - 最后导出MCS动量分辨率贡献 $R = \frac{p}{0.3B}$
  - 这一部分贡献只是一个大概估算，实际情况取决于hit误差与MCS相对贡献大小等

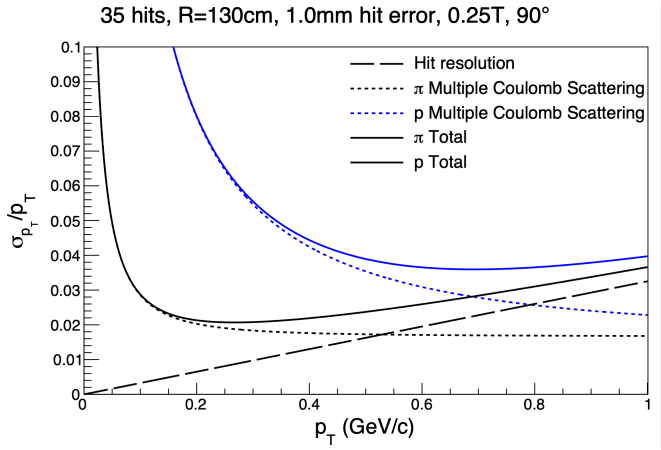
径迹探测器动量分辨率

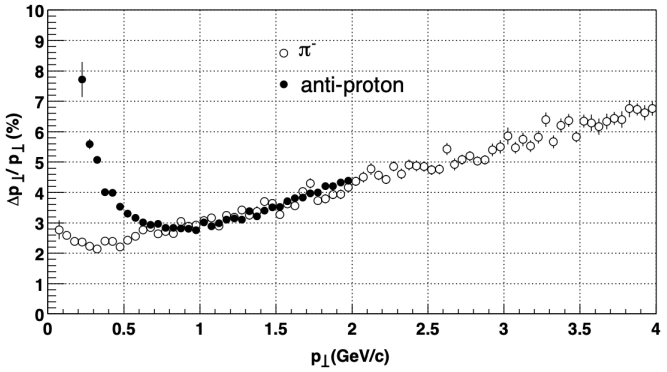
CEE box TPC





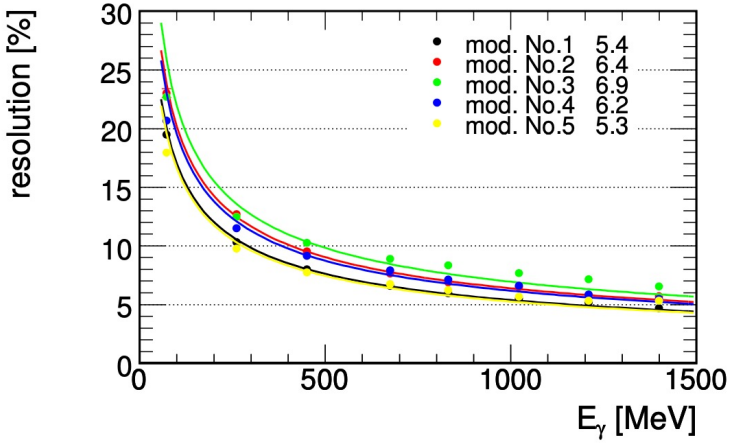
STAR TPC

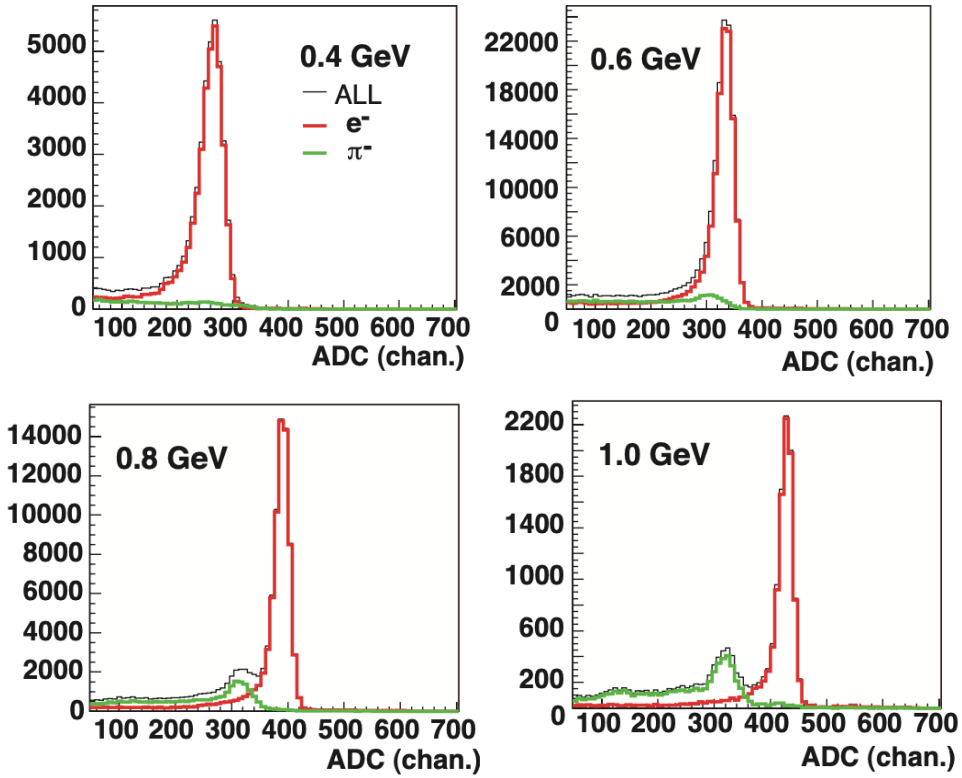




- CEE、STAR实验使用公式和模拟结果基本相符

铅玻璃





- HADES EMC
- 能量分辨率 ~6% @ 1GeV，~25% @ 50MeV
- 时间分辨~215ps （0.8 GeV电子）
- 成型时间~0.5 μs
- 强子簇射切伦科夫光产额低于电子簇射，有利于压低中子、 π本底
- 造价：~<1000万

EMC抗辐照性能要求估计

- 电离辐射剂量
  - 100MHz事例率，每个事例1.8GeV能量，一半能量均匀沉积在前角40cm半径，25cm厚的晶体里，则一个月的辐射剂量为
  - 100e6*1.8*3600*24*30*1.60218e-10*0.5 / (3.14*40*40*25*4.51/1000) = 66 Gy
- 中子辐射剂量：
  - 100MHz事例率，每个事例4个中子，一半均匀射向前角40cm半径晶体，则一个月的总中子通量量为
  - 100e6*4*3600*24*30*0.5 / (3.14*40*40) = 1e11 n / cm^2
- 与mu2e实验测试使用剂量(900 Gy、 9e11 n / cm^2)在一个量级 *J. Phys.: Conf. Ser.* **928** 012041
- 可以通过150°C高温退火去除辐射影响 Nuclear Instruments and Methods in Physics Research A 432 (1999) 138

缪子探测器

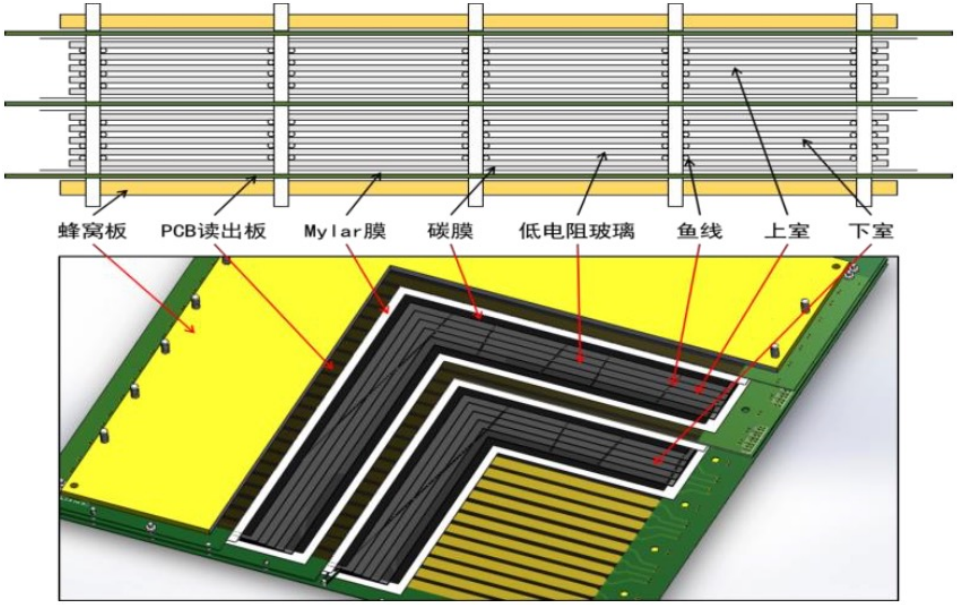
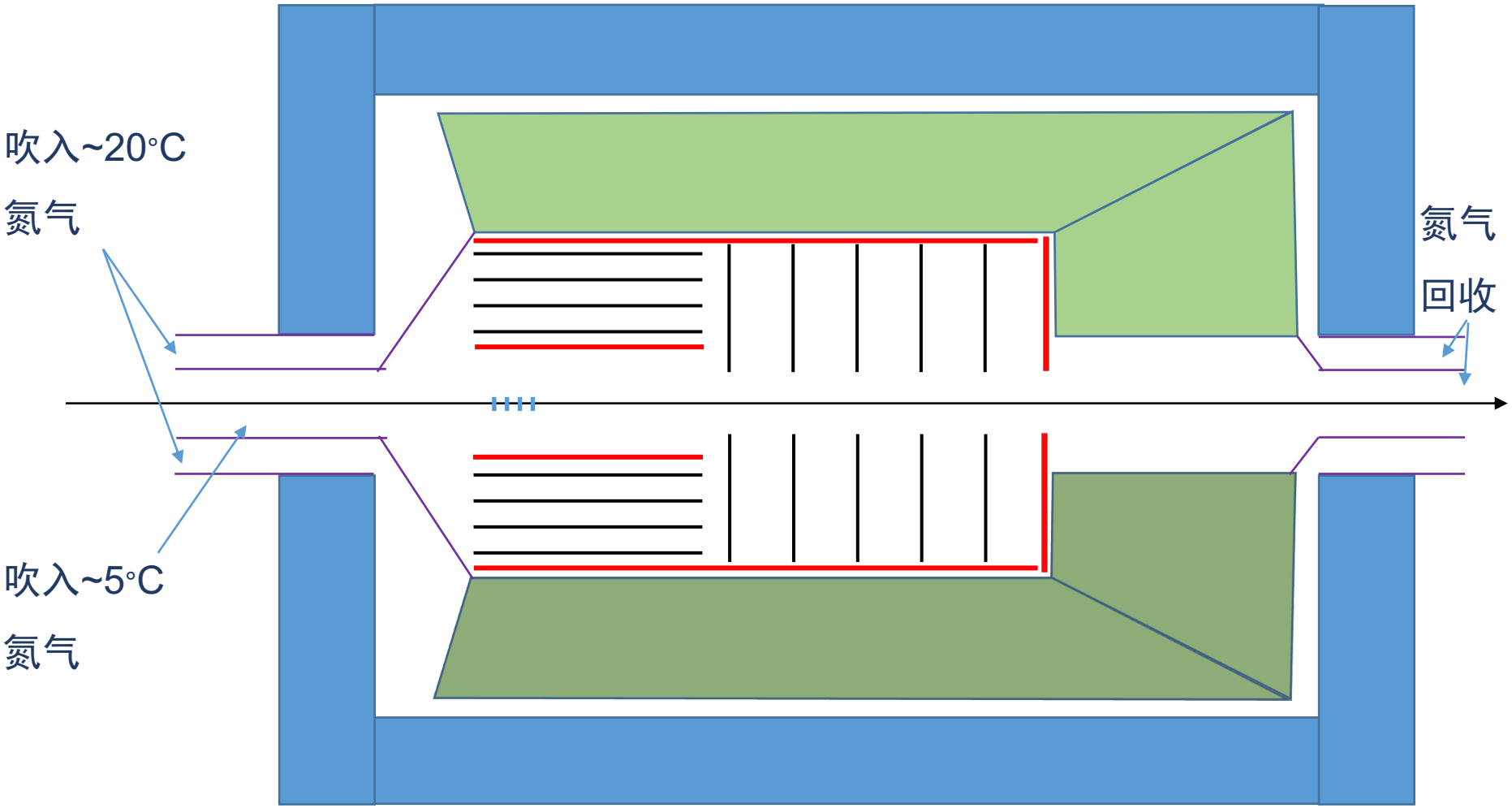


图 10　eTOF MRPC 结构示意图。

- MRPC，类似CEE ETOF
- 读出条pitch 25mm；双端读出时间差得到沿读出条方向位置信息：100ps*c=30mm
- 两个维度均可得到cm量级的位置分辨率，与几十ps的时间分辨配合，可以与径迹进行4维配对，压低强子簇射本底
- 面积：3.14*0.55*0.55 + 3.14*0.8*0.8 + 2*3.14*0.55*1 + 2*3.14*0.8*1 = 11 m^2
- 造价：CEE ETOF 8m^2， 350万 ⇒ 11 m^2, 500万

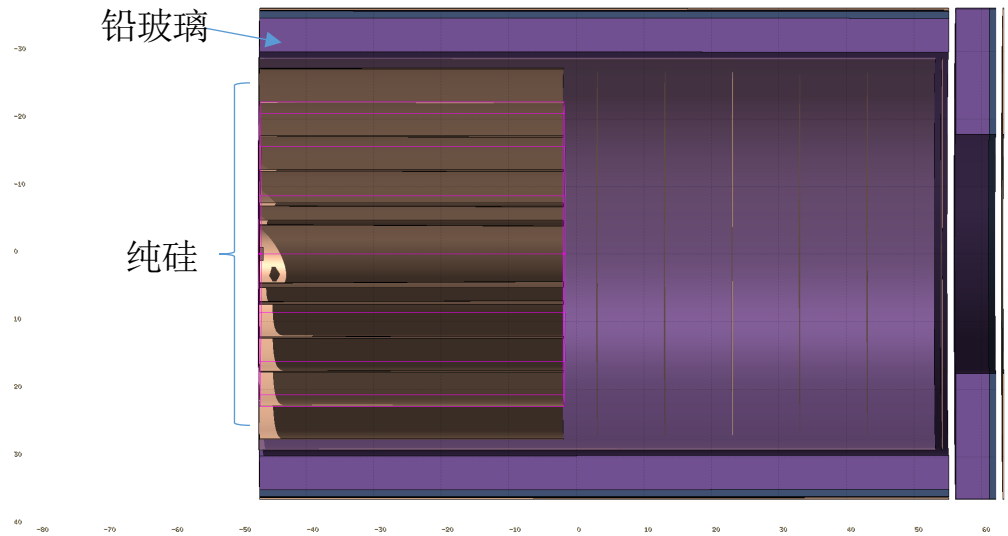
预冷气散热概念设计



模拟设置

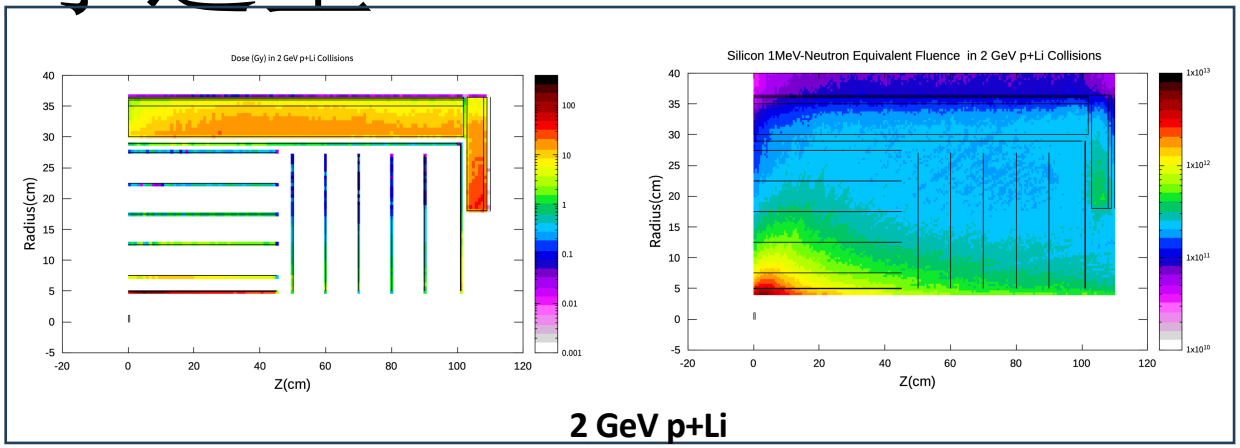
探测器

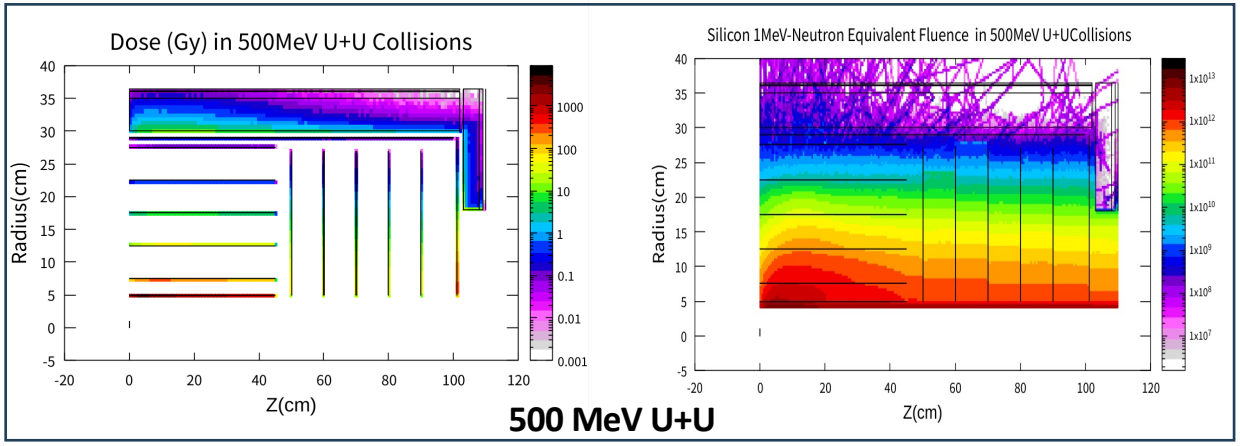
- 硅径迹探测器：纯硅，100微米厚度
- LGAD：纯硅，300微米
- 电磁量能器（1层铅玻璃+CsI+硅）



- **事件产生**: Fluka
- 500MeV U+U: 靶厚度250微米, 非弹散射事件率：2%
  - 单束流粒子剂量 ⇒ 一个月剂量：1MHz / 0.02 × 3600s/h × 24h/d × 30d
- 2GeV p+Li: 靶厚度5毫米, 非弹散射事件率：0.4%
  - 单束流粒子剂量 ⇒ 一个月剂量：100MHz / 0.004 × 3600s/h × 24h/d × 30d

一个月运行辐射剂量和1MeV等效中子通量





一个月运行辐射剂量和1MeV等效中子通量

	2 GeV p+Li（100MHz 1 month）		500 MeV U+U（1MHz 1 month）		探测器可承受参考剂量/通量		
	Dose (Gy)	Si1MeV fluence (n_{eq}/cm^2)	Dose (Gy)	Si1MeV fluence (n_{eq}/cm^2)	探测器/材料/元件	Dose (Gy)	Si1MeV fluence (n_{eq}/cm^2)
最内层Si	200	3×10^{12}	3000	3×10^{12}	pixel	2×10^{4} [1] 1×10^{6} [3]	1.7×10^{13} [1] 1×10^{13} [2] 1×10^{15} [3]
					LGAD		1×10^{15} [4]
量能器	20 50（前角局部）	3×10^{11}	20	10^{9}	铅玻璃	20 [5]	
					SiPM		1×10^{14} [6]

[1] ALPIDE抗辐射（ALICE IST upgrade已大规模使用）： $1.7\times10^{13}n_{eq}/cm^2$
https://indico.cern.ch/event/695271/contributions/2956083/attachments/1637991/2614211/CERN_LHC_Rad_symp_23042018_HHI.pdf
[2] CMOS pixel探测器抗辐射（Supix-1, CEPC，山大）： $1.\times10^{13}n_{eq}/cm^2$ https://arxiv.org/abs/2202.11471
[3] DMAPS抗辐射（MALTA2, HL-HLC）： $1.\times10^{15}n_{eq}/cm^2$ https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10246423&tag=1
[4] LGAD抗辐射（NDL, HL-LHC，高能所、北师大）： $1.\times10^{15}n_{eq}/cm^2$ https://www.sciencedirect.com/science/article/pii/S0168900220310056
[5] 铅玻璃抗辐射（TF101）：20Gy辐照后透光率降低1% https://doi.org/10.1016/0168-9002(94)90990-3
[6] SiPM抗辐射综述： $1.\times10^{14}n_{eq}/cm^2$
https://indico.ipmu.jp/event/166/contributions/2761/attachments/2145/2627/SiPM-rad-dam-review_PD18_Musienko-v3.pdf

- pixel、LGAD、SiPM，已有同类探测器满足抗辐射要求，需要研发和选型时确定抗辐射指标并实现
- 铅玻璃受到的辐射剂量与现有产品的抗辐射能力接近，需要专门研发提高，或每次实验后拆卸高温淬火恢复

e & muon

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+\pi^-$
- CP Violation (Type I – P and T odd , C even): $\eta \to 4\pi^o \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to \pi^o \ell^+\ell^-$ **and** $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
- CP inv. via γ^* polarization studies: $\eta \to \pi^+\pi^-e^+e^-$ & $\eta \to \pi^+\pi^-\mu^+\mu^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-e^+e^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-\pi^+\pi^-$
- CP invariance in μ polar. in studies: $\eta \to \pi^o \mu^+\mu^-$
- T invar. via μ transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polar. in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi\mu^+\nu$ - γ polar. in $\eta \to \gamma\gamma$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+e^- + c.c.$
- Radiative Lepton Flavor Violation: $\eta \to \gamma(\mu^+e^- + c.c.$
- Double lepton Flavor Violation: $\eta \to \mu^+\mu^+e^-e^- + c.c.$

Non-η/η′ based BSM Physics

- Neutral pion decay: $\pi^o \to \gamma A' \to \gamma e^+e^-$
- ALP's searches in Primakoff processes: p Z → p Z a → l^+l^- (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$
- Dark photon and ALP searches in Drell-Yan processes: qqbar → A′/a → l^+l^-

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \to \pi^o H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$
- Dark photon searches: $\eta \to \gamma A'$ with $A' \to \ell^+\ell^-$
- Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to \pi^+\pi^-$
- QCD axion searches : $\eta \to \pi\pi a_{17}$ with $a_{17} \to e^+e^-$
- New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$
- Lepton Universality
- $\eta \to \pi^o H$ with $H \to \nu N_2$, $N_2 \to h'N_1$, $h' \to e^+e^-$

Other Precision Physics measurements

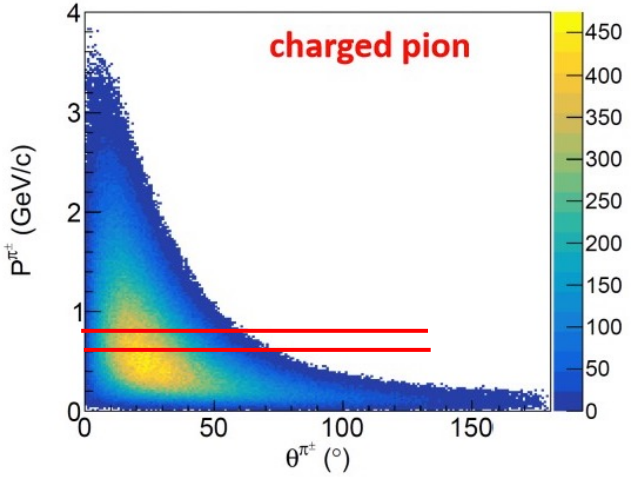
- Proton radius anomaly: $\eta \to \gamma\mu^+\mu^-$ vs $\eta \to \gamma e^+e^-$
- All unseen leptonic decay mode of η / η ′ (SM predicts 10^{-6} -10^{-9})

High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

- 绝大部分eta衰变道研究需要电子 & / 缪子

缪子鉴别

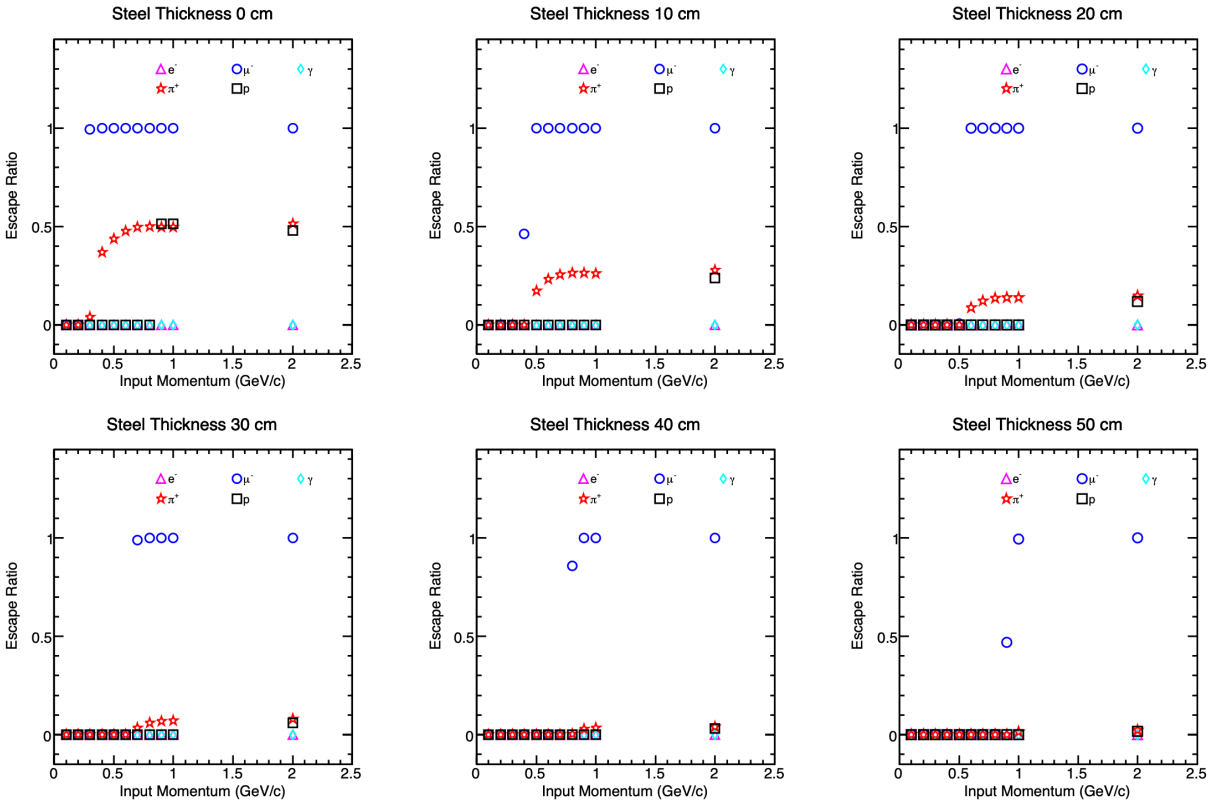


eta衰变的pi+-分布

近似为衰变缪子分布

王荣

孙旭



- 低动量下鉴别缪子、高效排除pi+-，很困难 ⇒ 可能只需要覆盖前角10-60度范围
- 可以调节EMC+铁的厚度，选取一定动量以上的缪子进行鉴别
- 例如，选取25cm CsI + 20cm铁，可以选择0.6GeV/c以上缪子，pi+-排除在7倍左右
- 选取25cm CsI + 40cm铁，可以选择0.8GeV/c以上缪子，pi+-排除在30倍左右
- 需要结合真实物理eta、本底产额、衰变运动学进行模拟，决定最佳铁厚度

量能器（晶体）

Table 6.2 Properties of scintillating crystals applied in particle physics experiments

	NAI(Tl)	CsI(Tl)	CsI	BaF_2	CeF_3	BGO	$PbWO_4$	LYSO
Density [g cm^{-3}]	3.67	4.51	4.51	4.89	6.16	7.13	8.3	7.1
Radiation length [cm]	2.59	1.85	1.85	2.06	1.68	1.12	0.89	1.16
Molière radius [cm]	4.8	3.5	3.5	3.4	2.6	2.3	2.0	2.07
Interaction length [cm]	41.4	37.0	37.0	29.9	26.2	21.8	18.0	20.3
dE/dx)mip [MeV cm^{-1}]	4.79	5.61	5.61	6.37	8.0	8.92	9.4	9.2
Refractive index [at λ_{peak}]	1.85	1.79	1.95	1.50	1.62	2.15	2.2	1.8
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Emission spectrum, λ_{peak}								
Slow component [nm]	410	560	420	300	340	480	510	
Fast component [nm]			310	220	300		510	420
Light yield rel. to NaI								
Slow component	100	45	5.6	21	6.6	9	0.3	
Fast component			2.3	2.7	2.0		0.4	75
Decay time [ns]								
Slow component	230	1300	35	630	30	300	50	
Fast component			6	0.9	9		10	35

林德旭

- 考虑到几百MHz的事例率，需要光衰减时间~ns量级
- 初步考虑纯CsI，紫外扩展的SiPM，只对6ns快成分敏感 ~3个事件堆积，可以接受
  - 能量分辨率~2.3%@1GeV，总造价约1亿，科大STCF正在进行相关预研
- BaF2快成分光衰减时间0.9ns，但比CsI贵2-3倍 ⇒ ~2亿量能器造价，可能太贵了

REDTOP detector

Central Tracker
~ 1m x 1.5 m
Thin LGAD
98% coverage

ADRIANO2 Calorimeter (tiles)
Scint. + heavy glass sandwich
35 X_0, 2.9λ_I (~ 64 cm deep)
Triple-readout +PFA
96% coverage

μ-polarizer
Active version (from TREK exp.) - optional

CTOF
~ 1m x 1.5 m
Lead-glass tiles
98% coverage

10x Be or Li targets
•0.33 mm thin
•Spaced 10 cm

Fiber tracker or ITS3
for rejection of γ-conversion and vertexing

