新型量能器的研究

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近代物理系，粒子物理与原子核物理

近代物理进展讲座

11/19/2026

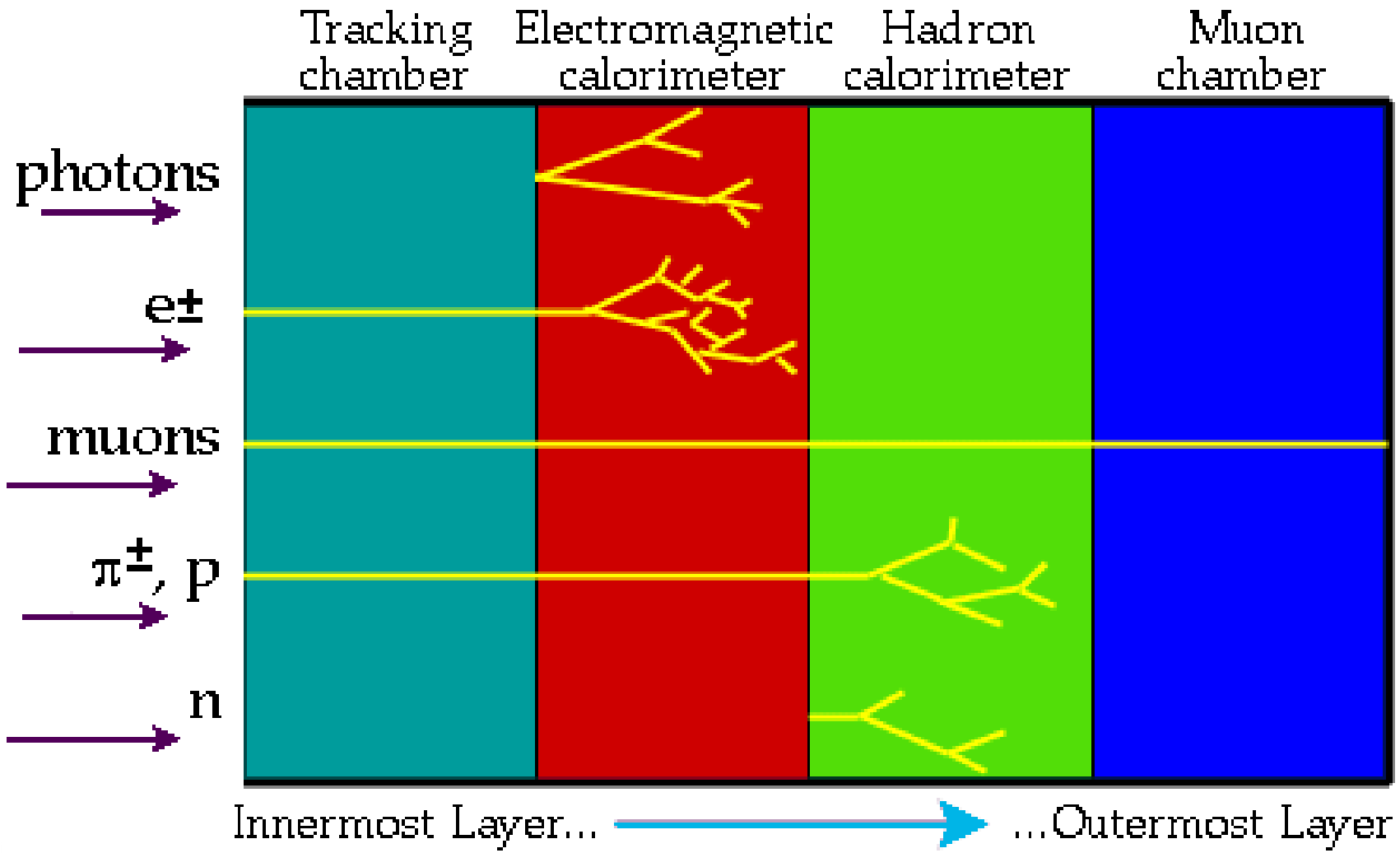


报告提纲

- 量能器技术前沿
- 高颗粒度量能器
- 新型晶体型量能器
- 总结

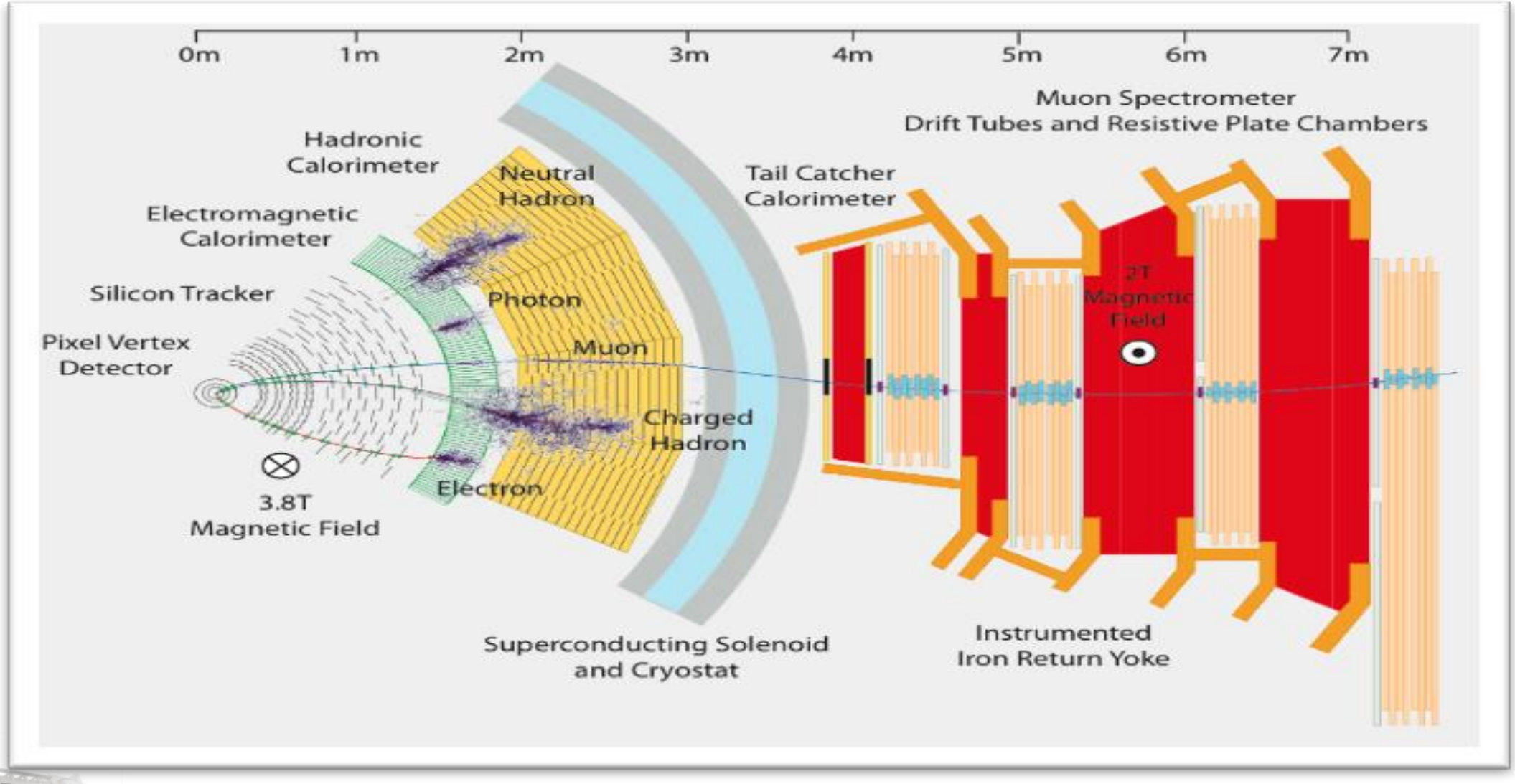


粒子探测谱仪


Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon chamber
photons
e±
muons
π±, p
n
Innermost Layer...
...Outermost Layer

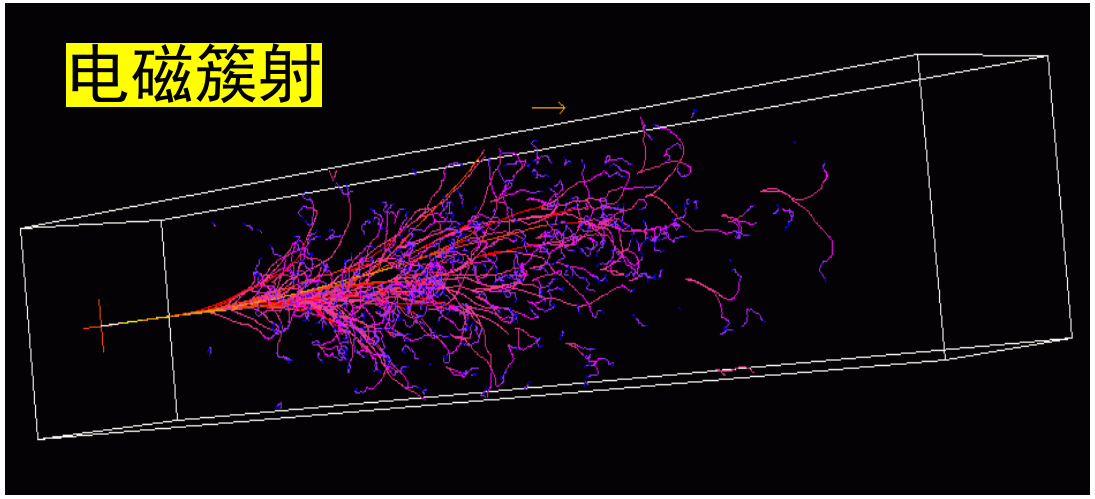


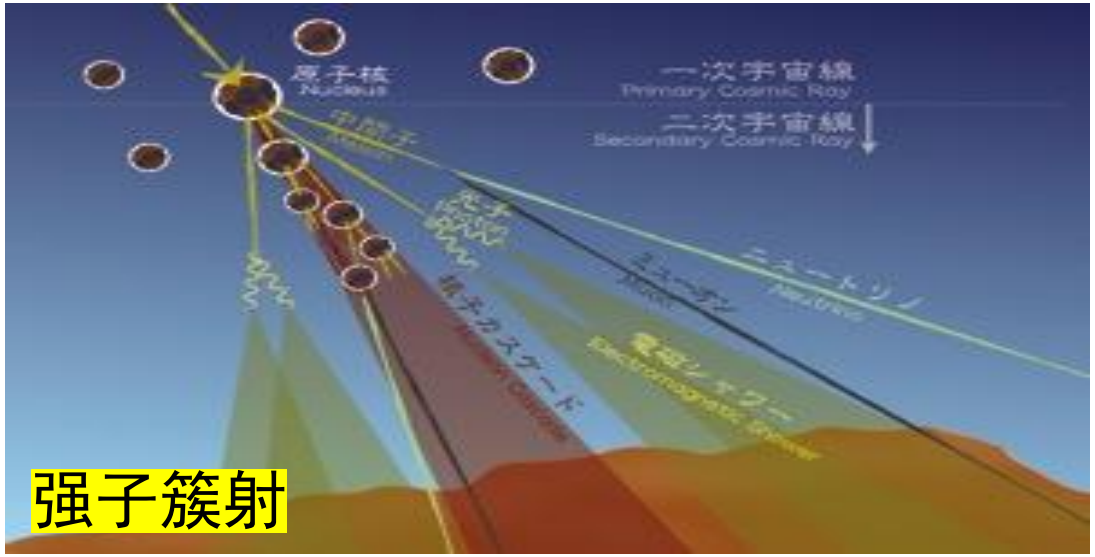
粒子探测谱仪


0m
1m
2m
3m
4m
5m
6m
7m
Muon Spectrometer
Drift Tubes and Resistive Plate Chambers
Hadronic
Calorimeter
Neutral
Hadron
Tail Catcher
Calorimeter
Electromagnetic
Calorimeter
Silicon Tracker
Photon
2T
Magnetic
Field
Pixel Vertex
Detector
Muon
Charged
Hadron
Electron
3.8T
Magnetic Field
Superconducting Solenoid
and Cryostat
Instrumented
Iron Return Yoke

量能器

- 量能器是测量粒子能量的探测器
  - 电磁量能器
  - 强子量能器
- 高能粒子通过高能簇射把能量沉积在量能器中
  - 电磁簇射深度：~20 cm
  - 强子簇射深度：~1 m

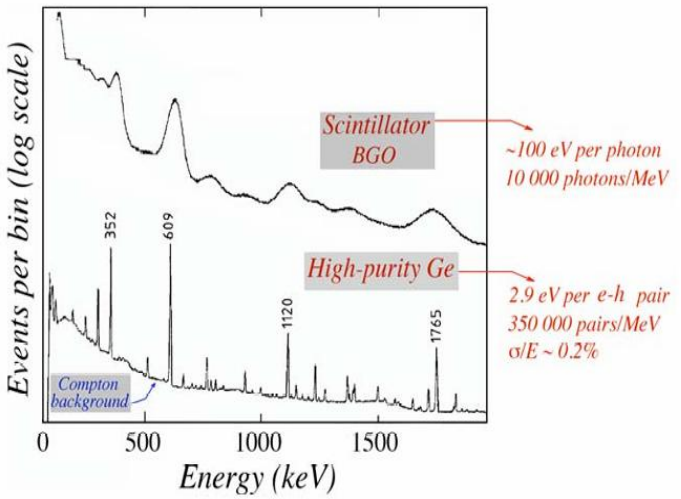


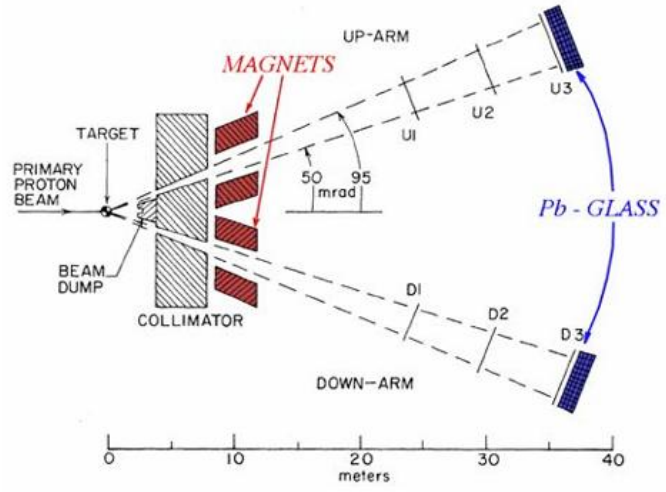




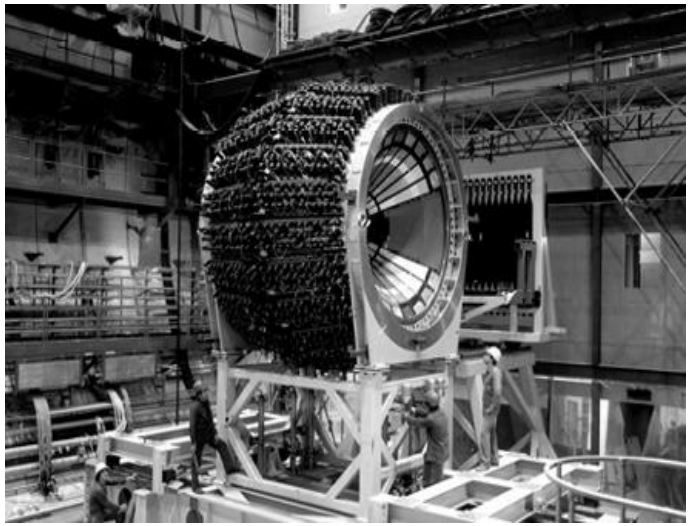
量能器的历史

- 1950s，闪烁晶体在核物理实验中用于伽马能谱测量
- ~1970，量能器开始应用于粒子物理实验，用于测量中性粒子，作为shower counter
- 1980，量能器在对撞实验谱仪中扮演了重要的功能，分成电磁量能器和强子量能器





Fermilab E-70实验



CERN UA2实验

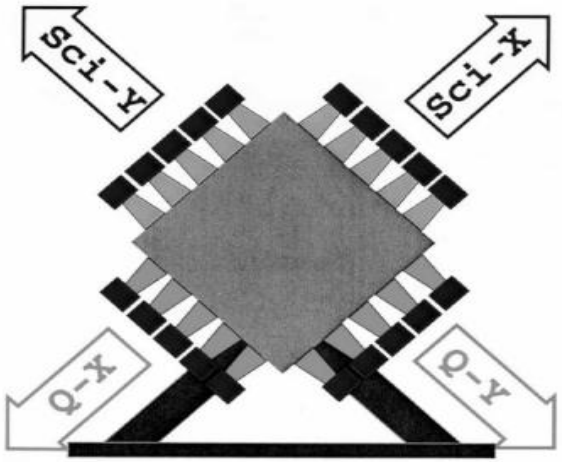


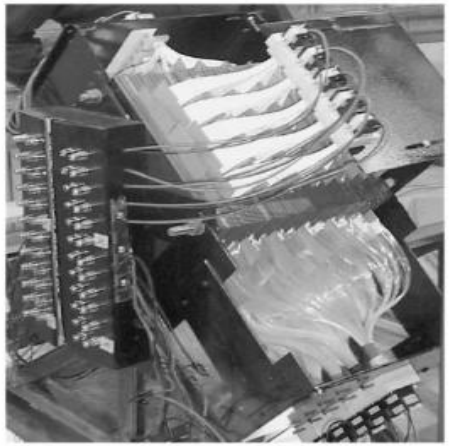
量能器的历史

- 提高量能器对强子响应的能量分辨
- 补偿型
  - 优化量能器对高能粒子簇射过程中的电磁成分和强子成分的响应，使得e/h=1
- 荧光-切伦科夫光双读出
  - 利用切伦科夫光的信号，修正强子簇射中电磁成分的涨落



补偿型（~1990），SPACAL in CERN

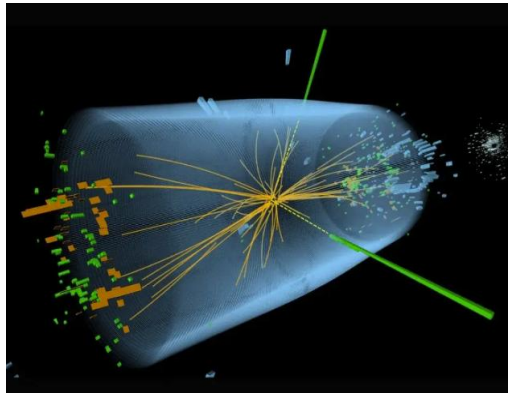


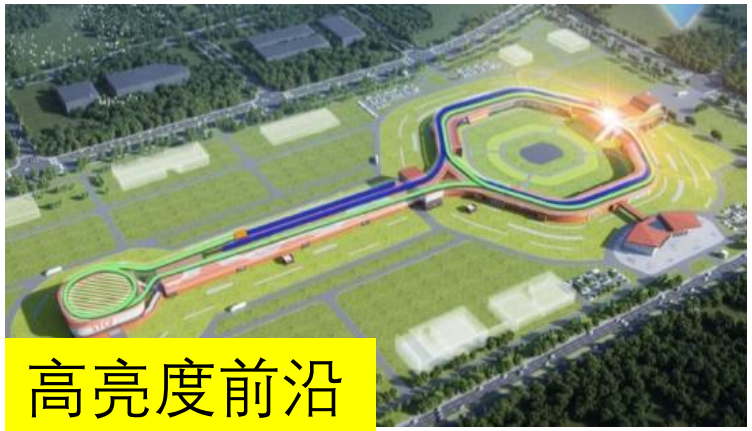


双读出（~2000），ACCESS in NASA

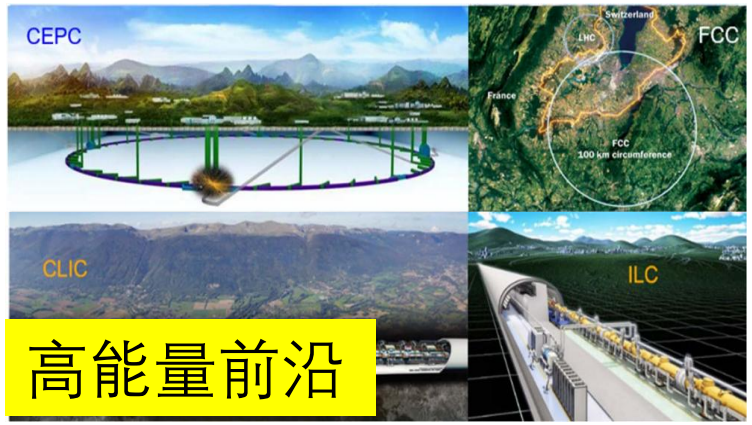
下一代加速器对撞实验

- ◆高亮度和高能量是下一代对撞实验的两个发展方向
- ◆都对探测技术提出了新的需求

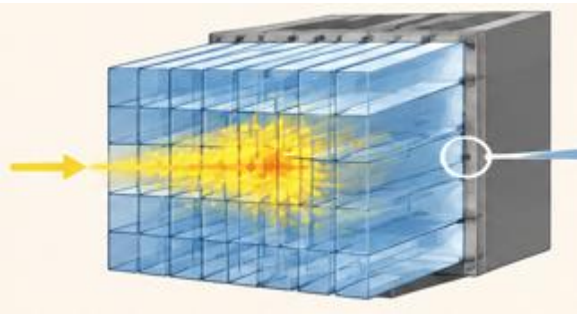


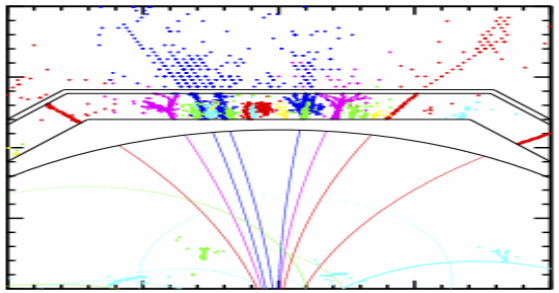


高亮度前沿



高能量前沿

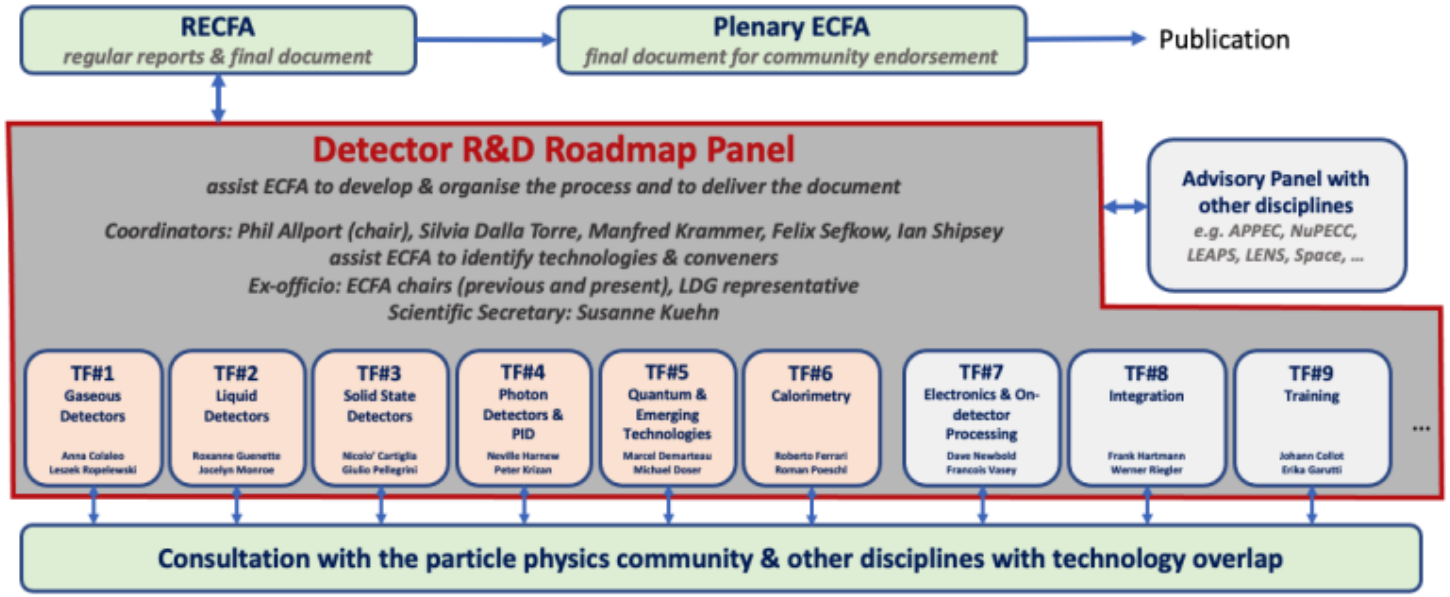


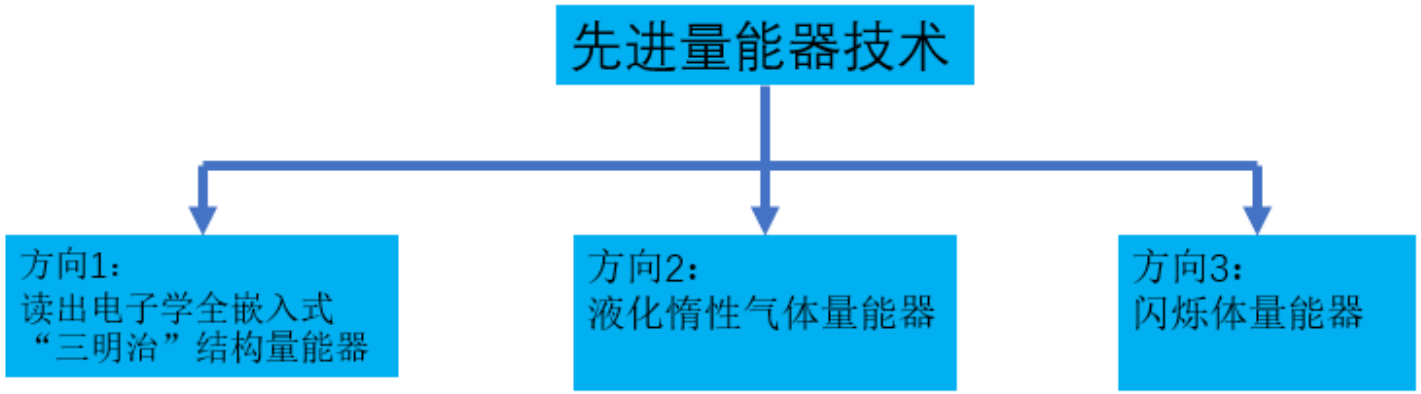


新型量能器



量能器技术前沿


RECFA
regular reports & final document
Plenary ECFA
final document for community endorsement
Publication
Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document
Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chairs (previous and present), LDG representative
Scientific Secretary: Susanne Kuehn
Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, Space, ...
TF#1 Gaseous Detectors
TF#2 Liquid Detectors
TF#3 Solid State Detectors
TF#4 Photon Detectors & PID
TF#5 Quantum & Emerging Technologies
TF#6 Calorimetry
TF#7 Electronics & On-detector Processing
TF#8 Integration
TF#9 Training
Consultation with the particle physics community & other disciplines with technology overlap


先进量能器技术
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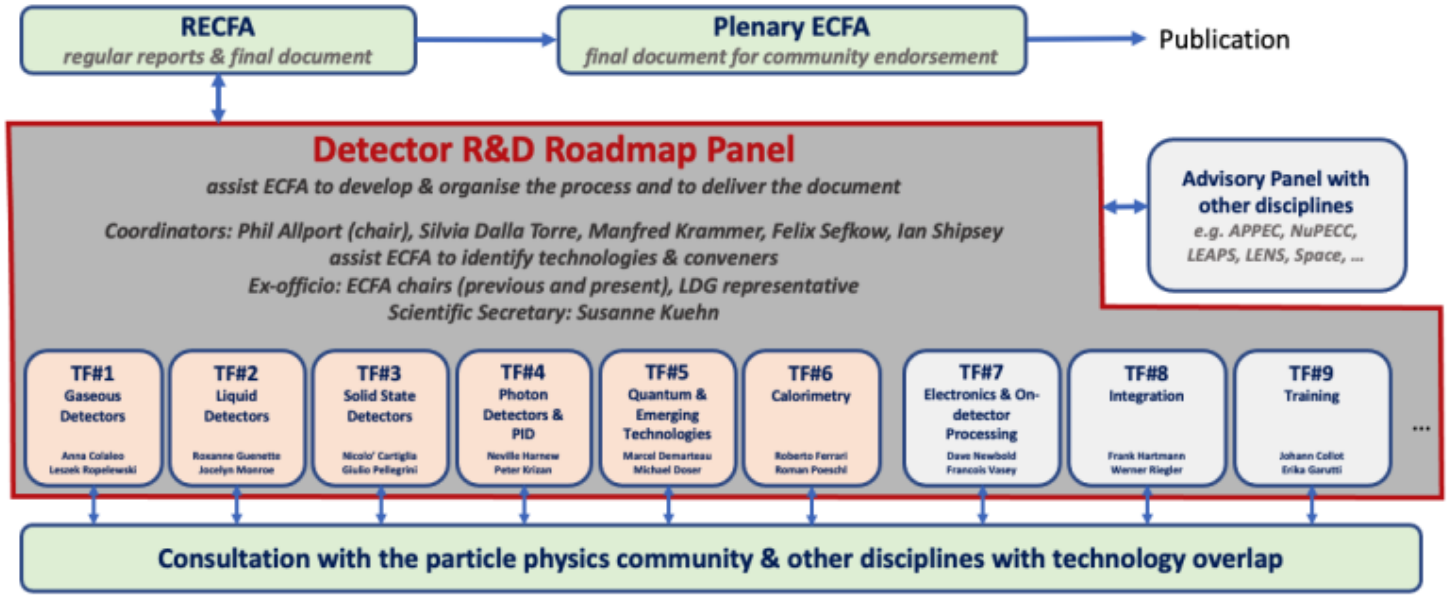
读出电子学全嵌入式
“三明治”结构量能器
方向2：
液化惰性气体量能器
方向3：
闪烁体量能器



量能器技术前沿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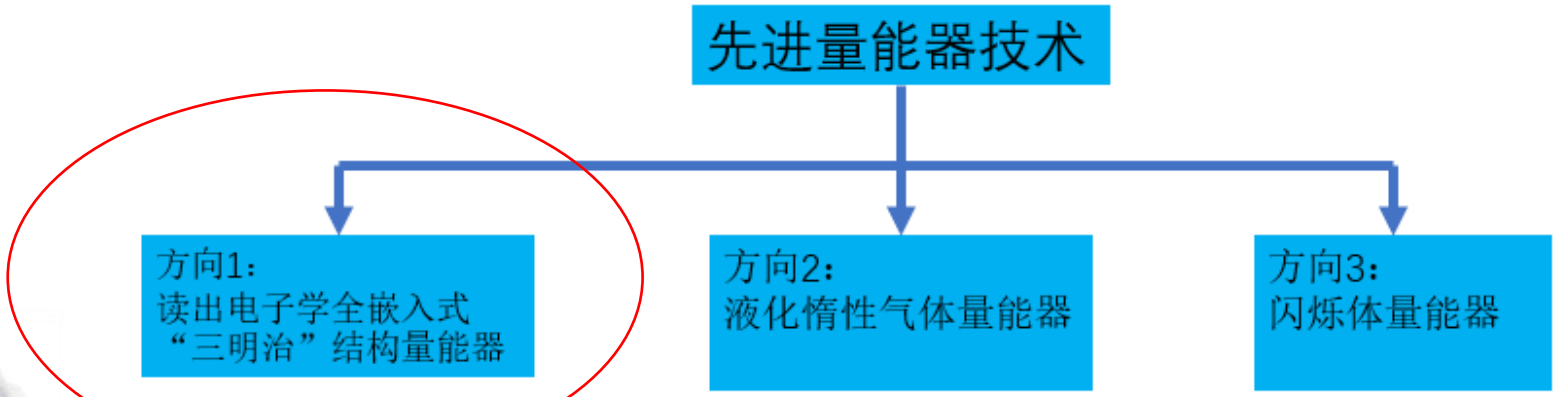
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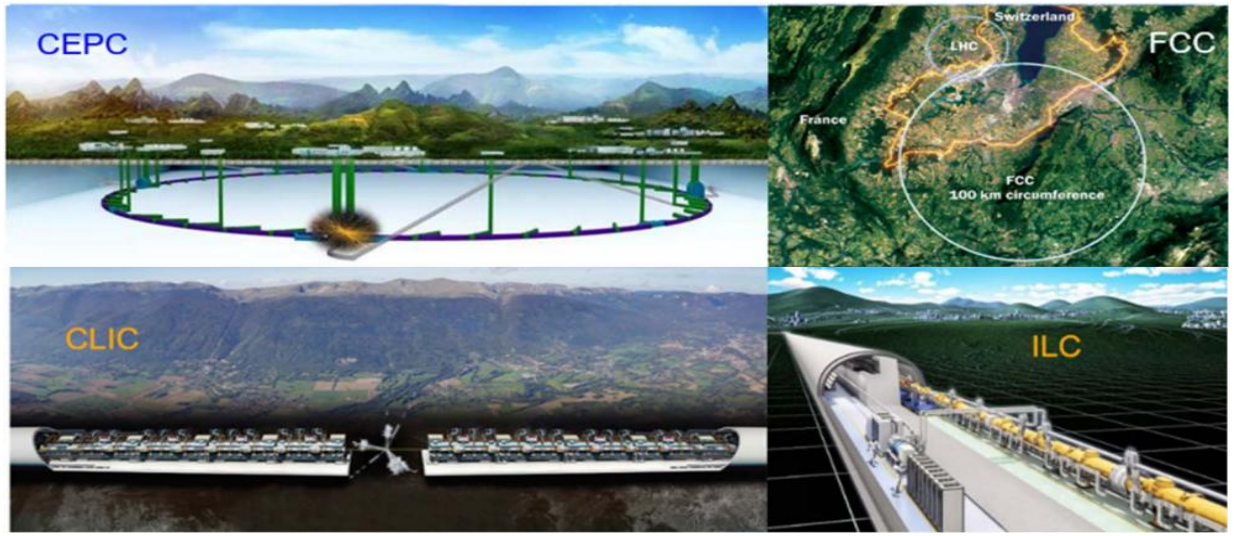
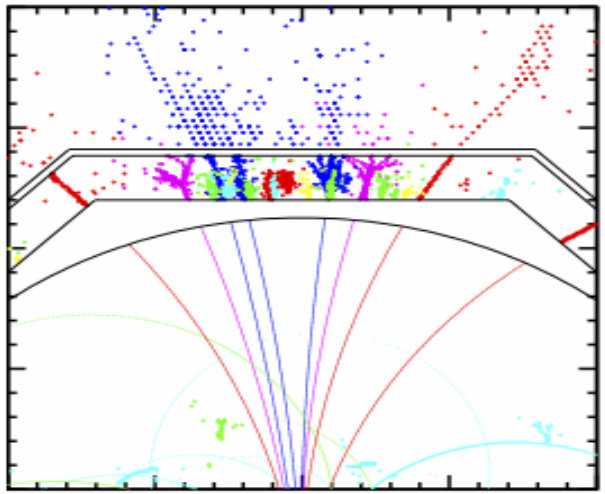
下一代高能量前沿实验需求

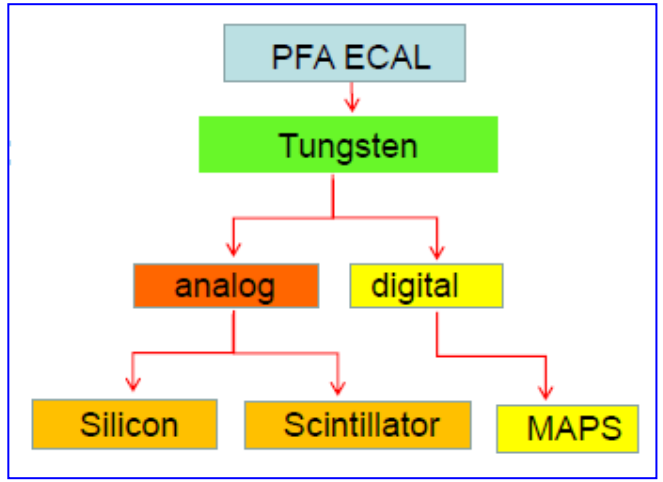
Challenges:

- **Momentum:** $\sigma_{1/p} < 5\times10^{-5}\ \mathrm{GeV}^{-1}$
- **Impact parameter:** $\sigma_{r\phi} = 5 \oplus 10/(p\cdot\sin^{\frac{3}{2}}\theta)\ \mu\mathrm{m}$
- **Jet energy:** $\frac{\sigma_E}{E} \approx 3-4\%$



- The Particle Flow Algorithm (PFA) calorimeter concept was proposed
  - High granularity
  - Good track finding
  - Good energy resolution



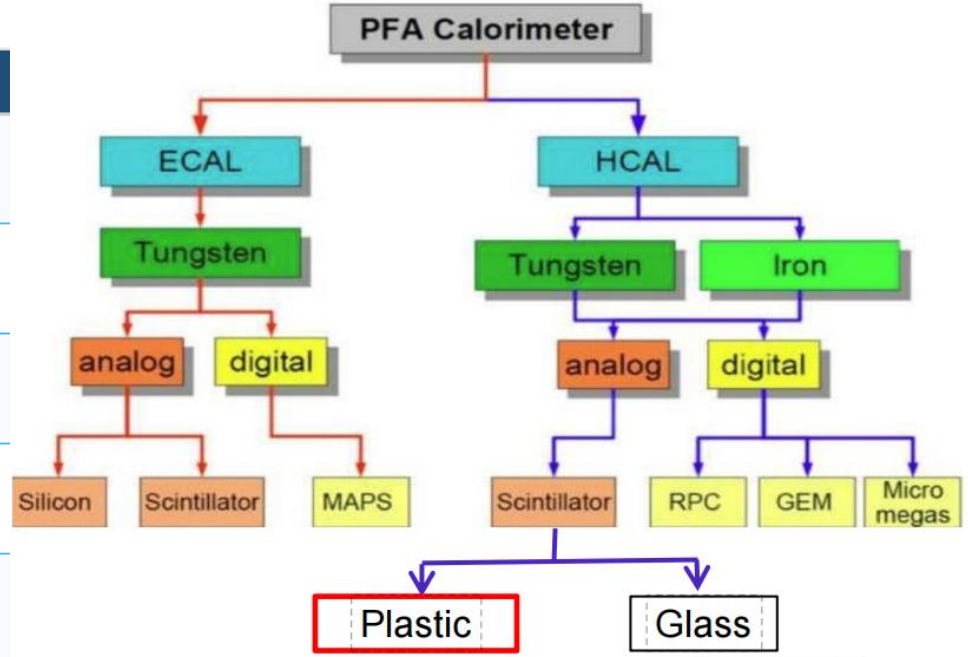


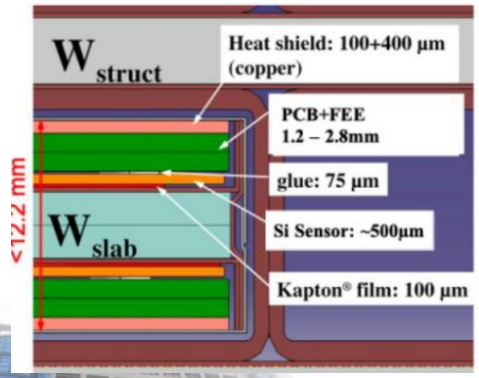


高颗粒度量能器样机

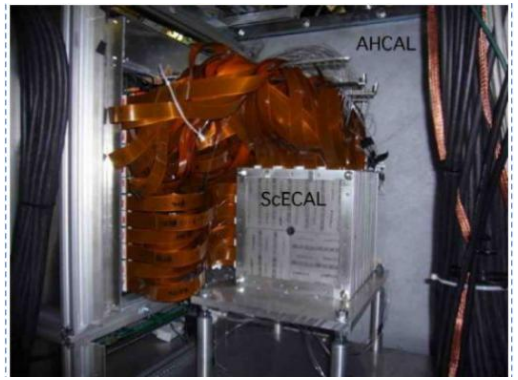
- 国际上粒子流量能器主要由CALICE合作组推动

装置	材料	颗粒度	结构
CALICE SiW-ECAL	Si PIN + W	1×1 cm² cells；	9720 cells；30 层；18×18 cm²；24 X_0
CALICE ScECAL	Scintillator strip + W-based	45×10 mm² strips；水平/垂直交替	468 channels；30 层；18*18cm²；21.5X_0
CALICE AHCAL	Scintillator tile + steel/W	中心区域 3×3 cm² tiles；	7608 channels；38 层；72×72 cm² 5. 3 λ_0
CALICE DHCAL	RPC + steel/W	1×1 cm²	52层；接近 5×10^5 channels ；96×96 cm²; 2.08 λ_0
CALICE SDHCAL	Glass RPC + steel a	1×1 cm²	48 层；460,000 channels; 100*100 cm², 5.76 λ_0





SiW-ECAL



Sc-ECAL



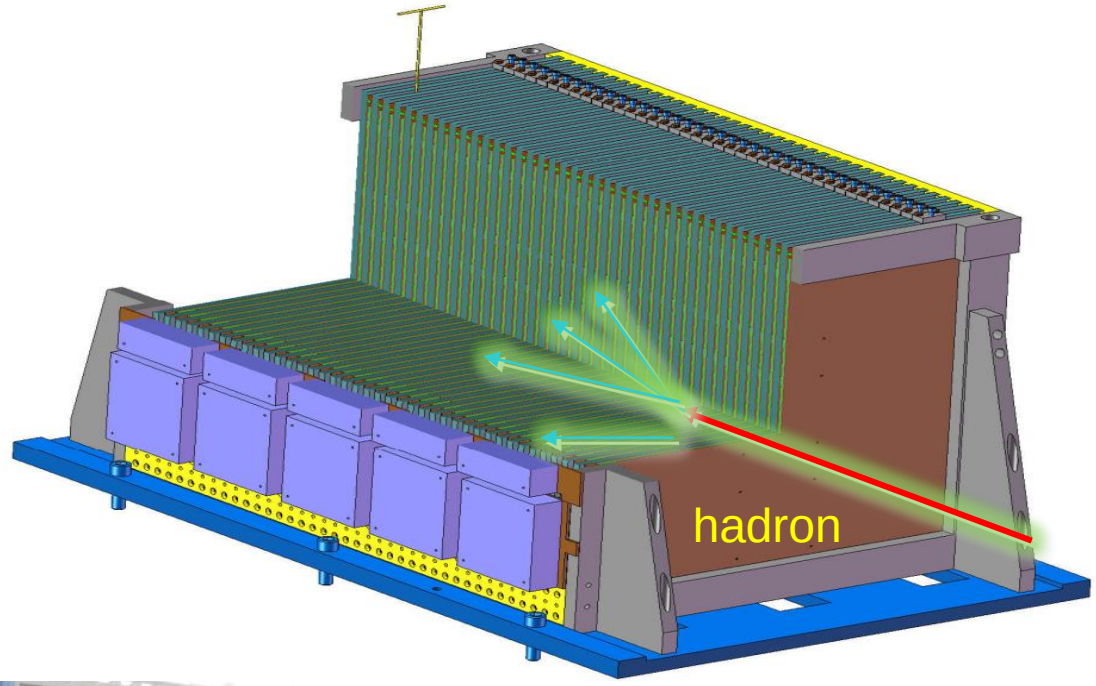
SDHCAL



DHCAL

高颗粒度量能器样机

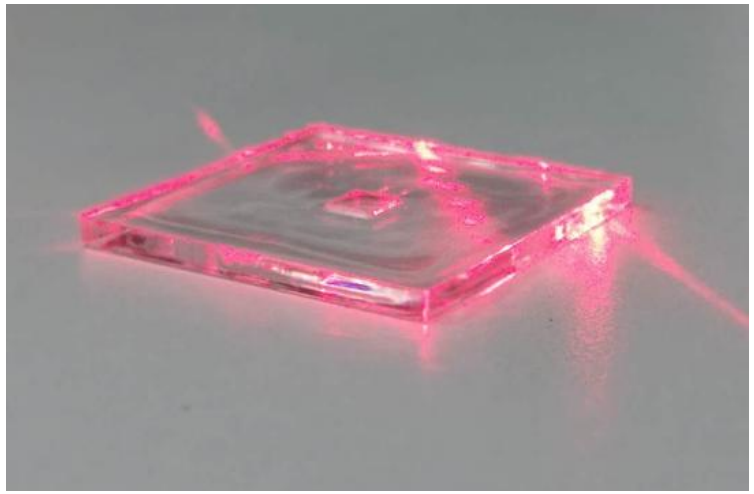
Calo	Sampling No.	Sensitive detector	Absorber	Granularity	Electronics	Absorb length	Energy Resolution	weight
AHCAL	40	PSD+SiPM	Fe	40mm×40 mm	SP-2E	4.7 NIL	60%@ 1 GeV	5.0 T



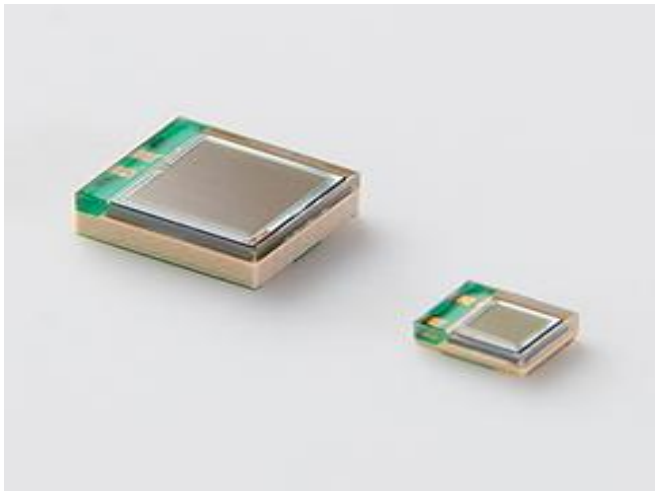


强子量能器单元

- 基于MC模拟优化探测器单元尺寸、确定读出动态范围等
  - 塑料闪烁体尺寸：40 mm×40 mm×3 mm
  - SiPM：像素尺寸为15 um，共~7300像素
  - 电子学芯片：SPIROC，36 channels/chip,30fC - 300 pC



塑料闪烁体单元



SiPM (1.3mm×1.3mm)

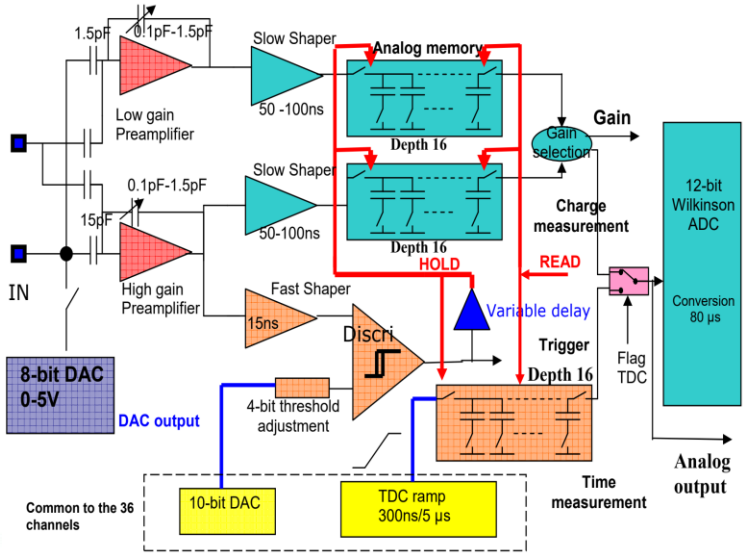


SPIROC chip

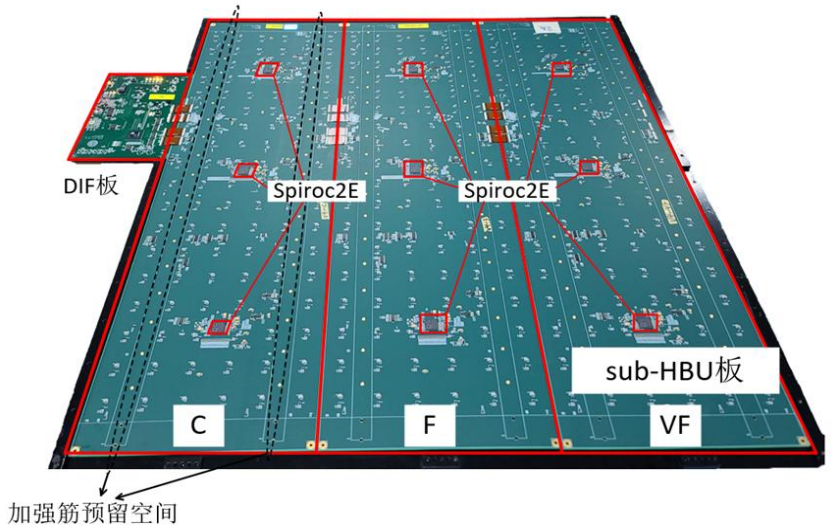


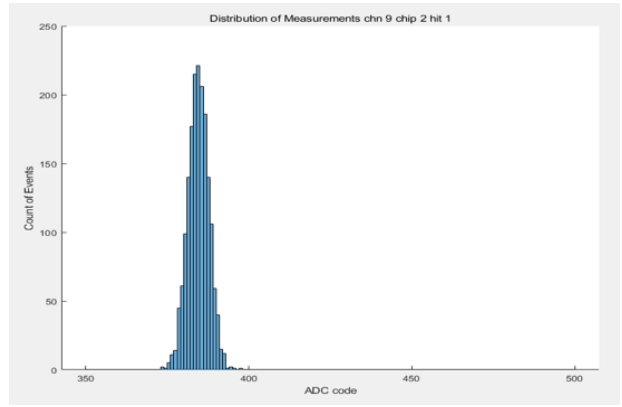
读出电子学

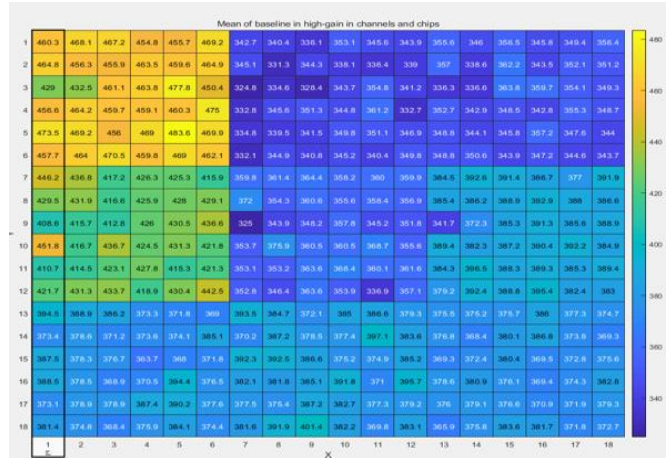
- SPIROC芯片
  - 36 模拟回路+1 ADC
  - 高低双增益
  - 功耗：6 mW/channel
  - 时间窗：4 μs



- HCAL Board Unit(HBU)
  - 信号读出
    - 9 SPIROC + 324 灵敏单元
  - 监测刻度
    - 324 LED + 48 温度芯片





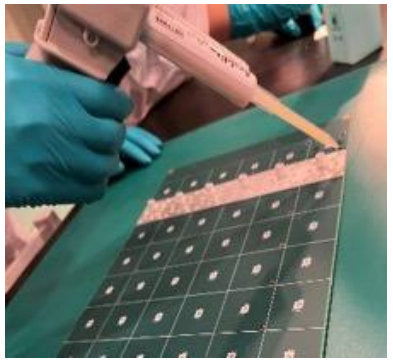
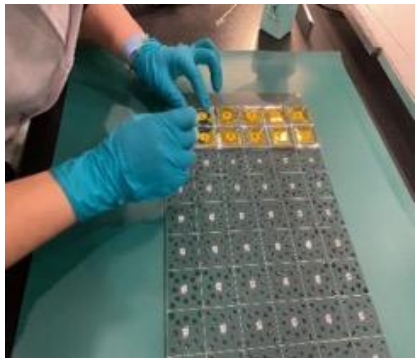
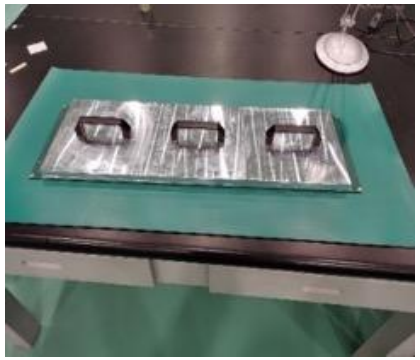
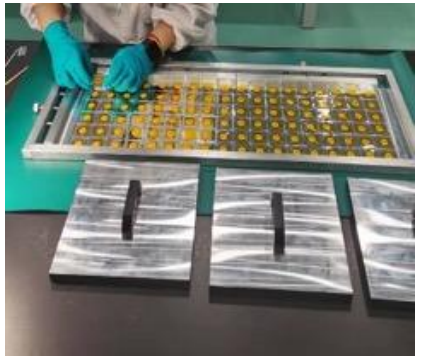


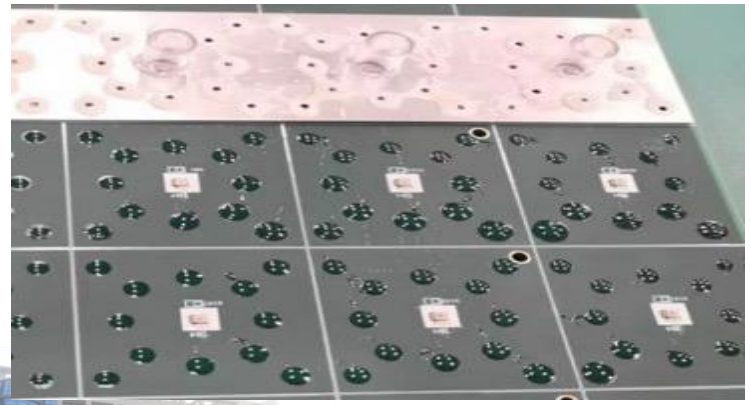
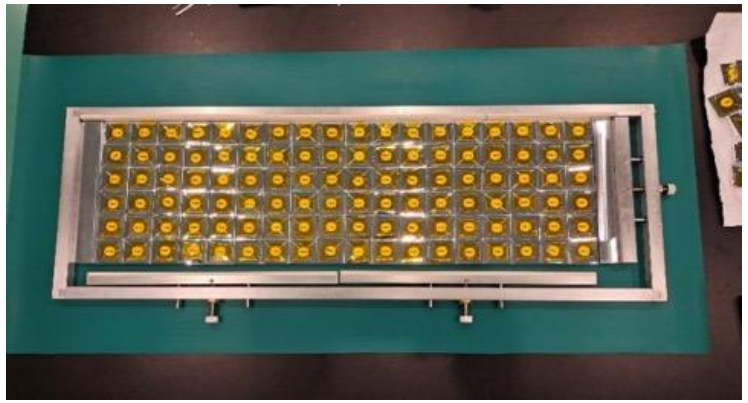
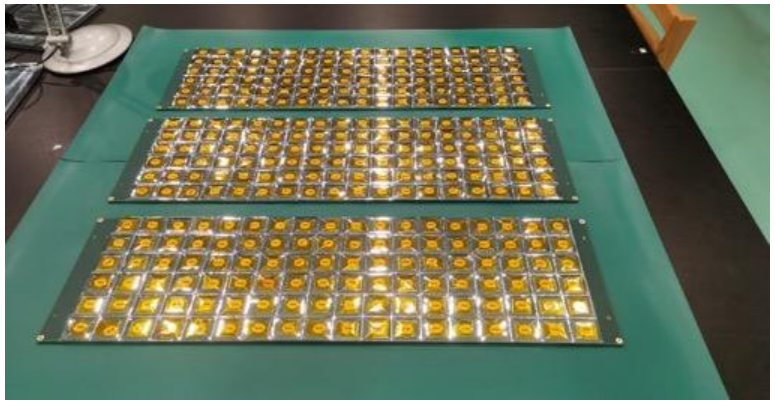
台基噪声分布

闪烁体组装

◆Developed a procedure dedicated to fitting scintillator tiles onto the HBU boards

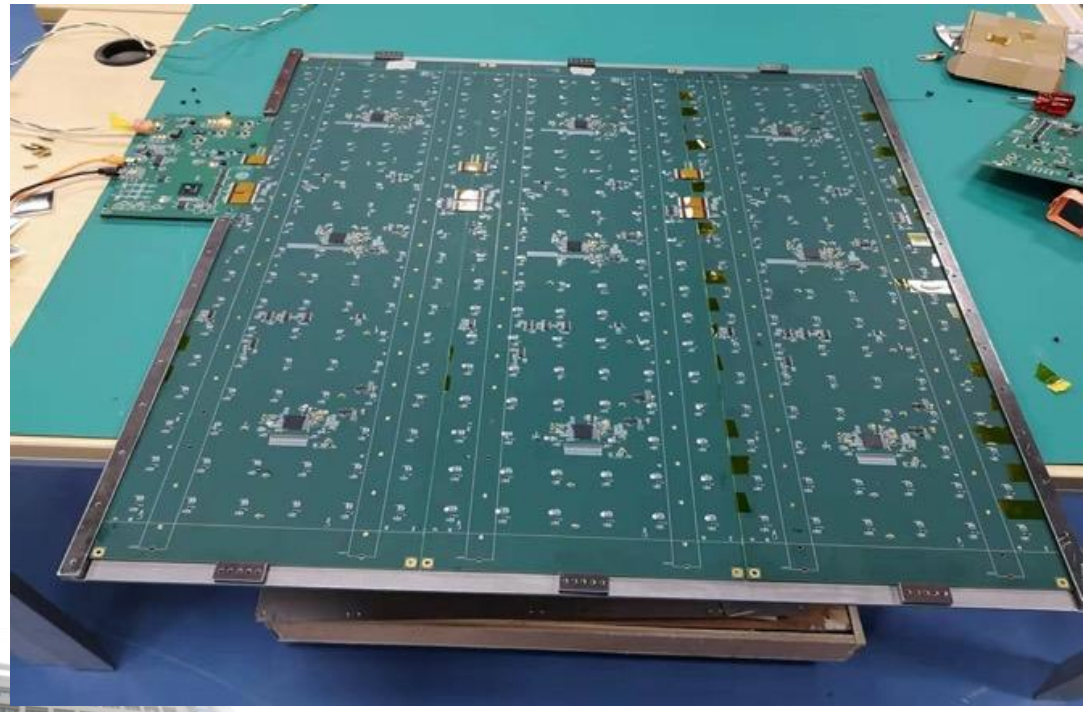
inspection gluing mounting curing inspection

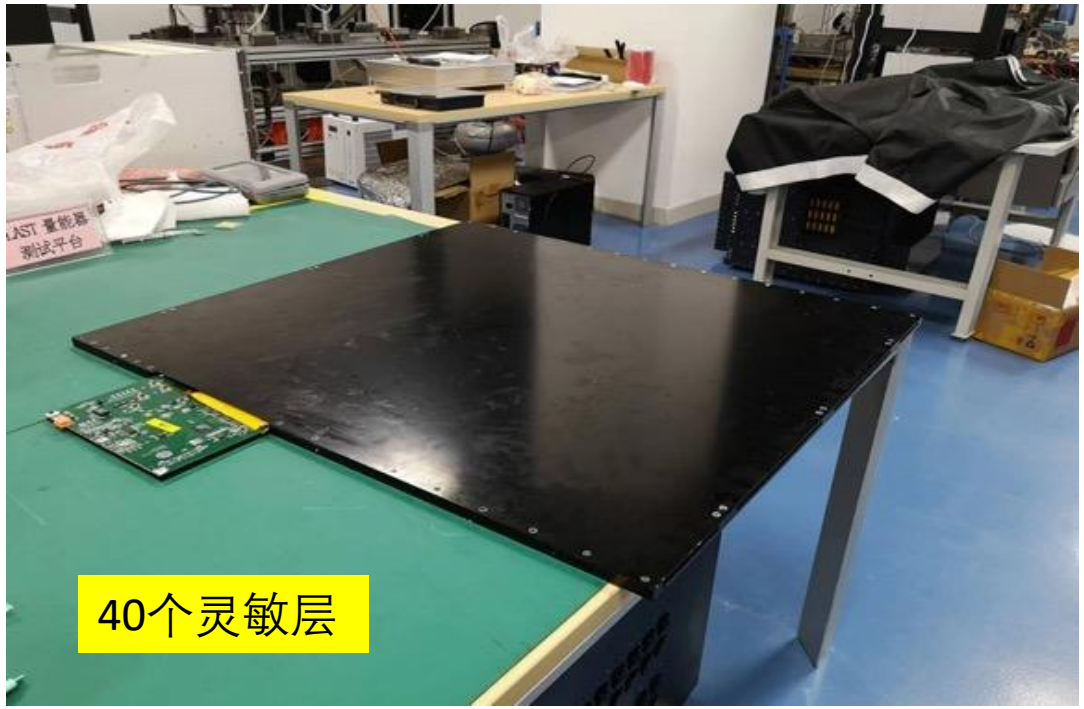






灵敏层组装

- Fitting a HBU into a cassette
  - Scintillation titles facing down and electronic components facing up
  - Rubber strips were used to support the two large plates of the cassette to prevent the plates from contacting the readout chips





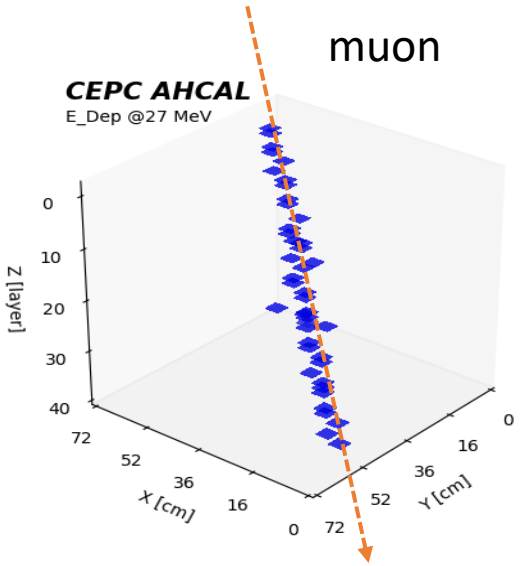
量能器组装

- 量能器包含40层Fe吸收体，每层16 mm厚度，Fe的作用是对入射粒子进行“阻挡”
- 把40层灵敏层等间隔组装到量能器中





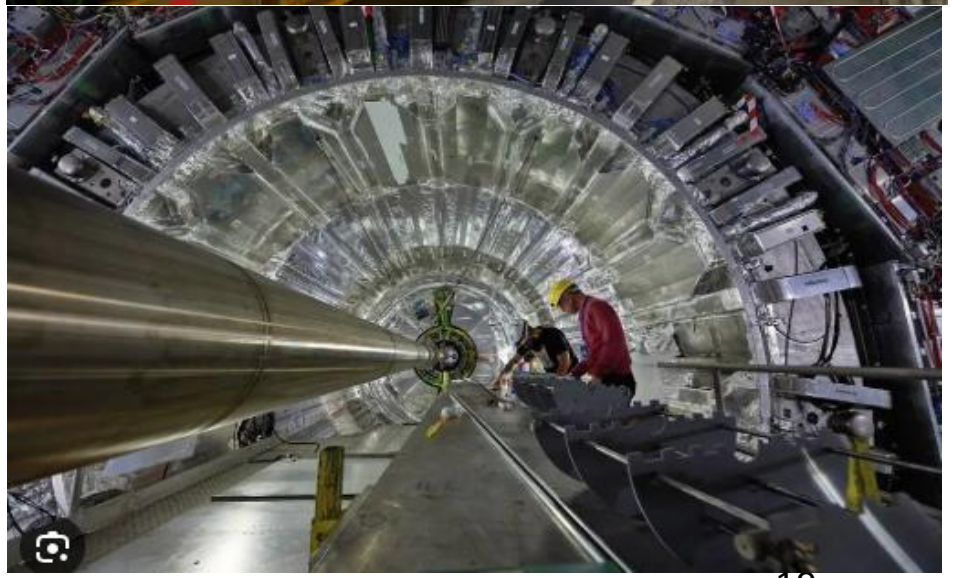




高能粒子束测试


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

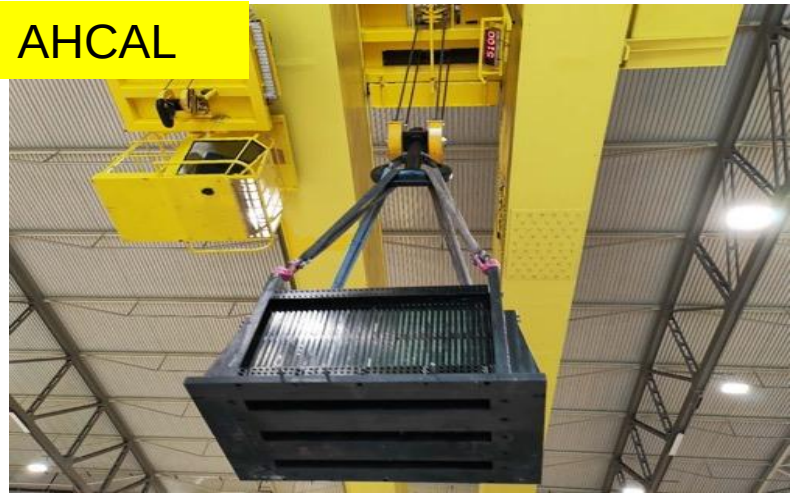

CERN

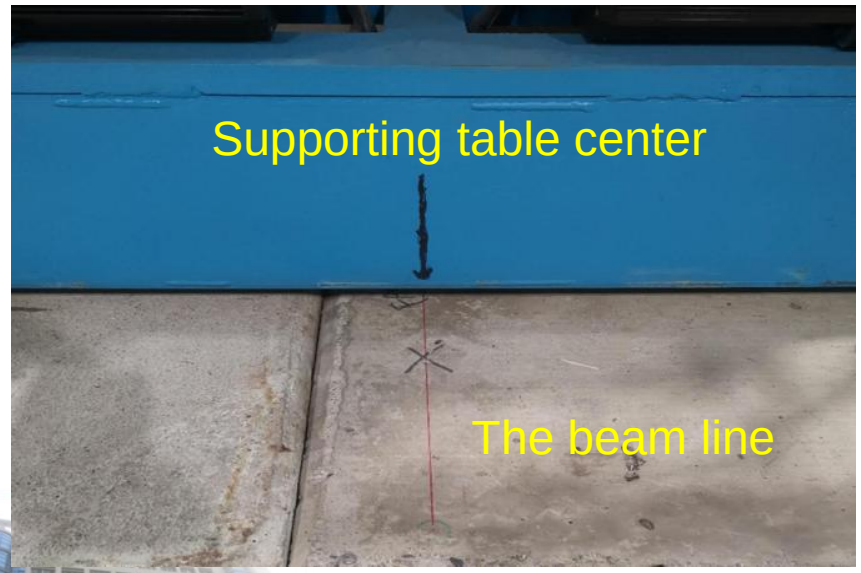


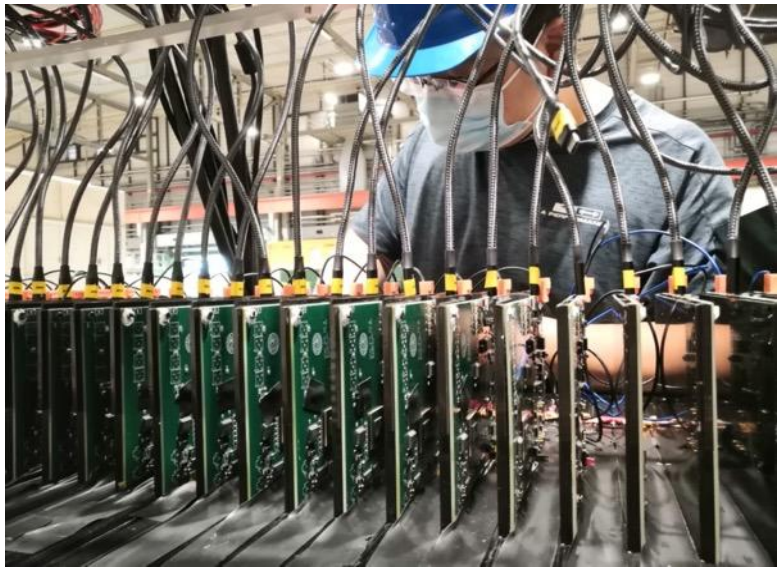
束流测试


Supporting Table


ECAL

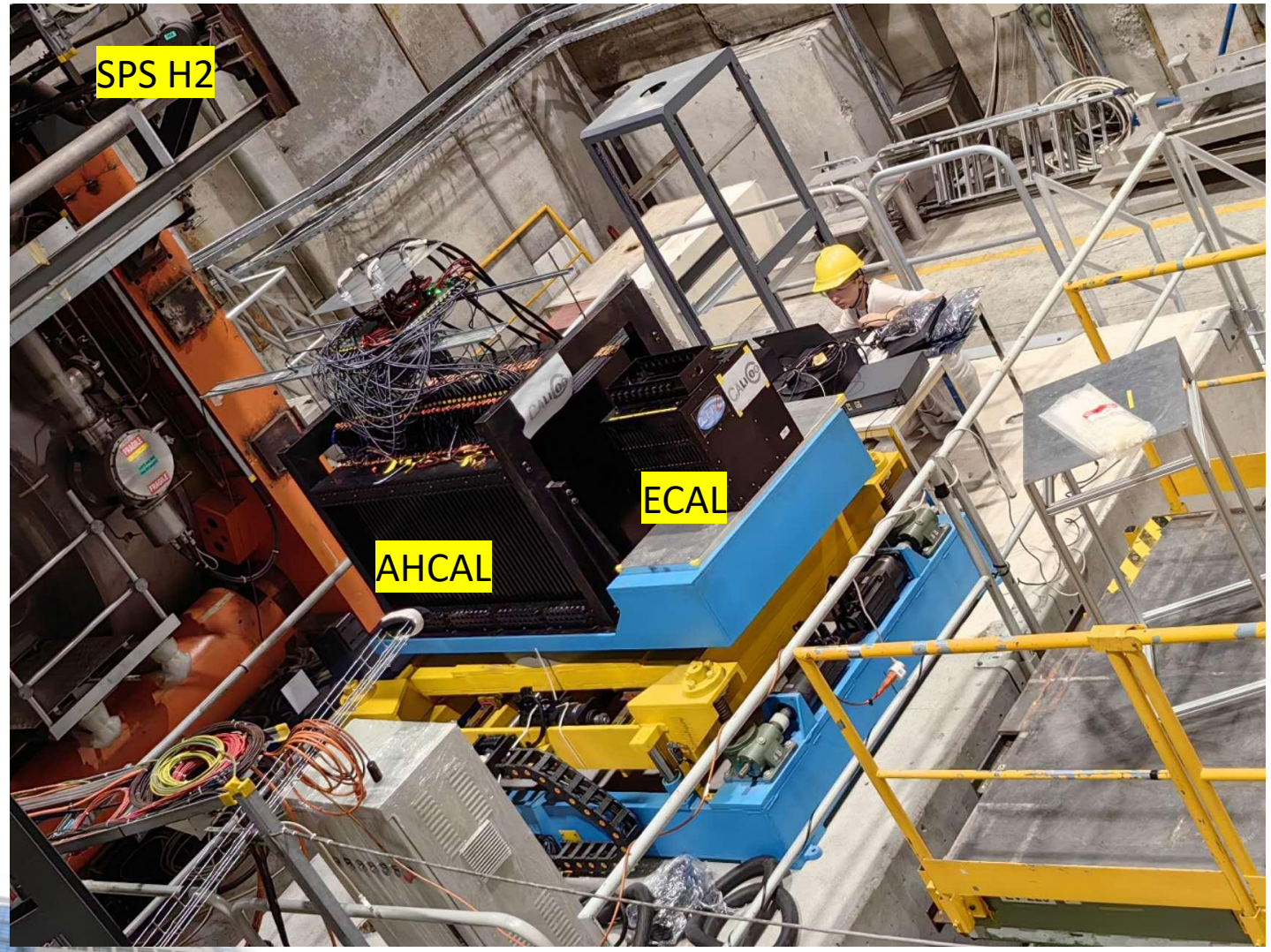

AHCAL


Supporting table center
The beam line

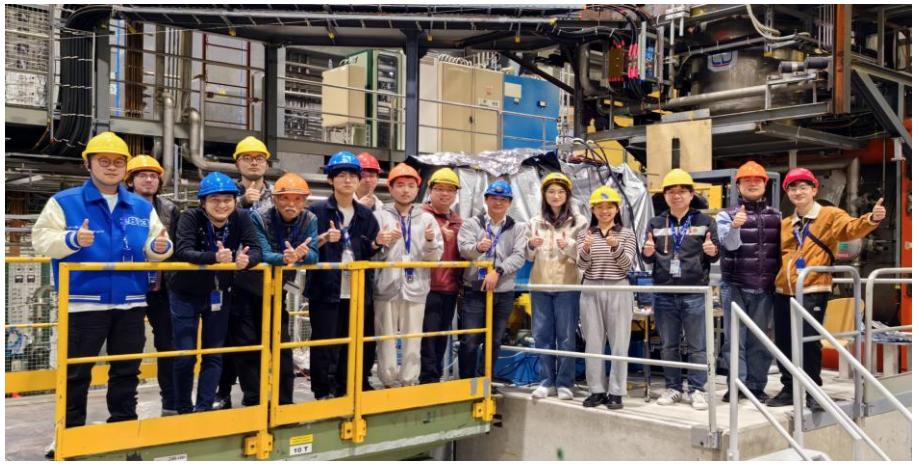



ECAL
HCAL
Table

束流测试

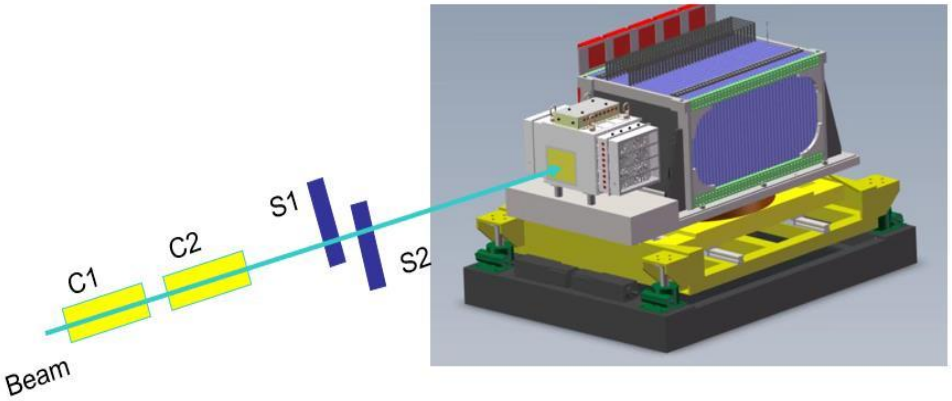


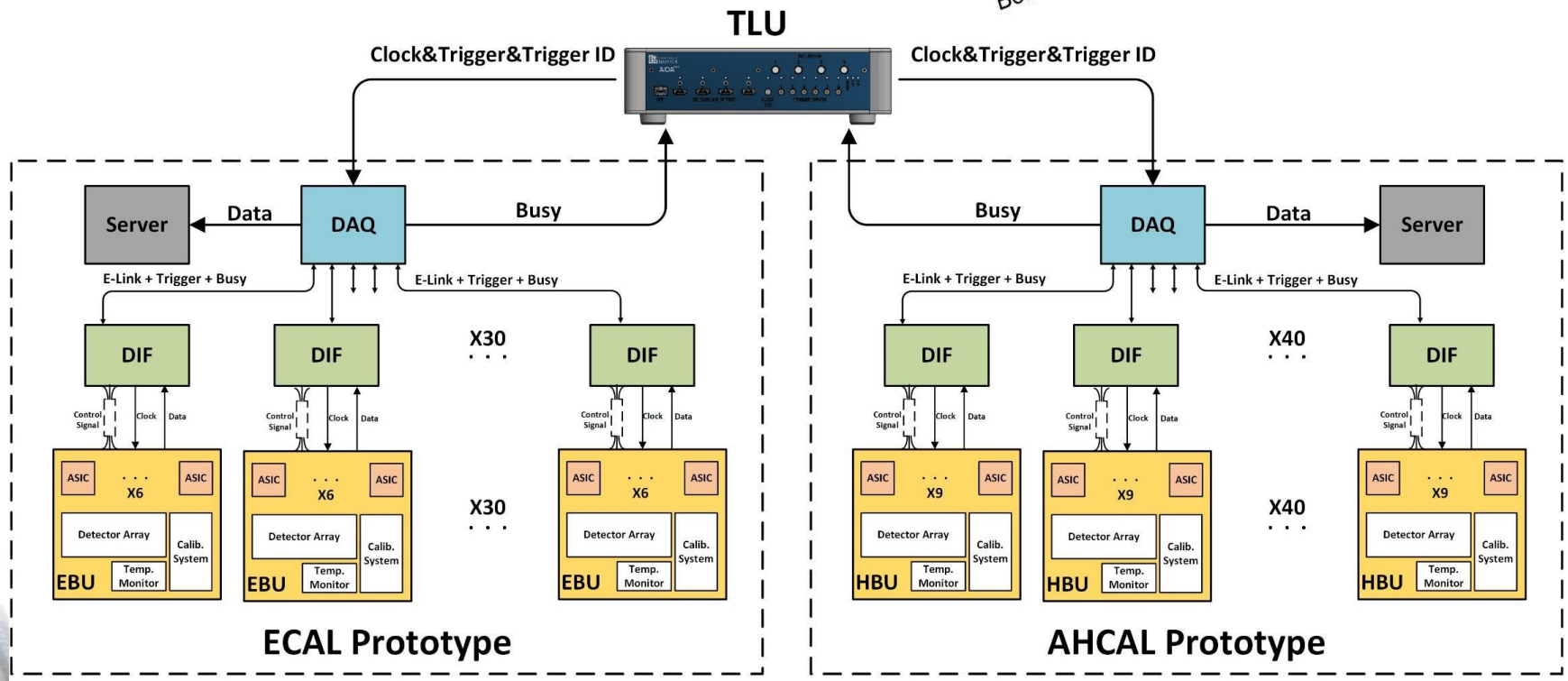




束流测试

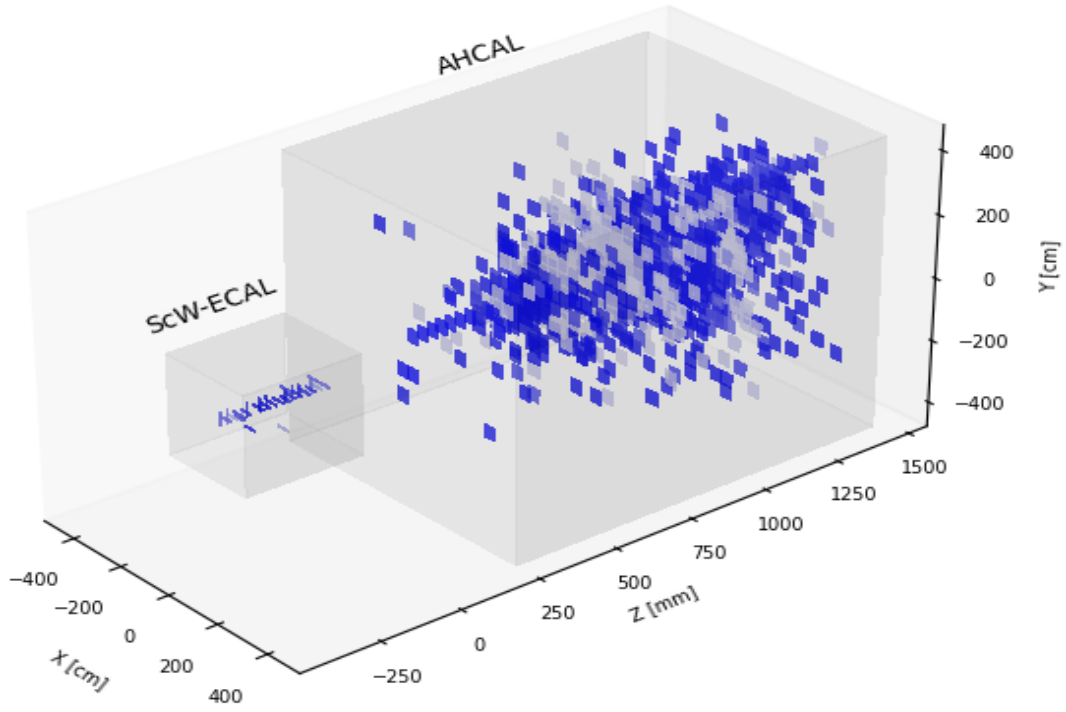
- **DAQ system for ECAL and AHCAL Prototypes**
  - **ECAL has 32 DIFs, AHCAL has 40 DIFs**
  - **Using TLU to synchronize two systems**





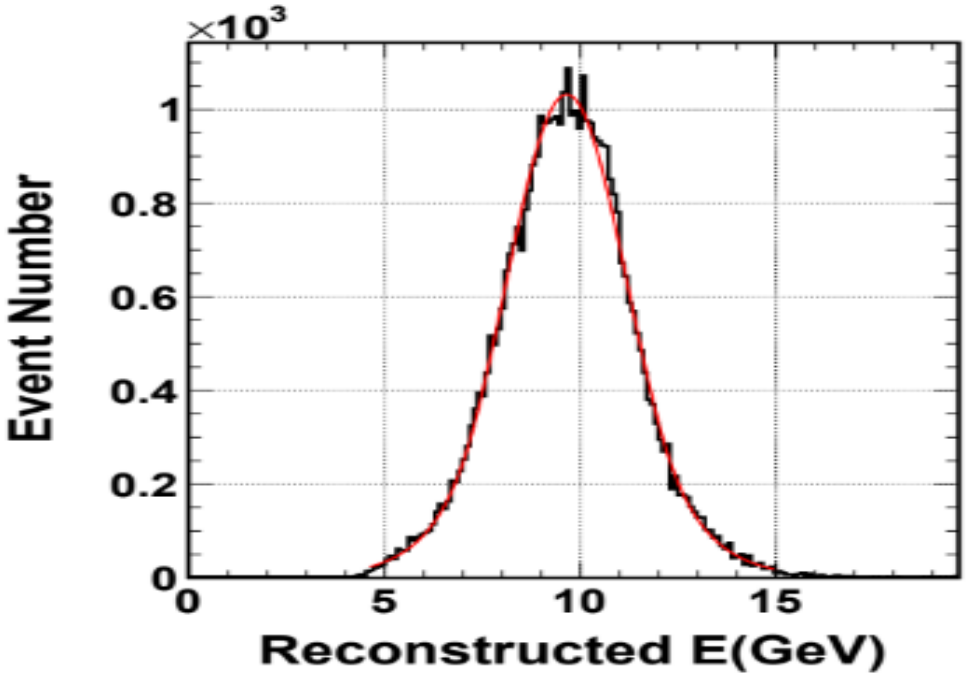
束流测试

- Muon Test
  - Momentum： 100 GeV/c， 10 GeV/c
  - 11 million
- Pion- test
  - 1 – 120 GeV/c， 350 GeV/c
  - 50 million
- Electron Test
  - 1 – 250 GeV/c
  - 10 million
- Proton, 350 GeV/c
  - 1 million

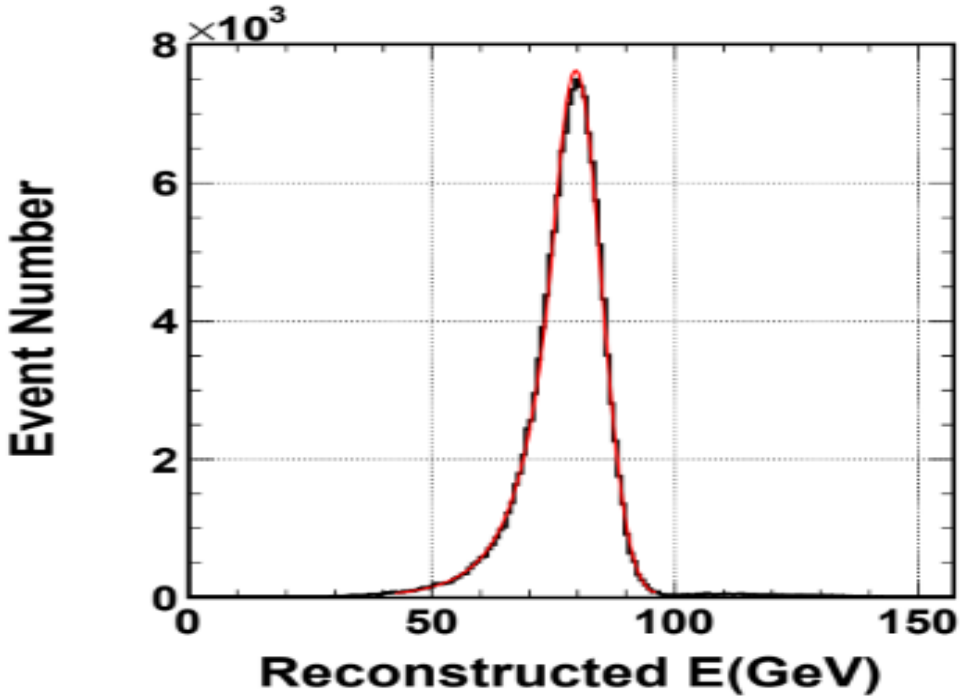


束流事例显示

AHCAL对强子的能量响应



10 GeV pion

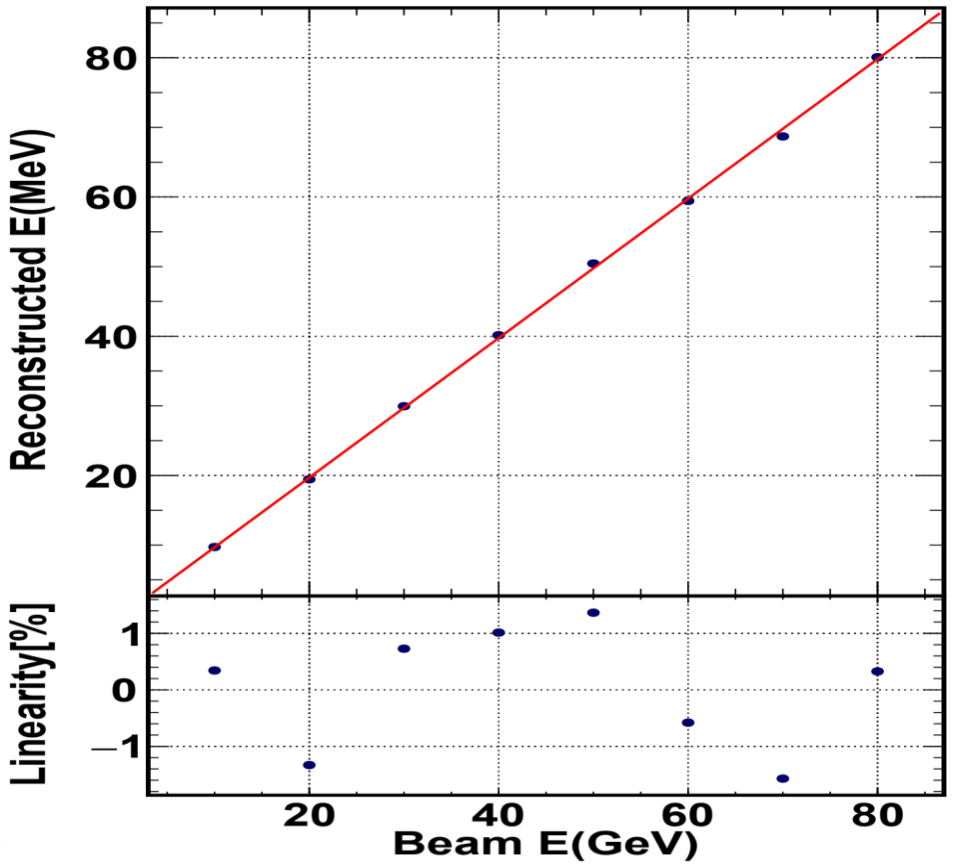


80 GeV pion

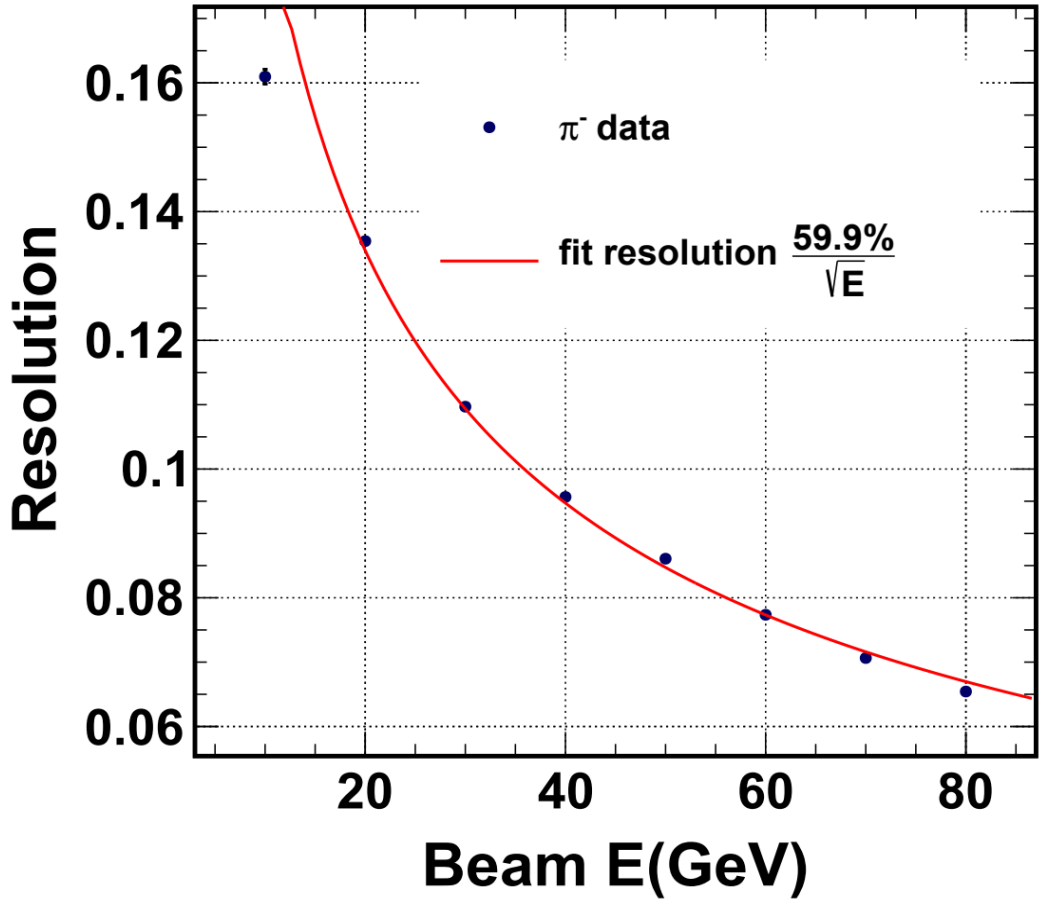


AHCAL对强子的能量响应

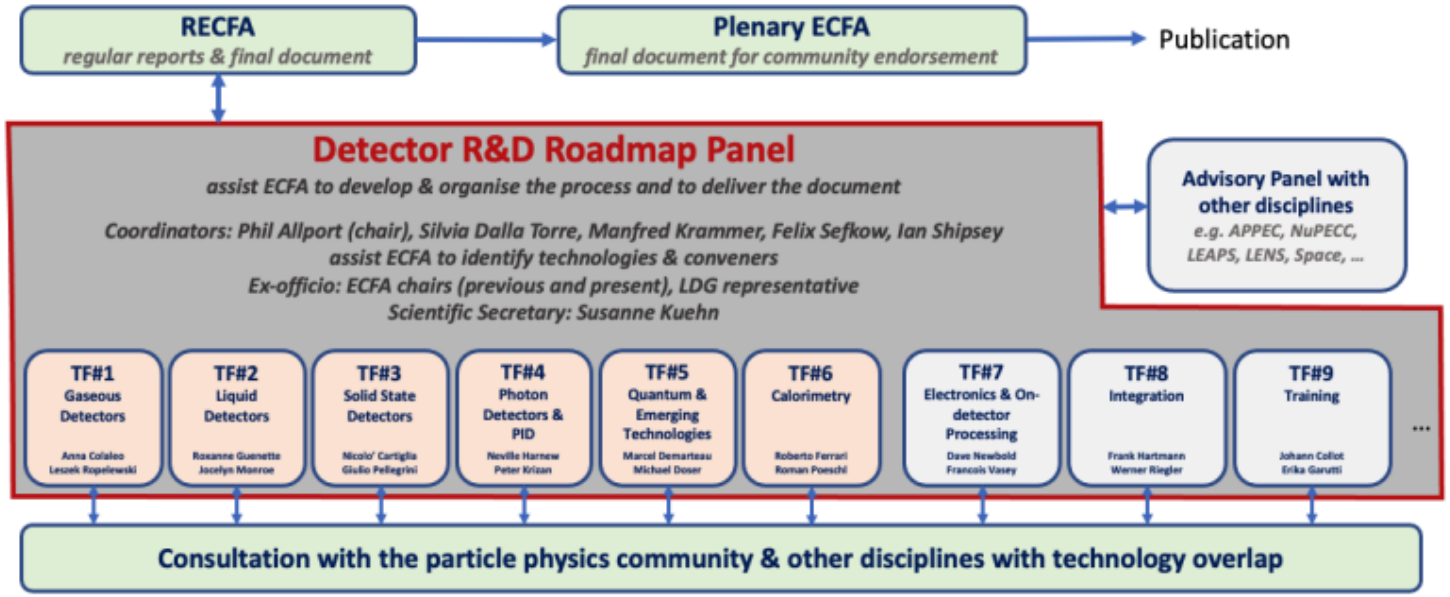
能量线性

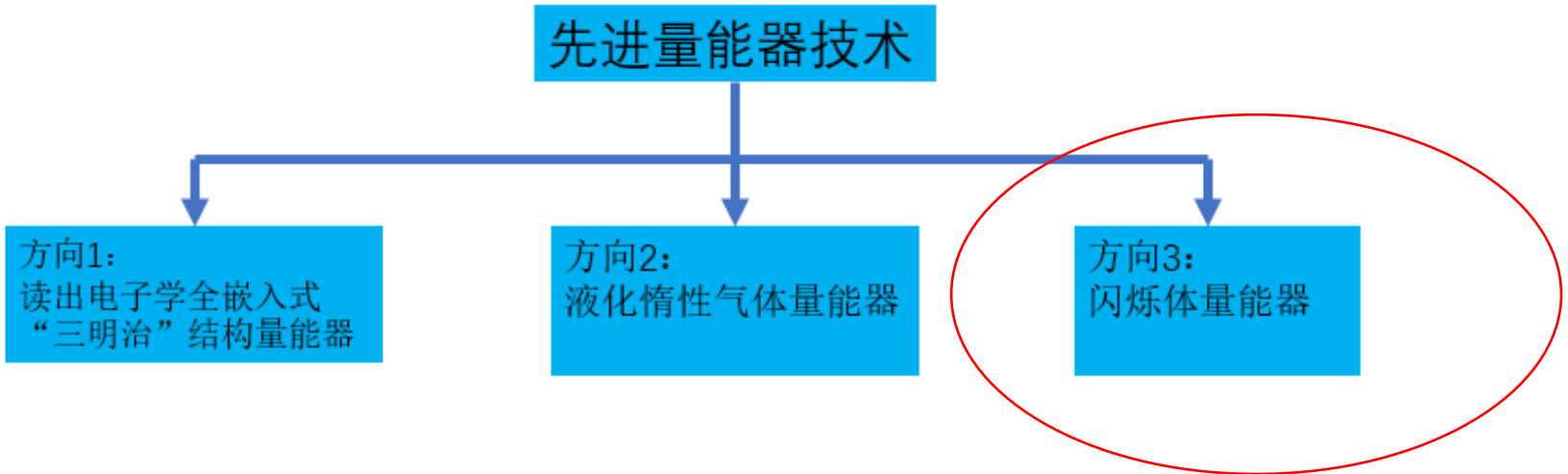


能量分辨



量能器技术前沿

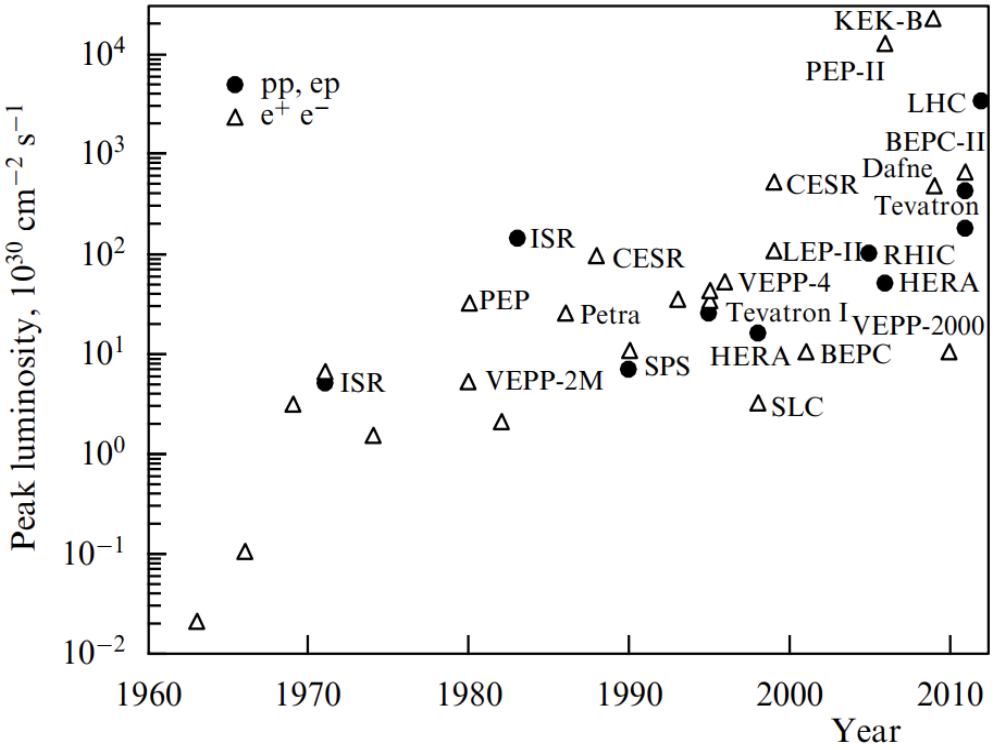

RECFA
regular reports & final document
Plenary ECFA
final document for community endorsement
Publication
Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document
Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chairs (previous and present), LDG representative
Scientific Secretary: Susanne Kuehn
Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, Space, ...
TF#1 Gaseous Detectors
TF#2 Liquid Detectors
TF#3 Solid State Detectors
TF#4 Photon Detectors & PID
TF#5 Quantum & Emerging Technologies
TF#6 Calorimetry
TF#7 Electronics & On-detector Processing
TF#8 Integration
TF#9 Training
Consultation with the particle physics community & other disciplines with technology overlap


先进量能器技术
方向1：
读出电子学全嵌入式
“三明治”结构量能器
方向2：
液化惰性气体量能器
方向3：
闪烁体量能器



高亮度实验

- 高亮度实验是粒子物理发展的一个重要方向
  - 高的物理事例率
  - 极高的本底事例率
    - 事例堆积、辐照剂量
- 这对量能器提出了新的需求与挑战
  - 在极高的（本底）事例率下实现高精度测量
    - MHz？
  - 量能器的抗辐射能力
    - 百 kRad？

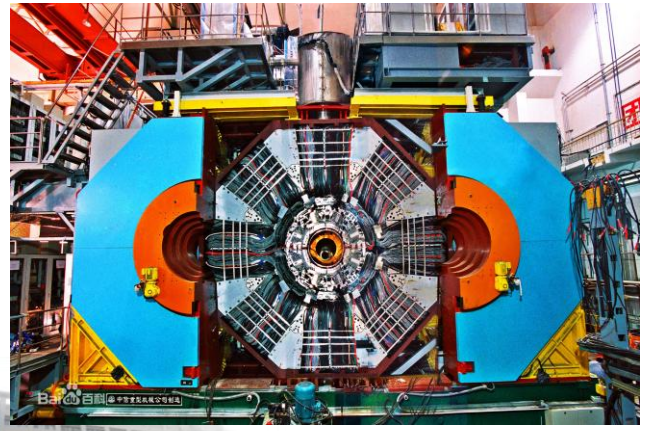




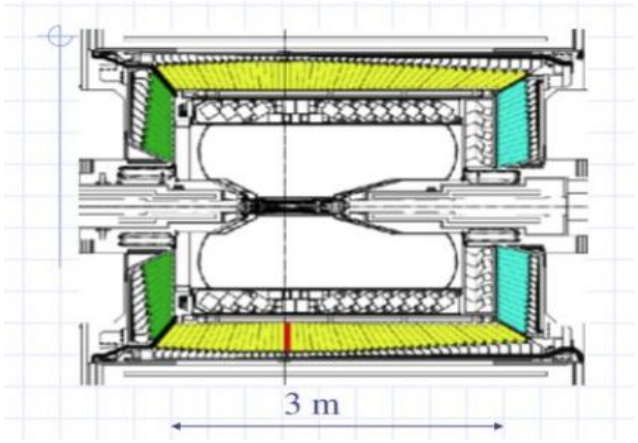
晶体量能器

- 晶体量能器能量分辨好、抗辐射性能优
- 是粒子物理实验电磁量能器的重要选择之一

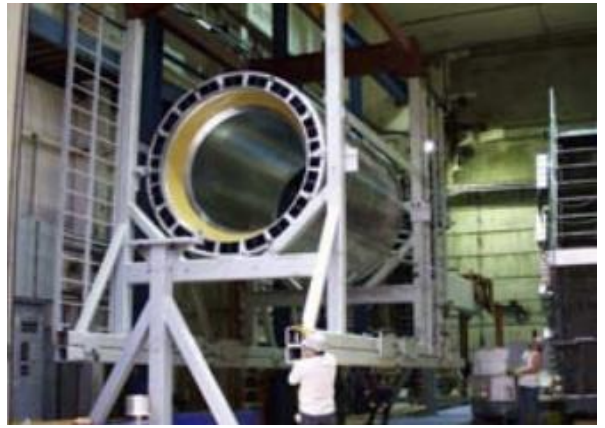
- BESIII 量能器
  - CsI(Tl)全吸收型
  - 能区：20 MeV – 2 GeV
  - 能量分辨：优于2.5% @ 1 GeV
  - 位置分辨：6 mm @ 1 GeV



- BELLE 量能器
  - CsI(Tl)全吸收型
  - 能区：20 MeV – 8 GeV
  - 能量分辨：优于2% @ 1 GeV
  - 位置分辨：6 mm @ 1 GeV



- Babar 量能器
  - CsI(Tl)全吸收型
  - 能区：15 MeV – 8 GeV
  - 能量分辨：优于3% @ 1 GeV
  - 角分辨：4.16 mrad @ 1 GeV



高亮度前沿：超级陶粲装置（STCF）

第三代正负电子对撞机，国际粒子物理领域高亮度前沿核心装置之一，是研究物质深层次结构、探索夸克如何构成物质的独特大科学装置



超宽连续可调能量
2 ~ 7 GeV

超高亮度
$0.5\times10^{35}\ cm^{-2}\ s^{-1}$

具备进一步提升性能的能力

下一代晶体量能器的选择

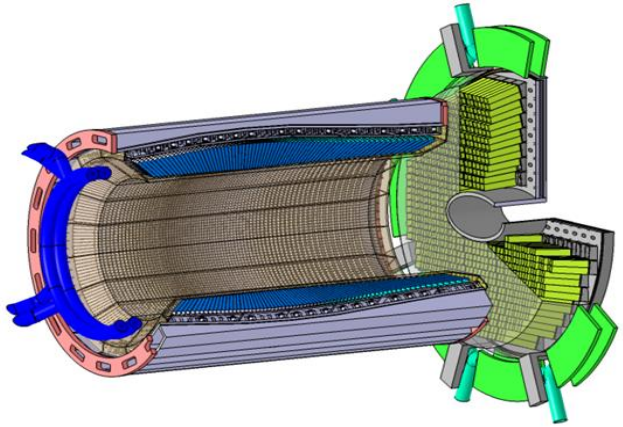
- 下一代晶体量能器
  - 要求晶体具有更快的发光衰减时间
  - 更高的抗辐照能力

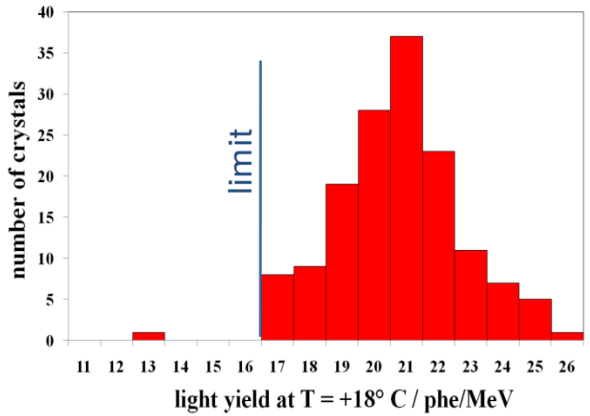
Crystal	Pure CsI	LYSO	GSO	YAP	PWO	BaF:Y
Density (g/cm^3)	4.51	7.40	6.71	5.37	8.30	4.89
Melting Point (°C)	621	2050	1950	1872	1123	1280
Radiation Length (cm)	1.86	1.14	1.38	2.70	0.89	2.03
Moliere Radius (cm)	3.57	2.07	2.23	4.50	2.00	3.10
Refractive index	1.95	1.82	1.85	1.95	2.20	1.50
Hygroscopicity	Slight	No	No	No	No	No
Luminescence (nm)	310	402	430	370	425 420	300 220
Decay time (ns)	30 6	40	60	30	30 10	600 1.2
Light yield (%)	3.6 1.1	85	20	65	0.3 0.1	1.7 4.8
Dose rate dependent	No	No	TBA	TBA	Yes	No
D(LY)/dT (%/°C)	-1.4	-0.2	-0.4	TBA	-2.5	TBA
Experiment	KTeV Mu2e				CMS ALICE PANDA	
单价	0.5	4	-	-	1（参考）	1.3



PANDA实验

- PANDA实验组选择了新型PWO(PWO II)晶体作为其电磁量能器的灵敏探测单元
  - 相对光产额，0.6，比PWO高1.5倍
- PANDA组的一个关键技术攻关：提高PWO II光产额
  - 两个大面积APD与PWO II晶体耦合
  - 量能器运行在-25度环境下，光产额提高4倍
  - 最终实现了约100 pe/MeV水平

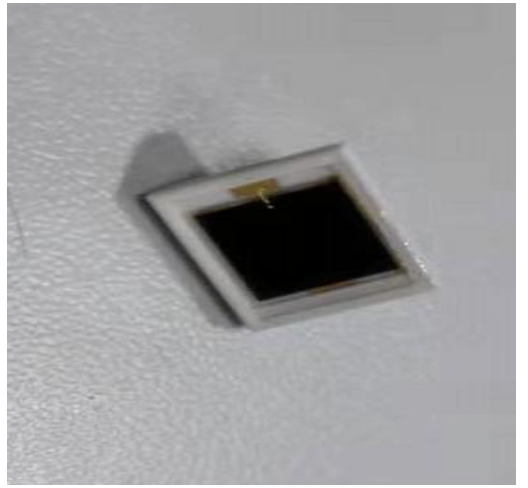


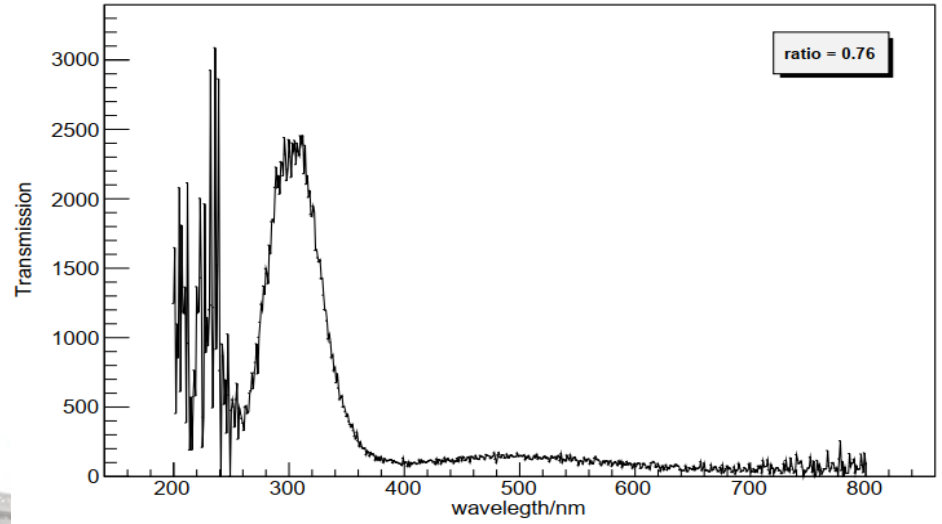


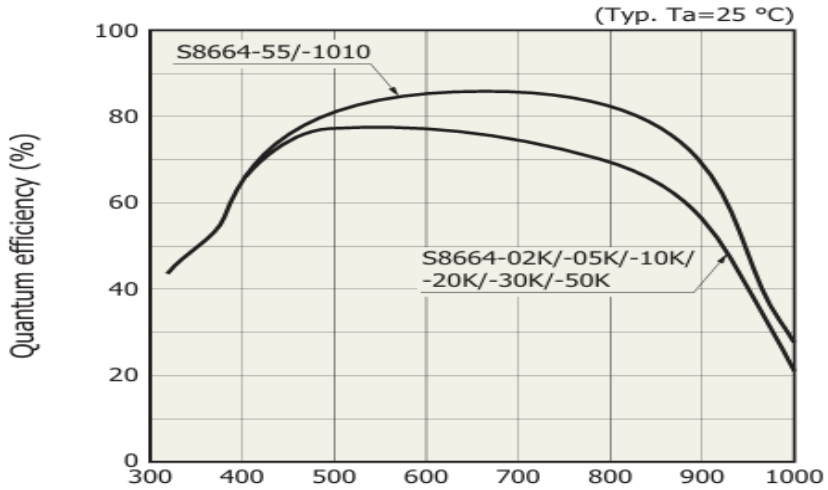


BELLE II实验组

- BELLE II实验组选用了pCsI晶体开展了预研
- pCsI晶体光衰减时间：6ns（f),30ns（s）
- 荧光产额：1.1 （f），3.6 （s）
- 发光波段在310 nm附近，与常规APD的QE匹配度不好
  - QE~40%@310 nm



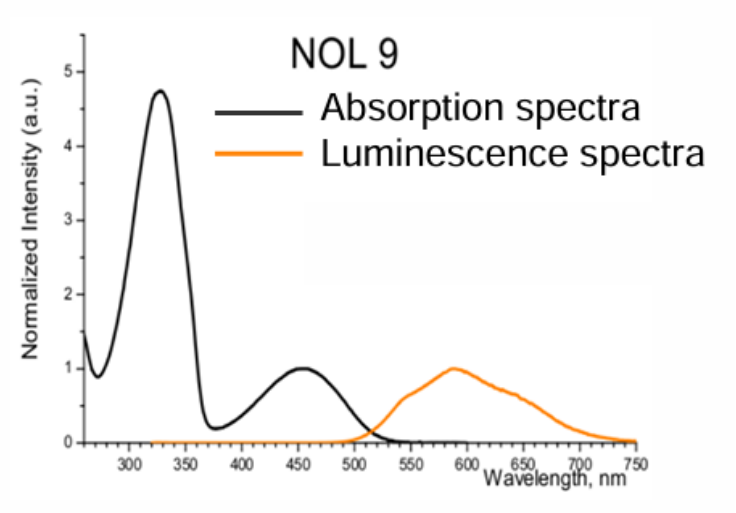


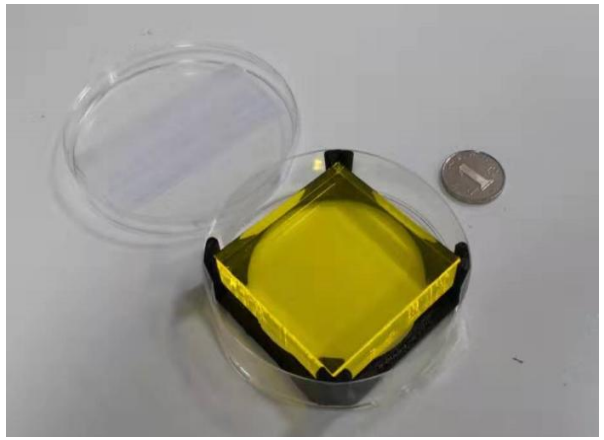


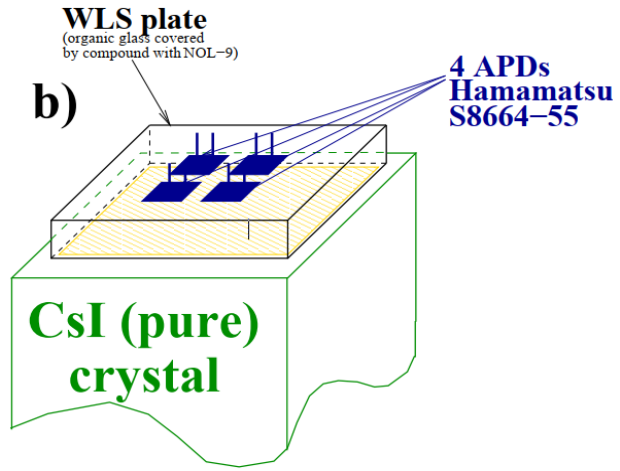


BELLE II实验组

- BELLE II实验组尝试了一种新型的波长位移材料,NOL-9
- 可以把~310 nm的荧光转换到588nm，与APD更好匹配，取得了很好的效果
- 光产额提高到~100 pe/MeV



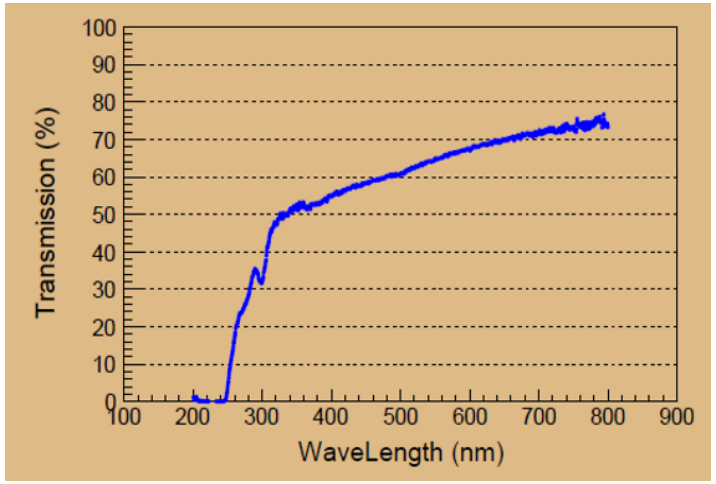




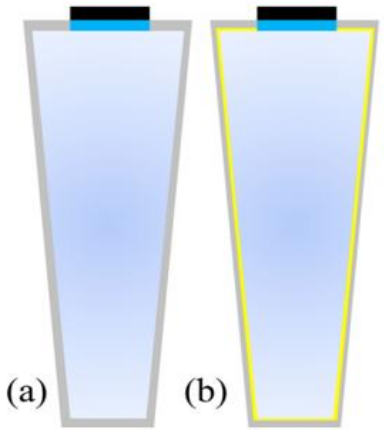


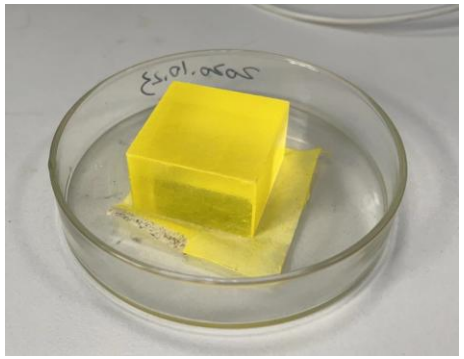
新的尝试

- 对于大尺寸晶体，晶体的荧光自吸收效应不能忽略
  - ~30%@310nm
  - ~70%@600nm
- 可以把晶体表面喷涂NOL波长位移材料，在荧光光子第一次与晶体表面作用时就被转换
  - 模拟结果显示，光产额可以提高近2倍

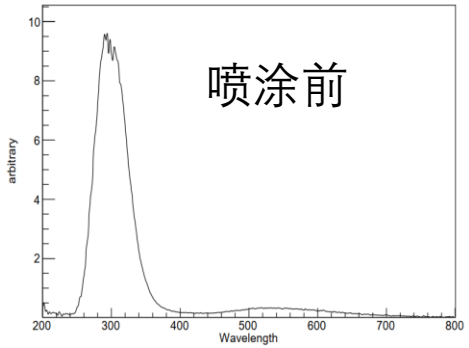


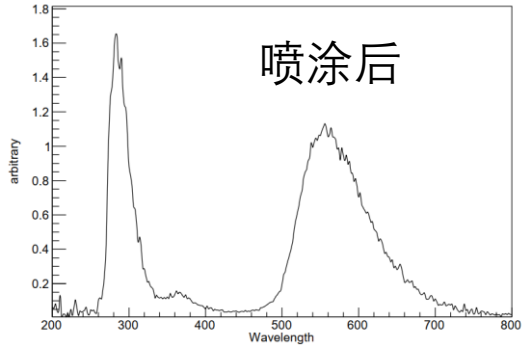
28cm长pCsI晶体荧光传输效率





pCsI喷涂尝试

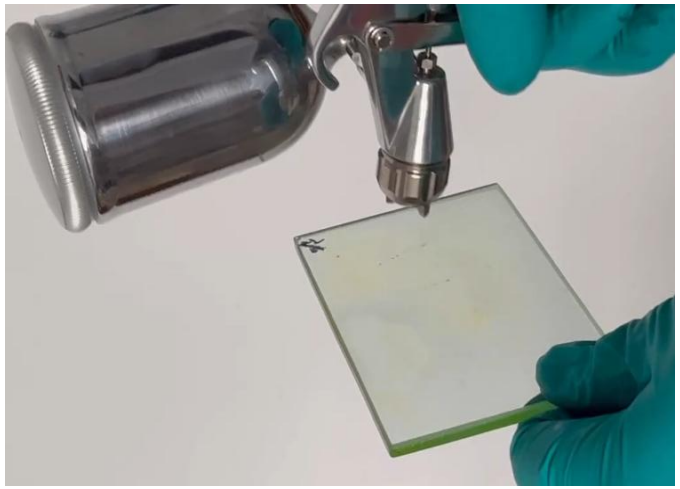




长波段光子大量增加

pCsI晶体荧光产额

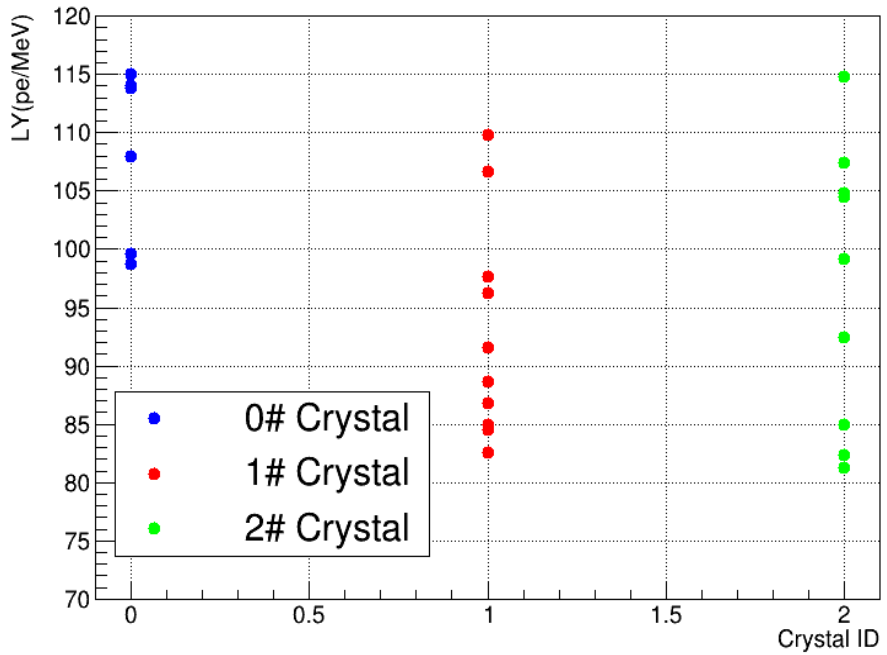
- 利用喷枪摸索喷涂工艺
- 把WLS材料喷涂在晶体表面
  - 玻璃、小晶体、大晶体



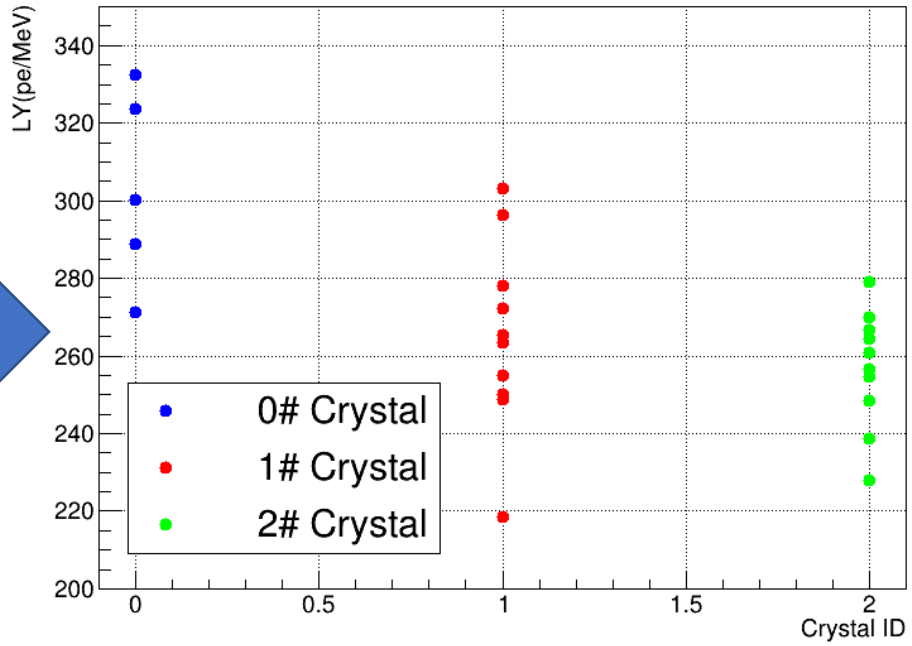




pCsI晶体荧光产额



喷涂前后



喷涂WLS前

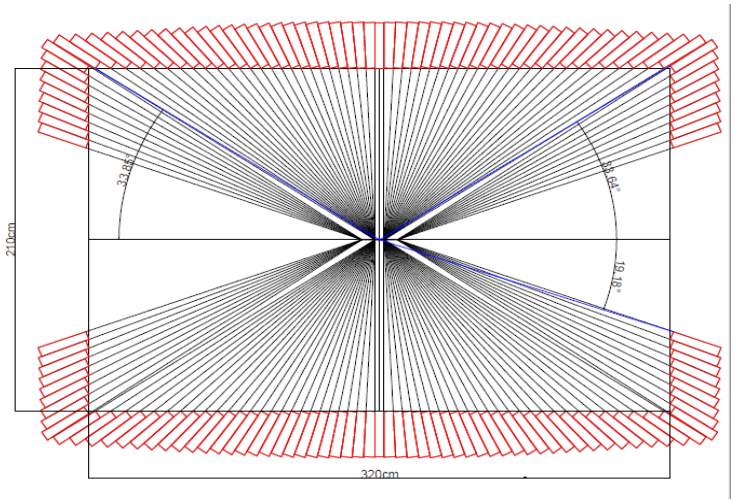
0#型号晶体平均光产额：108.2 pe/MeV
1#型号晶体平均光产额：92.4 pe/MeV
2#型号晶体平均光产额：98.7 pe/MeV

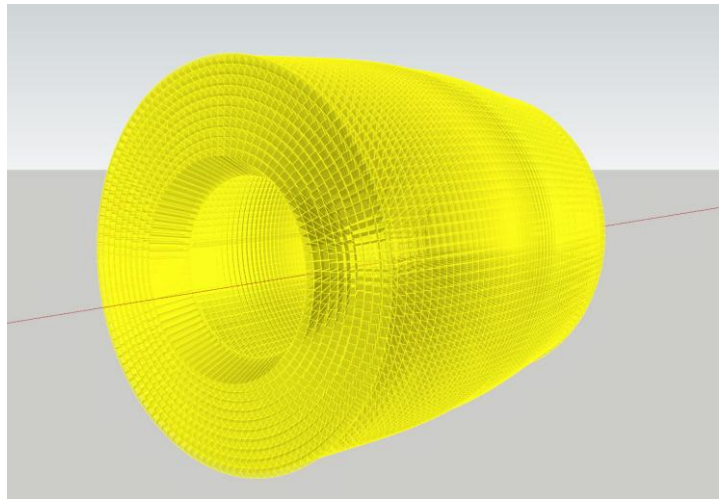
喷涂WLS后

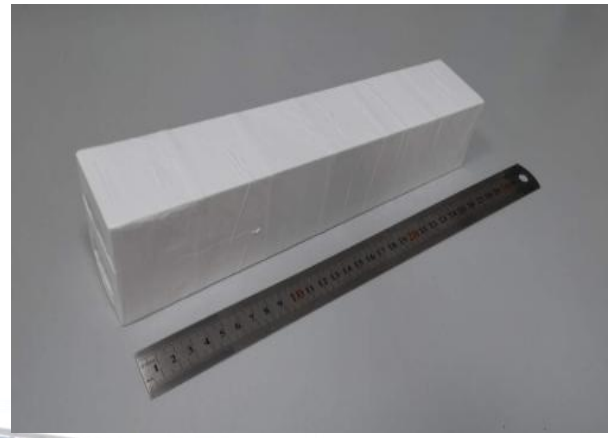
0#型号晶体平均光产额：302.8 pe/MeV
1#型号晶体平均光产额：265.7 pe/MeV
2#型号晶体平均光产额：256.7 pe/MeV

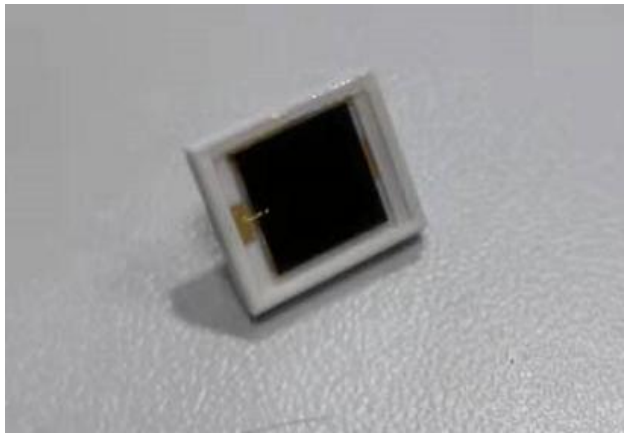
电磁量能器

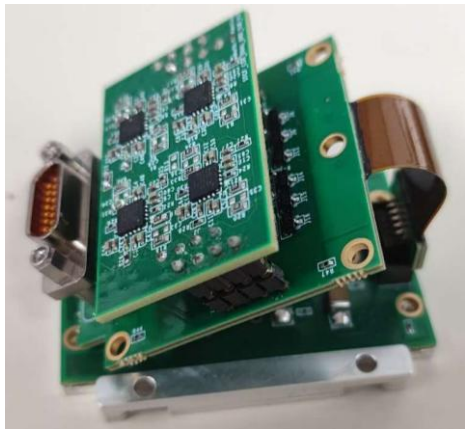
- 纯碘化铯晶体
  - 晶体数：8670
- 雪崩光二极管
  - 大面积阵列拼装
- 电荷灵敏方案，波形采样读出







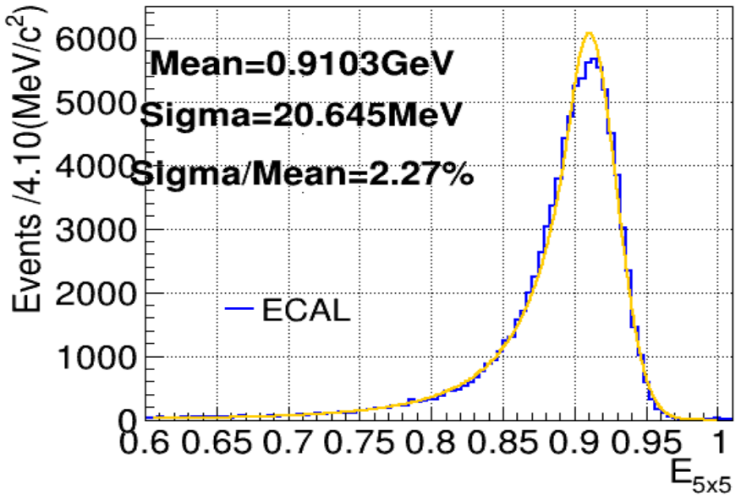


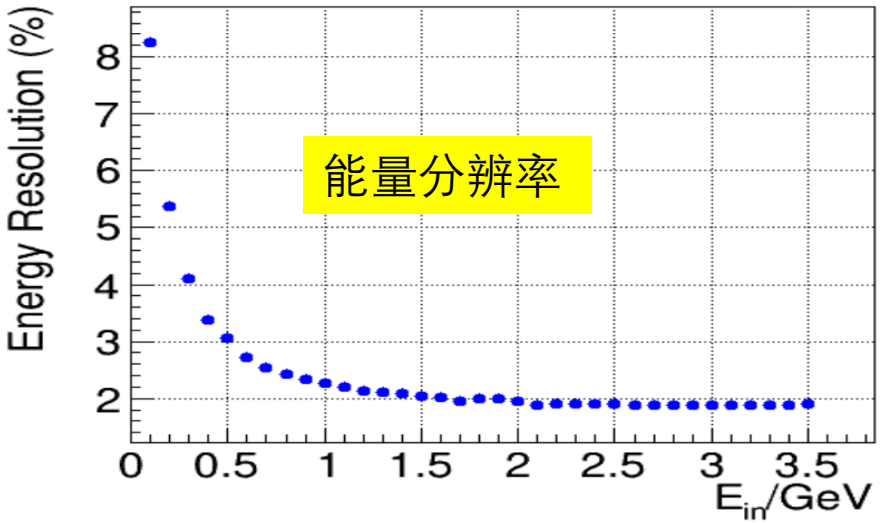


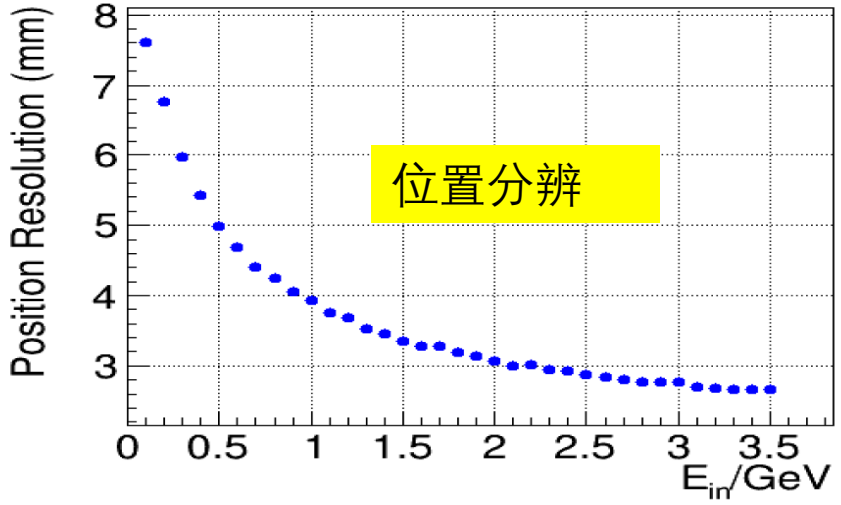


电磁量能器性能模拟研究

- 能量分辨率~2.5% @ 1 GeV
- 位置分辨~5 mm @ 1 GeV

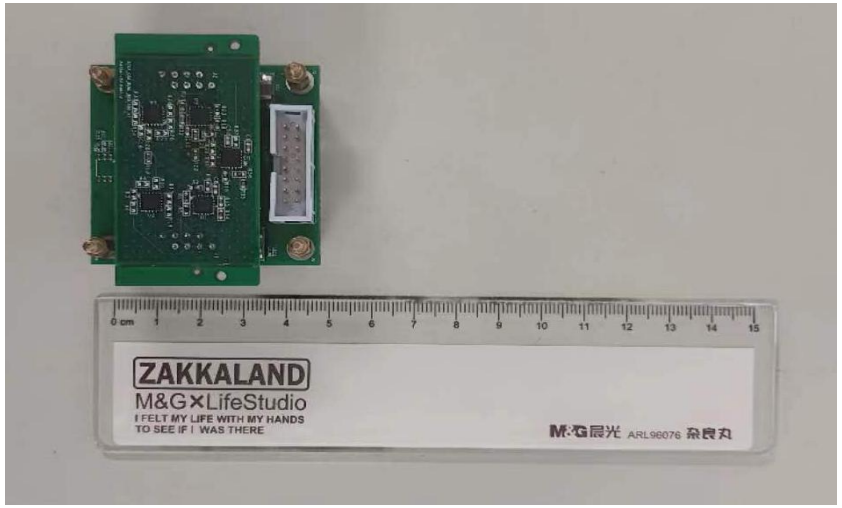


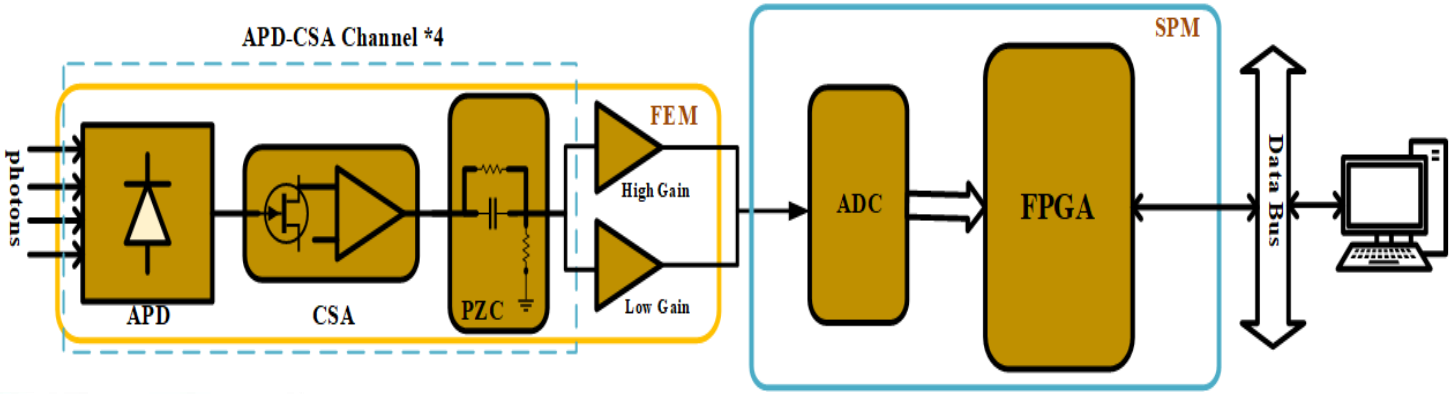


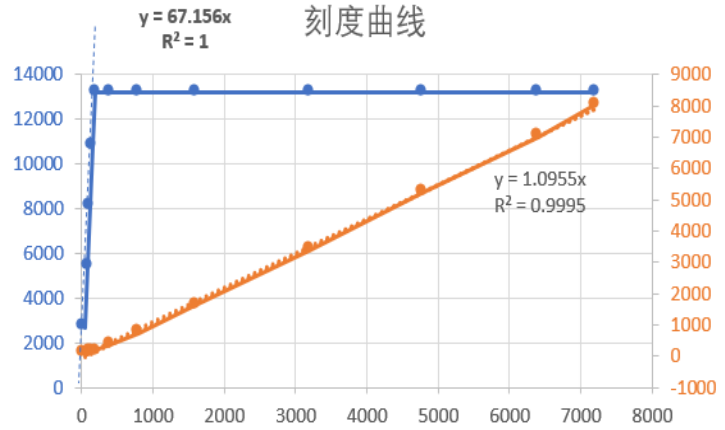


读出电子学的设计

- 低噪声大动态范围测量读出电子学
  - 采用电荷灵敏方案
  - 波形采样读出
  - 噪声水平：小于1 MeV
  - 动态范围：大于1000倍

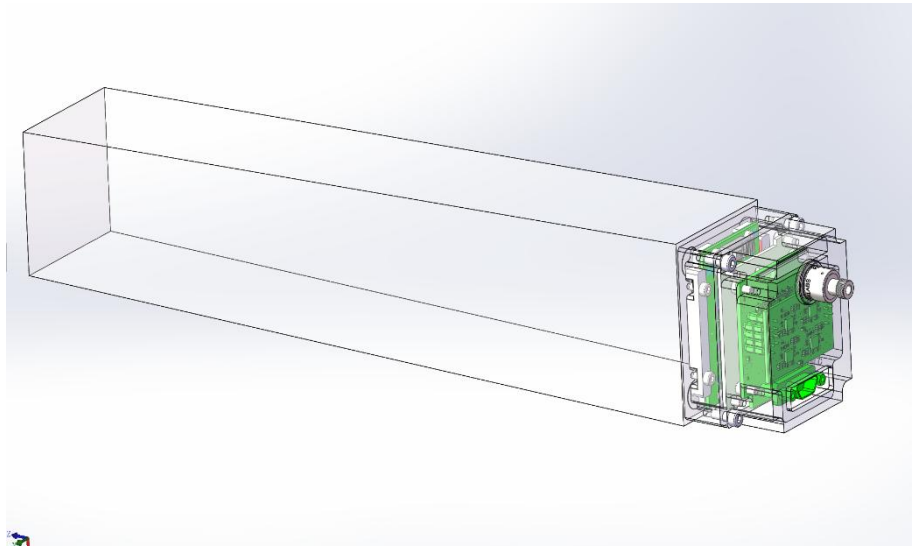


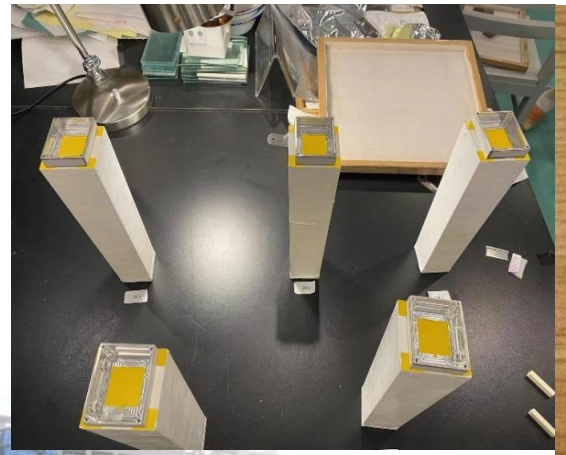


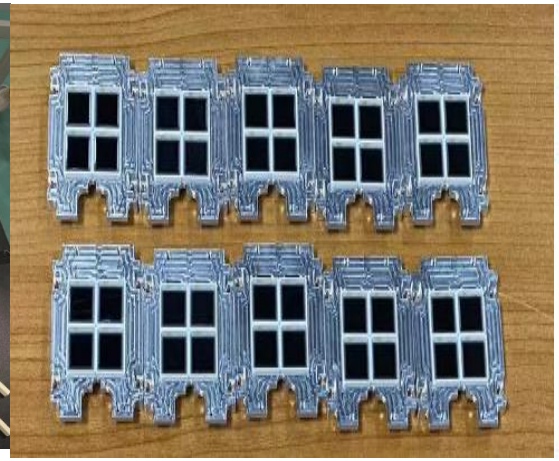


晶体封装

- 晶体的封装
  - 晶体表面包裹一层镀铝的mylar膜（Al-Mylar）进行电磁屏蔽
  - Al-Mylar与前放盒良好接触
  - 封装后的晶体，初步结果显示光产额下降<10%
    - 耦合面部分区域粘接前放盒导致





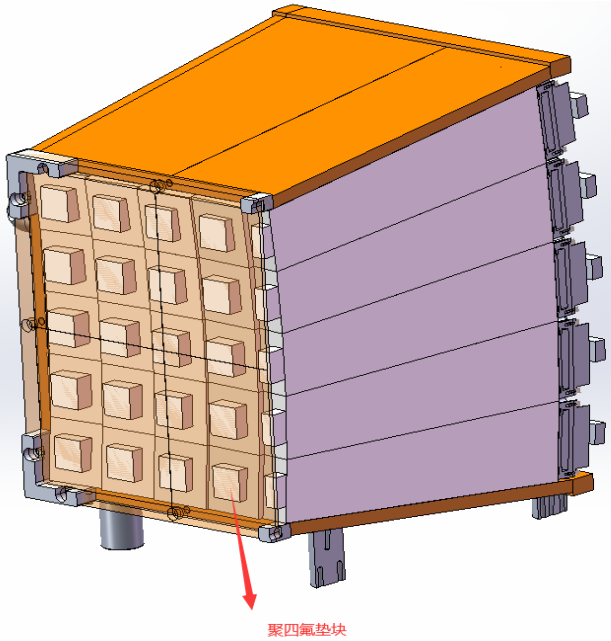






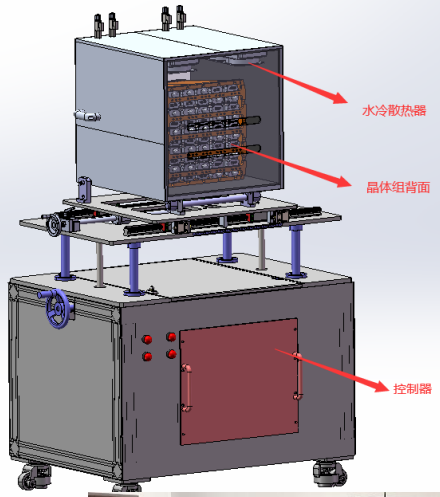
样机的组装，及束流测试台的加工

- **ECAL样机**
  - 5 × 5 晶体阵列
  - PXI 机箱控制
  - 温控装置



样机结构





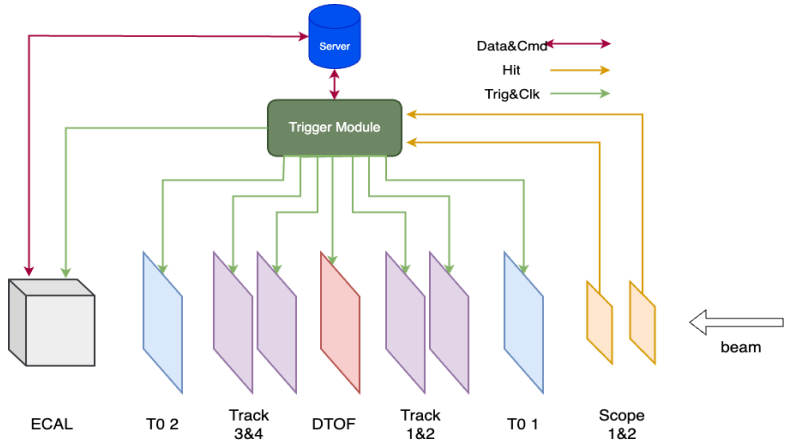




ECAL 样机

束流测试

- **束流测试**
  - CERN PS T09 beam line
  - Multi-system beam test
    - T0 Detector
    - Track Detector
    - PID Detector——DTOF
    - ECAL
  - Beam particle and momentum



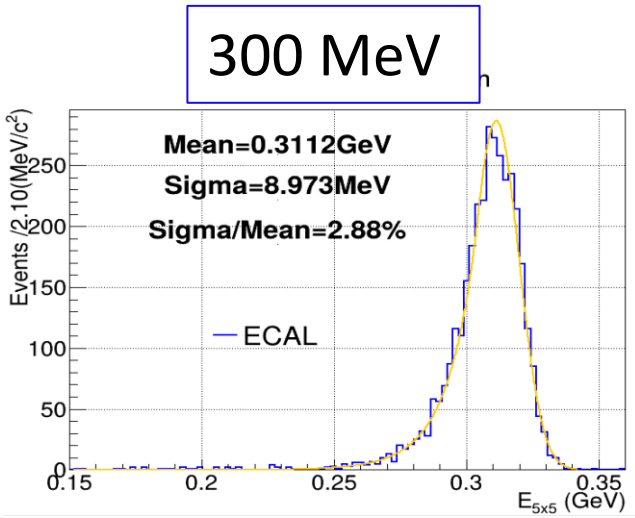
Particle	Momentum
μ^+	~ 5 GeV/c
e^+	0.5-5 GeV/c
$hardon^+$	1-5 GeV/c

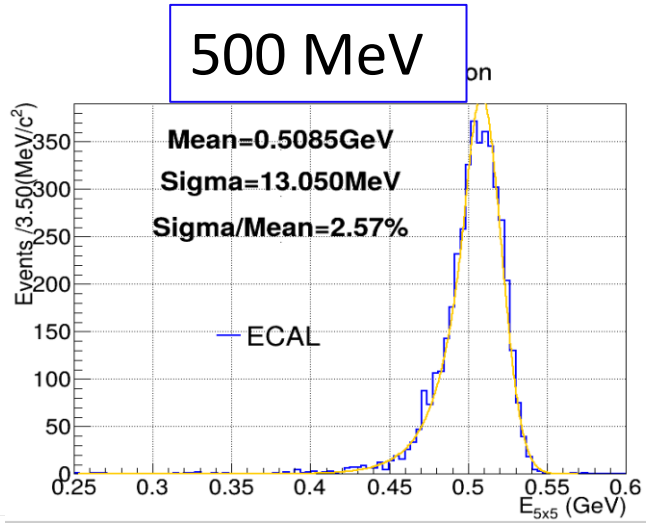


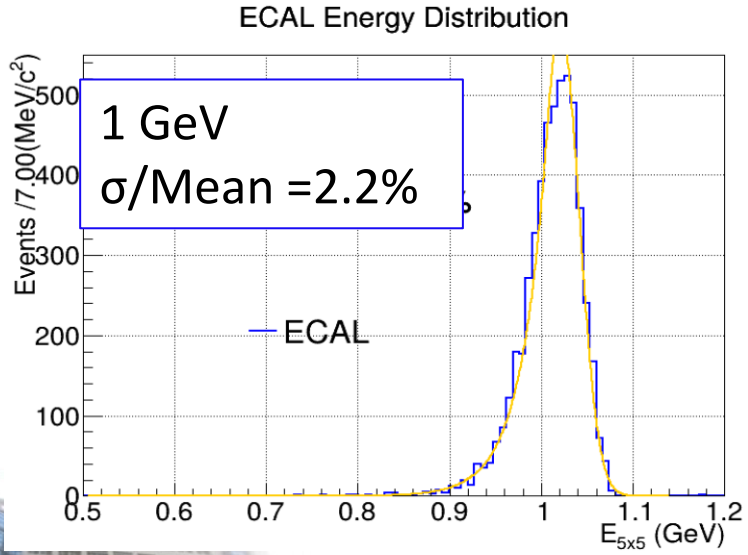


性能研究——能量响应

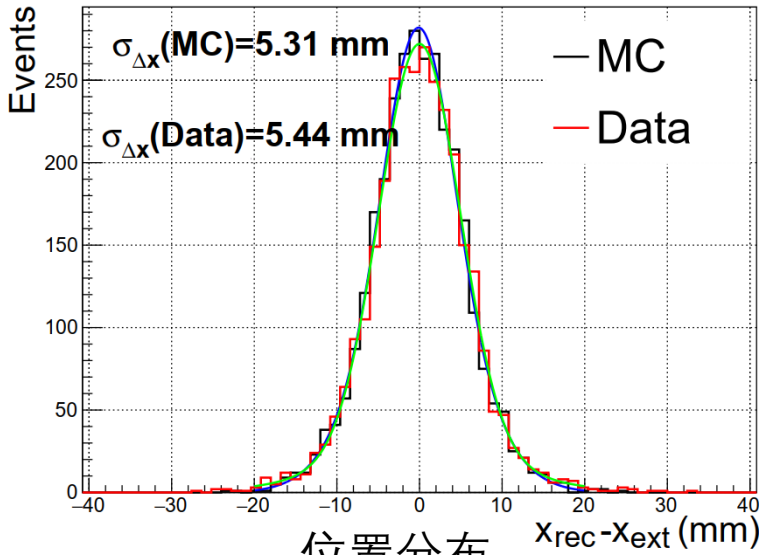
- 1 – 3.5 GeV电子
- 能量分辨率 ~ 2.2% @ 1 GeV
- 位置分辨~5 mm @ 1 GeV
- 时间分辨~290 ps @ 1 GeV



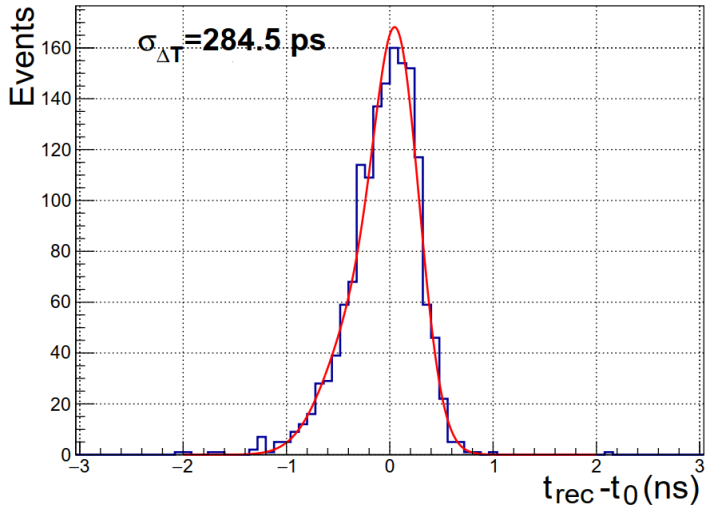




能量分布



位置分布



时间分布

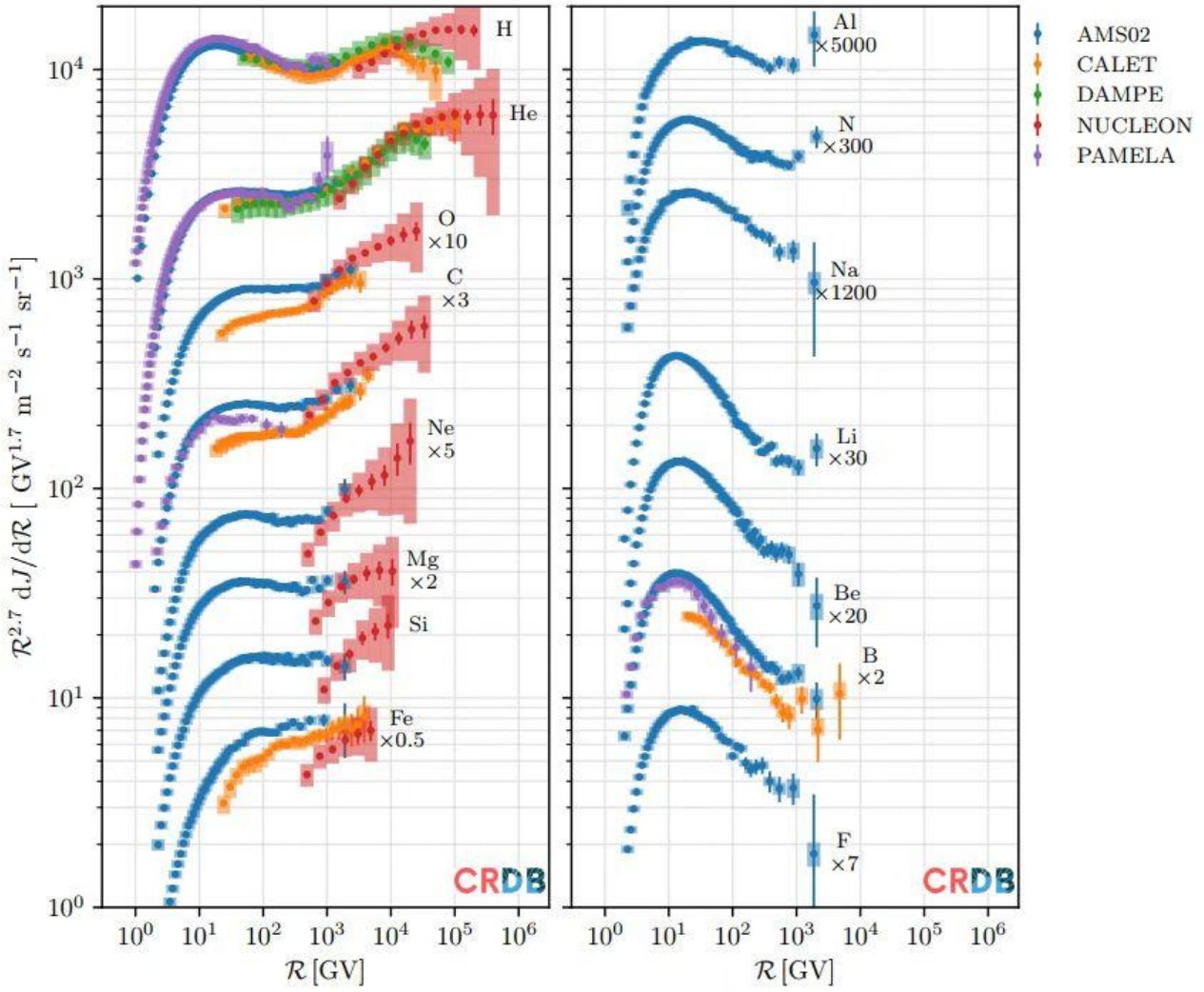
量能器应用实例



研究背景

高能宇宙线探测

- 探索暗物质的本质
- 了解天体物理源中的粒子加速和银河系中宇宙射线的传播
- 研究银河系和河外源的伽马射线发射。

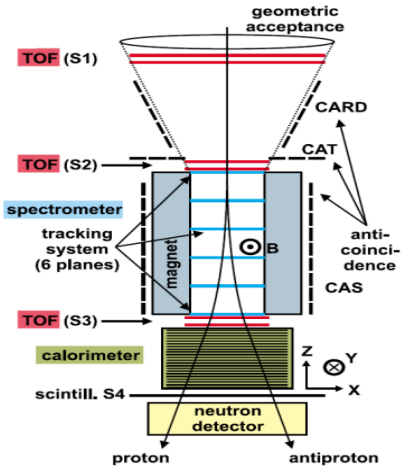




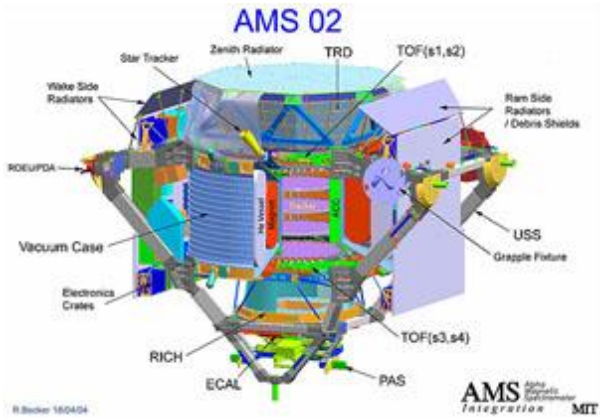
空间实验

- 基于卫星/空间站平台，在轨直接探测高能宇宙线
- 探测装置
  - 磁谱仪
  - 非磁谱仪

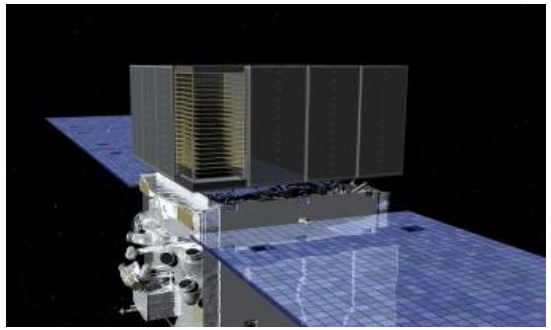
PAMELA



AMS02



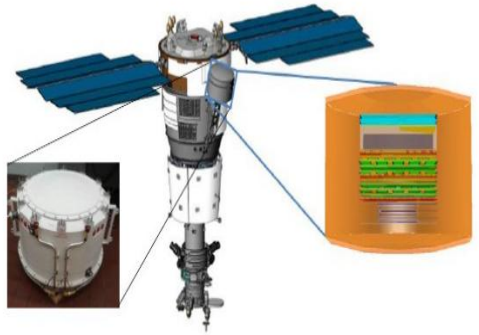
Fermi-LAT



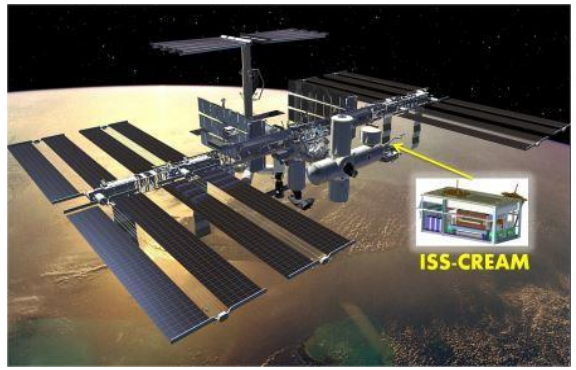
CALET



NUCLEON



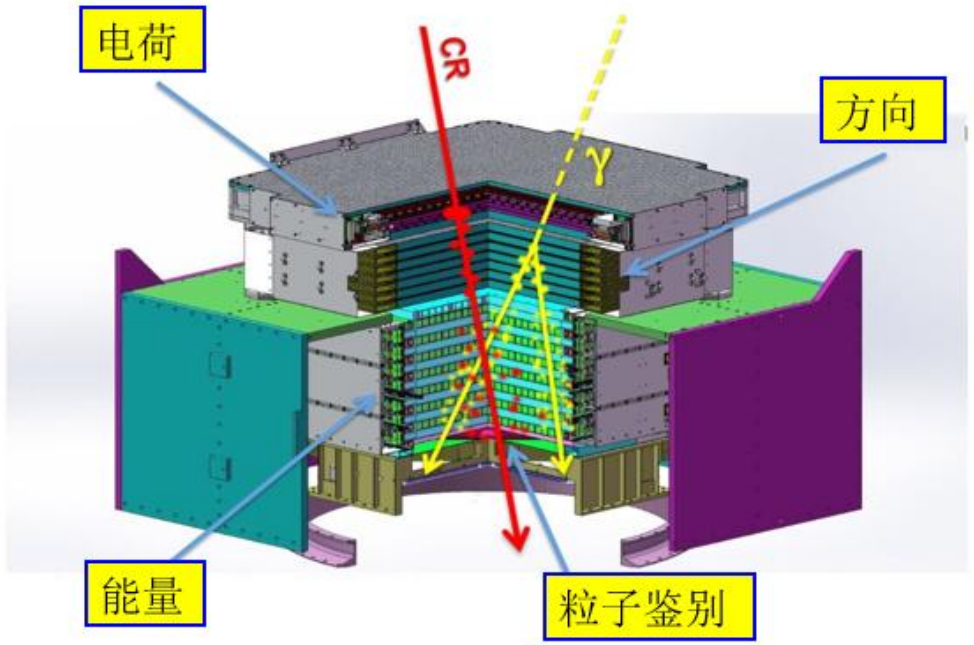
ISS-CREAM



“悟空”号（DAMPE）

DAMPE包含4个子探测器

- 塑闪阵列探测器—电荷测量
- 硅径迹探测器—方向测量
- **BGO量能器—能量测量、粒子鉴别、提供触发**
- 中子探测器—粒子鉴别





塑闪阵列探测器



硅径迹探测器



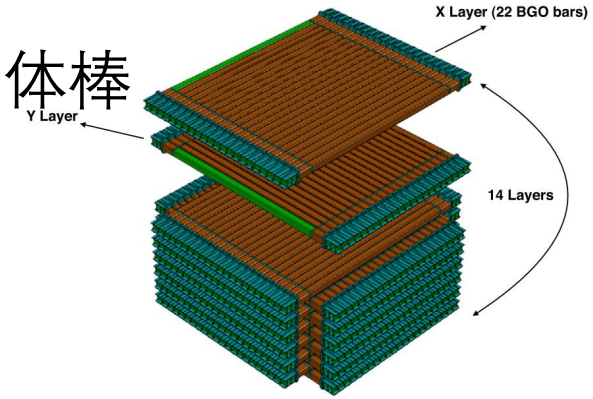
BGO量能器



中子探测器

BGO 量能器研制

- BGO 量能器有 308 BGO 晶体棒
- 616支PMT
- 近2000路读出





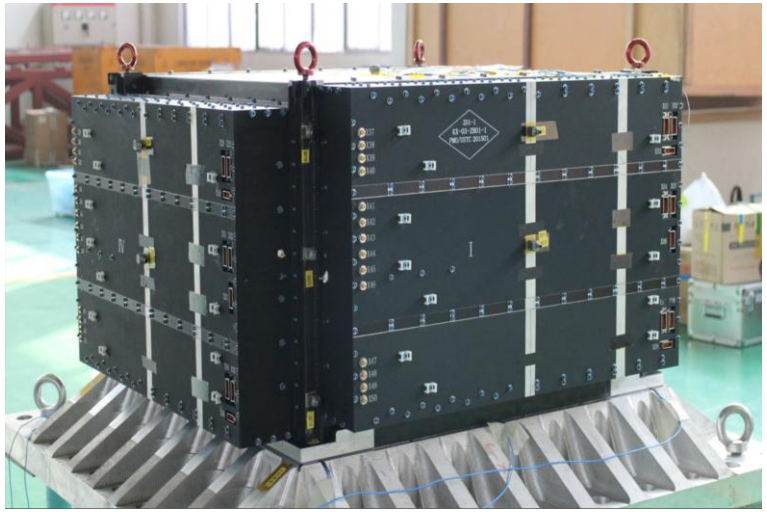




安琪主任及部分量能器研制成员

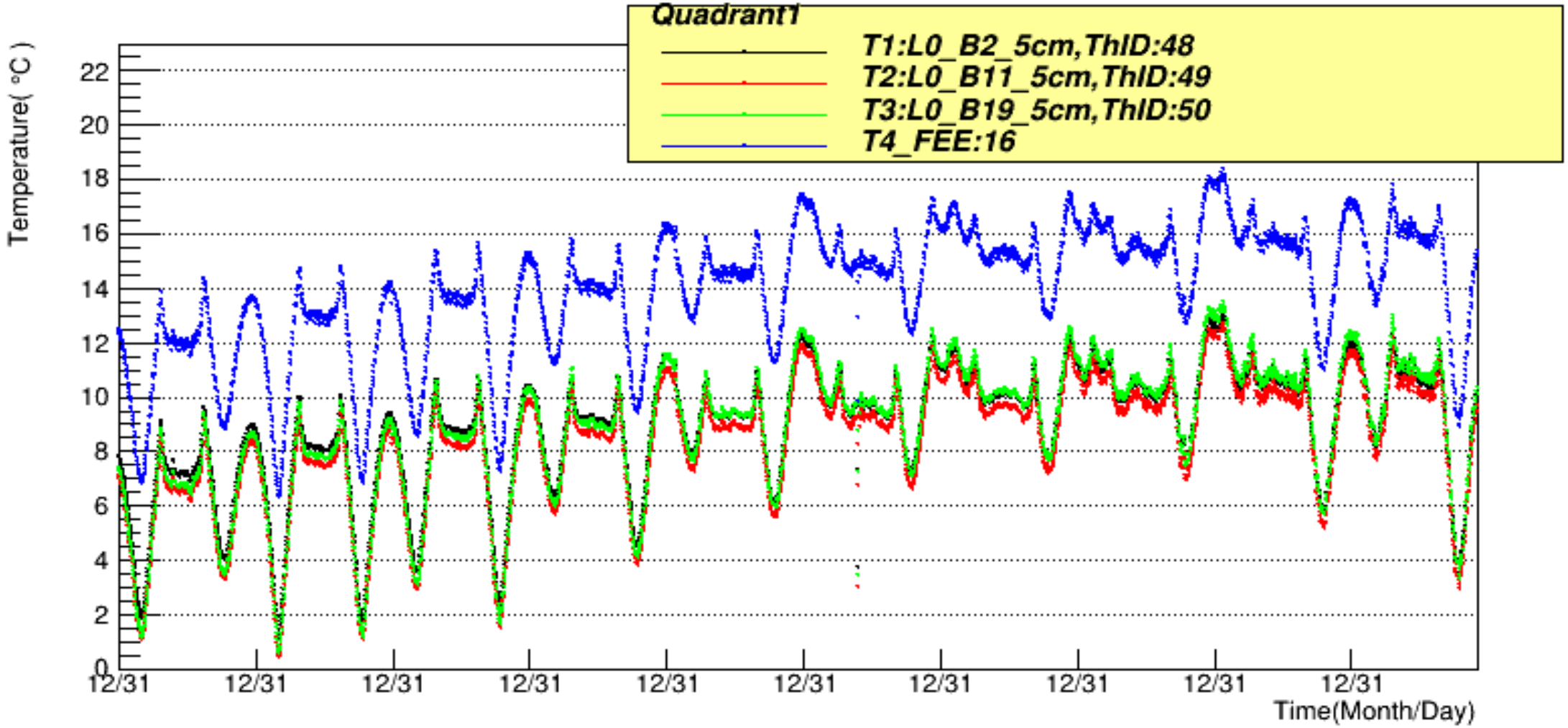


逸丰安装BGO晶体



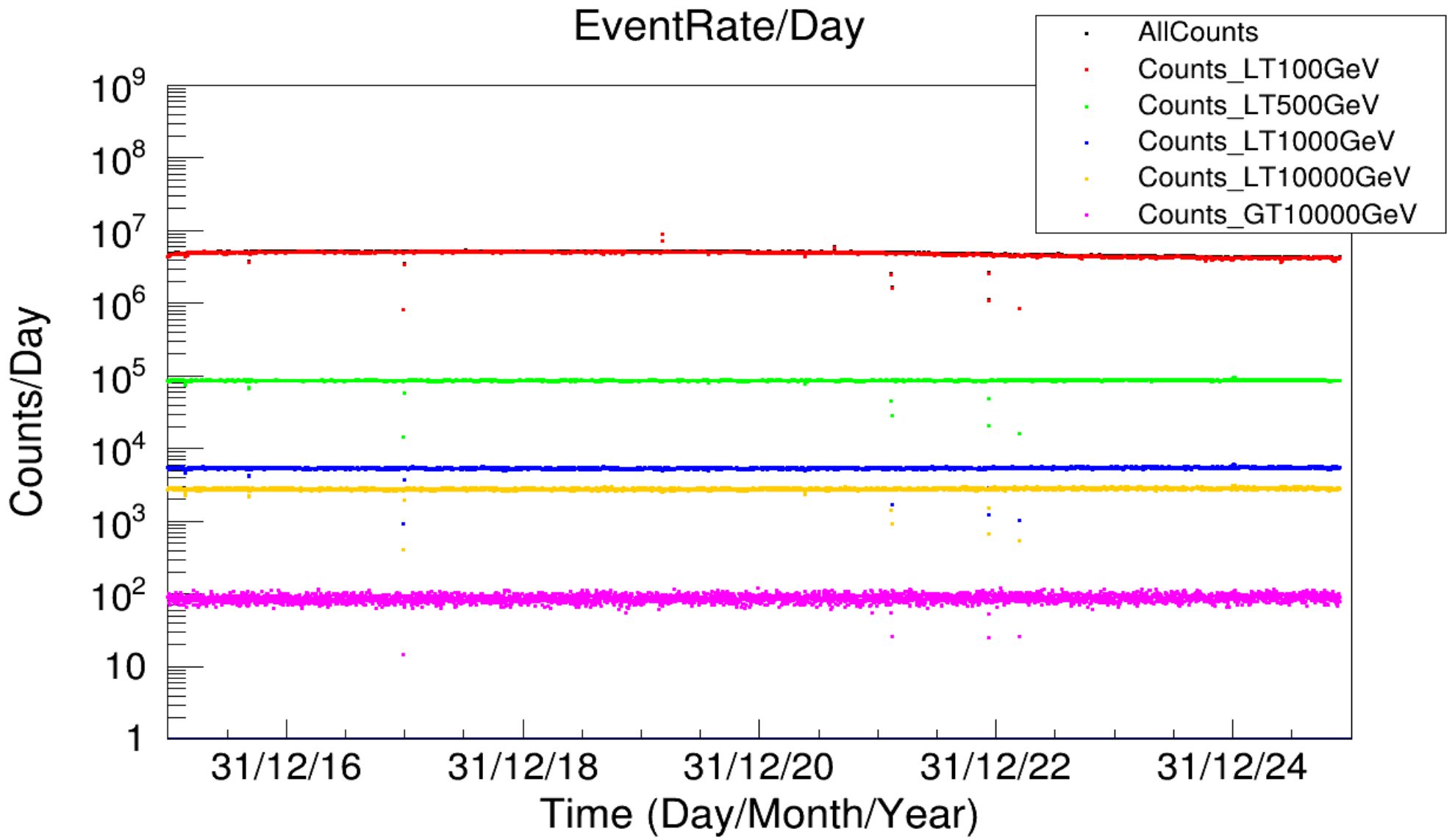
BGO量能器

在轨温度变化

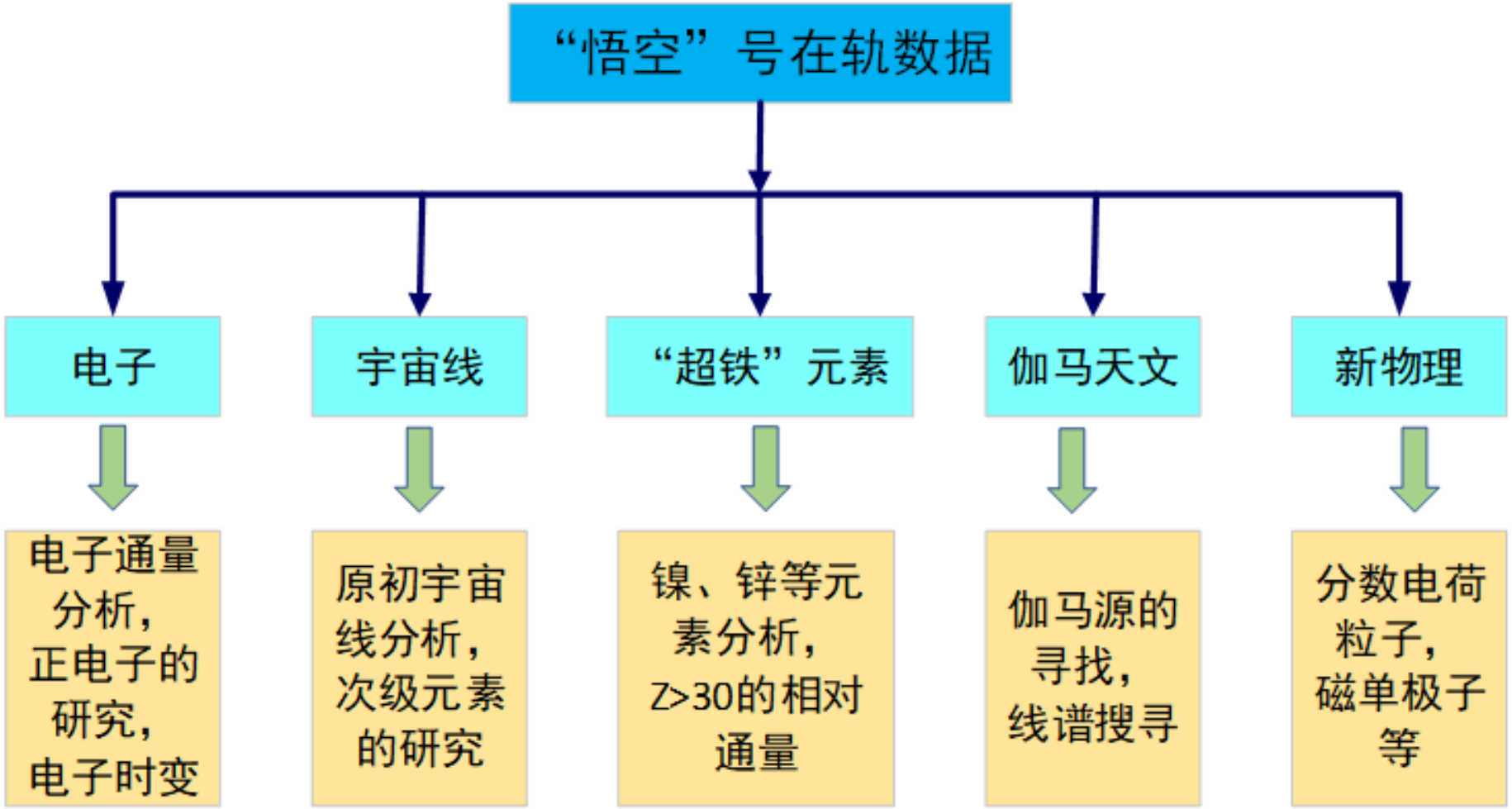

Quadrant1
T1:L0_B2_5cm,ThID:48
T2:L0_B11_5cm,ThID:49
T3:L0_B19_5cm,ThID:50
T4_FEE:16
Temperature(°C)
22
20
18
16
14
12
10
8
6
4
2
0
12/31
12/31
12/31
12/31
12/31
12/31
12/31
12/31
12/31
12/31
Time(Month/Day)



数据率


EventRate/Day
AllCounts
Counts_LT100GeV
Counts_LT500GeV
Counts_LT1000GeV
Counts_LT10000GeV
Counts_GT10000GeV
Counts/Day
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
31/12/16
31/12/18
31/12/20
31/12/22
31/12/24
Time (Day/Month/Year)

物理成果


“悟空”号在轨数据
电子
宇宙线
“超铁”元素
伽马天文
新物理
电子通量分析，正电子的研究，电子时变
原初宇宙线分析，次级元素的研究
镍、锌等元素分析，Z>30的相对通量
伽马源的寻找，线谱搜寻
分数电荷粒子，磁单极子等



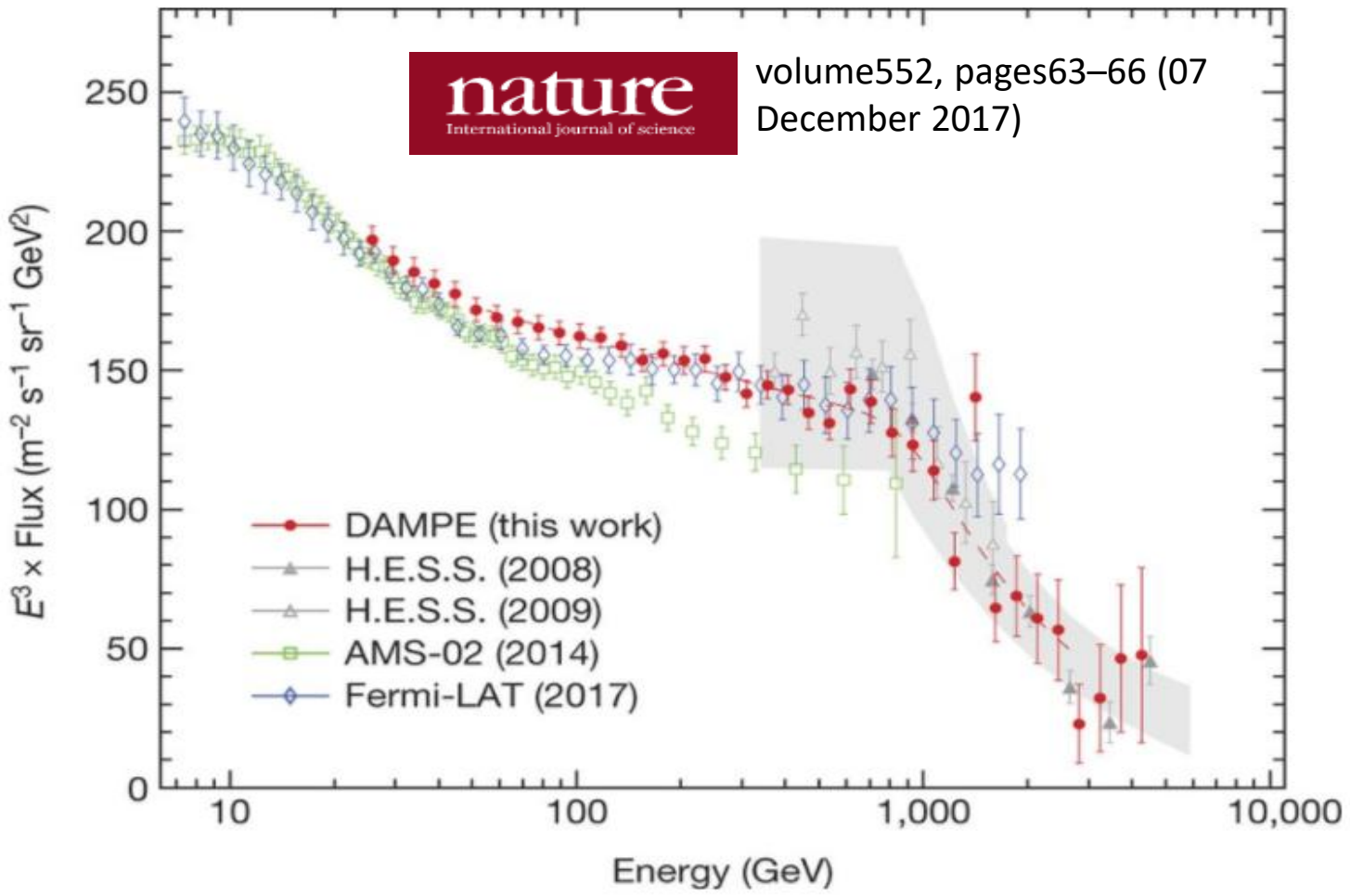
电子（e^++e^-）

◆ 正负电子通量谱

➢能区：20 GeV to 5 TeV

➢首次直接观测到了电子~0.9 TeV的拐折现象

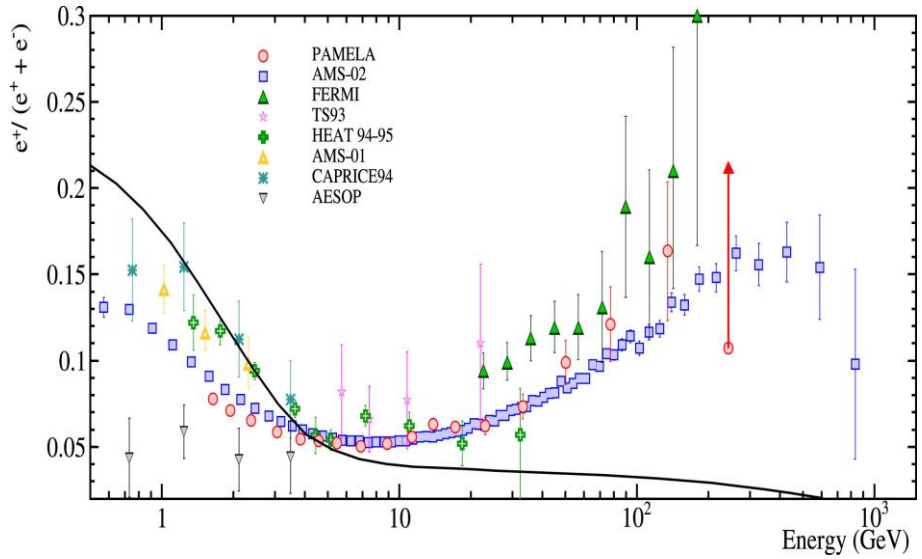
➢该结果表明，“悟空”号在TeV能区打开了一扇观测宇宙的窗口

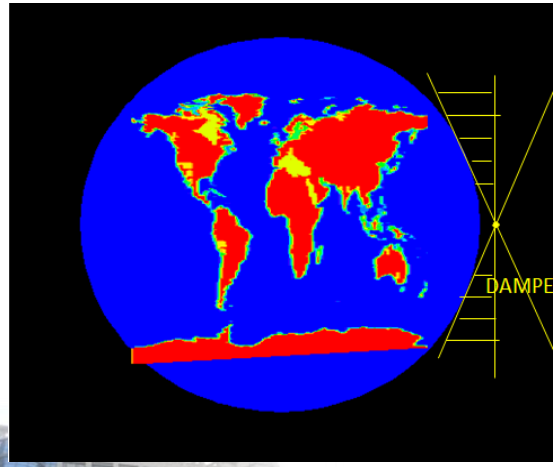




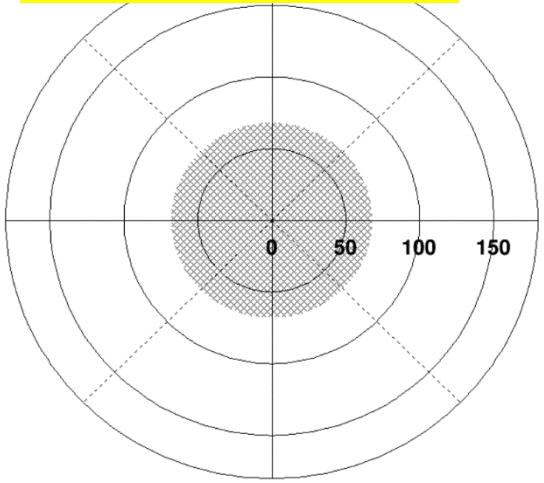
“反”电子

- 正电子是研究暗物质的灵敏探针
- 如何鉴别正、负电子？
- 地磁场可以对$e^{\pm}$的径迹进行偏转，相当于改变了地球阴影的形状
- 可以在电子的地球阴影区寻找正电子，反之亦然



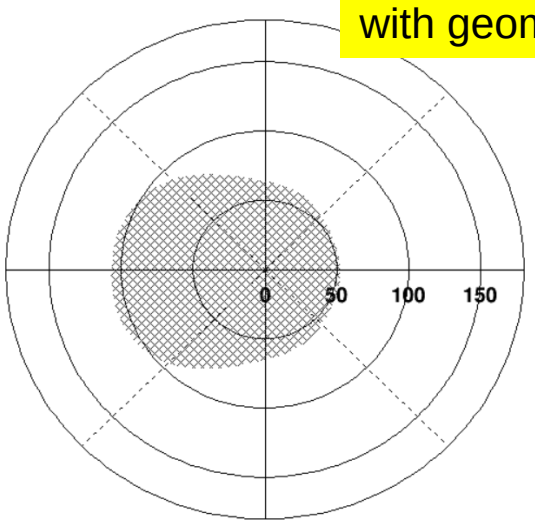


without geomagnetic

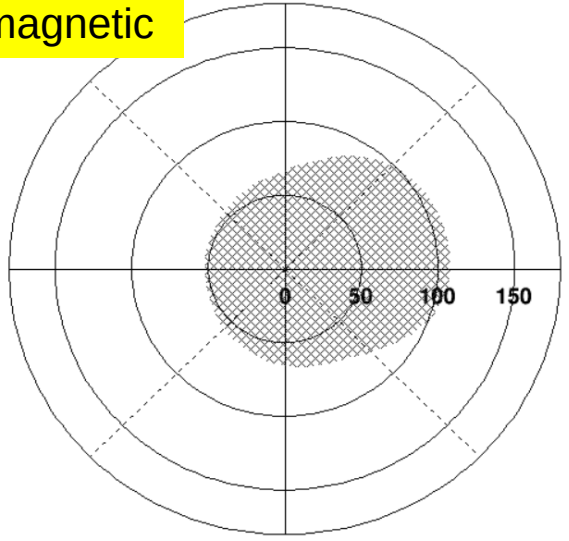


$e^{\pm}$ earth shadow

with geomagnetic



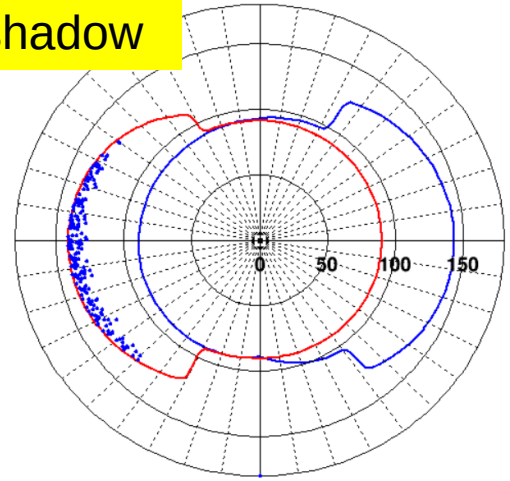
e- earth shadow



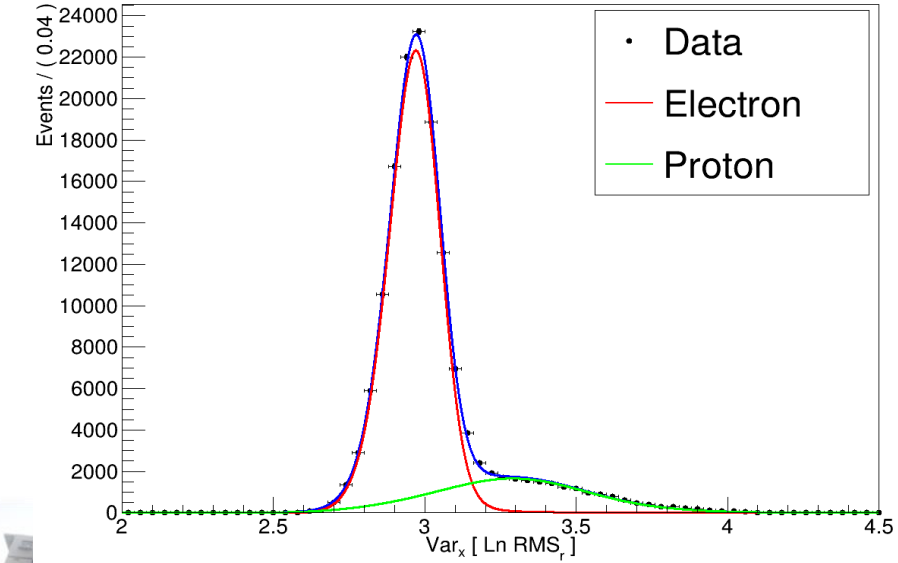
e+ earth shadow

“反”电子

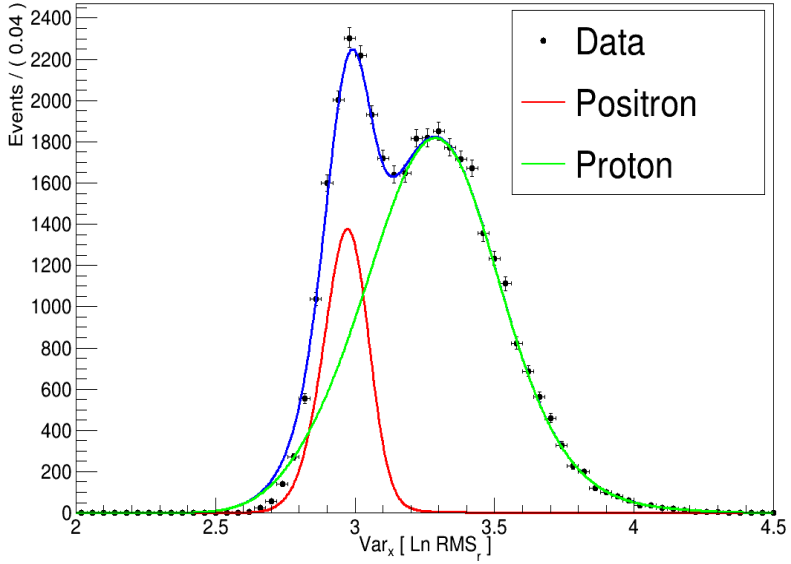
The events in e- shadow



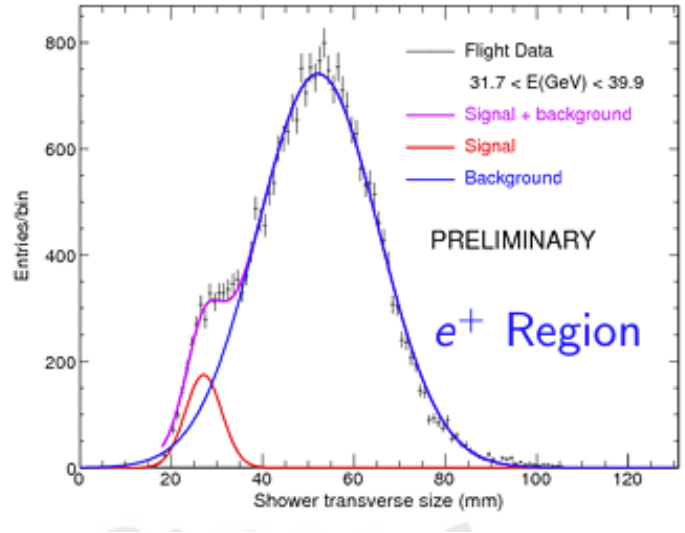
- 基于DAMPE的数据，开展了正/负电子的分析
- 同时根据粒子簇射轮廓在量能器中的行为开展粒子鉴别
  - 质子是正/负电子的主要本底
- 因为卫星指向原因，我们只能针对一个相对较窄的能区开展研究



11.5 – 13.2 GeV 负电子

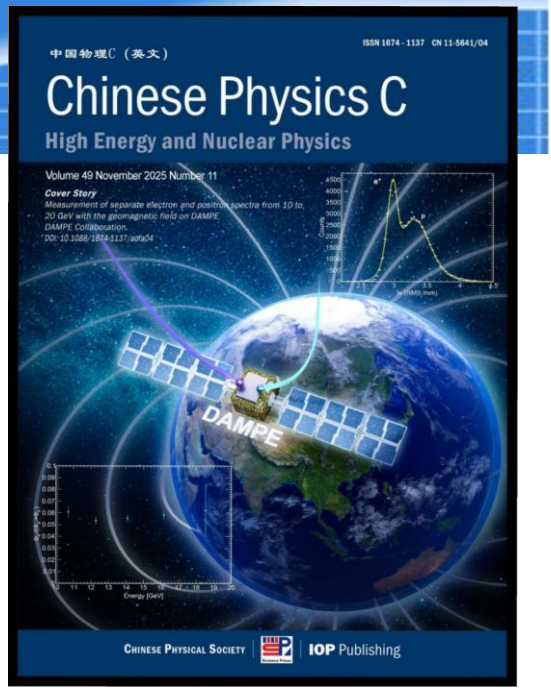


11.5 – 13.2 GeV 正电子



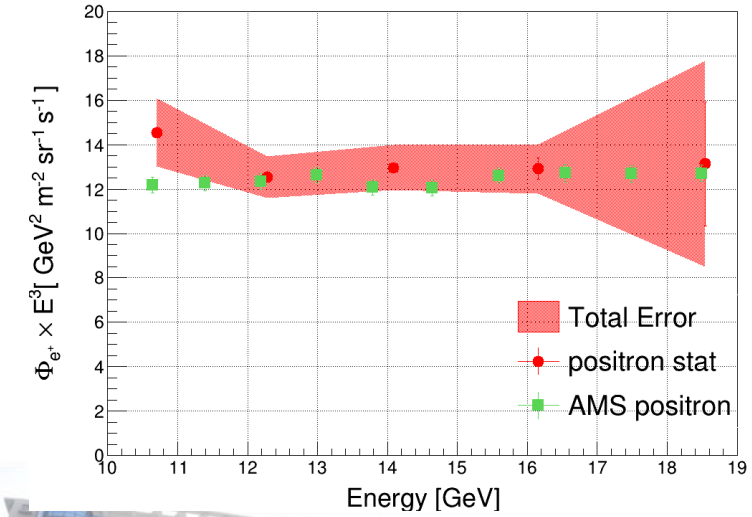
FERMI-LAT

“反”电子

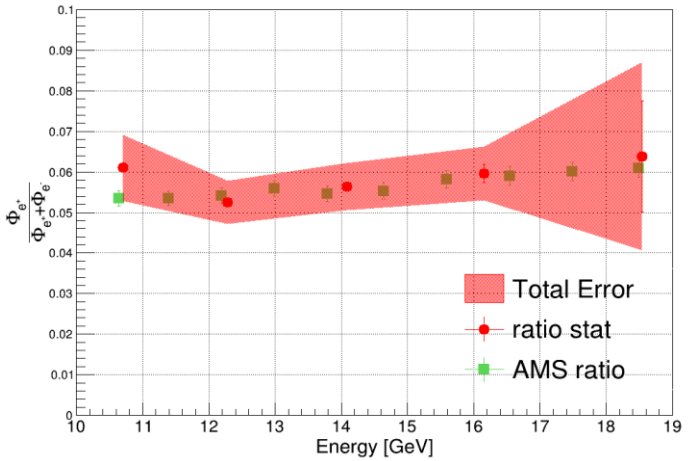


- 得到了10 -20 GeV能区的正/负电子微分通量谱
- 该结果与AMS02磁谱仪测试的结果一致，拓展了FERMI-LAT低能区间

正电子



正电子比例



Cover Story (Issue 11, 2025) The Earth-Magnet Assists DAMPE in Studying Cosmic Anti-Electrons

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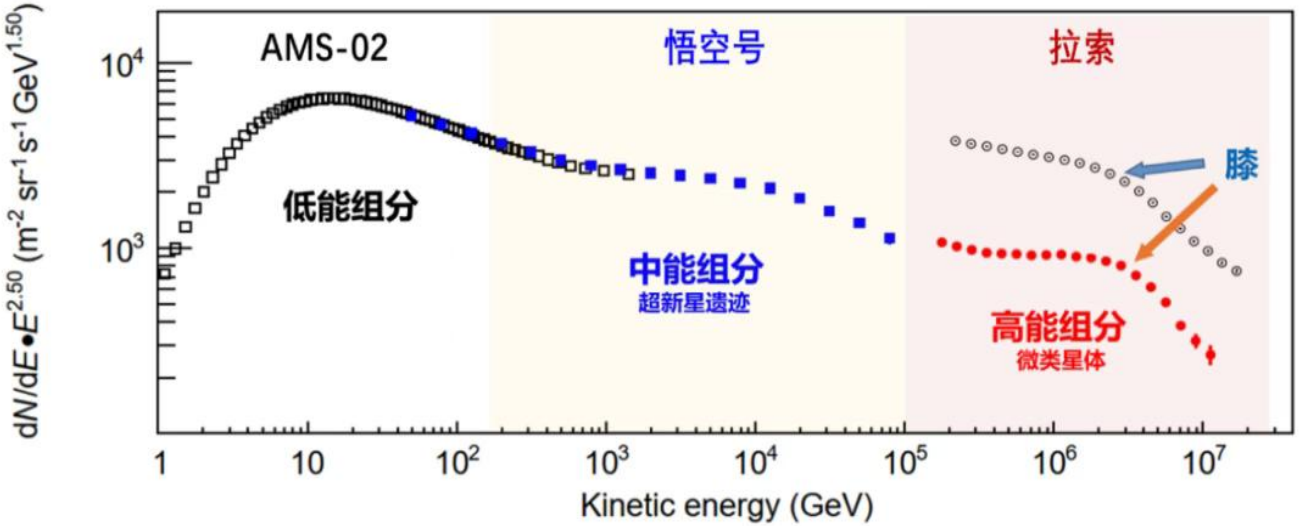
Cover Story (Issue 11, 2025): The Earth-Magnet Assists DAMPE in Studying Cosmic Anti-Electrons

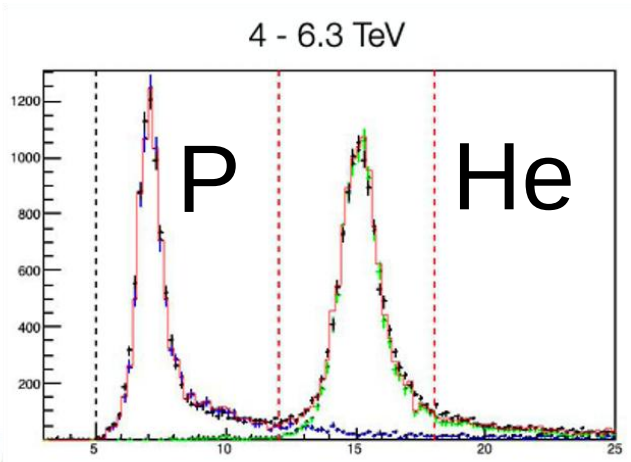
Author: Shuang-Nan Zhang (Institute of High Energy Physics, Chinese Academy of Sciences)

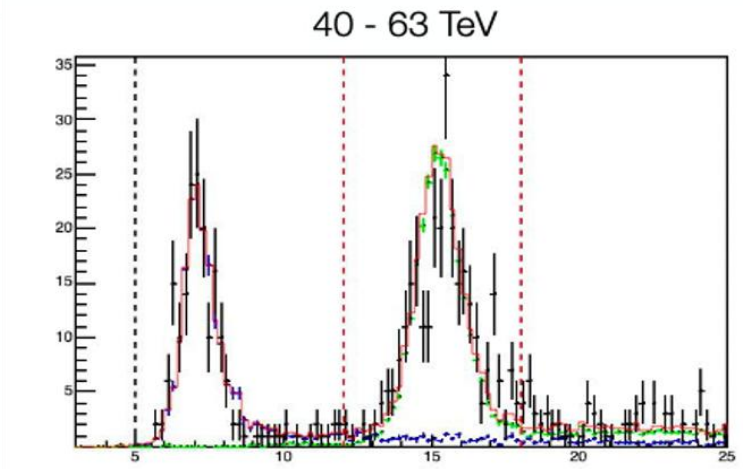


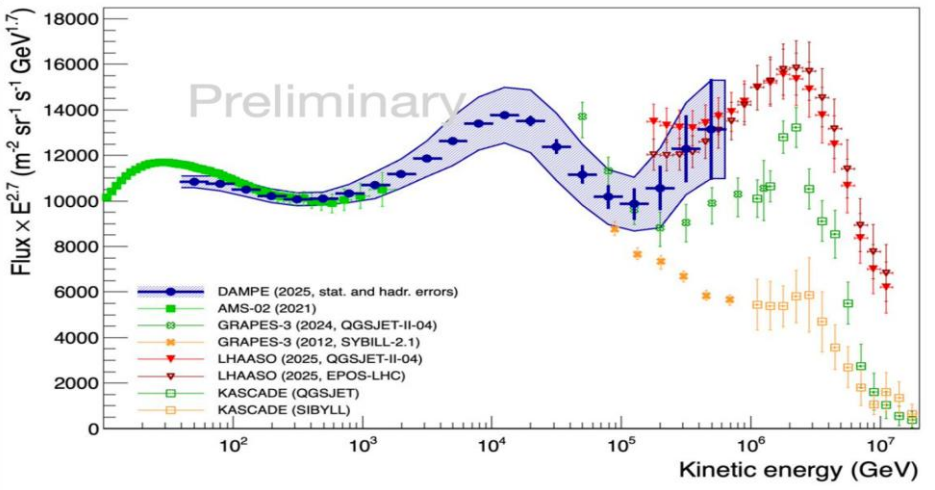
p and He （in Progress）

- DAMPE与LHAASO的结果在100 TeV能区有个gap
- 下一步继续往高能区延伸



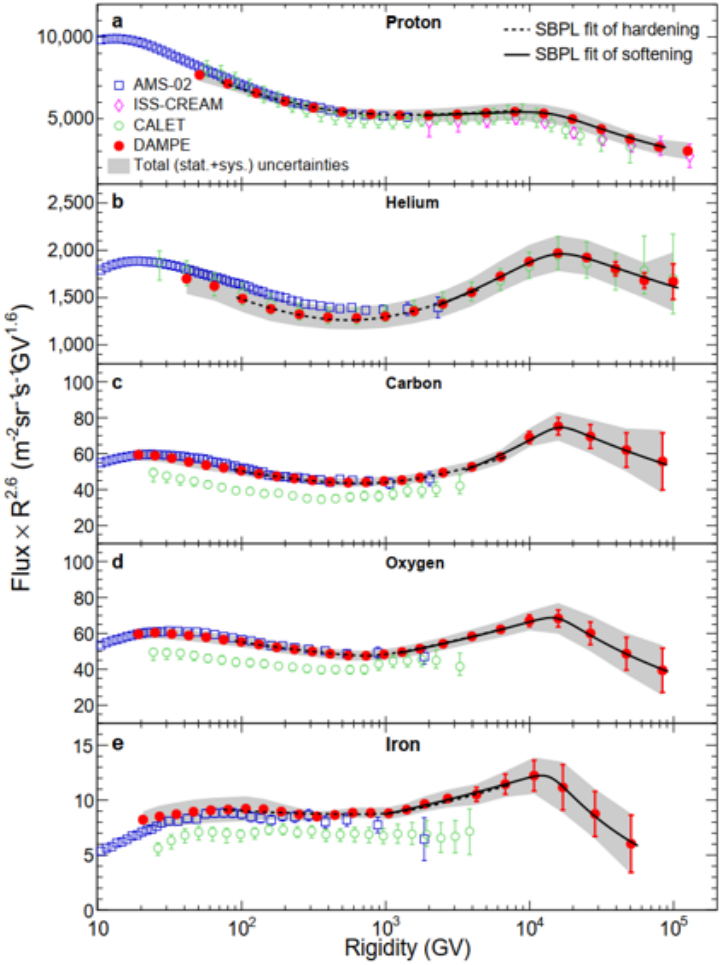


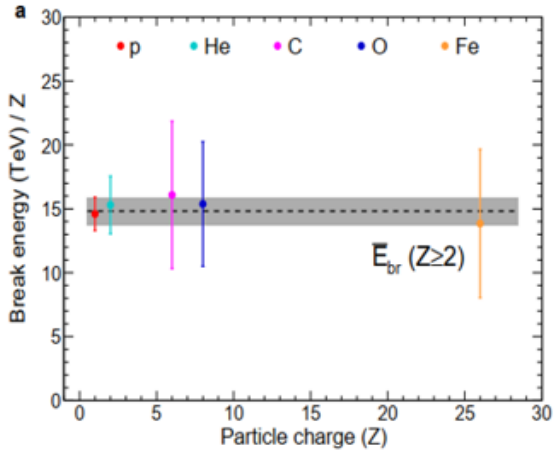


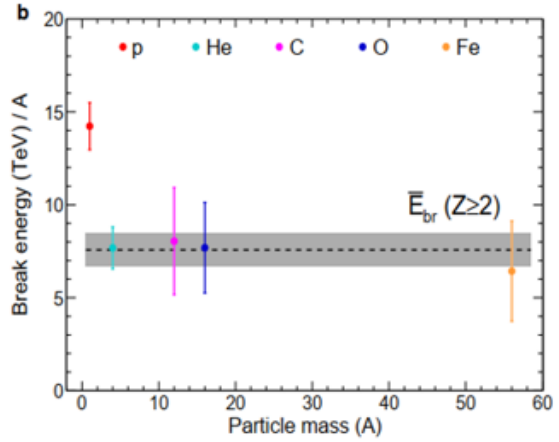


原初宇宙线C、O、Fe

- 基于9年的观测数据
- 首次给出了碳、氧（20 GV~100 TV）和铁（20 GV~60 TV）元素的分析结果
- 发现这些原初宇宙线在刚度为~15 TV附近出现“普适性软化”现象





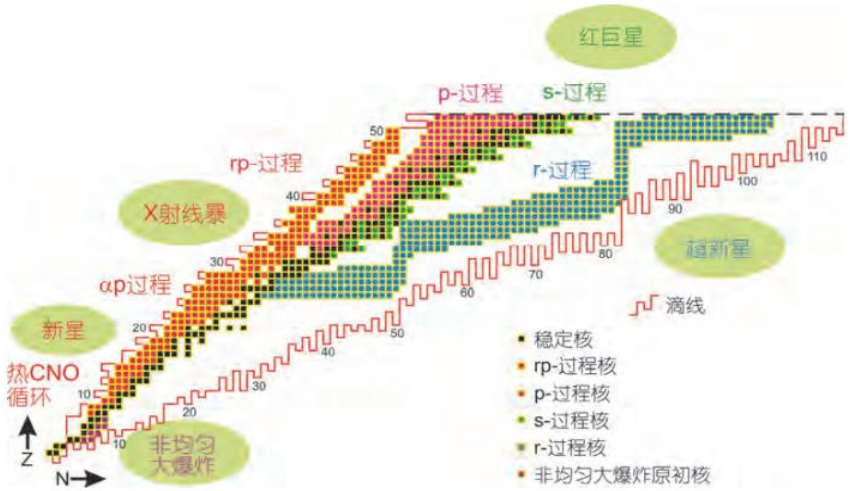




“超铁元素”

- “从铁到铀元素是如何产生的”被美国国家科学委员会列为21世纪待解决的11个重大物理问题之一
- 2025年中国科学院马余刚院士领衔发布的《核科技前沿十问》中的“第五问”
  - 核天体物理与元素起源：宇宙中重元素的合成过程，关联超新星、中子星碰撞等事件
- 超铁元素的起源等是当今核物理、天体粒子物理的前沿课题

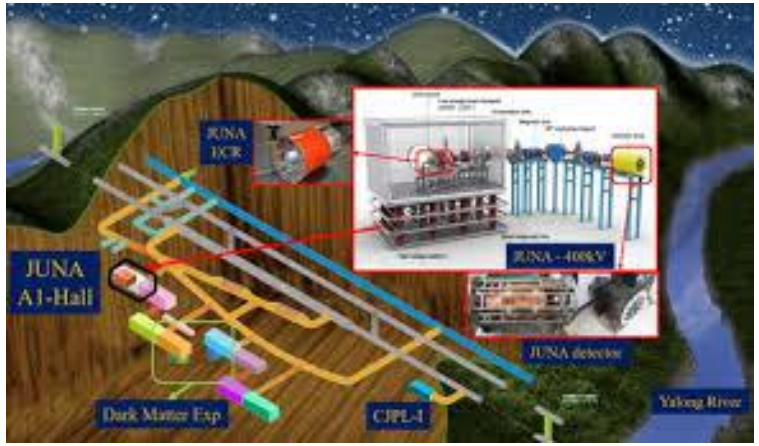




超铁元素

深地实验

- 在地下实验室建造加速器
- 利用低能强流加速器开展关键天体核反应的直接精确测量



JUNA

地面实验

- 在地面建造大型重离子加速器装置
- 直接产生与r-过程有关的丰中子核素



HIAF

空间实验

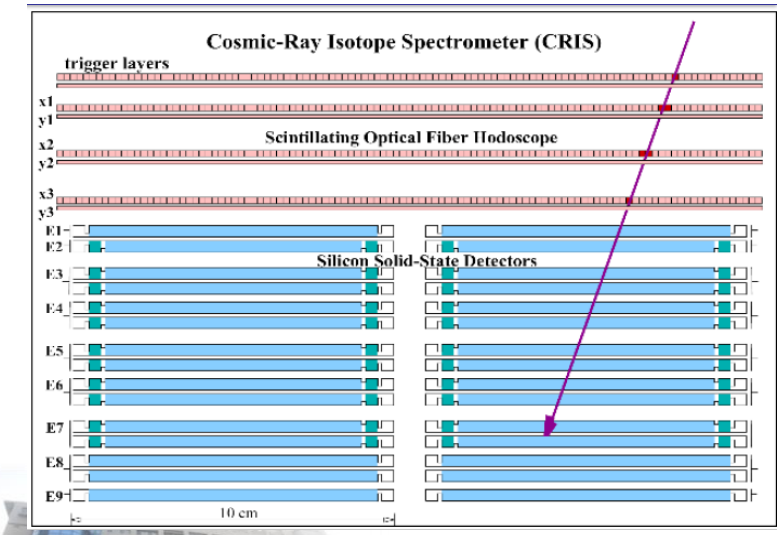
- 借助气球或卫星平台放置大型探测器
- 直接在宇宙线中开展超重元素的测量



HEAO

超铁宇宙线

- 超铁宇宙线（UHGCR）从哪里来，是如何产生的？
- UHGCR如何加速的？他们的寿命是多少？
  - Fe之后的核素通量急剧下降，探测困难
  - 必须到高空去探测（容易碎裂），这对测量这些核素提出了巨大的挑战



CRIS



The SuperTIGER-II payload is suspended from a crane during a "hang test" at the Long Duration Balloon Facility, with Mount Erebus in the background.

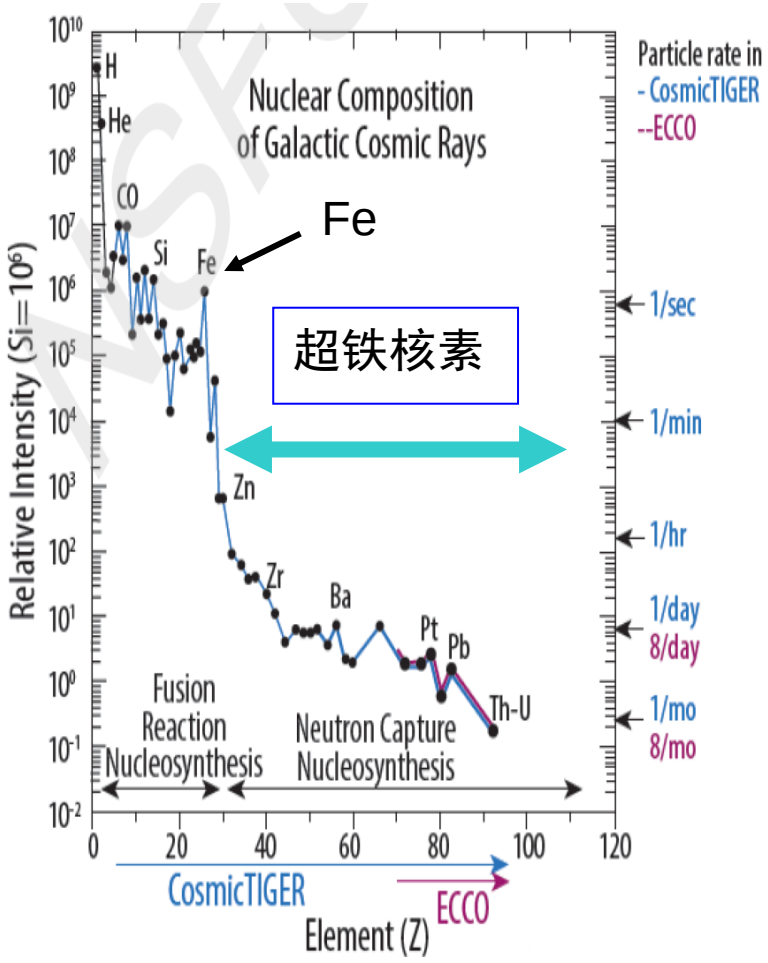
Photo Credit: Mike Lucibella

Heavy Cosmic Rays - Part I: The Flight Of SuperTIGER-II

Up In The Sky! It's A Bird! It's A Plane! It's SuperTIGER-II!

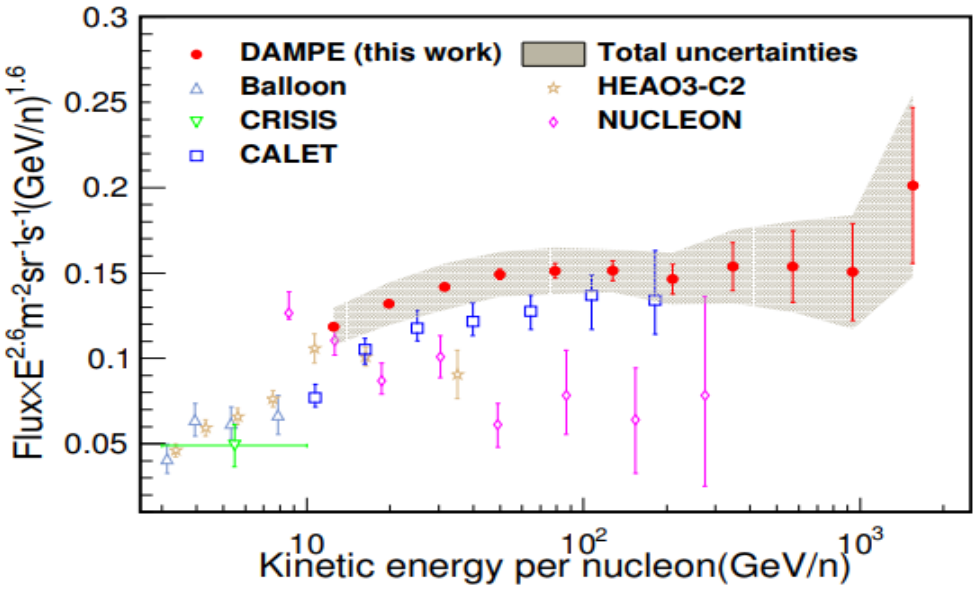
BY MICHAEL LUCIBELLA, *ANTARCTIC SUN* EDITOR
Posted September 14, 2020

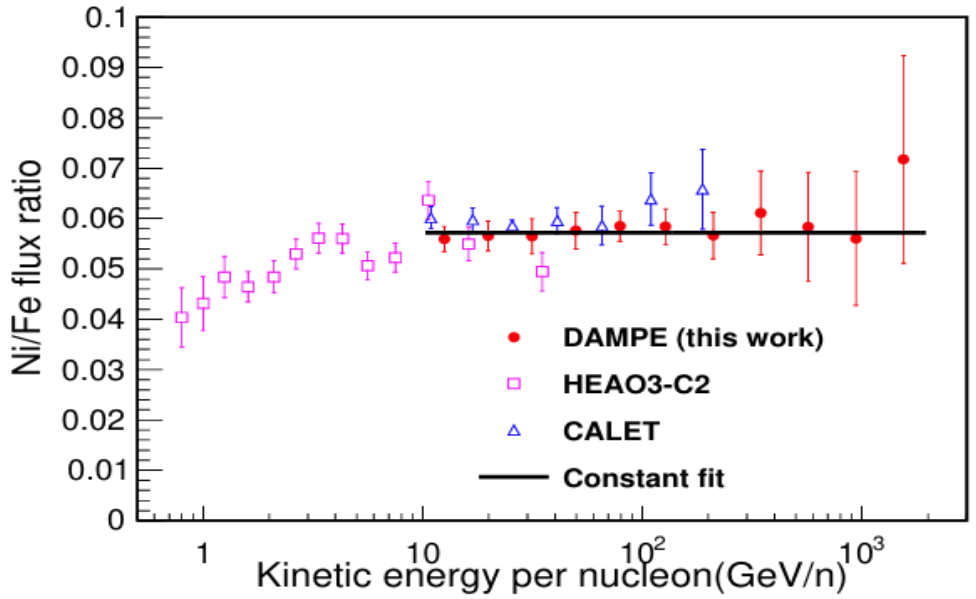
Super-Tiger



Ni元素

- Ni元素的微分通量谱
  - 能区：10 GeV/n – 2000 GeV/n，比之前结果高约一个数量级
- Ni/Fe约为0.05

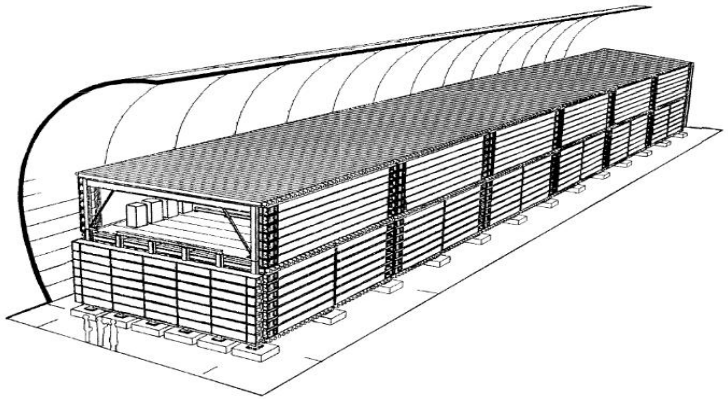




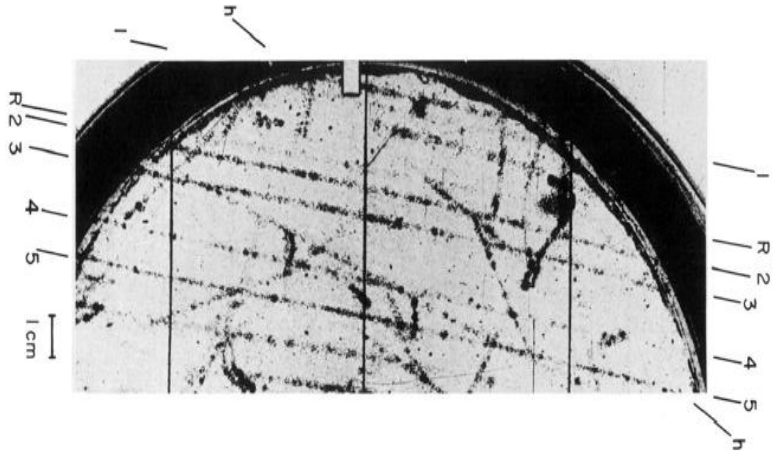


新物理——分数电荷粒子

- 为什么基本粒子的电荷是0、±1/3e、±2/3e 以及±1e （e为电子电荷量）？
- 迄今为止都没有观察到携带分数电荷的自由粒子存在的确信证据
- 从深地、高山、空间实验多个方面开展相关实验



MACRO实验



McCusker曾宣称利用云室看到大气簇射中的疑似事件



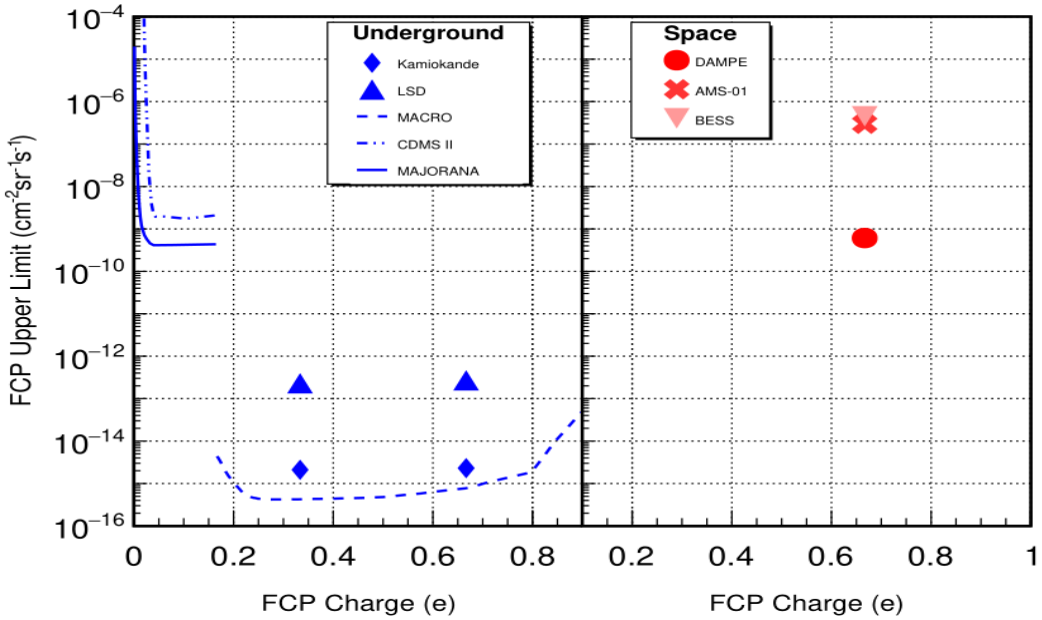
BESS磁谱仪（气球实验）

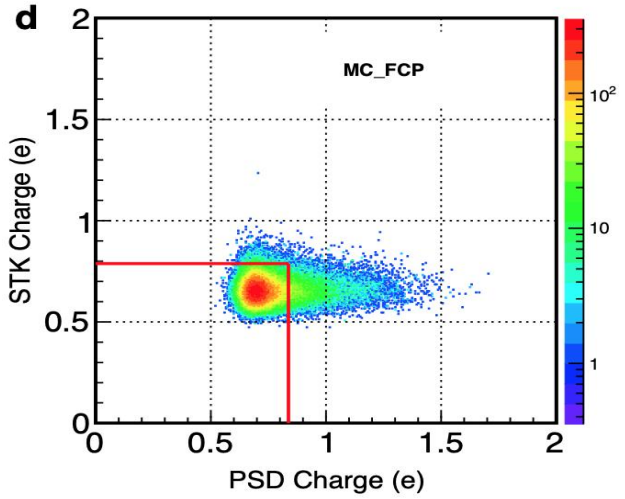


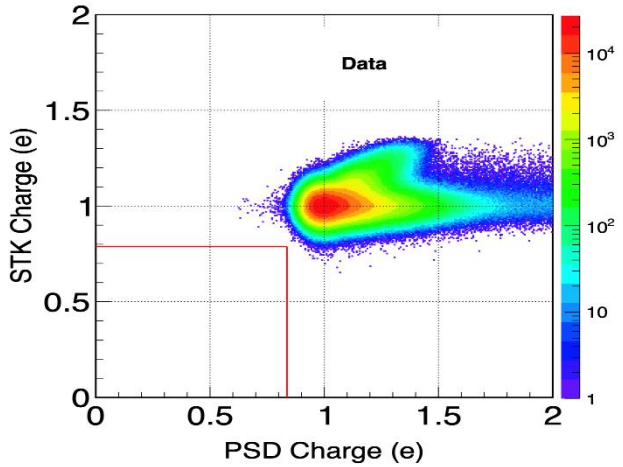
分数电荷粒子

- 分数电荷 (FCP) 粒子被认为是一种类轻子，其来源有
  - 宇宙大爆炸产生
  - 剧烈的天体活动
- 利用“悟空”号可以直接对其进行寻找
  - 基于重轻子假设，灵敏度比同类实验高3个数量级

Phys. Rev. D 106.6: 063026 (2022)









总结

- 量能器是粒子物理实验谱仪的重要探测器之一
- 下一代宇宙线实验，高能量前沿和高亮度前沿对量能器有着不同的需求
  - 高颗粒度量能器
  - 晶体型快响应量能器
- 研制了不同类型的量能器样机，并开展了束流测试
- 高颗粒度强子量能器样机
  - 实现了4cm×4cm的颗粒度，对强子能量分辨好于60%@1 GeV
- 新型晶体量能器
  - 基于pCsI晶体实现能量分辨2.5%@1 GeV
  - 时间分辨好于300 ps@1GeV



总结

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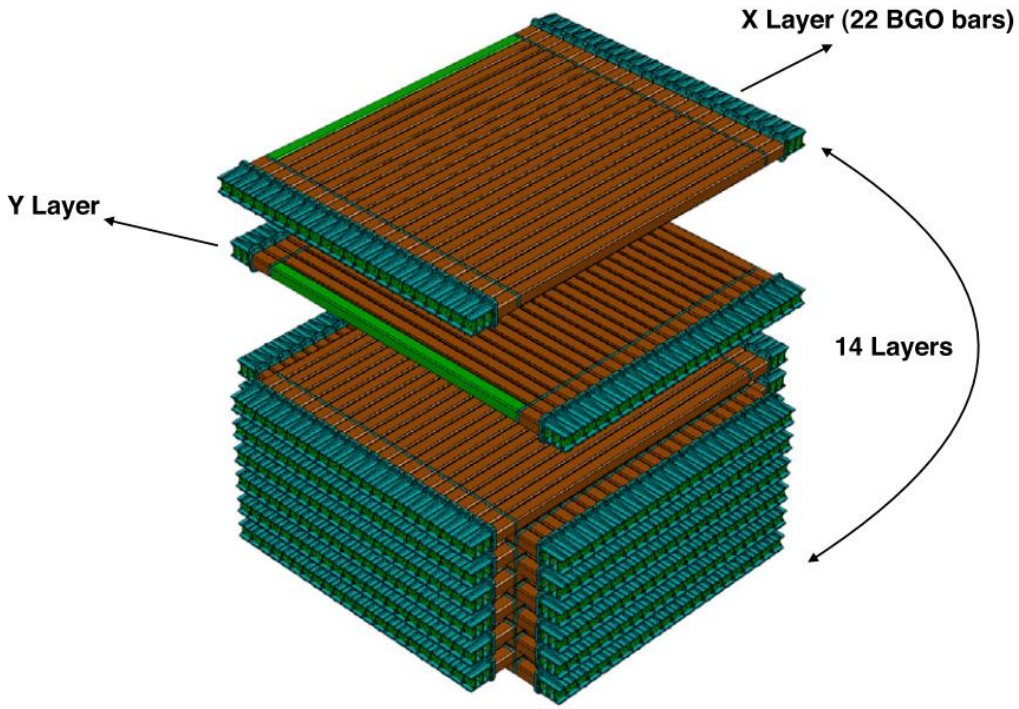
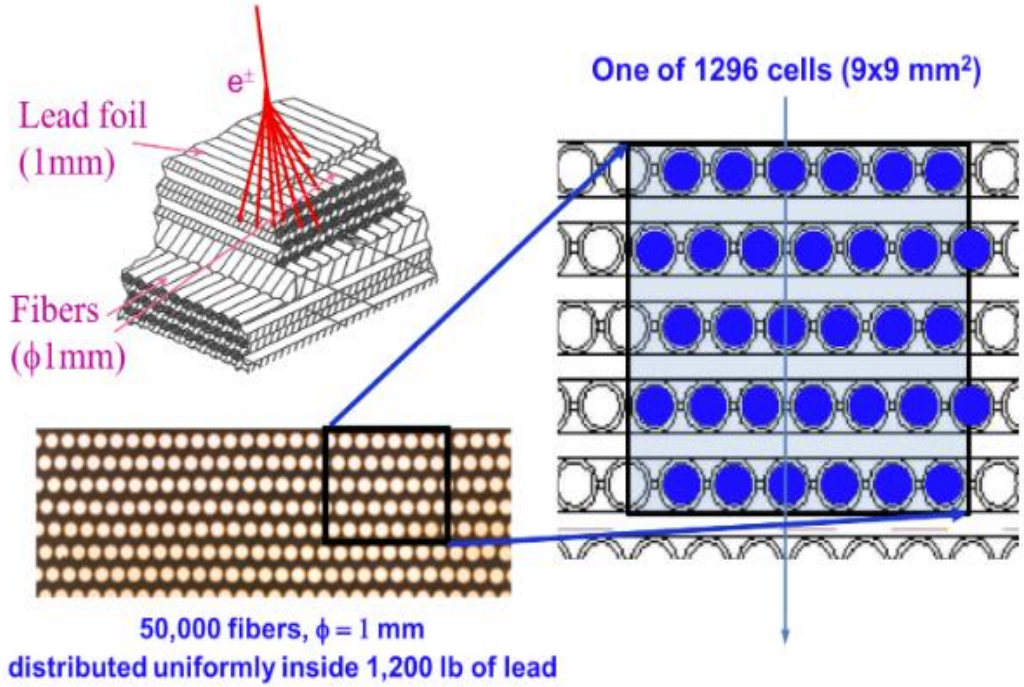
backup



高能宇宙线实验中的量能器



悟空号BGO量能器

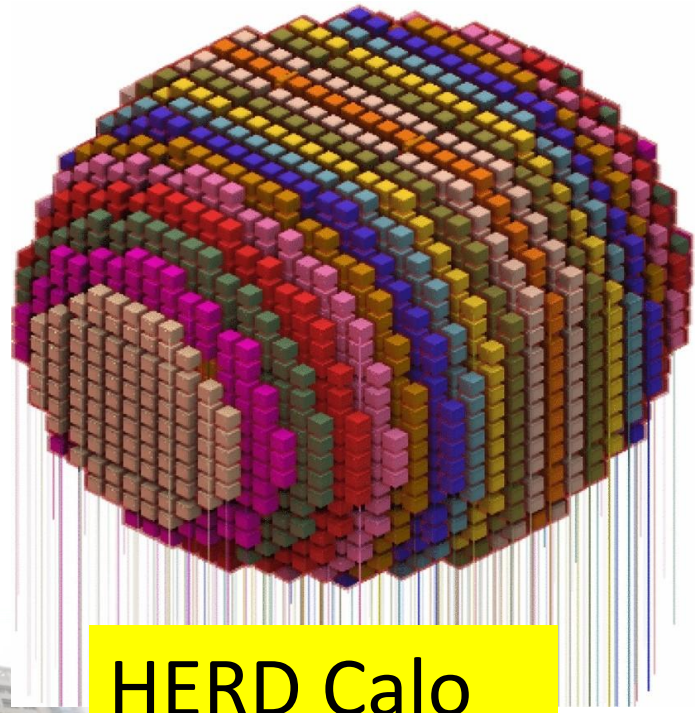


AMS02量能器



下一代高能宇宙线探测对量能器的需求

- 采用立方小单元组合的高颗粒度量能器
  - 各向同性，接收度大
  - 粒子鉴别能力好



HERD Calo

