ALICE硅像素探测器升级和物理研究项目进展

殷中宝

华中师范大学

汇报提纲

- 项目基本信息
- 探测器研究进展
- 物理研究进展
- 总结与展望

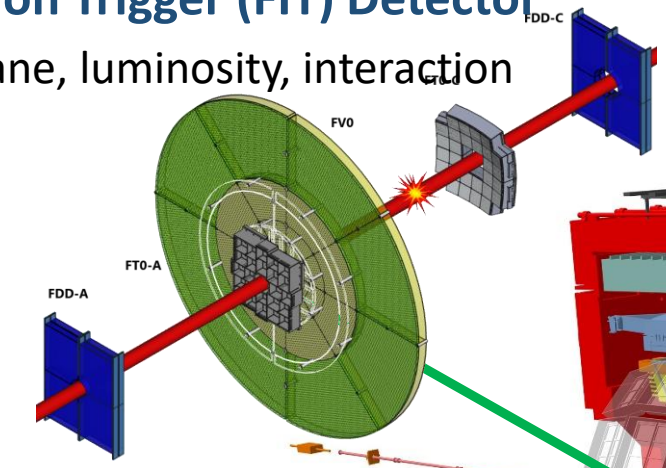
项目基本信息

- 项目名称：ALICE硅像素探测器升级和物理研究
- 项目执行期：2016年12月-2021年11月
- 项目经费：752.56万元（申请经费3400万元）
- 项目承担单位：华中师范大学
- 项目参与单位：中国原子能科学研究院；中国科学技术大学；中国科学院上海应用物理研究所→复旦大学

ALICE探测器升级

New Fast Interaction Trigger (FIT) Detector

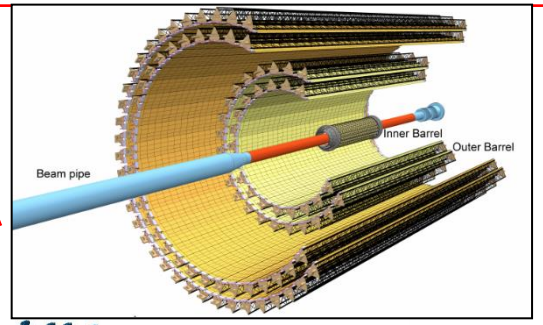
-Centrality, event plane, luminosity, interaction time

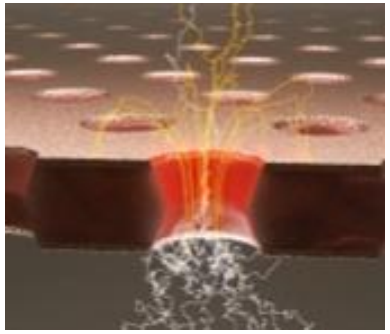


New Inner Tracking System (ITS)

-CMOS pixel, MAPS technology

-Improved resolution, less material, faster readout





New TPC Readout Chambers (ROCs)

-Gas Electron Multiplier (GEM) technology

-New electronics (SAMPA), continuous readout

with our contribution

Readout upgrade

-TOF, TRD, MUON, ZDC, Calorimeters

Integrated Online-Offline system (O^2)

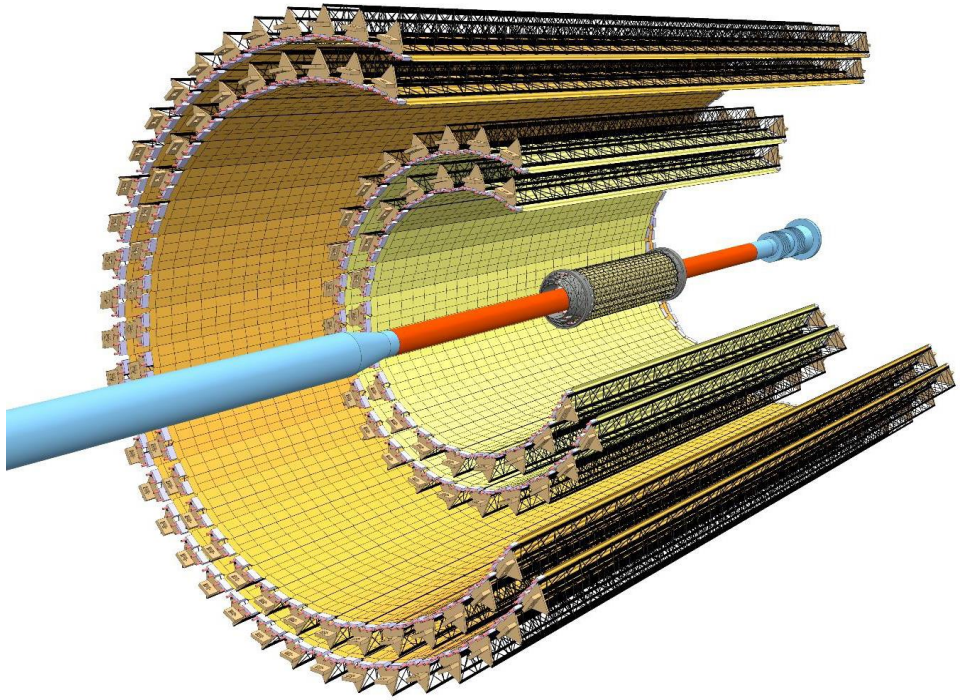
-Record MB Pb-Pb data at 50 kHz

New Muon Forward Tracker (MFT)

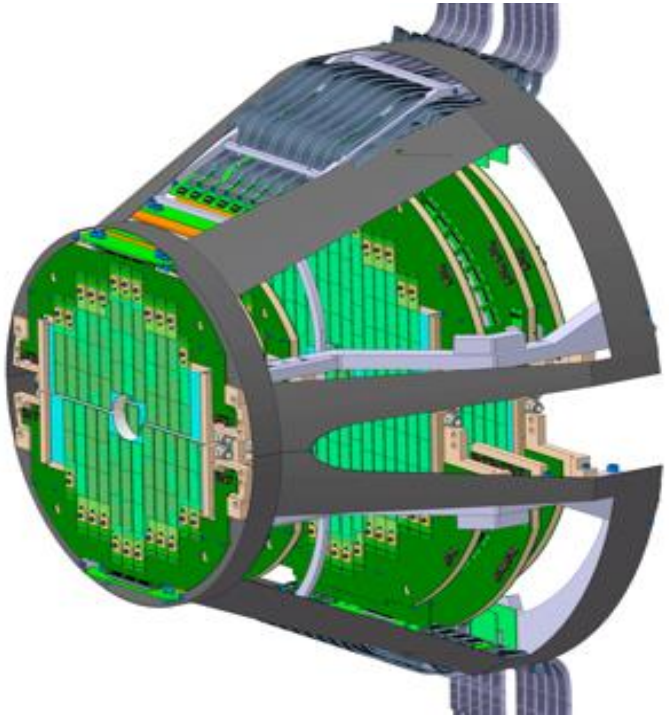
-CMOS Pixels, MAPS technology

-Vertex tracker at forward rapidity

硅像素探测器研制



中心区内部寻迹系统（ITS2）



向前快度区缪子寻迹系统（MFT）

- 基于单片有源硅像素传感器（MAPS）技术的ALPIDE芯片
- 探测器的基本构成单元：混合集成电路（HIC）

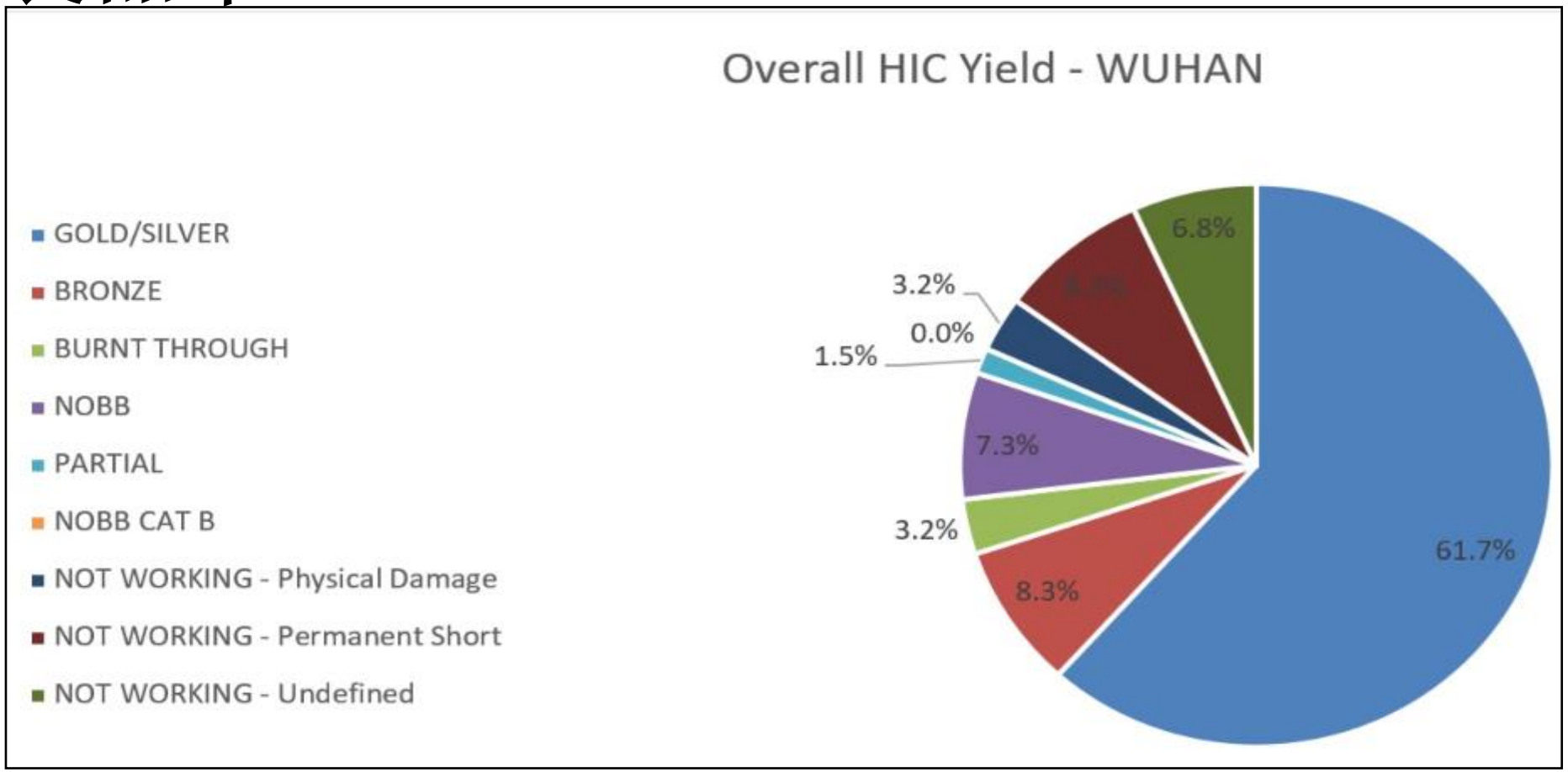
- 我们承担的升级任务：
  - ITS2 500个OB HIC模块研制
  - MFT读出链路板的研制

OB HIC模块的研制

✓2017年9月份启动预生产

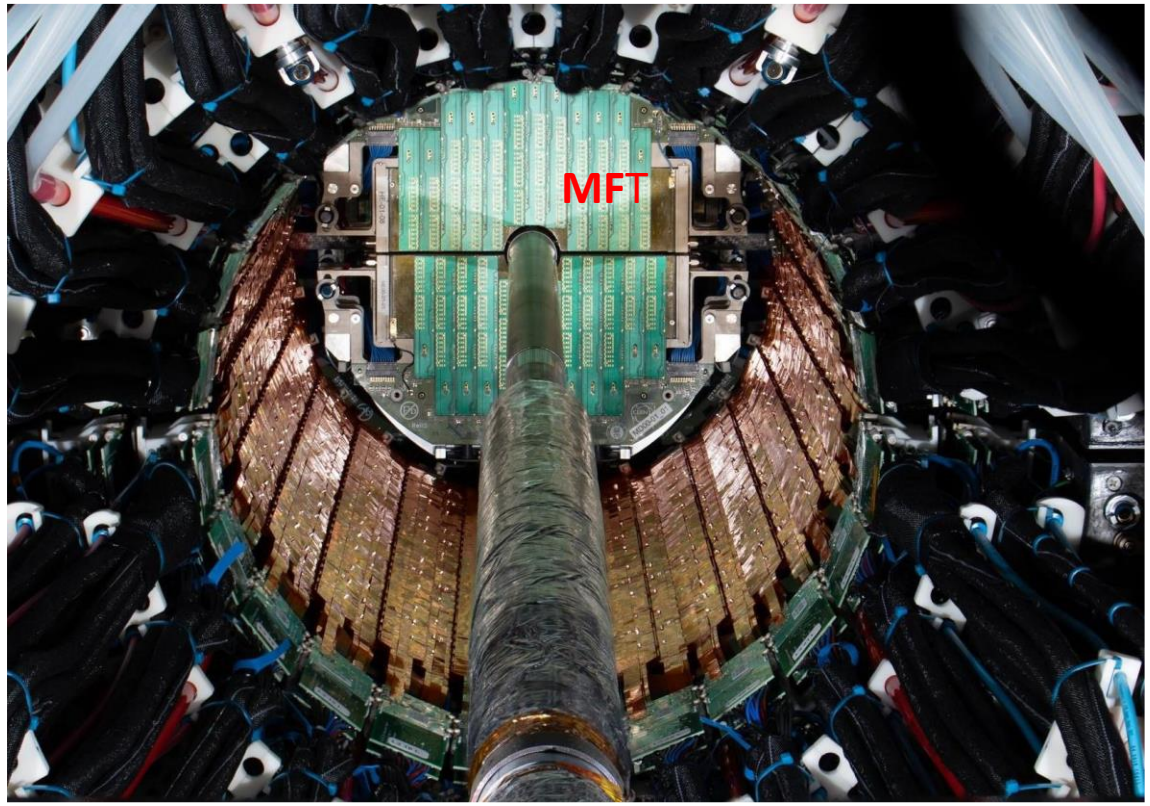
✓2018年4月份启动正式生产，于2019年8月完成（生产率为2 模块/天，共建造500个模块）

组装良品率

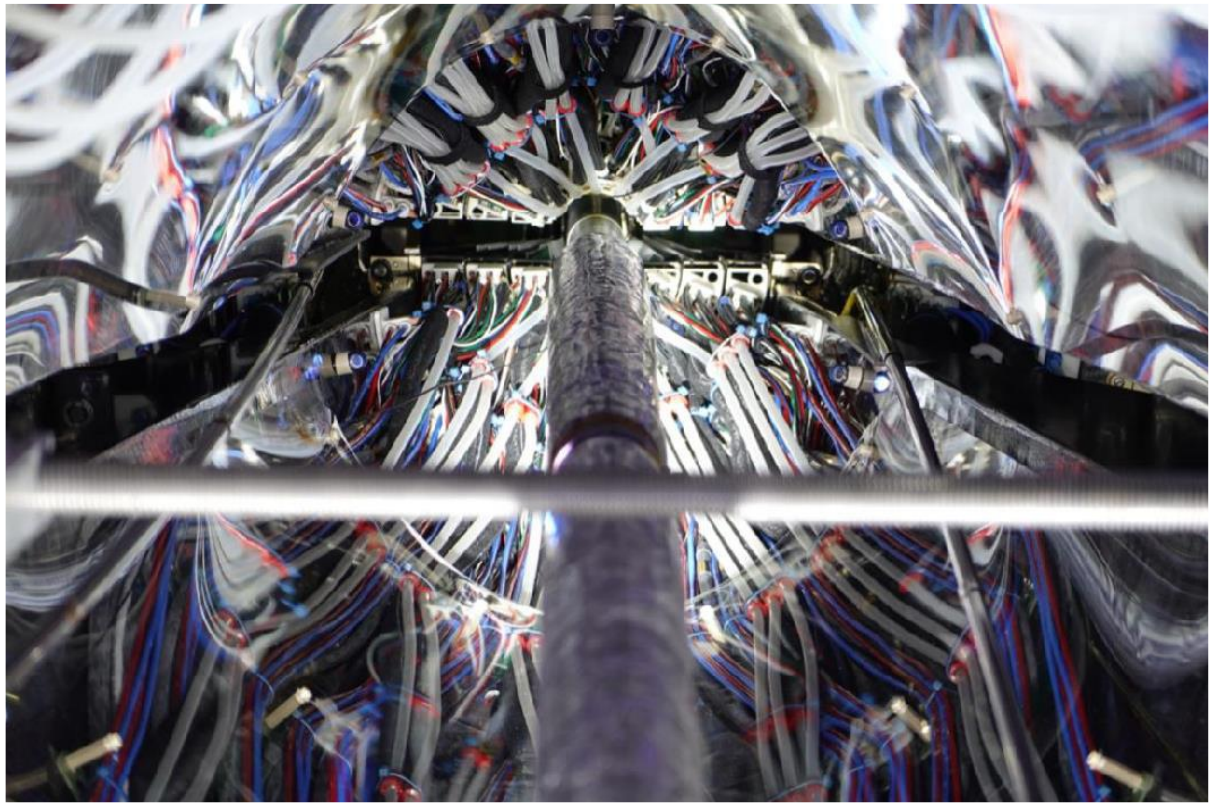


- 武汉组装点的良品率约81%
- 5个ITS OB HIC模块建造点的良品率约84%

ITS2安装

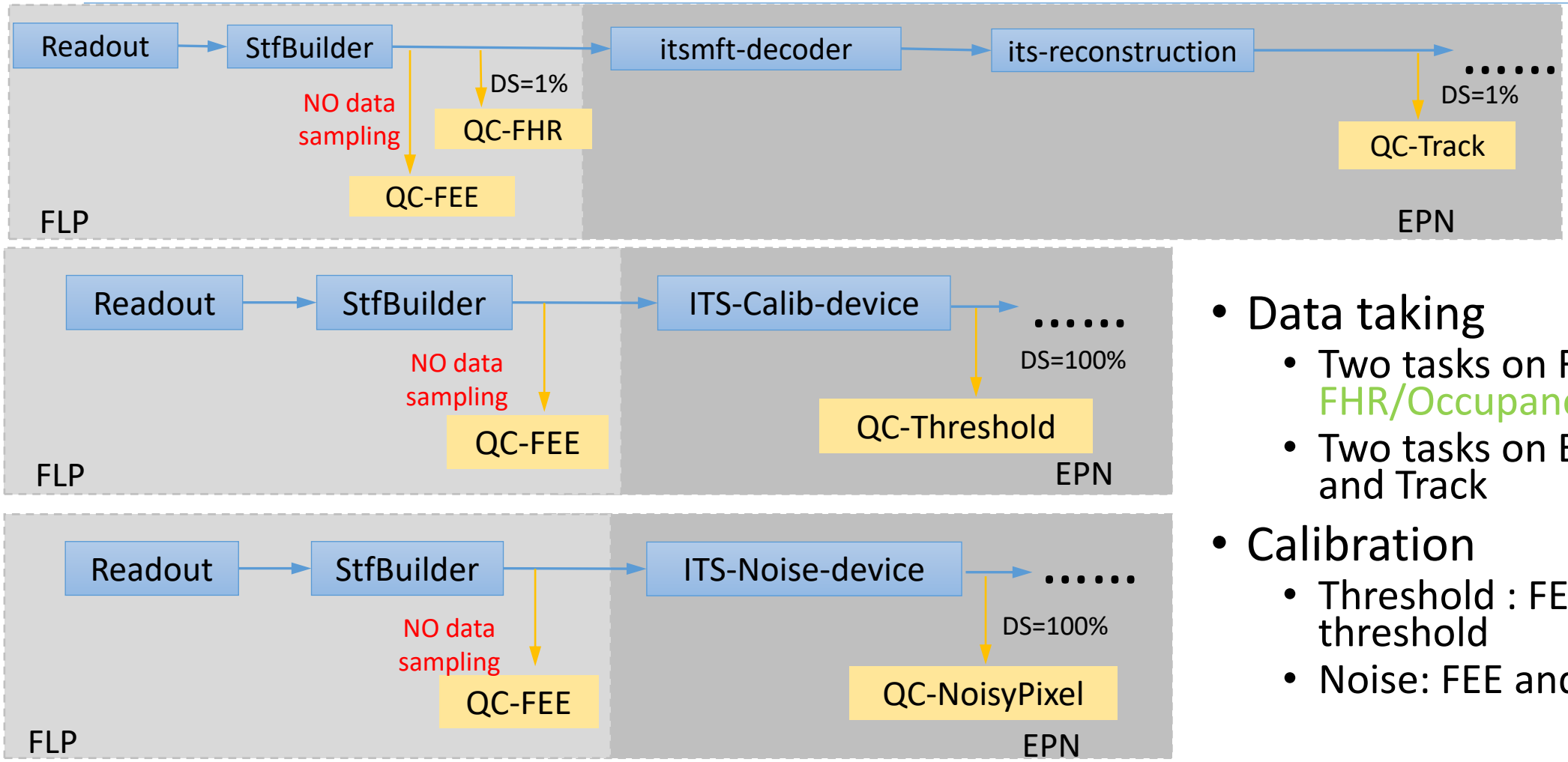


OB于2021年3月完成安装



IB于2021年5月完成安装

参与QC开发和测试（2019年9月始）



- Data taking
  - Two tasks on FLP: FHR/Occupancy and FEE
  - Two tasks on EPN: Cluster and Track
- Calibration
  - Threshold : FEE and threshold
  - Noise: FEE and NoisyPixel

QC现状

Status at P2

	FHR/Occupancy	FEE	Cluster	Track	Threshold	NoisyPixel	Post-processing
Detector data replay (noise + cosmics)							
MC data replay					N/A		
Online processing with detector (noise + cosmics)							
QC merger							
ECS integration							

Status

- FHR and FEE
  - Verified on IB and partial OB with Fake-hit Rate data taking
  - Bug fixed and InfoLogger verbosity redefined
- Cluster and Track
  - Regenerated ODC topology on EPN
  - Verified with data replay on EPNs at P2
- Tasks related to calibration and post-processing – to do
- QC plots for global commissioning - ongoing

	not yet started
	on going
	completed

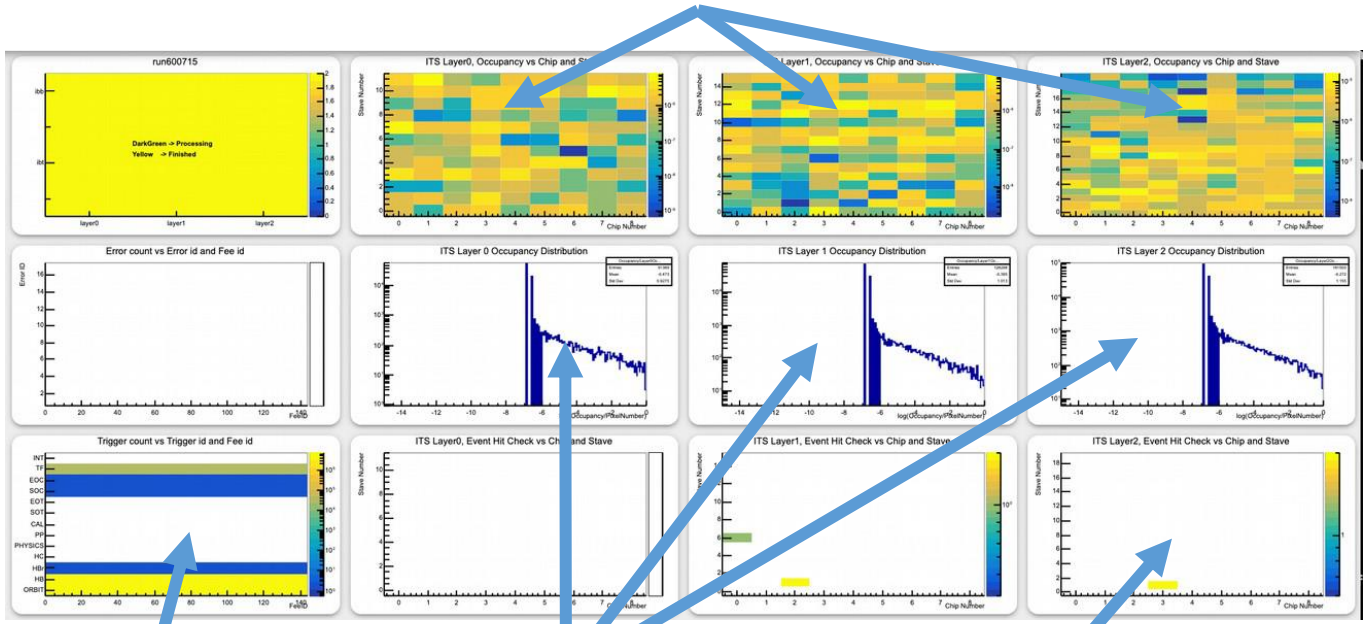
FHR QC

6 QC online tasks(online monitoring on data subsets)

- Fake-hit rate: monitoring of detector FHR, noisy pixels, etc.
- Front-end electronics: data integrity check without payload decoding of all events
- Noisy pixels: for detector noise calibration
- Threshold: monitoring of pixel threshold and dead pixel
- Cluster: monitoring cluster size, topology, etc.
- Tracks: monitoring track multiplicity, angular distribution, #clusters, etc.

Example for FHR Task with IB chips

Chip-by-chip FHR(hits/pixel/event):L0, 1, 2



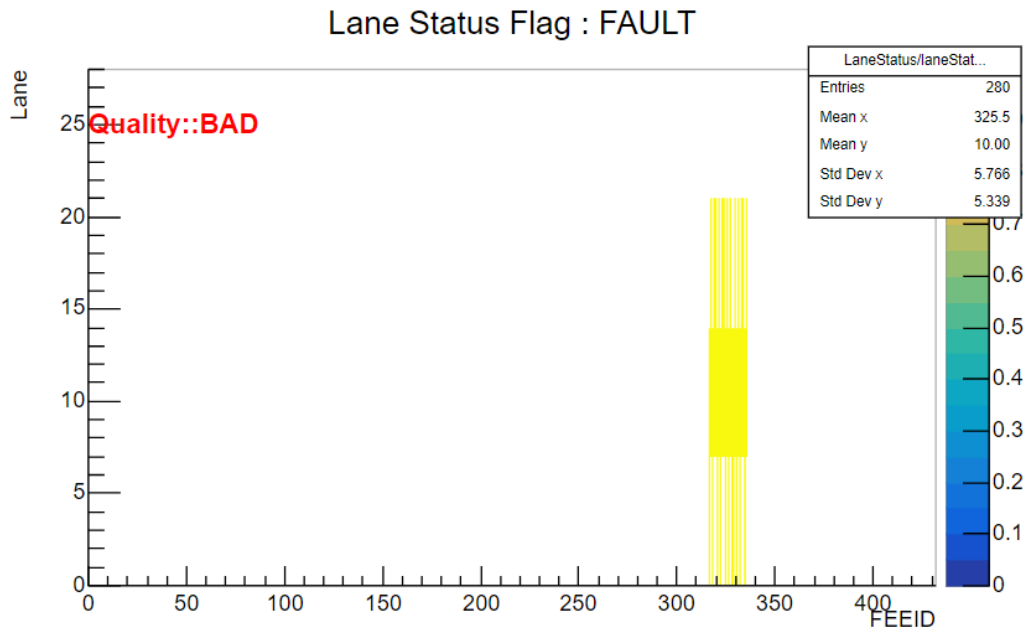
Trigger types

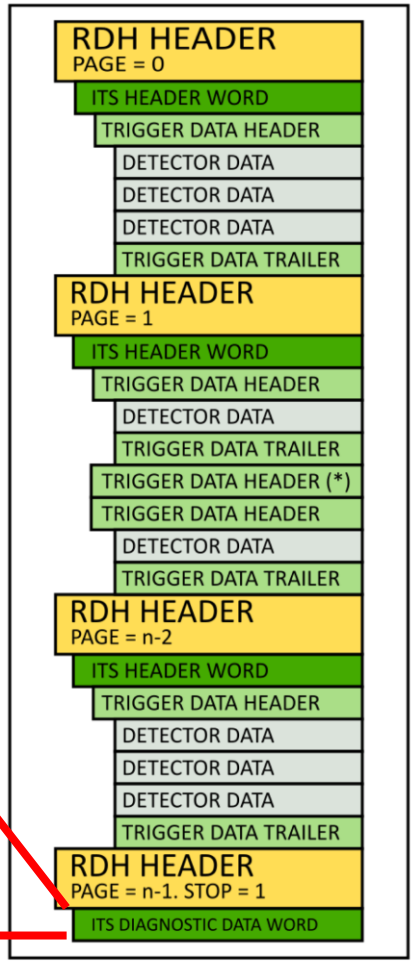
Pixel occupancy distribution

Chips with > 100 hits/event

FEE QC

- Data integrity check without payload decoding of all events
- Special data word “DIAGNOSTIC DATA WORD” will describe the status.





For the first DDW with index 0:

Field	Field	Value	Purpose
DDW0[79:72]	ID	0xE4	Identifier of the DDW
DDW0[71:68]	DDW index	0	Index of Diagnostic Data Word in the Diagnostic Data Block (curre
DDW0[67:65]			Cumulative logic OR of corresponding bits of the TDTs
DDW0[64:56]		0	RESERVED
DDW0[55: 0]	`lane_status`		Cumulative logic OR of corresponding bits of the TDTs

物理研究进展

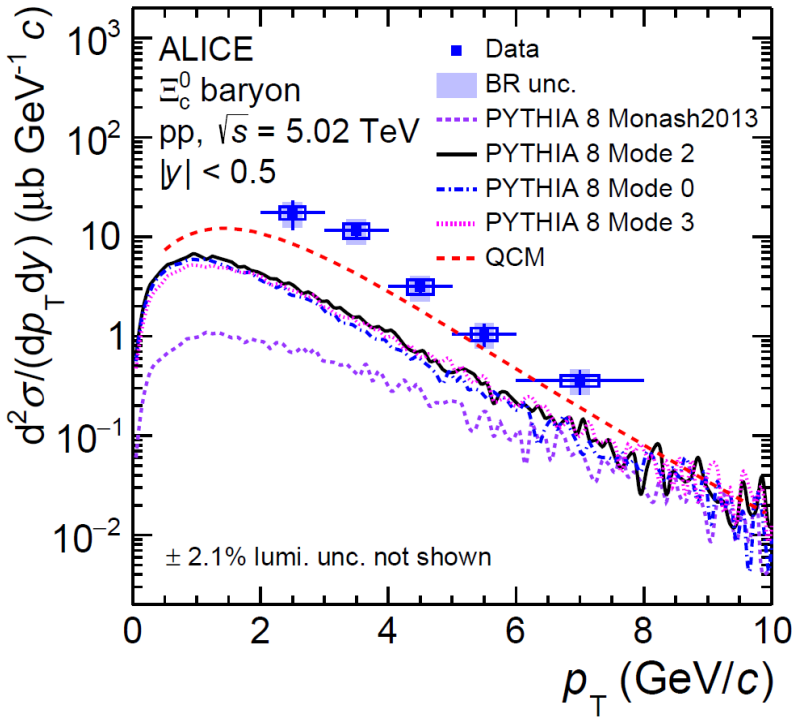
- 热密夸克物质的性质研究
  - 喷注淬火效应的研究
  - 集体运动性质的研究
- 冷核物质效应
- 质子–质子碰撞中粒子产生及其多重数依赖
- 奇特粒子态寻找和手征反常效应

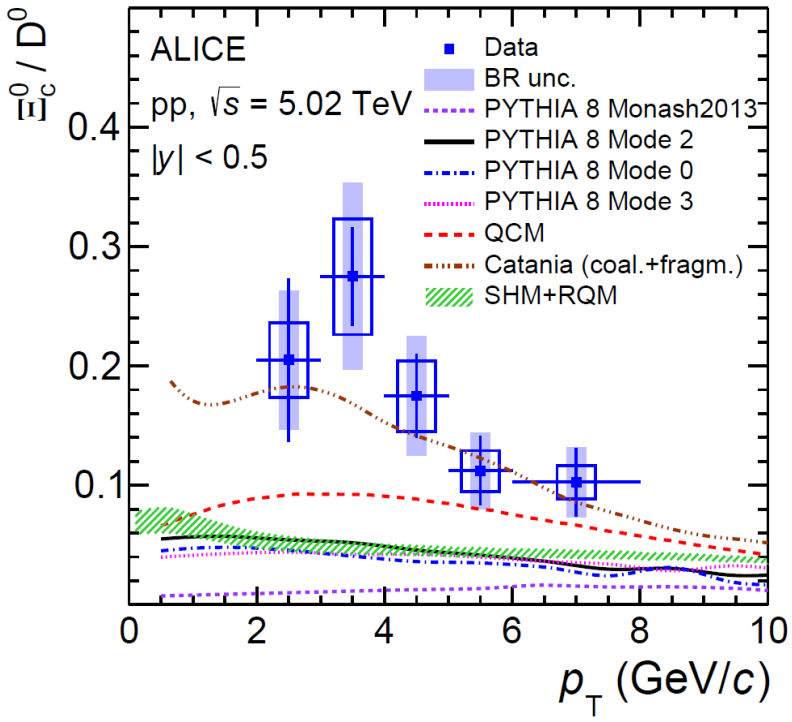
1. Production of muons from heavy-flavour hadron decays in p-Pb collisions at sqrt(s_NN) = 5.02 TeV, ALICE Collaboration, Phys.Lett. B770 (2017) 459-472.
2. Production of π0 and η mesons up to high transverse momentum in pp collisions at 2.76 TeV，ALICE Collaboration, Eur.Phys.J. C77 (2017) no.5, 339, Erratum: Eur.Phys.J. C77 (2017) no.9, 586.
3. W and Z boson production in p-Pb collisions at sqrt(s_NN) = 5.02 TeV， ALICE Collaboration, JHEP 1702 (2017) 077.
4. Jet-like correlations with neutral pion triggers in pp and central Pb–Pb collisions at 2.76 TeV，ALICE Collaboration, Phys.Lett. B763 (2016) 238-250
5. Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions, ALICE Collaboration, Nature Phys. 13 (2017) 535-539
6. Measurement of D^0, D^+, D^{*+} and D_s^+ production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, ALICE collaboration, JHEP 10 (2018) 174.
7. D-meson azimuthal anisotropy in mid-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV， ALICE collaboration, Phys. Rev. Lett. 120 (2018) 102301.
8. First measurement of jet mass in Pb-Pb and p-Pb collisions at the LHC, ALICE Collaboration, Phys. Lett. B776 (2018) 249
9. Neutral pion and η meson production in p-Pb collisions at √sNN = 5.02 TeV， ALICE Collaboration, Eur. Phys. J. C78 (2018) 624.
10. Non-strange and strange D-meson and charm-baryon production in heavy-ion collisions measured with ALICE at the LHC, Xinye Peng (for the ALICE collaboration), Nucl. Phys. A 982 (2019) 667-670.
11. Production of muons from heavy-flavour hadron decays in pp collisions at √s = 5.02 TeV, ALICE Collaboration, JHEP (2019) 8
12. Measurement of charged jet cross section in pp collisions at √s = 5.02 TeV, ALICE Collaboration, PRD 100 (2019) 092004.
13. Multiplicity dependence of (multi-)strange hadron production in proton-proton collisions at √s = 13 TeV, ALICE Collaboration, Eur.Phys.J. C80 (2020) no.2, 167.
14. Anisotropic flow fluctuations of charged and identified hadrons in Pb-Pb collisions with the ALICE detector, Ya Zhu (for the ALICE Collaboration), Nucl. Phys. A 1005 (2021) 121997.

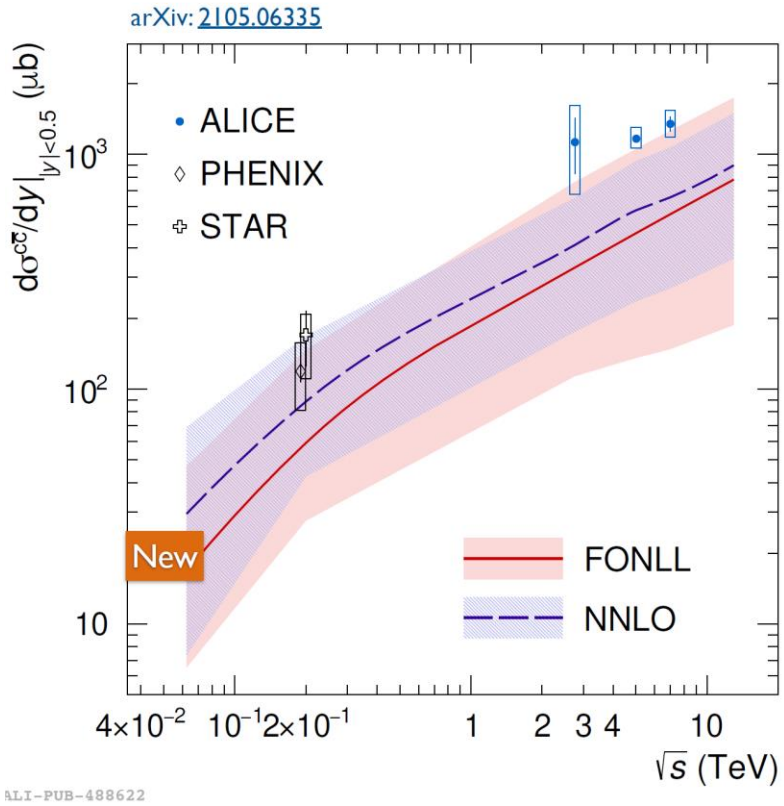
已发表实验论文十余篇，唯象论文十余篇。

Ξ_c^0 in pp at 5 TeV

arXiv: 2105.05616

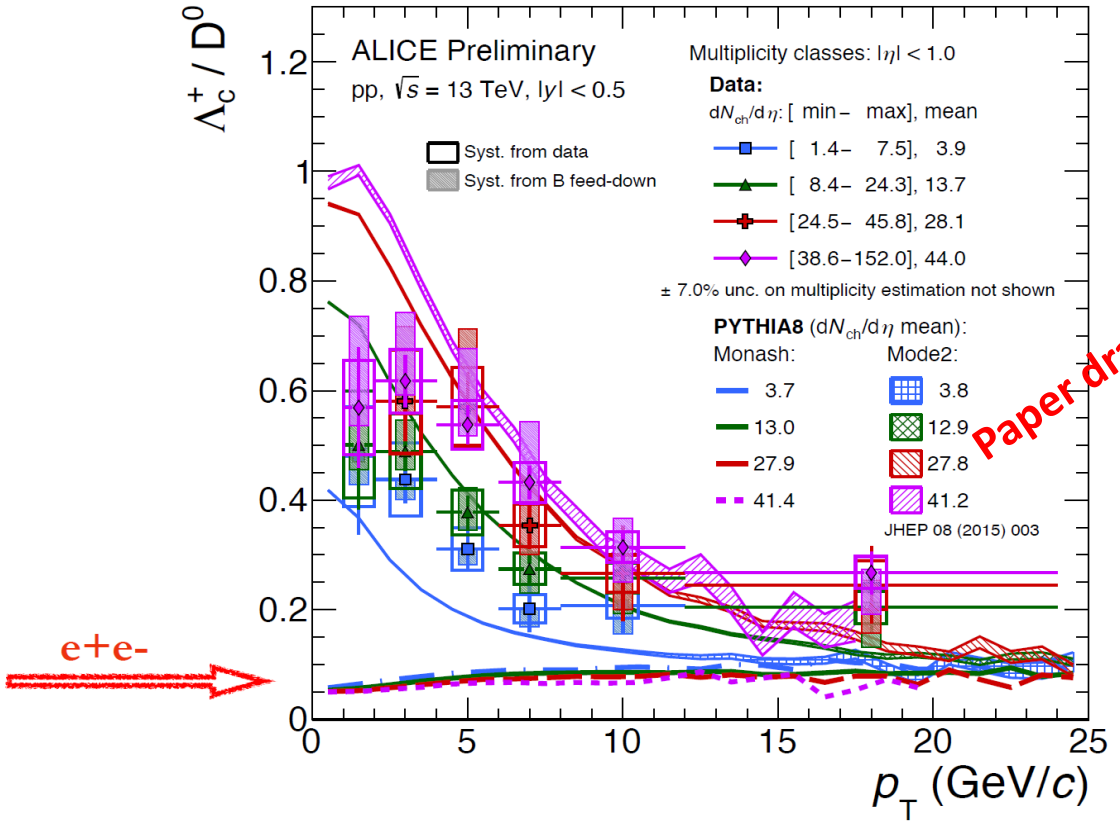




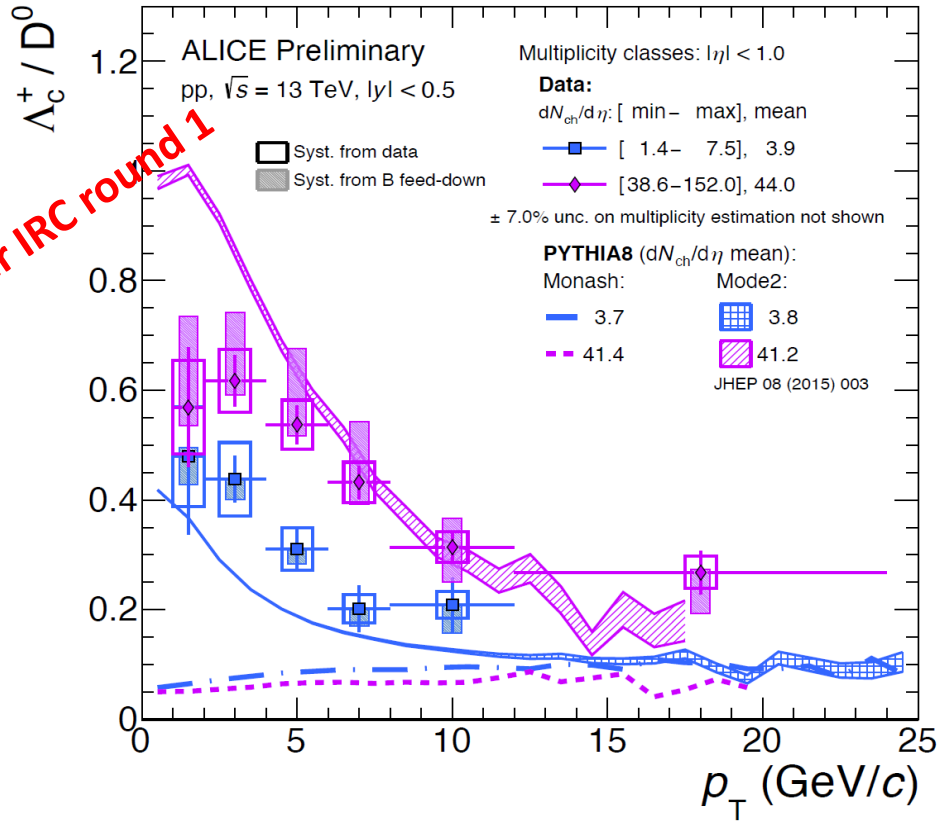


Paper submitted

Charmed baryon to meson ratio



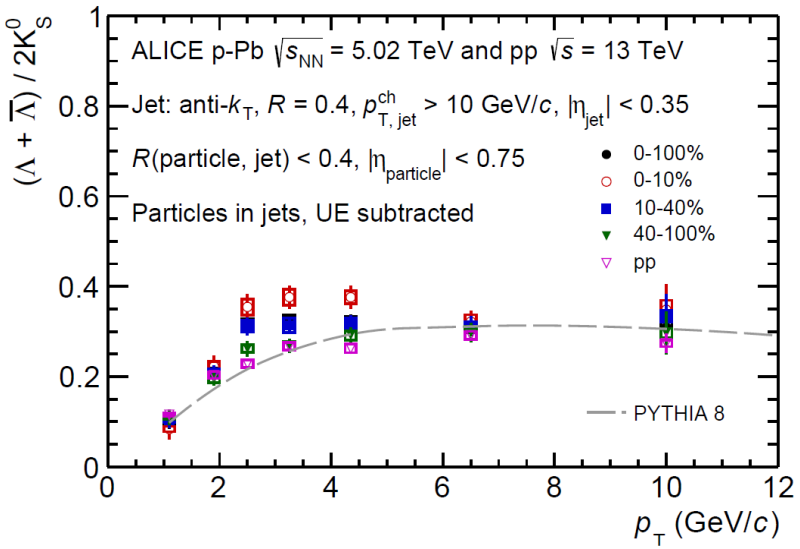
e+e-

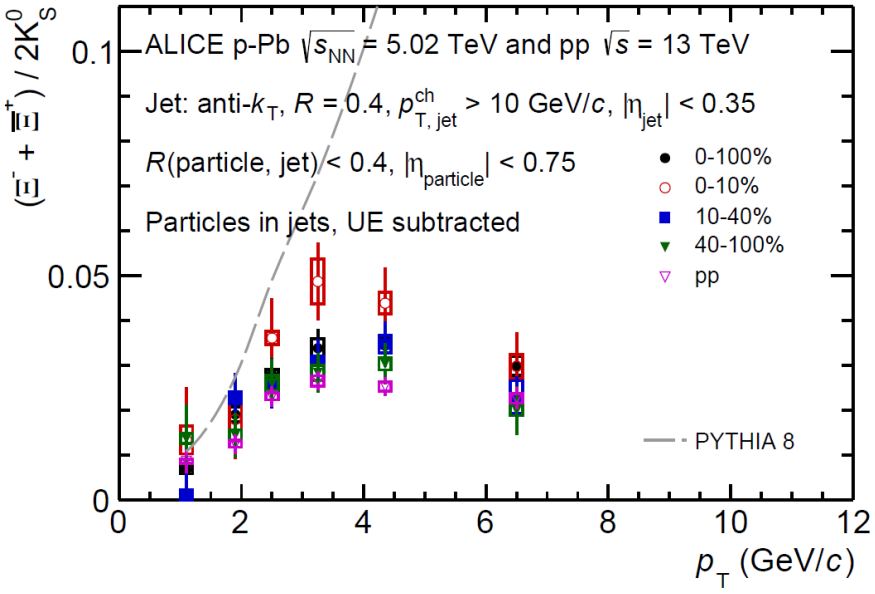


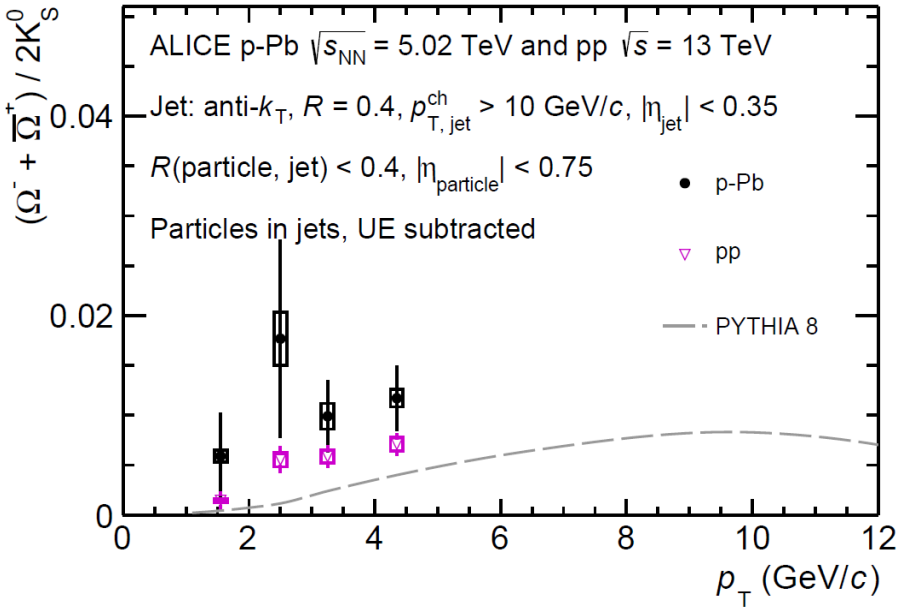
Paper draft under IRC round 1

- Even low multiplicity bin is much higher than e^+e^-
- Multiplicity bins are good agreement with the Pythia 8 Mode 2 which include color-reconnection processes
- Showed an enhancement in the whole p_T range comparing the highest to the lowest multiplicity interval

Strangeness in jets

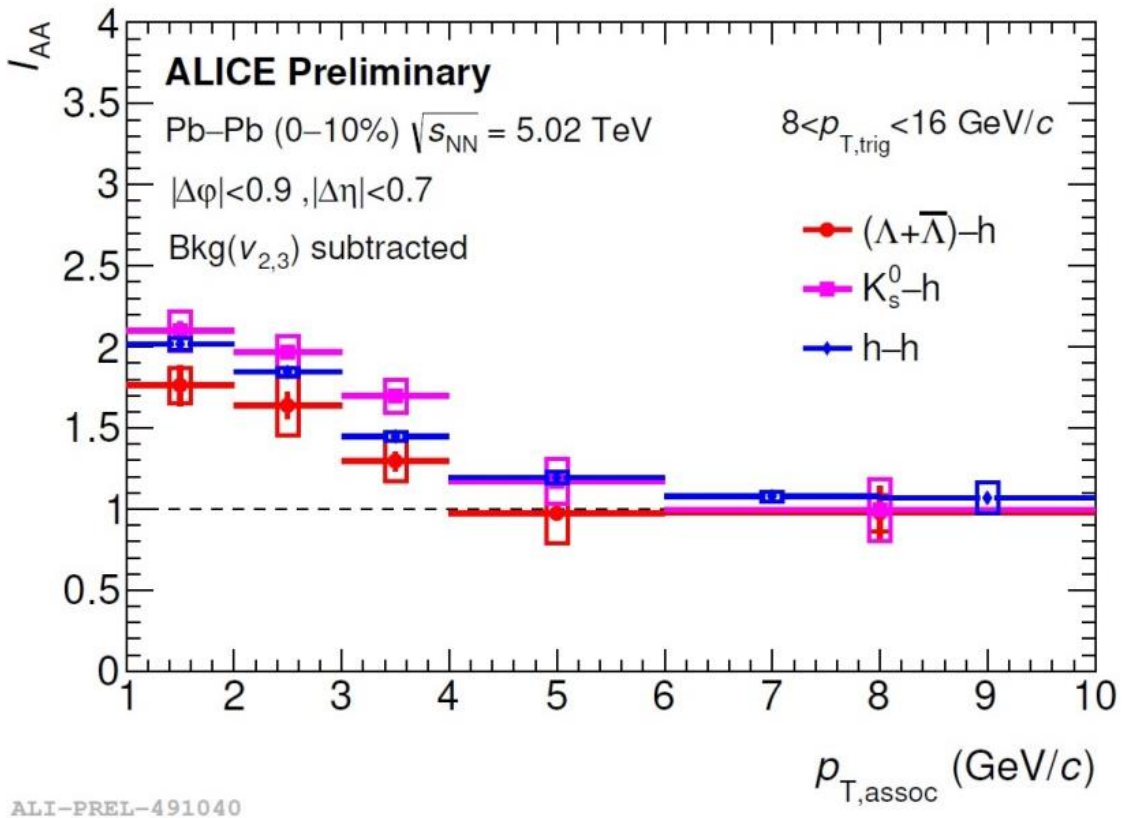


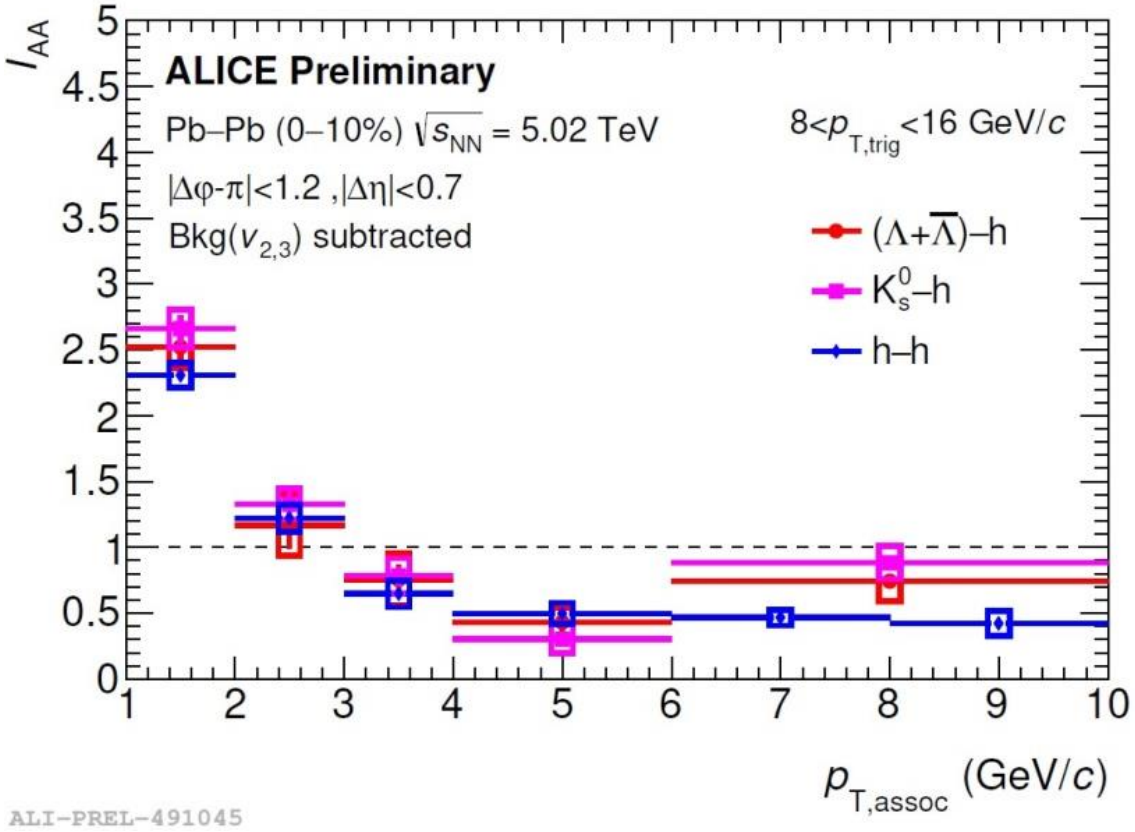




Paper draft under IRC round 1

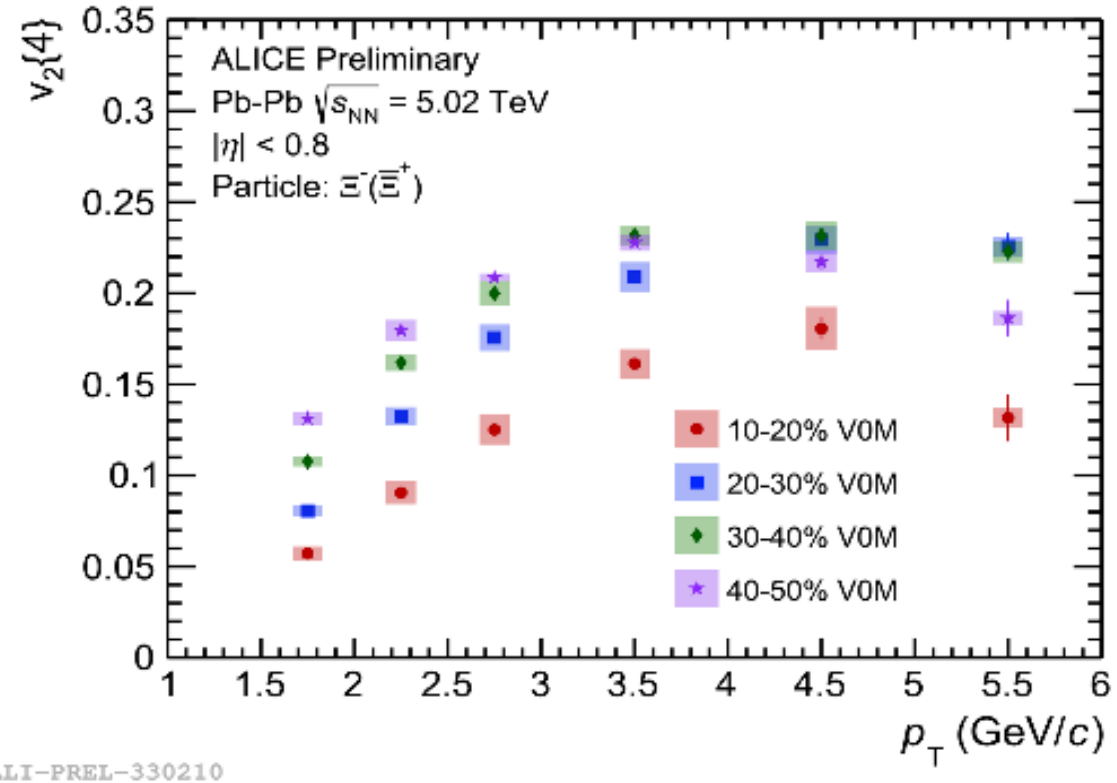
V0-hadron correlations



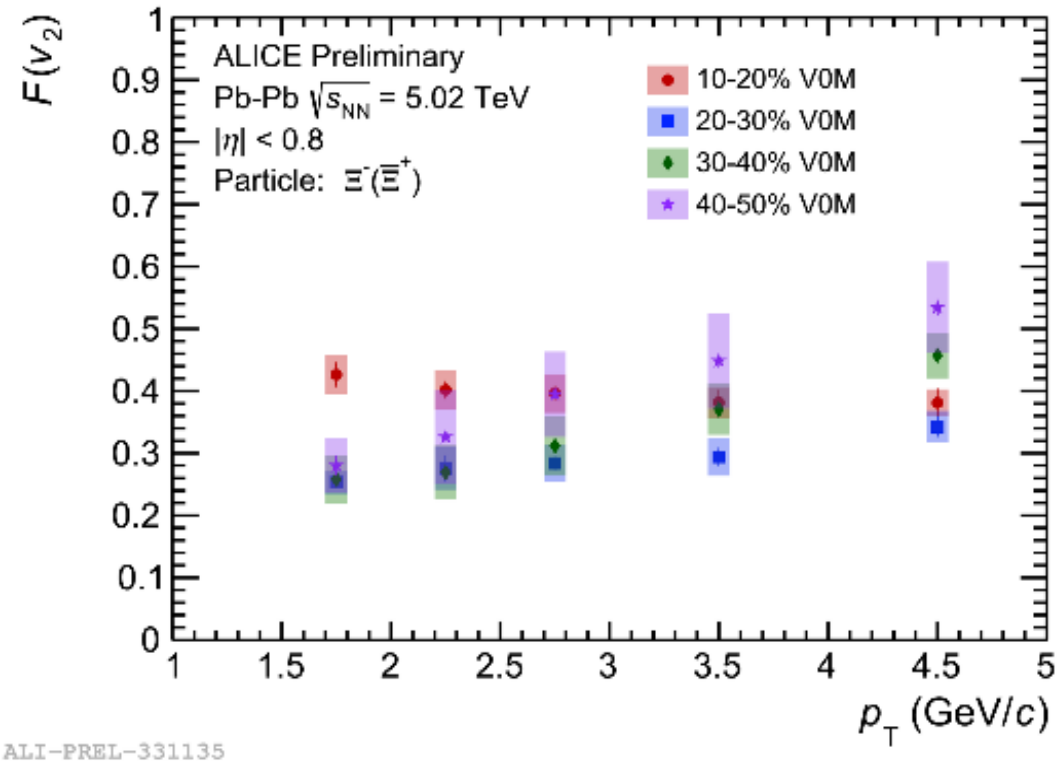


Paper proposal soon

PID flow fluctuation



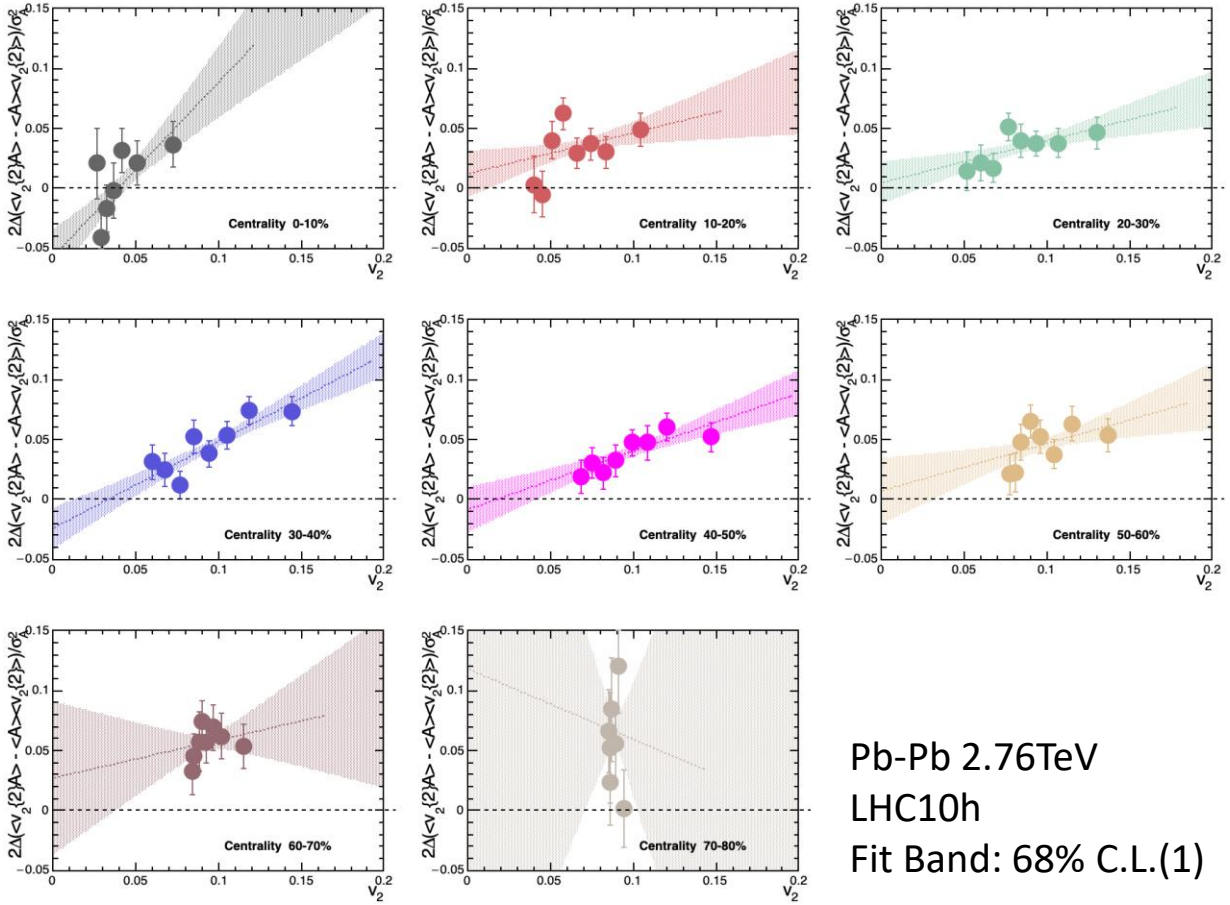
ALI-PREL-330210



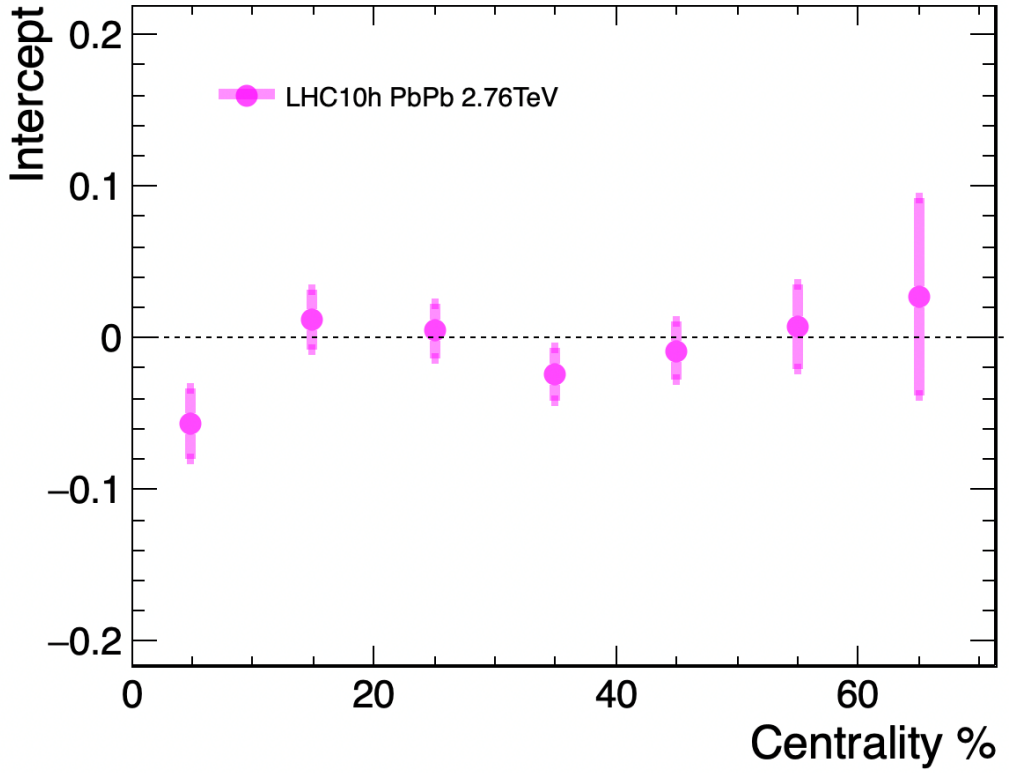
ALI-PREL-331135

Paper draft in preparation

ESE方法对手征磁波（CMW）信号与背景的分析



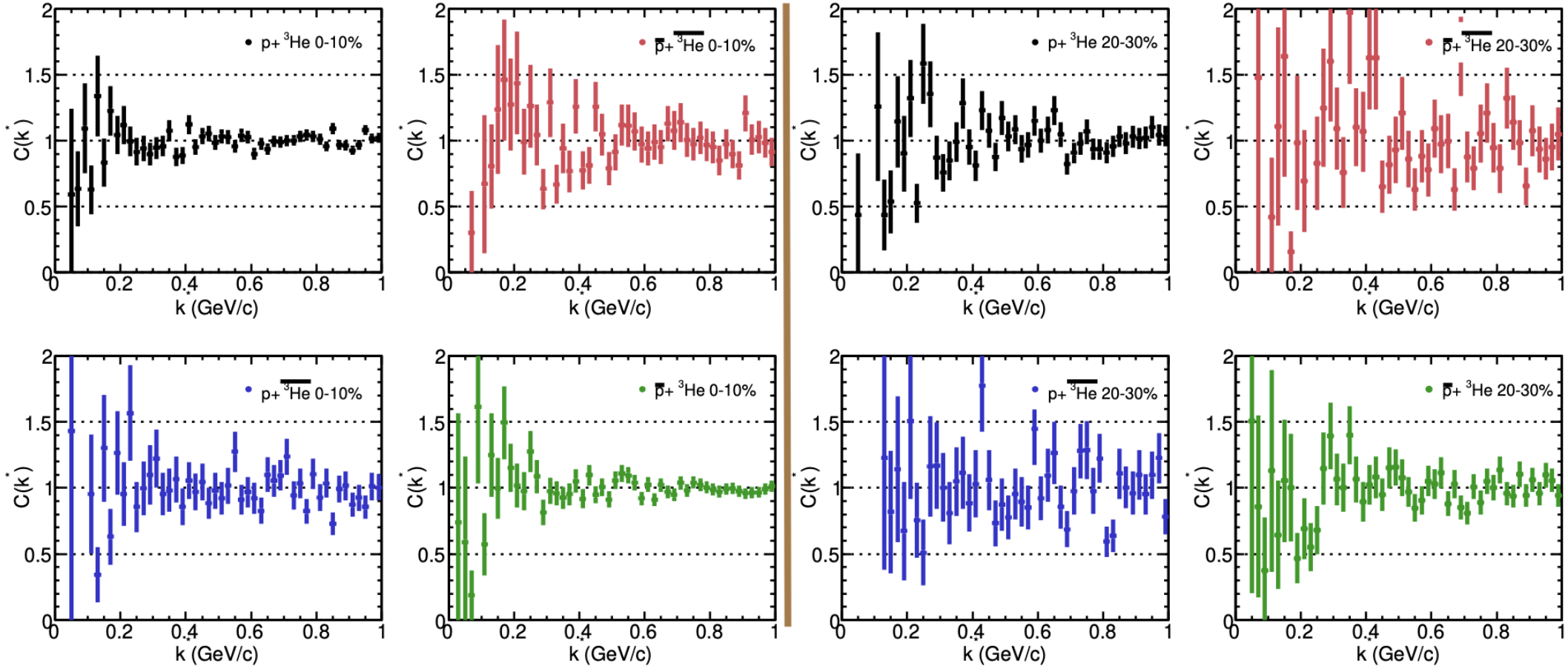
Pb-Pb 2.76TeV
LHC10h
Fit Band: 68% C.L.(1)



- 在ALICE实验数据中证实了ESE方法完全可行，有望首次对CMW的信号和背景强度做出定量估计
- 2021年3月PAG-Flow汇报；计划：全部统计+系统误差

质子–轻核动量关联

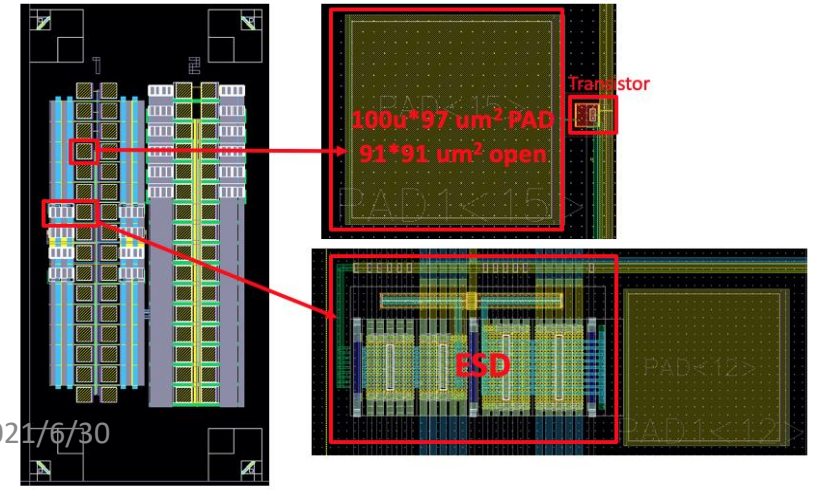
- 不稳定核素，作为对比关联测量具有一定参考价值
- 有助于揭示轻核产生相关的物理机制



总结与展望

- 完成了所承担的ALICE硅像素探测器升级研制任务
  - 掌握了MAPS芯片设计技术，研发出MIC4等芯片
  - 掌握了研制大面积GEM膜技术，研发出50x50 cm^2 GEM膜
  - 拓展ALPIDE芯片的应用，合作研发出基于ALPIDE的束流望远镜
  - 积极参与了ITS2安装和试运行，参与质量控制系统研发
- 物理研究取得了一些阶段性成果。

- 参与ITS3晶圆尺寸的超薄硅像素芯片的研发
- 积极参与FoCal探测器像素层的研发



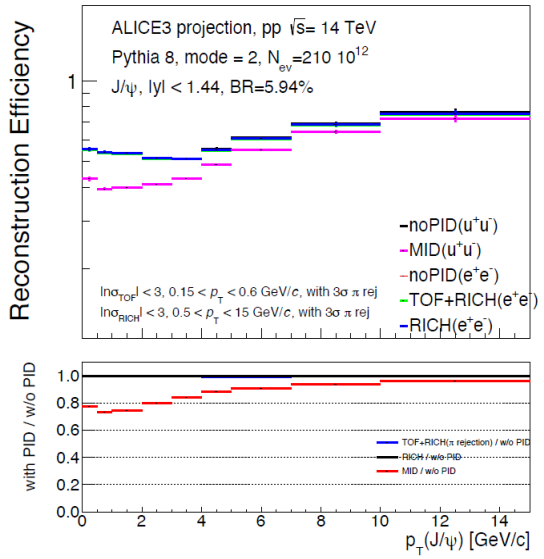
参与ALICE3预研：J/ψ

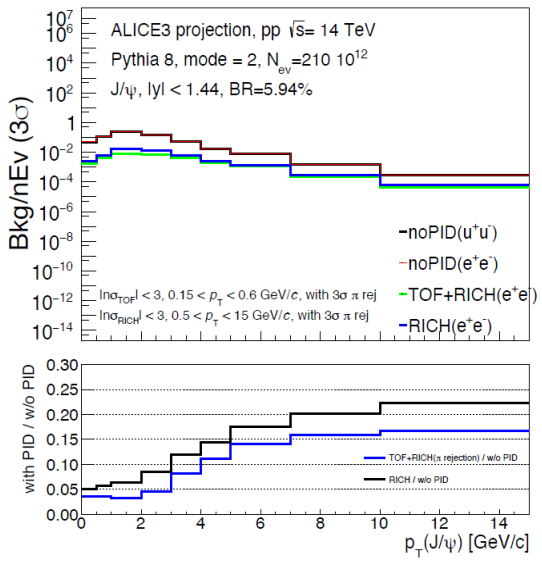
J/ψ reconstruction to study different aspects of ALICE3 detector design:

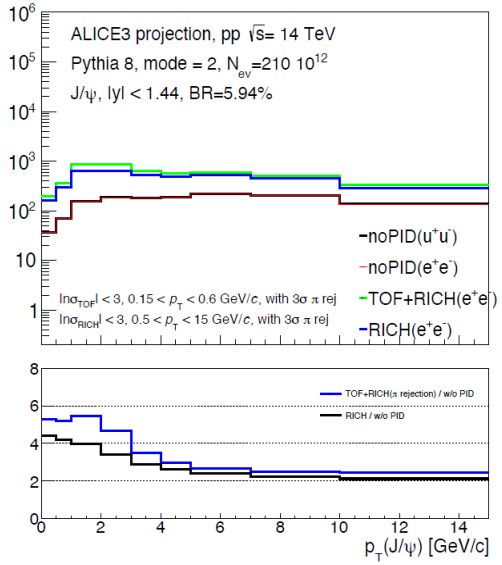
→ Dilepton acceptance

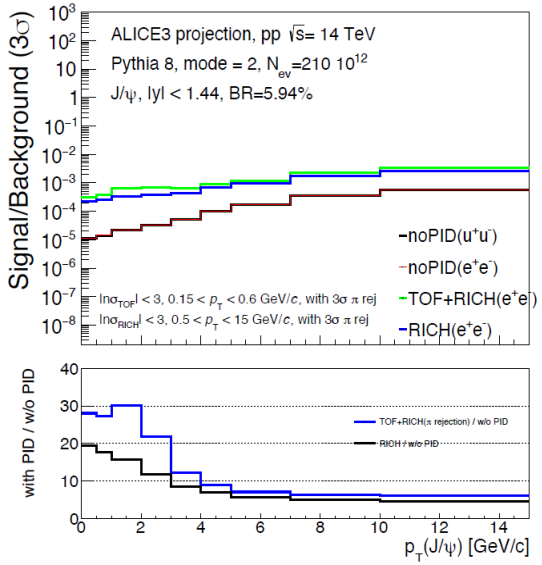
→ Capability of TOF, RICH and MID

J/ψ performance study also as a baseline for X(3872) → J/ψ π⁺π⁻ and χ_c → J/ψ γ reconstruction





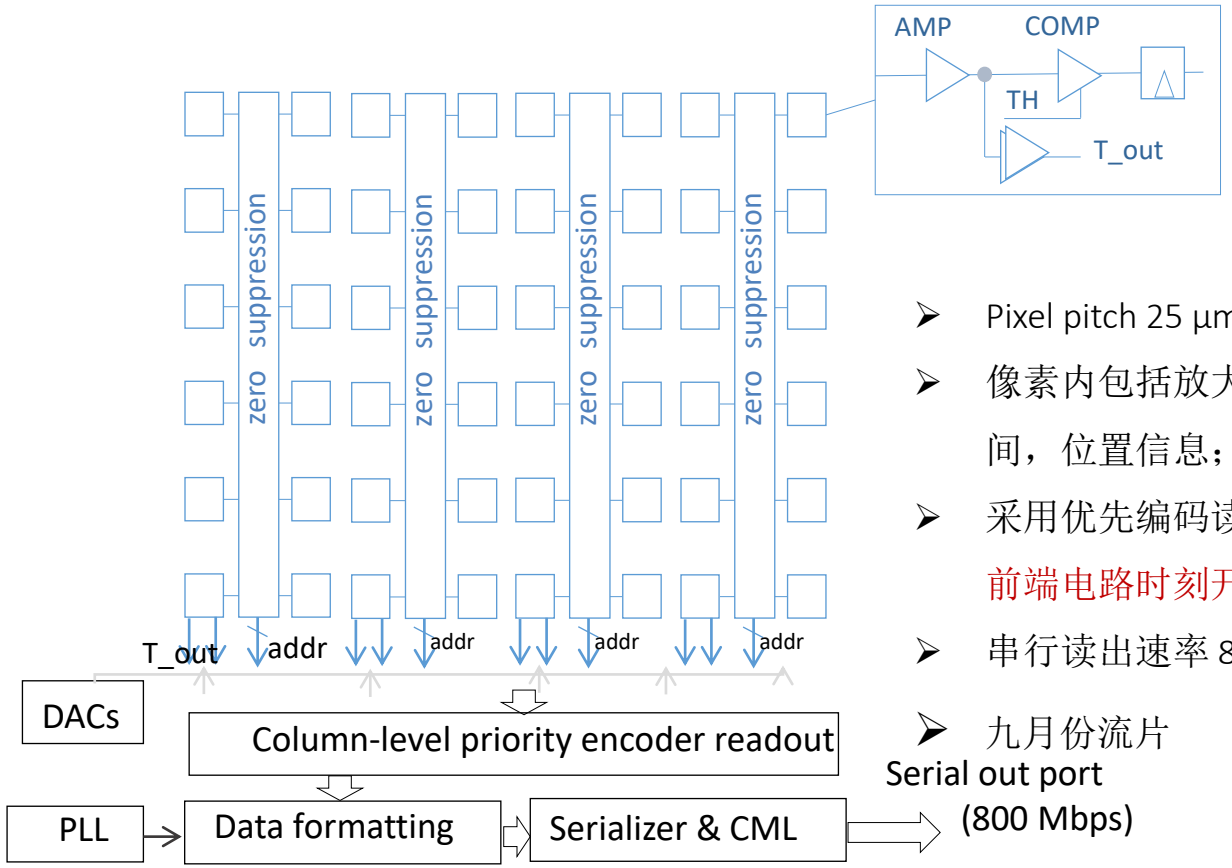




1. J/ψ reconstruction efficiency with different PID case
2. Background estimation from sideband of MB production, RICH and TOF+RICH show strong bkg suppression
3. Significance estimation with different PID case, significance be improved at the low p_T after combine TOF + RICH PID
4. S/B ratio be improved at the low p_T after combine TOF + RICH PID

感谢项目成员的努力工作！
感谢各位专家的关心与指导！

MIC5



- Pixel pitch 25 μm
- 像素内包括放大器，比较器，测量粒子达到时间，位置信息；
- 采用优先编码读出，阵列直接输出地址；PIXEL 前端电路时刻开启；
- 串行读出速率 800Mbps
- 九月份流片

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Switzerland

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E-mail : Federico.Antinori@cern.ch

To Whom It May Concern

Geneva, 4th July 2017

With this letter I would like to recognise the contribution of Prof. Dr. Zhong-Bao Yin to the study of the production of strange and multi-strange particles in high-multiplicity proton-proton collisions at the LHC.

Prof. Yin has been one of the initiators of these studies, to which he gave very important contributions. The results, published on Nature Physics 13 (2017) 535 in the paper entitled "Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions", and announced by CERN with a press release on 24 April 2017, showed that proton-proton collisions at high multiplicity present the same peculiar pattern of strangeness enhancement that had been observed since long time in collisions of heavy nuclei, and is considered one of the hallmarks of the formation of Quark Gluon Plasma (QGP), the primordial state that was present in the very first millionths of life of the Universe and can be recreated in high-energy nuclear collisions.

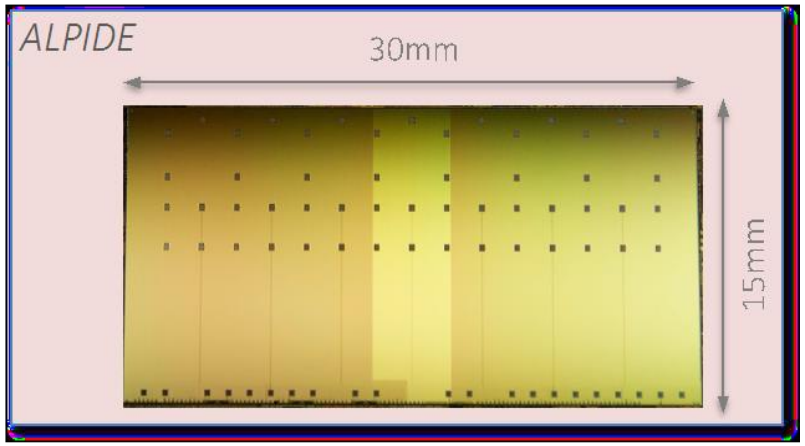
The physics insight and the dedicated work of Prof. Yin contributed to this spectacular observation, that has opened a completely new window for the understanding of the mechanisms of strangeness production in the QGP.

Sincerely Yours,

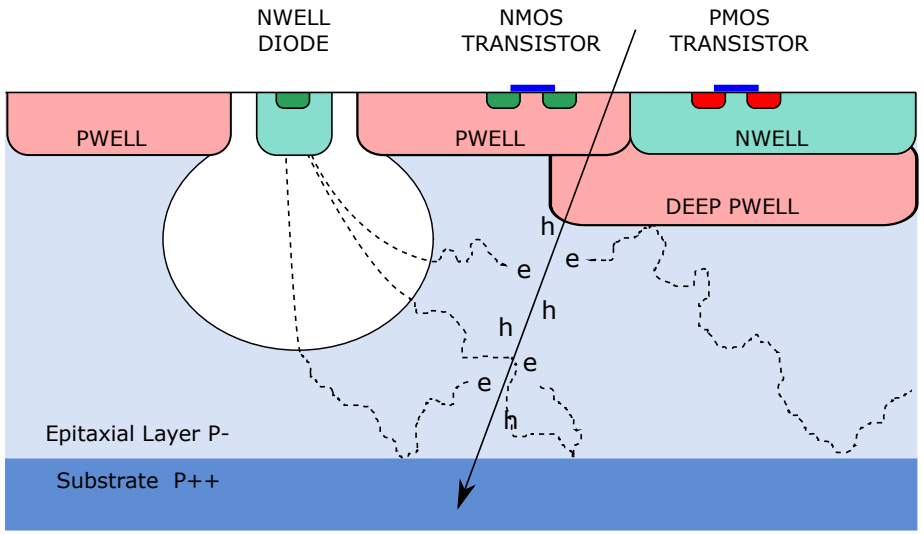
Federico Antinori

Spokesperson, ALICE Experiment

ALPIDE芯片



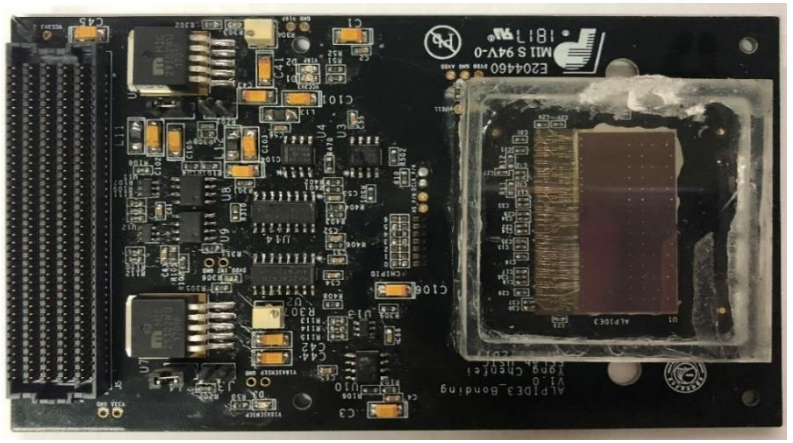
- 芯片的尺寸为30 mm X 15 mm
- 像素数: 1024 cols x 512 rows
- 像素大小: 29 μm x 27 μm
- 超低功耗: ~40 mW/cm^2
- 读出时间：< 4 μs
- 探测效率：>99%
- 位置分辨率：< 5 μm
- 最大接受粒子率：100 MHz/cm^2
- 假命中率：<<10^{-6}/pixel/event
- 触发率：100 kHz 铅-铅碰撞，1 MHz 质子-质子碰撞
- 连续或触发读出
- 抗辐照：> 270 krad TID, > 1.7x10^{12} 1 MeV n_{eq}/cm^2 NIEL



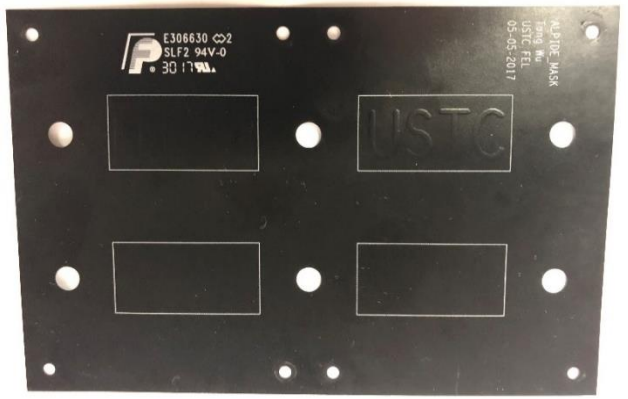
- ALPIDE于2016年定型，并于2016年12月份开始量产
- CCNU参与该芯片设计：
  (1) 芯片读出结构;
  (2)像素模拟前端电子学改进

- 外延层：高阻抗 （> **1 kΩ cm** ），25 μm厚
- 读出二极管直径仅为2 μm
  =>电容小(~fF)，低噪声
- 反向偏压：-6 V～0V，增大耗尽层，提升电荷收集速度

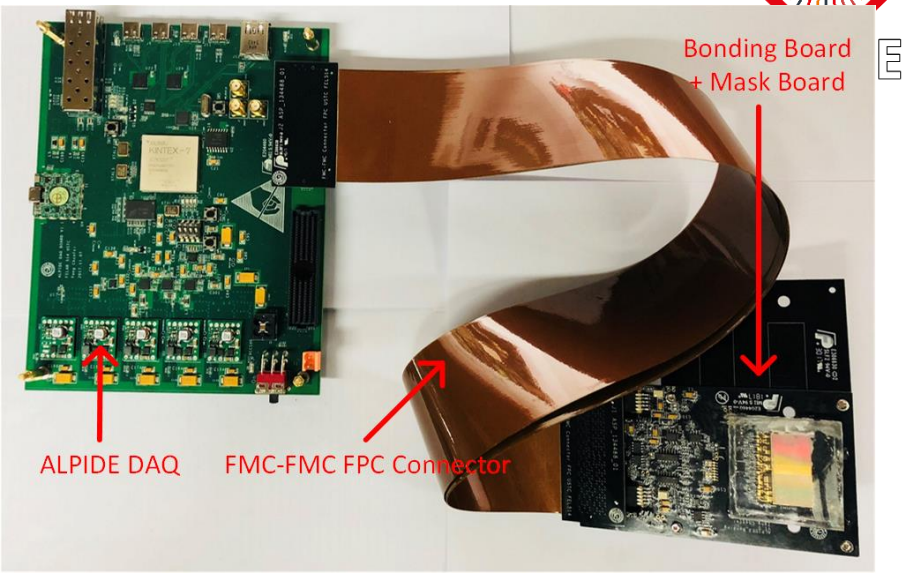
ALIPIDE测试



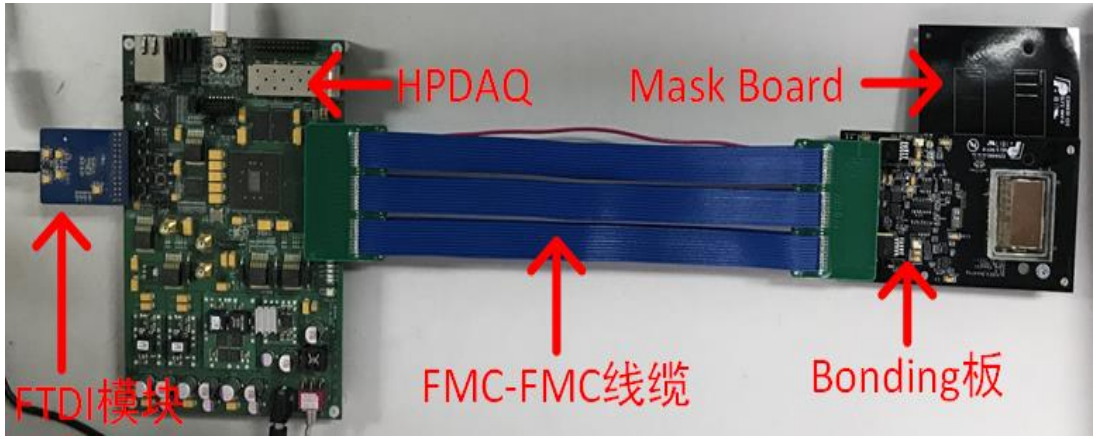
科大开发的ALPIDE绑定板



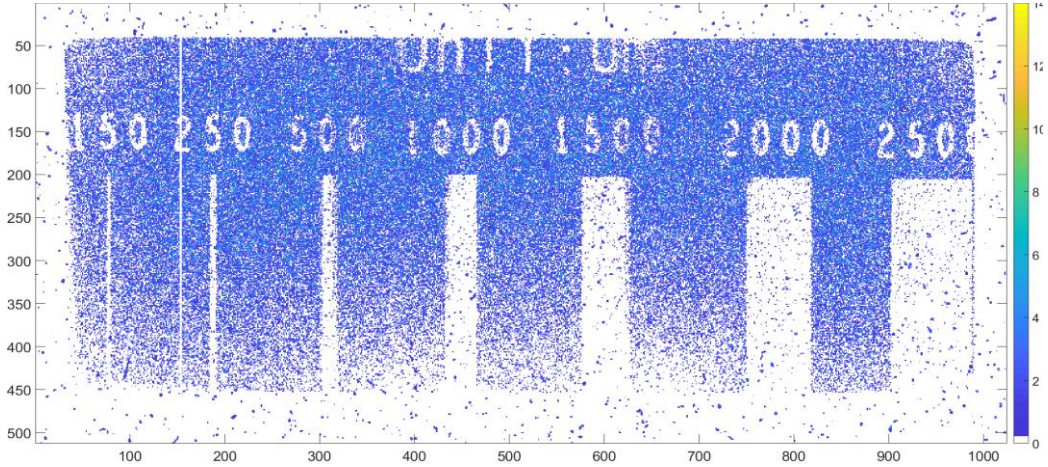
基于柔性PCB工艺的掩模板



基于开发的ALPIDE DAQ板的读出电子学系统

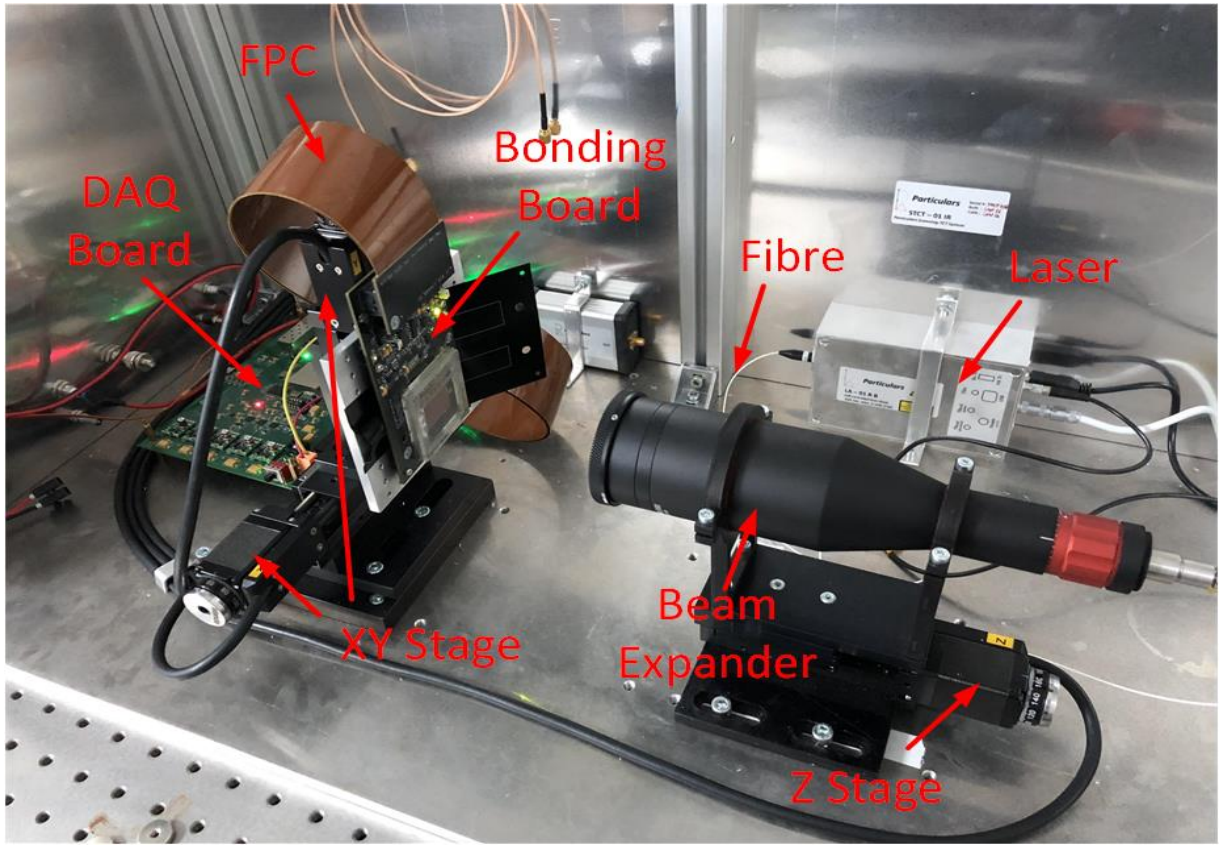


基于HPDAQ和绑定板的读出电子学系统

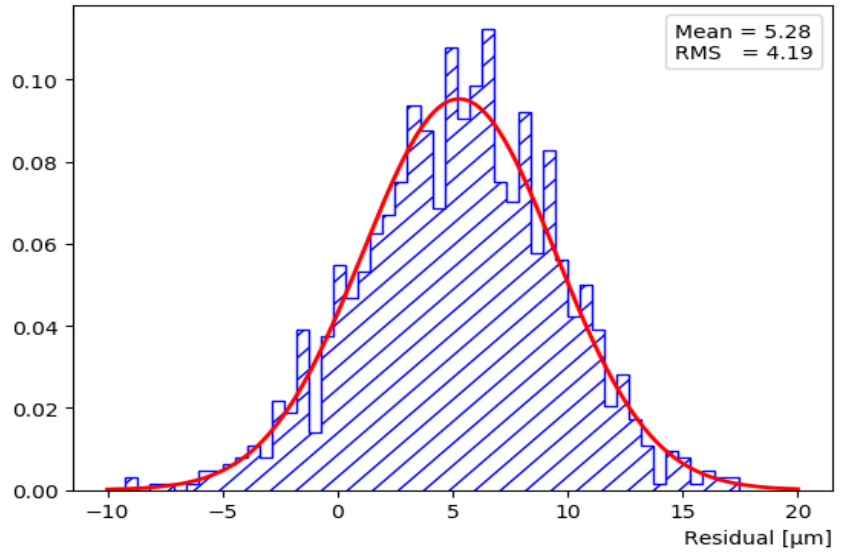


掩模板的x光成像

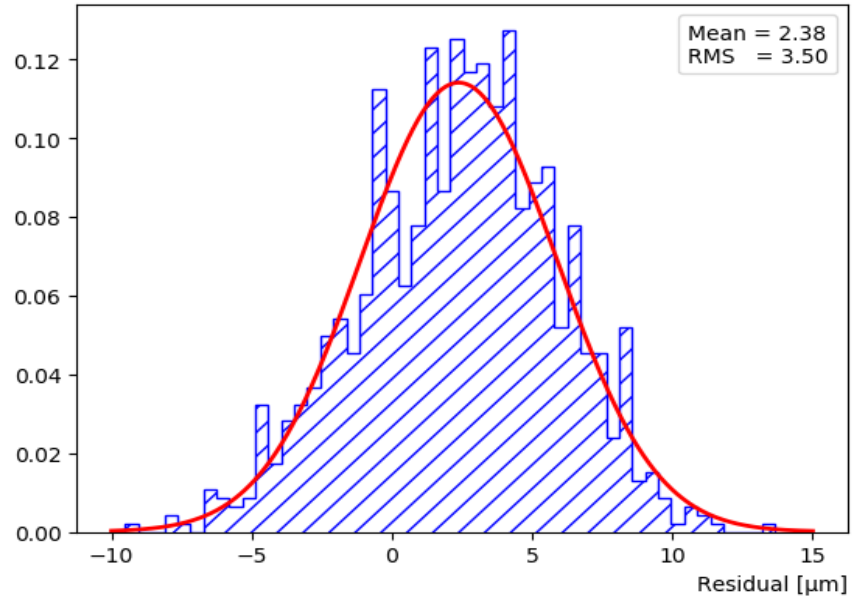
ALPIDE测试



激光测试

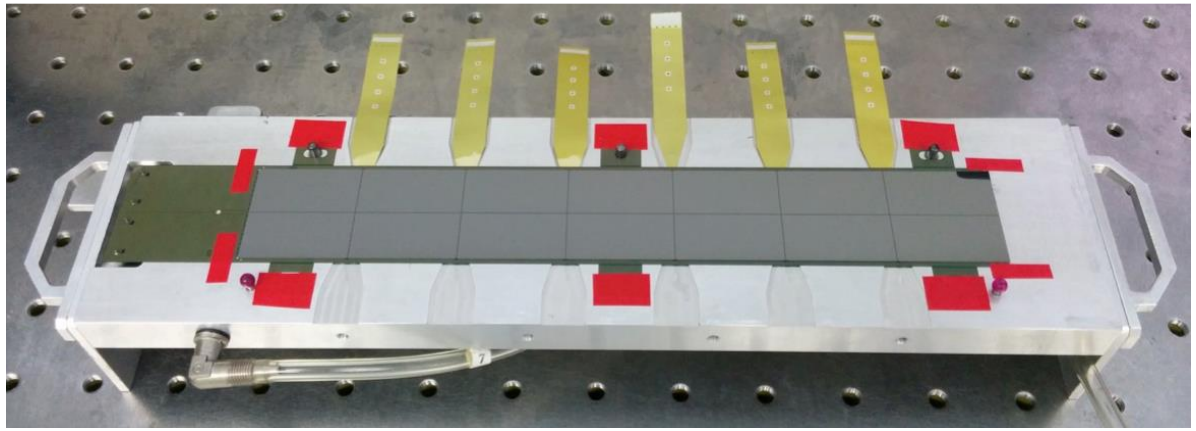


X方向像素尺寸为29.24 μm，测得位置分辨率为4.19 μm

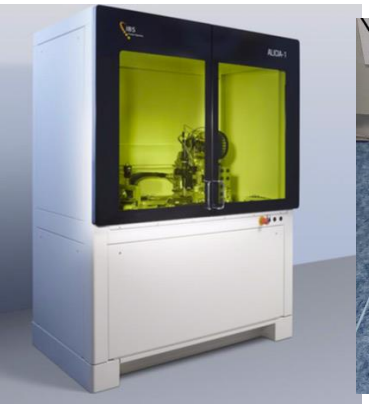


Y方向像素尺寸为26.88 μm，测得位置分辨率为3.50 μm

OB HIC组装和测试流程



- OB-HIC 模块由一块柔性印刷电路板（FPC）和14 个芯片组成
- 14 个芯片摆放成2x7 的阵列，摆放精度小于5 um

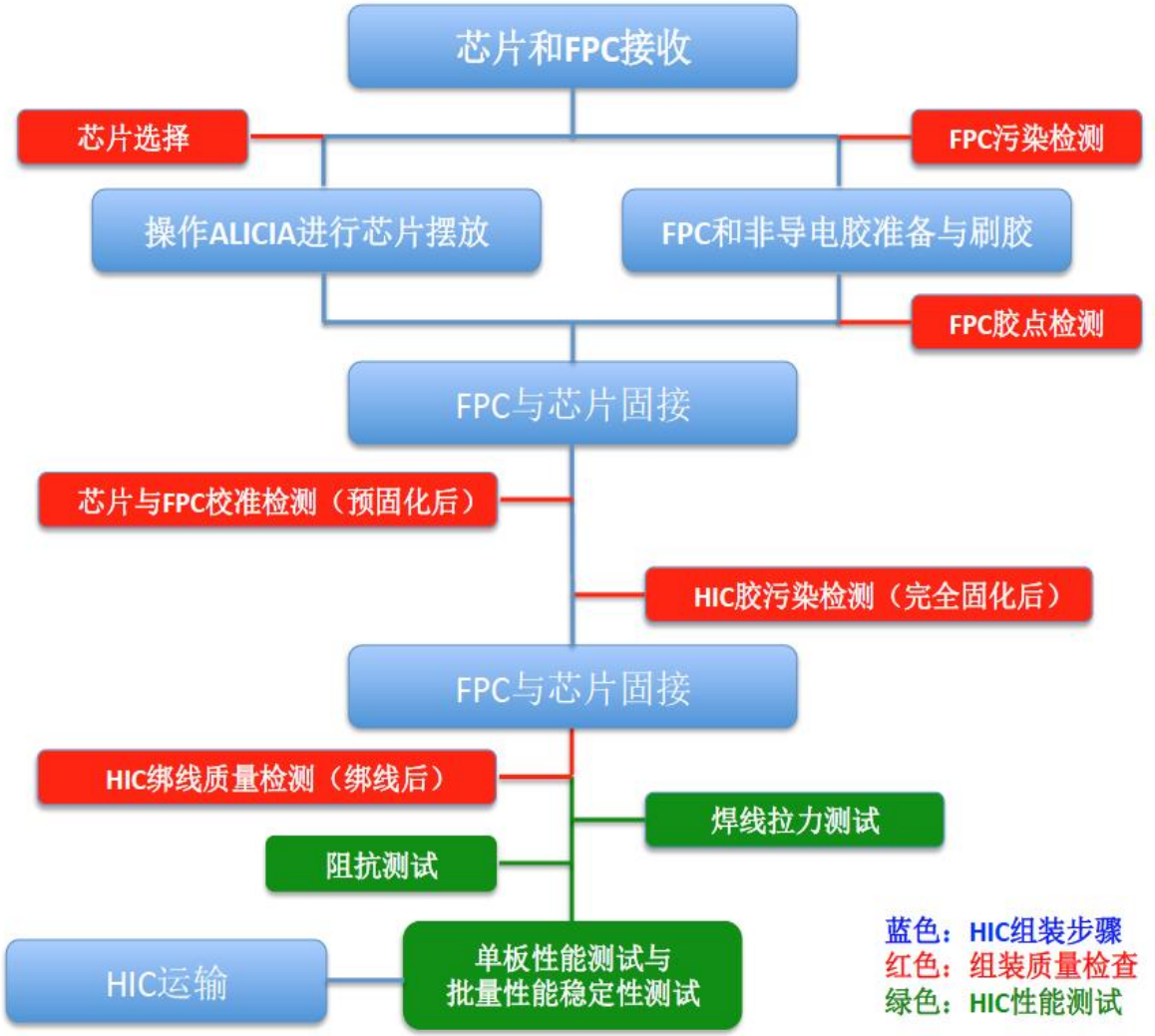


ALICIA

拌胶机

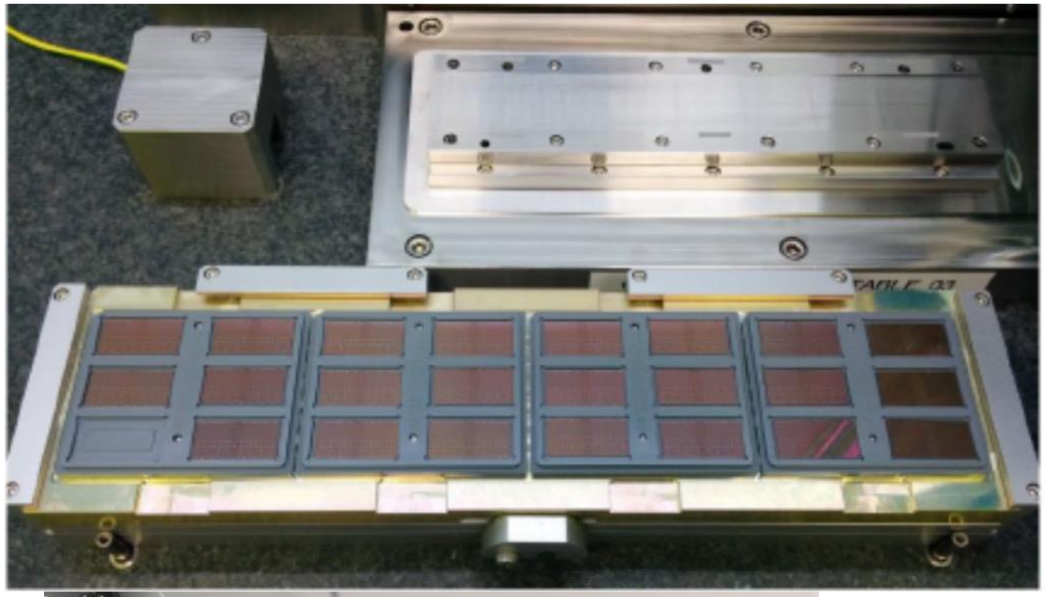
绑线机

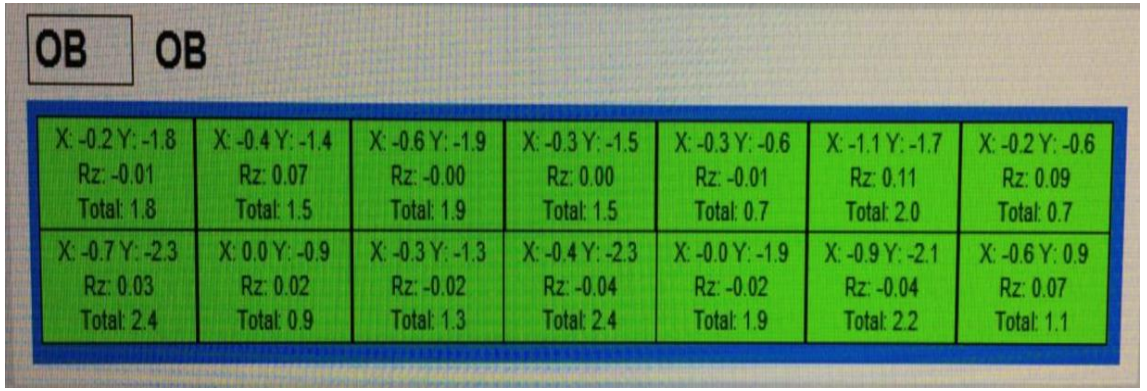
拉力测试机

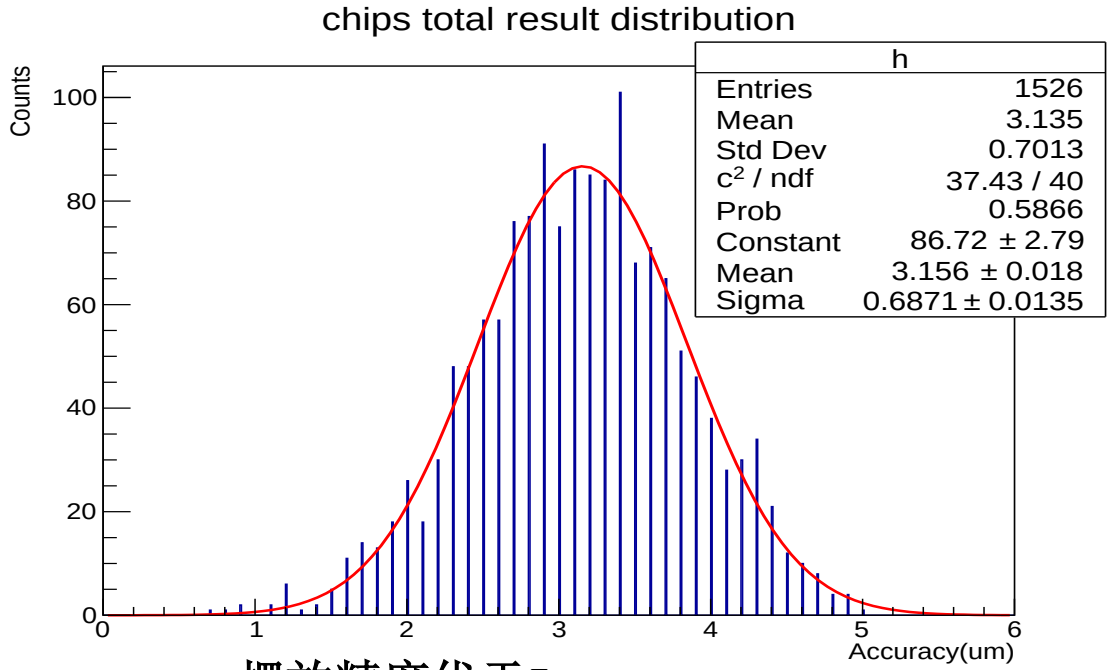


组装+质量检测+性能测试

ALICIA实现芯片自动摆放

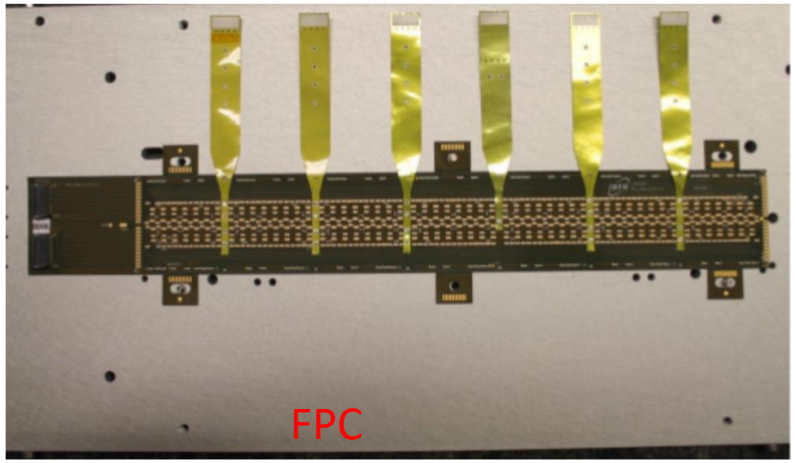


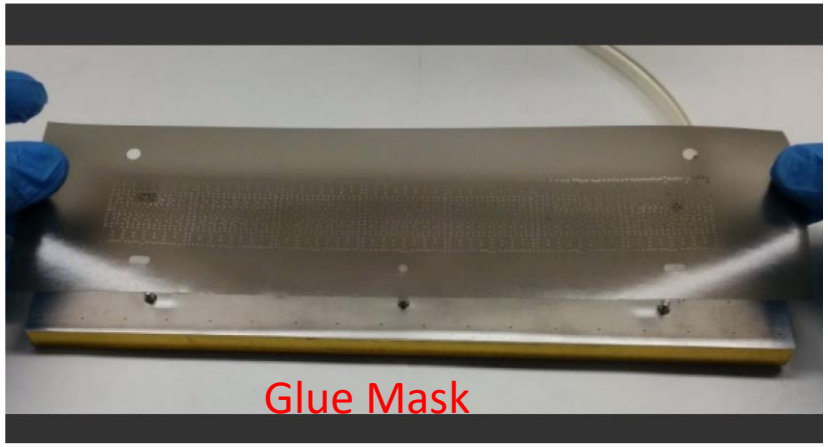


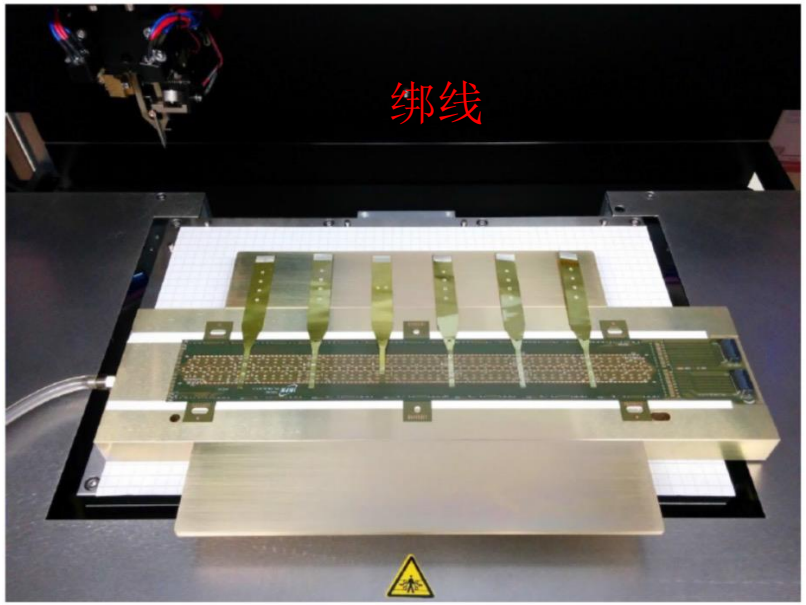


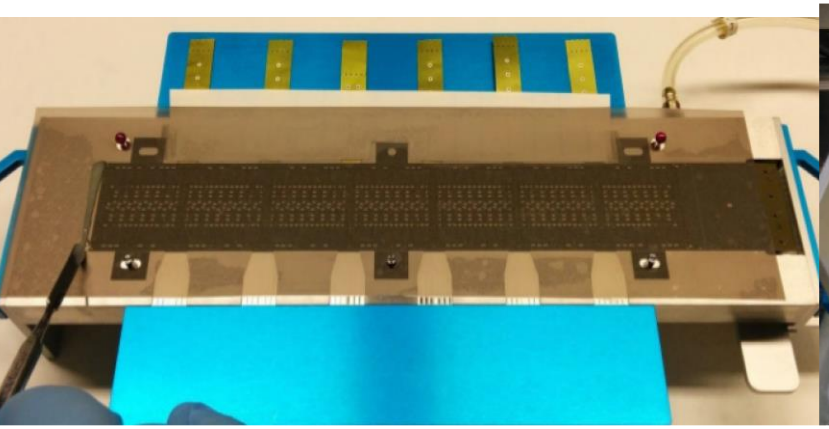
摆放精度优于5 μm

FPC-芯片固接

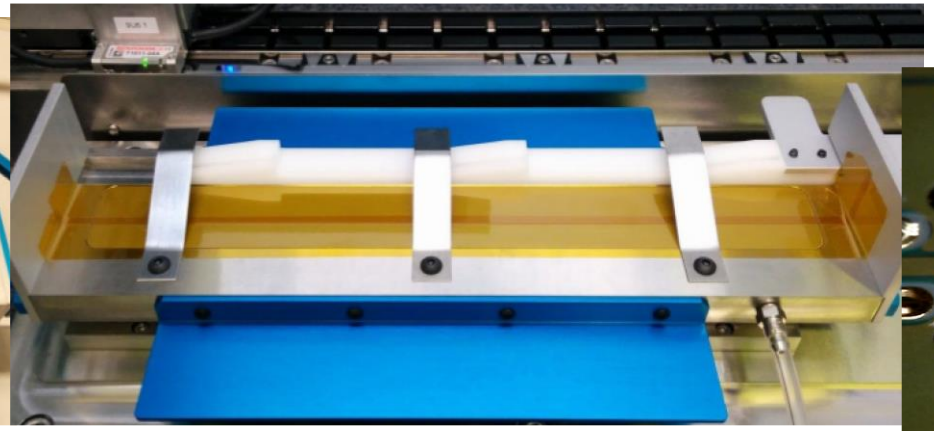




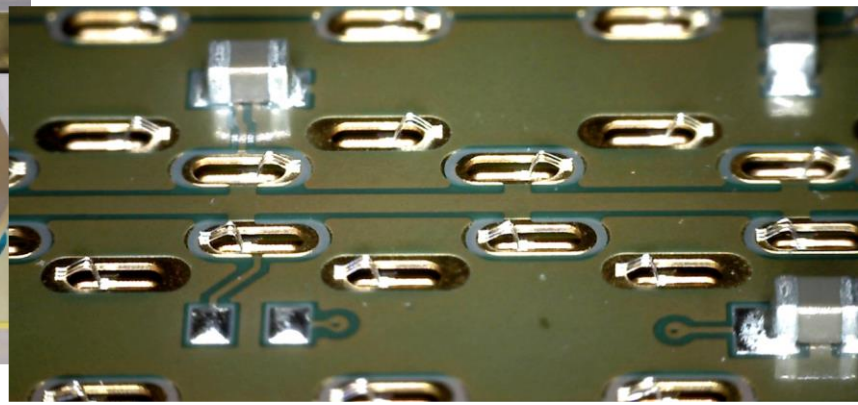




刷胶

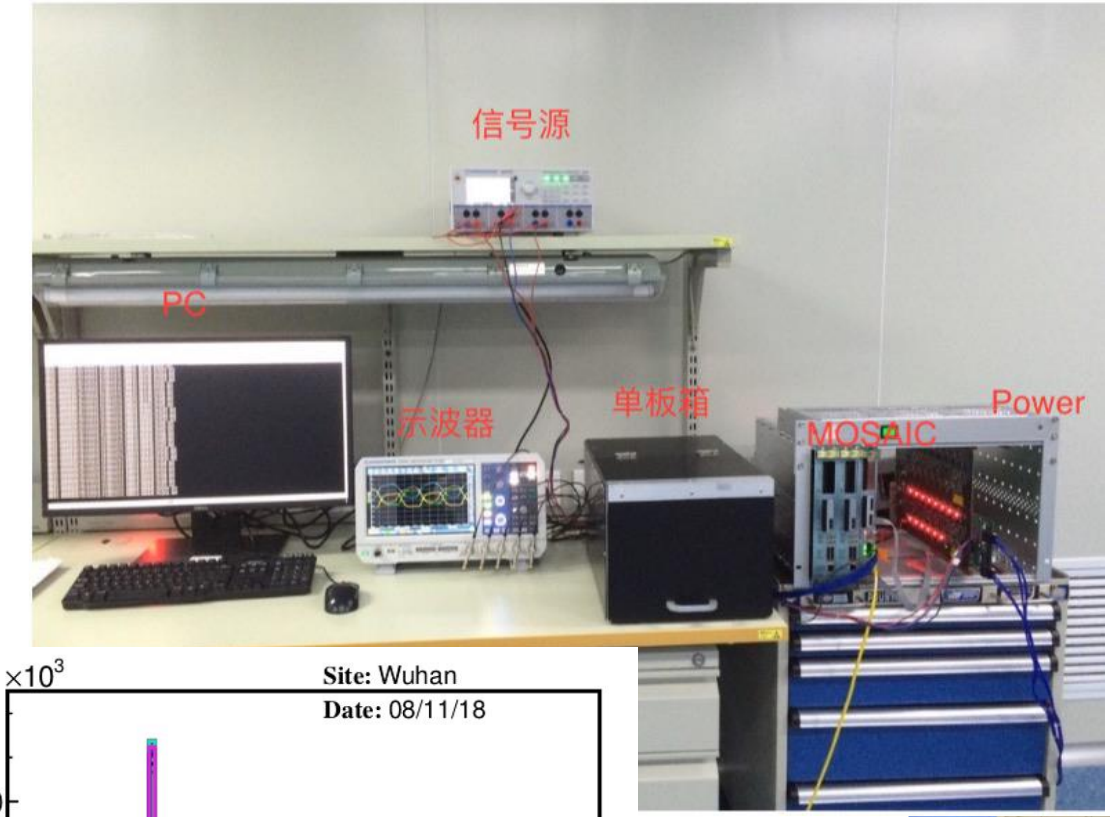


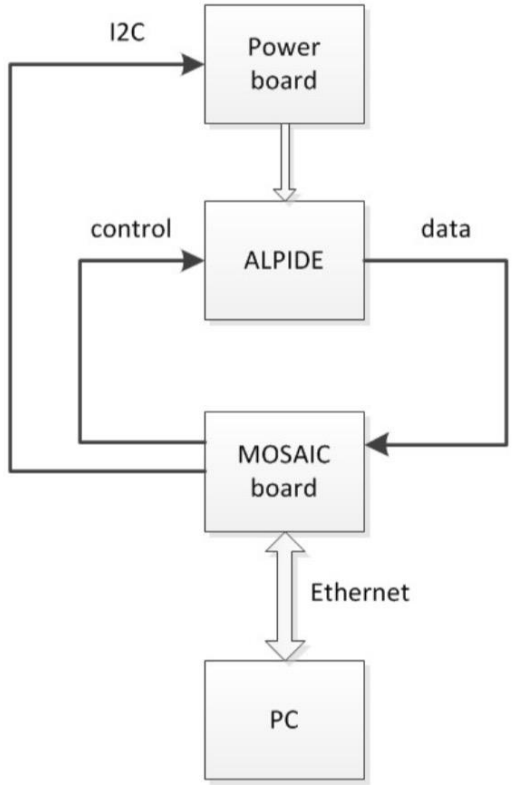
FPC-芯片固接

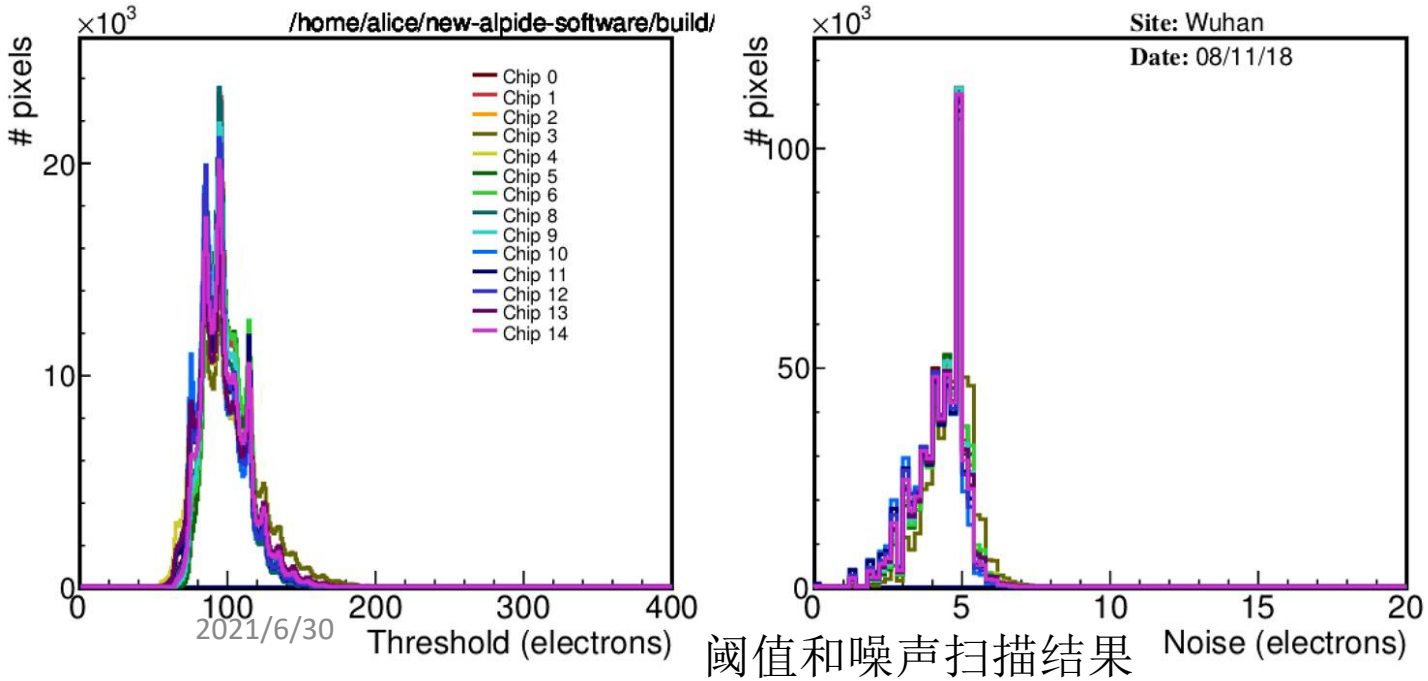


电学测试

- 阻抗测试
- 性能测试
- 耐久测试（10个模块，7天）

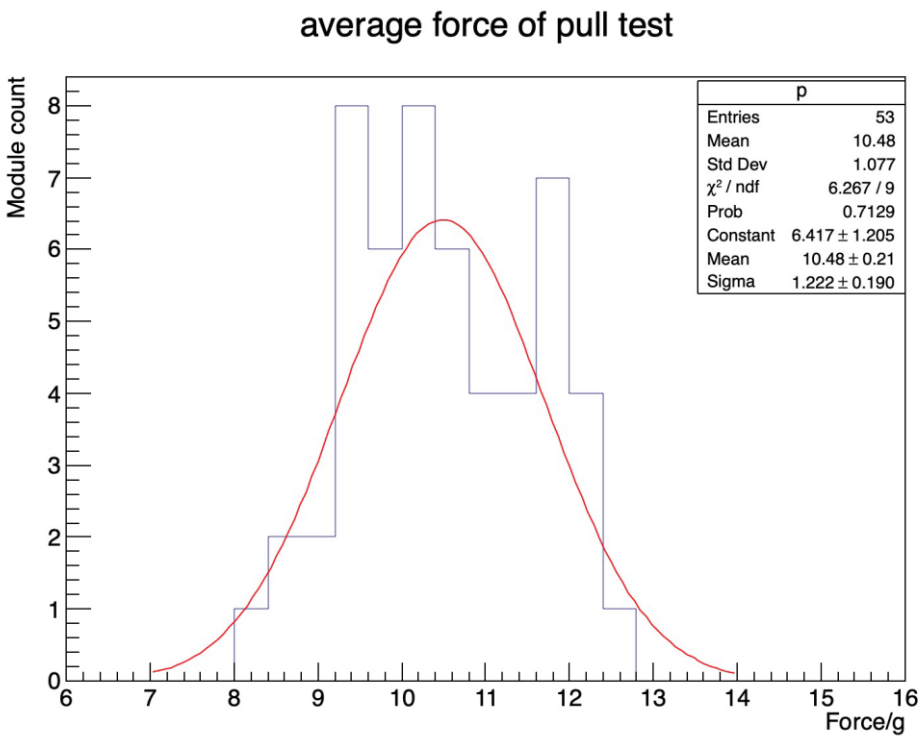


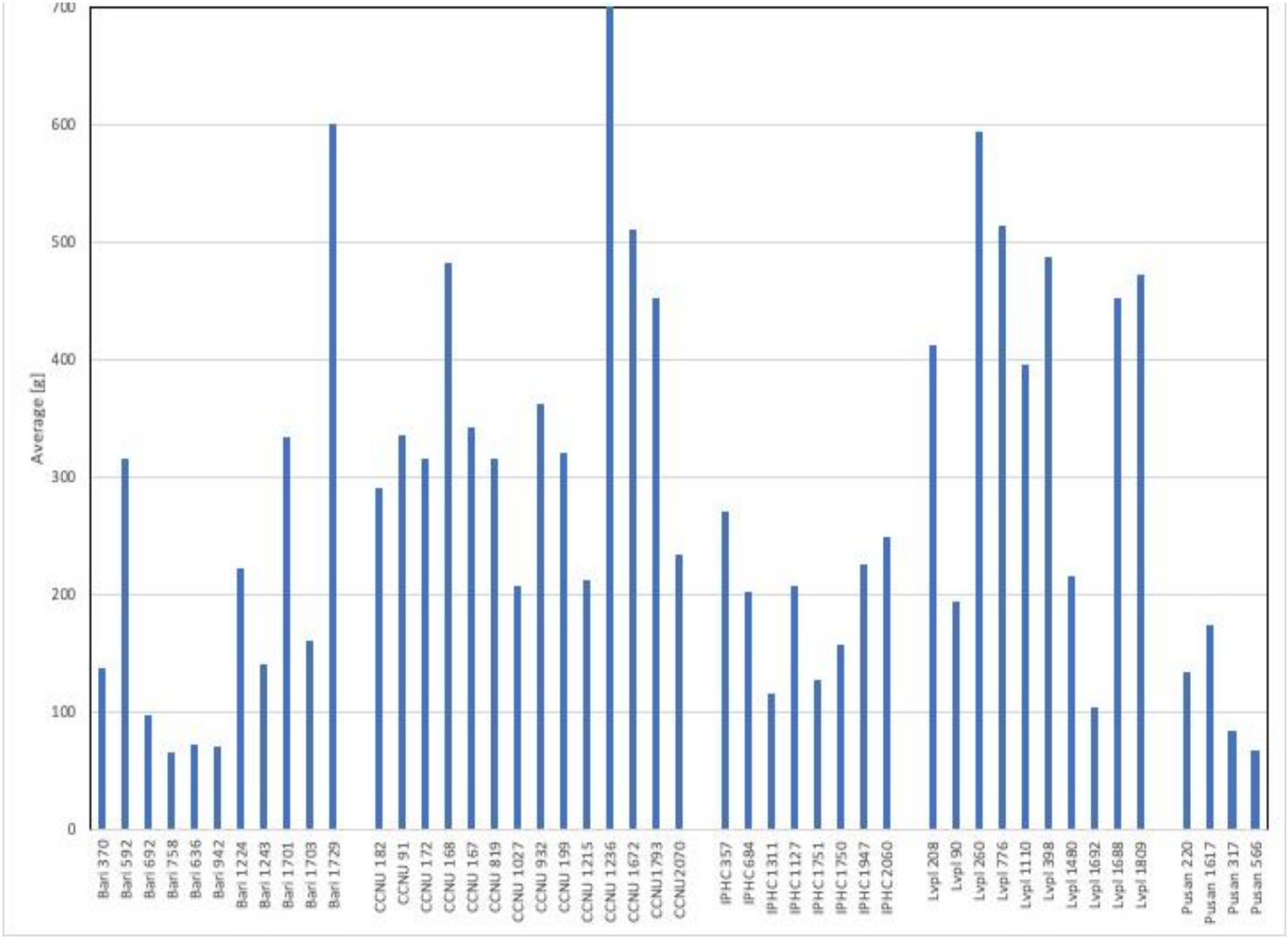




阈值和噪声扫描结果

拉力测试


average force of pull test
Module count
Force/g
p
Entries 53
Mean 10.48
Std Dev 1.077
χ² / ndf 6.267 / 9
Prob 0.7129
Constant 6.417 ± 1.205
Mean 10.48 ± 0.21
Sigma 1.222 ± 0.190

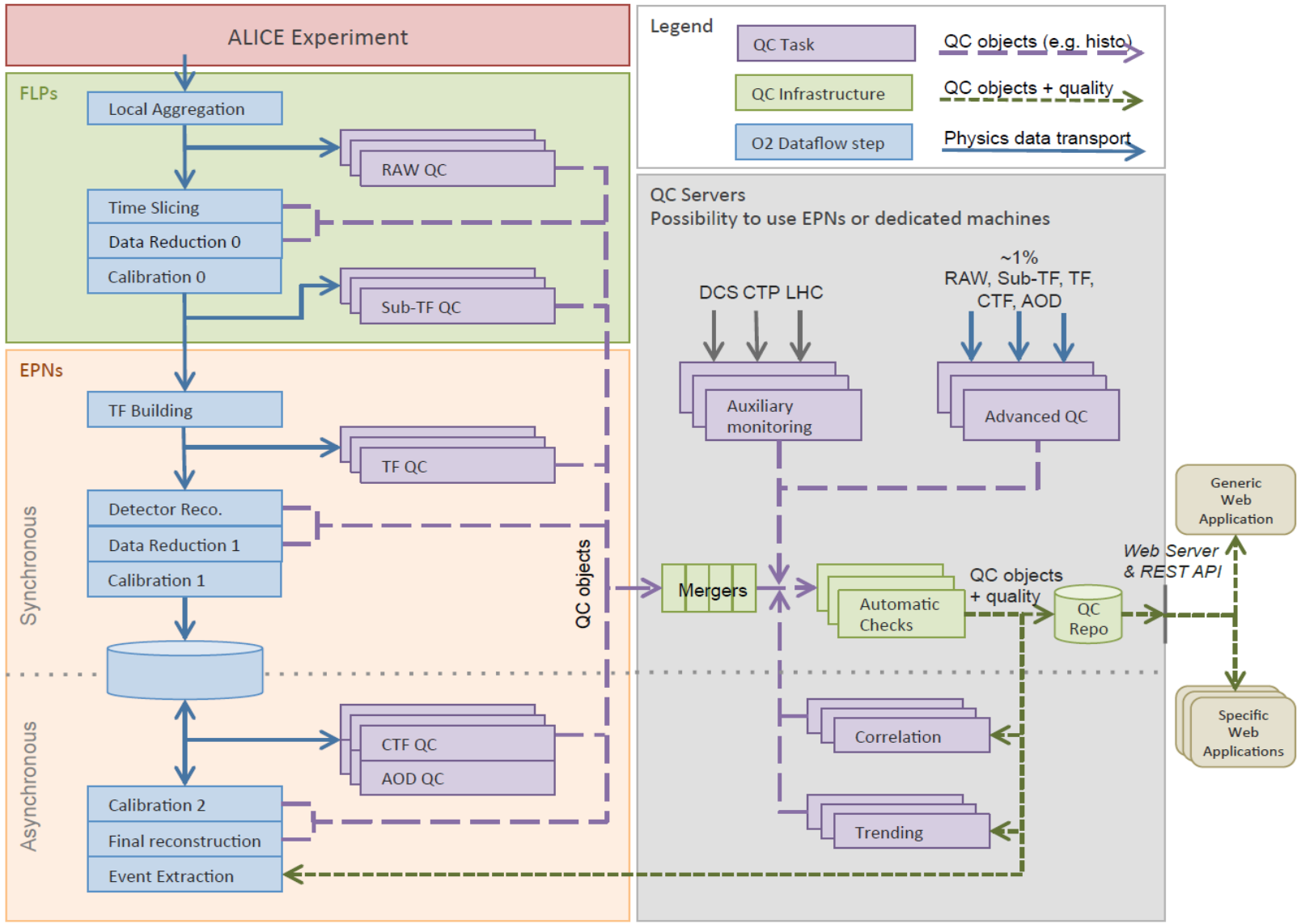

Average [g]
Bari 370
Bari 592
Bari 692
Bari 758
Bari 636
Bari 942
Bari 1224
Bari 1243
Bari 1701
Bari 1703
Bari 1729
CCNU 182
CCNU 91
CCNU 172
CCNU 168
CCNU 167
CCNU 819
CCNU 1027
CCNU 932
CCNU 199
CCNU 1215
CCNU 1236
CCNU 1672
CCNU1793
CCNU2070
IPHC357
IPHC684
IPHC1311
IPHC1127
IPHC1751
IPHC1750
IPHC1947
IPHC2060
Lvpl 208
Lvpl 90
Lvpl 260
Lvpl 776
Lvpl 1110
Lvpl 398
Lvpl 1480
Lvpl 1692
Lvpl 1688
Lvpl 1809
Pusan 220
Pusan 1617
Pusan 317
Pusan 566

参与ITS2试运行

- 读出链路测试
  - RU组装与测试
- 质量控制系统开发

数据质量控制系统

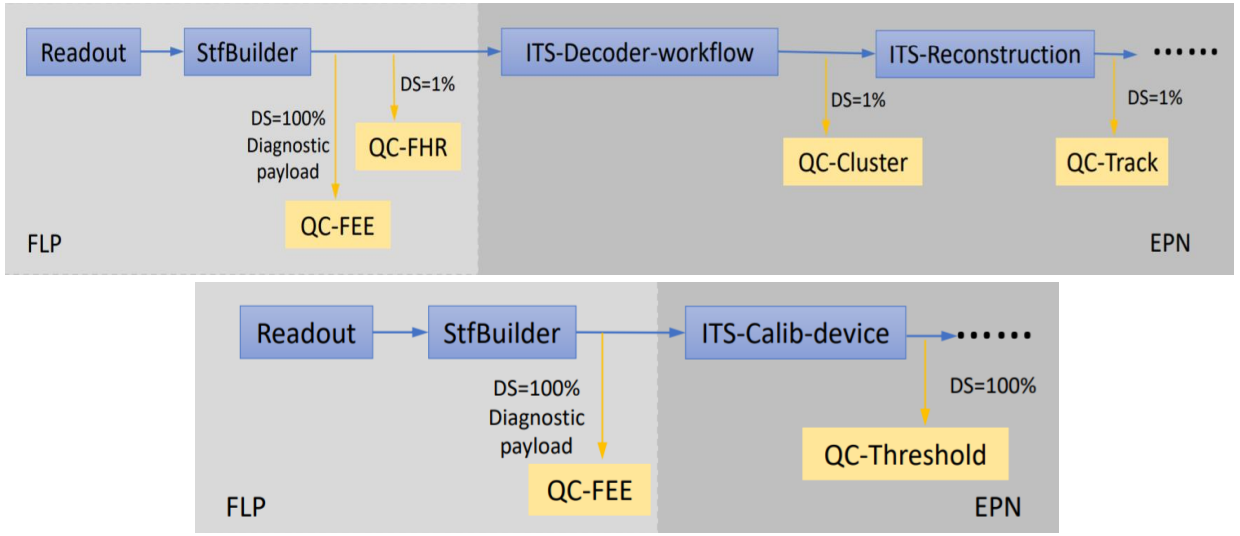
- 包含**Online**的数据质量监控和**Offline**数据质量检查
- 快速识别问题，以为物理分析提供高质量的数据
- 保证校准和重建的行为符合预期，尤其是在与数据采集同步运行



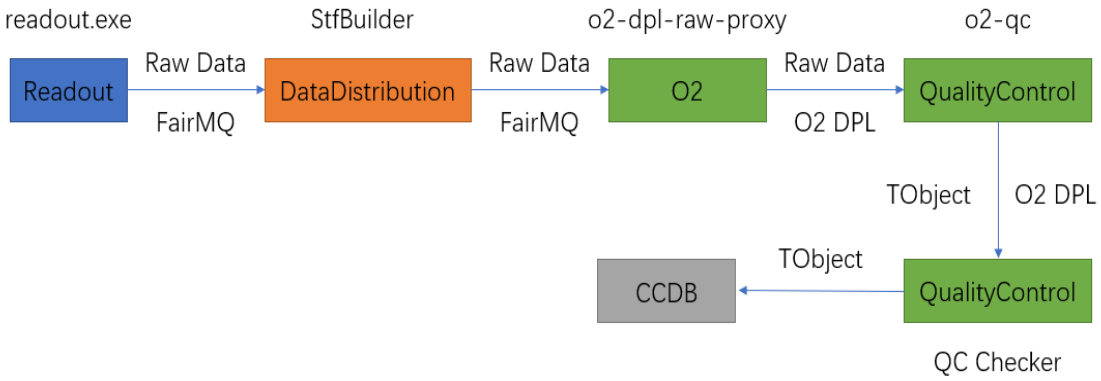
ALICE QC结构图

ITS2 质量控制模块开发

- ITS QC模块分为：Fake-hit rate（FHR）、Threshold、Cluster、Track、FEE及其相应的Post-Processing。
- FHR 负责监控探测器的假命中率，找出高噪像素道（noisy pixels）等工作。
- Threshold负责监控像素的阈值以及噪声，找出死像素道（dead pixels）等工作。
- Cluster负责监控簇团（cluster）的大小、以及其拓扑结构等工作。
- Track负责监控径迹（track）的数量、及其角度分布等工作。
- FEE负责验证100%的诊断有效载荷（diagnostic payload）。
- 相应的在线和离线的post-processing负责监控所感兴趣的量随着时间（或者试运行阶段的run number）的变化

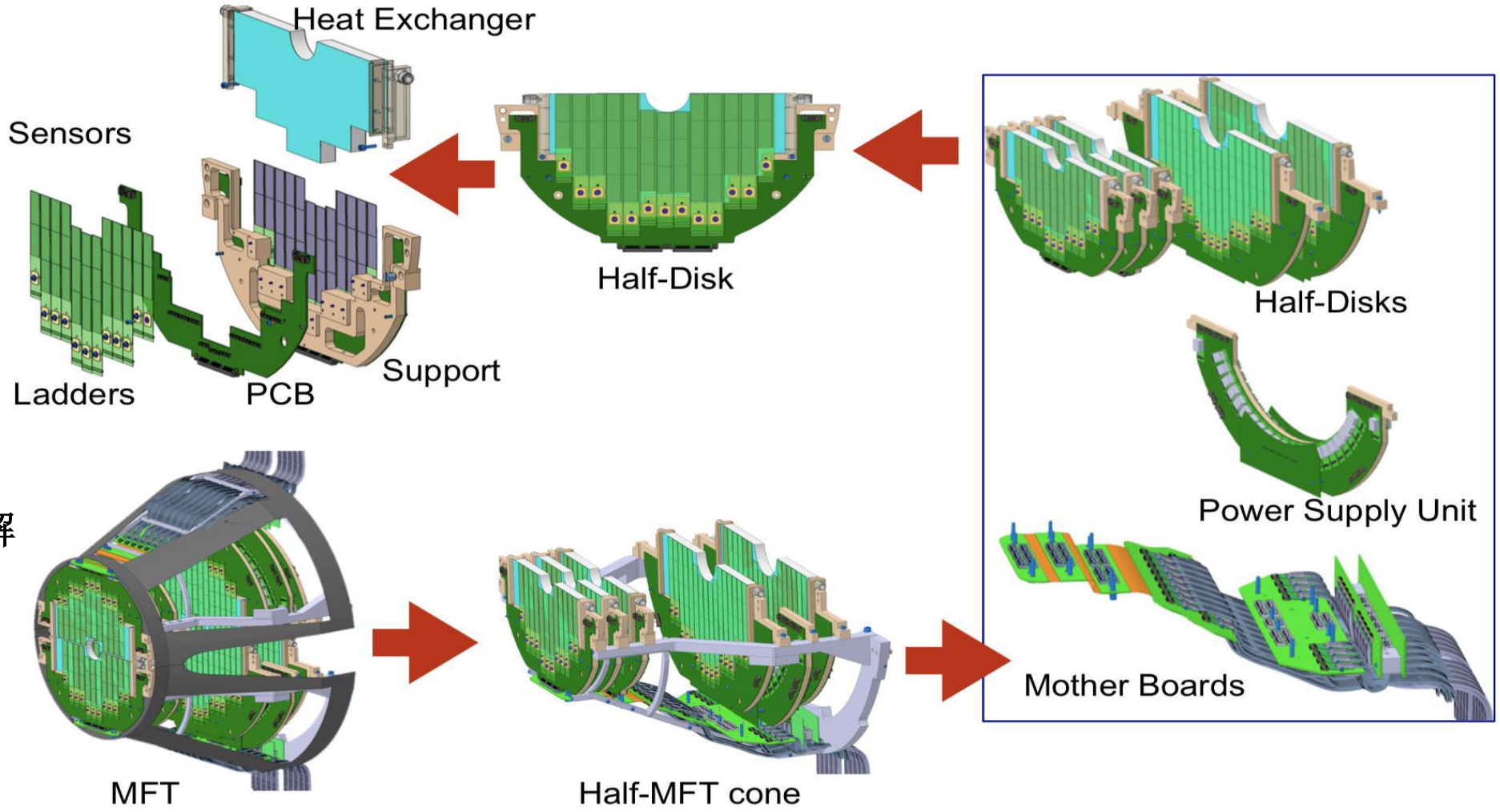


ITS QC运行结构框图



QC FHR在线工作流程

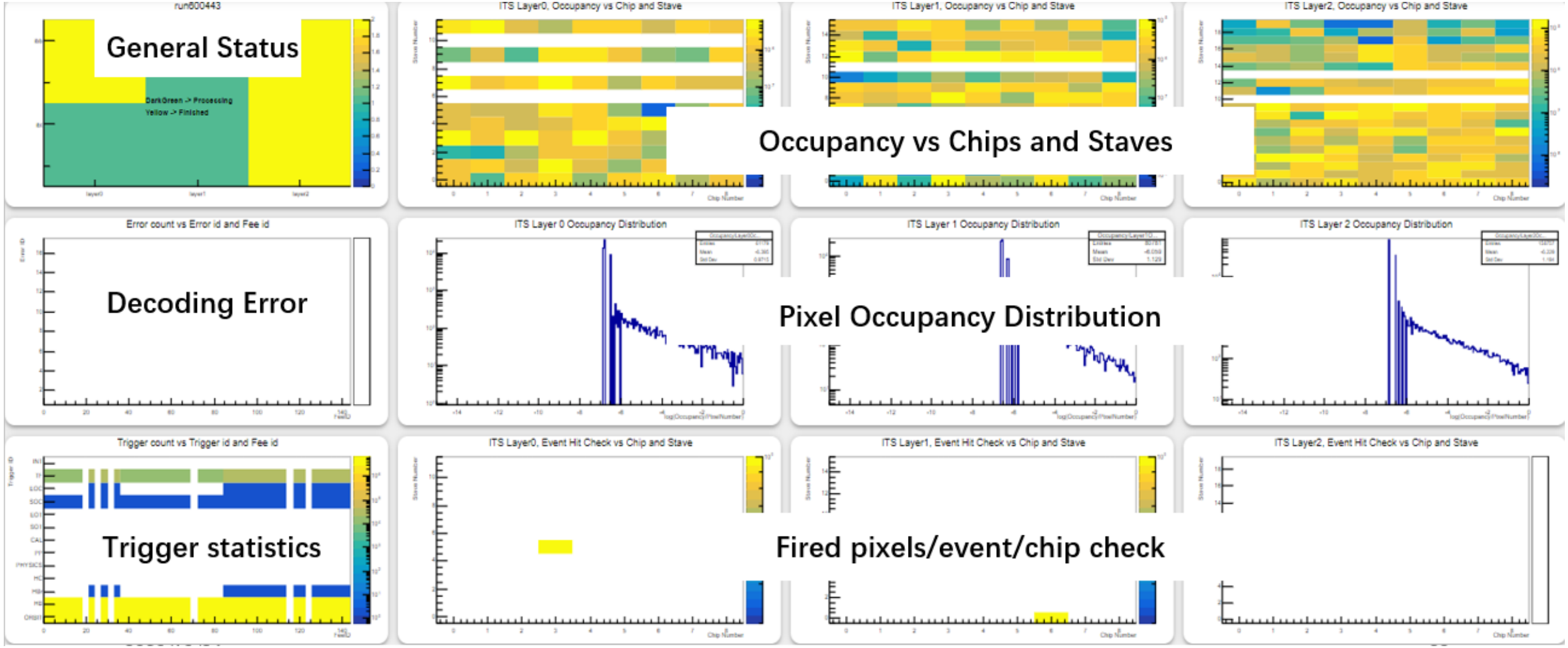
MTF读出链路板研制



MFT构造分解

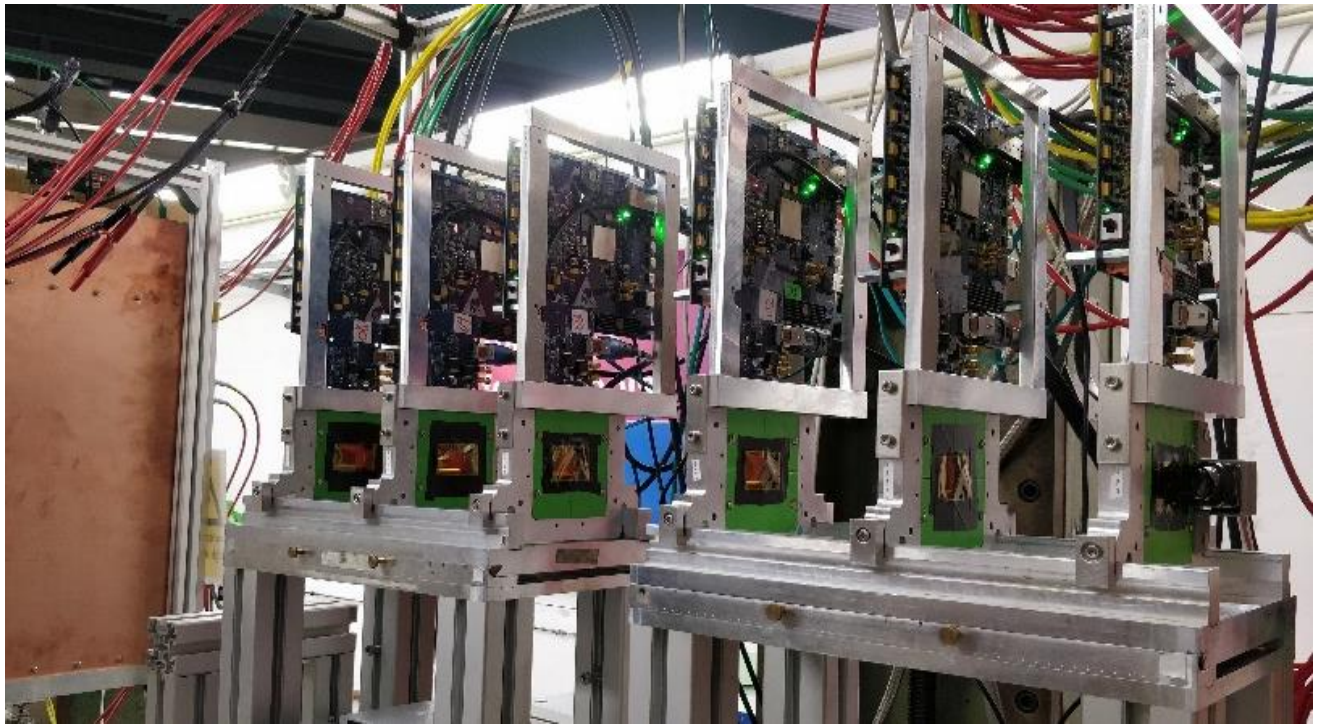
- 承担5个Disk的链路板的研制任务
- 2019年完成

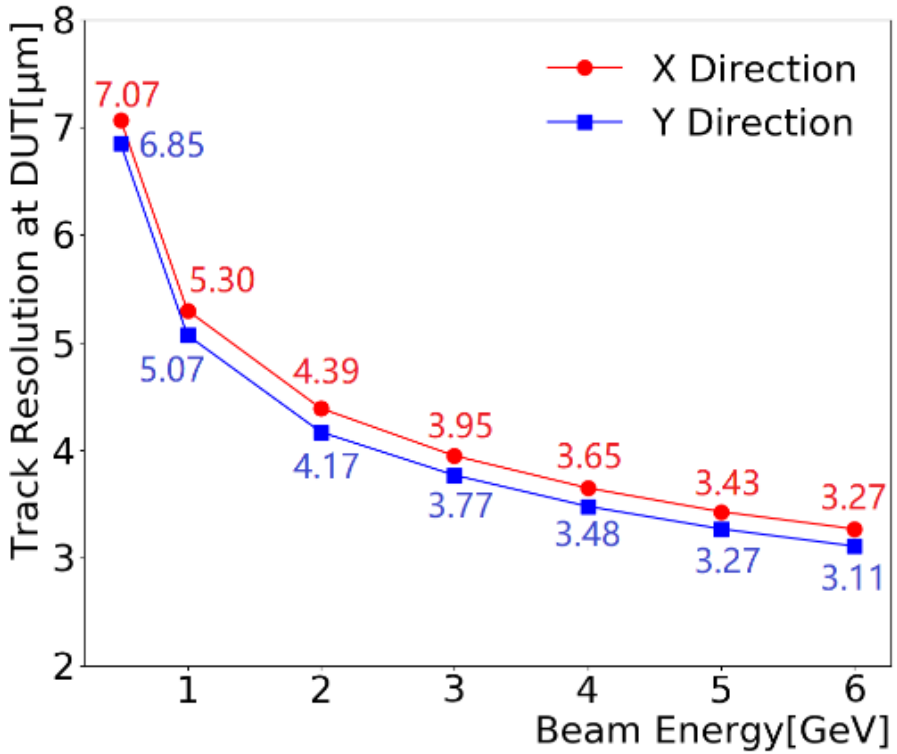
QC运行结果


General Status
DarkGreen -> Processing
Yellow -> Finished
Occupancy vs Chips and Staves
Decoding Error
Pixel Occupancy Distribution
Trigger statistics
Fired pixels/event/chip check

基于ALPIDE应用研究

- 合作研制基于ALPIDE芯片的束流望远镜



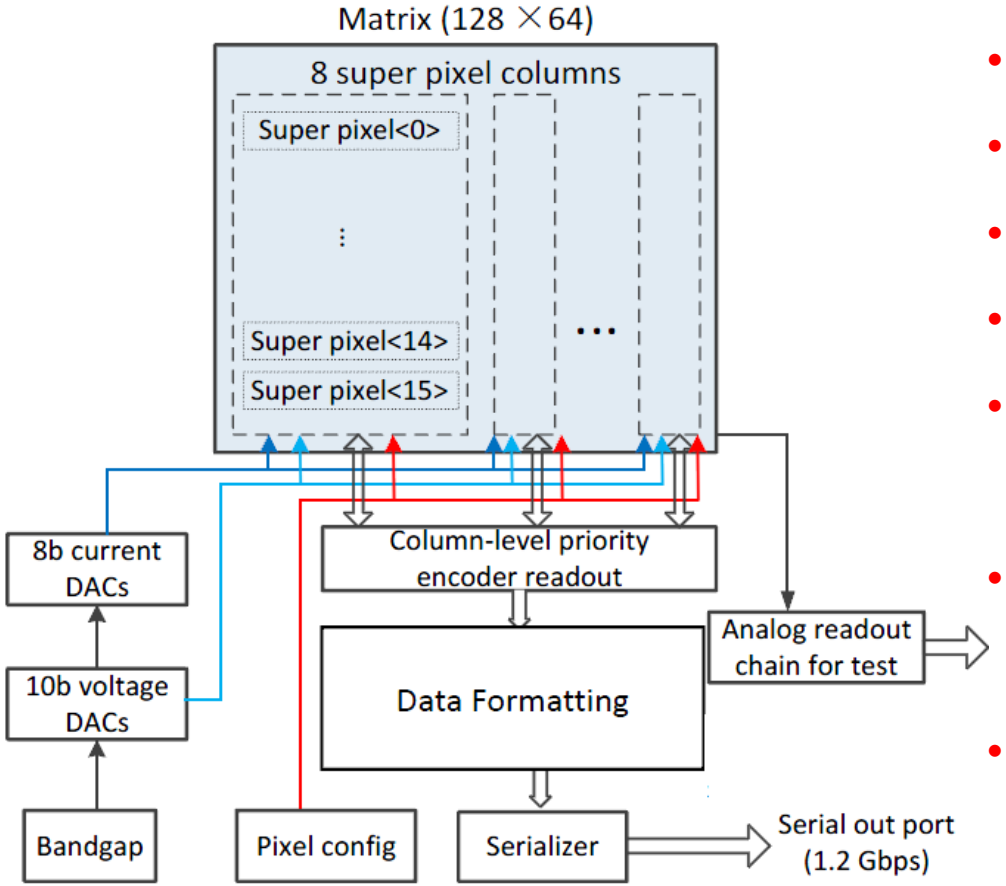


- 已研制完成第一版新型的望远镜原型系统，2019年成功开展了三次束流实验

实测结果：**径迹分辨可达3.3um**；与DESY原有系统相比，**触发率提高20倍，噪声降低百万倍**

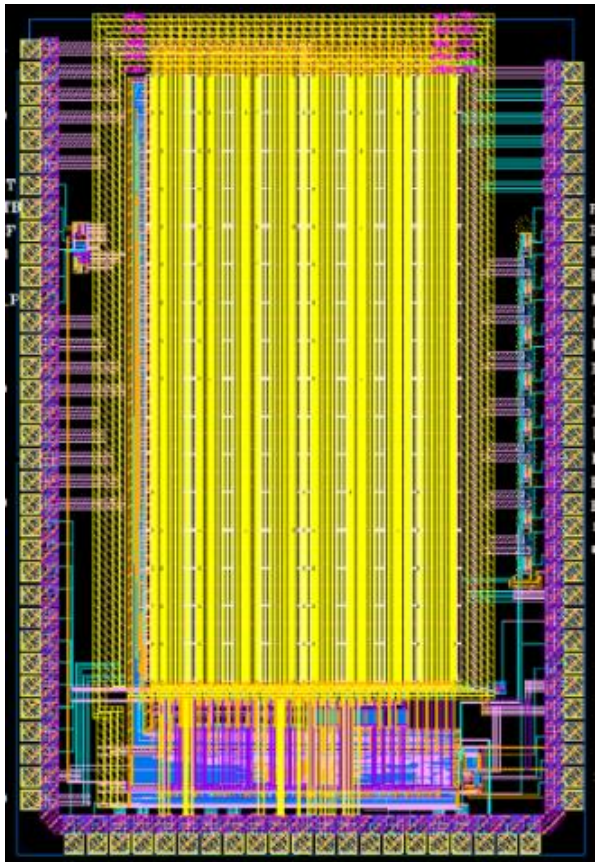
基于MAPS技术硅像素芯片研发

- 参与ALICE硅像素探测器升级后，利用所掌握的芯片设计技术在国内研发设计了一款新的非零压缩读出模式的单片像素传感器芯片（MIC4）。



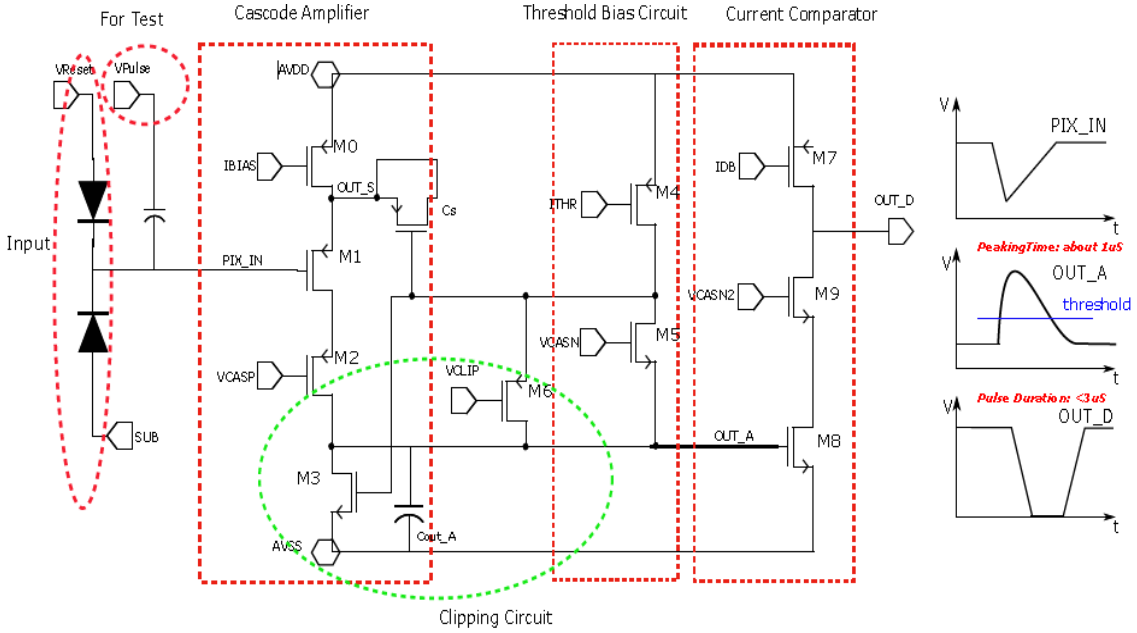
框图

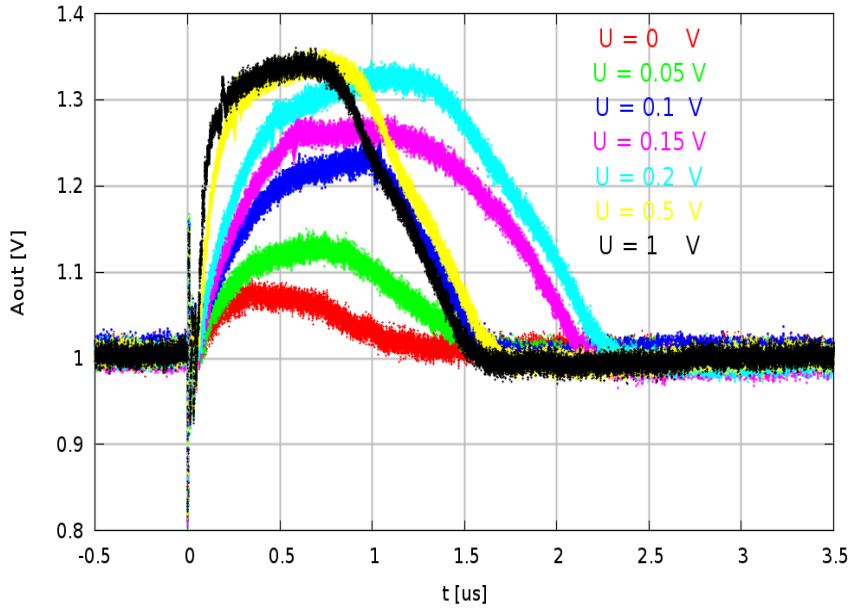
- 像素大小: 25 um x 25 um
- 像素阵列: 128 rows x 64 columns
- 两个不同的前端
- 零抑制读出-> 读出时间为几微秒
- 电压DAC和电流DAC为像素阵列提供合适的偏置
- 数字外围没有存储器，实时读出，串行读出率达 1.2 Gbps
- 阵列底部包括模拟读出测试链，只有最后一行像素由列控制器进行模拟输出测试



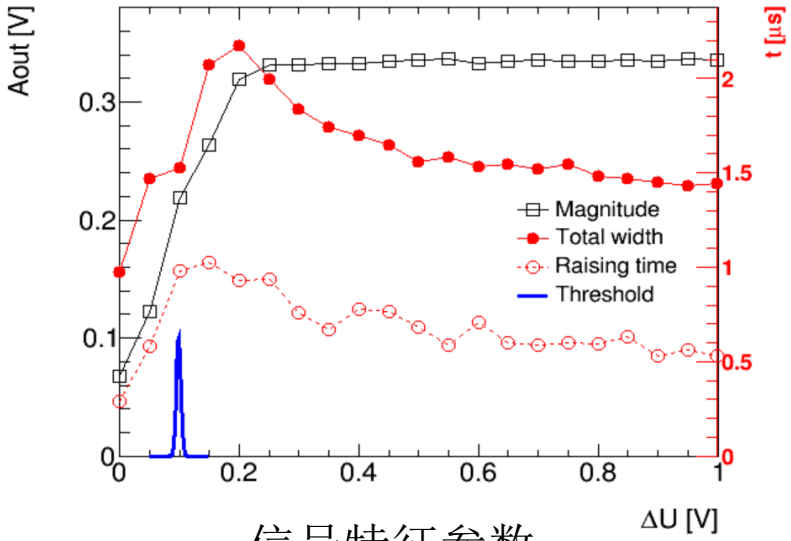
版图

MIC4 PIXEL数字前端设计





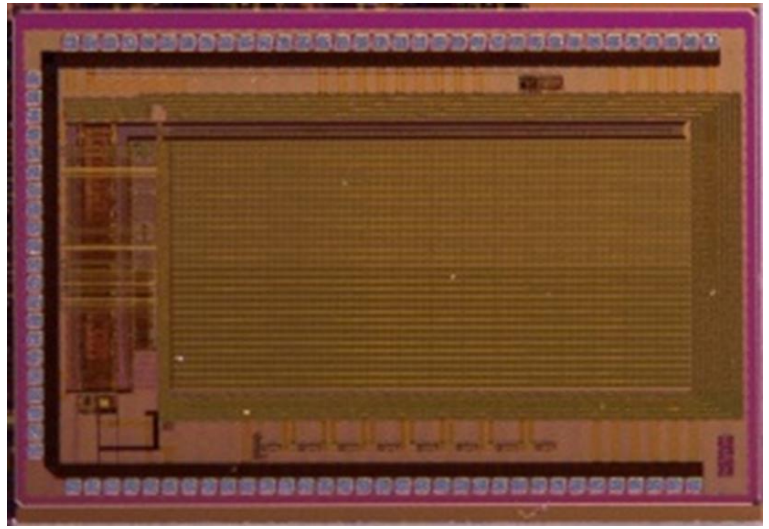
不同Vpulse输入时模拟输出波形



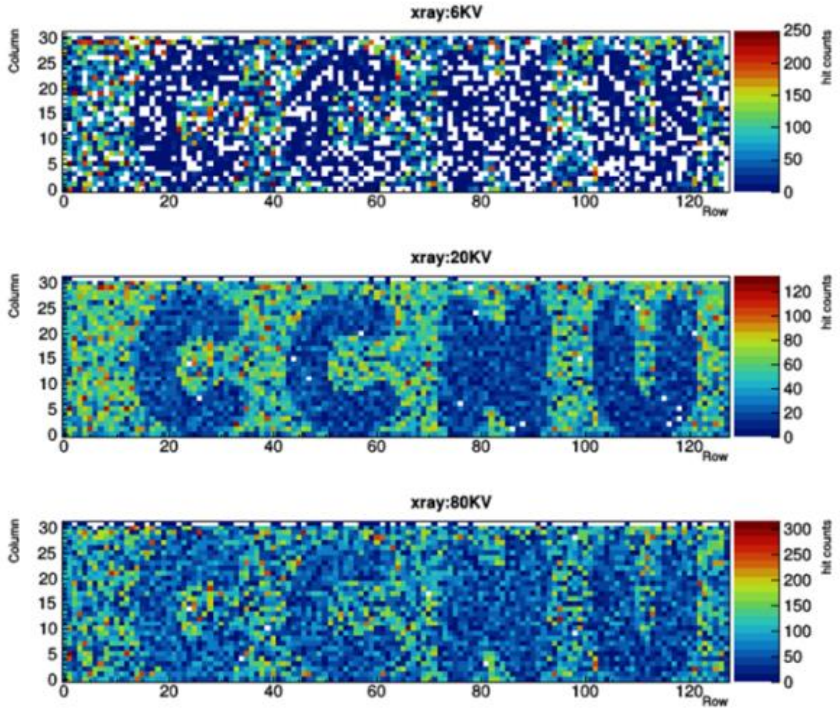
信号特征参数

- 采用与ALPIDE相同的前端结构，功耗: 110 nW/pixel
- 峰值时间为1 µs，甄别脉冲的脉宽时间为3 µs
- 平均阈值为99 e^-
- 噪声平均为：固有噪声（FPN） ~ 31 e^-，瞬态噪声（TN） ~ 6 e^-

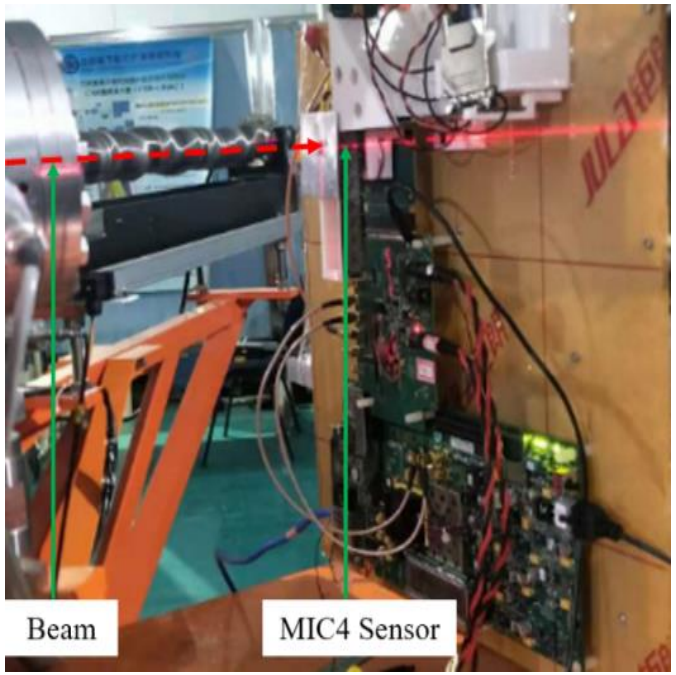
MIC4测试



3.2 × 3.7 mm^2



X射线测试



束流测试设置

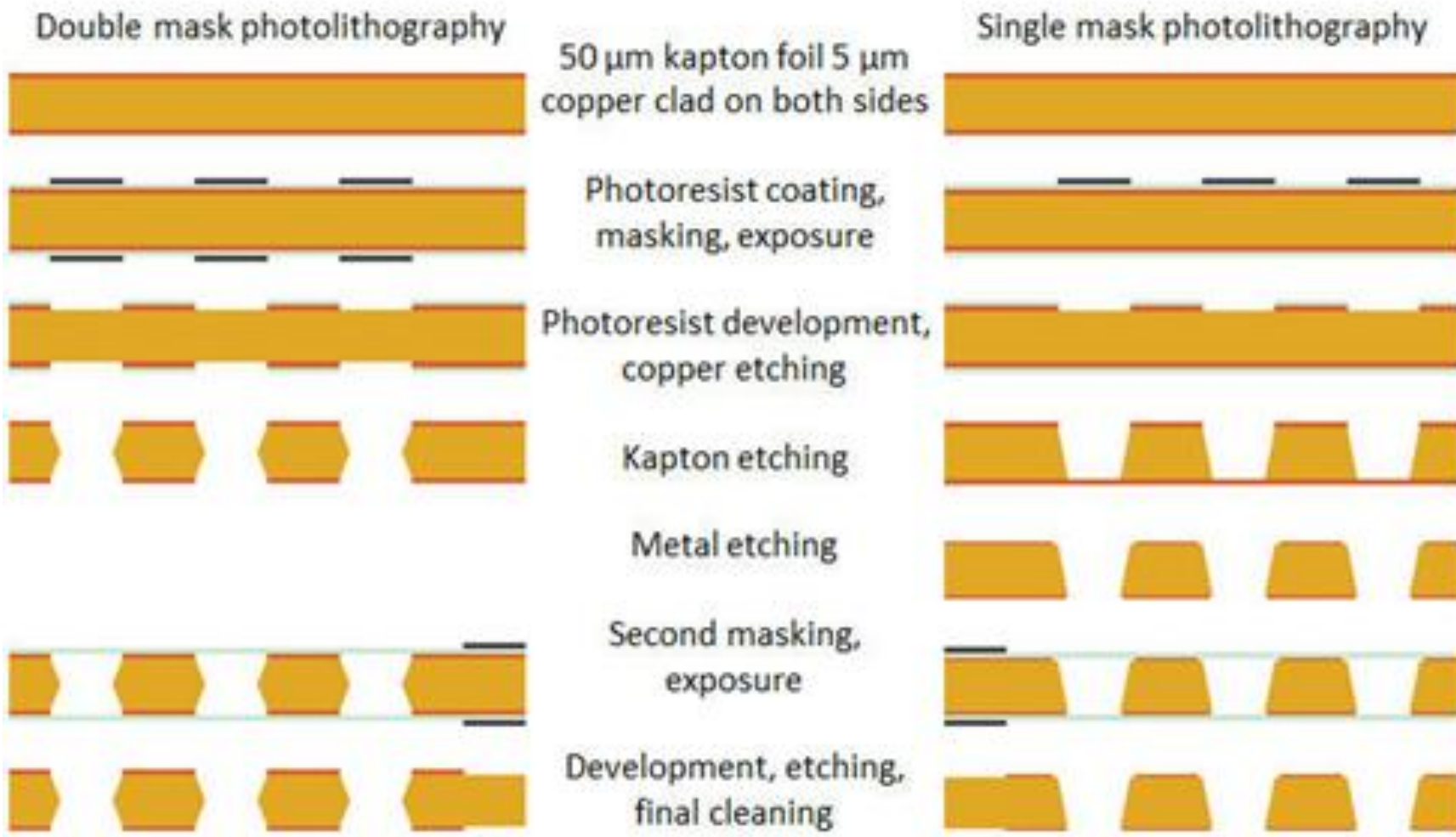
束流测试正在进行中……

- 外延层厚度为18 µm
- 芯片厚 ~700 µm
- 当LET为20.05 MeV cm^2/mg时，

$\sigma_{SEL} = 1.02 \times 10^{-6}$

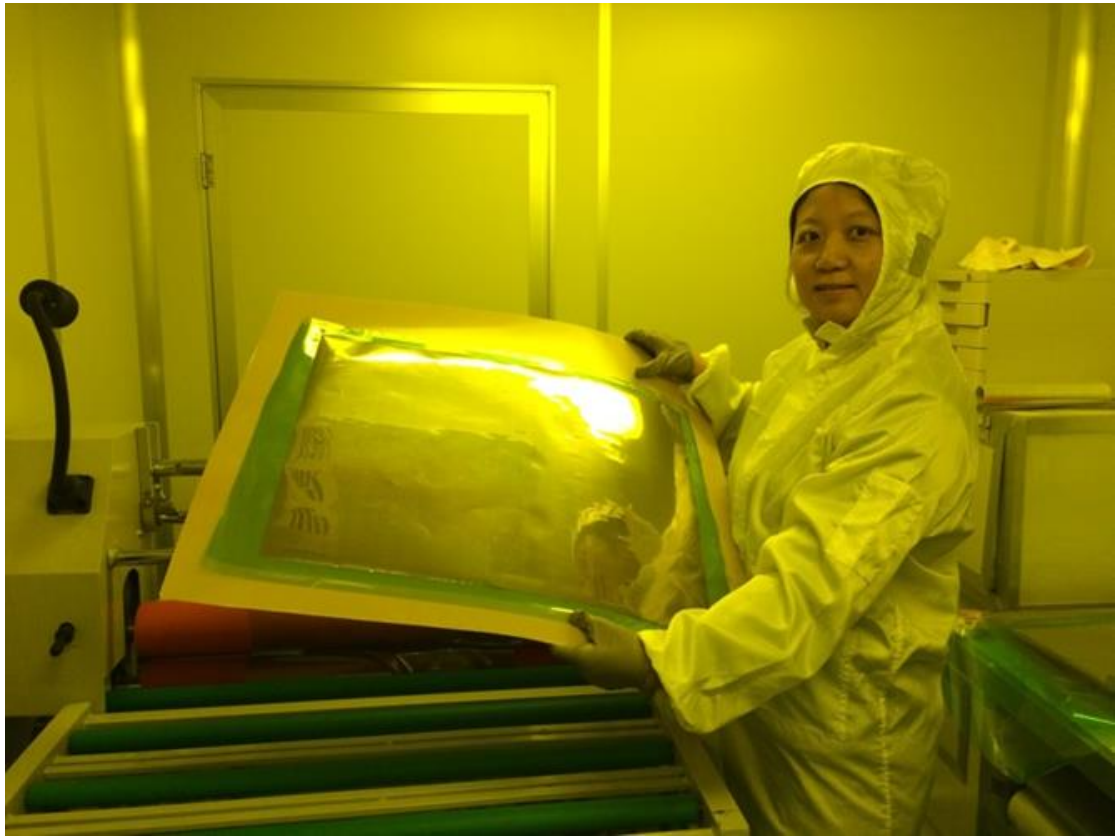
GEM膜研制

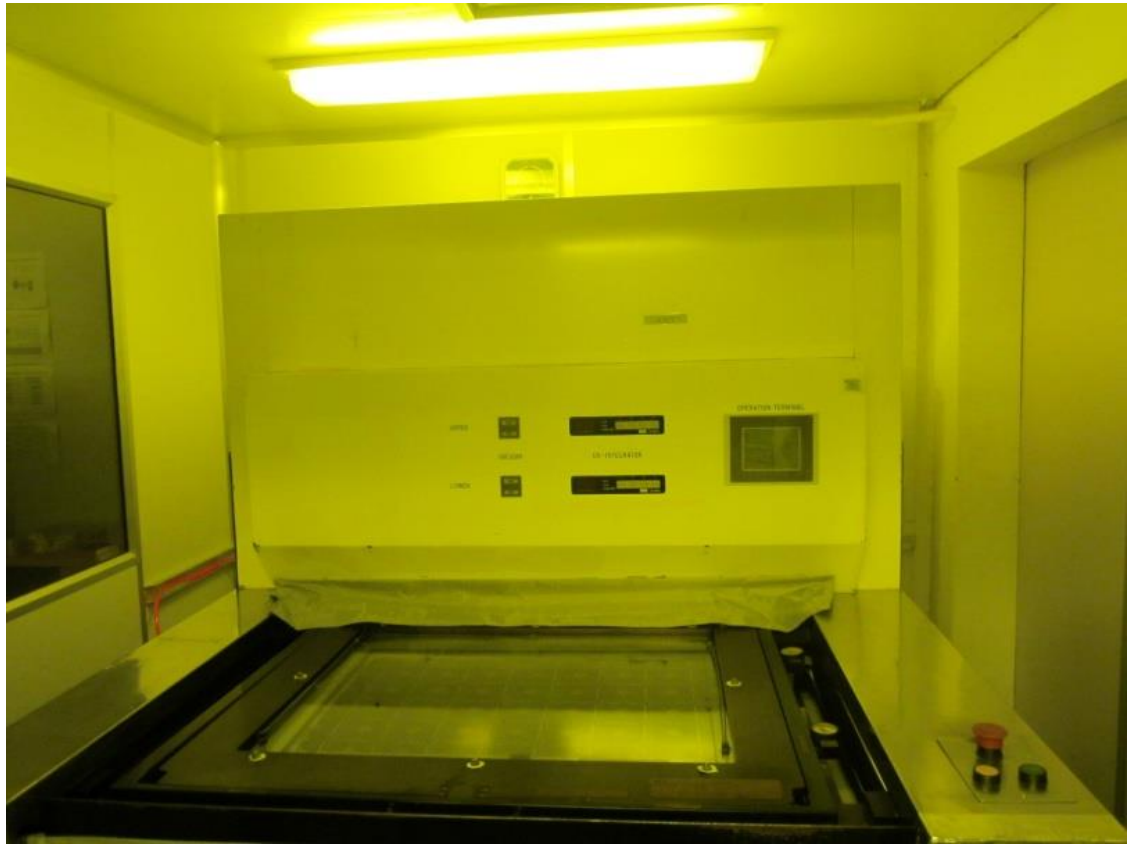
- 通过与CERN合作，掌握了制作大面积GEM膜的关键技术
- GEM膜制作的流程，包括光刻胶层压、掩膜、光刻、酸刻、碱刻、清洗、钝化和测试等步骤
- 在两项新技术和新方法上有所突破，即大面积双面自动覆膜技术和曝光机对焦系统自动化改造方法



GEM膜制作流程

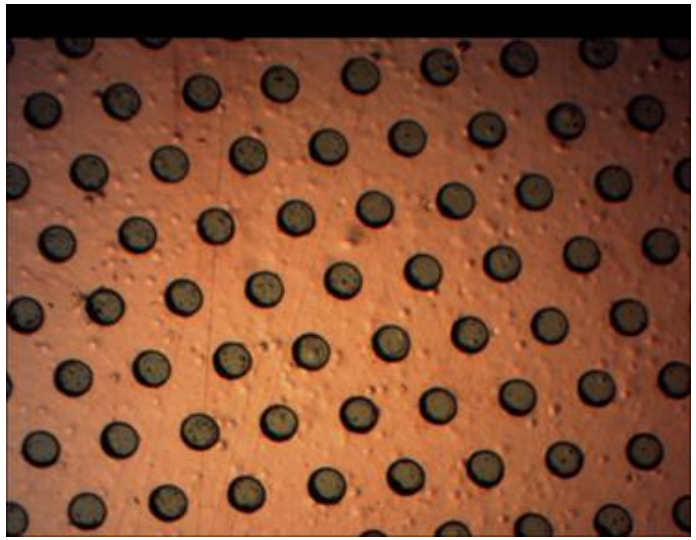
干膜光刻胶的层压与曝光

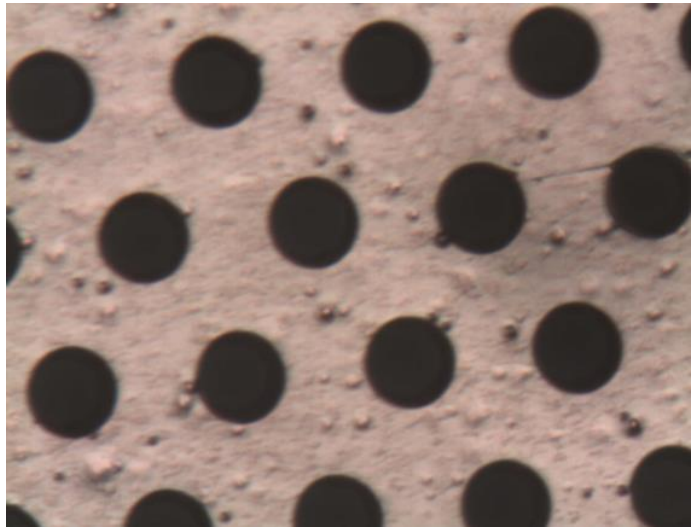




- 干膜光刻胶的层压与曝光是决定GEM膜生产成败的至关重要的一步
- 原子能院建立了一个黄光区，引入了热轧层压机和曝光系统

50x50 cm^2大面积GEM膜

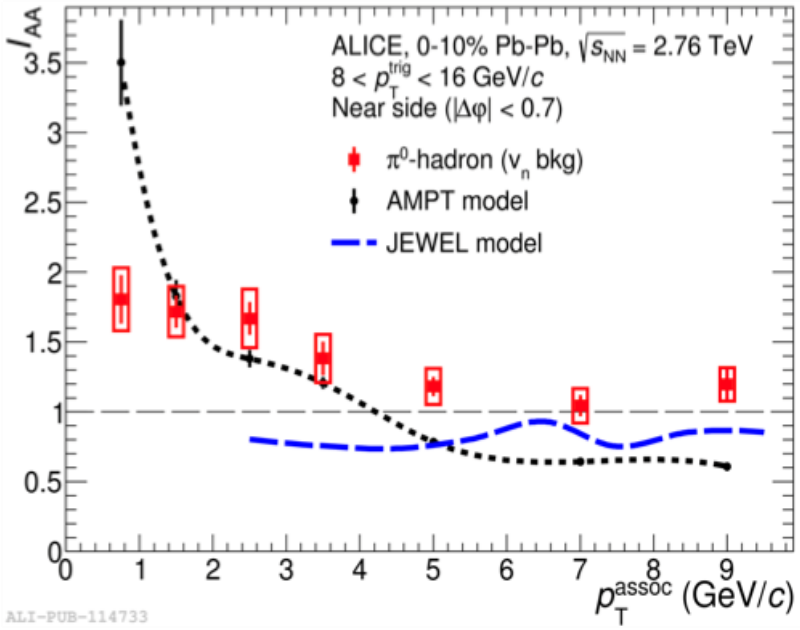


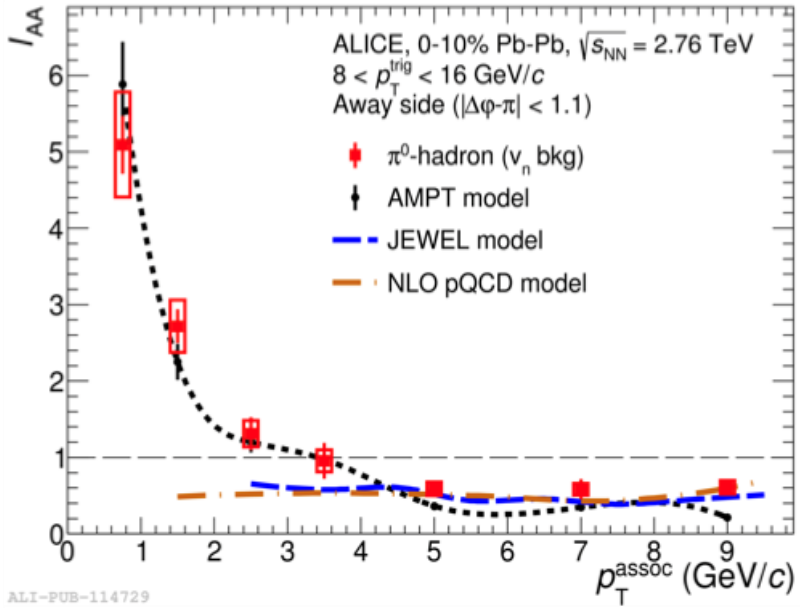


- 利用单面掩模技术成功研制出50x50 cm^2大面积GEM膜

喷注与热密物质相互作用效应

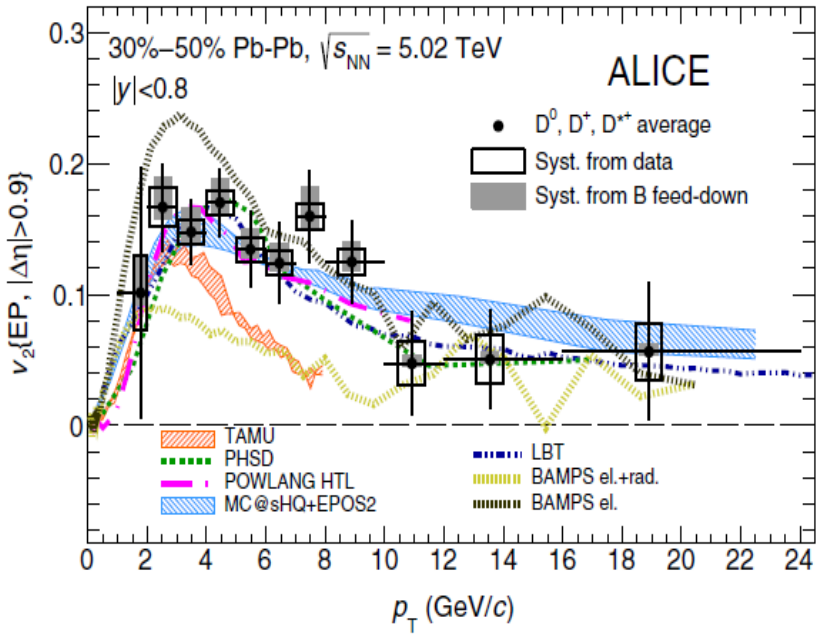
Phys. Lett. B763 (2016) 238





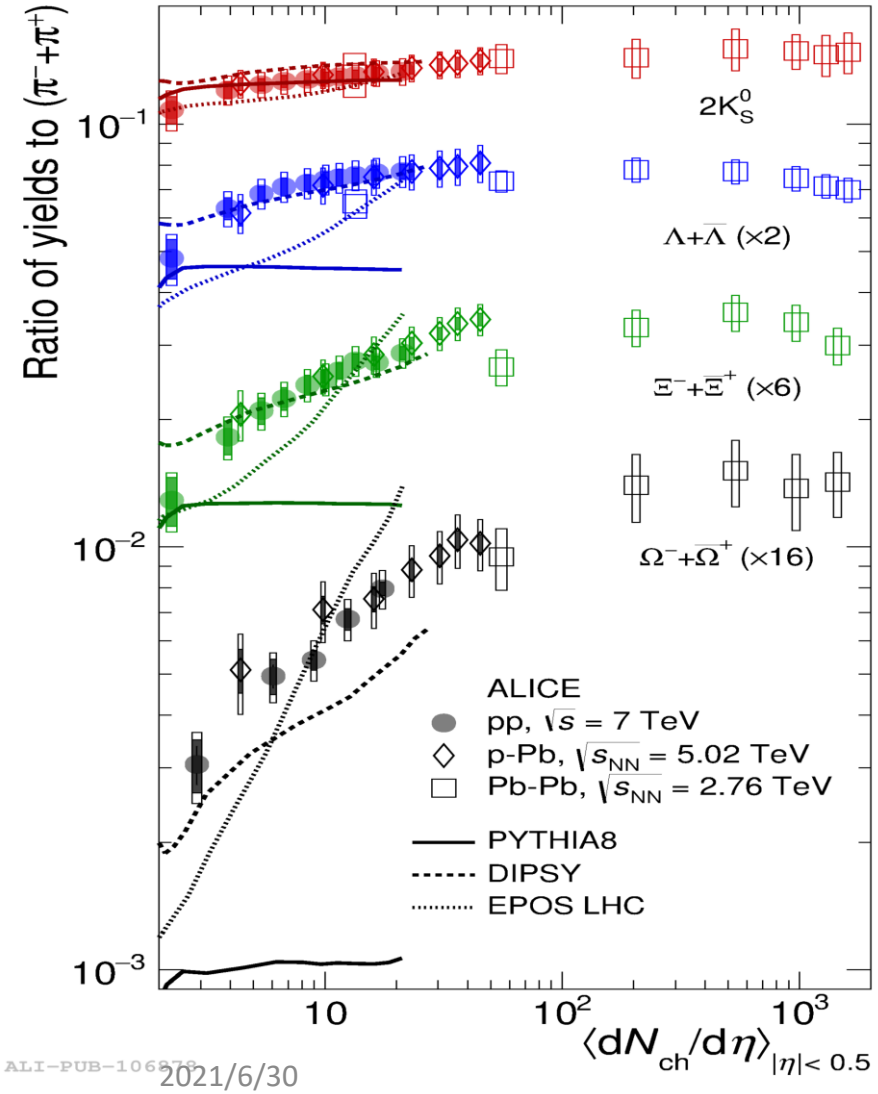
- 低横动量区域关联产额显著增强，体现了由介质效应软化的碎裂方程或介质激发效应
- 背侧高横动量关联强子产额存在明显压低，表明初始硬部分子因与热密物质发生相互作用而损失了能量

Phys. Rev. Lett. 120 (2018) 102301



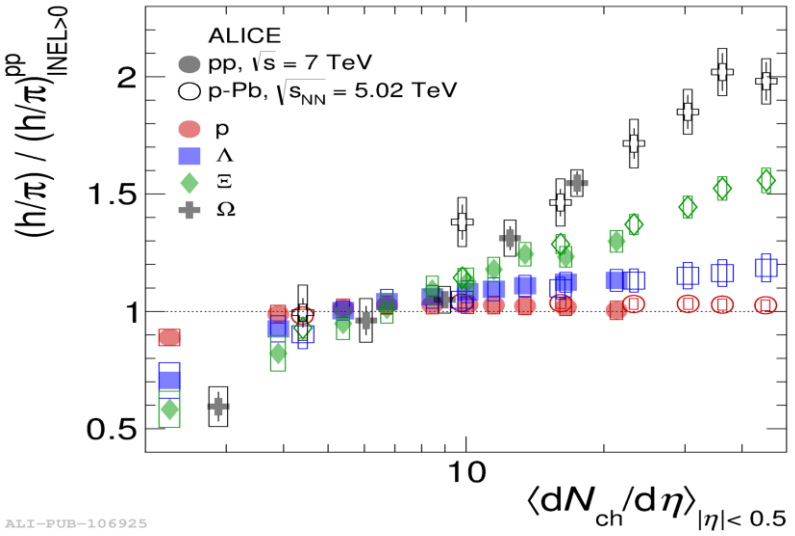
- 观测到粲强子存在显著的椭圆流
- 粲夸克的扩散系数限定在 D_s = (1.5-7)/2π T_c的范围内

质子–质子碰撞中奇异强子产生的多重数依赖

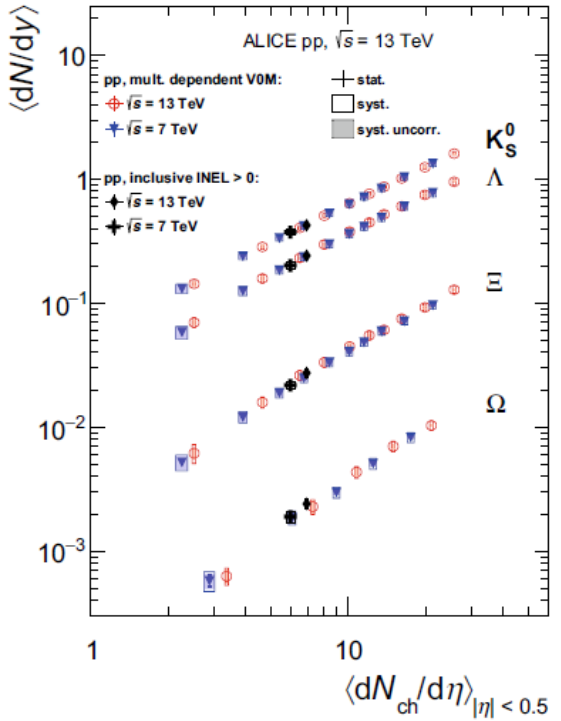


Nature Phys. 13 (2017) 535-539， *EPJC* 80 (2020) no.2, 167

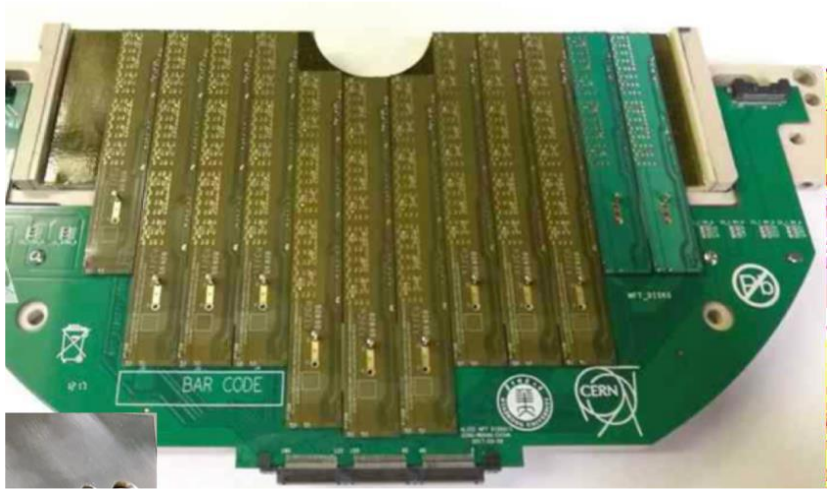
- 观测到在质子-质子和质子-铅碰撞中奇异粒子产额随多重数显著增强
- 奇异强子/π介子产额比在高多重数事例中趋于铅-铅碰撞的结果



- 小系统中奇异重子增强程度亦表现出奇异夸克数目依赖性



- 奇异粒子产额只依赖于粒子多重数，与碰撞能量无关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