Heavy-ion collision experiment
(Lecture 4)

Daicui Zhou
Central China Normal University

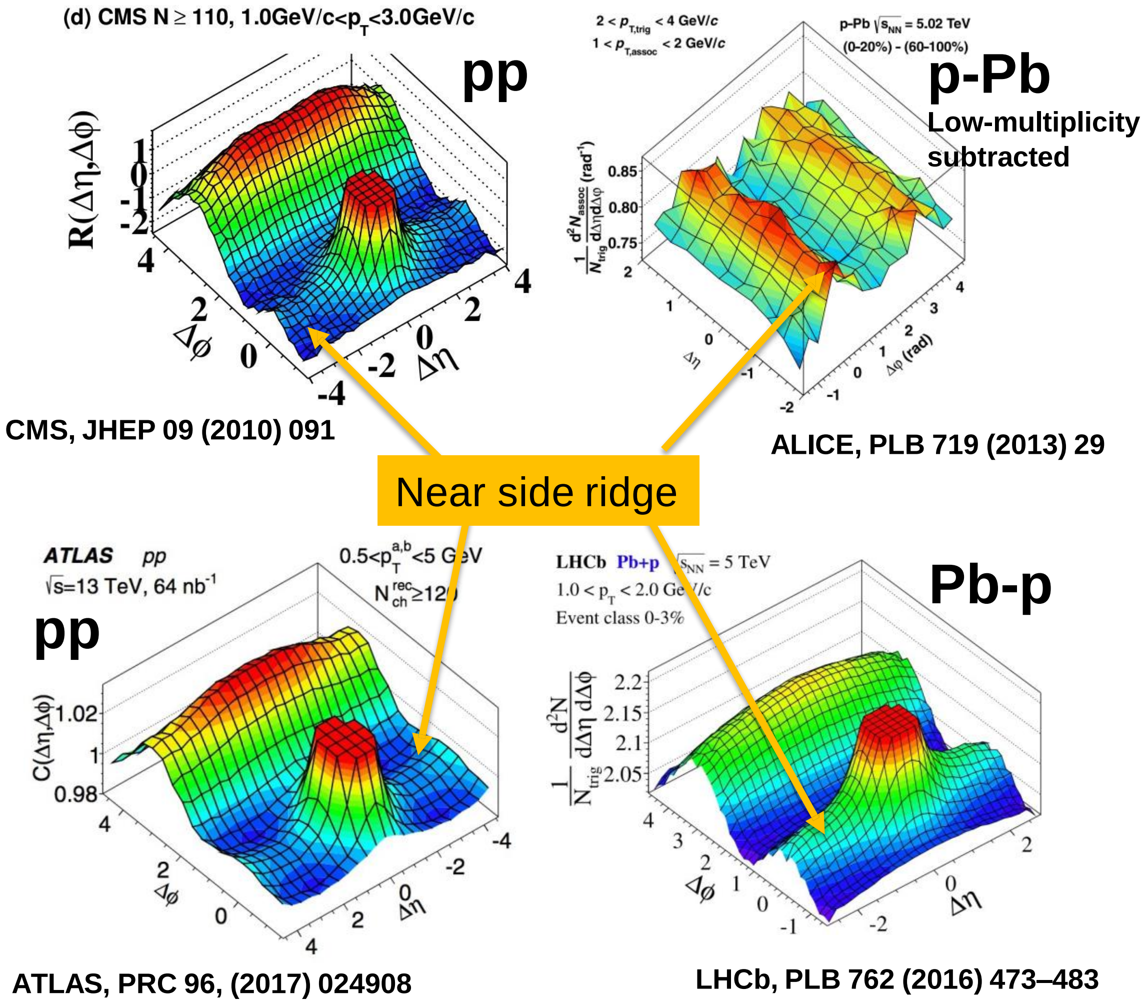
1. Introduction for relativistic heavy-ion collisions
2. Particle yields and statistical model
3. Hard probes of QGP: Jets and heavy flavors
4. Hard probes of QGP: Jets and heavy flavors
5. Quarkonia
6. Highlights from small systems
7. Summary and outlook

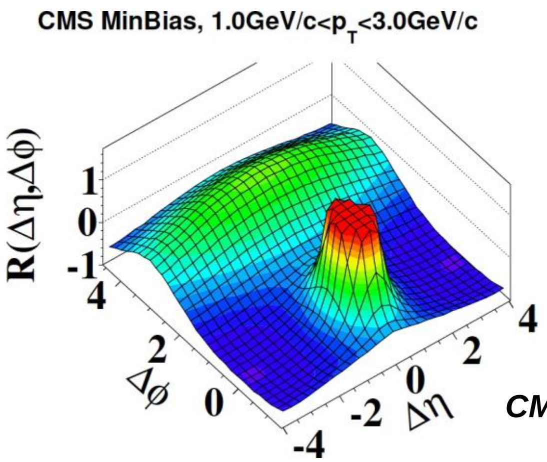
6. Highlights from small systems

Signs of collectivity in small systems

Signs of collectivity in **small systems** "discovered" at the LHC in terms of long-range ($2 < |\Delta\eta| < 4$) near-side ($\Delta\phi = 0$) "ridge" in 2-particle correlations, visible in **high multiplicity** pp, p-Pb, Pb-p collisions

Are these long-range correlations coming from (hydrodynamic) flow?



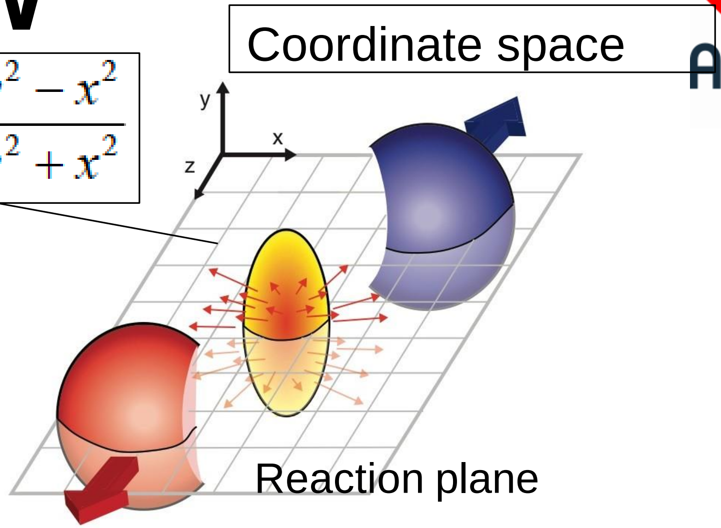


CMS, JHEP *09 (2010) 091*

Anisotropic flow

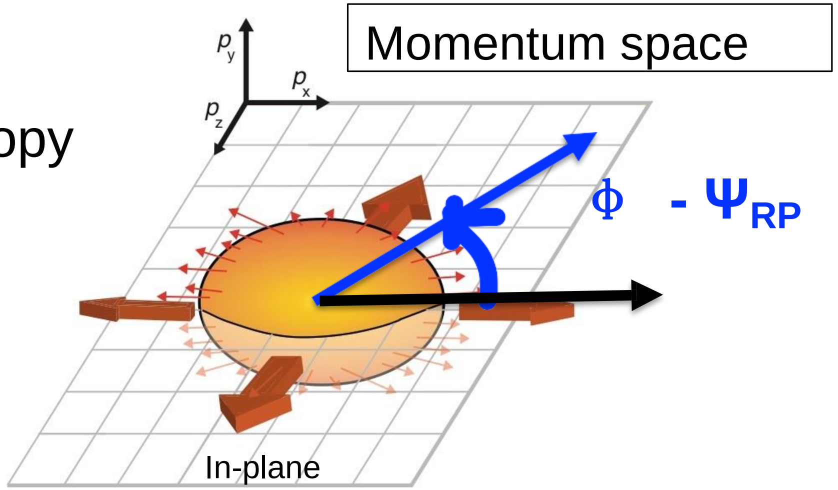
- Initial geometrical anisotropy ("almond" shape) in non-central HI collisions → eccentricity

$$\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$$



- **Pressure gradients** develop → more and faster particles along the reaction plane than out-of-plane

Scatterings among produced particles convert **anisotropy** in coordinate space into an observable momentum anisotropy
→ **anisotropic flow**
→ quantified by a Fourier expansion in azimuthal angle !



v_n = **harmonics**

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right),$$

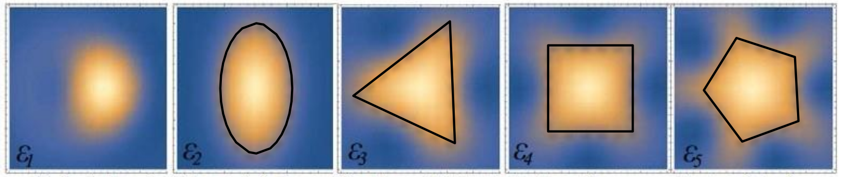


Fig. 2. (color online) Characteristic shapes of the deformed initial state density profile, corresponding to anisotropies of $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, $\mathcal{E}_4$ and $\mathcal{E}_5$ (from left to right).

Elliptic flow from large to small systems

Elliptic flow from two(multi)-particle correlations:

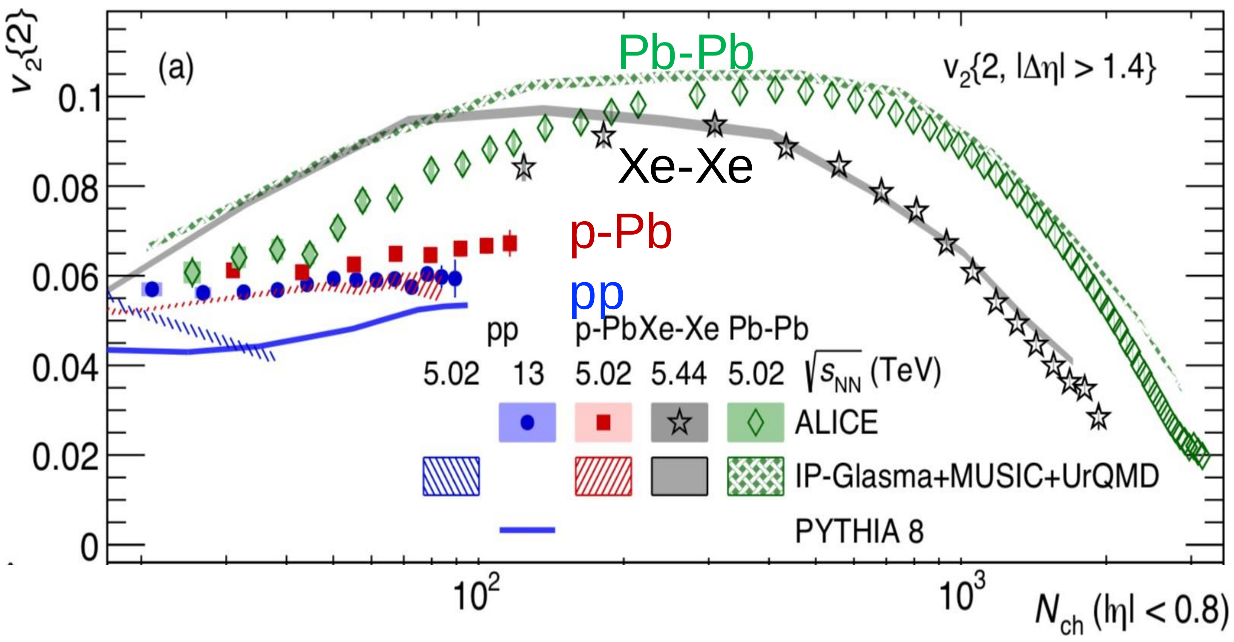
$v_2\{2\} > 0$

- subtract jets and other physical 2-particle correlations due to non-flow
- measure with rapidity gap

In AA collisions, collectivity originates from the presence of a strongly-interacting QGP

OPEN QUESTION: what is the origin of the emerging collectivity in pp, p-Pb collisions?

Elliptic flow from multi-particle correlations in all systems

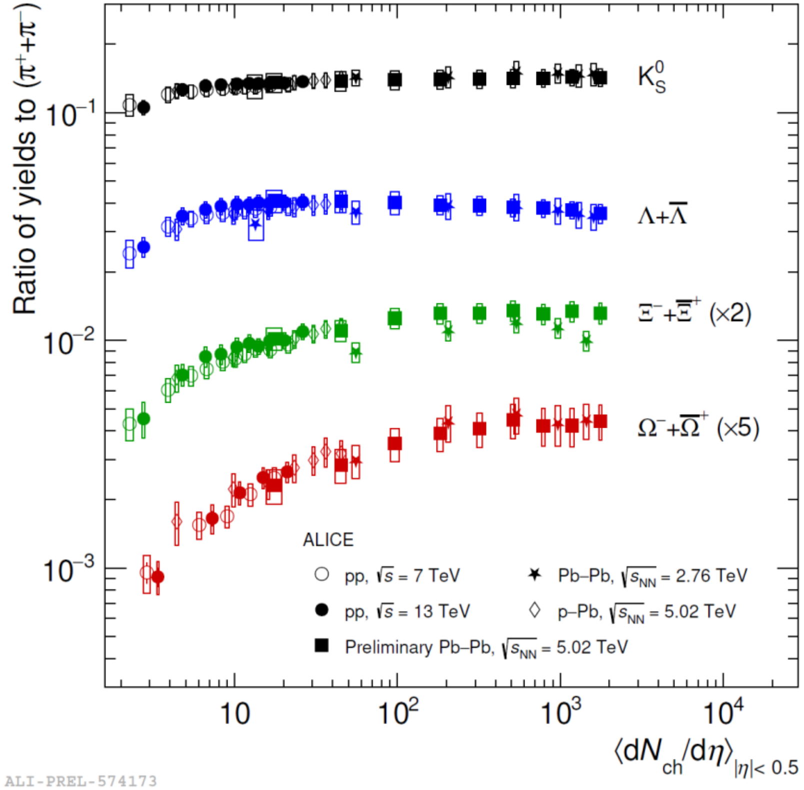


PRL 123 (2019)142301

- 初始几何
- 流体力学演化
- 夸克"聚并"强子化

小系统碰撞中的奇异增强

ALICE：*Nature Phys.* 13 (2017) 535-539



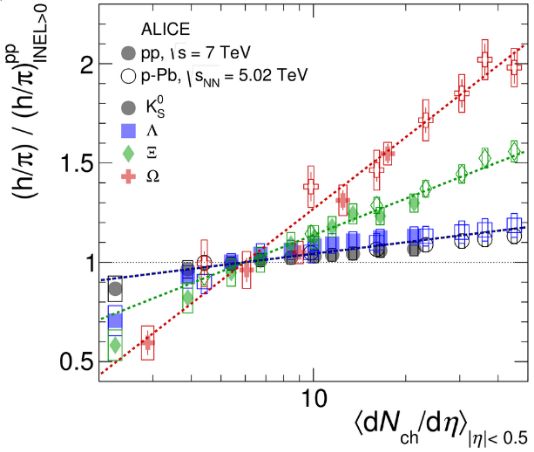
nature physics LETTERS
PUBLISHED ONLINE: 24 APRIL 2017 | DOI: 10.1038/NPHYS4111
OPEN

Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions

ALICE Collaboration†

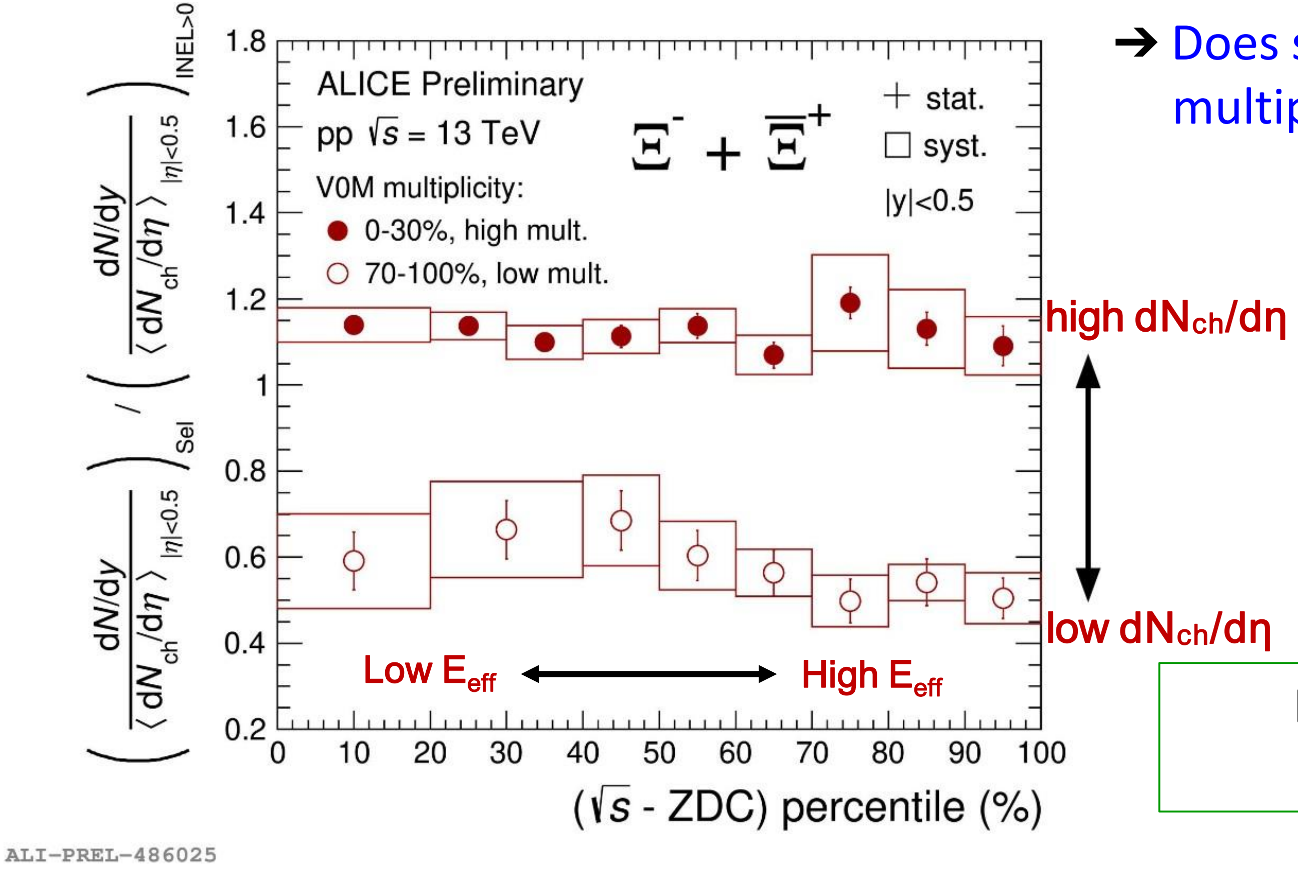
At sufficiently high temperature and energy density, nuclear matter undergoes a transition to a phase in which quarks and gluons are not confined: the quark–gluon plasma (QGP)[1]. Such an exotic state of strongly interacting quantum chromodynamics matter is produced in the laboratory in heavy nuclei high-energy collisions, where an enhanced production of strange hadrons is observed[2–6]. Strangeness enhancement, originally proposed as a signature of QGP formation in nuclear collisions[7], is more pronounced for multi-strange baryons. Several effects typical of heavy-ion phenomenology have been observed in high-multiplicity proton–proton (pp) collisions[8,9], but the enhanced production of multi-strange particles has not been reported so far. Here we present the first observation of

equilibrium and can be described using a grand-canonical statistical model[12,13]. In peripheral collisions, where the overlap of the colliding nuclei becomes very small, the relative yields of strange particles to pions decrease and tend toward those observed in pp collisions, for which a statistical-mechanics approach can also be applied[14,15]. Extensions of a pure grand-canonical description of particle production, such as statistical models implementing strangeness canonical suppression[16] and core–corona superposition[17,18] models, can effectively produce a suppression of strangeness production in small systems. However, the microscopic origin of enhanced strangeness production is not known, and the measurements presented in this Letter may contribute to its understanding. Several effects, such as azimuthal correlations and mass-dependent hardening of p_T distri- … typically attributed to the

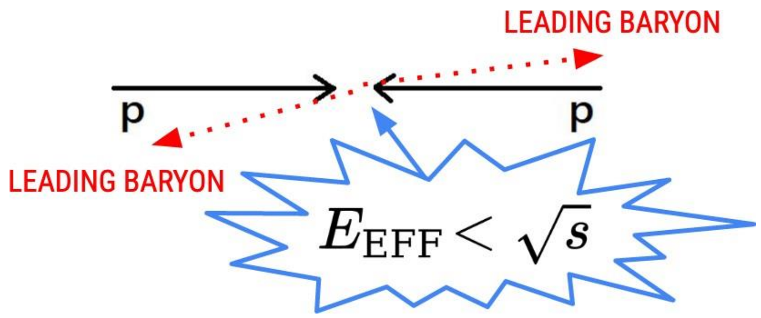


- 首次在小系统pp和p-Pb碰撞中观测到奇异粒子产额随多重数增强的现象，并与核-核碰撞光滑链接；
- 没有碰撞能量依赖性; 高奇异数粒子增强更强
- 物理模型难于解释（粒子产生的微观机制)
  - ➢ 奇异产额增强否是QGP物质生成的信号 (thermalization, equilibration？)
  - ➢ 对碎裂函数的普适性和因子化的一种挑战 (string overlap, color reconnection? Hadron scattering)

Differential studies of strangeness production



➔ Does strangeness production increases with multiplicity independent of effective energy?



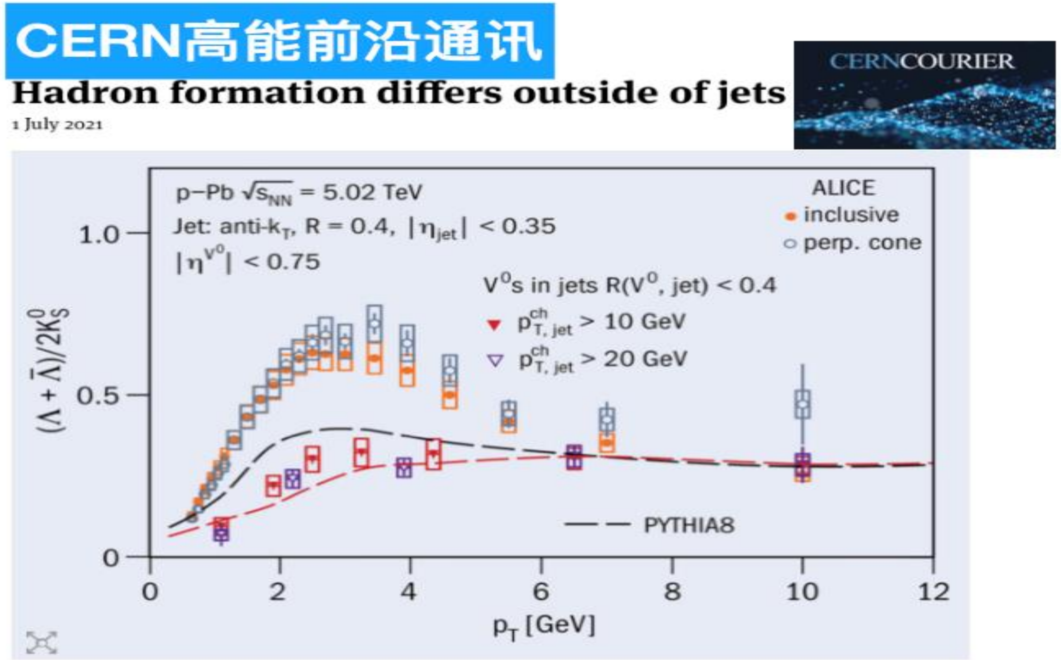
$$E_{\mathrm{eff}} = \sqrt{s} - (E_{\mathrm{leading}\,1} + E_{\mathrm{leading}\,2})$$

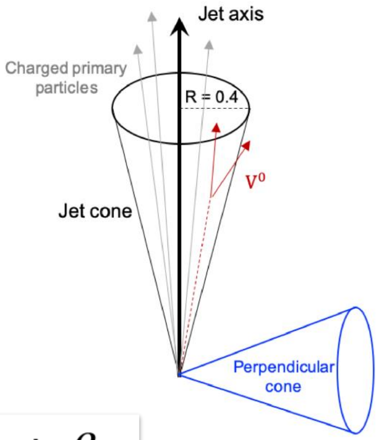
Energy available for particle production in the initial state

- Ξ to average charged-particle multiplicity (normalized to INEL>0) ratio vs. effective energy classes for given the multiplicity
- Effective energy does not play a significant role in strangeness enhancement
- Effect driven by multiplicity

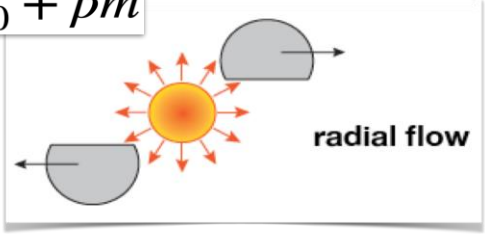
Strange baryon-to-meson enhancement in p-Pb coll.

- Understanding hadronization & non-perturbative effects of the underlying event
- Baryon-to-meson enhancement observed in A+A: flowing medium + quark coalescence





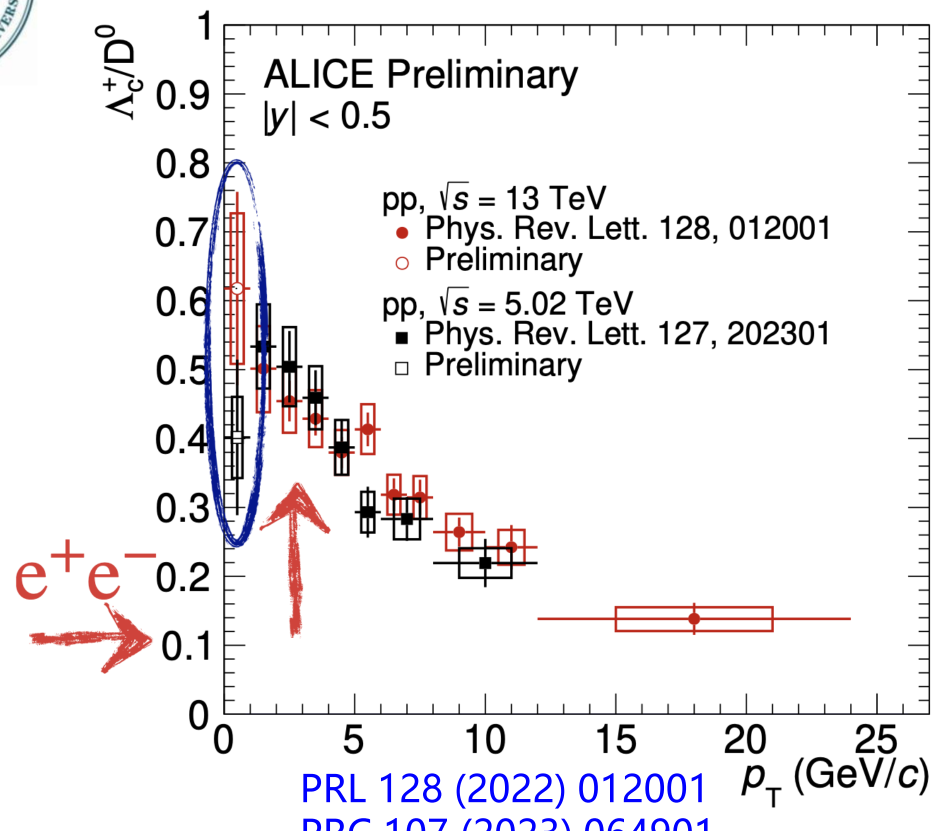
$$p = p_0 + \beta m$$



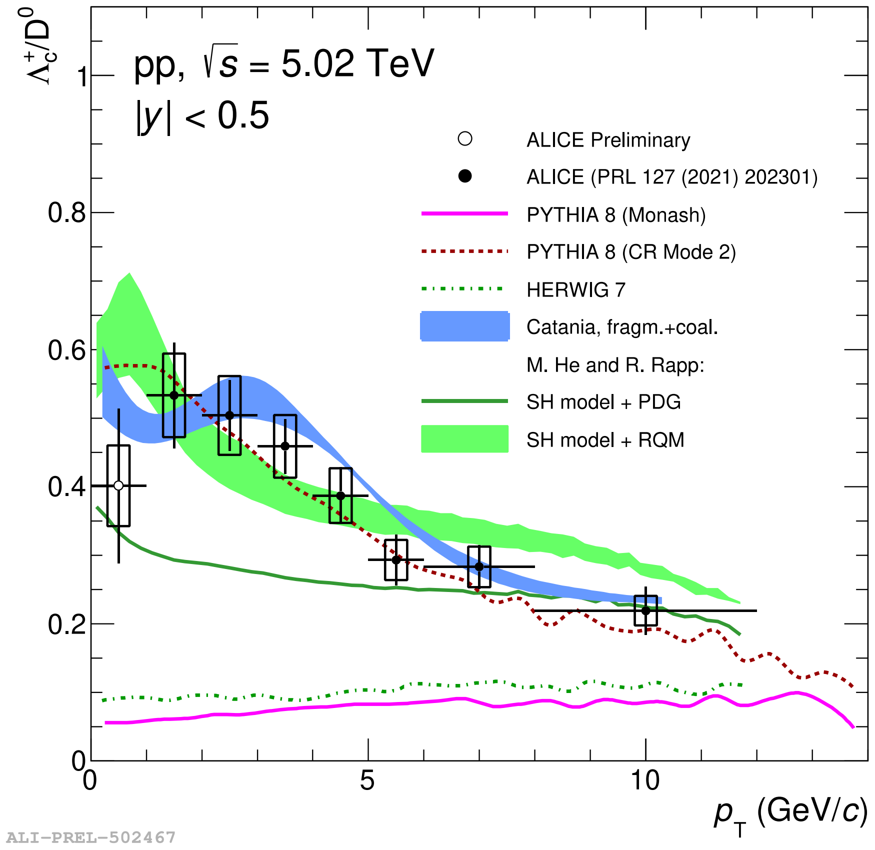
PLB 827 (2022) 136984, JHEP 07 (2023) 136

- Ratio in jets does not show a maximum at intermediate p_T, ratio with UE selection is systematically higher than the inclusive in 2 < p_T < 5 GeV/c
- PYTHIA 8 hard QCD is consistent with ratio in jets but does not reproduce the inclusive ratio at low and intermediate p_T
- No baryon-to-meson enhancement observed in jets , only soft contribution from bulk –> property of soft UE
- input to modelling (hadronization / coalescence

Charmed baryon/meson enhancement ratio observed in pp



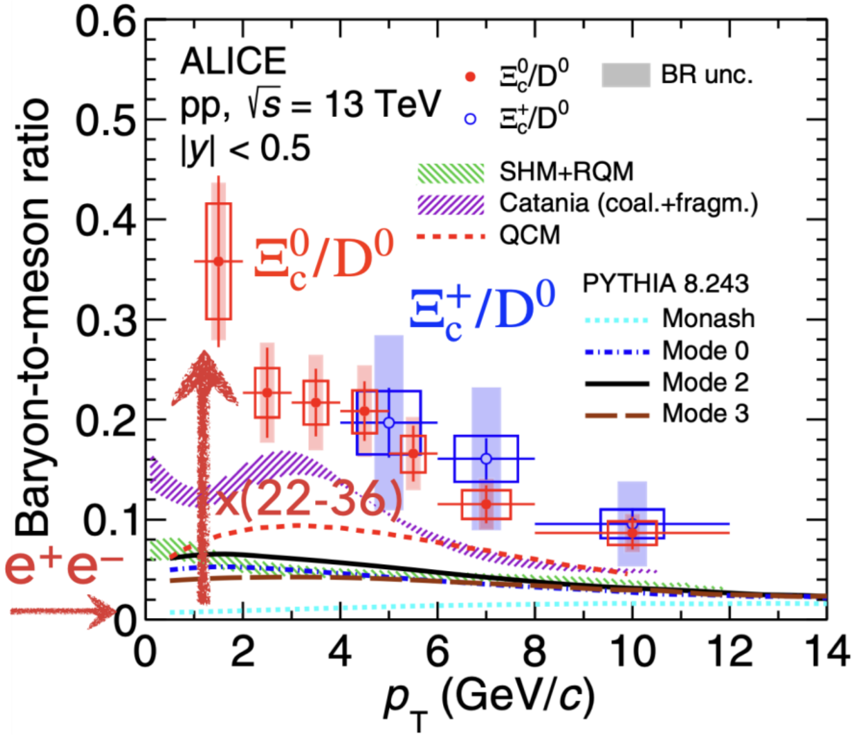
PRL 128 (2022) 012001
PRC 107 (2023) 064901



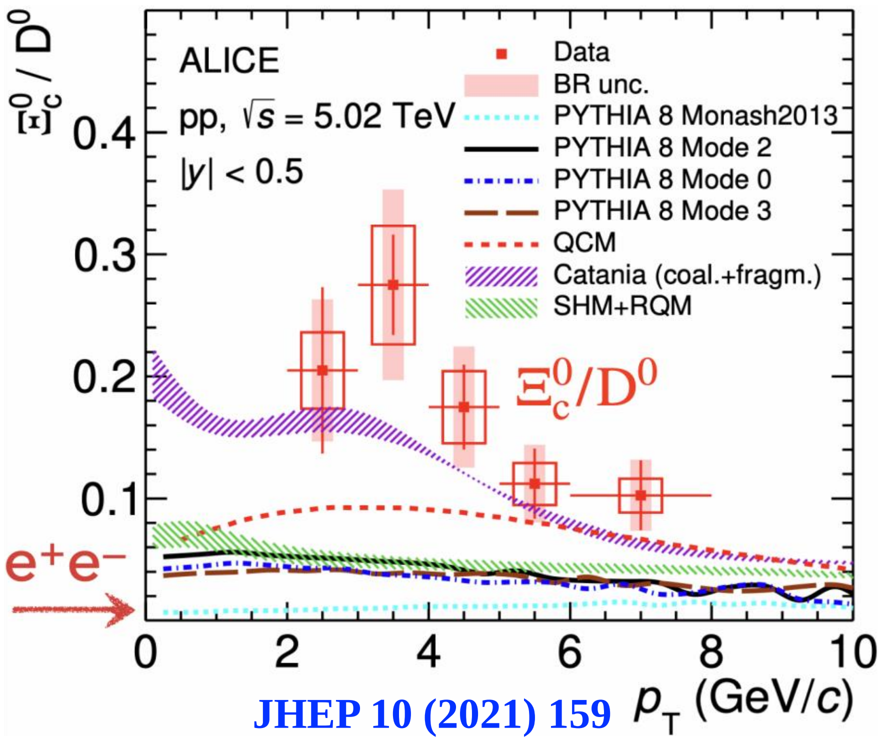
- Λ_c/D^0 significant enhancement observed in pp collisions relative to e^+e^- results
- Largely underestimated by PYTHIA 8 Monash[1], which used e^+e^- fragmentation functions
- Well described by PYTHIA 8 CR Mode2[2], SHM[3]+RQM[4], Catania[5]
  - PYTHIA 8 CR Mode2: color reconnection beyond leading color approximation
  - Catania: transport model with hadronization via coalescence+fragmentation
  - SHM+RQM: statistical hadronization model with augmented set of charm-baryon states according to relativistic quark model

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] V. Minissale, et al., PLB 821 (2021) 136622

Strange-charm baryon/meson ratio enhancement in pp collisions



PRL 127 (2021) 272001; JHEP 12 (2023) 086



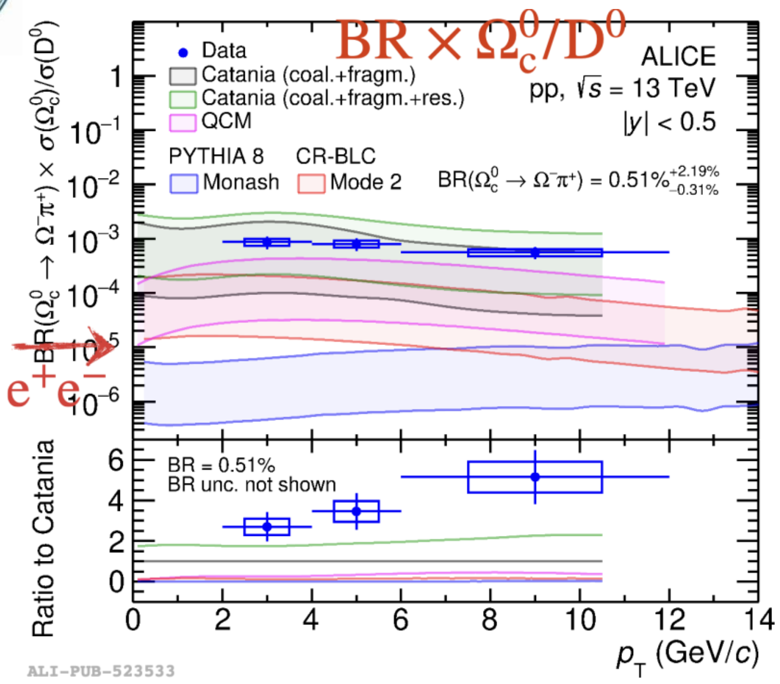
JHEP 10 (2021) 159

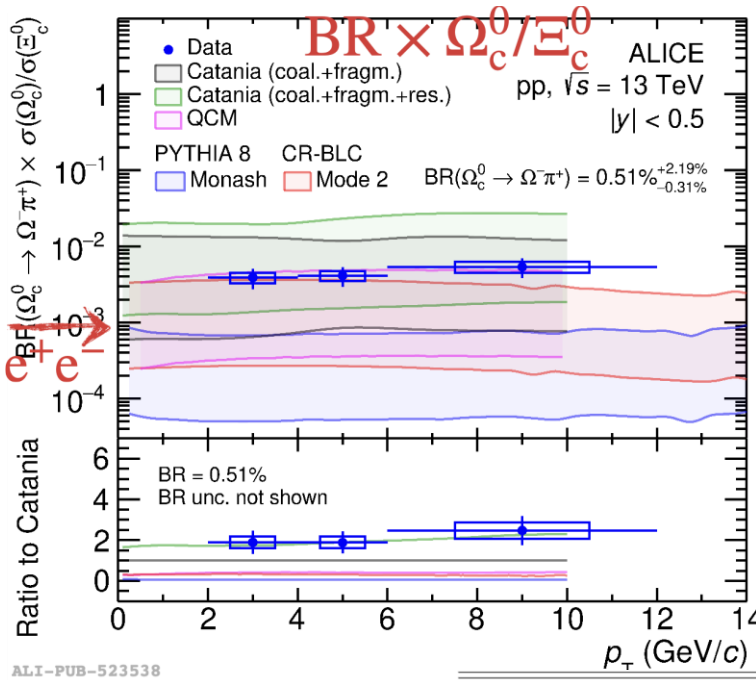
朱剑辉：CERN seminar邀请报告，ICHEP2020、SQM2021、ICHEP2022、QM2023报告

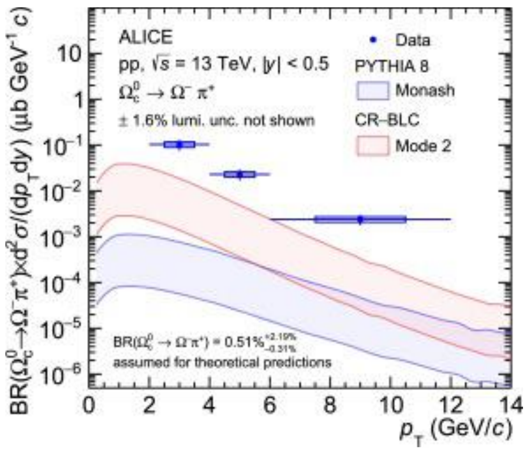
- Ξ_c^0/D^0 in agreement with Ξ_c^+/D^0; $\Xi_c^{0,+}/D^0$ similar p_T trend as Λ_c^+/D^0, no energy dependence
  - PYTHIA8 Monash[1] largely underestimates data
  - Catania[6] better describes measurements
  - 3 CR-BLC Modes[2] and SHM[3]+RQM[4] predict significantly larger ratio w.r.t. Monash, but largely underestimate data
  - QCM[5], further enhanced, still NOT describe the data

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] M. He and R. Rapp, PLB 795 (2019) 117-121
[4] D. Ebert, et al., PRD 84:014025, 2011
[5] J. Song, et al., EPJC (2018) 78: 344
[6] V. Minissale, et al., arXiv:2012.12001
[7] Belle e^+e^- : PRD 97 (2018) 7, 072005

Double strange-charm baryon/meson ratio enhancement







$$\frac{\Omega_c^0/\Lambda_c^+(\mathrm{pp})}{\Omega_c^0/\Lambda_c^+(e^+e^-)} \approx 9 \qquad \frac{\Omega_c^0/\Xi_c^0(\mathrm{pp})}{\Omega_c^0/\Xi_c^0(e^+e^-)} \approx 5$$

PLB 846 (2023) 137625

Ratio	ALICE (pp 13 TeV) $2 < p_T < 12$ GeV/c	Belle (e^+e^- 10.52 GeV) [28] visible
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)\times\sigma(\Omega_c^0)/\sigma(\Lambda_c^+)$	$(1.96\pm0.42\pm0.13)\times10^{-3}$	$(2.24\pm0.29\pm0.16)\times10^{-4}$
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)\times\sigma(\Omega_c^0)/\sigma(\Xi_c^0)$	$(3.99\pm0.96\pm0.96)\times10^{-3}$	$(8.58\pm1.15\pm1.98)\times10^{-4}$

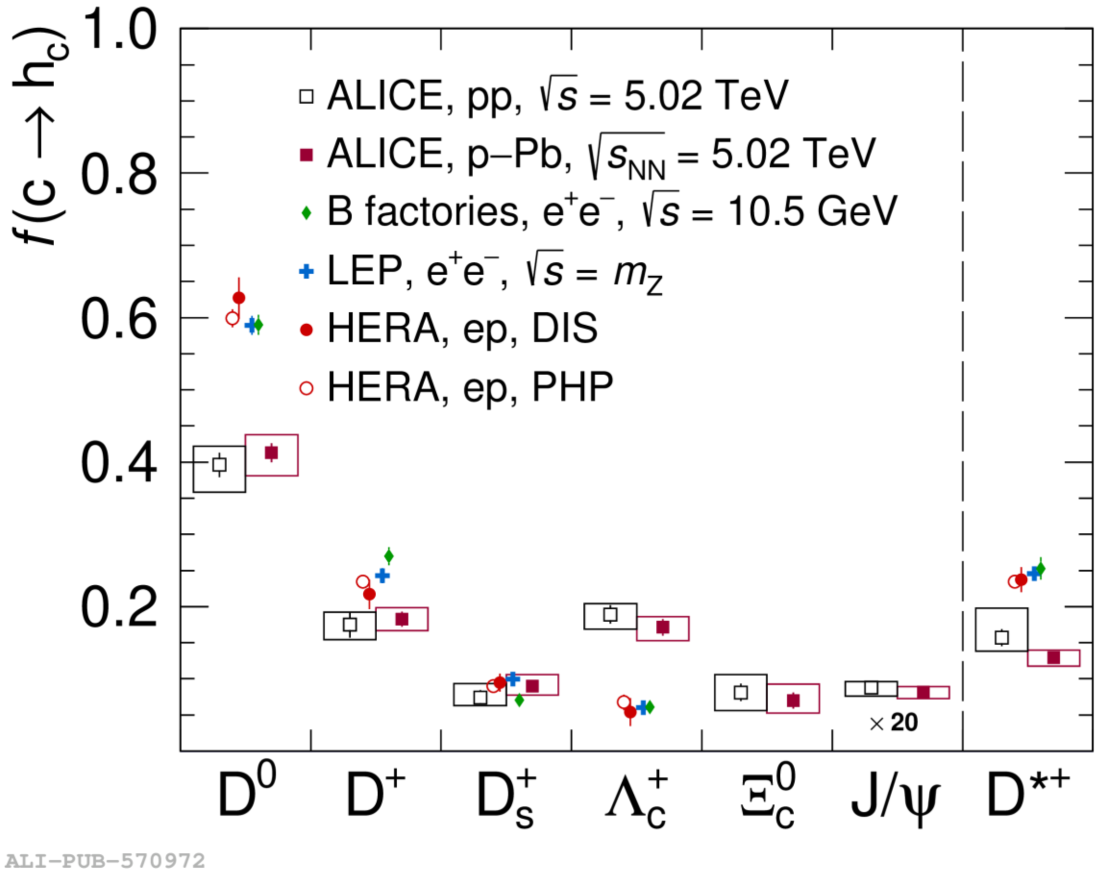
- Theoretical calculations: $\mathrm{BR}(\Omega_c^0 \to \pi^+\Omega^-) = 0.51^{+2.19}_{-0.31}\%$
- PYTHIA8 Monash[1] largely underestimates Ω_c^0/D^0 and Ω_c^0/Ξ_c^0
  - Do not reproduce strangeness enhancement in pp
- PYTHIA8 CR-BLC[2] NOT enough to describe the measurement
- Further enhancement with simple coalescence QCM[3] still shows a hint of underestimation
- Catania[4] closer to data points, additional resonances decay considered

[1] P. Skands, et al., EPJC 74 (2014) 3024
[2] J. Christiansen, et al., JHEP 08 (2015) 003
[3] J. Song, et al., EPJC (2018) 78: 344
[4] V. Minissale, et al., arXiv:2012.12001
[5] Belle e^+e^-: PRD 97 (2018) 7, 072005

Charm fragmentation fractions

- Charm fragmentation fractions in hadronic collisions at 5.02 TeV
  - pp: PRD 105 (2022) 1, L011103
  - p-Pb:
    - D^0, Λ_c^+ (new): measured down to $p_T = 0$
    - D^+, D_s^+: extrapolated to $p_T = 0$ using POWHEG+PYTHIA
    - Ξ_c^0 not measured $\rightarrow \sigma_{pp}(\Xi_c^0) \times 208 \times R_{pPb}(\Lambda_c^+)$
- pp and p-Pb results compatible
- Significant baryon enhancement w.r.t. e^+e^- and e^-p

A challenge to the universality of charm fragmentation fraction !



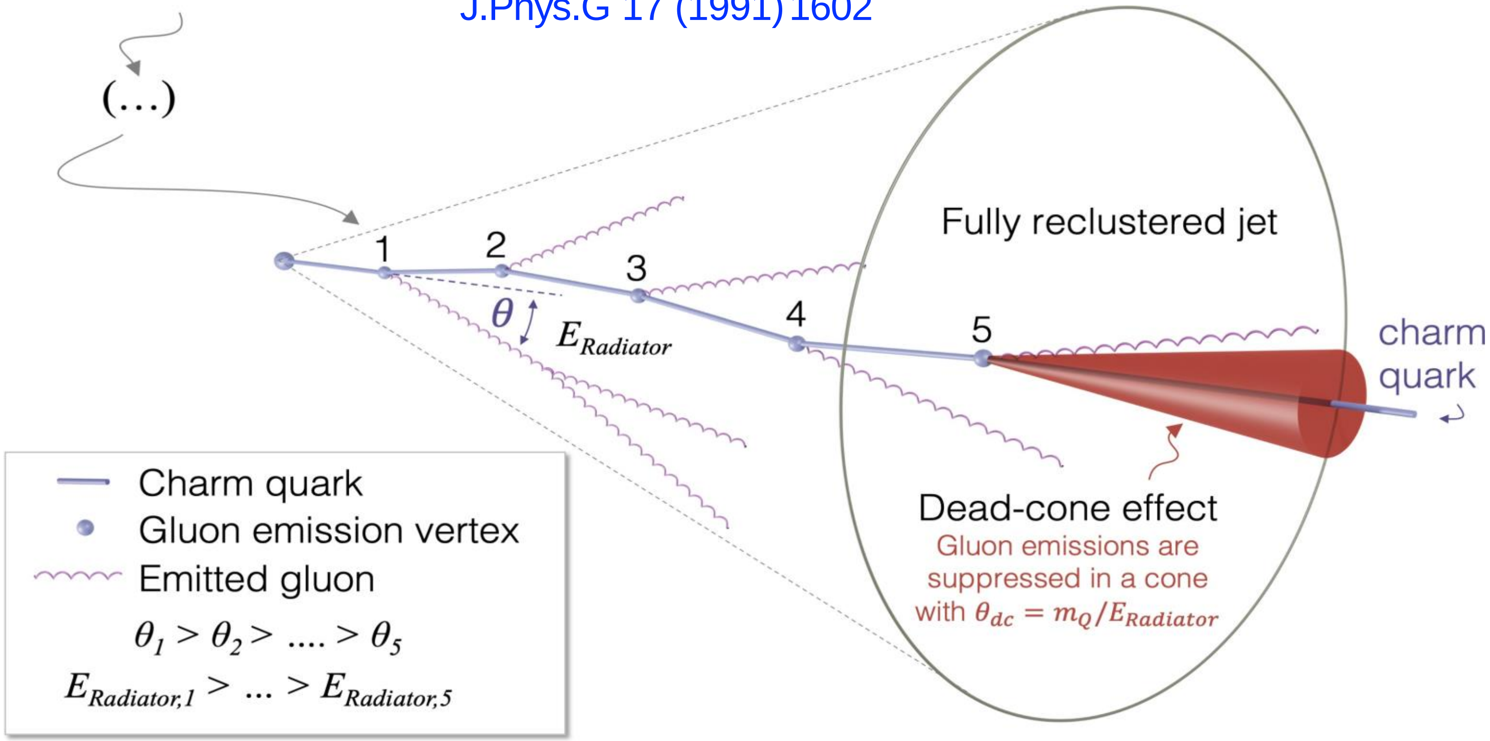
PRD 105 (2022) L011103
JHEP 12 (2023) 086
arXiv:2405.14571 (Submitted to EPJC)

[1] B factories: EPJC 76, (2016) 397 [2] LEP: EPJC 75, (2015) 19 [3] HERA: EPJC 76, (2016) 397 [4] ALICE: JHEP 10 (2021) 159

The dead-cone effect in QCD

Gluon emission of a heavy quark

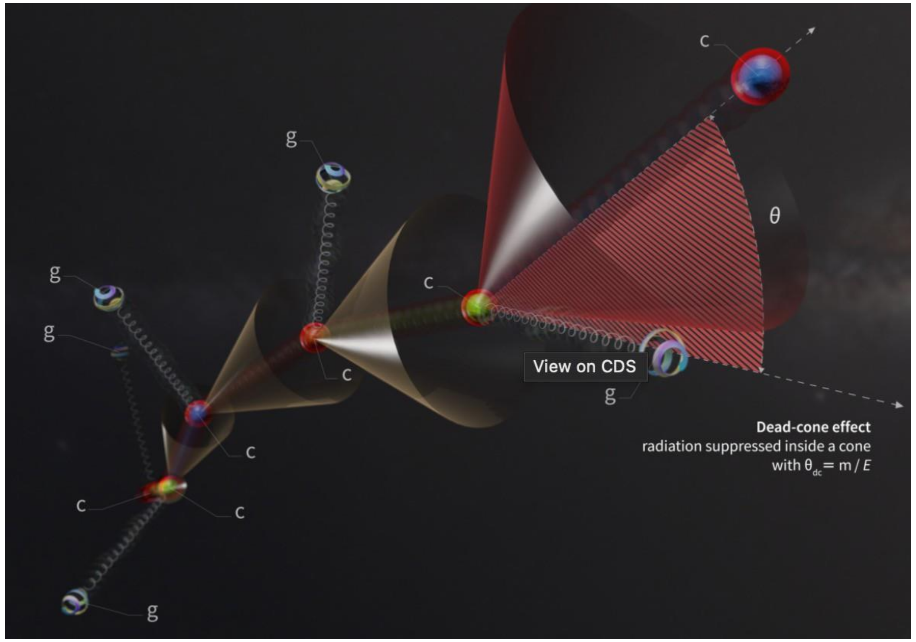
- Reduction of gluon radiation from heavy quarks at small angle: Dokshitzer, Khoze, Troian, J.Phys.G 17 (1991) 1602



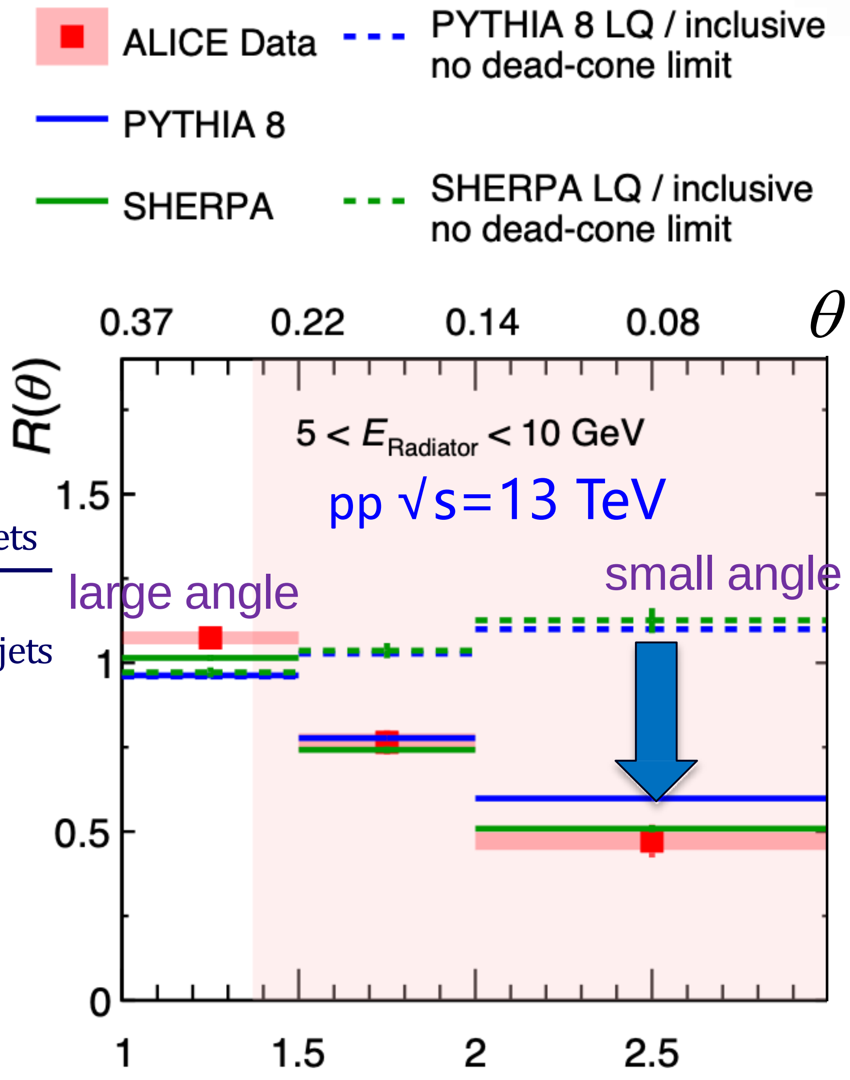
QCD dead cone effect:
Gluon emission suppressed in a cone with $\theta_{dc} = m_Q / E_{radiator}$

A fundamental QCD features (holds for all gauge quantum field theories)

In pp: dead-cone effect exposed by ALICE



$$R(\theta) = \frac{dn/d\ln 1/\theta|_{\mathrm{D0\ jets}}}{dn/d\ln 1/\theta|_{\mathrm{incl.,jets}}}$$



- First direct observation observed using jet iterative declustering and **Lund plane** analysis of jets that contain a soft D^0 meson

How is it in QGP?

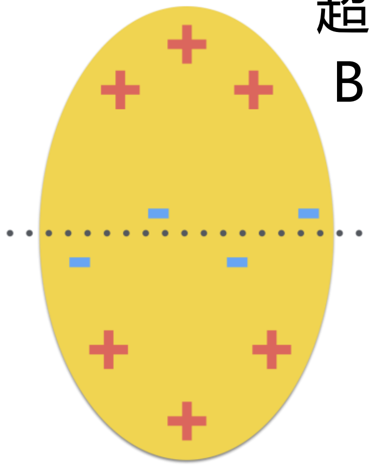
ALICE: Nature 605 (2022) 7910, 440

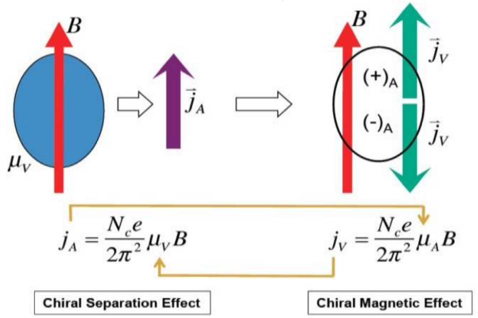
手征反常效应：手征磁波测量

手征反常效应：检验强相互作用下CP对称性、理解非微扰QCD新颖拓扑结构；

超高能原子核碰撞可以产生自然界最强电磁场：

B ~10^{14-16} 特斯拉，量子电动力学+量子色动力学





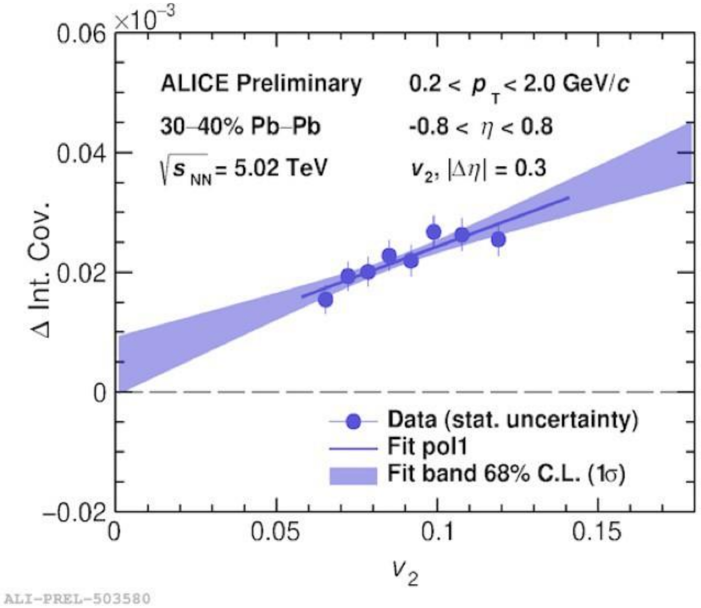
CMW

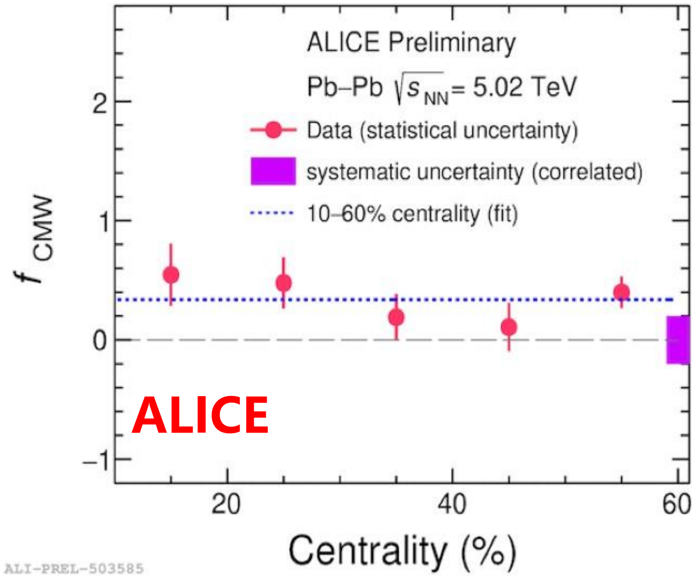
Possible effect: Out-of-plane quadrupole dipole moment

Observables: Charge asymmetry dependent v_2

$$\Delta v_2 = v_2^- - v_2^+ \sim rA_{ch}$$

with $A_{ch} = (N^+ - N^-) / (N^+ + N^-)$





- 提出采用事件形状选择（ESE）方法分离手征磁波测量中的局域电荷守恒背景
- 首次提取出手征磁波信号强度

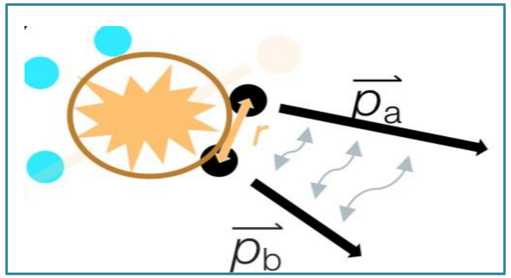
揭示质子-超子间强相互作用

ALICE： Nature 558 223-238(2020)

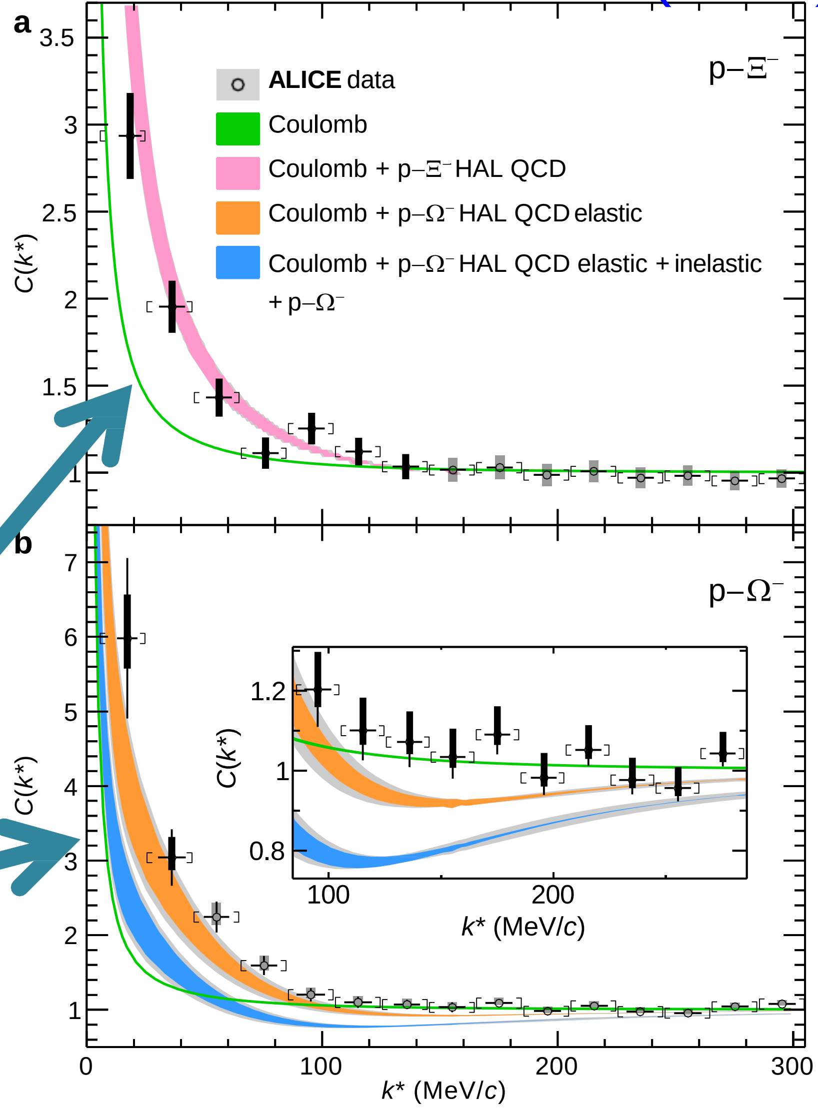
- Proton-hyperon (p-Y) strong interaction poorly known
  - Traditional scattering measurements mostly limited to proton-proton
  - Relevant to neutron star modeling in the case of Λ and Σ

如何从第一原理出发理解原子核中夸克含量不同的强子之间的有效相互作用，在核物理中是一个挑战

- Momentum-correlation of p-Y pairs produced by a source of well-measured size in pp and p-Pb → big jump in precision
- Latest result: attractive strong interaction precisely measured for **p-Ξ^-** and **p-Ω^-**



Correlation peak at small momentum difference $k^* = |\boldsymbol{p}_a - \boldsymbol{p}_b|/2$ induced by interaction



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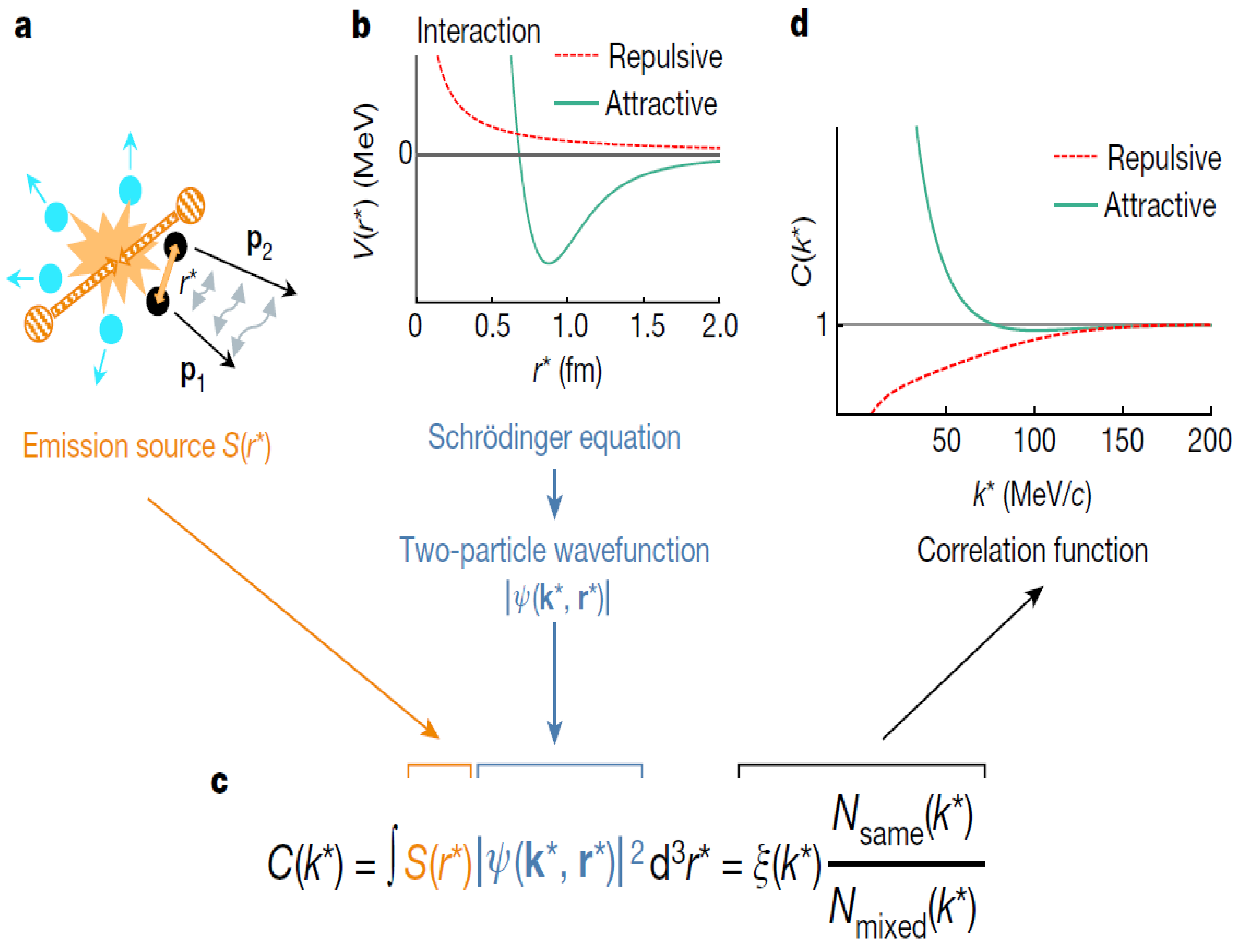

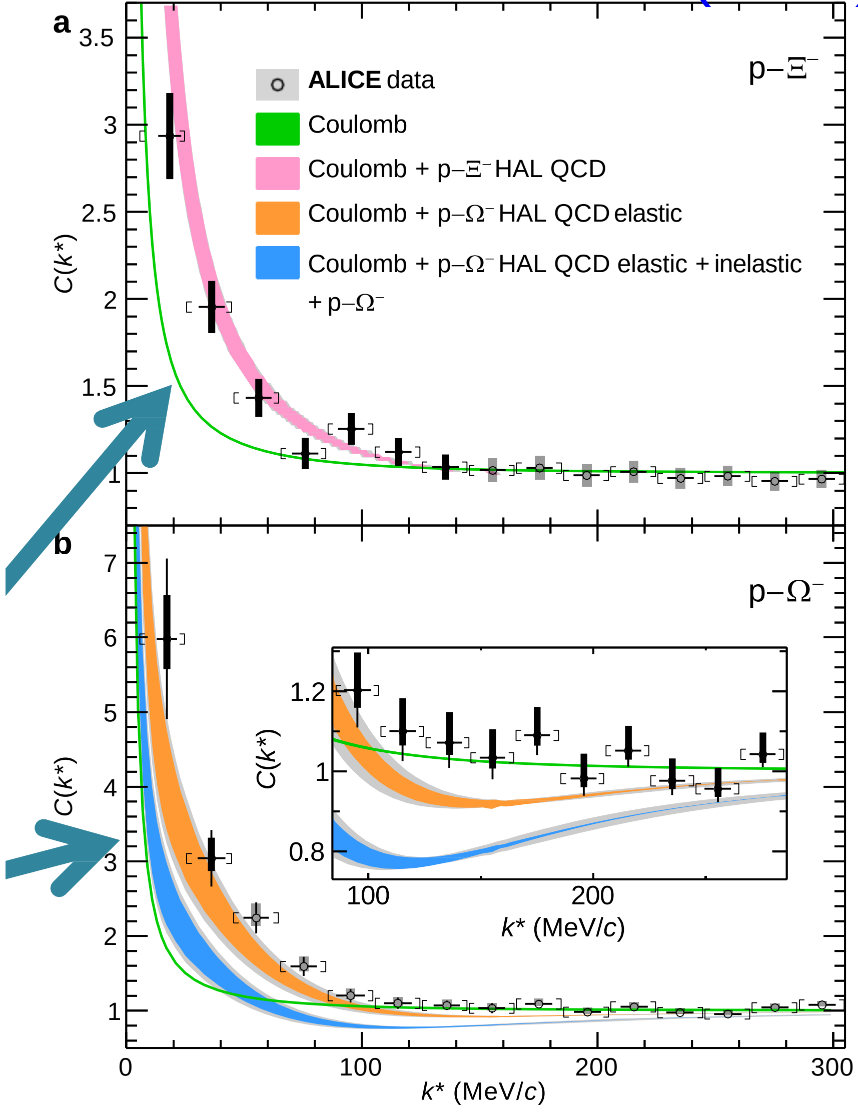

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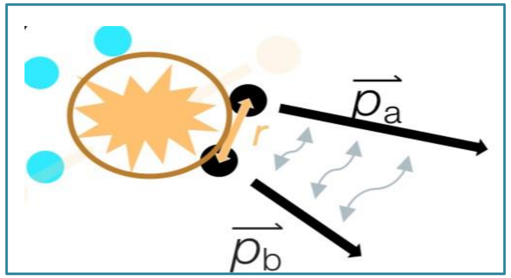

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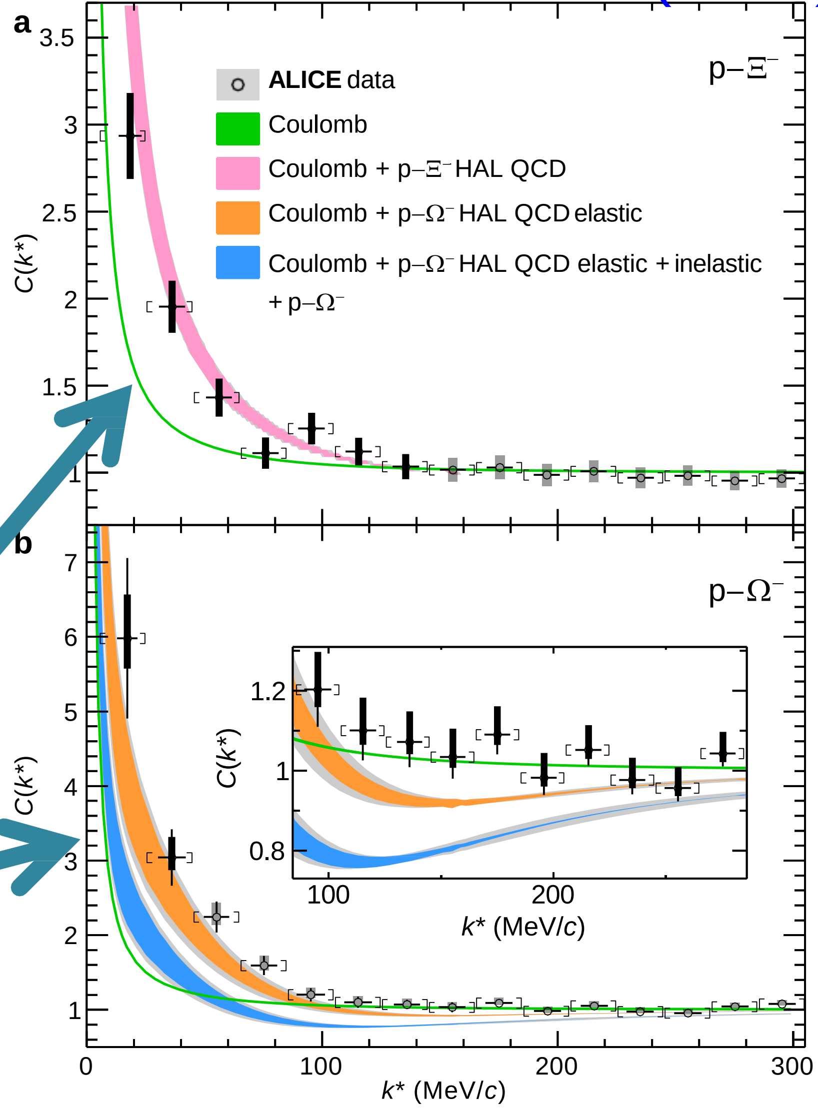


7. Summary and outlook

The evidence of the QGP formation observed in heavy-ion collisions

- Strong jet quenching and medium-induced modification
- Quarkonium suppression induced by melting of states at high temperature
- Regeneration and partial thermalisation of charm
- Collective behavior of a QGP with very low shear viscosity (η/s) observed
- Statistical hadronisation production from $\sqrt{s_{NN}}$ = 2 to 5040 GeV described → T_{ch}, $T_{f.o}$
- QGP-like effects observed in small colliding systems (pp and p-Pb)
- QCD dead cone effect and baryon strong interaction also observed in pp collisions

Many open questions are expected to be addressed in Run 3, Run 4 and beyond:

- Is there QGP in small systems?
- Can we explain these effects without a QGP?
- Can we describe these emerging phenomena in one unified picture across systems?
- Temperature with in QGP system
- The evolution of temperature in QGP system

……

中国ALICE组中长期物理研究计划

Run 3 — Run 6: 亮度、精度、读出速率大幅提高

聚焦关键物理课题如下：

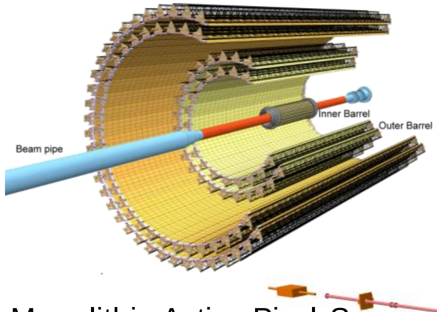
- 夸克物质性质硬探针的精确测量
- 夸克物质强相互作用动力学
- 手征磁、手征涡旋及手征反常研究
- 冷核效应及末态强子化行为
- 奇特物质结构及新粒子寻找

LS2 upgrades for Run 3 (2022-2025) and Run 4 (2028-2030)

objective: operation at high interaction rates (50 kHz of Pb–Pb collisions)

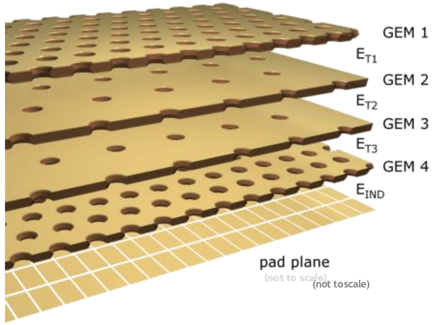
→ continuous (i.e. untriggered) readout for core detectors → x 50 faster readout

All-pixel Inner Tracking System

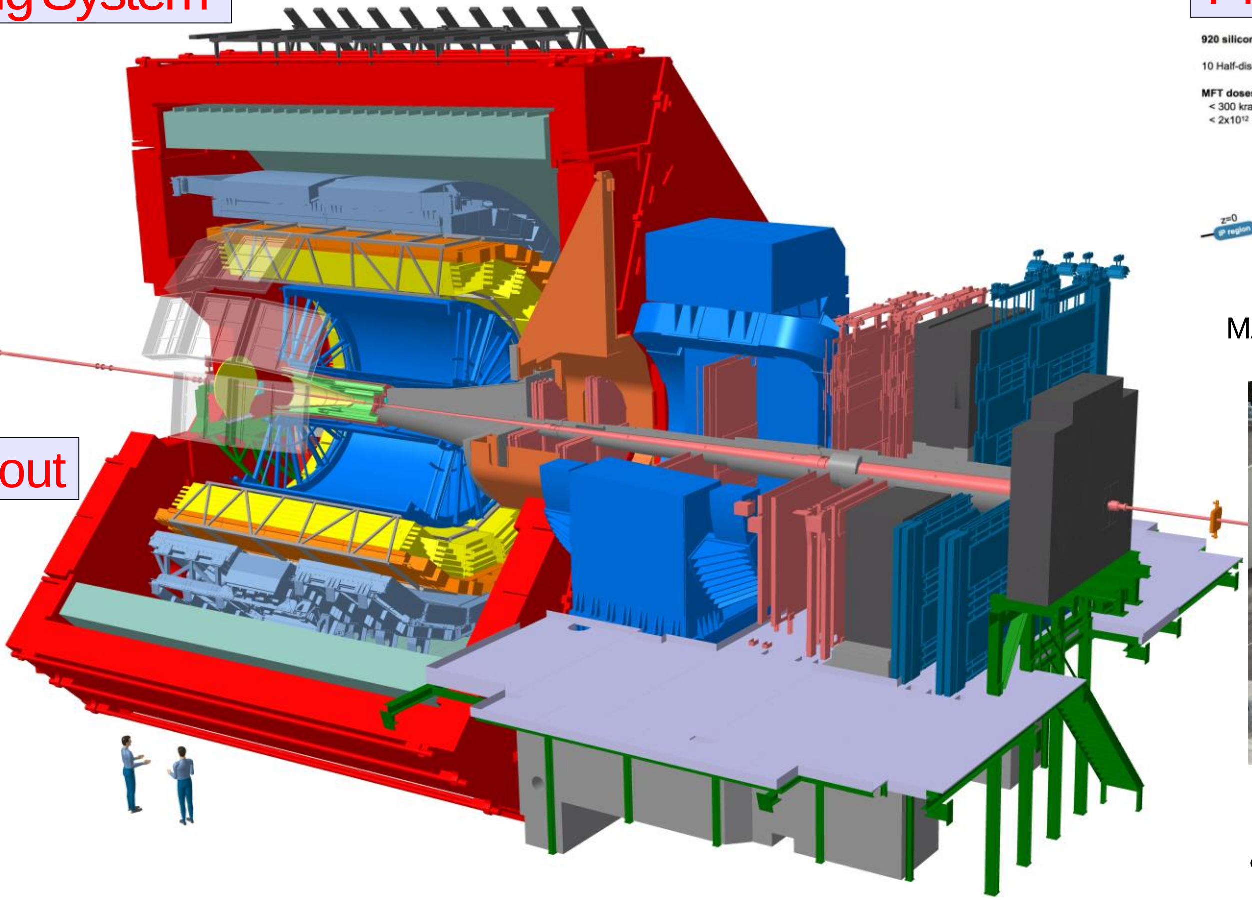


Monolithic Active Pixel Sensors

GEM-based TPC readout



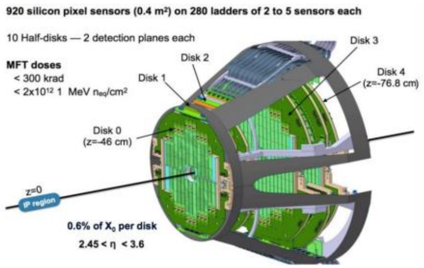
GEM readout chambers



- Improve tracking resolution at low p_T

→ thinner, more granular

Pixel Muon Forward Tracker

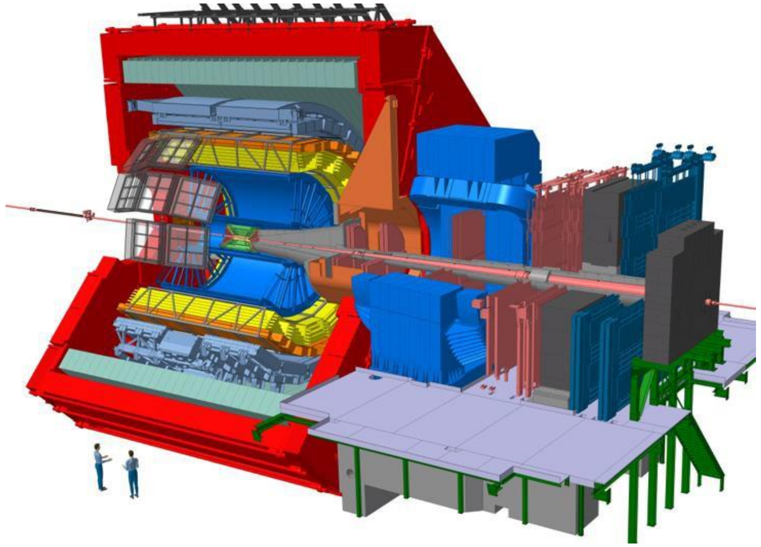


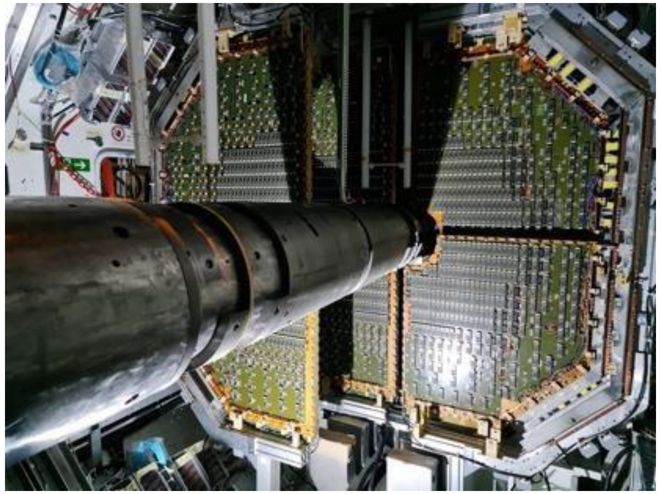
MAPS-based forward tracker

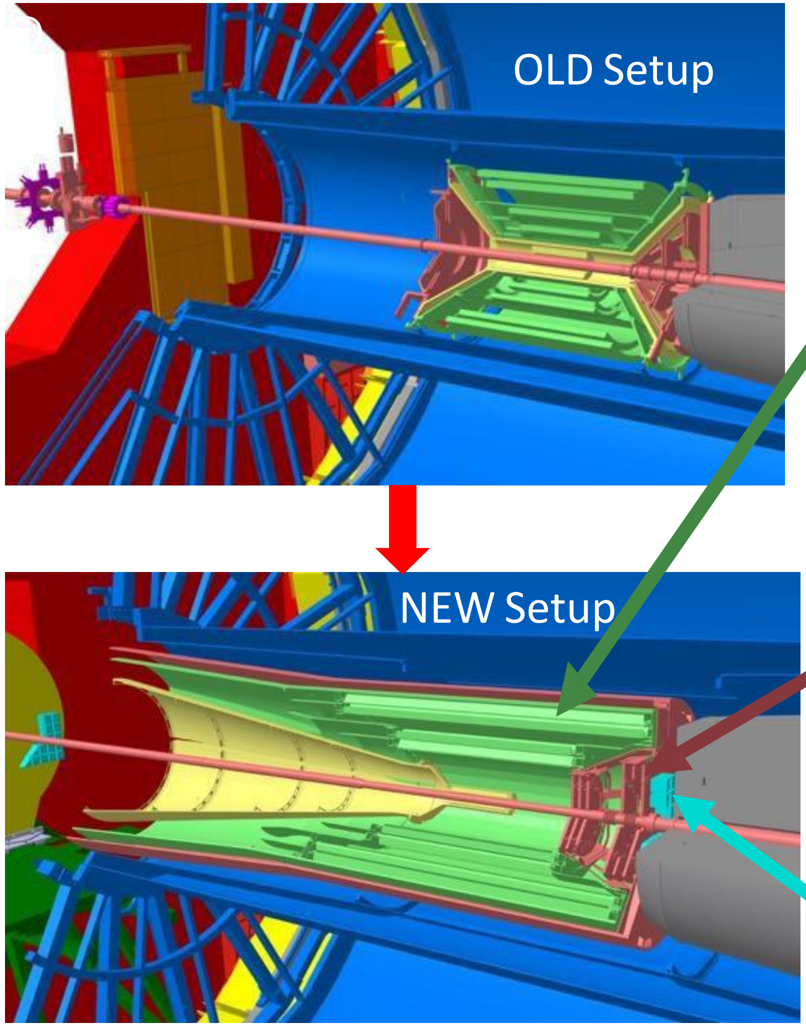
… and much more:

- Fast Interaction Trigger
- New Online-Offline system
- Readout upgrade of MUON, TOF, EMCAL, PHOS

ALICE 2 – selected subsystems







Reconfiguration of the inner tracker region

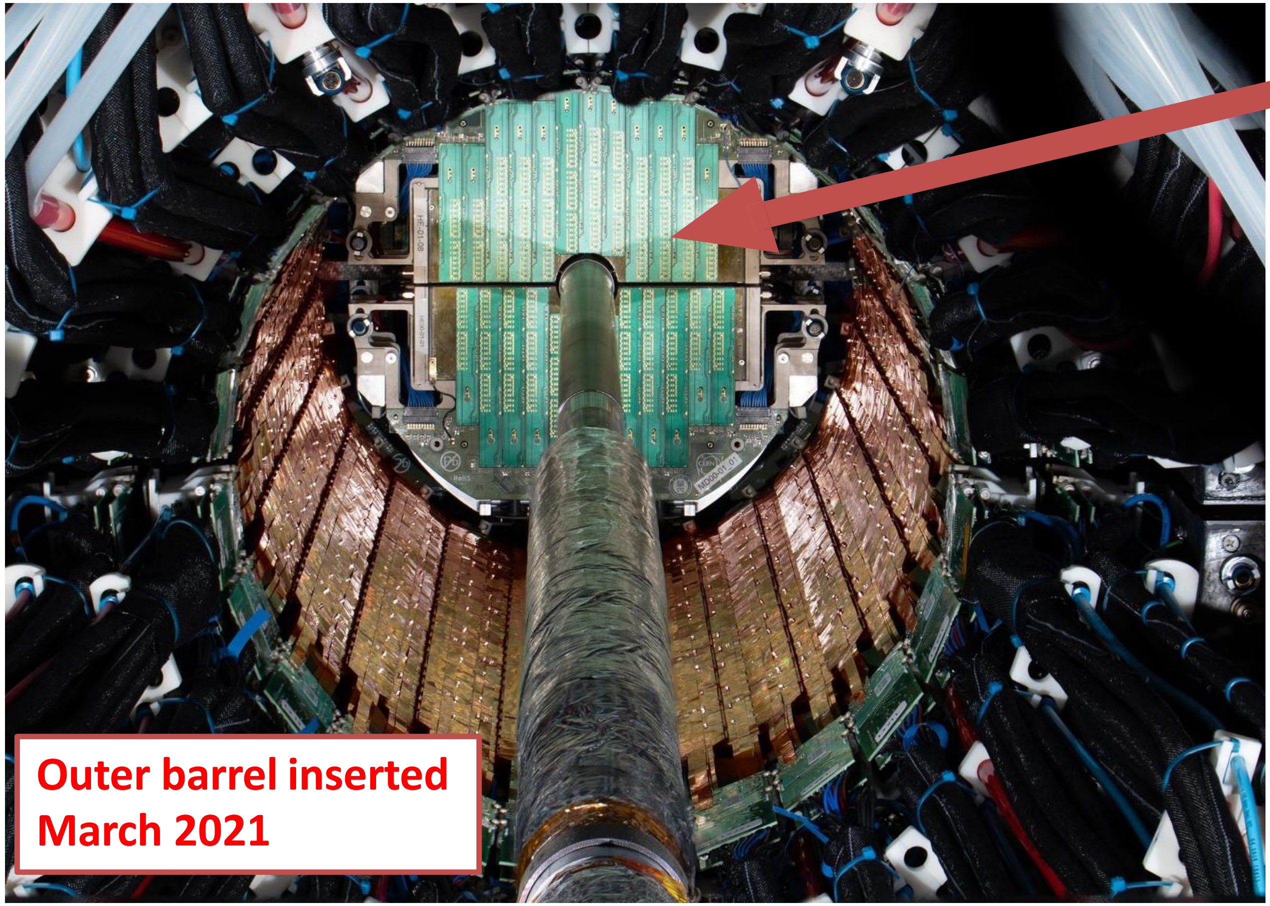
New Inner Tracking System (ITS2)
- Improved pointing precision
- Monolithic CMOS sensors (ALPIDE)
- Smaller beampipe, 1st layer closer

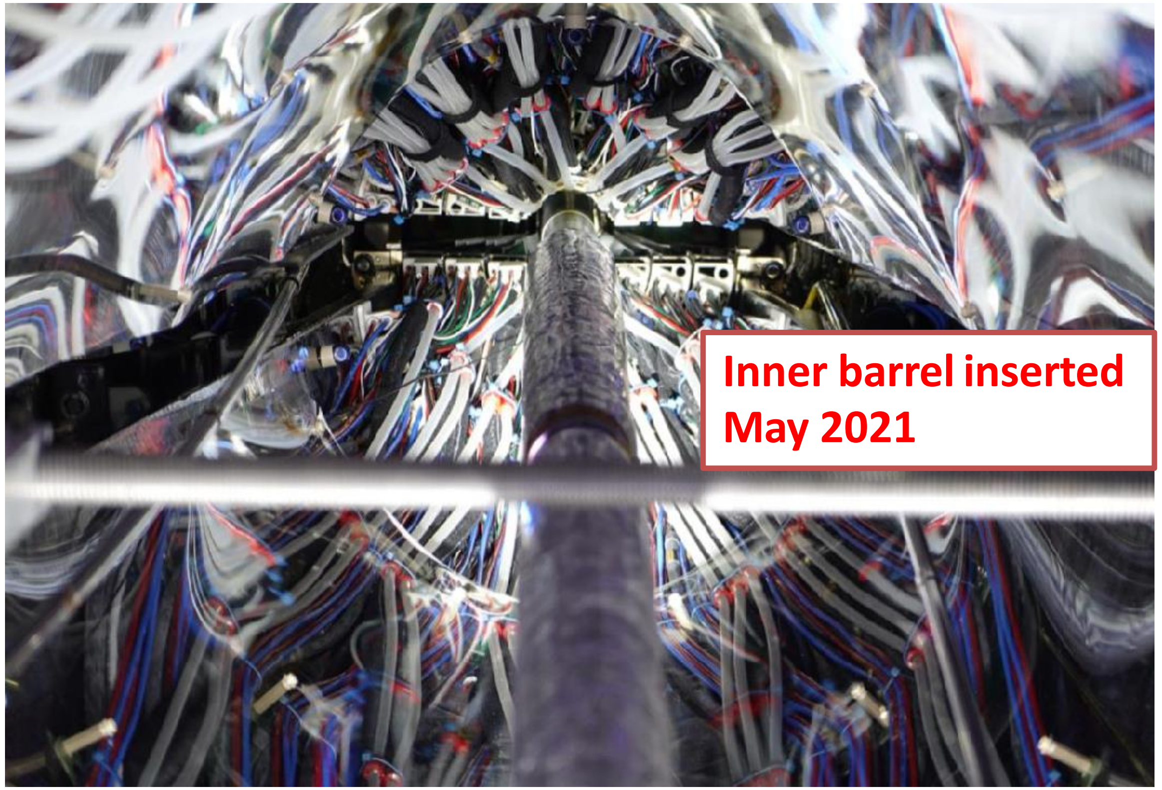
Muon Forward Tracker (MFT)
- New tracker based on ALPIDE
- Improved MUON pointing
- precision, promt vs. decay muons

New Trigger Detectors (FIT)

New Inner Tracker System and MFT installed

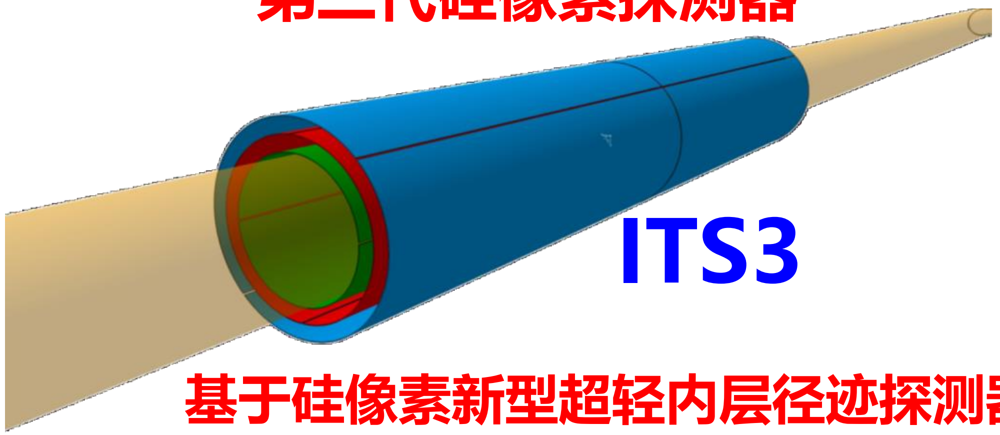
The new Muon Forward Tracker



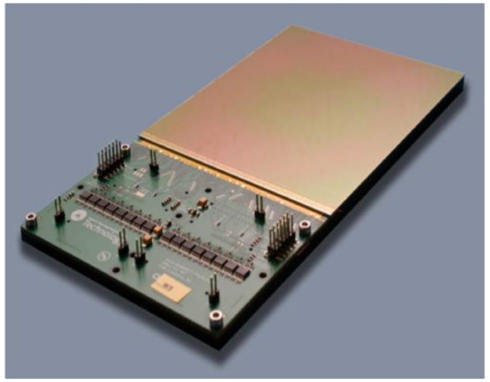


ALICE 探测器升级（2029-2032）

第三代硅像素探测器



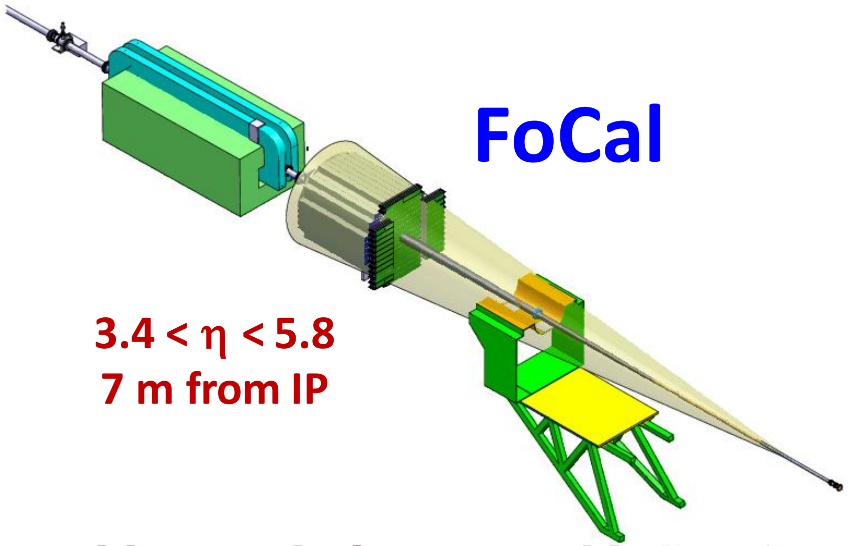
基于硅像素新型超轻内层径迹探测器



- 提升分辨率和低动量带电粒子重建效率
- 测量强衰变的稀有粒子

Letter of Intent https://cds.cern.ch/record/2703140
On track for TDR in 2022

前向（电磁和强子）量能器



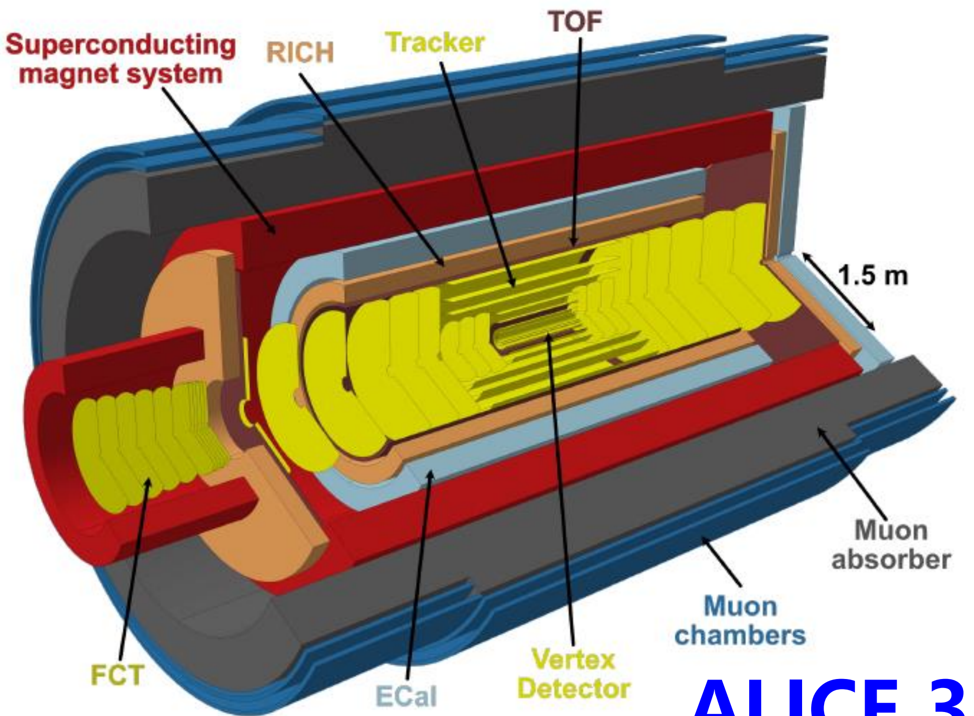
基于硅像素和PAD技术量能器

- 质子和核内胶子分布函数
- 非线性QCD演化方程
- 小系统中类流长程关联的根源
- ……

TDR-https://inspirehep.net/literature/2797164
LoI - CERN-LHCC-2020-009 ; LHCC-I-036

ALICE 探测器升级（2036-2042）

- high-resolution, wide η coverage, high rates for precision QGP physics
- Heavy-ion physics to the fb^{-1} luminosity era* with unique kinematic reach



ALICE 3

全新的硅像素探测器

高分辨率、大快度、高事例率

arXiv:1902.01211

key requirements

- **ultra-low material budget** for low p_T tracking
  - X/X_0 ~ 0.05 % / layer
- **fast** to sample large luminosity
  - 50 - 100x Run 3/4
- **large acceptance**
  - $|\eta| < 4 \Rightarrow \Delta\eta = 8$ (total)
  - $|\eta| < \sim 1.4$ (central barrel)
- **excellent spatial resolution** for tracking and vertexing
  - innermost layers: σ < 3 μm
  - outer layers: σ ~ 5 μm
- **precise time measurement** for particle identification
  - σ ~ 20 ps

中国组正在参与全新的ALICE第三代探测器研发和物理分析可行性研究

科学问题

- **如何从QCD第一性原理出发理解夸克物质性质?**
- **能否证明核环境中手征对称性的恢复?**
- **核环境中是否存在量子场论基本特性的破坏，以及超出标准模型的新物理现象?**

中国ALICE组已经、正在和未来将完成的工作

- **已完成**
  - 光子谱仪（PHOS）及其前端电子学研制
  - 双喷注电磁量能器（DCal）研制
  - 第二代内寻迹系统（ITS2）研制
  - 前向缪子寻迹系统（MFT）读出链路板研制

- **正在参与的工作**
  - 用于ITS3的晶圆尺寸的超薄硅像素芯片的研发
  - FoCal硅像素层的研发

- **未来将完成和参与的工作**
  - 合作研发出用于ITS3的晶圆尺寸的超薄硅像素芯片
  - 合作研制出 FoCal 电磁量能器的硅像素层
  - 参与 ALICE 3 探测器的R&D和探测器的建造

光子谱仪（PHOS）及前端电子学研制

合作研制ALICE光子谱仪前端电子学系统（1999–2015年）

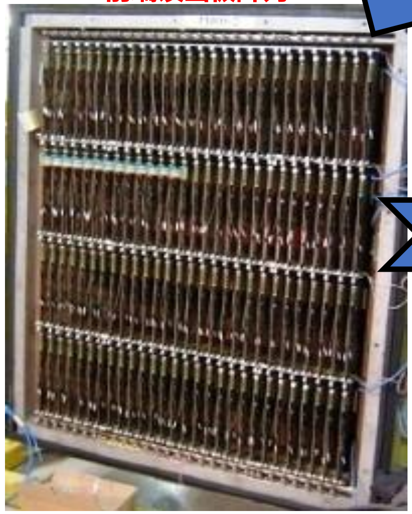
- 低噪声、大动态范围的电磁量能器读出
- 用以测量直接光子和衰变光子

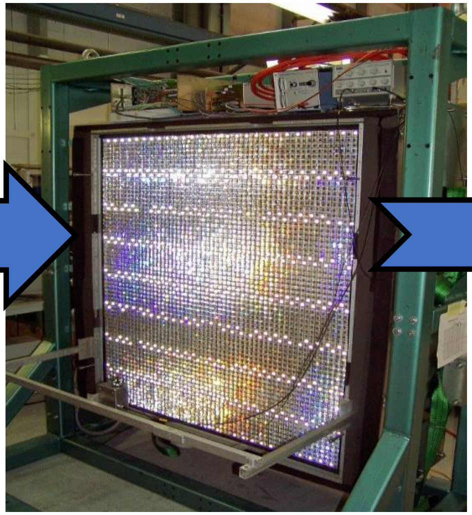
前置放大器

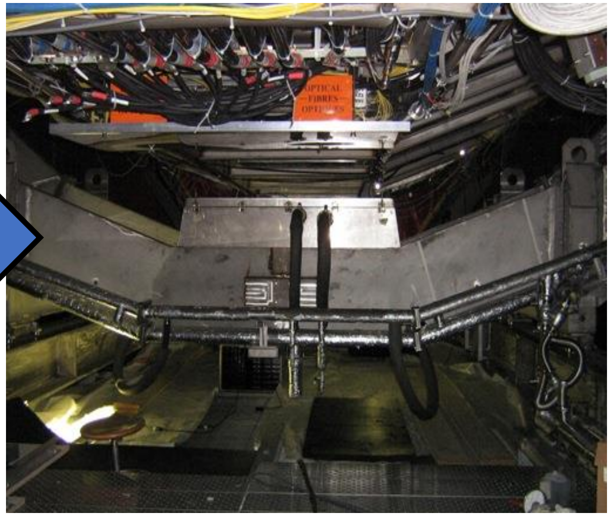
前端读出板

局域触发主板

前端读出板阵列



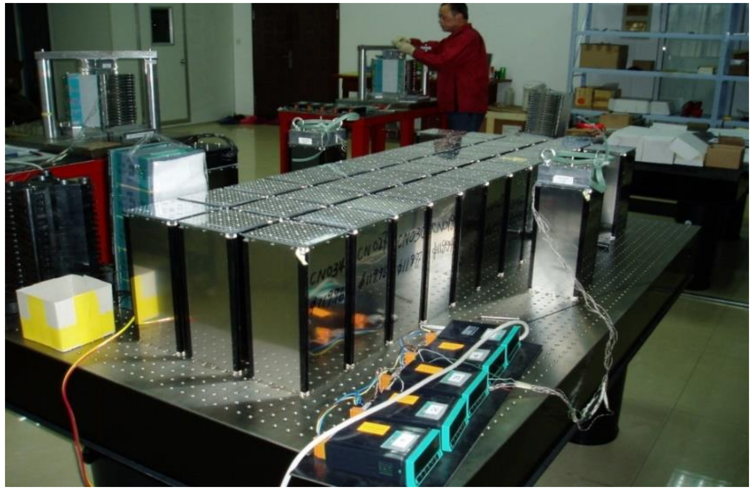
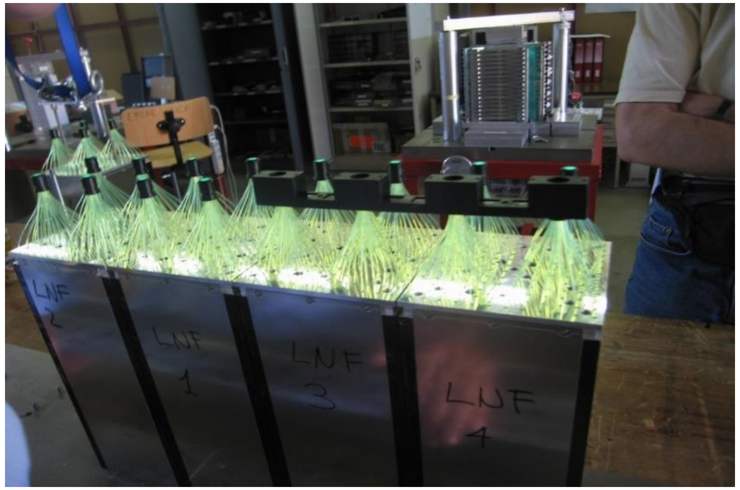
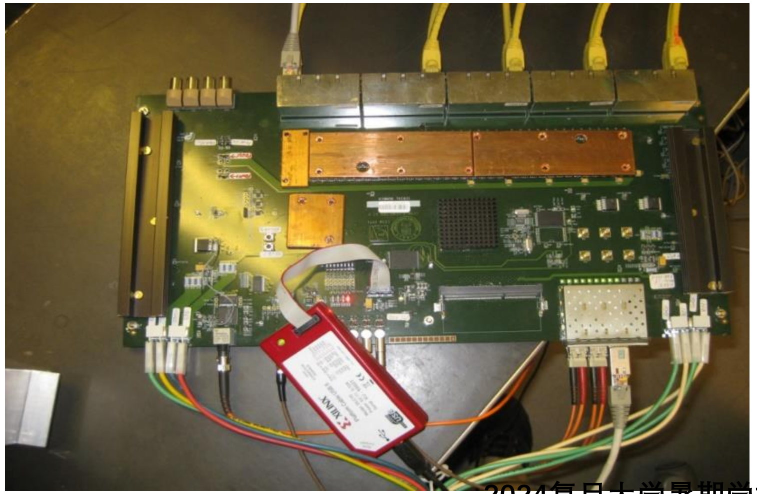
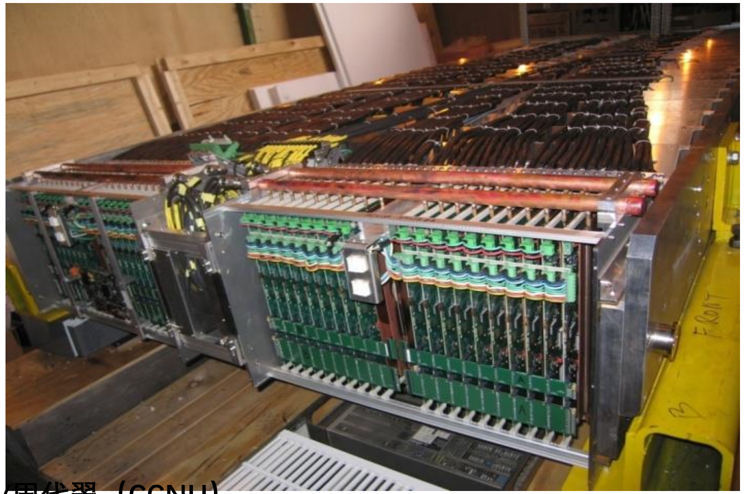




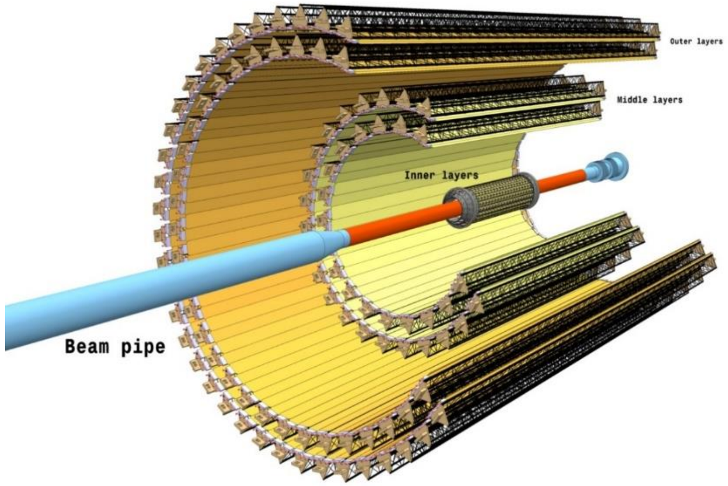
双喷注电磁量能器（DCAL）及其读出电子学

合作研制ALICE取样电磁量能器及其读出系统（2009–2015年）

- 中方建造了一个超级模块及读出系统，掌握了Shashlik取样量能器研制技术
- 测量双喷注、光子-喷注

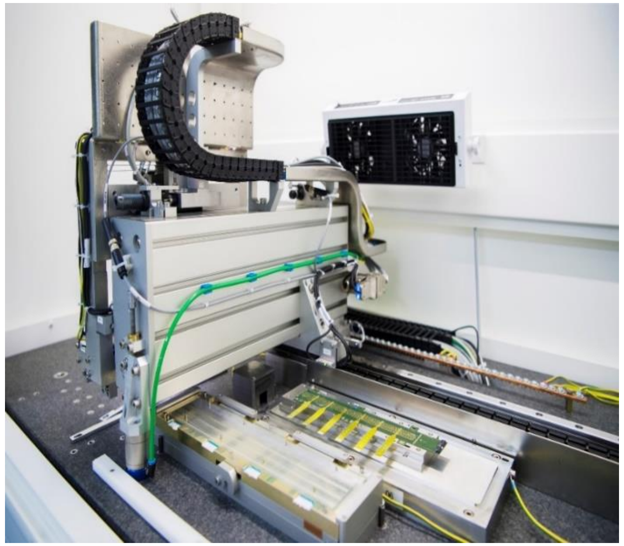
硅像素寻迹探测器ITS2芯片设计及硅像素模块研制

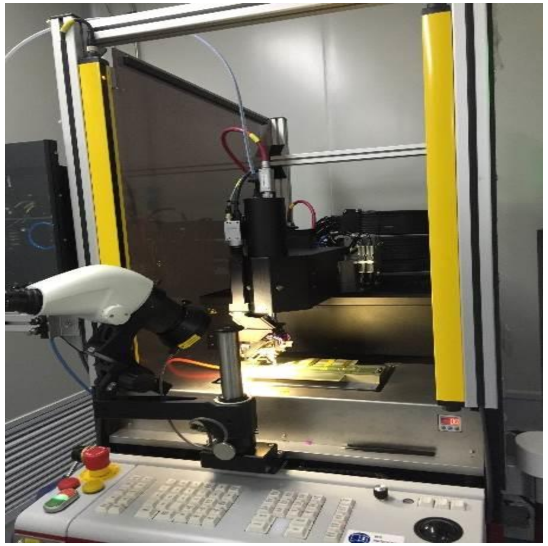


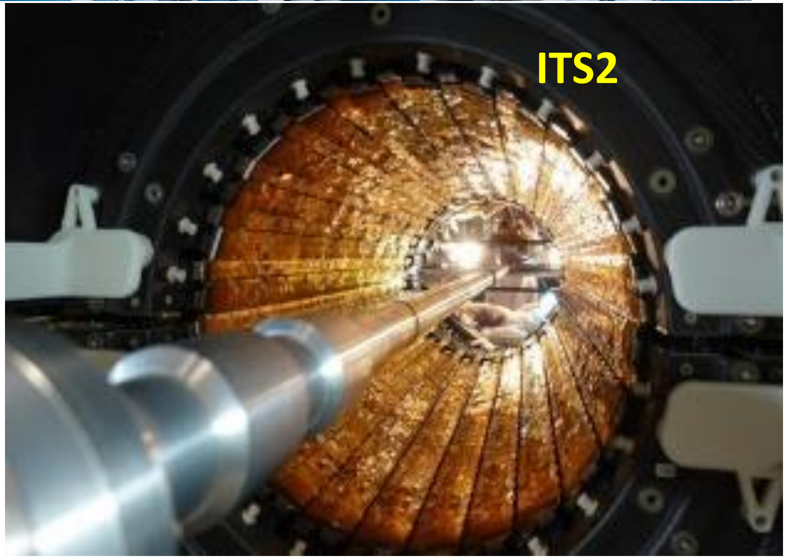
- 基于0.18 μm工艺单片有源硅像素传感器技术
- 用于顶点及带电粒子的高精度测量

（空间分辨率提高10倍以上，读出速率提高50倍以上）

- 参与硅像素芯片设计；完成了升级探测器1/5芯片模块的建造与安装调试

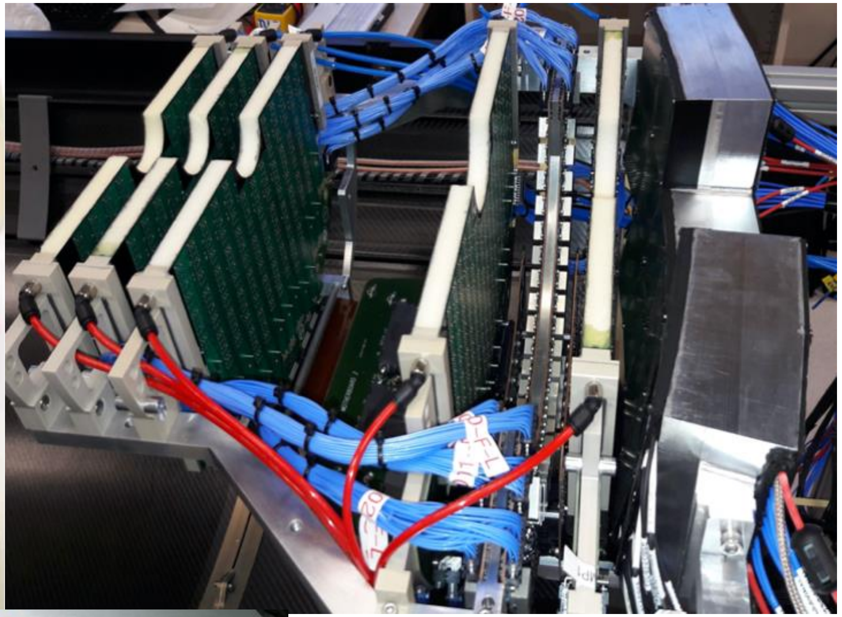


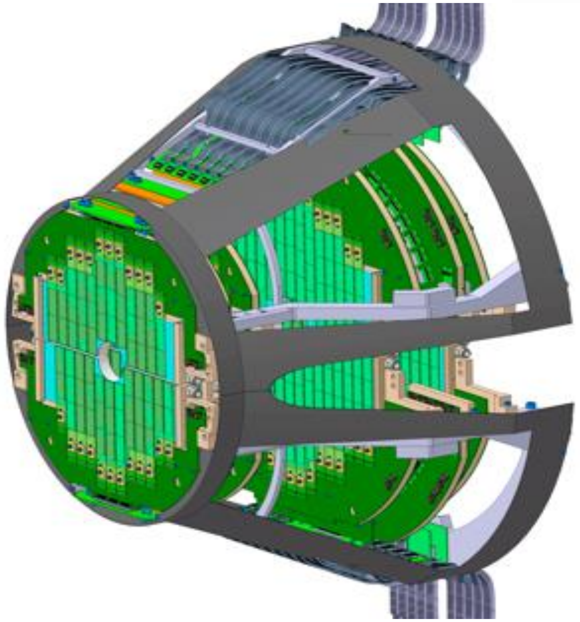


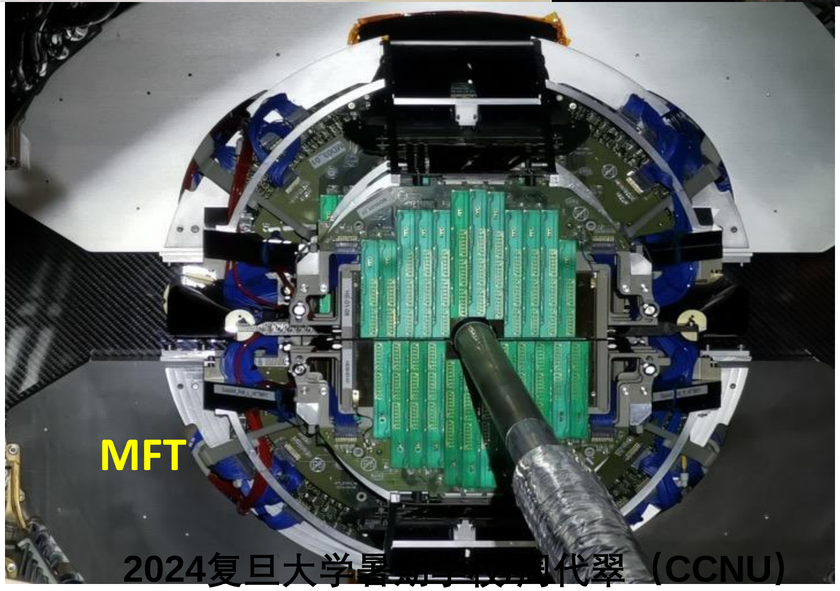


ITS upgrade HIC assembly at CCNU/Wuhan

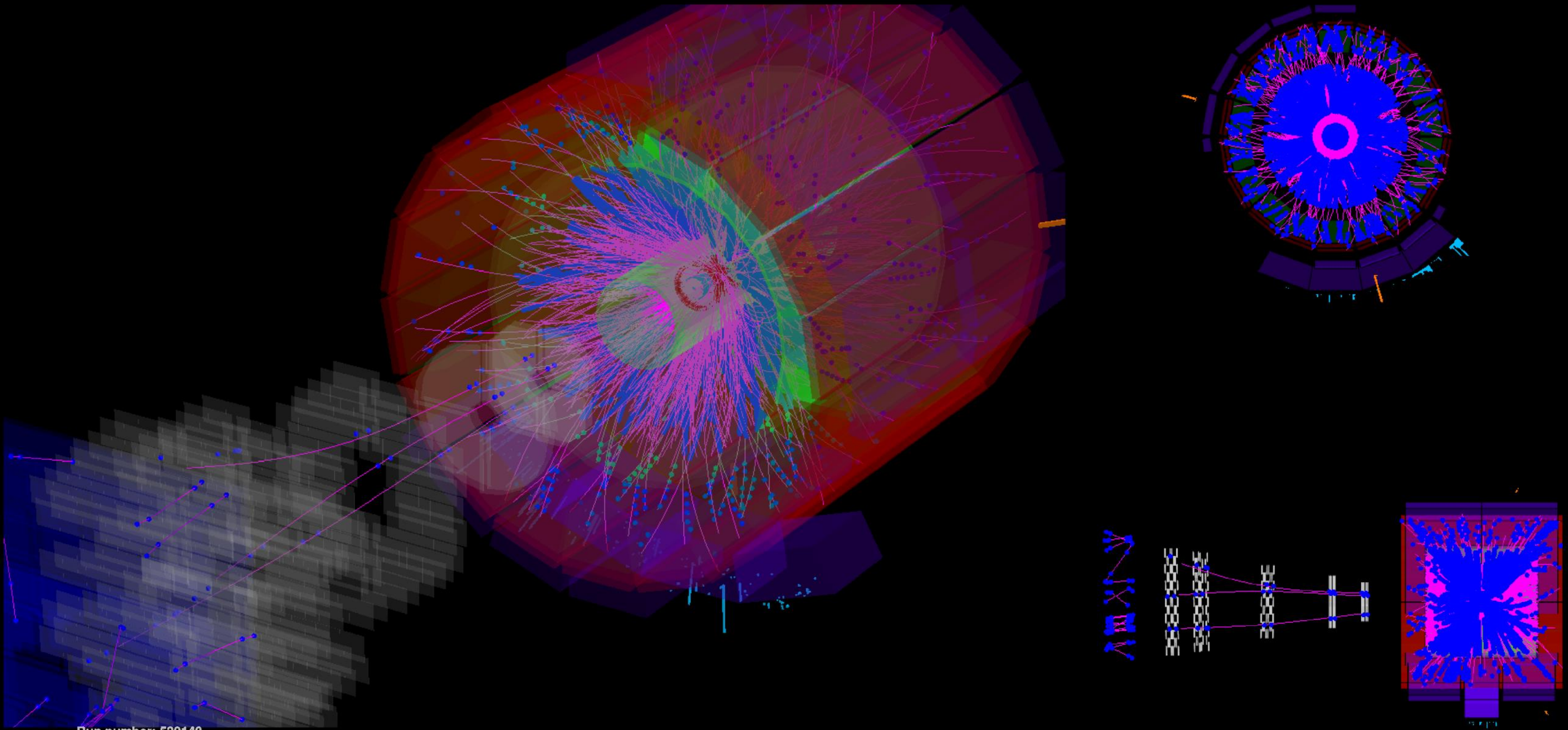
硬件贡献四：前向缪子径迹探测器—MFT电子学母版研制







- 参与探测器研发及物理分析可行性研究
- 完成了探测器核心电子学母板设计与建造
- 用于高精度测量重夸克衰变顶点



Run number: 520143
First TF orbit: 692888
Date: Tue Jul 5 16:53:05 2022
Detectors: ITS,TPC,TRD,TOF,PHS,EMC,MFT,MCH,MID

Thanks for your attention !

and

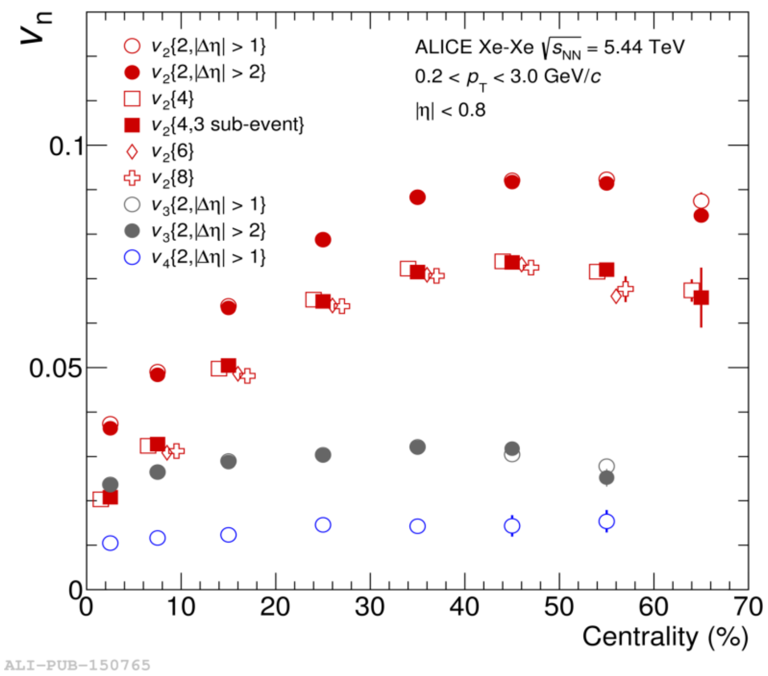
Many thanks to Francesca Bellini, Jan Fiete Grosse-Oetringhaus, Xiaoming Zhang , Jianhui Zhu, Yuanjie Li, Johanna Stachel, Peter Braun-Munzinger, Andrea Dainese, Federico Antoniri, Nuciano Musa, Xinye Peng, Siyu Tang for their inspiring previous lecture slides and useful discussion, and to Yugang Ma, Jinhui Chen, Guoliang Ma, Xuguang Huang, Jie Zhao, Dingyu Shao, Li Yan, xiankan Deng and Fudan team for the nice organization of the summer school.

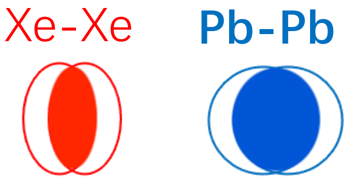
Backup

Anisotropic flow

The **strong centrality dependence** of v_2 reflects the degree of "anisotropy" in initial geometry.

Fluctuations of the initial state energy-density lead to different shapes of the overlap region
→ **non-zero higher-order flow** coefficients ("harmonics")





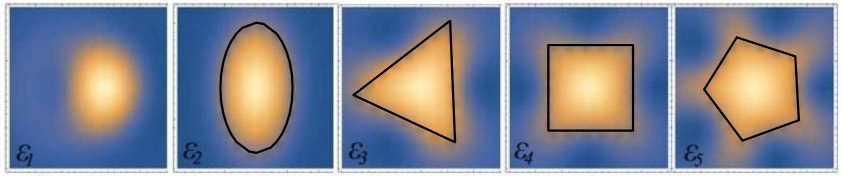
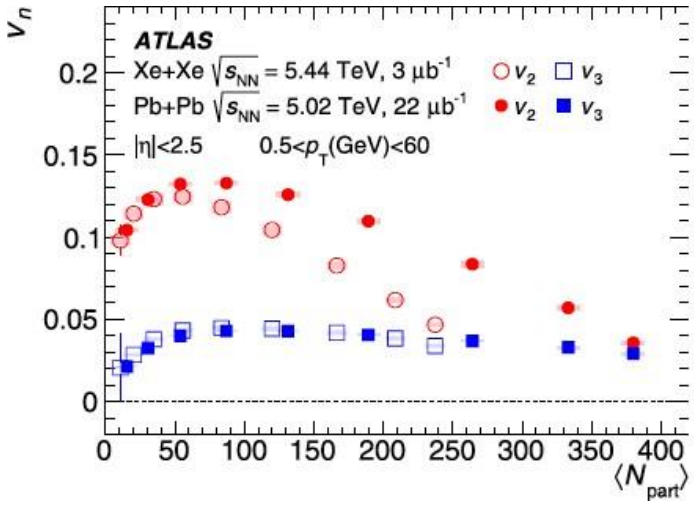
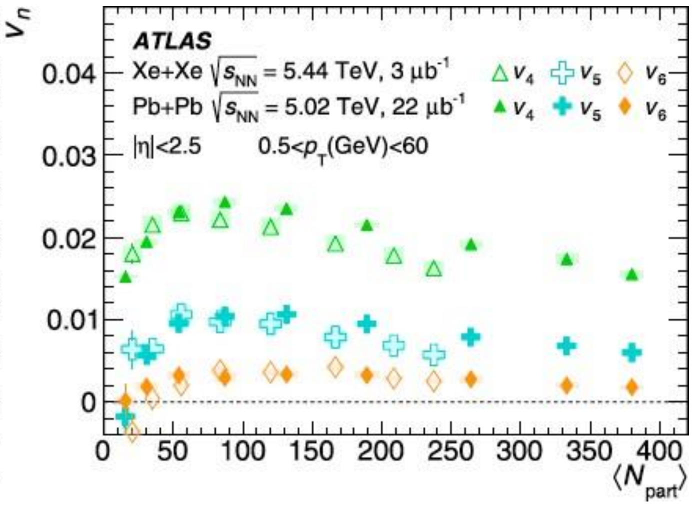


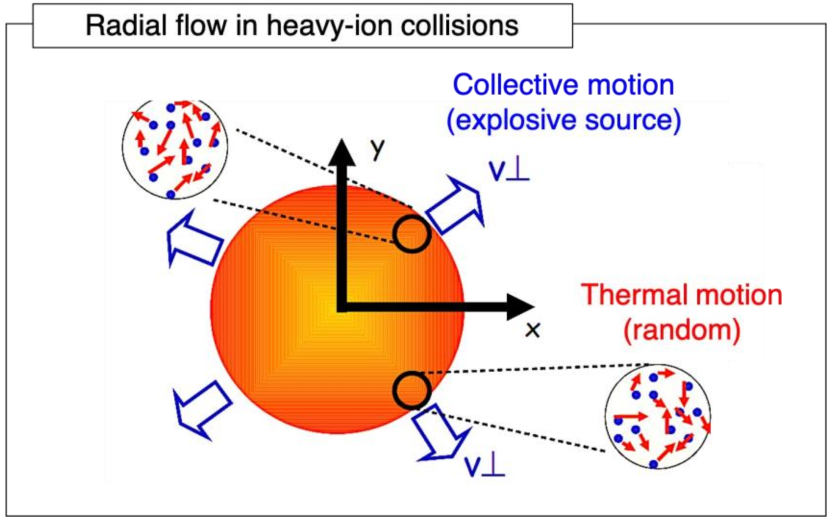
Fig. 2. (color online) Characteristic shapes of the deformed initial state density profile, corresponding to anisotropies of $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, $\mathcal{E}_4$ and $\mathcal{E}_5$ (from left to right).





Radial flow

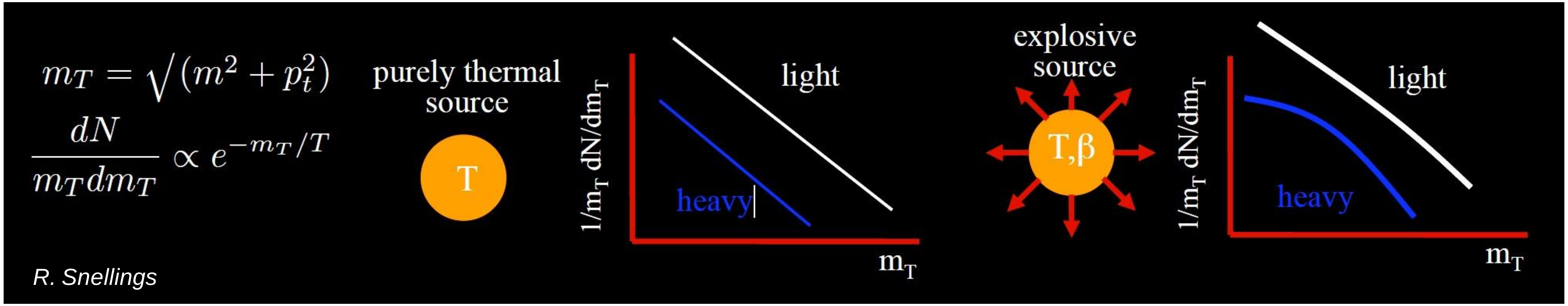
A **collective motion** is superimposed to the thermal motion of particles → the system as a **medium**



Radial flow

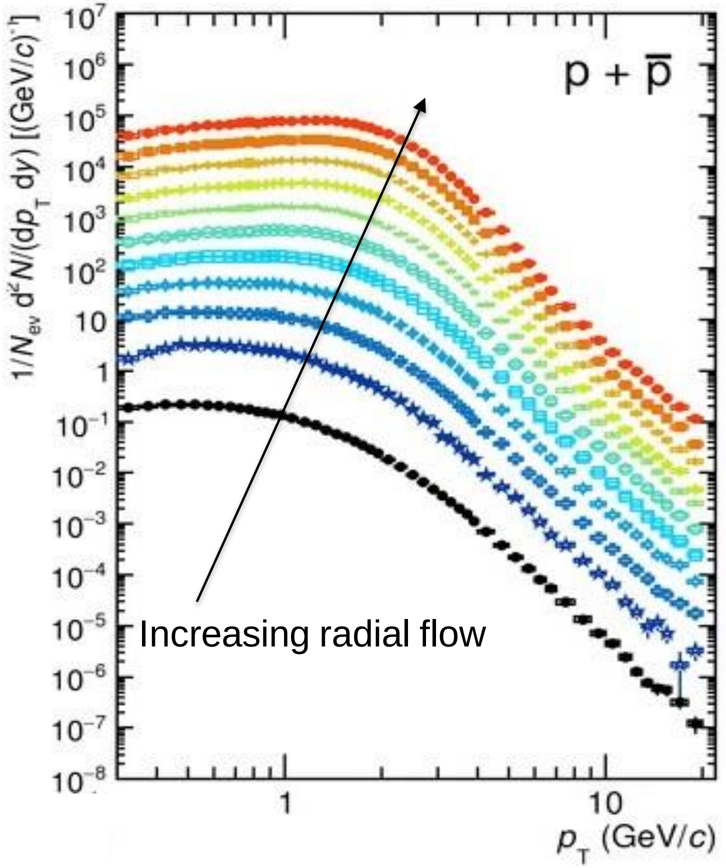
radial expansion of a medium in the vacuum under a common velocity field

→ Affects the low p_T distribution of hadrons and their ratios depending on their mass



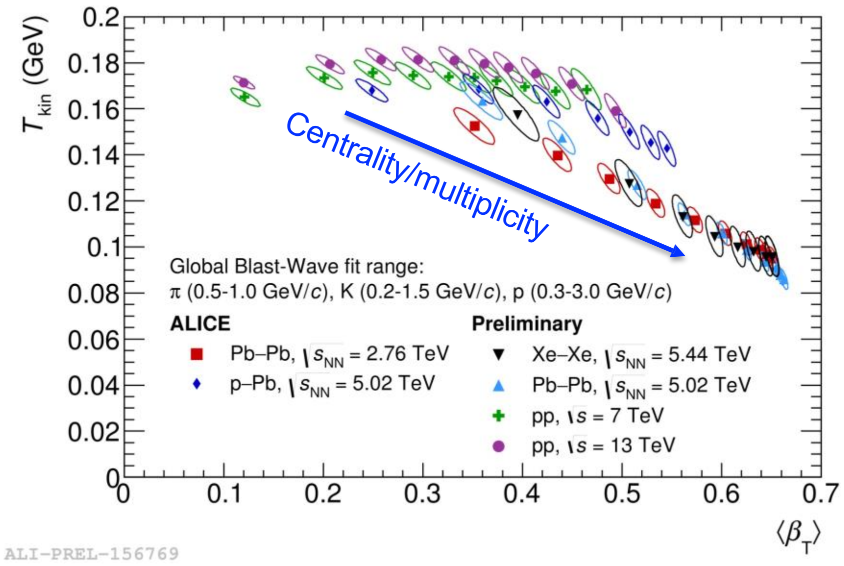
35

Radial flow



At low p_T, the radial flow "pushes" particles to higher momenta
→ spectra get "harder" for more central collisions
→ mass dependence

A simplified hydrodynamical model, the Boltzmann-Gibbs blast - wave model is used to **quantify radial flow and the kinetic freeze-out temperature.**



More central (higher multiplicity) events have

lower T_{kin} and higher flow velocity

T_{kin} ~ 100-140 MeV

Hadronisation by fragmentation and recombination

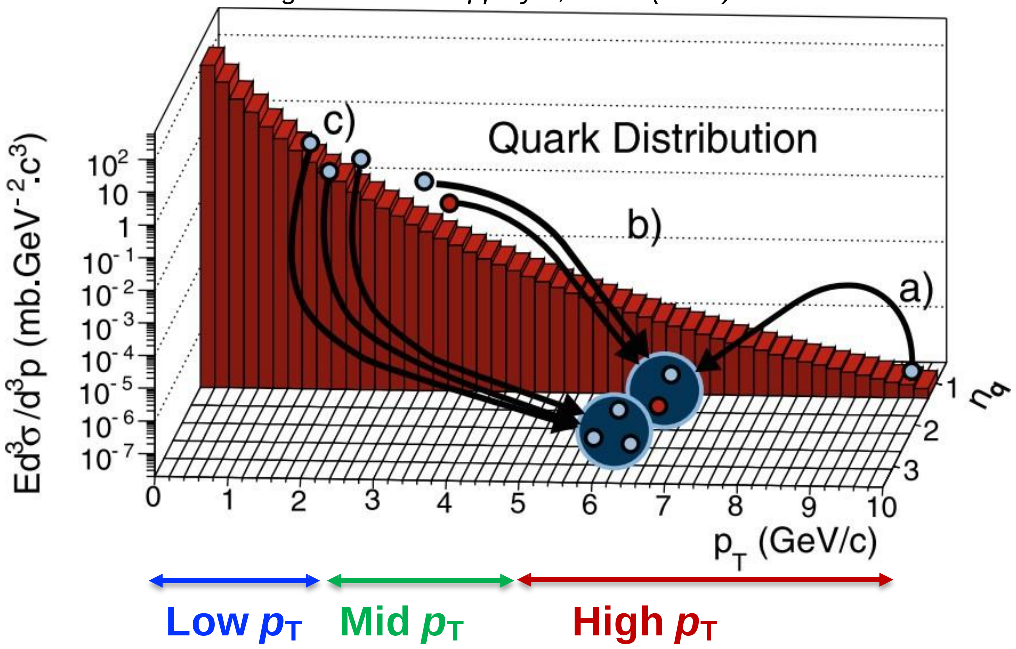
Ratios of production distribution of baryons to mesons are sensitive to competing particle production mechanisms, depending on transverse momentum

Fragmentation (a) of high-p_T partons into mid-p_T hadrons

Recombination (b,c) of low-p_T partons close in phase space into mid-p_T hadrons via coalescence

+ influence of **collective flow**

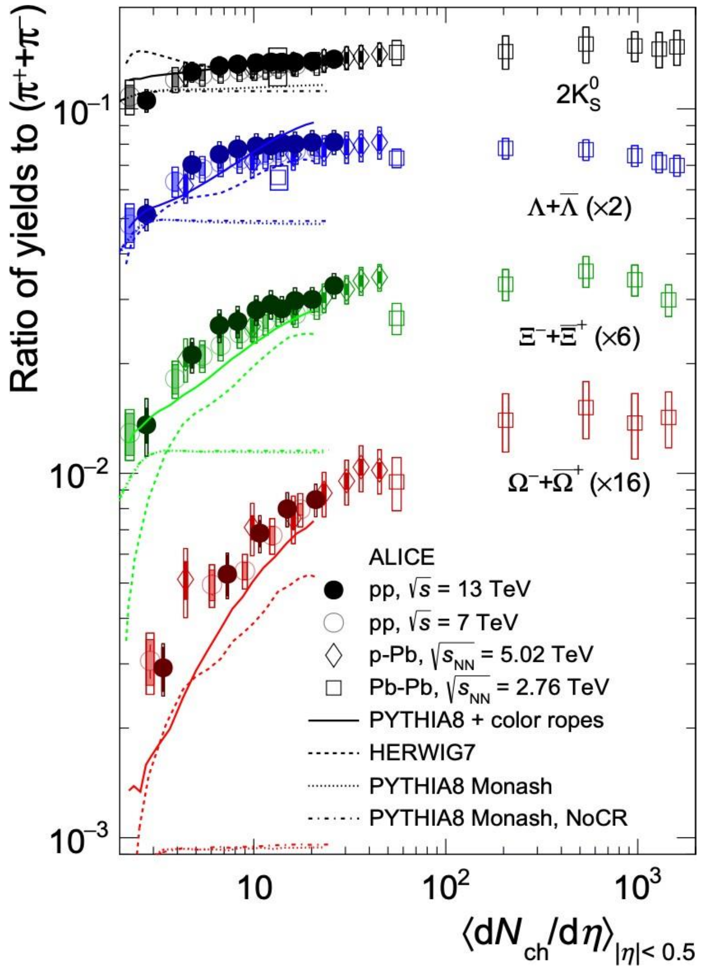
Figure from B. Hippolyte, EPJC (2009) 62: 237–242



Strengeness enhancement from small systems

Nature Physics 13 (2017) 535-539,
EPJC 80, (2020) 167 and 693

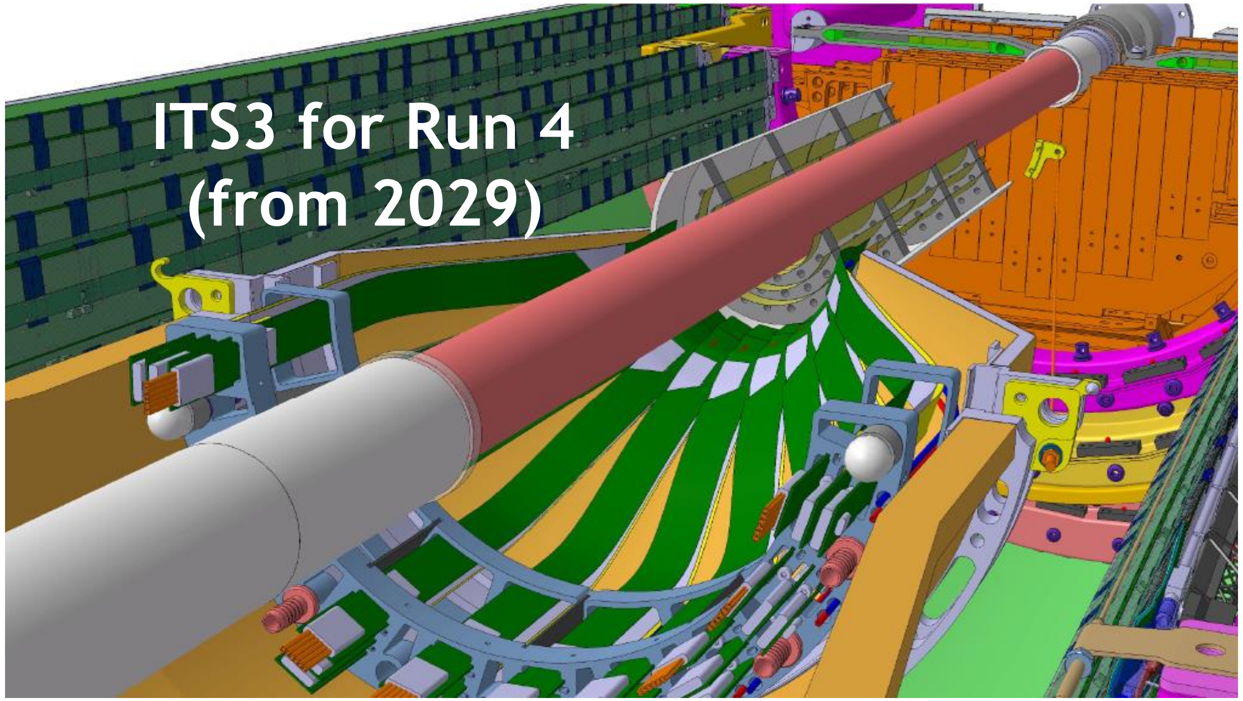
- Multi-strange yields increase significantly and smoothly with multiplicity in pp, p–Pb to saturation of Pb-Pb collisions
- strangeness enhancement relative to pp suggested as QGP signature
- Particle composition evolves smoothly across collision systems, depending only on final-state multiplicity

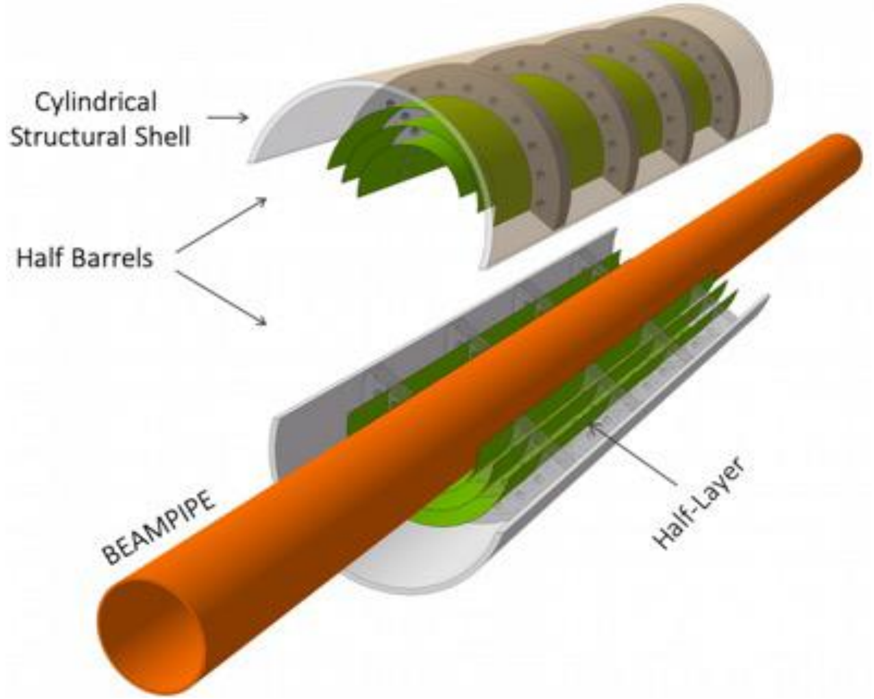


Challenge for models :

On microscopic mechanisms for hadron production (string overlap, color reconnection) **to the onset of a QGP** (thermalization, equilibration)**?**

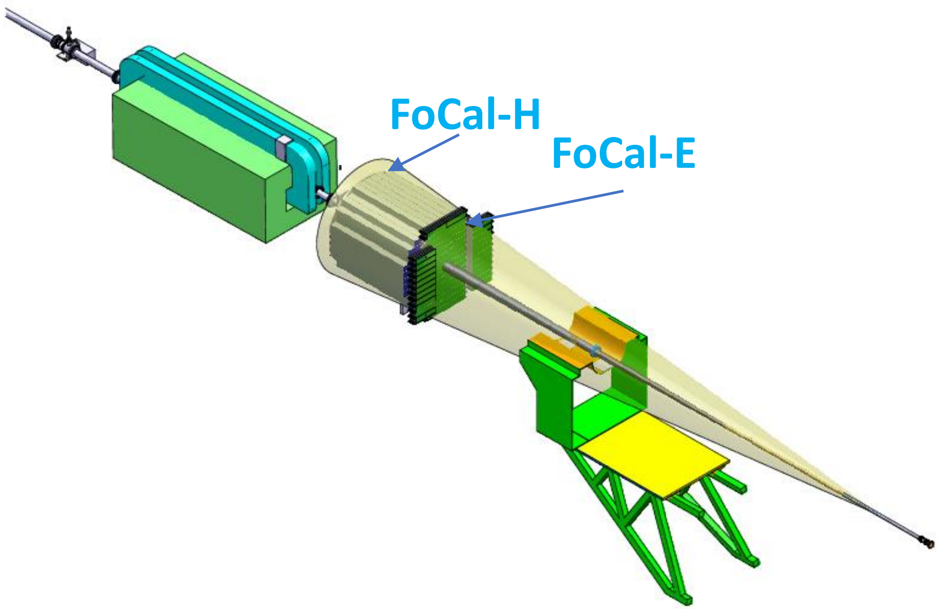
LS3期间的ALICE升级：ITS3

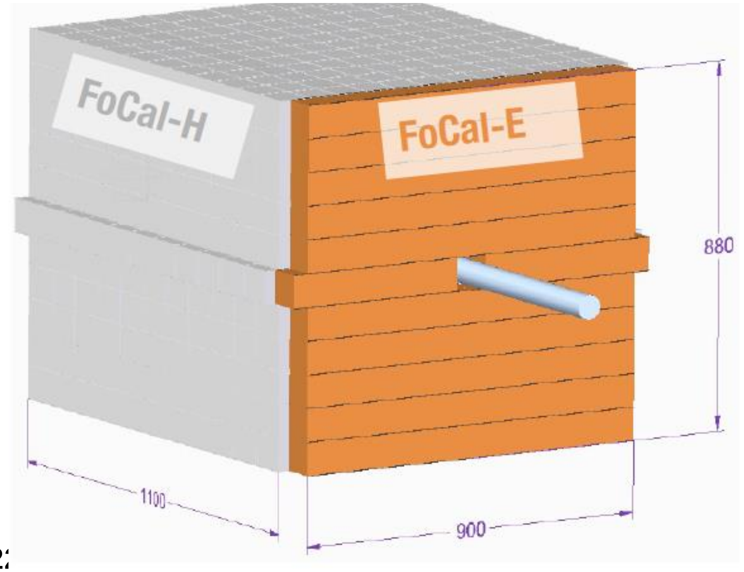




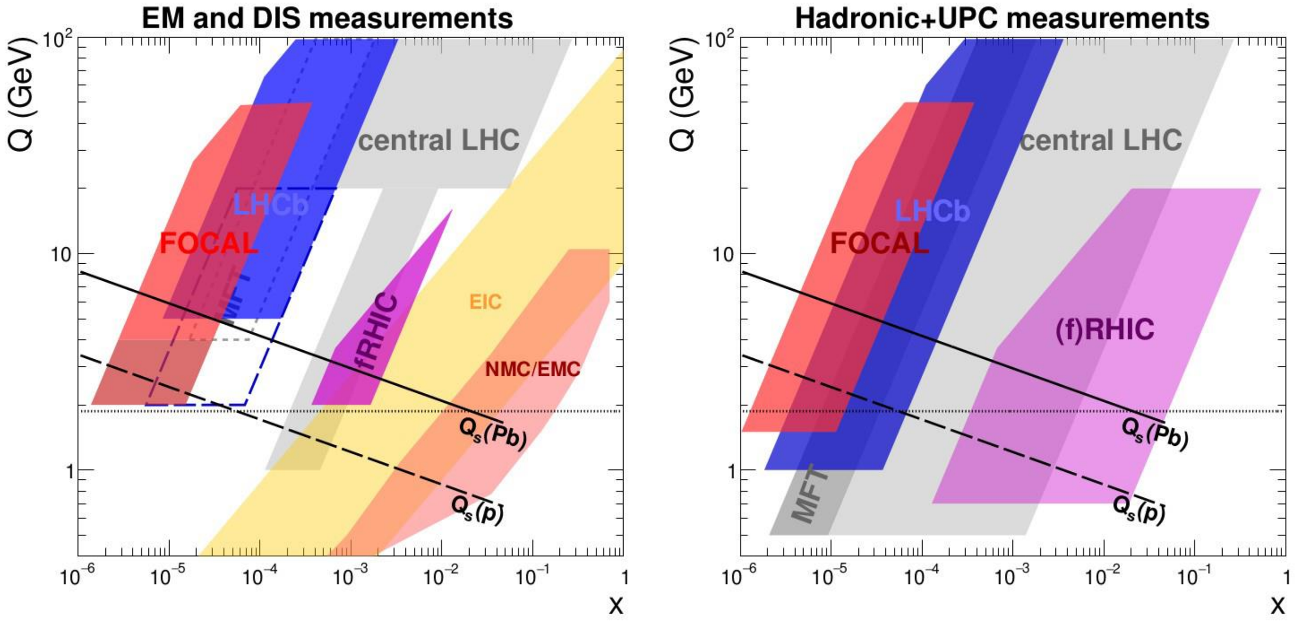
- 非常小的探测器材料辐射长度（$0.05\%X_0$）
- 非常均匀的材料分布，减小系统误差
- 更细的束流管，探测器最内层半径更小
- 进一步提升内寻迹系统的位置分辨性能和低横动量带电粒子重建本领

LS3期间ALICE升级： FoCal



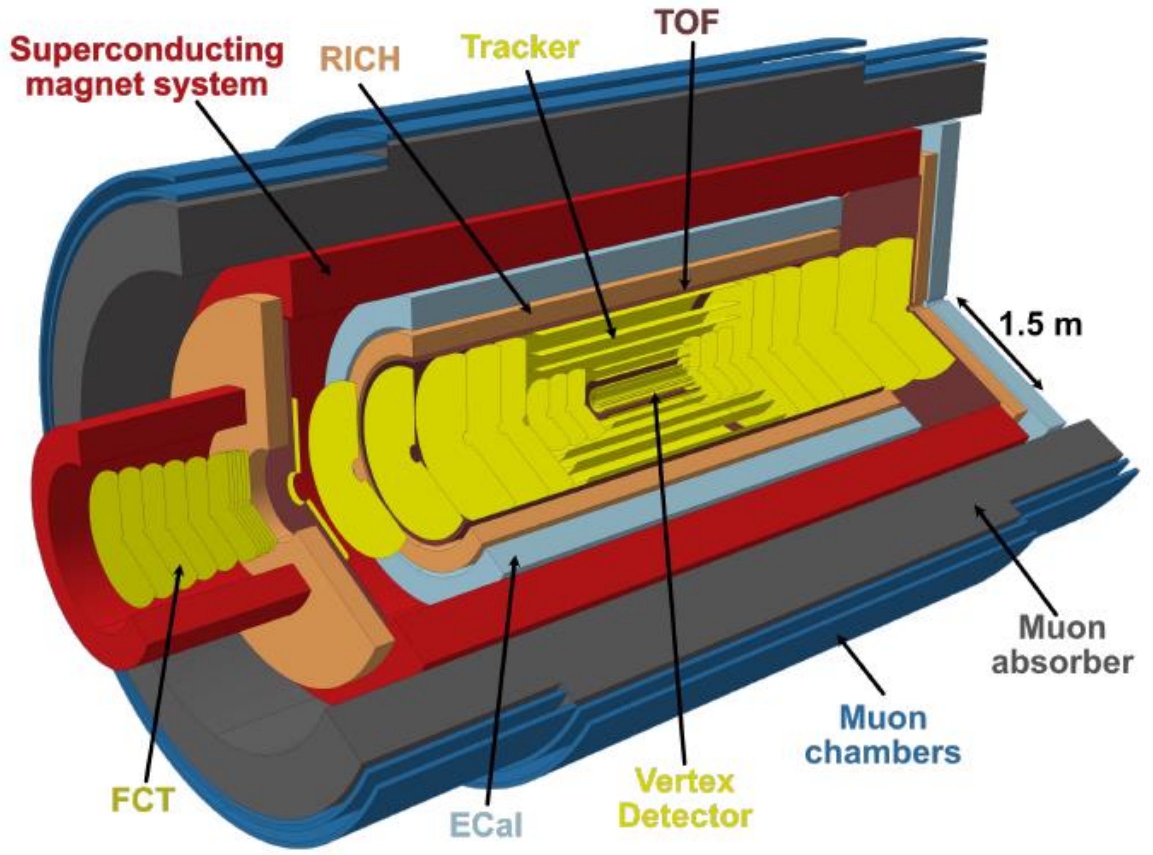


- **FoCal-E: 18层粒度为1x1cm2硅片+2层硅像素层取样型电磁量能器**
- **Focal –H: 铜管+闪烁光纤意大利面型强子量能器**



- **FoCal将拓展*Q-x*探测区域**
- **研究小*x*物理及QCD非线性动力学**

LS4期间的ALICE全新探测器：ALICE3



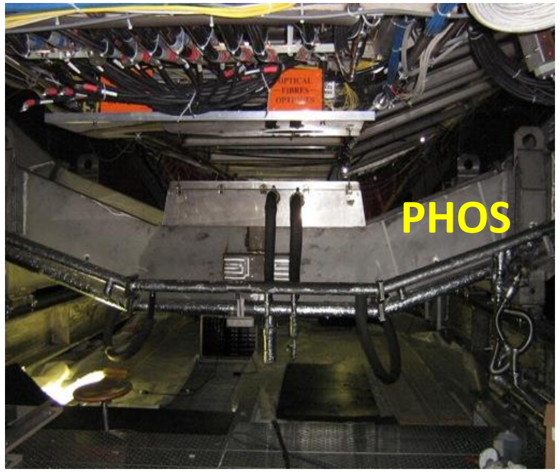
- 紧凑、超轻的全硅寻迹系统
  - 高动量分辨能力
  - 高顶点分辨本领
- 大接收度
- 优良的带电粒子鉴别能力（TOF+RICH）
- 缪子鉴别
  - 横动量低至1.5 GeV/*c*
- 电磁量能器
  - 大快度区探测光子和喷注
  - 高能量分辨率
- 2 T的超导磁铁系统
- 连续读出和在线数据处理系统

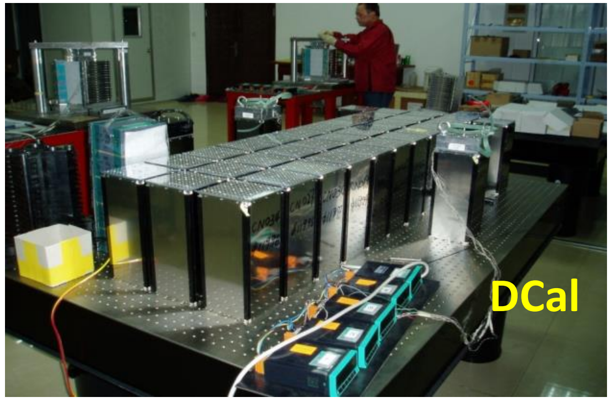
— Letter of Intent: CERN-LHCC-2022-009

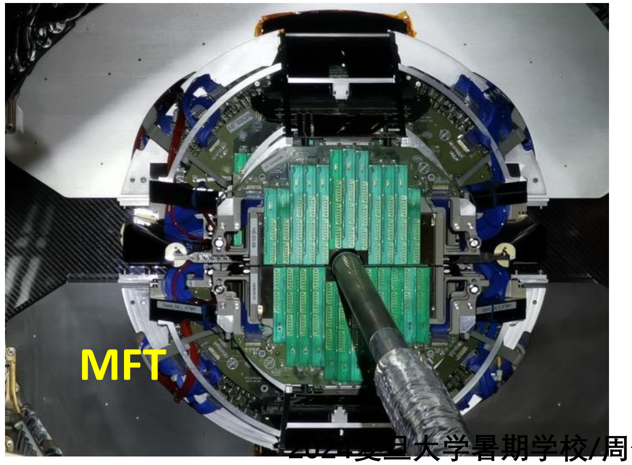
- ALICE3基于创新技术的新型探测器概念
- 她将研究在极端能量密度下QCD物质的基本特性
  —low-pT heavy-flavour
  —electromagnetic radiation from QGP
- 将也在其他领域开辟重要的新物理的研究机遇

中国ALICE组已经、正在和未来将完成的工作

- 已完成
  - 光子谱仪（PHOS）及其前端电子学研制
  - 双喷注电磁量能器（DCal）的研制
  - 第二代内寻迹系统（ITS2）的研制
  - 前向缪子寻迹系统（MFT）的读出链路板研制







- 正在参与的工作
  - 用于ITS3的晶圆尺寸的超薄硅像素芯片的研发
  - FoCal硅像素层的研发

- 未来将完成的工作
  - 合作研发出用于ITS3的晶圆尺寸的超薄硅像素芯片
  - 合作研制出FoCal电磁量能器的硅像素层
  - 参与ALICE3探测器的R&D和探测器的建造