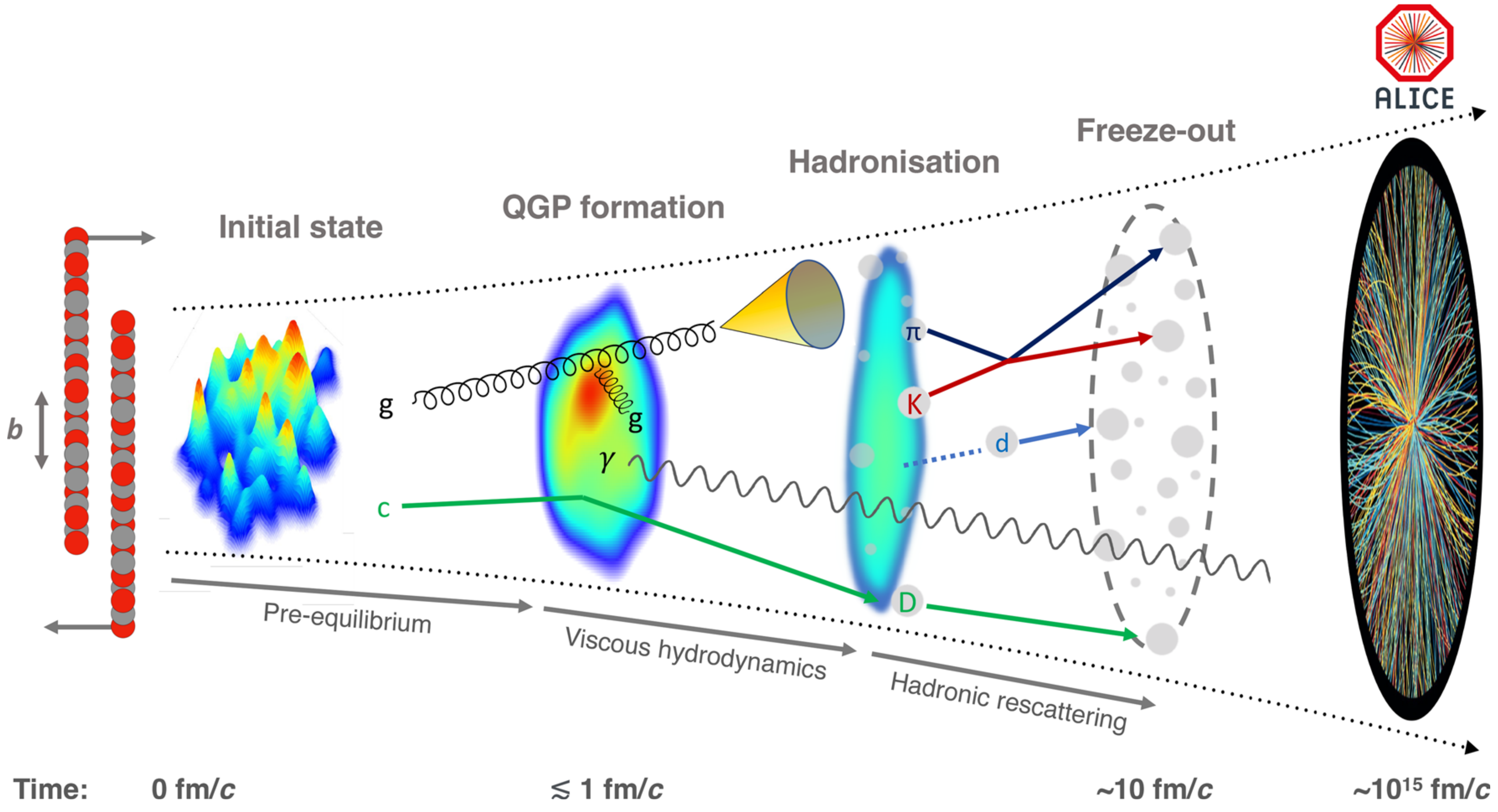
ALICE Highlight

권민정
인하대학교

2025.11.20
KSHEP fall workshop 2025


빅뱅 수 마이크로 초 직후,
고온 고밀도의 강한 상호작용을 하는 쿼크와 글루온으로 이뤄진 물질이 생성됨
쿼크-글루온 플라즈마 (QGP)
가장 근원적인 물질의 상태!

ALICE 실험; LHC를 이용해 중이온을 충돌시켜 초기 우주 재현



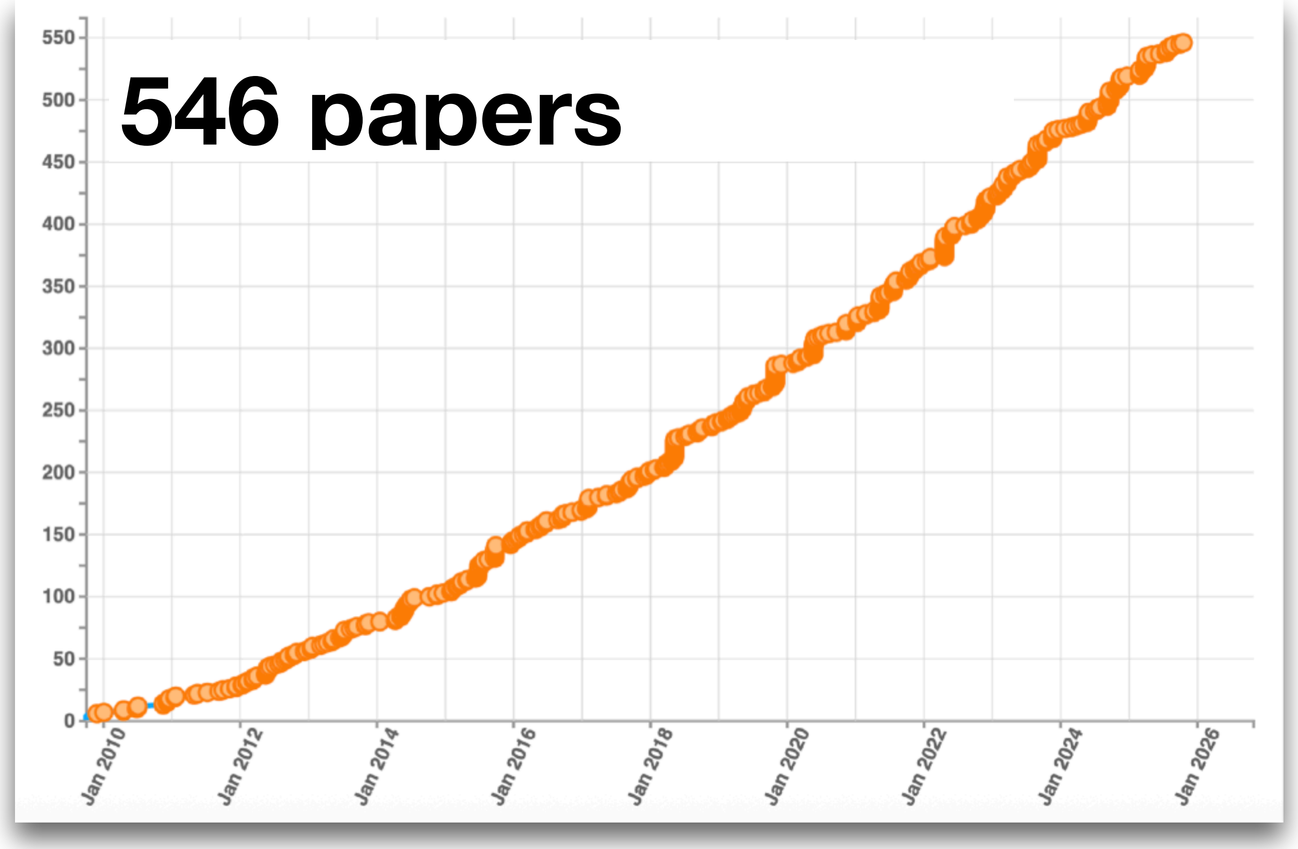
ALICE review paper

Eur. Phys. J. C 84, 813 (2024)

ALICE/KoALICE collaboration

ALICE Collaboration

- 1041 authors, 1861 members
- 147 member institutes, 23 associate
- 40 countries



KoALICE

Participants: 56

- 7개 대학
- 교수급: 10
- 박사후 연구원 : 8
- 대학원생: 35
- 기타 : 3

* KISTI: 다른 소스 참여 기관 (1)

LHC ALICE, CMS, ATLAS, LHCb
2025년 Breakthrough 기초물리학상 공동 수상

🏆 Breakthrough Prize

- 기초과학의 오스카상, 3백만 달러 상금의 과학 최고 권위 상, 기초과학분야에서 혁신적인 발견과 탁월한 업적을 이룬 연구자들에게 수여되는 세계 최고 수준의 상
- 설립: 2012년, 후원: 실리콘밸리의 주요 기업가들(마크 저커버거 등)
- **목적: 탁월한 과학 연구를 통해 인류의 지식 경계를 확장한 이들을 기리며, 과학이 사회로부터 존경받는 문화를 만드는 것**
- 2025년 상은 기초물리학, 생명과학, 수학 등 총 6개 부문에서 수상

🏆 ALICE, CMS, ATLAS, LHCb 실험 기초물리학 분야 공동 수상

- LHC Run 2 데이터에 기반한 연구 성과 인정
- 주요 공로
  - **ALICE:** 빅뱅 직후 수 마이크로초 동안 존재했던 쿼크-글루온 플라즈마 상태 연구
  - **CMS, ATLAS:** 힉스 보존 발견 및 특성 정밀 규명, 표준모형 너머의 물리 이론을 정밀하게 검증
  - **LHCb:** 물질-반물질 간의 미세한 차이 정밀 측정, 72종 이상의 새로운 강입자 발견
- 총 상금 3백만달러 전액은 CERN & Society 재단에 기부 (박사과정생 장학금)

High-energy heavy-ion physics: 무얼 알아냈을까?

Understanding the fundamental properties of strongly interacting quark gluon-plasma (QGP) remains one of the key goals in high-energy nuclear physics.

What is the bulk behavior of QCD?

What are the collective features of QCD (Dynamics of heavy-ion collisions)?

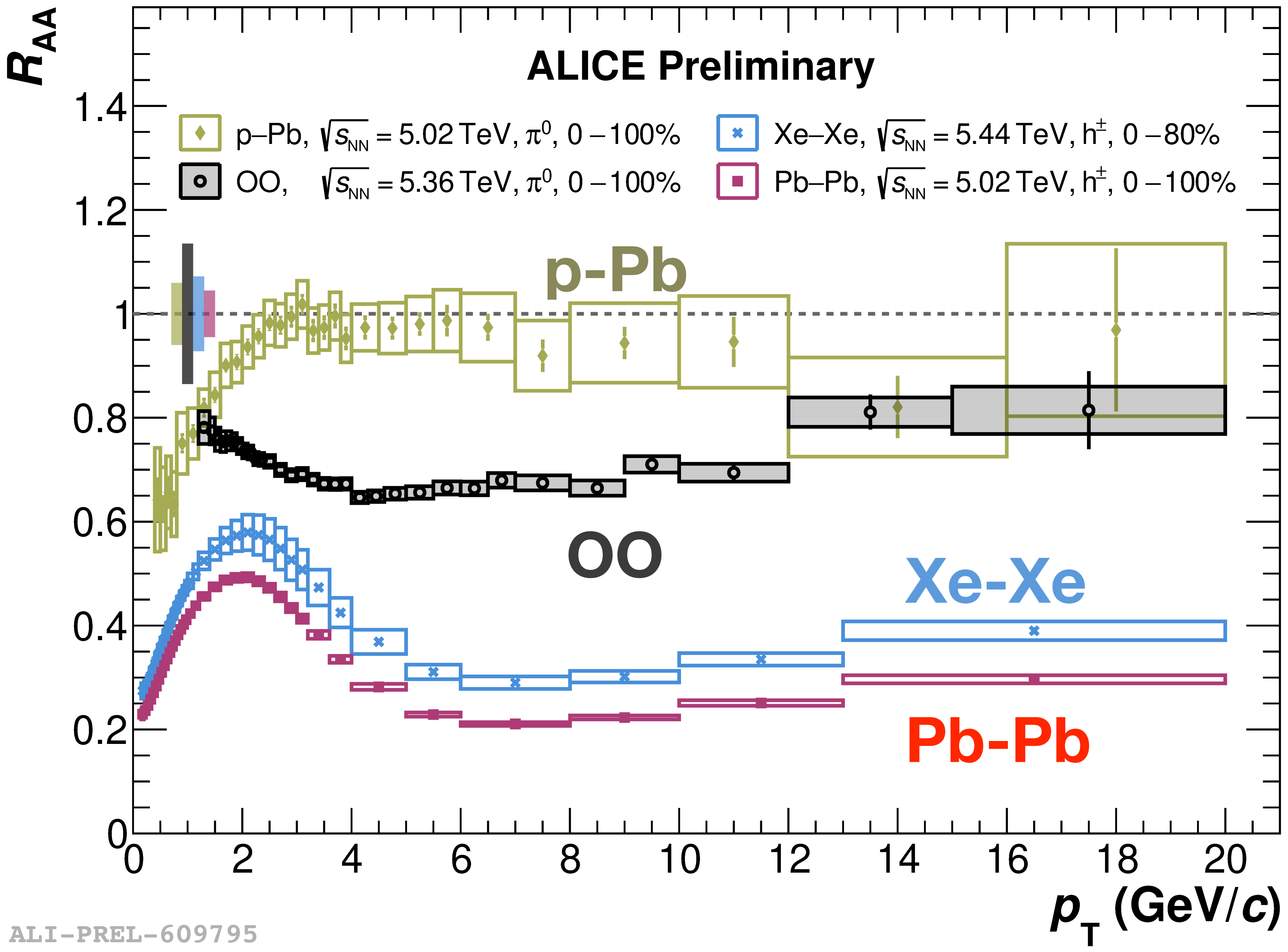
How does the transition from confined matter to deconfined QGP occur?

➡ ALICE is the LHC experiment dedicated to heavy-ion physics!

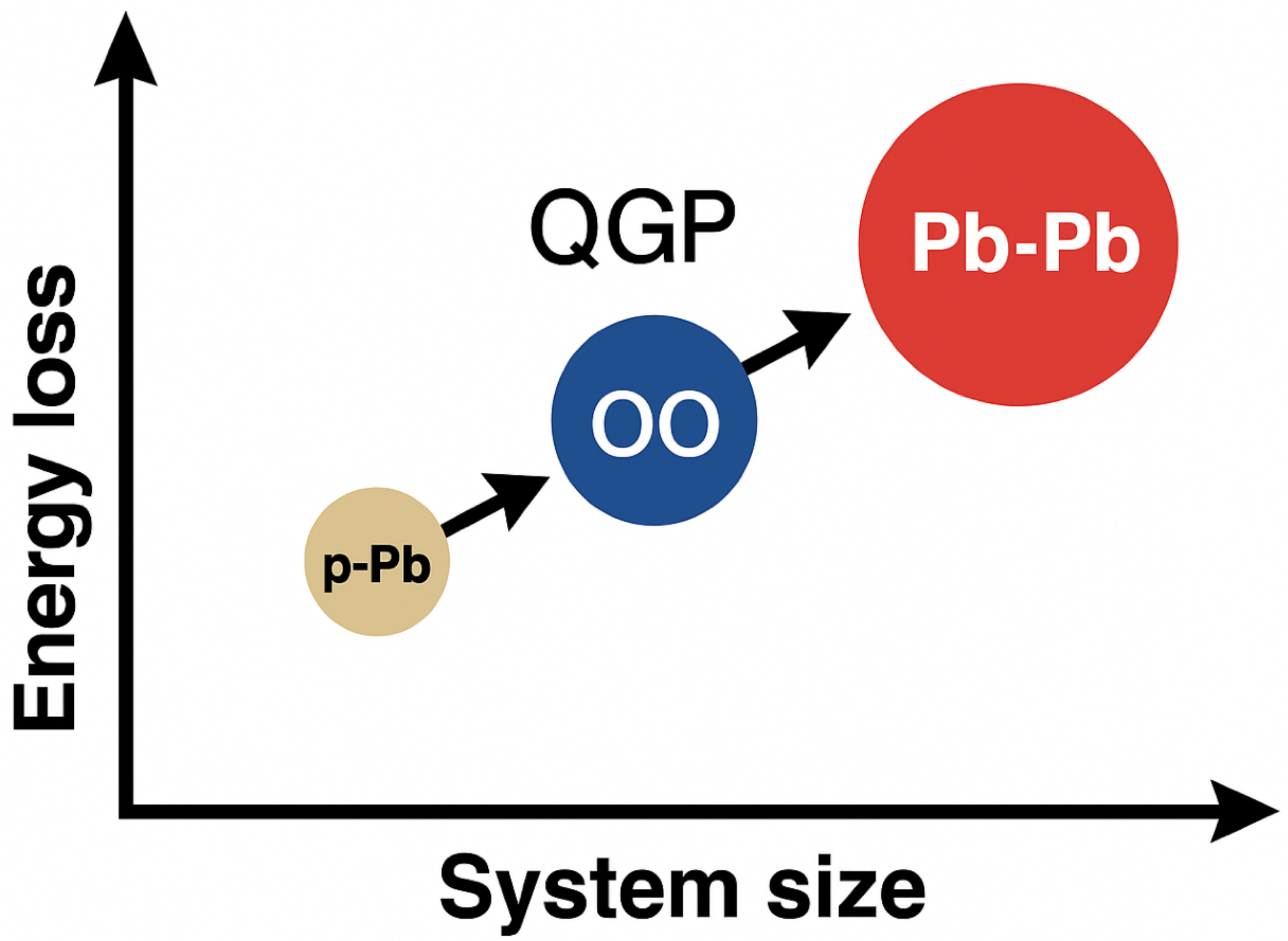
QGP as seen at the LHC

- Energy density > 10 GeV/fm^3
- Colour charge deconfined
- Strong energy loss for hard partons
- Hydro-dynamic expansion like a very-low viscosity liquid
- Hadronization as in thermal equilibrium

QGP의 존재 및 특성 규명: QGP에서의 에너지 손실



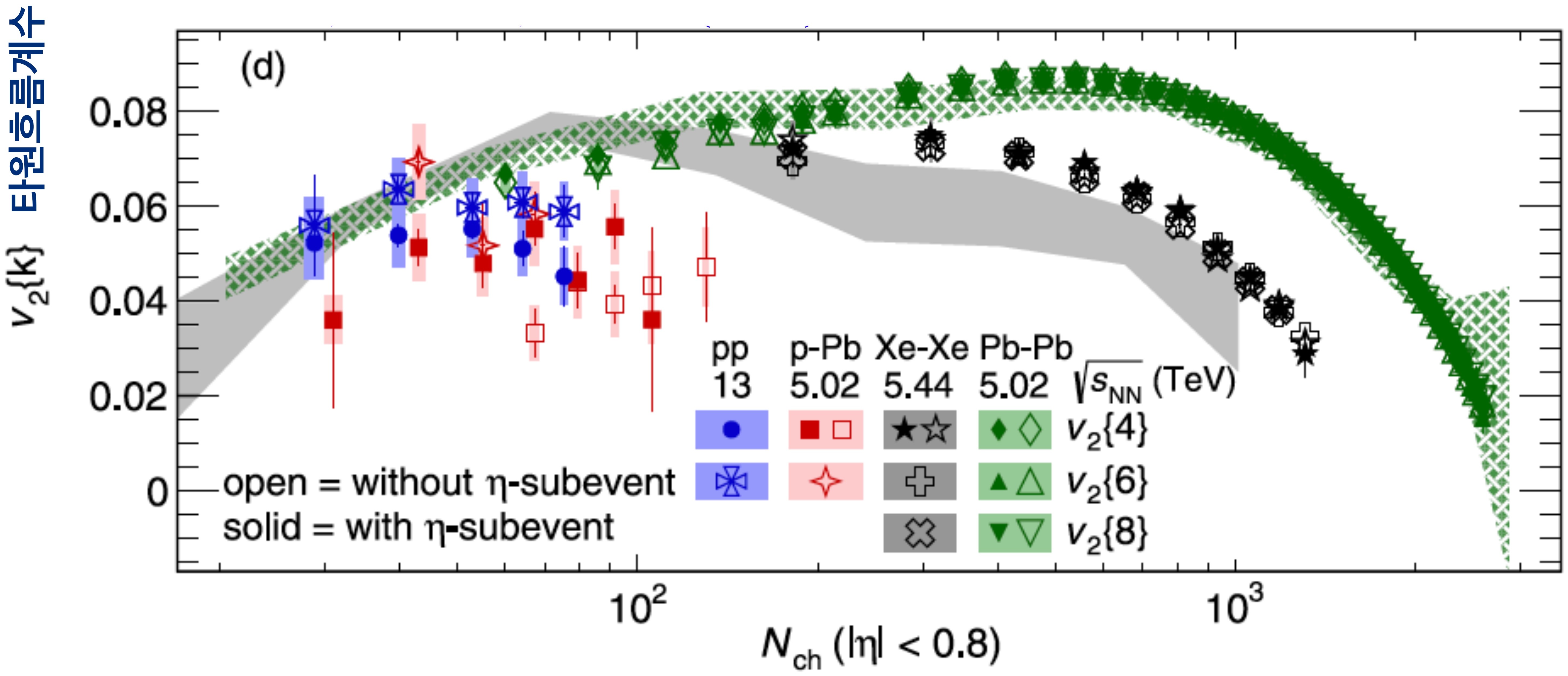
10^12 K 이상의 고온 고밀도 QCD 매질!

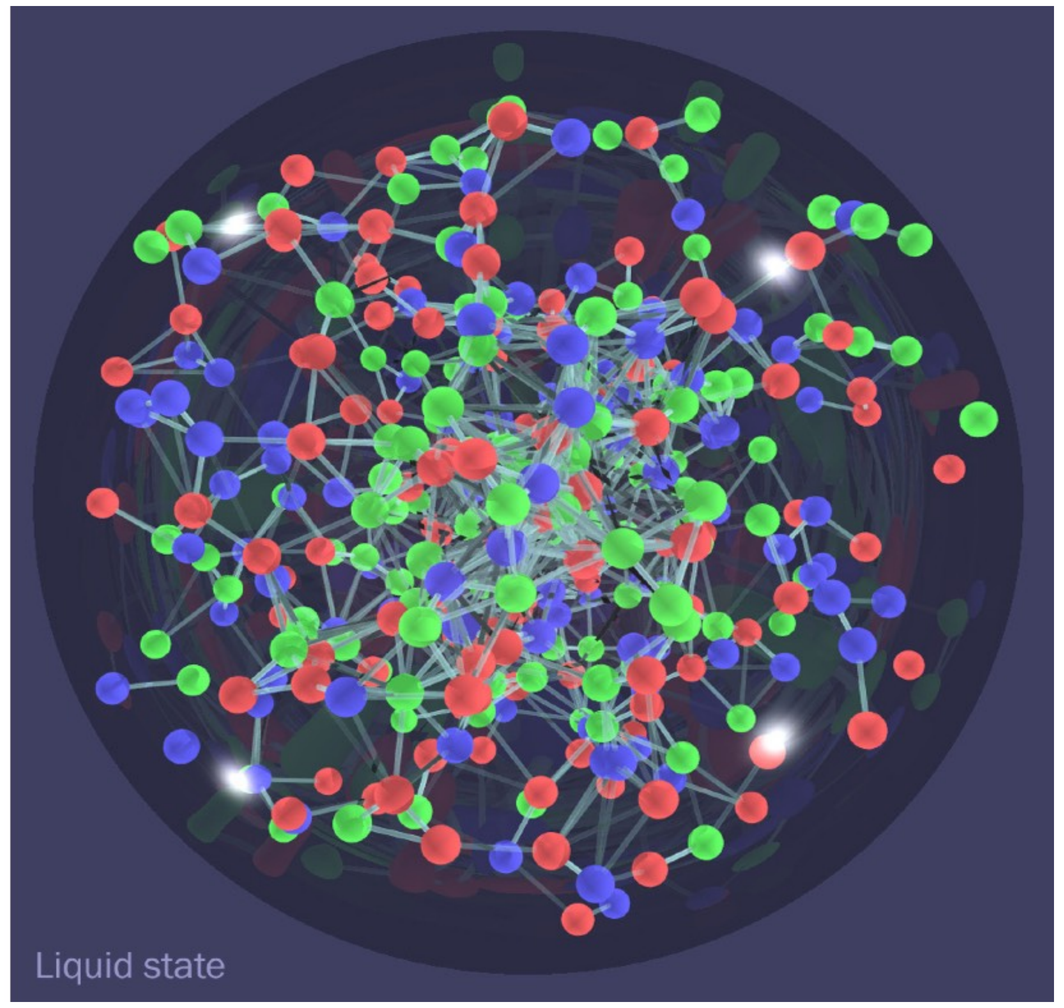


- 시스템이 클수록, QGP가 더 크고 뜨거워져서 입자들이 더 많은 에너지를 잃음 (R_{AA}<1)
- 경량 핵(OO) 충돌에서도 에너지 손실 패턴이 보임
  → 작은 시스템에서도 QGP가 만들어질 수 있는가? 라는 질문에 중요한 단서 제공

QGP의 존재 및 특성 규명: QGP의 흐름 (유체적 성질)

Perfect fluid 처럼 집단적으로 흐르는 strongly coupled system!





- 타원흐름은 충돌 규모가 커질수록 증가함 (타원흐름이 클 수록 QGP의 유체적 성질이 강하게 나타남)
- 충돌에서 생성된 입자수가 충분히 커지면, 작은 시스템에서도 타원흐름이 나타남

→ 양성자-양성자 충돌과 같은 작은 충돌 시스템에서도 유체적 흐름 발견!

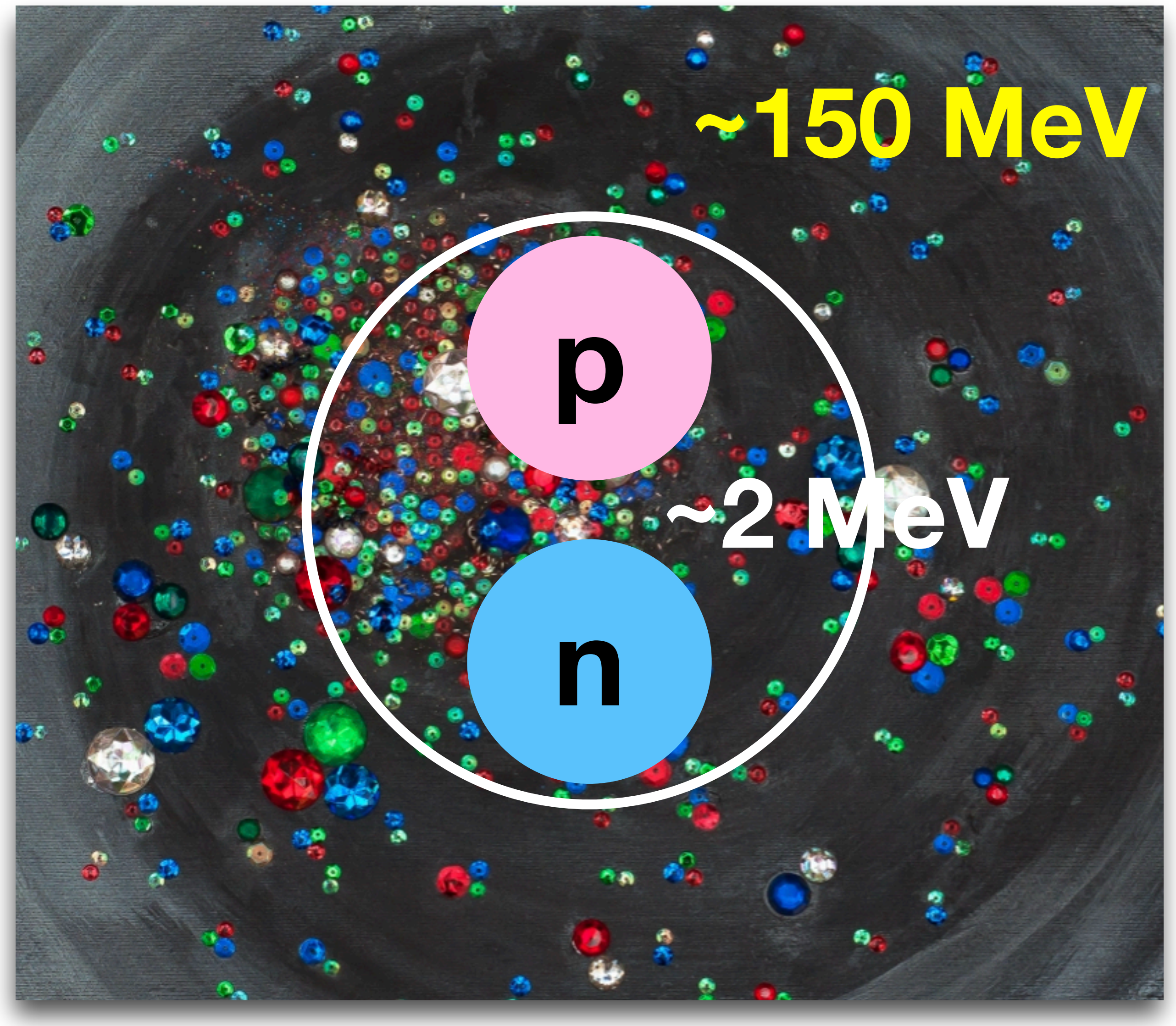
ALICE, 중수소 생성 메커니즘을 규명하다!: 2025년 Nature Accepted

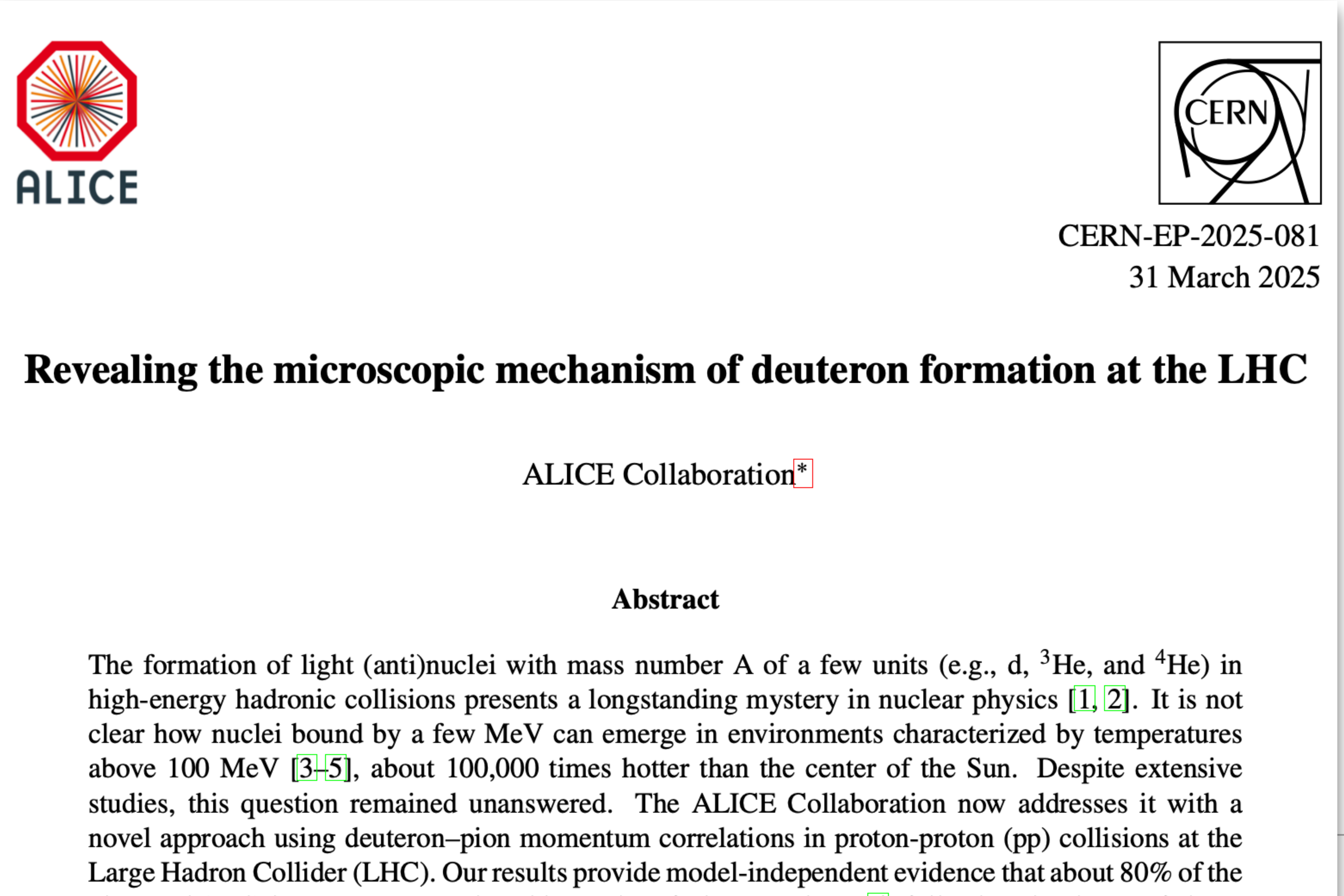
결합에너지가 2.2 MeV 밖에 안되는 deuteron이

어떻게 극한 환경에서 생성되고 살아남을까?

충돌 직후 생성되는 Δ와 같은 짧은 수명의 공명 상태가 붕괴하면서 생성된 핵자들이 서로 결합해 중수소

(deuteron)을 만든다는 것을 실험적으로 증명!





ALICE

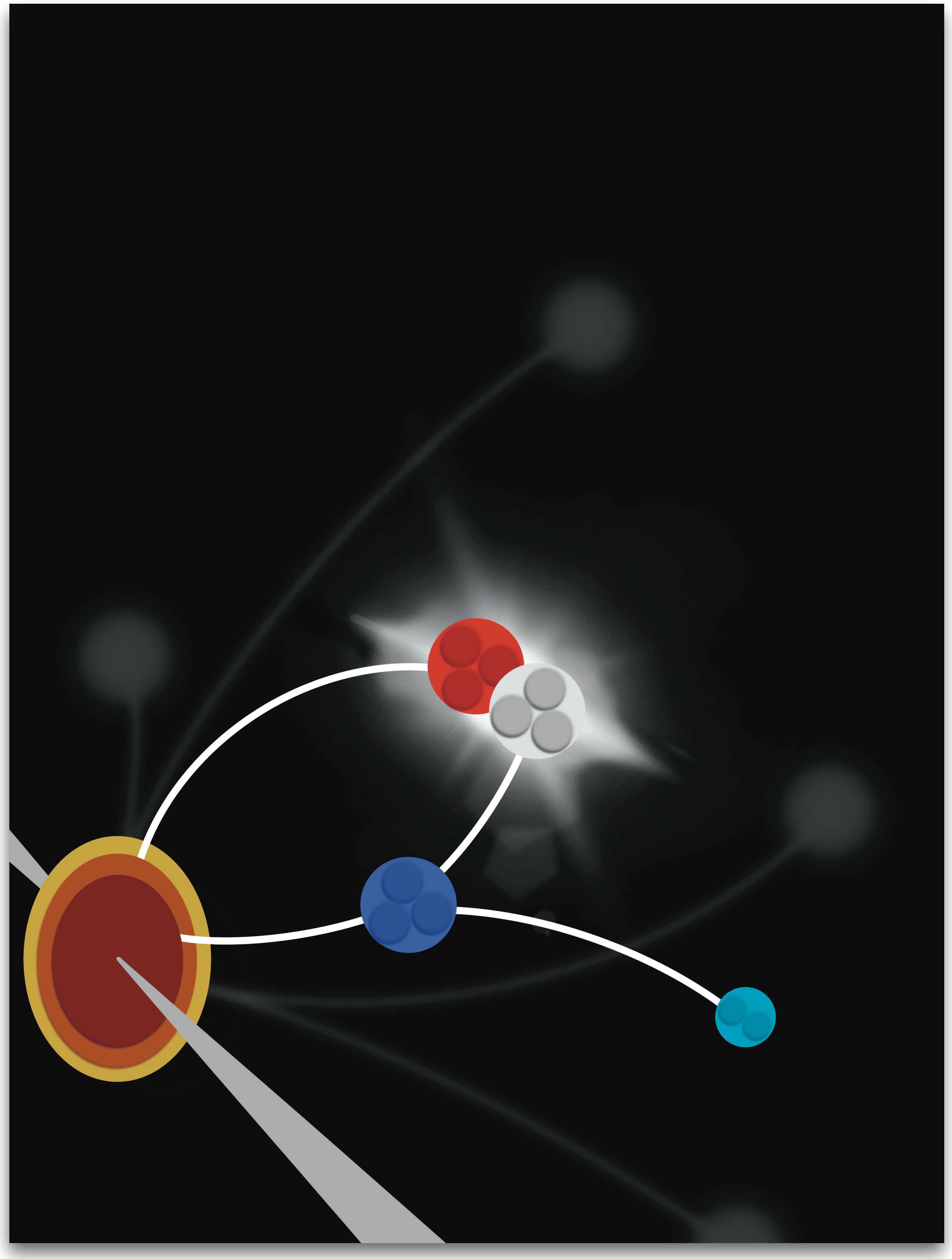
CERN-EP-2025-081
31 March 2025

Revealing the microscopic mechanism of deuteron formation at the LHC

ALICE Collaboration*

Abstract

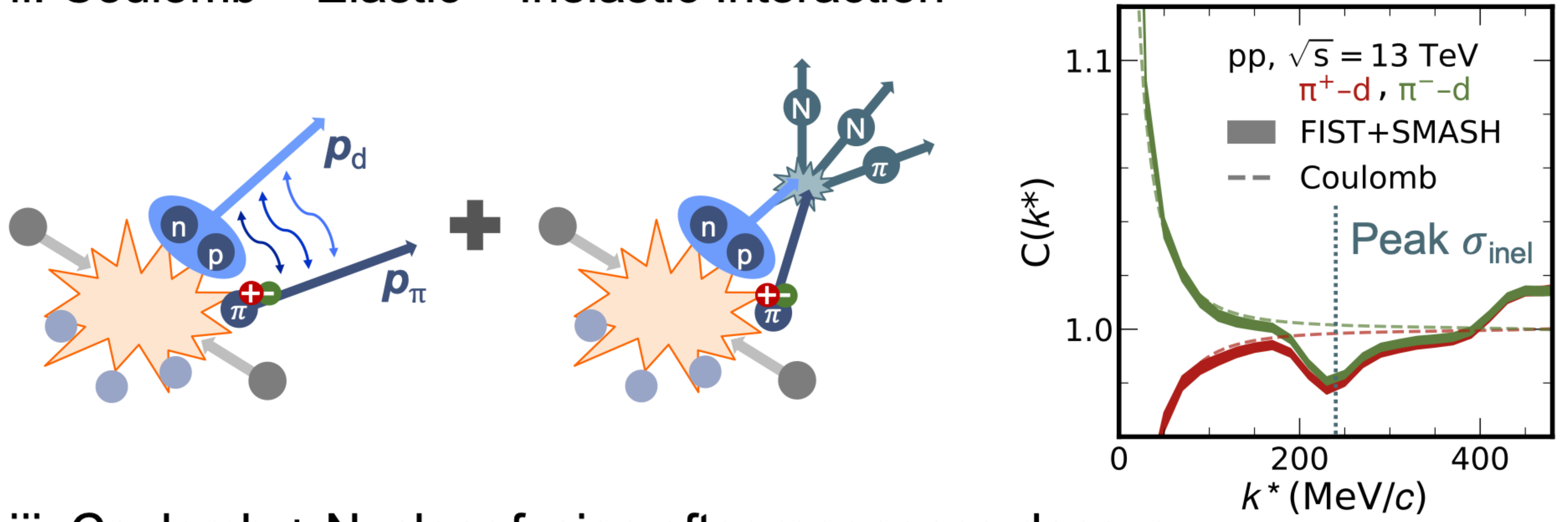
The formation of light (anti)nuclei with mass number A of a few units (e.g., d, ^{3}He, and ^{4}He) in high-energy hadronic collisions presents a longstanding mystery in nuclear physics [1, 2]. It is not clear how nuclei bound by a few MeV can emerge in environments characterized by temperatures above 100 MeV [3–5], about 100,000 times hotter than the center of the Sun. Despite extensive studies, this question remained unanswered. The ALICE Collaboration now addresses it with a novel approach using deuteron–pion momentum correlations in proton-proton (pp) collisions at the Large Hadron Collider (LHC). Our results provide model-independent evidence that about 80% of the



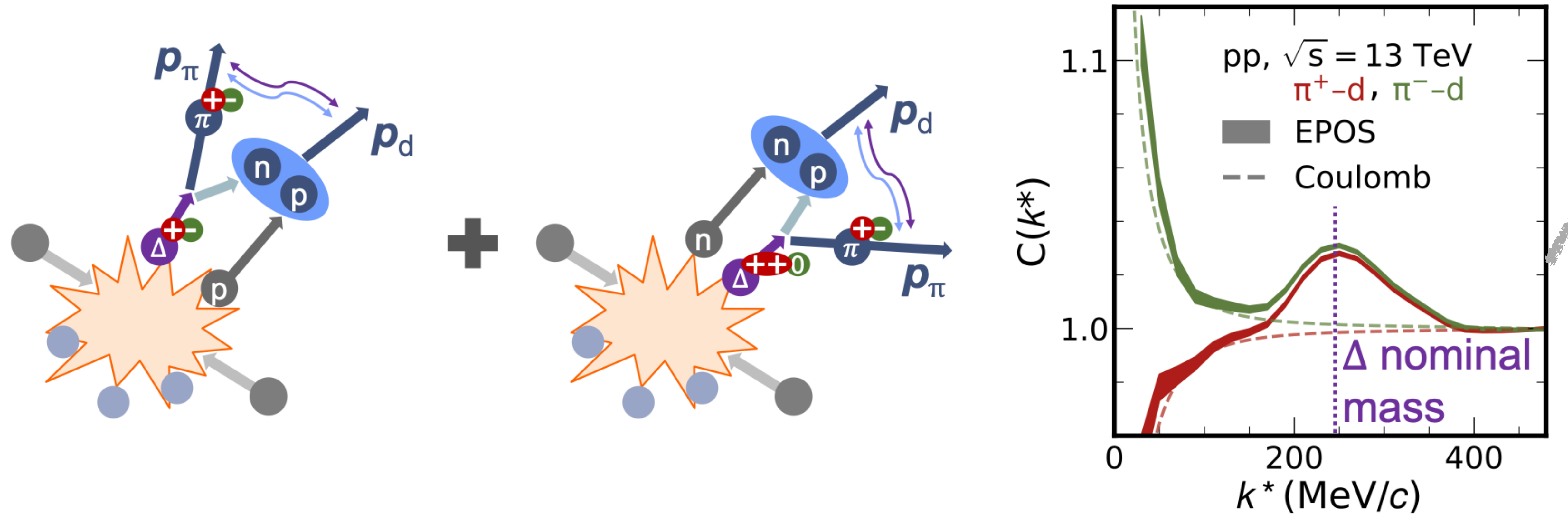
강한 상호작용이 핵 구조 형성에 어떻게 기여하나?

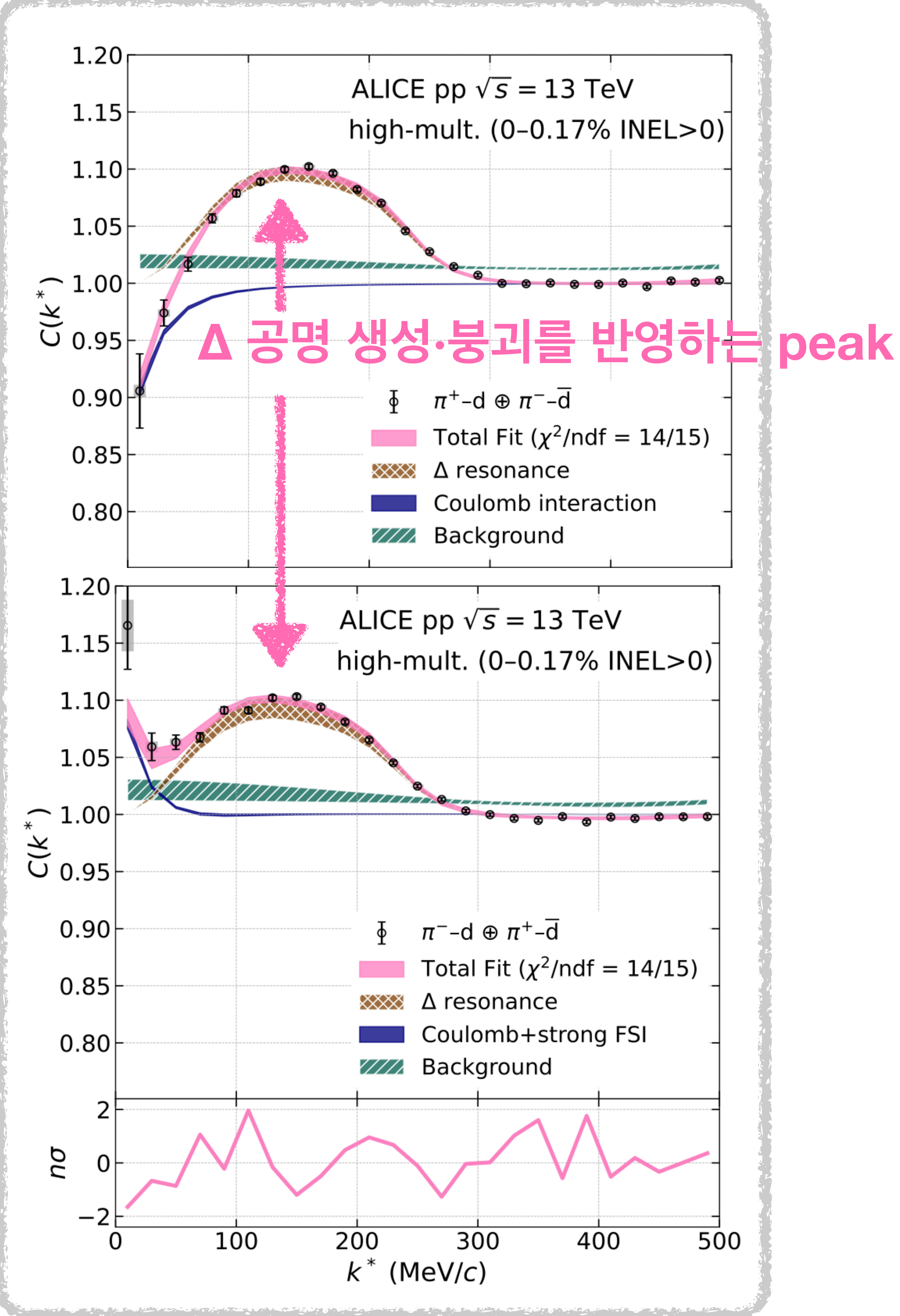
- 충돌에서 π–d 상관 함수를 통해 deuteron 생성의 실제 미시적 mechanism을 실험적으로 밝힘
  - Δ(1232) → N + π resonance decay가 deuteron 생성의 핵심 경로?
  - → 단순한 coalescence가 아니라 deuteron 중 거의 80%는 Δ가 붕괴하며 생기는 융합때문임

ii. Coulomb + Elastic + Inelastic Interaction



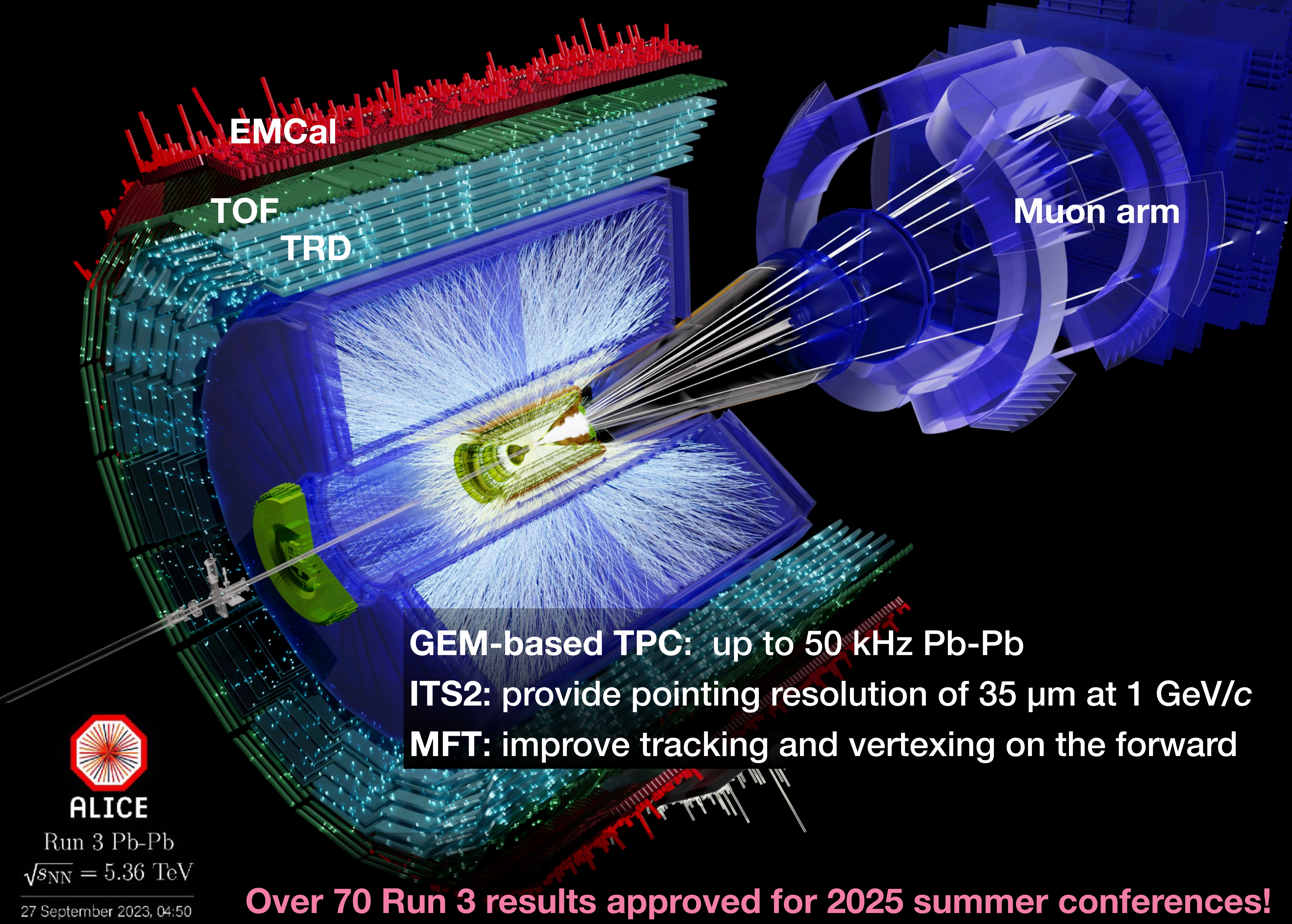
iii. Coulomb + Nuclear fusion after resonance decays






2010-2012
2015-2018
2022-2025
2029-2032
2035-2037
Run 1
LS1
Run 2
LS2
Run 3
LS3
Run 4
LS4
Run 5
LS5
Run 6
ALICE 1
phase I upg
ALICE 2
phase IIb upg
ALICE 3
한국팀 내부 반도체 검출기 (ITS2) 제작에 큰 기여
2010-2021 LS2 검출기 R&D 및 제작
2021 설치 완료!
2022부터 현재까지 Run3 data taking!
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

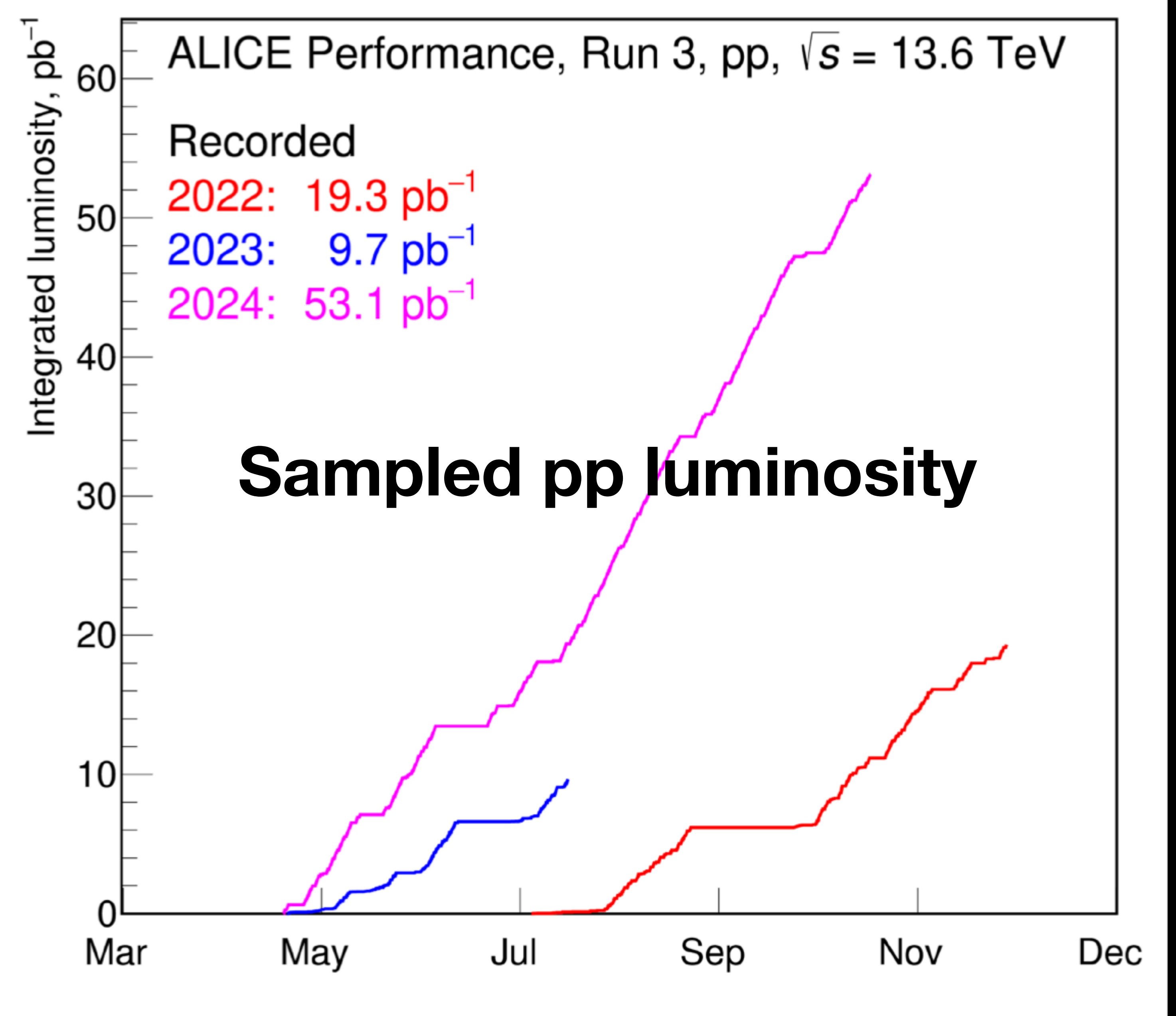
Run 3 (2022-2026) data taking

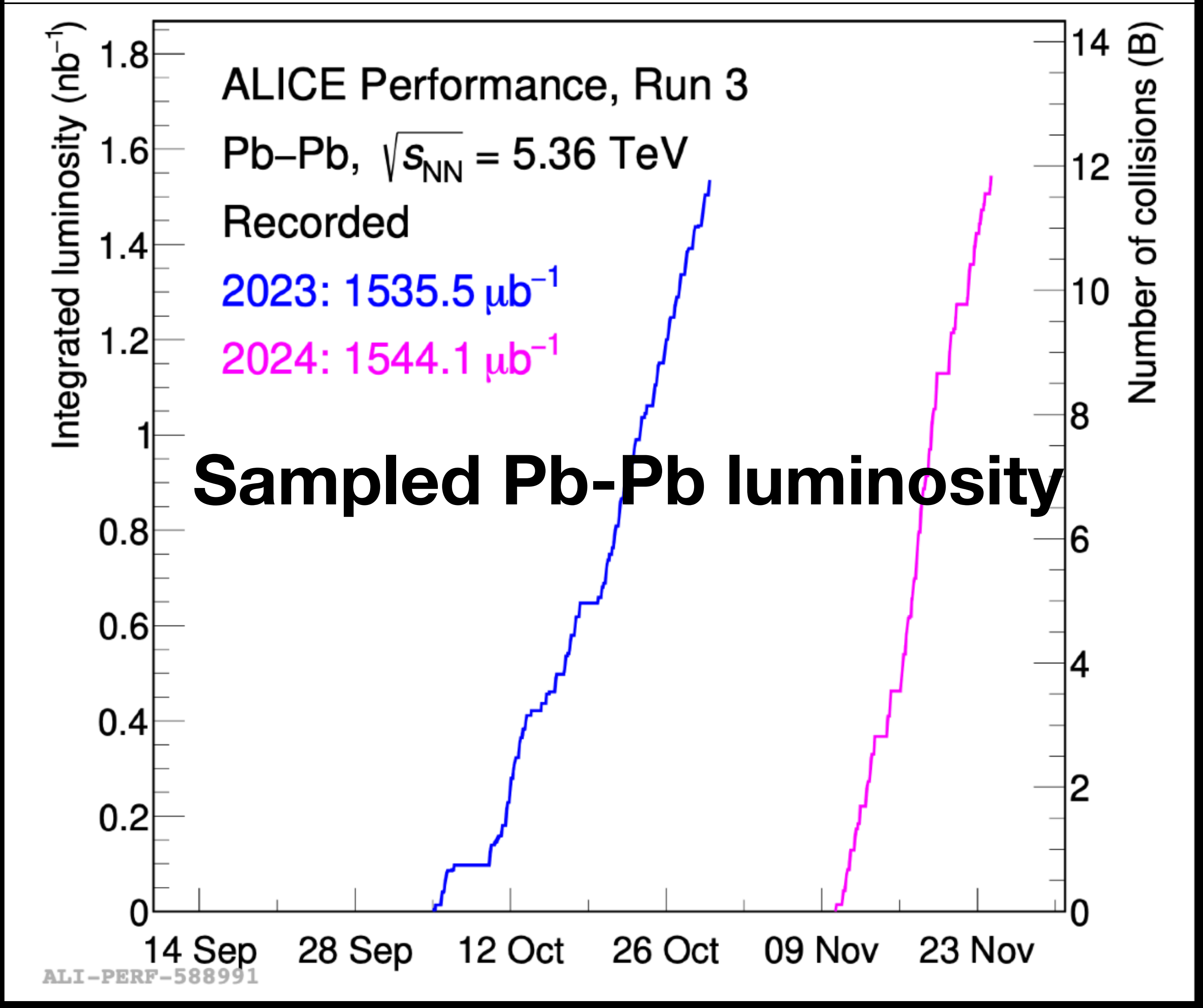


GEM-based TPC: up to 50 kHz Pb-Pb

ITS2: provide pointing resolution of 35 μm at 1 GeV/*c*

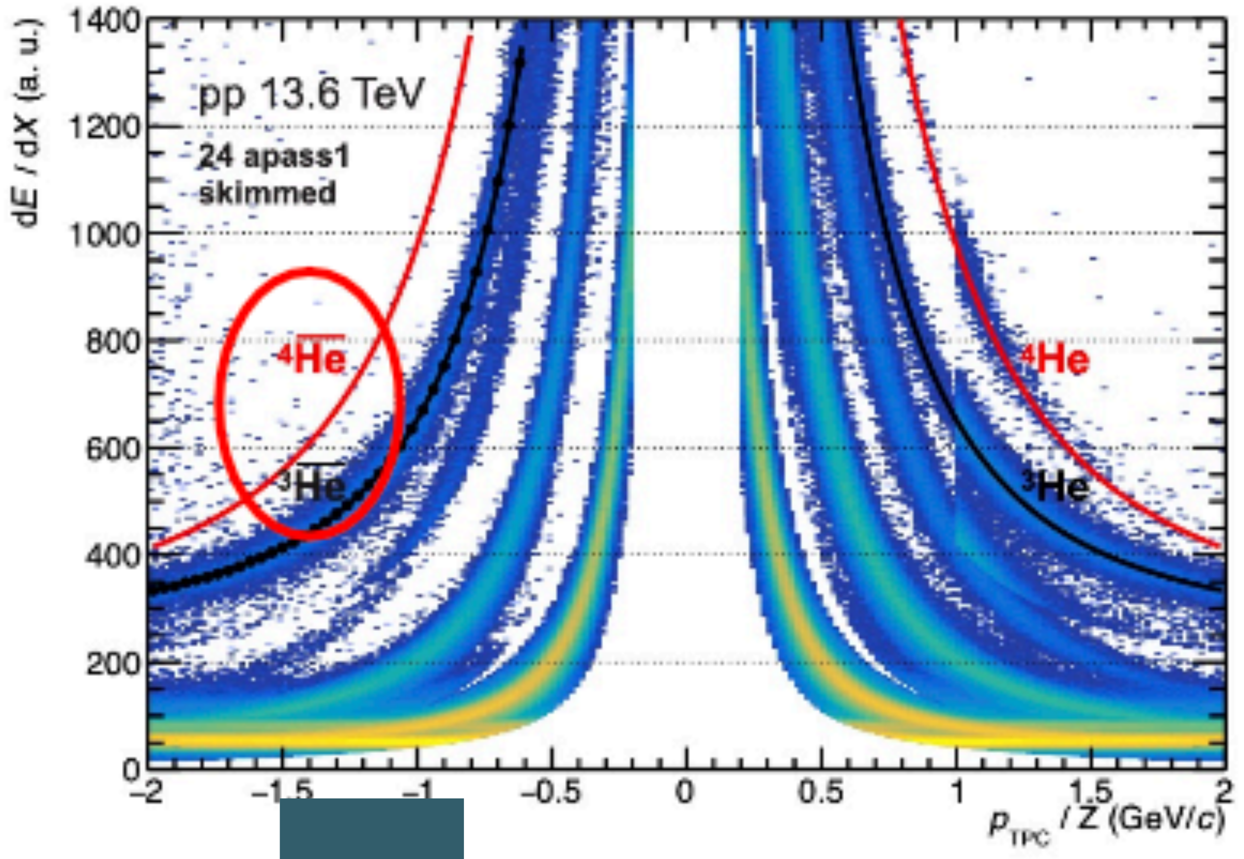
MFT: improve tracking and vertexing on the forward



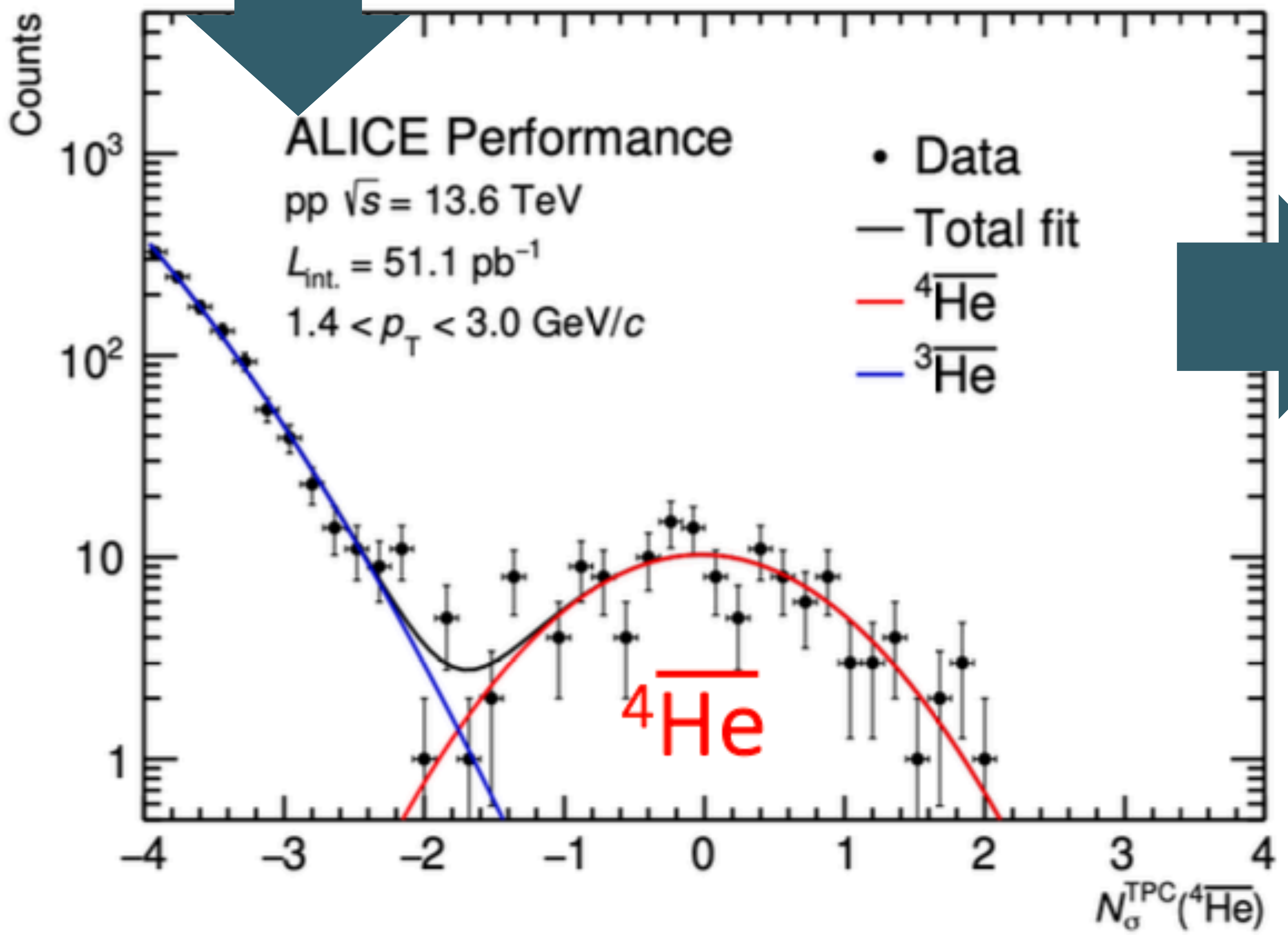


Over 70 Run 3 results approved for 2025 summer conferences!

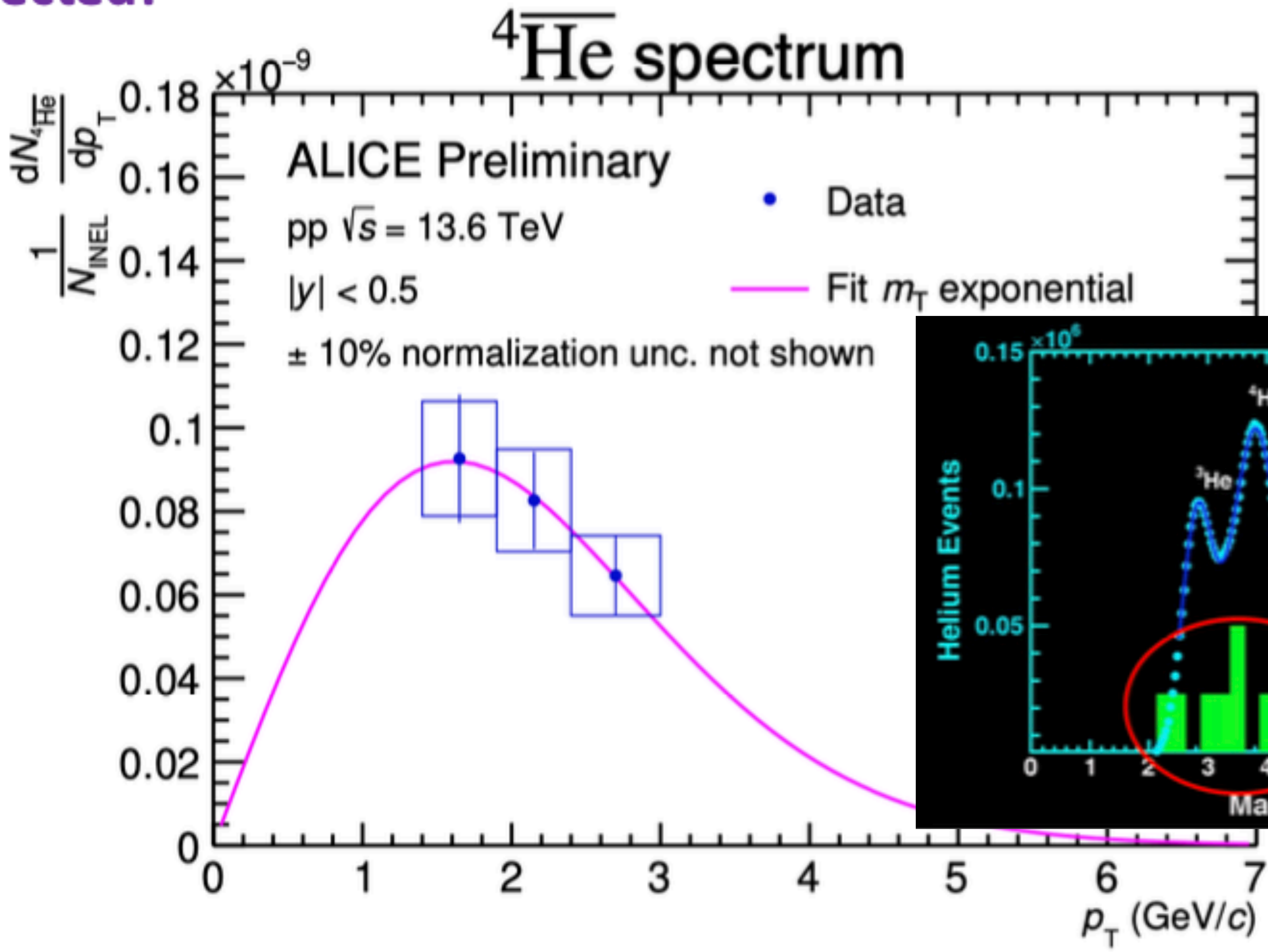
First observation of $^{4}\overline{\mathrm{He}}$ in pp collisions



3 trillion events inspected!

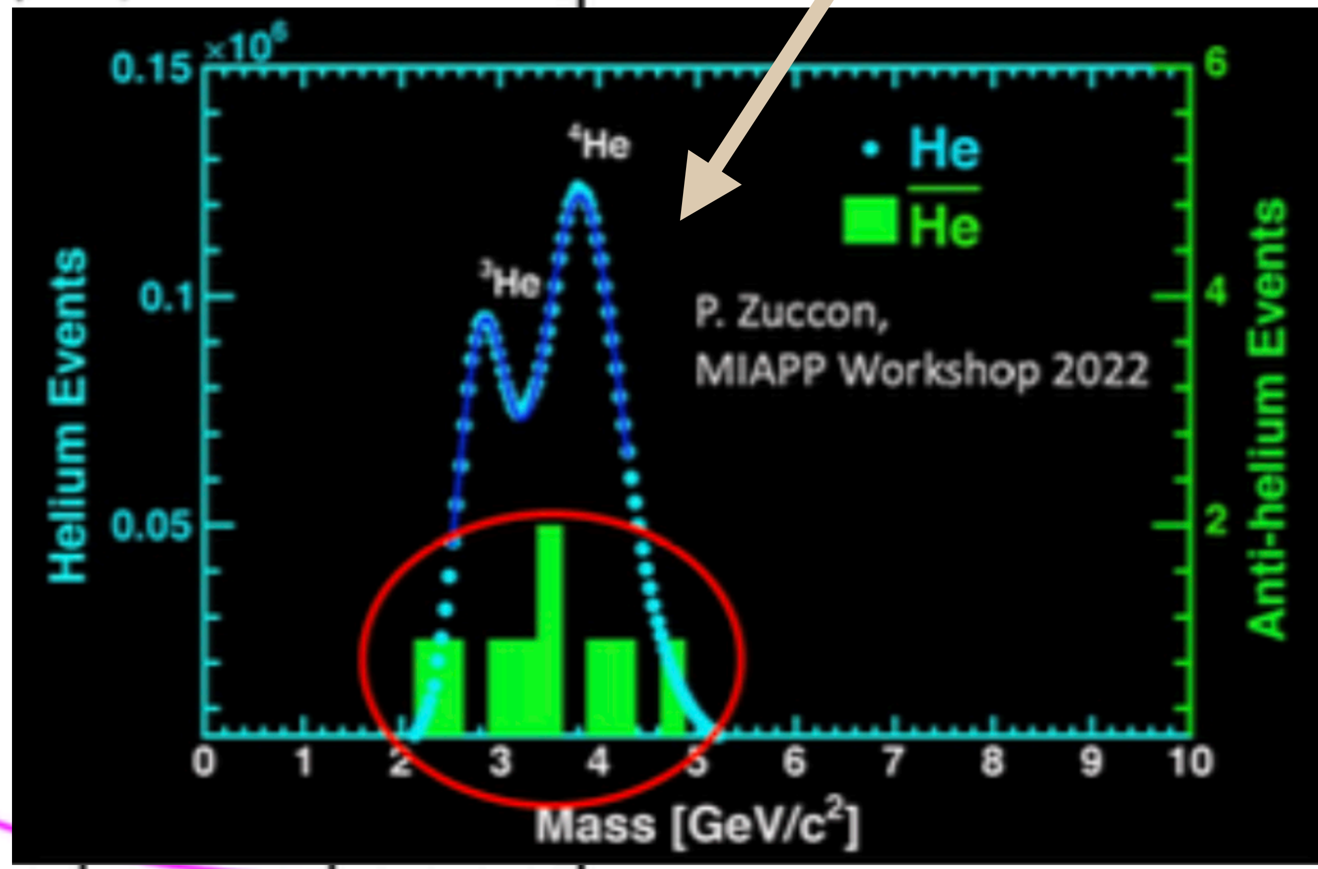


ALI-PERF-595970



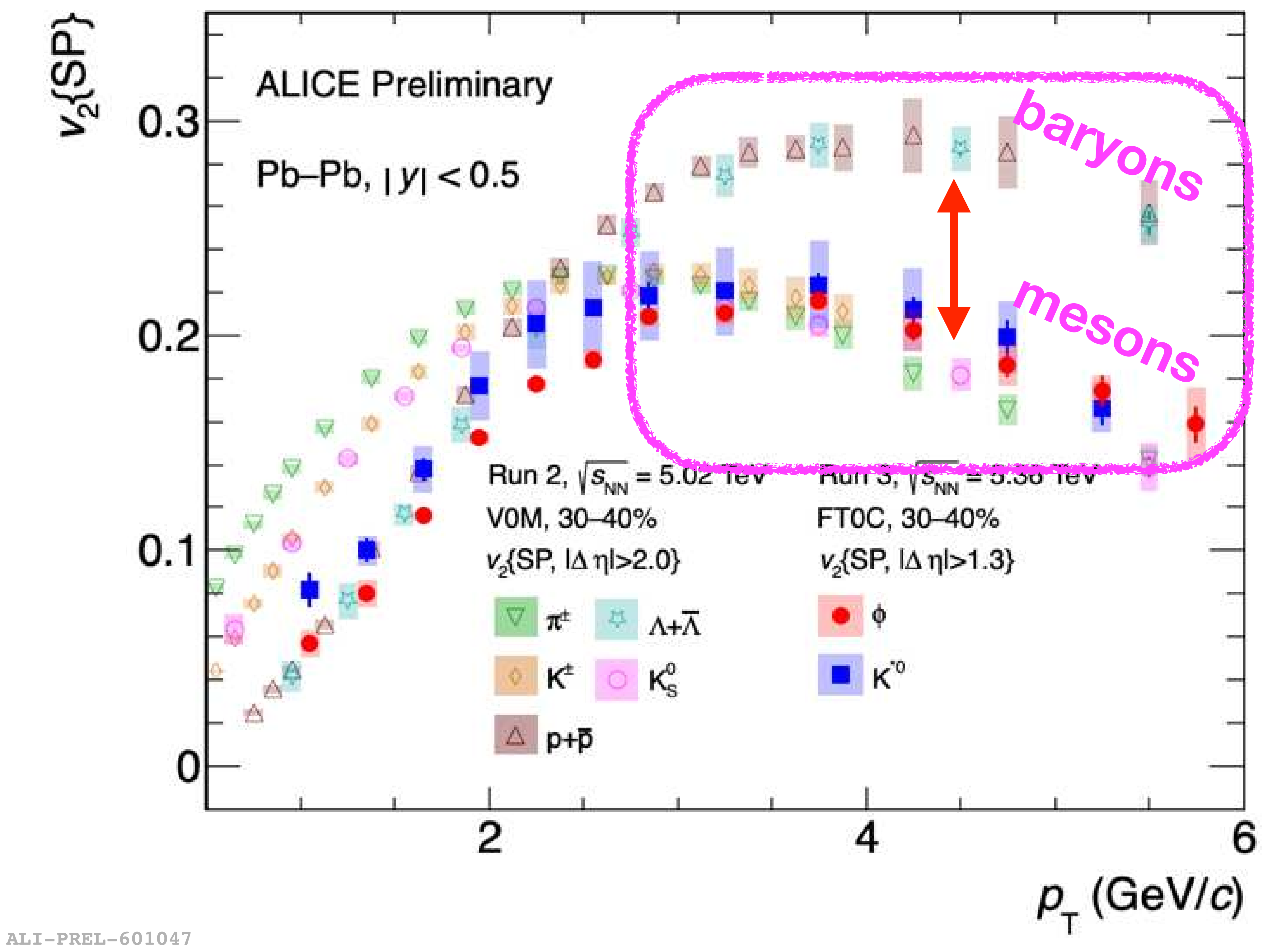
ALI-PREL-596070

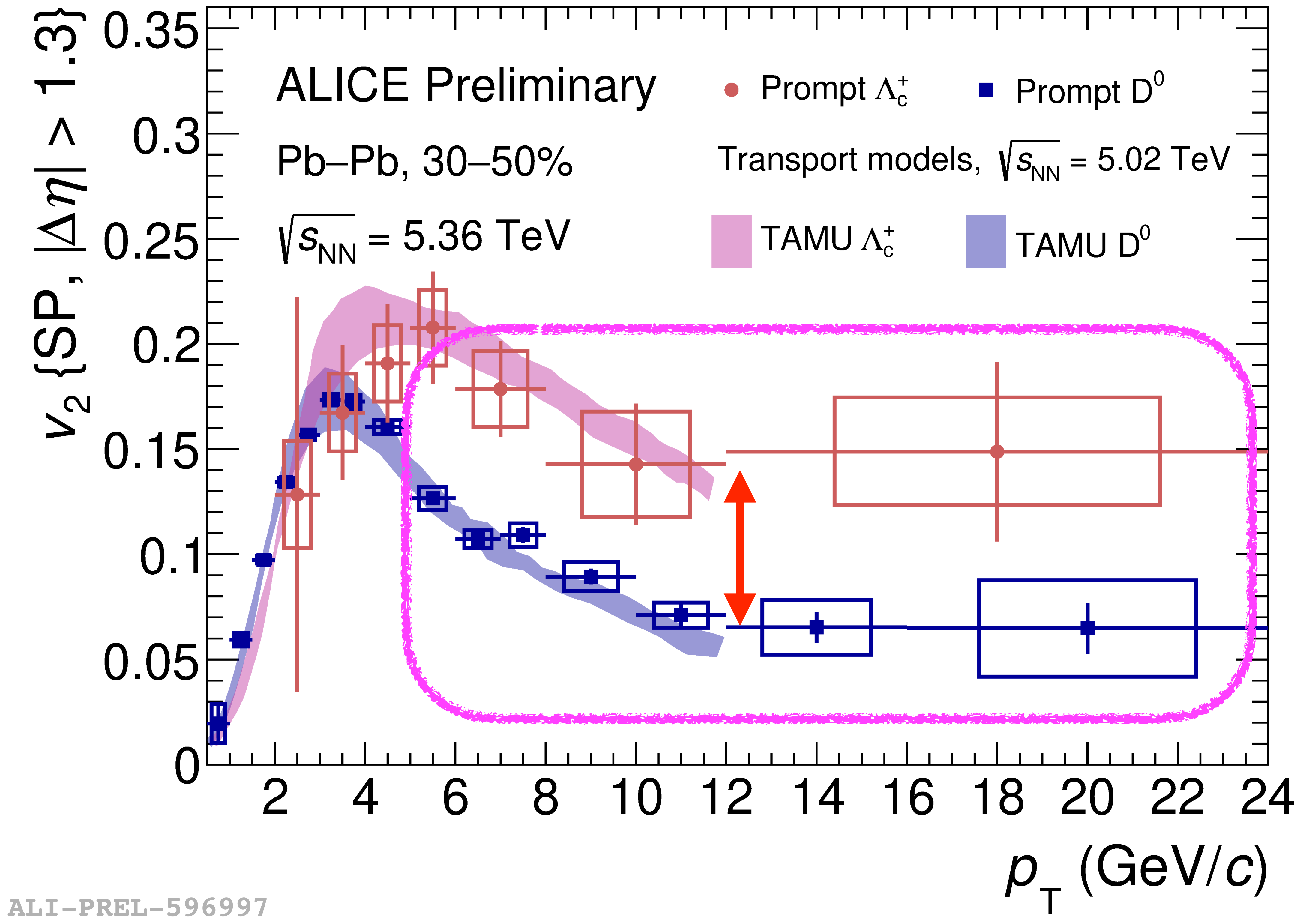
Anti-^{4}He events in AMS-02



- Clear anti-^{4}He peak in TPC dE/dx
- Important for anti-nuclei searches in space

World-first measurement of Λ_c^+ baryon flow in Pb-Pb



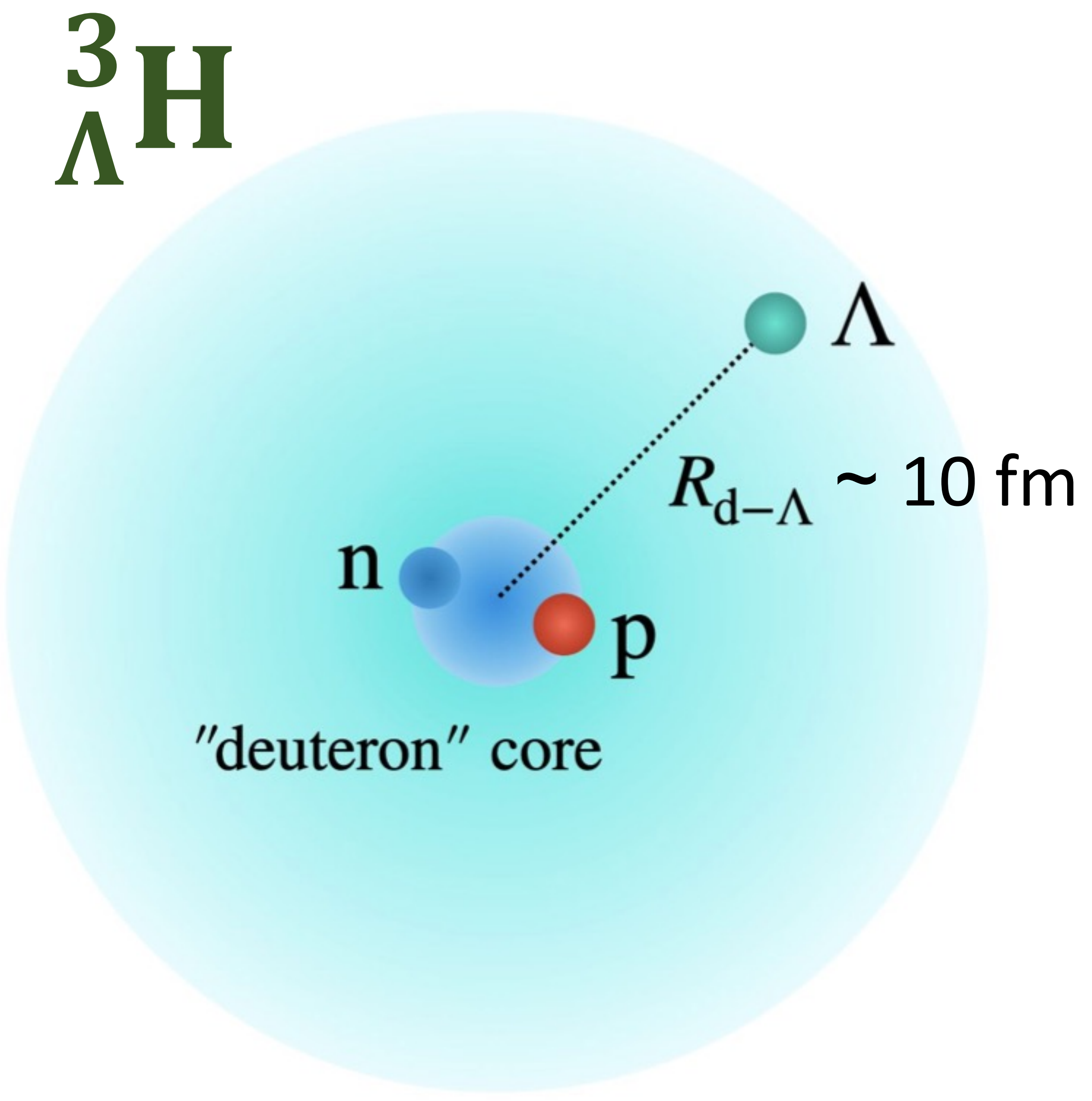


First prompt charm-baryon v_2 measurement in heavy-ion collisions

First evidence of charm baryon/meson splitting at intermediate/high p_T

- TAMU: includes quark coalescence → captures the trend

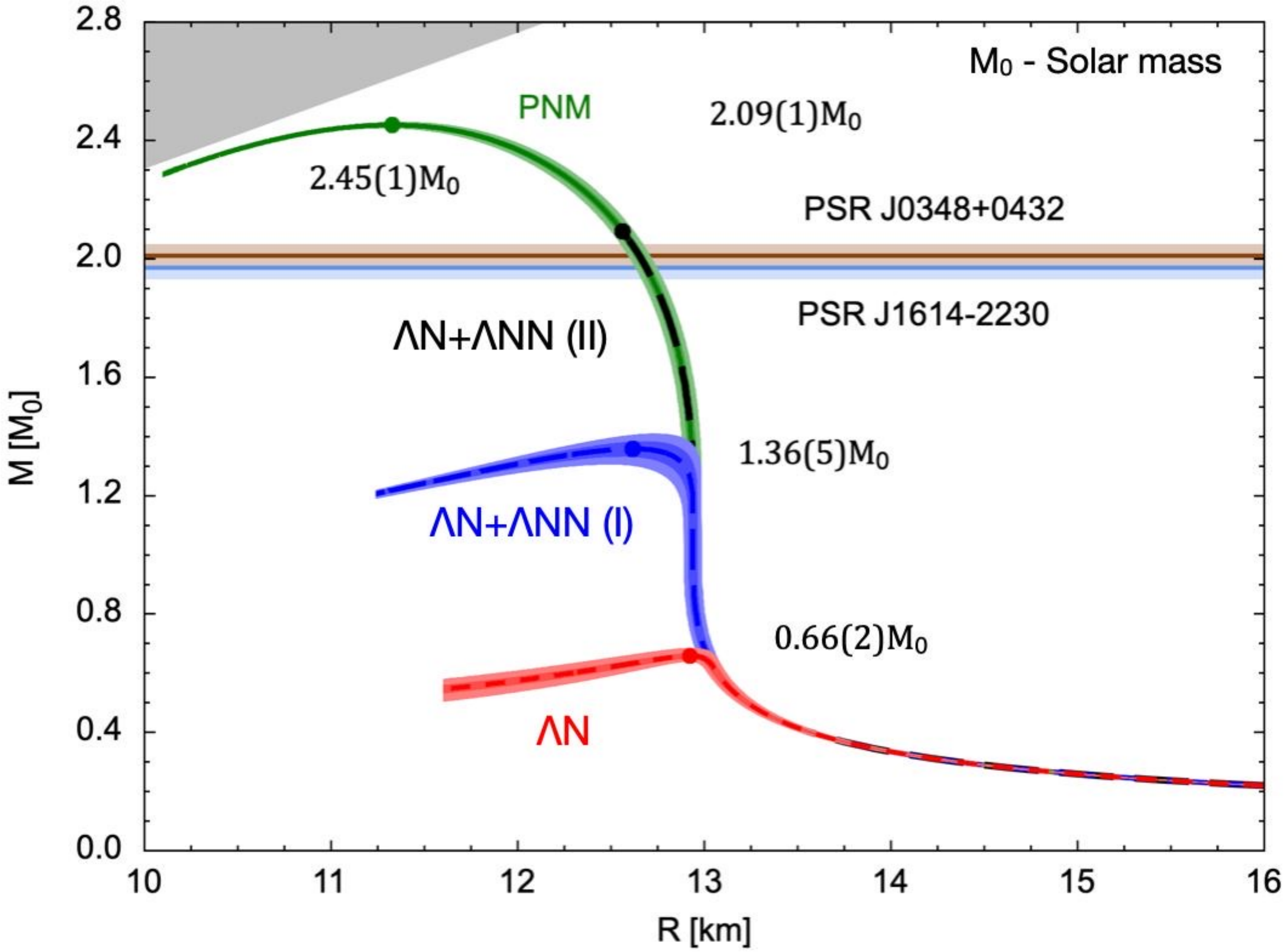
Hypertriton production, application to neutron star



Lightest hyper nucleus

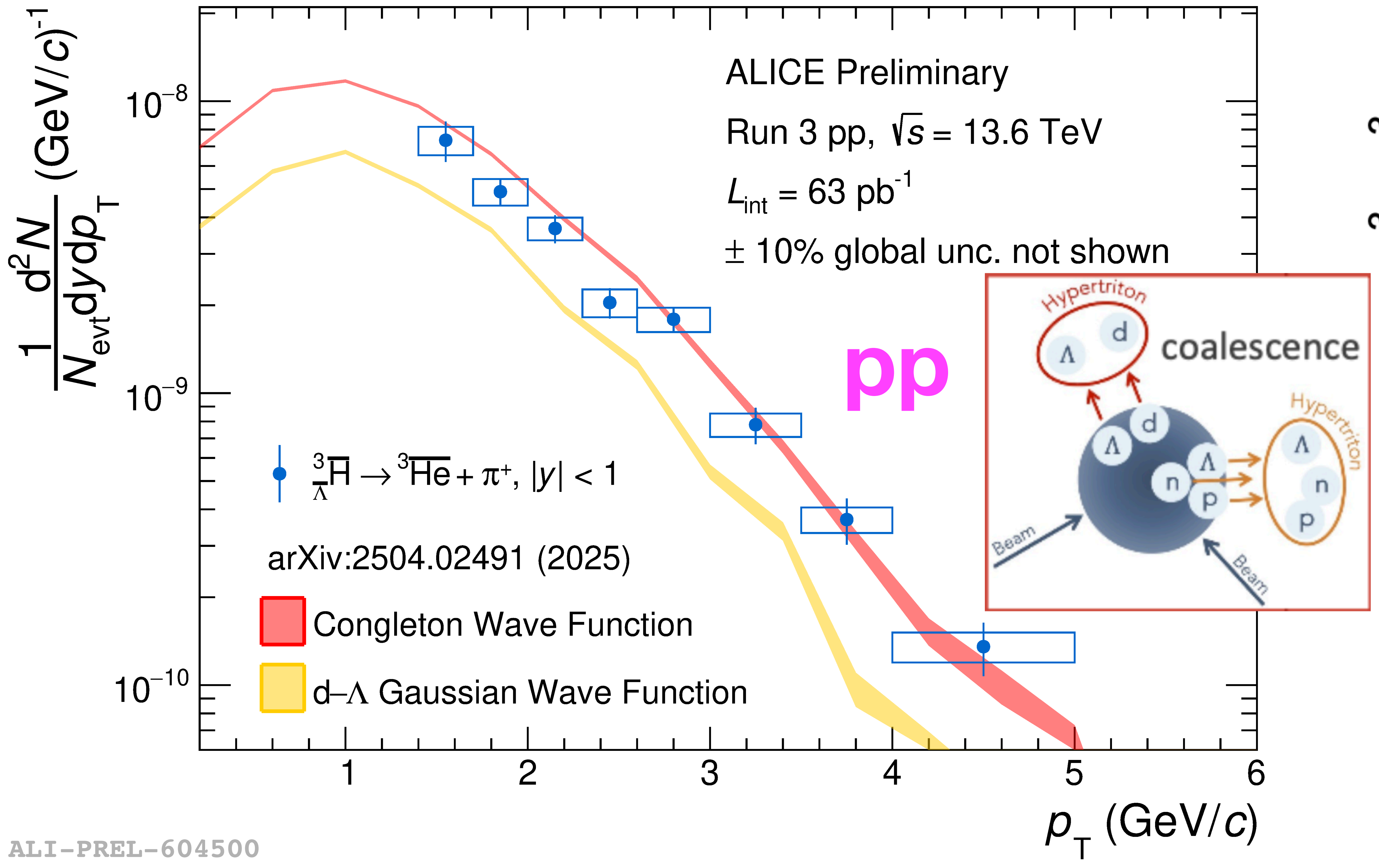
D. Lonardoni et al., PRL 114, 092301 (2015)

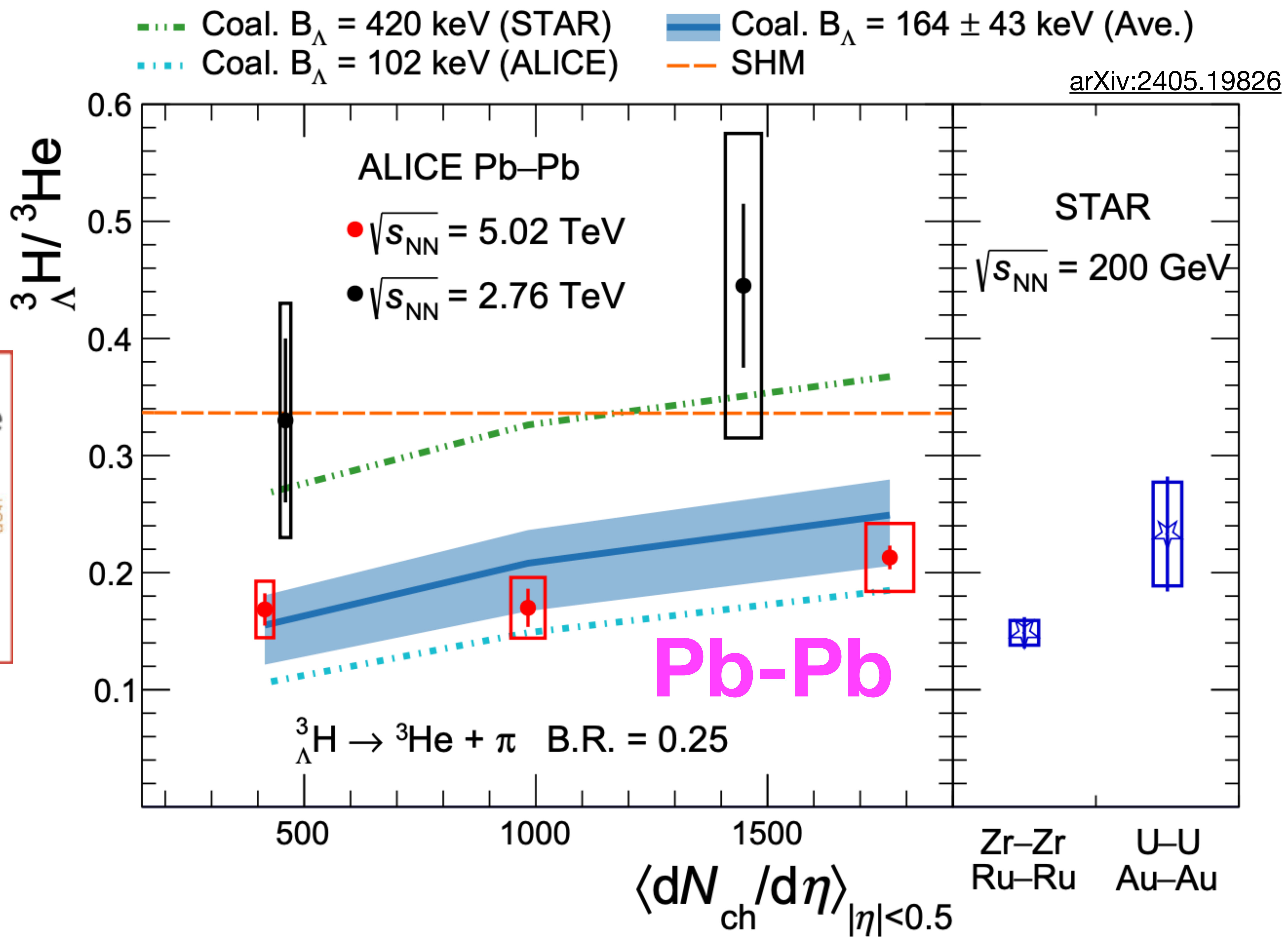
arXiv:2405.19826



- At the LHC, $^{3}_{\Lambda}\mathrm{H}$ has been measured in pp, p-Pb, and Pb–Pb collisions
- $^{3}_{\Lambda}\mathrm{H}$ powerful probe for investigating the nucleon–Λ interaction
- Crucial for the calculation of the equation of state (EoS) and the neutron star mass-radius relation

Hypertriton production in pp & Pb-Pb collisions





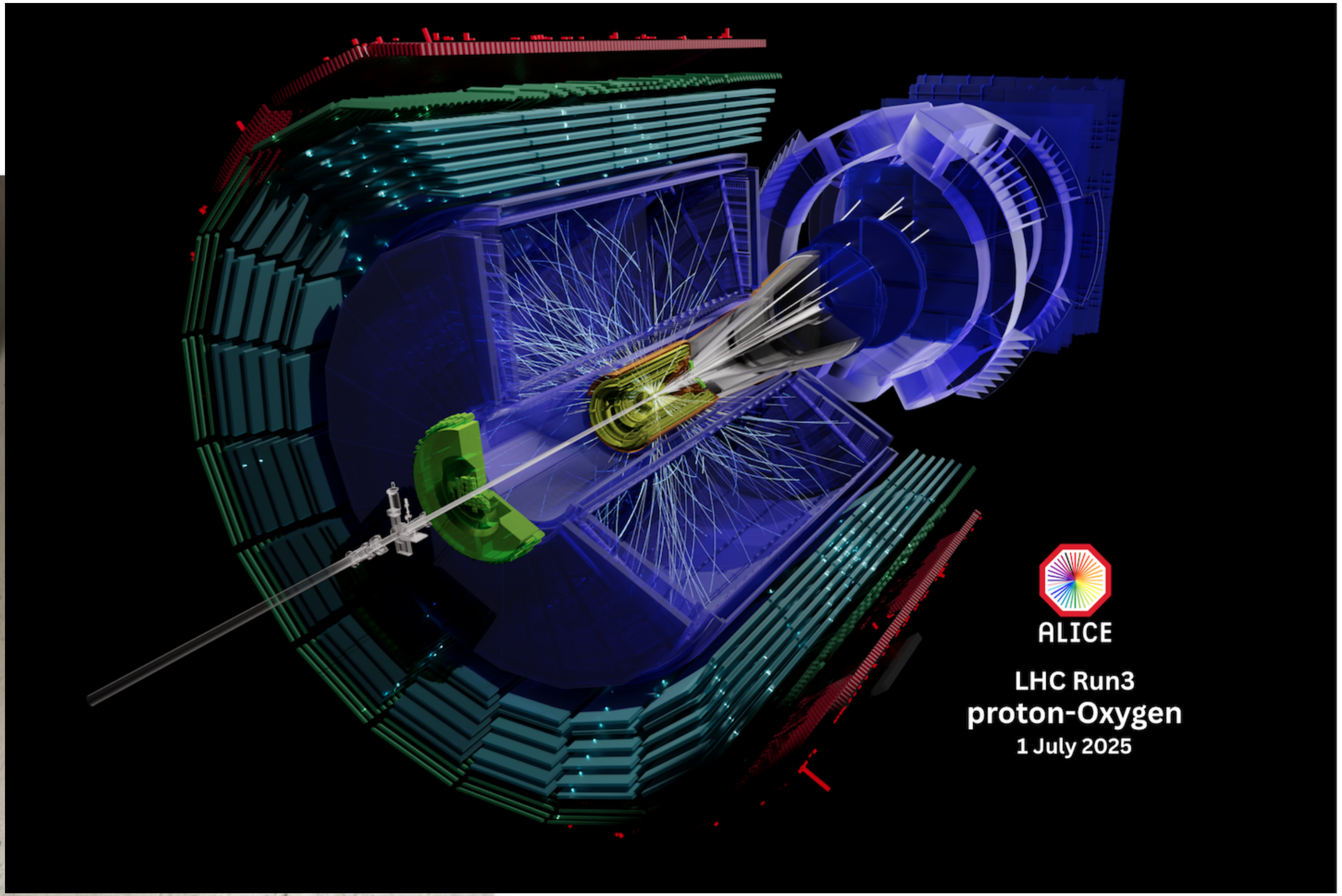
- Hypertriton production in pp & Pb-Pb collisions consistent with coalescence model → powerful tool to investigate the mechanism of nuclear production

- **coalescence** → interplay between the spatial extension of the nucleus wavefunction and the system size
- **SHM** predicts a flat ratio: sensitive to their similar masses, but insensitive to their size

First-ever collisions of oxygen at the LHC

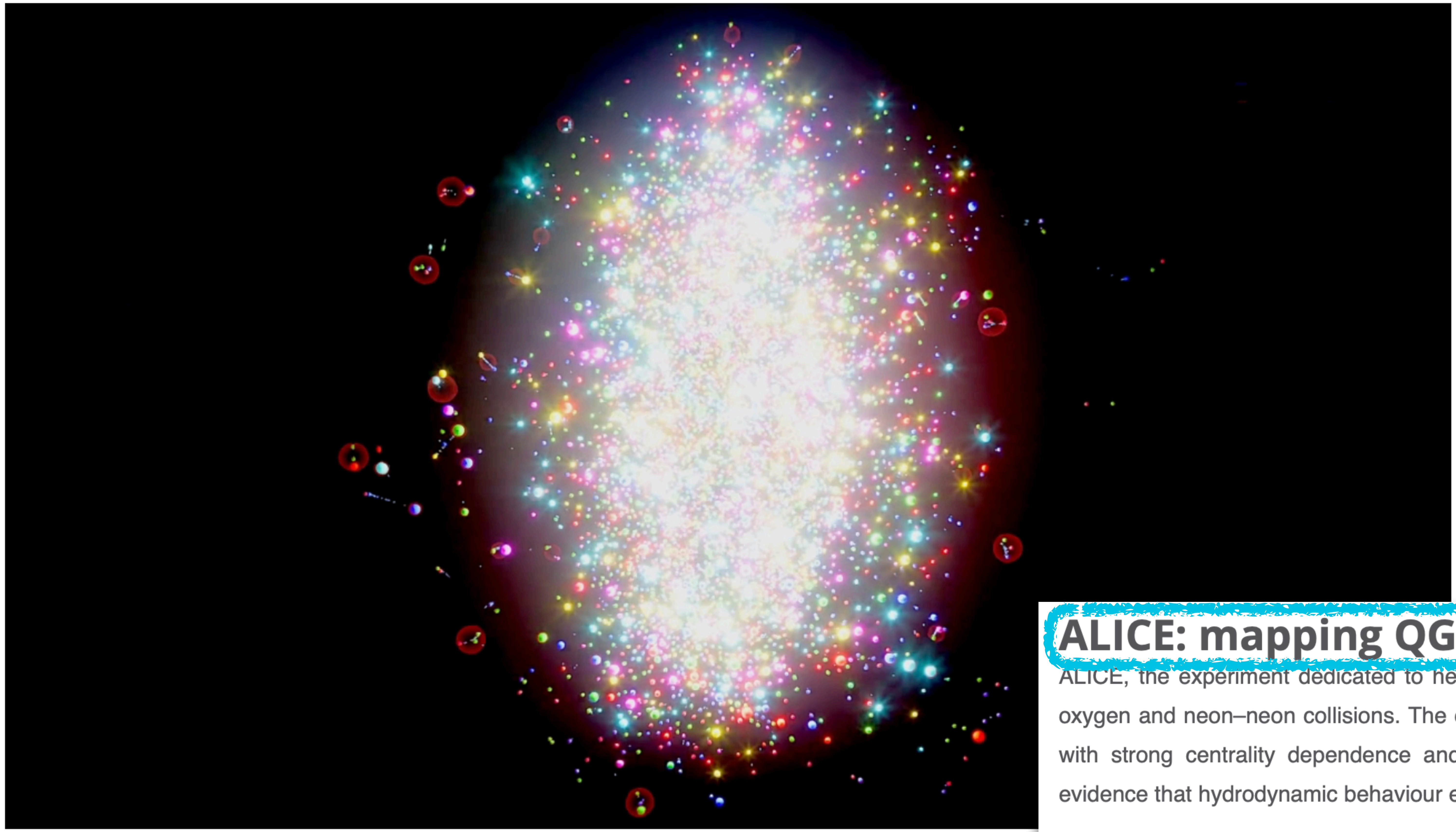
The Large Hadron Collider gets a breath of fresh air as it collides beams of protons and oxygen ions for the very first time. Oxygen–oxygen and neon–neon collisions are also on the menu of the next few days

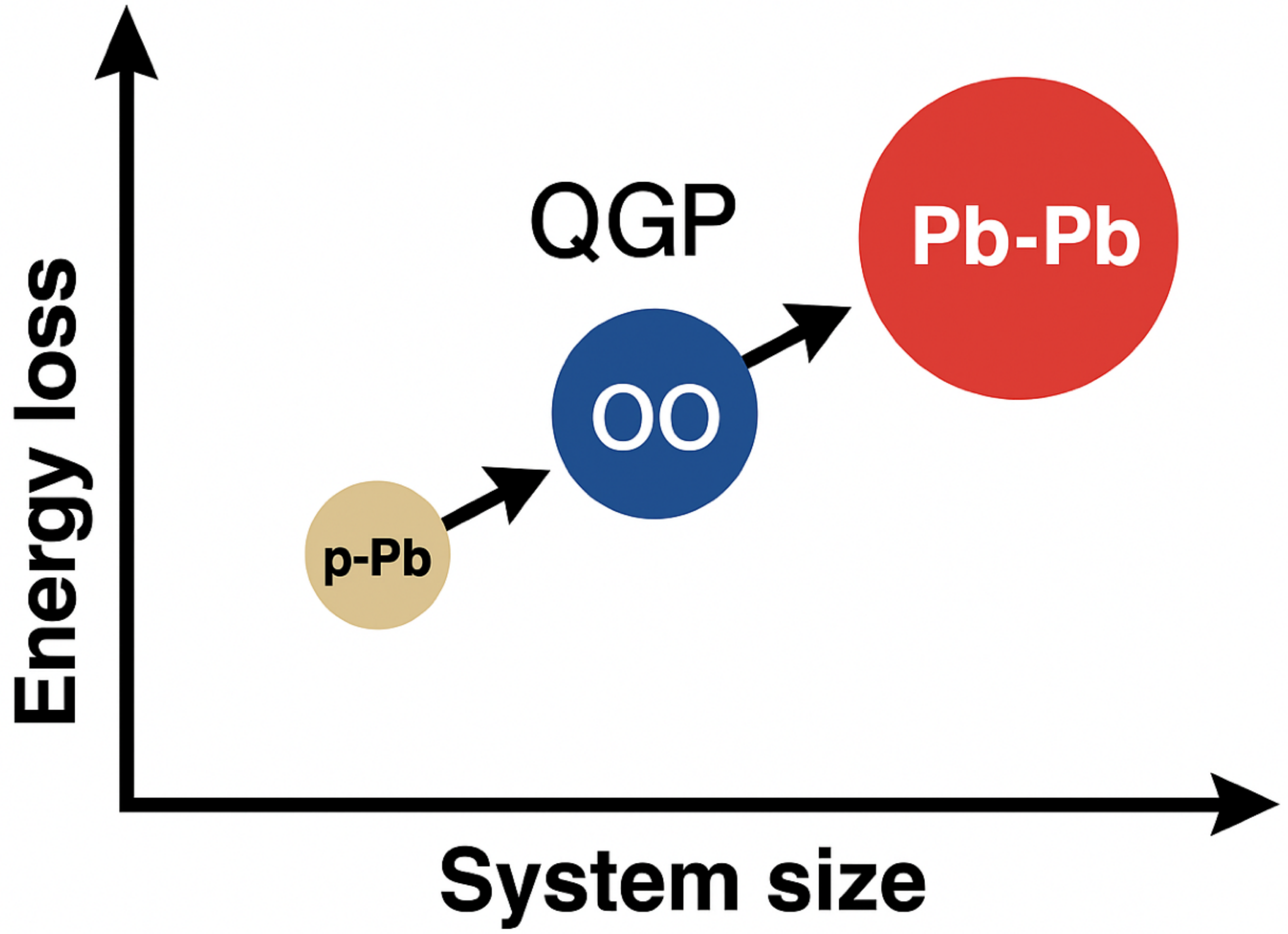
1 JULY, 2025 | By Anaïs Schaeffer



Light ions at the LHC: first results from oxygen–oxygen and neon–neon collisions

Panos Charitos 6th Oct 2025



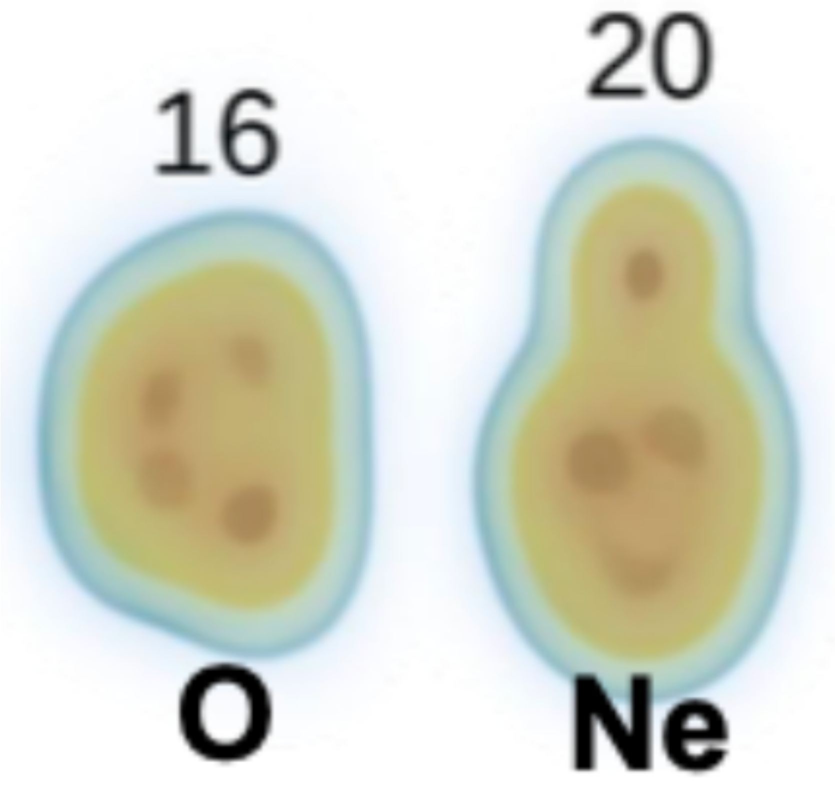


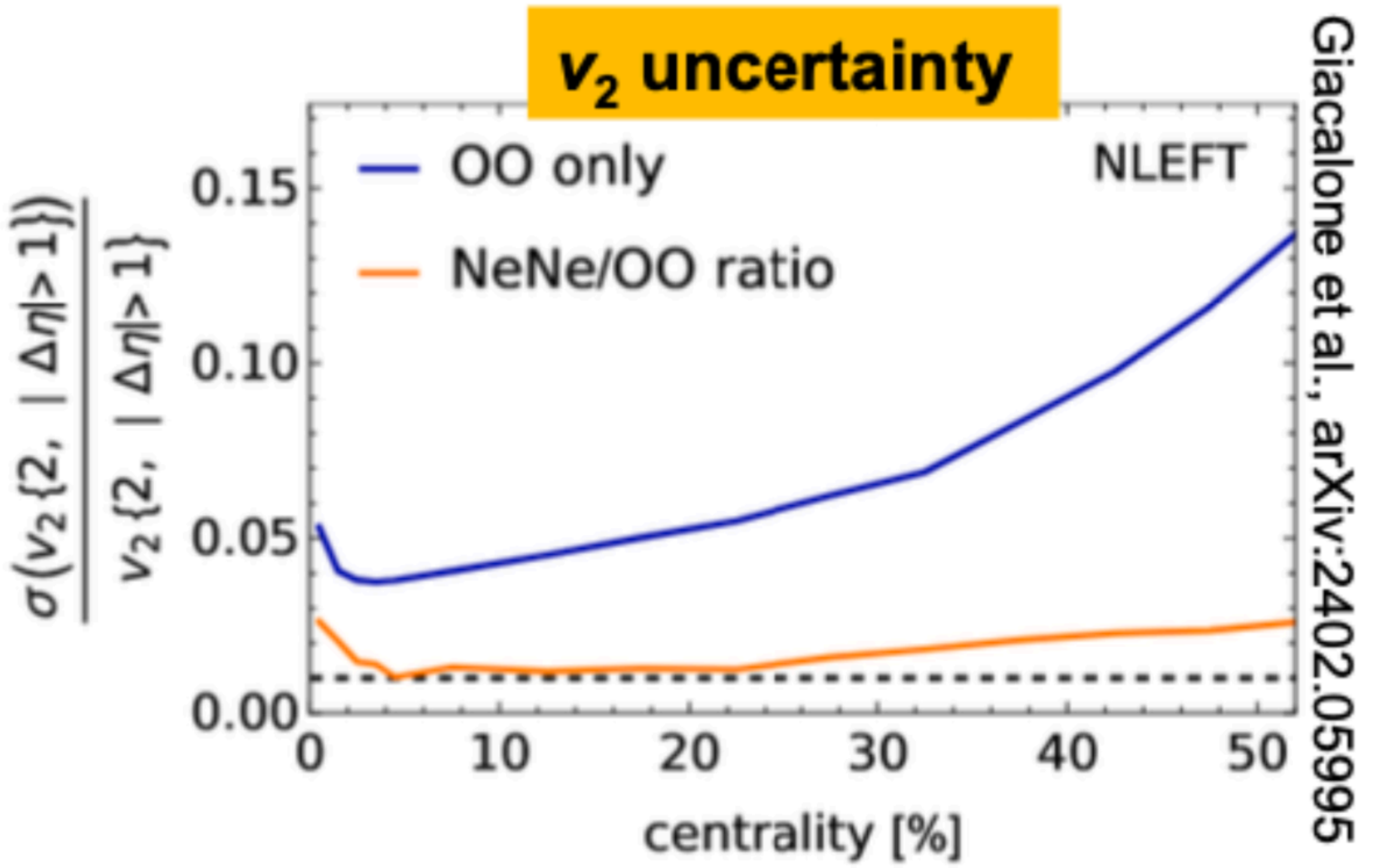
ALICE: mapping QGP across system sizes

ALICE, the experiment dedicated to heavy-ion physics, carried out a comprehensive programme of measurements in oxygen–oxygen and neon–neon collisions. The collaboration reported clear signals of elliptic (v_2) and triangular (v_3) flow in both systems, with strong centrality dependence and magnitudes comparable to those in heavier systems. These results strengthen the evidence that hydrodynamic behaviour emerges even in small collision systems.

ALICE also measured **charged-particle multiplicity distributions**, which are essential to characterising the initial conditions of the collisions. Together with **particle spectra** and the first nuclear modification factor (R_{AA}) studies in light-ion collisions, these results extend ALICE's longstanding programme of scanning QGP properties across system sizes, from Pb–Pb through Xe–Xe down to O–O and Ne–Ne. The measurements already show sensitivity to the nuclear structure of oxygen and neon, underlining ALICE's central role in establishing the minimal conditions for QGP formation.

Oxygen and Neon run at LHC



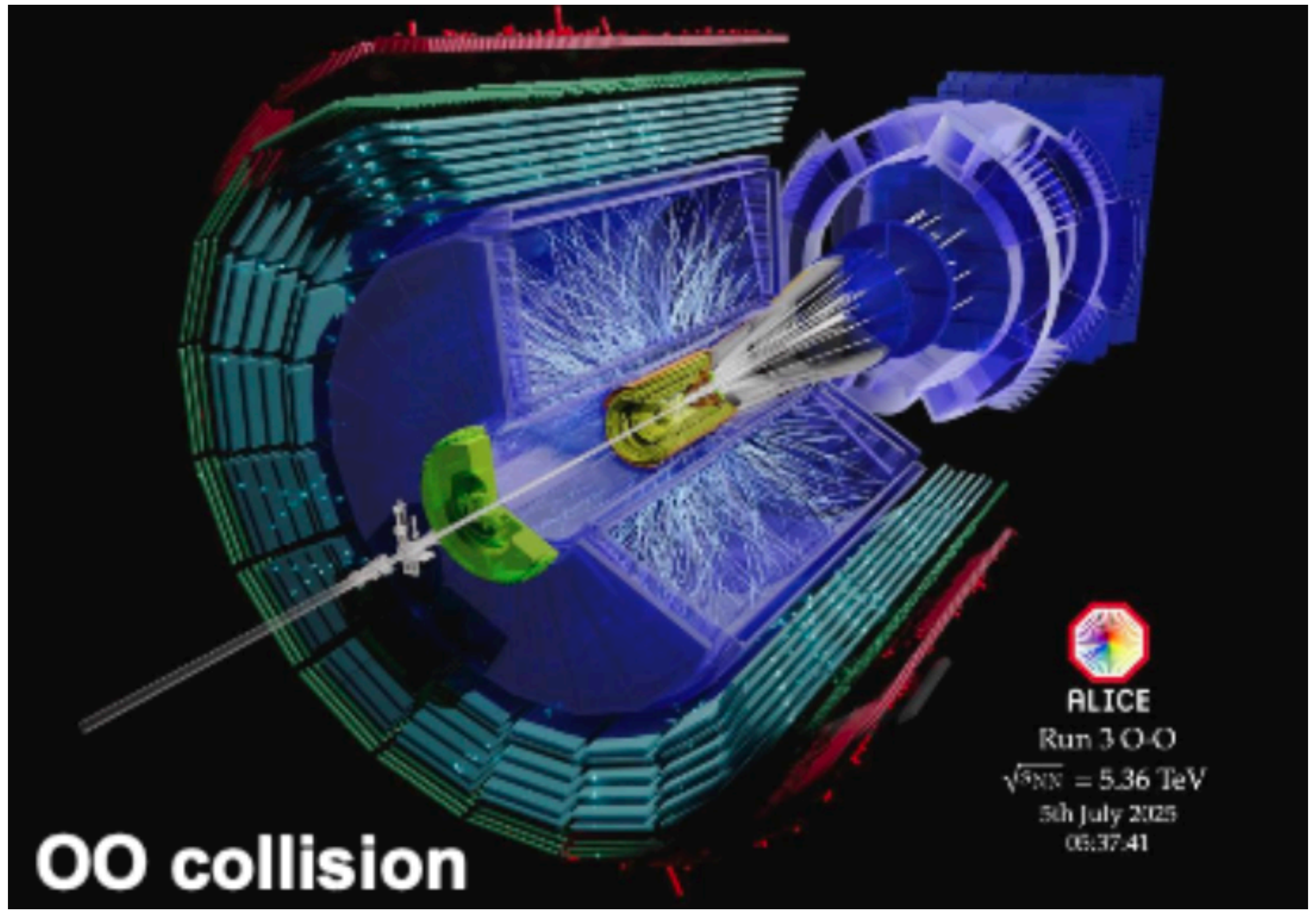


Special run week in July dedicated to collisions of **light lions (O and Ne)**

Modeling uncertainties cancel in light-ion ratio

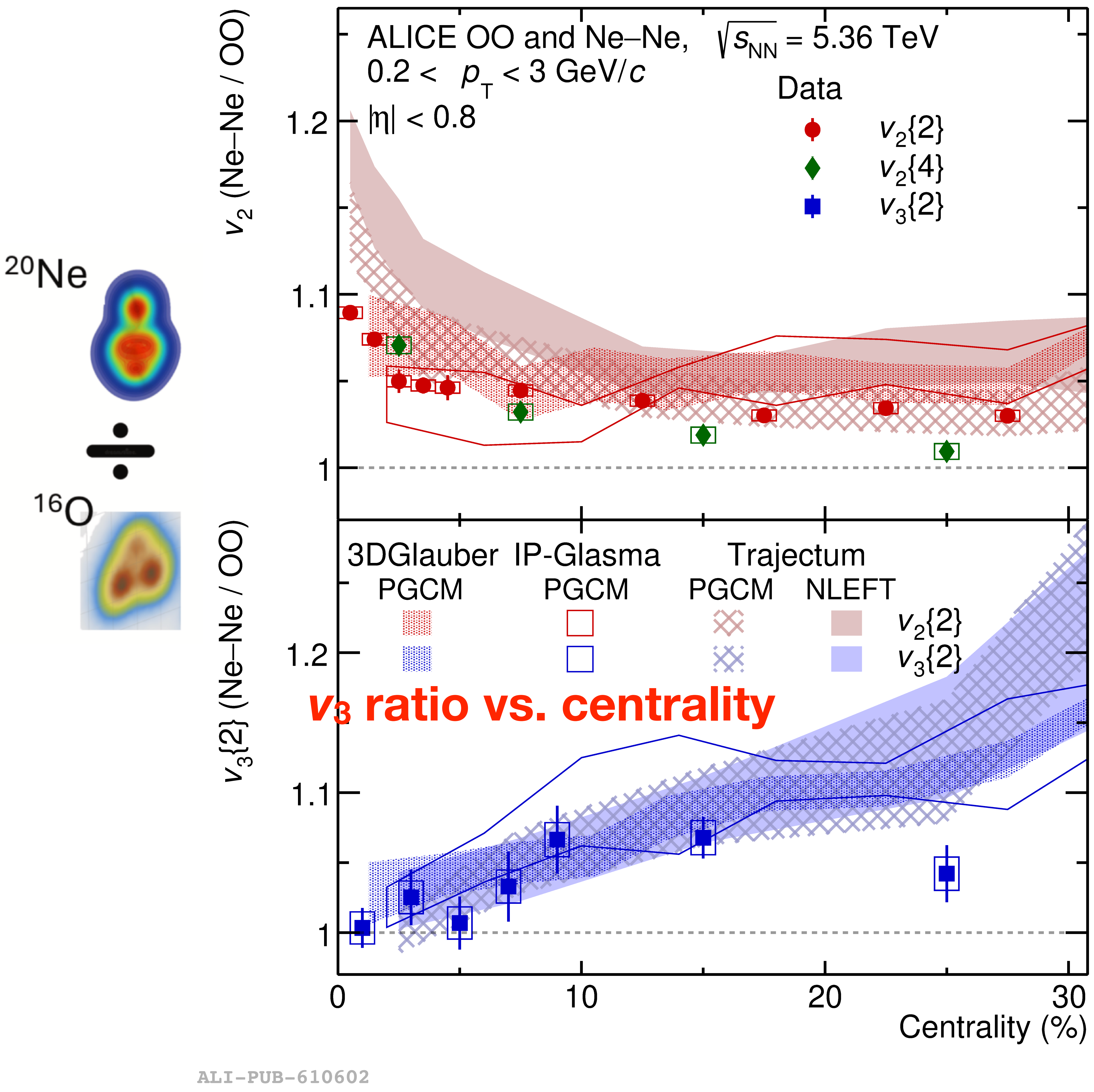
LHC and ALICE performed with excellence

- pO: recored 7.27 nb^{-1} | $3x10^{9}$ events
- OO: recored 5.01 nb^{-1} | $6x10^{9}$ events
- NeNe: recored 0.84 nb^{-1} | 10^{9} events



Oxygen and Neon run at LHC

v_2 ratio vs. centrality



v_3 ratio vs. centrality

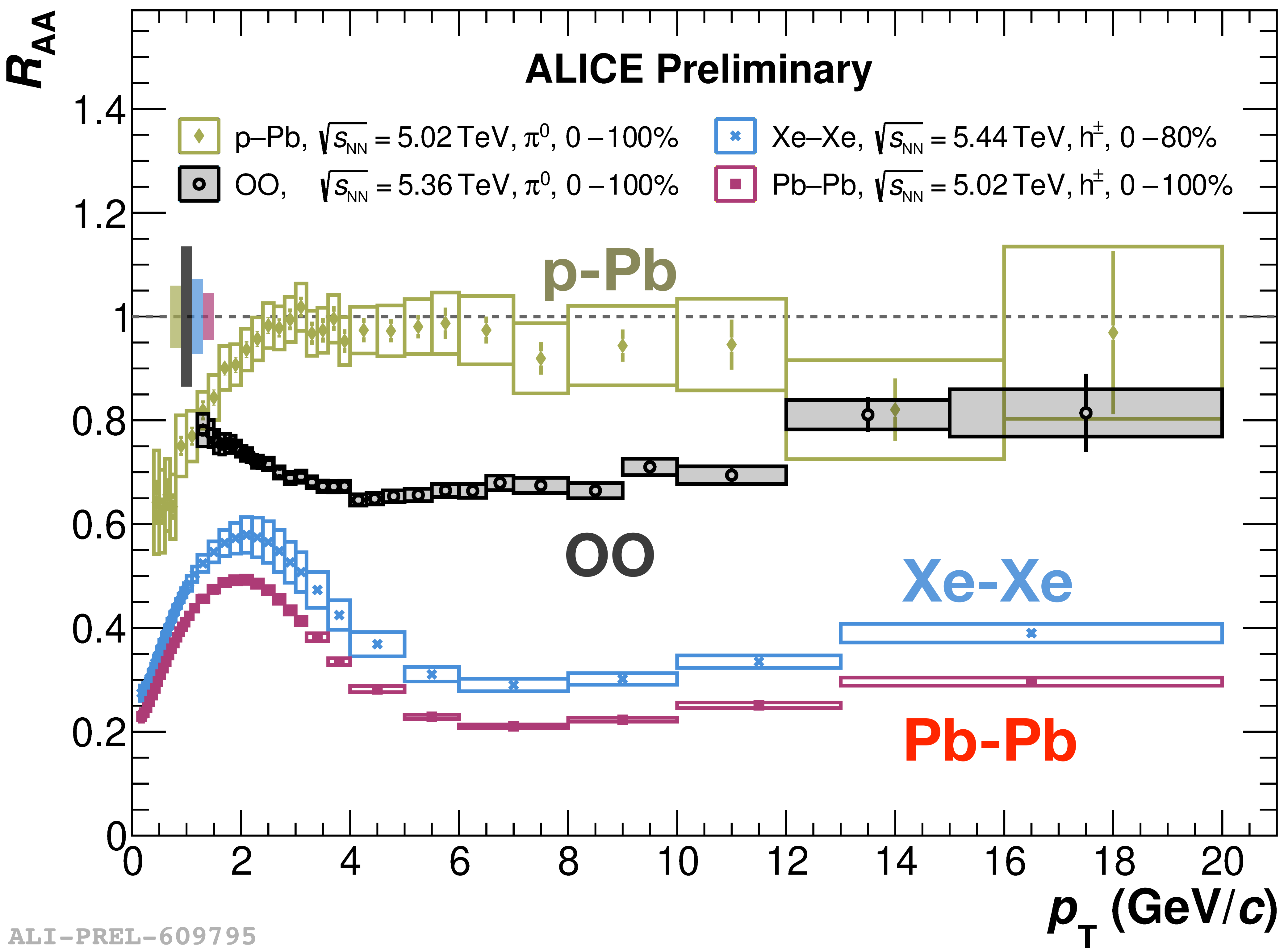
Ratios between OO and Ne-Ne reduces uncertainties (< 0.01 exp. for v_2)

- v_2 peaks for central: stronger quadropole deformation of Ne compared to tetrahedral O
- v_3 increases with centrality: in ultra central collision, tetrahedral O leads to larger v_3

IP-Glasma captures ratios well

Trajectum overestimates ratio in 0-10%

π^0 R_{AA} for in OO collisions



PbPb collisions: **strong suppression** → clear evidence for parton energy loss in QGP

pPb collisions: **no suppression** → no QGP formation?

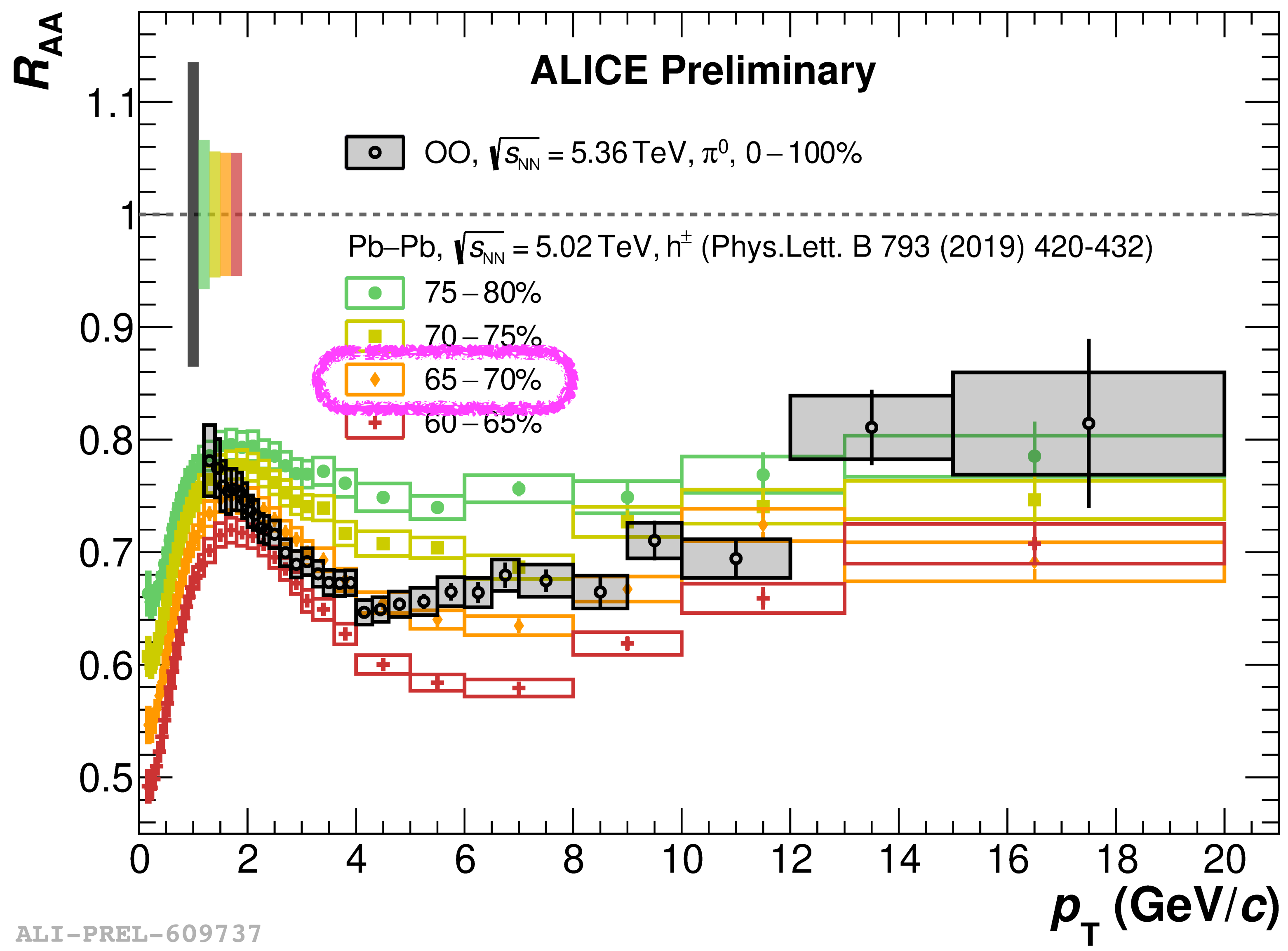
OO sits between these two

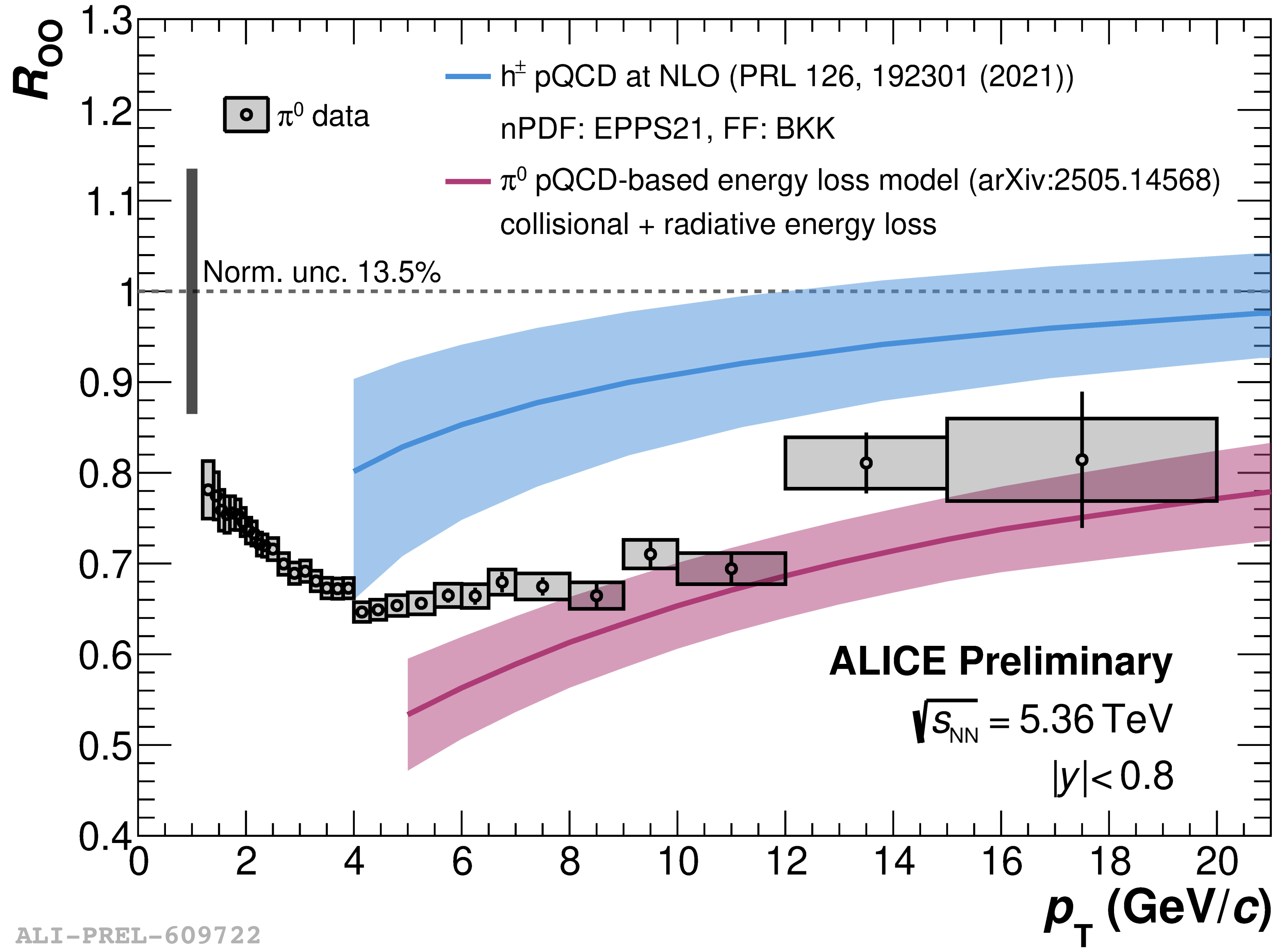
→ Is a medium dense enough to quench high p_T hadrons formed?

π^0 R_{AA} measured using EMCal

- 0-100% centrality
- R_{AA} ~ 0.65 at 4 GeV/c (4σ from unity)
- Values between pPb and PbPb → implies moderate parton energy loss → formation of small QGP?
- This trend supports a smooth system-size dependence of jet quenching and energy loss

π^0 R_{AA} for in OO collisions





Most similar to R_{AA} of 65-70% PbPb collision

→ OO medium behaves like peripheral heavy-ion collisions?

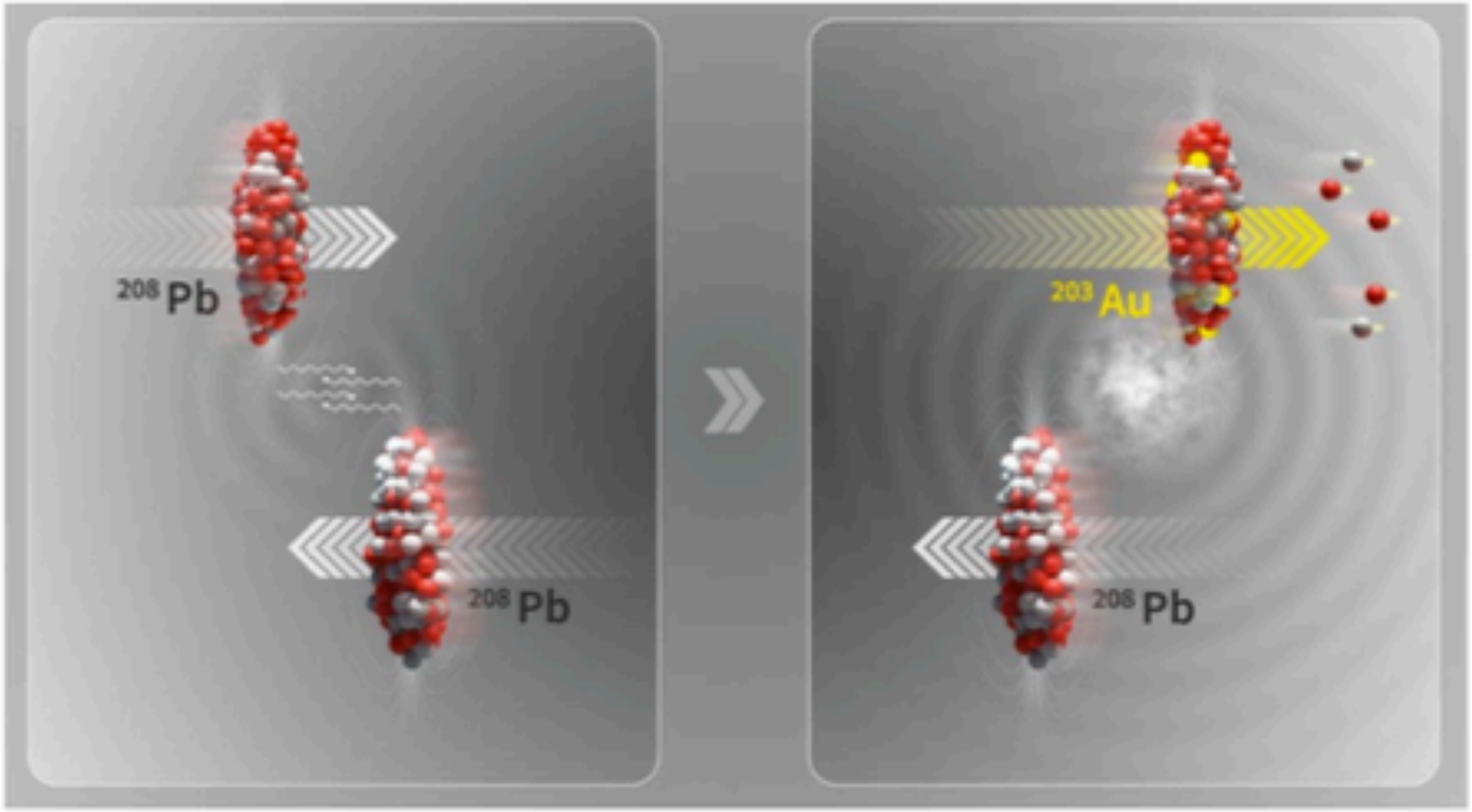
Do we see energy loss?

- R_{AA} ~ 0.65 at 4 GeV/c (4σ from unity)
- Compared to CNM (shadowing, nuclear PDFs) pQCD without energy loss: data differ by 2.4σ
- Compatible with energy loss calculation (collisional + radiative) (Faraday, horowitz, 2505.14568)

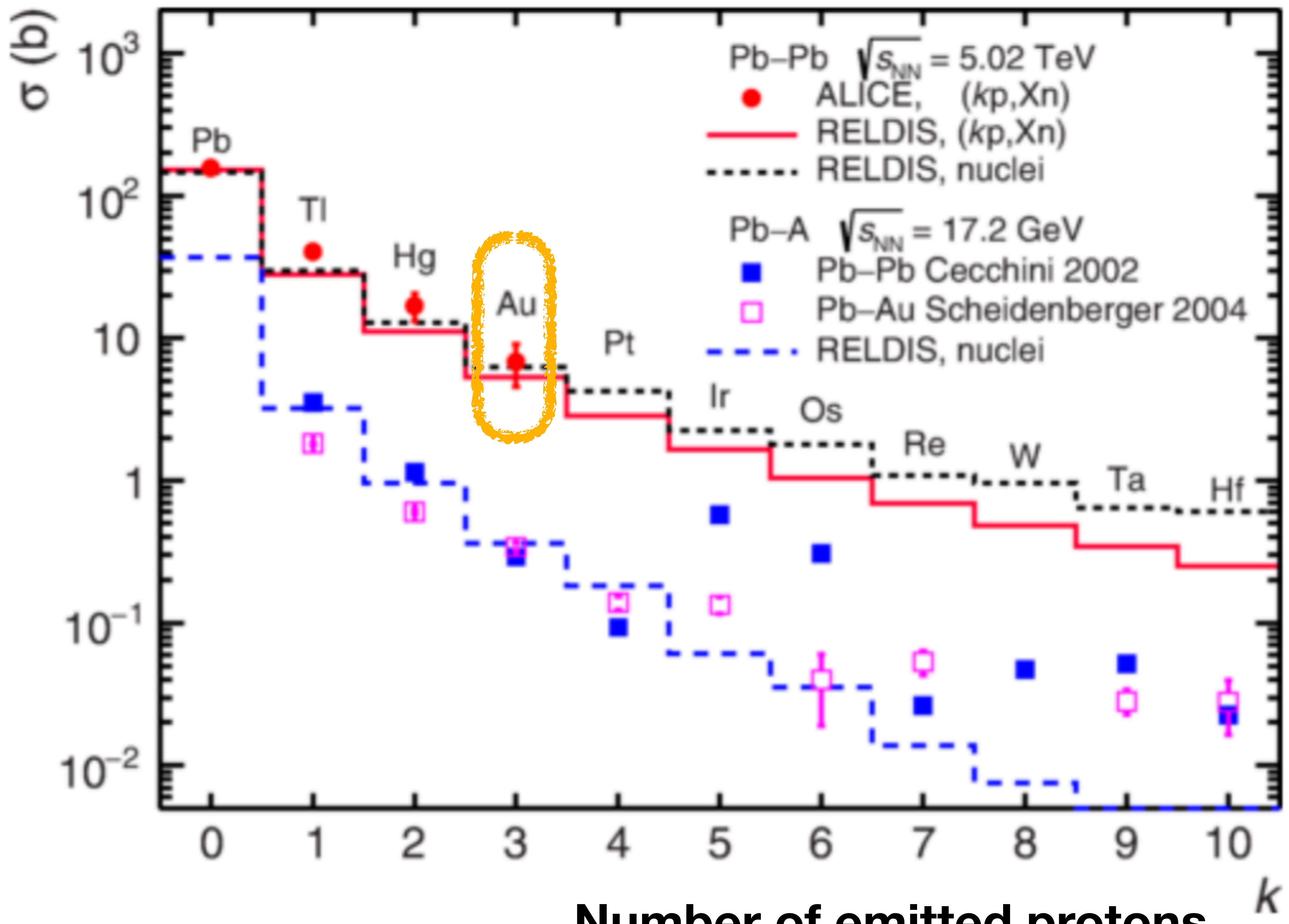
  → **Presence of parton energy loss?**

Alchemy at ALICE: turning lead to gold

Phys. Rev. C 111 (2025) 054906



https://home.cern/news/news/physics/alice-detects-conversion-lead-gold-lhc



Number of emitted protons

- Photons exchanged during a UPC collision can also excite Pb nucleus that decays into Au
- Cross-section roughly same as producing QGP → Over 1500 'news clippings' world wide

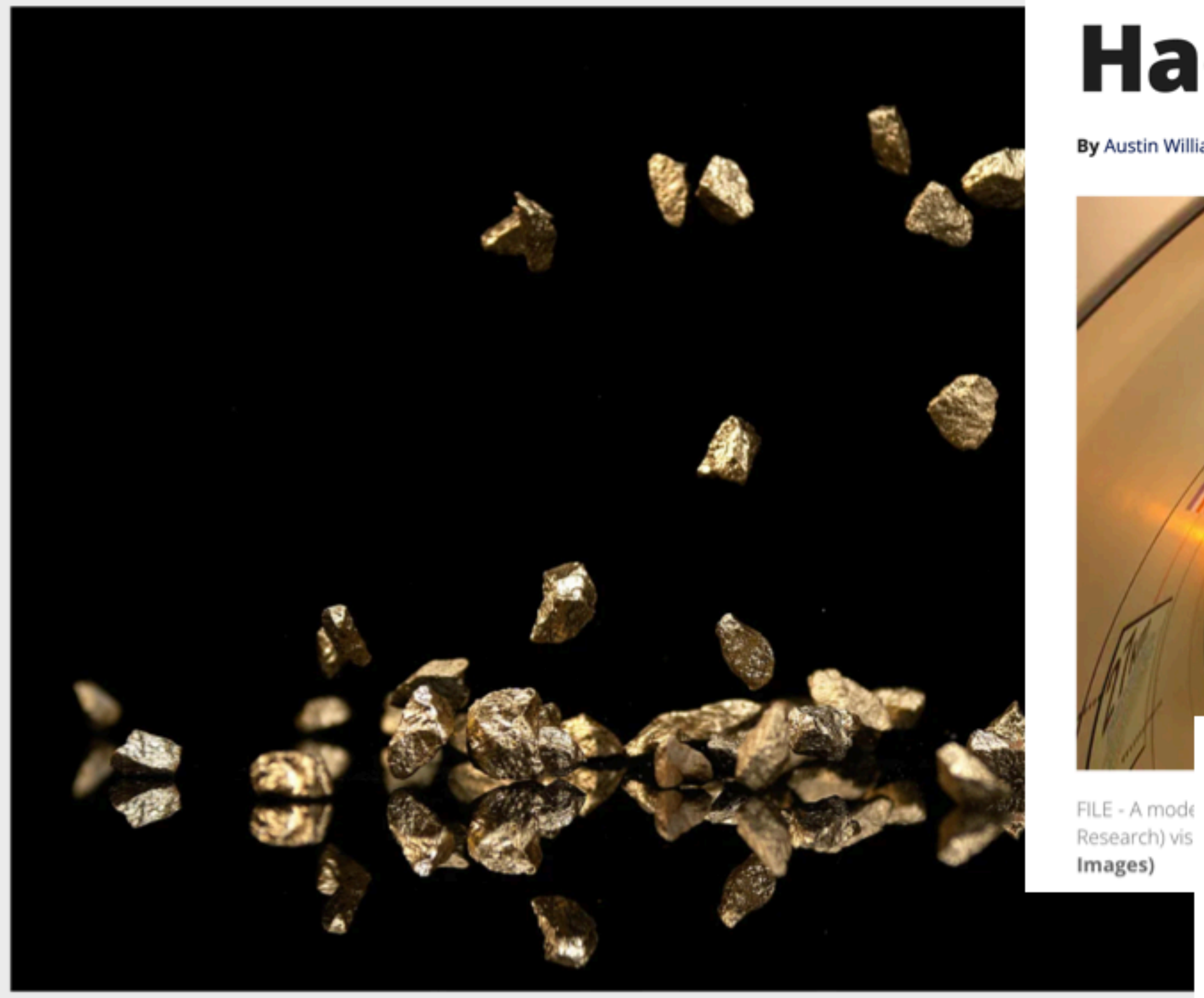
In press

MAY 9, 2025 | 2 MIN READ

Physicists Turn Lead into Gold—For a Fraction of a Second

Scientists at Europe's famous particle collider briefly create
lead in a modern twist on the alchemical goal

BY ELIZABETH GIBNEY & NATURE MAGAZINE



LHC experiments don't create large gold nuggets — but some particles within a beam of lead ions can turn into gold for about a micro
Images

Is alchemy real? Physicists turn lead into gold using the Large Hadron Collider

By Austin Williams | Published May 9, 2025 8:33pm EDT | Science | FOX Local |

FILE - A mode
Research) vis
Images)

Trending

1 'Senior bonus' explained: What Trump's budget bill means for Social Security taxes

2 Government plans to fight flesh-eating maggot by breeding billions of flies

3 Costco issues recall for several items, urges consumers not to use

L SUISSE

Ils ont transformé le plomb en or! Le CERN pratique l'alchimie moderne

Dans l'accélérateur de particules du CERN, des chercheurs ont observé la transmutation du plomb en or, un phénomène qui fascine depuis l'Antiquité.

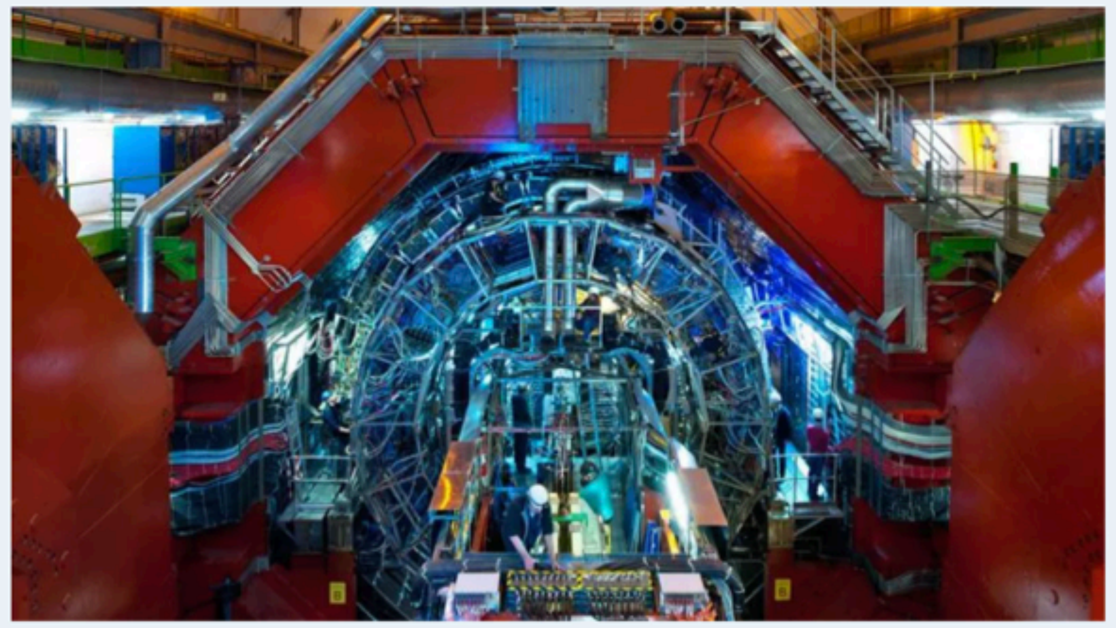
PARTAGER

Trasmutare il piombo in oro: ecco il "miracolo" al Cern di Ginevra

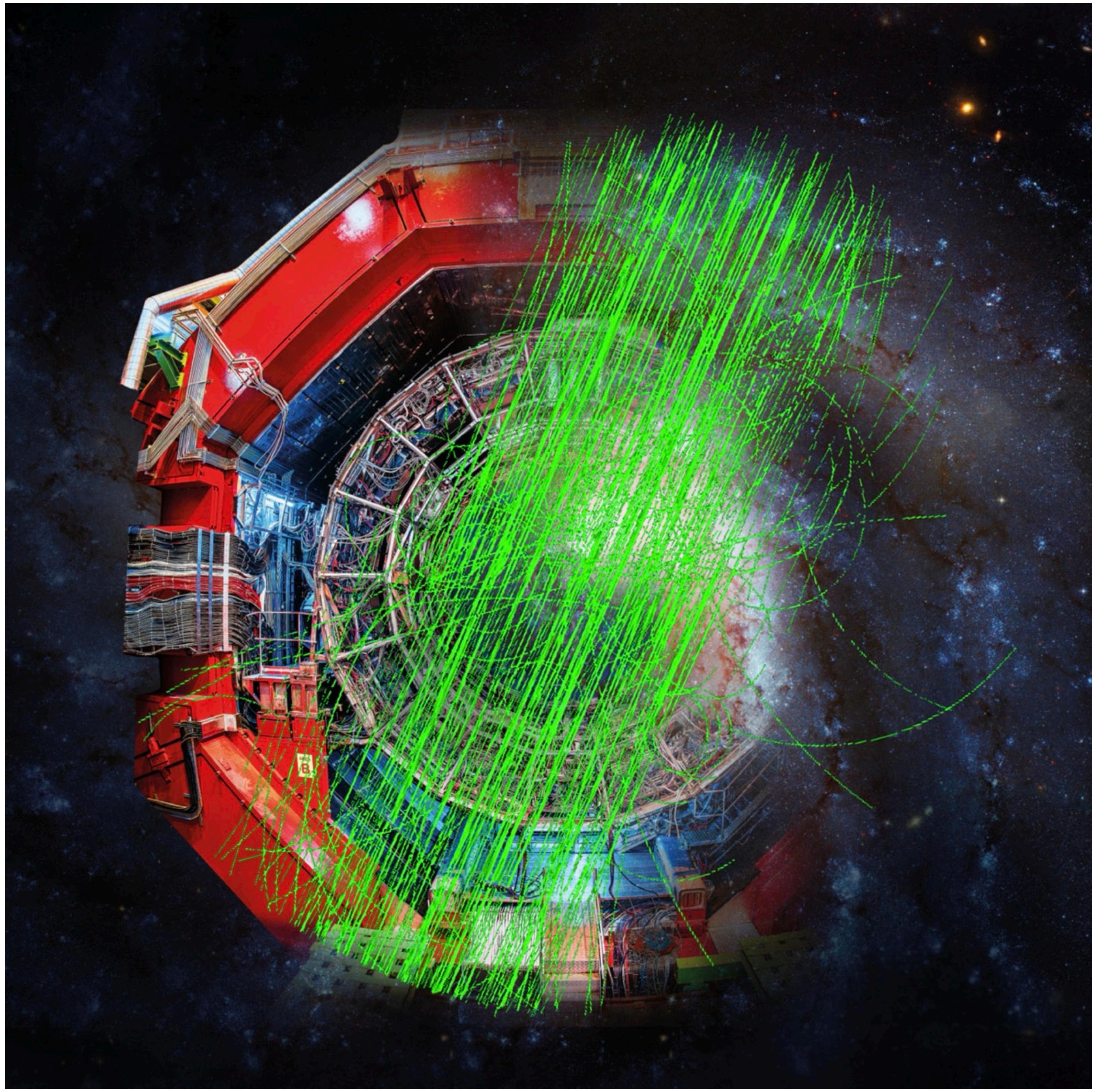
"Strappati" tre protoni da alcuni nuclei. La ricercatrice dell'Infn Chiara Oppedisano: un processo in cui le forze in gioco sono quelle elettromagnetiche. Ora si aprono nuove prospettive per i futuri acceleratori di particelle

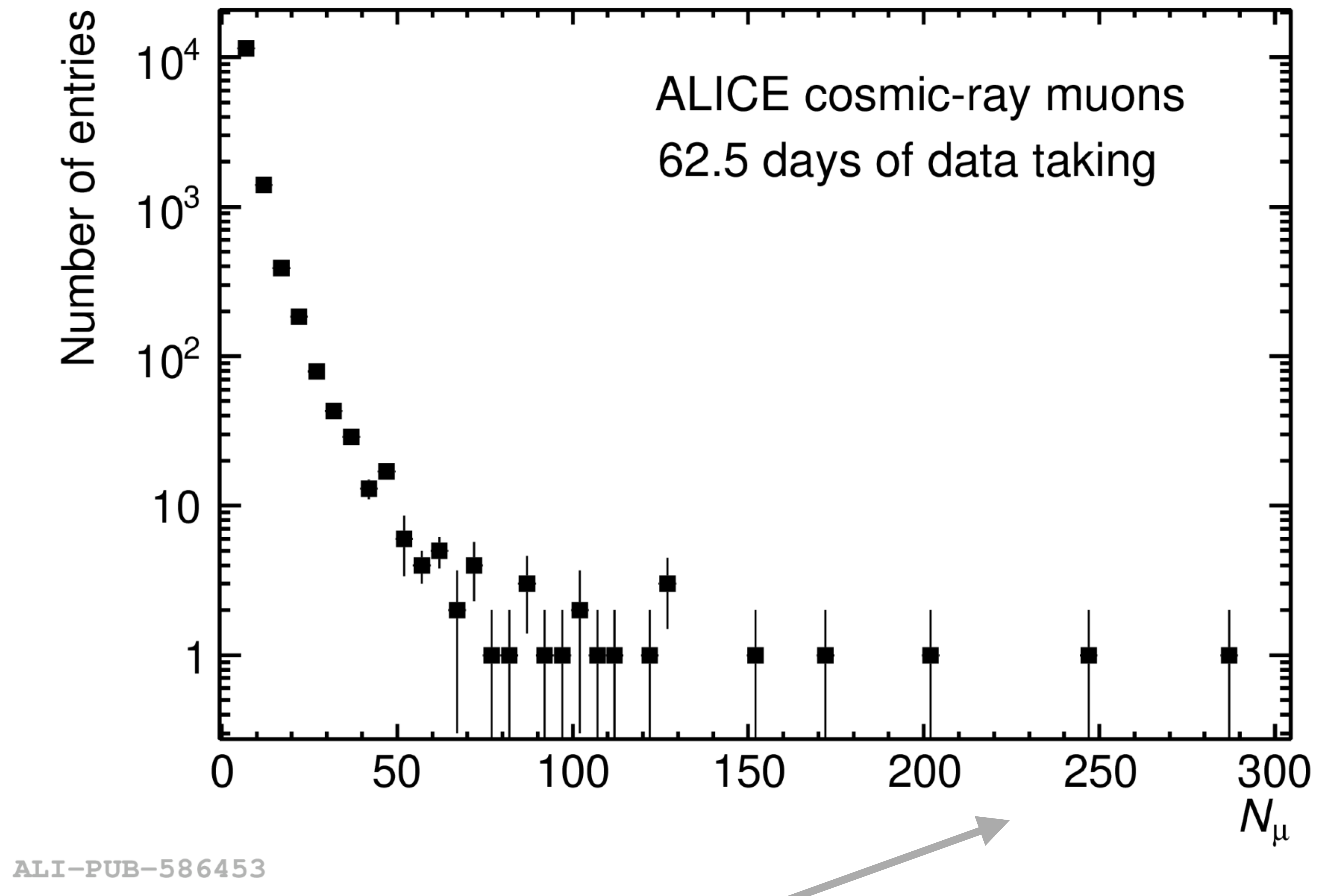
Silvia Bandelloni

04 Giugno 2025 alle 06:00 | 3 minuti di lettura



62.5일 동안 측정한 뮤온 다중도 분포: beam이 없을때!



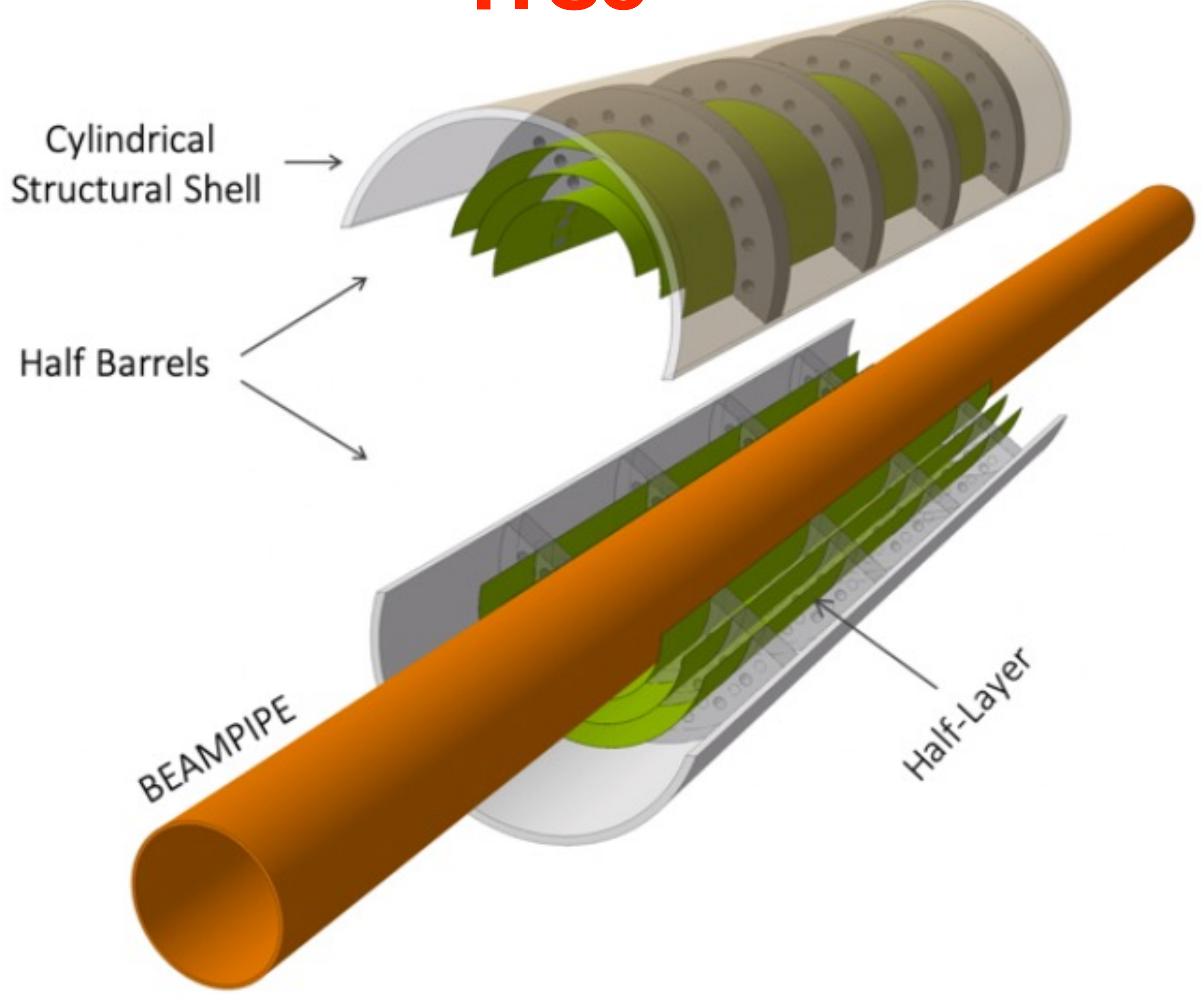


10^{14}–10^{16} eV 수준의 높은 에너지를 갖는 우주선이
대기 원자핵과 충돌하여 생성된 거대한 air shower가 ALICE 도달
→ 우주선의 에너지 스펙트럼 및 hadronic interaction model 테스트

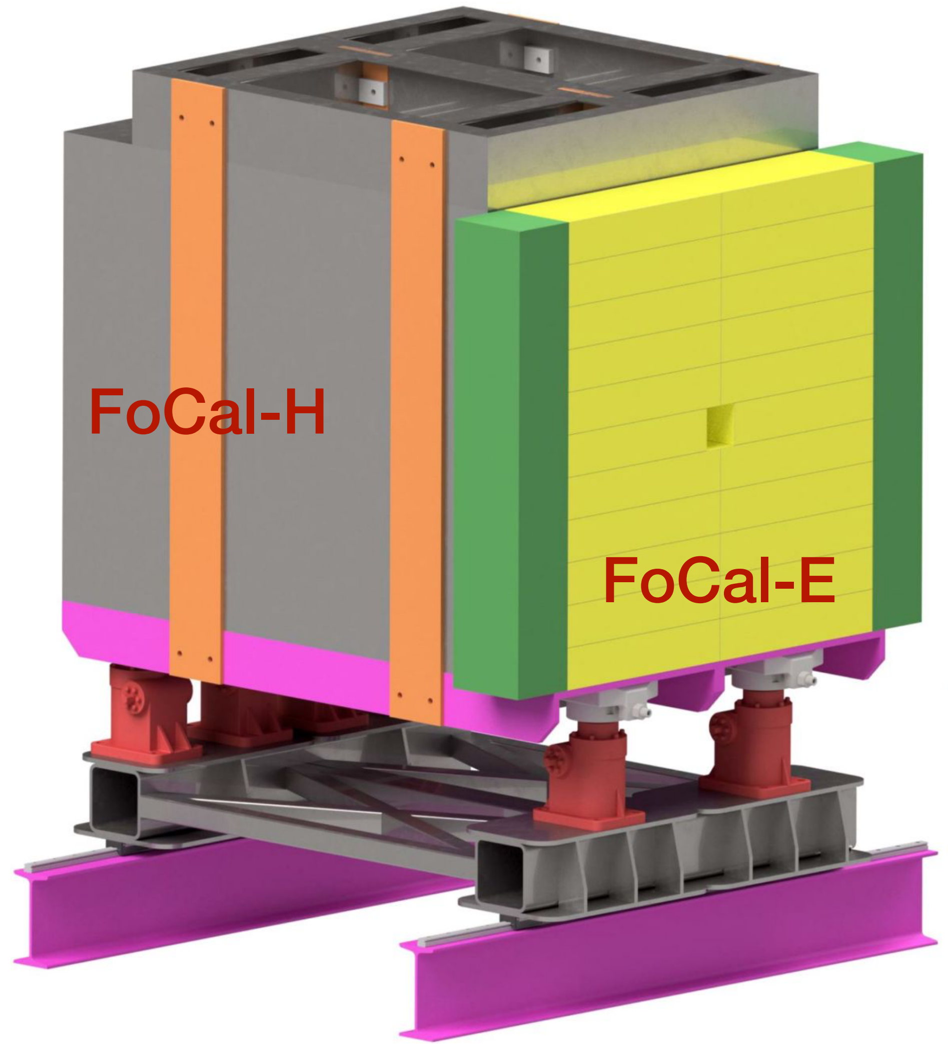
ALICE upgrades, beyond Run 3

Run 3	LS3				Run 4				LS4		Run 5	
	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037

ITS3



FoCal



ITS3 & FoCal

- Specific upgrades in LS3 (2026-29)
- TDRs approved in March 2024
- Moving towards "production" phase

ITS3 TDR: CERN-LHCC-2024-003

FoCal TDR: CERN-LHCC-2024-004

ALICE upgrades, beyond Run 4

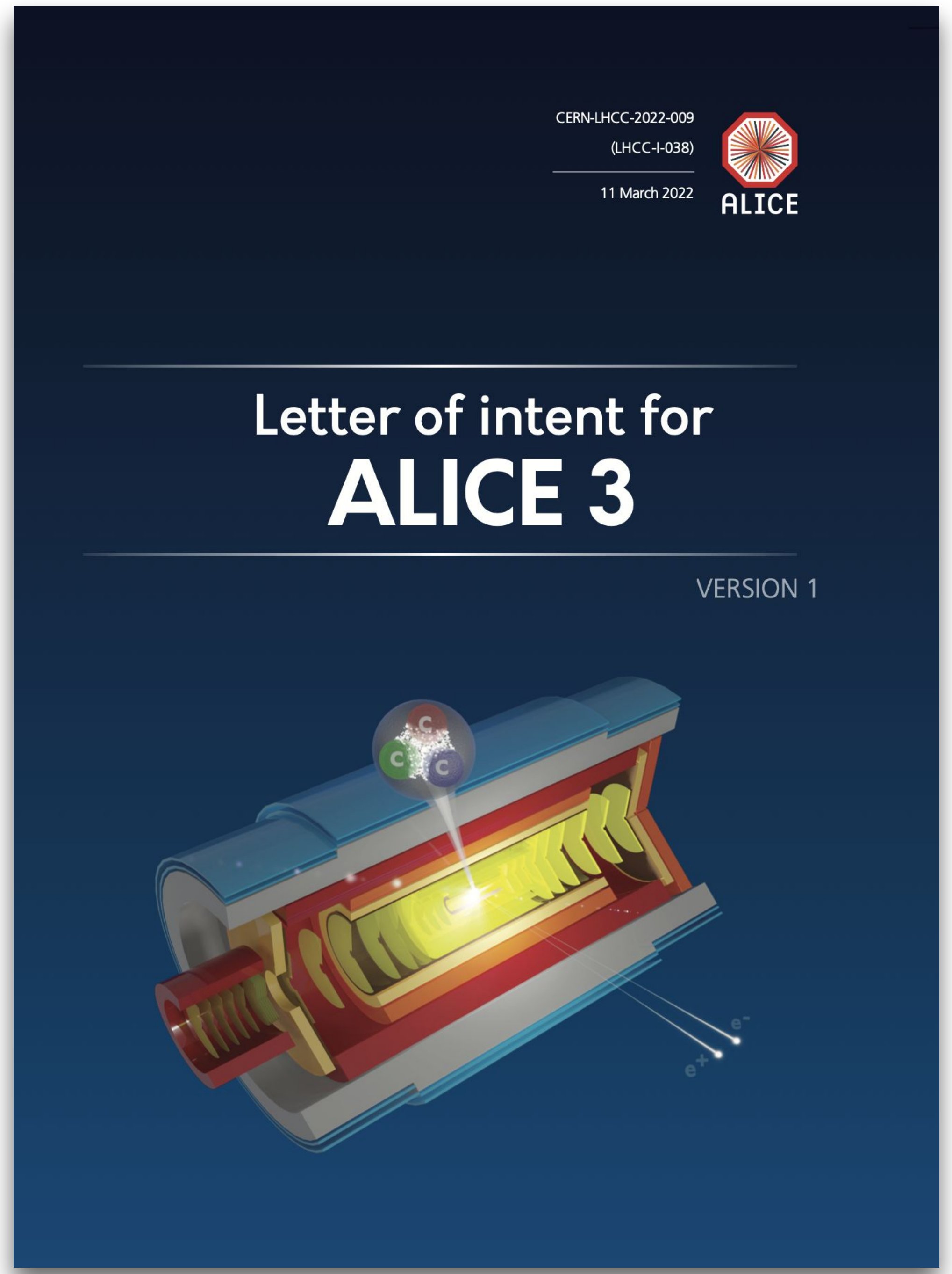
Run 3	LS3				Run 4				LS4		Run 5	
	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037

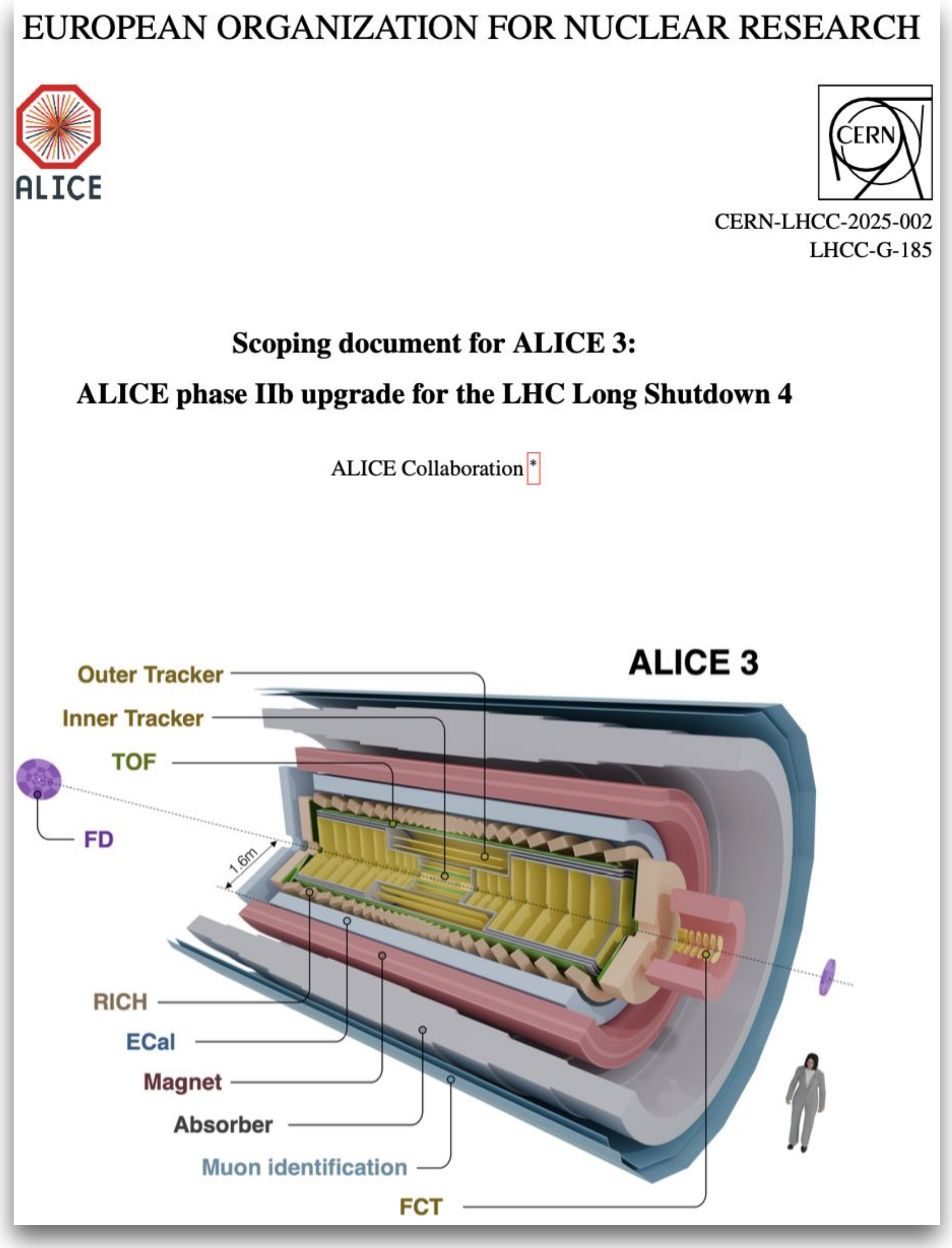
ALICE 3: Major upgrade in LS4 (2034-35)

→ **Next-generation heavy-ion experiment** - First ideas at Heavy-Ion town meeting in 2018 (arXiv:1902.01211)

→ **Letter of Intent:**
Review by the LHCC in March 2022 (arXiv:2211.02491)

→ **Scoping Document:**
Review completed w/ positive feedback (CERN-LHCC-2025-002)




EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

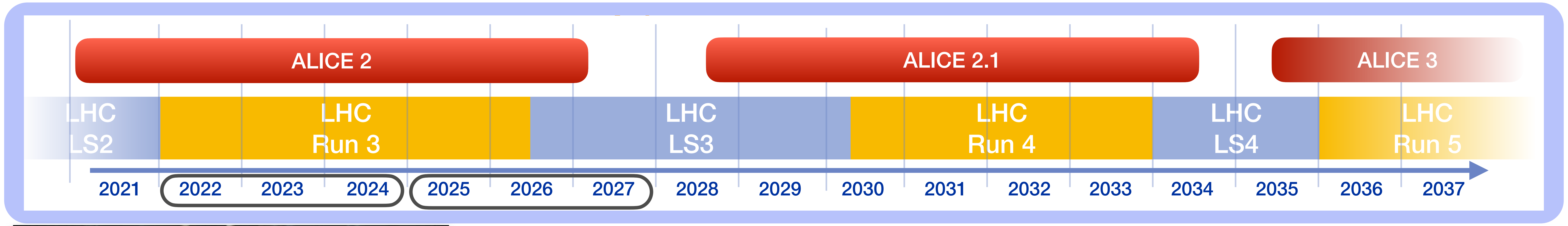
CERN-LHCC-2025-002
LHCC-G-185

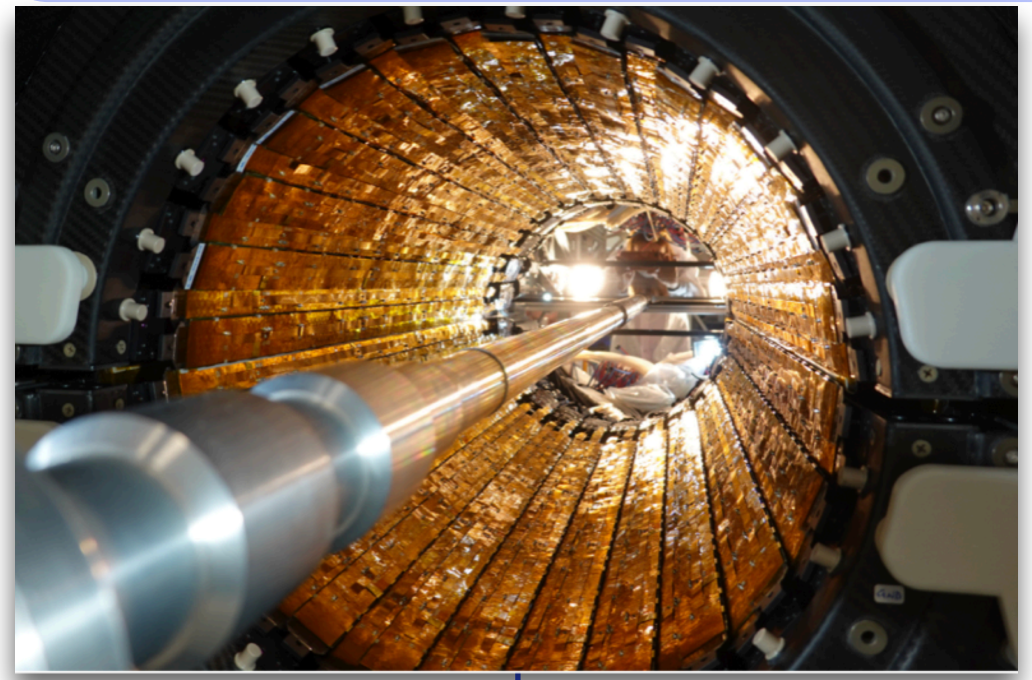
Scoping document for ALICE 3:
ALICE phase IIb upgrade for the LHC Long Shutdown 4

ALICE Collaboration*

● Moving towards **"comprehensive R&D" phase**

ALICE 검출기 업그레이드 로드맵과 KoALICE의 역할

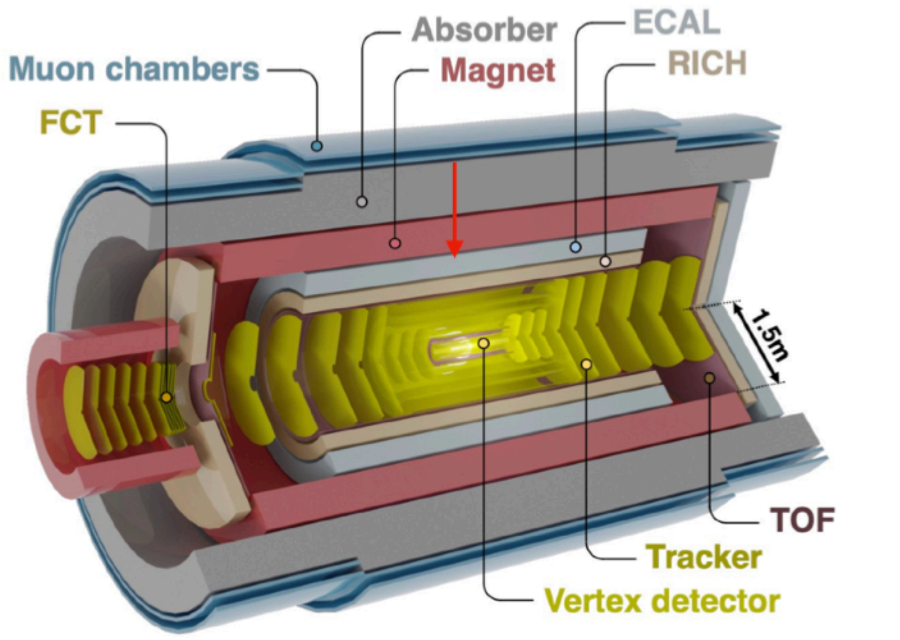




ITS3 (LS3)

CMOS 웨이퍼를 스티칭하여 통으로 구부려 사용하는 혁신 기술 (HEP 분야 최초)

주도적 R&D 참여

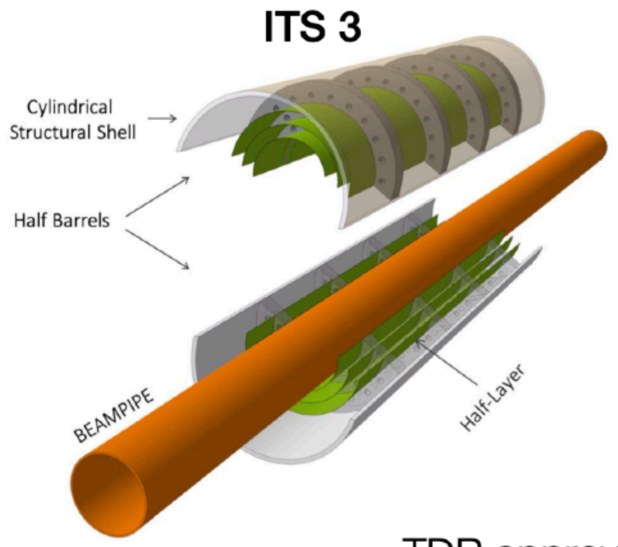


ALICE 3 LoI: CERN-LHCC-2022-009

1

2

3



TDR approved

ITS2 (Run 3)

현재 운용 단계

R&D 및 제작 참여를 통해 실리콘 검출기 전문성 확보

ALICE3 (LS4)

모든 검출기가 반도체 센서로 이루어짐 →반도체 기술 집약

차세대 R&D 주도

KoALICE 실리콘 검출기 R&D 역사

1단계: 2013~2021 ITS2 R&D 및 제작 참여 → 2단계: 2021~현재 ITS3 주도적 R&D 참여 → 3단계: 2023~현재 ALICE3 차세대 R&D 주도

ITS3 R&D 및 제작 한국팀 성과

CERN ITS3 핵심 팀과의 긴밀한 공동 연구를 통해 실리콘 검출기 전문가를 체계적으로 양성하고, 한국으로의 기술 이전 및 독자적인 연구 인프라를 성공적으로 구축

01

1세대 Engineering Run 센서 R&D

CERN 및 국내에서 센서 R&D 참여,
센서 테스트 및 각종 보드 국내 제작 수행

02

2세대 Engineering Run 셋업 R&D

CERN에서 센서 테스트 셋업 공동 연구 진행

03

빔테스트 수행

CERN PS 빔테스트 공동 수행 및 데이터 분석

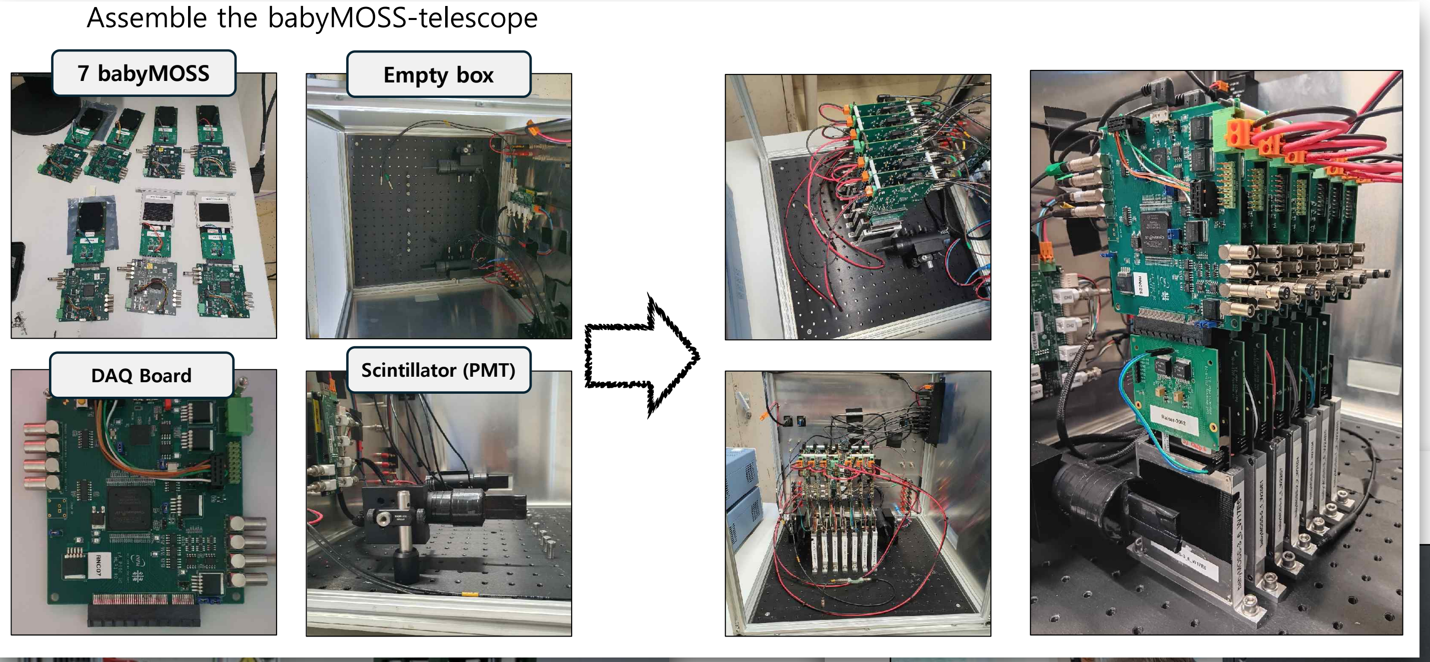
04

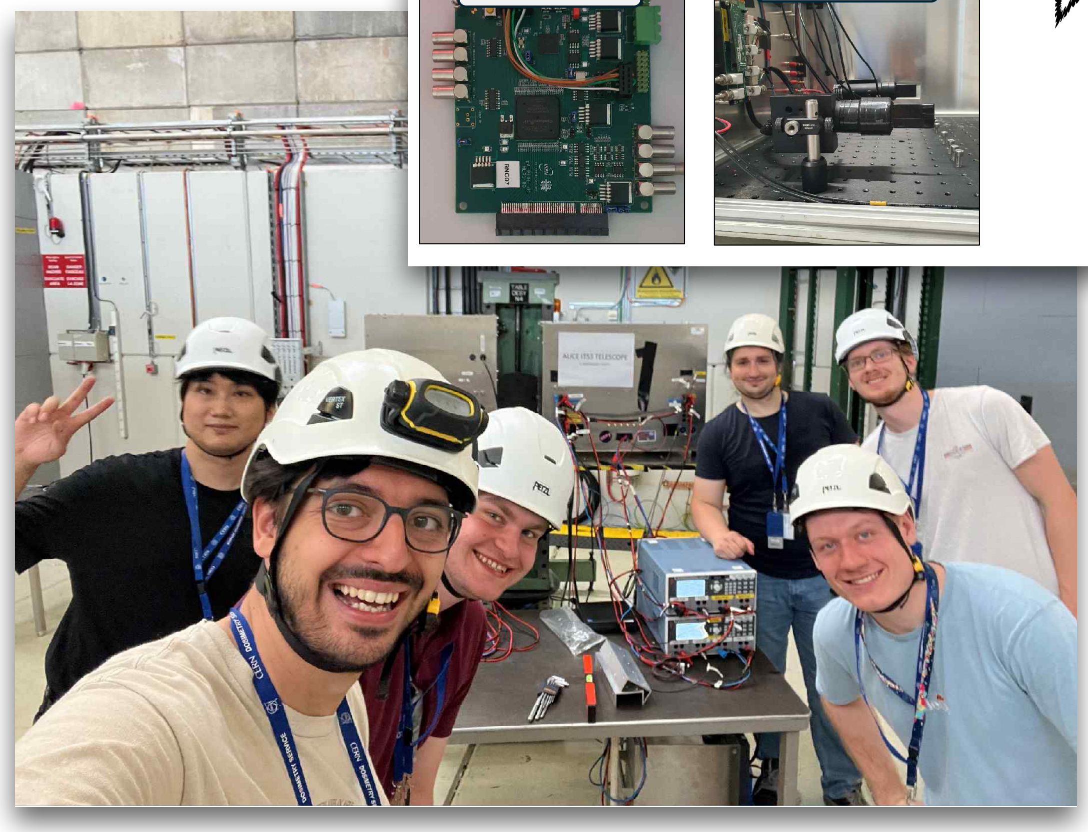
국내 텔레스코프 검출기 제작

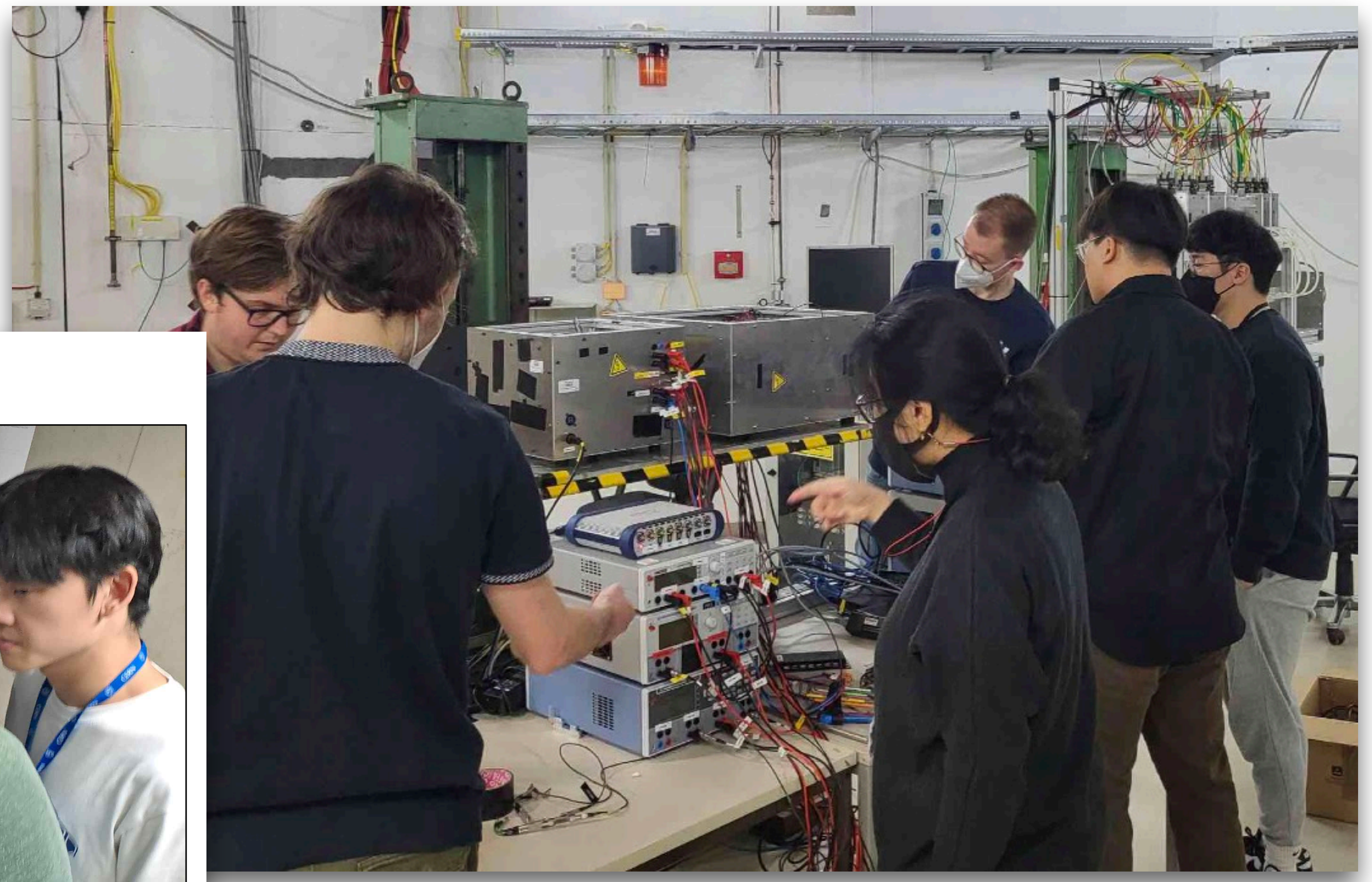
독자적인 기술력으로 아시아 최초의 MAPS
기반 텔레스코프 완성

기관별 전문 연구 분야

- 센서 디자인
  연세대
- 센서 특성 연구
  인하대, 부산대, 성균관대, 세종대
- Interconnection technology
  MEMSPACK, 인하대, 부산대
- 프로브카드 및 전자보드 생산
  NOTICE, MEMSPACK, 연세대, 인하대, 부산대
- 텔레스코프 제작 및 빔테스트
  부산대, 인하대, 성균관대, 세종대







아시아 최초 MAPS 기반 텔레스코프 검출기 개발 및 빔테스트

- 한국에서 아시아 최초의 MAPS 기반 실리콘 칩 텔레스코프 검출기(Korean ALICE TeleScope, KATS)를 개발하고, 이를 이용하여 일본 KEK에서 빔 테스트를 수행

2024년 3월

1

첫 번째 KEK 빔테스트

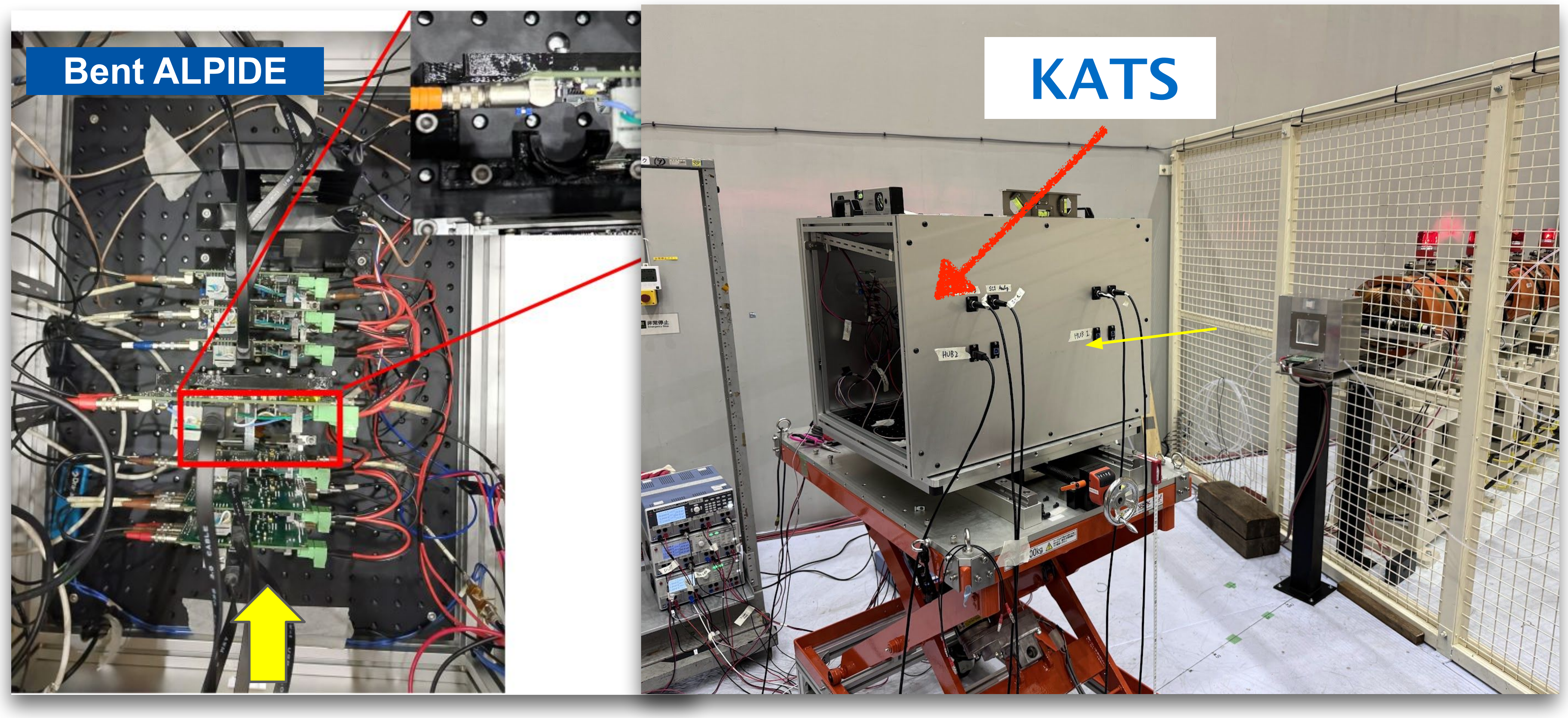
KATS 시스템의 첫 검증을 일본 KEK에서 성공적으로 완료. 검출기의 기본 성능과 데이터 수집 시스템의 안정성 확인

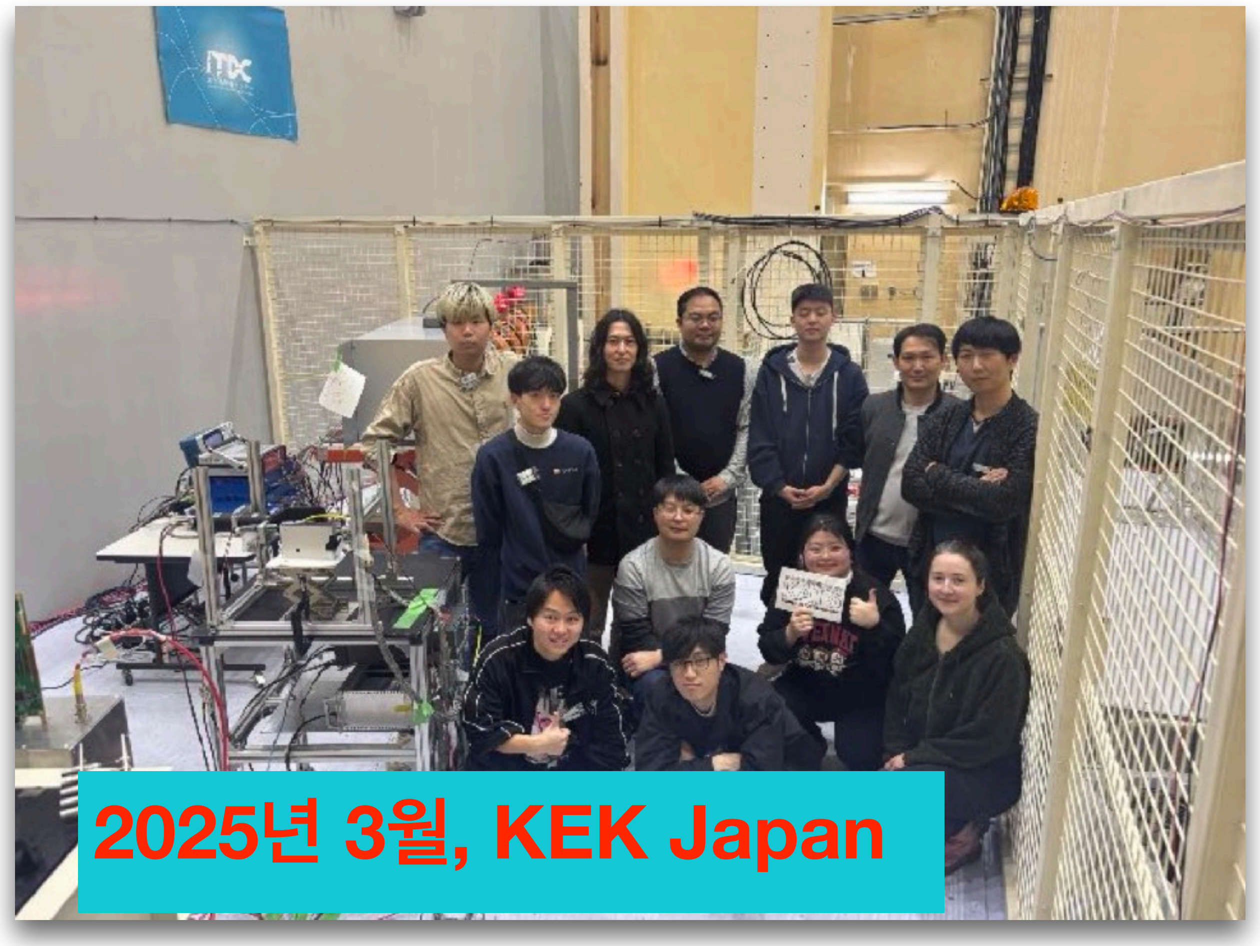
2

2025년 3월

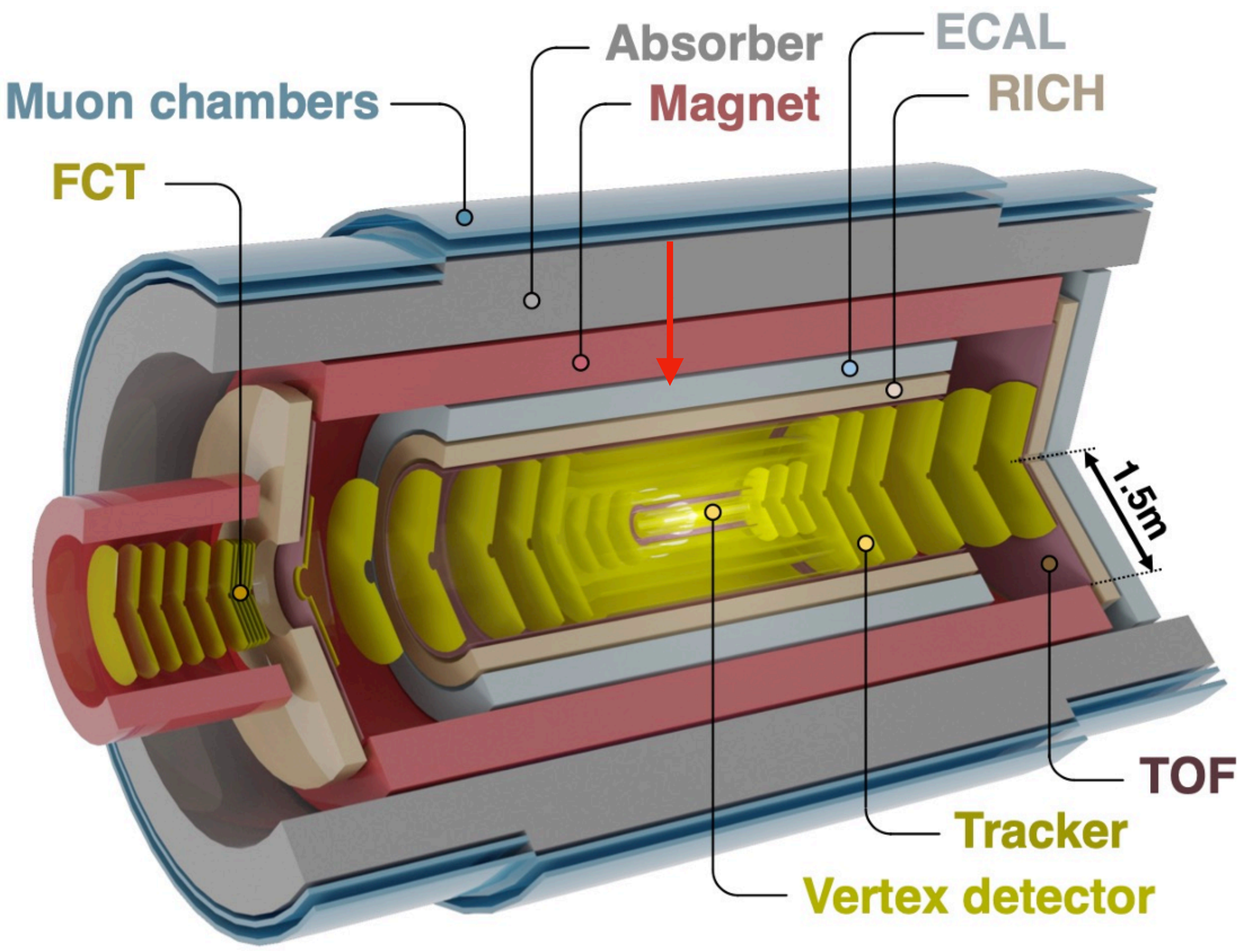
두 번째 KEK 빔테스트

개선된 KATS 시스템으로 고급 성능 평가 수행. 공간 분해능, 시간 분해능, 효율성 등 핵심 지표에서 설계 목표 달성.





Future ALICE: ALICE 3 업그레이드 (Run 5/6)



모든 검출기가 반도체 센서로 이루어짐!
→ 반도체 기술 집약

Vertexer : CMOS 실리콘 픽셀 검출기. 휘어지는 웨이퍼 크기 칩 이용 (ITS3 기술 기반 + 최첨단 기술을 이용해 빔파이프 안쪽에 설치)

Outer Tracker (OT): CMOS 실리콘 픽셀 검출기. 업그레이드 된 ALPIDE 칩 이용.
ITS2 검출기 면적의 6배: 100 억개 픽셀 x 6 = 600 억개 픽셀

TOF: 시간 분해능이 매우 뛰어난 반도체 검출기. CMOS 기반 센서

한국팀 ALICE3 Outer Tracker 주도

- 한국팀의 전략적 접근

  ITS2 제작 기간 동안 쌓은 전문성 및 인프라 확장 → 국내 기업과 협업하여 large scale industrial prodution → Outer Tracker 프로젝트 참여

한국팀 ALICE3 Outer Tracker R&D 주도

웨이퍼 후공정 정밀도

EngiON Thinning/dicing 기술로 웨이퍼 후공정의 정밀도를 확인하고 최적화

모듈 조립 자동화

R&D 진행 중인 조립 자동화 시스템 (MEMSPACK)으로 정확도를 검증
플립칩 본딩 기술 R&D (NNFC)

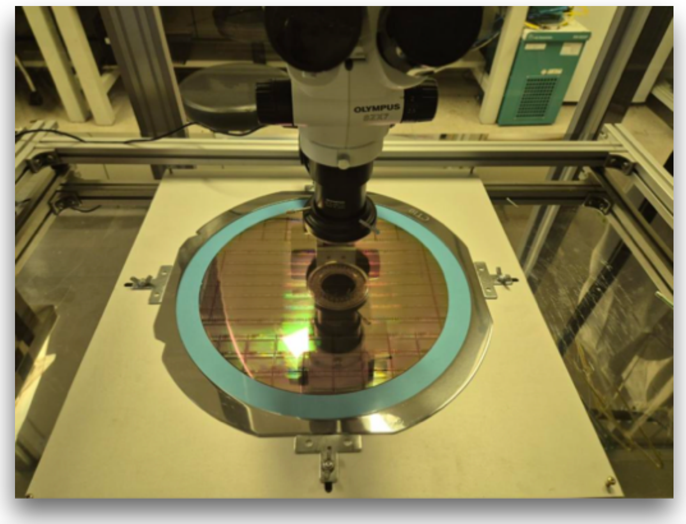
칩/웨이퍼 프로빙 시스템

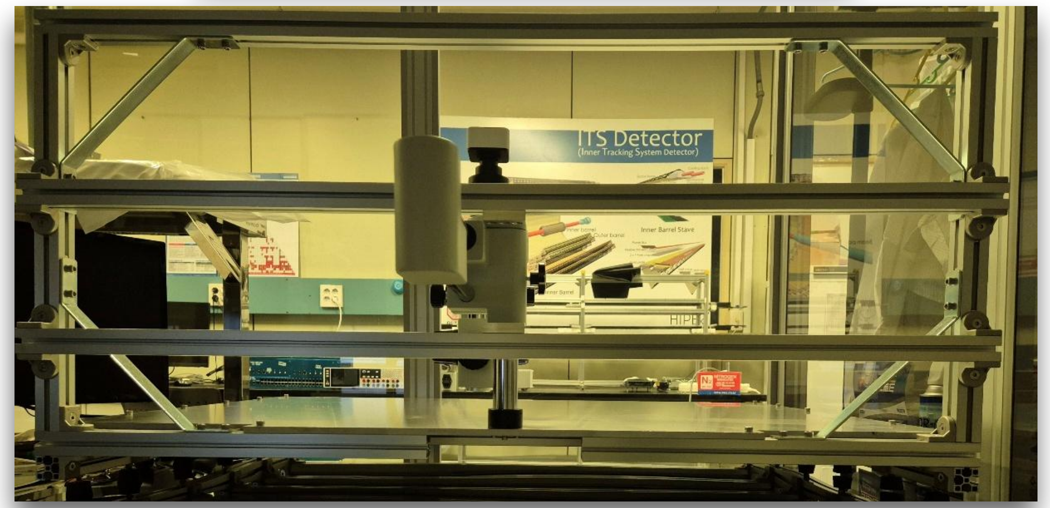
시스템 운용 및 기업을 통한 대량 프로빙/테스트(두산테스나) R&D 수행
칩대량테스트 장비 제작(C-ON Tech)

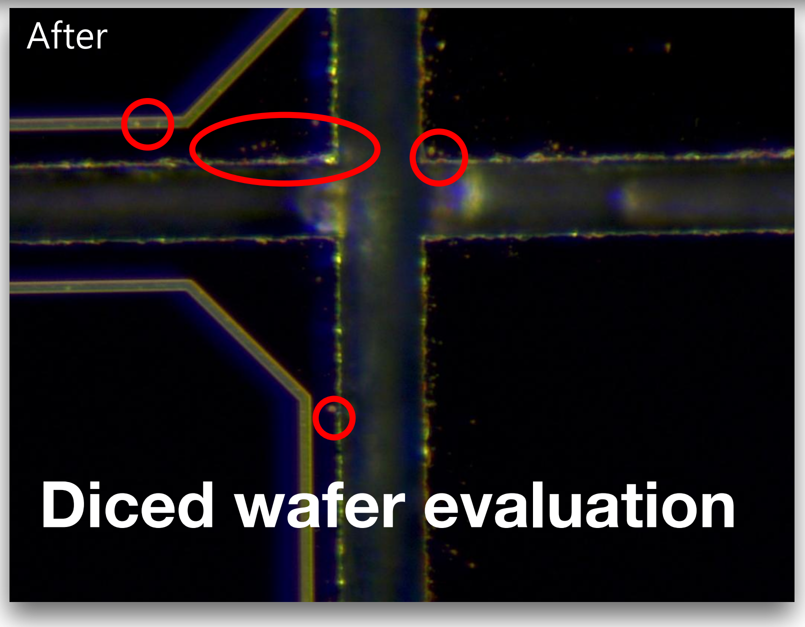
쿨링테스트용 센서 대량 생산

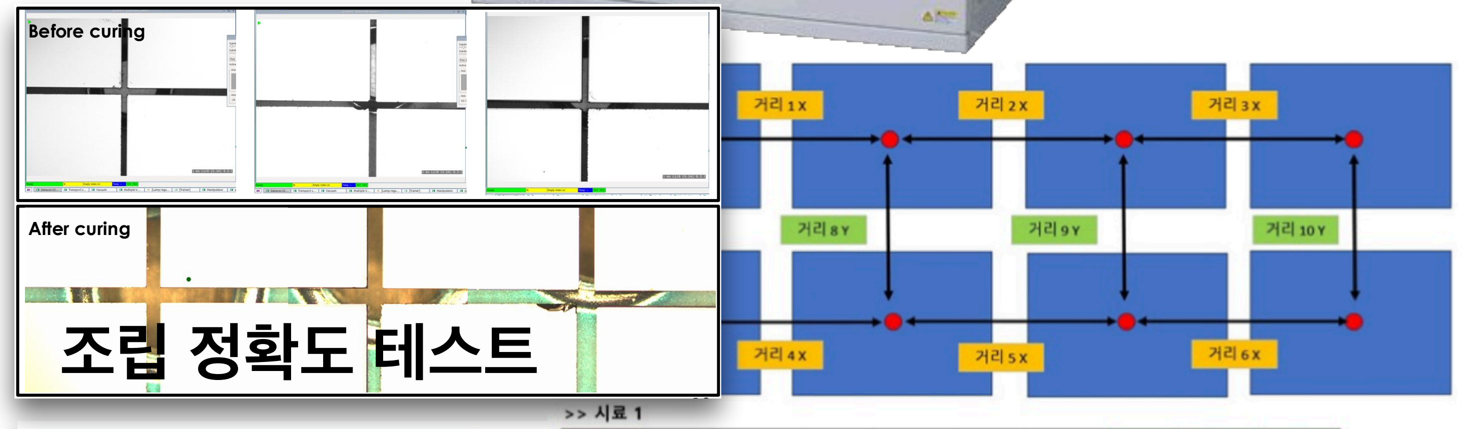
냉각 시스템 R&D를 위한 센서 대량 양산 체계 구축 및 생산 (ETRI)

Setup at Pusan National University





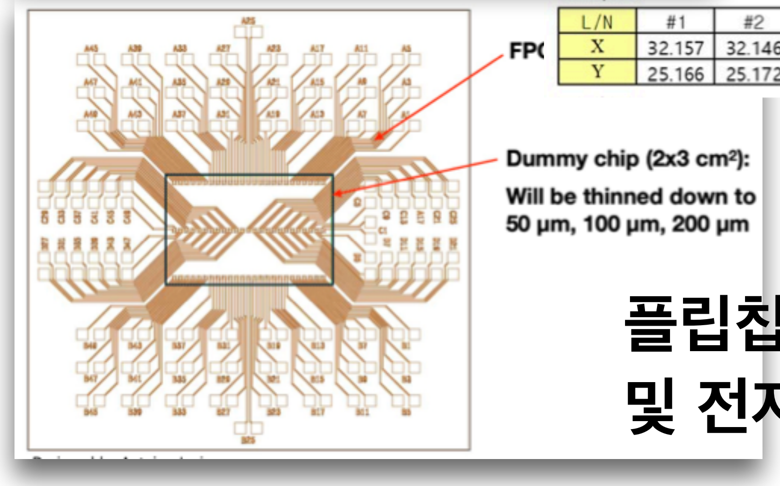




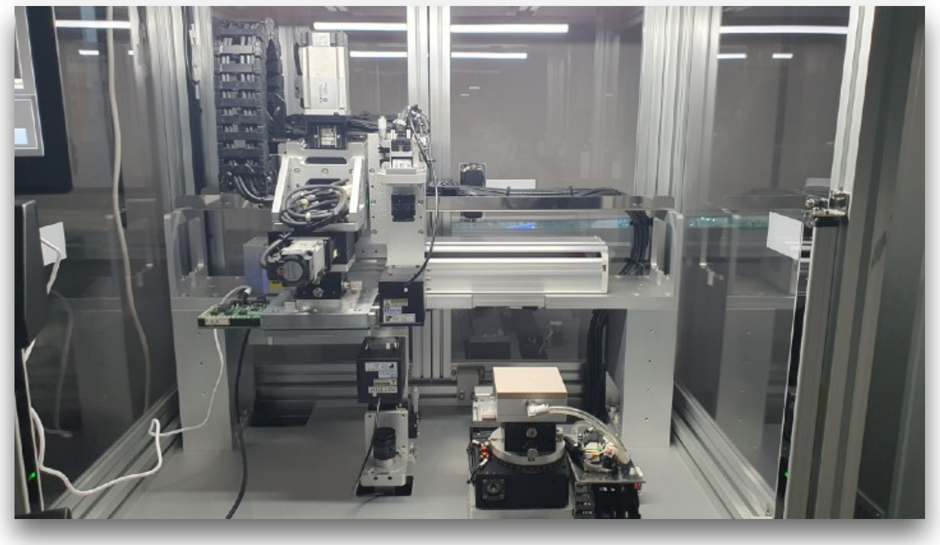
>> 시료 1

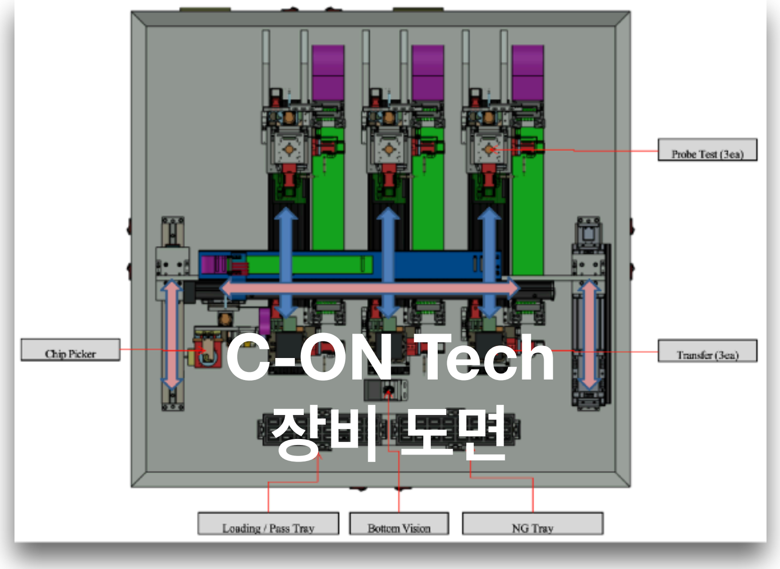
L/N	#1	#2	#3	#4	#5	#6	MIN	MAX	AVG
X	32.157	32.146	32.141	32.169	32.159	32.15	32.141	32.169	32.154
Y	25.166	25.172	25.145	25.154			25.145	25.172	25.159

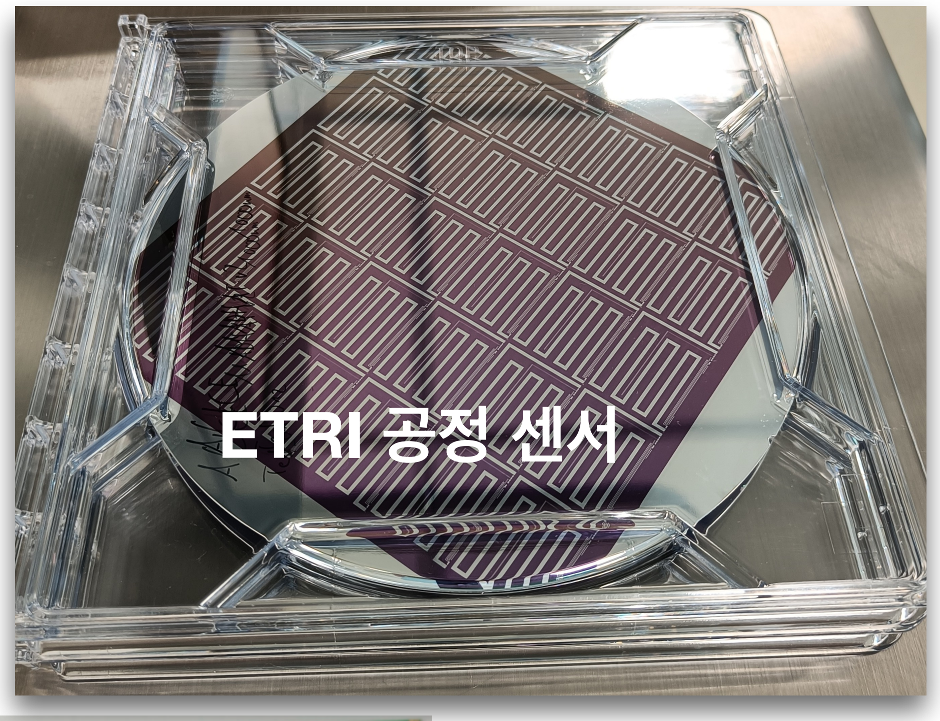
100 µm

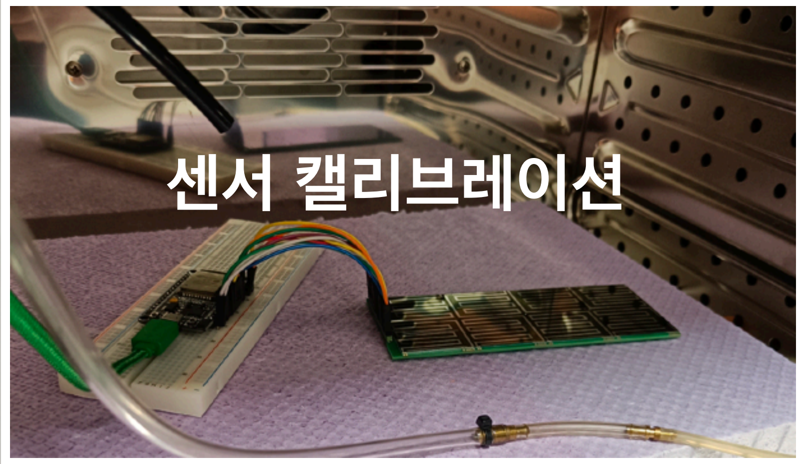


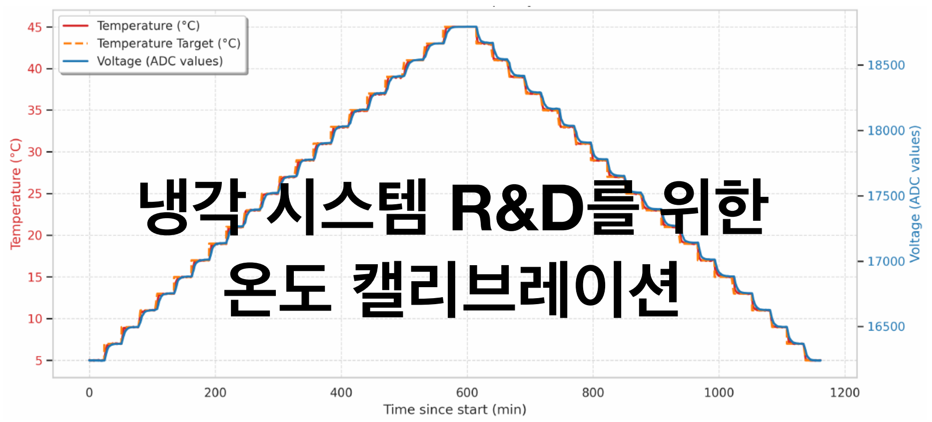
Setup at Inha University



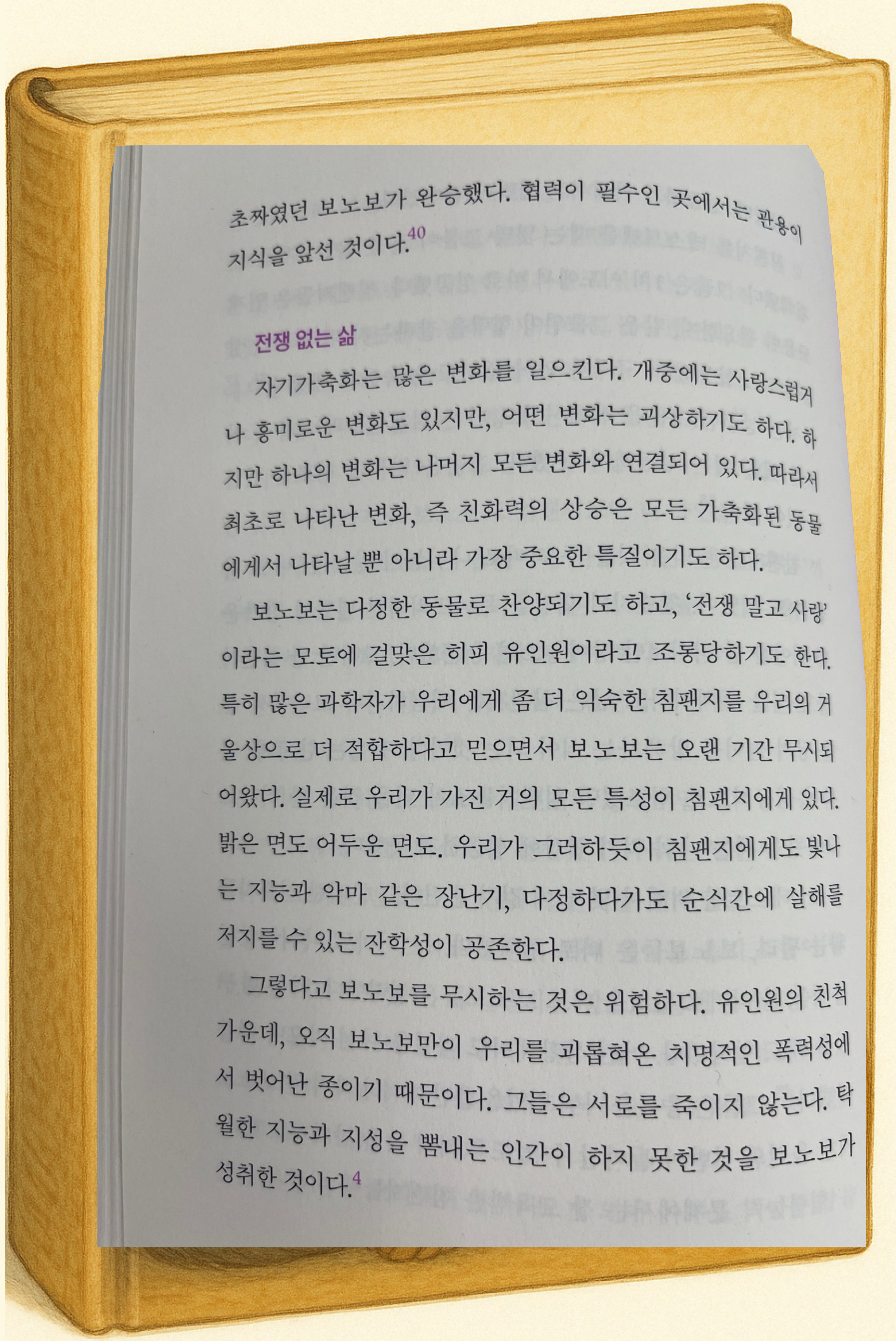








거대과학에 수여된 Berakthrough 상의 의미를 되새기며, AI 시대를 살아가며…


초짜였던 보노보가 완승했다. 협력이 필수인 곳에서는 관용이 지식을 앞선 것이다.[40]

전쟁 없는 삶

자기가축화는 많은 변화를 일으킨다. 개중에는 사랑스럽거나 흥미로운 변화도 있지만, 어떤 변화는 괴상하기도 하다. 하지만 하나의 변화는 나머지 모든 변화와 연결되어 있다. 따라서 최초로 나타난 변화, 즉 친화력의 상승은 모든 가축화된 동물에게서 나타날 뿐 아니라 가장 중요한 특질이기도 하다.

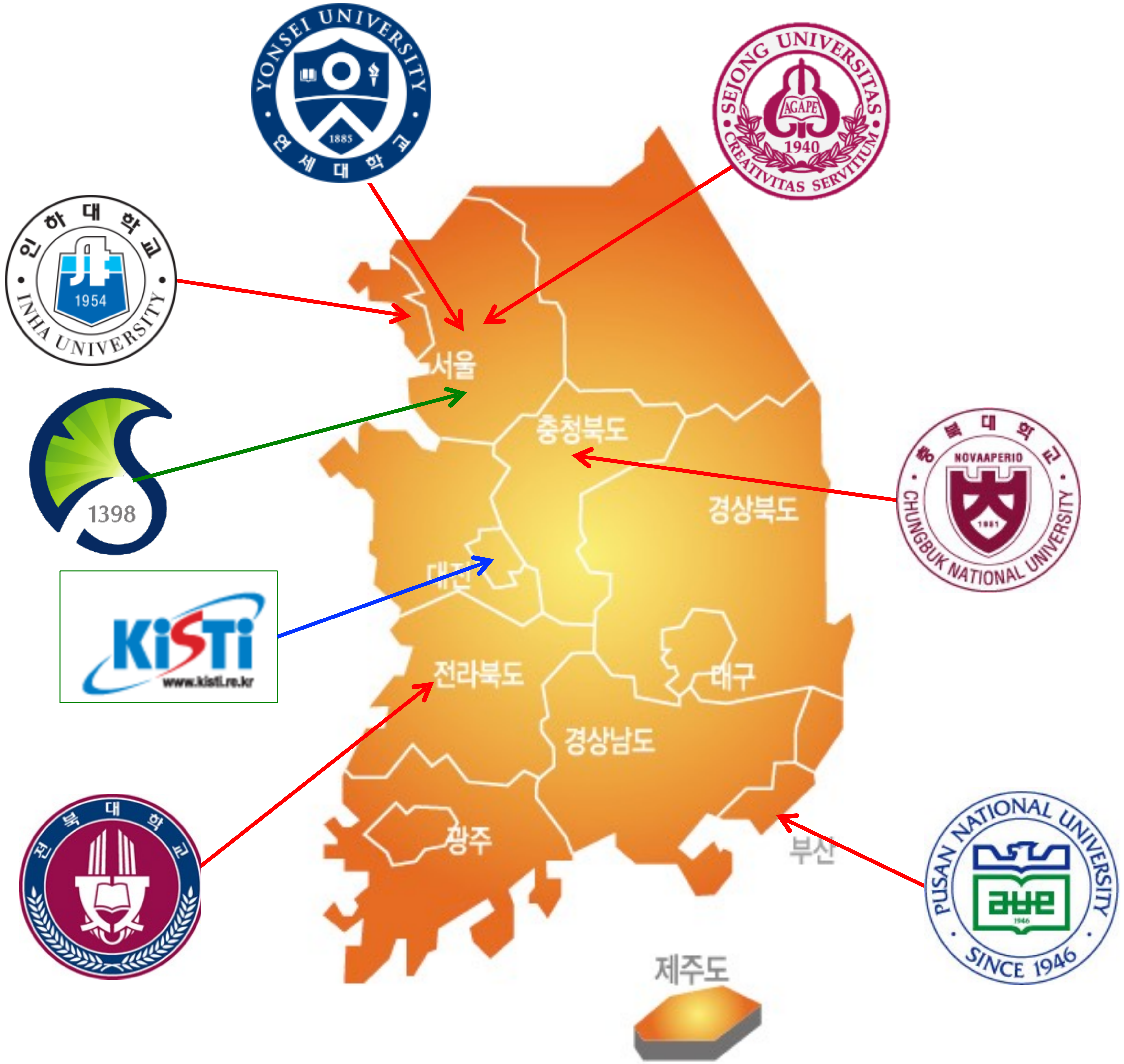
보노보는 다정한 동물로 찬양되기도 하고, '전쟁 말고 사랑'이라는 모토에 걸맞은 히피 유인원이라고 조롱당하기도 한다. 특히 많은 과학자가 우리에게 좀 더 익숙한 침팬지를 우리의 거울상으로 더 적합하다고 믿으면서 보노보는 오랜 기간 무시되어왔다. 실제로 우리가 가진 거의 모든 특성이 침팬지에게 있다. 밝은 면도 어두운 면도. 우리가 그러하듯이 침팬지에게도 빛나는 지능과 악마 같은 장난기, 다정하다가도 순식간에 살해를 저지를 수 있는 잔학성이 공존한다.

그렇다고 보노보를 무시하는 것은 위험하다. 유인원의 친척 가운데, 오직 보노보만이 우리를 괴롭혀온 치명적인 폭력성에서 벗어난 종이기 때문이다. 그들은 서로를 죽이지 않는다. 탁월한 지능과 지성을 뽐내는 인간이 하지 못한 것을 보노보가 성취한 것이다.[4]

인류가 성공한 이유는
'지능'이 아니라 '다정함'이다

Thank you for your attention!

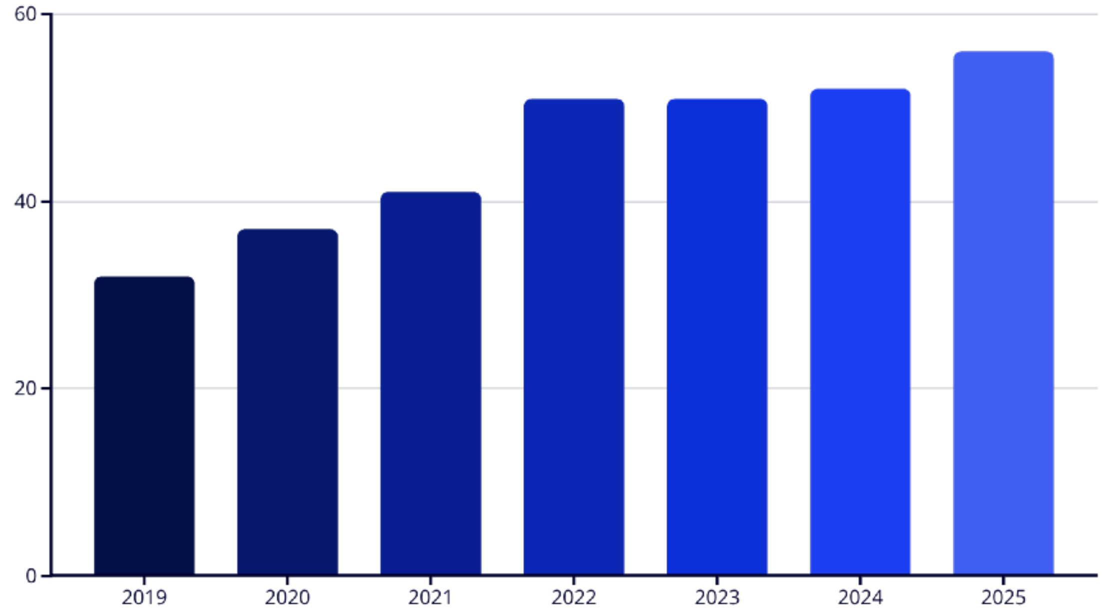
KoALICE 참여 기관 현황



	기관	교수	박사후연구원	대학원생	기타	총인원
2019	6→7	7→8	7	16	1	32
2020	7	8	7	21	1	37
2021	7→8	8→9	7	24	1	41
2022	8	10	9	31	1	51
2023	8	10	10	30	1	51
2024	8→7	10	8	33	1	52
2025	7	10	8	35	3	56

Participants : 56 (2025년 10월 현재)

- **7개 대학***
- **교수급: 10**
- **박사후 연구원 : 8**
- **대학원생: 35**
- **기타 : 3 (석사연구원 2인, 행정원 1인)**



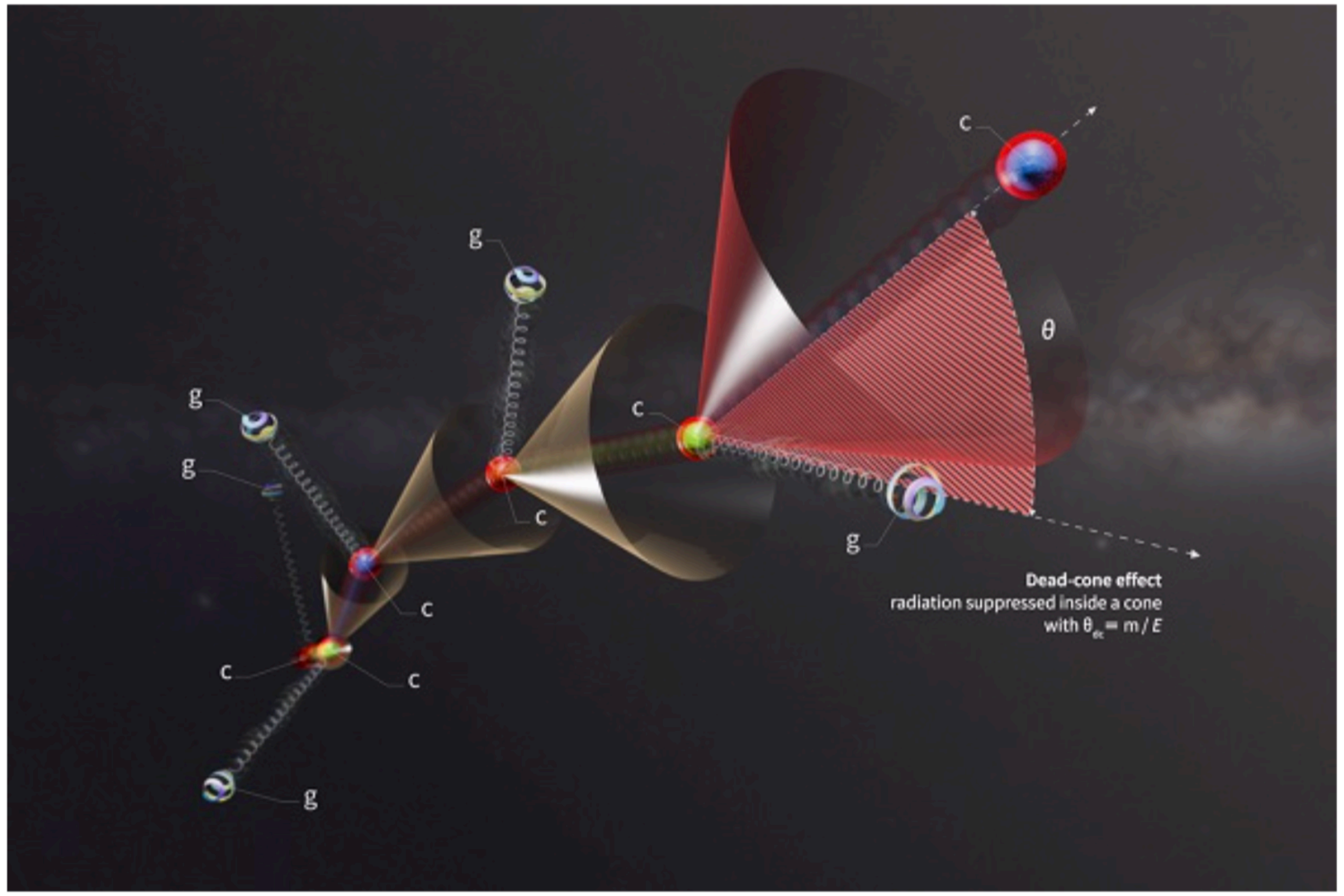
*** KISTI: 다른 소스 참여 기관 (1)**

Dead Cone 측정: 2022년 5월 Nature 출간

ALICE

LHC ALICE 실험: 마침내! 데드콘을 측정하다.

데드콘을 직접 측정해 양자색소역학의 근본적인 특성을 밝히다.



▲ 맵시 쿼크가 파톤 샤워 과정을 통해 글루온을 방사하며 에너지를 잃는 모습을 상상한 그림. 글루온이 방사되지 않는 사각지대인 '데드콘'을 원뿔로 도식화했다.(출처=CERN ALICE)

Article

Direct observation of the dead-cone effect in quantum chromodynamics

https://doi.org/10.1038/s41586-022-04572-w

Received: 29 June 2021

Accepted: 21 February 2022

Published online: 18 May 2022

Open access

Check for updates

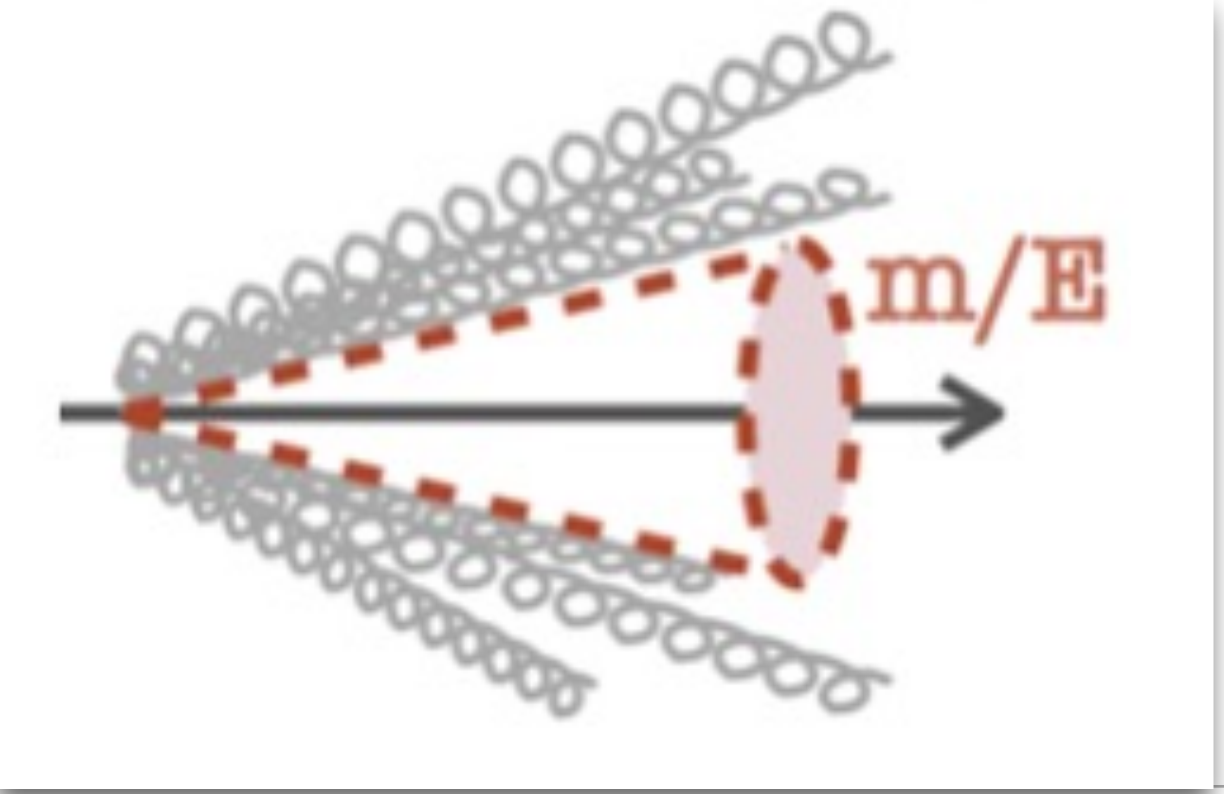
ALICE Collaboration*✉

In particle collider experiments, elementary particle interactions with large momentum transfer produce quarks and gluons (known as partons) whose evolution is governed by the strong force, as described by the theory of quantum chromodynamics (QCD)[1]. These partons subsequently emit further partons in a process that can be described as a parton shower[2], which culminates in the formation of detectable hadrons. Studying the pattern of the parton shower is one of the key experimental tools for testing QCD. This pattern is expected to depend on the mass of the initiating parton, through a phenomenon known as the dead-cone effect, which predicts a suppression of the gluon spectrum emitted by a heavy quark of mass m_Q and energy E, within a cone of angular size m_Q/E around the emitter[3]. Previously, a direct observation of the dead-cone effect in QCD had not been possible, owing to the challenge of reconstructing the cascading quarks and gluons from the experimentally accessible hadrons. We report the direct observation of the QCD dead cone by using new iterative declustering techniques[4,5] to reconstruct the parton shower of charm quarks. This result confirms a fundamental feature of QCD. Furthermore, the measurement of a dead-cone angle constitutes a direct experimental observation of the non-zero mass of the charm quark, which is a fundamental constant in the standard model of particle physics.

In particle colliders, quarks and gluons are produced in high-energy interactions through processes with large momentum transfer, which are calculable and well described by quantum chromodynamics (QCD). These partons undergo subsequent emissions, resulting in the production of more quarks and gluons. This evolution can be described in the collinear limit by a cascade process known as a parton shower, which transfers the original parton energy to multiple lower energy
particles. This shower then evolves into a multi-particl
with the partons combining into a spray of experimental
hadrons known as a jet[6]. The pattern of the parton showe
to depend on the mass of the emitting parton, through a p
known as the dead-cone effect, whereby the radiation fro
of mass m and energy E is suppressed at angular scales
m/E, relative to the direction of the emitter. The dead-co
fundamental feature of all gauge field theories (see ref. [3] fo
tion of the dead cone in QCD).

The dead-cone effect is expected to have sizeable imp
charm and beauty quarks, which have masses of 1.28 ± 0.0
$4.18^{+0.03}_{-0.02}$ GeV/c^2 (ref. [1]) in the minimal subtraction scheme,
at energies on the GeV scale. The emission probability in
region, which is the divergent limit of QCD at which the
most intense, is suppressed with increasing mass of the
leads to a decrease in the mean number of particles pro
parton shower. The DELPHI Collaboration at the LEP e^+e^- c
ured the multiplicity difference between events containing
by heavy beauty quarks and those containing light quar
or strange). They found that the differences depend only

mass[7], which was attributed to the suppression of collinear gluon radiation from the heavy quark because of the dead-cone effect. A measurement of the momentum density of jet constituents as a function of distance from the jet axis was also performed by the ATLAS collaboration at CERN[8], which pointed to a depletion of momentum close to the jet axis that was ascribed as a consequence of the dead-cone effect. The mass of the beauty quark was also estimated through a



*A list of authors and their affiliations appears at the end of the paper. ✉e-mai

From $^{3}\overline{\text{He}}$ inelastic cross section to dark matter

ALICE 검출기

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Article | Open Access | Published: 12 December 2022

Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy

The ALICE Collaboration

Nature Physics **19**, 61–71 (2023) | Cite this article

Abstract

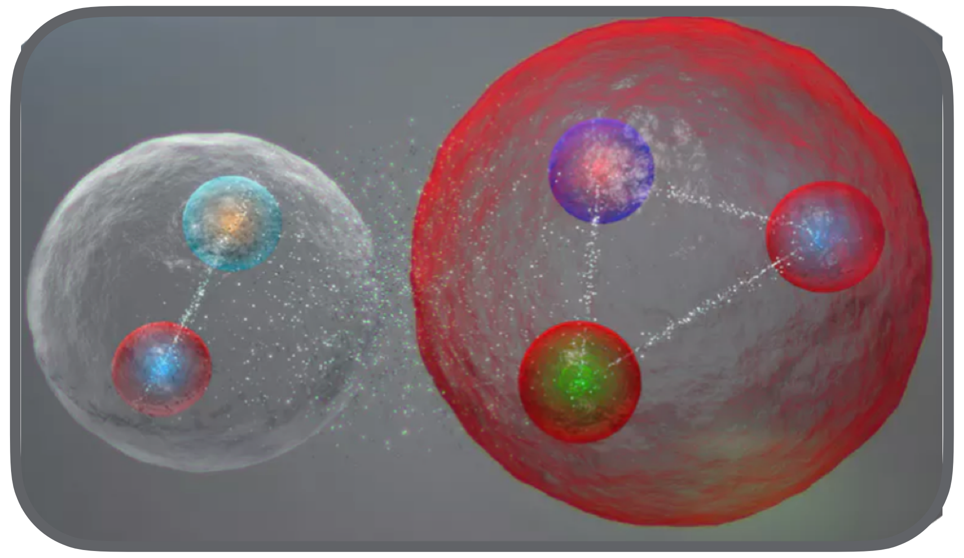
In our Galaxy, light antinuclei composed of antiprotons and antineutrons can be produced through high-energy cosmic-ray collisions with the interstellar medium or could also originate from the annihilation of dark-matter particles that have not yet been discovered. On Earth, the only way to produce and study antinuclei with high precision is to create them at high-energy particle accelerators. Although the properties of elementary antiparticles have been studied in detail, the knowledge of the interaction of light antinuclei with matter is limited. We determine the disappearance probability of $^{3}\overline{\text{He}}$ when it encounters matter particles and annihilates or disintegrates within the ALICE detector at the Large Hadron

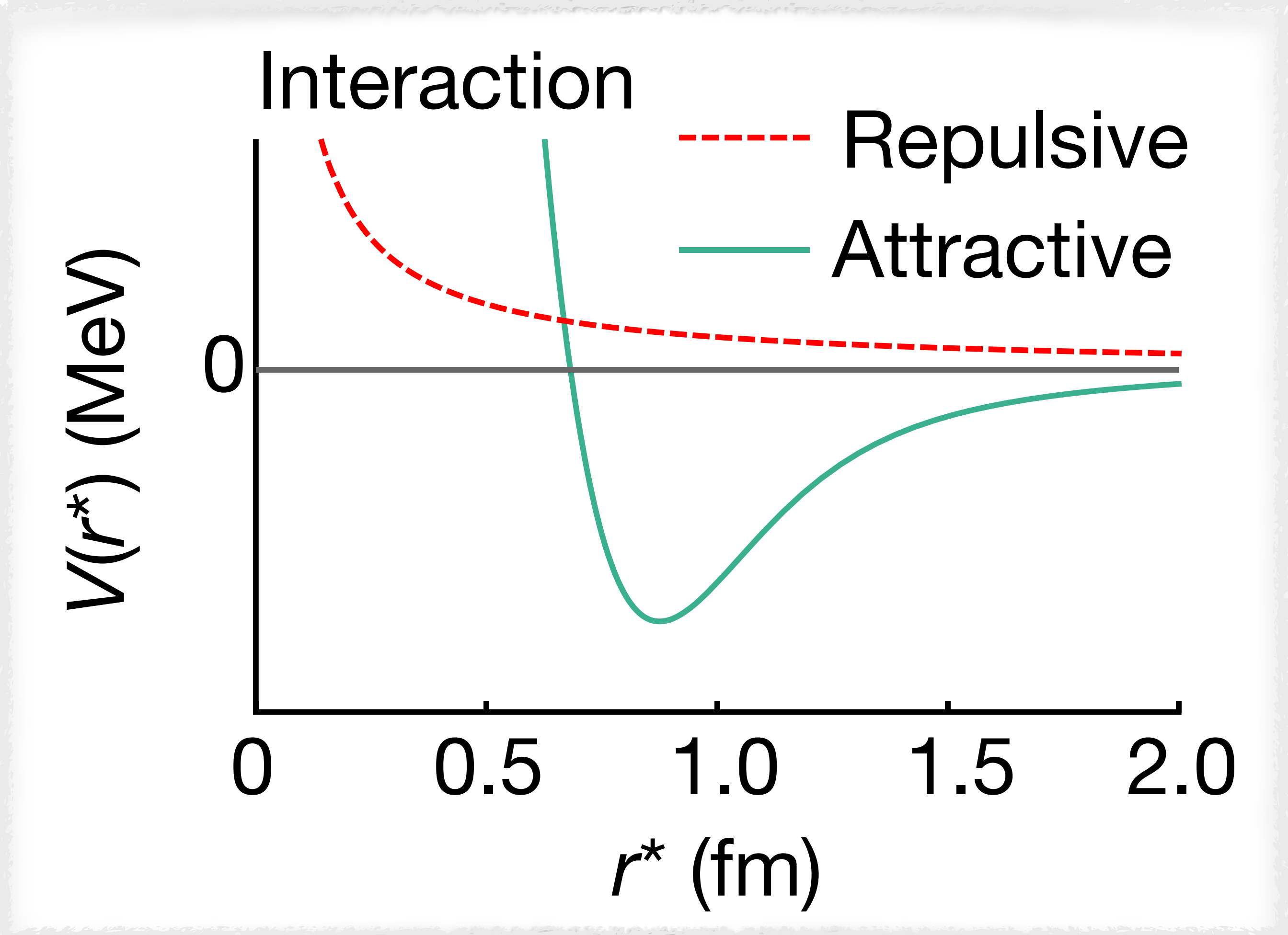
2022년 12월, Nature physics

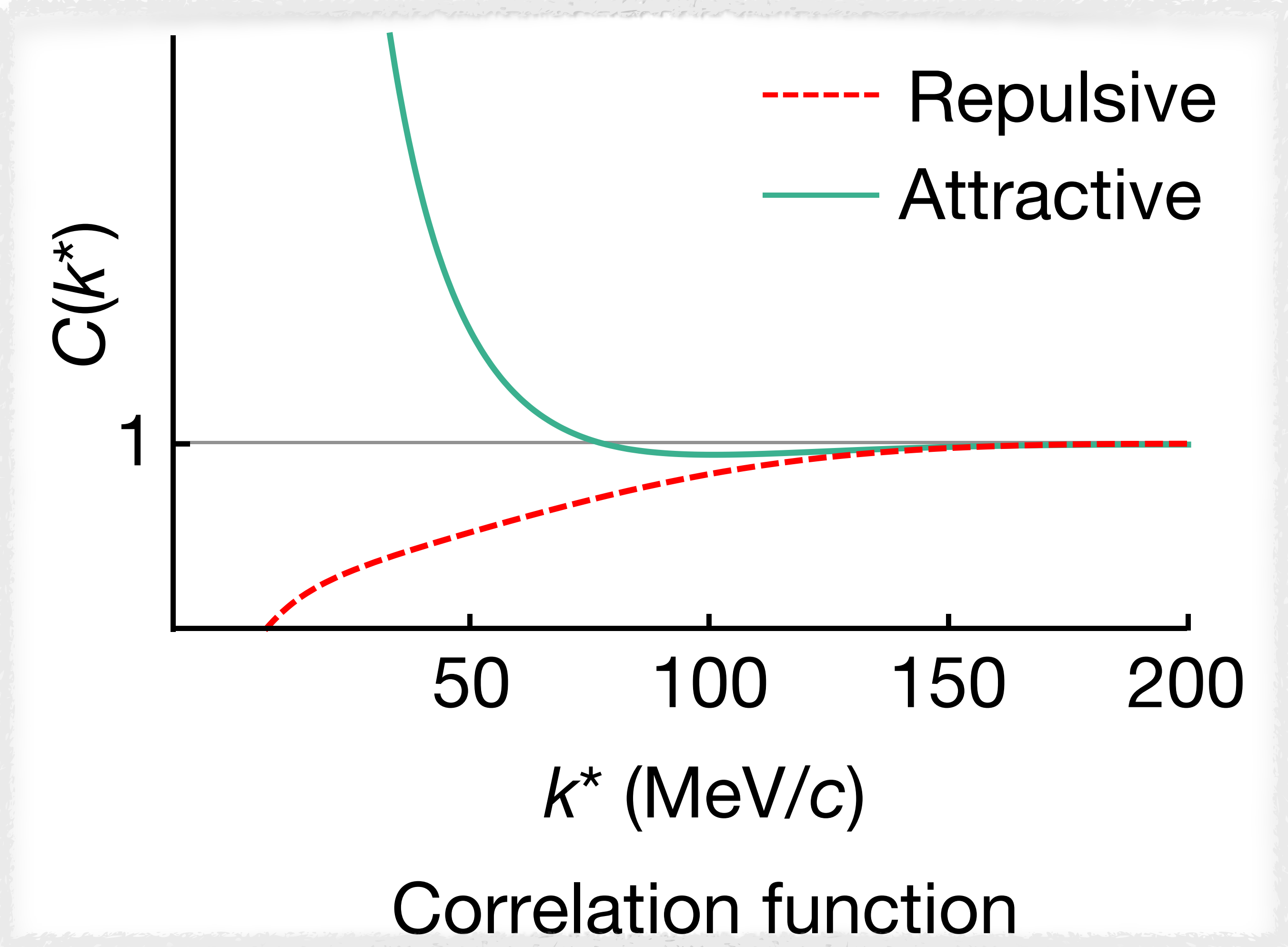
중수소 생성 메커니즘 규명: 2025년 Nature Accepted

ALICE

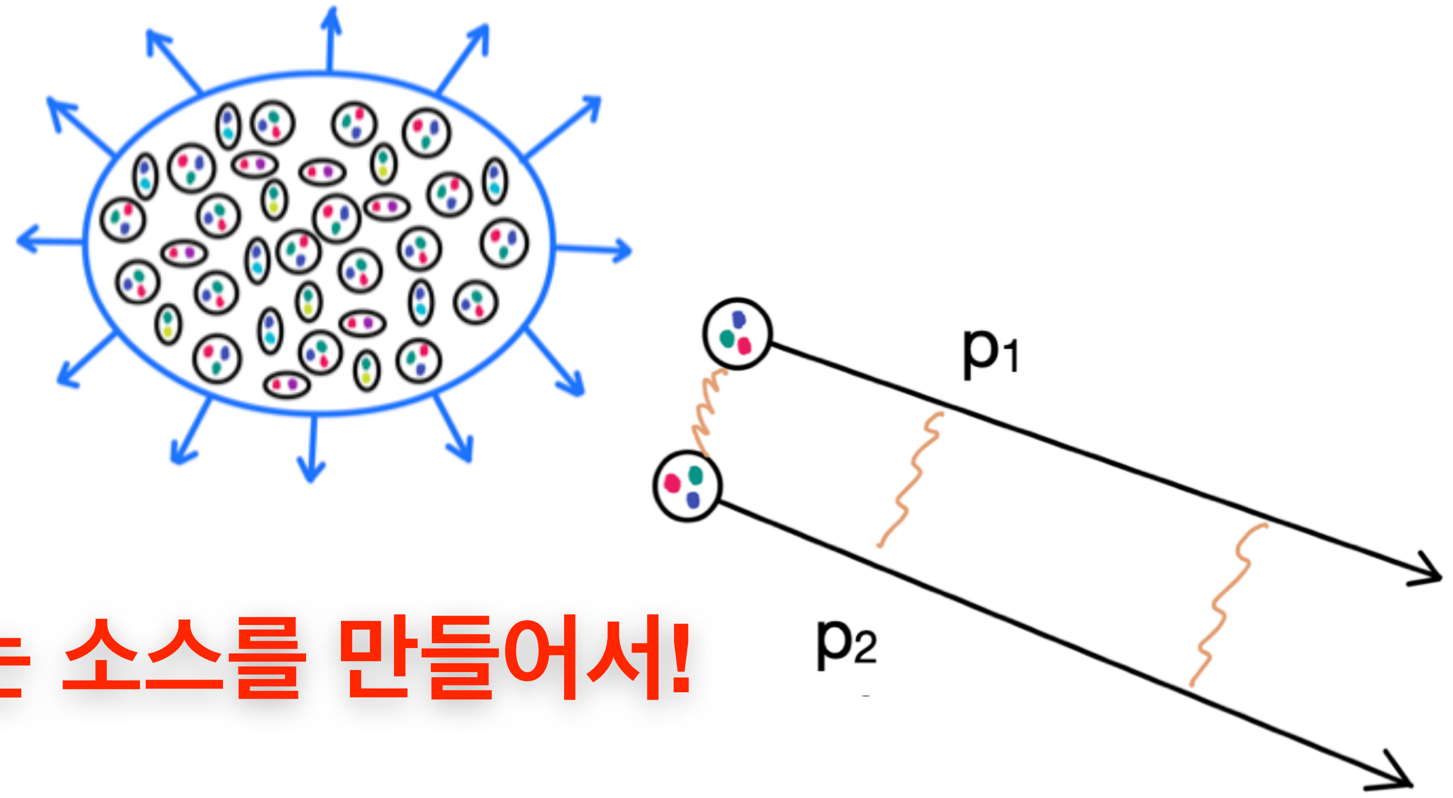
우리가 알고 싶은 것:
1 fm 스케일에서 강입자 사이의 상호작용







일반적으로는 두 입자의 scattering을 통해서...



우리는 소스를 만들어서!

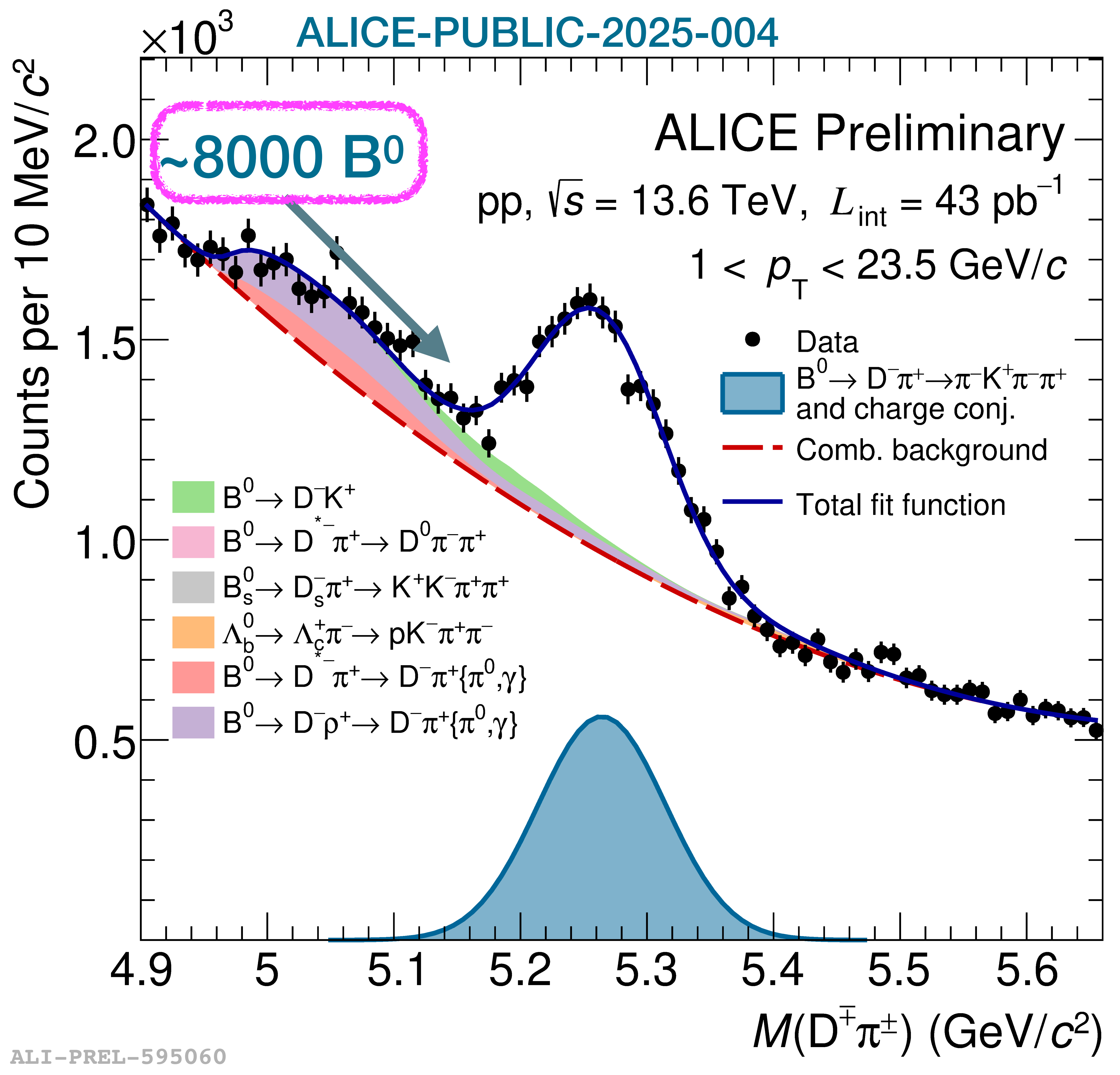
$$C(k^*) = \int S(r^*)\,|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2\, d^3r^*$$

이론에서 구한 포텐셜 넣고, 계산 가능한 물리량

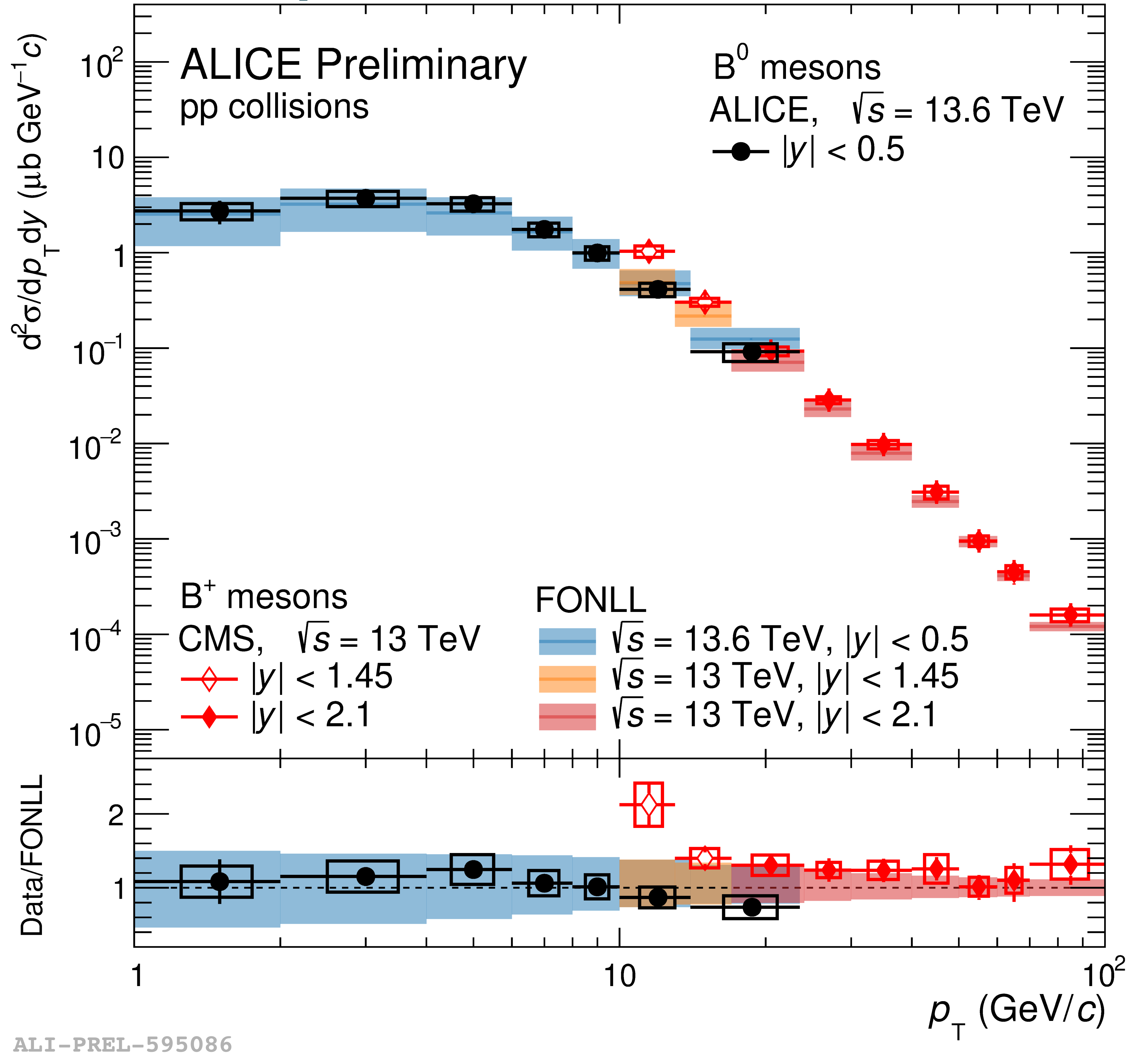
실험으로 측정 가능한 물리량

이 안에 포텐셜 있어요!

First full reconstruction of open-beauty hadrons at ALICE

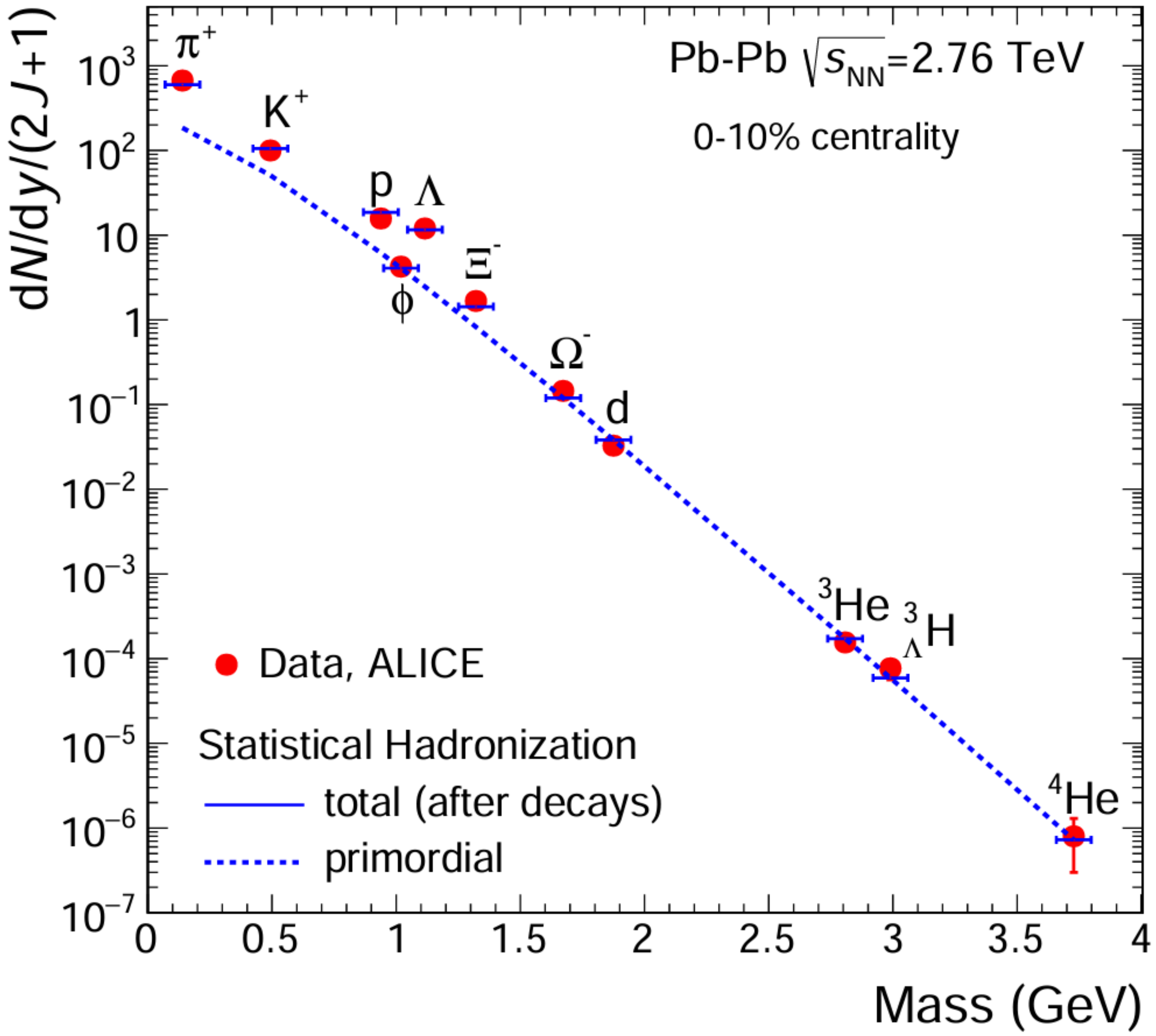


B⁰ production cross-section



- First measurement of B⁰ at mid rapidity down to p_T = 1 GeV
- In agreement with FONLL calculations (theory unc. >> exp. unc.)

Particle production in heavy-ion collisions



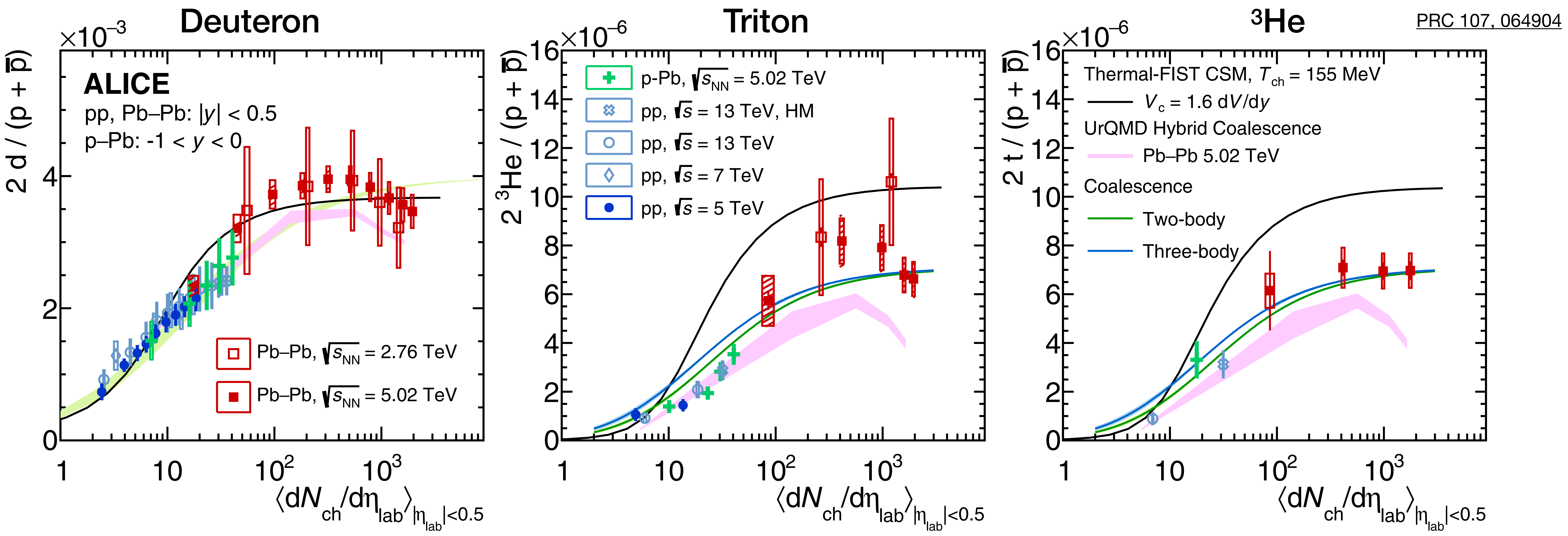
Andronic A., et al. Nature 561, 321-330

- Particle production in heavy-ion collisions follow statistical hadronization:

$$N \propto (2J+1)e^{-m/T}$$

- The yields depend solely on the mass and temperature, consistent with a thermal model. →supporting the thermal nature of the hadronization process.

Light nuclei production

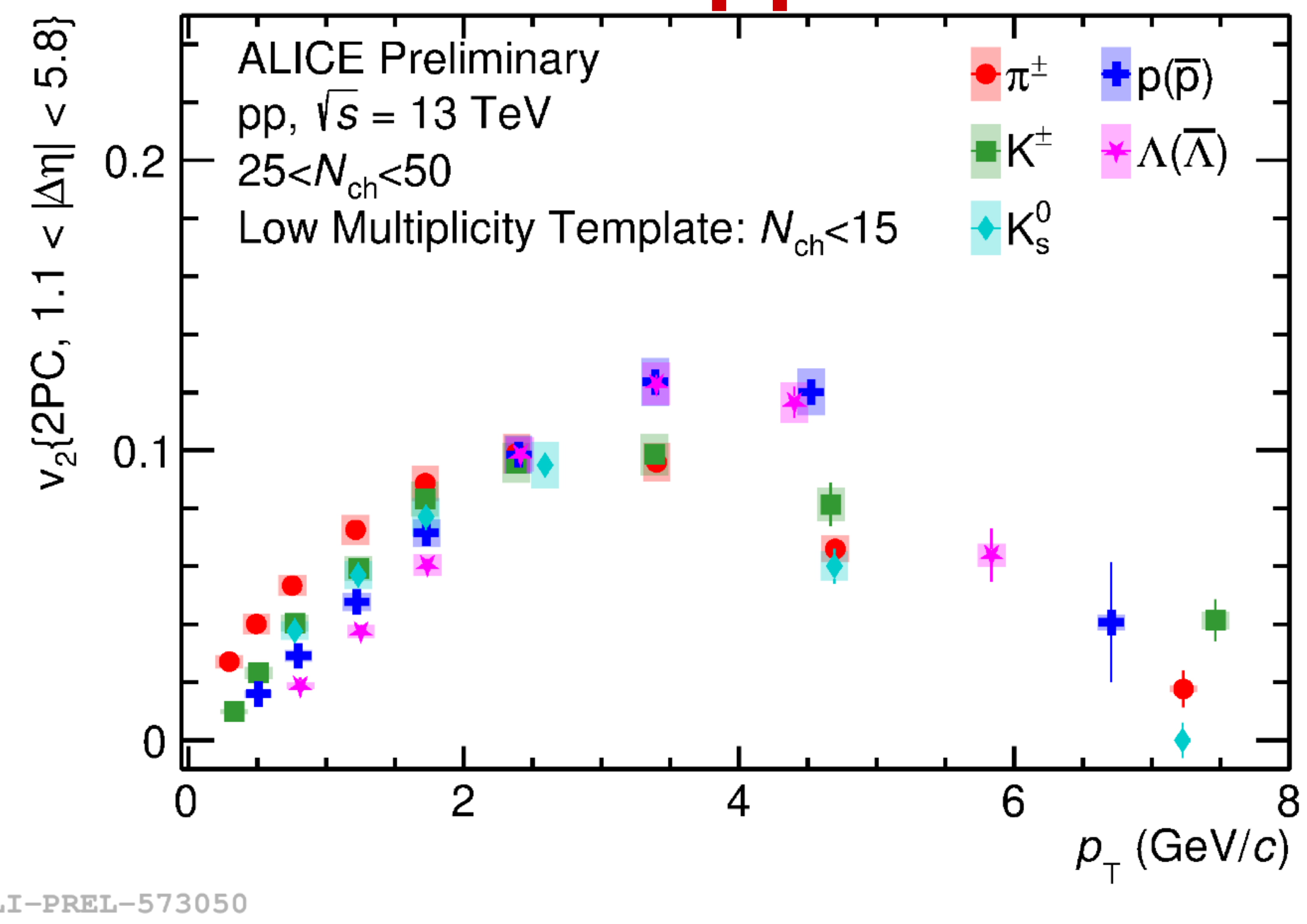


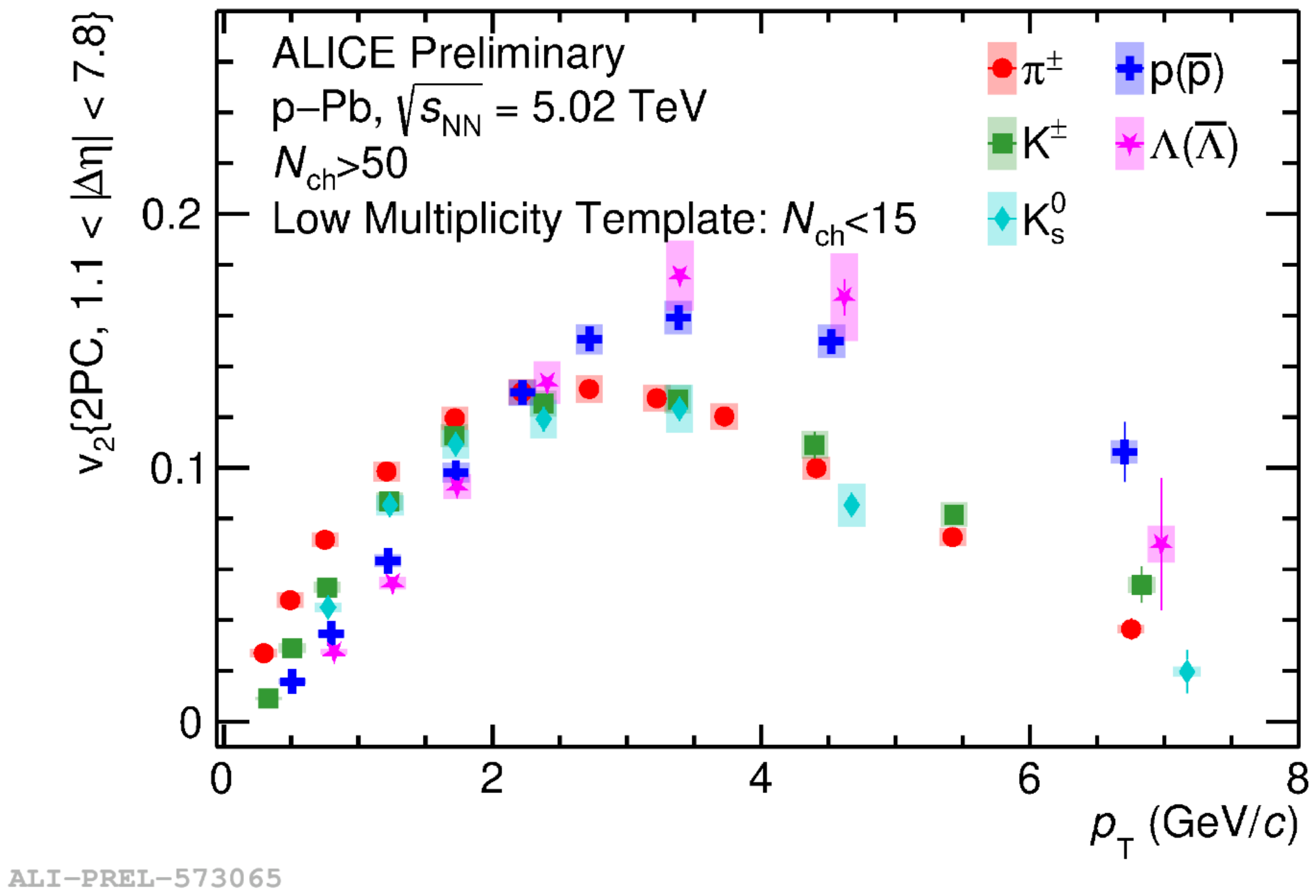
Thermal model prediction: Eur. Phys. J. A (2020) 56:280

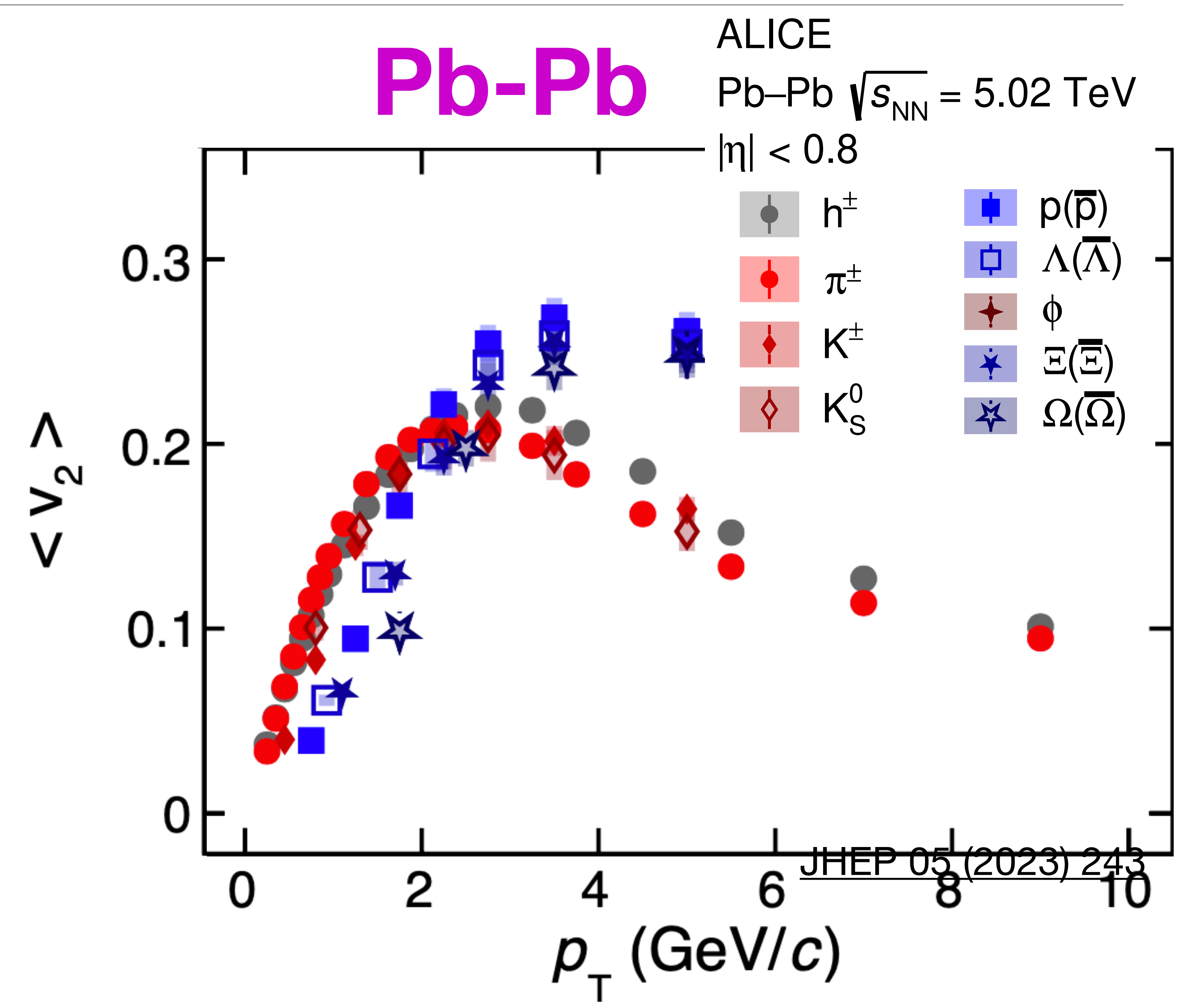
Light nuclei: binding energy O(10 MeV)
expect dissociation in rescattering phase
+ formation via coalescence of baryons
⇒ different evolution vs density

- Dependence of light-nuclei production on event multiplicity provides important insights into the mechanisms of light-nuclei formation
- ^{3}He, t favour coalescence models → likely formed through the coalescence of nucleons in the later stages of the collision

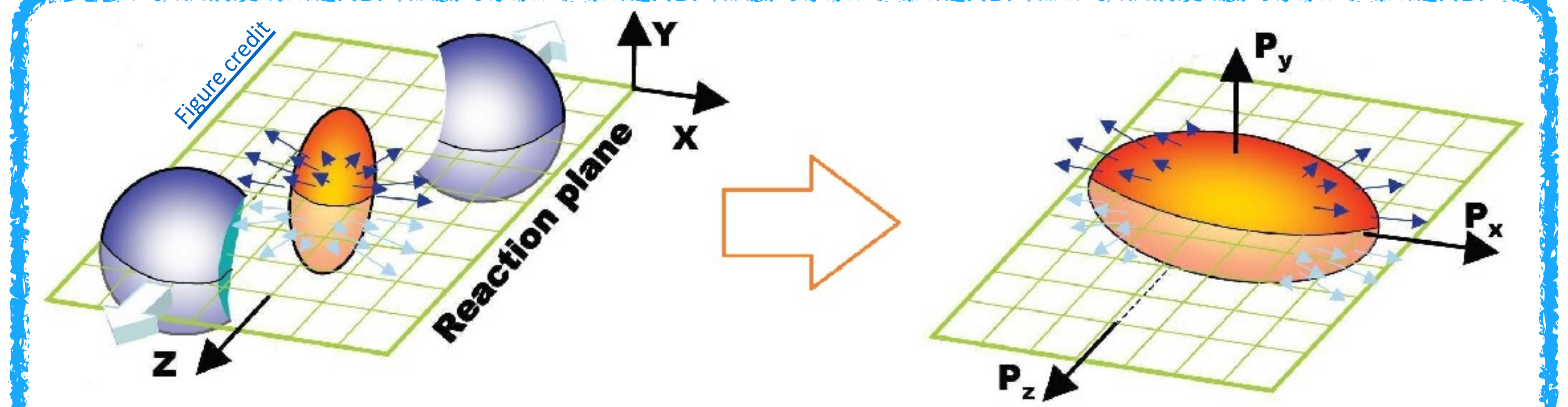
Elliptic flow (v_2) in small systems, similar to Pb-Pb?







- Similar observations in Pb-Pb, high multiplicity p-Pb and pp!
- Low p_T (p_T < 3 GeV/c) - Mass ordering
- Intermediate p_T (3 < p_T < 6 GeV/c): baryon-meson grouping, splitting between baryons and mesons v_2

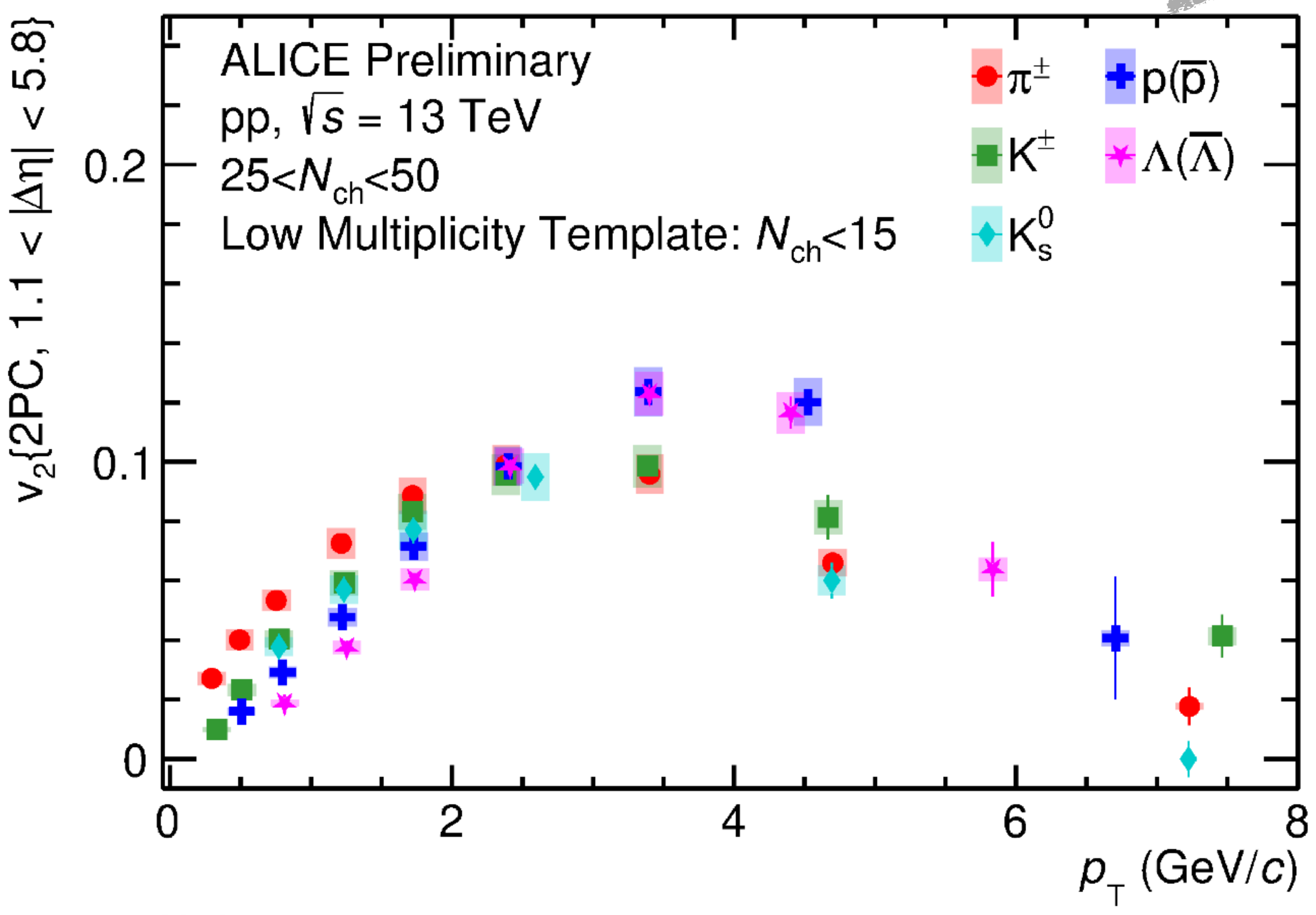


Spatial anisotropy → momentum anisotropy

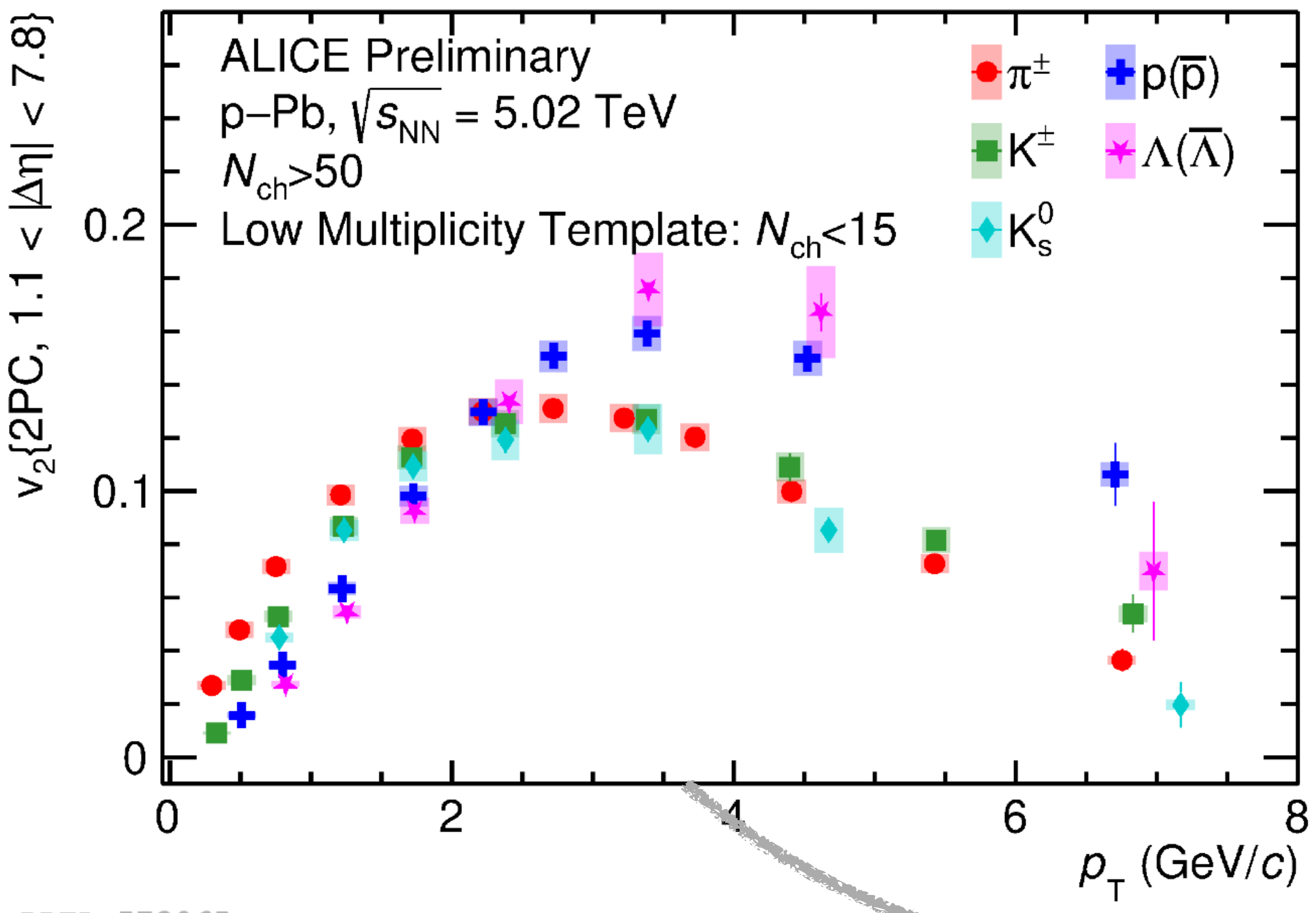
$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

Elliptic flow in small systems: model comparisons

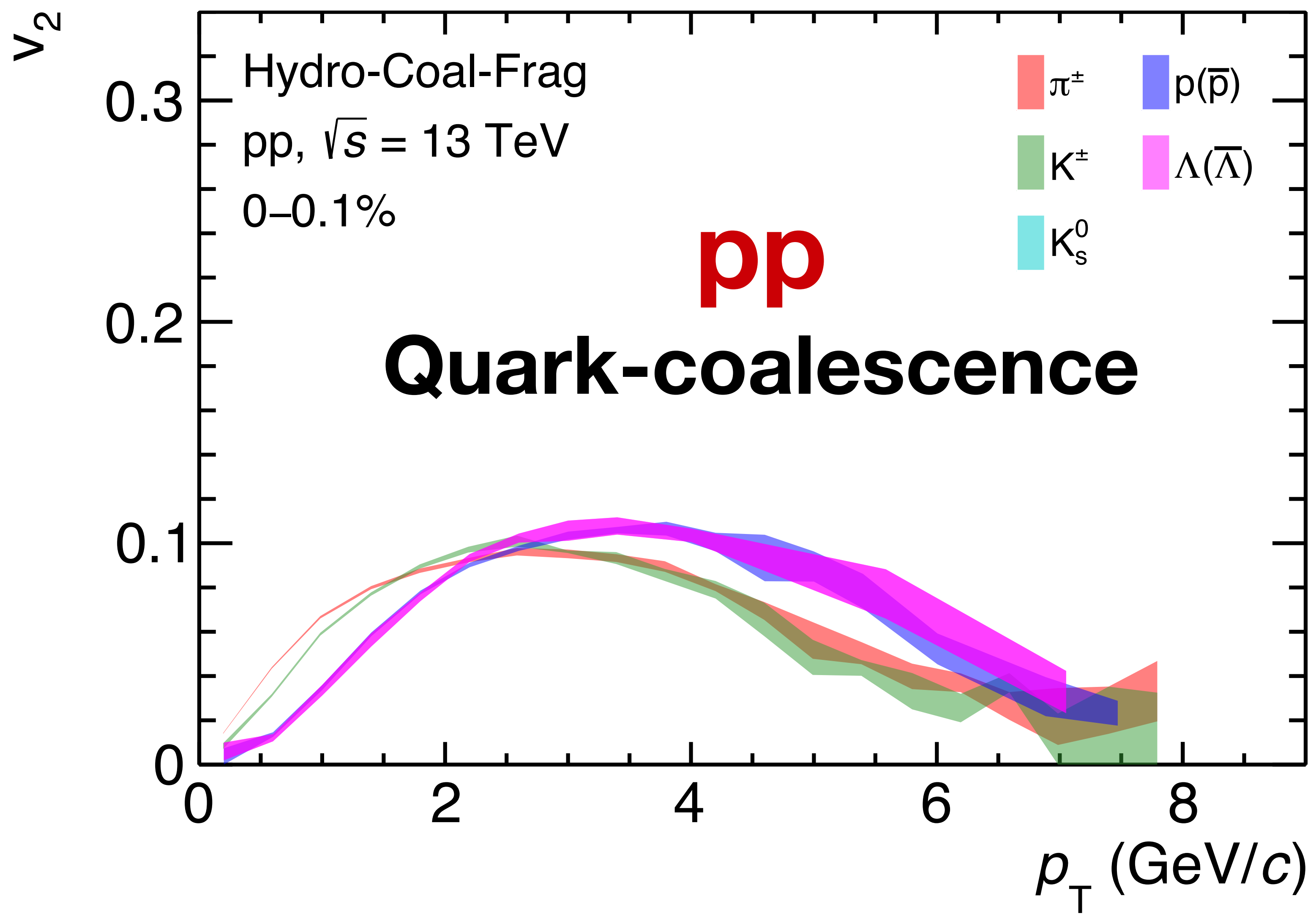
pp **p-Pb**

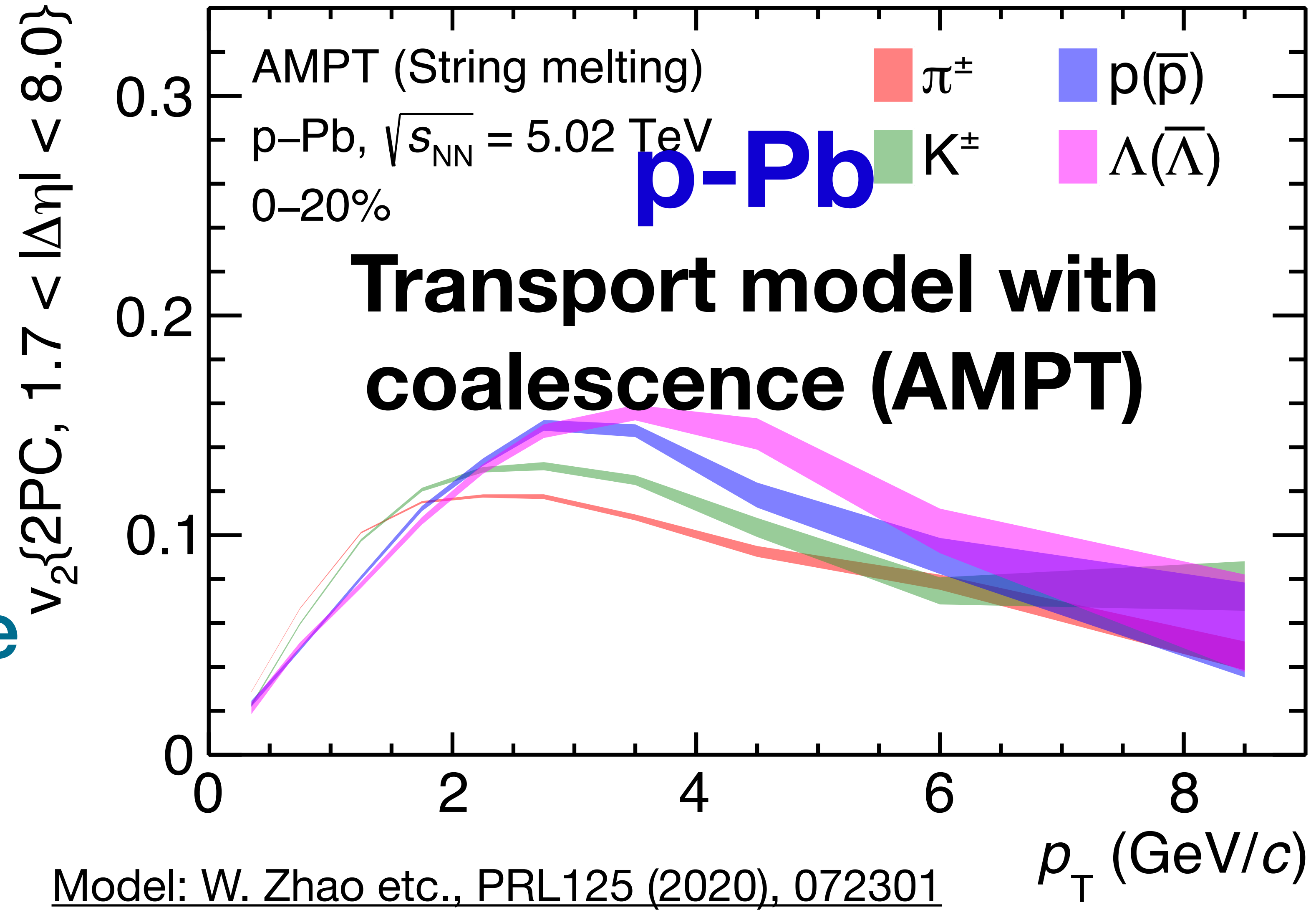


ALI-PREL-573050



ALI-PREL-573065





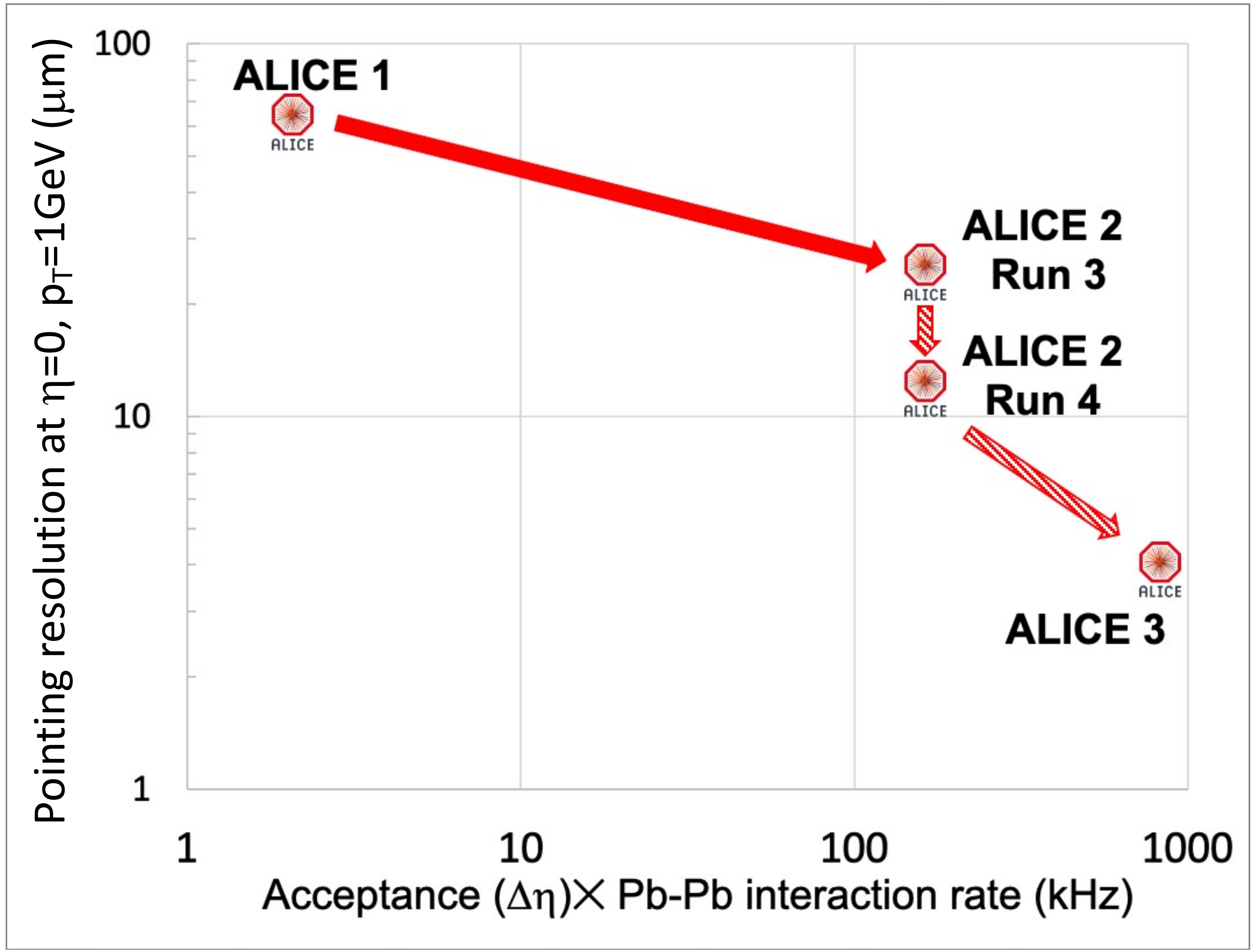
- With quark-coalescence in pp: successfully reproduces baryon/meson grouping and splitting
- In p-Pb, transport model with coalescence predicts only mass dependence

  → thorough investigations, including careful data and model comparisons, are needed to understand the underlying mechanism

Model: W. Zhao etc., PRL125 (2020), 072301
Y. Wang etc, arXiv:2401.00913
S. Tang etc, Nucl. Sci. Tech. 35 (2024) 32

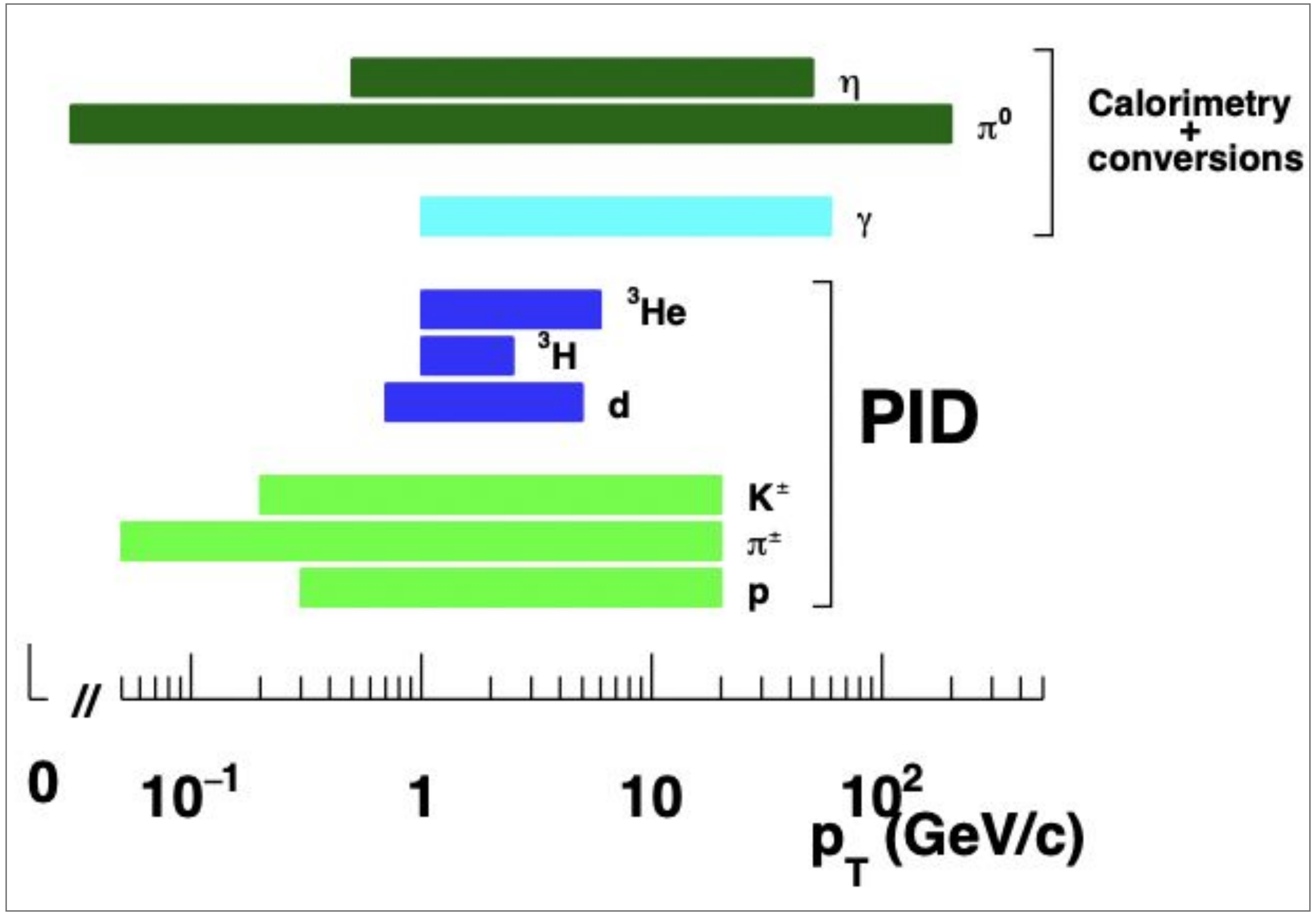
ALICE upgrade approach

Evolution towards higher pointing resolution and larger effective acceptance

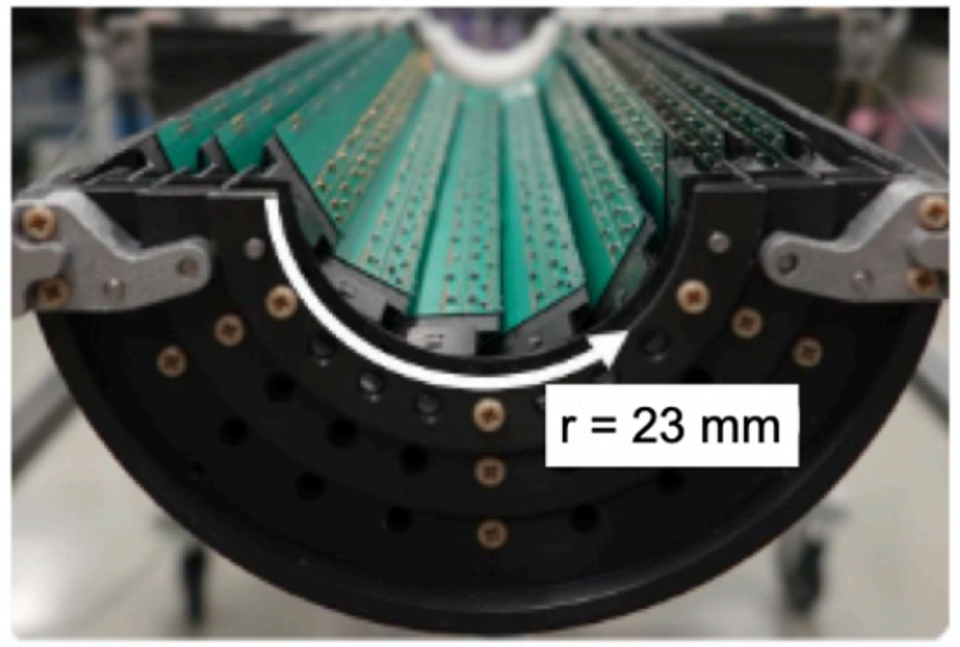


+

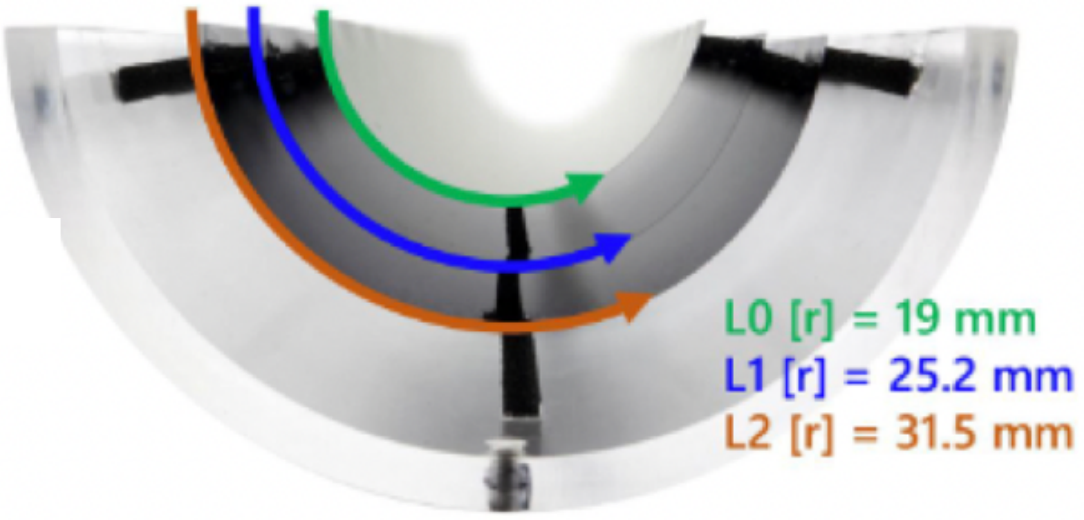
Maintain and enhance ALICE's unique capabilities in particle identification



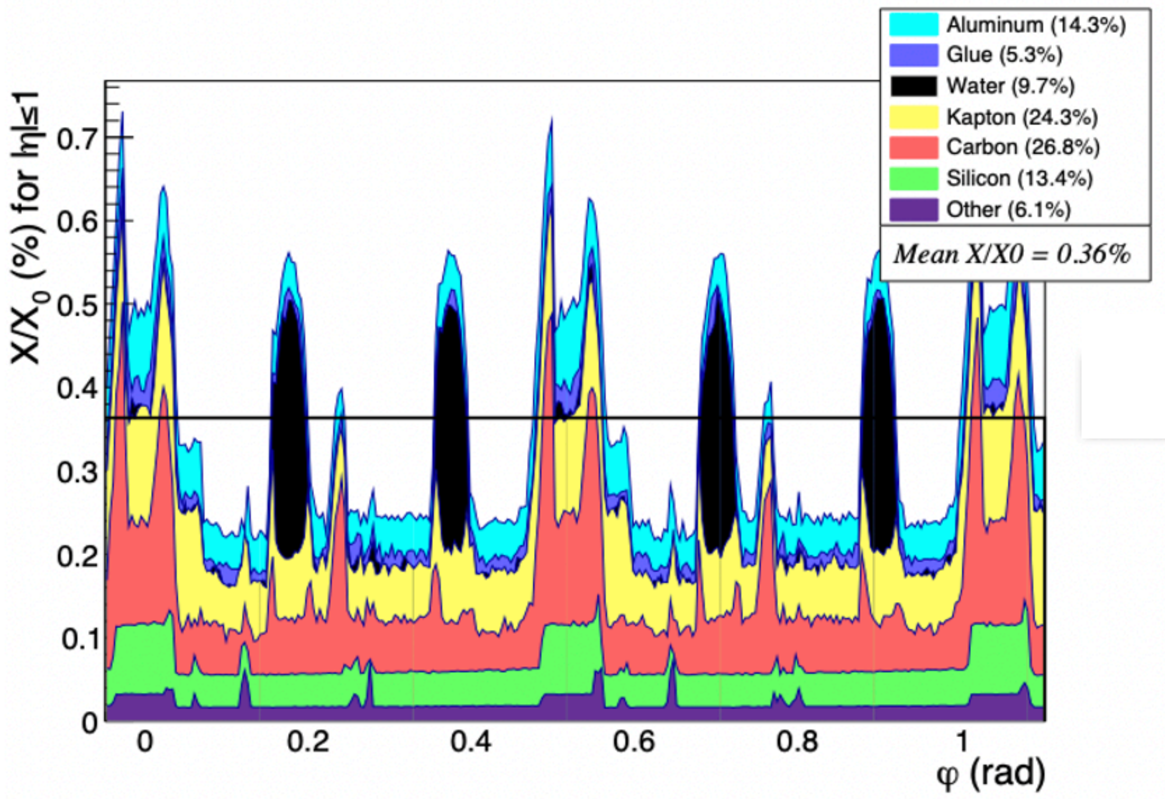
ITS3, ultra-light cylindrical pixel detector



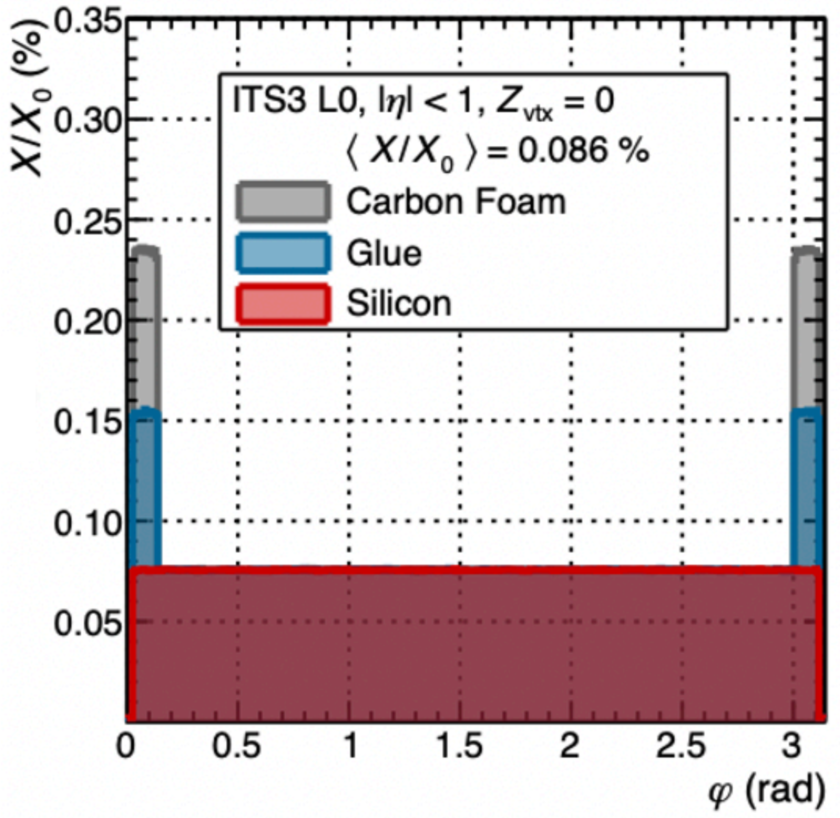
ITS2 Inner Barrel



ITS3 Engineering Model 1



ITS2 Layer 0

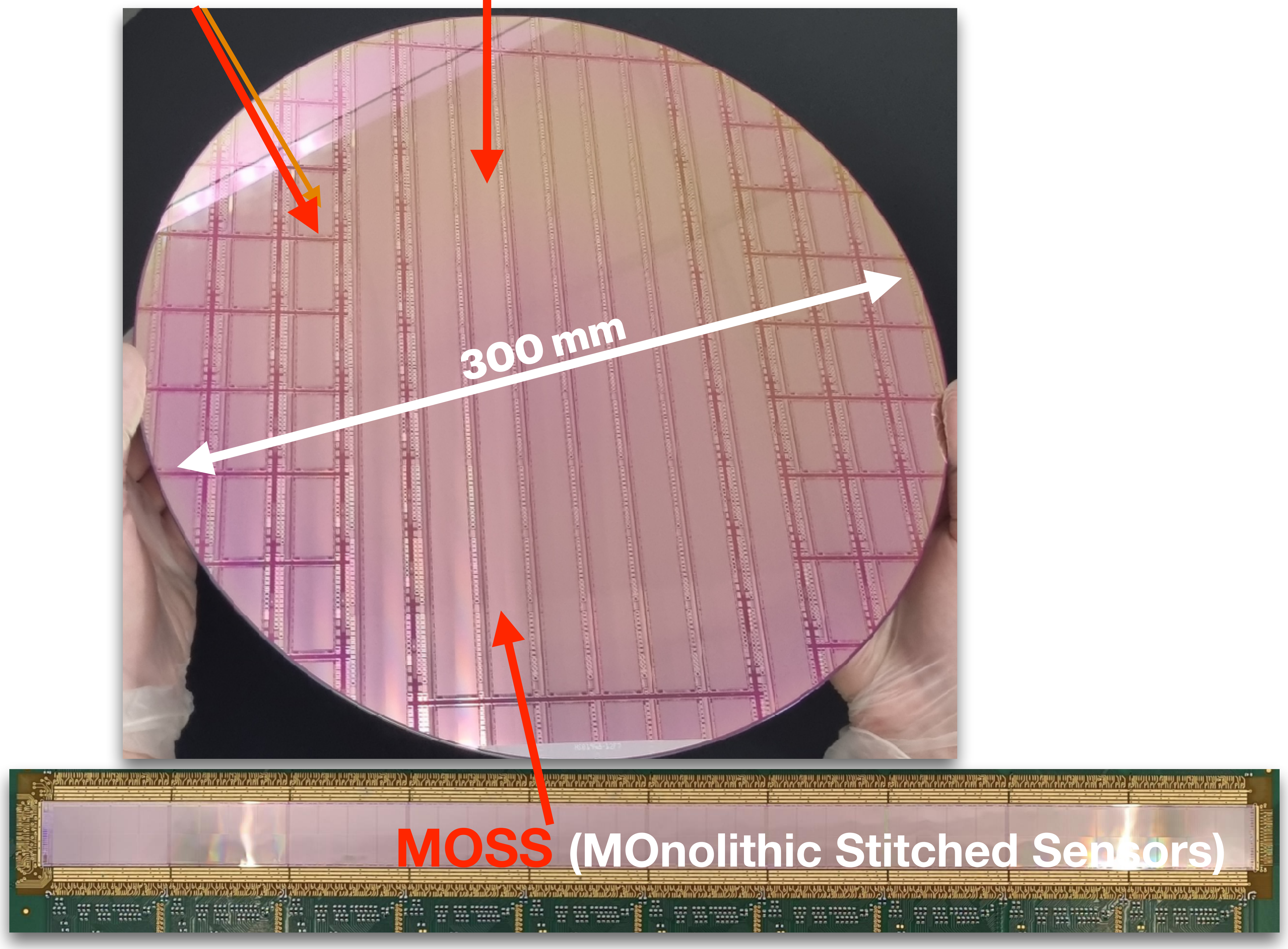


ITS3 Layer 0

ITS3 TDR: CERN-LHCC-2024-003

First prototypes

- Prototypes of stitched sensors successfully produced!
- Fully integrated detector modules
- Ideal construction elements for ultra-light detectors



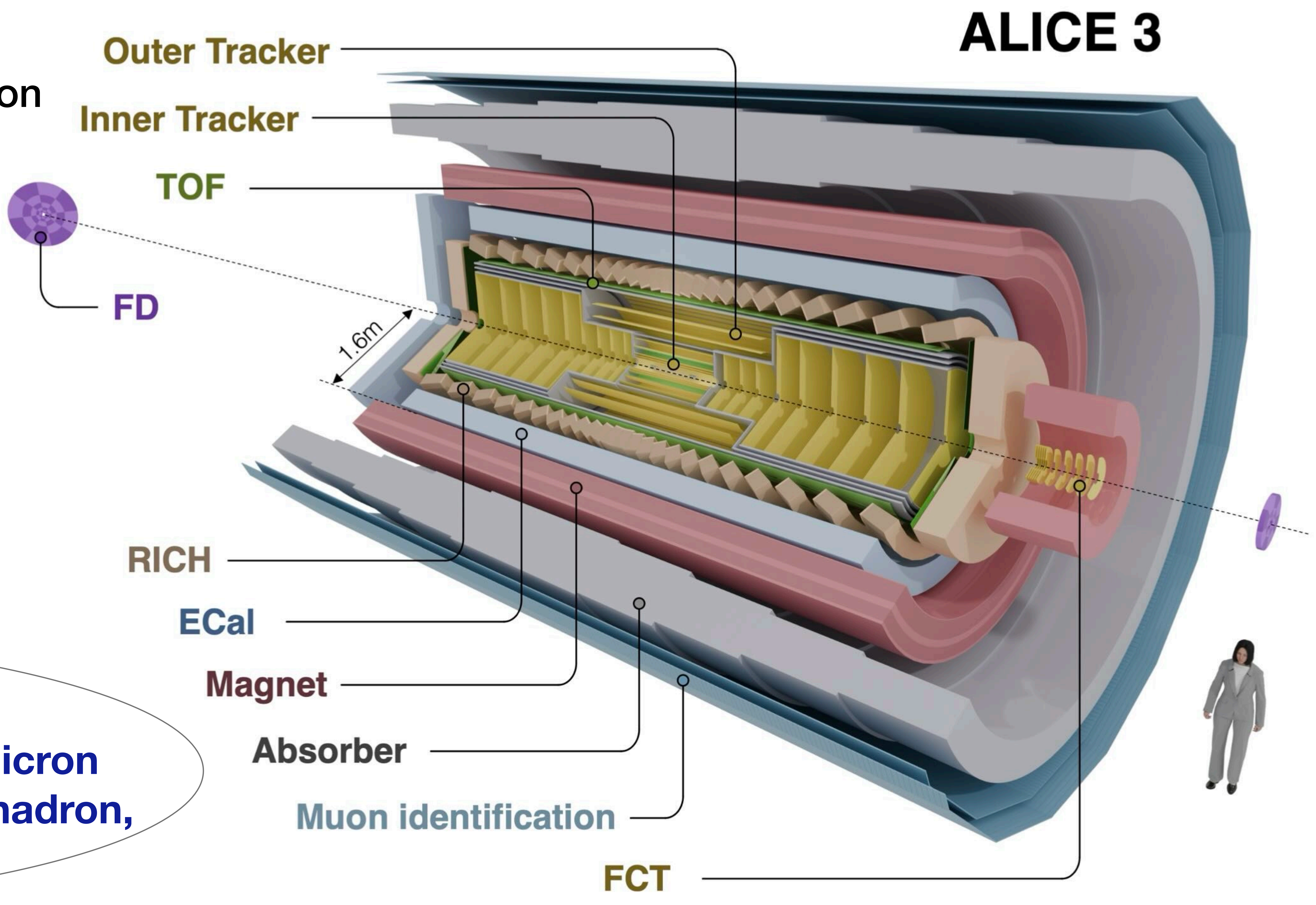
- Replacing the barrels by real half-cylinders (of bent, thin silicon)
- Rely on wafer-scale sensors (1 sensor per half-layer) in 65 nm Monolithic Active Pixel Sensors (MAPS) technology
- Minimized material budget → large improvement of vertexing precision and physics yield, x/X_0: 0.36% → 0.09%

ALICE 3, pushing the frontiers of tracking and PID

ALICE 3 SD: CERN-LHCC-2025-002

Detector concept

- Compact, ultra-lightweight all-silicon tracker
- Vertex detector with unprecedented pointing resolution
- Particle Identification over large acceptance
- Superconducting magnet system
- Continuous read-out and online processing



Acknowledged in LHCC review;

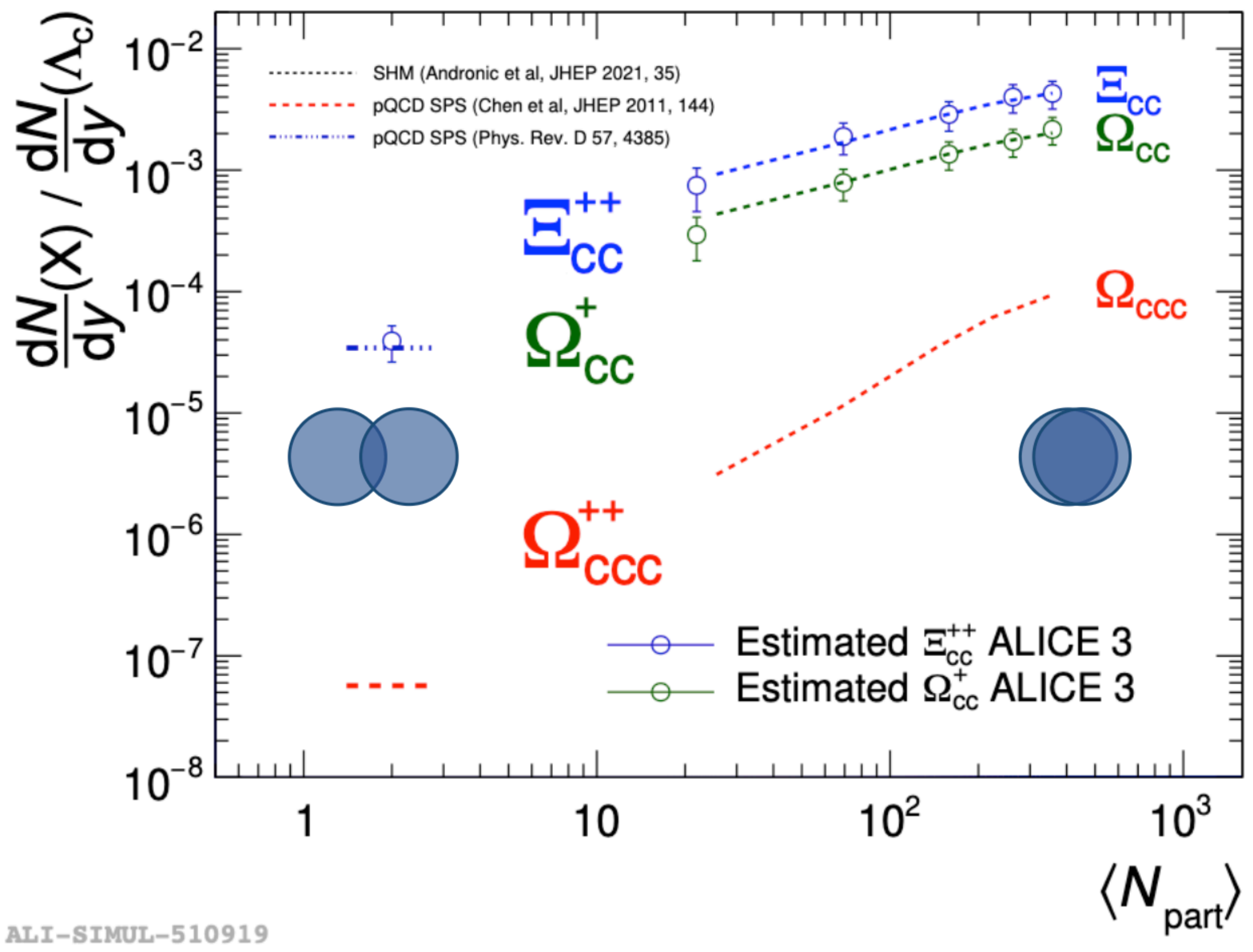
"ALICE 3 is a unique detector at the LHC

in terms of having a low material budget, a few-micron pointing resolution, a large acceptance in eta, and hadron, electron and muon identification."

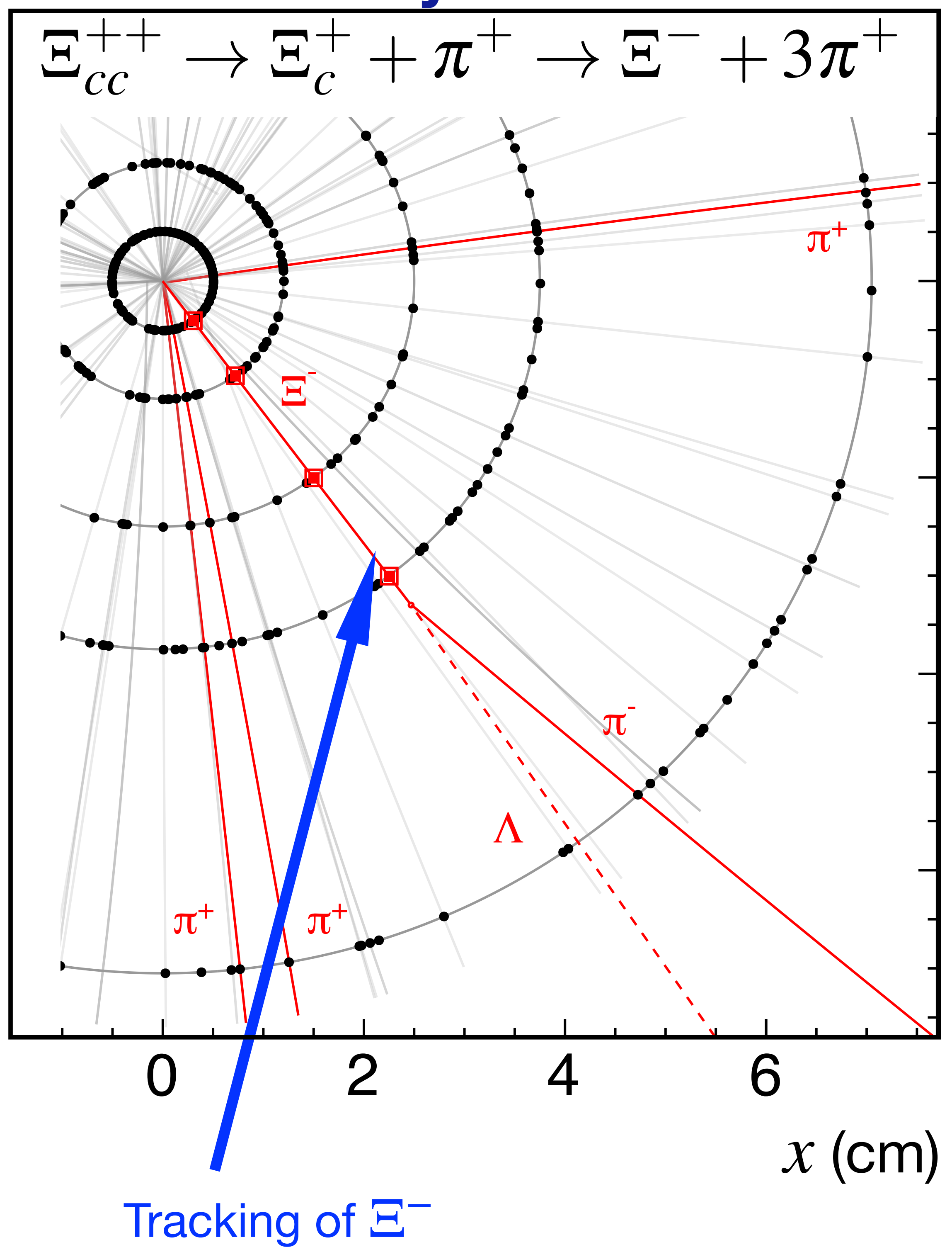
Unique ALICE 3 physics goals: key objectives

Multi-charm baryons at low p_T

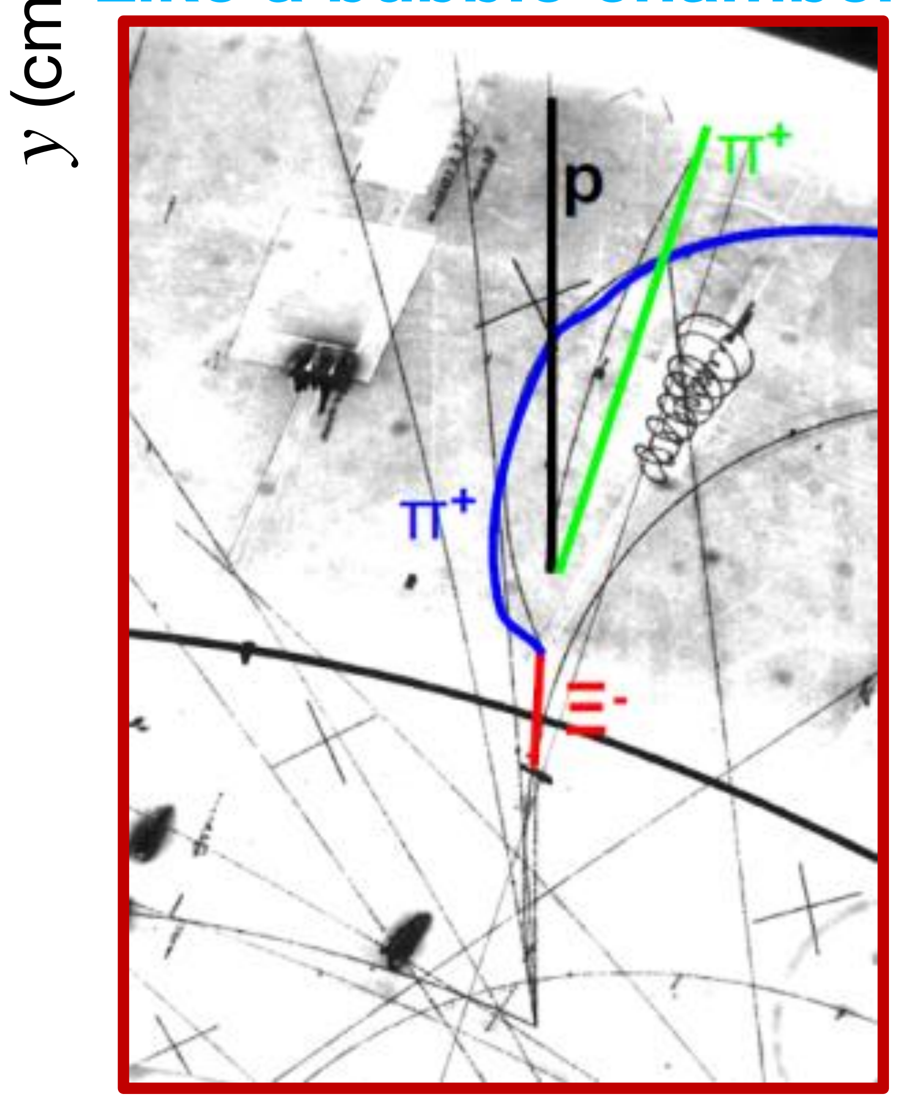
- How are hadrons formed in QGP?
- Recombination models predicts 2-3 orders of magnitude enhancement in Pb-Pb



Multi-charm baryon reconstruction



Strangeness tracking, Like a bubble chamber



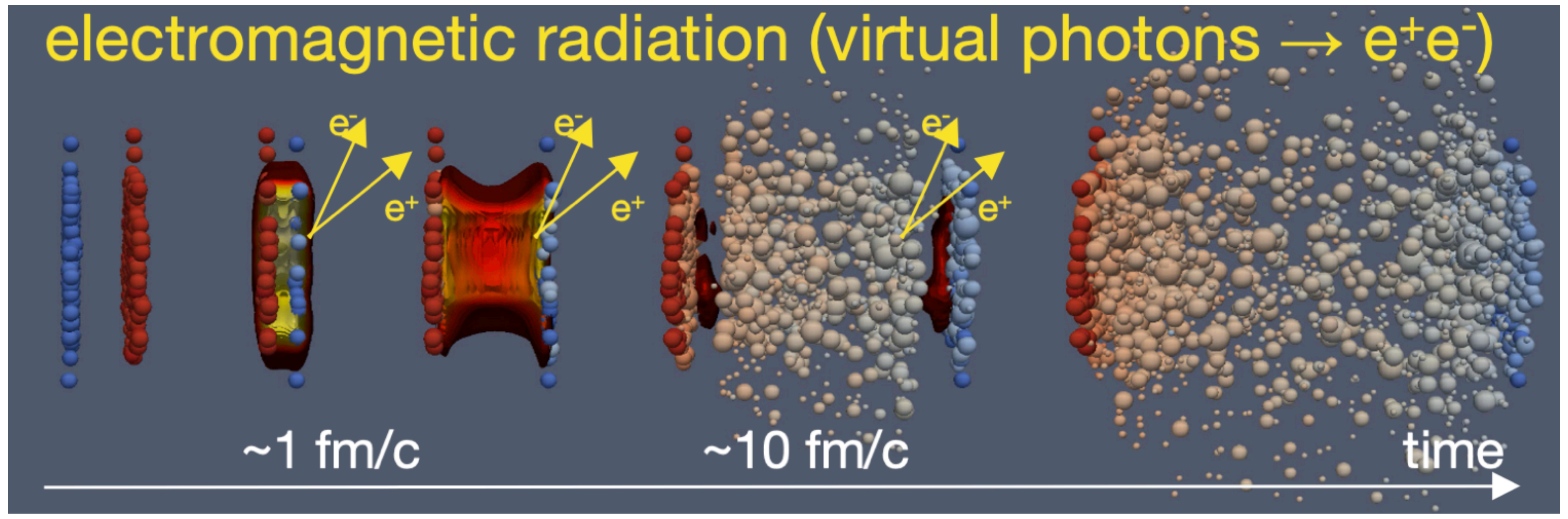
Track non-prompt Ξ baryon before it decays, novel technique

⇒ Unique access with ALICE 3 in Pb-Pb collisions

Unique ALICE 3 physics goals: key objectives

Temperature evolution of the QGP

- Precision differential measurements of **dielectrons**



Double differential spectra: T vs mass, $p_{\mathrm{T,ee}}$

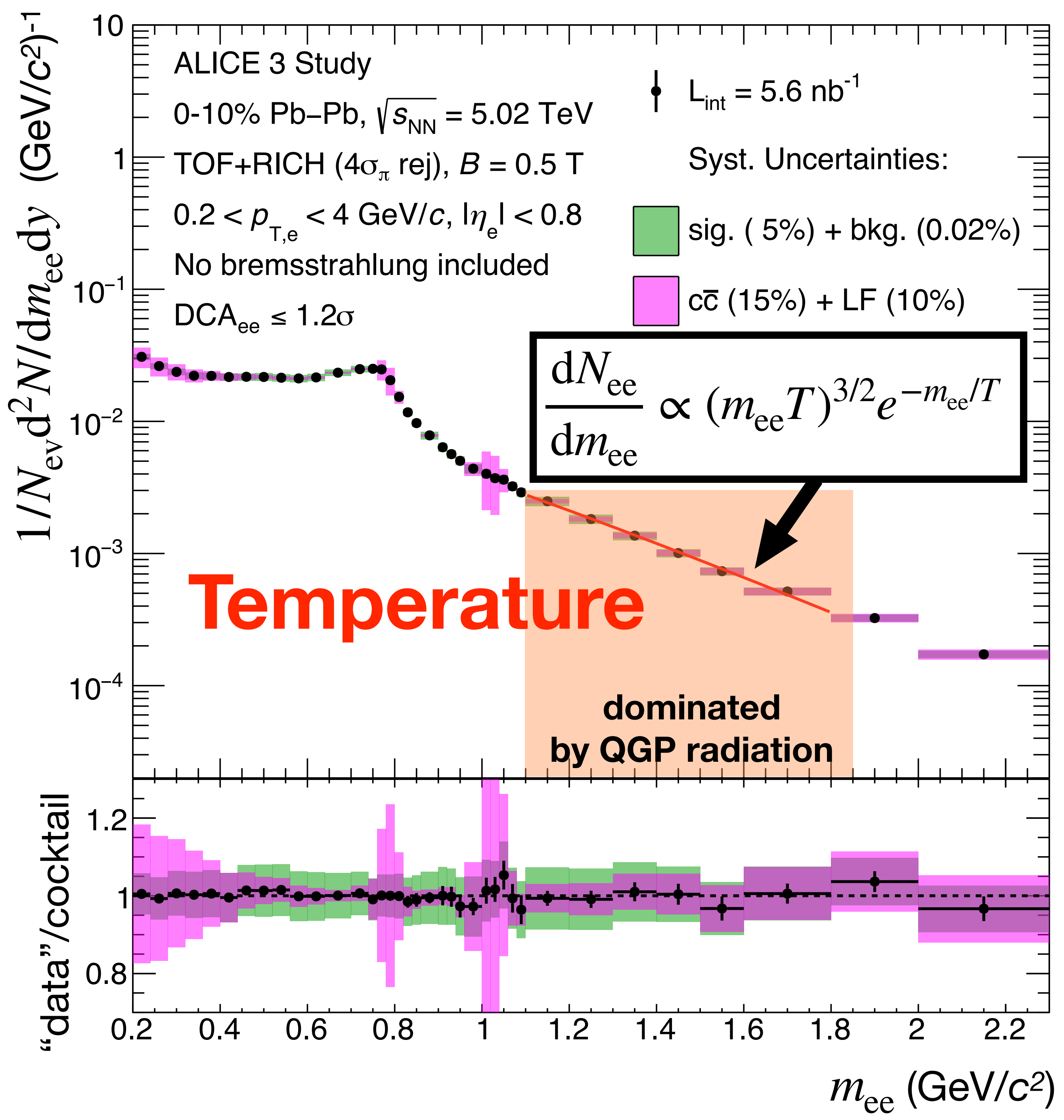
and…

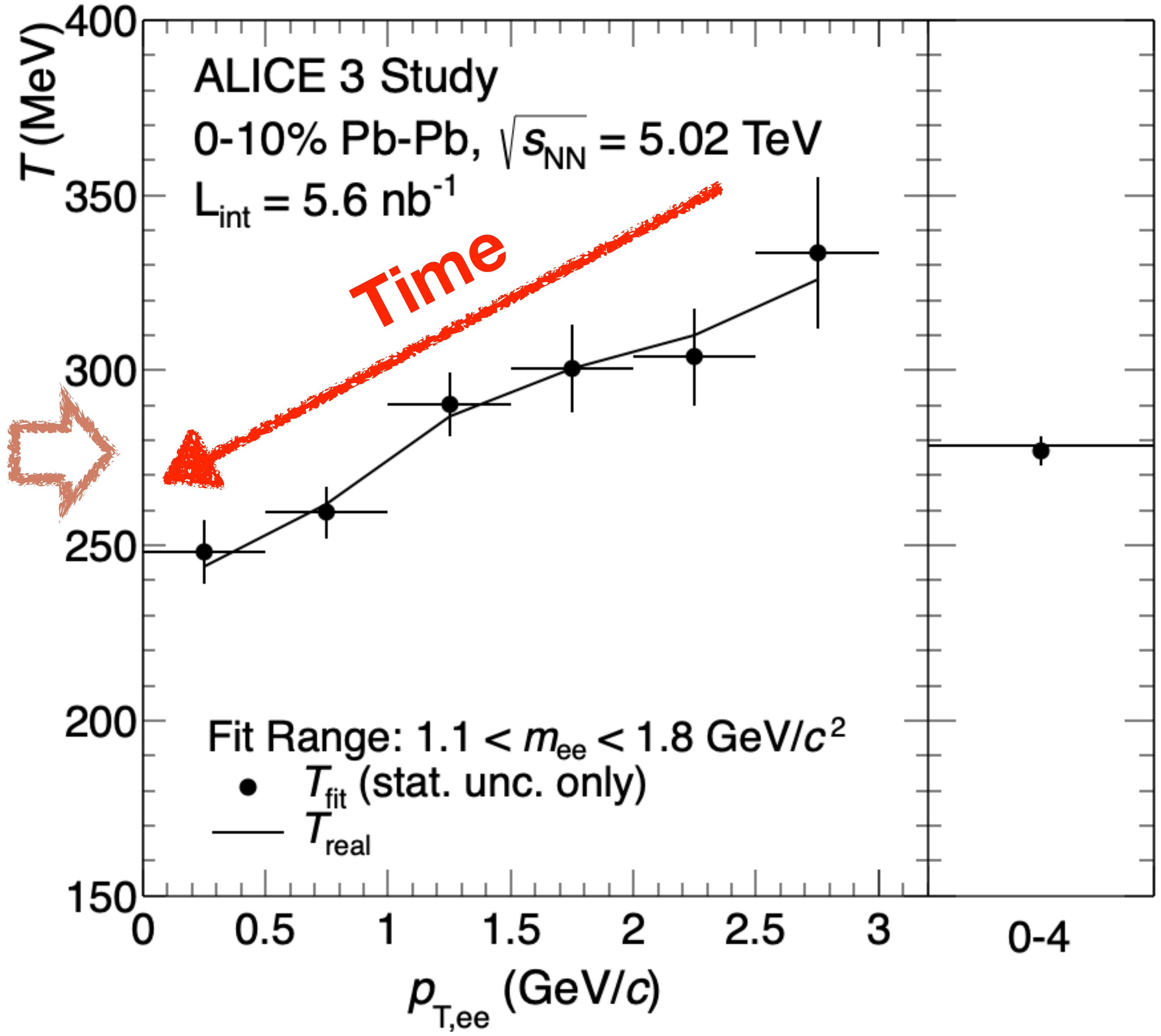
Fundamental aspects of the QCD phase transition

QCD bound states and hadron interactions

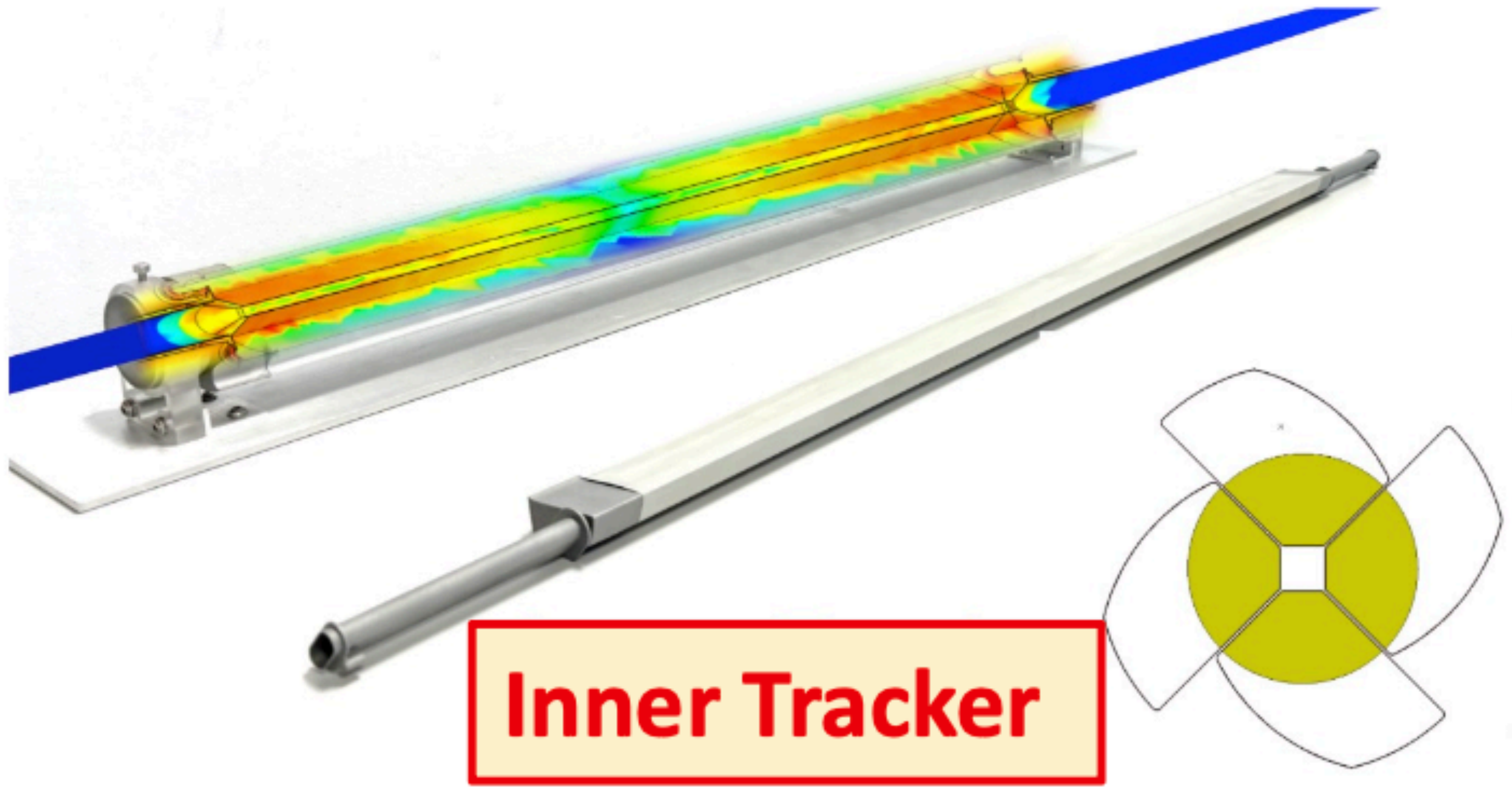
Much more…

ALICE 3 LoI: arXiv:2211.02491





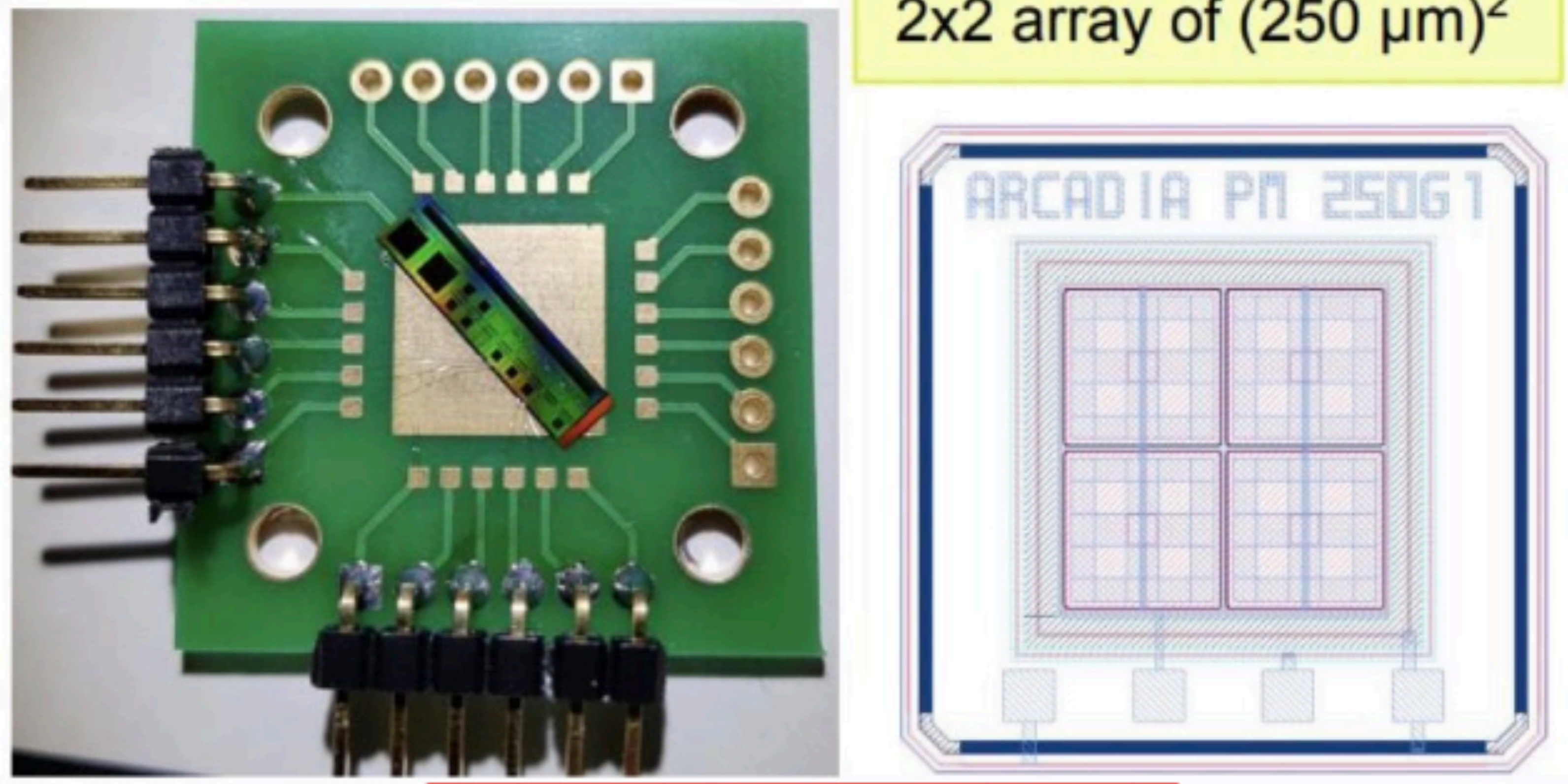
ALICE 3 R&D



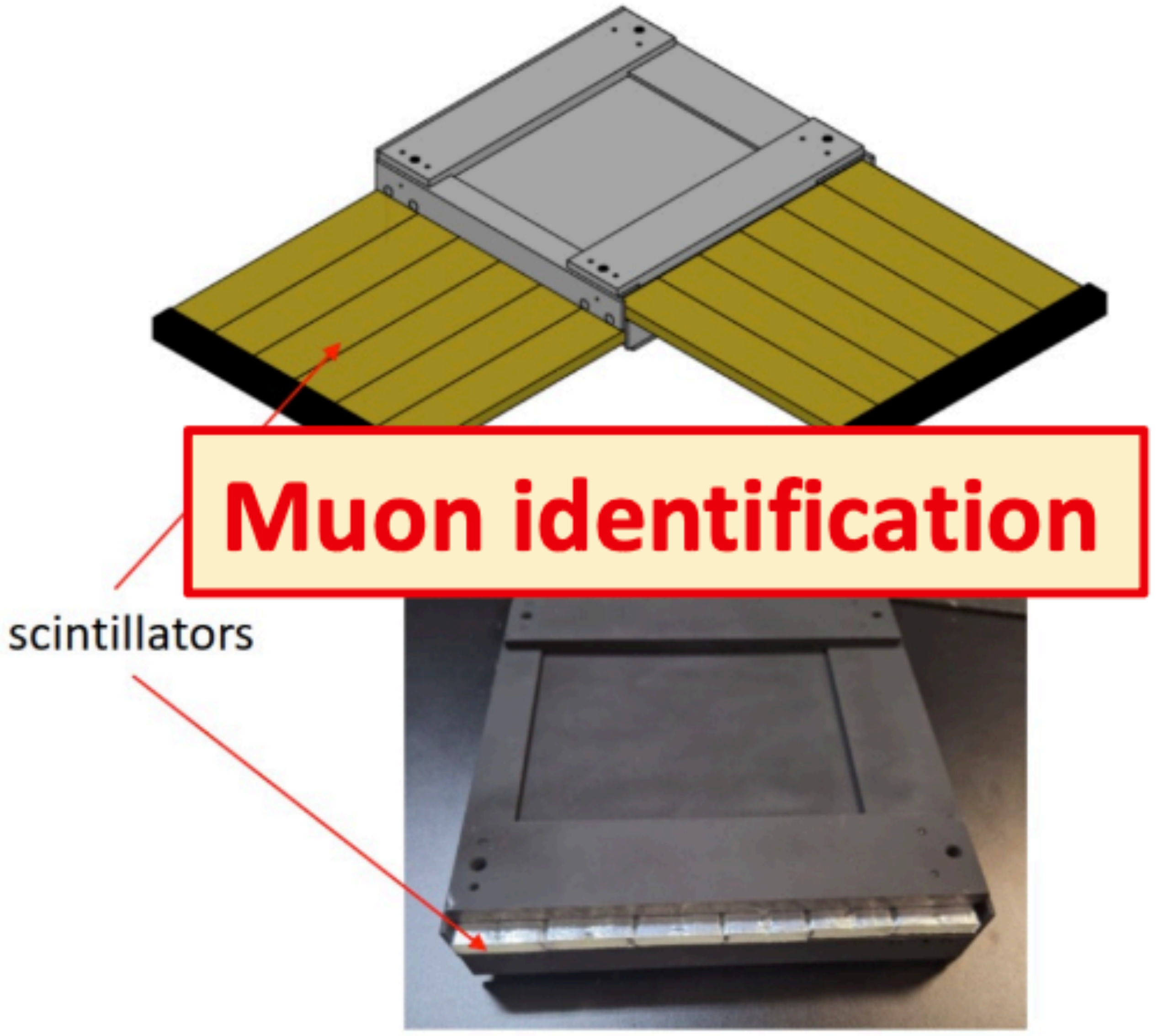
Inner Tracker

Bonded test devices

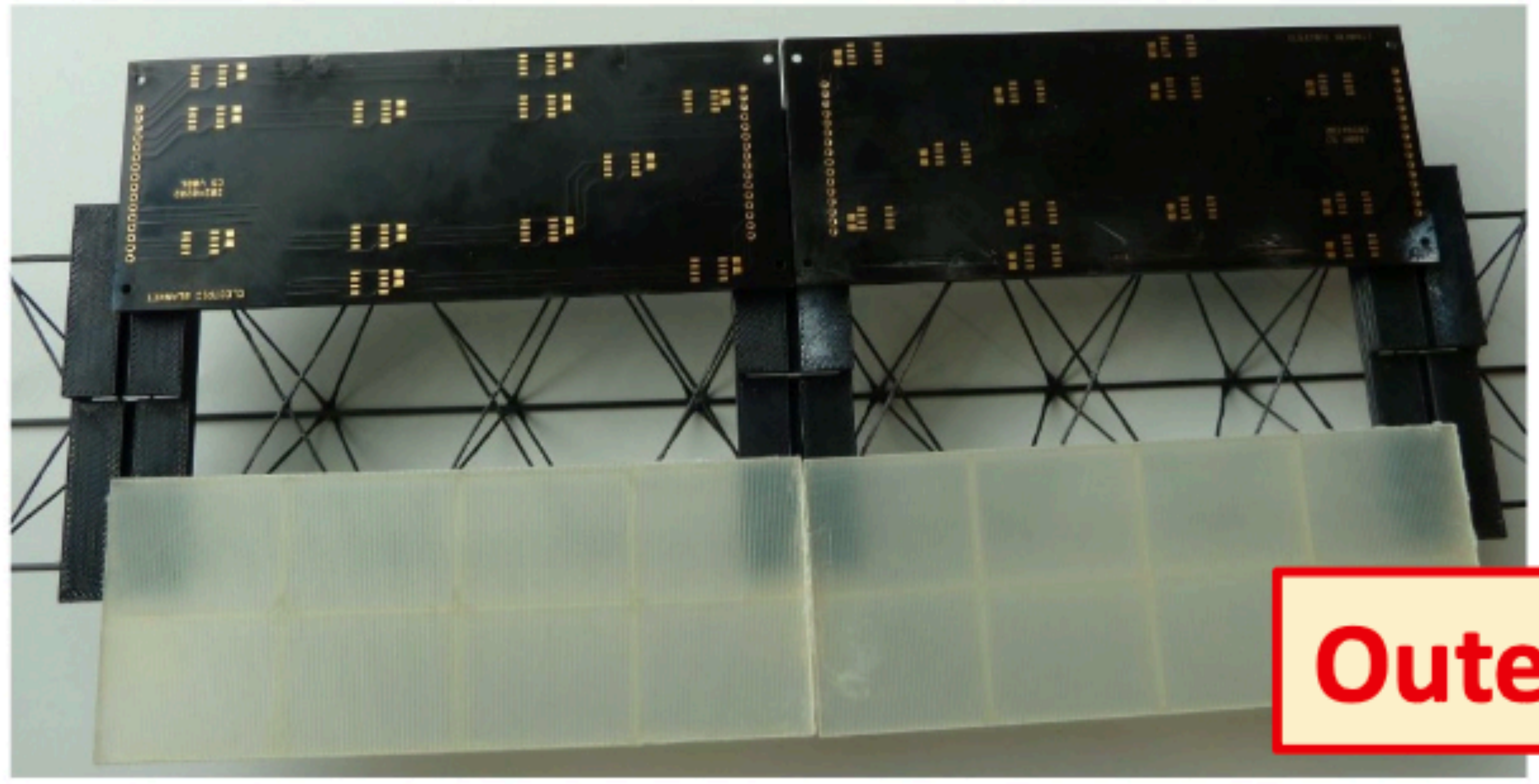
Test devices layout:
2x2 array of $(250\ \mu m)^2$

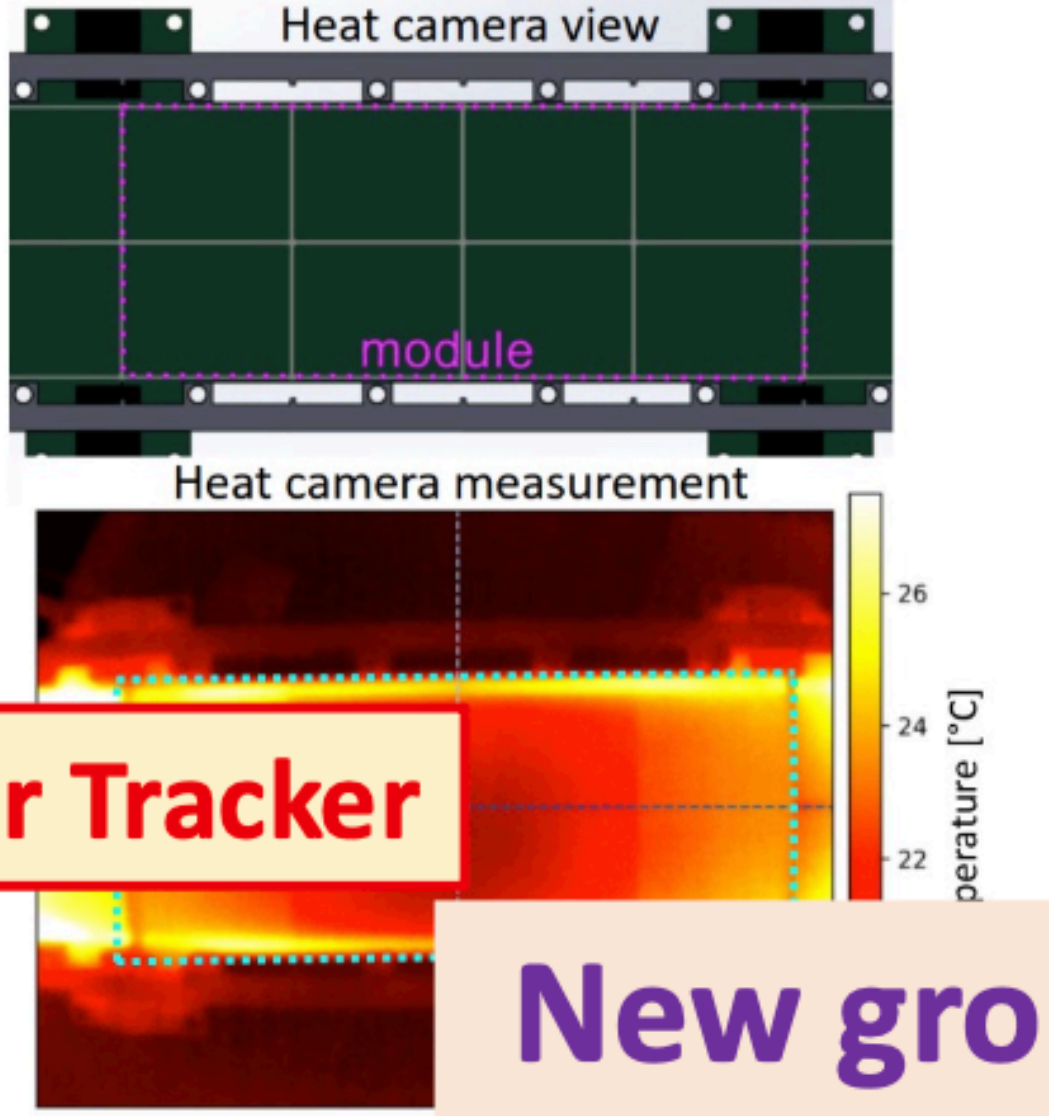


Time Of Flight

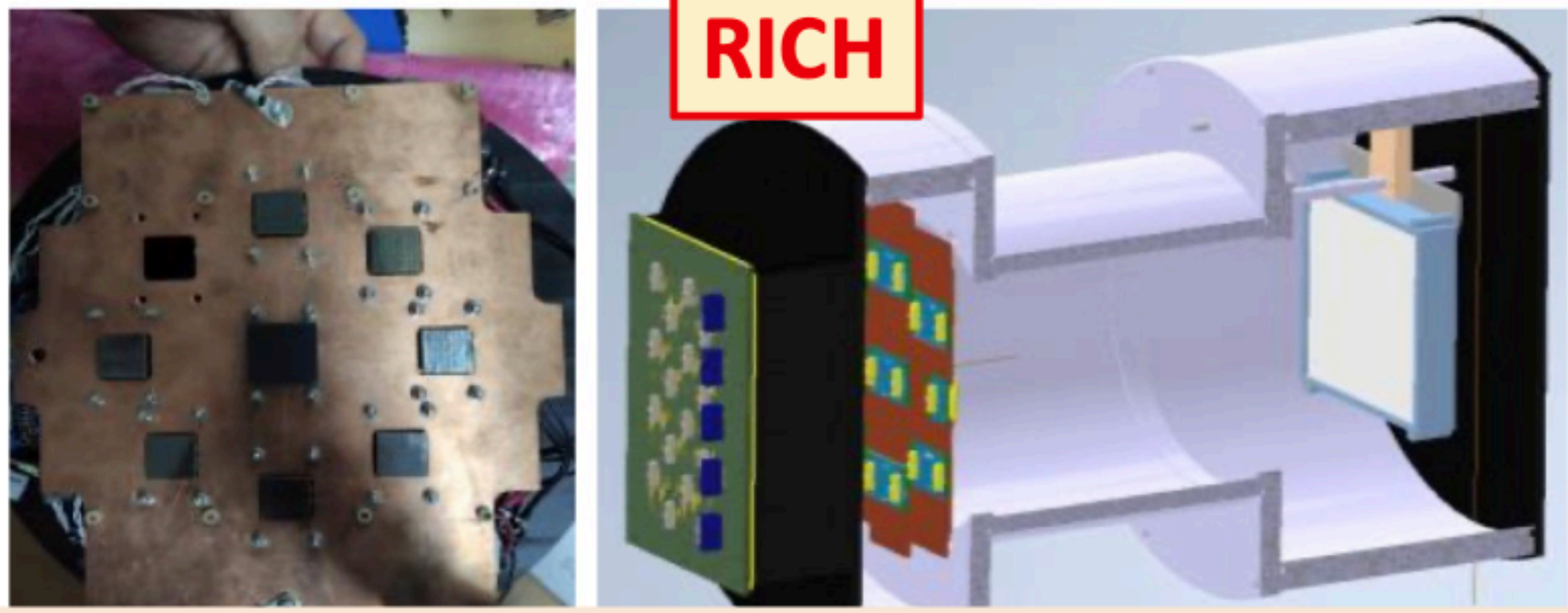


Muon identification





Outer Tracker



RICH

New groups are welcome to join ALICE 3!