Highlights from ALICE

Kai Schweda (GSI, CERN)

INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS

60th course

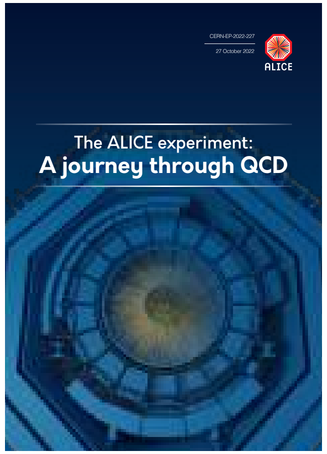
14 - 23 June, 2024
Erice, Sicily

OUTLINE

① ALICE 1 (2009 - 2018) — physics harvest

② ALICE 2 (2022 - 2032) — marvels of technology

③ ALICE 3 (2035 - 2041) — the future



SOME 50 YEARS AGO

“It would be **intriguing** to explore **new phenomena** by **distributing high energy** or **high nuclear matter** over a relatively **large volume**.”

“In this way one could temporarily **restore** broken **symmetries** of the physical vacuum and possibly **create** abnormal **states** of **nuclear matter**.”

T.D. Lee, Bear Mountain, NY, 1974.

source: Nobel foundation

“Nevertheless, such speculations reminds us that the **possibility** of totally **unexpected phenomena** may be the **most compelling** reason to consider **relativistic nucleus-nucleus collisions**. It is regrettable that It is so **hard** to **estimate** the **odds** for this to happen.”

J.D. Bjorken, FNAL, PRD 27 (1983) 140.

source: AIP

MOTIVATION

ALICE

Early universe governed by **phase transitions** of fundamental **quantum fields**

QCD quark/gluon-hadron transition at high temperature **accessible** in **collisions** of heavy nuclei at highest energies

→ Probe **QCD** as genuine **multi-particle theory**

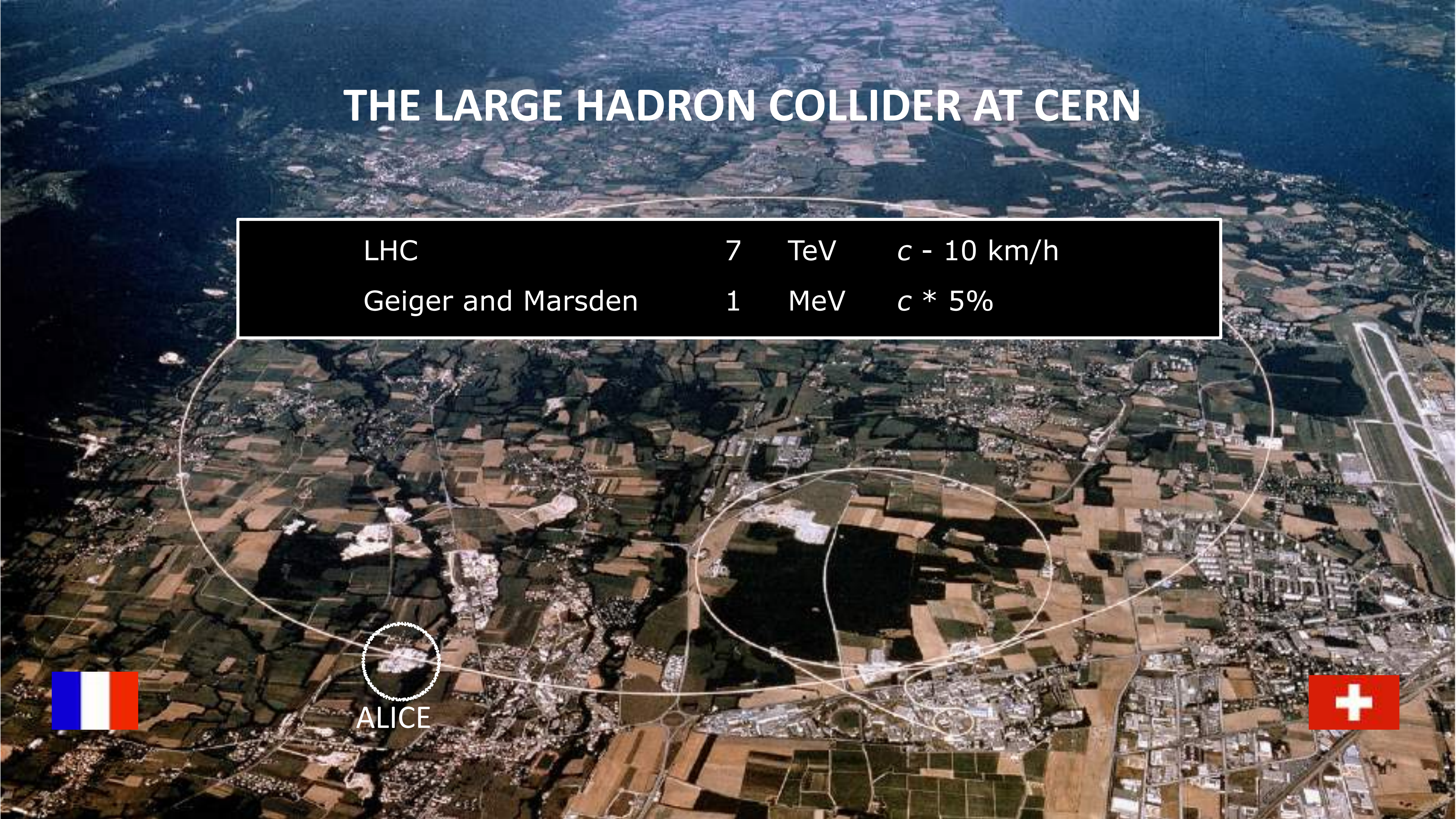
→ Relate **collective phenomena** to **fundamental interactions** in QCD

Source: Michael Turner, *National Geographic (1996)*


THE LARGE HADRON COLLIDER AT CERN
ALICE

THE LARGE HADRON COLLIDER AT CERN

LHC	7	TeV	c - 10 km/h
Geiger and Marsden	1	MeV	c * 5%

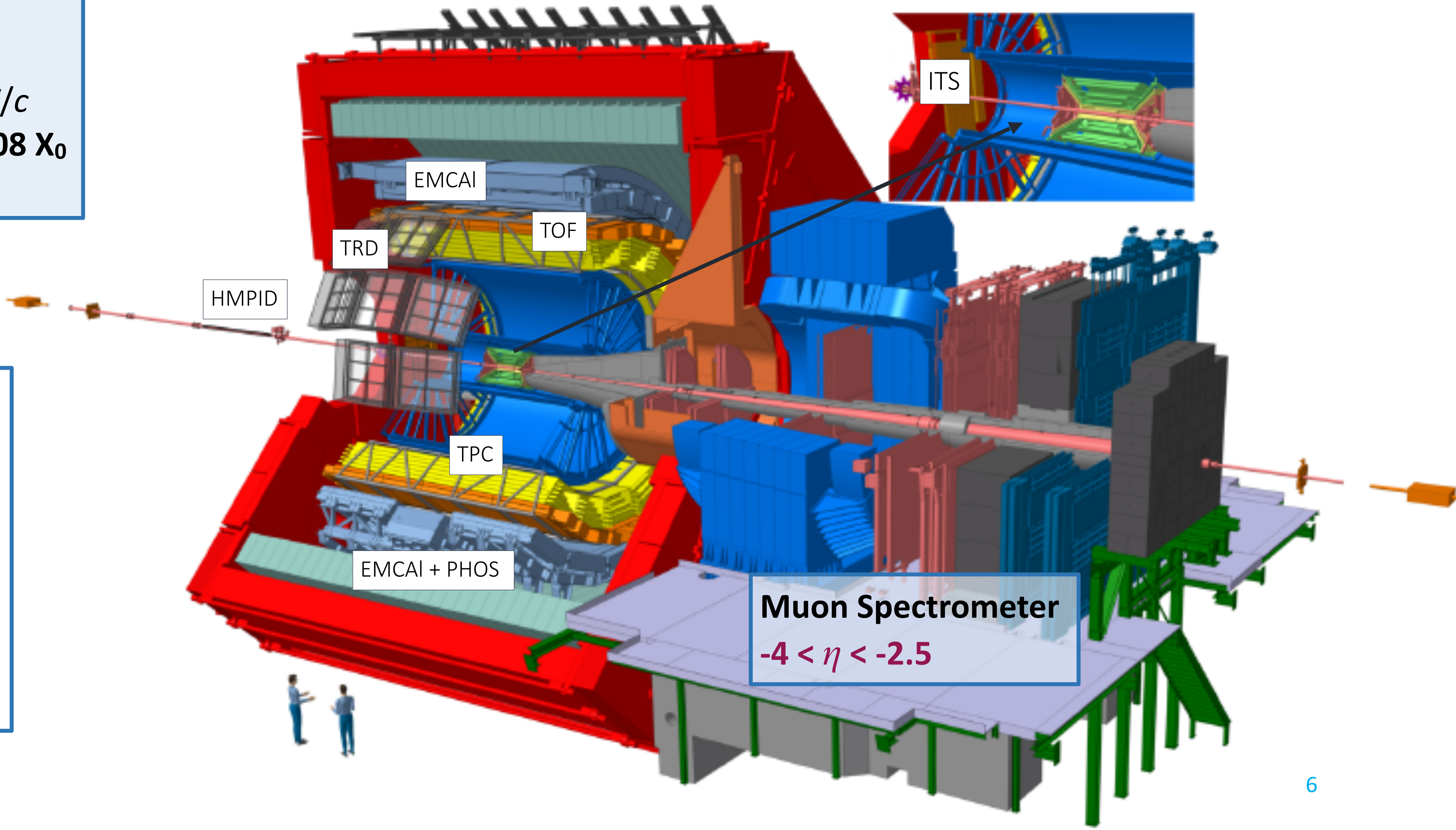


ALICE 1 (2009 - 2018): LHC RUN 1 & 2

Central Barrel $|\eta| < 0.9$
- Tracking
- PID, p = 0.1 - 20 GeV/c
- **Material budget: 0.08 X_0**
- EM-Calorimeters

ACORDE (cosmics)

Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD (N_{γ}, N_{ch})



Muon Spectrometer
$-4 < \eta < -2.5$

ALICE COLLABORATION

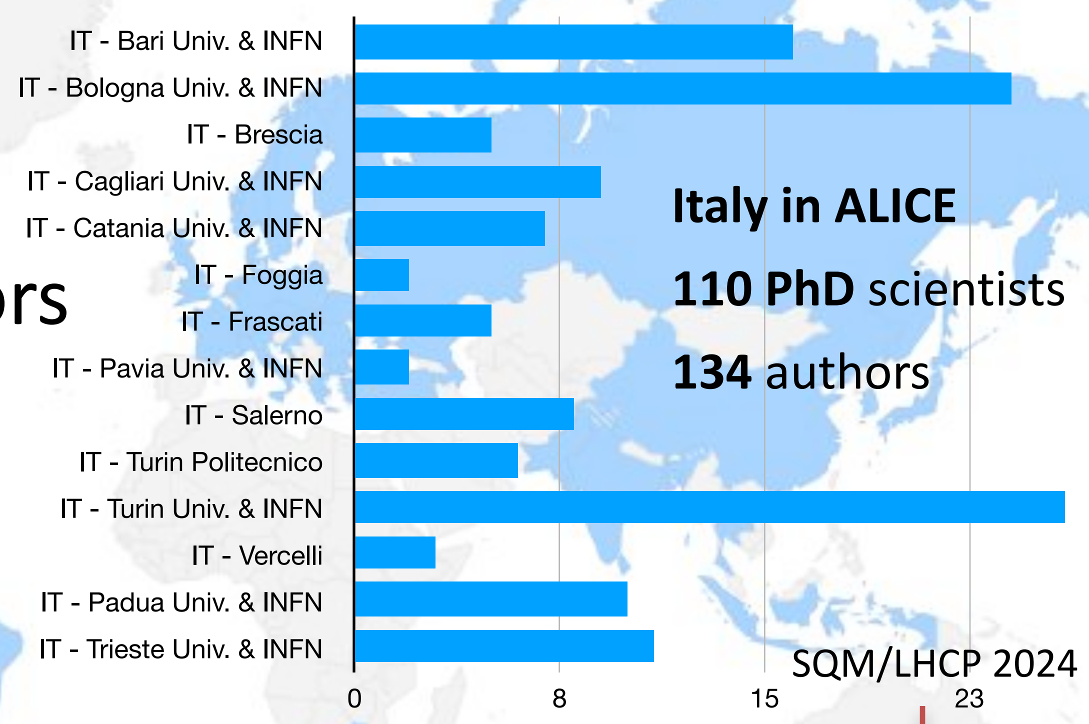
40 countries, 169 institutes

2002 members, 1034 scientific authors

377 doctoral students, 124 postdocs

Run 1 Run 2

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	~75 μb^{-1} ~800 μb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	~200 mb^{-1}, ~100 nb^{-1} ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1} ~36 pb^{-1}

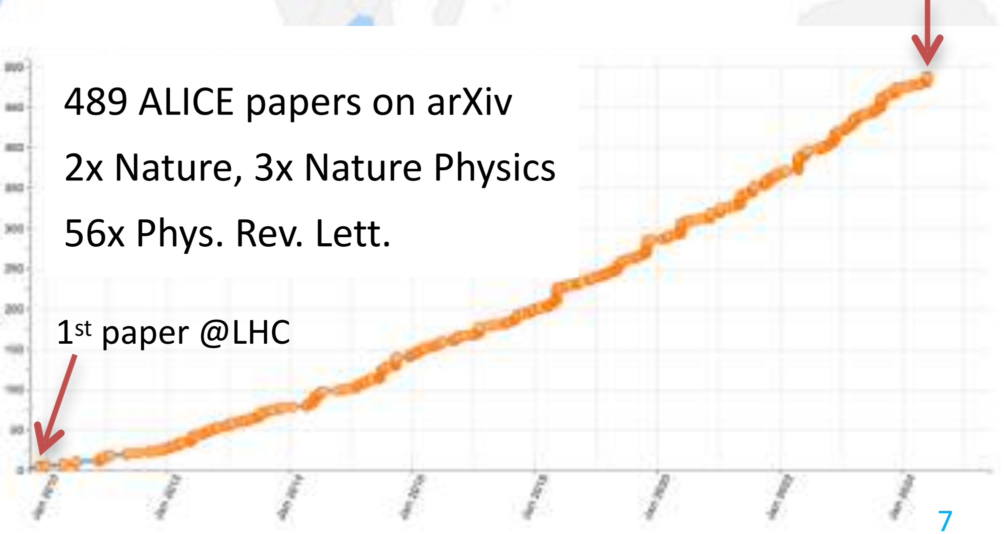


Italy in ALICE

110 PhD scientists

134 authors

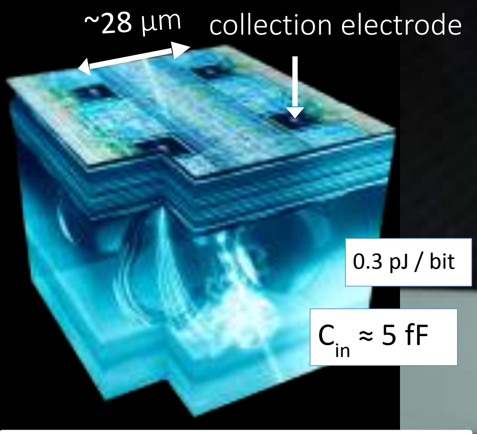
SQM/LHCP 2024



Inner Tracking System (ITS2)

7 layers, 10 m^2 silicon

based on MAPS, 12.5 G pixels



Q_{in} (MIP) ≈ 1300 e ⇨ V ≈ 40mV

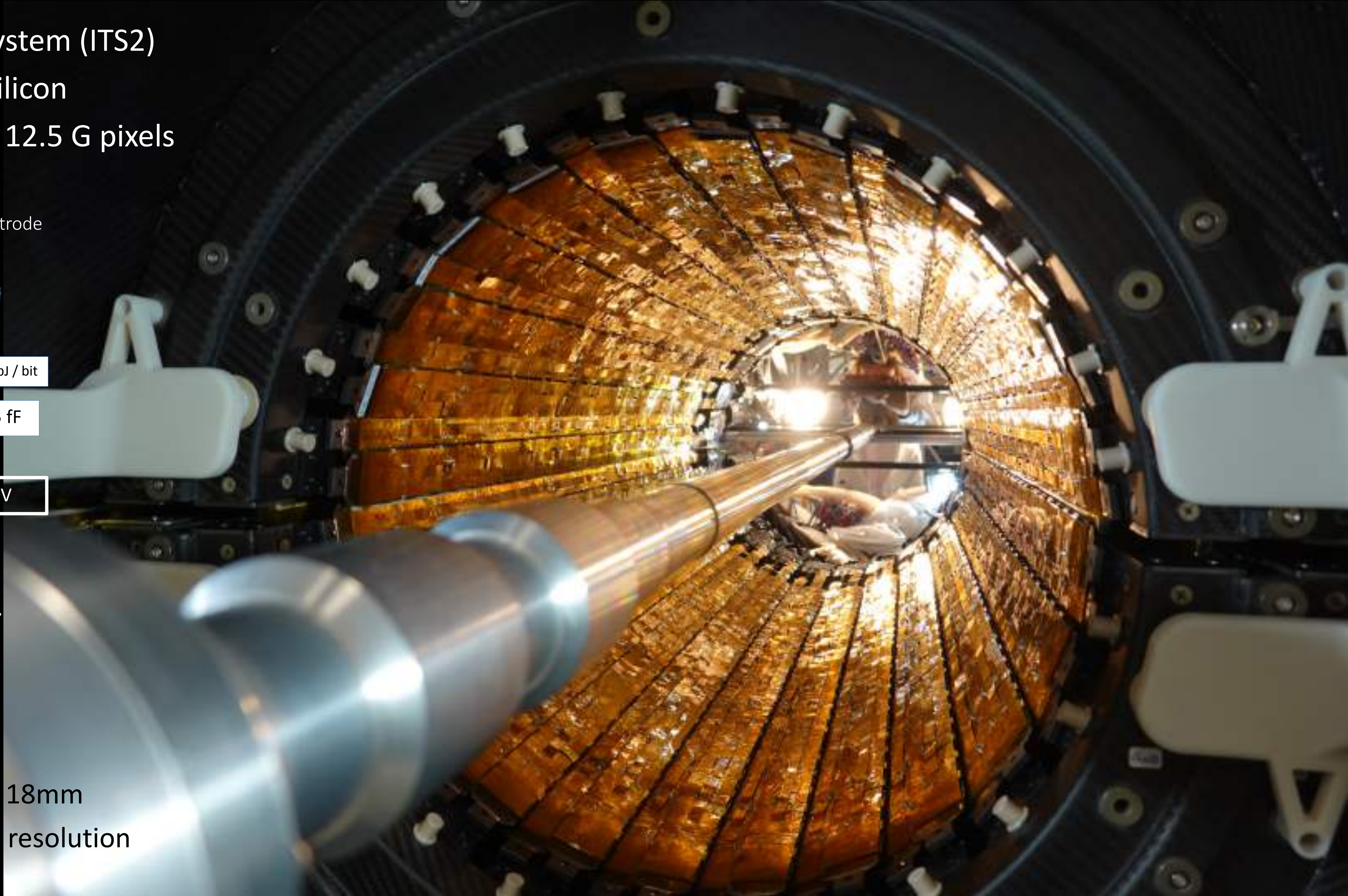
0.36% X_0 per layer

pixel size:

30 x 30 μm^2

beam pipe radius: 18mm

3x higher pointing resolution



Time Projection Chamber (TPC)

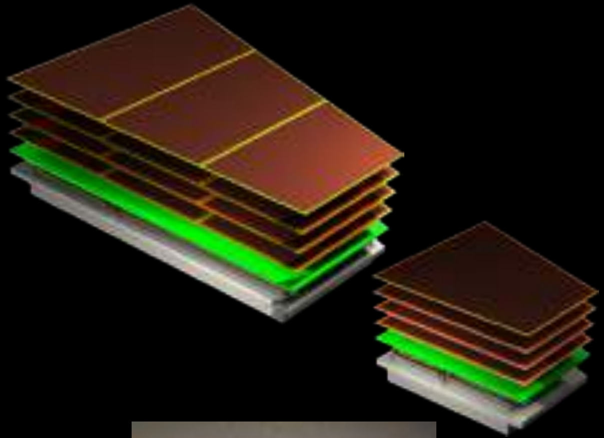
V = 88m³, $\Delta T < 0.1\ \mathrm{K}$

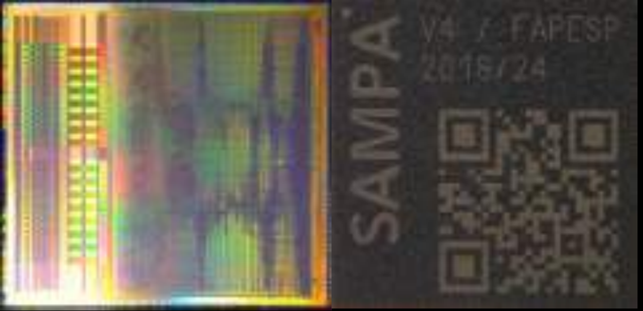
Multiwire proportional chamber

→ quadruple-GEM readout

→ continuous readout (100x faster)

3.4 TeraBytes/second





SAMPA chip

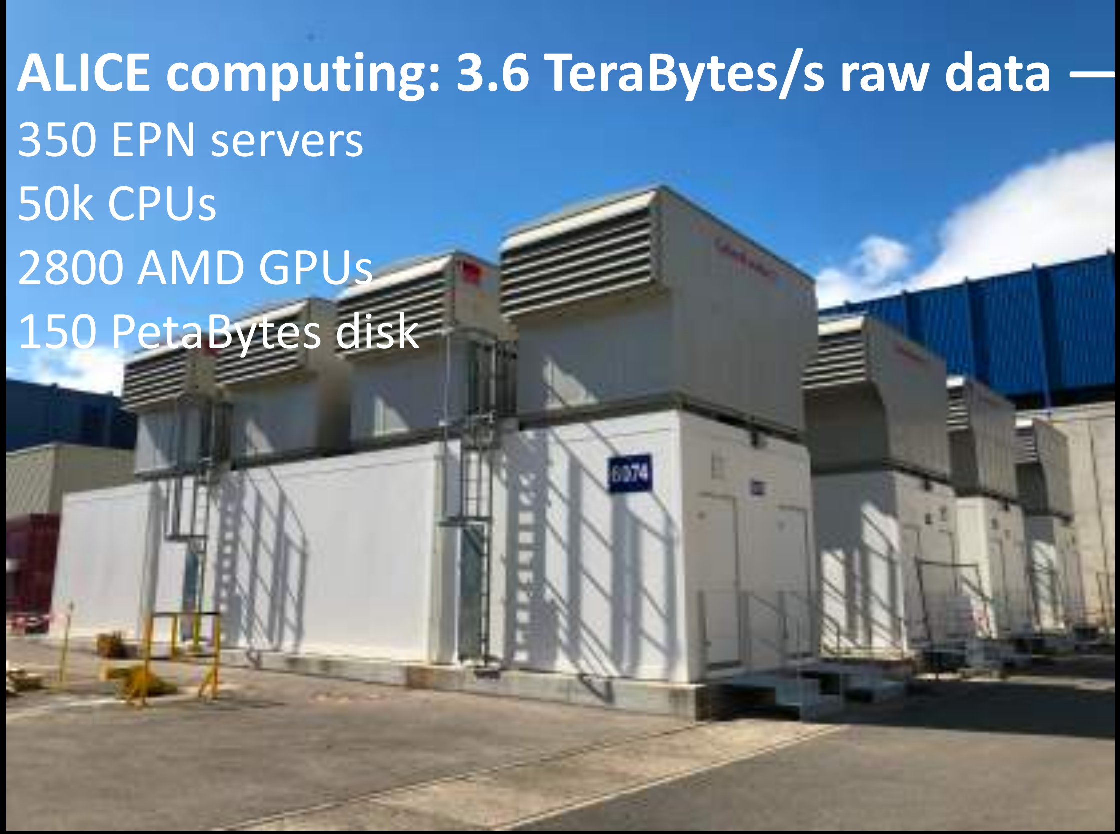
ALICE computing: 3.6 TeraBytes/s raw data —> up to 170 GBytes/s to disk

350 EPN servers

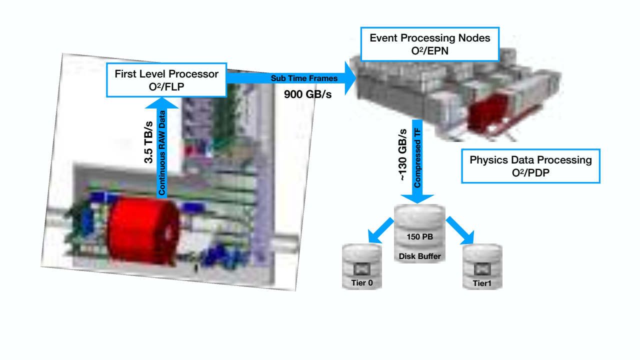
50k CPUs

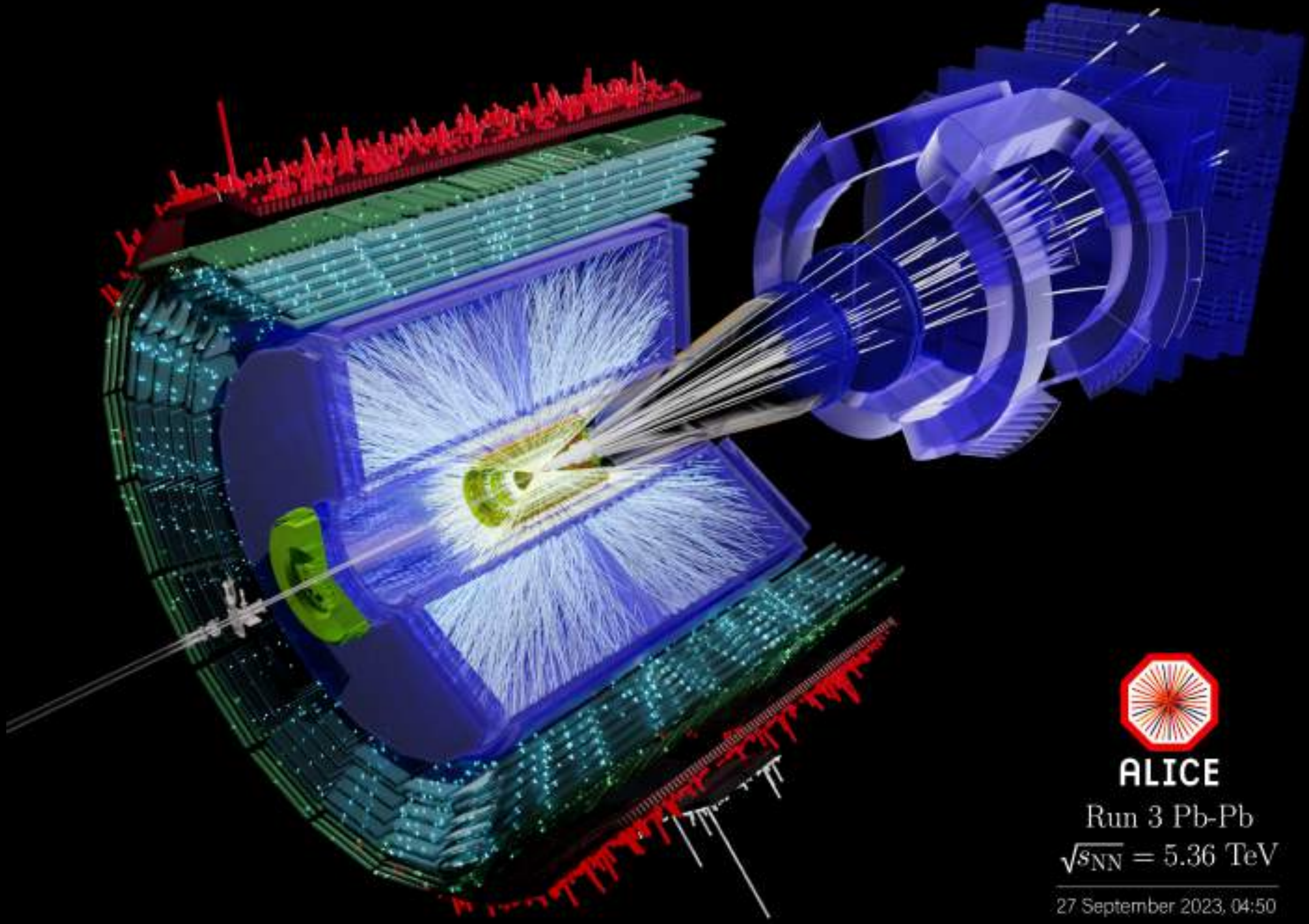
2800 AMD GPUs

150 PetaBytes disk

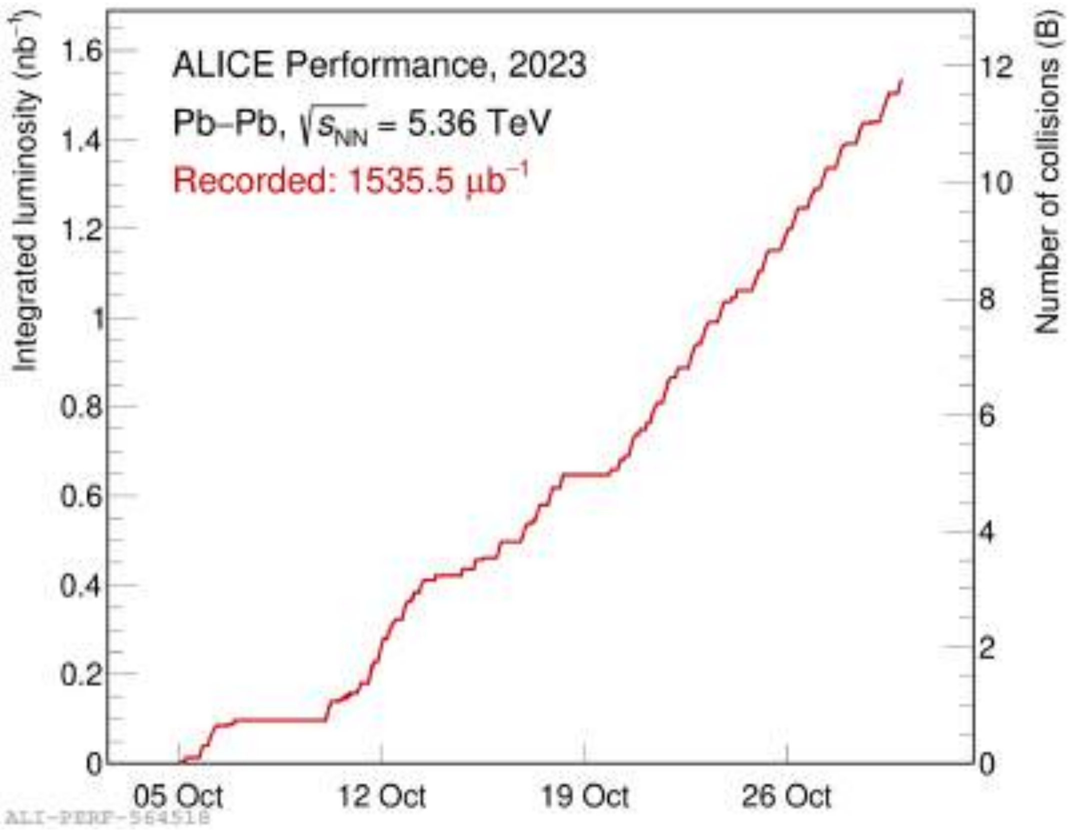


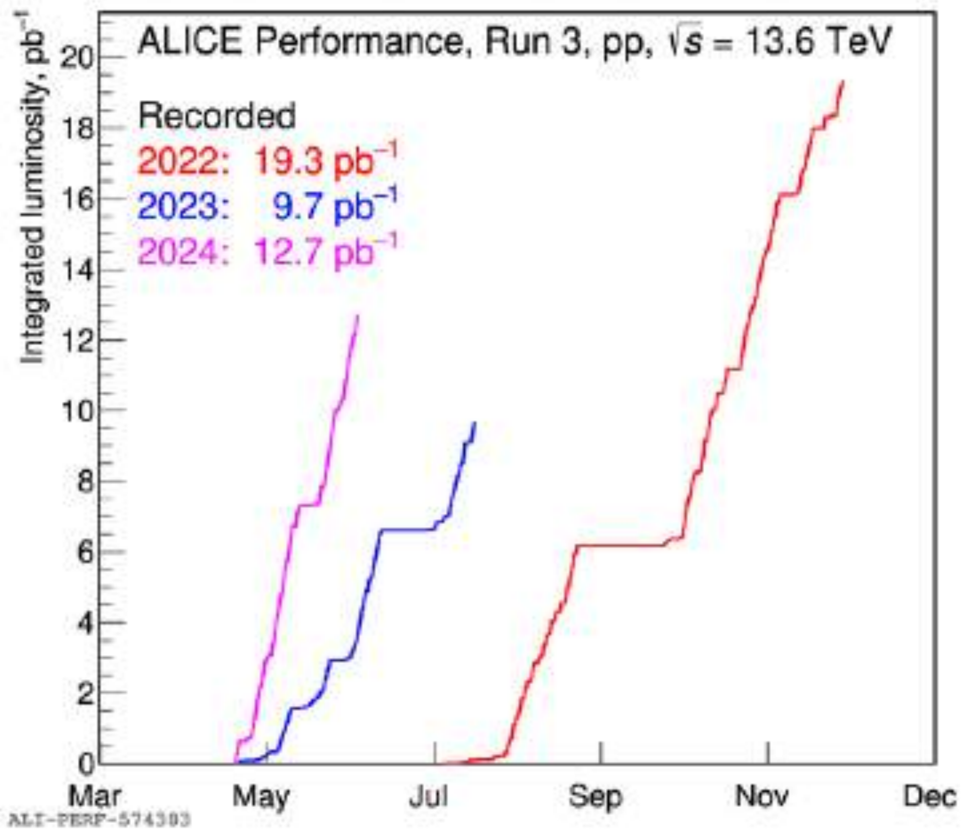
common readout unit
(world's largest FPGA)




ALICE
Run 3 Pb-Pb
$\sqrt{s_{NN}} = 5.36$ TeV
27 September 2023, 04:50

Run 3: INTEGRATED LUMINOSITY





2023 Pb-Pb: 12 billion minimum bias collisions

40x minimum bias, **6x central** wrt Run 1 + 2

expect similar data set in 2024

2024 pp: > half a trillion minimum bias collisions

still counting at **95%** data recording **efficiency**

expect still 3x more in 2024

THE HIGH-LUMINOSITY LHC (Pb-Pb)

instantaneous luminosity

$L = 6 \cdot 10^{27}\text{cm}^{-2}\text{s}^{-1}$

$\text{d}N/\text{d}t = L \cdot \sigma, \quad \sigma_{\text{Pb-Pb}} = 8\text{b}, 1\text{b} = 10^{-24}\text{cm}^2$

$\text{d}N/\text{d}t = 6 \cdot 10^{27} \cdot 8 \cdot 10^{-24}\ \text{s}^{-1} = 48000\ \text{s}^{-1}$

integrated luminosity for Pb-Pb (Run 3 + 4): 2023 - 2032

$\mathcal{L}_{\text{int}} = 13\text{nb}^{-1} \rightarrow$ 100 B zero-bias Pb-Pb collisions (!) in continuous readout

FINAL STATE: NUCLEI, HYPER-NUCLEI, AND HADRONIC INTERACTIONS

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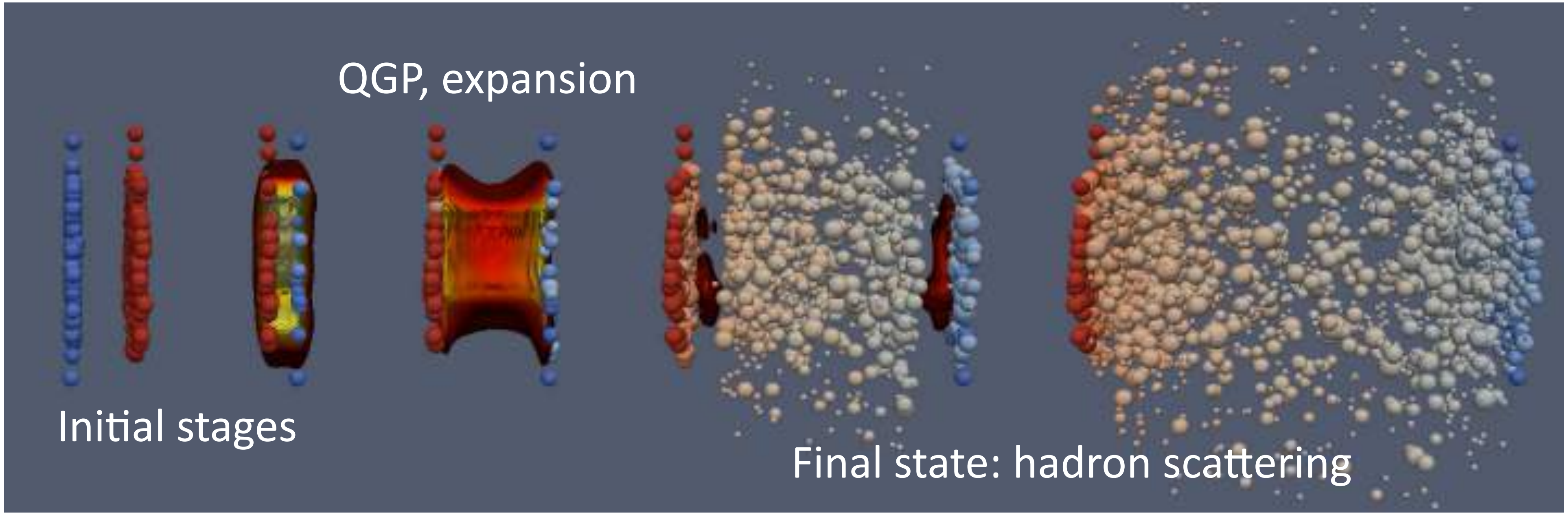

Emission of thermal radiation $\propto T^2$

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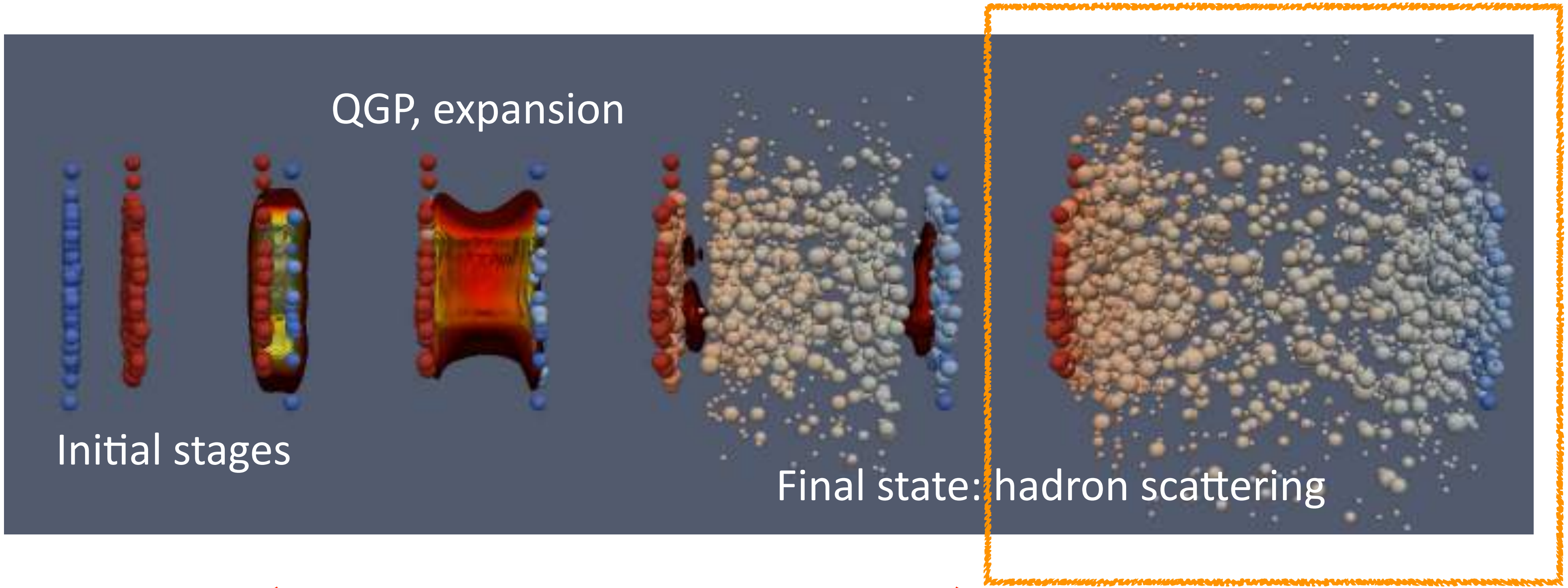

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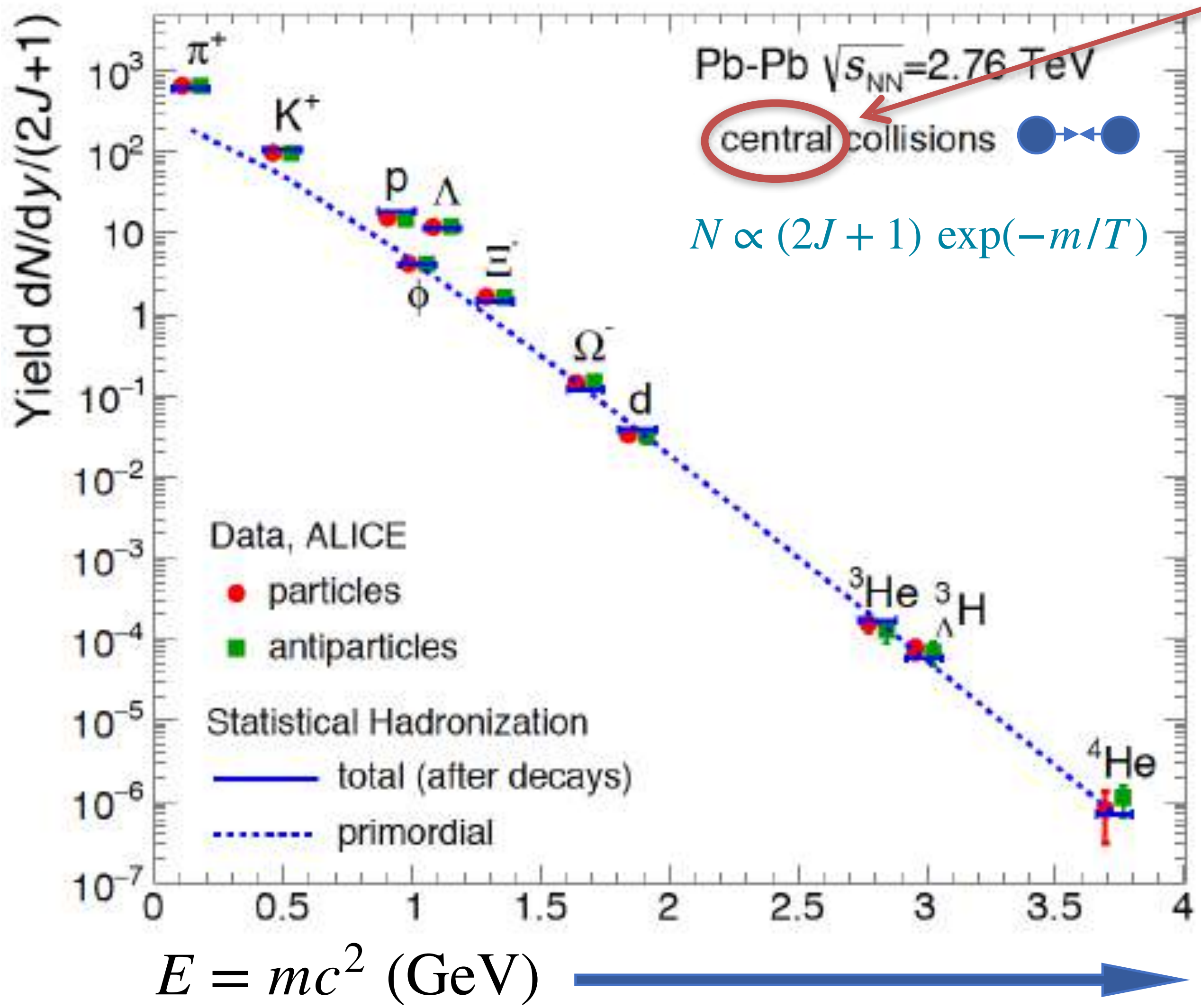
THERMAL PARTICLE PRODUCTION



Highest multiplicity

QCD-analog of **Planck spectrum**

T = 156.2 ± 2 MeV

Nature 561, 321 (2018)

Baryo-chemical potential

$$\mu_B = 0.71 \pm 0.45 \text{ MeV}$$

Particle and **antiparticles** created at almost **identical yields**

arXiv:2311.13332

Lattice-QCD results **agree**

T_{pc} = 156.5 ±1.5 MeV

A. Bazavov et al. (Hot QCD) arXiv:1812.08235

LF particle production, Adrian Nassirpour, Tue. 17h05

CHEMICAL FREEZE-OUT MODEL

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Hadron resonance ideal gas

P. Braun-Munzinger et al., nucl-th/0304013

Density of particle *i*

$$\rho_i = \frac{N_i}{V} = \frac{g_i}{2\pi^2} T_{ch}{}^3 \left(\frac{m_i}{T_{ch}} \right)^2 K_2(m_i/T_{ch})\, \lambda_q^{Q_i}\, \lambda_s^{s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

- q_i : 1 for u and d, -1 for ū and d̄
- s_i : 1 for s, -1 for s̄
- g_i : spin-isospin freedom
- m_i : particle mass

- T_{ch} : Chemical freeze-out temperature
- μ_q : light-quark chemical potential
- μ_s : strange-quark chemical potential
- V : volume term, drops out for ratios!

$\mu_B = 3\mu_q$

$\mu_S = \mu_q - \mu_s$

All resonances and unstable particles are decayed

Compare particle ratios to experimental data

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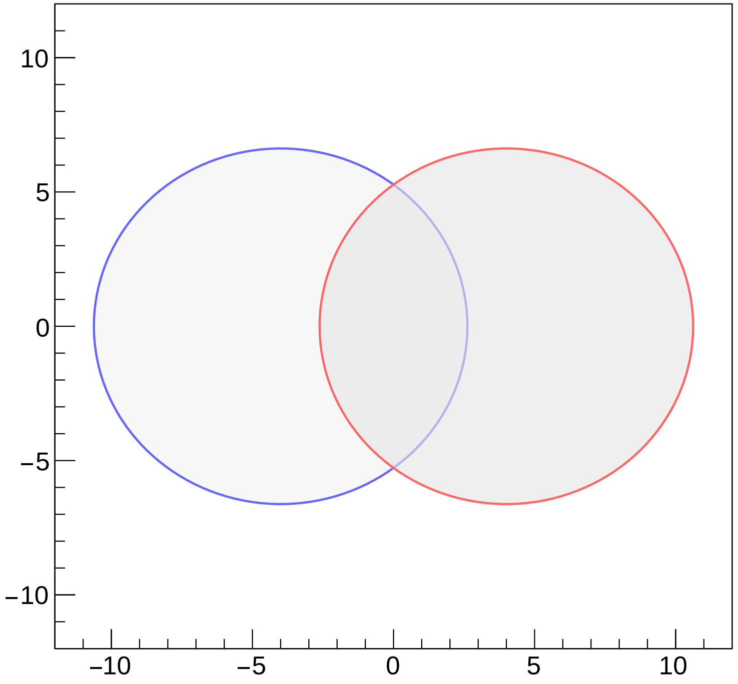
Azimuthal anisotropy: initial and final states

MC event: location of nucleons



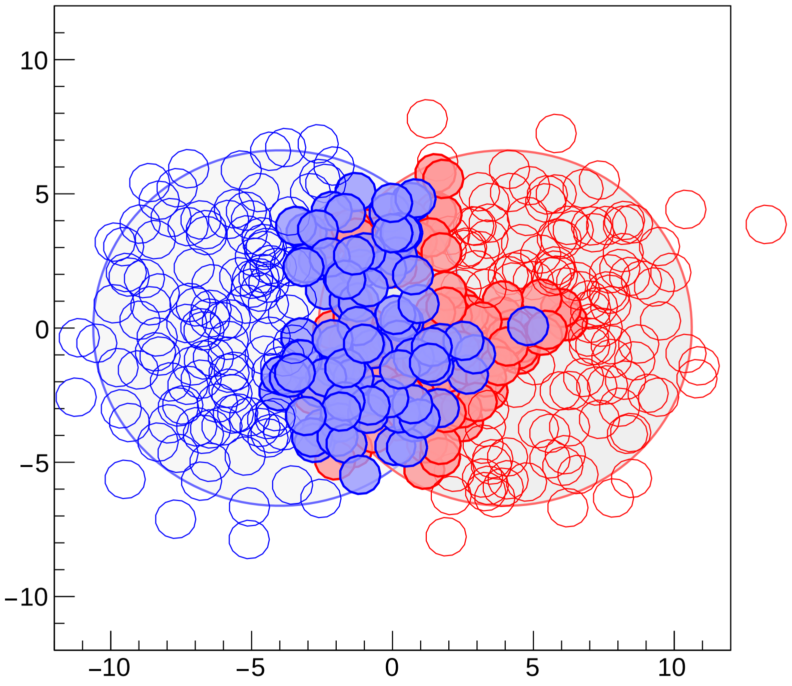
Characterise shape by harmonics:

$$\varepsilon_n = \frac{\sum r^2(\cos^2 n\varphi + \sin^2 n\varphi)}{\sum r^2}$$

Azimuthal anisotropy: initial and final states

ALICE

MC event: location of nucleons



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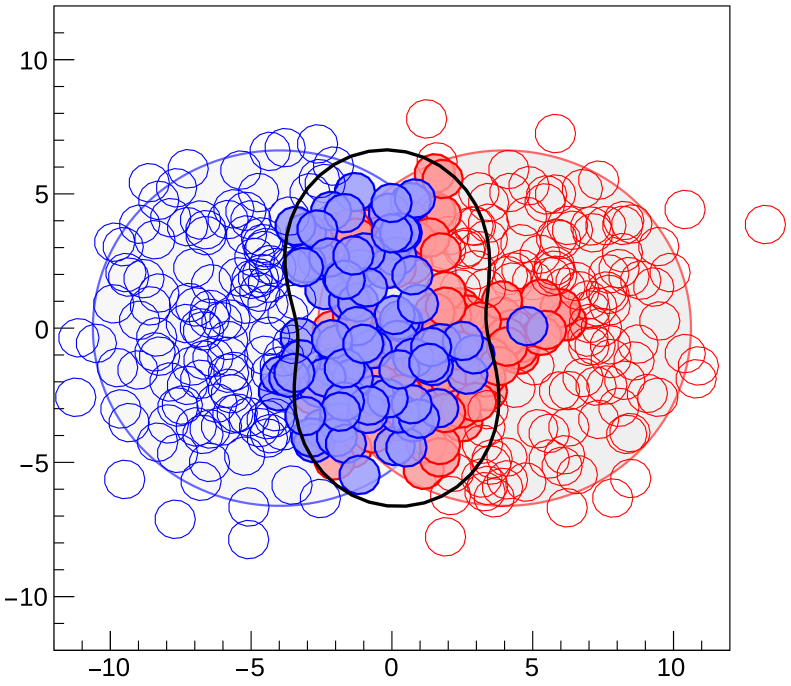

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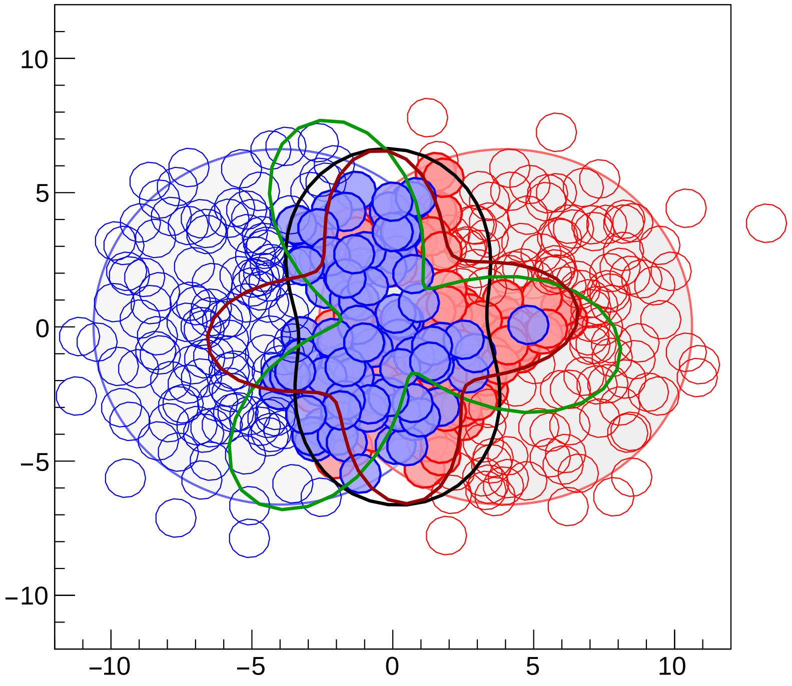

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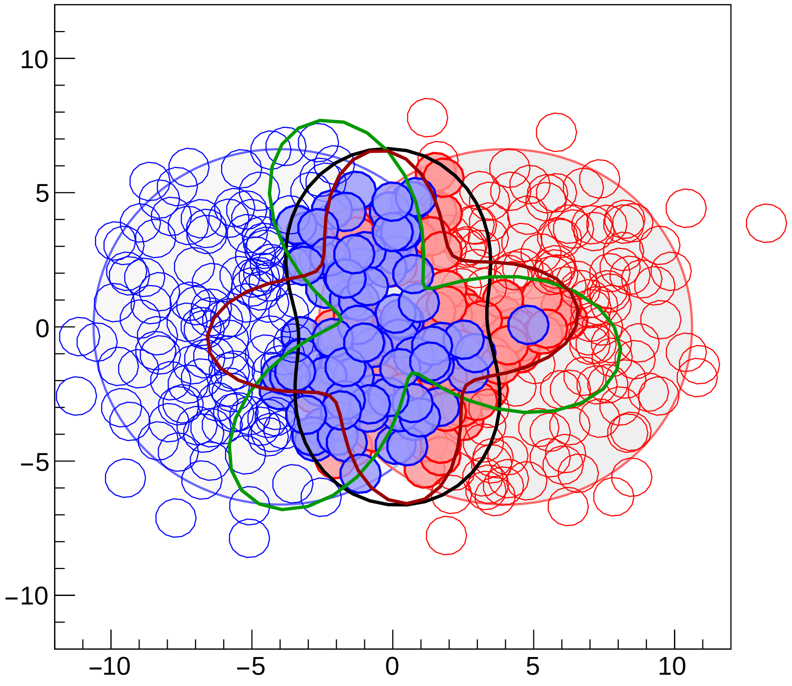
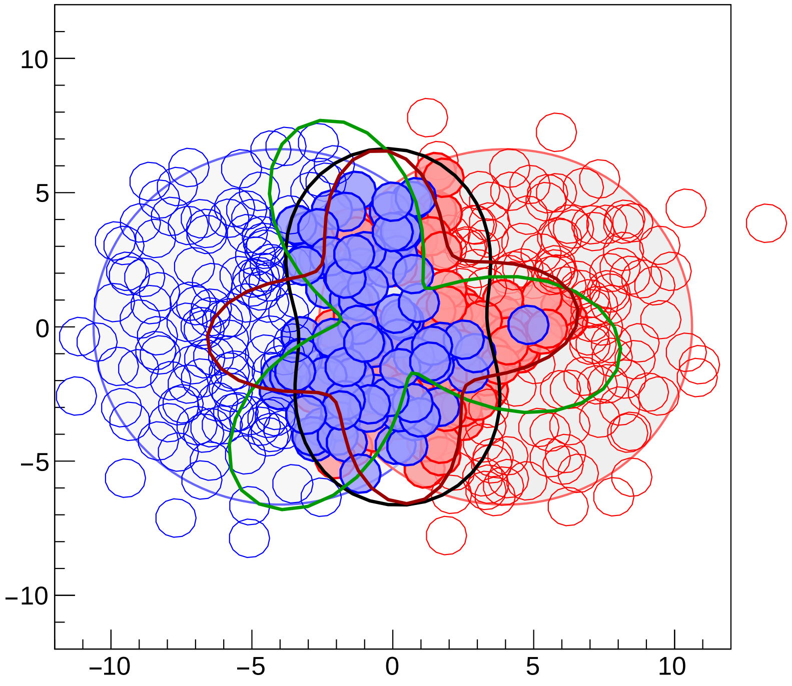


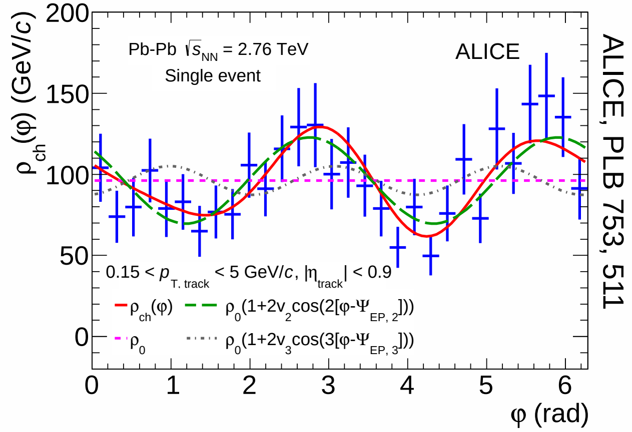
Initial state spatial anisotropies ε_n are transferred into
final state momentum anisotropies v_n
by pressure gradients, flow of the Quark Gluon Plasma

Azimuthal anisotropy: initial and final states

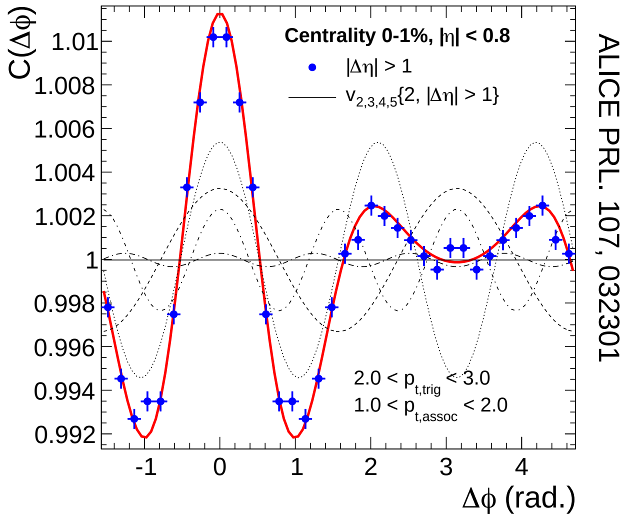
MC event: location of nucleons



Azimuthal distribution single event



Sum over many events

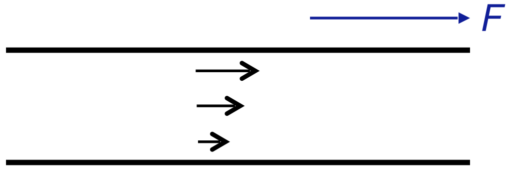


Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n by pressure gradients, flow of the Quark Gluon Plasma

Shear viscosity

Nature Physics , 1113 (2019)

Viscous liquids dissipate energy



$$\frac{F}{A} = \eta \frac{dv}{dz}$$

Dilute gas: $\eta = \frac{1}{3} np\lambda \qquad \lambda = \frac{1}{n\sigma}$

$$p \propto T^{\frac{1}{2}}$$

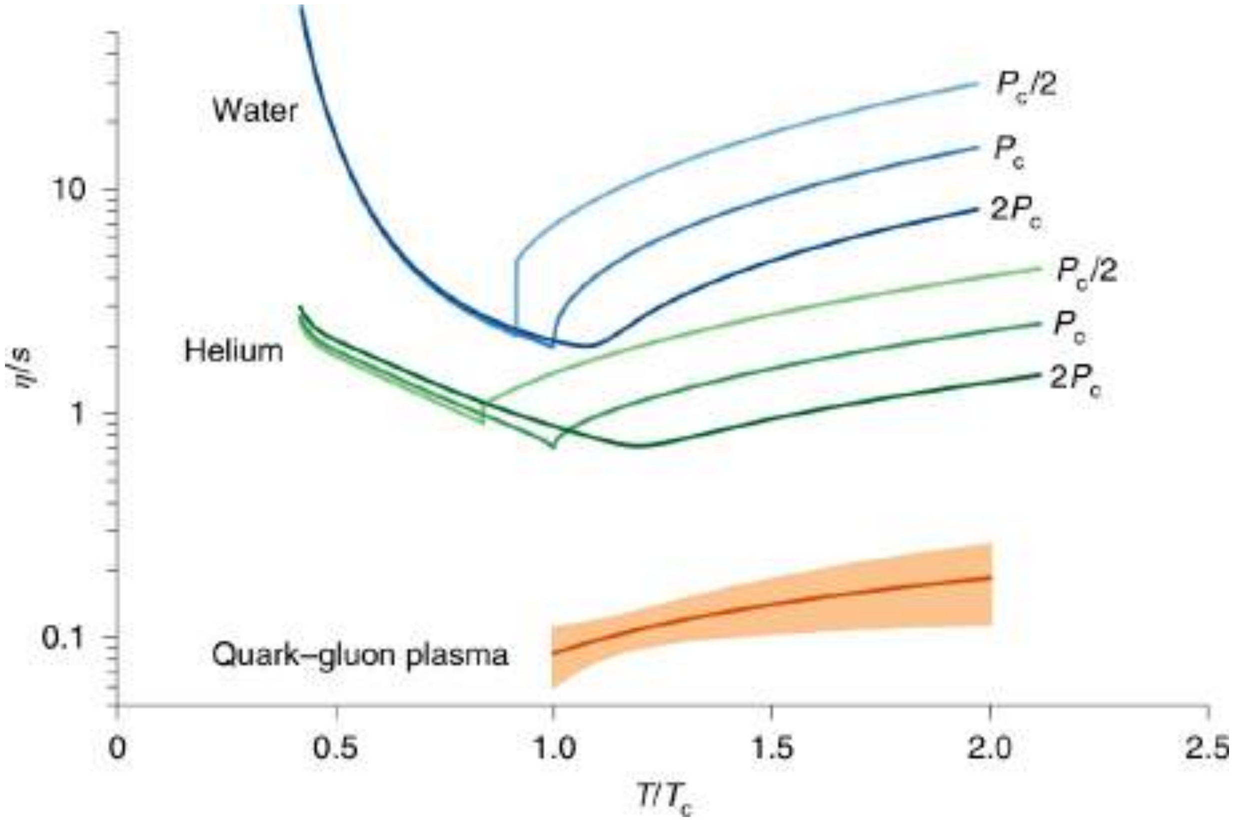
η increases with *T*

Liquid, densely packed: $\eta \propto e^{-E_{vac}/T}$

E_{vac}: activation energy for jumps of vacancies

η decreases with *T*

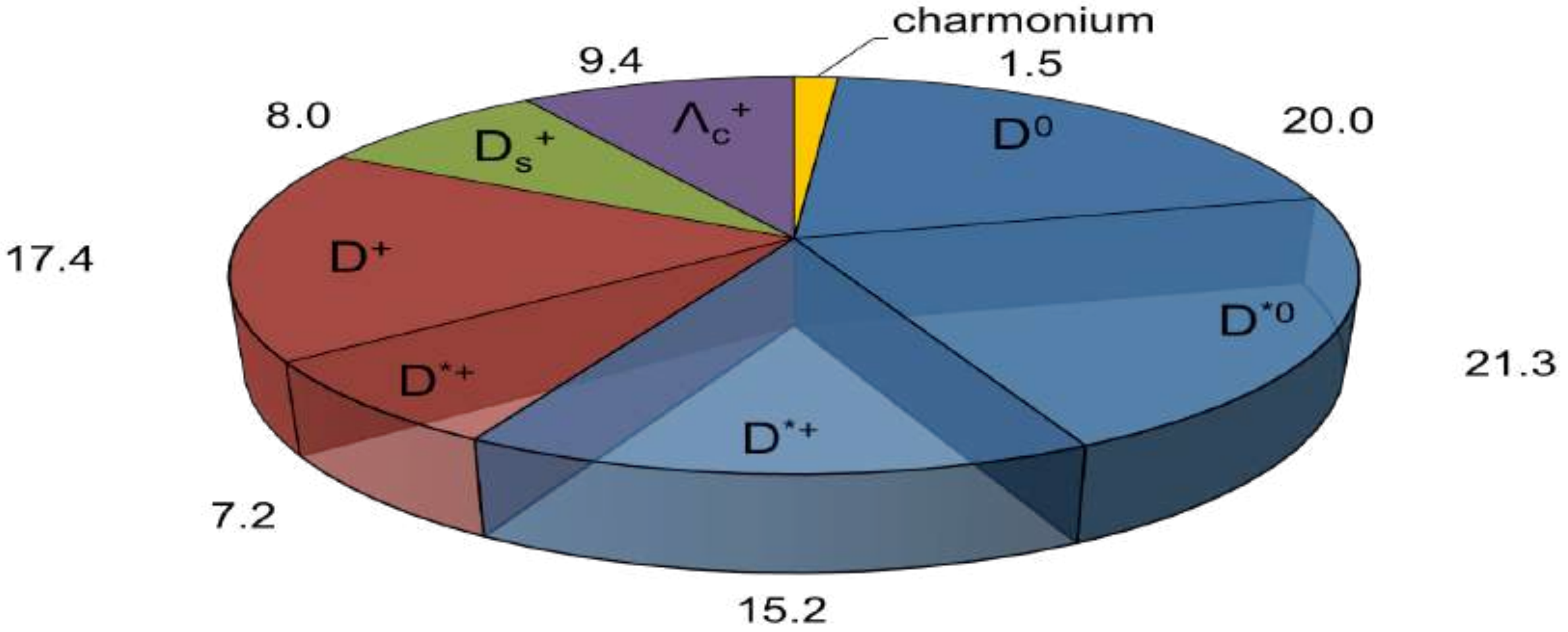
Temperature dependence of specific viscosity



Viscosity minimal at liquid-gas transition

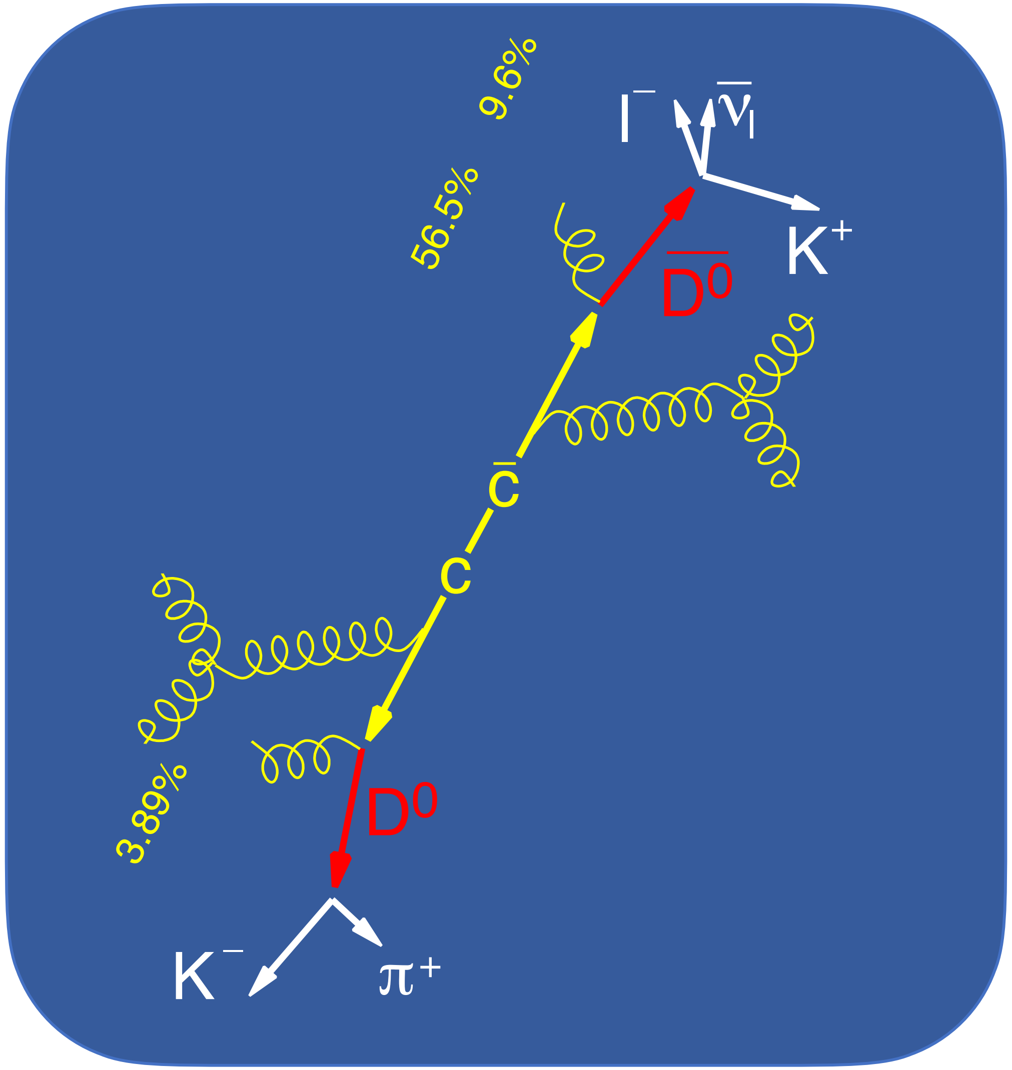
Specific viscosity η/s of QGP lower than any atomic matter:
strong interactions — short mean free path

WHERE DOES ALL THE CHARM GO ?



in vacuo (e^+e^- collisions): about **56%** of all **charm quarks** fragment into **D^0** mesons

HEAVY-QUARK DETECTION



e.g., D^0 ($c\bar{u}$)→ K^- + π^+ , cτ = 123 μm

displaced decay vertex is signature of heavy-quark decay

→ need sub-millimeter pointing precision to collision vertex

separation of time scales:

charm quark creation - 0.08 fm/c

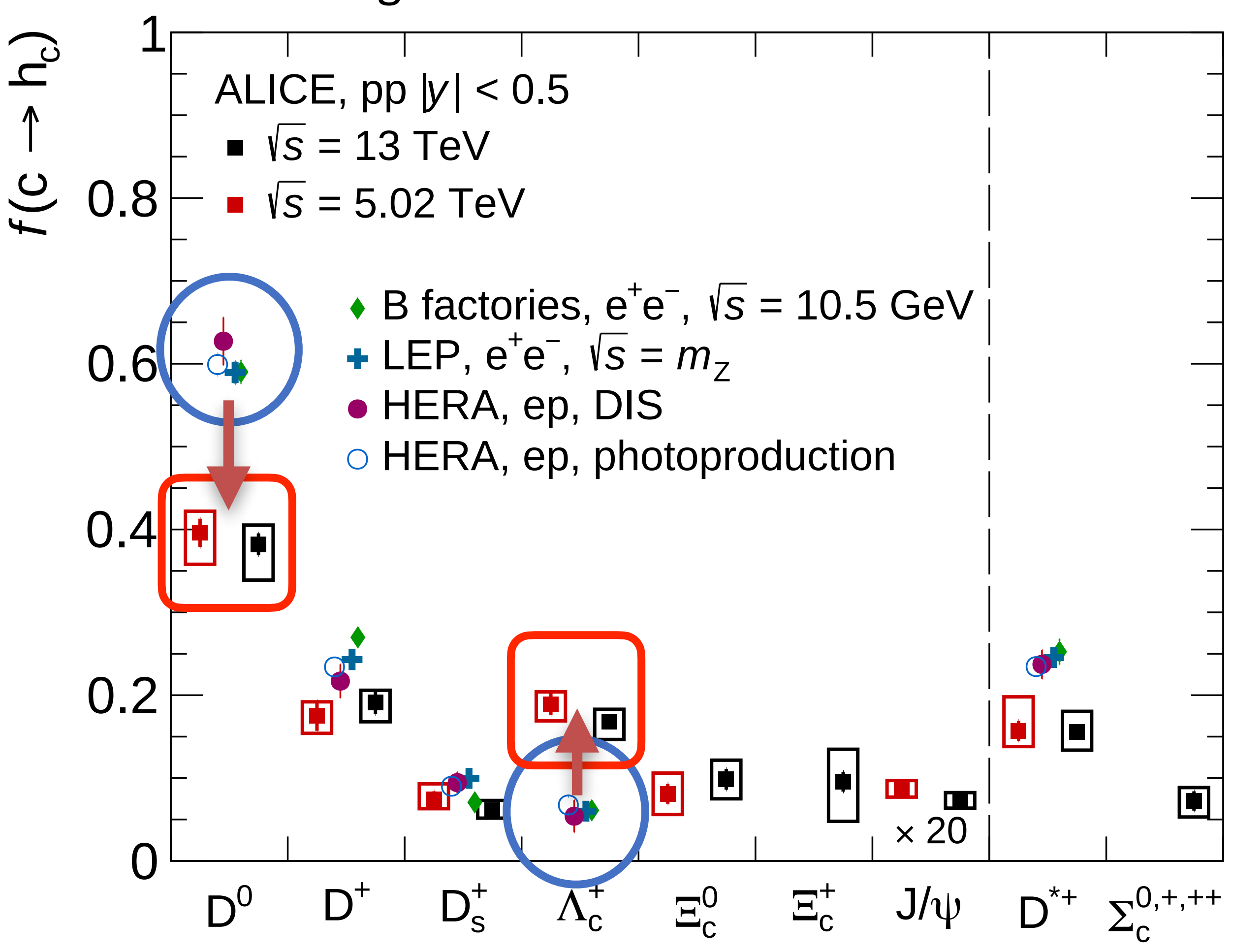
hadronization - 1 fm/c

D^0 decay - 10^{10} fm/c

plot: courtesy of D. Tlusty

CHARM PRODUCTION AND FRAGMENTATION

Charm fragmentation fraction



ALI-PUB-546222

Charmed baryon production **larger** in **pp** than in **e^+e^-**

Λ_c, Ξ_c, Σ_c measured

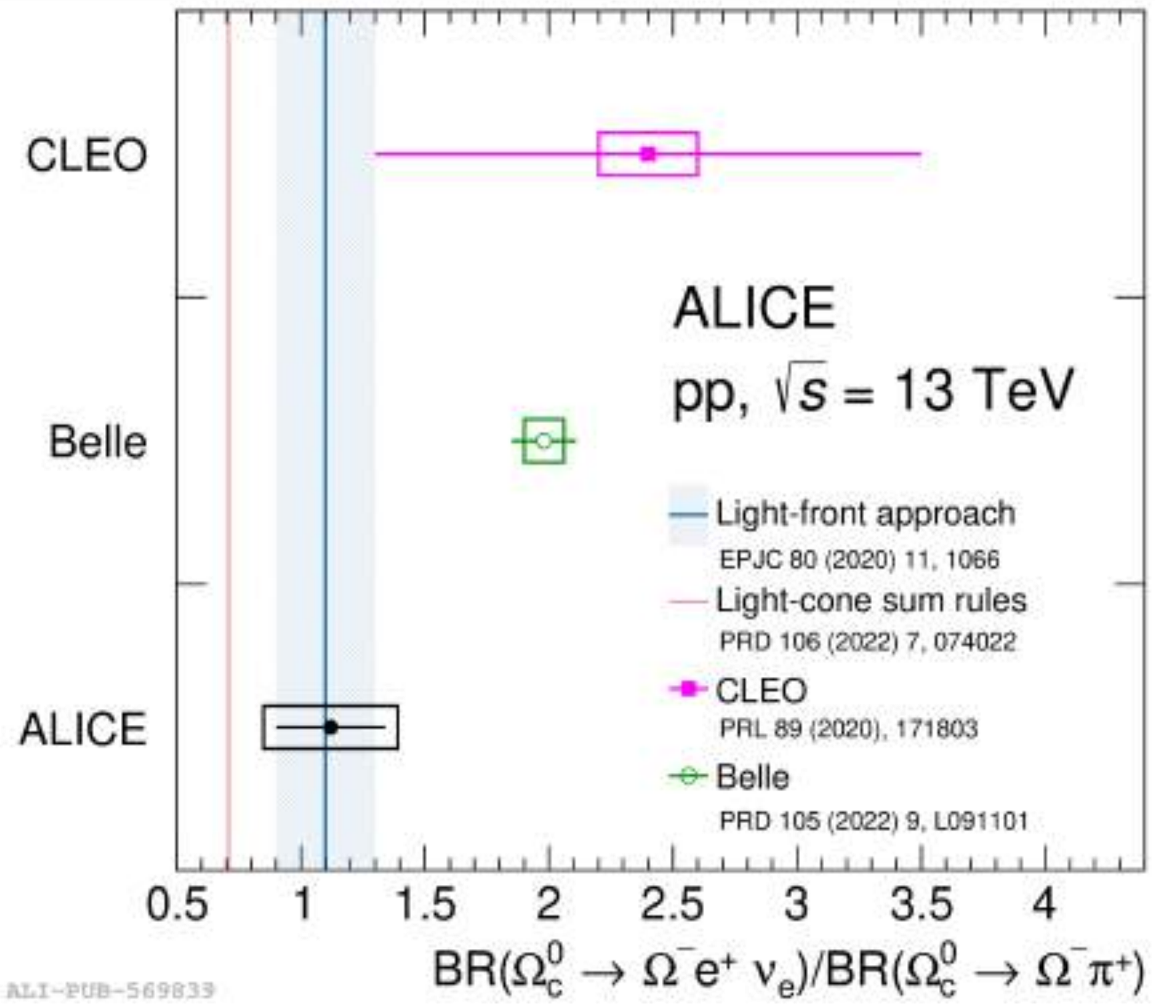
charm hadronization not universal

$\sigma_{c\bar{c}}$ **experimental precision** much **better** than **theory**

→ calls for N^3LO calculations

arXiv:2308.04877

BRANCHING RATIOS - $\Omega_c, |css\rangle$



branching ratios

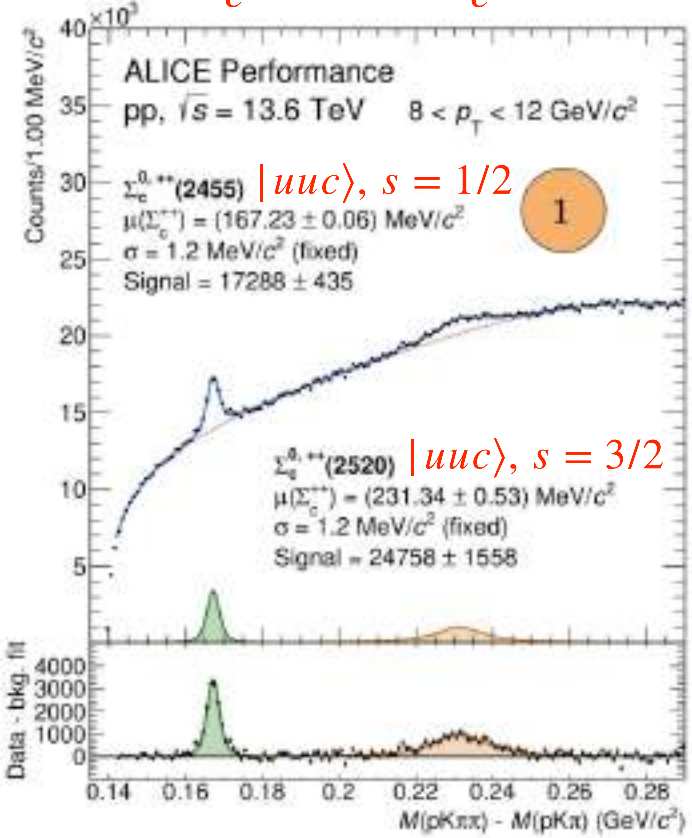
- check lepton universality
- essential for determining total charm production
- challenge to theory

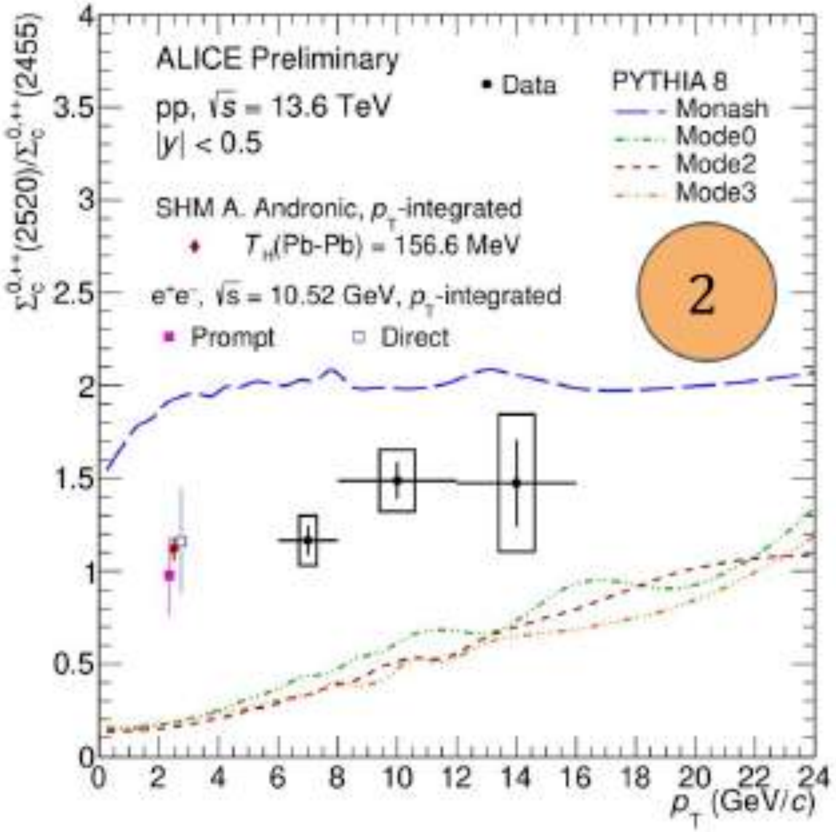
$\Xi_c^0 \to \Xi^- + \pi^+$, Federica Zanone, Tue. 16h39

arXiv:2404.17272

Σc0,++(2520)/Σc0,++(2455) in pp @ 13.6 TeV

$$\Sigma_c^{0,++} \rightarrow \Lambda_c^+ \pi^\mp$$

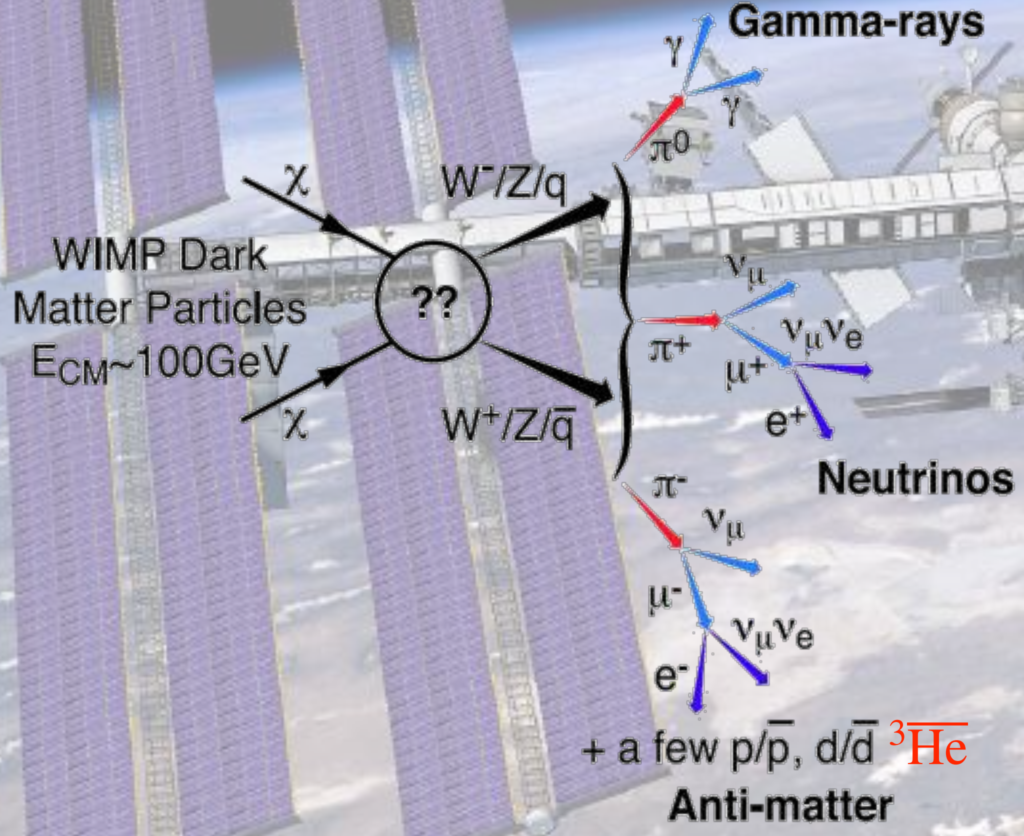




→ **Resonances** of **charmed baryons** might play an important role in the **baryon enhancement** discussion

→ **Run 3: Large pp data** set now allows to address this. **PYTHIA does not** describe the data in **contrast** to **SHM**.

DARK MATTER SEARCH – NEUTRALINO ANNIHILATION



Lightest **super-symmetric particle** is **dark matter candidate**

AMS-02@ISS is looking for $\chi\chi$ **annihilation**

Produces **(anti)-deuterons,** $^3\overline{He}$

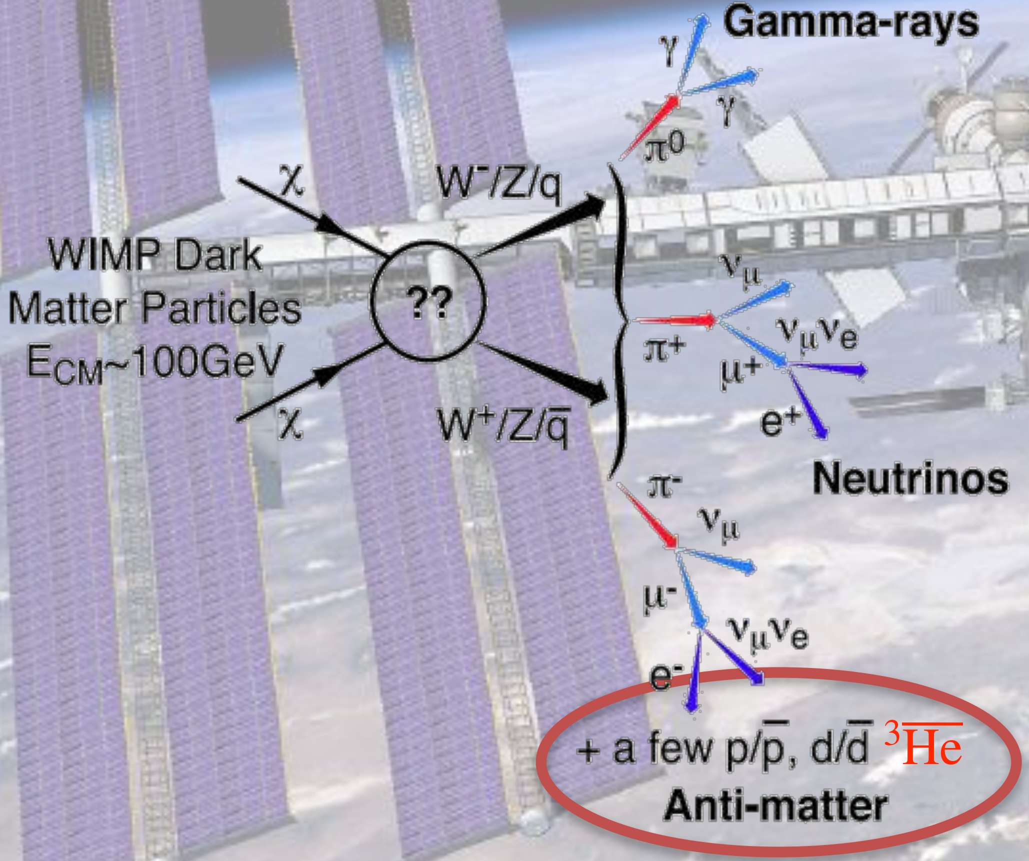
→ need to know **transparency** of **galaxy**

Cosmic protons + H (inter stellar medium)

→ $^3\overline{He}$ is irreducible **background**

→ **ALICE measures** this **background** in similar kinematic range!

DARK MATTER SEARCH – NEUTRALINO ANNIHILATION



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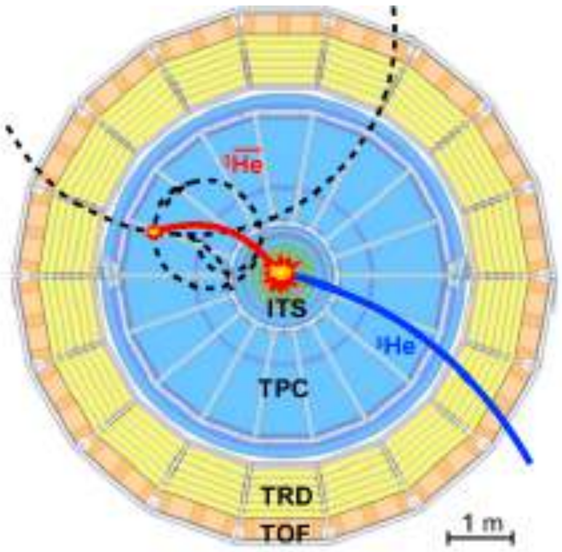
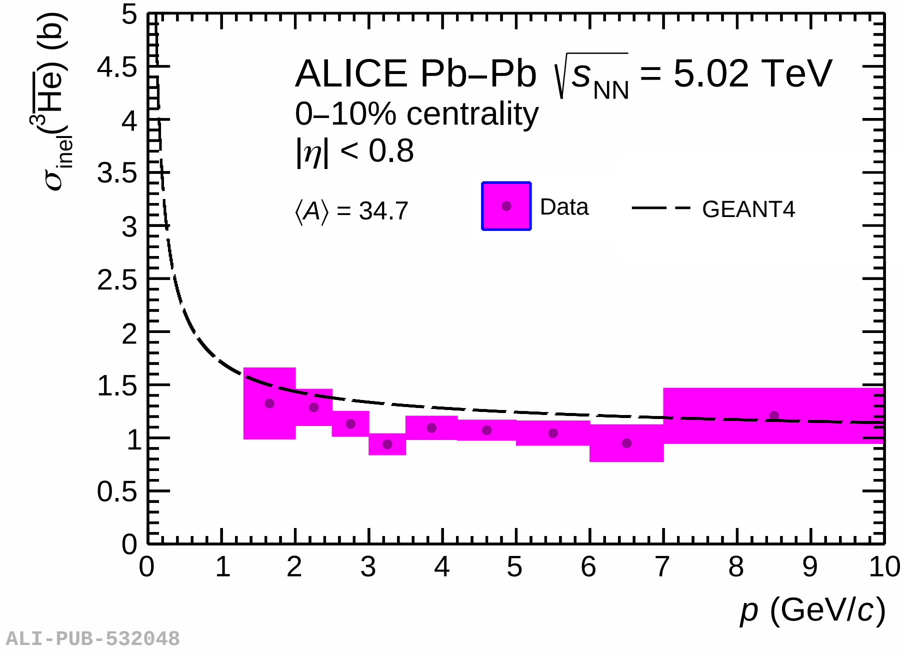
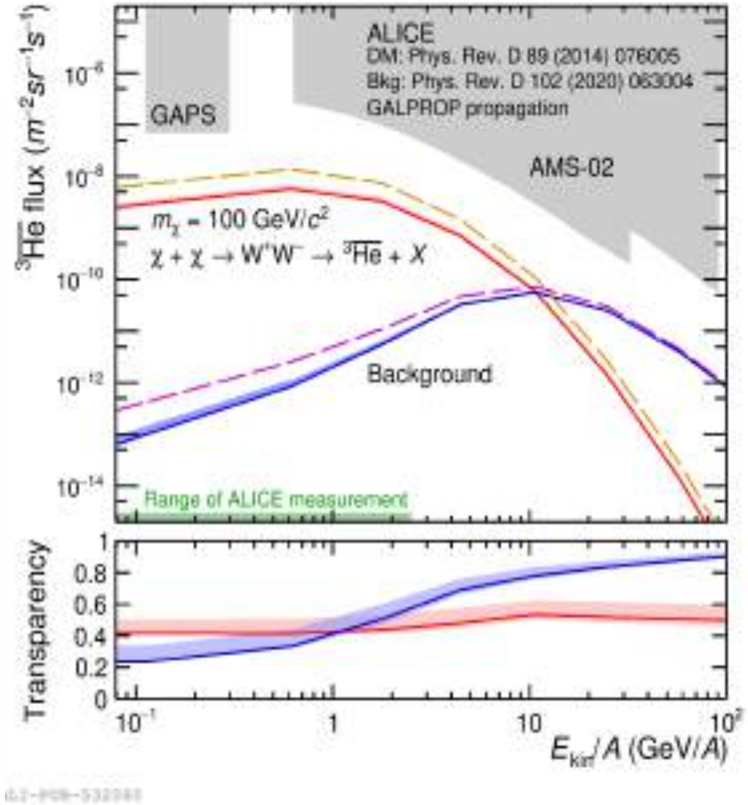
$^{3}\overline{\mathrm{He}}$ inelastic cross section

Nature Physics, volume 19, pages 61–71 (2023)







tag & probe $^{3}\overline{\mathrm{He}}$ nuclei:
detect disappearance
in detector material

measure inelastic cross section
over large momentum range

possible astrophysical source:
dark matter annihilation,
predicted flux depends on
disappearance in interstellar gas

to collide or not to collide ?

ALICE

collider*

$$s = (P_1 + P_2)^2 = P_1^2 + P_2^2 + 2P_1 \cdot P_2$$
$$= m_1^2 + m_2^2 + 2(E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2)$$
$$= 2(E_1E_2 + E_1E_2)$$
$$= 4E^2$$
$$\sqrt{s} = 2E$$
$$\text{at LHC} : \sqrt{s} = 2 \cdot 6.8\,\text{TeV} = 2 \cdot 13.6\,\text{TeV}$$

fixed-target

$$s = (P_1 + P_2)^2 = P_1^2 + P_2^2 + 2P_1 \cdot P_2$$
$$= m_1^2 + m_2^2 + 2(E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2)$$
$$= 2(E_1m_2 - 2\vec{p}_1 \cdot 0)$$
$$= 2E_1m_2$$

cosmic ray on proton at rest :

$$E_1 = s/(2m_2) \approx 10^{17}\,\text{eV}$$

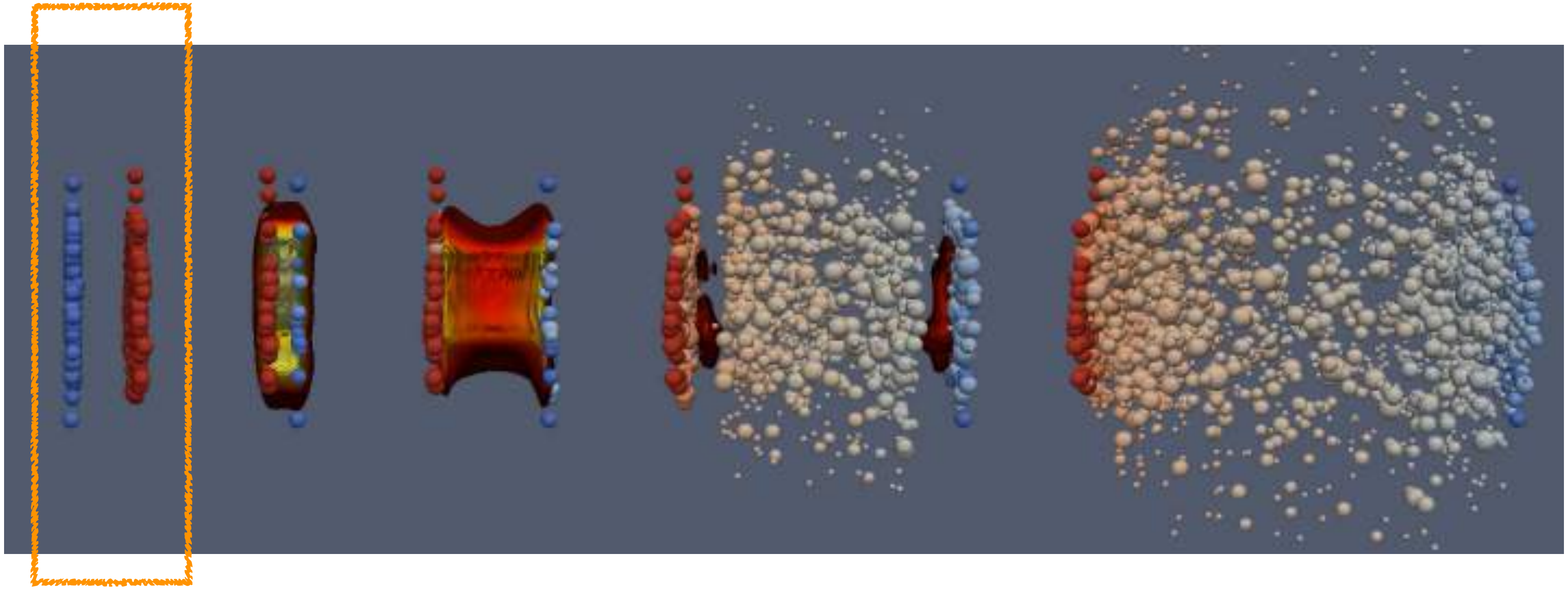
At **LHC**, **pp** collisions at $\sqrt{s}$ **= 13.6 TeV** resemble

high-energy cosmic ray **protons** (10^{19} eV) hitting **protons** (at rest) from the **insterstellar medium** in

fixed-target configuration.

*neglect particle masses, assume symmetric beams

CAN WE PROBE THE INITIAL STATE OF PB?



Probing the initial stage

Gluon-dominated

Color Glass Condensate?

Ultra-peripheral collisions - QED processes

$Z\alpha_{em} \approx 1$

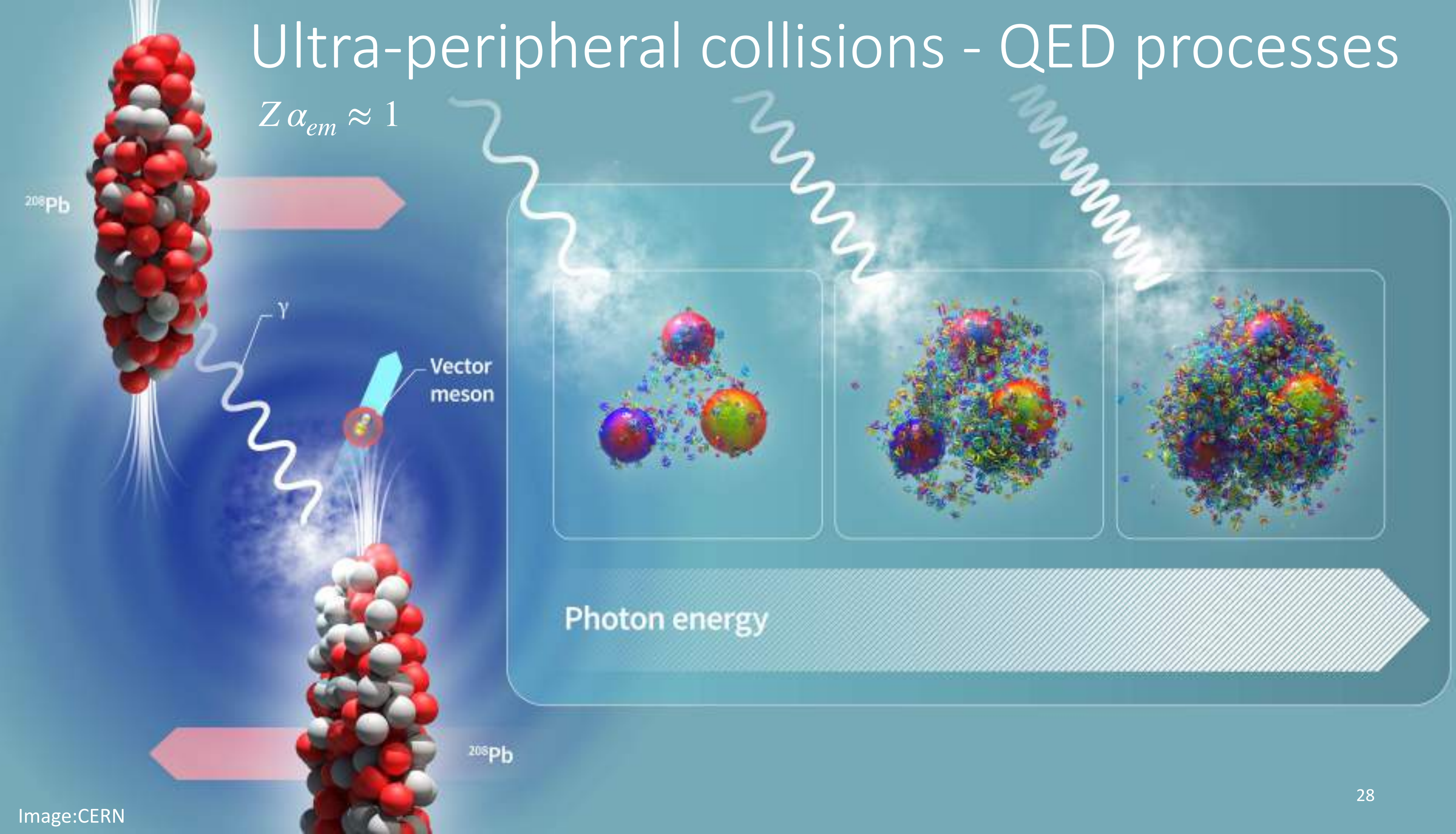
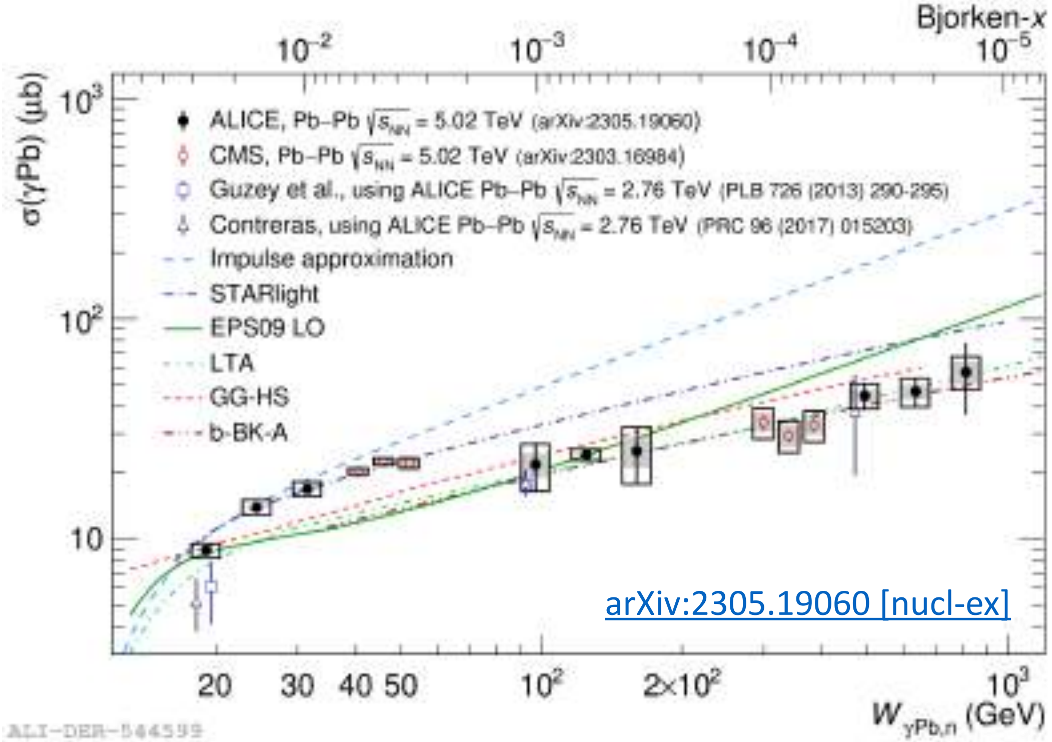


Image:CERN

(IN)COHERENT J/ψ PHOTOPRODUCTION

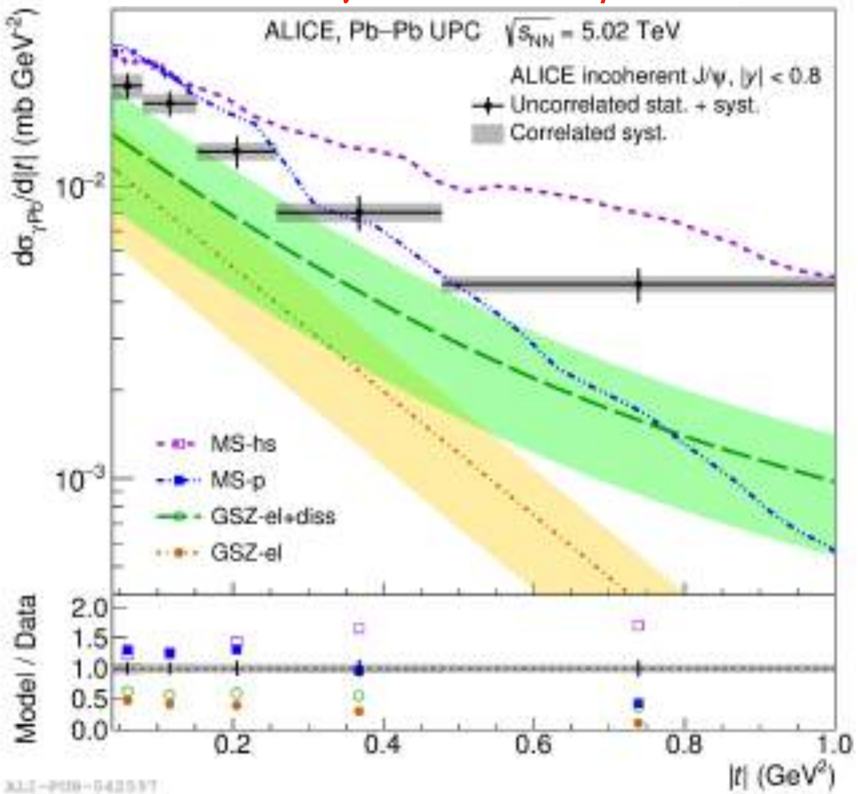
ALICE

Coherent $\gamma + \mathrm{Pb} \rightarrow \mathrm{J}/\psi + \mathrm{Pb}$



arXiv:2305.06169 [nucl-ex]

Incoherent $\gamma + \mathrm{Pb} \rightarrow \mathrm{J}/\psi + \mathrm{Pb}$



$\sigma(\gamma\mathrm{Pb})$ **sensitive** to **gluon distribution** inside nuclei

Clear **suppression** wrt **impulse approximation**

Results consistent with **gluon-saturation** models

→ constrain gluon density down to x ~ 10^{-5}

Models including scattering structures at a sub-nucleon scale (large $|t|$) provide a better description of the data including **large fluctuations of spatial distribution**, "gluonic hotspots"

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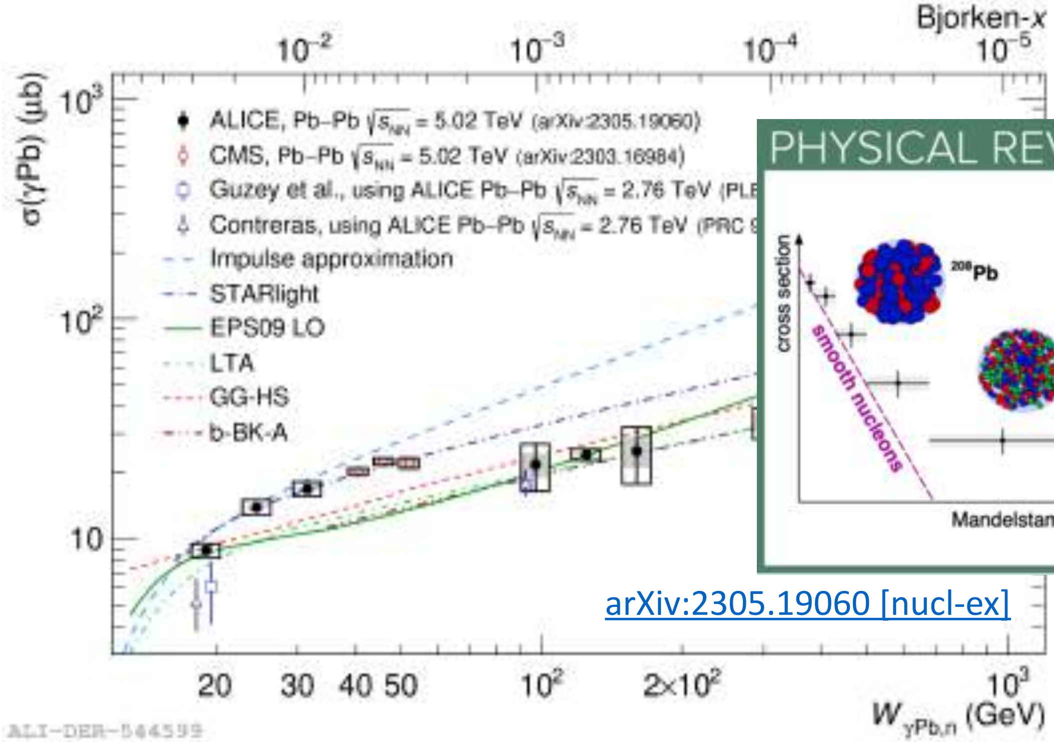
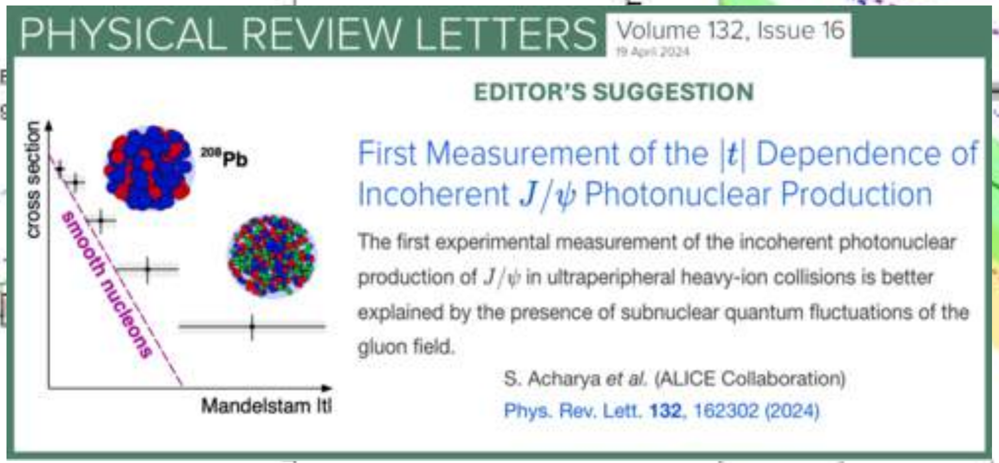
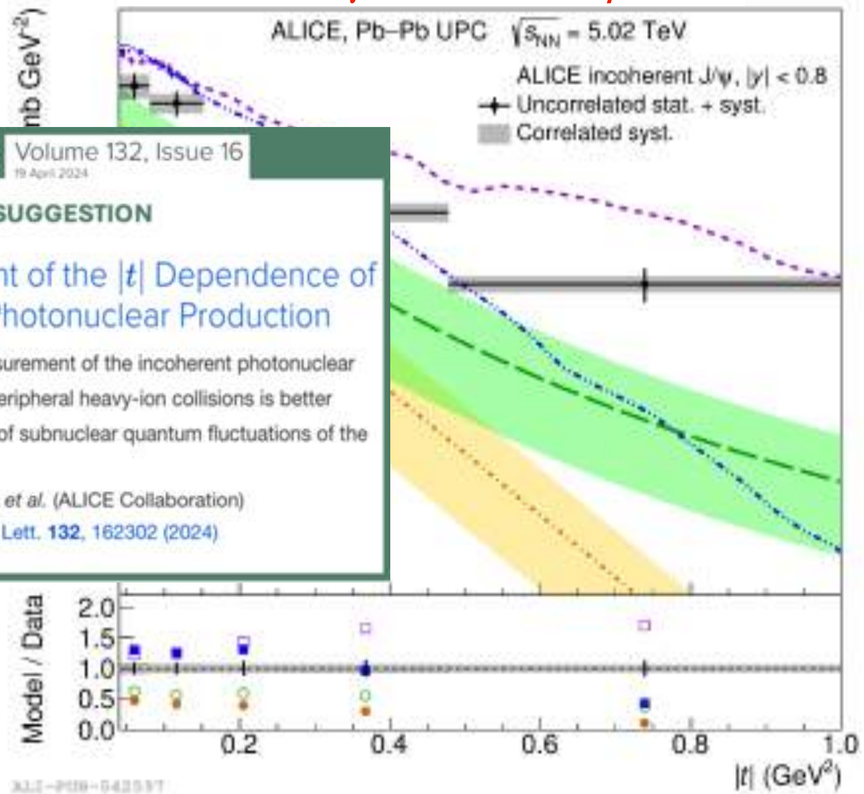


arXiv:2305.19060 [nucl-ex]





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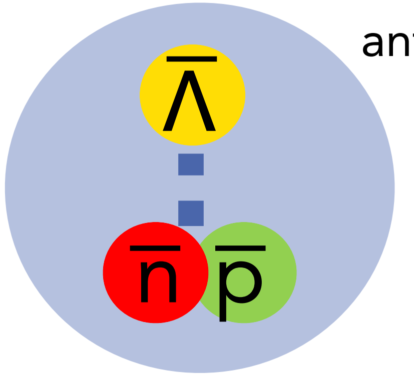
ALICE

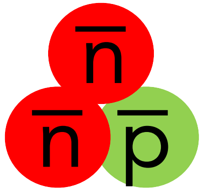
Results from Run 3: pp collisions at 13.6 TeV

Hypertriton in pp at 13.6 TeV (1)

anti-hyper-triton

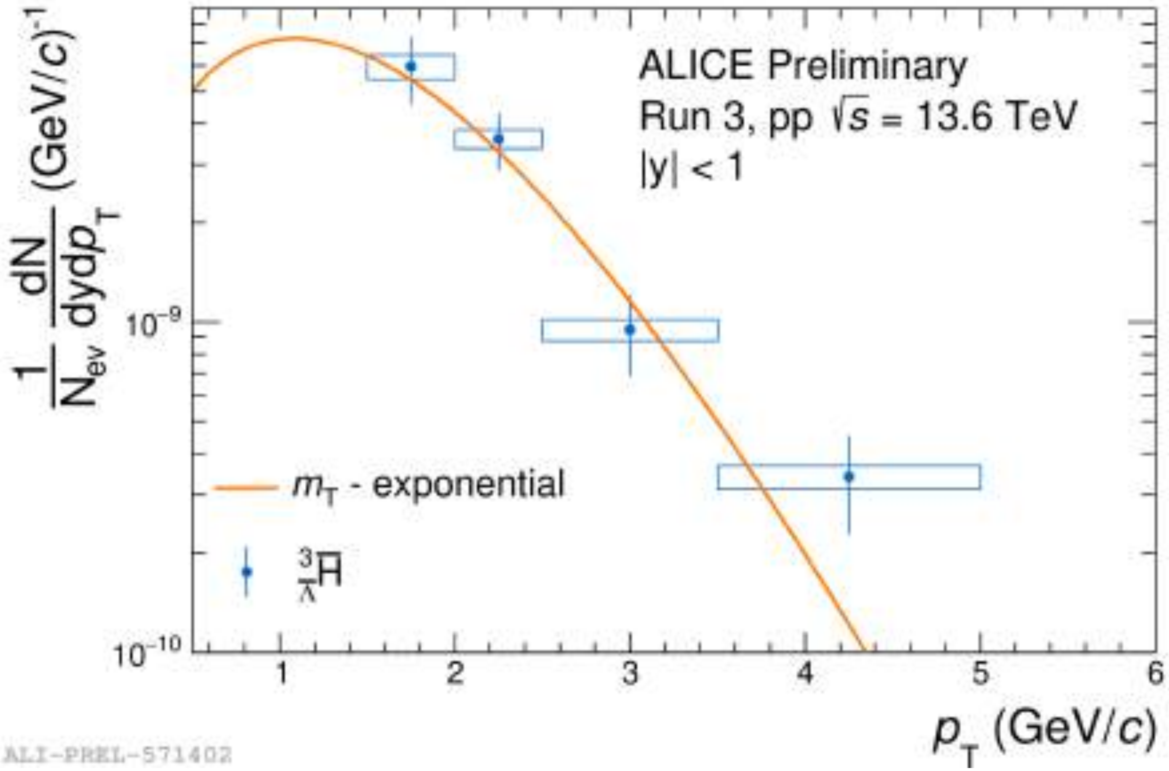


anti-triton

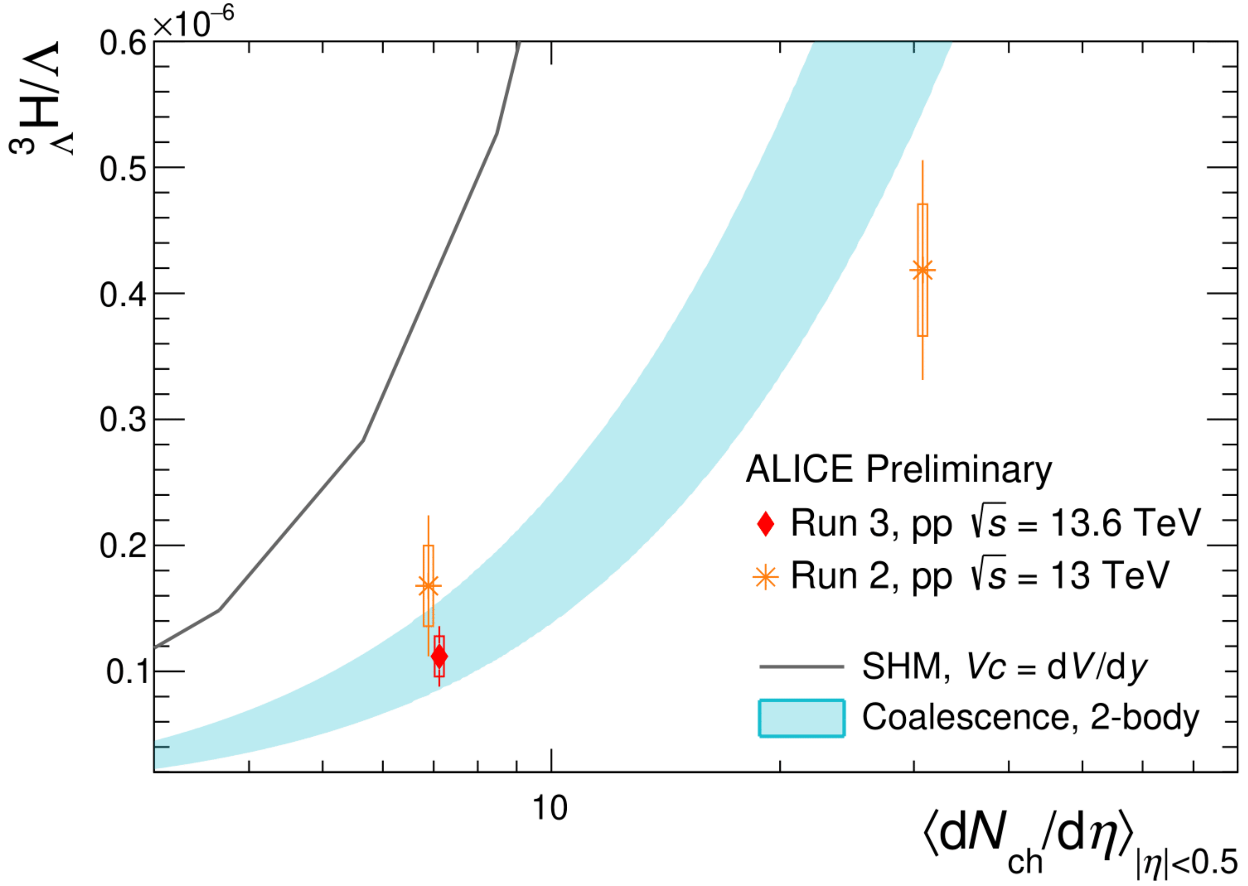


- First **p_T -differential** measurement of the **hypertriton** production in **pp collisions**
- Already now **challenging** the **precision** of the **Run 2** measurement.
- Favours coalescence model versus SHM production in pp collisions.

$$ {}^{3}_{\Lambda}\overline{\mathrm{H}} \rightarrow {}^{3}\overline{\mathrm{He}} + \pi^{+} $$



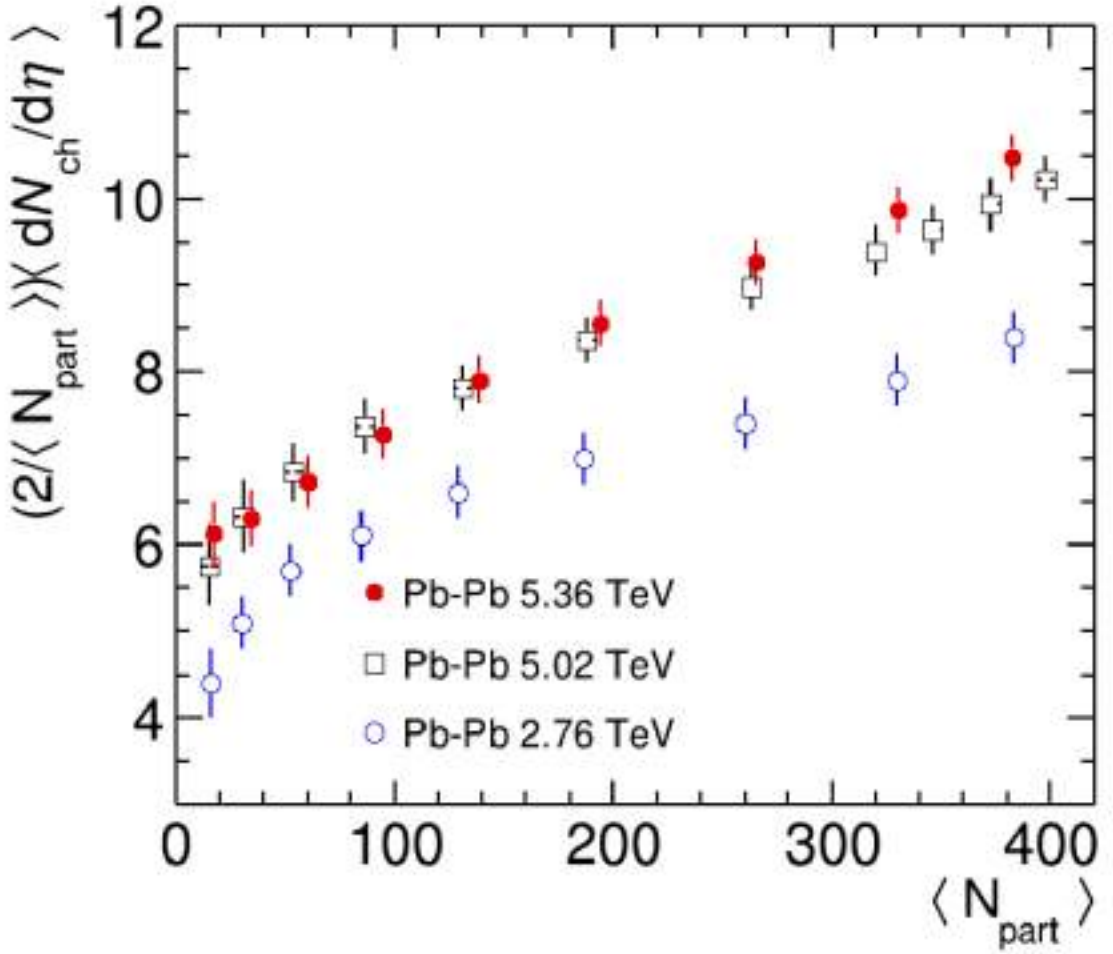
Hypertriton in pp at 13.6 TeV (2)

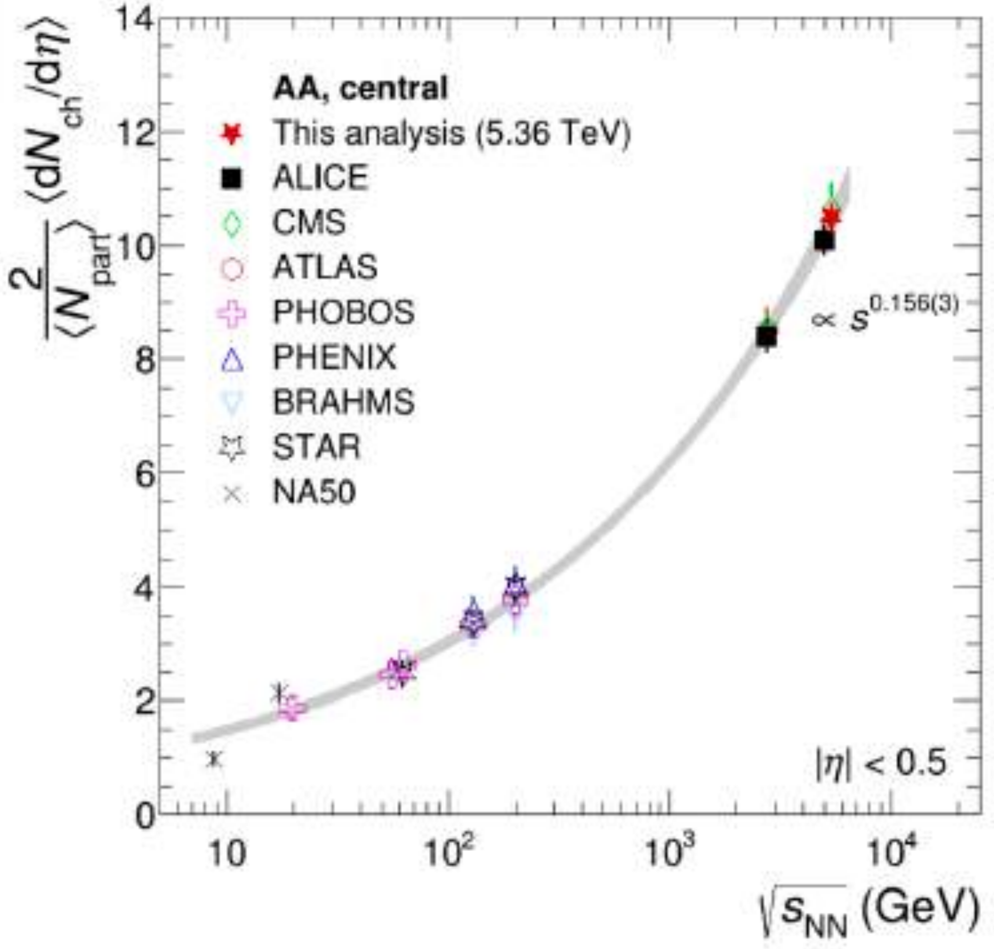


- First p_T -differential measurement of the hypertriton production in pp collisions
- Already now **challenging** the **precision** of the **Run 2** measurement.
- **Favours coalescence** model **versus SHM** production in **pp collisions**.

First results from Run 3: Pb-Pb collisions at 5.36 TeV

Charged-particle dN/dη

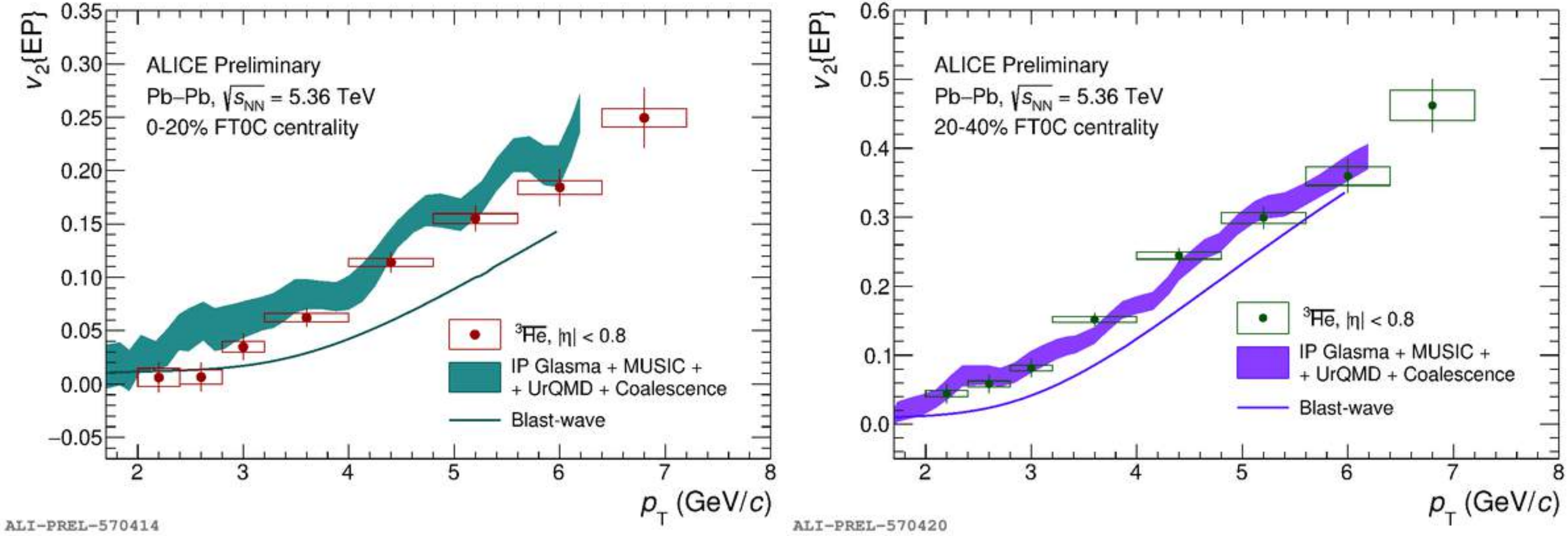




Important **baseline measurement** is in **agreement** with lower energy data

This gives us **confidence** in many basic calibrations, in particular **centrality calibration**

Elliptic flow of antinuclei - $^{3}\overline{\mathrm{He}}$



High statistics measurement of anti-nuclei **supersedes** precision of **Run 2** measurement

Data favours state-of-the-art coalescence models and disfavours blast-wave expectation

Only the high statistics Run 3 analysis now allows distinguishing these two models

ALICE 3 DETECTOR

ALICE

high-efficiency for heavy-quark identification and reconstruction of low-mass dielectrons e.g. **chiral symmetry restoration, proton mass**

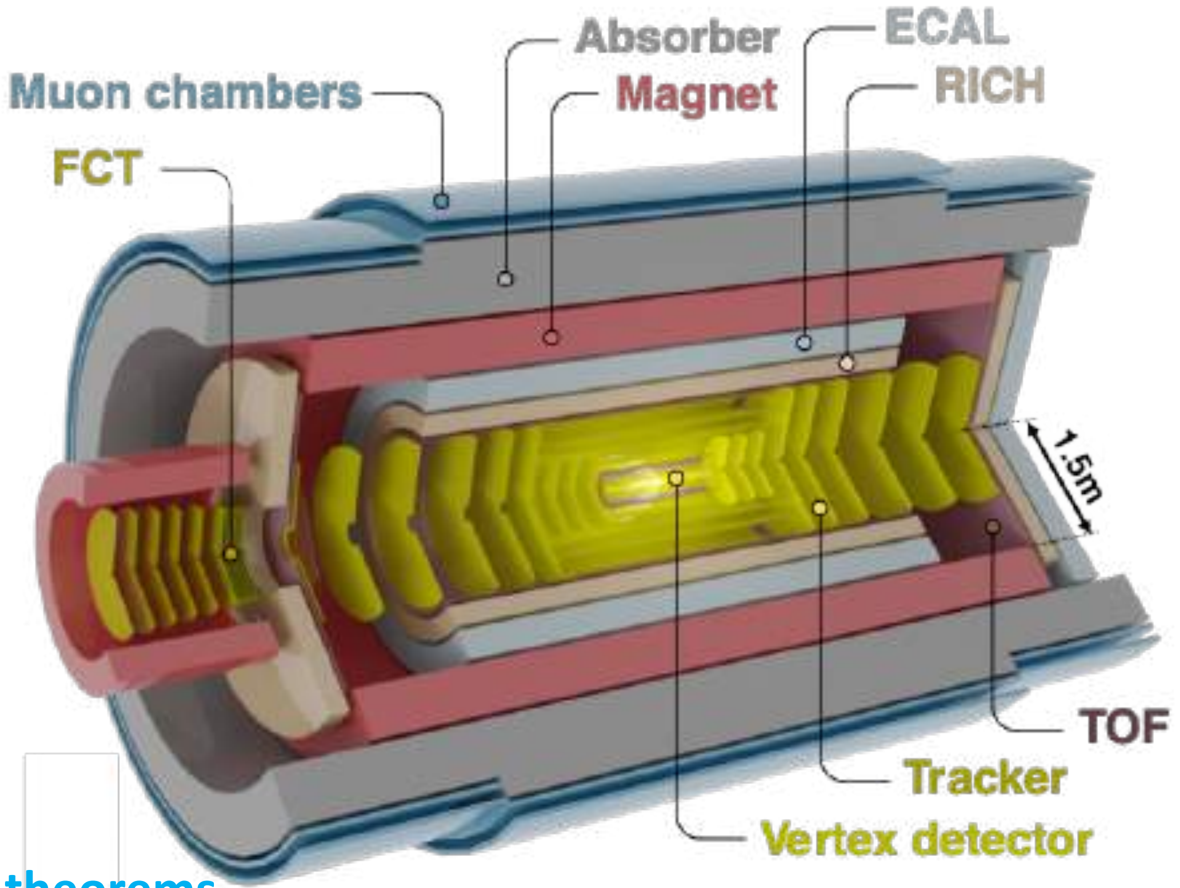
vertexing close to the beam with unprecedentedly low material budget

large acceptance with excellent coverage down to low p_T

excellent particle ID (muons, electrons, photons, hadrons)

- ➪ **Vertexing precision x 3**: 10μm at p_T = 200 MeV/c
- ➪ **Acceptance x 4.5**: $|\eta| < 4$ (with particle ID)
- ➪ **A-A rate x 5 (pp x 25)**

Forward conversion tracker (FCT) : **ultrasoft photons, soft theorems**



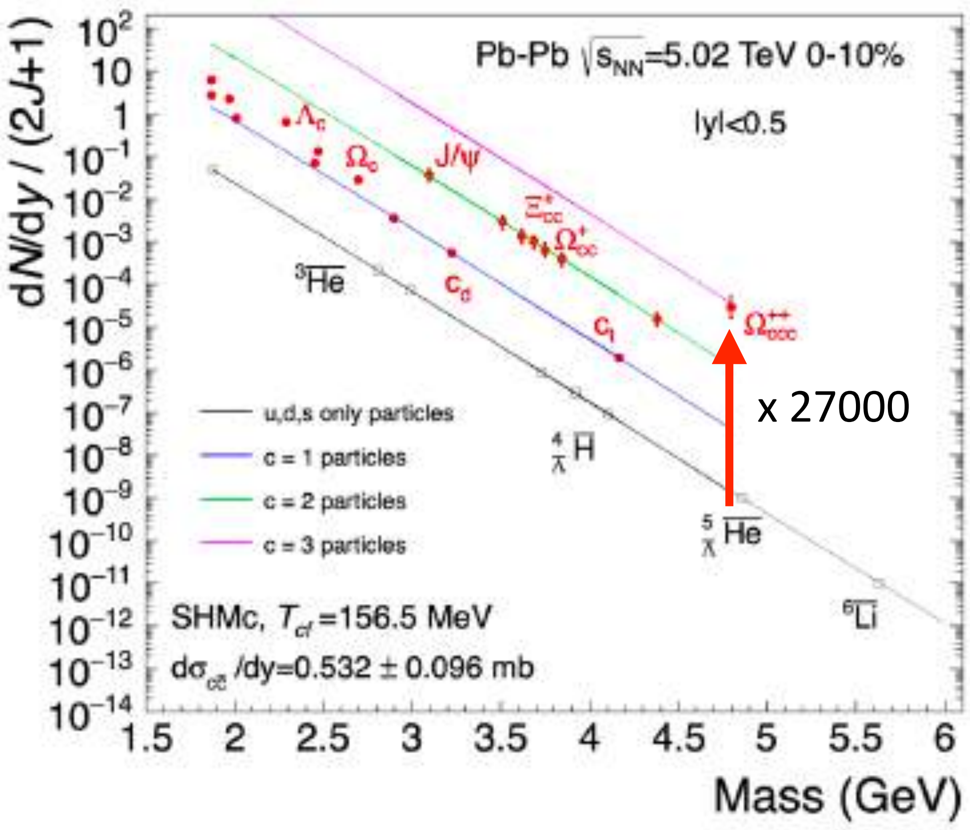
➪ **novel technologies relevant for future HEP and NP programs**

ACCEPTANCE × INTERACTION RATE: NEW OPPORTUNITIES

ALICE

Multiply-charmed baryons

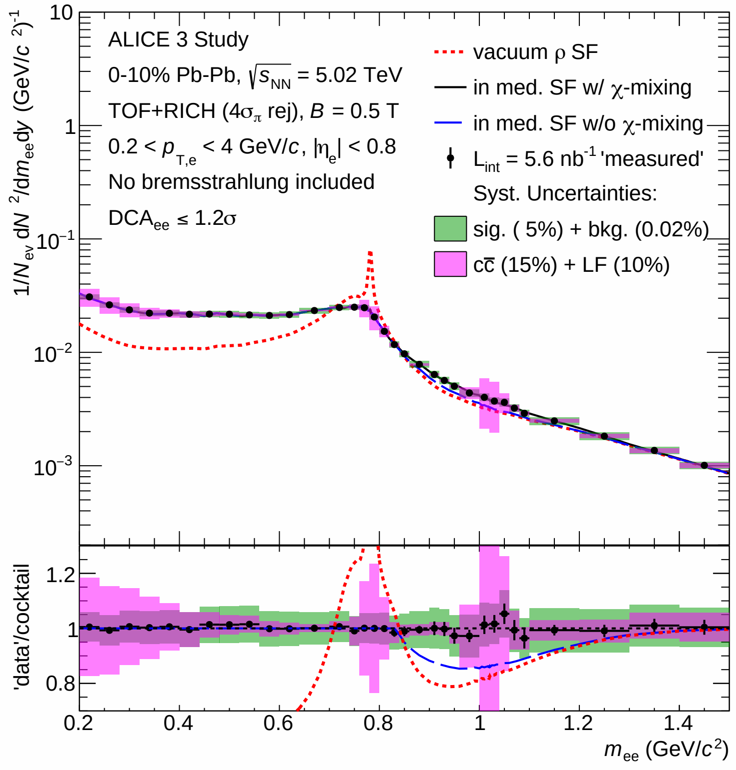
CERN-LHCC-2022-009



→ **charm oversaturated** through direct production

→ **factor 30** per **charm quark**, discovery potential

access $\rho - a_1$ mixing



chiral symmetry restored in quark-gluon plasma

→ explain **origin** of **99%** of **visible mass** in universe

CONCLUSIONS

- ALICE has a **broad physics** program adressing **non-perturbative QCD** and **high-field QED** in **pp**, **p-Pb** and **Pb-Pb** collisions at the LHC
- ALICE is **successfully recording** data in **Run 3** with the **upgrades**
- **ALICE 3** upgrade provides **long-term** continuation during **entire LHC operation**

backup

TIME PROJECTION CHAMBER

volume 95 m3

biggest TPC ever

3-d camera

voxel precision better

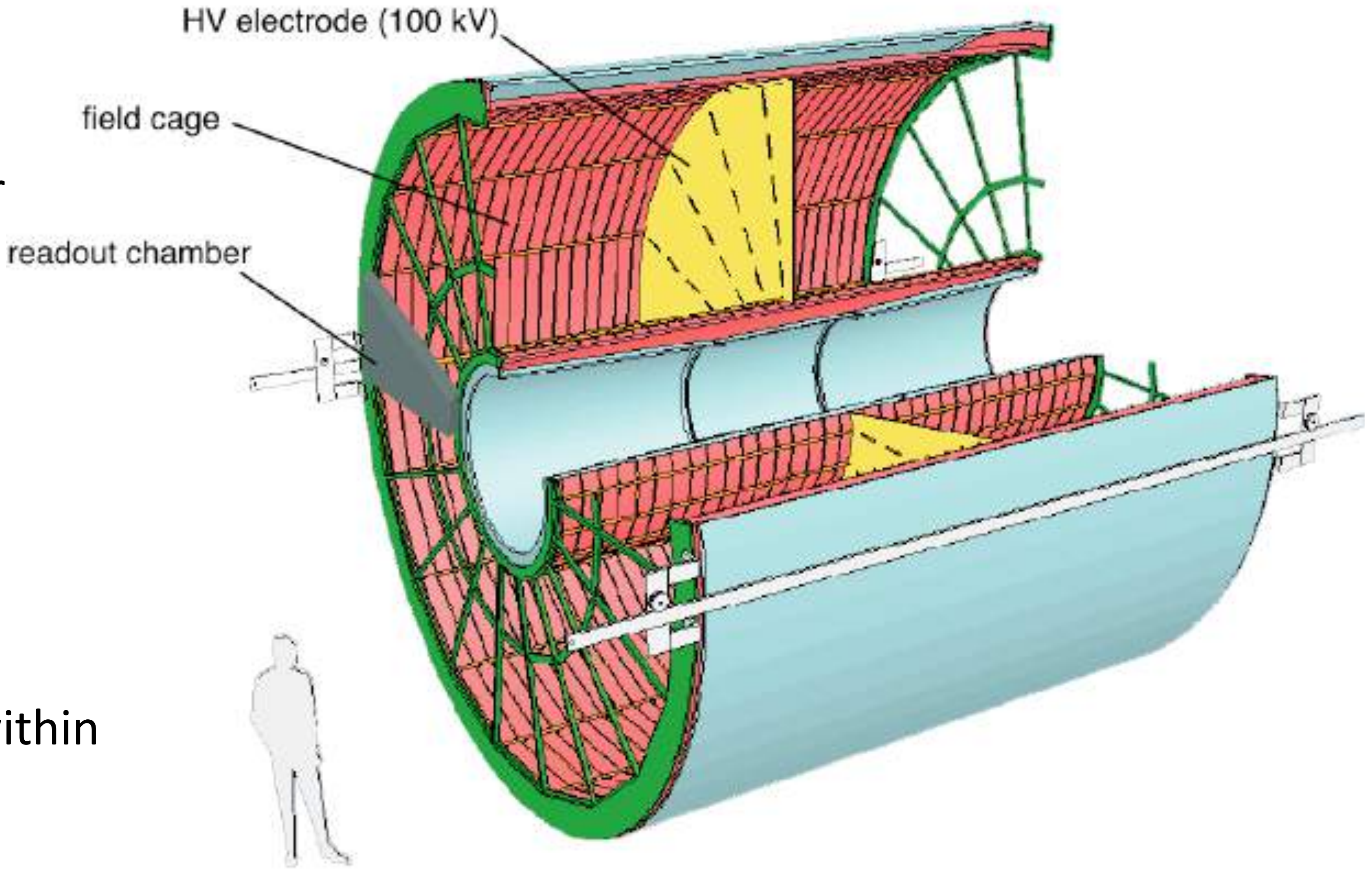
than 500µm

560 million voxels

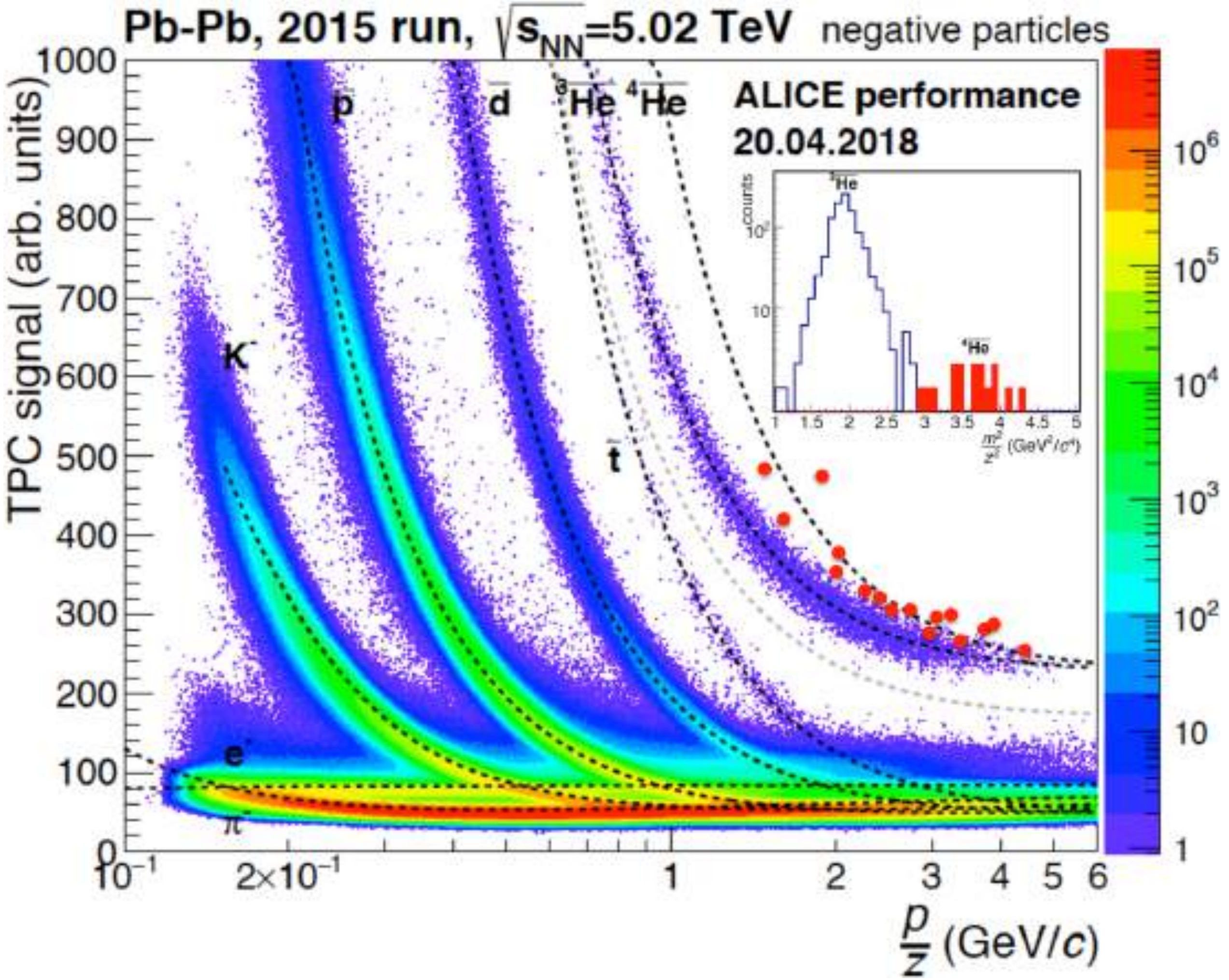
50 0000 pictures

per second

100 billion pictures within
next 10 years



SPECIFIC ENERGY LOSS IN TPC



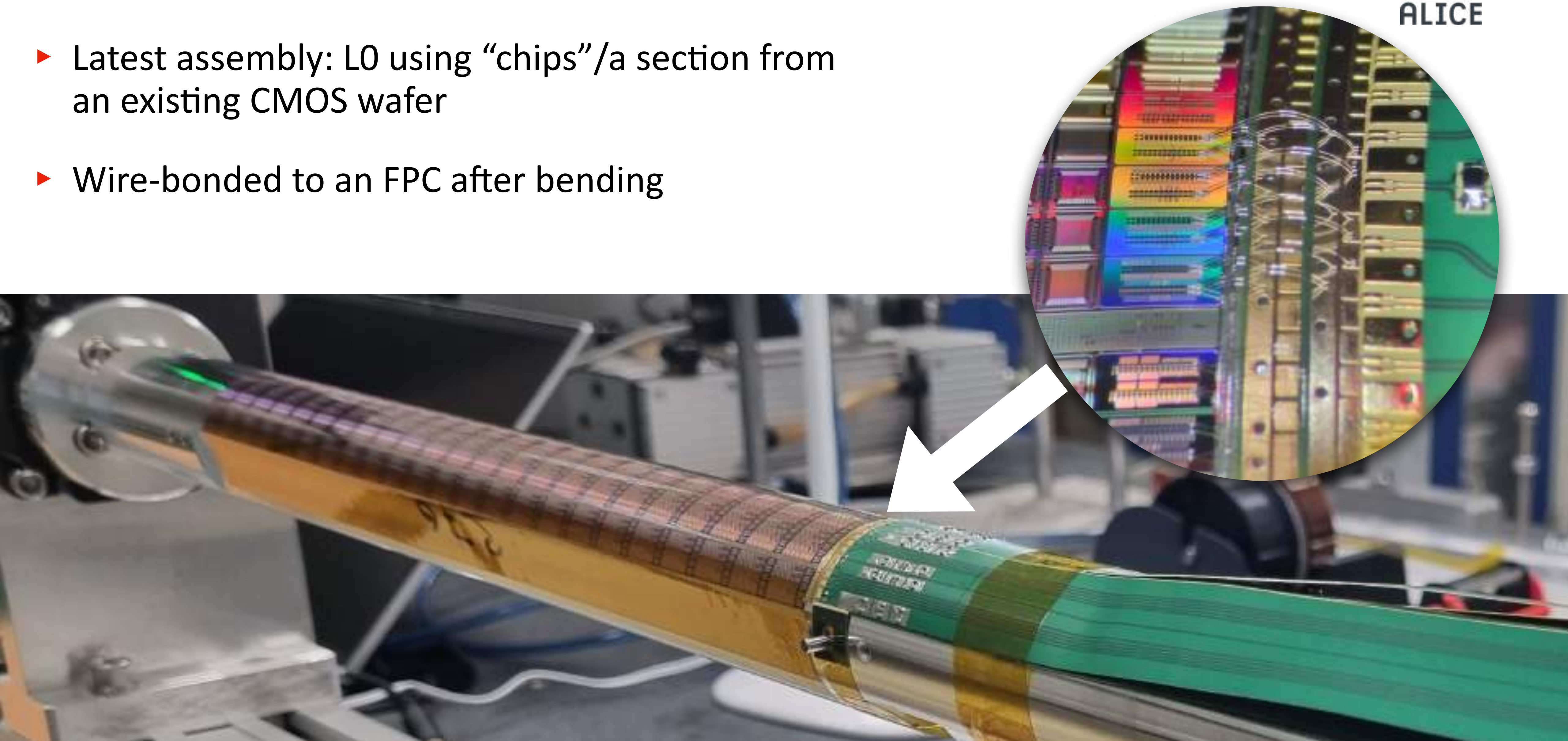
- Specific energy loss in TPC-gas
- Large dynamic range (20 x MIP)
- Low material budget: 0.08 X_0
- When addressing hadronization,

  PID is the only game in town

ITS3: ELECTROMECHANICAL INTEGRATION

ALICE

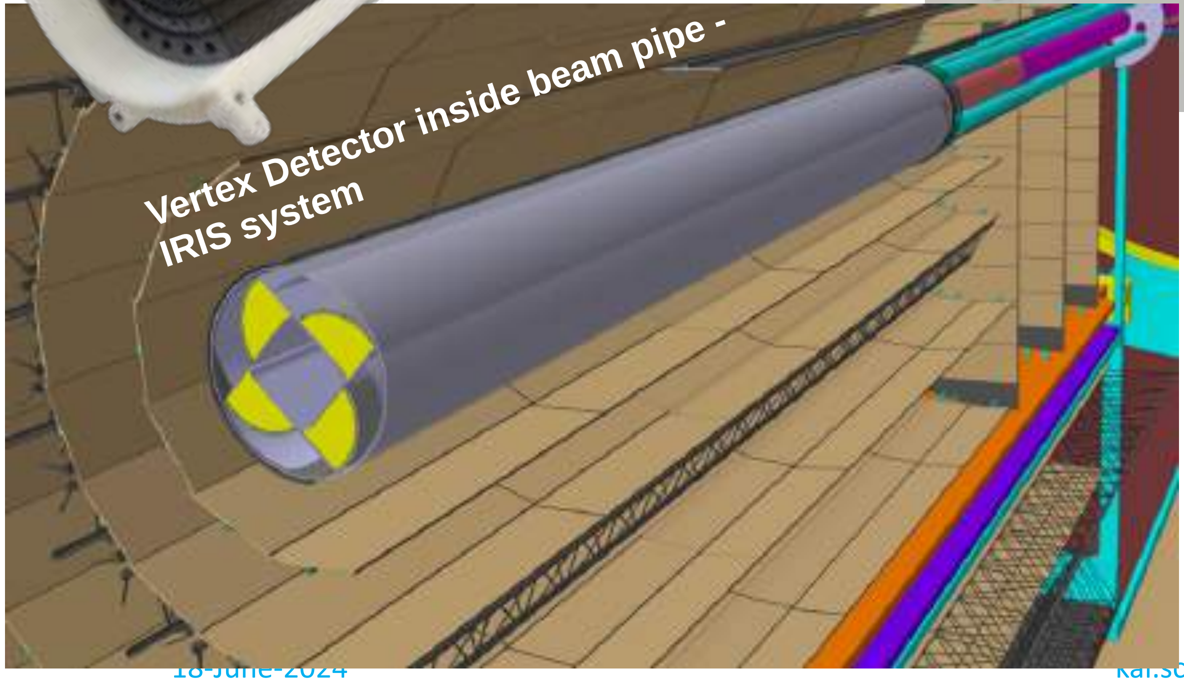
- Latest assembly: L0 using “chips”/a section from an existing CMOS wafer
- Wire-bonded to an FPC after bending



R&D FOR INNER TRACKER

Vertex Detector:
strongly relying on ITS3 R&D (sensor design, stitching, wafer-scale bent sensor)

ITS3 engineering model 2



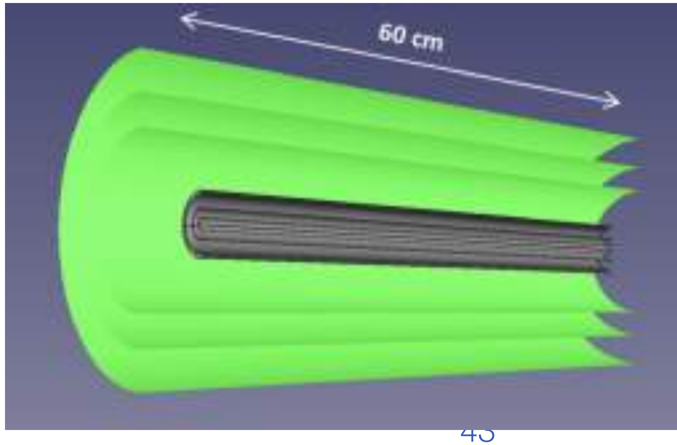
IRIS system:

- services integration being detailed
- study of protection between primary and secondary vacuum
- impact of vacuum on components, wire bonding, glued parts

Middle Layers:

- studying various options for ultra-light layers, leveraging on ITS3 technology
- benefits on tracking of soft electrons and of charged hyperons (Ξ^-, Ω^-)

Option with ultra-light curved sensor layers



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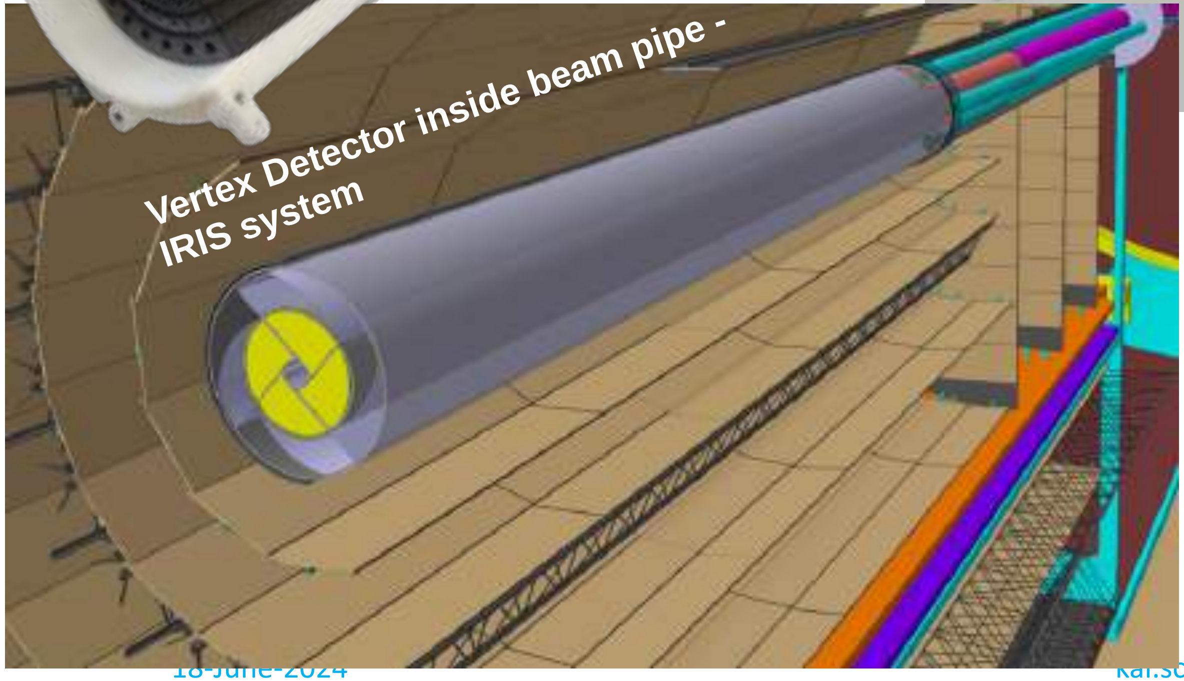

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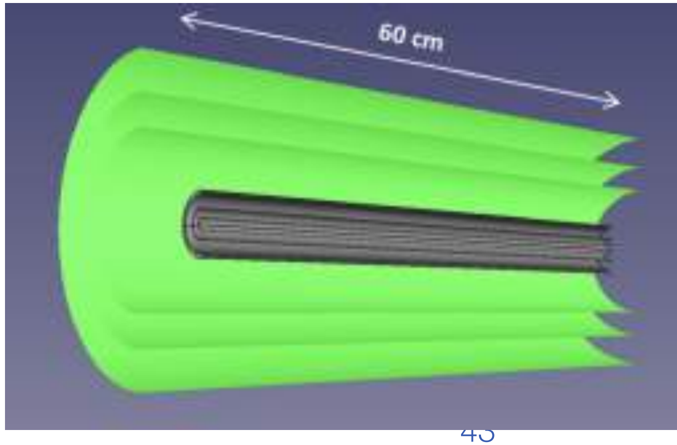
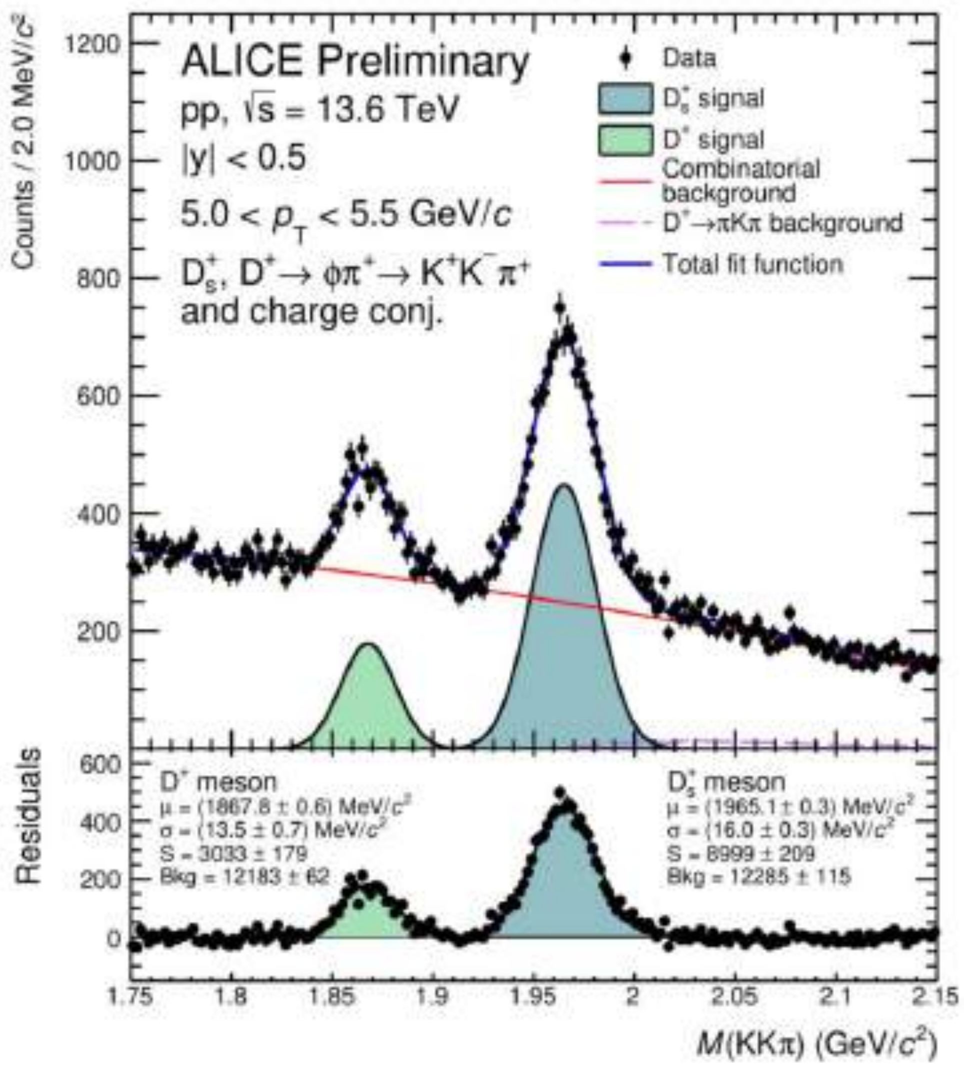


Ds+/D+ ratio in pp (1) - $|c\bar{s}\rangle / |c\bar{d}\rangle$

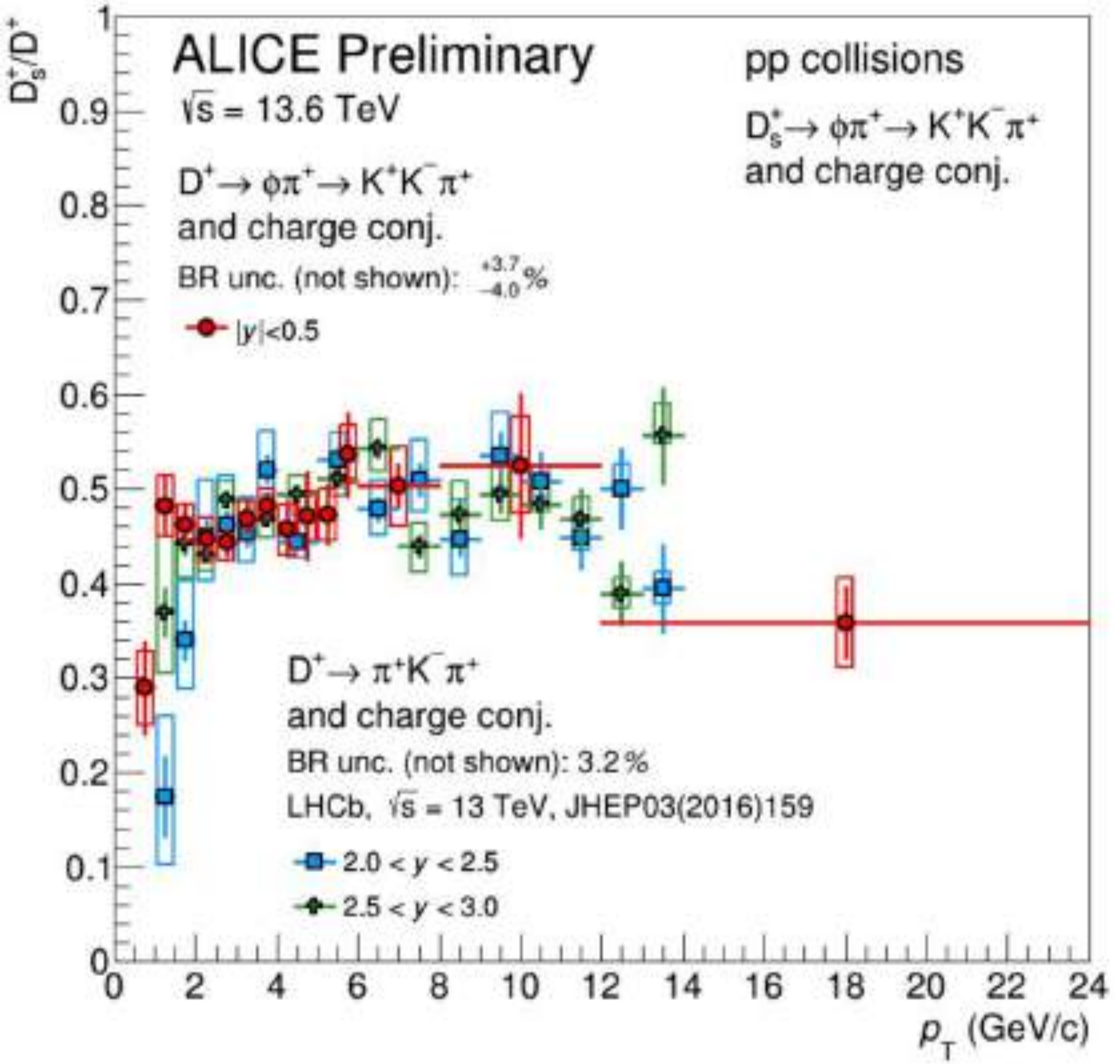


In Run 3, this ratio is measured in the same decay channel.

Overall a good agreement among different energies and with LHCb is observed.

Higher granularity of the measurement thanks to Run 3 larger data sample.

Ds+/D+ ratio in pp (2) - $|c\bar{s}\rangle / |c\bar{d}\rangle$



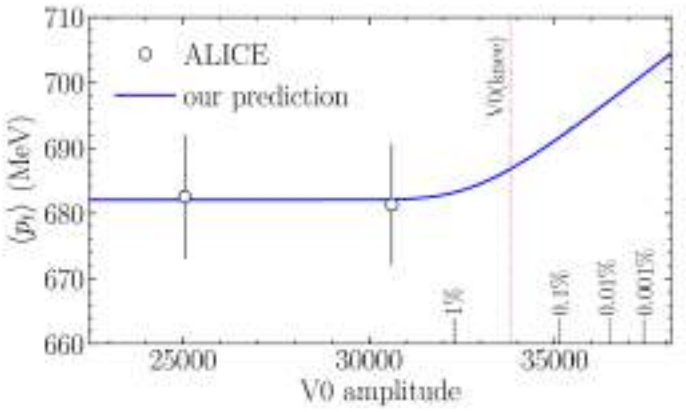
In Run 3, this ratio is measured in the same decay channel.

Overall a good agreement among different energies and with LHCb is observed.

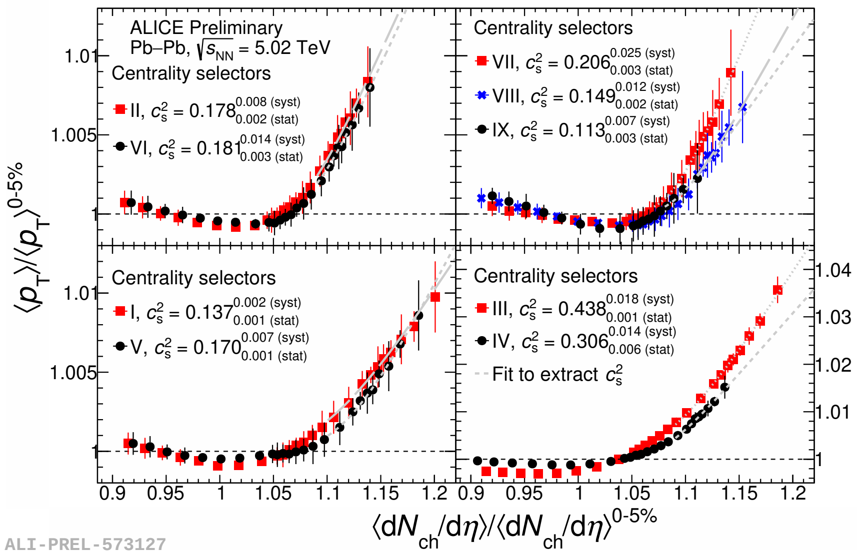
Higher granularity of the measurement thanks to Run 3 larger data sample.

Mean p_T versus multiplicity: speed of sound?

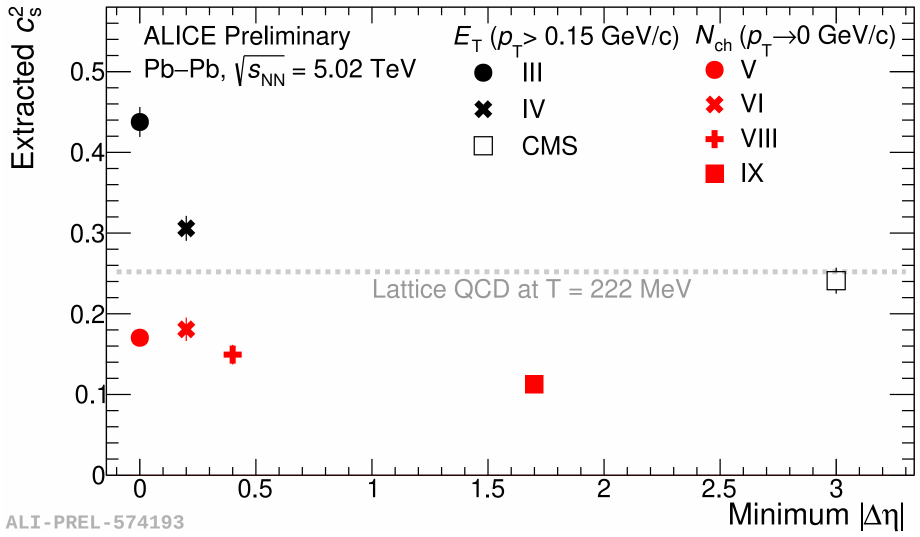
$\langle p_T \rangle$ vs $dN/d\eta$



$\langle p_T \rangle$ vs $dN/d\eta$
different centrality selectors



Extracted speed of sound vs rapidity gap



Idea: ultra-central events increase entropy at constant volume ⇒ measure speed of sounds

F Gardim et al, PLB 809, 135749

$$c_s^2 = \frac{d \ln \langle p_t \rangle}{d \ln N_{ch}}$$

First explored by CMS: arXiv: 2401.06896
ATLAS: ATLAS-CONF-2023-061

Slope of $\langle p_T \rangle$ vs $dN/d\eta$ depends on centrality estimator:
E_T-based selection give larger c_s than multiplicity-based

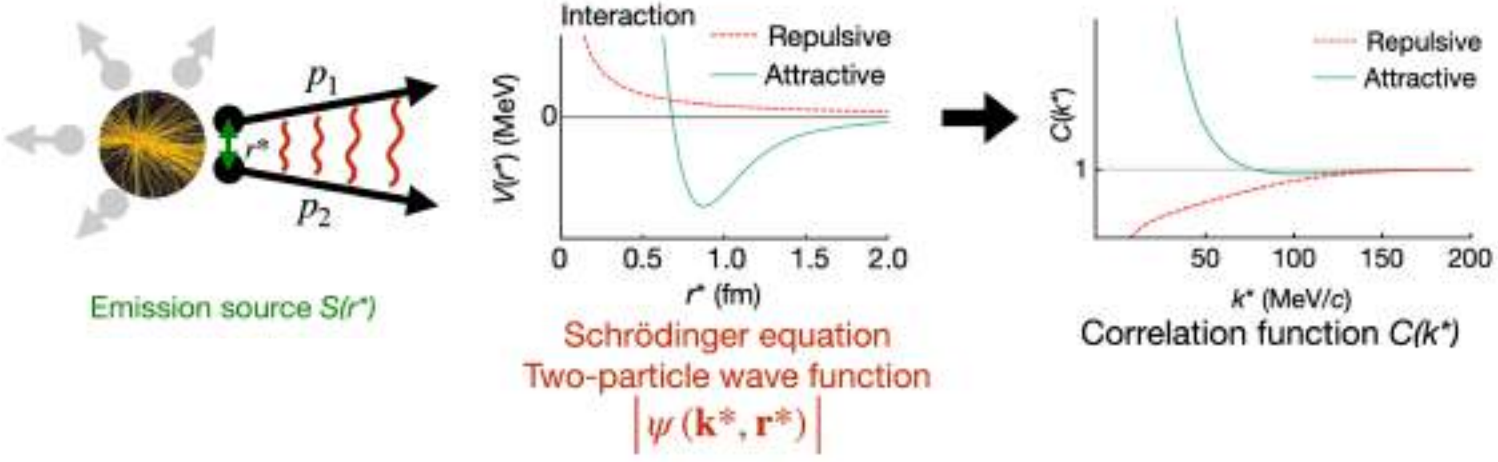
Observable less robust than initially thought?

G Nijs and W van der Schee, PLB 853, 138636

THREE-BODY HADRONIC INTERACTIONS

theory

experiment

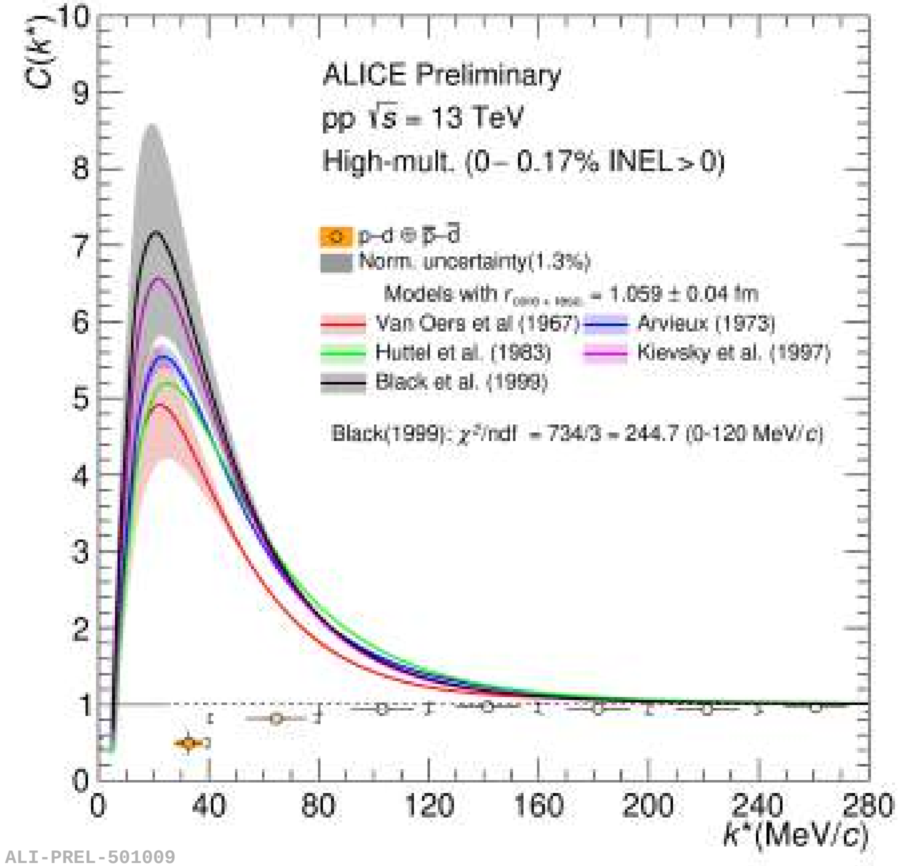


Experiment — Theory

$$C(\vec{k}^*) = \mathcal{N}\frac{N_{\text{same}}^{\text{pairs}}(k^*)}{N_{\text{mixed}}^{\text{pairs}}(k^*)} = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\, d^3r^*$$

k* relative momentum in rest frame

Nature 588, 232–238 (2020)



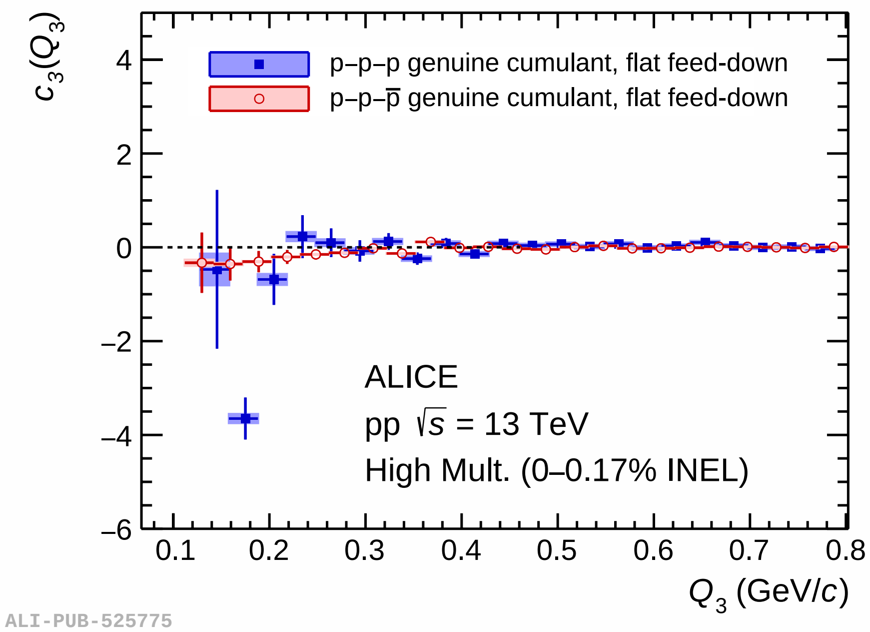
ALI-PREL-501009

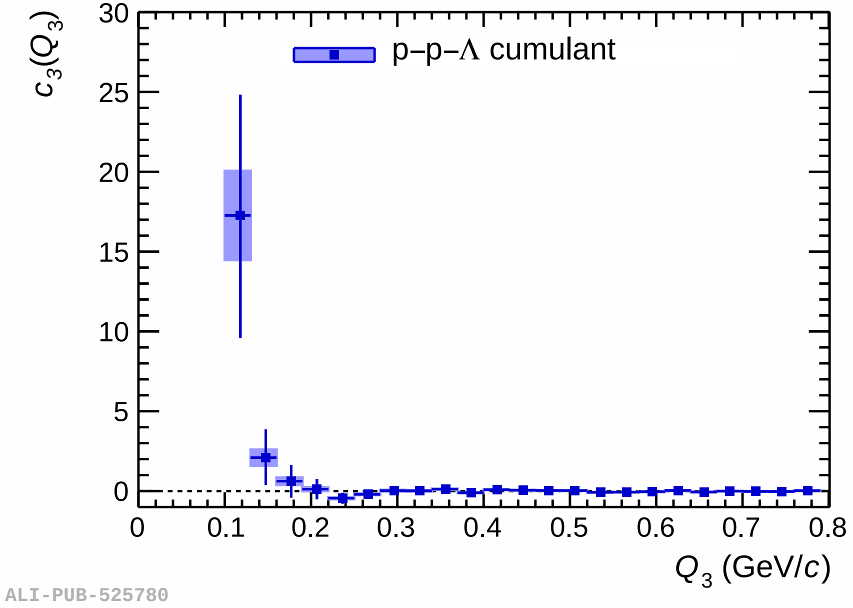
Koonin-Pratt equation, M.Lisa, S. Pratt et al., Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

THREE-PARTICLE CORRELATIONS

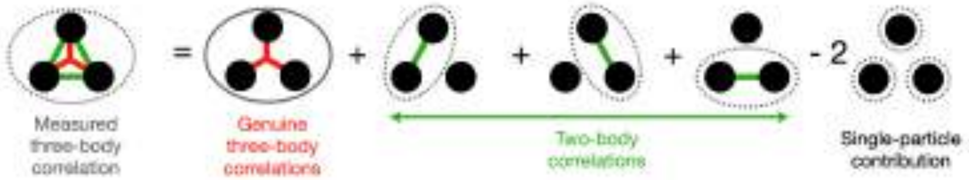
ALICE

Eur. Phys. J. A 59 (2023) 145





Three-body effects extracted using Kubo's cumulant method by subtracting pair-wise interactions →



ppp system: negative three-body correlation (Pauli blocking, 3-body force, Coulomb)

pppbar system: compatible with zero within uncertainties

Stronger constraints on three-body interactions with Run 3 data!