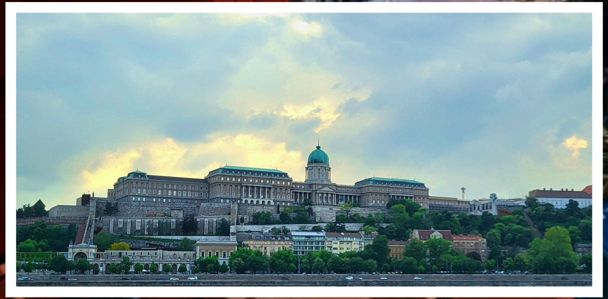
The ALICE Experiment at the LHC

Kai Schweda (GSI, CERN)

Particles & Plasma Symposium 2024

Budapest, Hungary

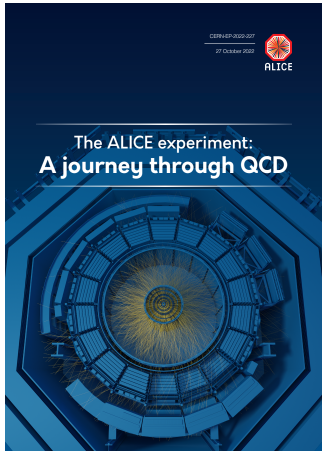


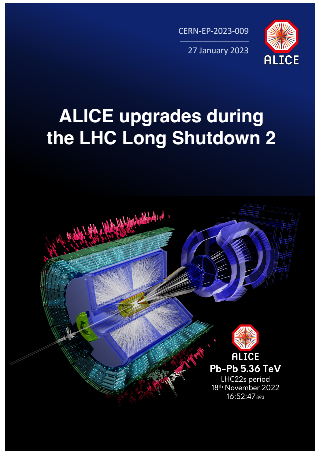
OUTLINE

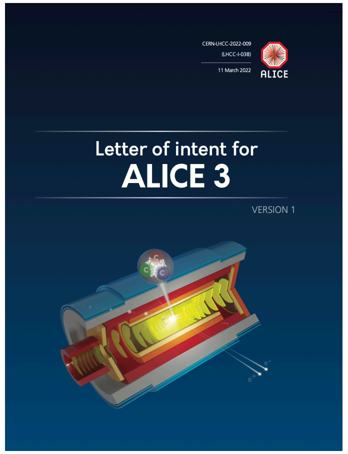
① ALICE 1 (2009 - 2018) — physics harvest

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

③ ALICE 3 (2034 - 2042) — the future



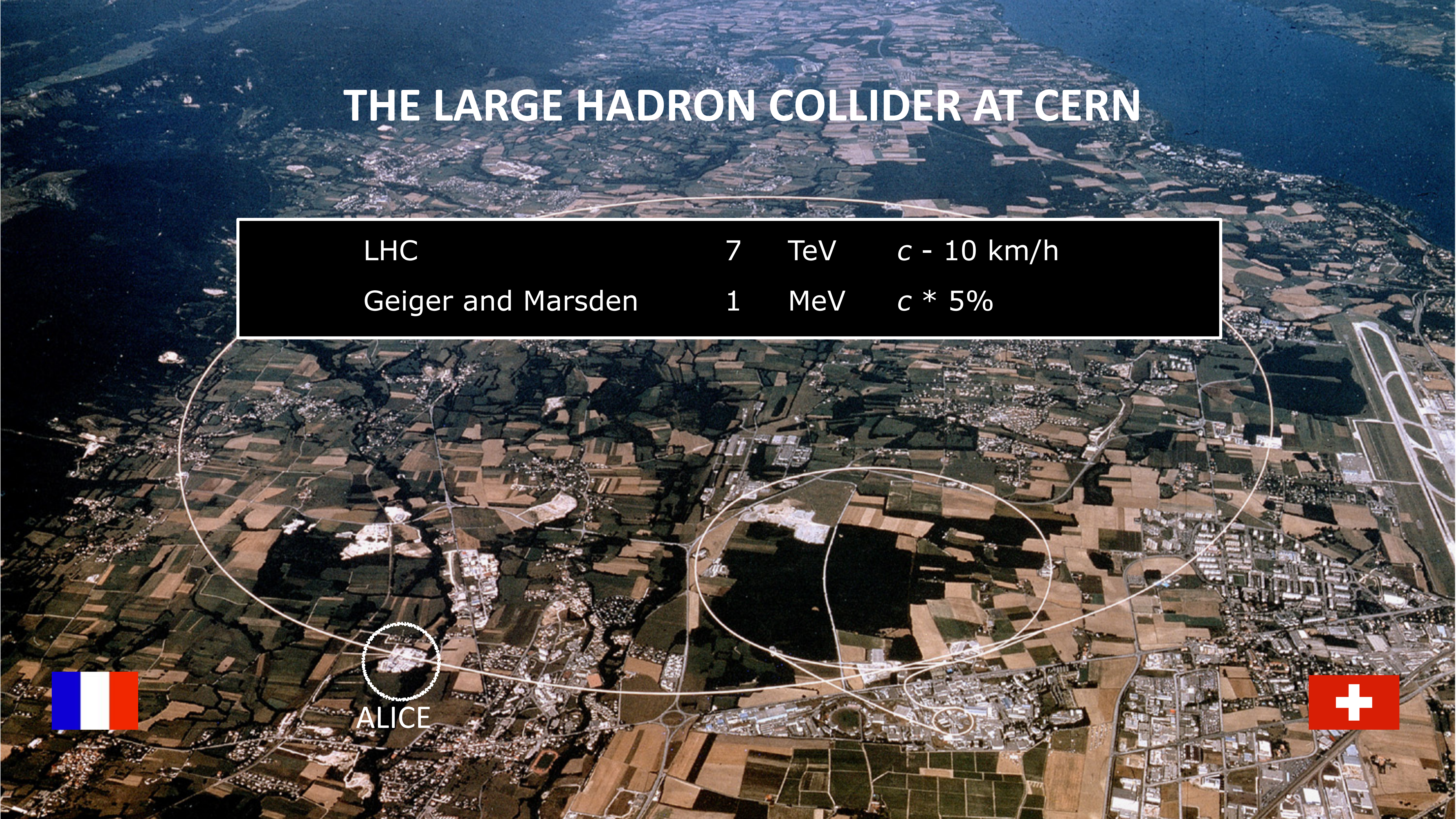





THE LARGE HADRON COLLIDER AT CERN
ALICE

THE LARGE HADRON COLLIDER AT CERN

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

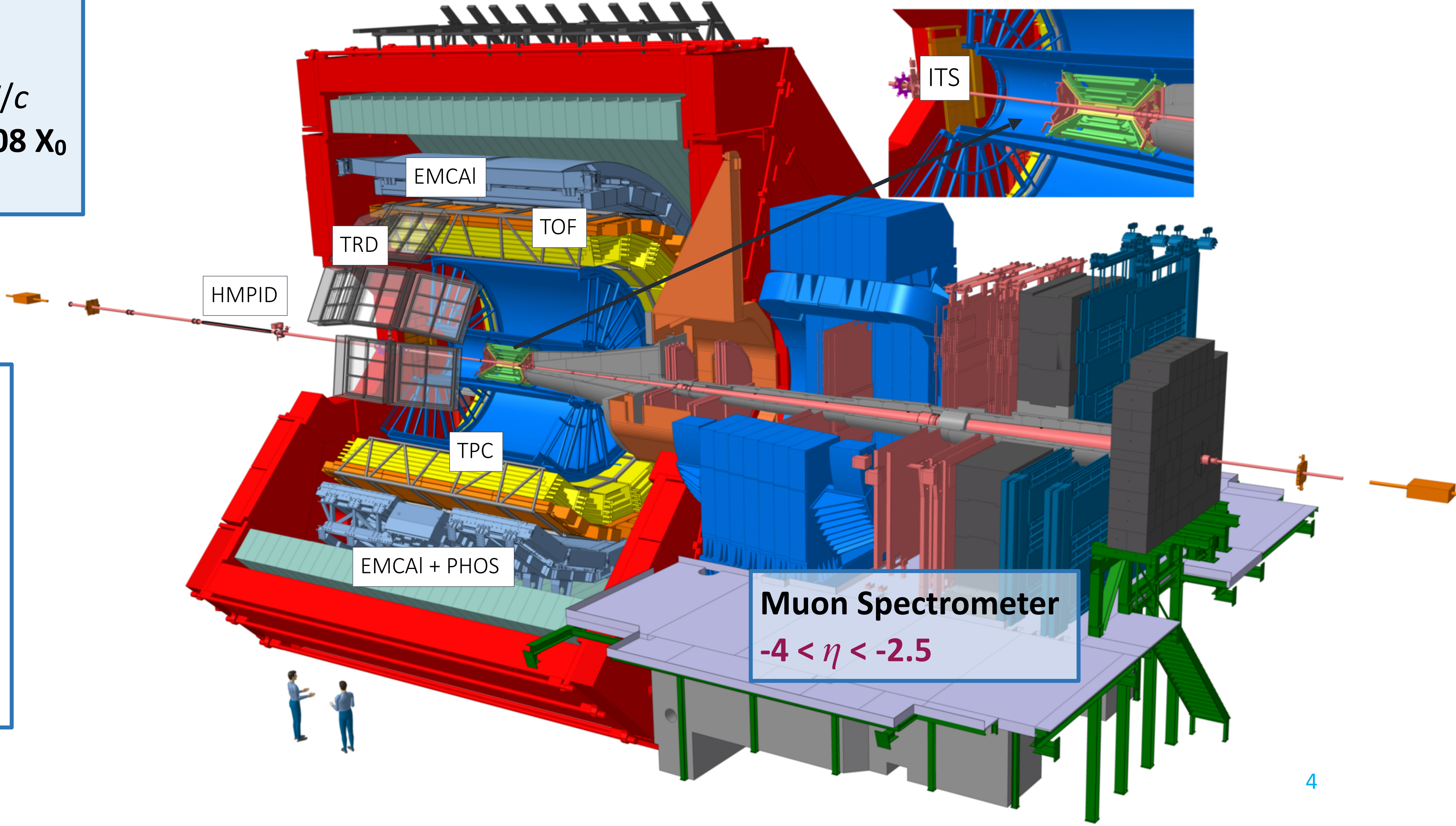


ALICE 1 (2009 - 2018): LHC RUN 1 & 2

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

ALICE

40 countries, 169 institutes

2002 members, 1034 scientific authors

377 doctoral students, 124 postdocs

Hungary in ALICE

Wigner Research Centre, Budapest

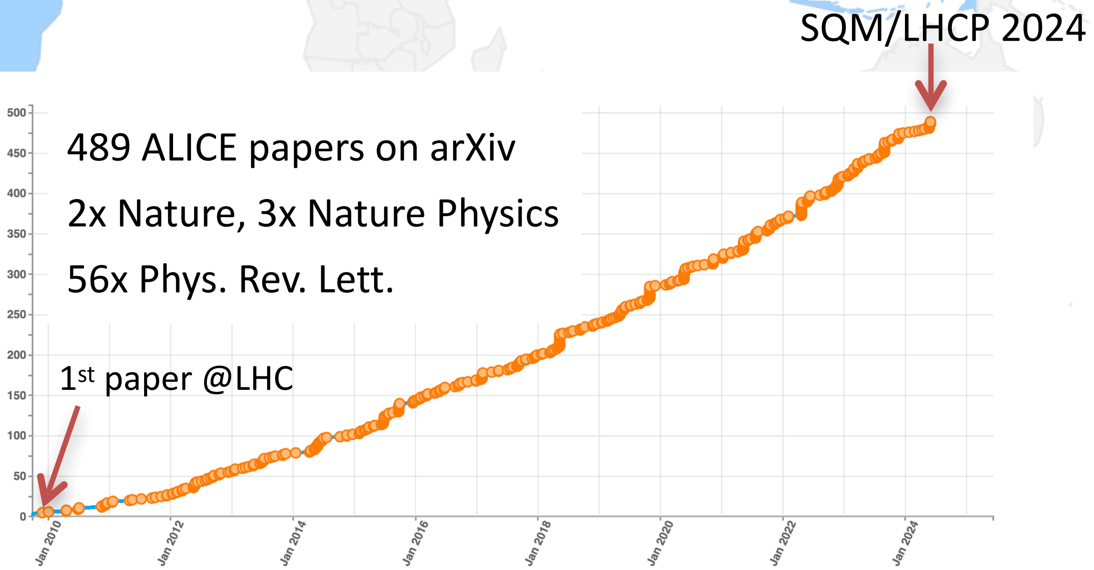
22 members

6 PhD scientists

10 authors

Run 1 | Run 2

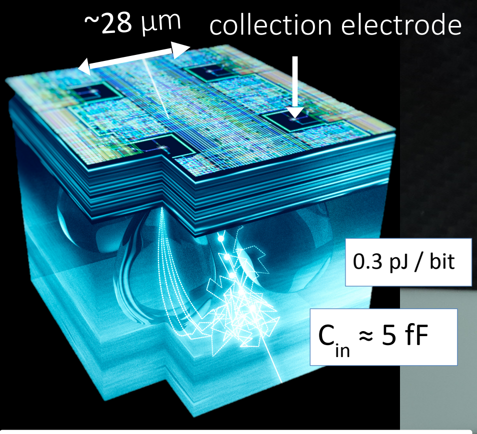
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	~75 μb^{-1} ~800 μb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	~200 mb^{-1}, ~100 nb^{-1} ~1.5 pb^{-1},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



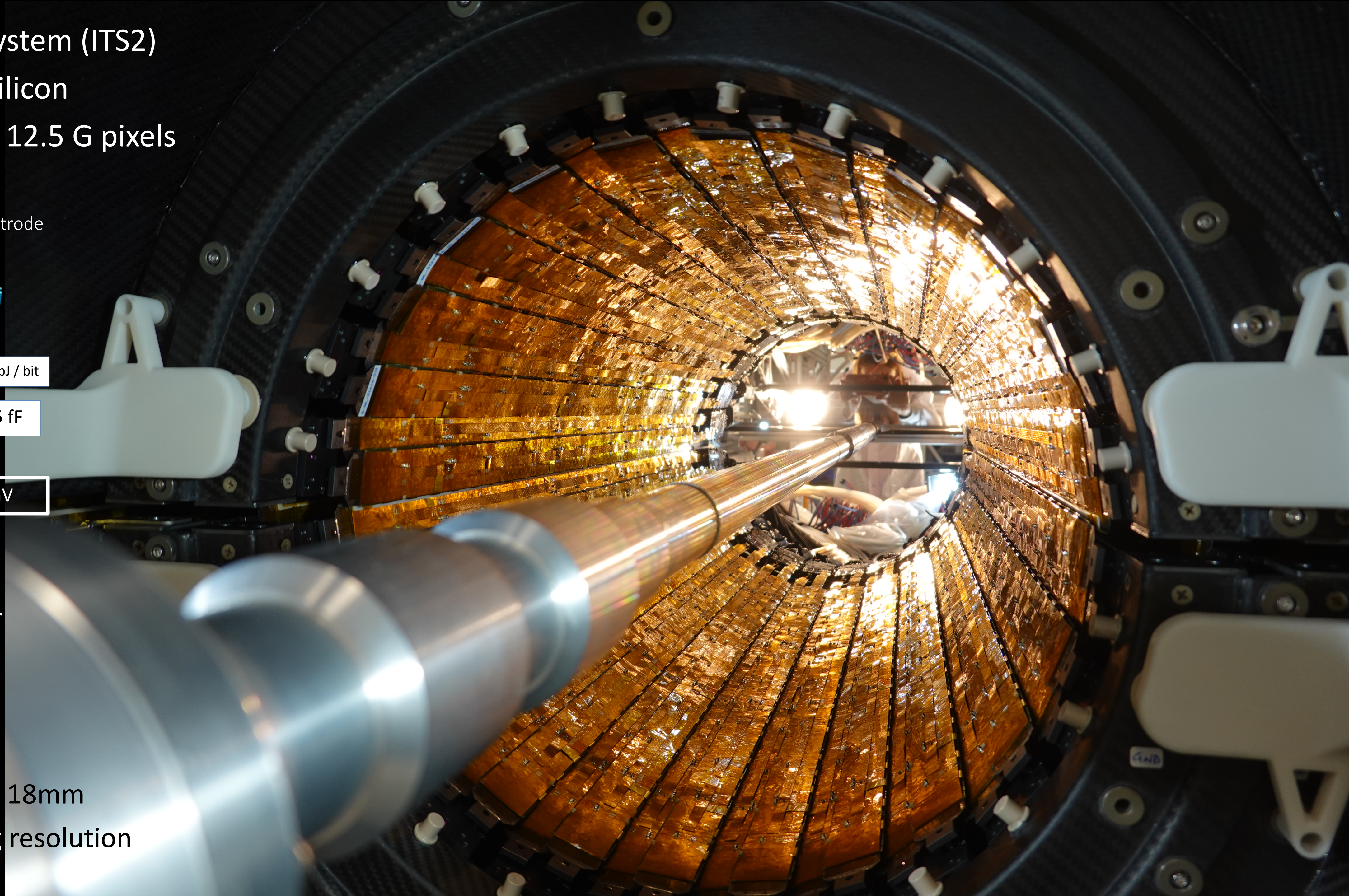
Inner Tracking System (ITS2)

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:

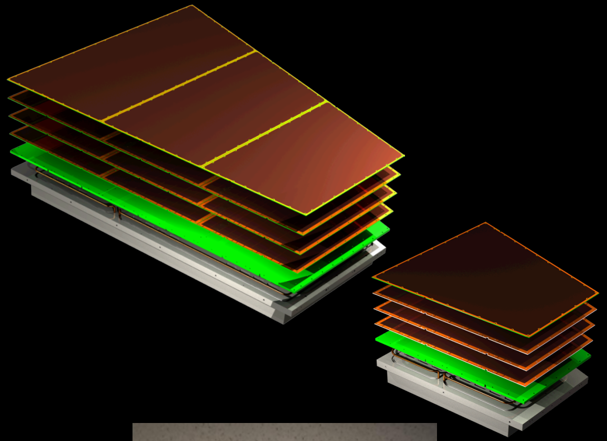
30 x 30 μm^2

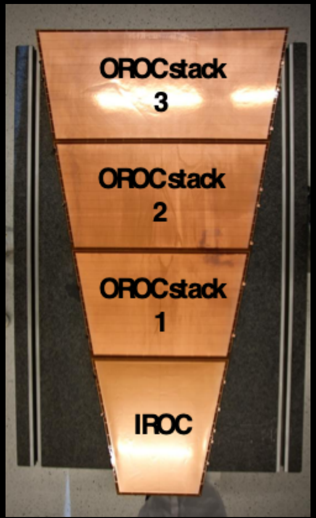
beam pipe radius: 18mm

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





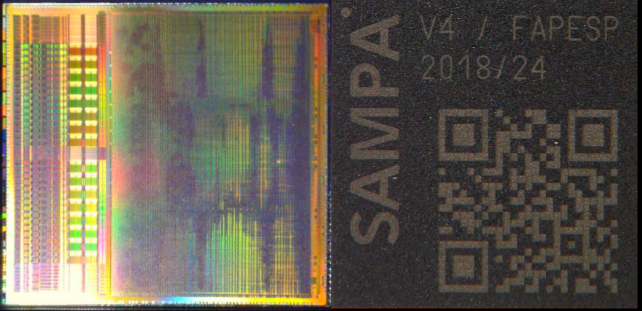
ALICE computing: 3.6 TeraBytes/s raw data —> up to 170 GBytes/s to disk

350 EPN servers

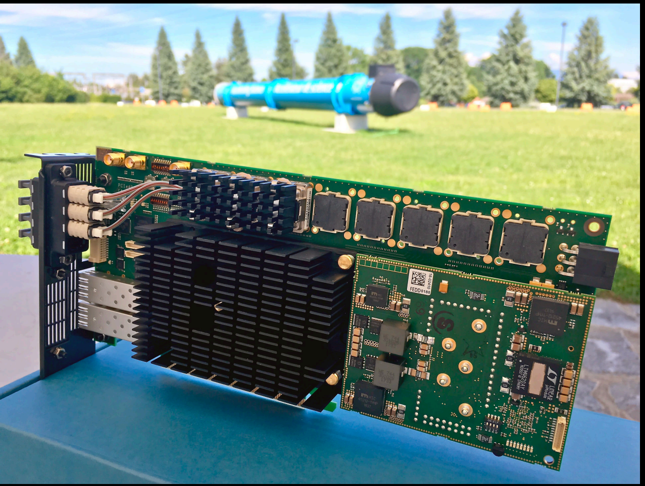
50k CPUs

2800 AMD GPUs

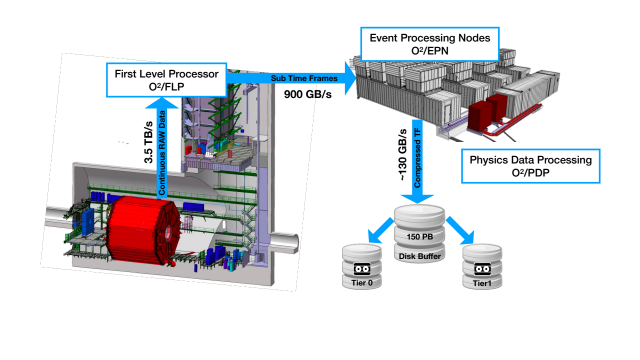
150 PetaBytes disk

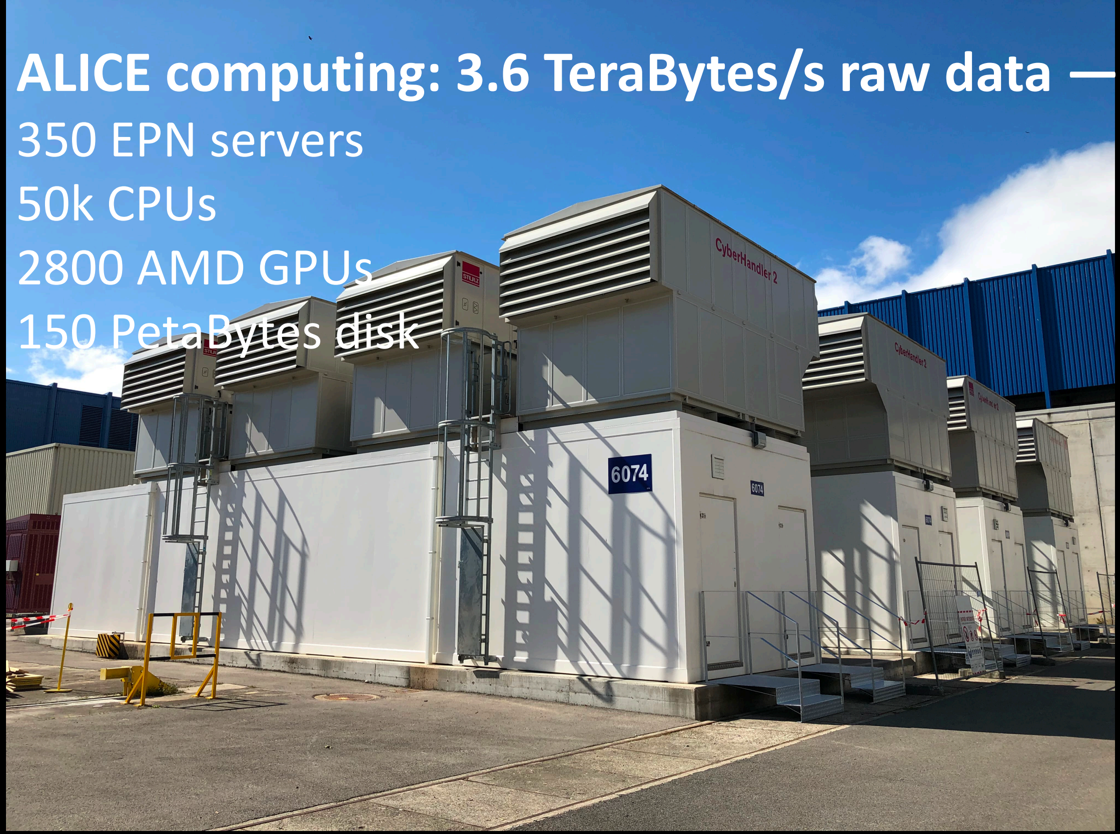


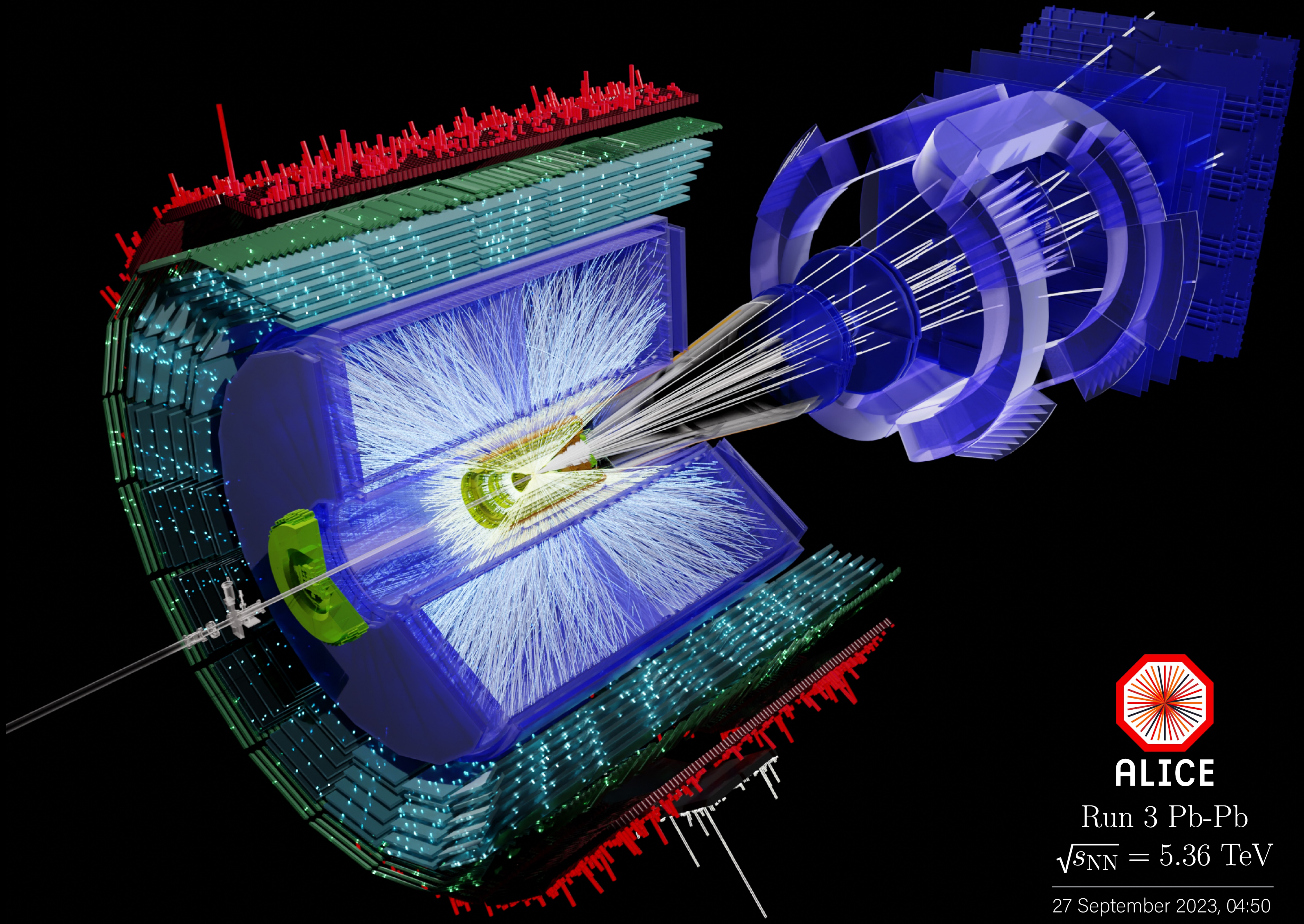
SAMPA chip



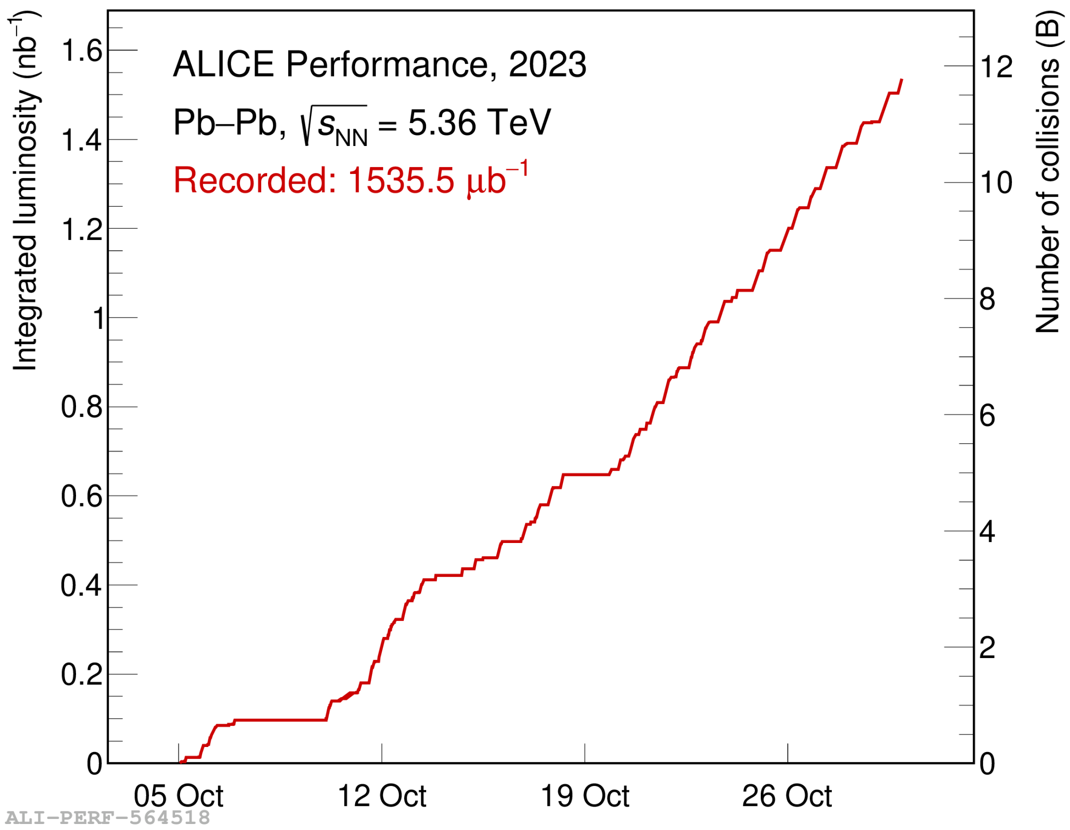
common readout unit
(world's largest FPGA)

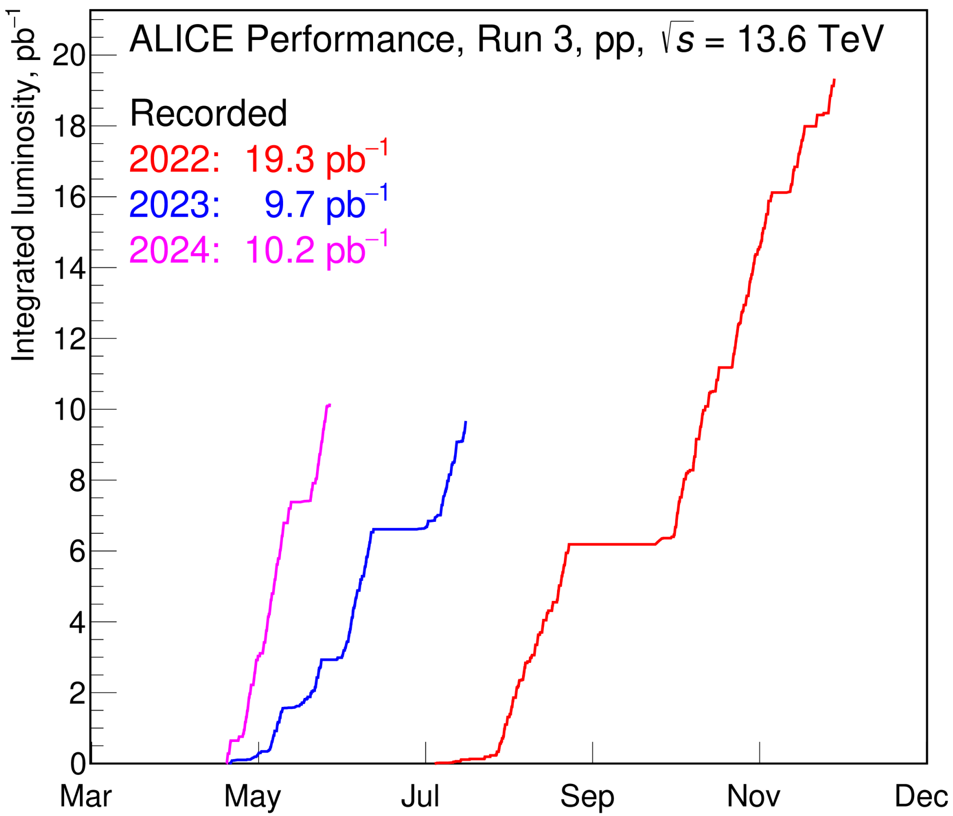





ALICE
Run 3 Pb-Pb
$\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV
27 September 2023, 04:50

RUN 3: INTEGRATED LUMINOSITY

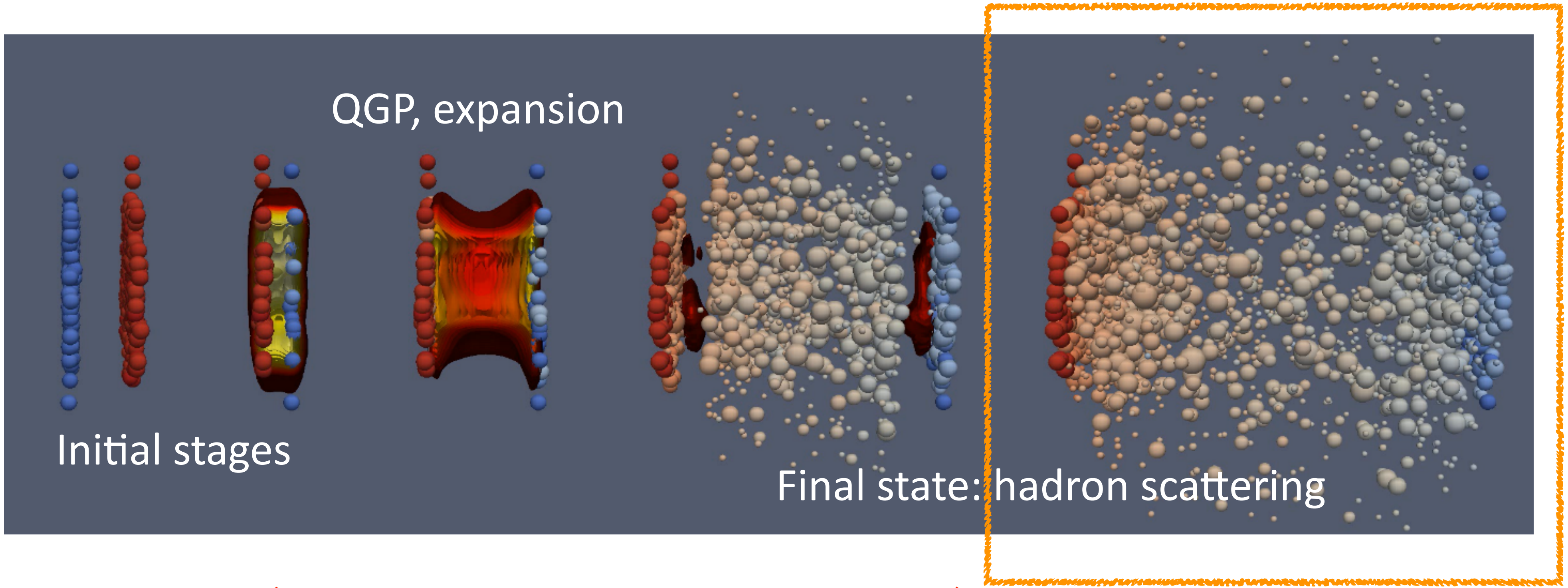




2023 Pb-Pb: 12 billion minimum bias collisions
40x minimum bias, **6x central** wrt Run 1 + 2
expect similar data set in 2024

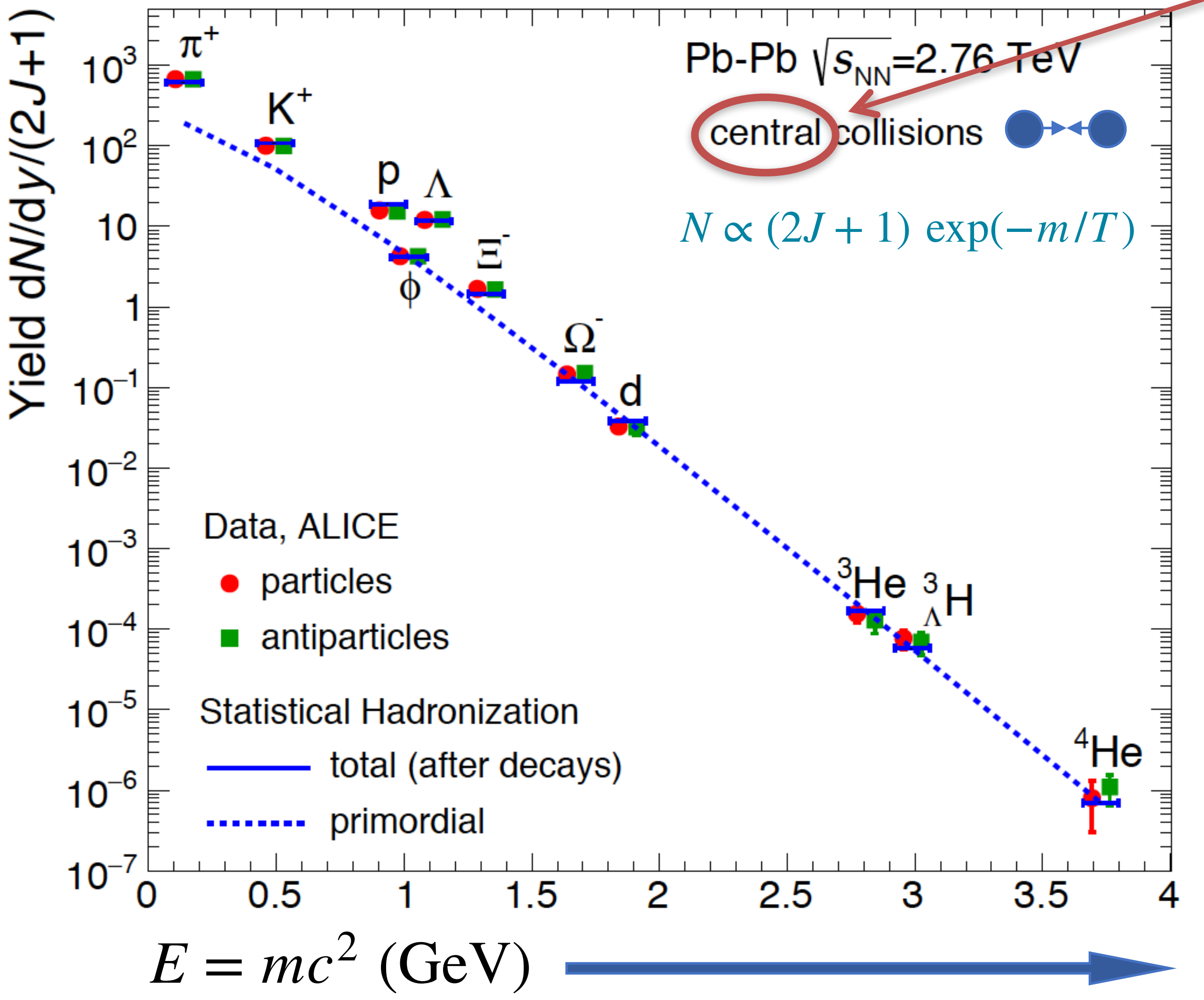
2024 pp: half a trillion minimum bias collisions
still counting at **95%** data recording **efficiency**
expect still 3x more in 2024

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



Emission of thermal radiation $\propto T^2$

THERMAL PARTICLE PRODUCTION



Highest multiplicity

QCD-analog of **Planck spectrum**

T = 156.2 ± 2 MeV

Nature 561, 321 (2018)

Baryo-chemical potential

$\mu_B = 0.71 \pm 0.45$ MeV

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

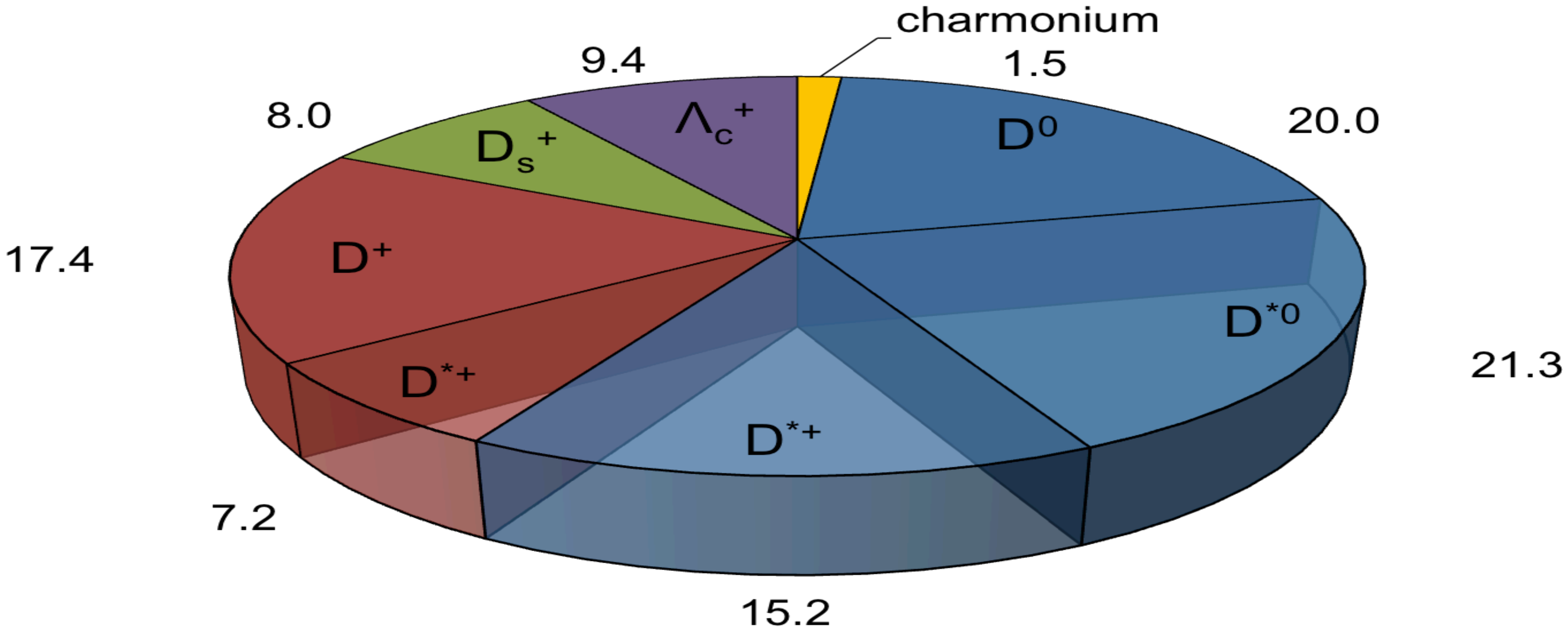
arXiv:2311.13332

Lattice-QCD results **agree**

T_{pc} = 156.5 ±1.5 MeV

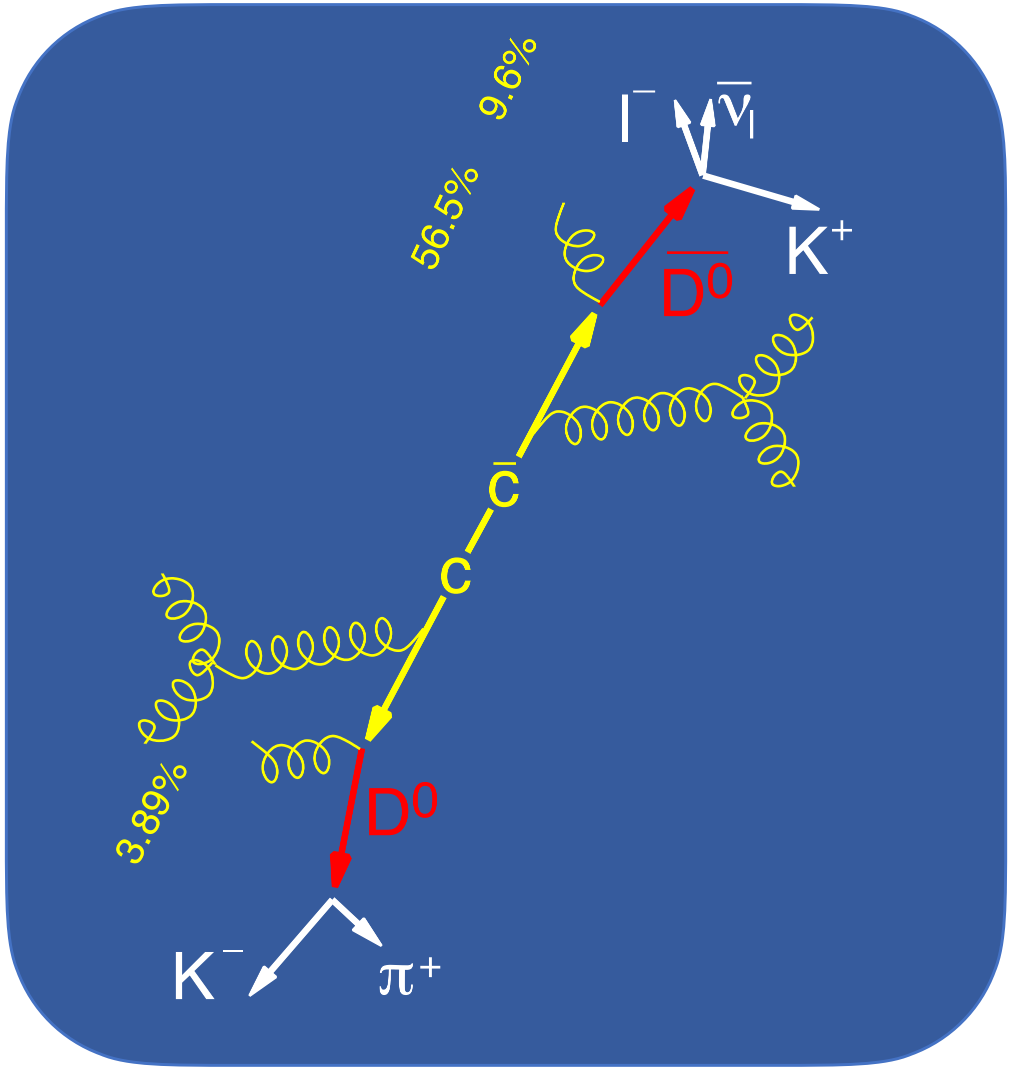
A. Bazavov et al. (Hot QCD) arXiv:1812.08235

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

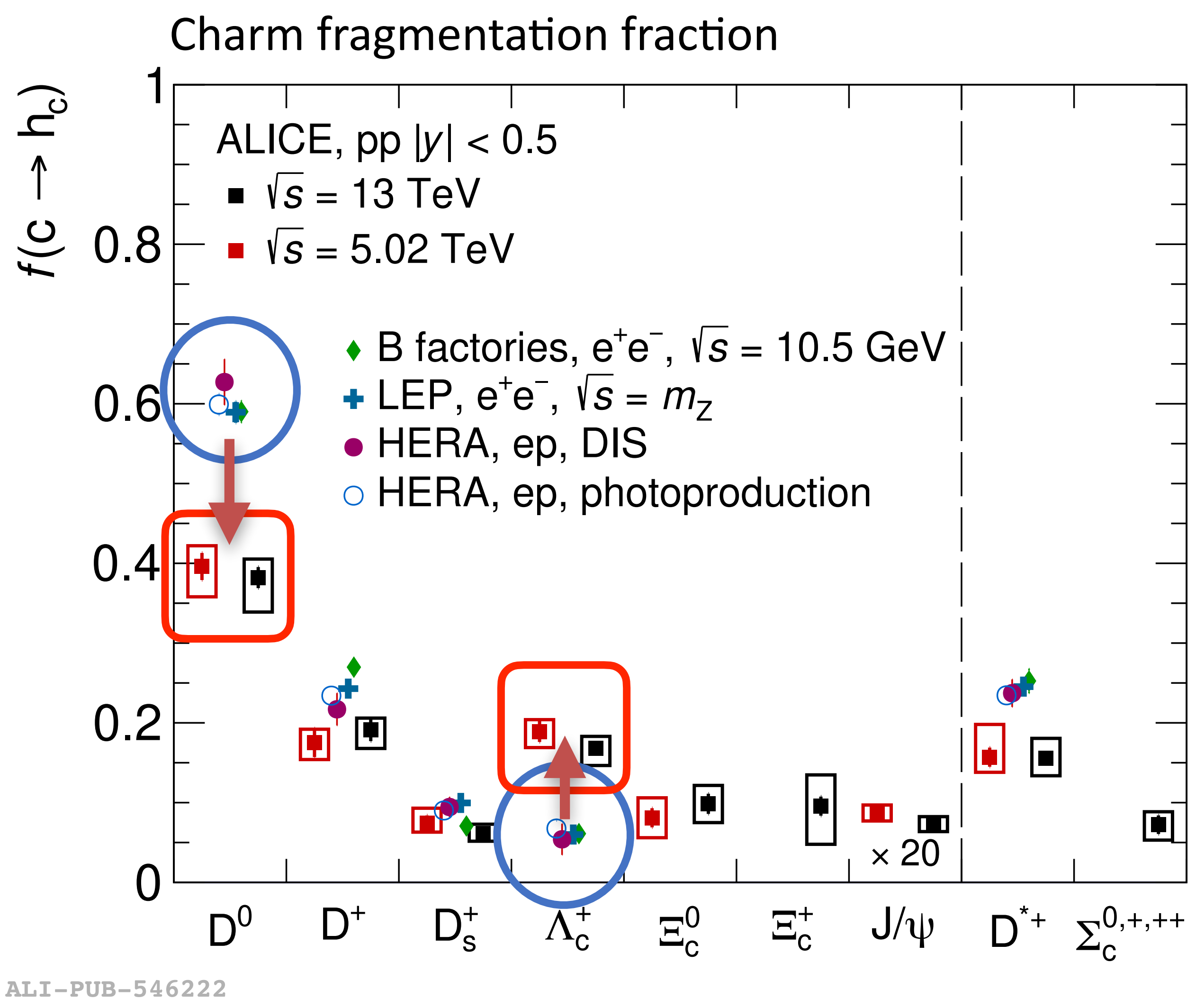
→ need sub-millimeter pointing precision to collision vertex

separation of time scales: charm quark creation - hadronization - decay

plot: courtesy of D. Tlusty

CHARM PRODUCTION AND FRAGMENTATION

ALICE



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

Λ_c, Ξ_c, Σ_c measured

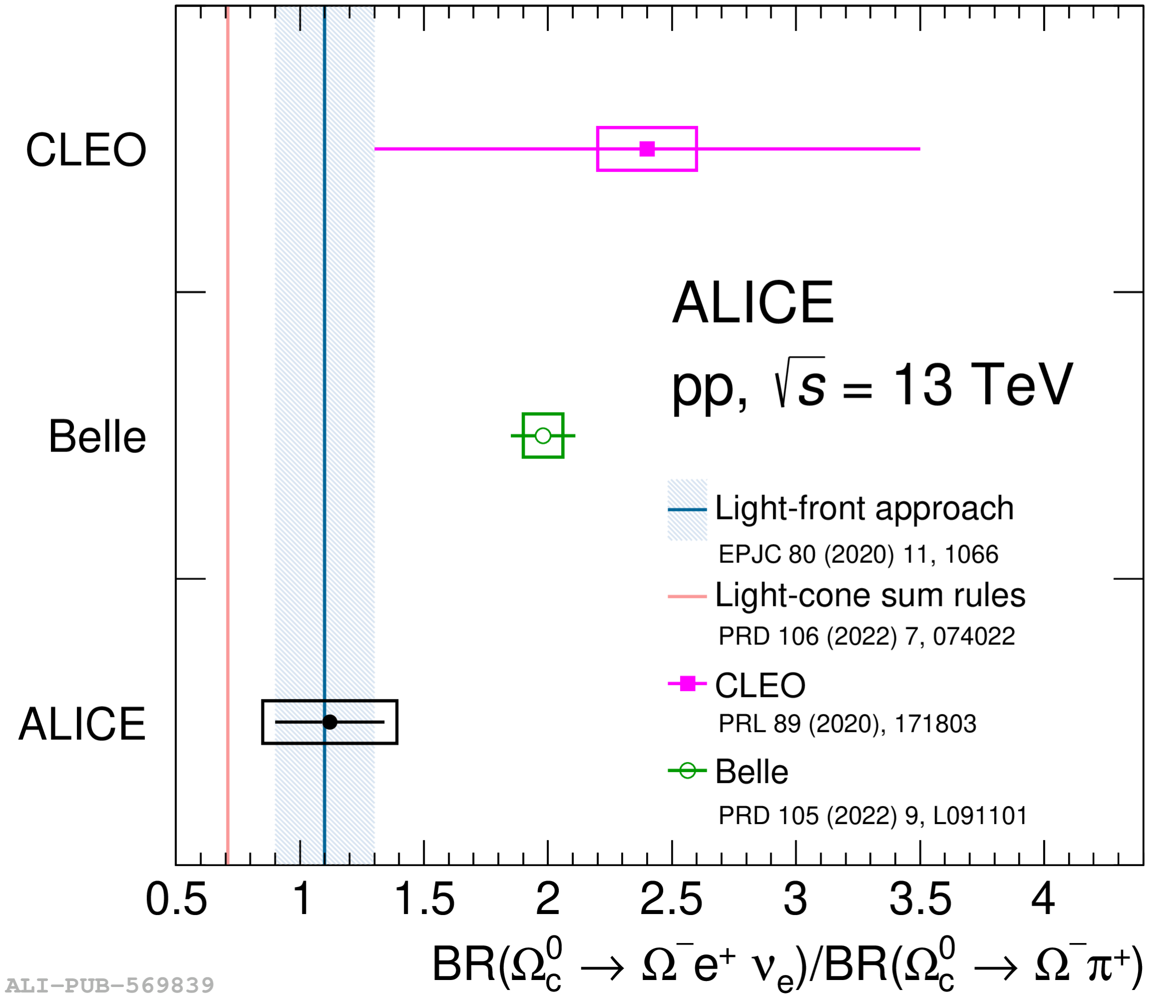
charm hadronization not universal

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

→ calls for N^{3}LO calculations

arXiv:2308.04877

BRANCHING RATIOS - Ω_c , $|css\rangle$



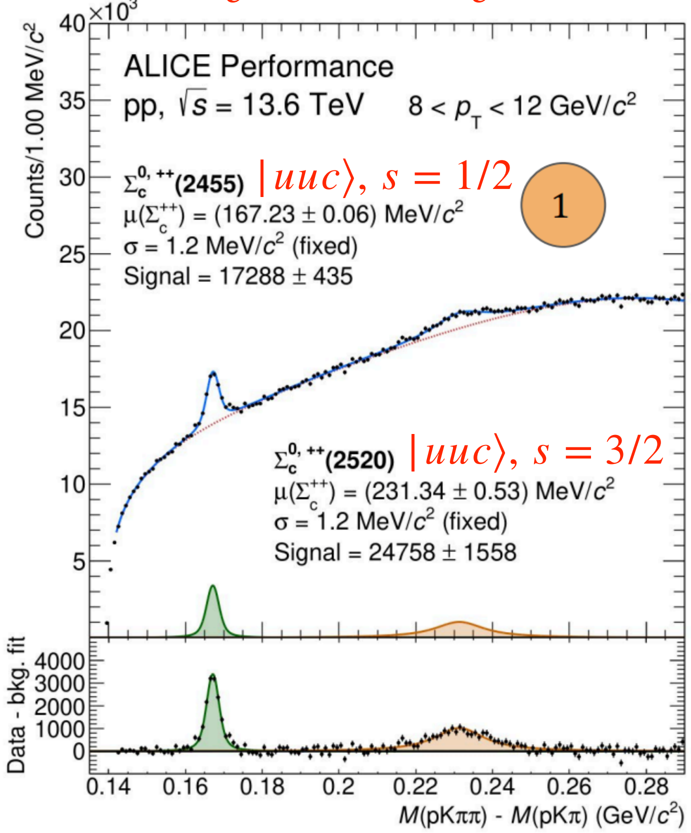
branching ratios

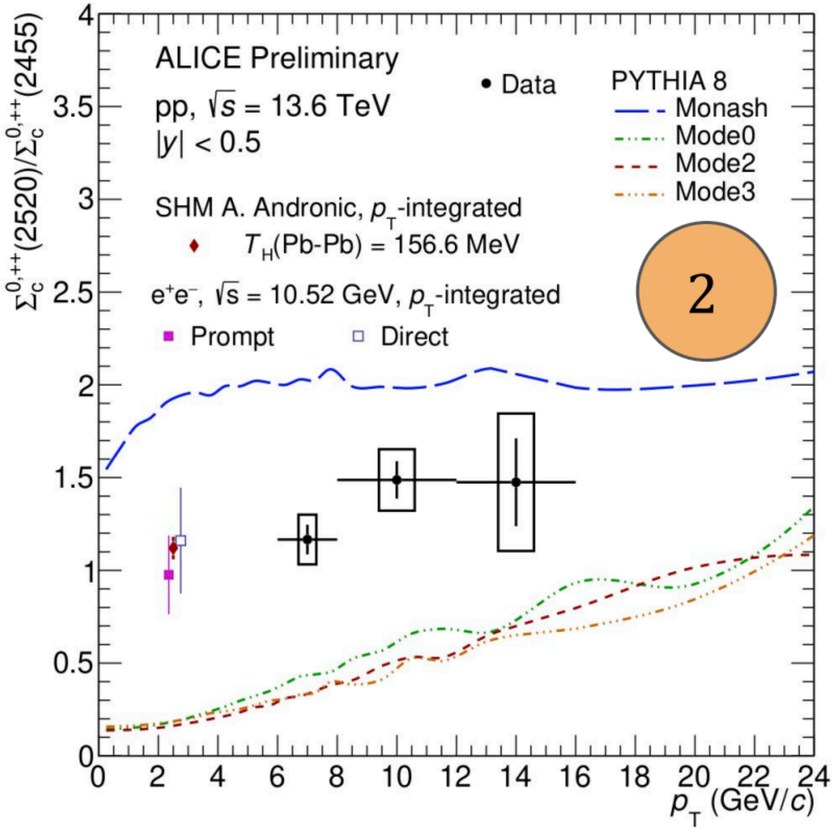
- check lepton universality
- essential for determining total charm production
- challenge to theory

arXiv:2404.17272

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

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

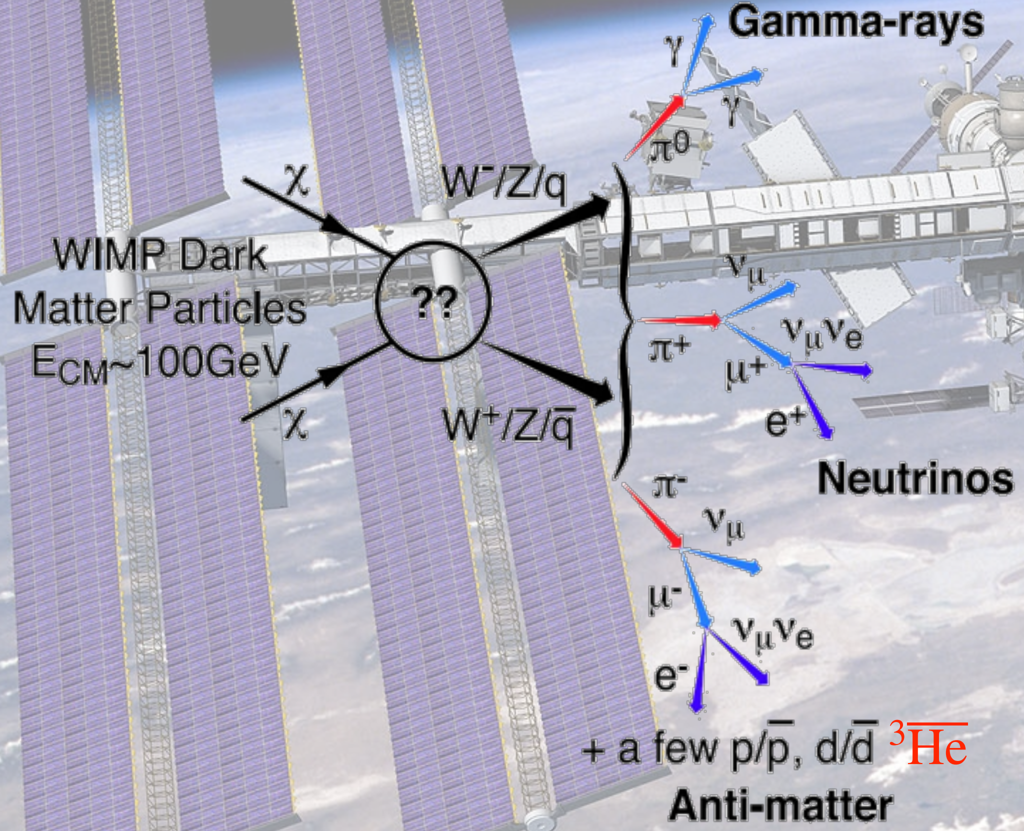




→ **Resonances** of **charmed baryons** might play an important role in the **baryon enhancement** discussion

→ **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 **X-X annihilation**

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

Cosmic protons + H (inter stellar medium)

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

→ **ALICE measures** this **background** in

similar kinematic range!

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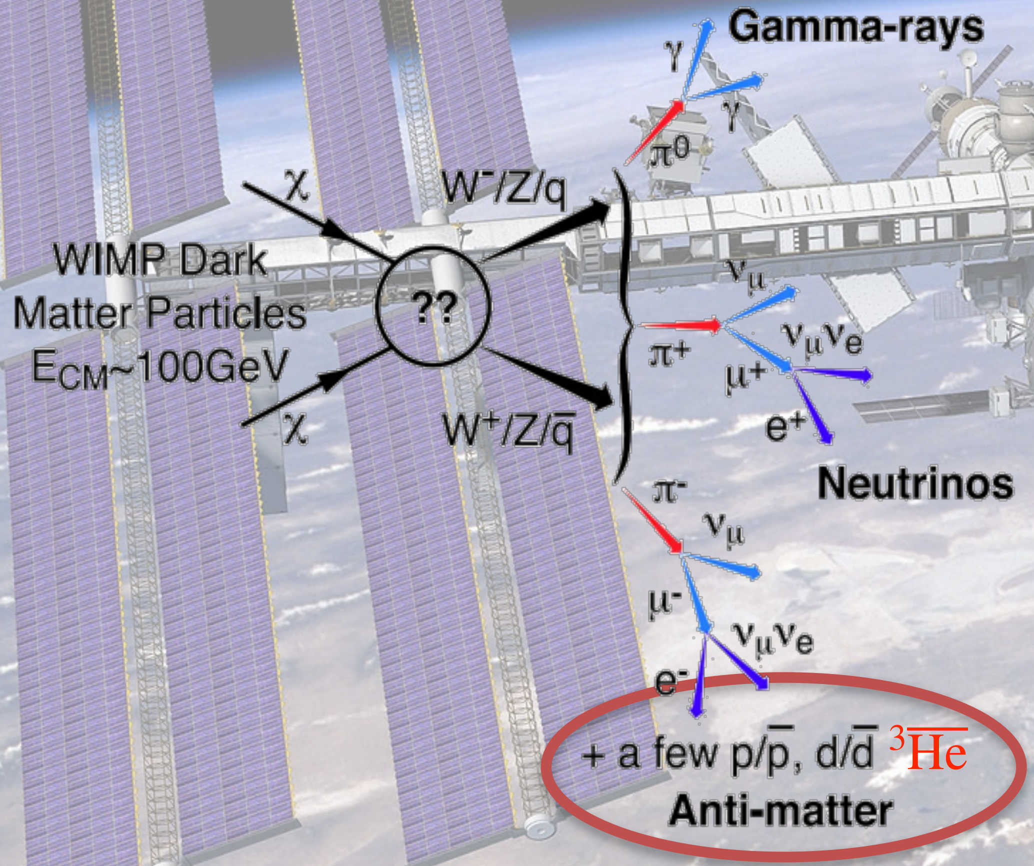

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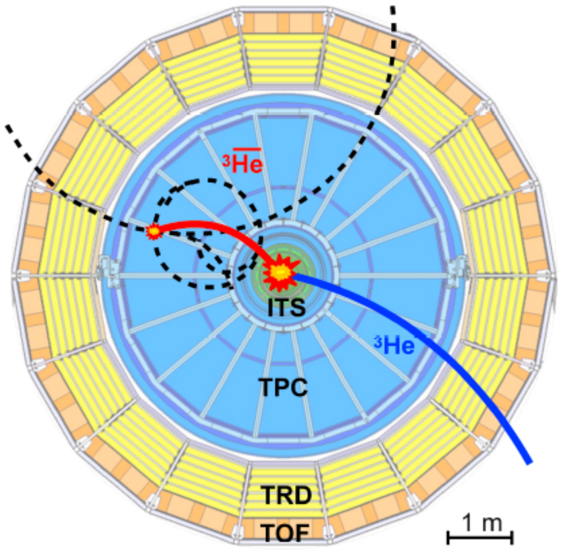
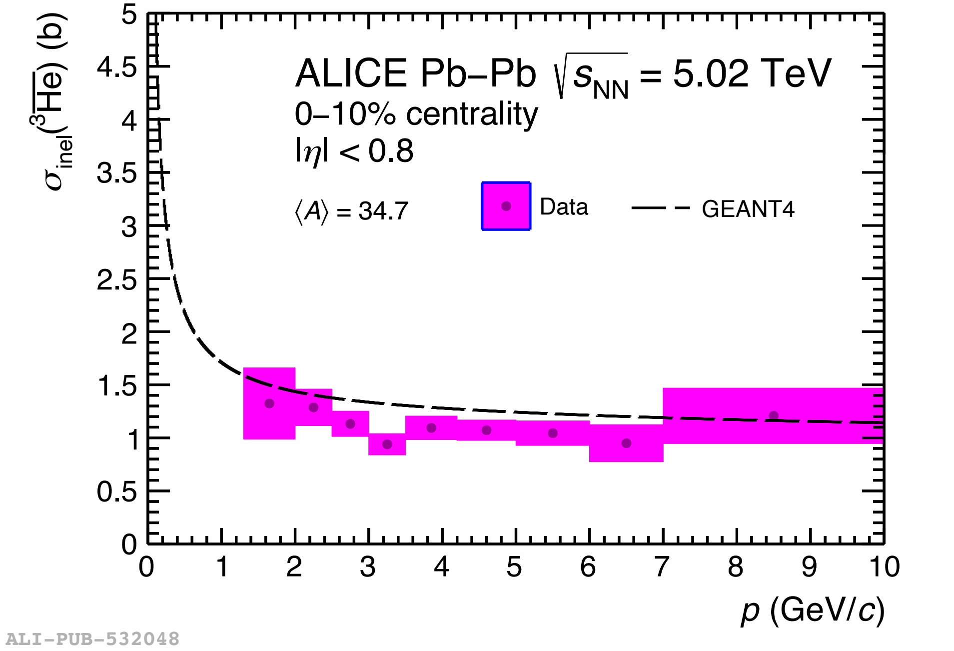
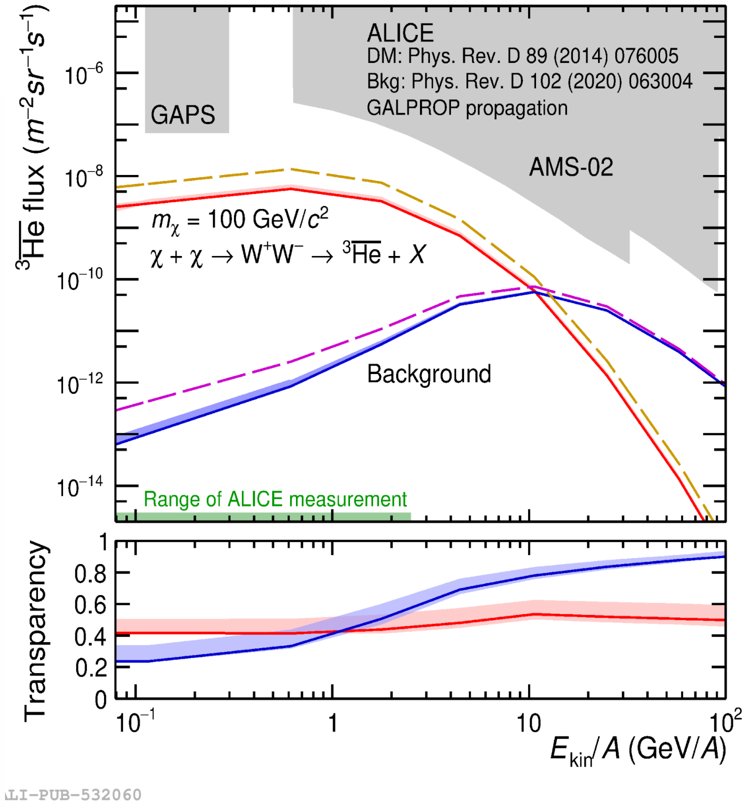
$^3\overline{\mathrm{He}}$ inelastic cross section

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





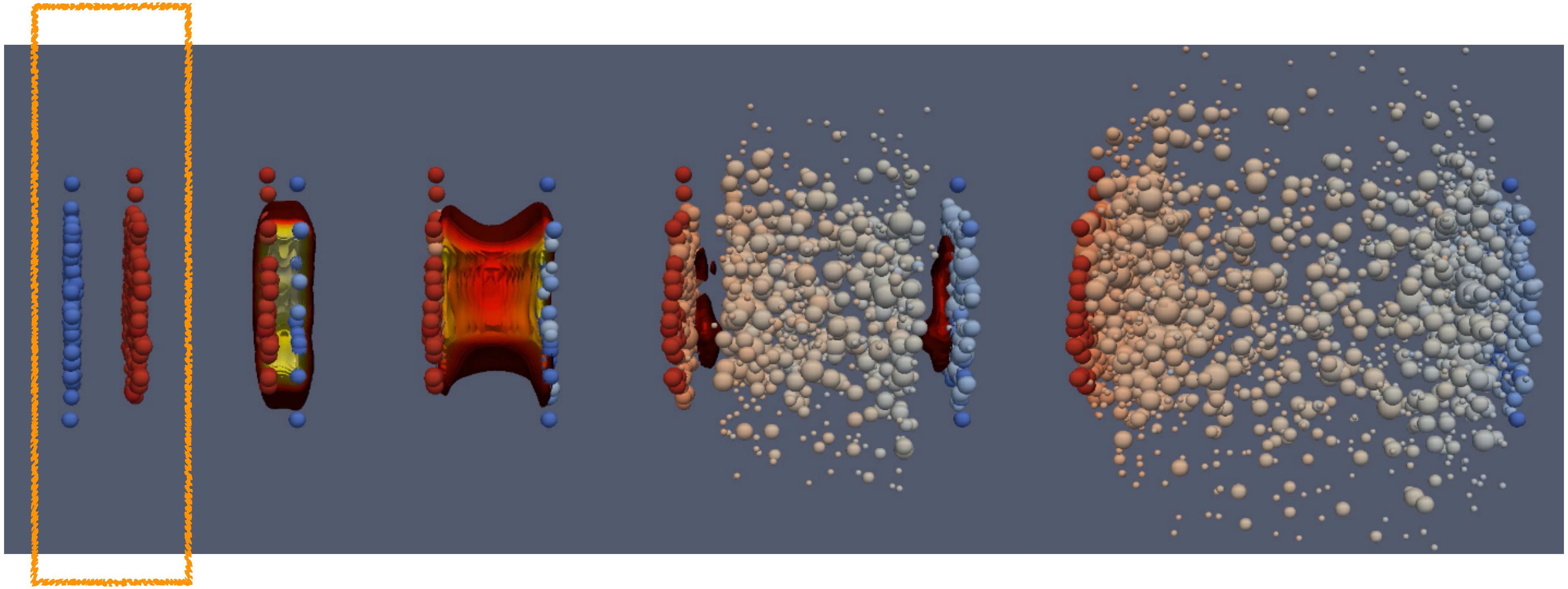


tag & probe $^3\overline{\mathrm{He}}$ nuclei:
detect disappearance
in detector material

measure inelastic cross section
over large momentum range

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

CAN WE PROBE THE INITIAL STATE OF PB?



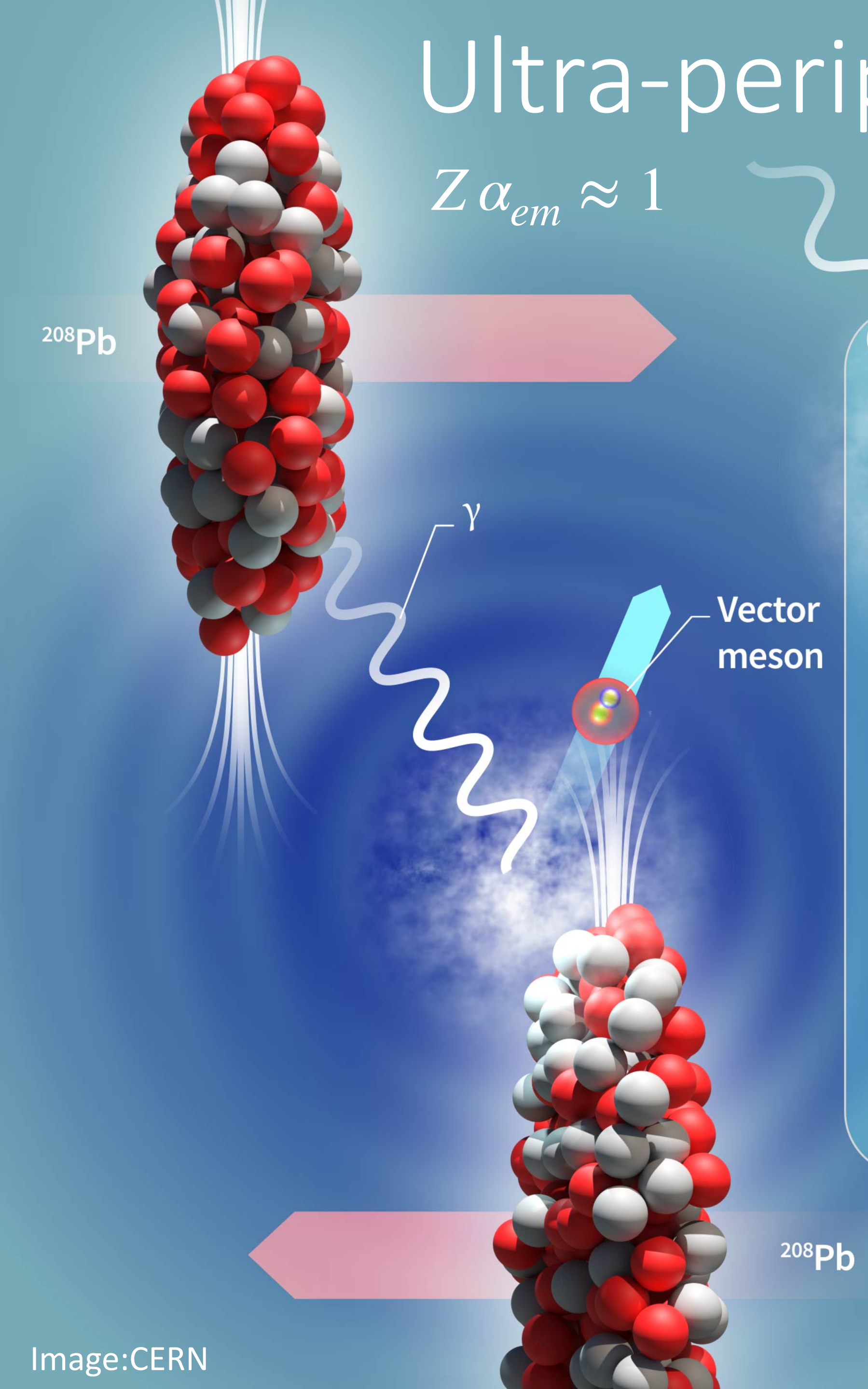
Probing the initial stage

Gluon-dominated

Color Glass Condensate?

Ultra-peripheral collisions - QED processes

$Z\,\alpha_{em} \approx 1$



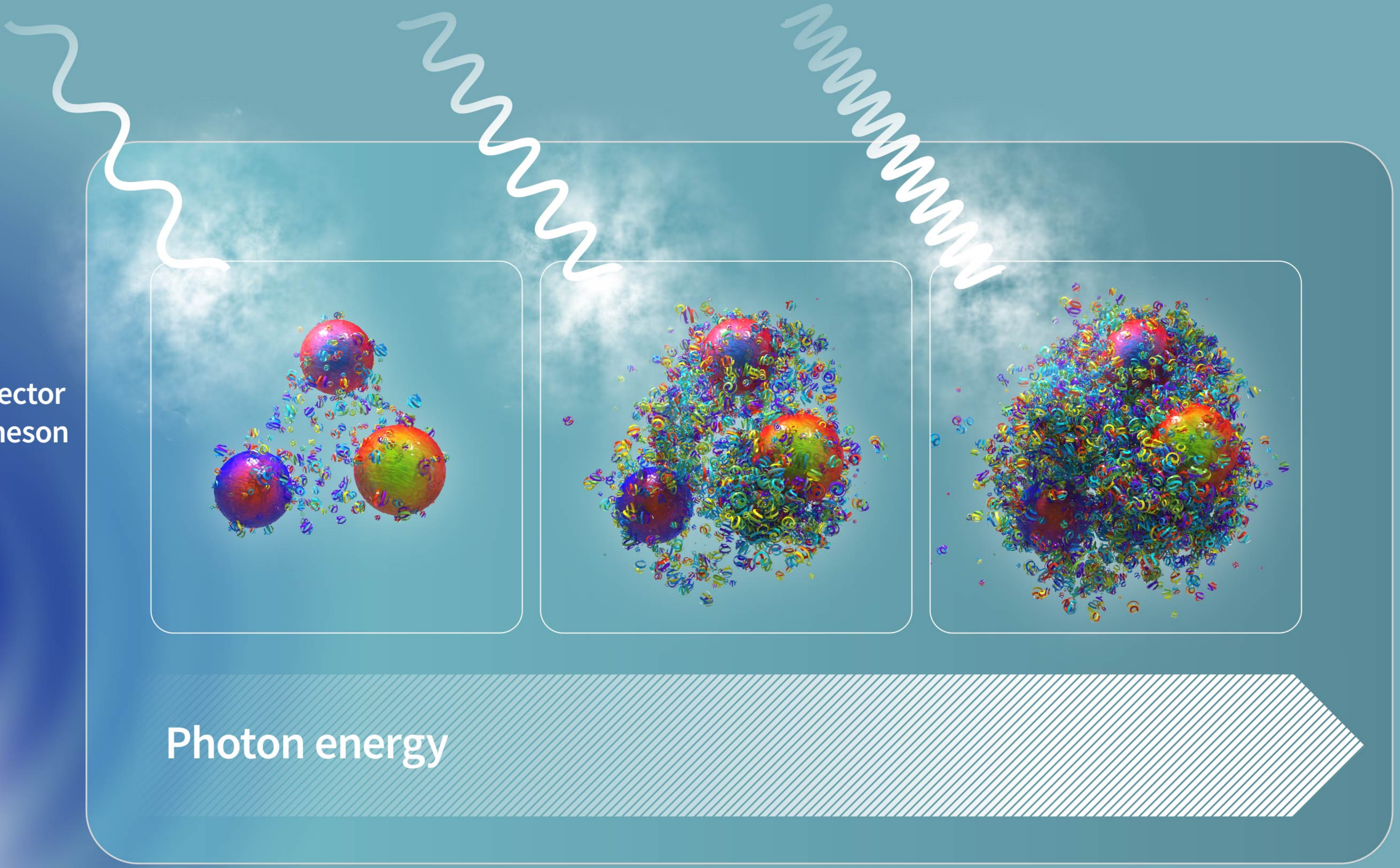


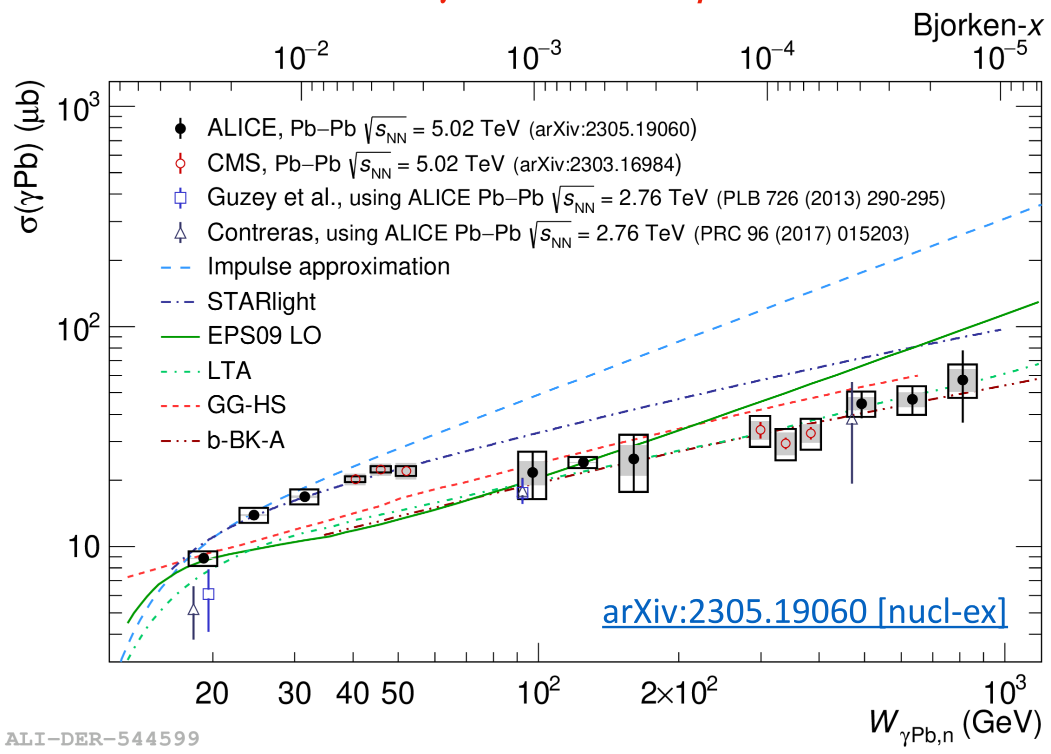
Image:CERN

(IN)COHERENT J/ψ PHOTOPRODUCTION

ALICE

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

arXiv:2305.06169 [nucl-ex]



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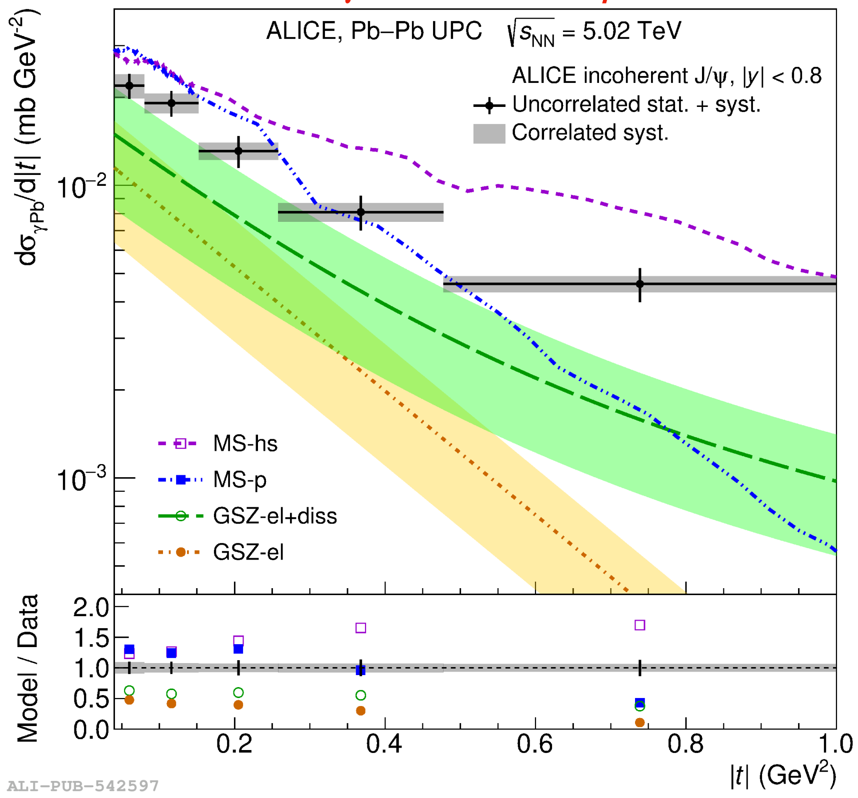

$\sigma(\gamma\mathrm{Pb})$ **sensitive** to **gluon distribution** inside nuclei

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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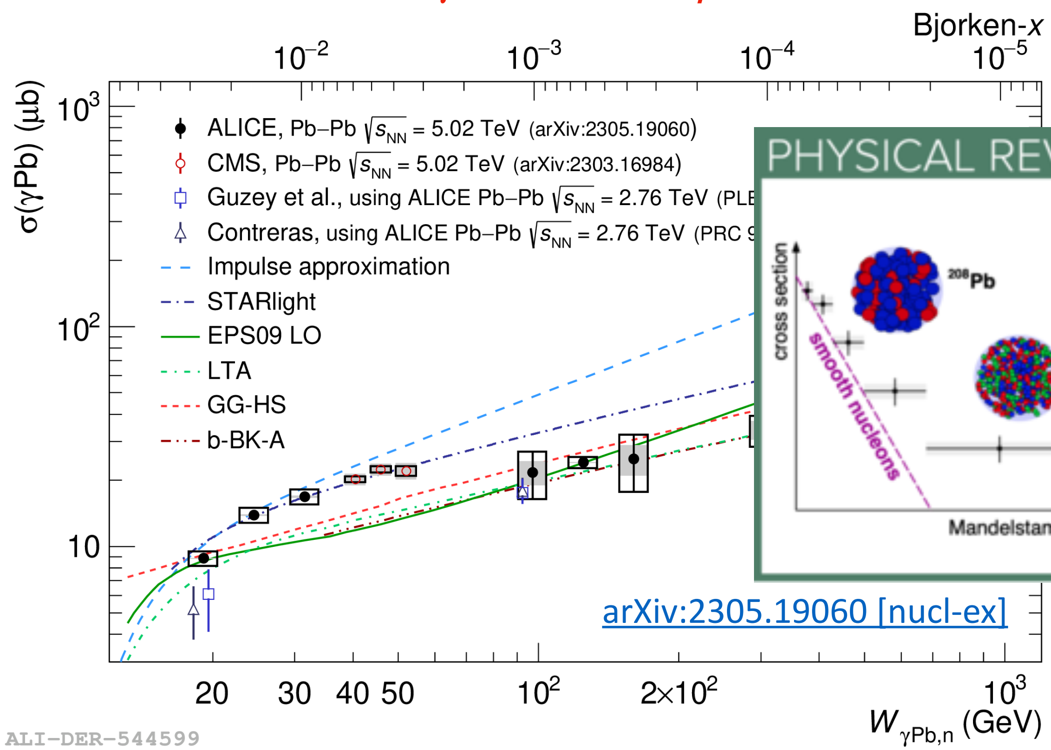
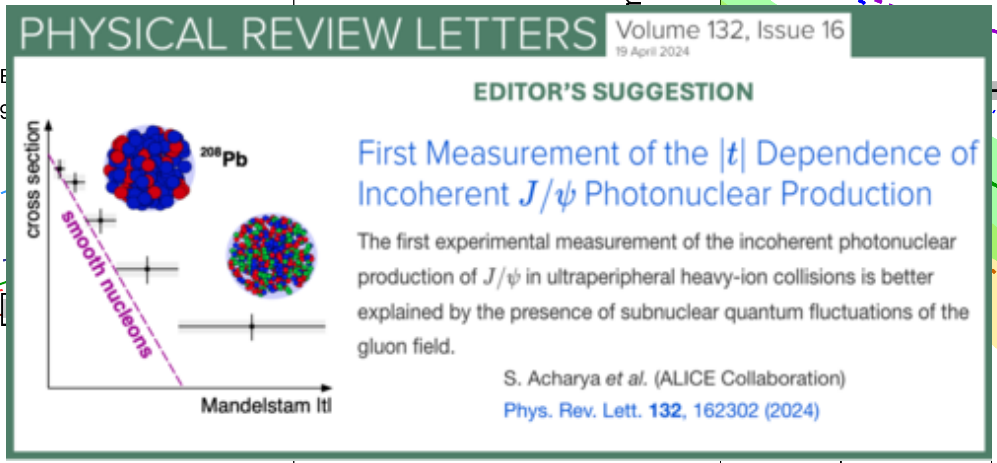



PHYSICAL REVIEW LETTERS Volume 132, Issue 16

19 April 2024

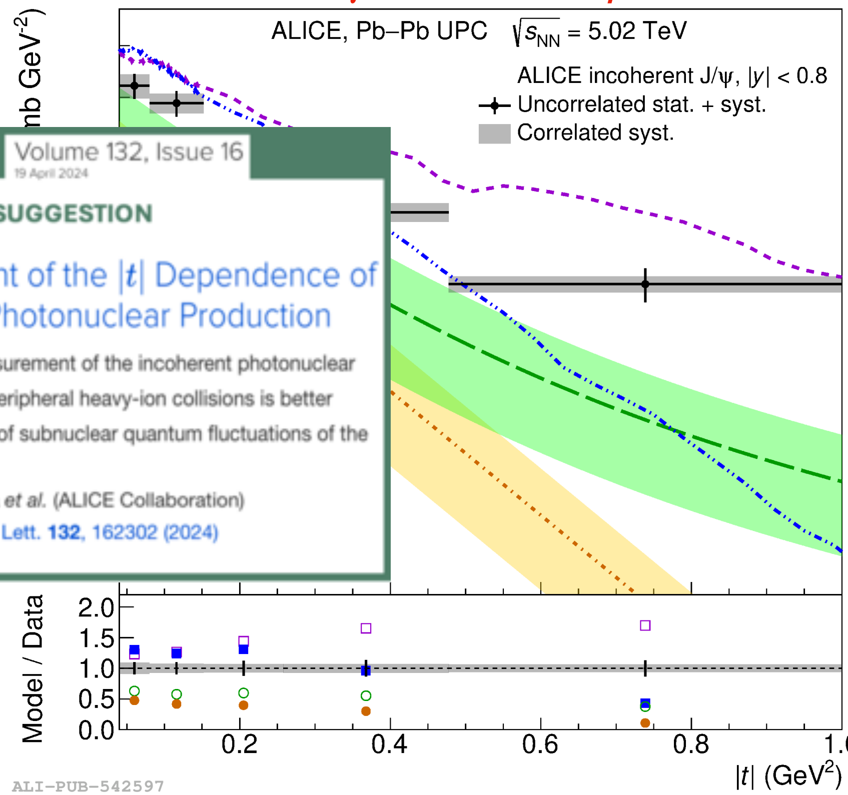
EDITOR'S SUGGESTION

First Measurement of the $|t|$ Dependence of Incoherent J/ψ Photonuclear Production

The first experimental measurement of the incoherent photonuclear production of J/ψ in ultraperipheral heavy-ion collisions is better explained by the presence of subnuclear quantum fluctuations of the gluon field.

S. Acharya *et al.* (ALICE Collaboration)

Phys. Rev. Lett. **132**, 162302 (2024)



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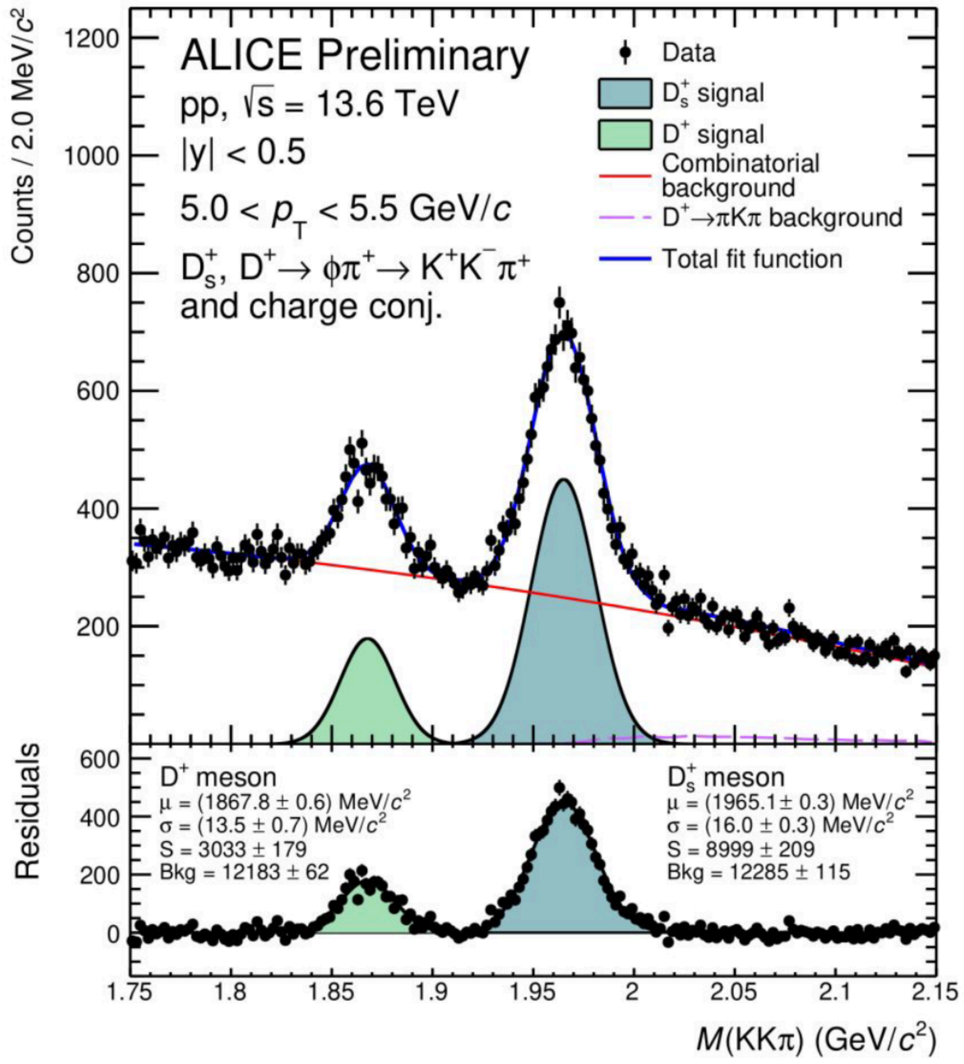
Results from Run 3: pp collisions at 13.6 TeV

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



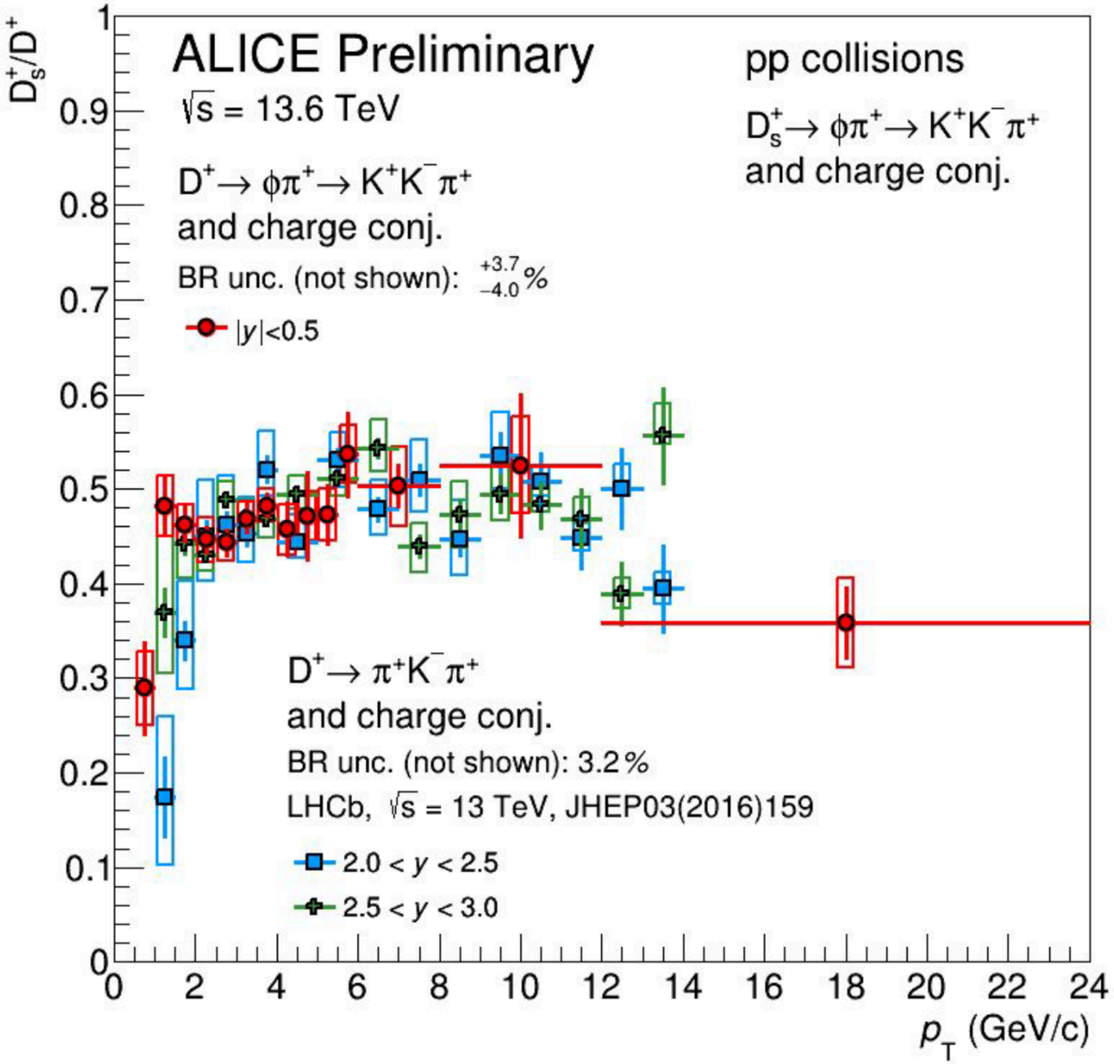
In Run 3, this ratio is measured in the same decay channel.

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) - $|c\bar{s}\rangle / |c\bar{d}\rangle$

ALICE



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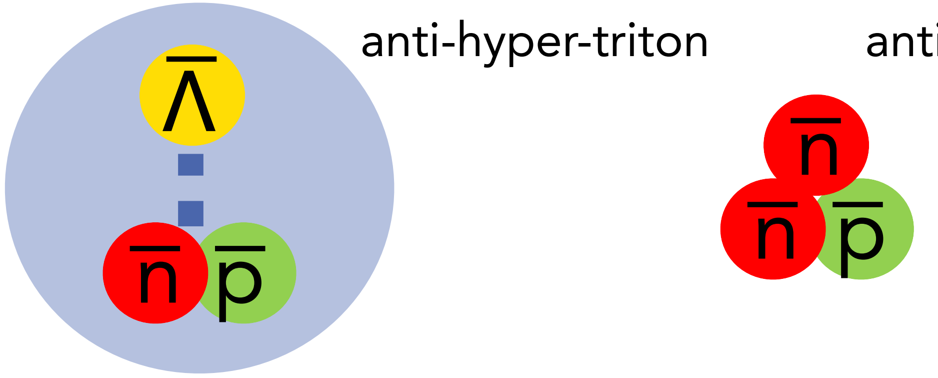
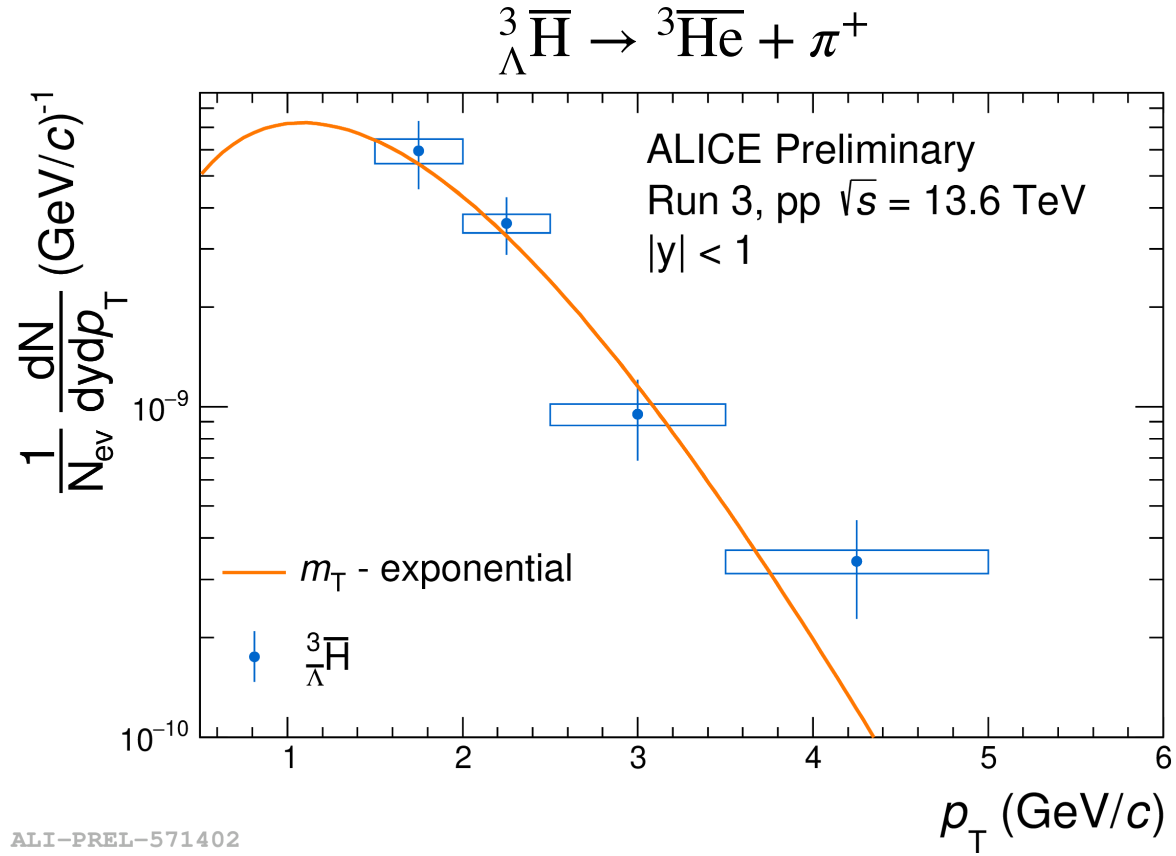
Hypertriton in pp at 13.6 TeV (1)

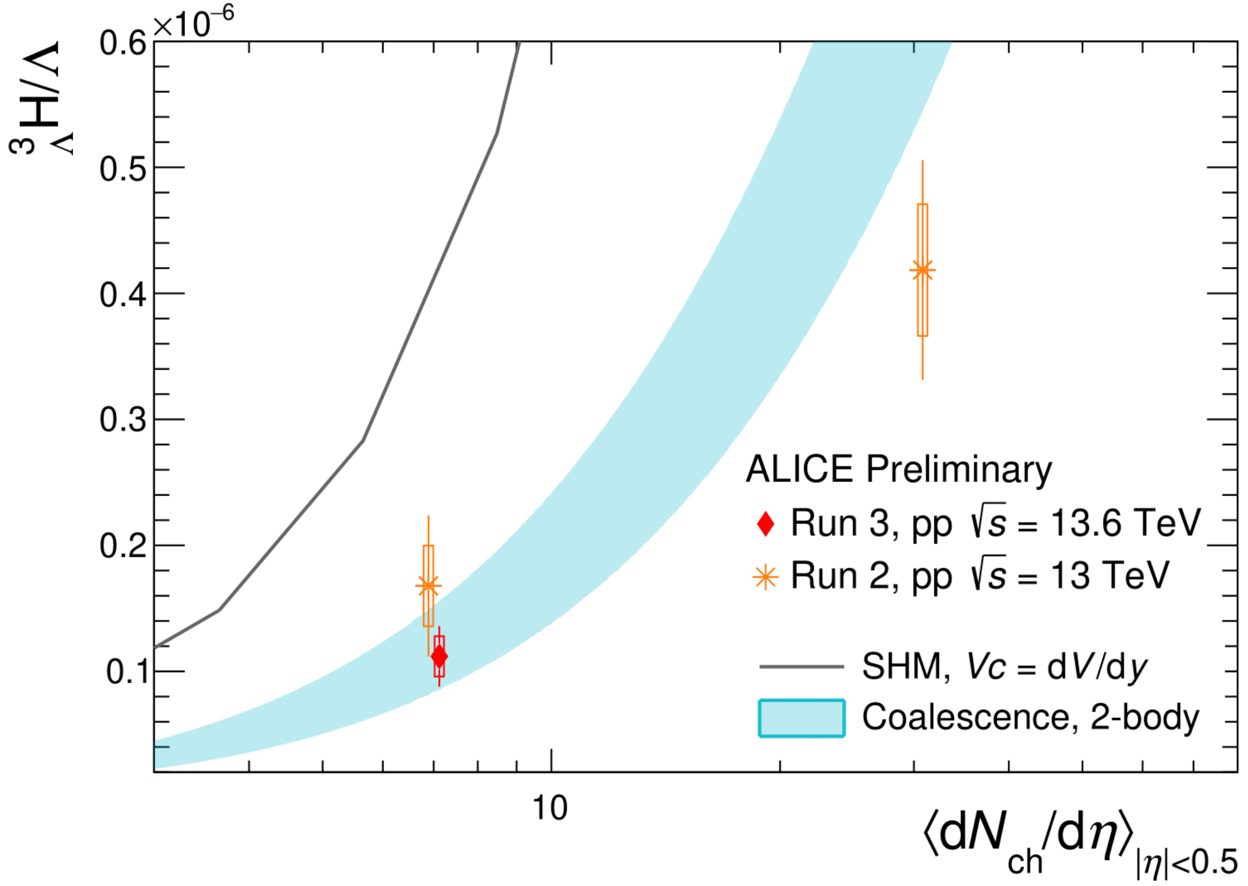
anti-hyper-triton anti-triton



- First $\mathbf{p_T}$ **-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.



Hypertriton in pp at 13.6 TeV (2)



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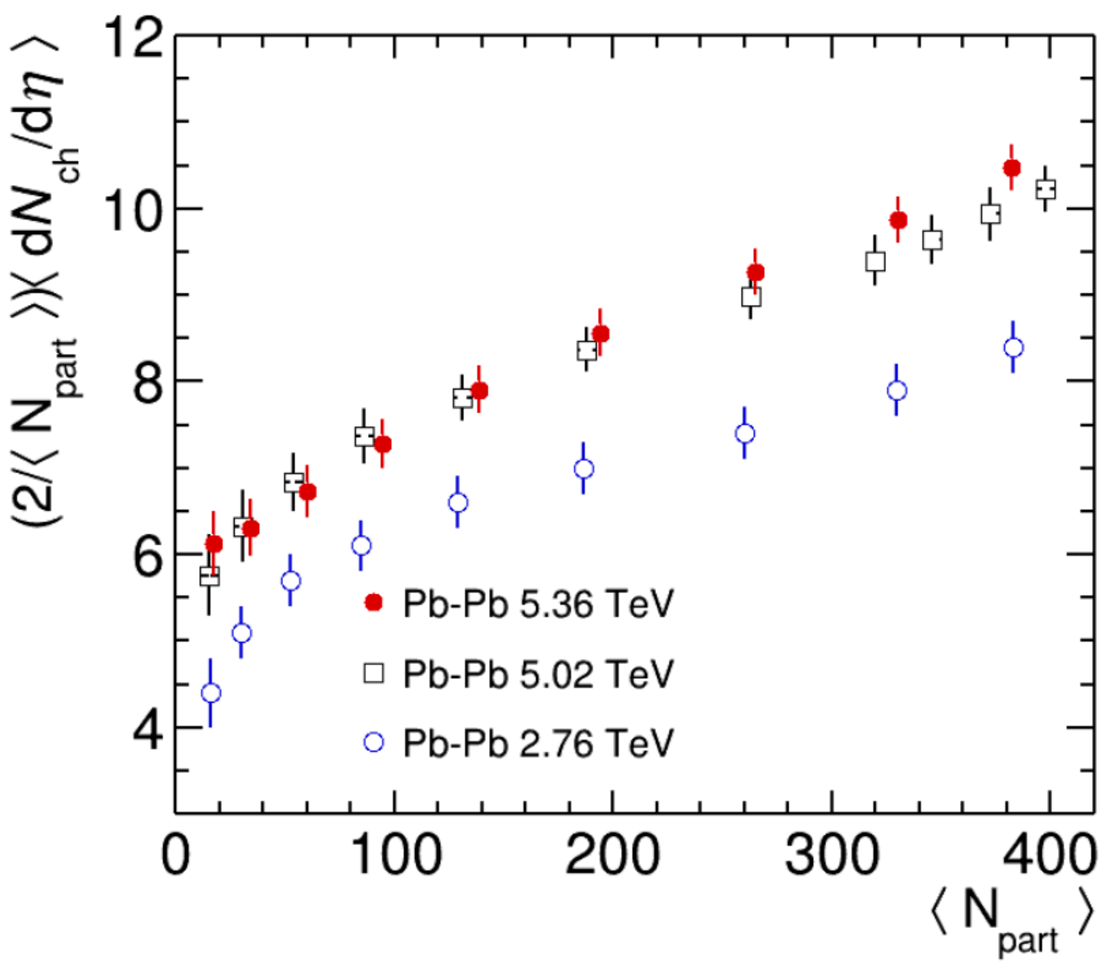
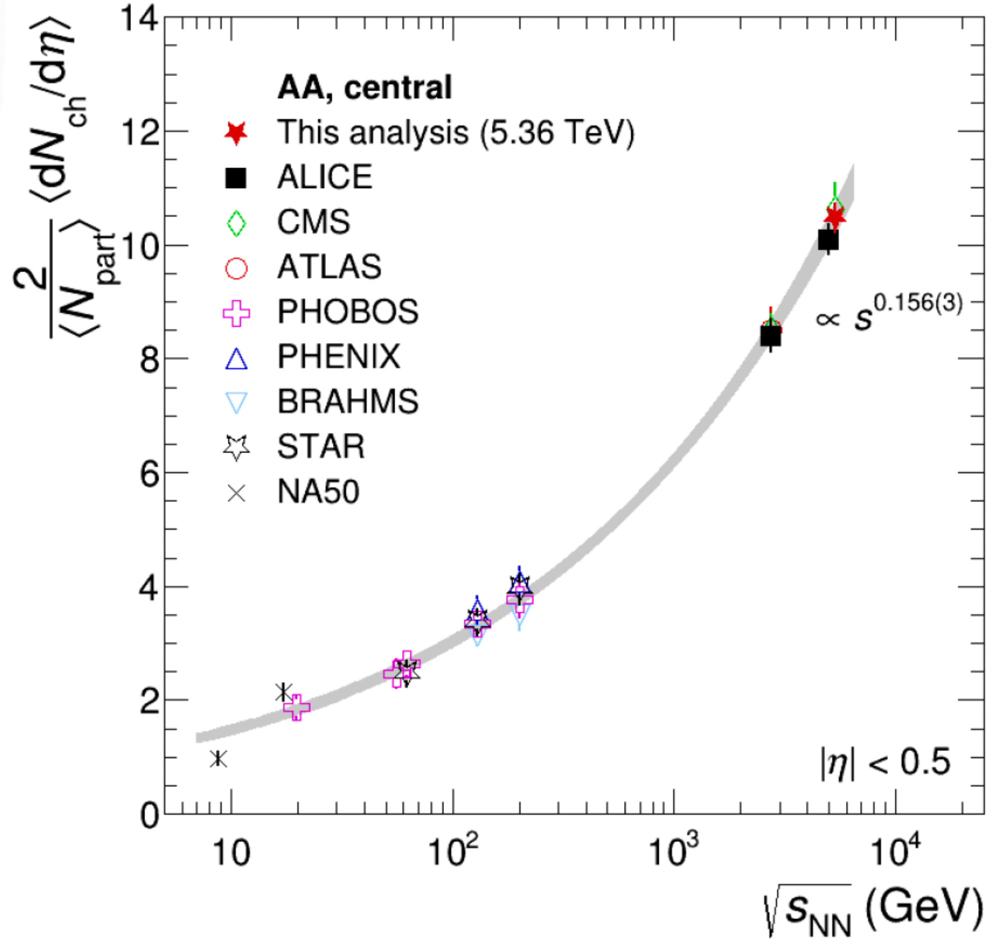
- Already now **challenging** the **precision** of the **Run 2** measurement.
- **Favours coalescence** model **versus SHM** production in **pp collisions**.

ALICE

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

Charged-particle dN/dη

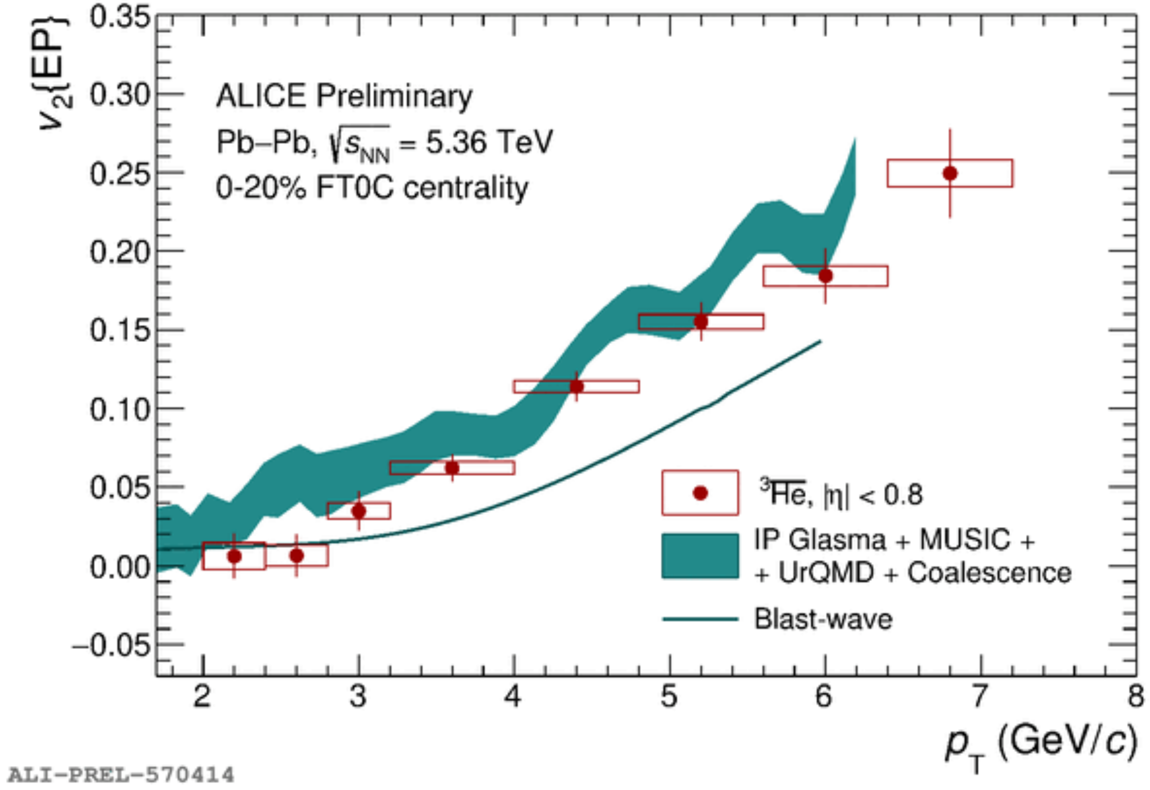


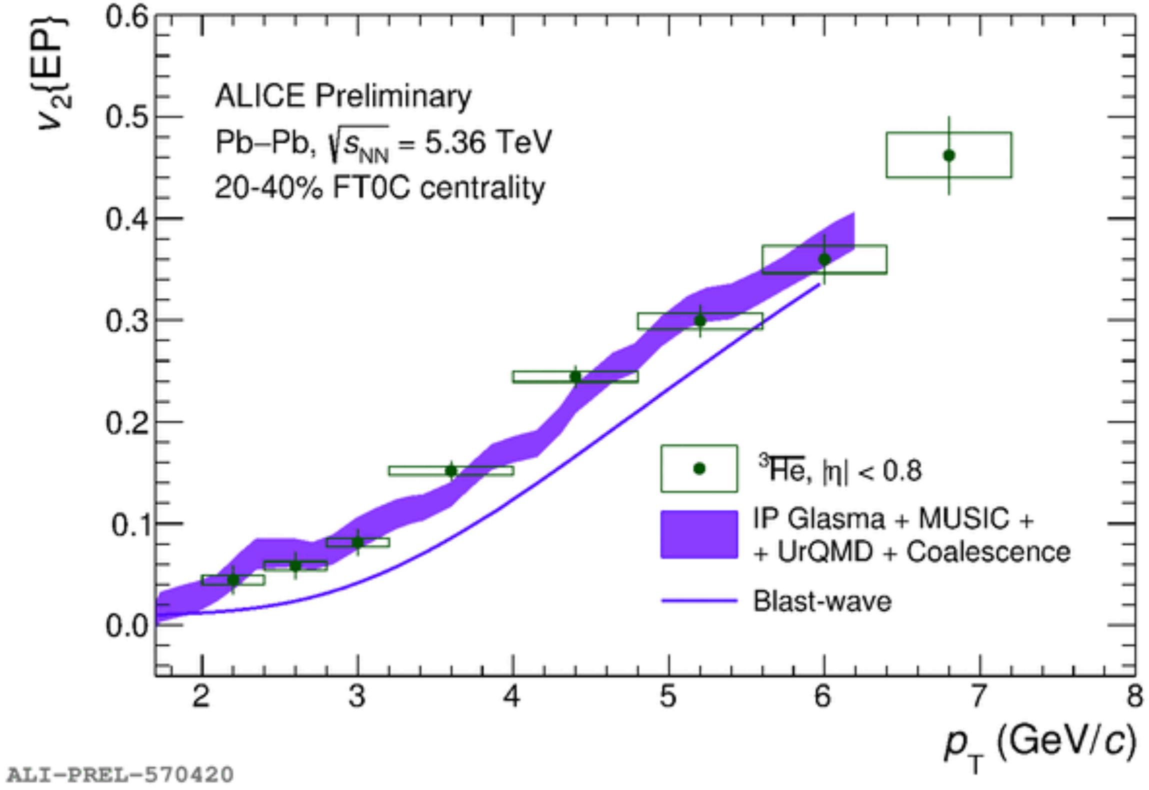


Important **baseline measurement** is in **agreement** with lower energy data

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

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

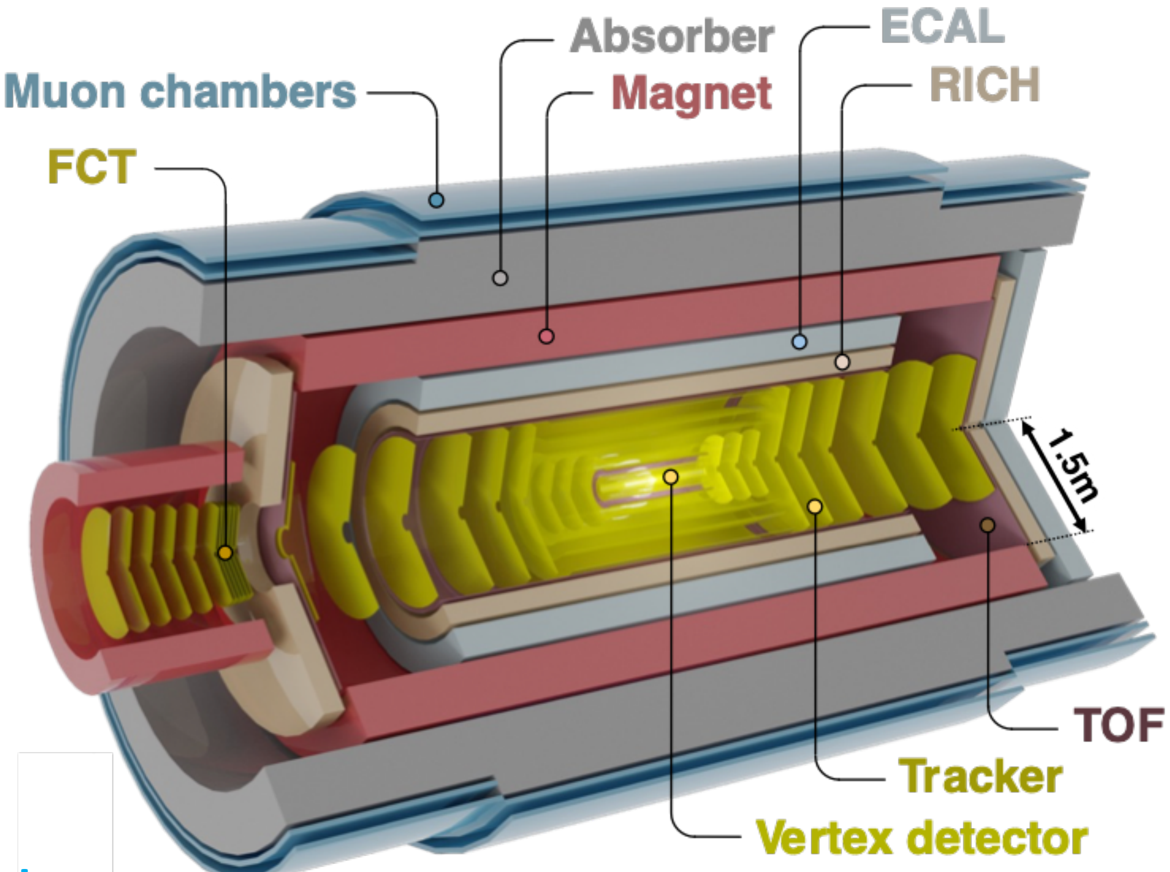
large acceptance with excellent coverage down to low p_T

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**

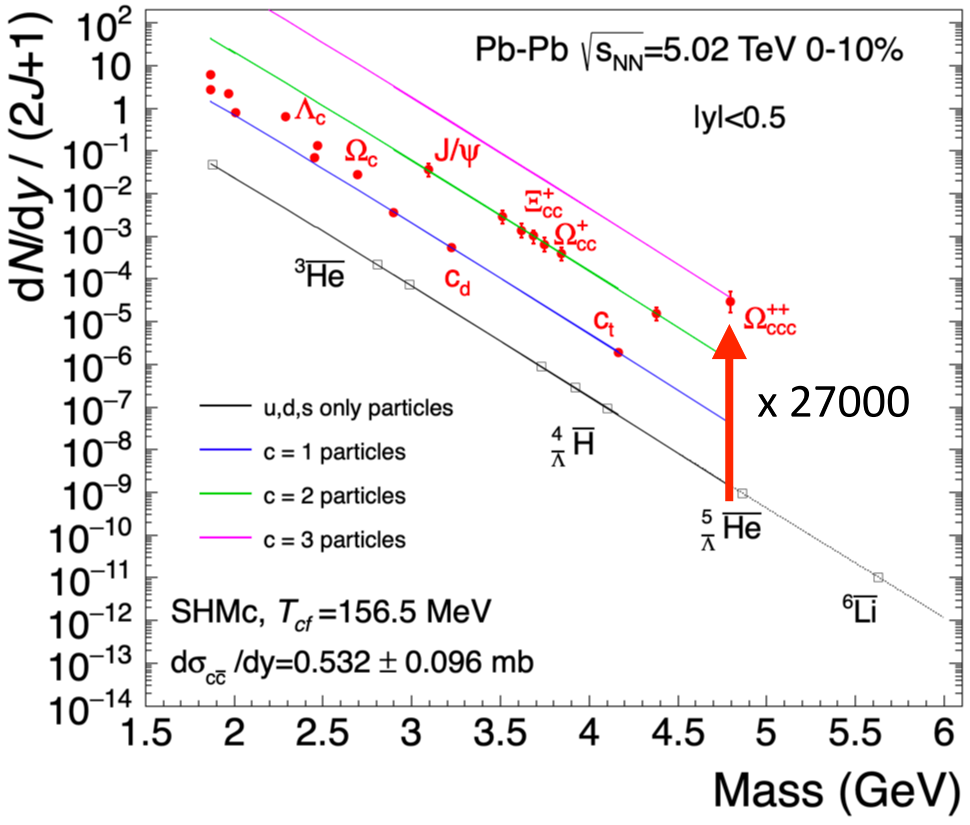
⇨ **novel technologies relevant for future HEP and NP programs**

ACCEPTANCE × INTERACTION RATE: NEW OPPORTUNITIES

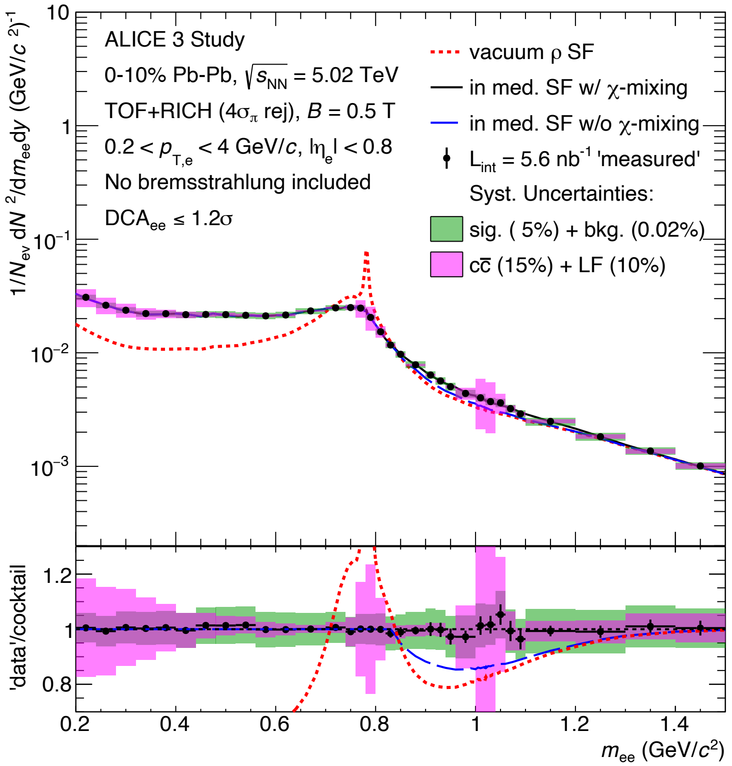
ALICE

Multiply-charmed baryons

CERN-LHCC-2022-009



access $\rho - a_1$ mixing



→ **charm oversaturated** through direct production
→ **factor 30** per **charm quark**, discovery potential

chiral symmetry restored in quark-gluon plasma
→ explain **origin** of **99%** of **visible mass** in universe

CONCLUSIONS

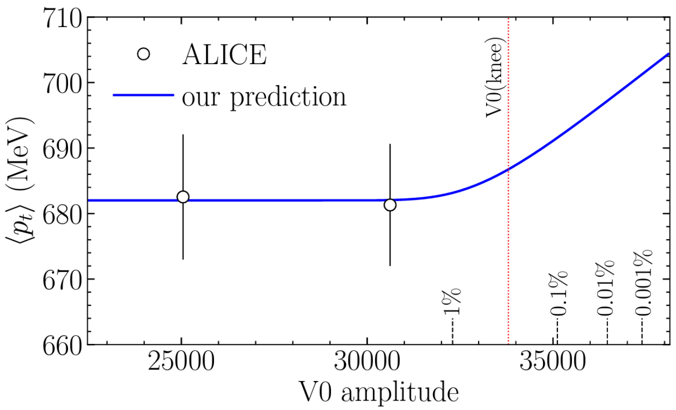
- ALICE has a **broad physics** program adressing **non-perturbative QCD** and **high-field QED** in **pp**, **p-Pb** and **Pb-Pb** collisions at the LHC
- ALICE is **successfully recording** data in **Run 3** with the **upgrades**
- **ALICE 3** upgrade provides **long-term** continuation during **entire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

backup

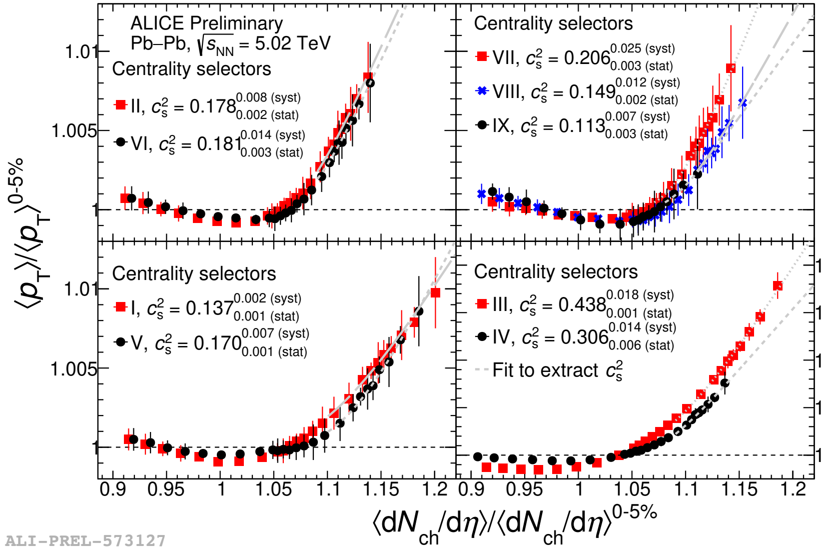
Mean p_T versus multiplicity: speed of sound?

ALICE

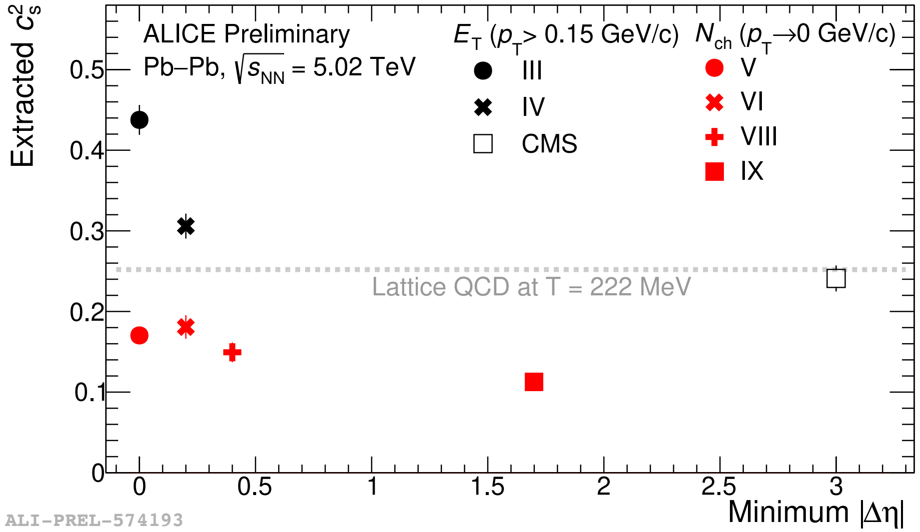
$\langle p_T \rangle$ vs $dN/d\eta$



$\langle p_T \rangle$ 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

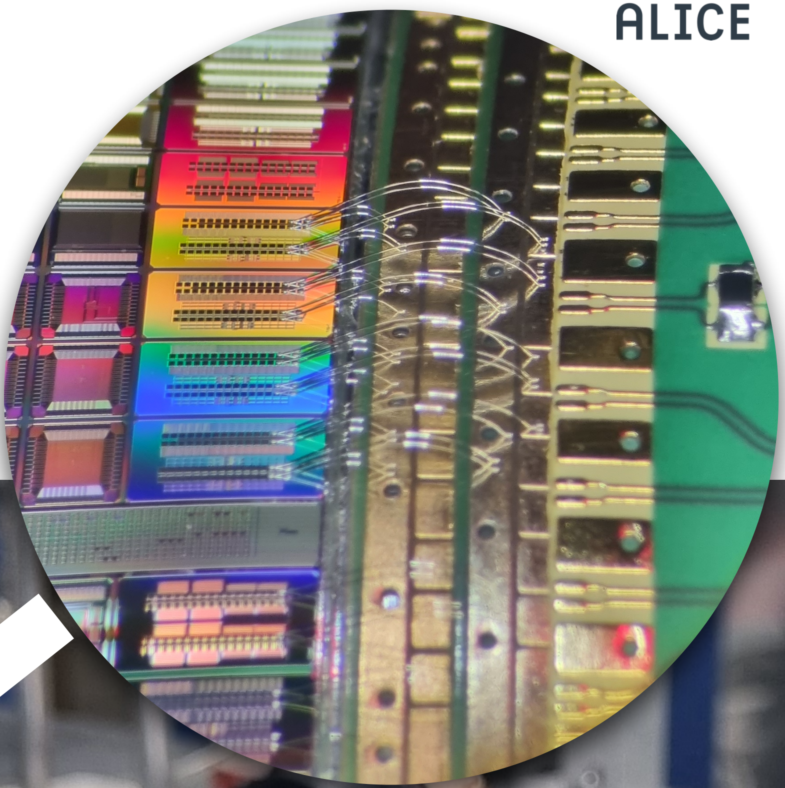
Slope of $\langle p_T \rangle$ vs $dN/d\eta$ depends on centrality estimator:
E_T-based selection give larger c_s than multiplicity-based

Observable less robust than initially thought?

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

ITS3: ELECTROMECHANICAL INTEGRATION

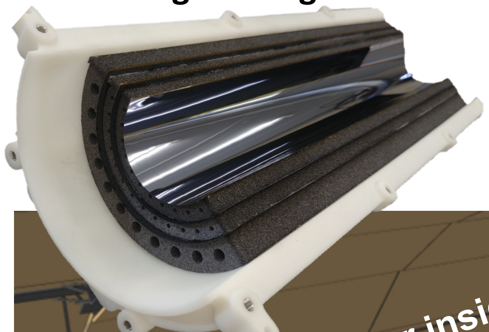
- Latest assembly: L0 using “chips”/a section from an existing CMOS wafer
- Wire-bonded to an FPC after bending

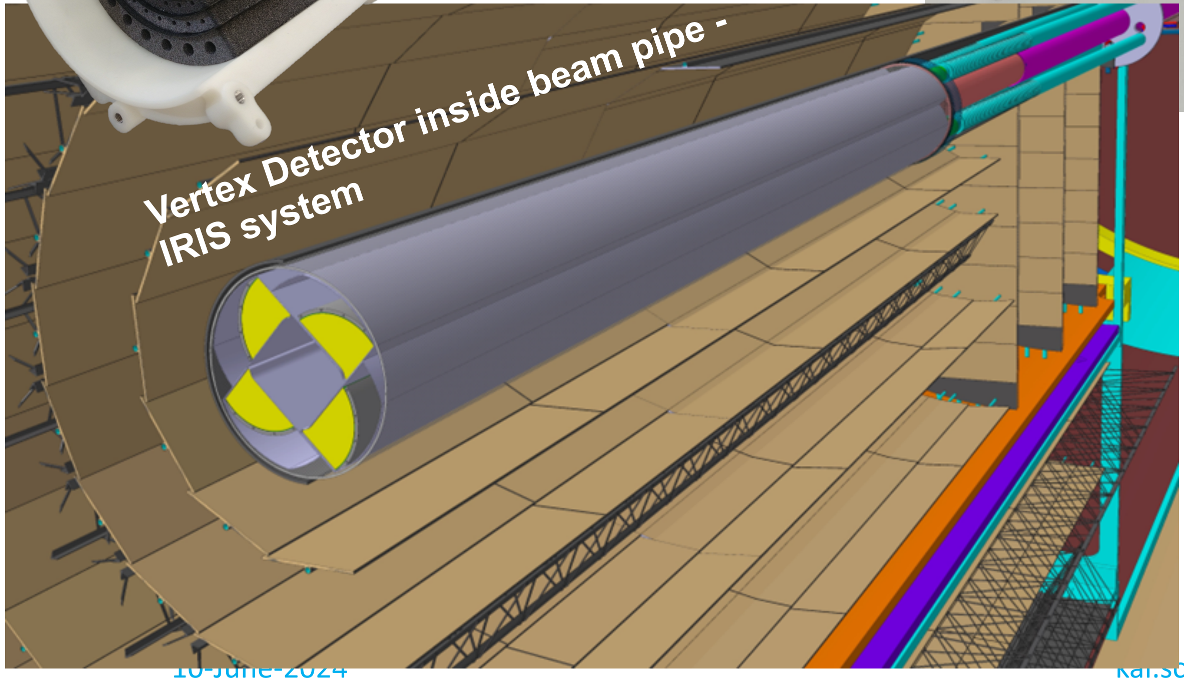


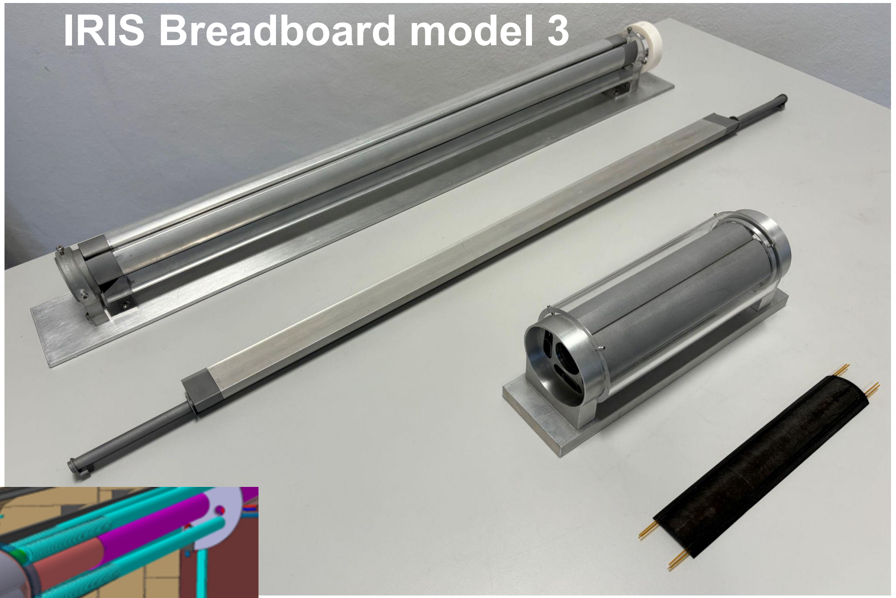
R&D FOR INNER TRACKER

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

ITS3 engineering model 2







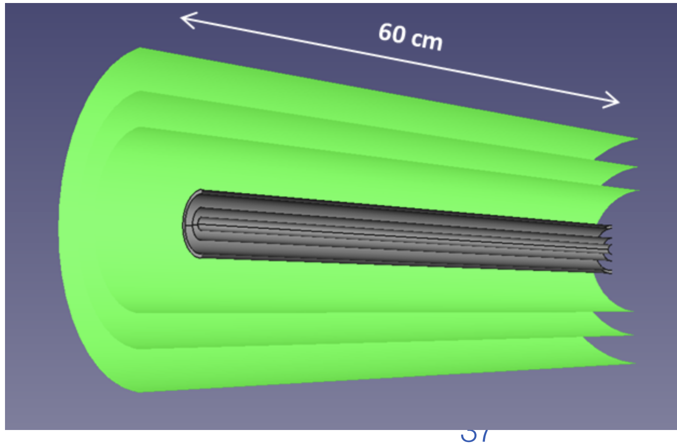
IRIS system:

- 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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ALICE

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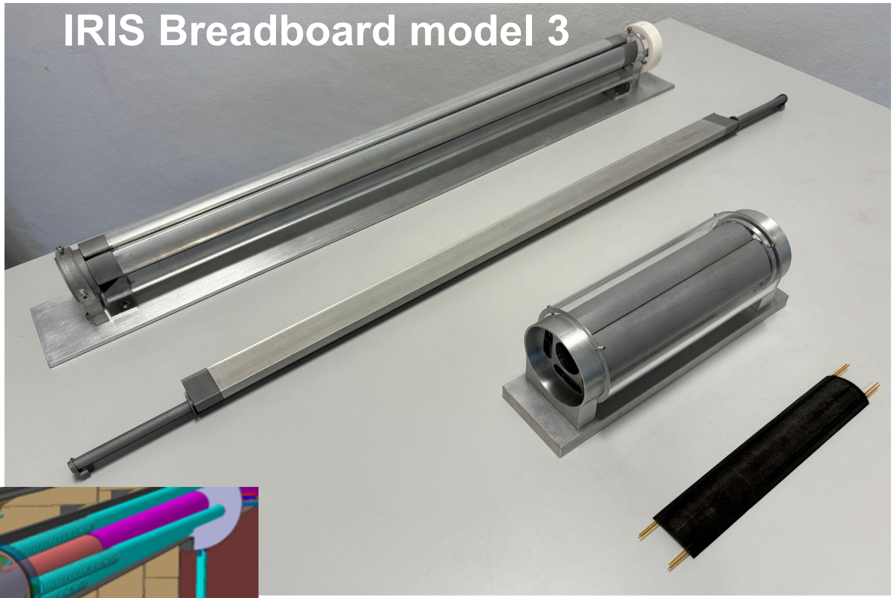

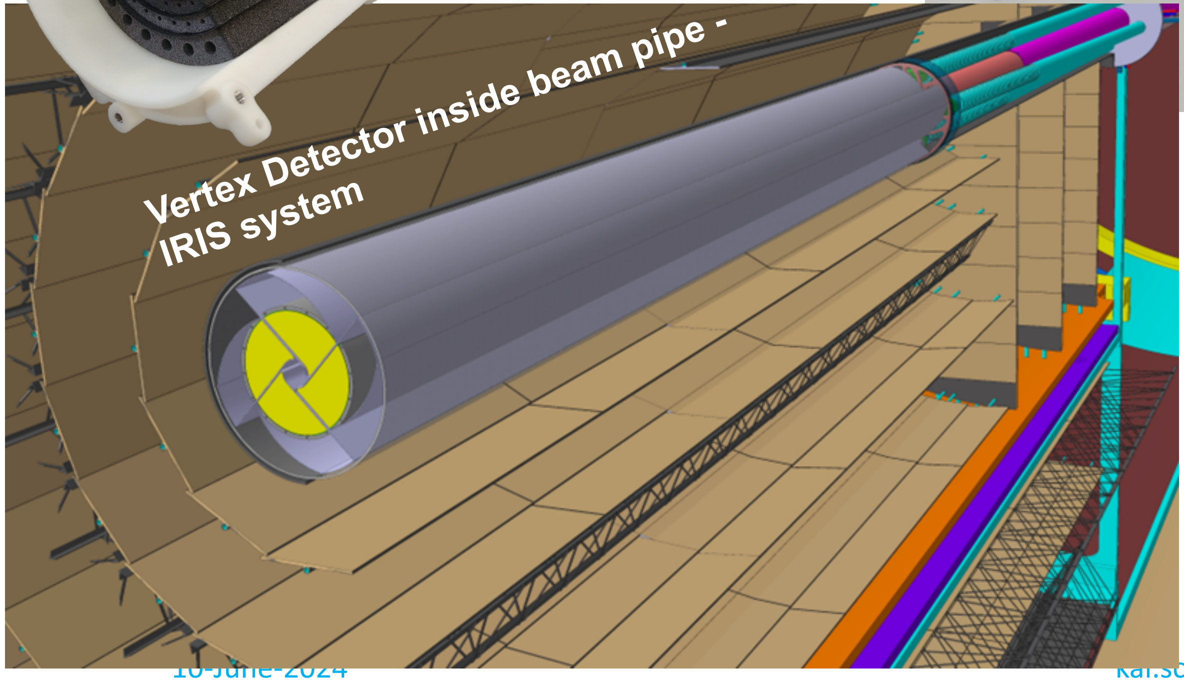

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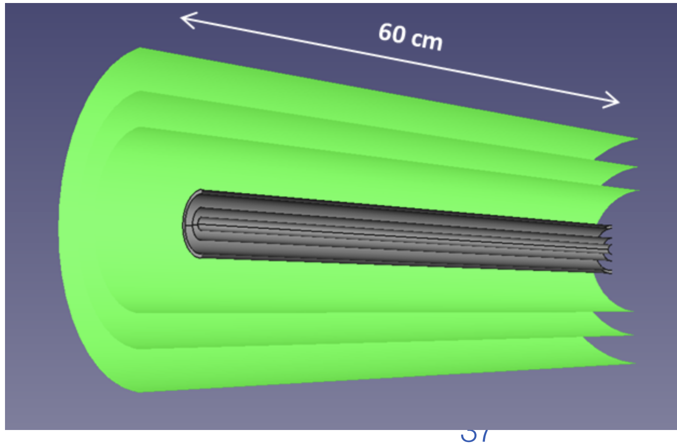

CHEMICAL FREEZE-OUT MODEL

Hadron resonance ideal gas

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

Density of particle *i*

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

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

- 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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