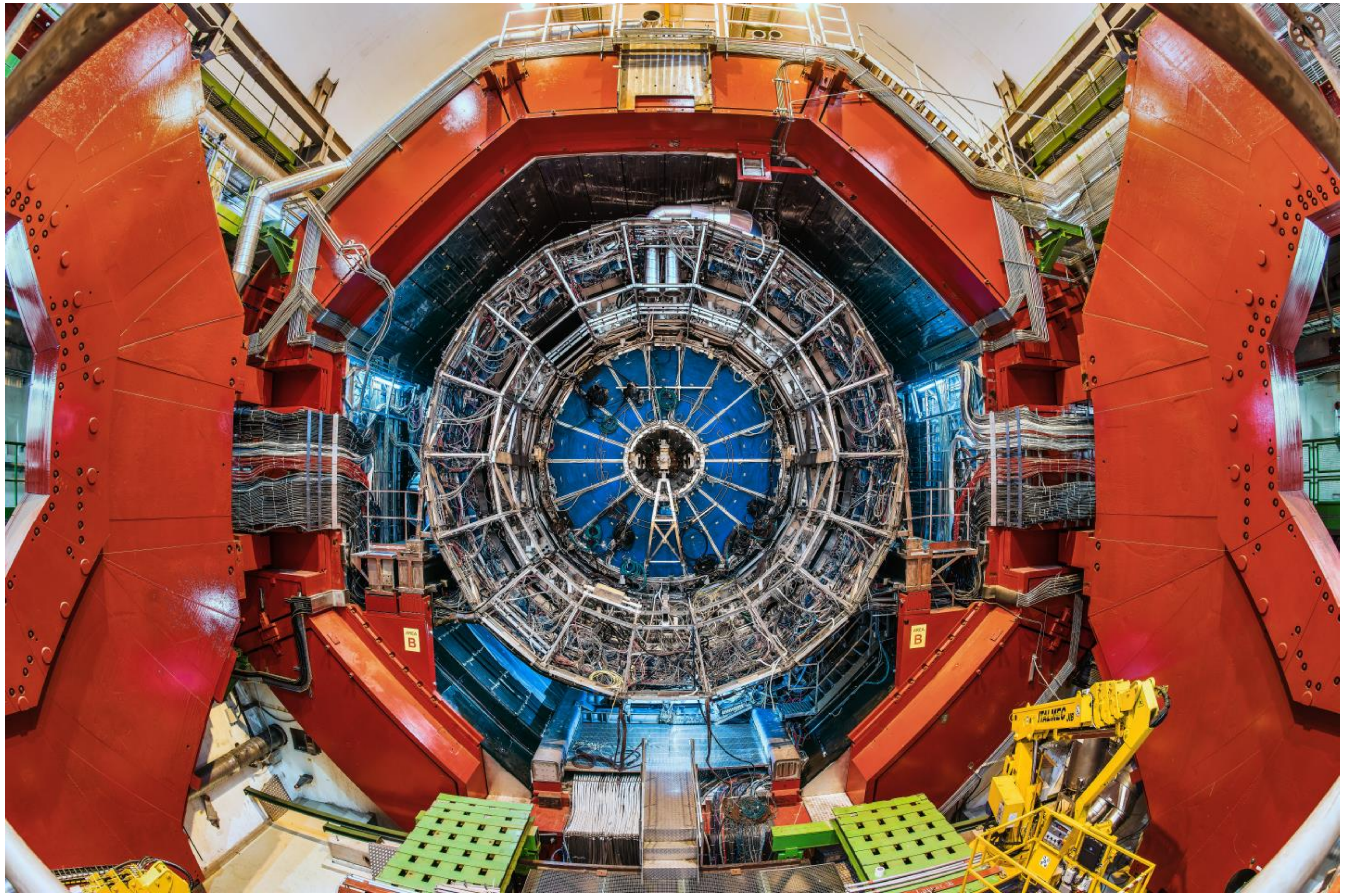
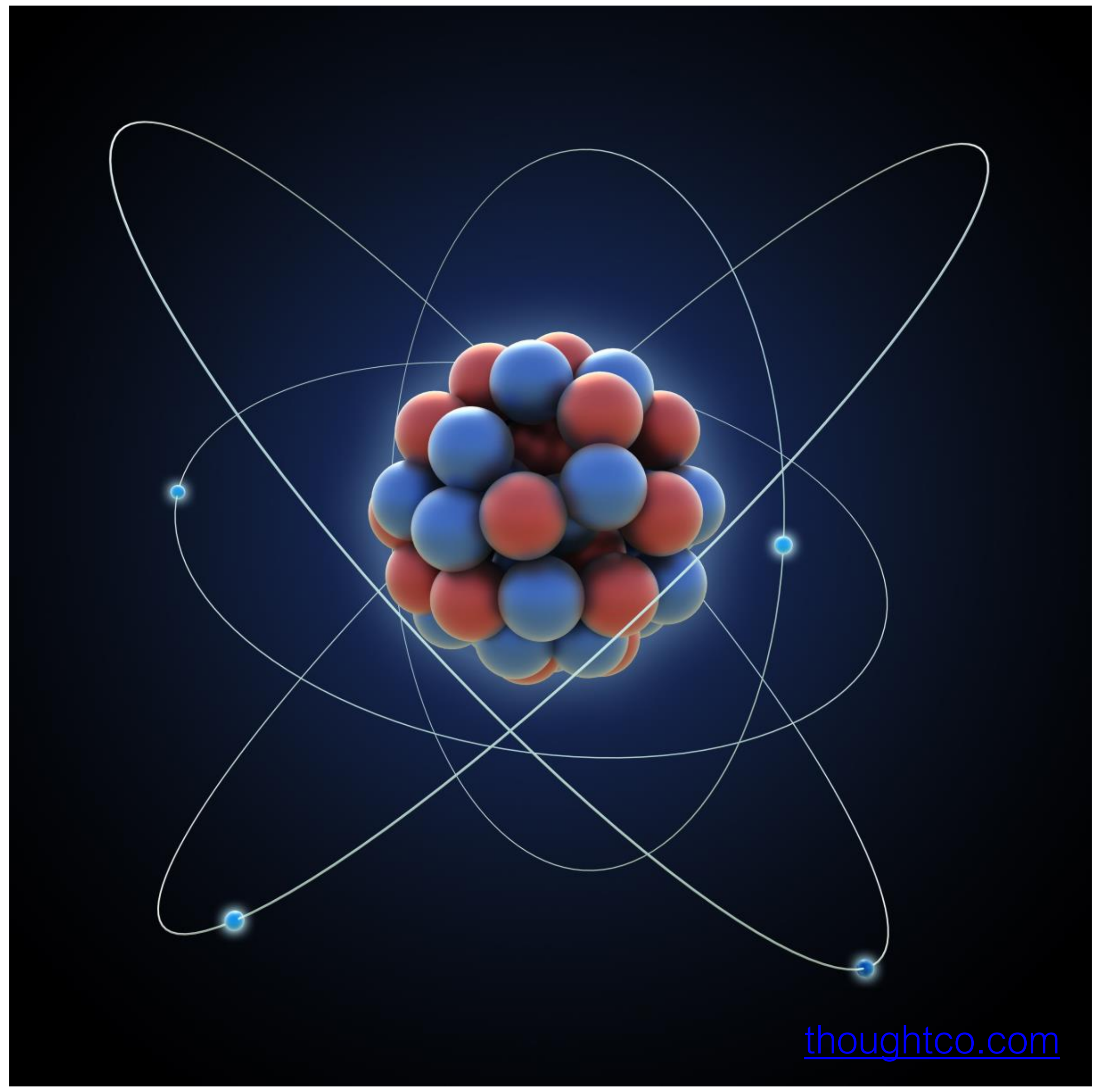
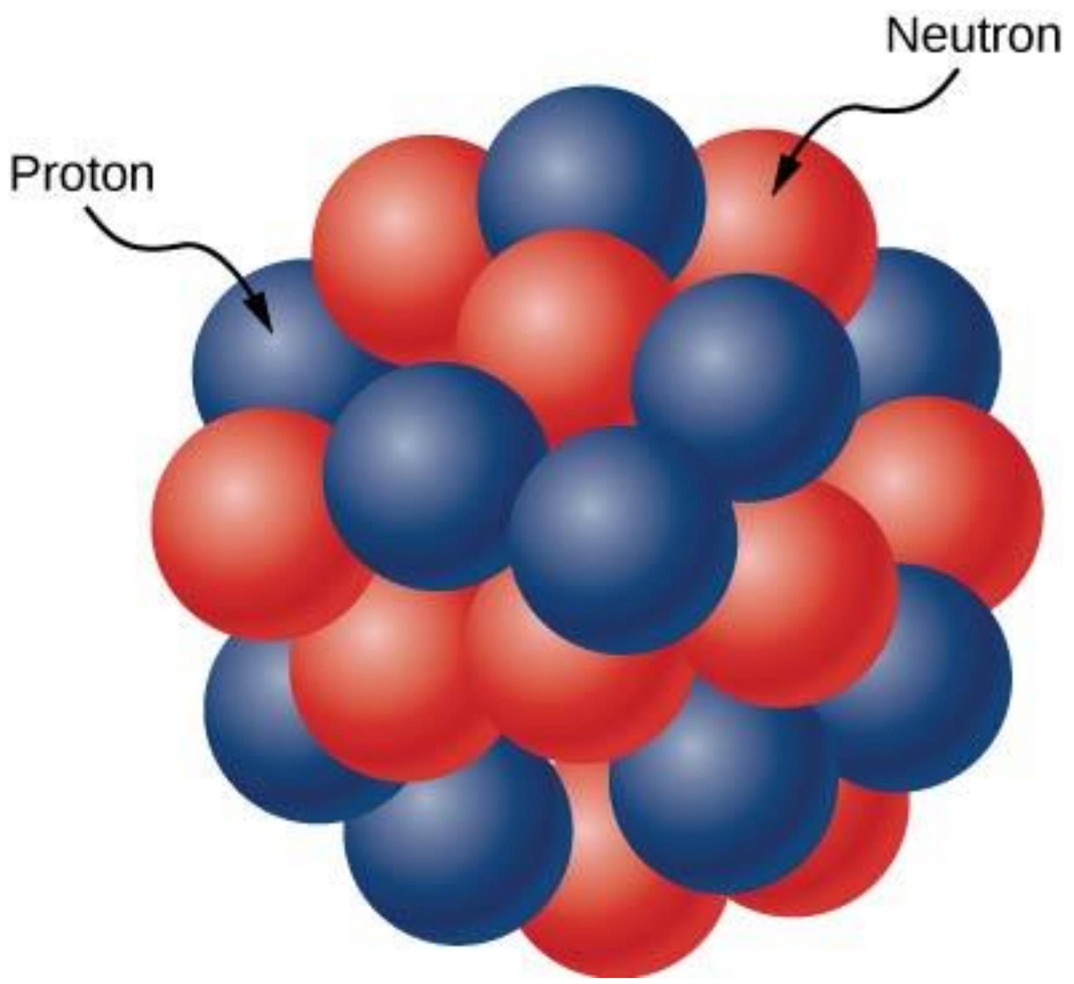
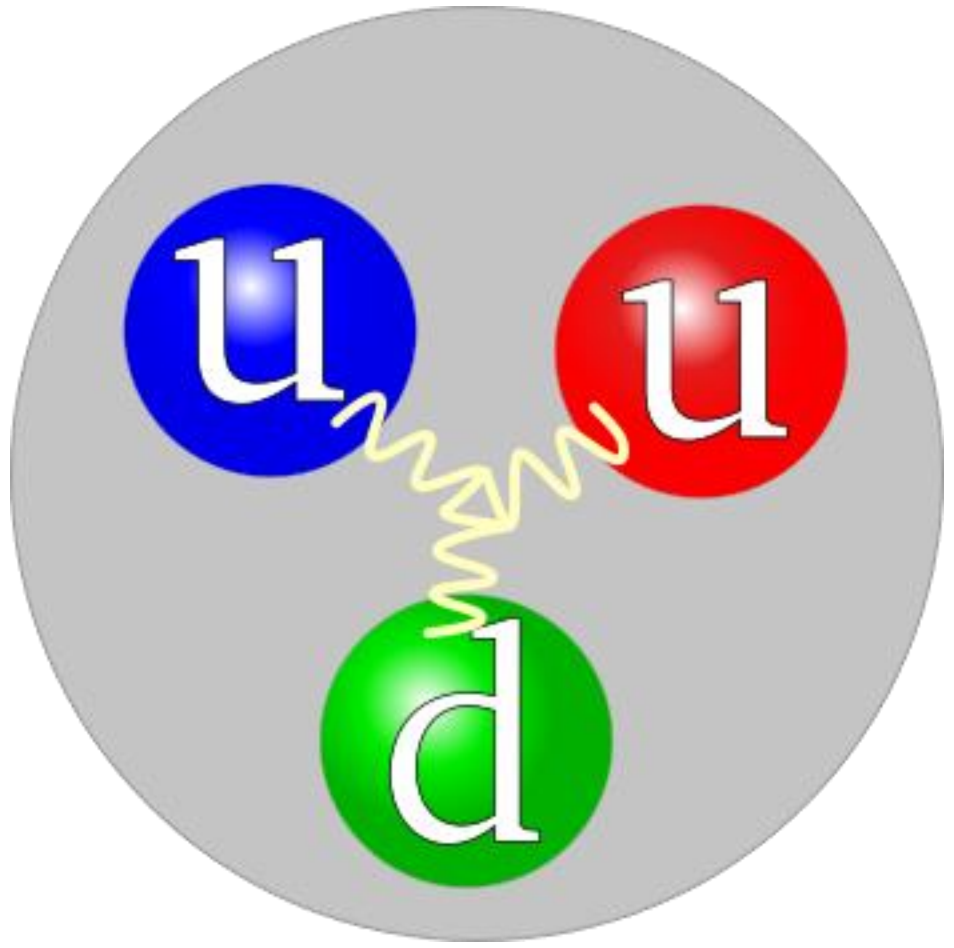
The ALICE experiment
Where are we now?

Marco van Leeuwen, Nikhef and CERN

SA-CERN 15 years workshop
20-21 January 2025
iThemba Labs, Summerset West



Matter and energy scales — temperatures

Atom	Atomic nucleus	Hadron (proton)
		

Wikimedia Commons image by Jacek Rybak

Binding force: electromagnetic

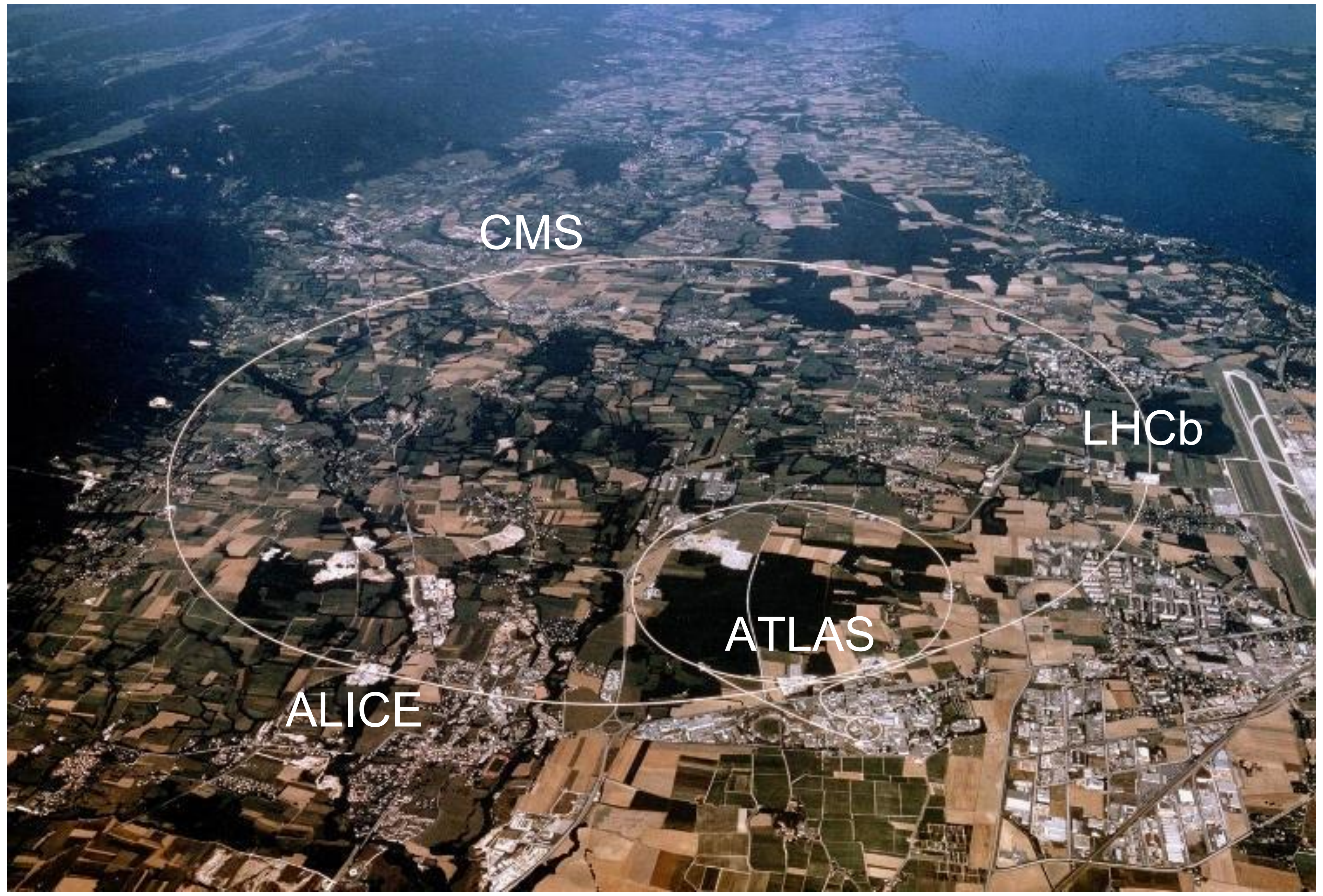
Binding force: strong nuclear force

	Atom	Atomic nucleus	Hadron (proton)
Binding energy	5 eV - 100 keV	1 - 10 MeV	> 100 MeV
Temperature (K)	10^4 - 10^9	10^{10} - 10^{11}	10^{12}

Heavy-ion collisions: study properties of strongly interacting ‘bulk’ matter — Quark-Gluon Plasma and understand how they emerge from the underlying theory

ALICE at the Large Hadron Collider

The Large Hadron Collider

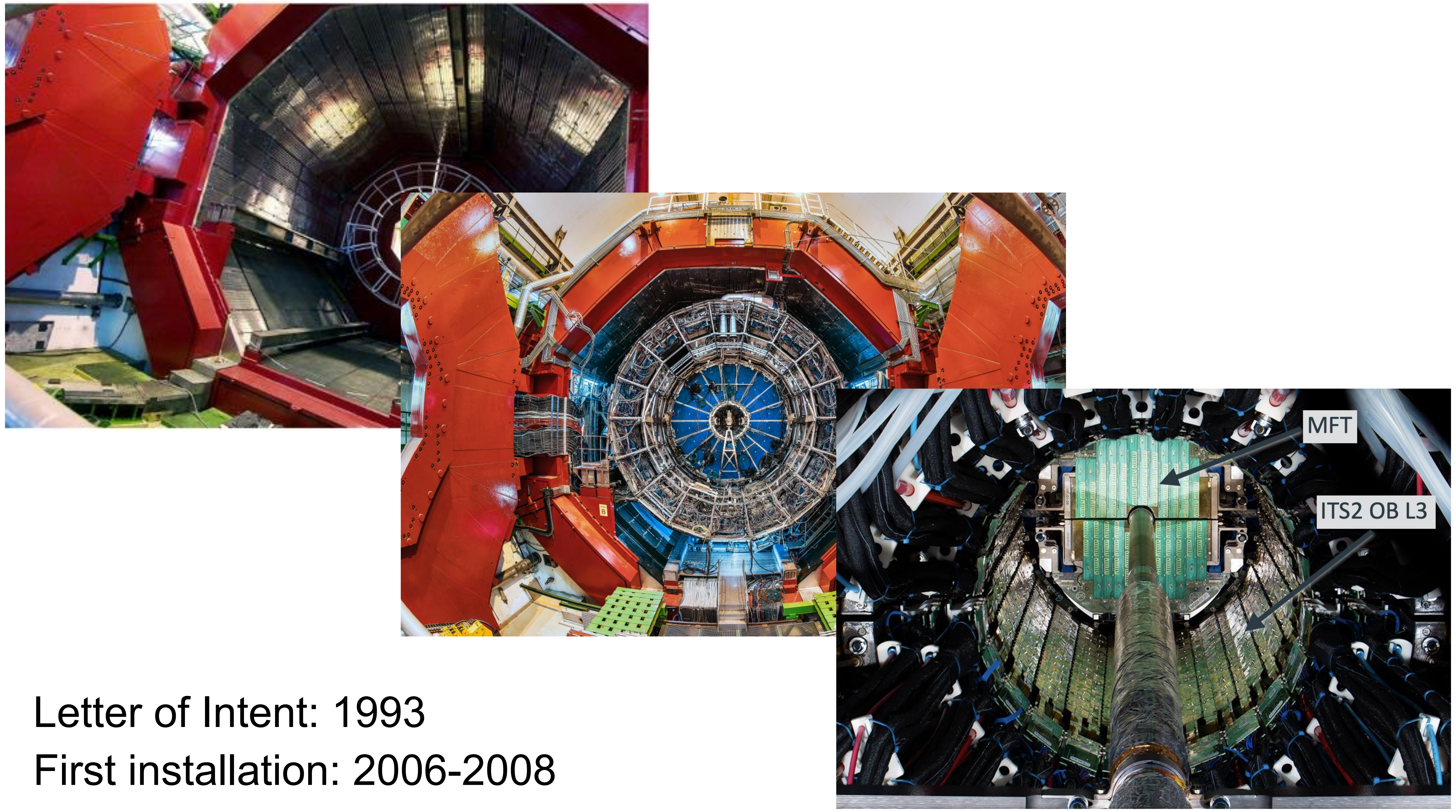


pp collisions $\sqrt{s}$ = 7, 8, 13, **13.6 TeV**

Pb-Pb collisions: $\sqrt{s_{NN}}$ = 2.76, 5.02, **5.36 TeV**

other systems: p-Pb, Xe-Xe, O-O, p-O

ALICE: A Large Ion Collider Experiment

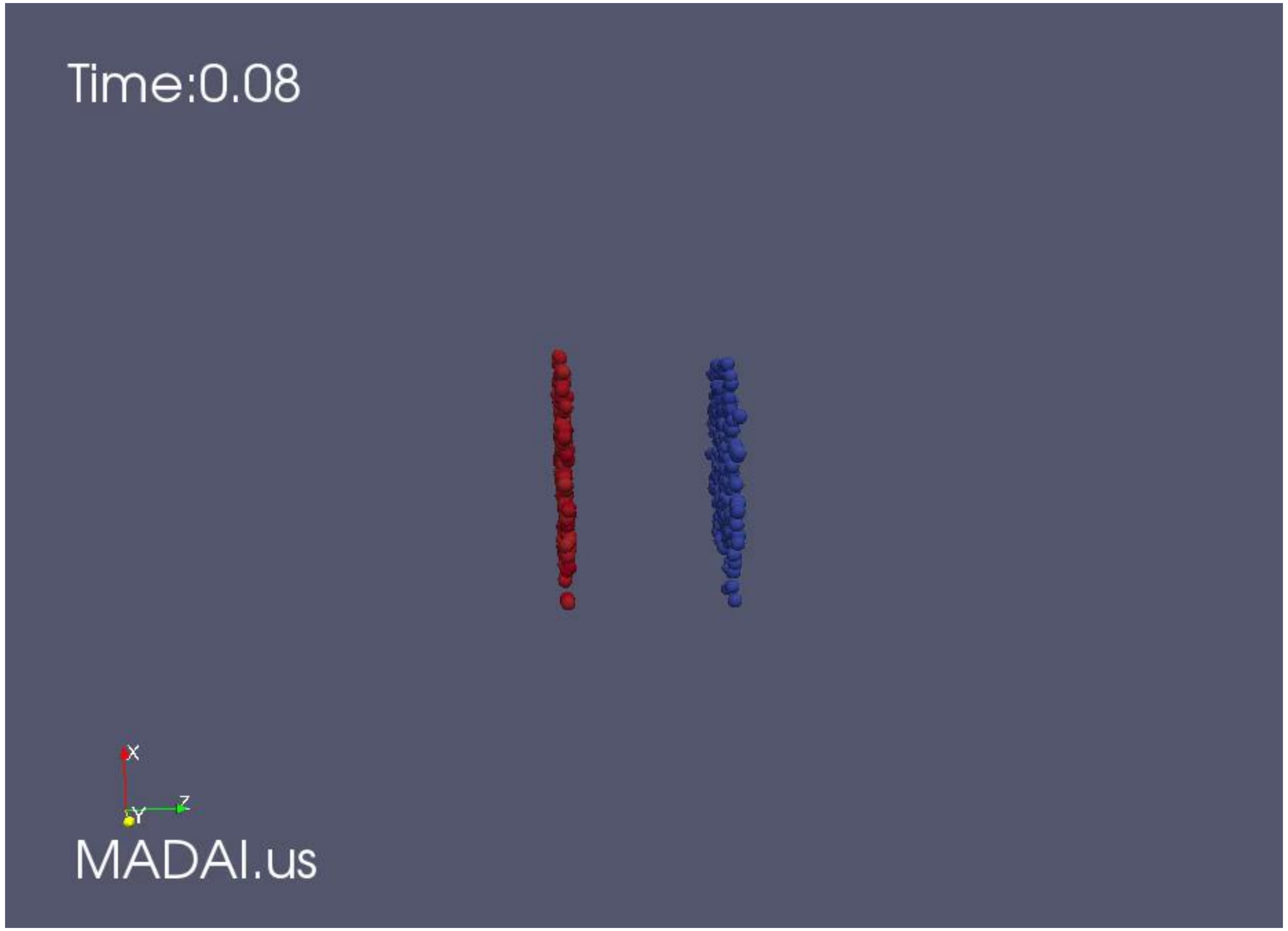


Letter of Intent: 1993
First installation: 2006-2008
Major upgrades installed: 2018-2022

Low-mass detectors — **excellent pointing resolution**
Particle identification: dE/dx in TPC, TRD, TOF, HMPID, EMCal, Muon system

Upgraded to streaming readout, 50 kHz PbPb

Heavy ion collisions: Little Bangs



MADAI

Stages of the collision: initial stages — QGP/fluid stage — hadron formation (freeze out)

'Little Bang': recreate primordial matter in the laboratory

ALICE: A Large Ion Collider Experiment

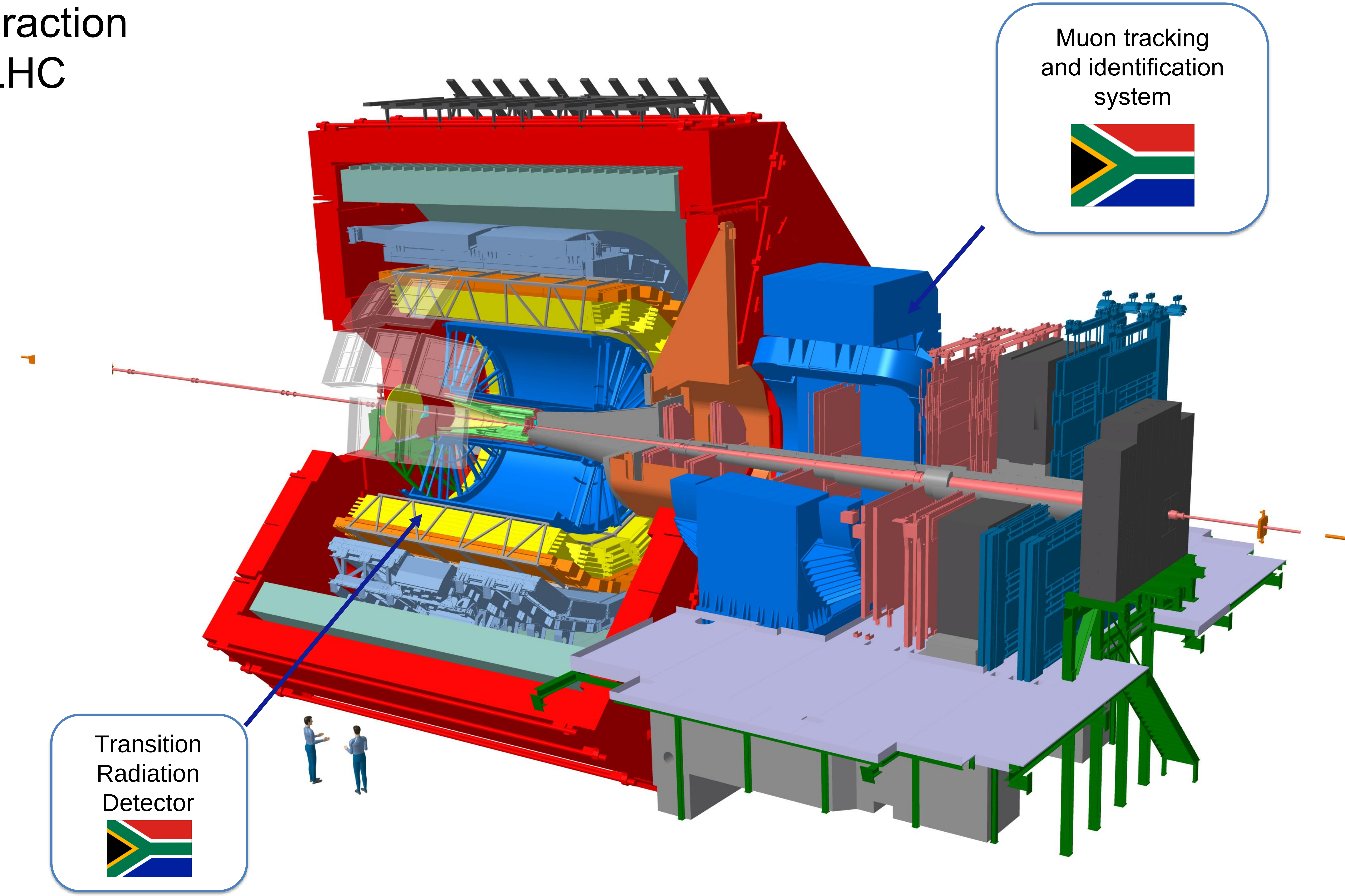
Optimised to study the strong interaction
in Heavy-ion collisions at the LHC

Particle tracking at high multiplicity

- Inner Tracking System and Time Projection Chamber
- Low material budget
- High granularity and pointing resolution

Particle identification

- Time Projection Chamber
- Transition Radiation Detector
- Time-of-Flight system
- High-momentum PID
- Calorimeters: EMCal, PHOS
- Muon systems (fwd direction)



ALICE collaboration

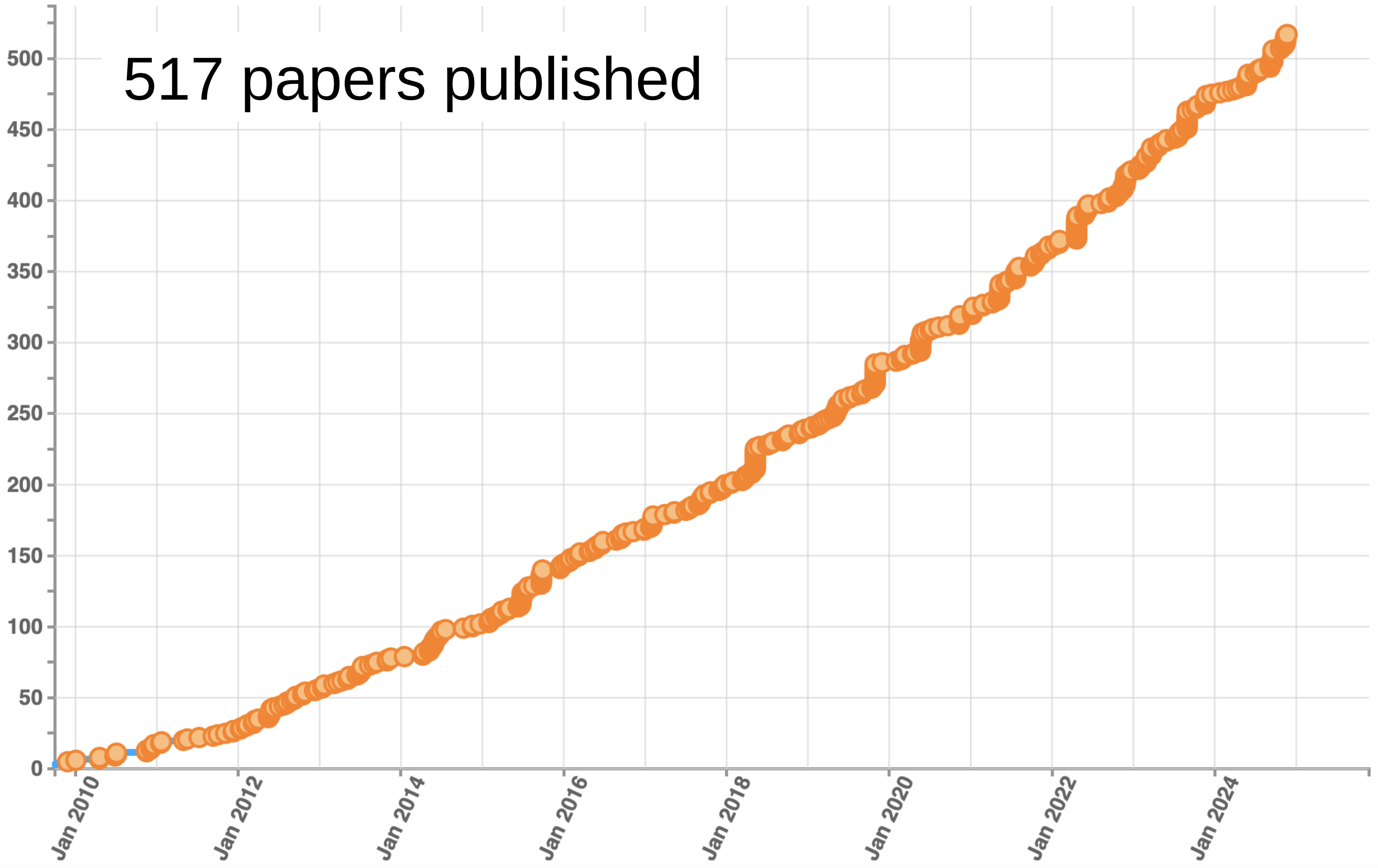
- 1069 authors, 1944 members
- 157 member institutes, 24 associate
- 40 countries

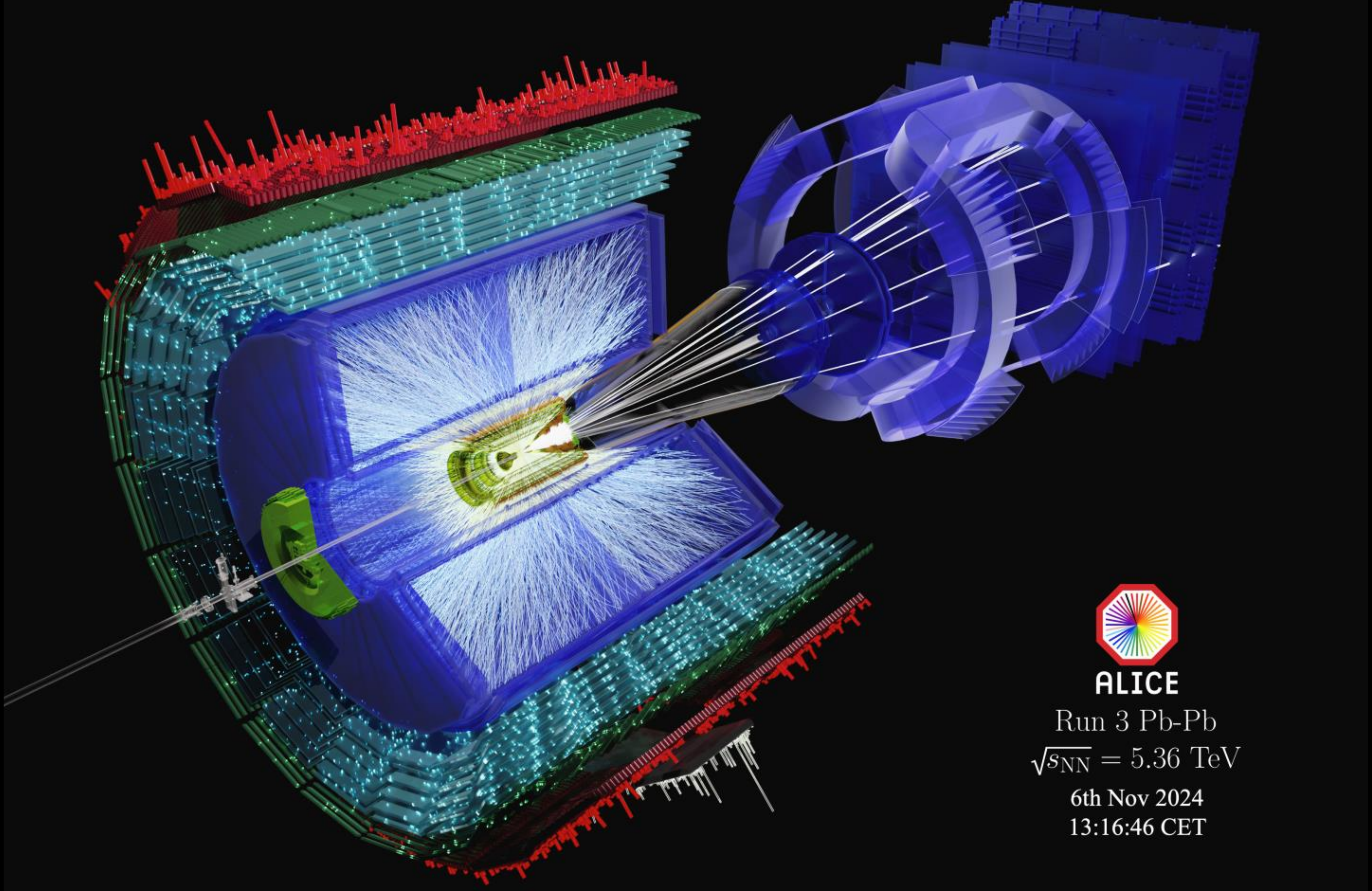
SA: iThemba, UCT, Wits, CHPC
+ collaborating Universities

ALICE Week March 2024 at CERN

Broad physics program on *multi-body dynamics of QCD*

- Properties and formation of quark gluon plasma
- Hadron production and multi-parton interaction in pp and p-Pb collisions
- Ultra-peripheral collisions
- Hadron structure and interactions




ALICE
Run 3 Pb-Pb
$\sqrt{s_{NN}} = 5.36$ TeV
6th Nov 2024
13:16:46 CET

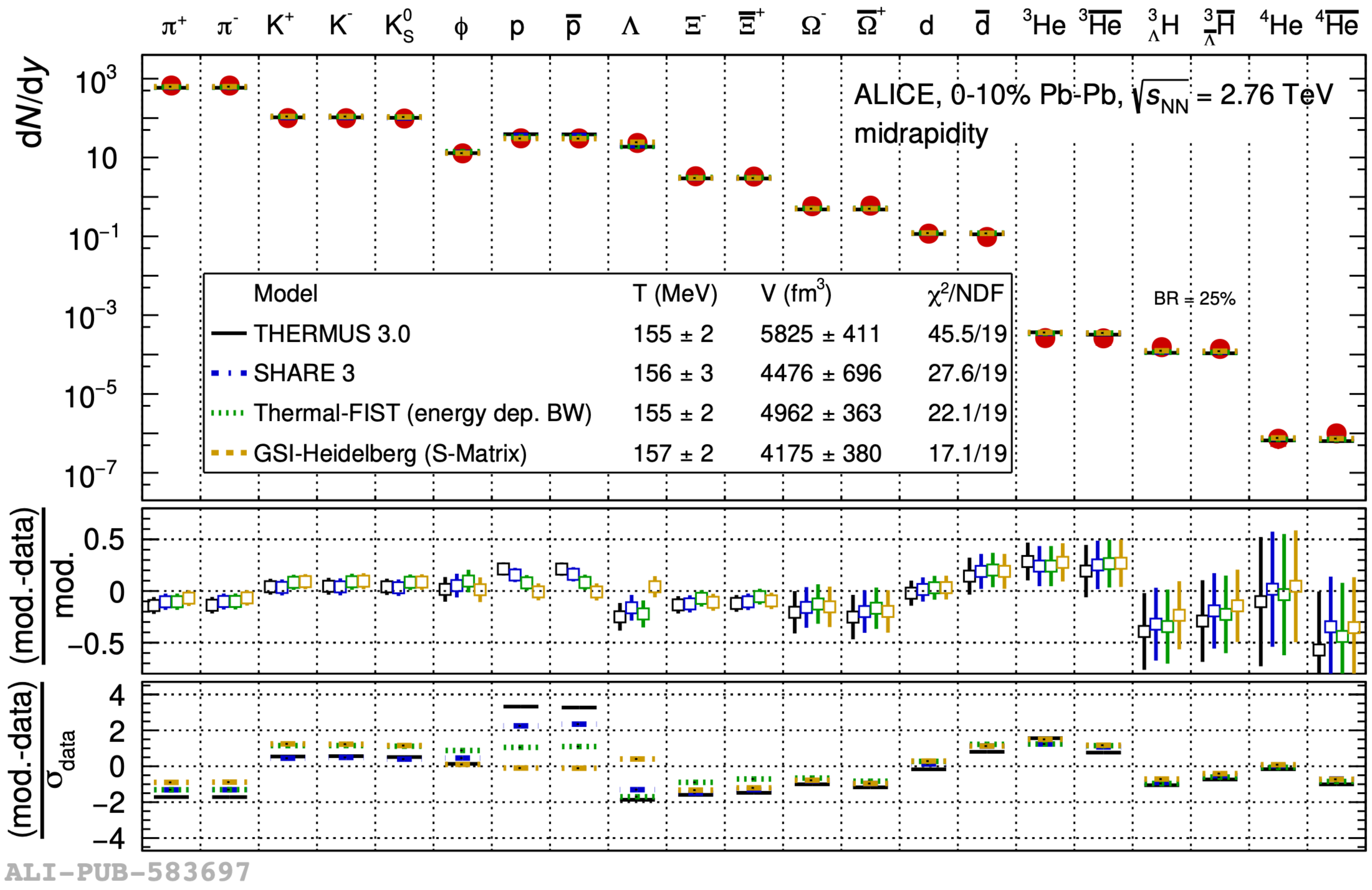
Measuring the temperature: particle yields

Particle yields follow a thermal distribution

$$N_i = V2(J+1)e^{-m_i/T}$$

T = 156 ± 2 MeV

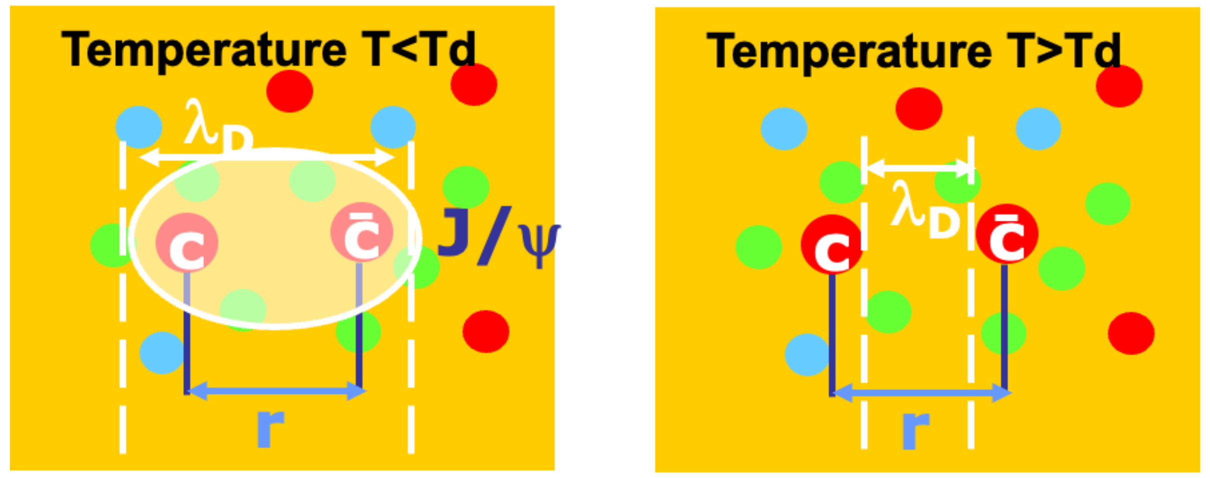
Yields determined by **single temperature: hadronic freeze-out**



Eur. Phys. J. C 84, 813

THERMUS: Weaton, Cleymans, et al
SHARE: Letessier, Rafelski et al
Thermal FIST: Vovchenko, Stöcker et al
GSI-Heidelberg: Andronic, Braun-Munzinger, Redlich, Stachel et al

Temperature: dissociation of quarkonia



Binding force screened when

$r > \lambda_d$

Binding of quarkonia

($b\bar{b}$, $c\bar{c}$ bound states) screened at high temperature, density

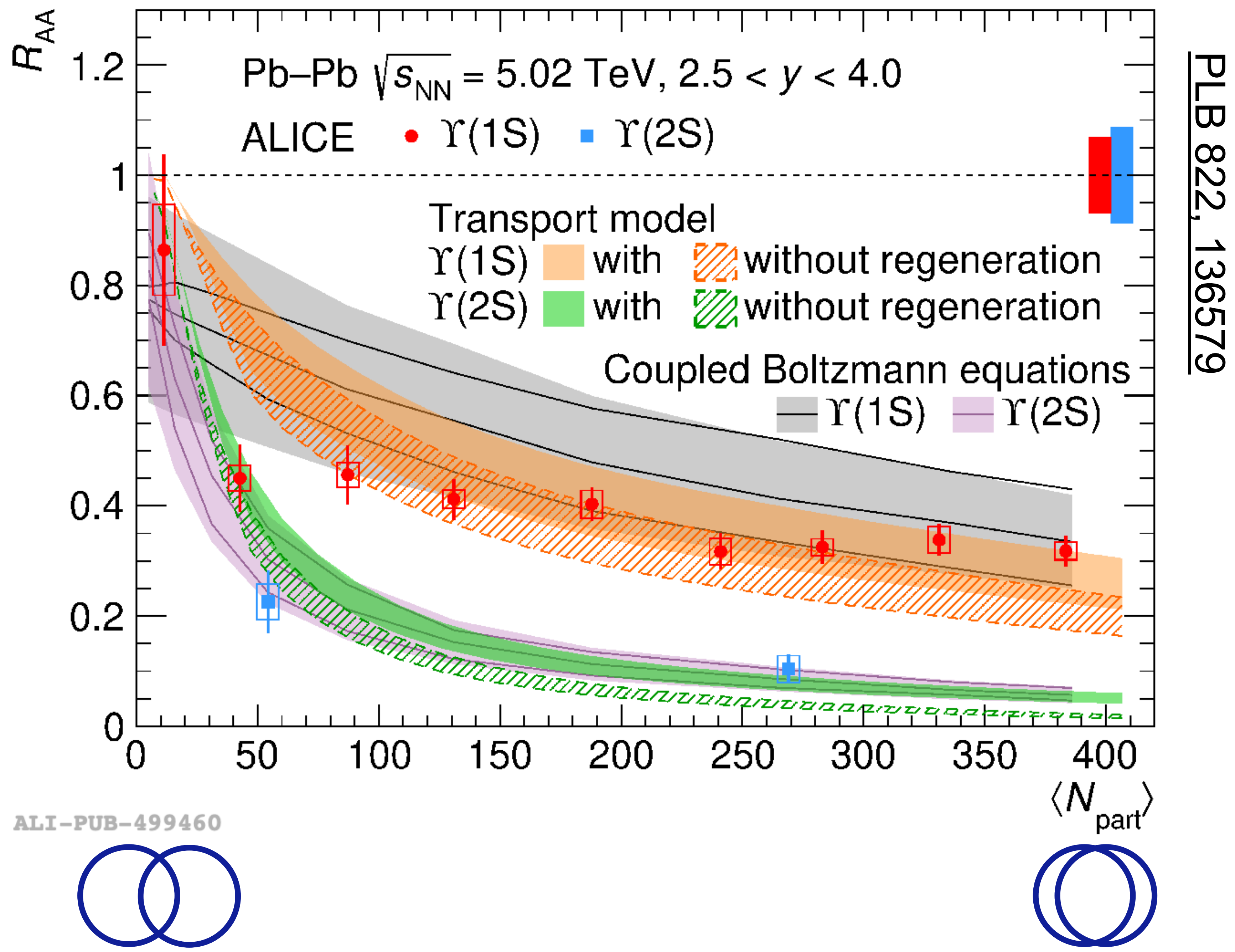
Nuclear modification factor

$$R_{AA} = \frac{dN/dp_T|_{AA}}{\langle N_{coll}\rangle dN/dp_T|_{pp}}$$

R_{AA} = 1: no effect

R_{AA} = 0: complete suppression

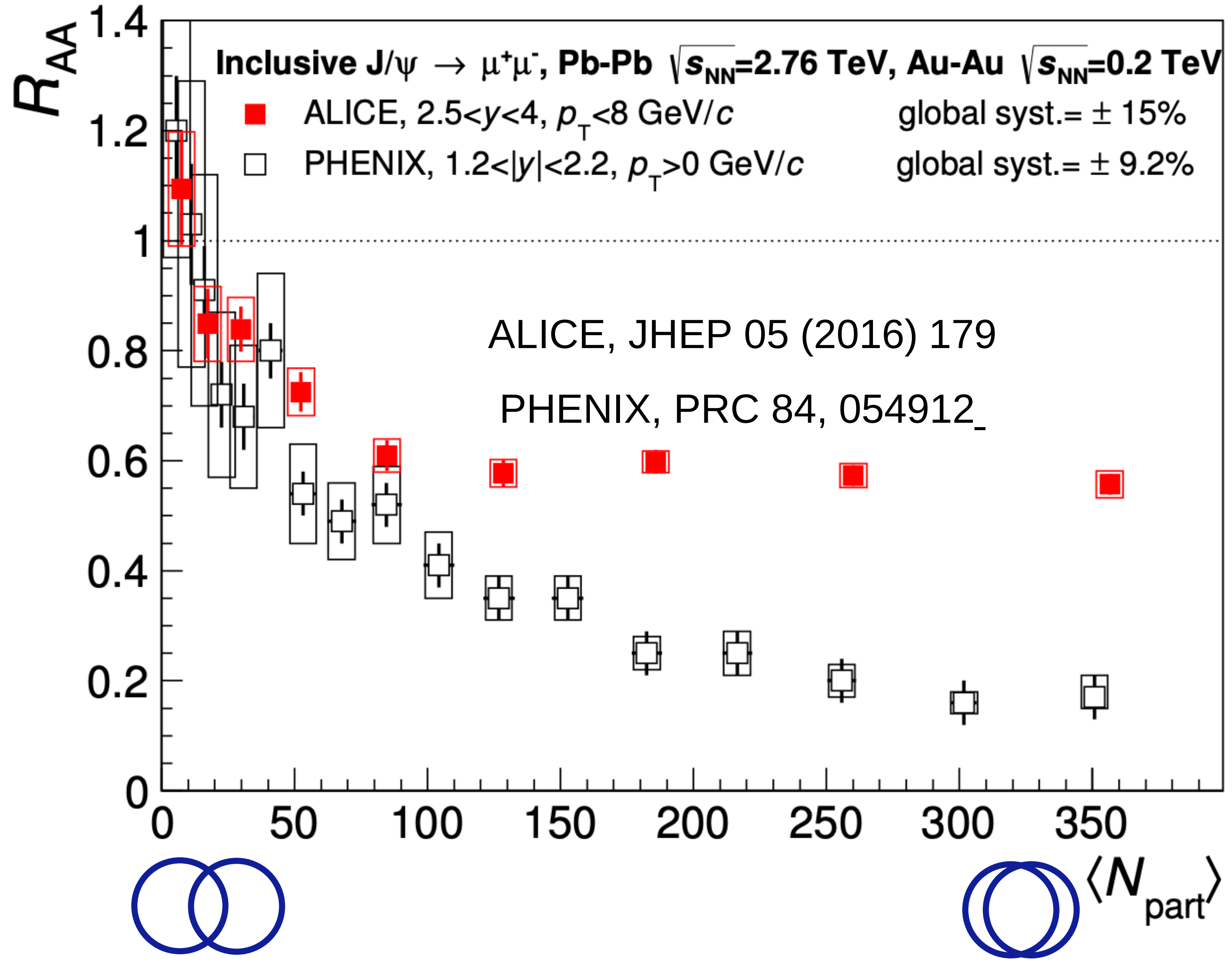
$\Upsilon(b\bar{b})$ nuclear modification vs centrality



Large suppression — dissociation in central events

Larger effect for higher states — weaker binding

$J/\psi(c\bar{c})$ modification vs centrality

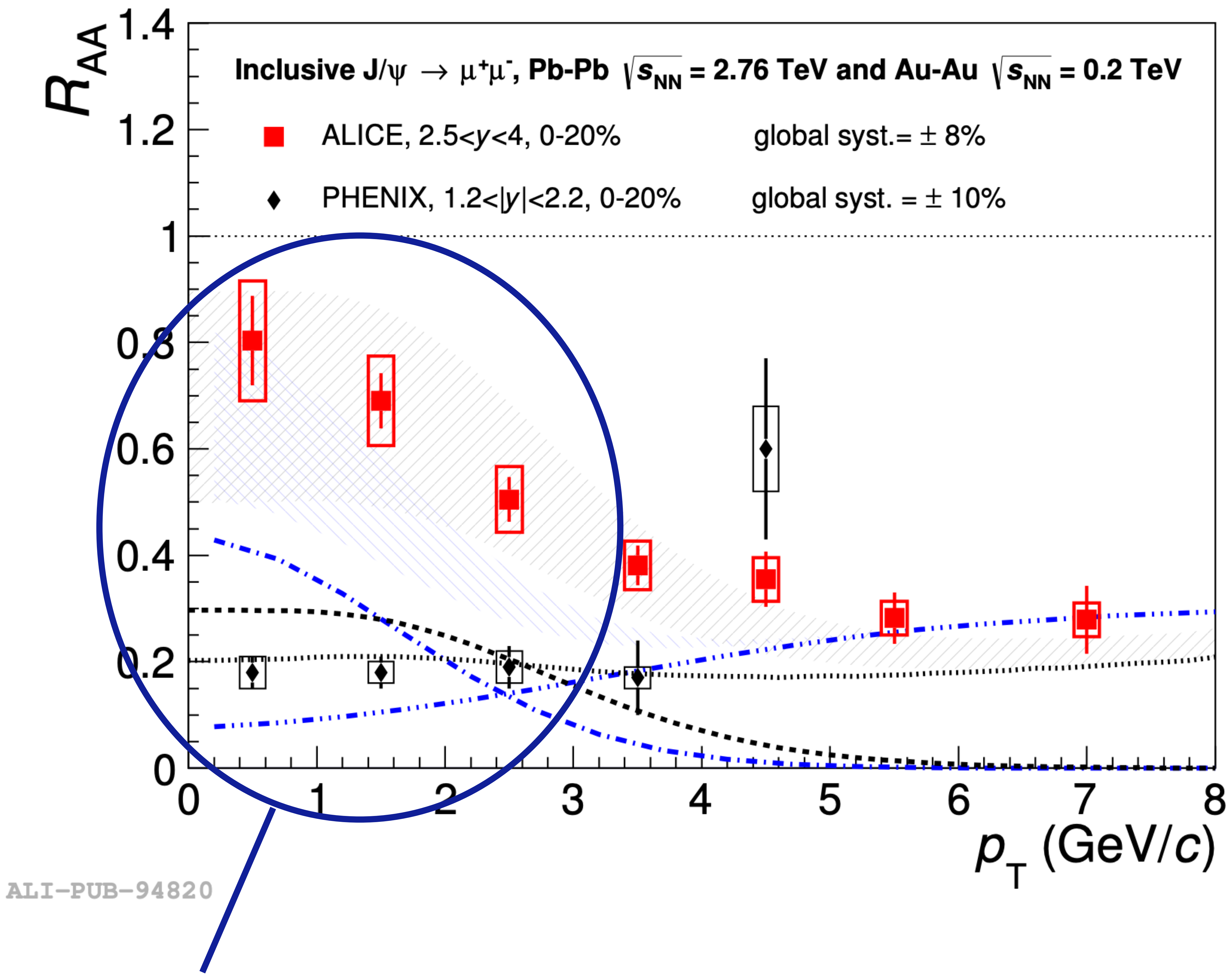


J/ψ : $c\bar{c}$ bound state

shows smaller suppression

Early stage temperature: melting of charmonia (J/ψ)

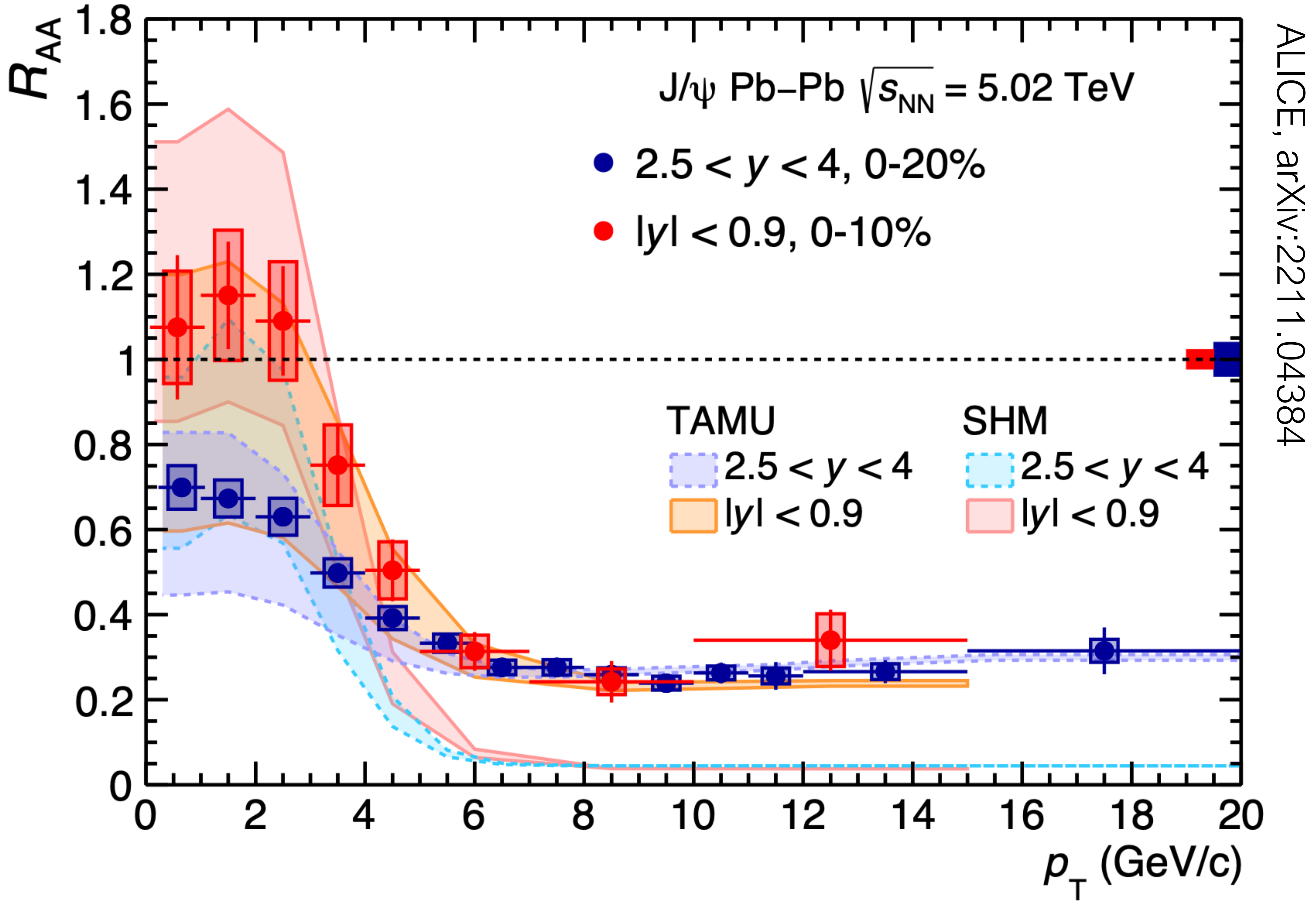
J/ψ modification vs p_T



Less suppression at low p_T

$c\bar{c}$ recombination

J/ψ modification at forward and mid-rapidity

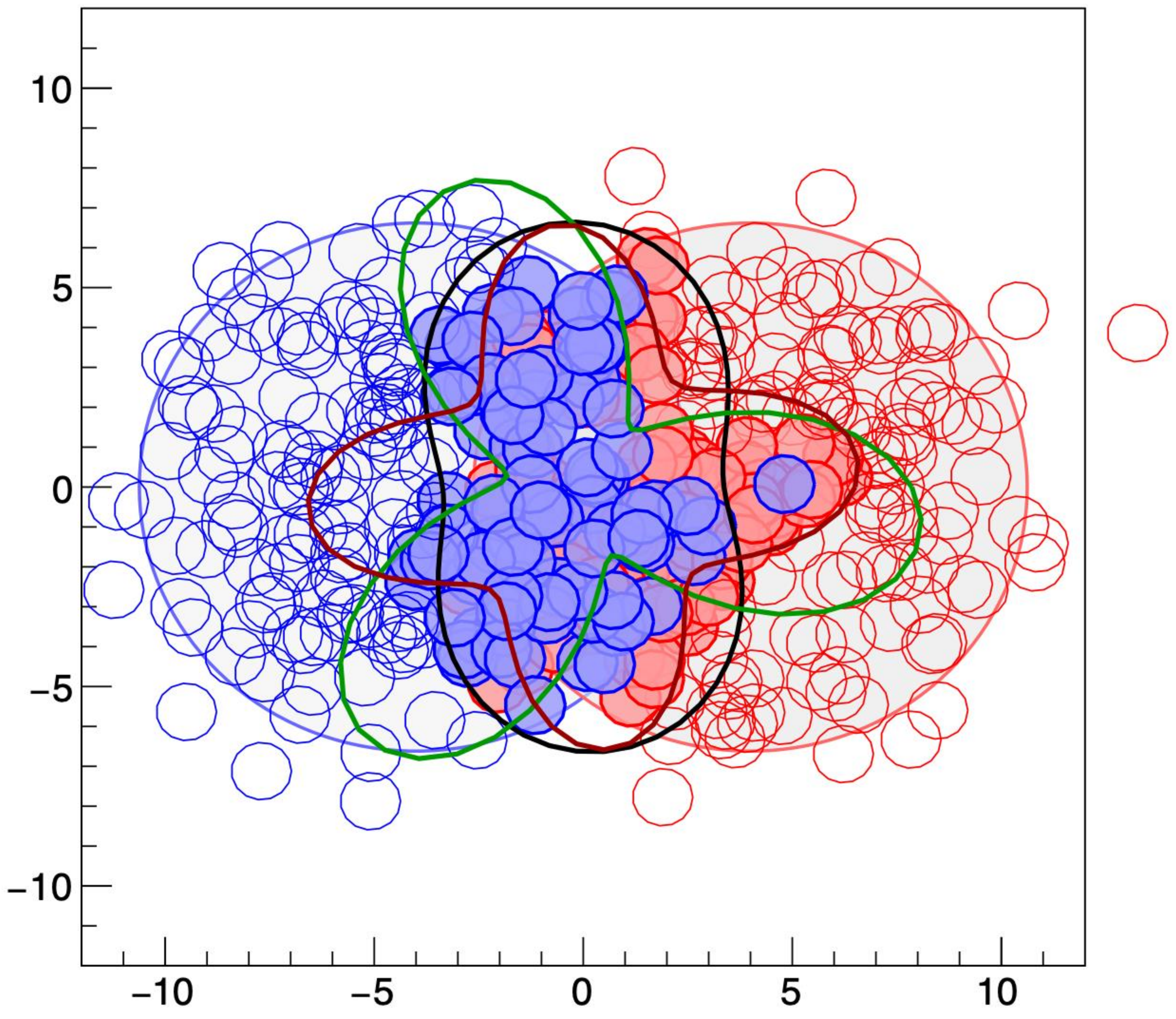


In agreement with coalescence expectation:
larger $c\bar{c}$ density at mid-rapidity

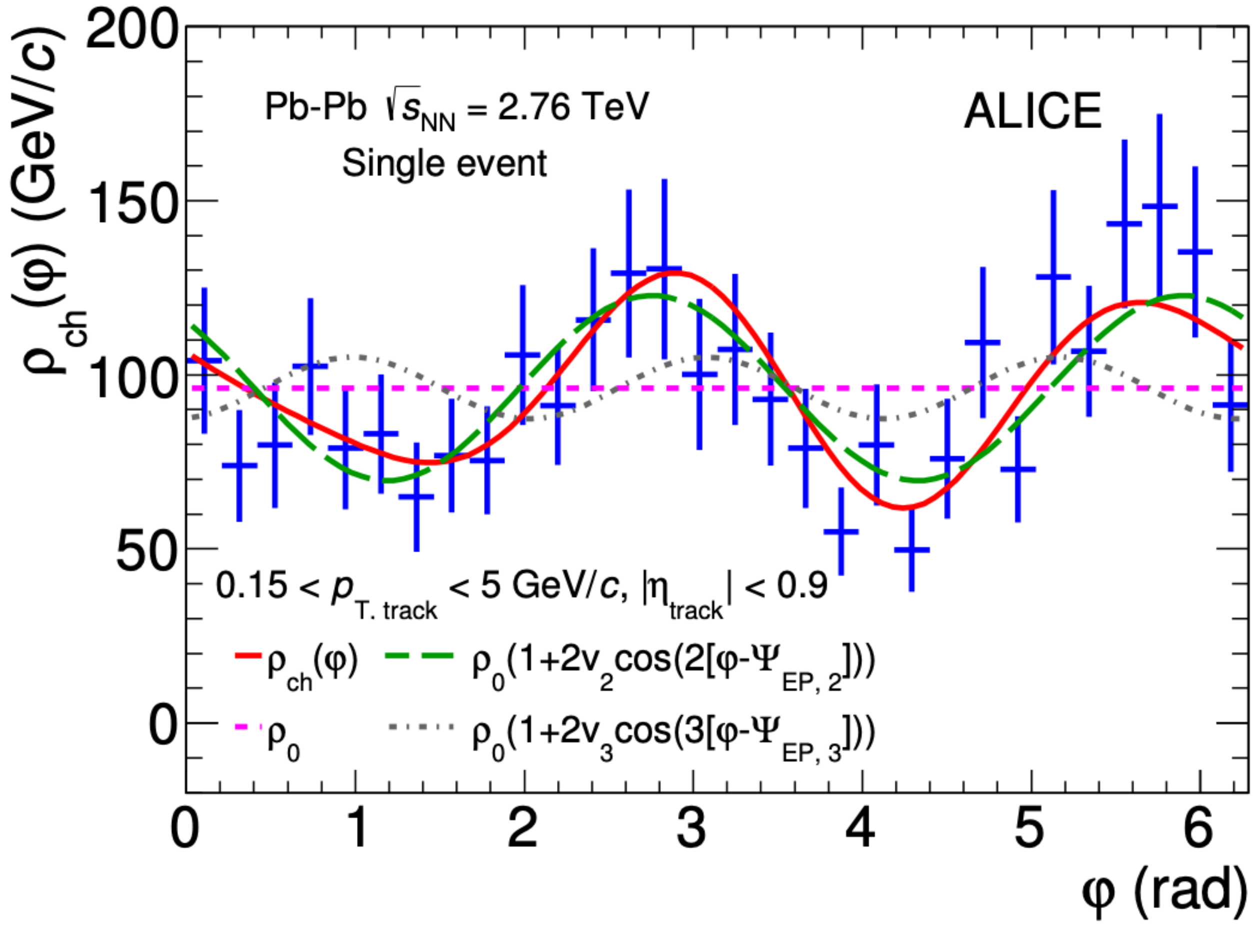
ALICE, arXiv:1506.08804 PHENIX, arXiv:1103.6269
Transport models: arXiv:1102.2194, arXiv:1401.5845

Azimuthal anisotropy: initial and final states

Simulated event: location of nucleons

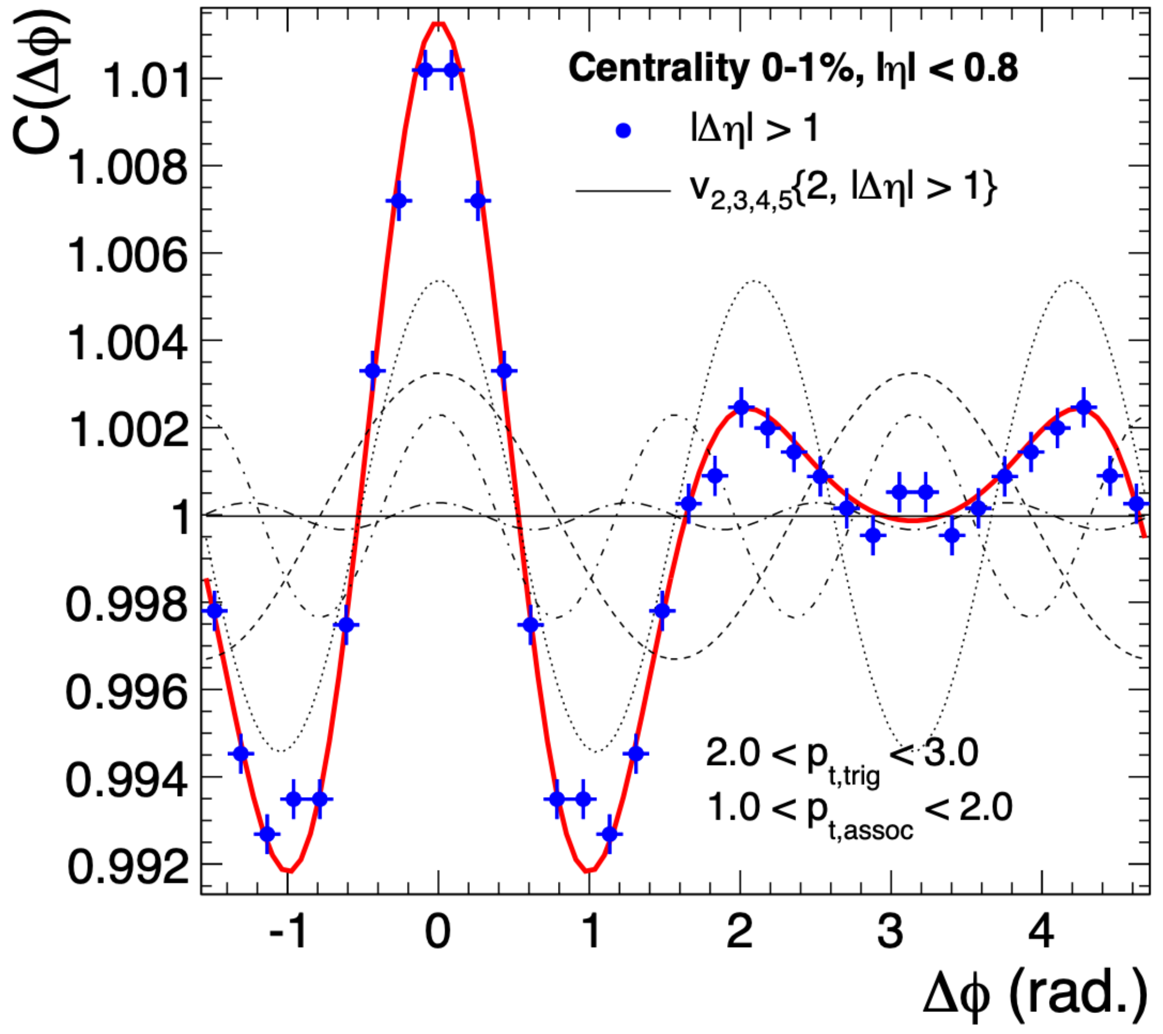


Azimuthal distribution single event



ALICE, PLB 753, 511

Sum over many events

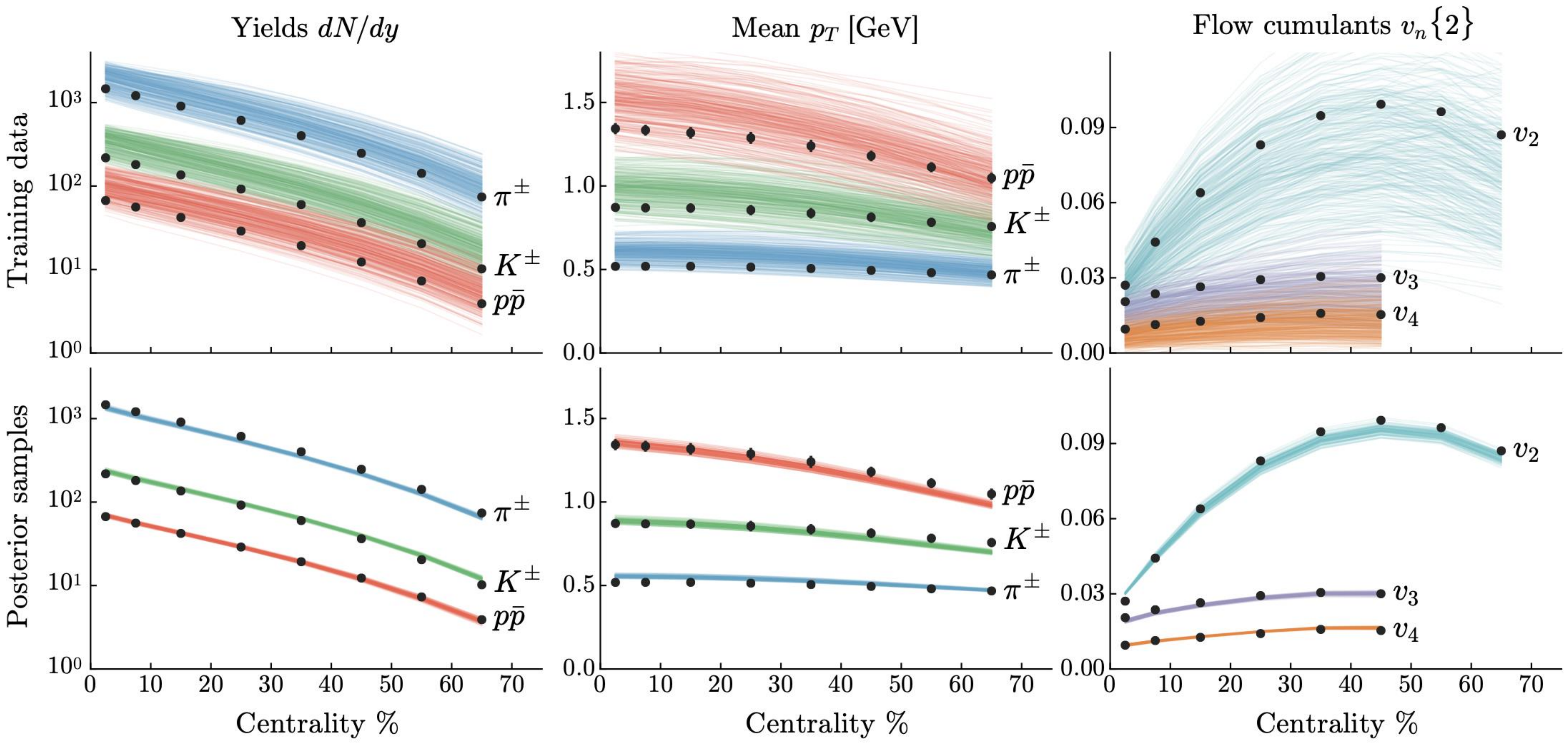


ALICE PRL. 107, 032301

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

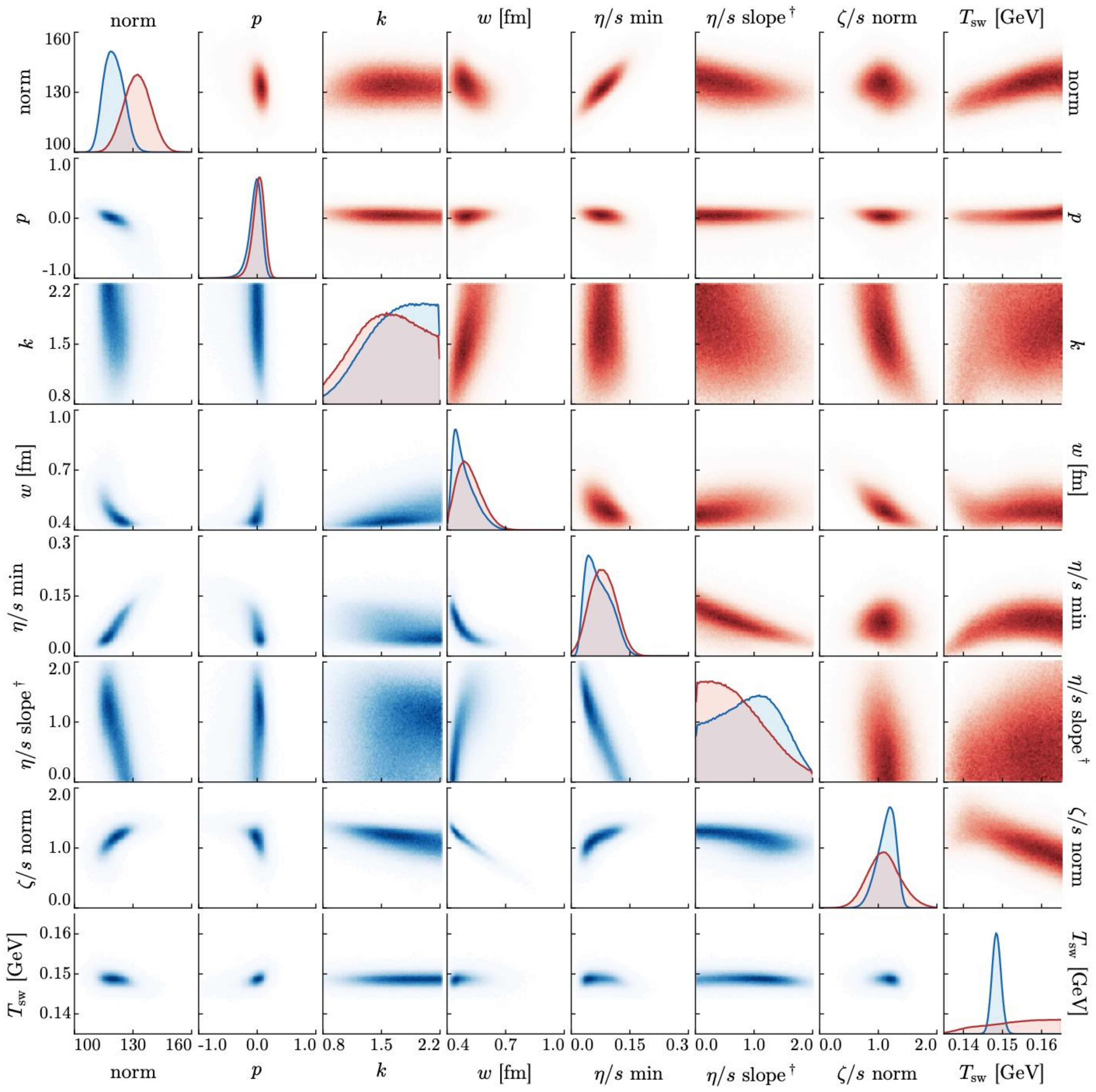
Constraining initial state and plasma properties simultaneously: Bayesian inference

Experimental input: yields, mean p_T and harmonic flow vs p_T



J. E. Bernhard et al, PRC 94, 024907

Model parameters — posterior



Model: initial anisotropies + medium response

Exploration of a large parameter space: investigate reliability/robustness of the model

A global fit to anisotropic flow: main result

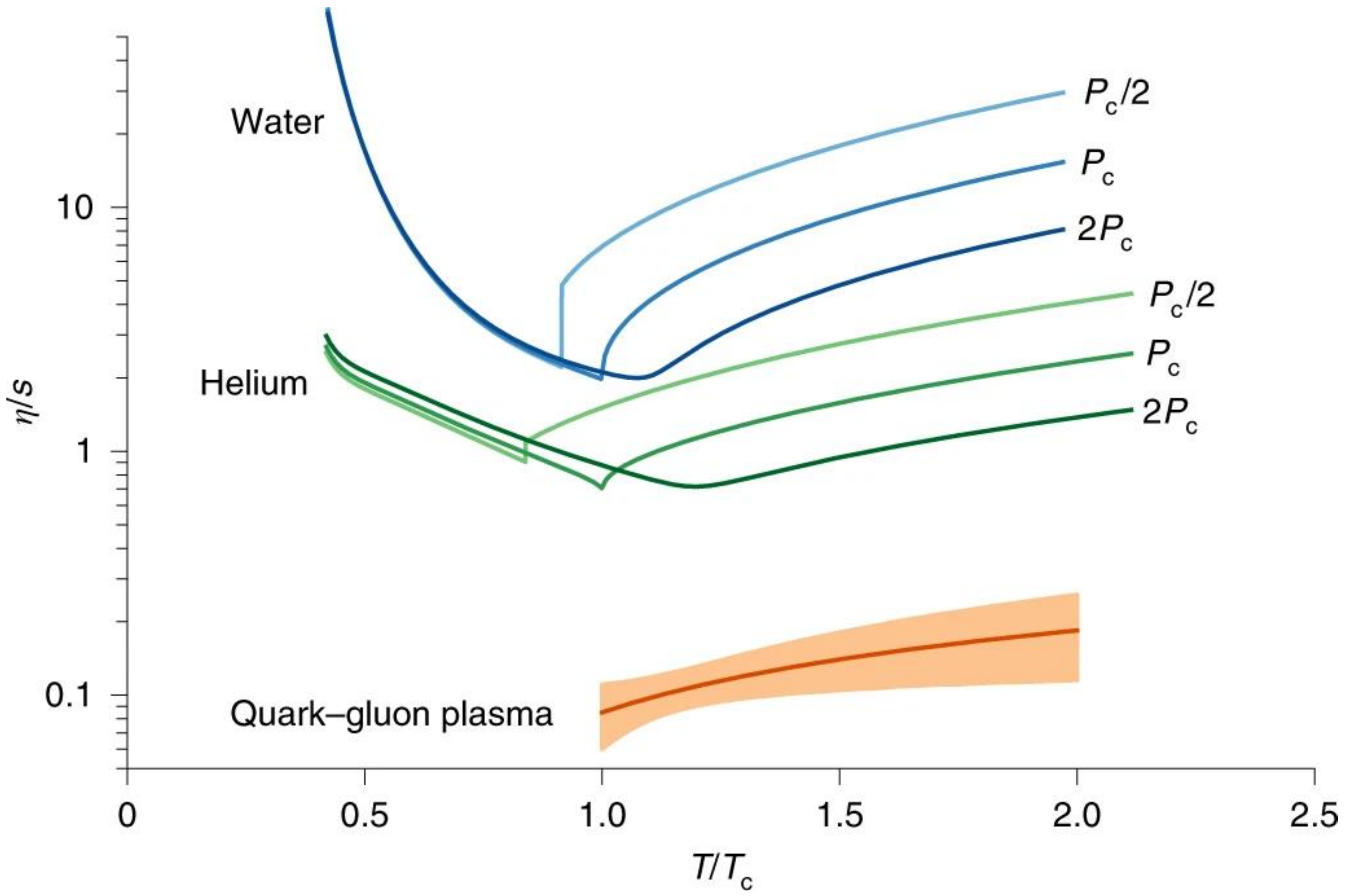
Viscosity of the QGP compared to ‘regular’ liquids

Viscosity-to-entropy ratio: dimensionless quantity

$$\eta = \frac{1}{3}\bar{p}\lambda$$

Small viscosity ⇒ small mean free path

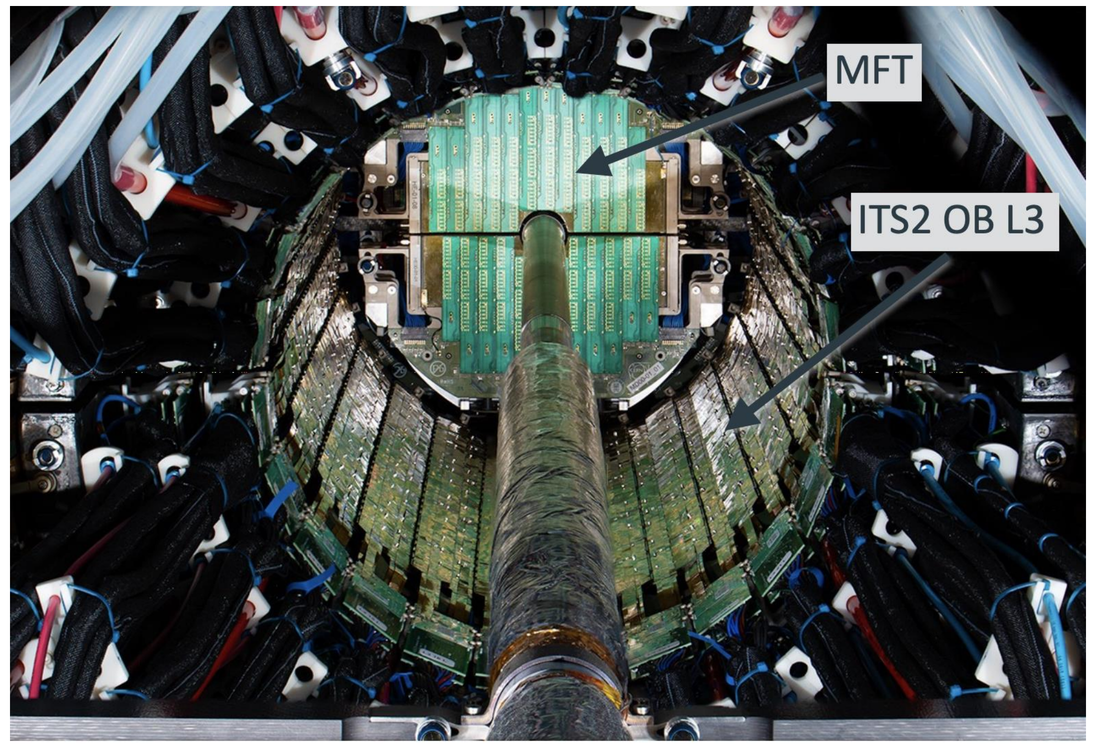
QGP is a strongly interacting gas (liquid)



J. E. Bernhard et al, Nature Physics 15, 1113–1117, PRC 94, 024907

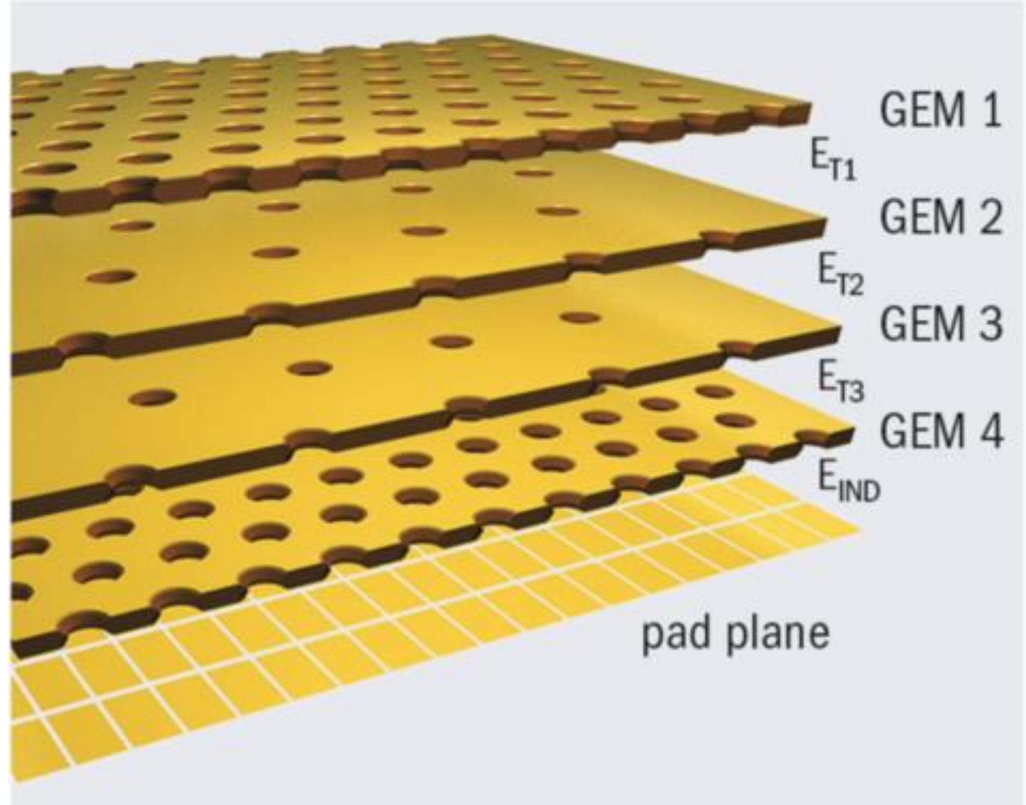
ALICE upgrades installed in 2019-2021

New ITS and MFT



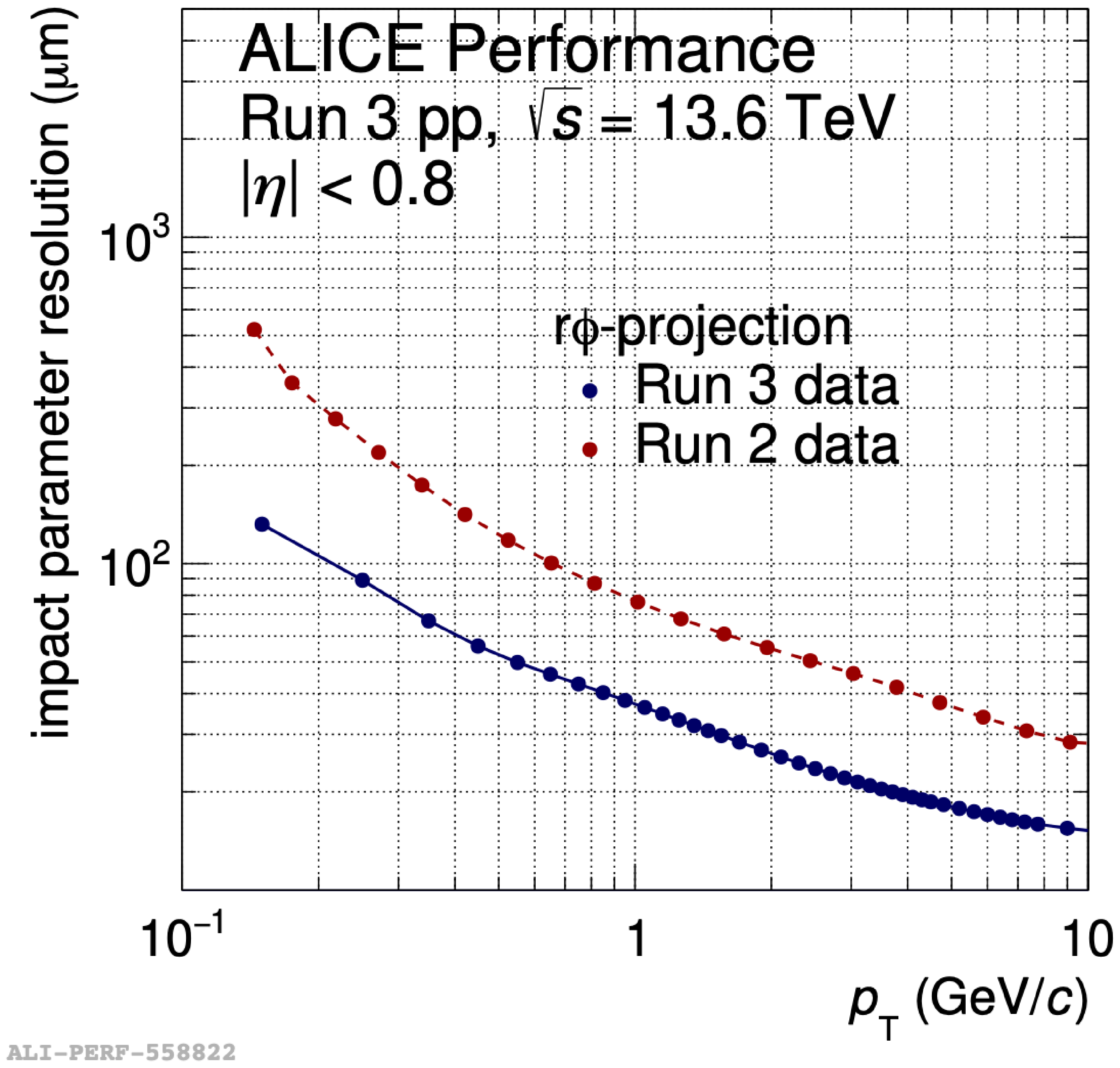
Full pixel detector 13 Gpixels
Improved spatial resolution

TPC: GEM readout

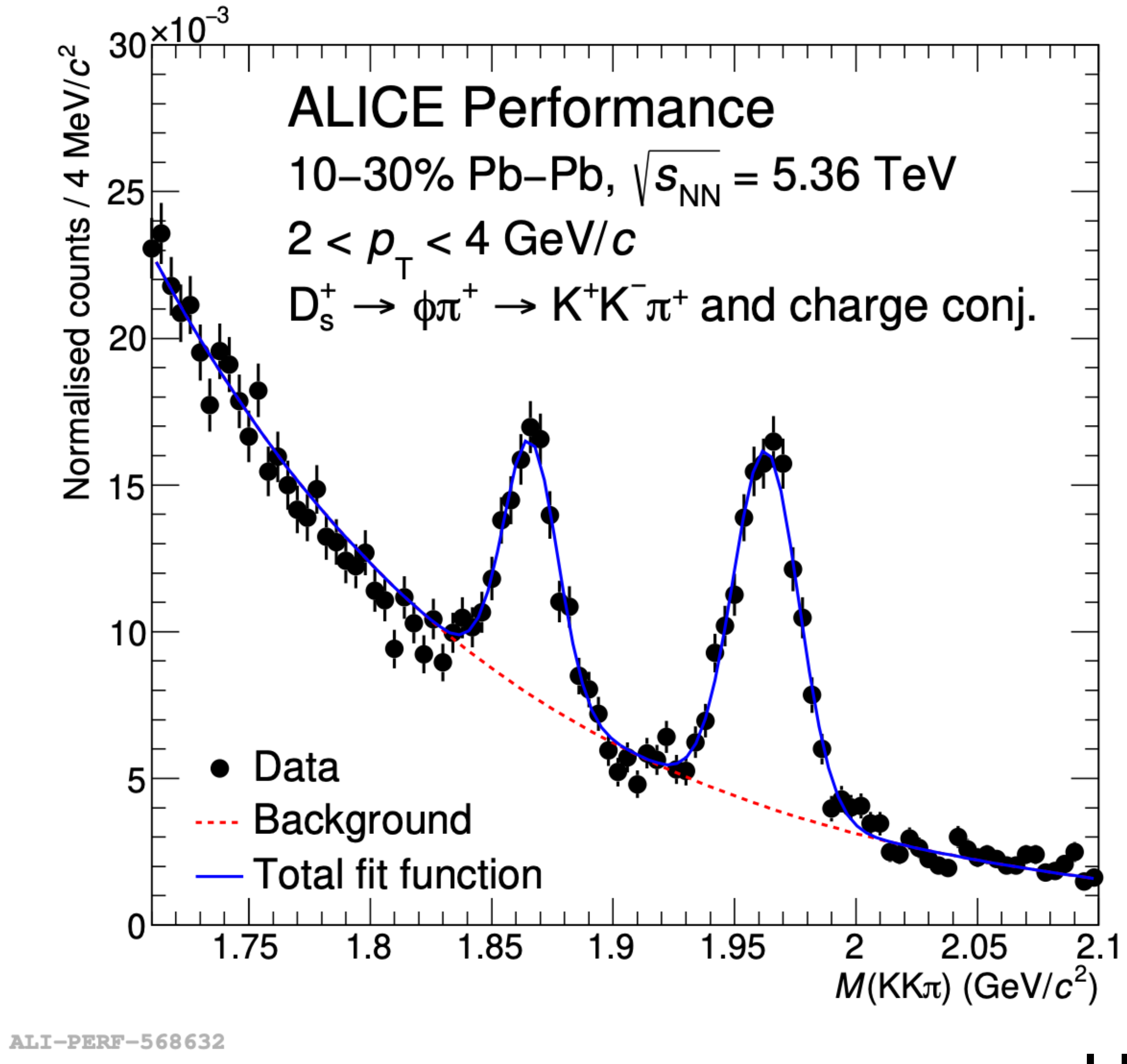


ALICE LS2 upgrade paper: [arXiv:2302.01238](https://arxiv.org/abs/2302.01238)

Impact parameter resolution

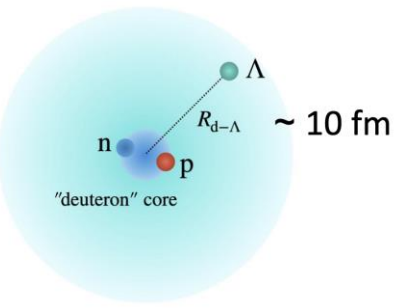


D^+ and D_s^+ in Pb-Pb

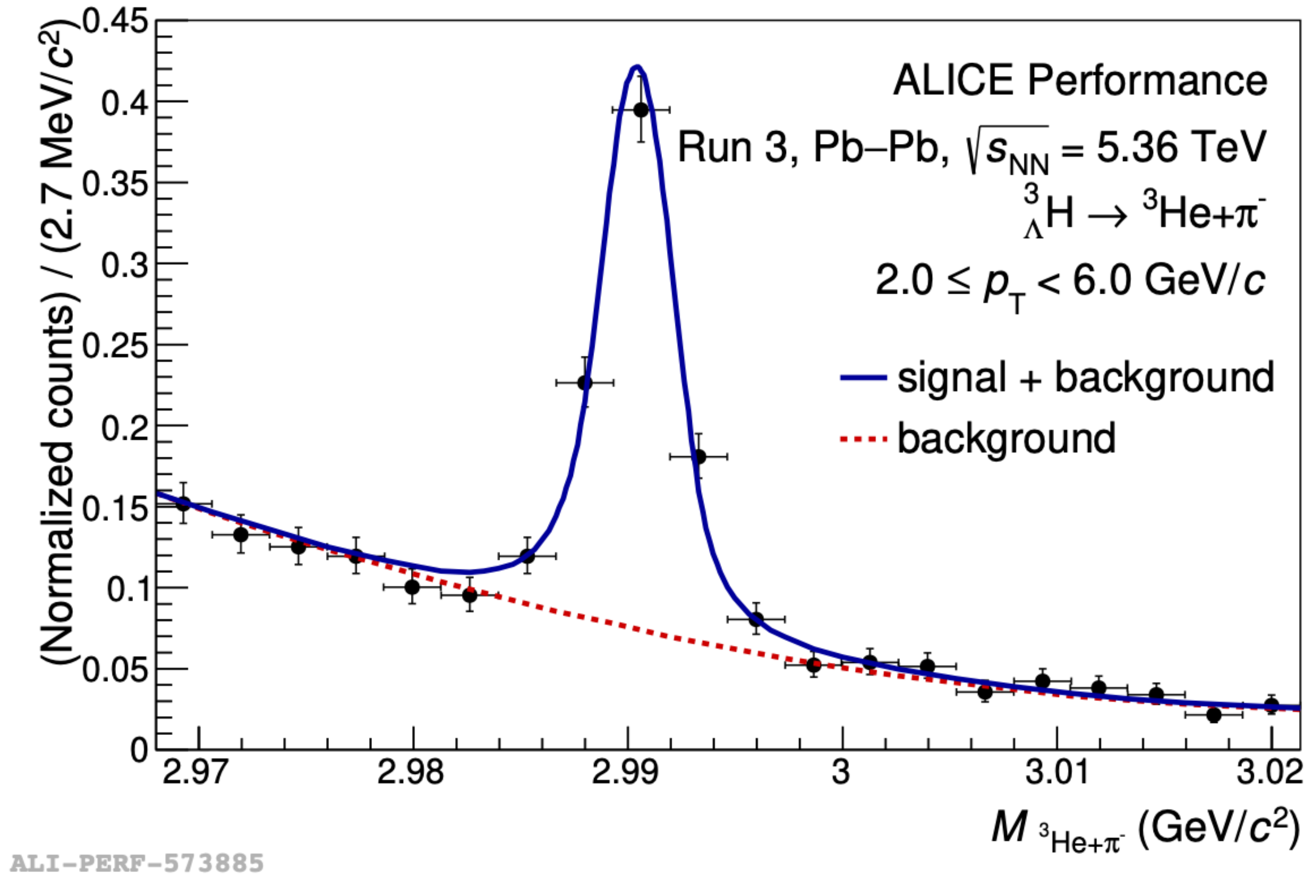


Hypertriton

$^{3}_{\Lambda}H$

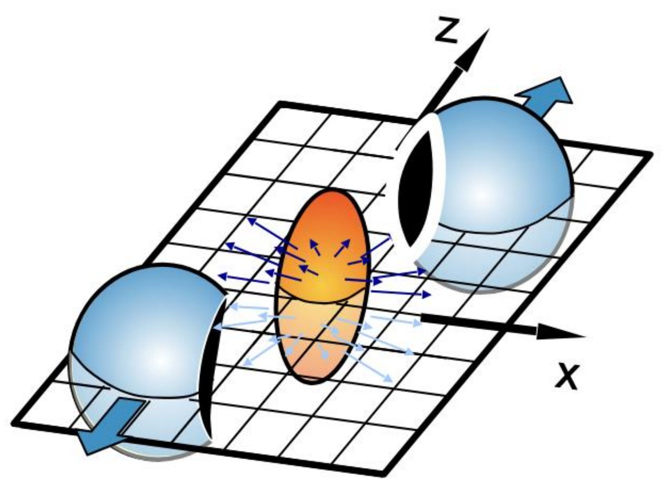


$^{3}_{\Lambda}H \to ^{3}He + \pi$

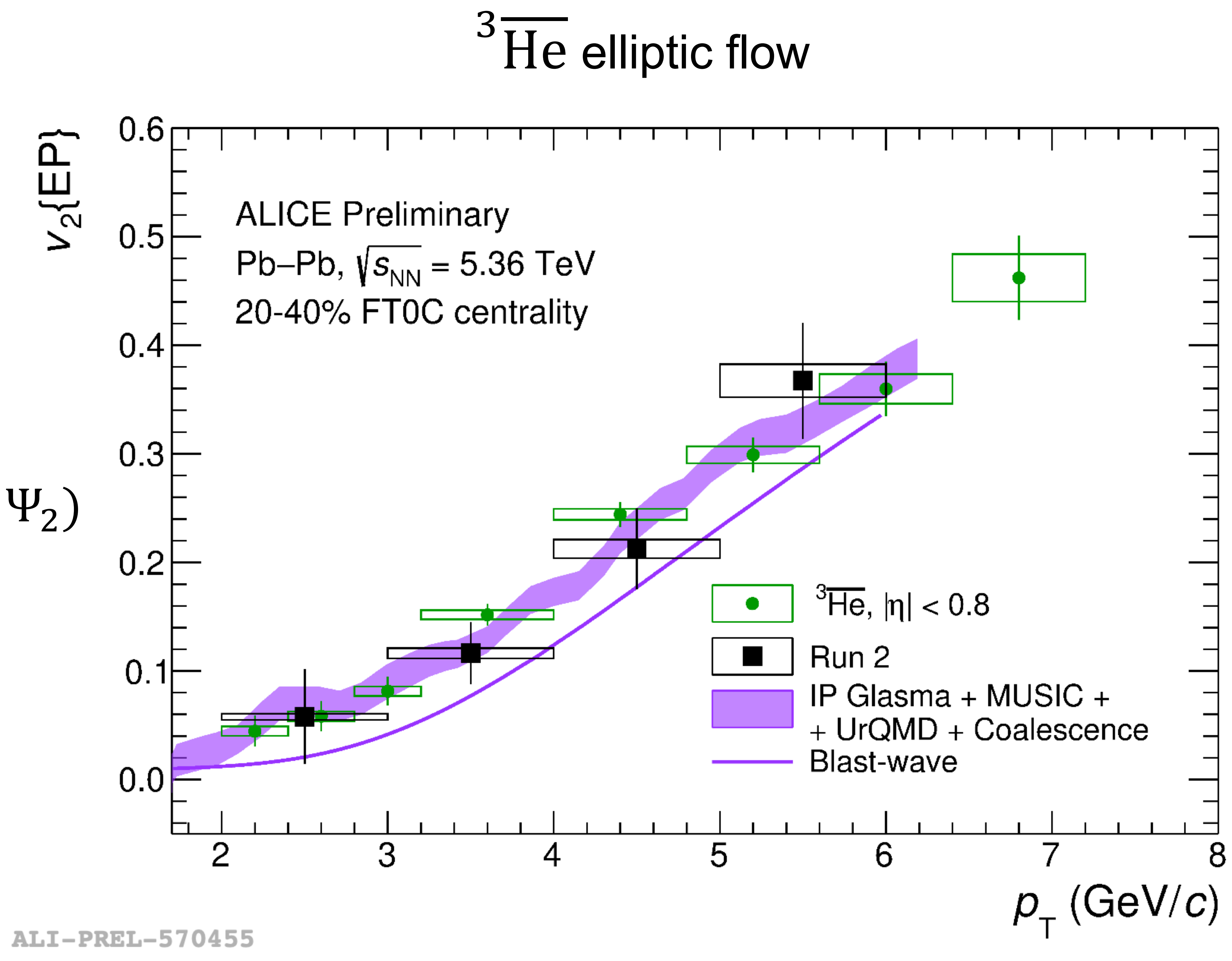


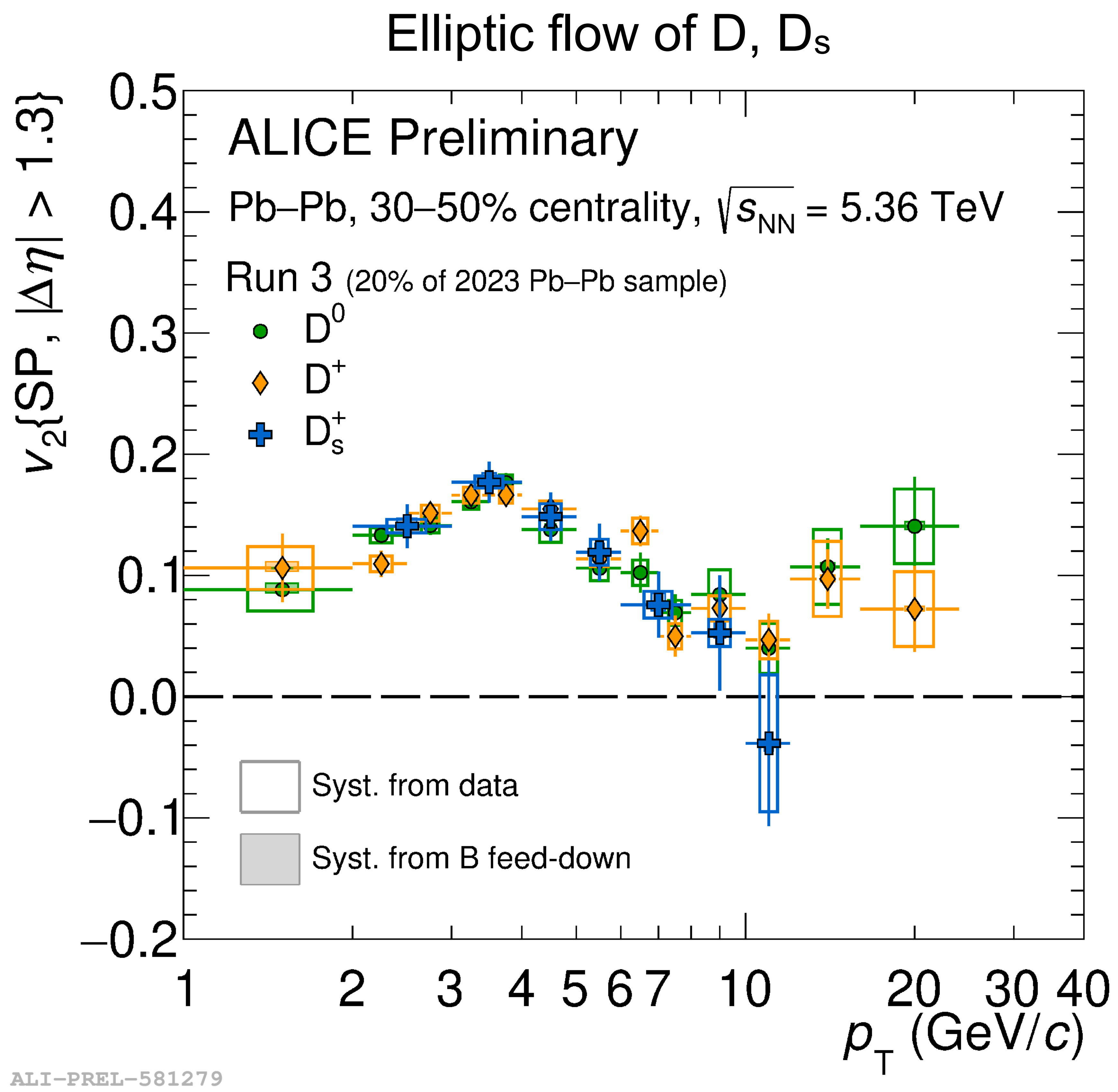
Improved pointing resolution and readout rate:
record 50 kHz Pb-Pb collisions (50x more minimum bias events)

Run 3 results: elliptic flow of anti-nuclei and charm mesons



$$\frac{dN}{d\phi} \propto (1 + v_2)\cos(\phi - \Psi_2)$$





First large Pb-Pb data sample with upgraded detectors collected in 2023

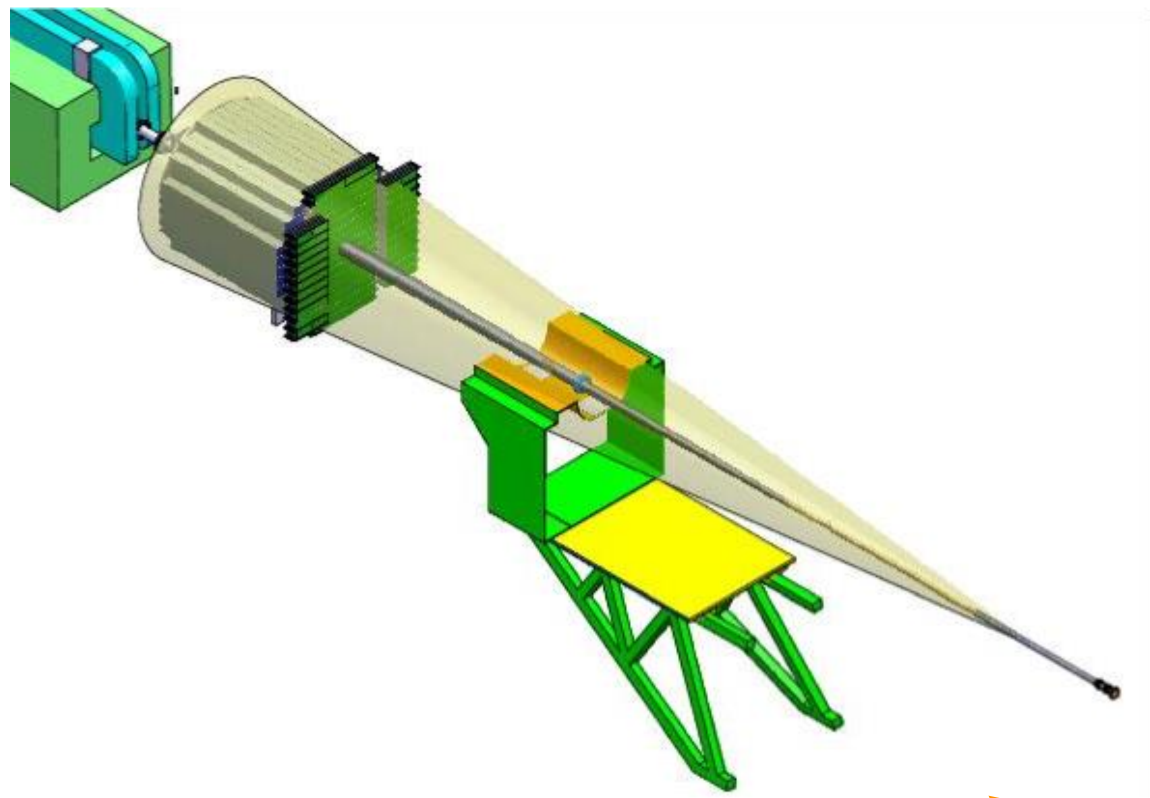
Larger samples, better pointing resolution: improved precision

Much more to come!

ALICE future upgrades

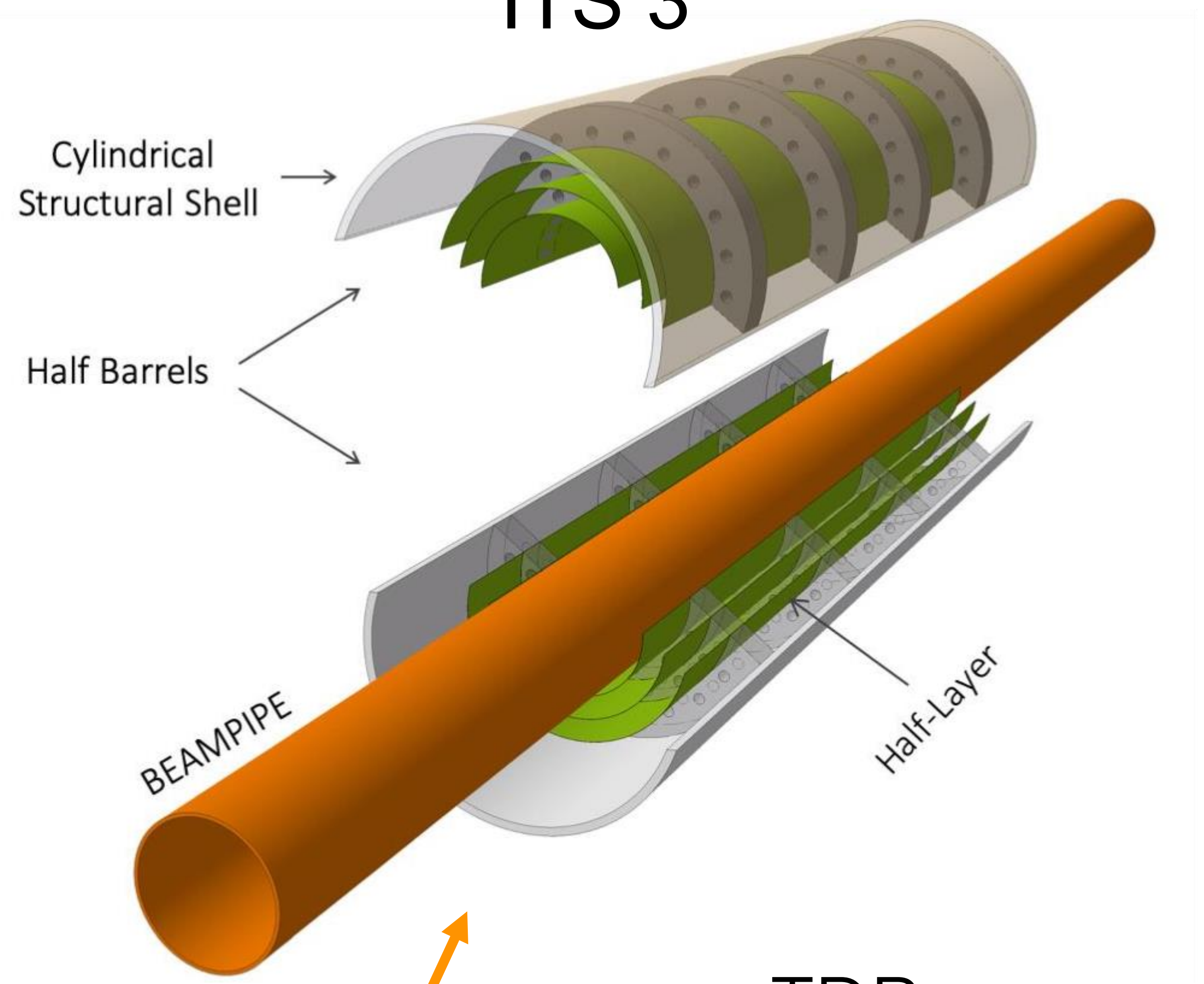
LS3 upgrades

Forward Calorimeter



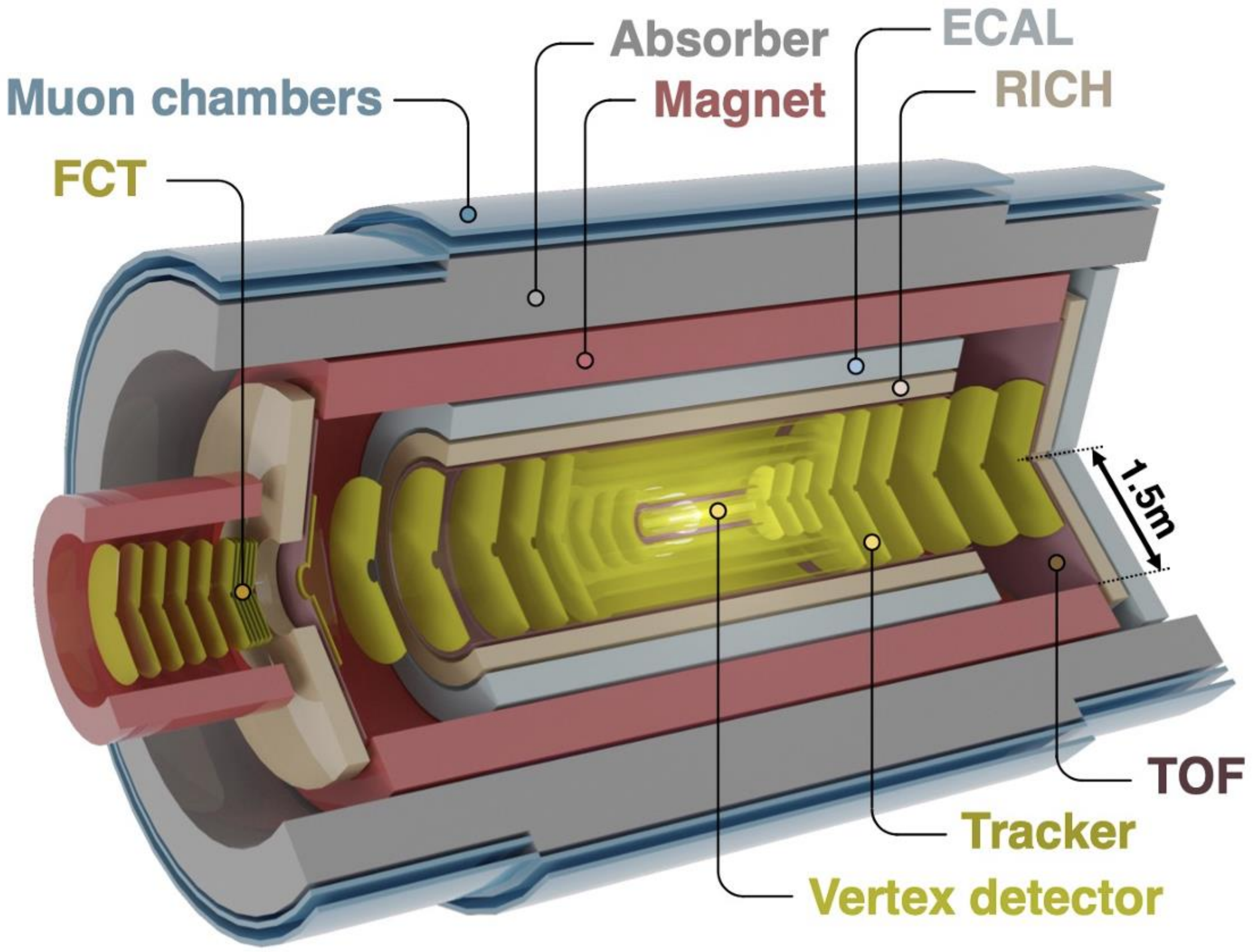
TDR approved

ITS 3

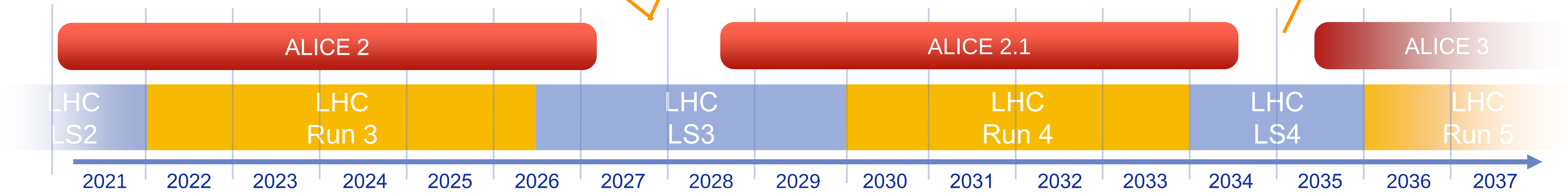


TDR approved

LS4: ALICE 3

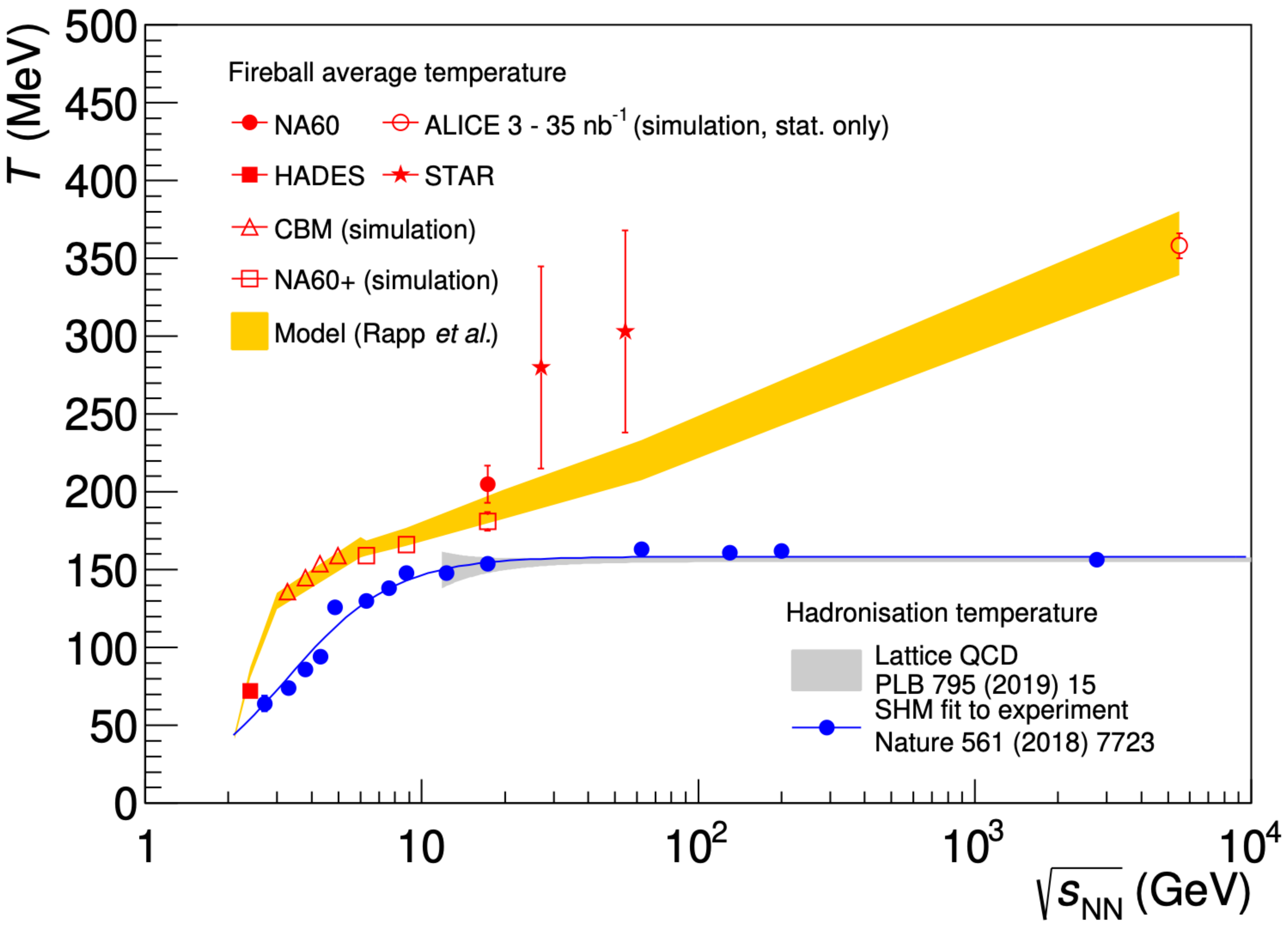


ALICE 3 LoI:
CERN-LHCC-2022-009



Temperature of the QGP: electromagnetic radiation

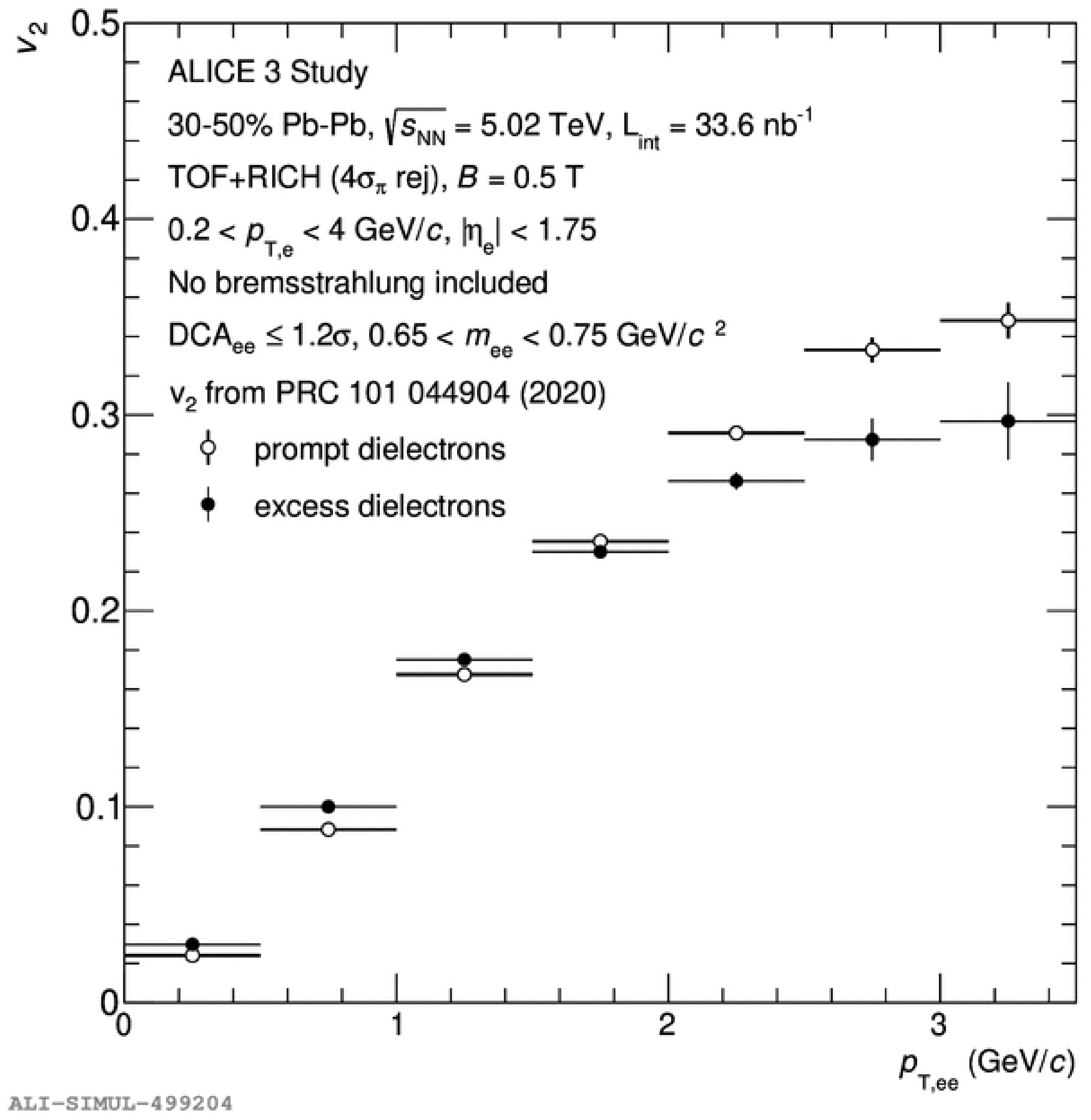
T vs energy



Projected temperature from electromagnetic radiation

Temperature from hadron abundances 'chemical freeze-out'

Dielectron v_2



Light flavour hadron abundances consistent with common chemical freeze-out

- Limiting temperature: ~155 MeV

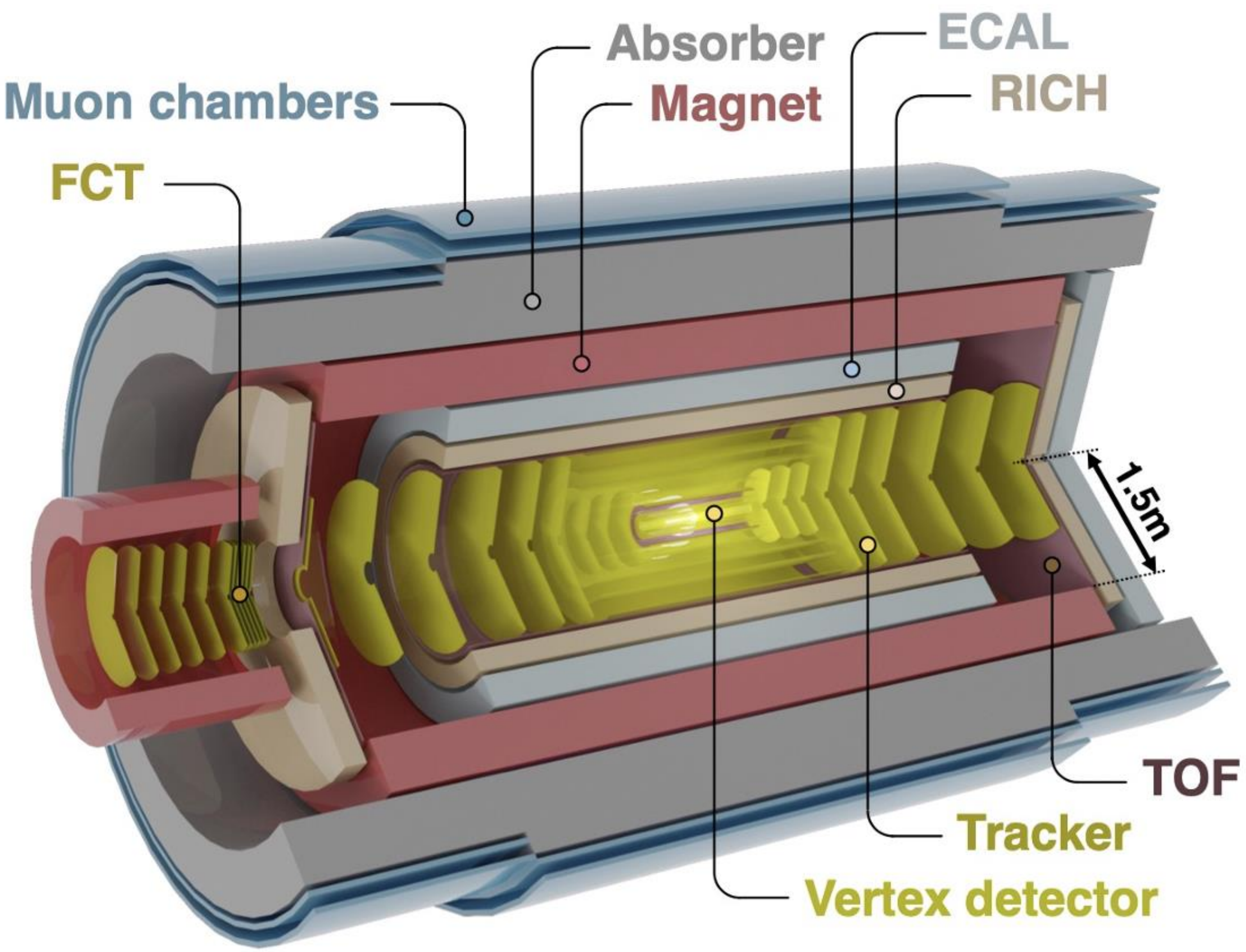
Electromagnetic radiation gives access to **temperature of QGP before hadronisation**

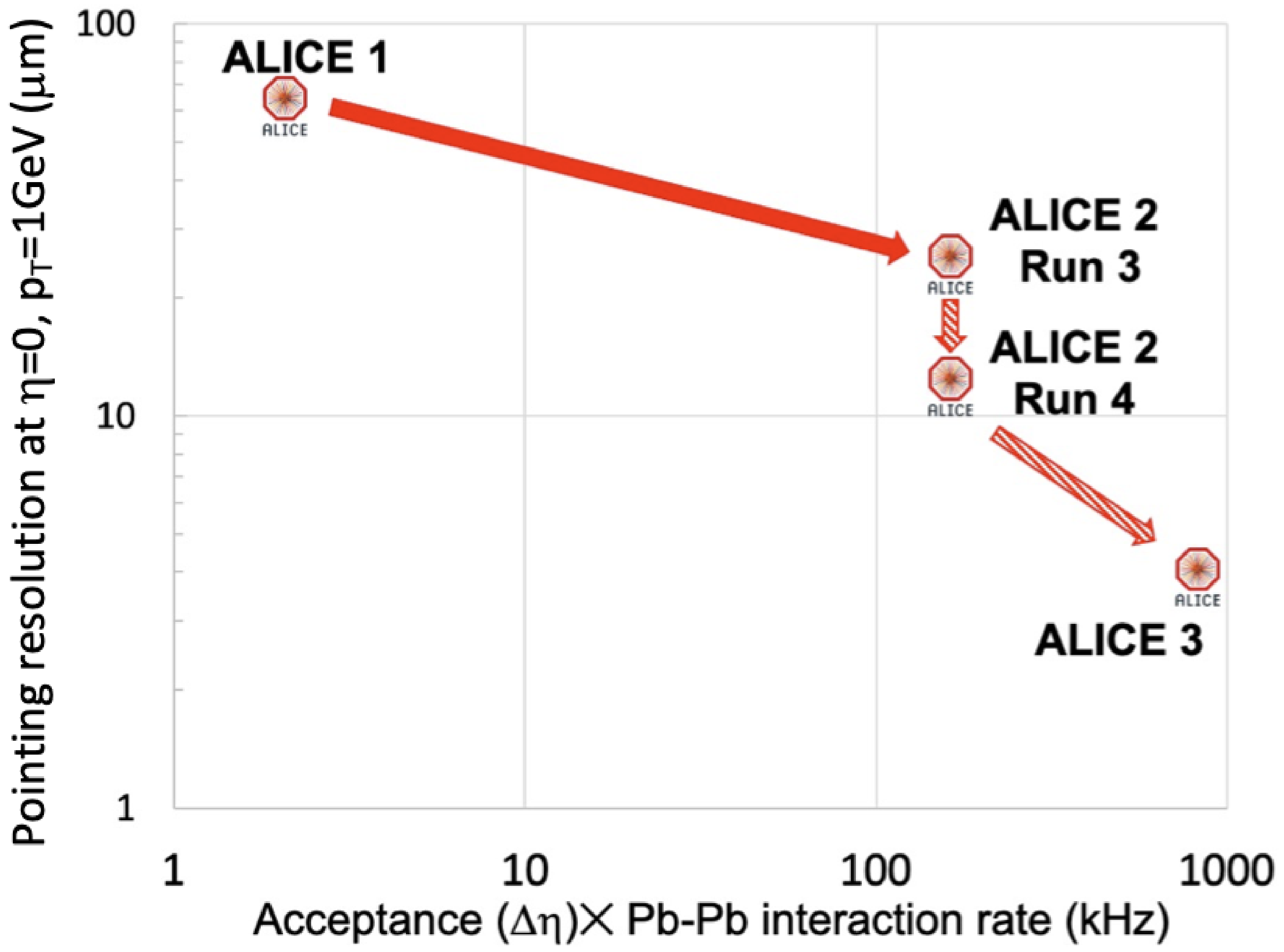
- Cleanest signal: dilepton pairs
- Expected *T* at LHC: 300-400 MeV

Unique access to **time evolution of temperature** via v_2, p_T dependence of T

Next-generation experiment: ALICE 3

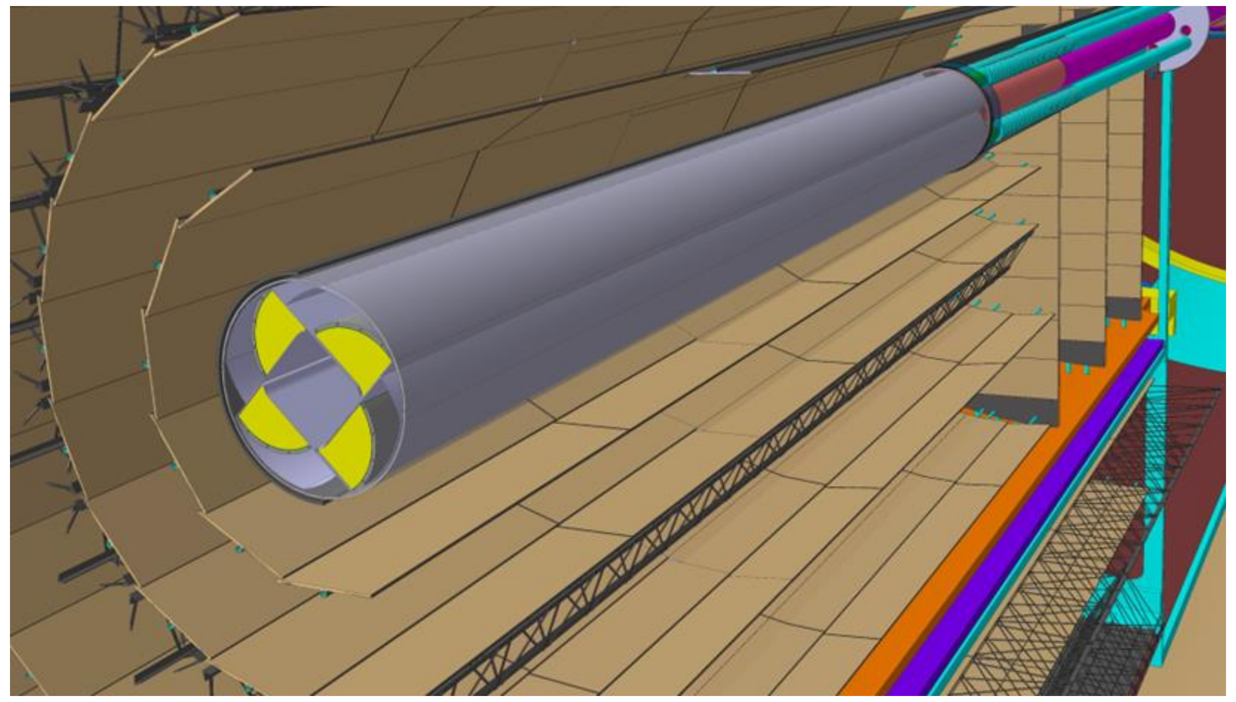
- Compact all-silicon tracker with high-resolution vertex detector:
  excellent pointing resolution
- **Particle Identification over large acceptance**: muons, electrons, hadrons, photons
- Fast read-out and online processing

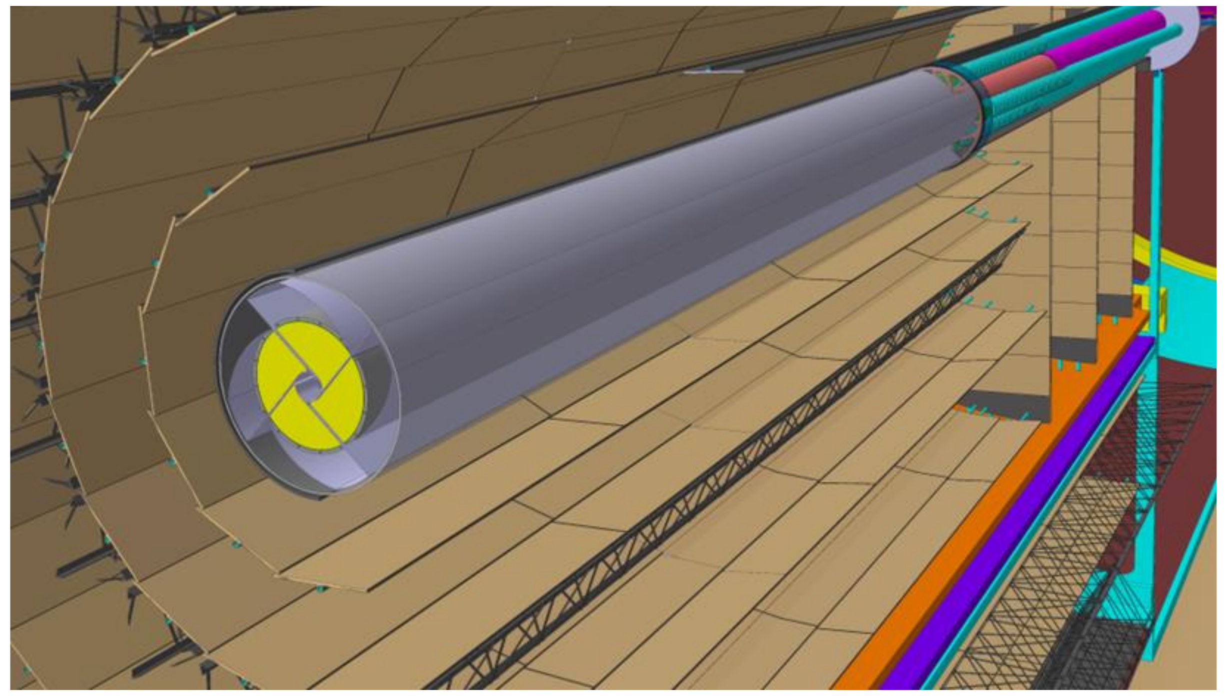




Upgrades: improvements in precision, rate, acceptance

Retractable vertex tracker



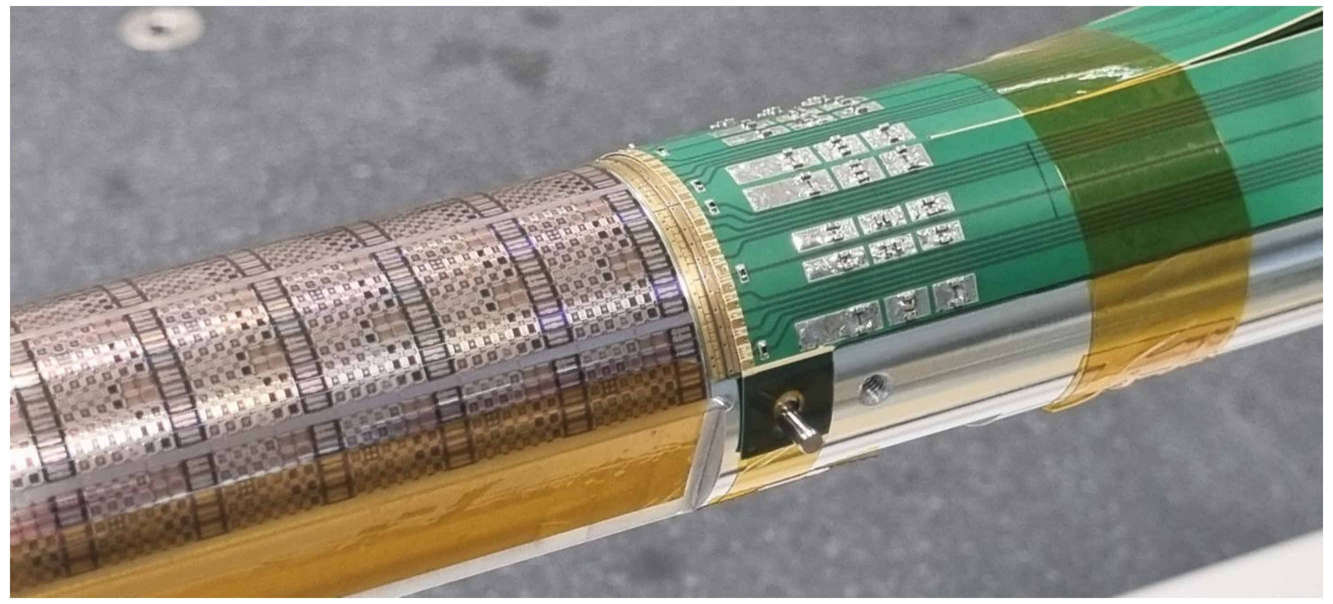


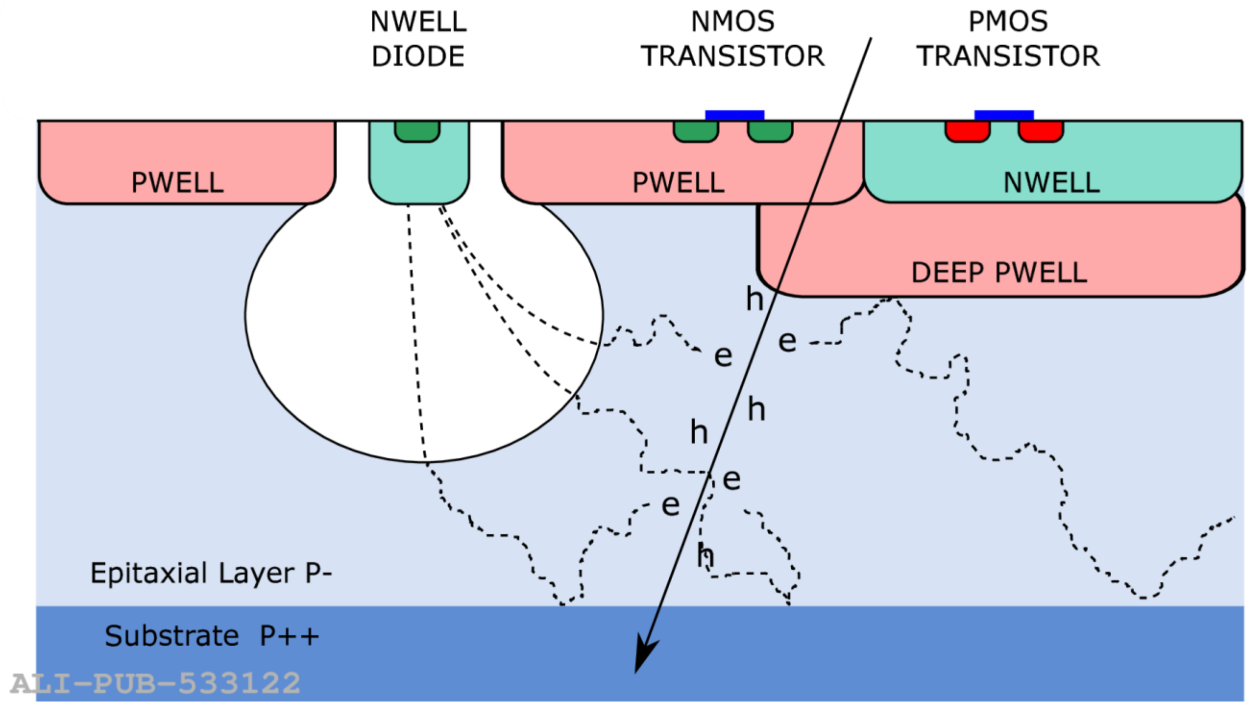
ALICE 3 Letter of Intent
(CDS: LHCC-2022-009)

ALICE 3 vertex detector

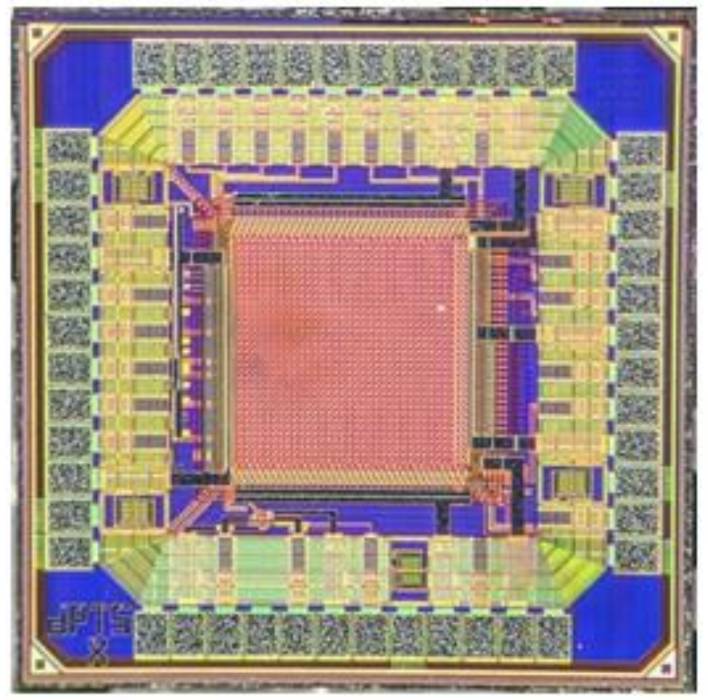
Monolithic active pixel sensors

Sensor and electronics in one: low material budget





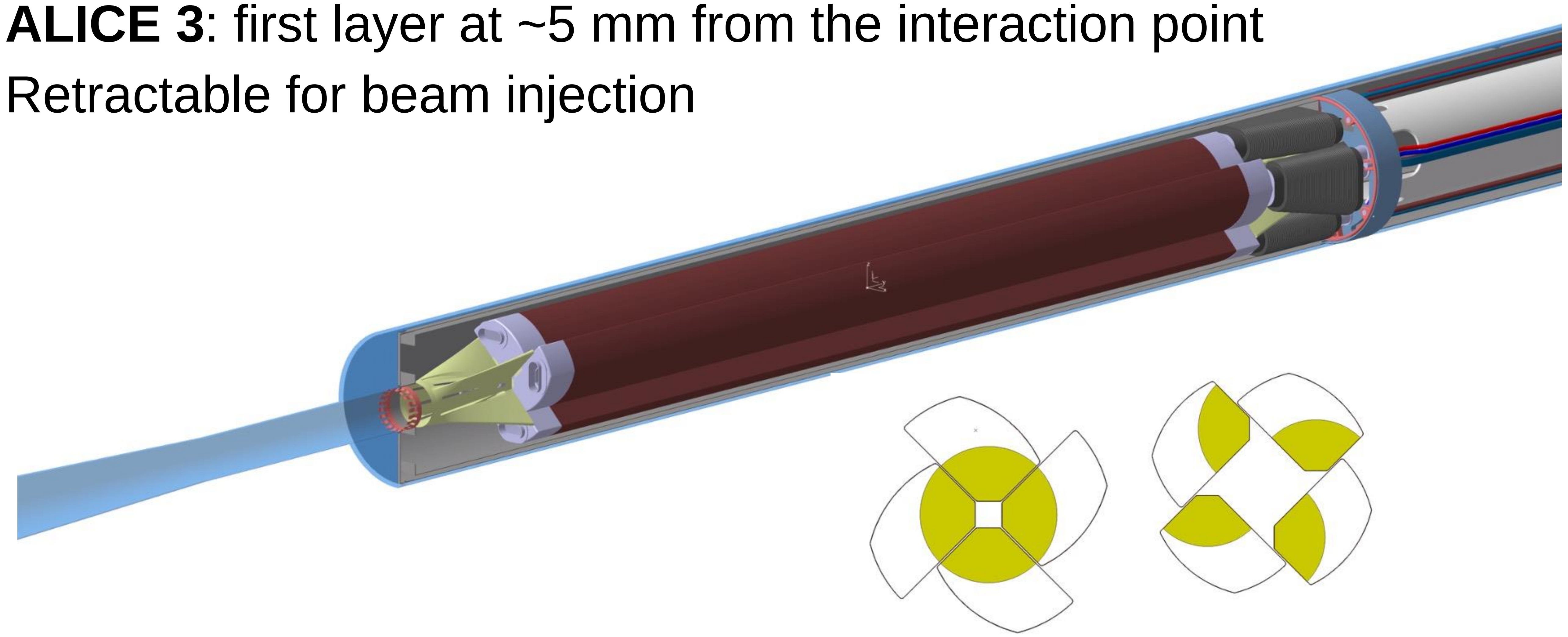
ITS3 development

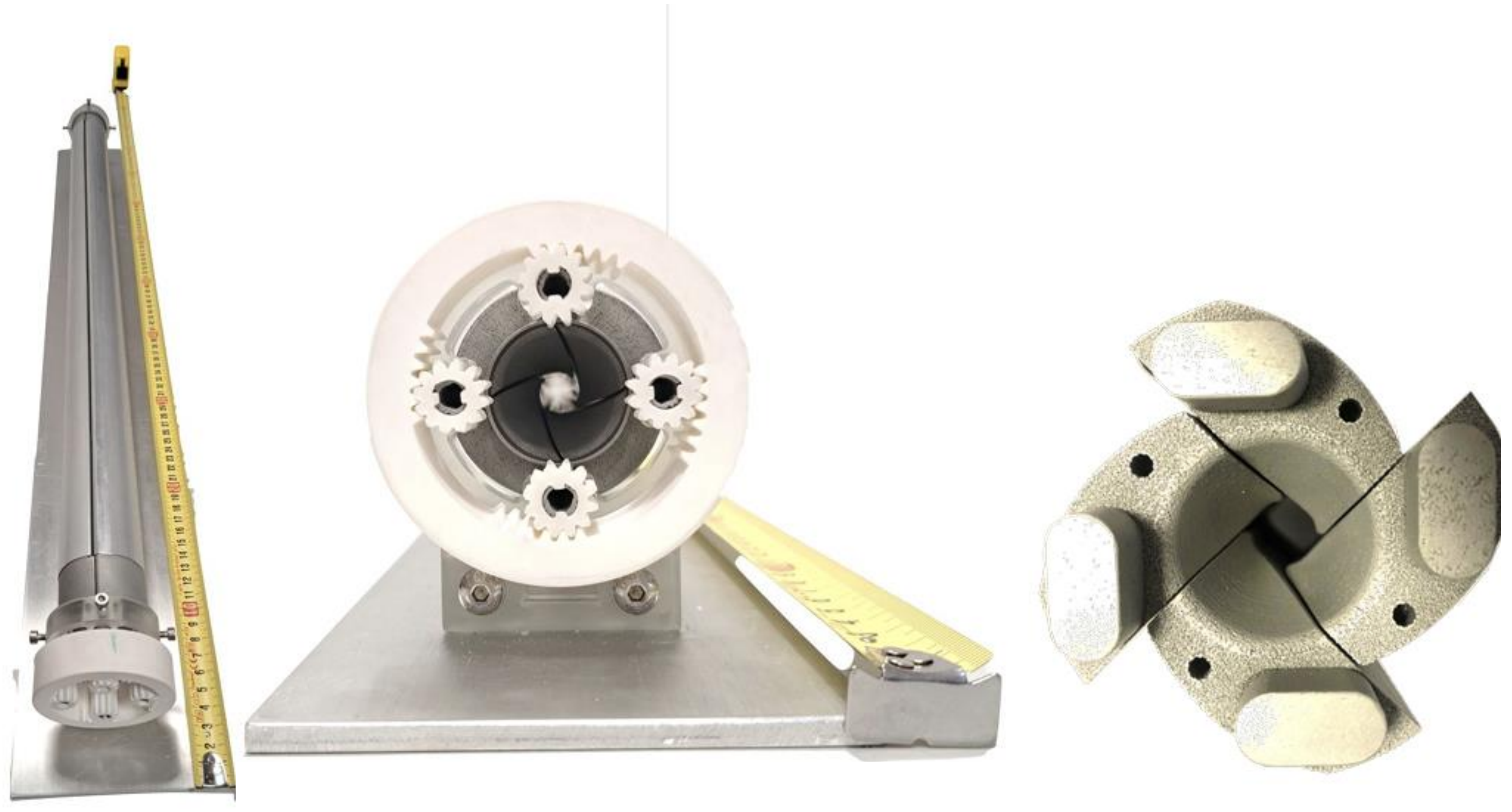


DPTS test paper arXiv:2212.08621

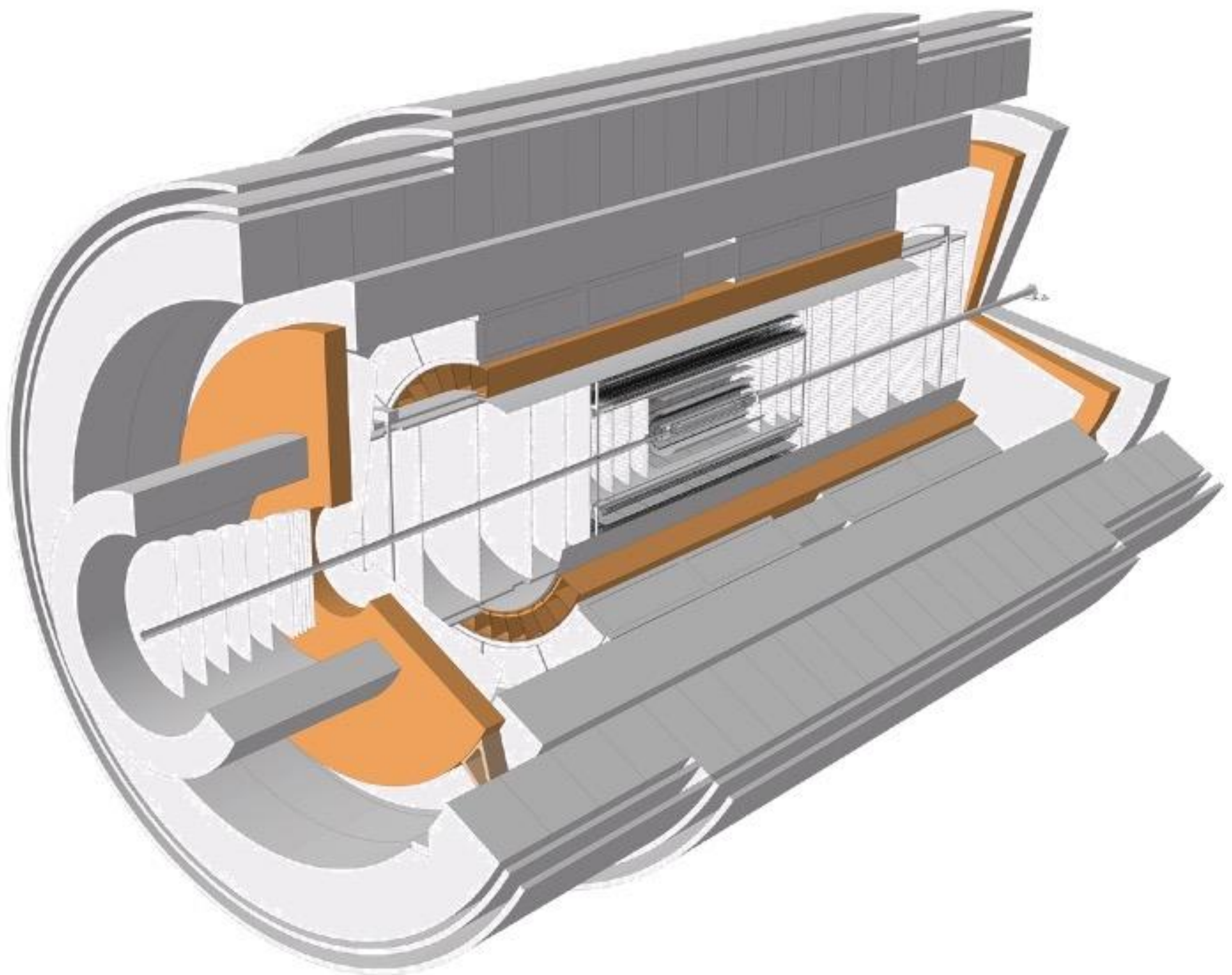
ALICE 3: first layer at ~5 mm from the interaction point

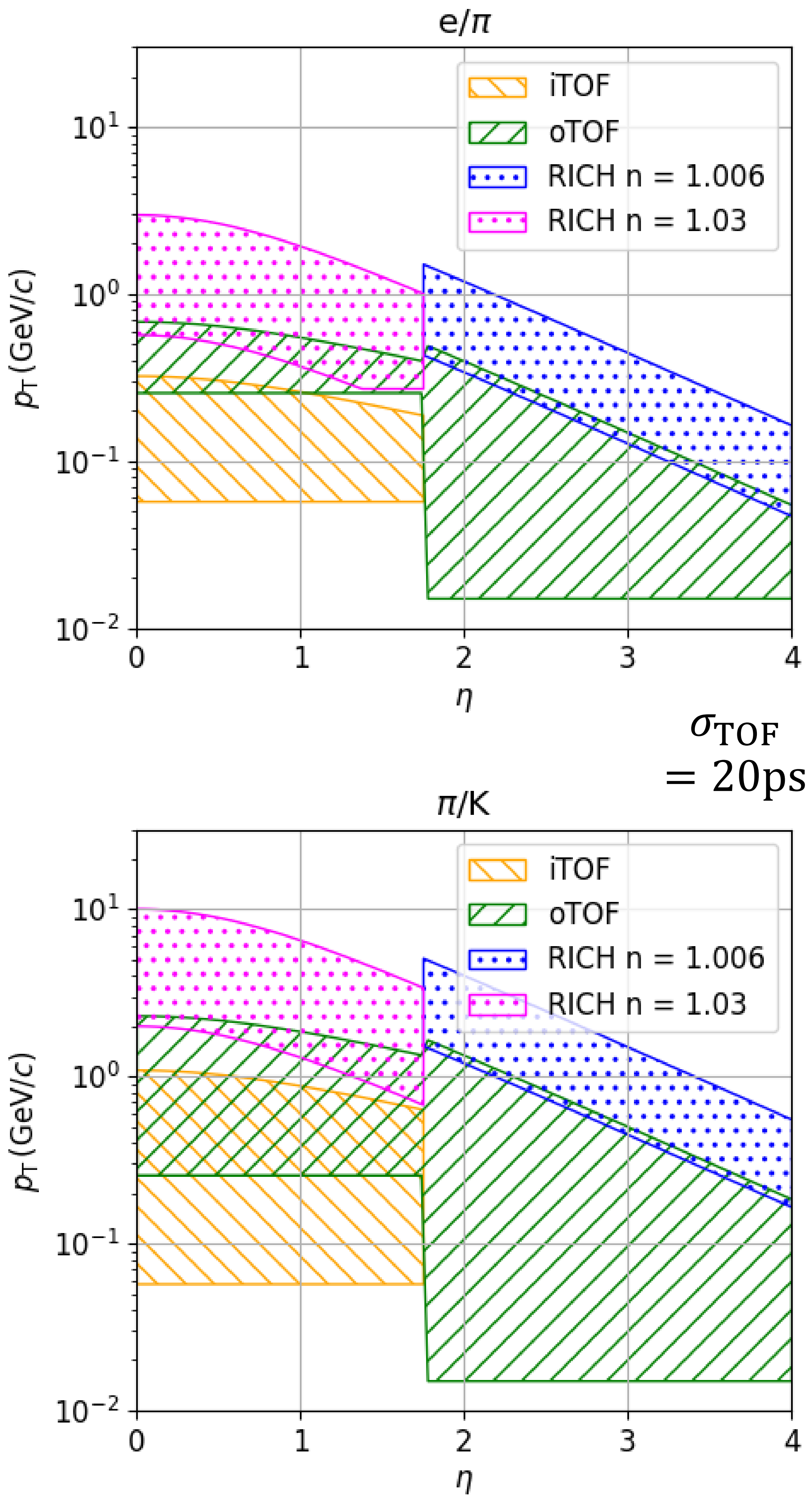
Retractable for beam injection





ALICE 3 Particle identification





$\sigma_{\mathrm{TOF}} = 20\mathrm{ps}$

- **TOF** and **RICH** provide hadron and electron identification
  - Complementary p_T ranges
  - Electron ID up to p_T = 1.5 GeV/*c*: thermal dilepton production measurements
  - Kaon and proton PID up to 6-10 GeV/*c*: HF measurement
- **Muon ID**: measurements of J/ψ down to p_T = 0, χ_c, exotic states
- **EMCal** for photon ID: ALPs, χ_c, jets

R&D for Time Of Flight: CMOS LGAD with gain

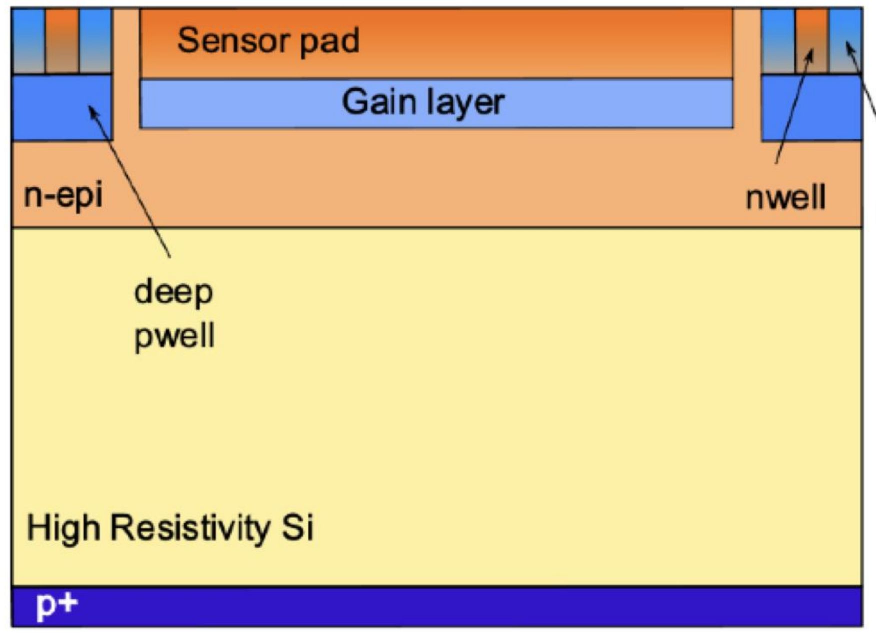
Time-of-flight system for particle identification

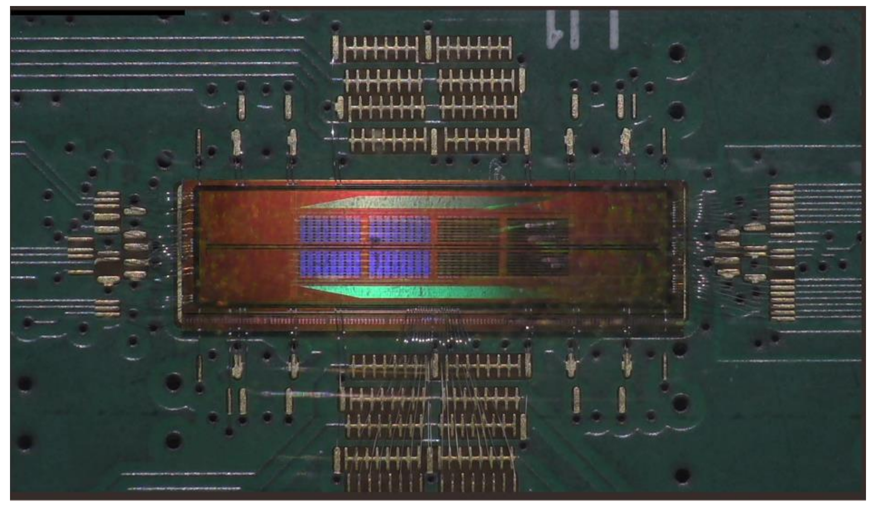
- Required time resolution: 20 ps

R&D for monolithic LGAD sensors

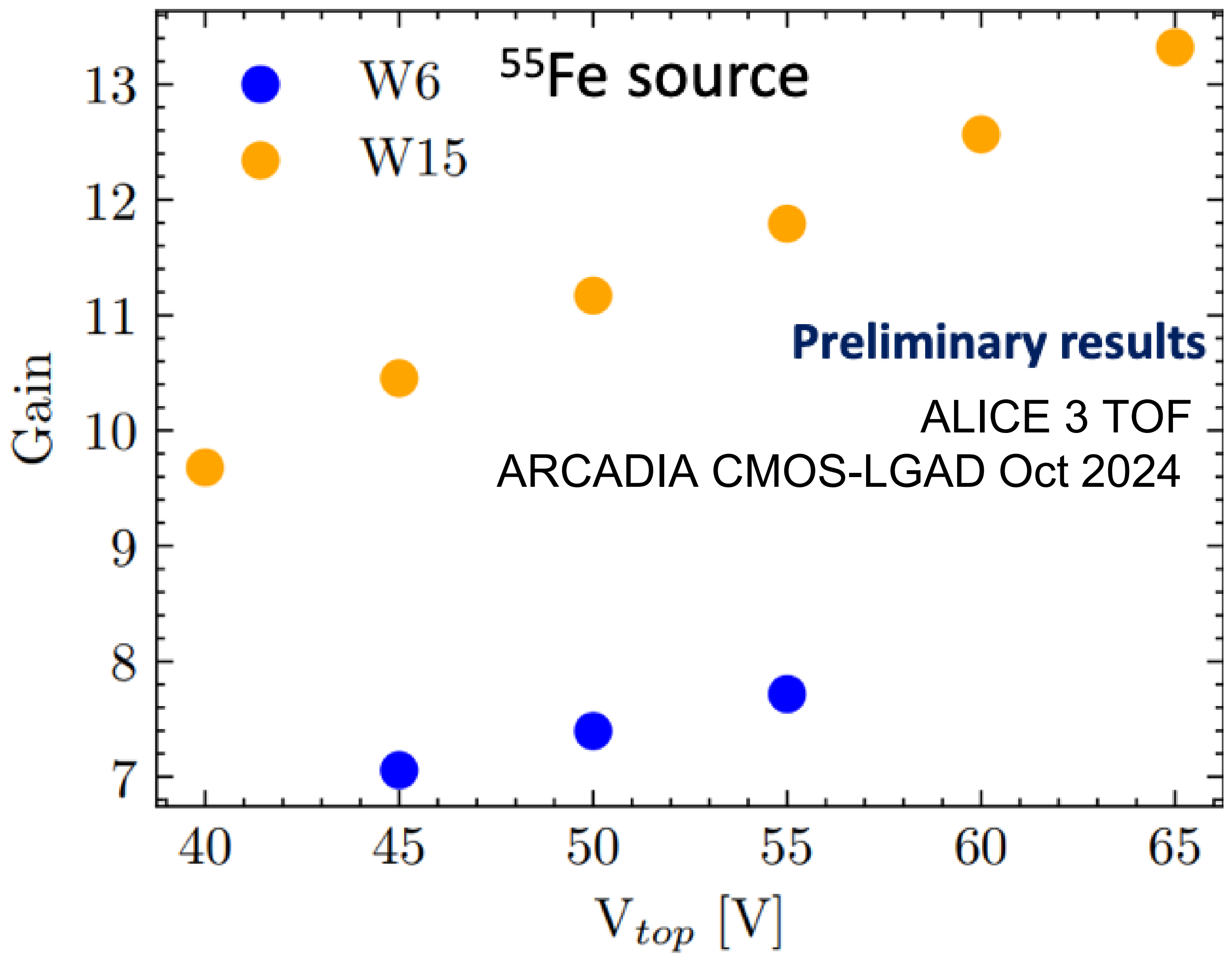
- First prototypes with 50 μm thickness tested
- Time resolution: 75 ps, agrees with simulations
- Next step: thinned sensors

CMOS LGAD pad sensor

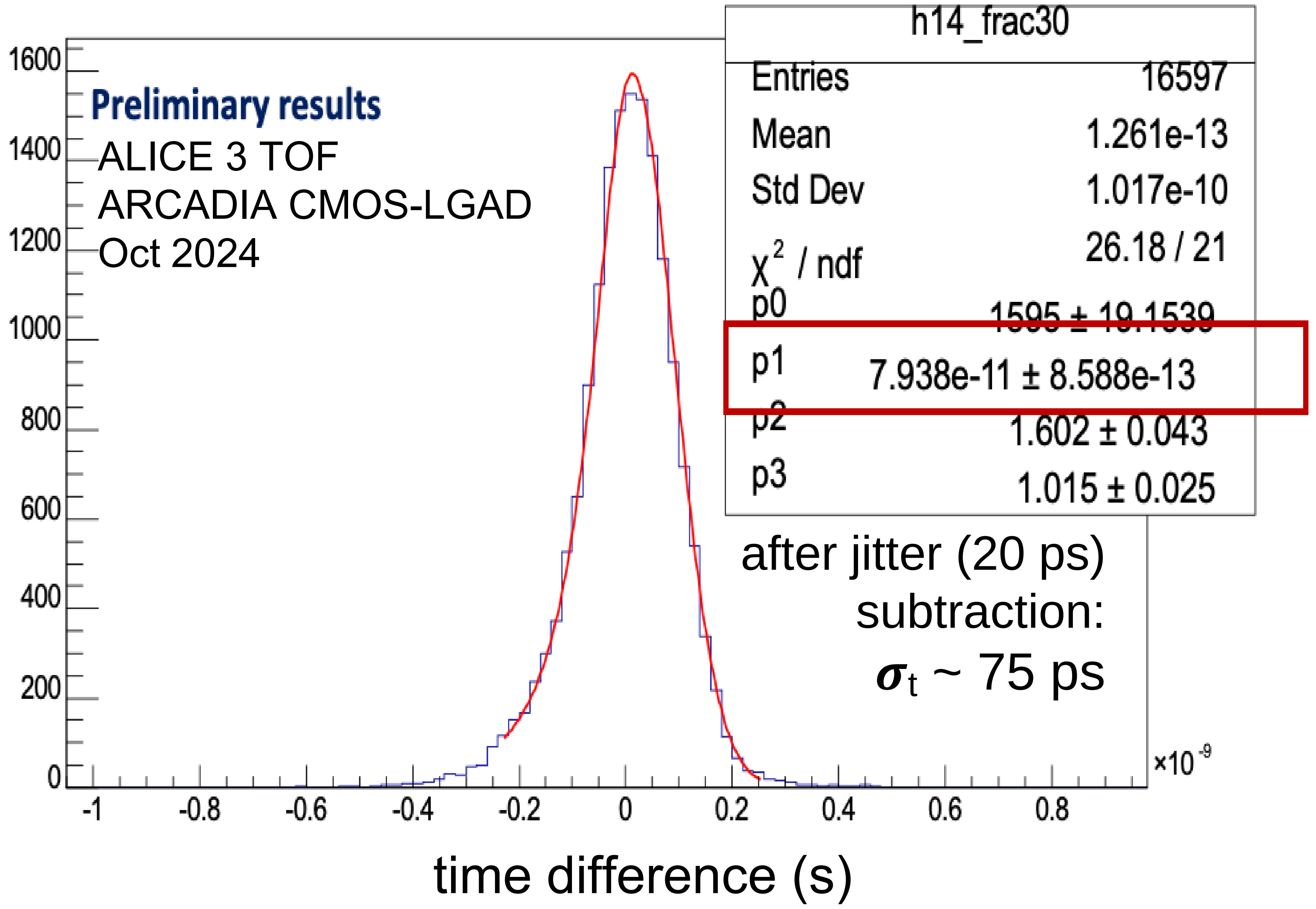


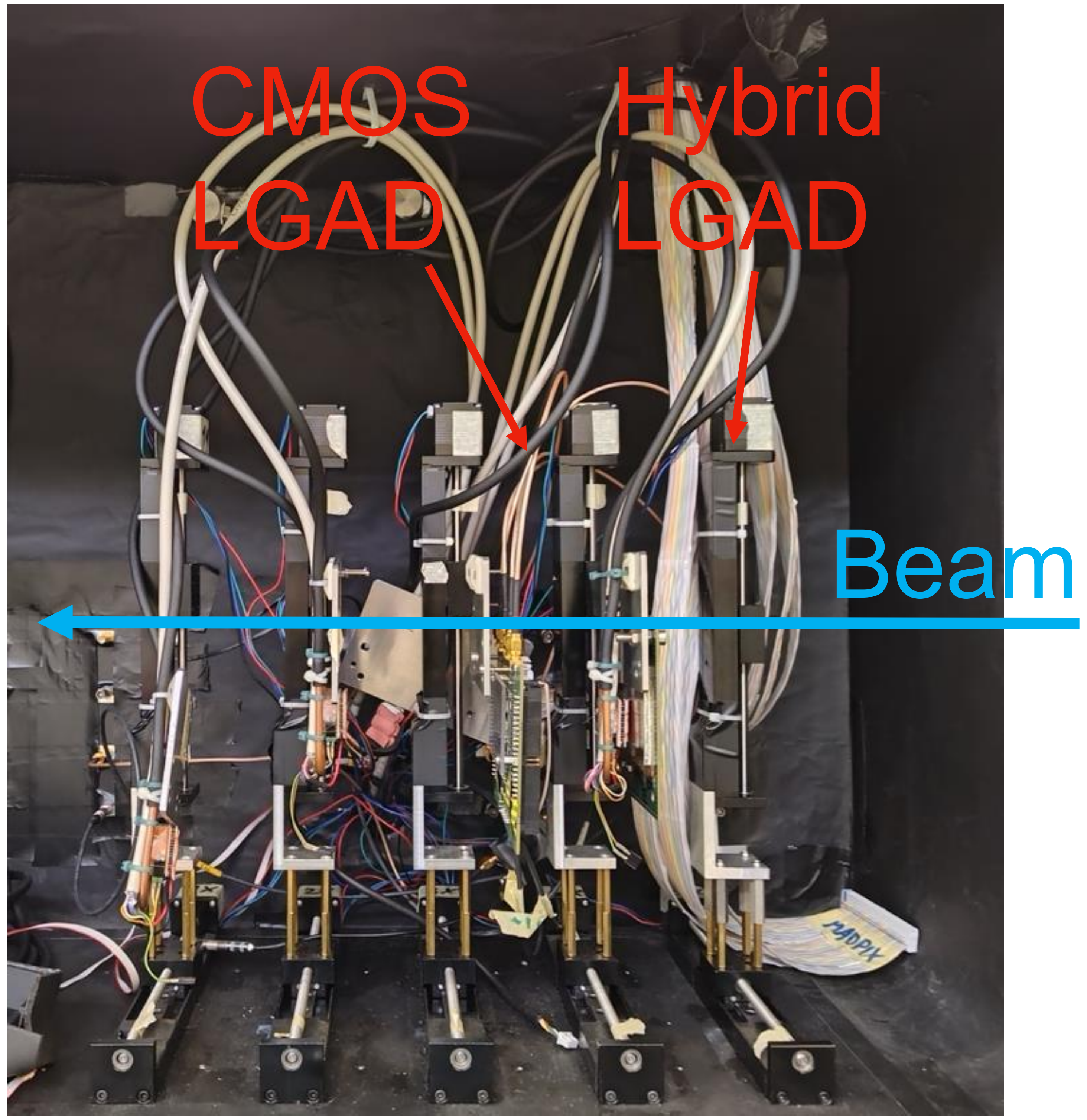


Gain measurement



Time distribution





Conclusion

- Heavy-ion collisions at LHC provide unique laboratory to study strongly interaction matter
  - Hottest and densest matter available in the laboratory
  - Properties: low viscosity, short mean free path

- Large upgrade for Run 3: improved precision, new channels
  - Many new results to come in the next years

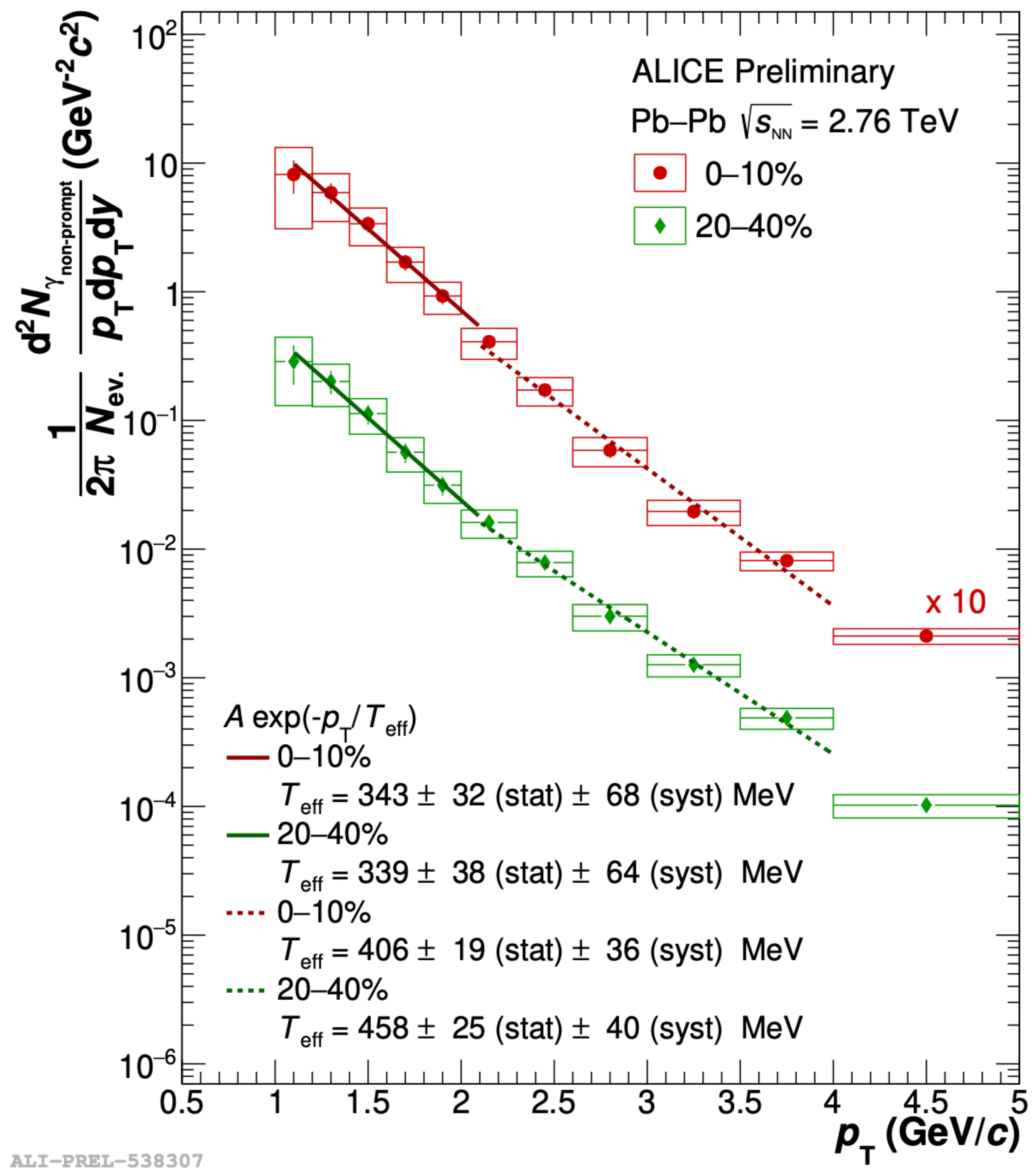
- Future upgrades: focus on thermal radiation, chiral symmetry restoration, thermalisation, structure of exotic hadrons (interaction potentials)

Thanks for your attention

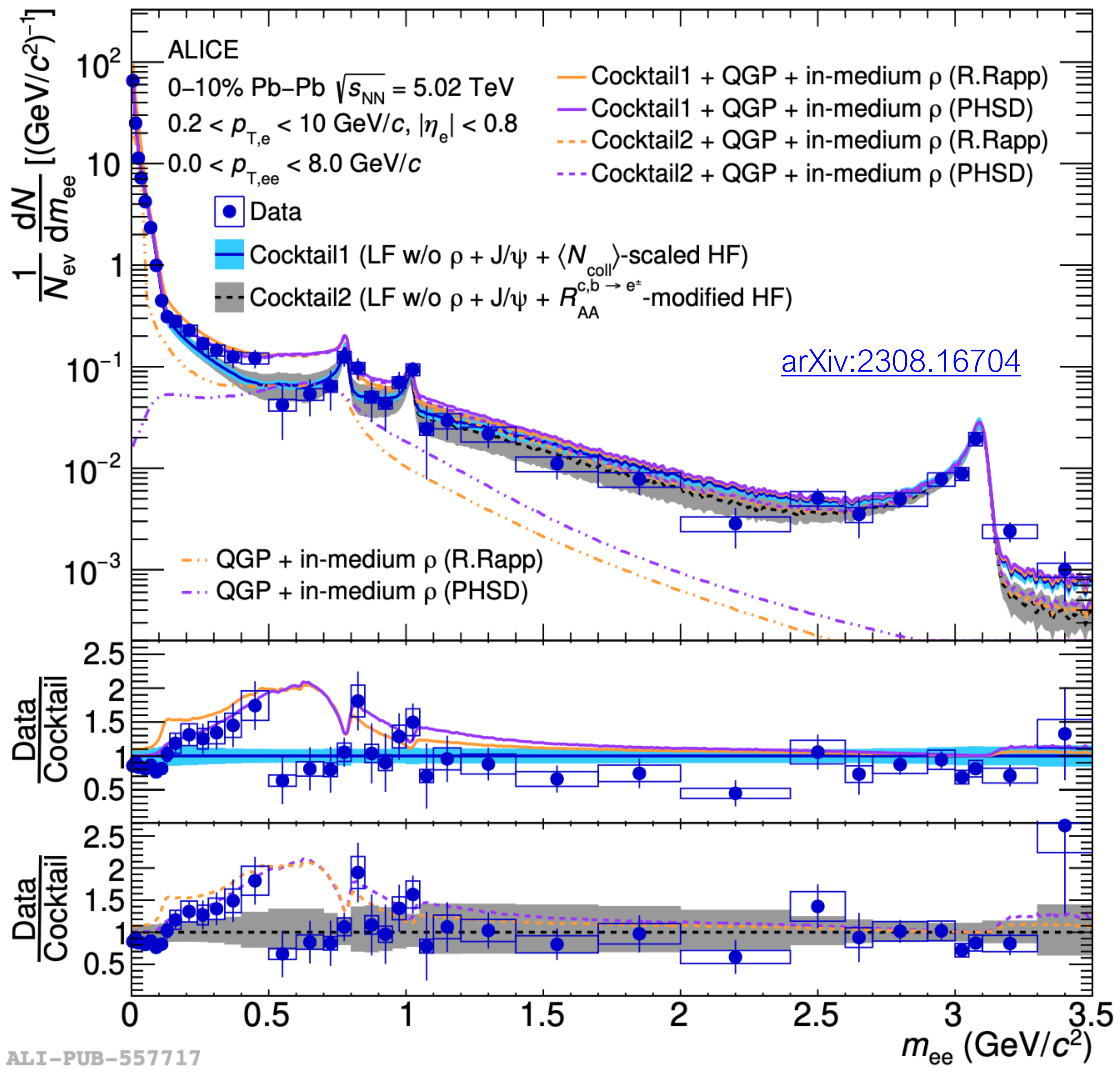
Start of heavy-ion run 6 November 2024: the quest continues…

Taking the temperature: photons and dileptons

Direct photon excess spectrum



Dielectron mass spectrum



Electromagnetic radiation **(real) photons** and **dielectrons (virtual photons)** measure the temperature of the QGP

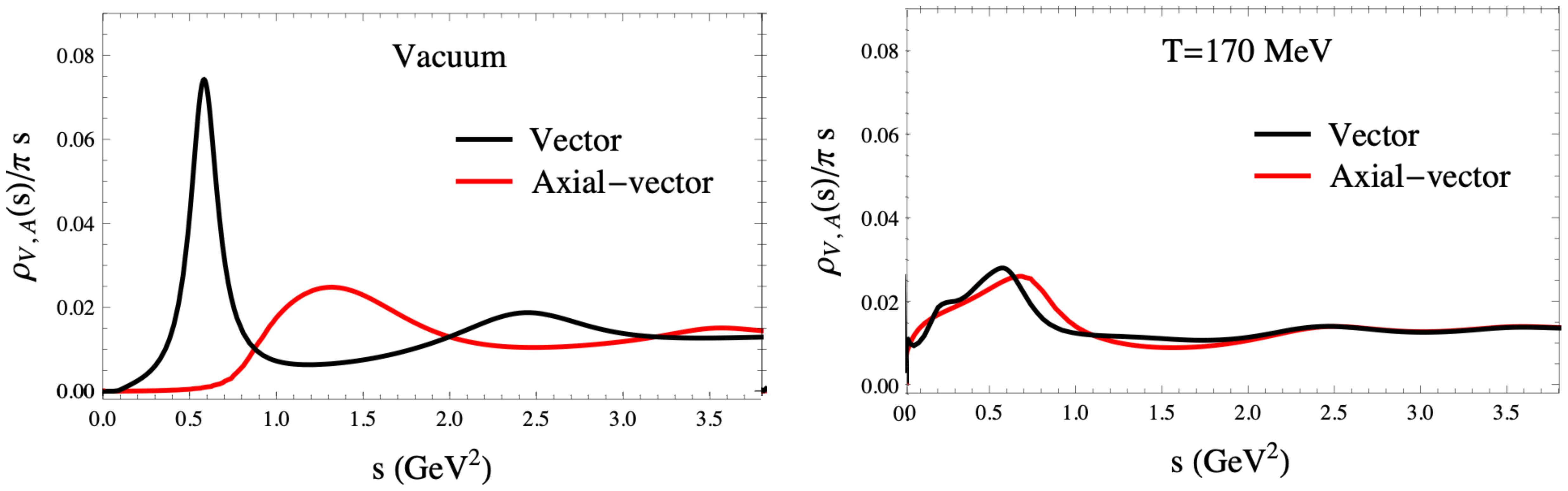
Challenging measurement: large background from hadronic decays

Apparent (blue-shifted) temperature $T \approx 350$ MeV

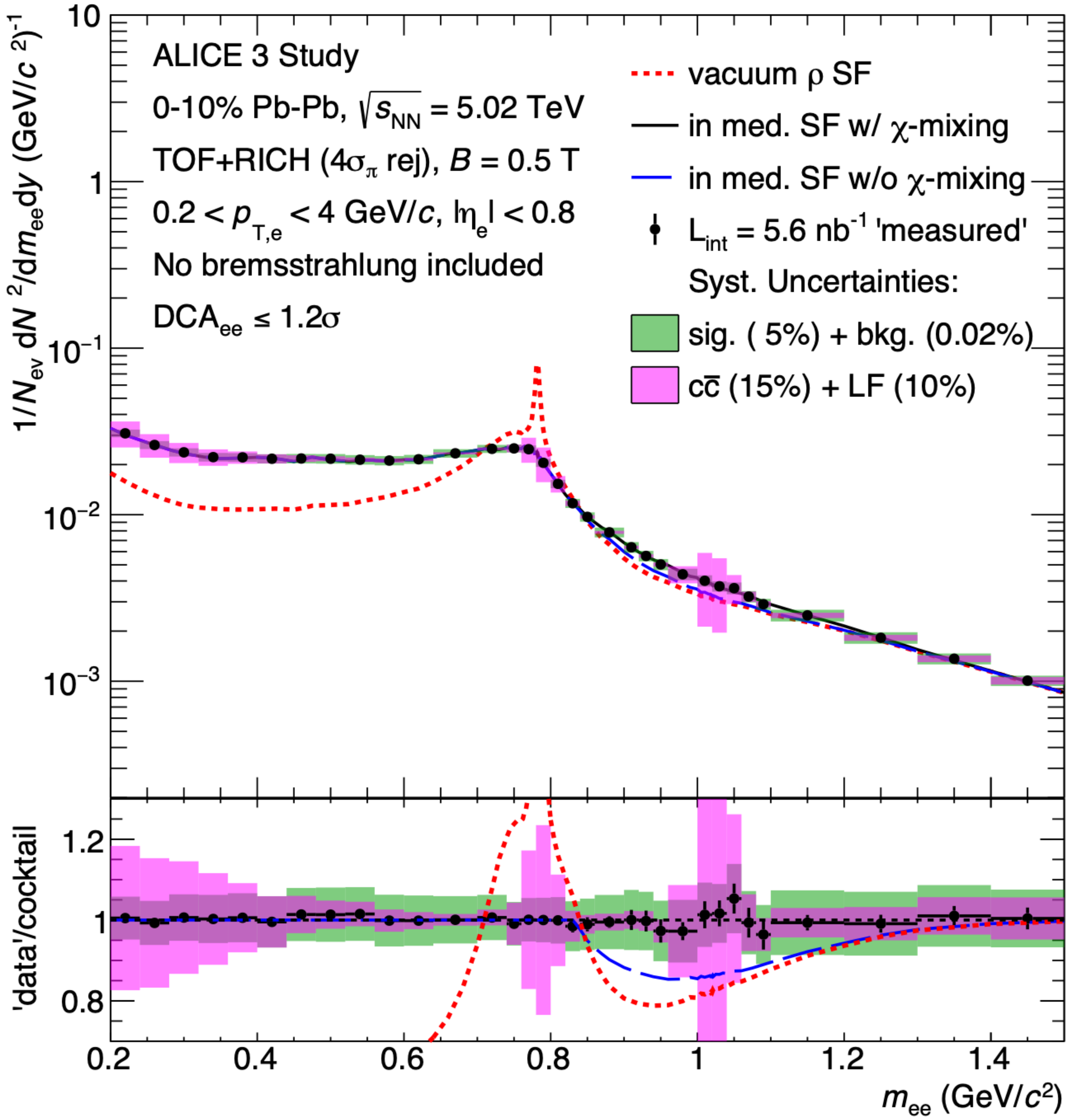
Chiral symmetry restoration: $\rho - a_1$ mixing

- Spontaneous breaking of chiral symmetry generates **hadron masses in QCD**
  - Large mass difference between ρ (770 MeV) and a_1 (1260 MeV)
- **Chiral symmetry restored in QGP**
  - ρ and a_1 degenerate: mixing
- ALICE 3 provides experimental access to chiral symmetry restoration mechanism

ρ and a_1 spectral function



Hohler and Rapp, PLB 731,103

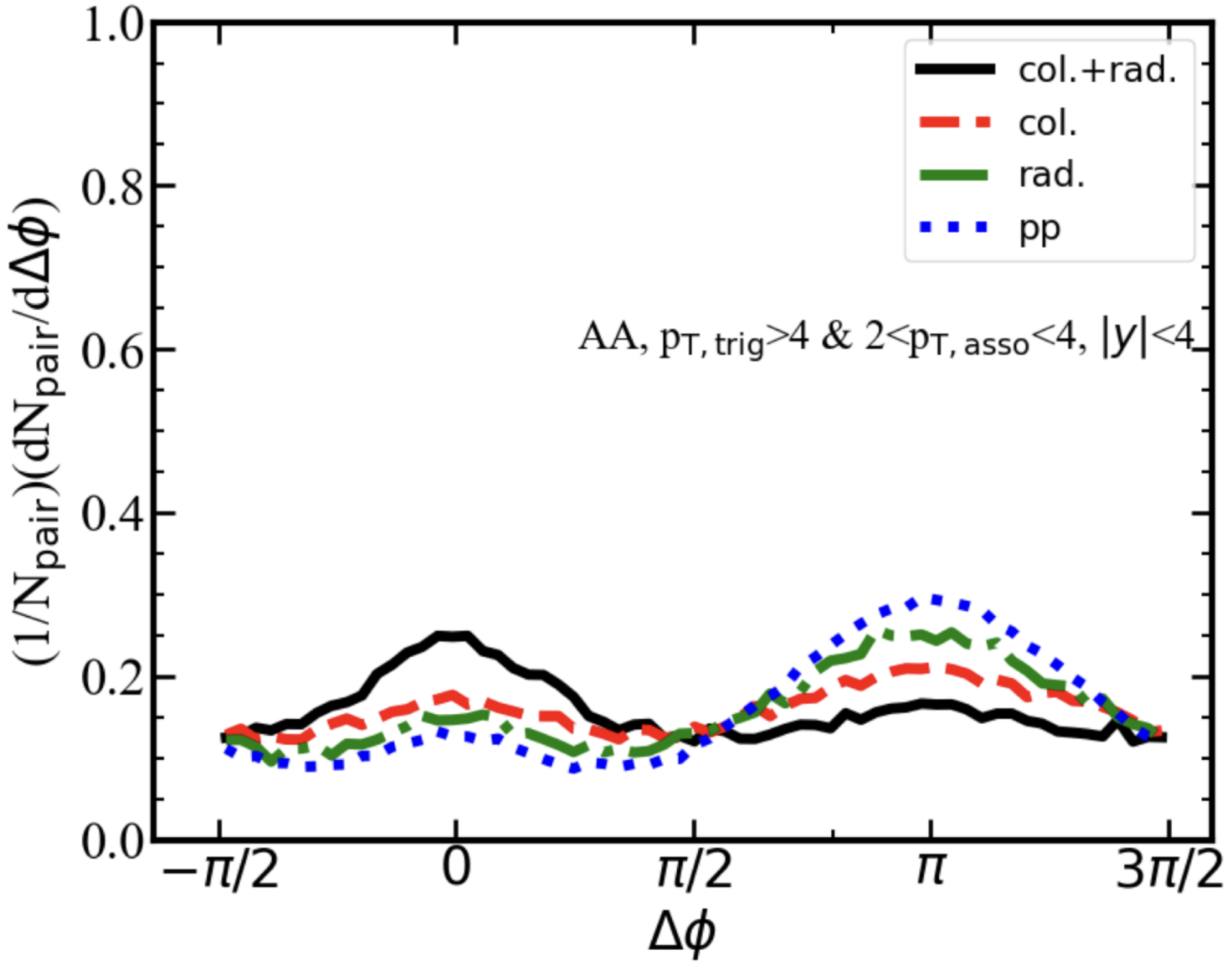


$\rho - a_1$ mixing affects mass spectrum above ρ peak

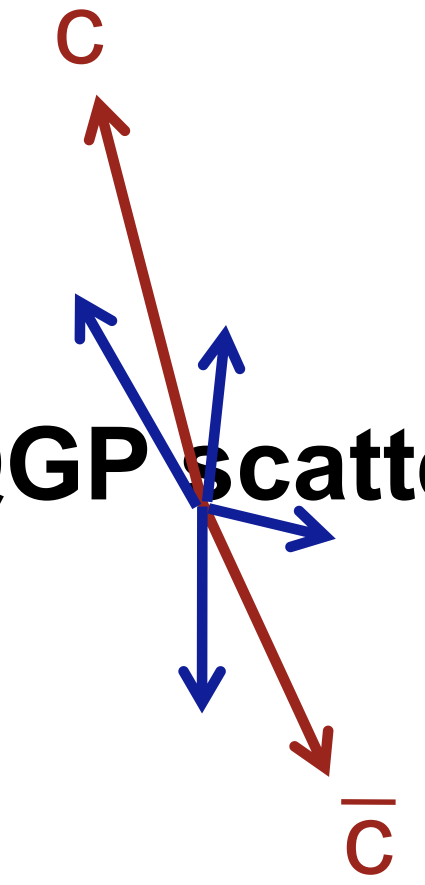
ALICE 3 provides necessary precision

Heavy-flavour transport: $D\bar{D}$ azimuthal correlations

Charm azimuthal correlations



S. Cao et al., private comm., based on PLB 838 (2023) 137733

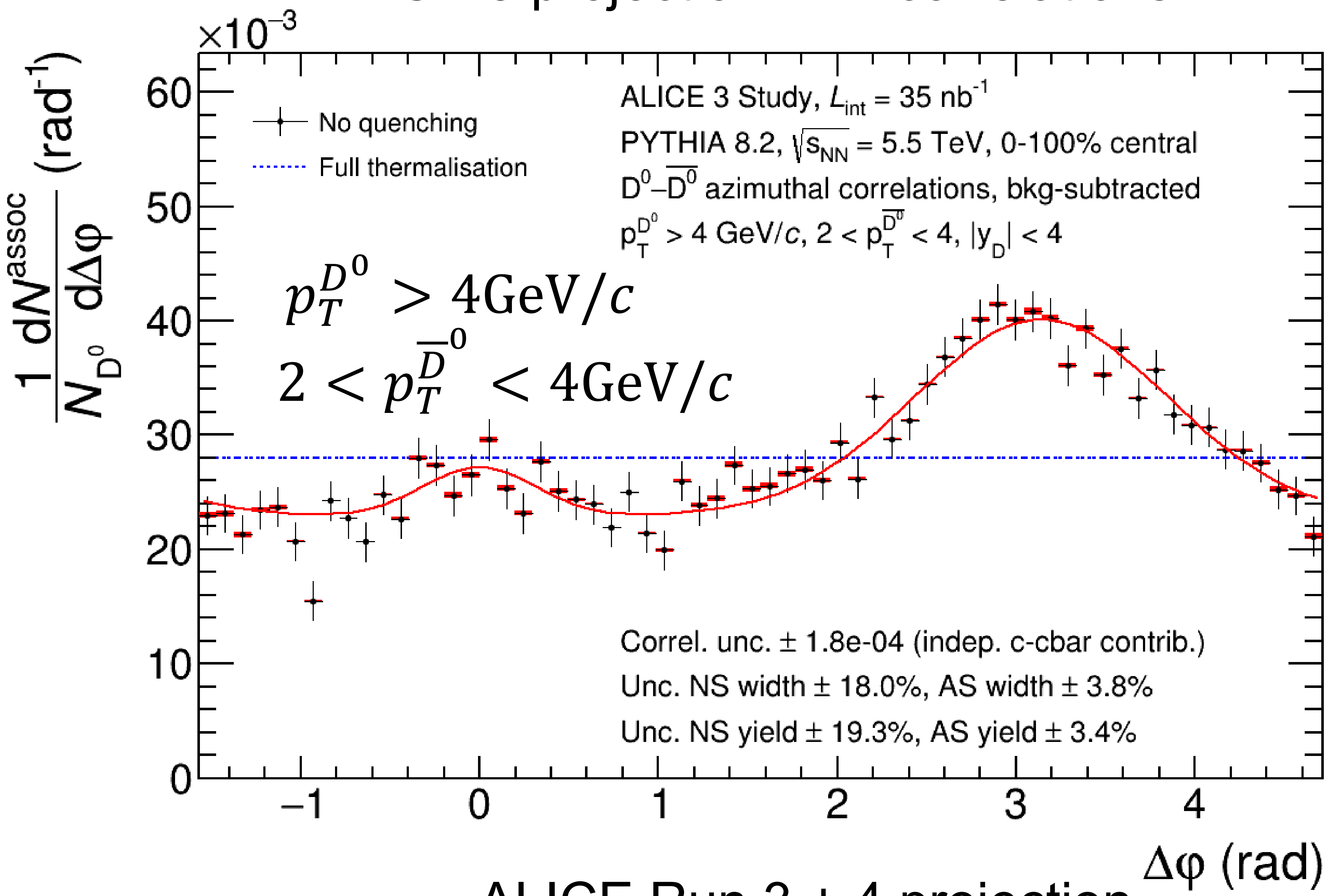


…robes QGP scattering

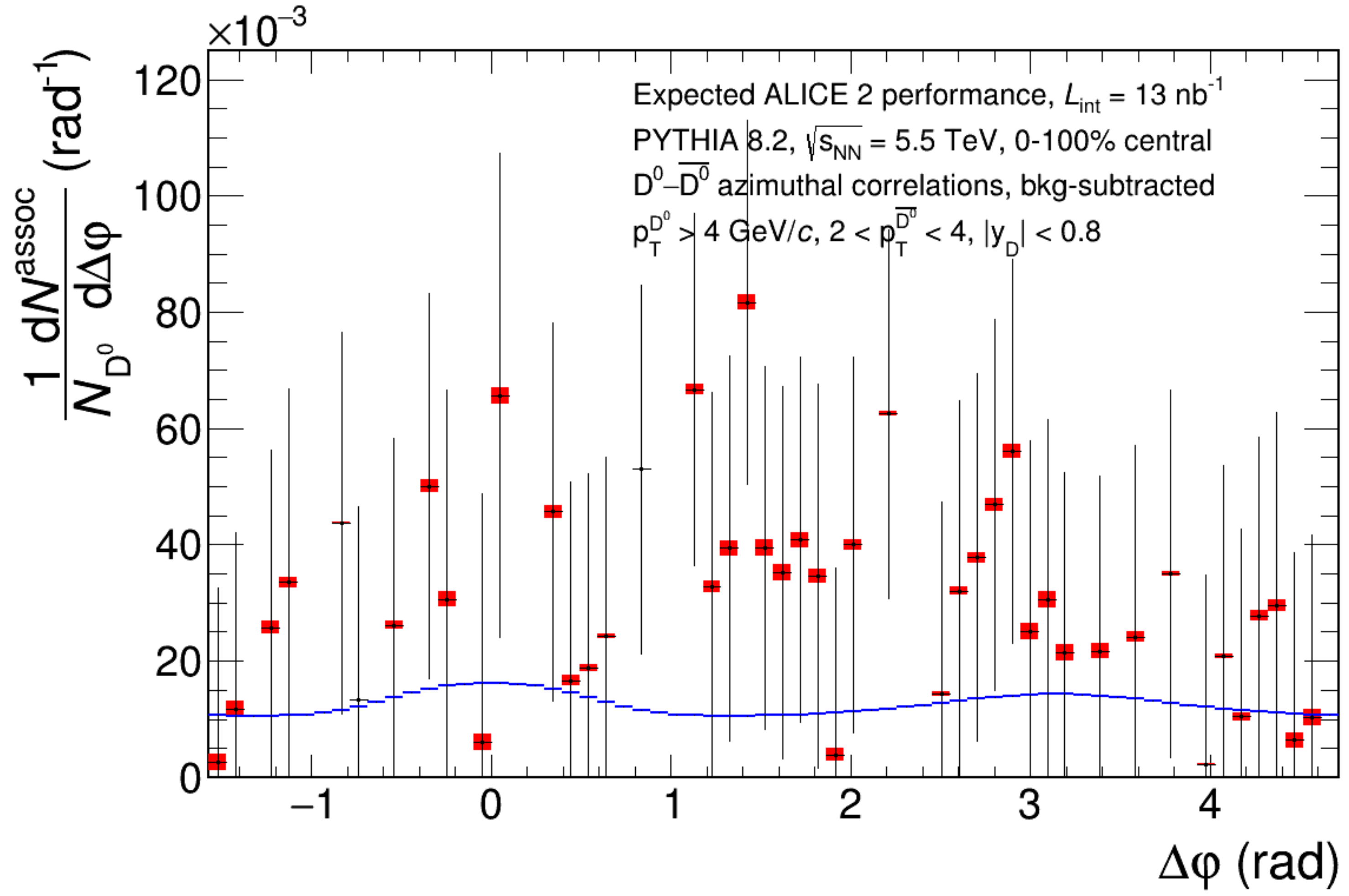
… η coverage

… y possible with ALICE 3

ALICE 3 projection: $D\bar{D}$ correlations

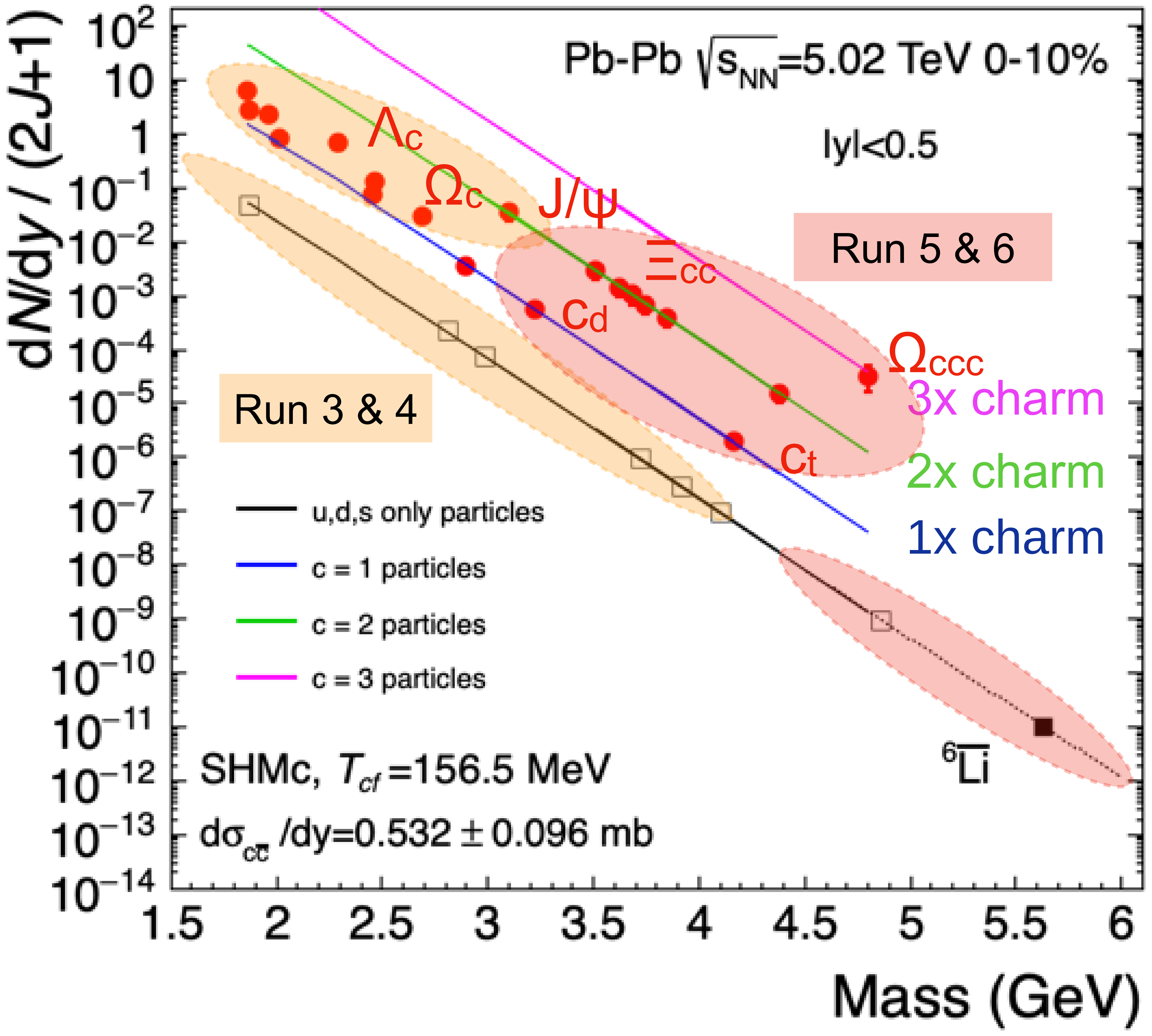


ALICE Run 3 + 4 projection



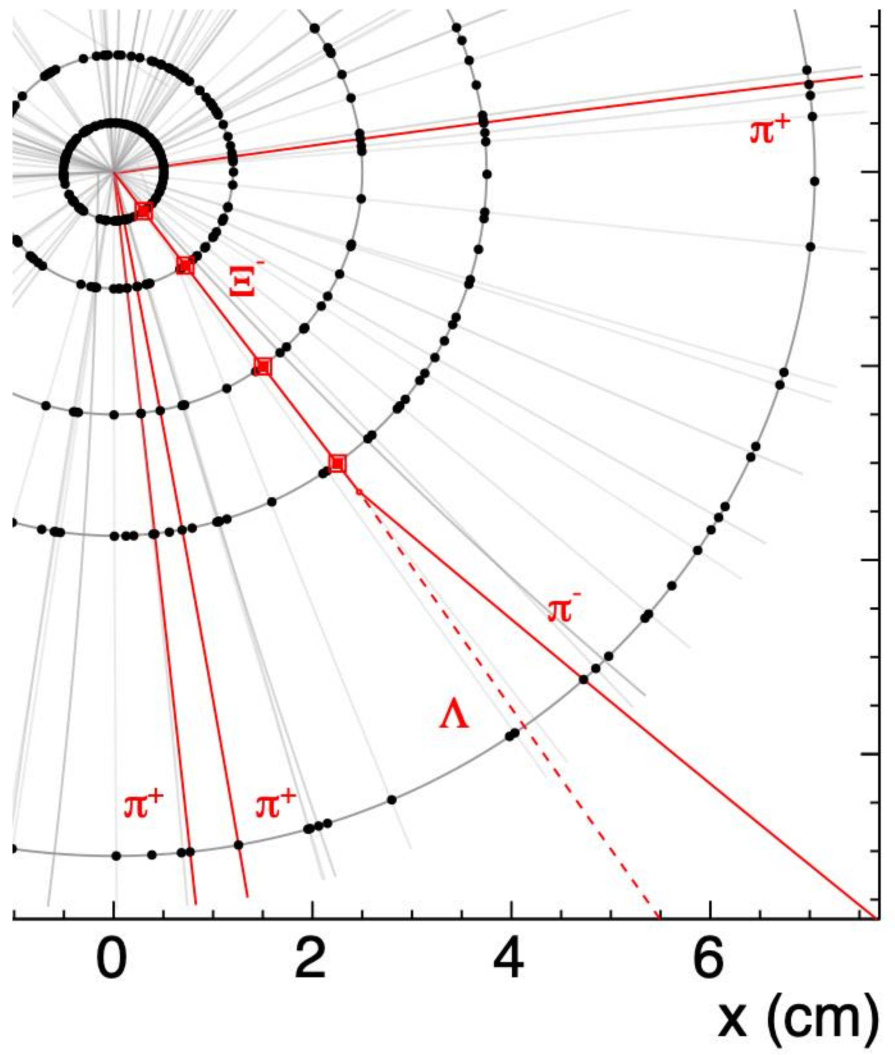
Hadron formation: multi-HF hadrons

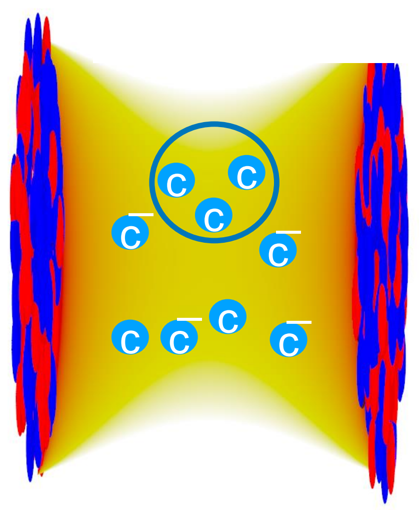
Yield vs mass



A Andronic et al, JHEP 07 (2021) 035

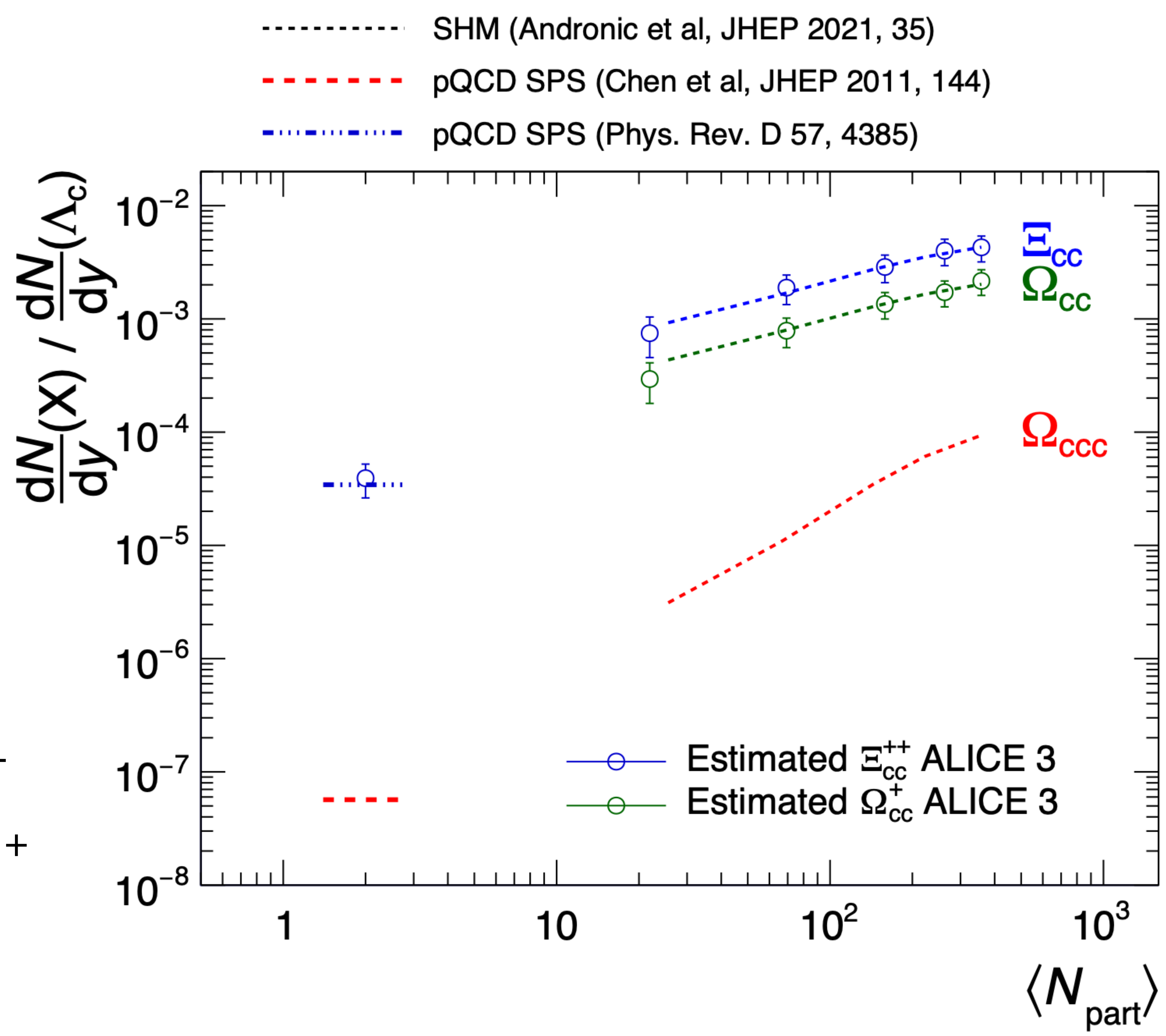
Strangeness tracking





$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+$$

$$\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$$



Multi-charm baryons: unique probe of hadron formation

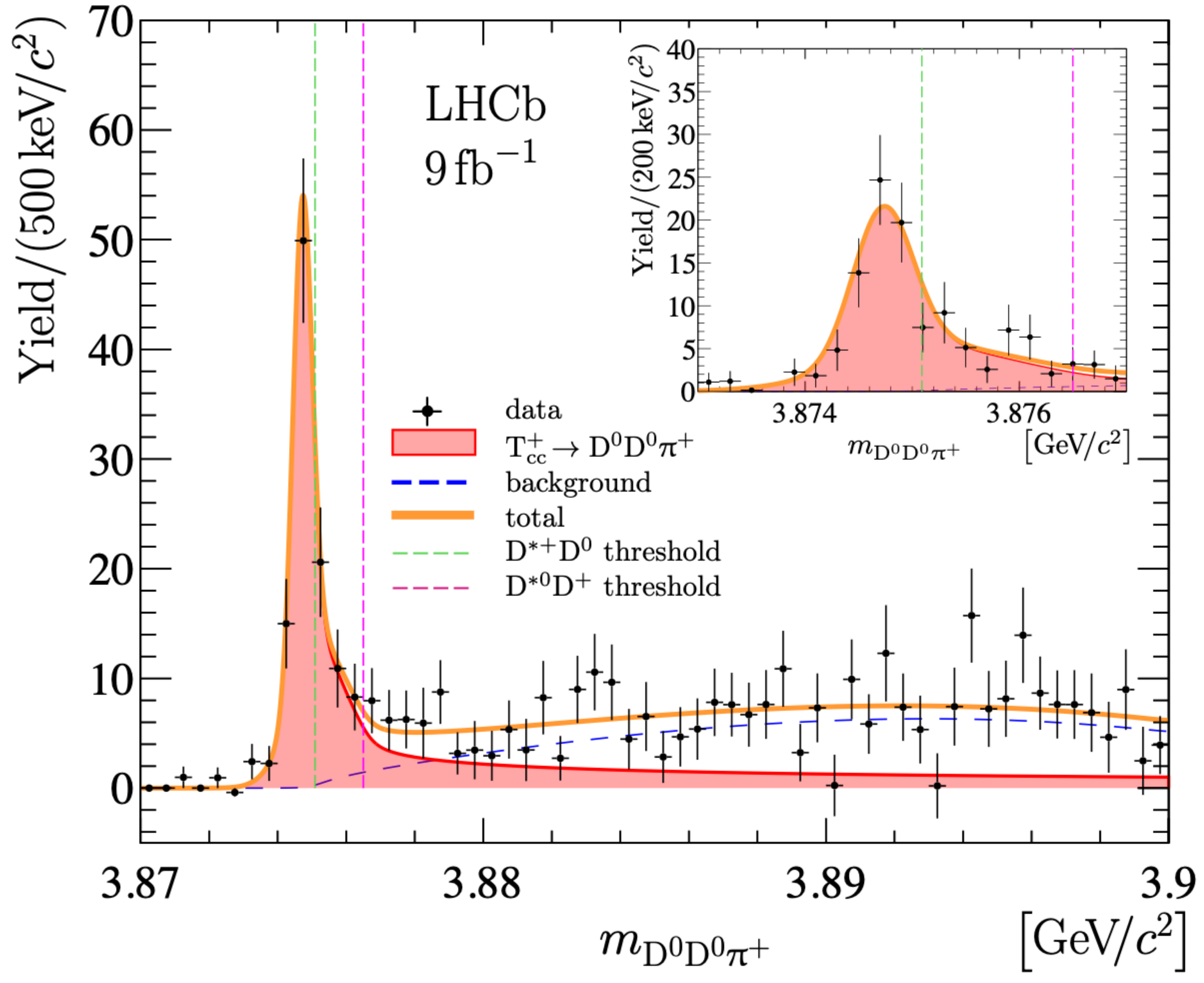
Statistical hadronisation model: **very large enhancement** in AA

- Specific relation between yields: g_c^n for *n*-charm states

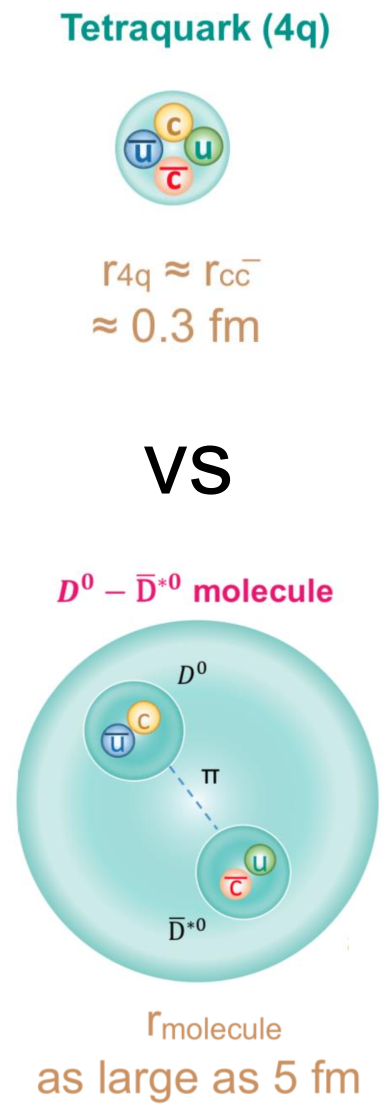
ALICE 3: unique experimental access to multi-charm baryons

Heavy-ion collisions as a laboratory for hadron physics

T_{cc}^{+} discovery

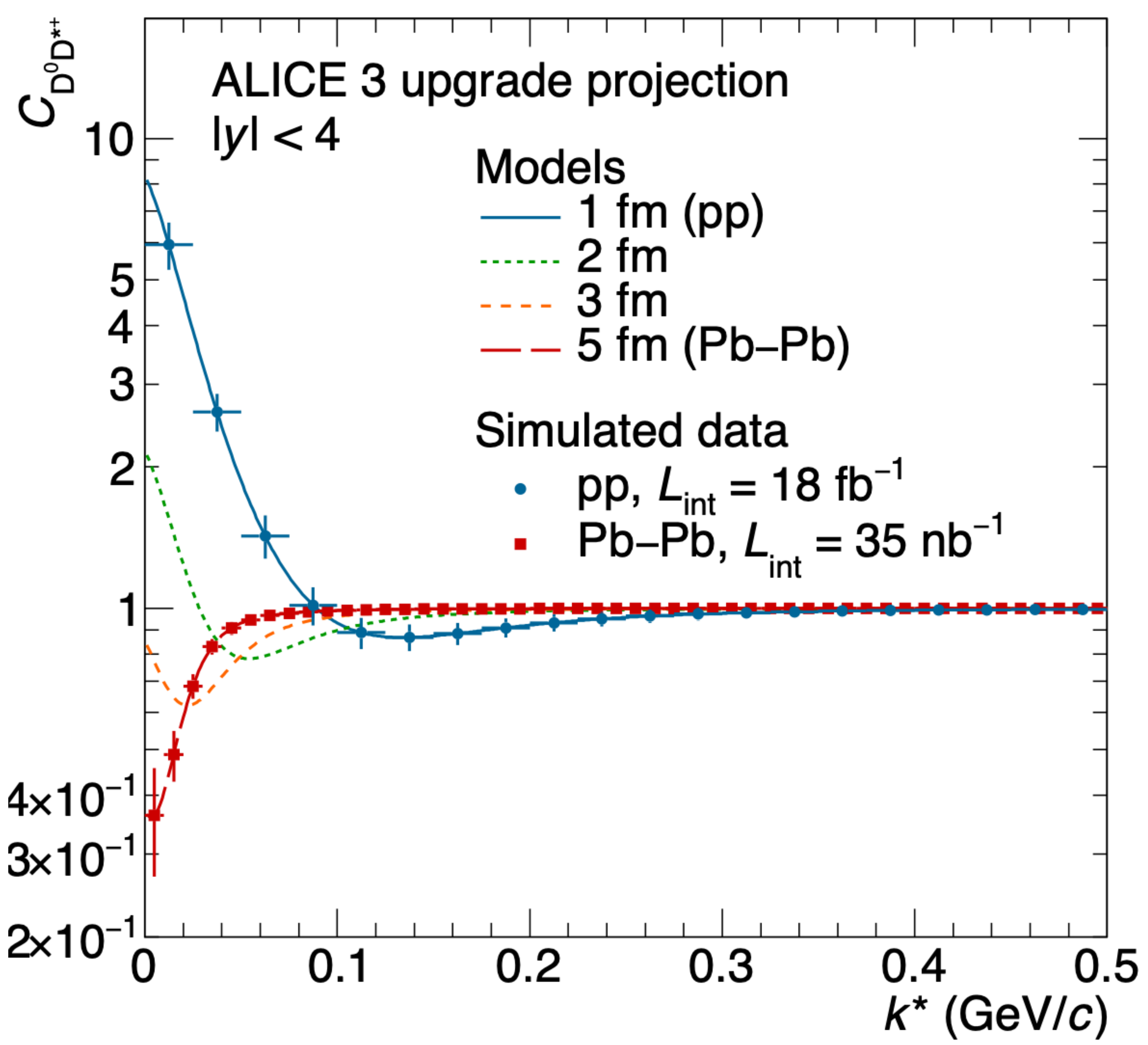


LHCb, Nat Phys 18 (2022) 7, 751

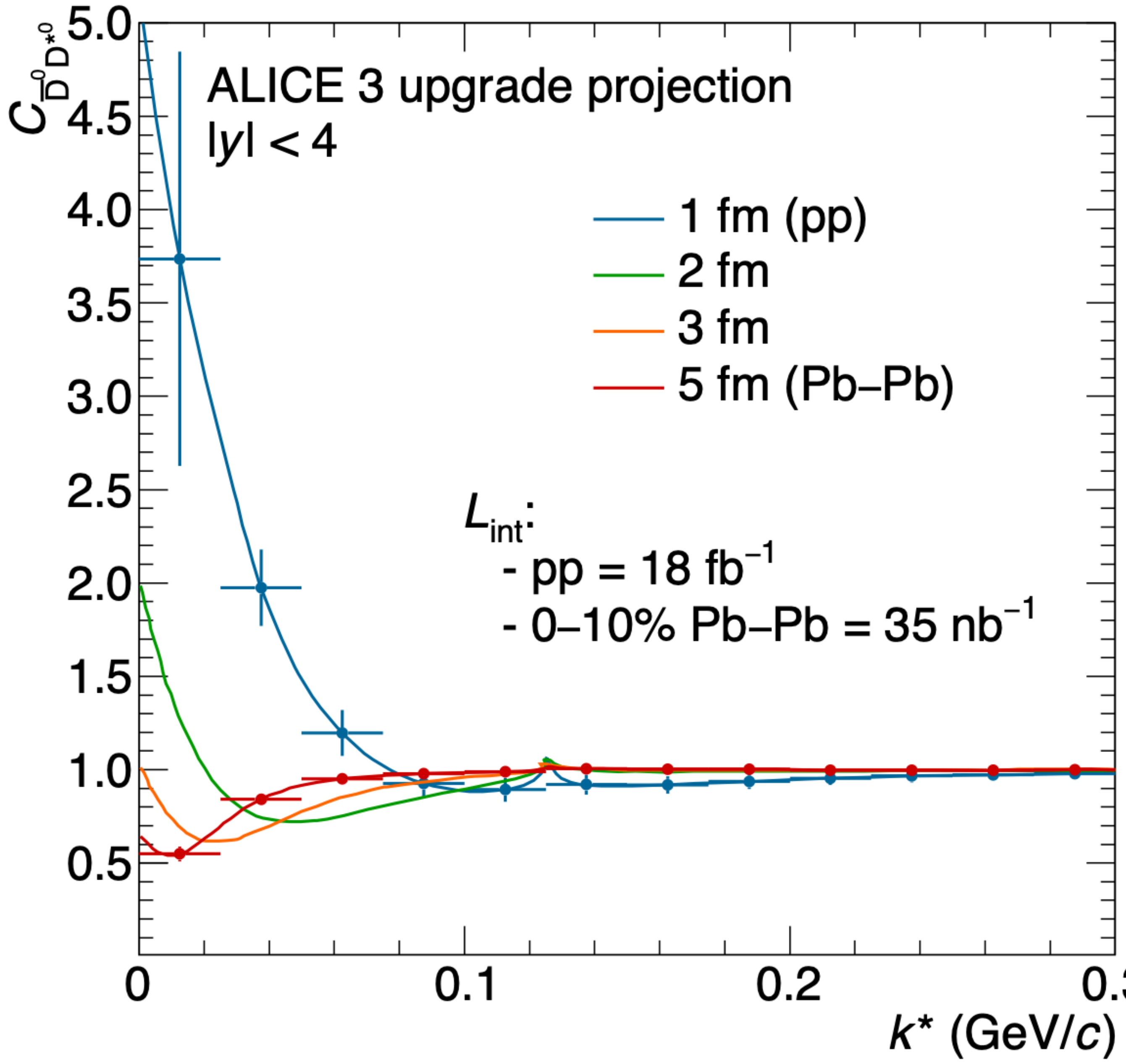


DD* momentum correlation

D^0D^{*+}



$D^0\overline{D}^{*0}$



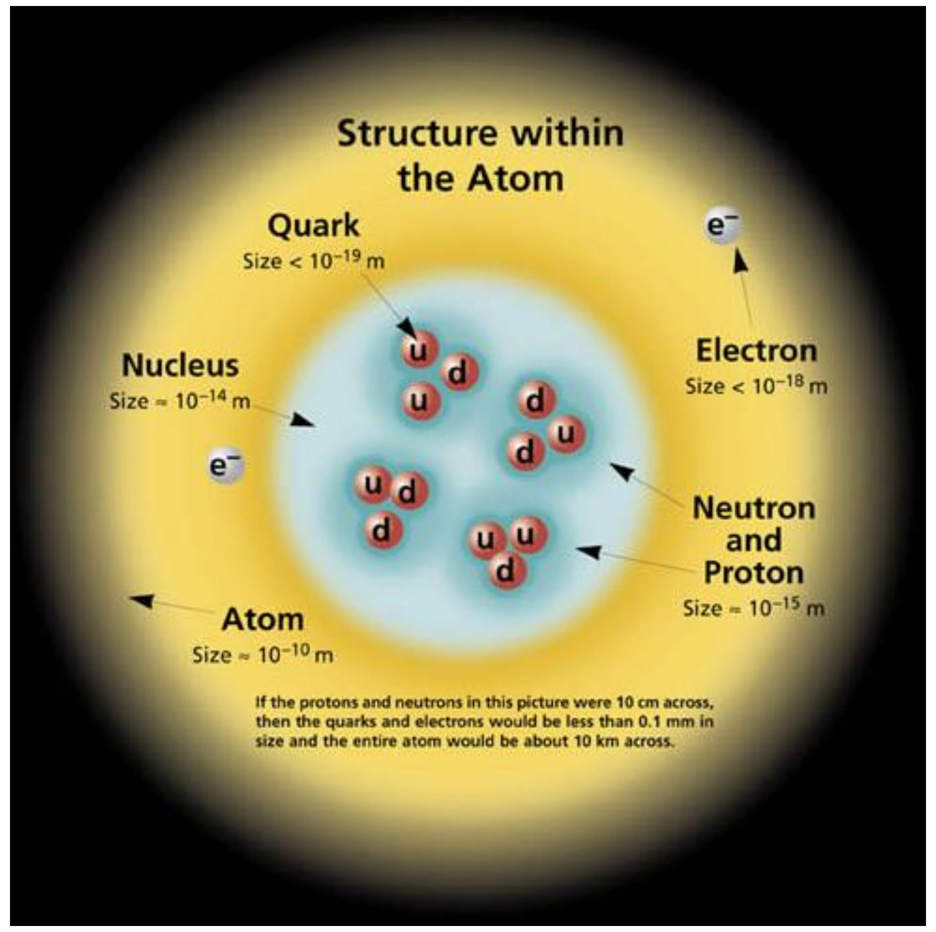
D^0D^{*+}: nature of T_{cc}^{+}

$D^0\overline{D}^{*0}$: nature of $\chi_{c1}(3872)$

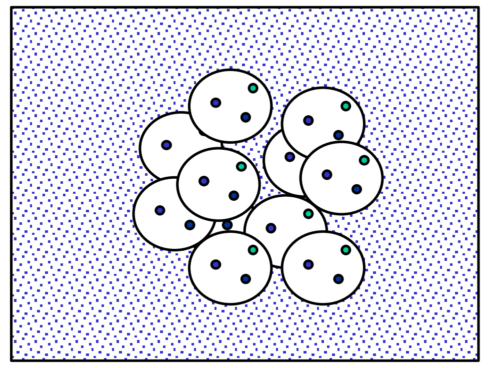
- Several exotic heavy flavour states identified
- Loosely bound meson molecule or tightly bound tetraquark?
- Study binding potential with final state interactions 'femtoscopic correlations'

Bound states produce specific pattern vs system size

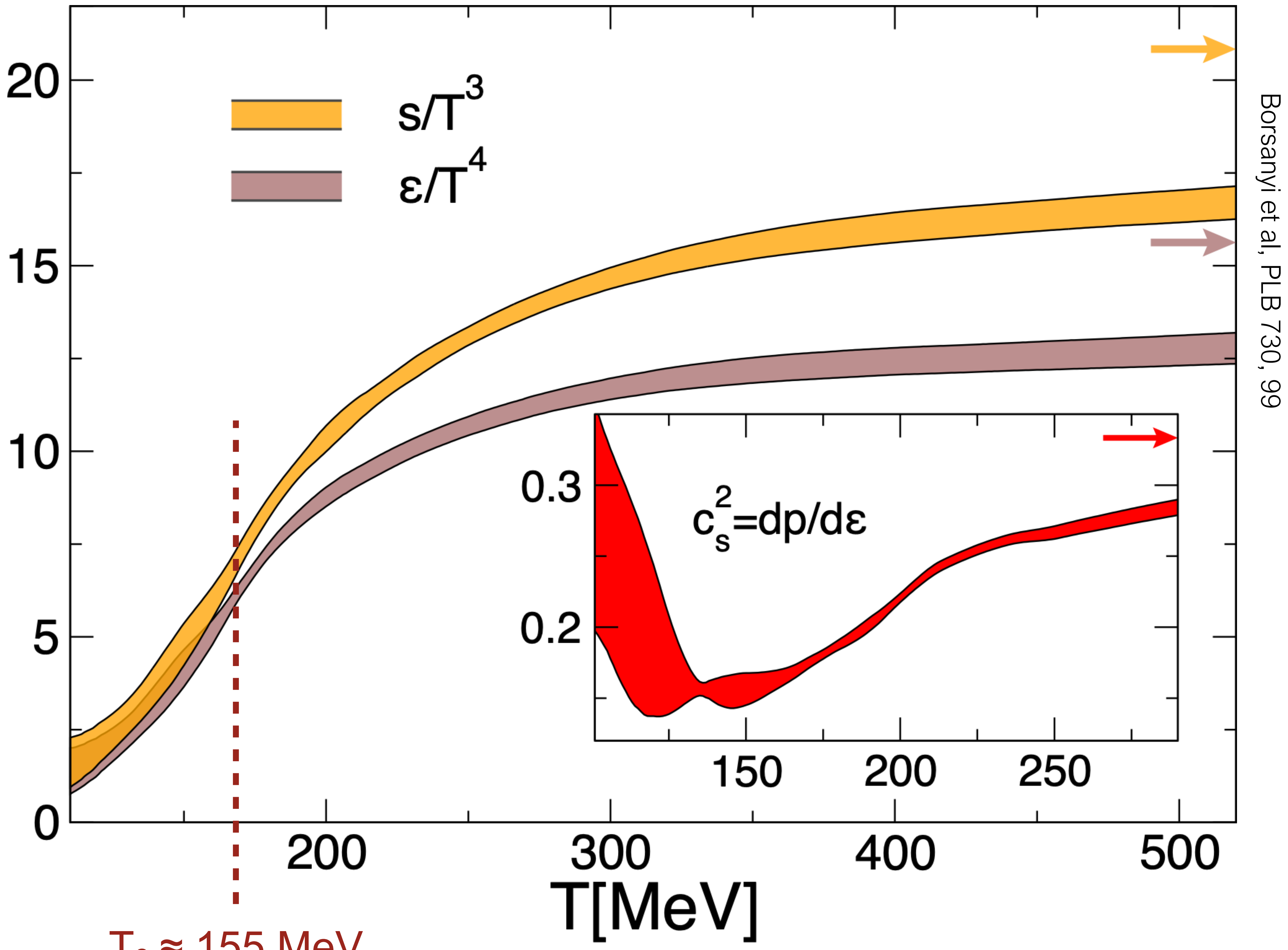
QCD and the quark-gluon plasma



Nuclear matter



Energy density vs temperature

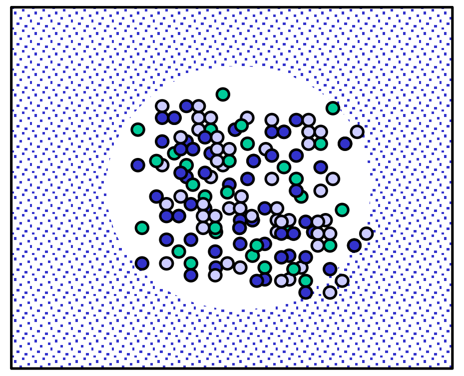


$T_c \approx 155$ MeV (10^{12} K)

$\varepsilon \propto gT^4$

g: degrees of freedom

Quark Gluon Plasma



Quarks and gluons

- Fundamental particles of the strong interaction
- Normally confined inside protons, neutrons

At high temperature, density: deconfinement phase transition