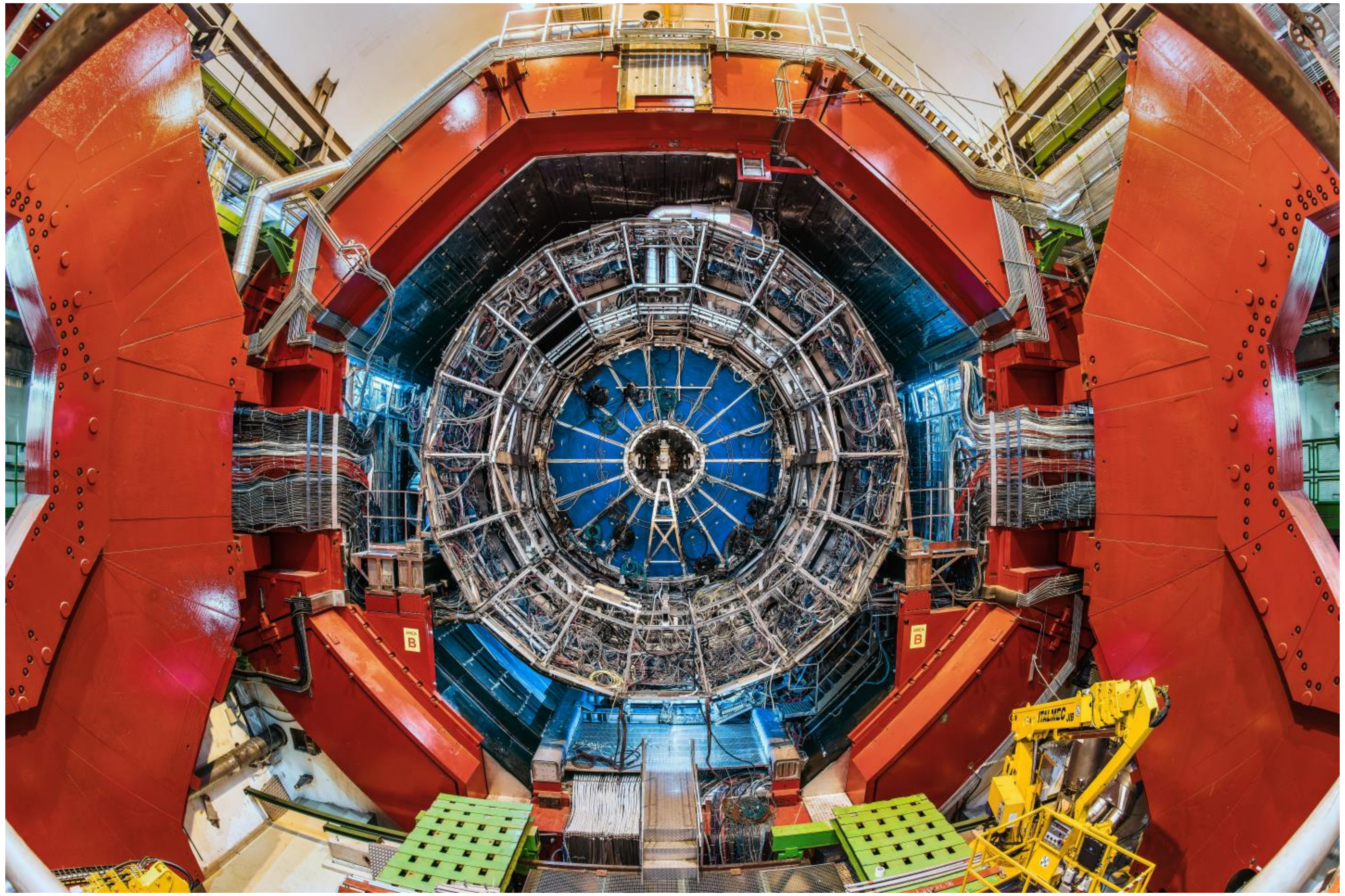
ALICE and the Quark-Gluon Plasma

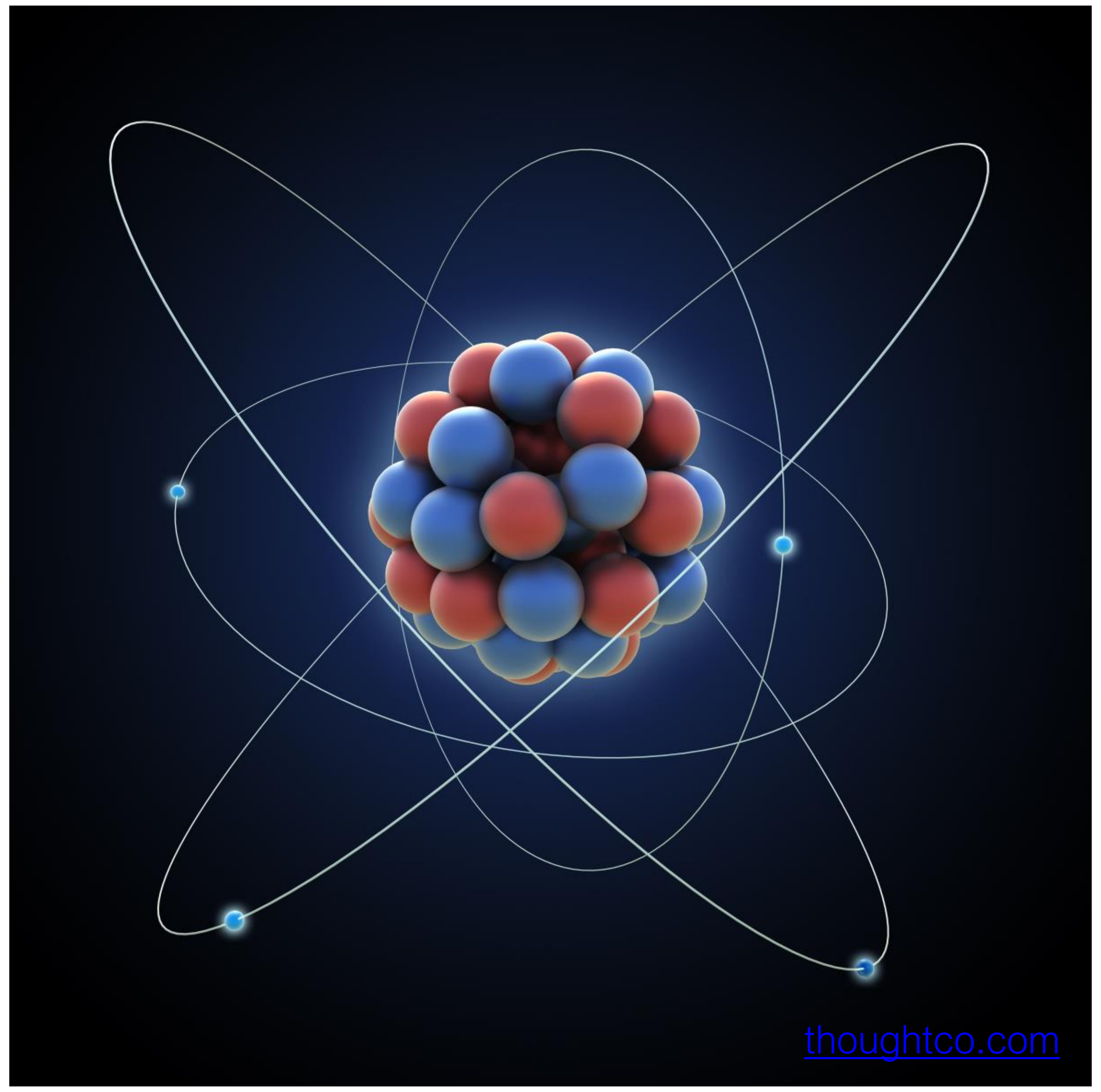
Marco van Leeuwen, Nikhef and CERN

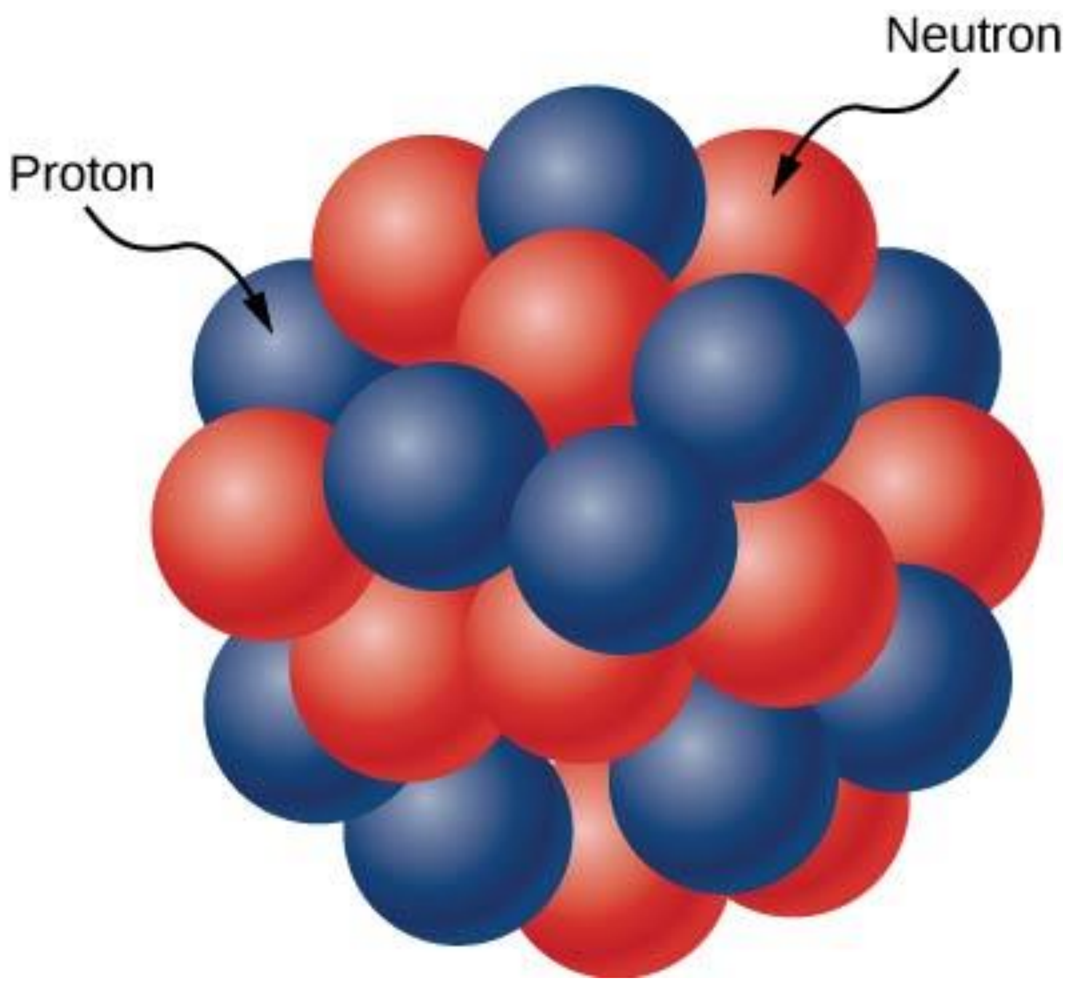
20 Years of Stefan Meyer Institute
11 November 2024

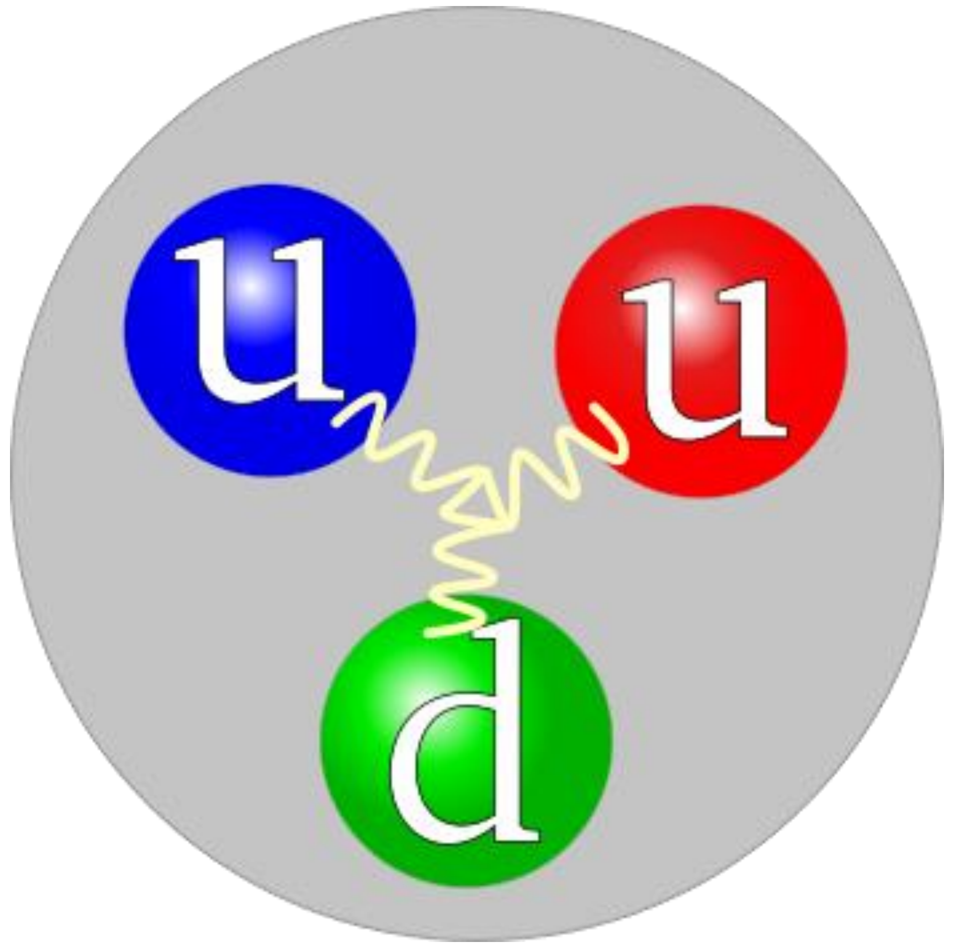


Energy scales: ionisation energy

Atom	Atomic nucleus	Hadron (proton)





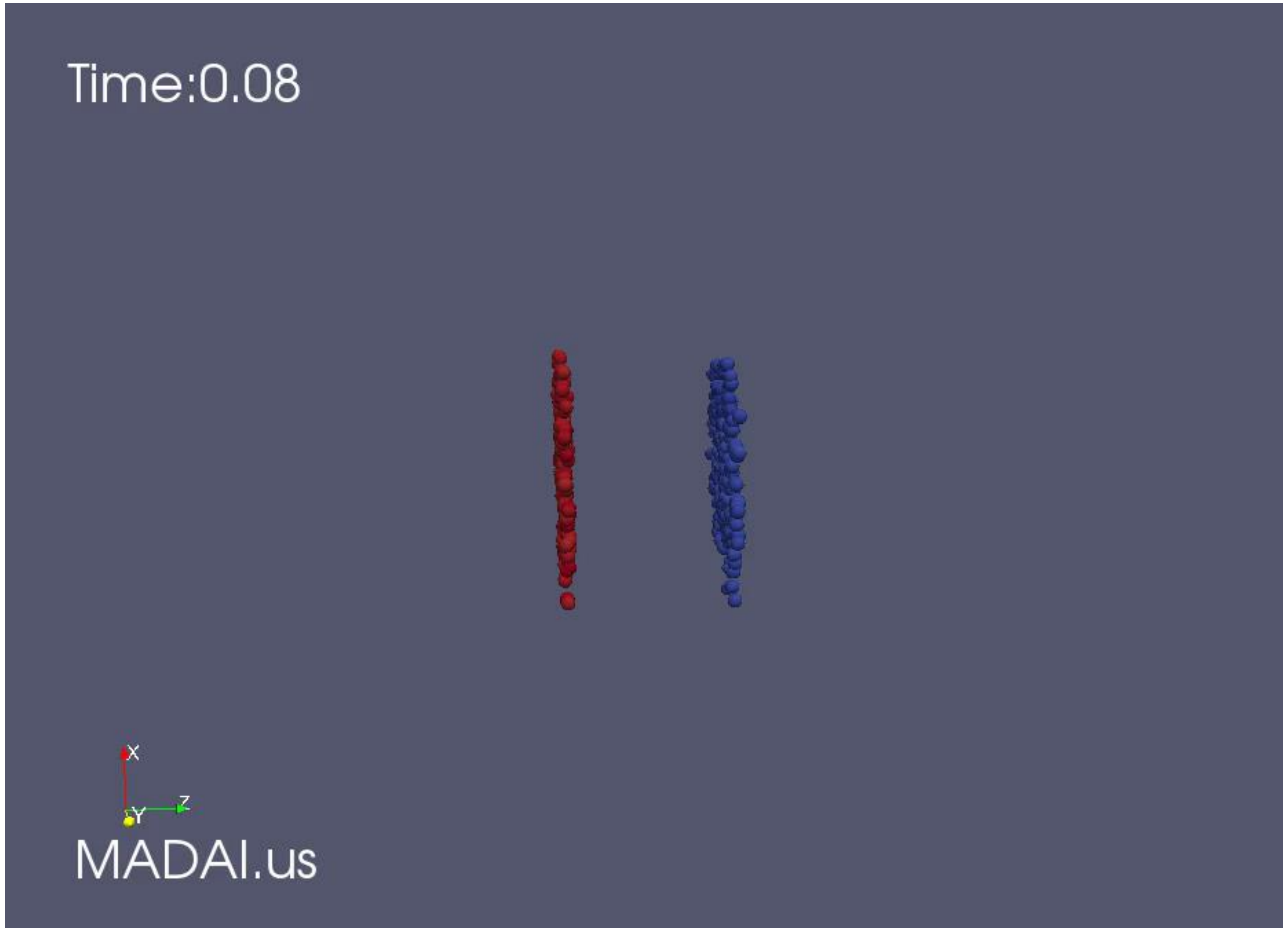


Wikimedia Commons image by Jacek Rybak

	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

Heavy ion collisions: Little Bangs



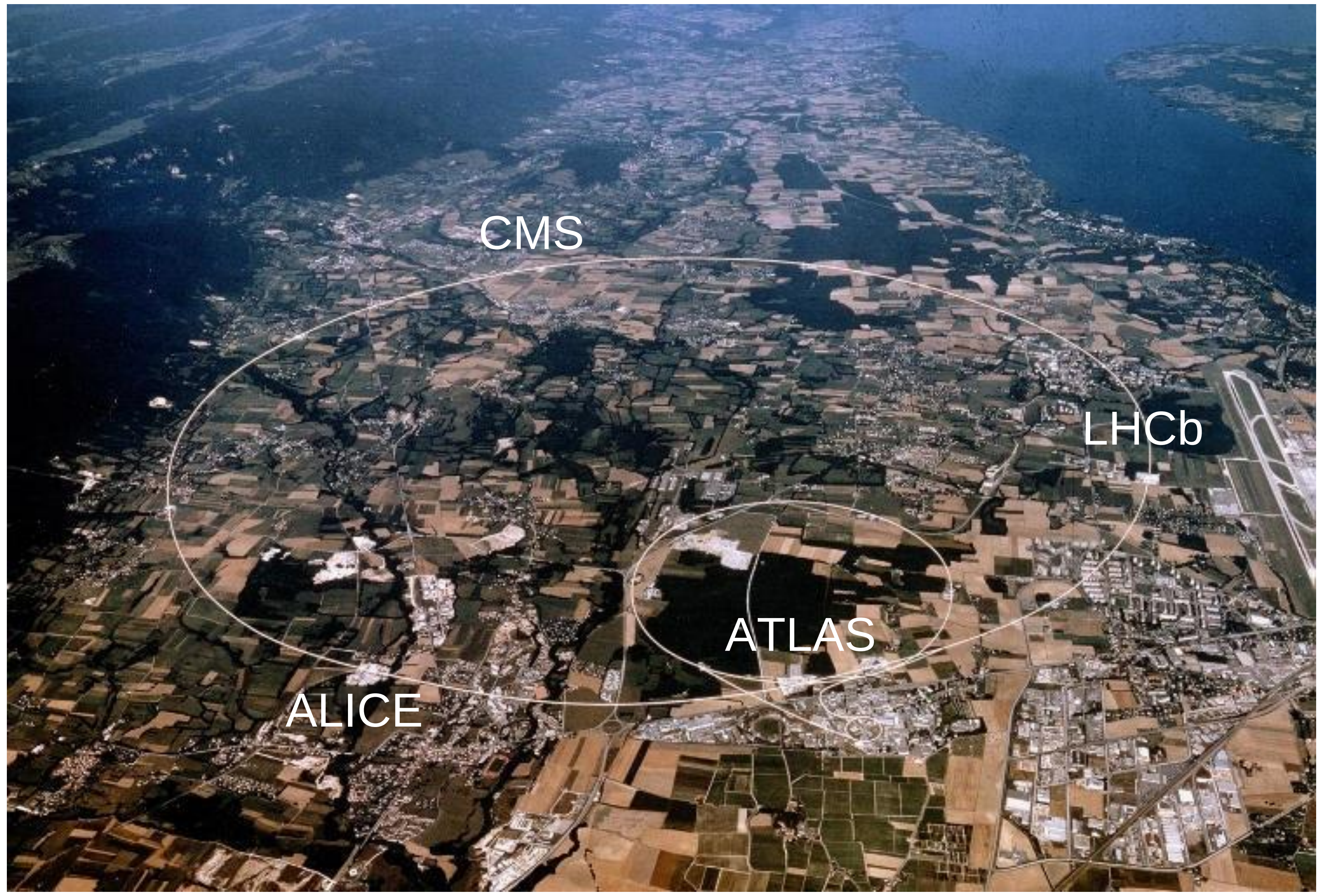
MADAI

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

‘Little Bang’: recreate primordial matter in the laboratory

ALICE at the Large Hadron Collider

The Large Hadron Collider

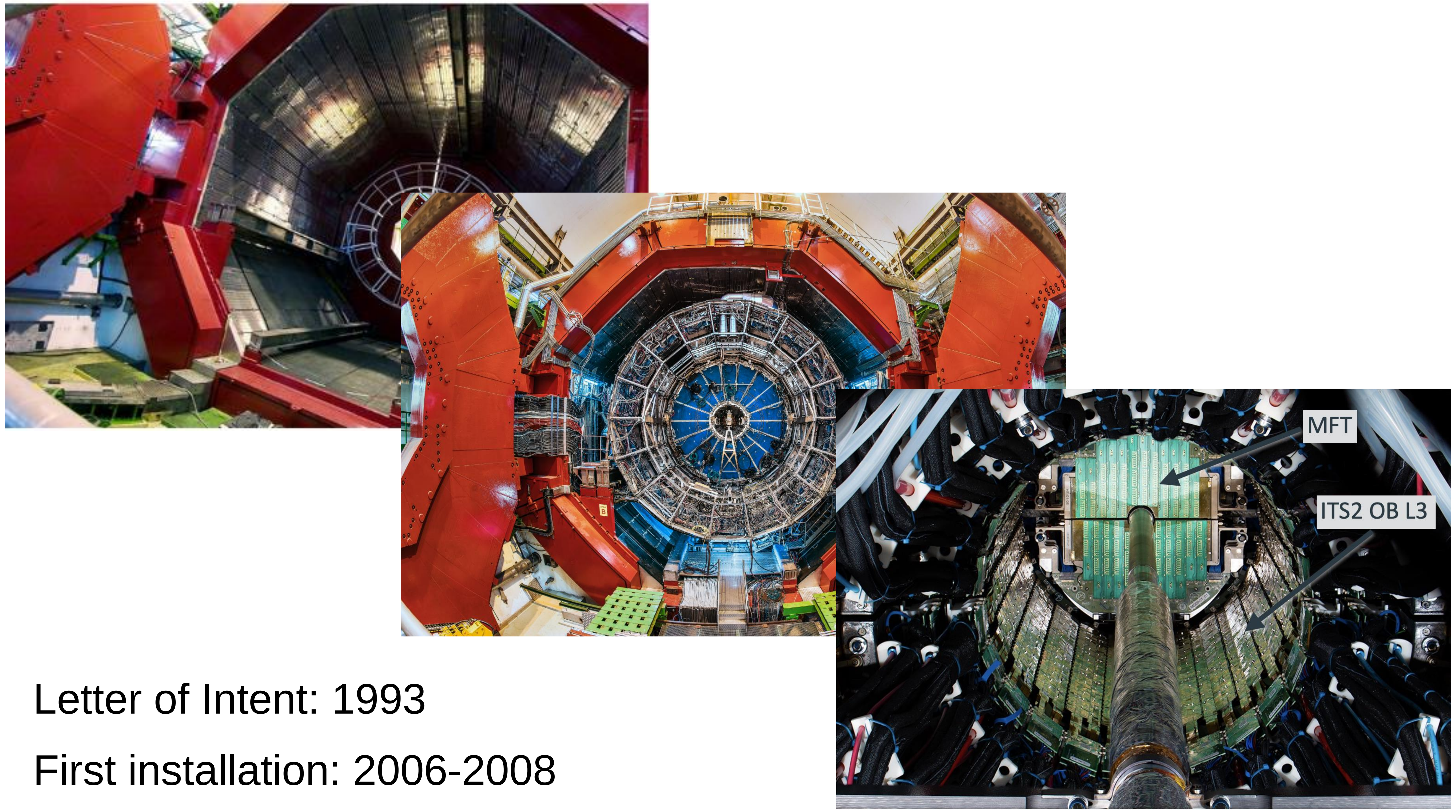


pp collisions √s = 7, 8, 13, **13.6 TeV**

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

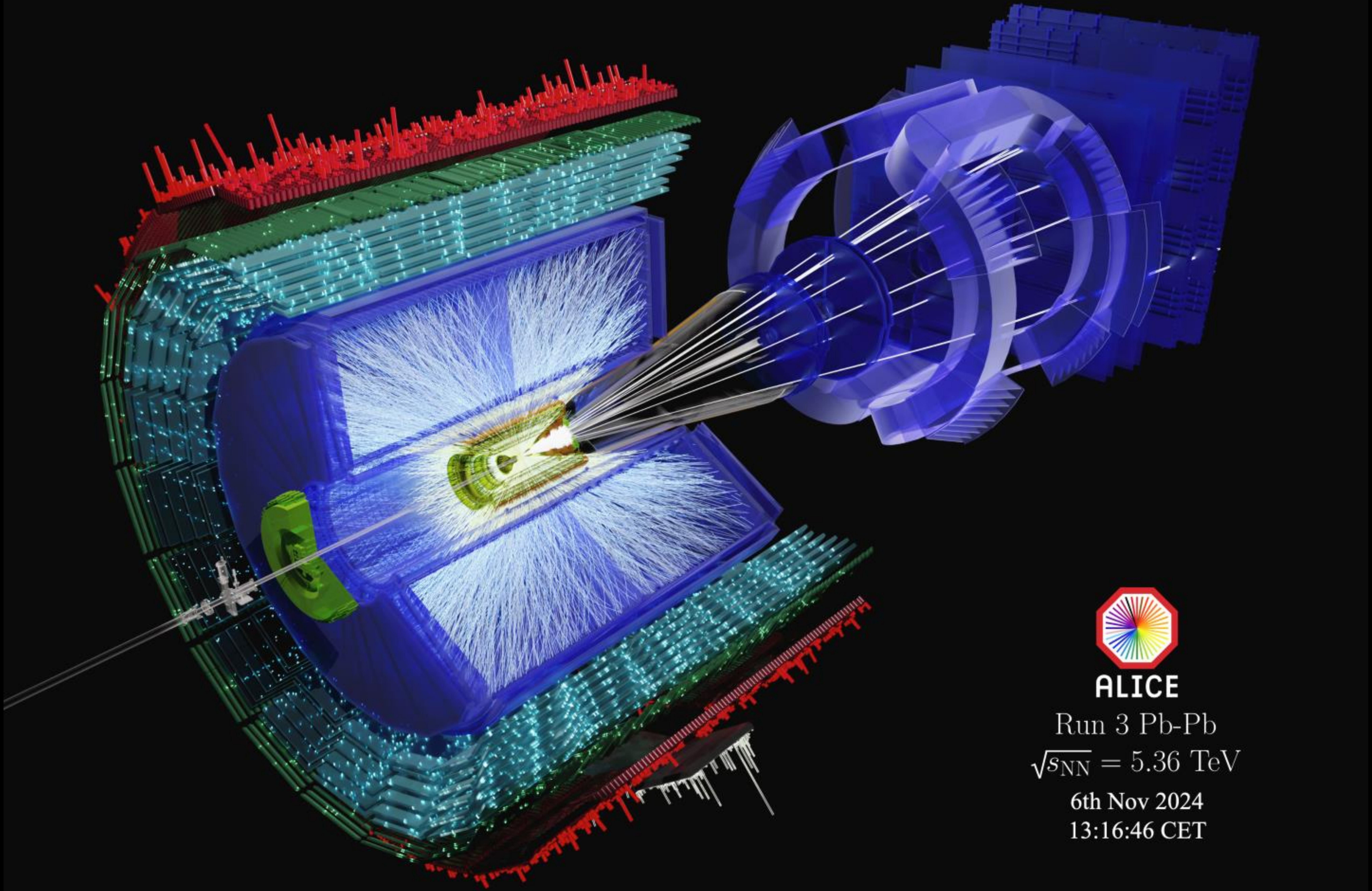
First installation: 2006-2008

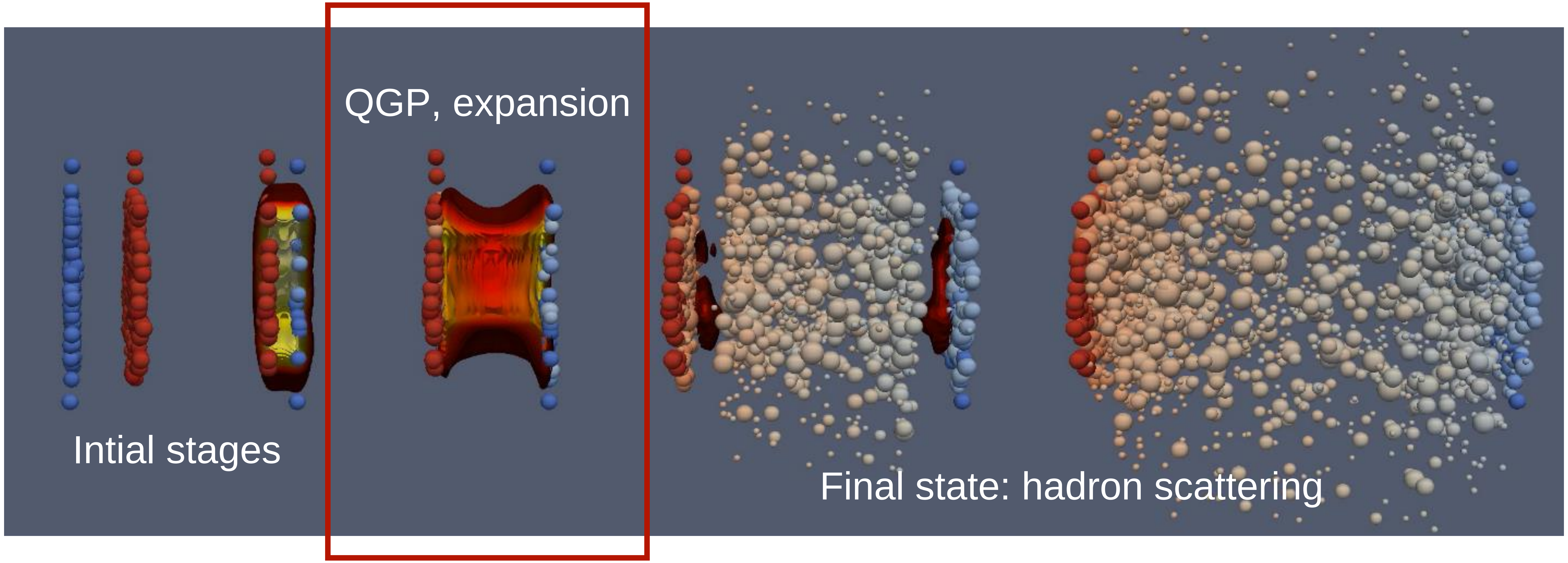
Major upgrades installed: 2022

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

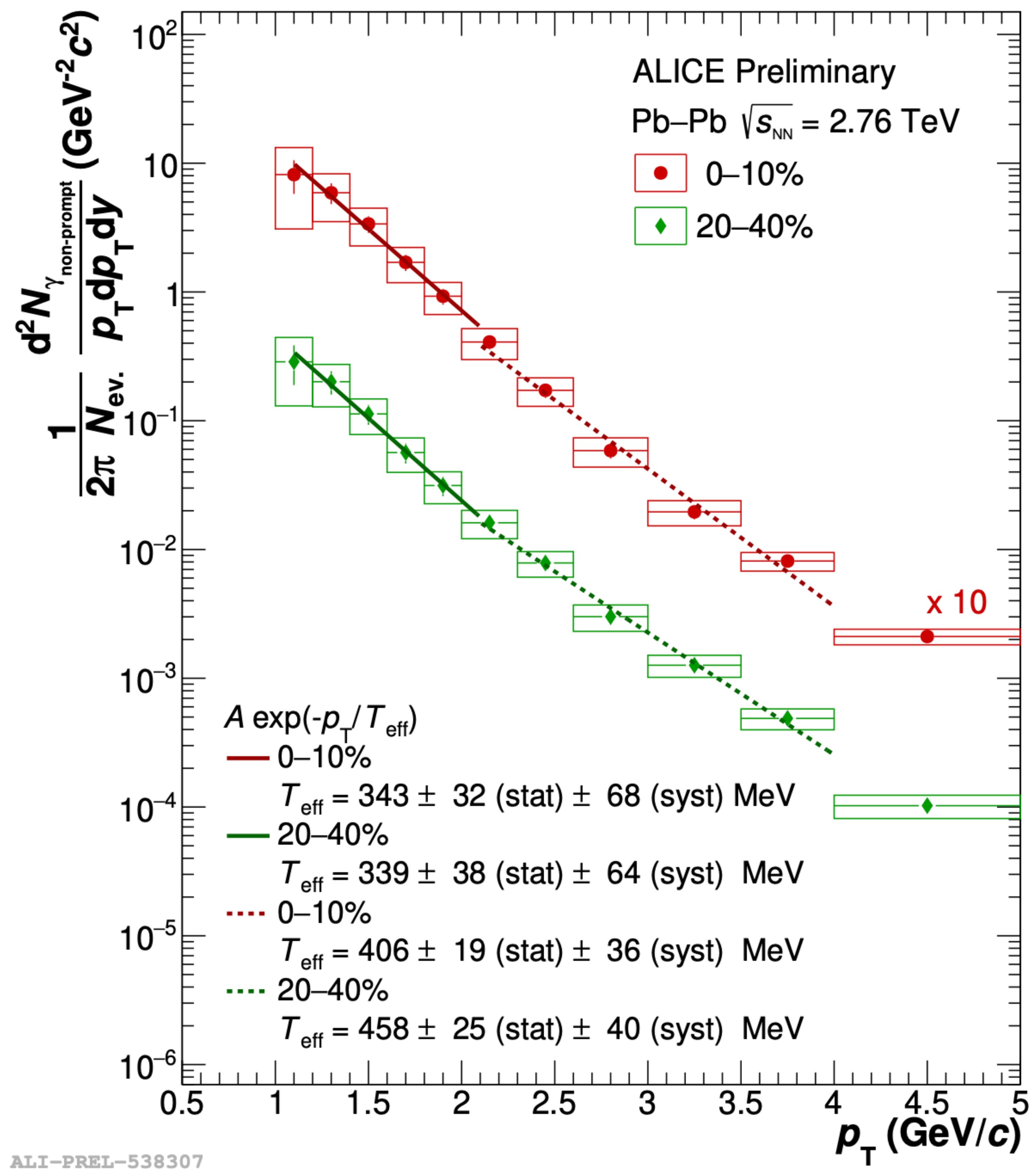

ALICE
Run 3 Pb-Pb
$\sqrt{s_{NN}} = 5.36$ TeV
6th Nov 2024
13:16:46 CET



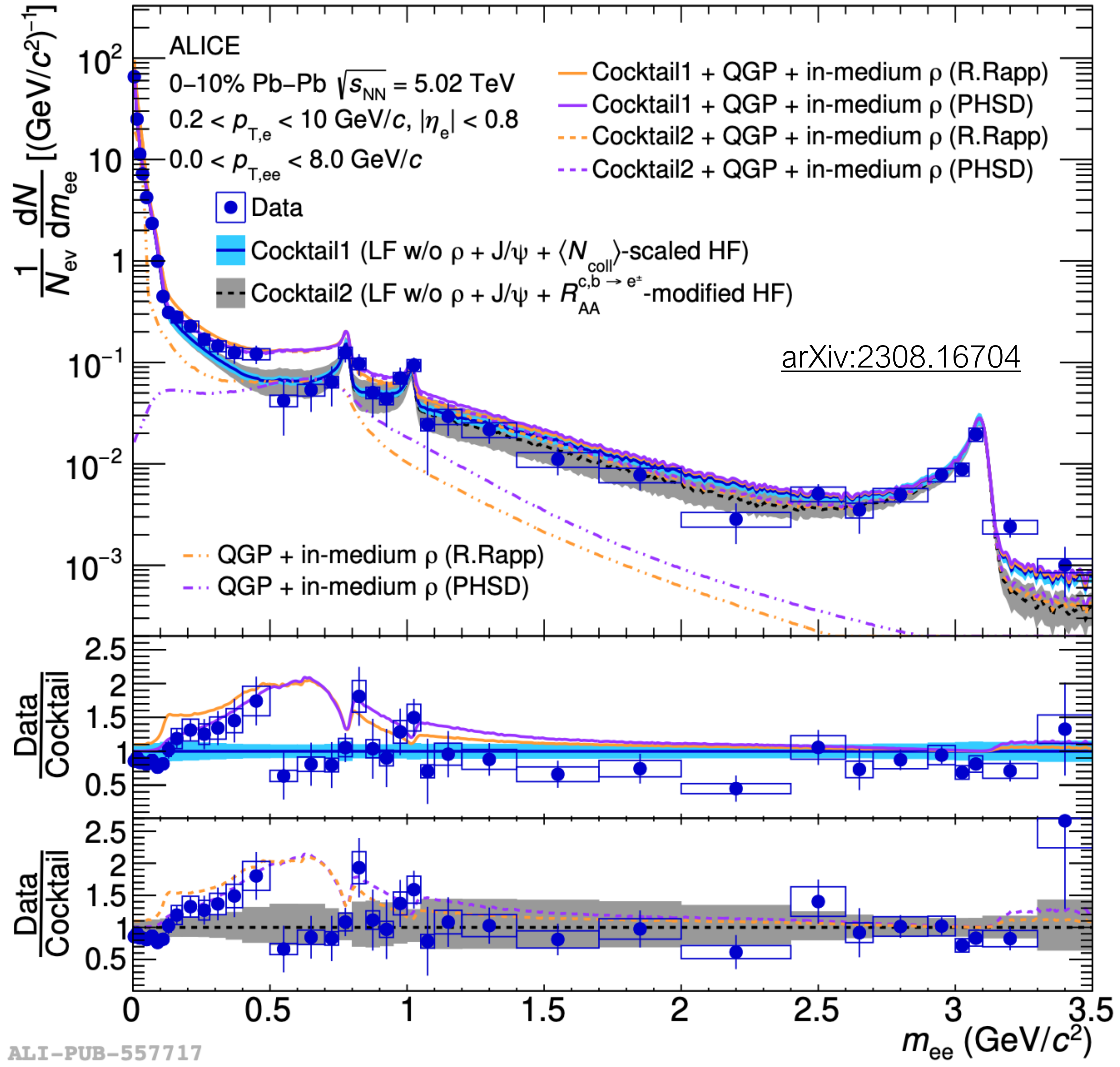
Step 1: temperature

Taking the temperature: photons and dileptons

Direct photon excess spectrum



Dielectron mass spectrum

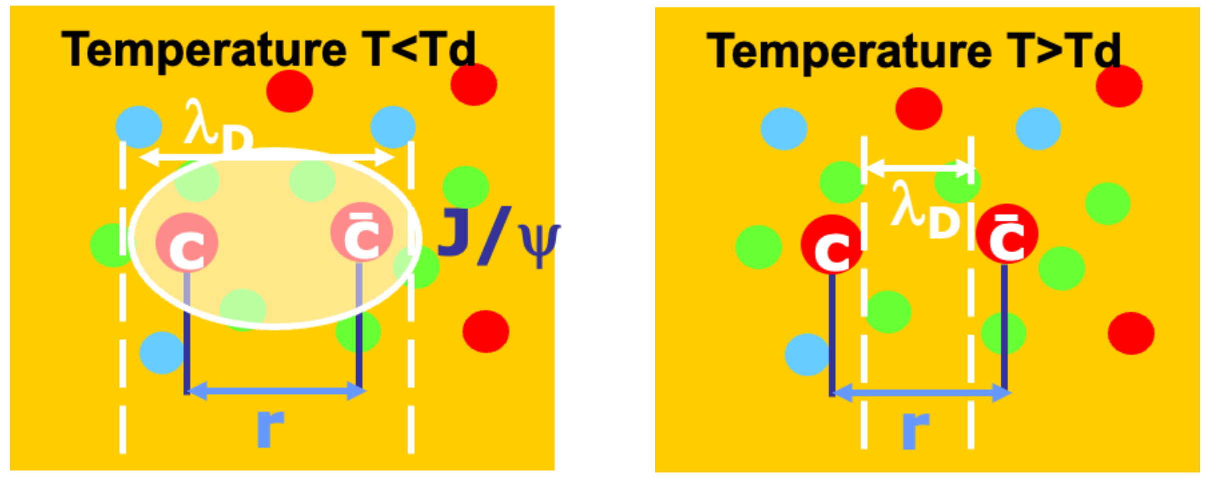


Electromagnetic radiation **(real) photons** and **dielectrons (virtual photons)** measure the temperature of the QGP

Challenging measurement: large background from hadronic decays

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

Quarkonia: nuclear modification factor



Binding force screened when
$r > \lambda_d$

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

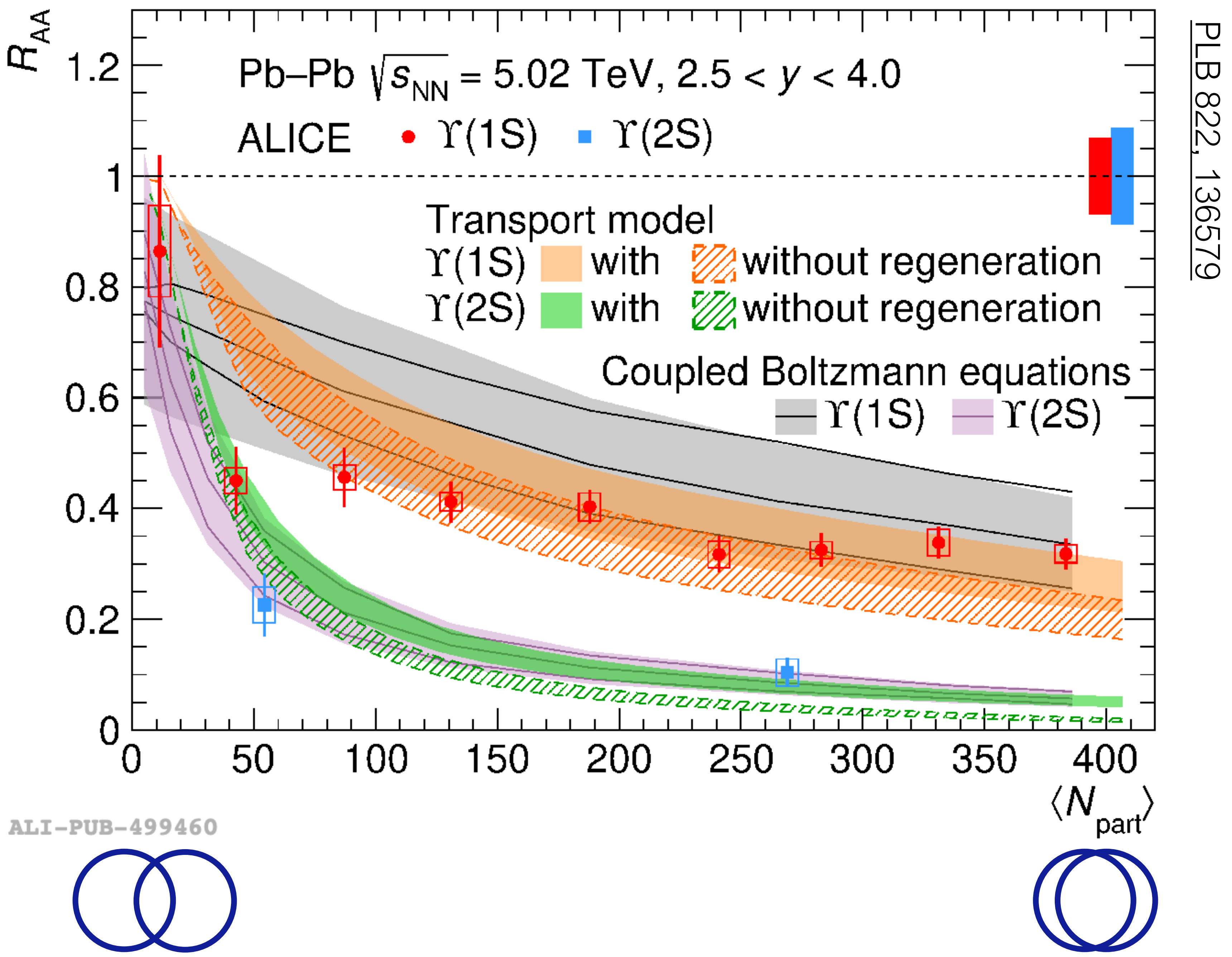
Nuclear modification factor

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

R_{AA} = 1: no effect

R_{AA} = 0: complete suppression

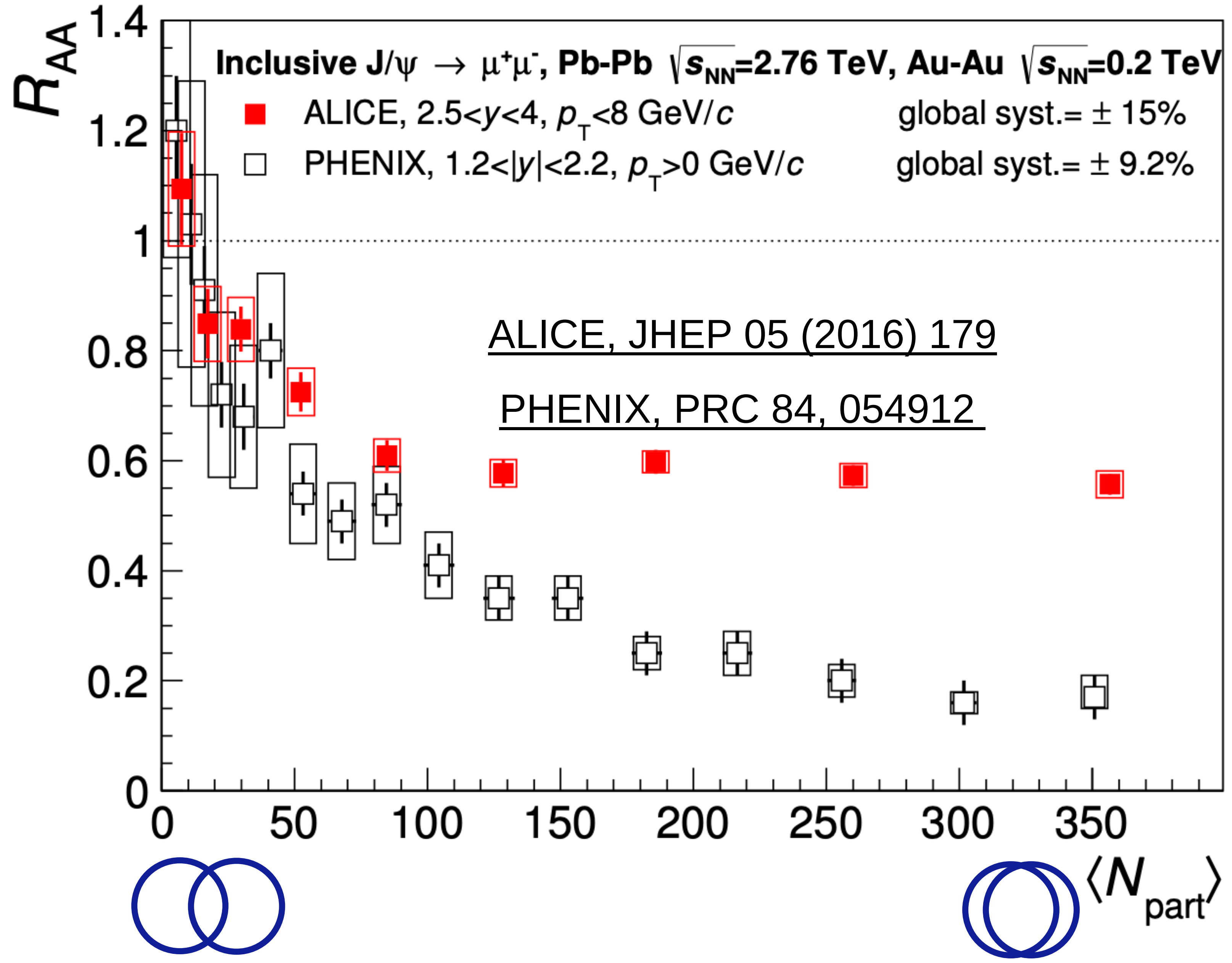
Nuclear modification vs centrality



Large suppression — dissociation in central events

Larger effect for higher states — weaker binding

J/ψ modification vs centrality

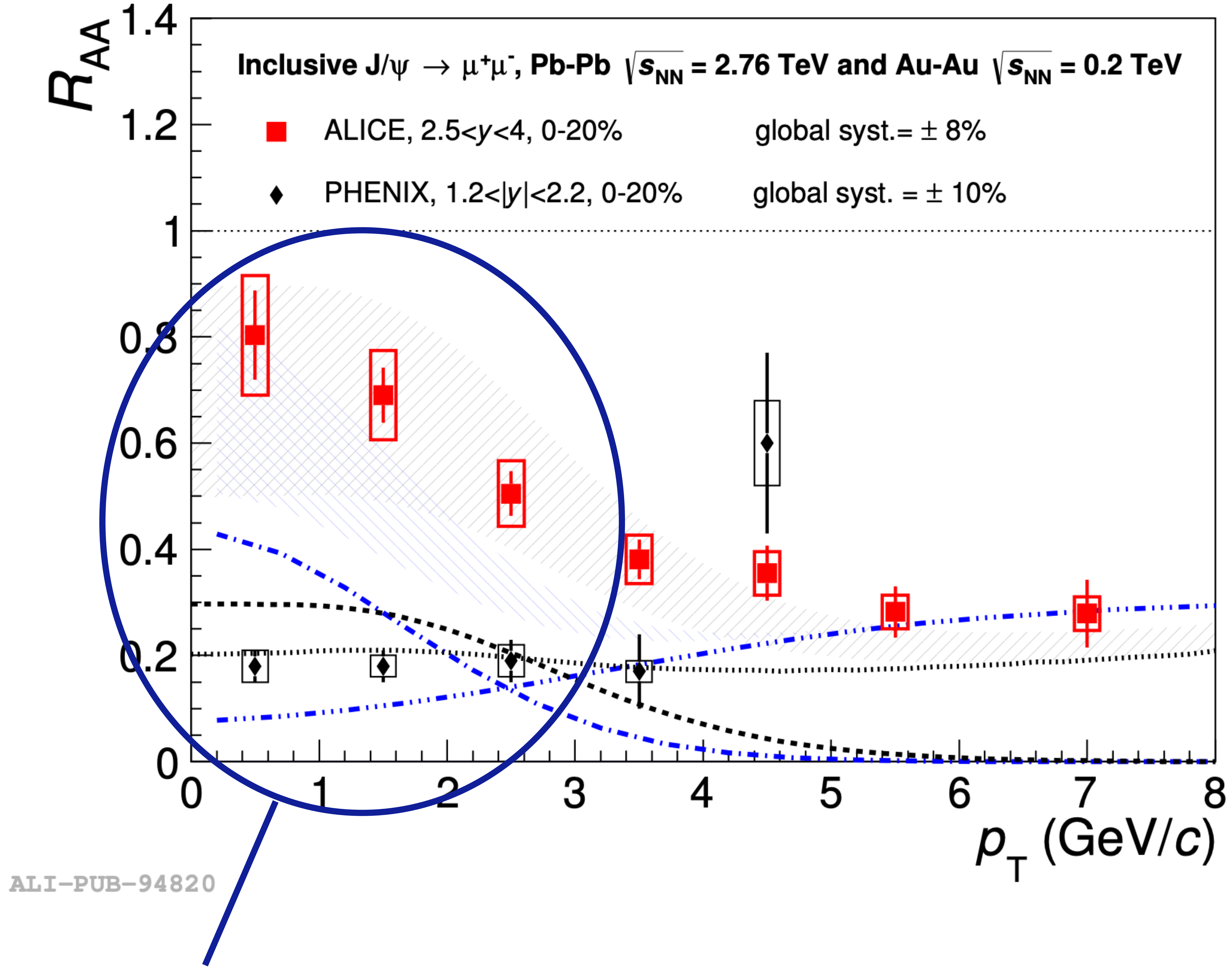


J/ψ : $c\bar{c}$ bound state

shows smaller suppression

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

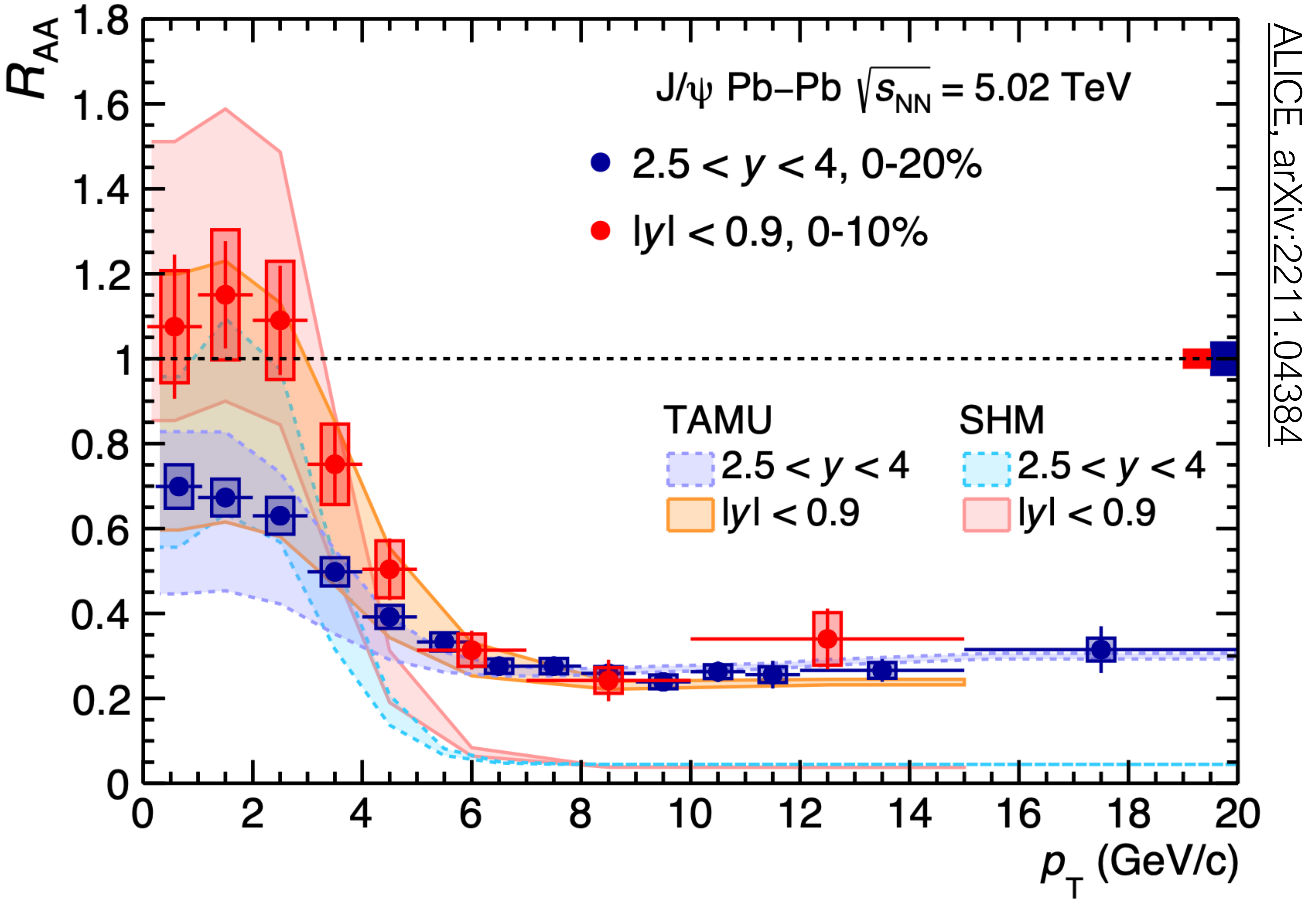
J/ψ modification vs p_T



Less suppression at low p_T

$c\bar{c}$ recombination

J/ψ modification at forward and mid-rapidity

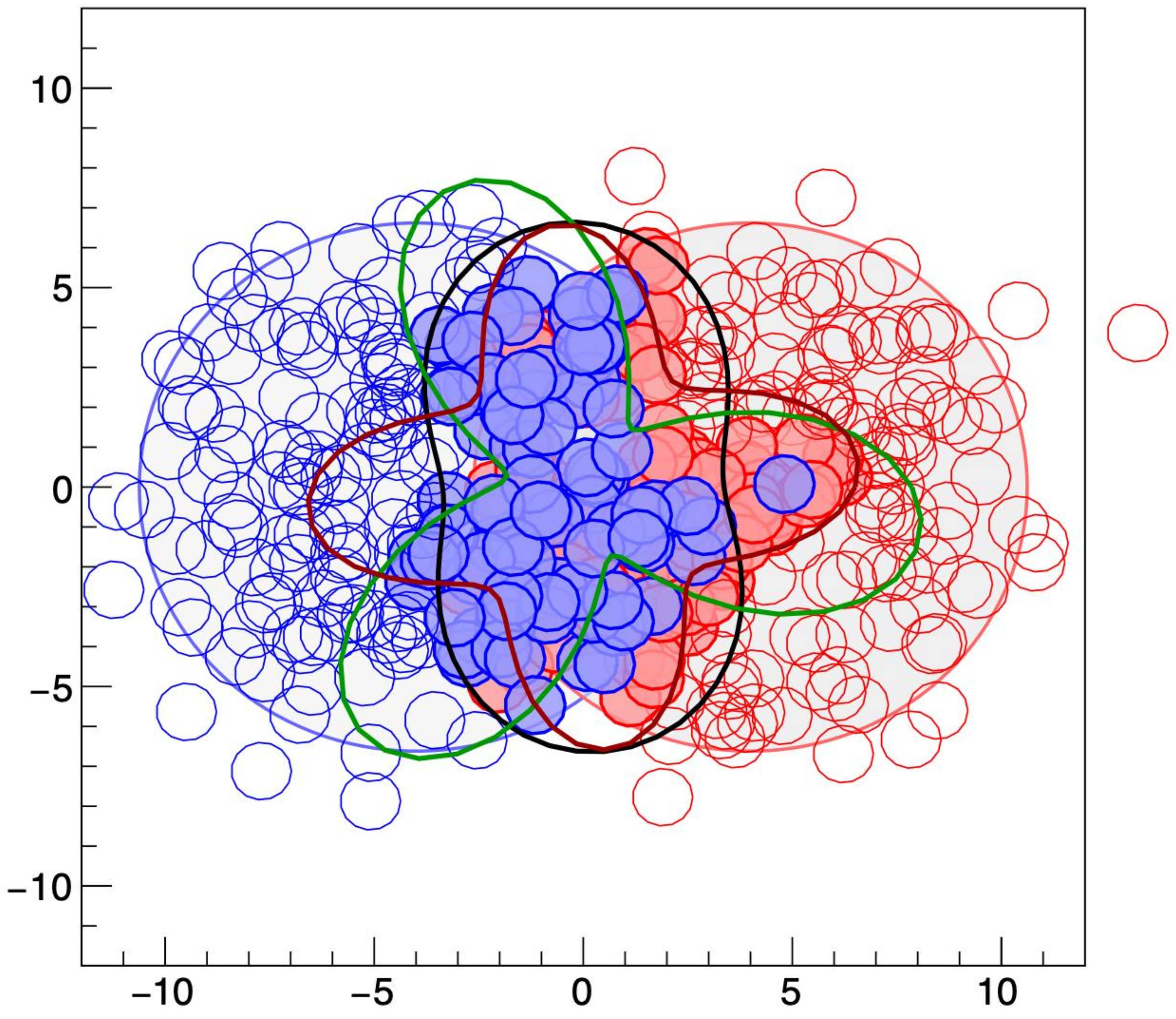


In agreement with coalescence expectation: larger $c\bar{c}$ density at mid-rapidity

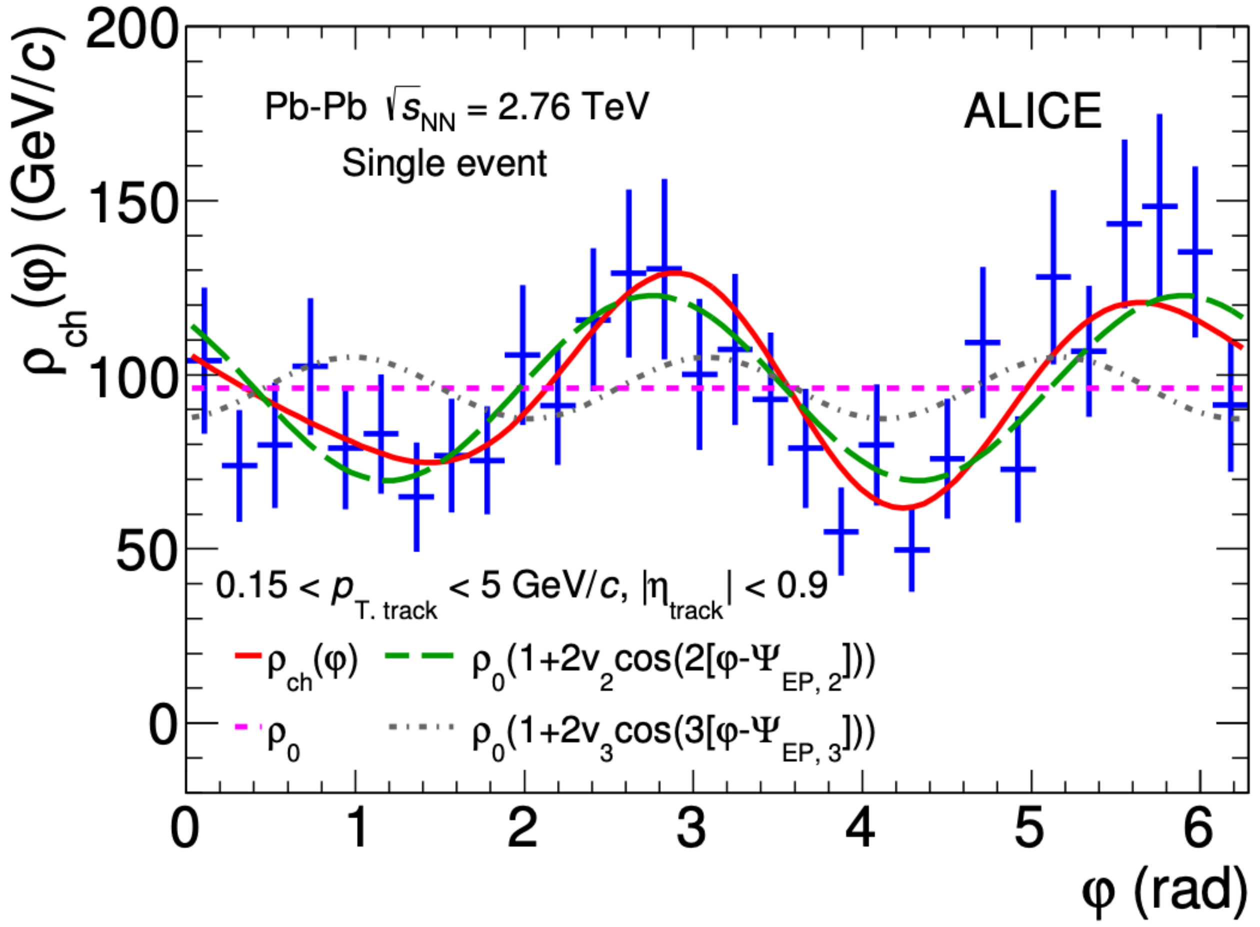
ALICE, arXiv:1506.08804 PHENIX, arXiv:1103.6269
Transport models: arXiv:1102.2194, arXiv:1401.5845

Azimuthal anisotropy: initial and final states

Simulated event: location of nucleons

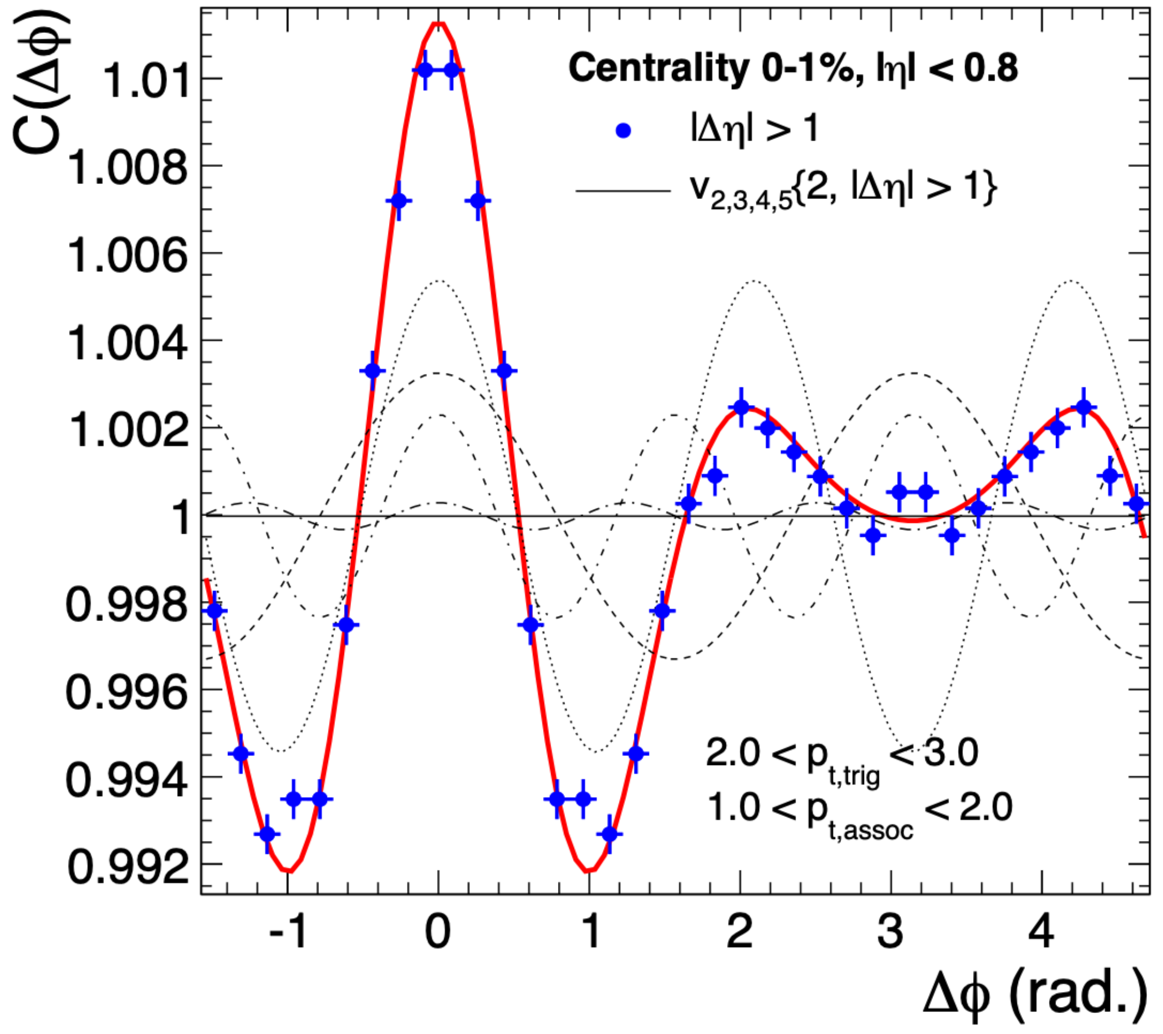


Azimuthal distribution single event



ALICE, PLB 753, 511

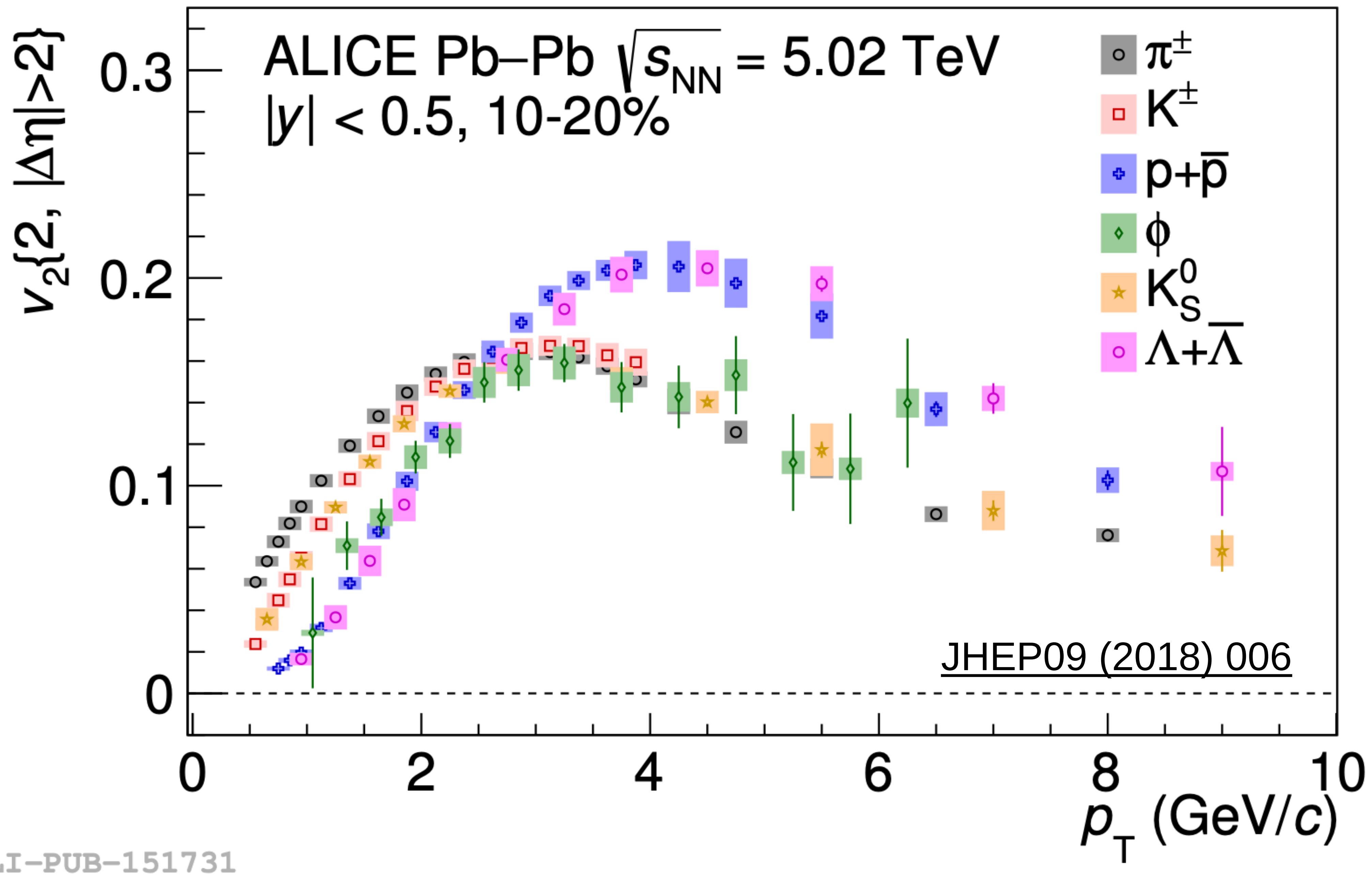
Sum over many events



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

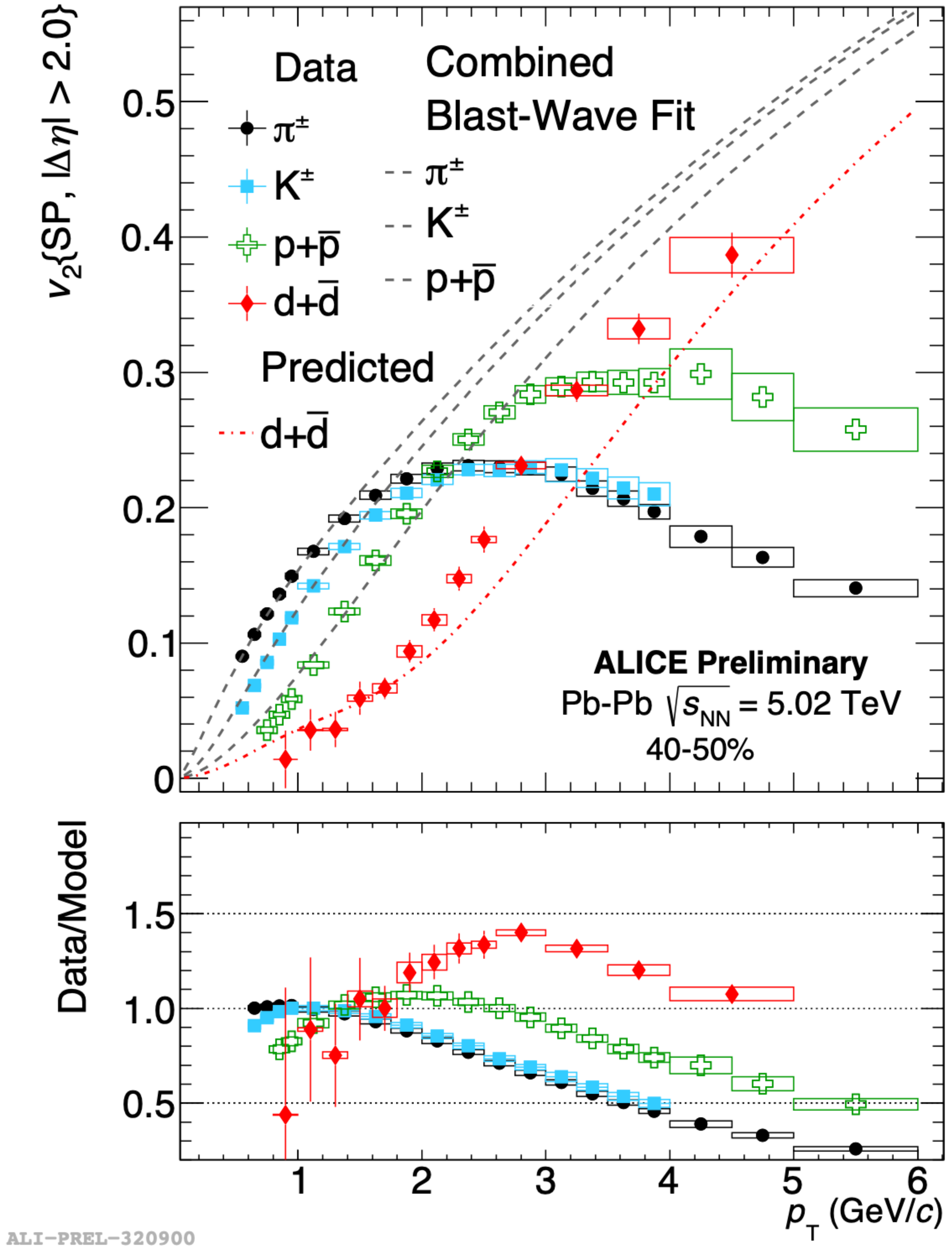
Anisotropic flow: initial state and QGP expansion

Elliptic flow v_2



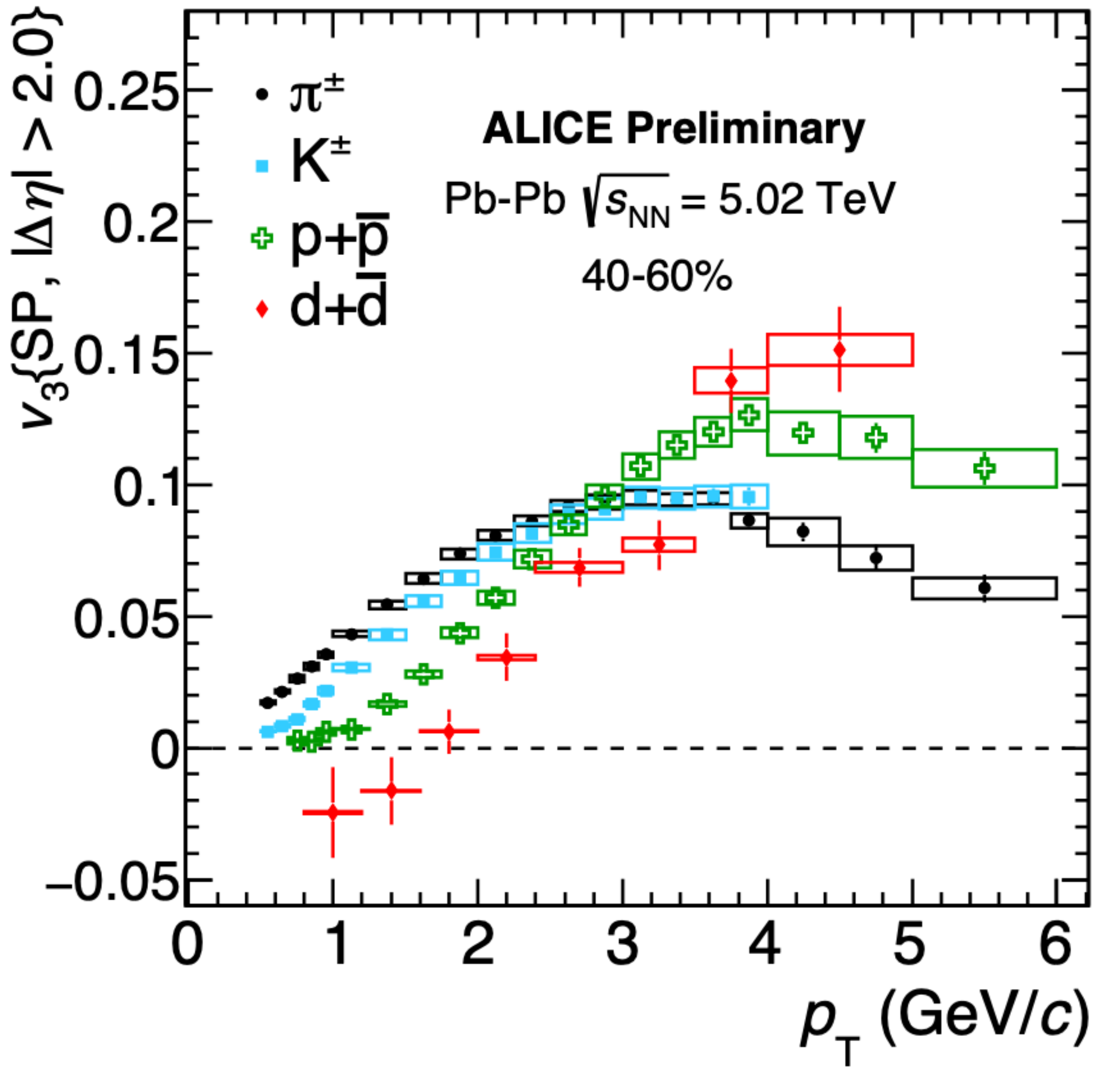
Mass-dependence of v_2 measures flow velocity

v_2 of deuterons

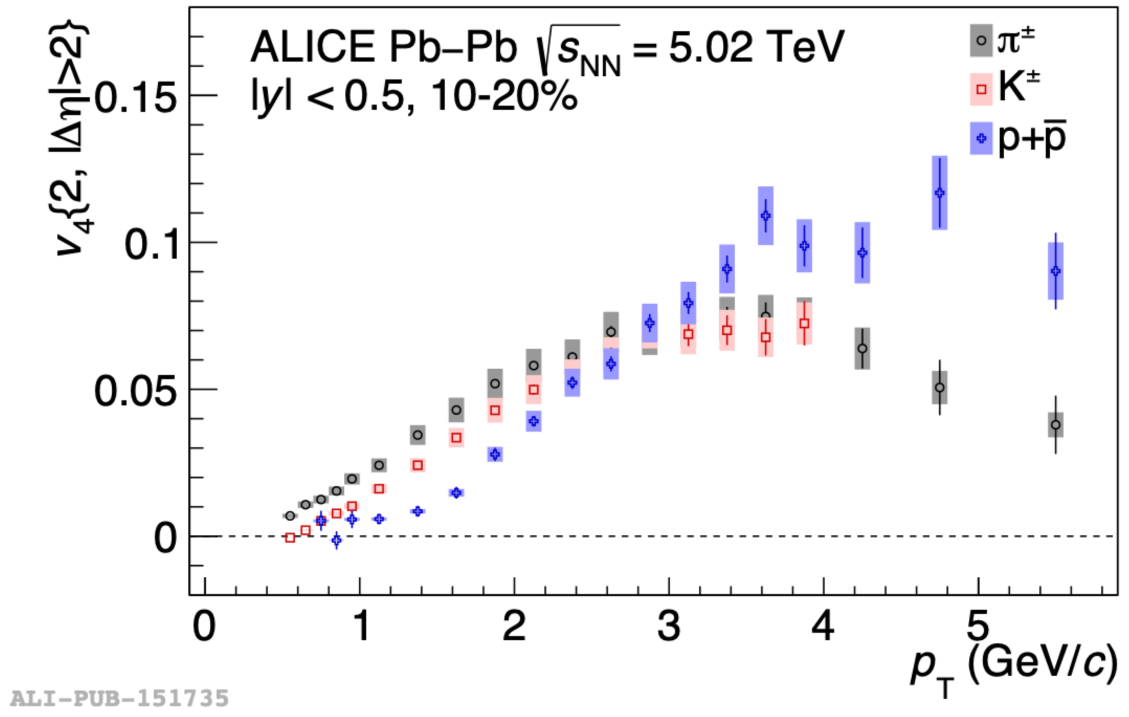


Even light nuclei flow !

v_3

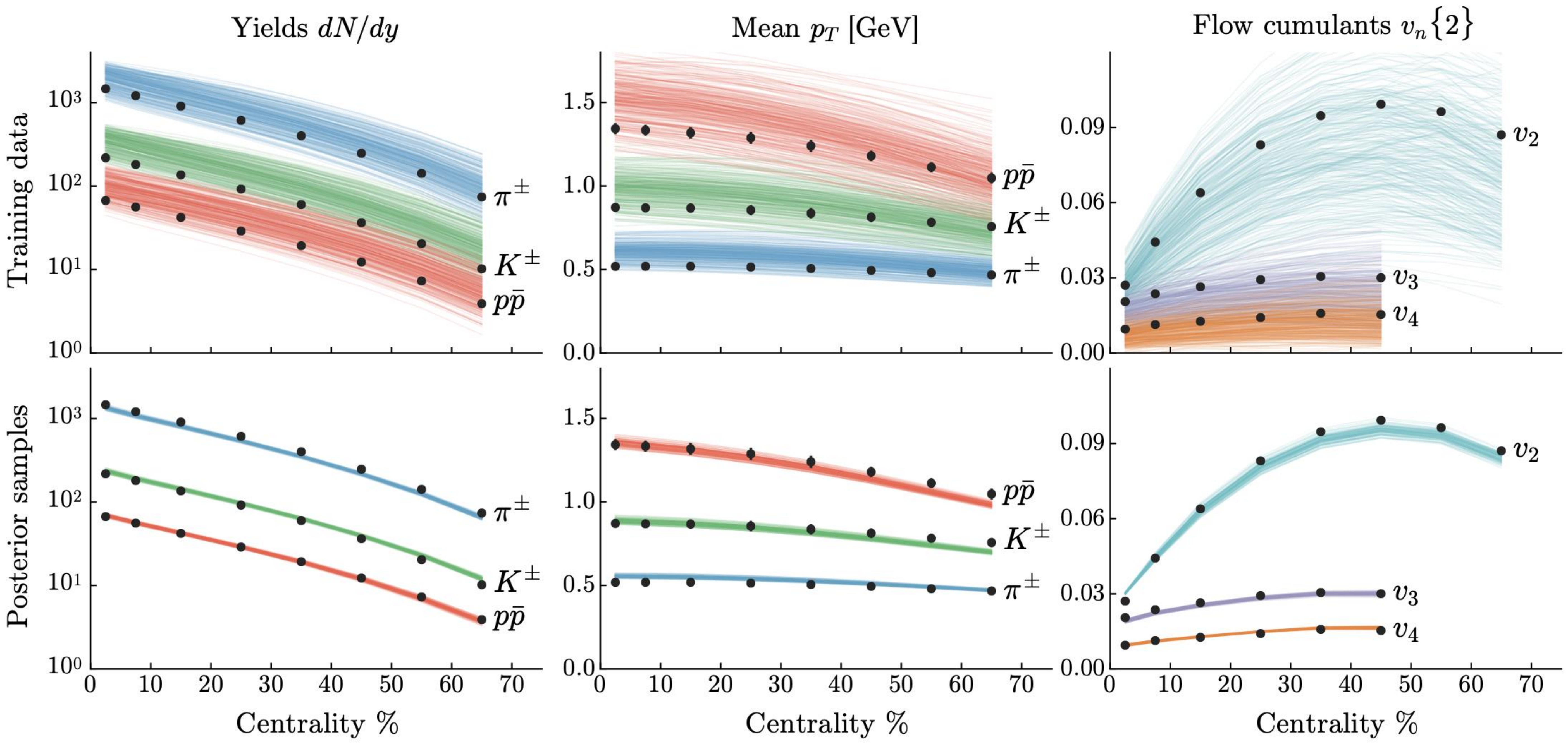


v_4



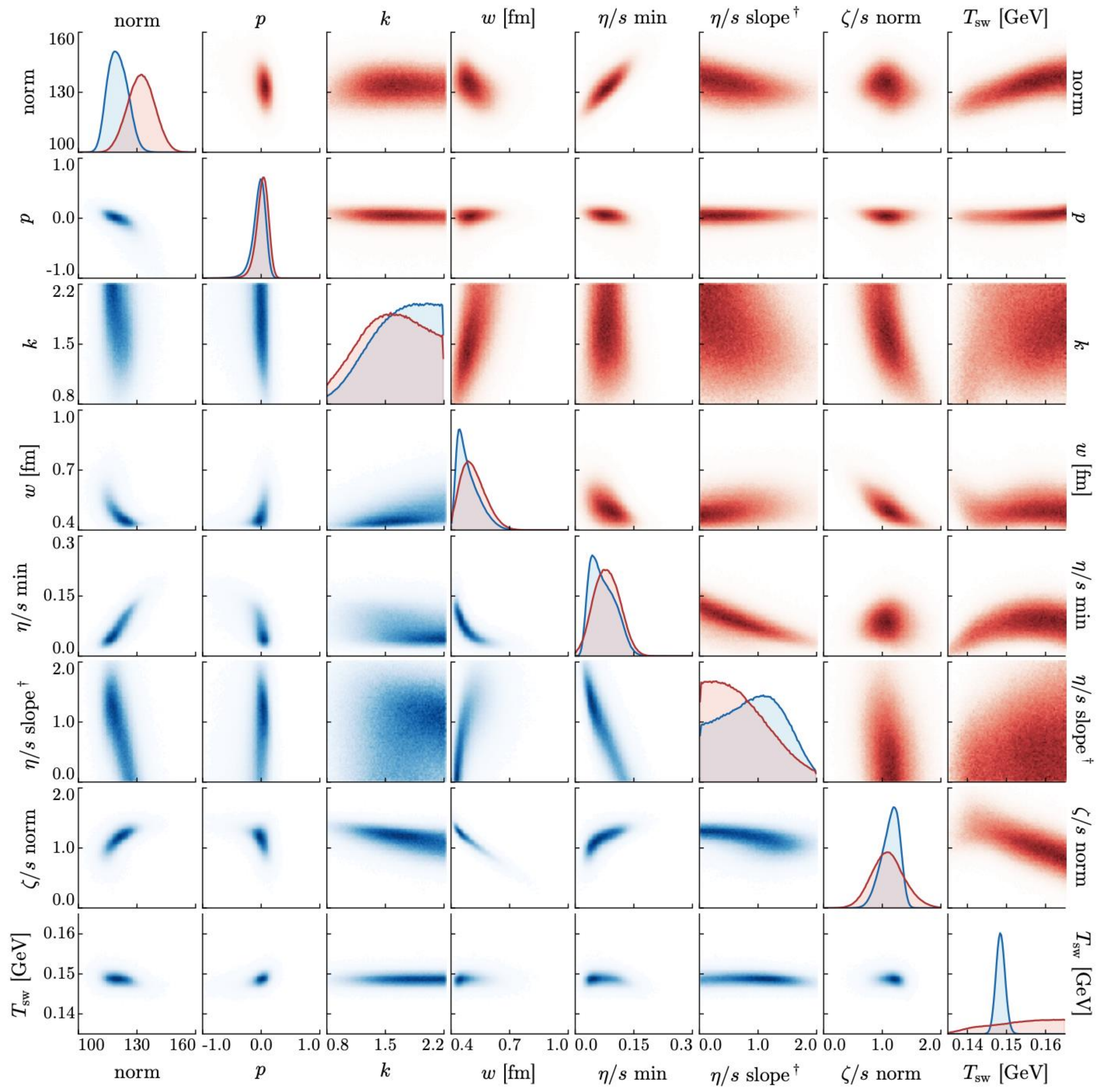
Constraining initial state and plasma properties simultaneously: Bayesian inference

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

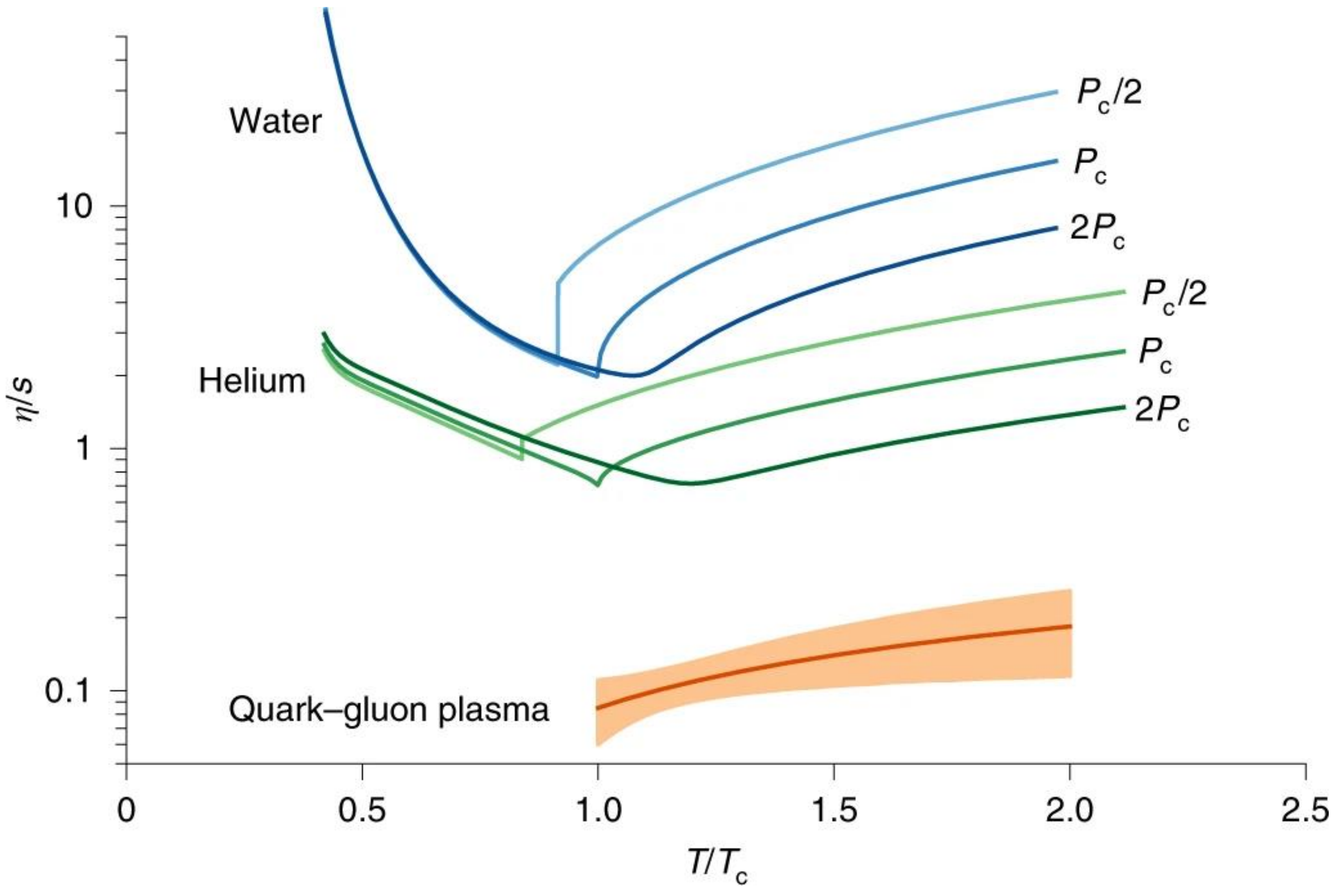
Viscosity of the QGP compared to 'regular' liquids

Viscosity-to-entropy ratio: dimensionless quantity

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

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

Messengers of the Plasma: soft and hard processes

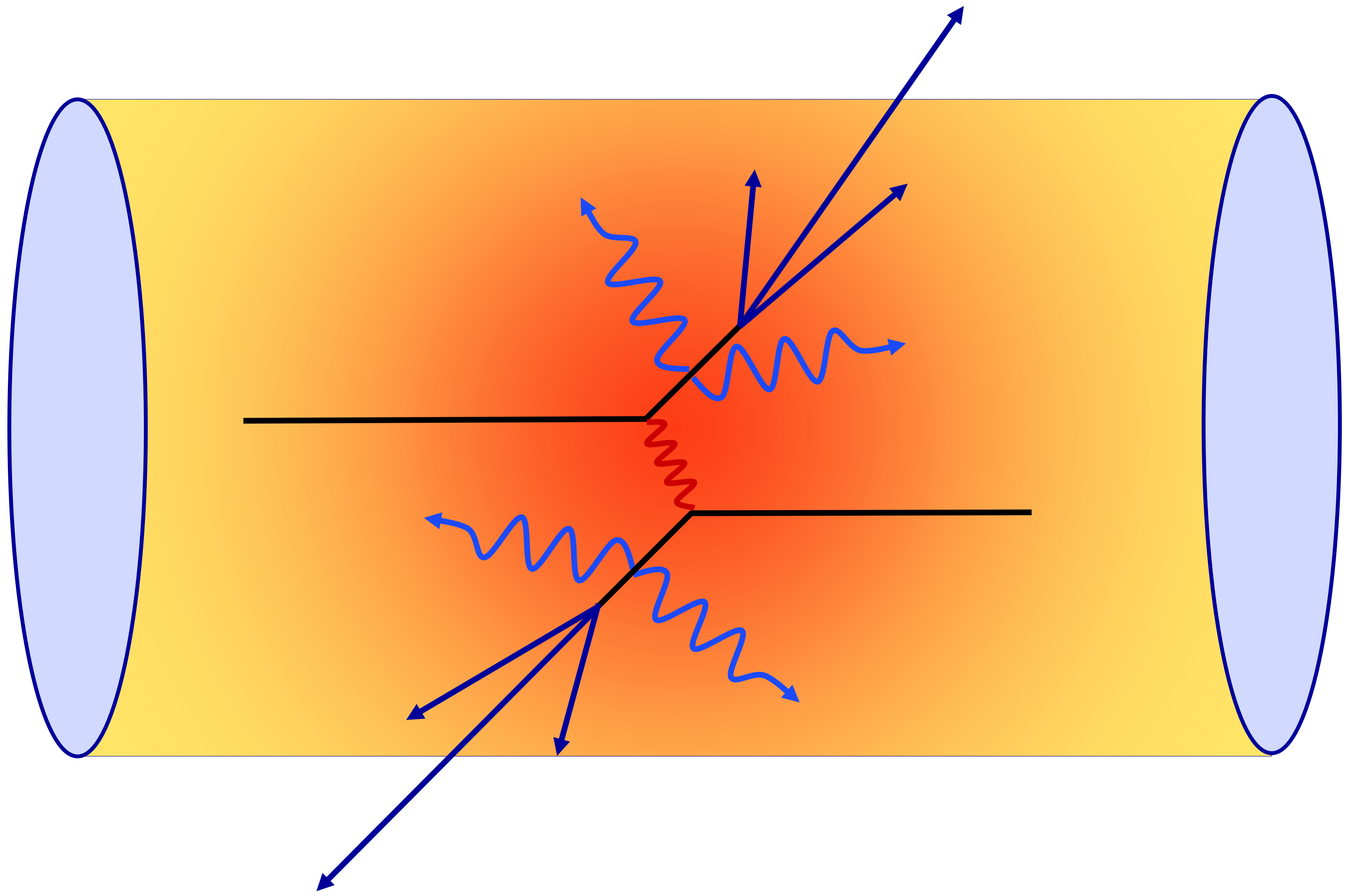
Soft processes

Momenta comparable to QGP temperature

$$p_T \lesssim 3\mathrm{GeV}/c$$

Near thermal equilibrium with the plasma

'particles from the QGP'



Hard processes: large momenta >> T_{QGP}

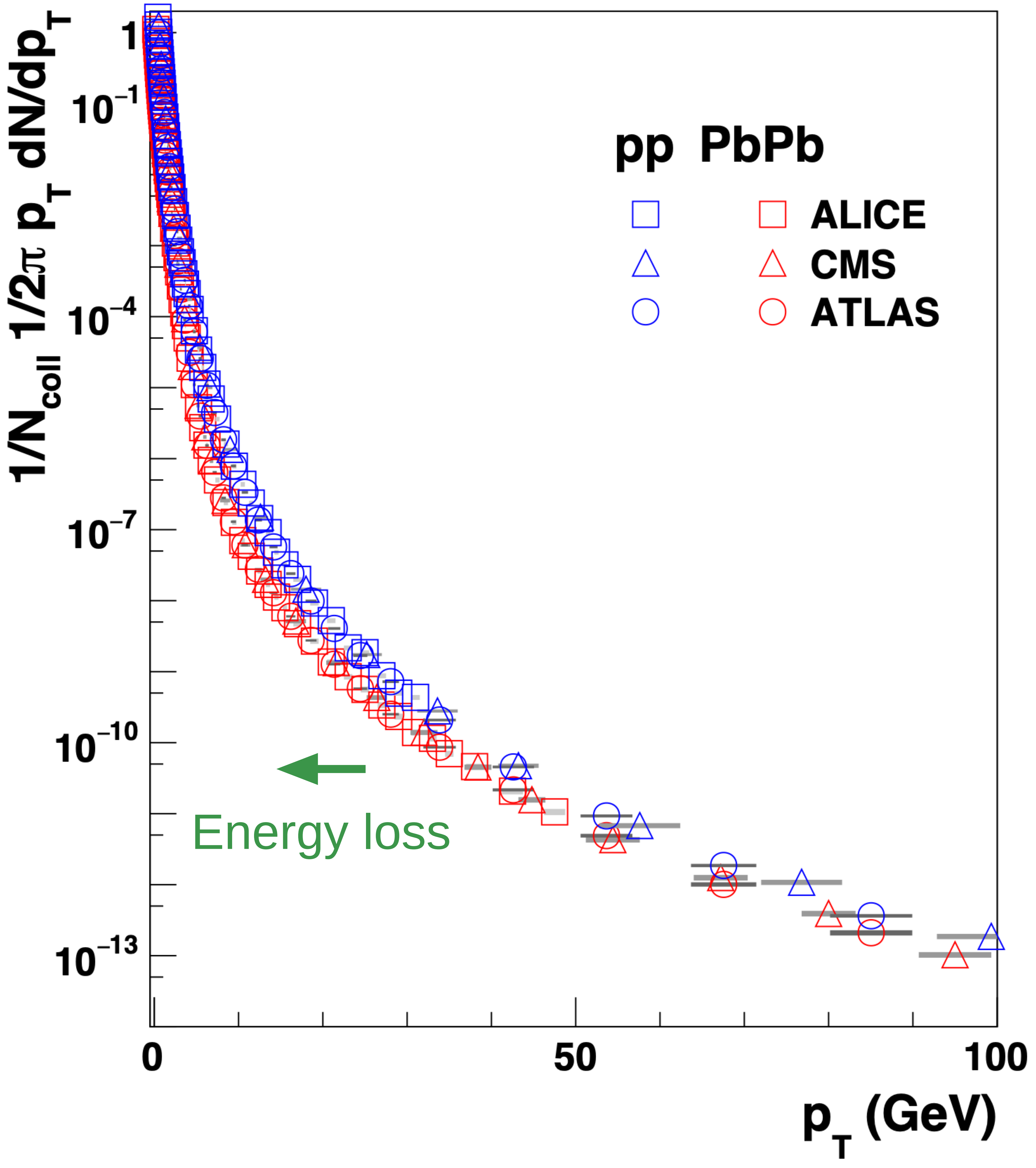
- Short formation time: initial production independent of QGP formation
- Start out far out of thermal equilibrium: **approach equilibrium through interactions**
- Short life time: expect only partial equilibration

'Hard probes' of interactions with the QGP

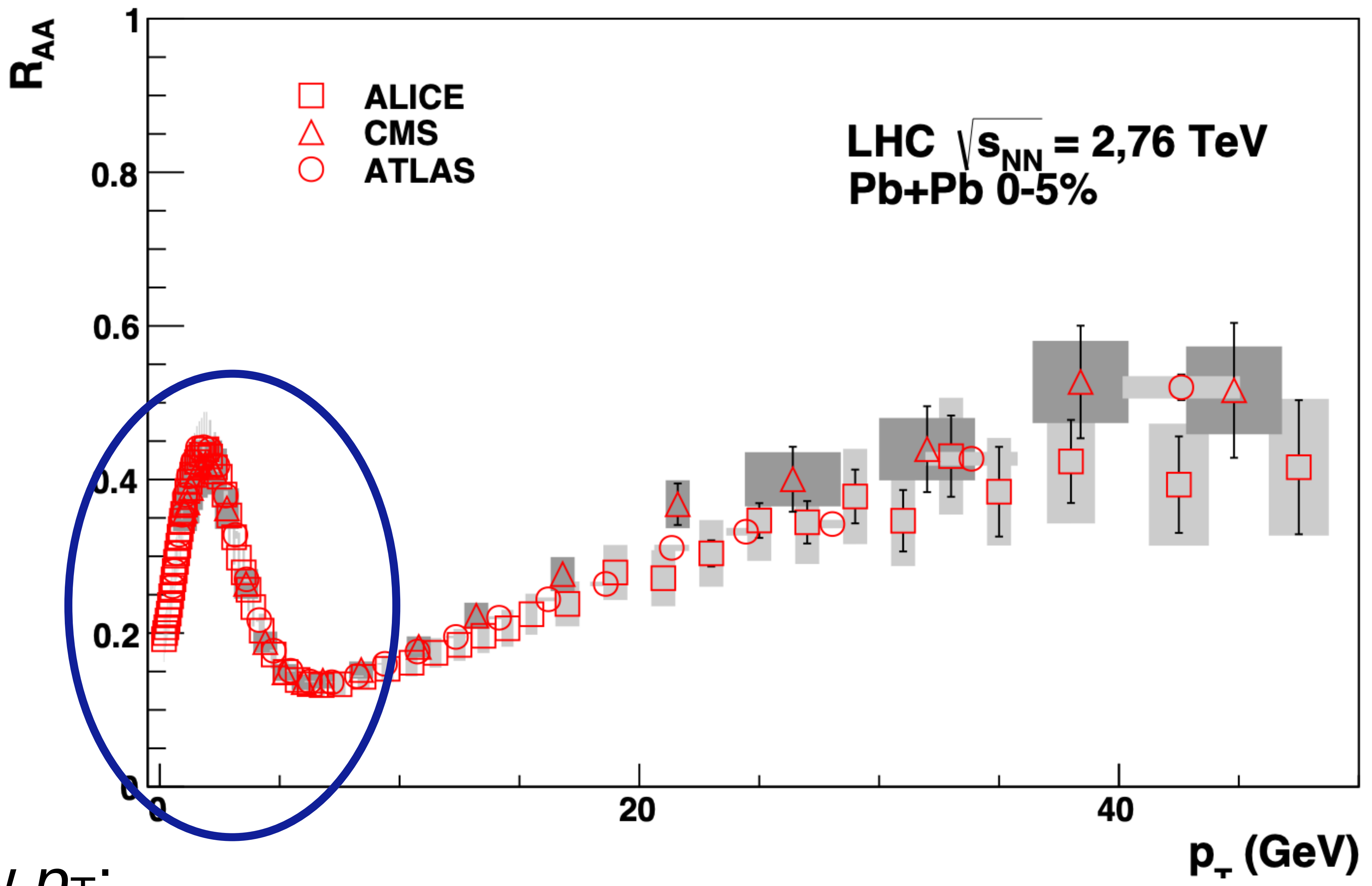
Nuclear modification of p_T spectra

ALICE, PLB720, 52
CMS, EPJC, 72, 1945
ATLAS, arXiv:1504.04337

Charged particle p_T spectra

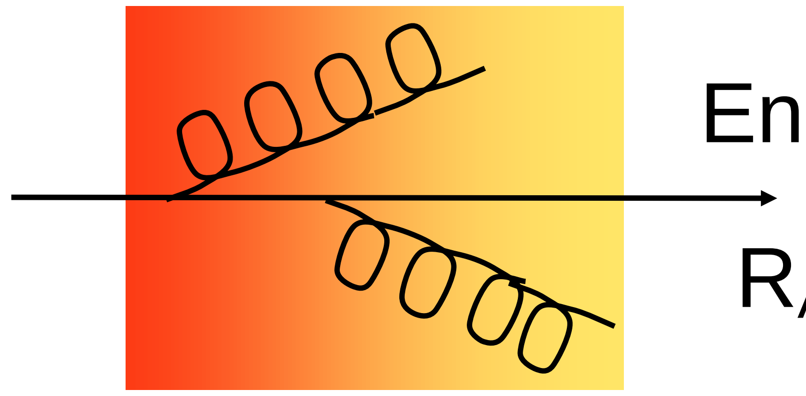


Nuclear modification factor



Low p_T:
soft production,
N_{part} scaling

$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$



Energy loss

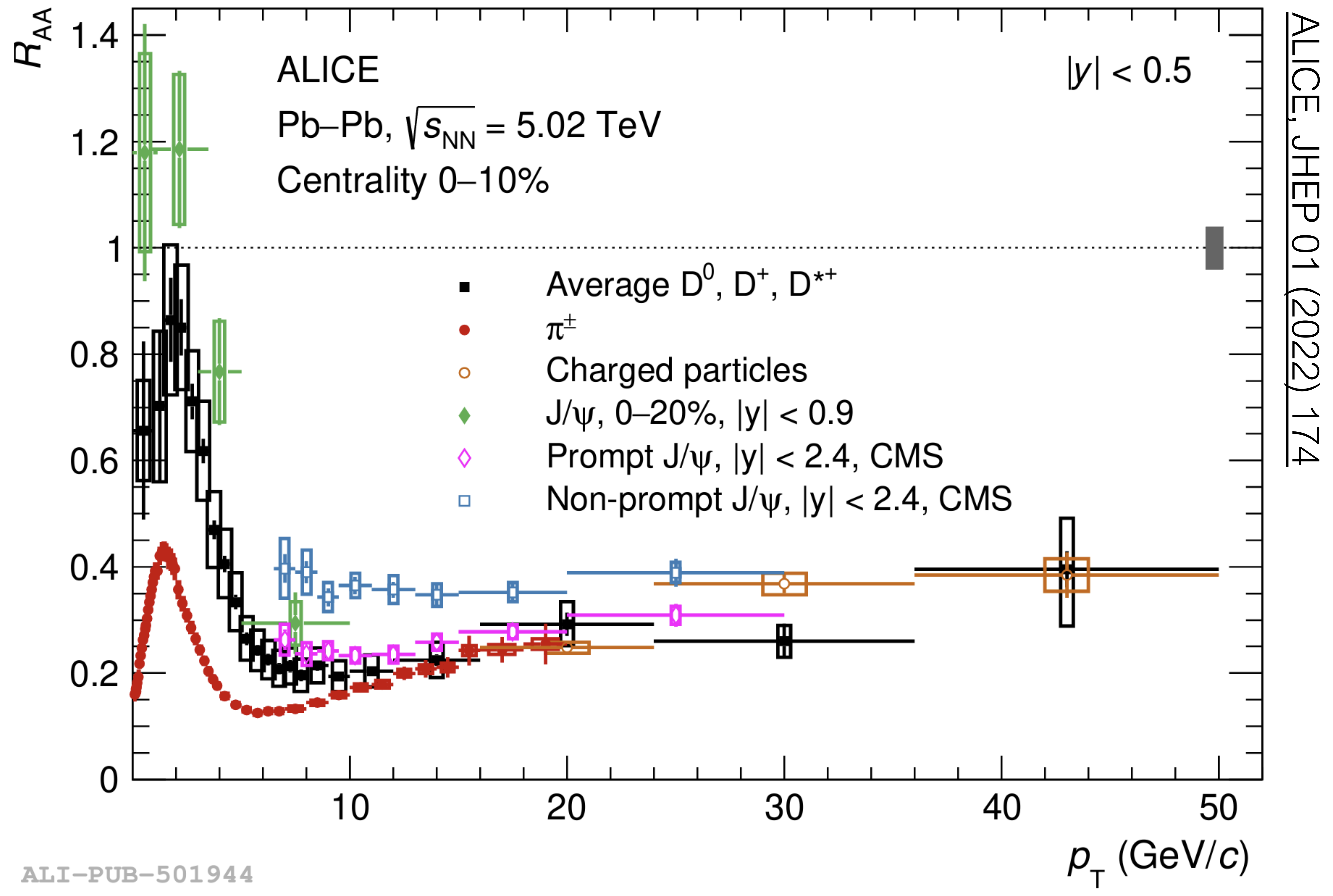
$R_{AA} < 1$

Pb+Pb: clear suppression ($R_{AA} < 1$): parton energy loss

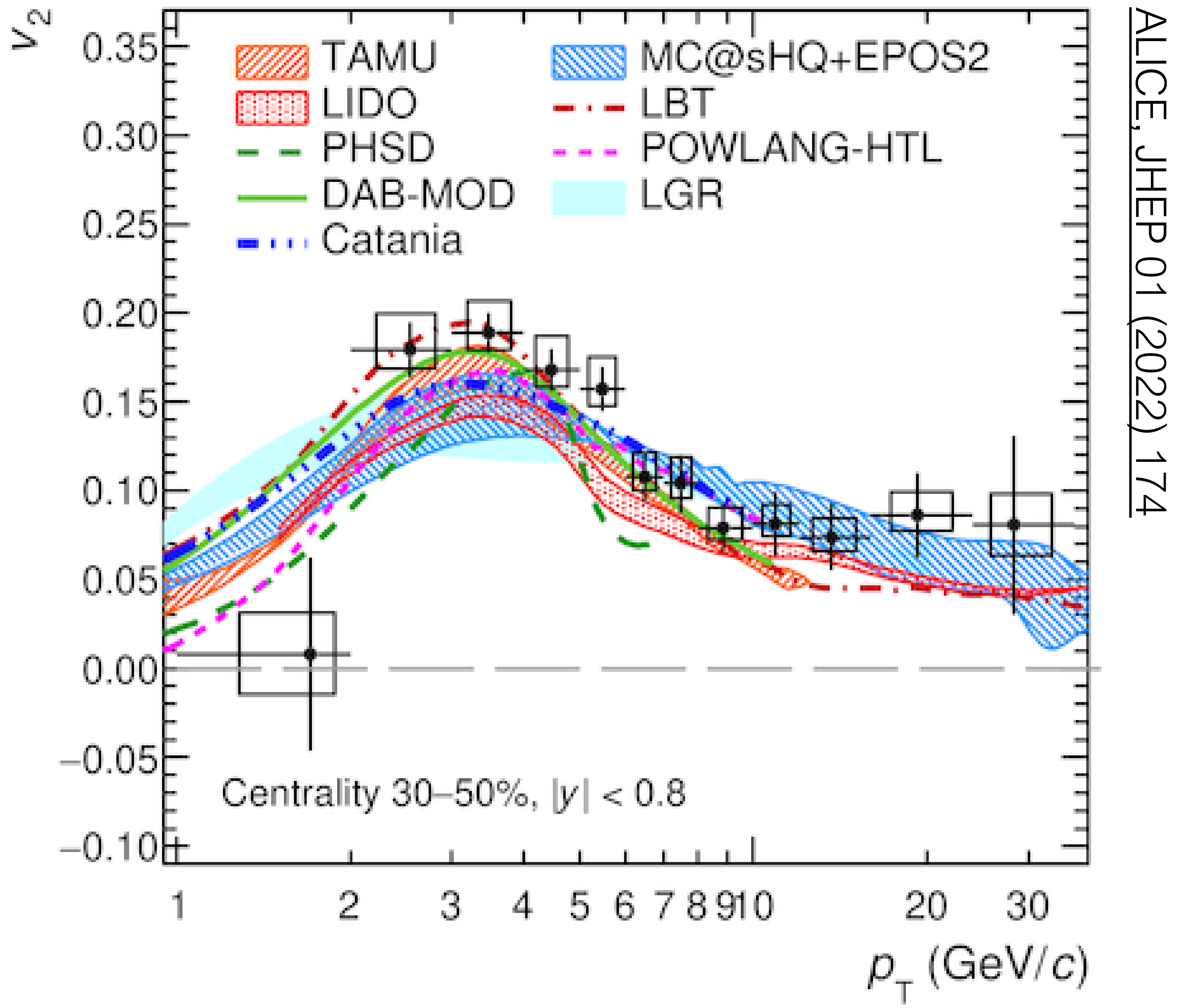
Nuclear modification and elliptic flow of D mesons

charm quarks, m >> T are produced in an initial hard scattering

Nuclear modification factor: light and heavy flavours



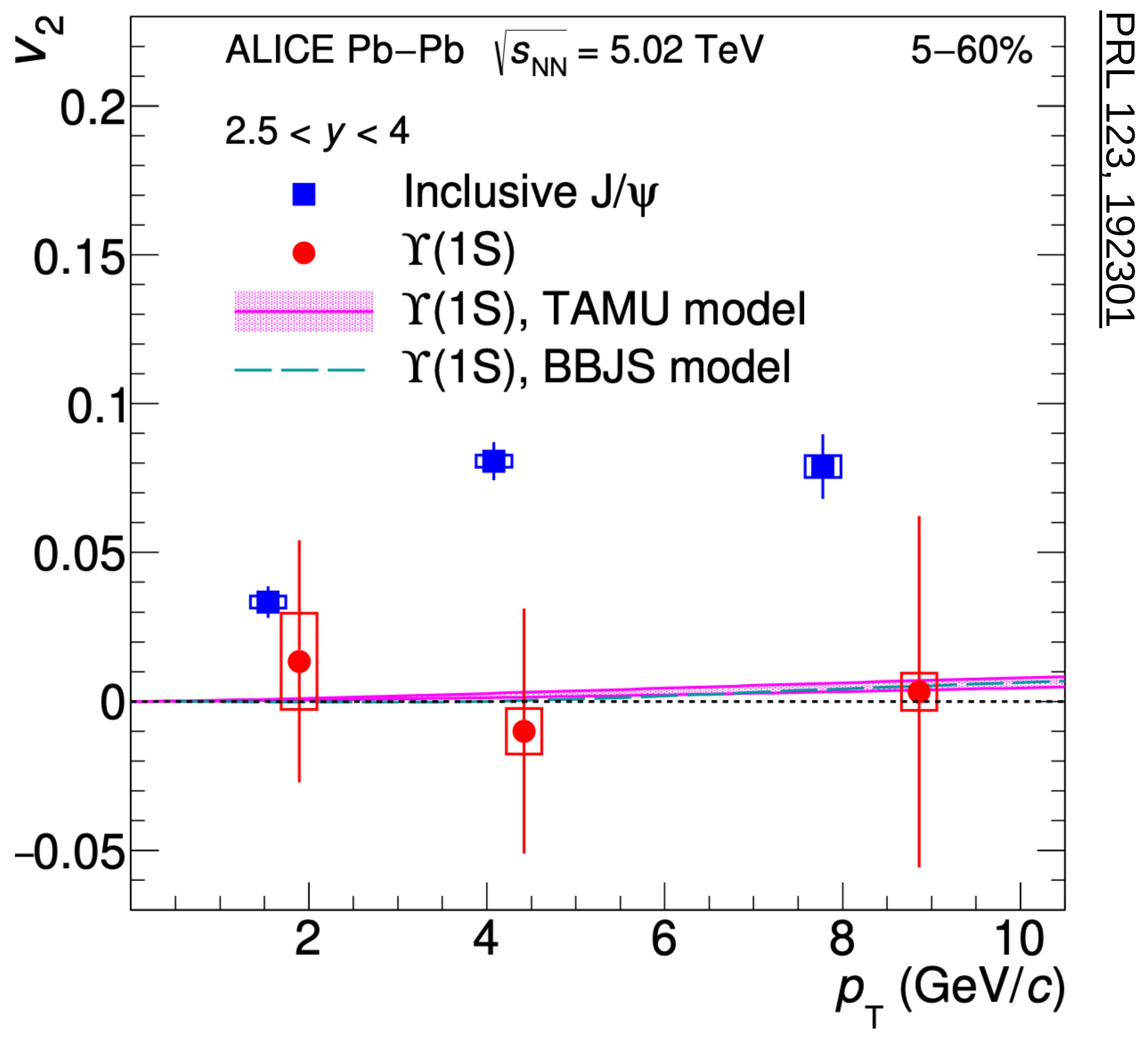
Elliptic flow v_2



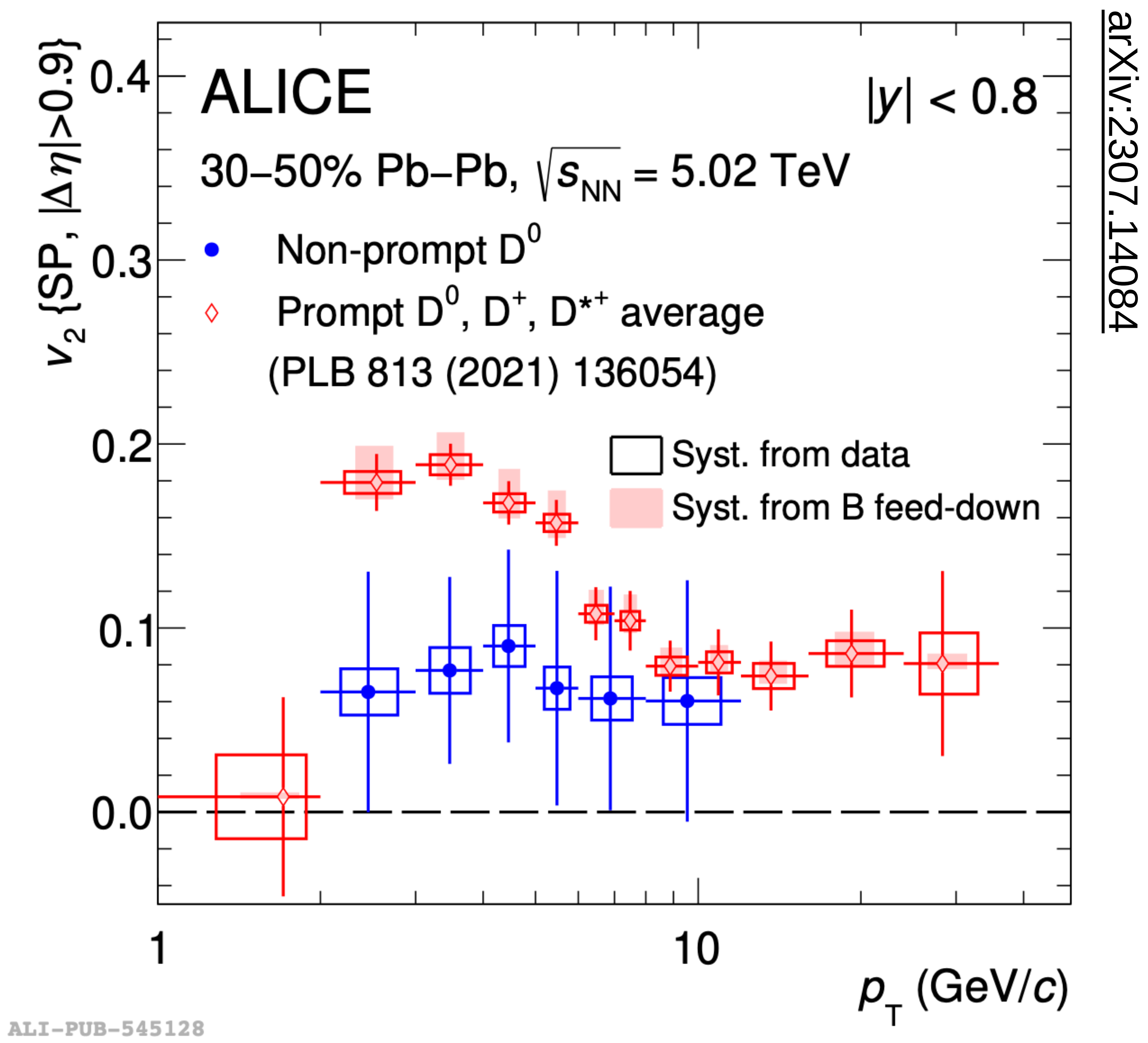
Initial production isotropic: azimuthal asymmetry due to interactions
⇒ approach to thermal equilibrium

Elliptic flow of charm and beauty quarks: mass dependence

J/ψ ($c\bar{c}$) and Υ ($b\bar{b}$) elliptic flow



Open charm, beauty elliptic flow



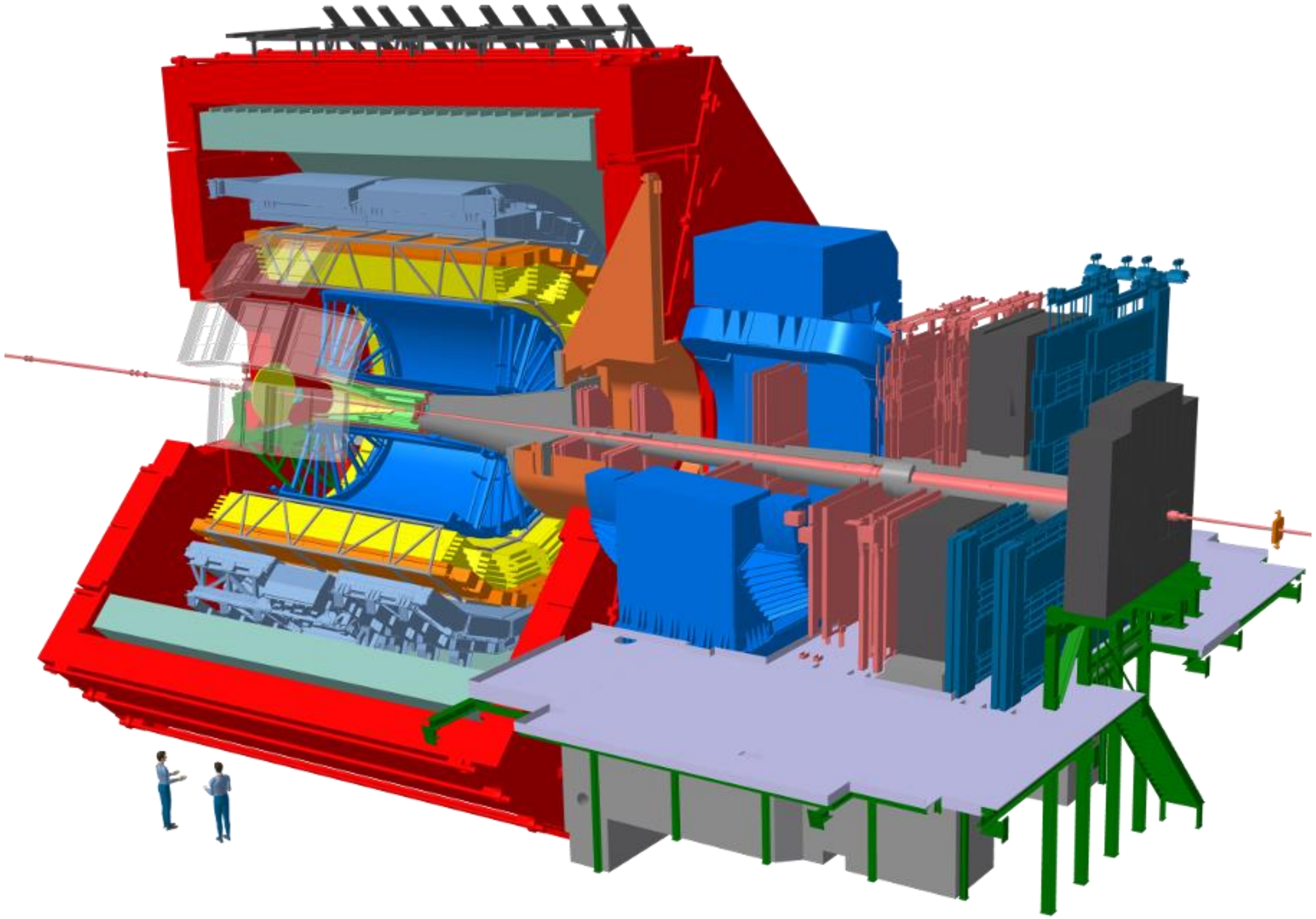
Quarkonia: flow generated by quark flow and coalescence
Charmonia: large elliptic flow — Bottomonia: compatible with no flow

Non-prompt D mesons (open beauty) show smaller v_2

Beauty quarks flow less than charm quarks: larger mass, slower thermalisation

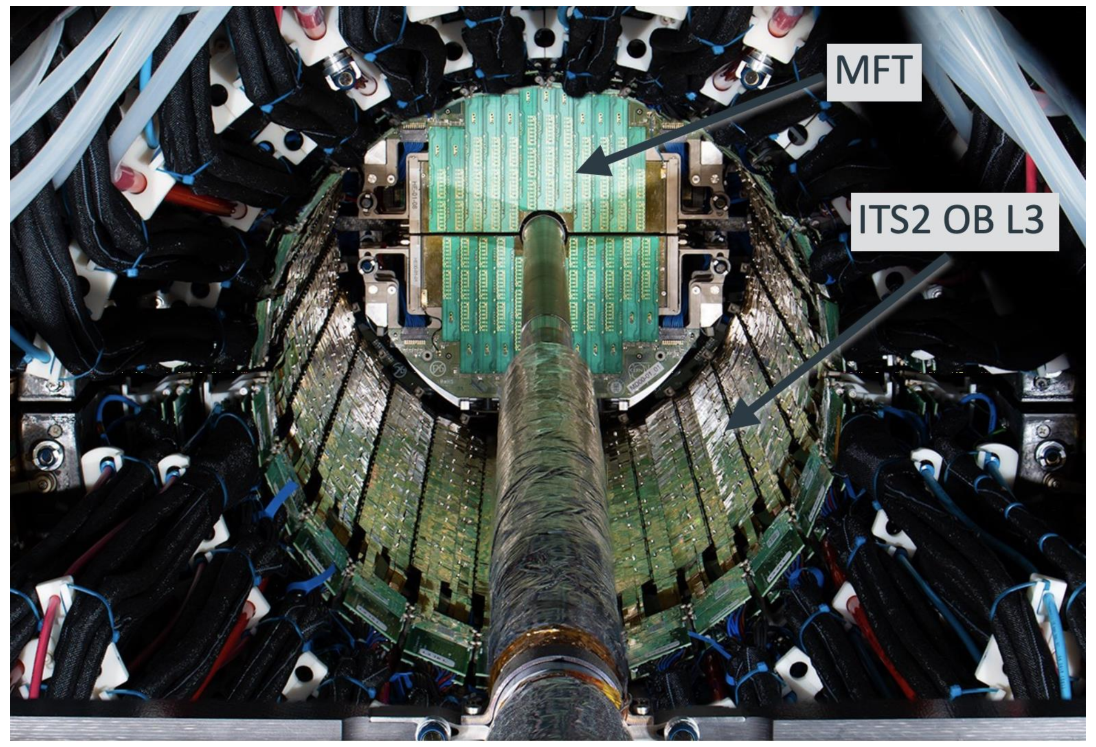
Open and hidden flavor allow to investigate impact of hadronisation, light quark flow

Detector upgrades



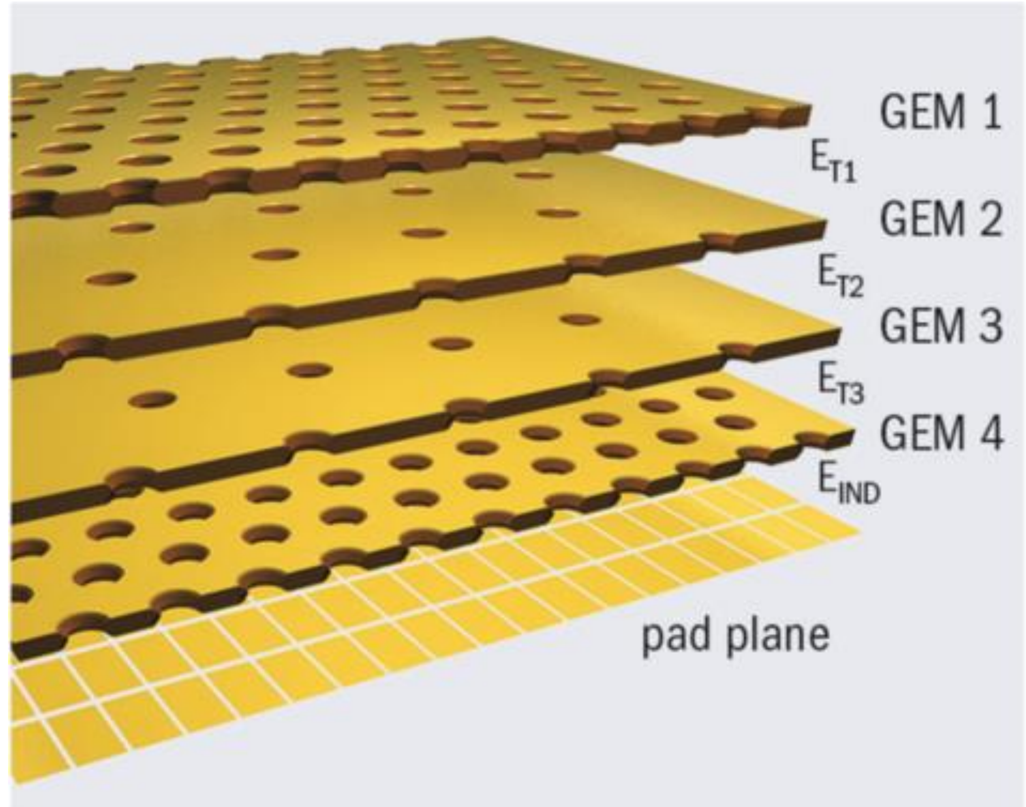
Recent ALICE upgrades

New ITS and MFT



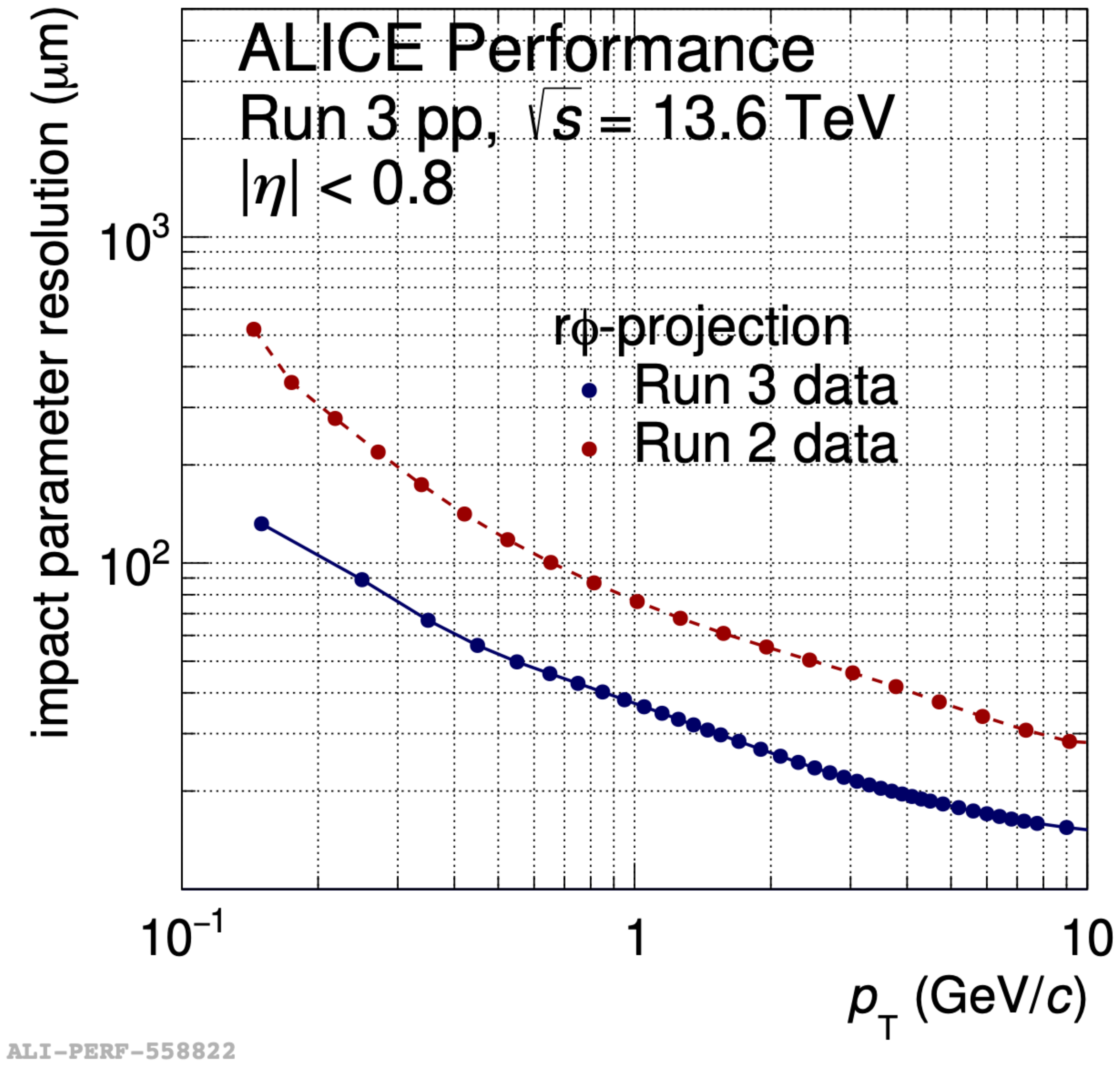
Full pixel detector 13 Gpixels
Improved spatial resolution

TPC: GEM readout

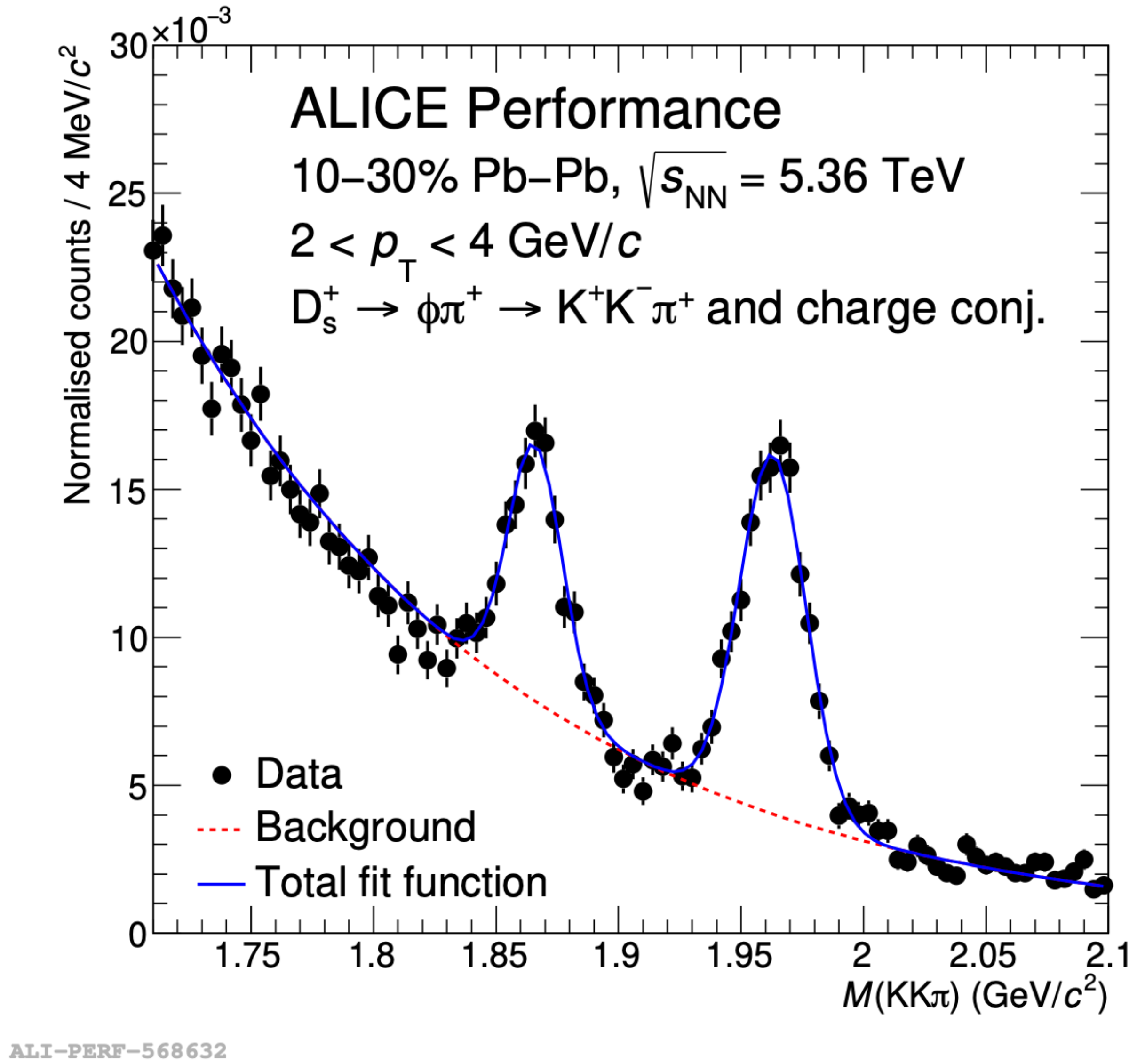


ALICE LS2 upgrade paper: arXiv:2302.01238

Impact parameter resolution

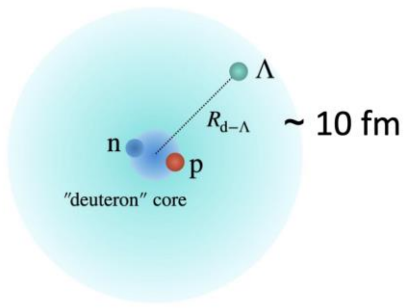


D^+ and D_s^+ in Pb-Pb

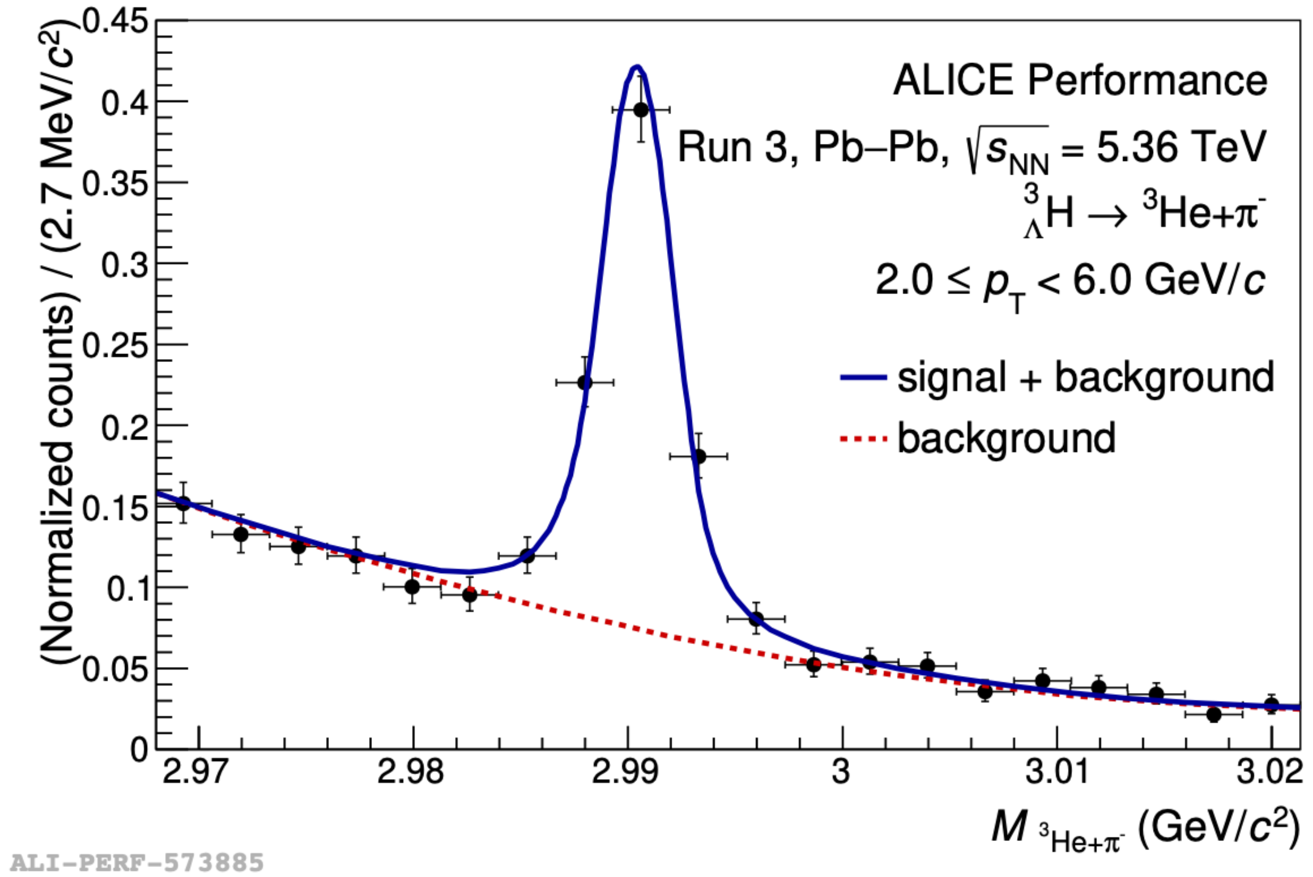


Hypertriton

$^3_\Lambda$H

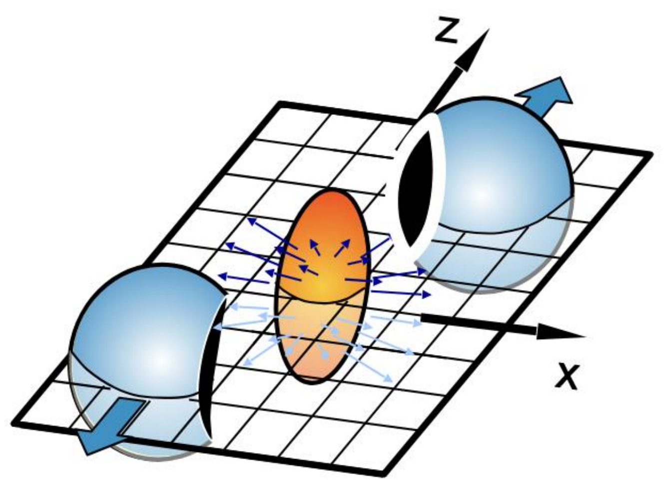


$$^3_\Lambda H \rightarrow ^3He + \pi$$



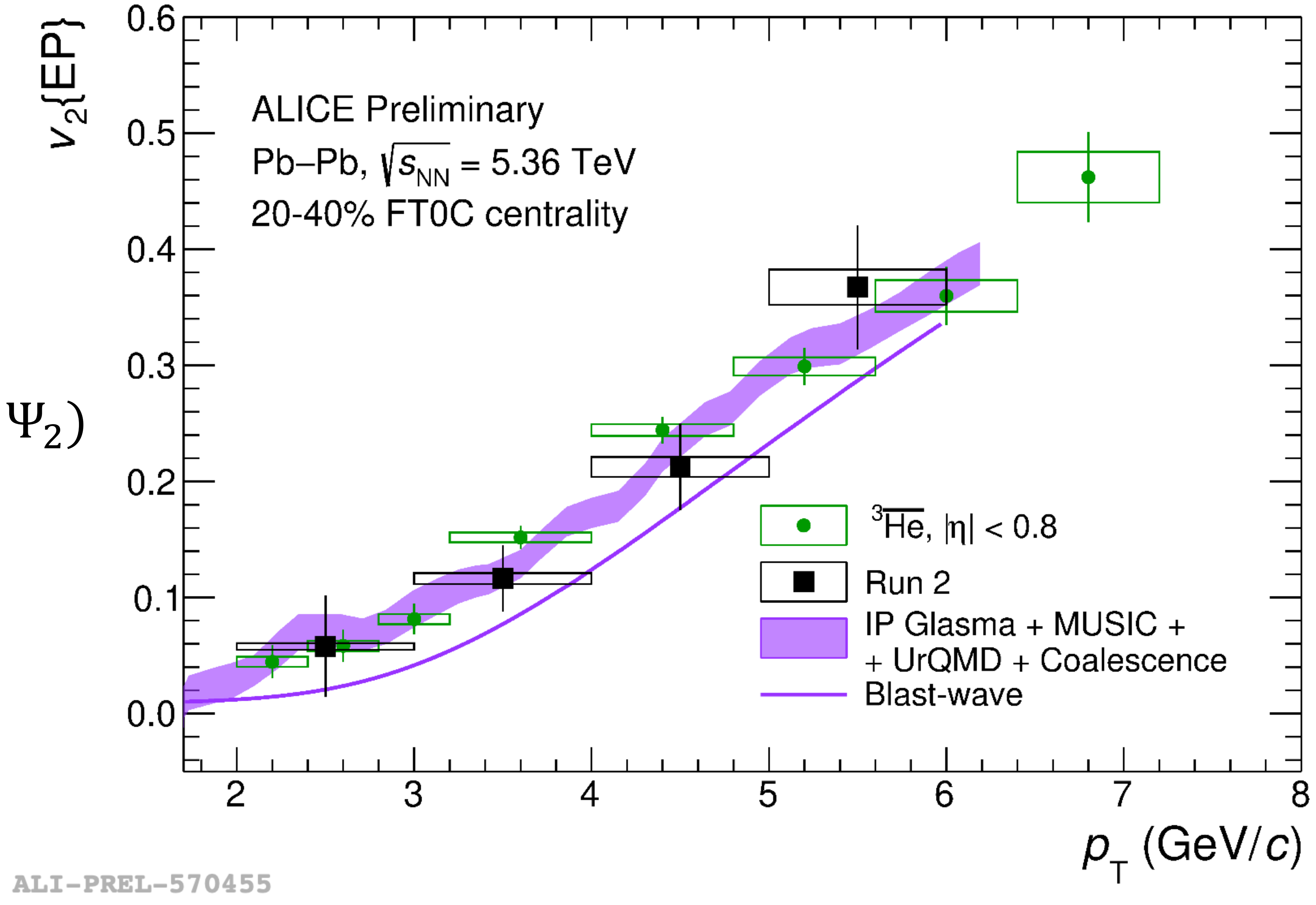
Improved pointing resolution and readout rate:
record 50 kHz Pb-Pb collisions (50x more minimum bias events)

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

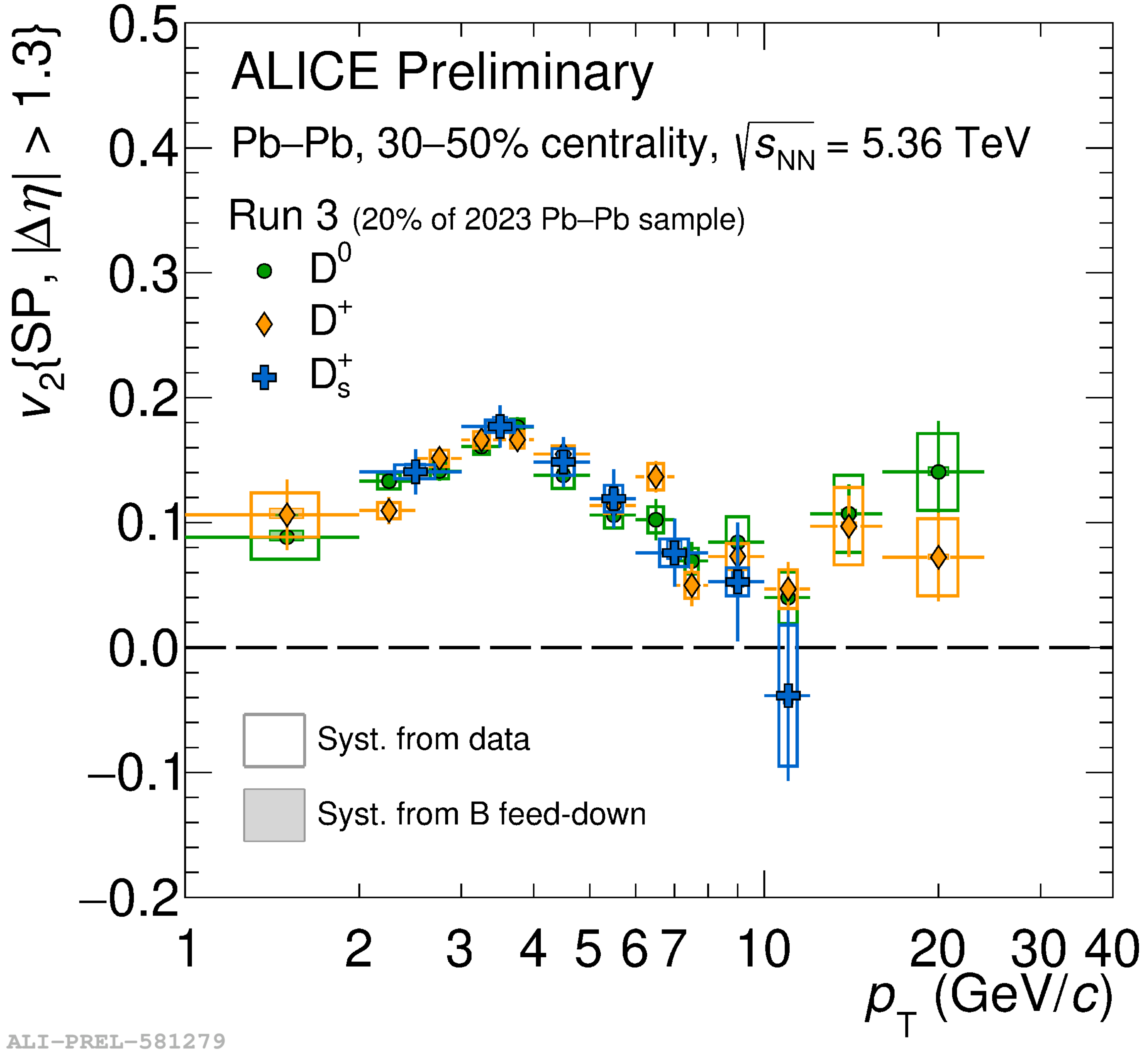


$$\frac{dN}{d\phi} \propto (1 + v_2)\cos(\phi - \Psi_2)$$

$^{3}\overline{\mathrm{He}}$ elliptic flow



Elliptic flow of D, Ds



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

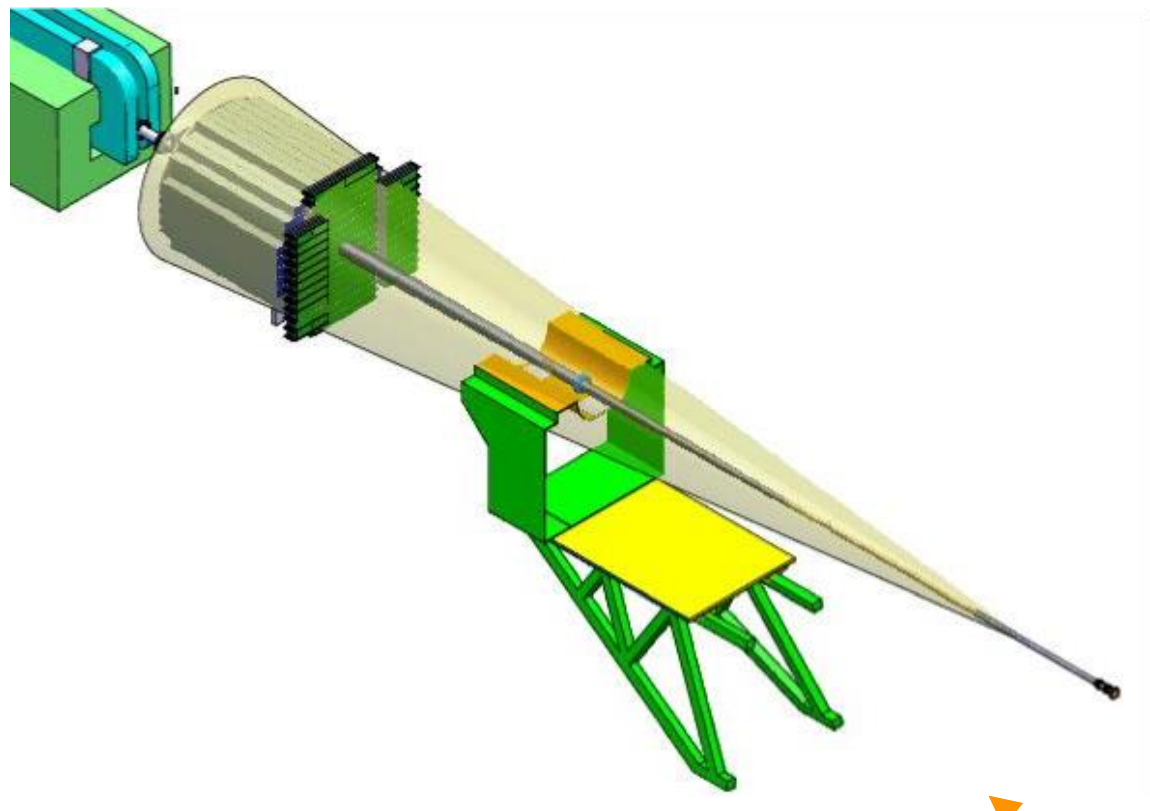
Larger samples, better pointing resolution: improved precision

Much more to come!

ALICE upgrade projects

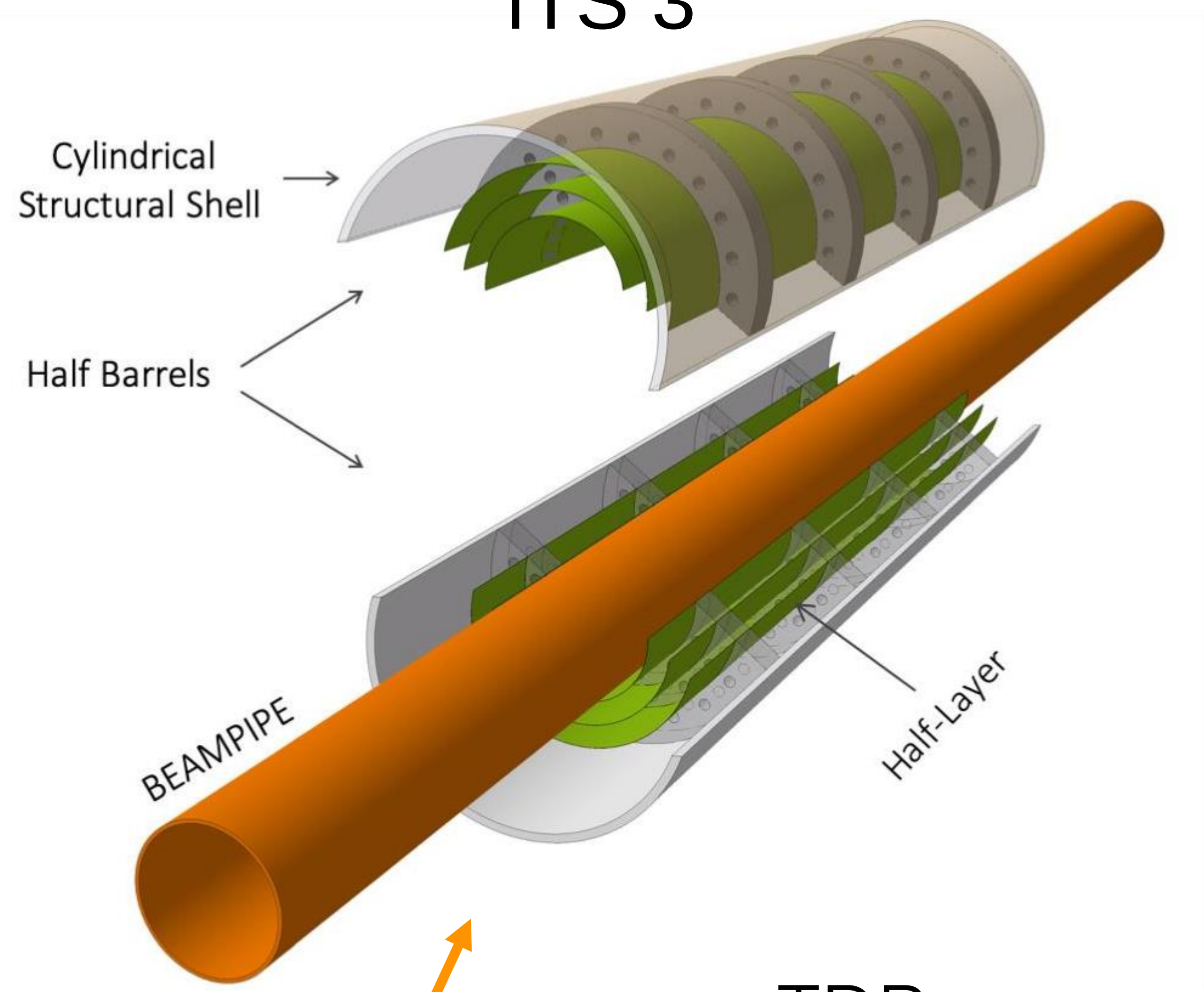
LS3 upgrades

Forward Calorimeter



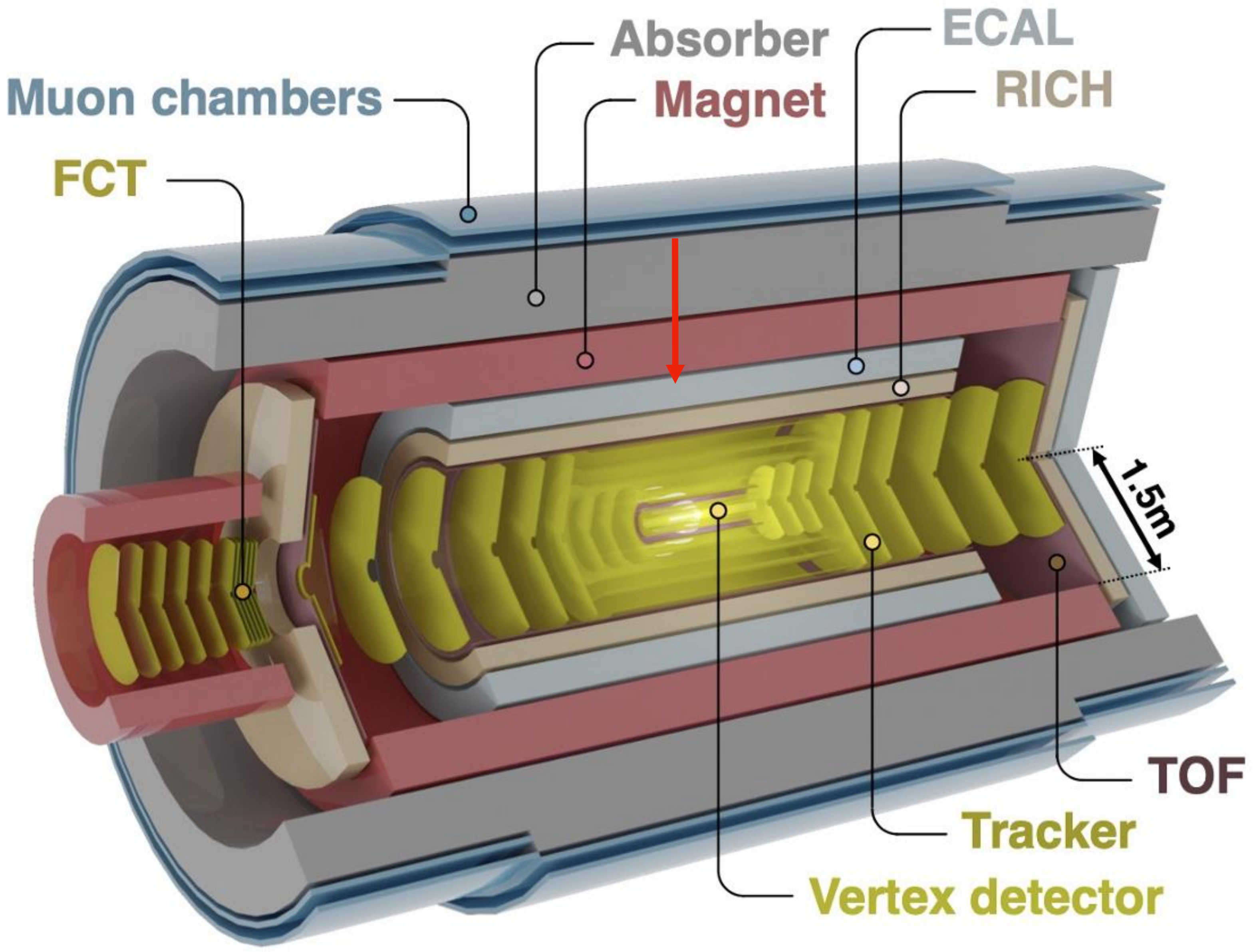
TDR approved

ITS 3

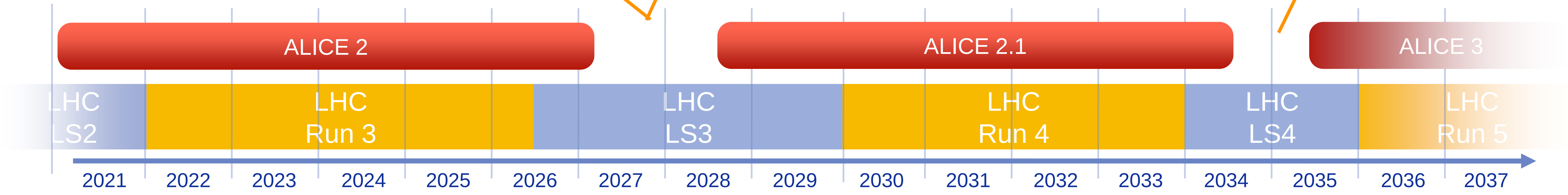


TDR approved

LS4: ALICE 3



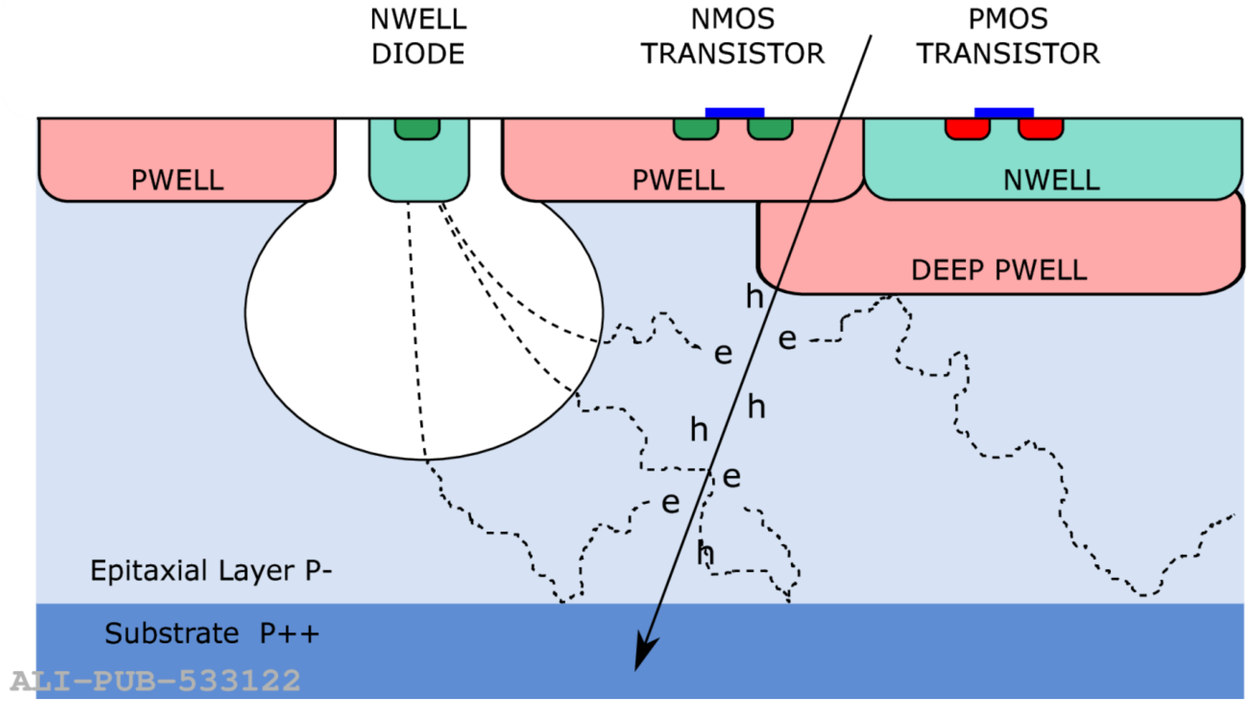
ALICE 3 LoI: CERN-LHCC-2022-009

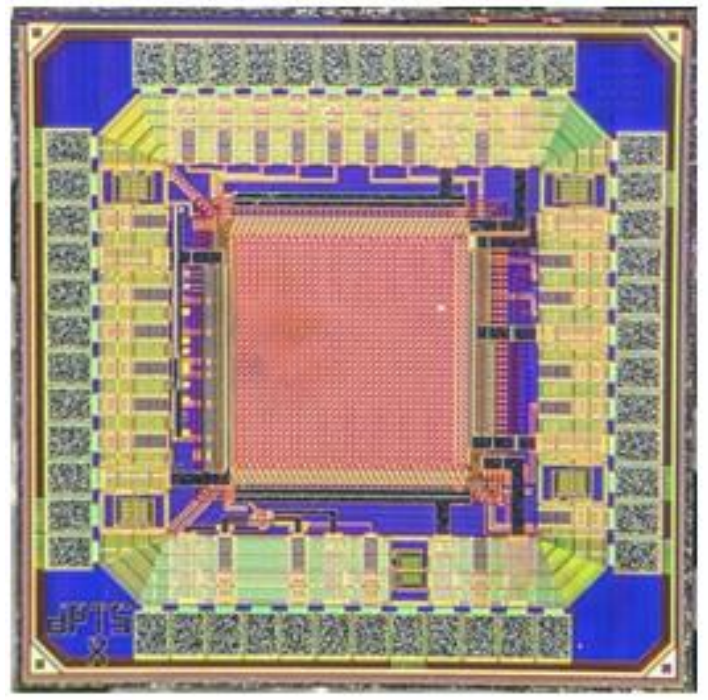


Silicon pixel sensor development

High-resolution, low-mass vertex detectors are crucial for detection/identification of **heavy flavour hadrons** and electron-positron pairs (**thermal radiation**)

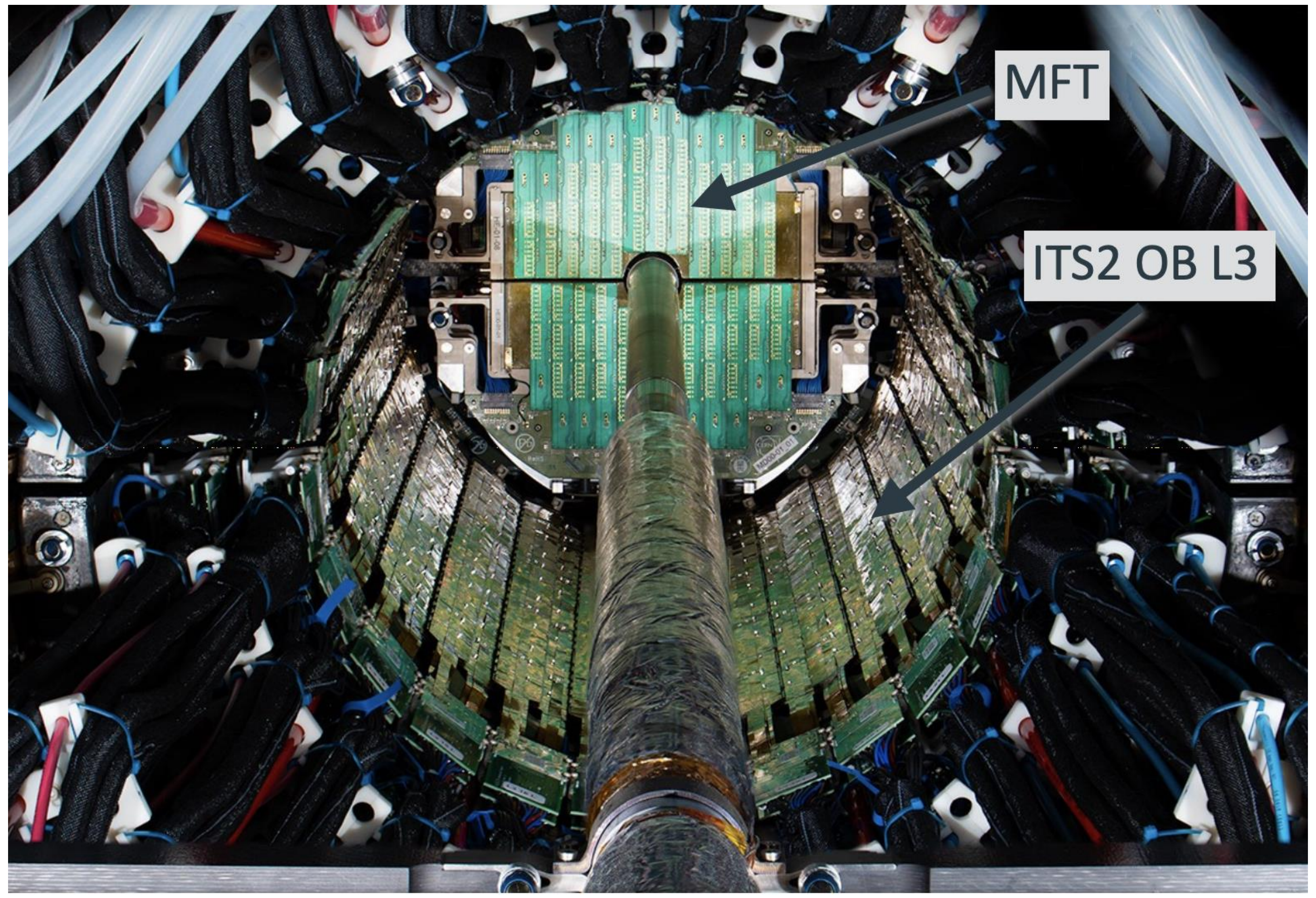
Development and adoption of monolithic active pixel sensors in CMOS technology



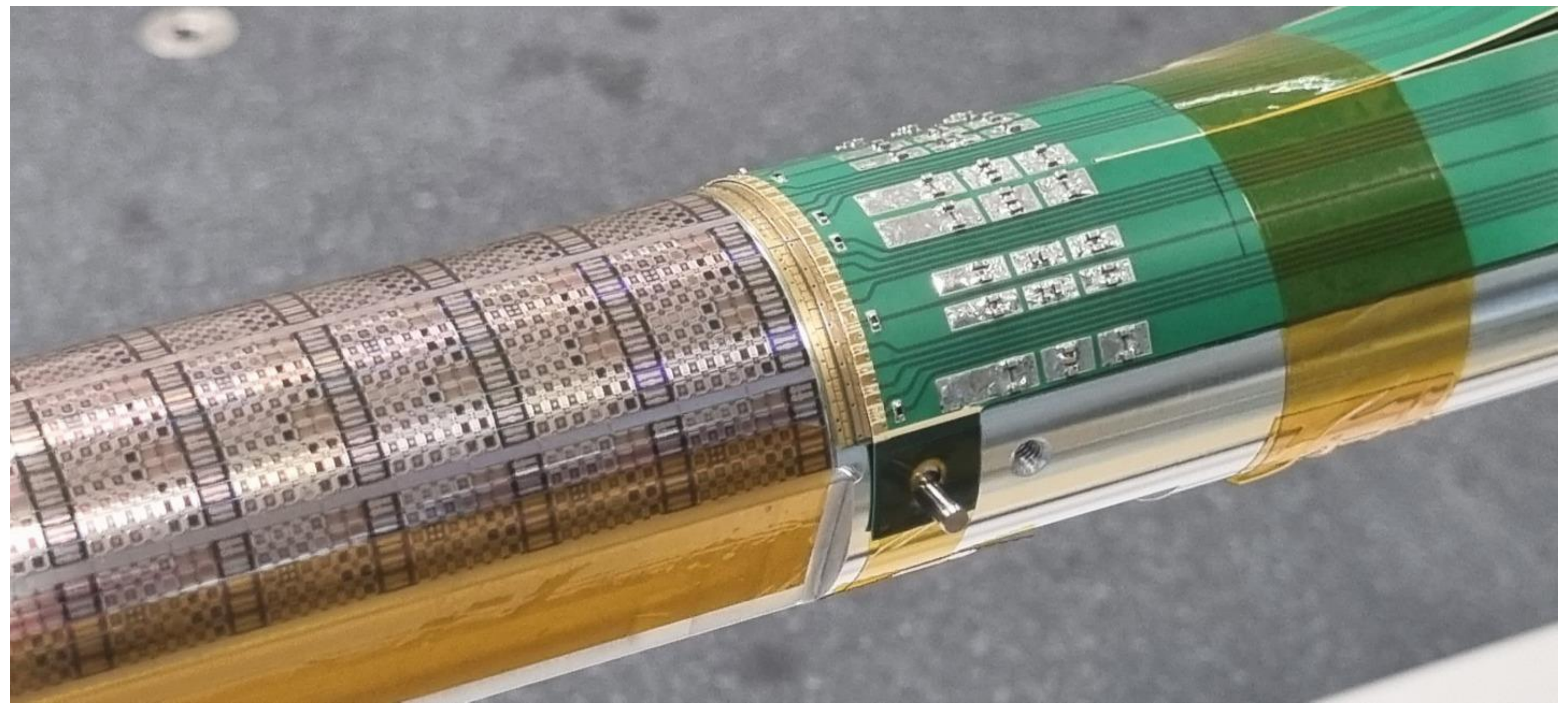


DPTS test paper arXiv:2212.08621

Inner tracking system



ITS3 development

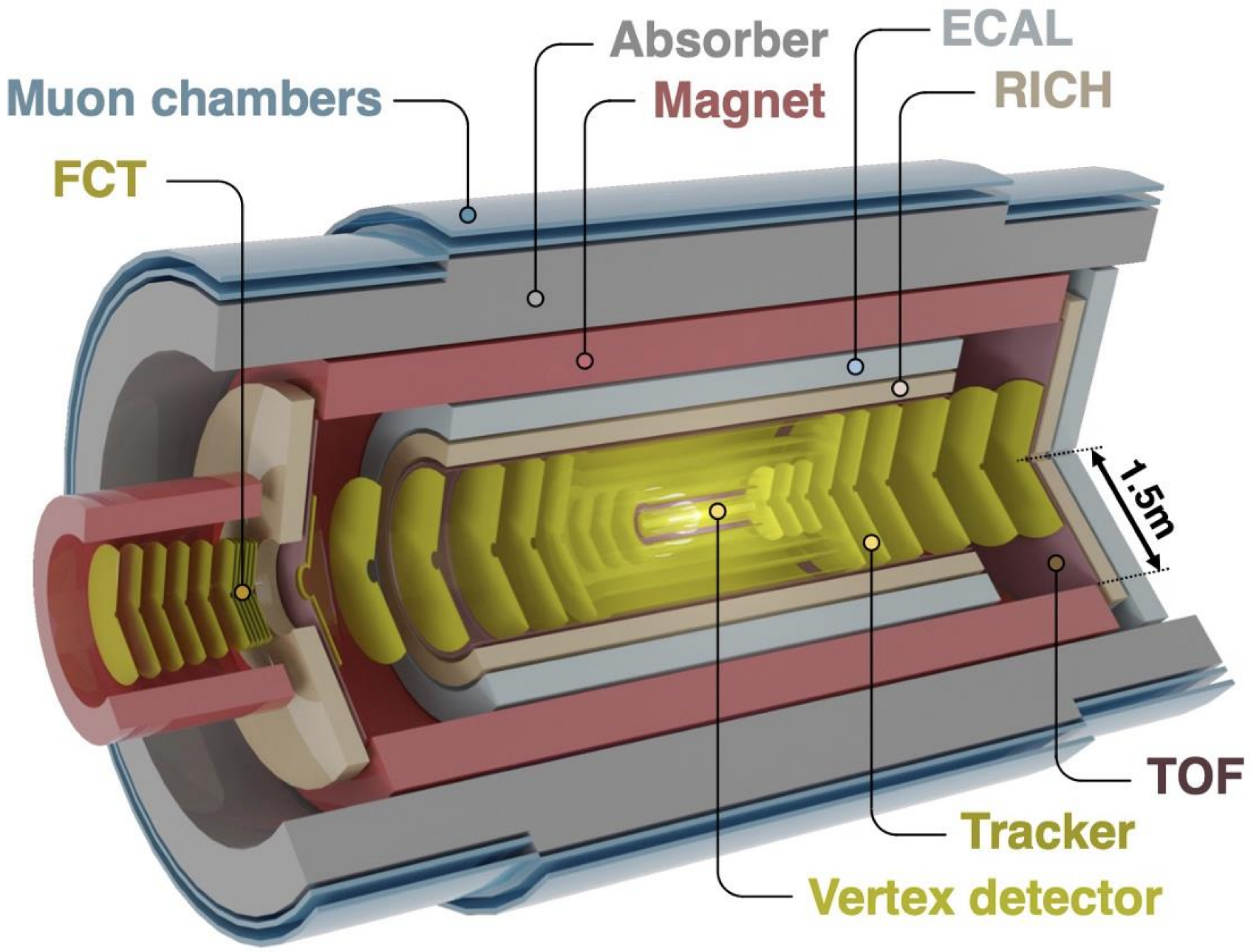


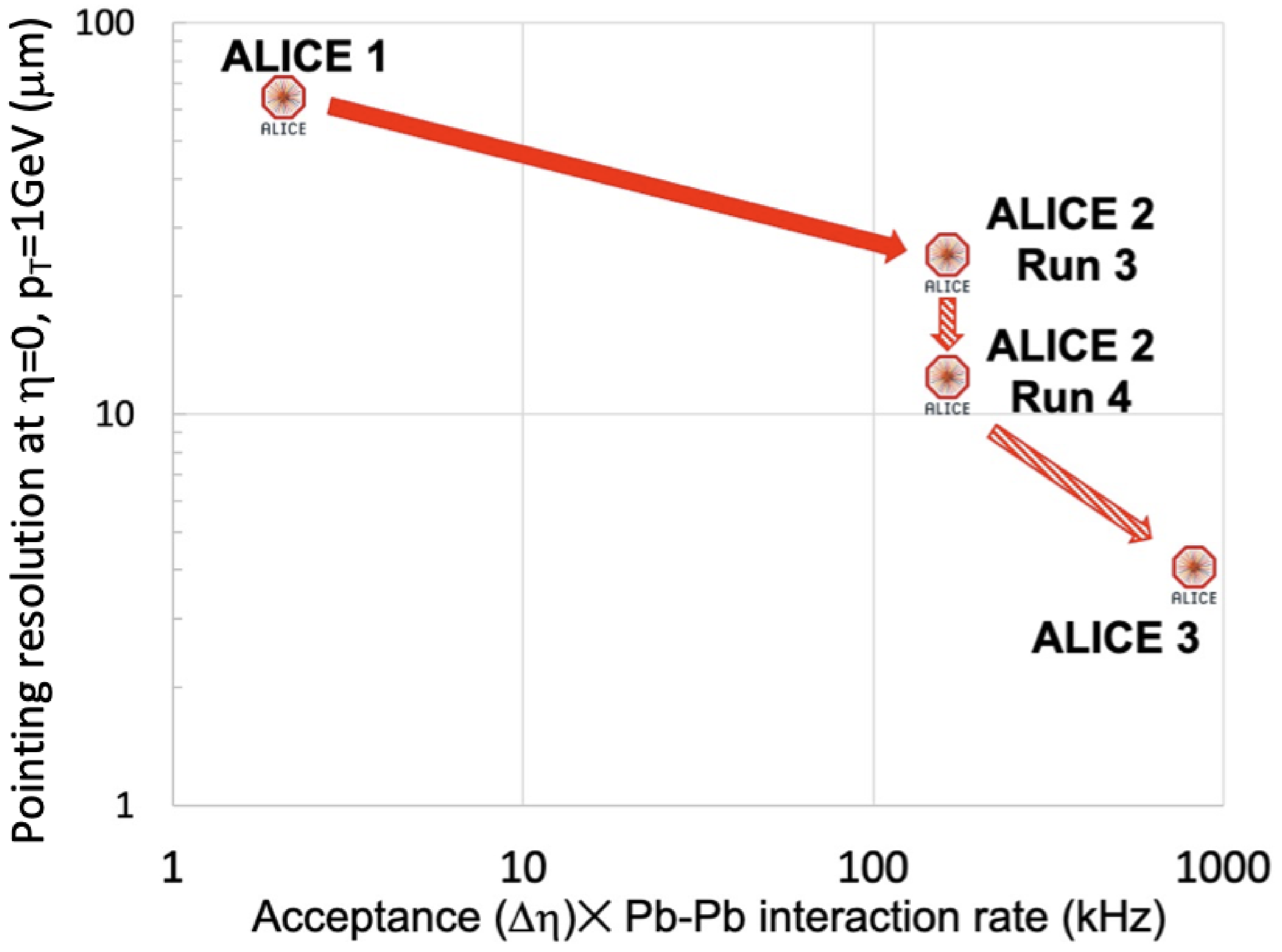
Thinned silicon can be curved: ultra-light structures

LHC Run 5 and 6: ALICE 3

Compact detector system with

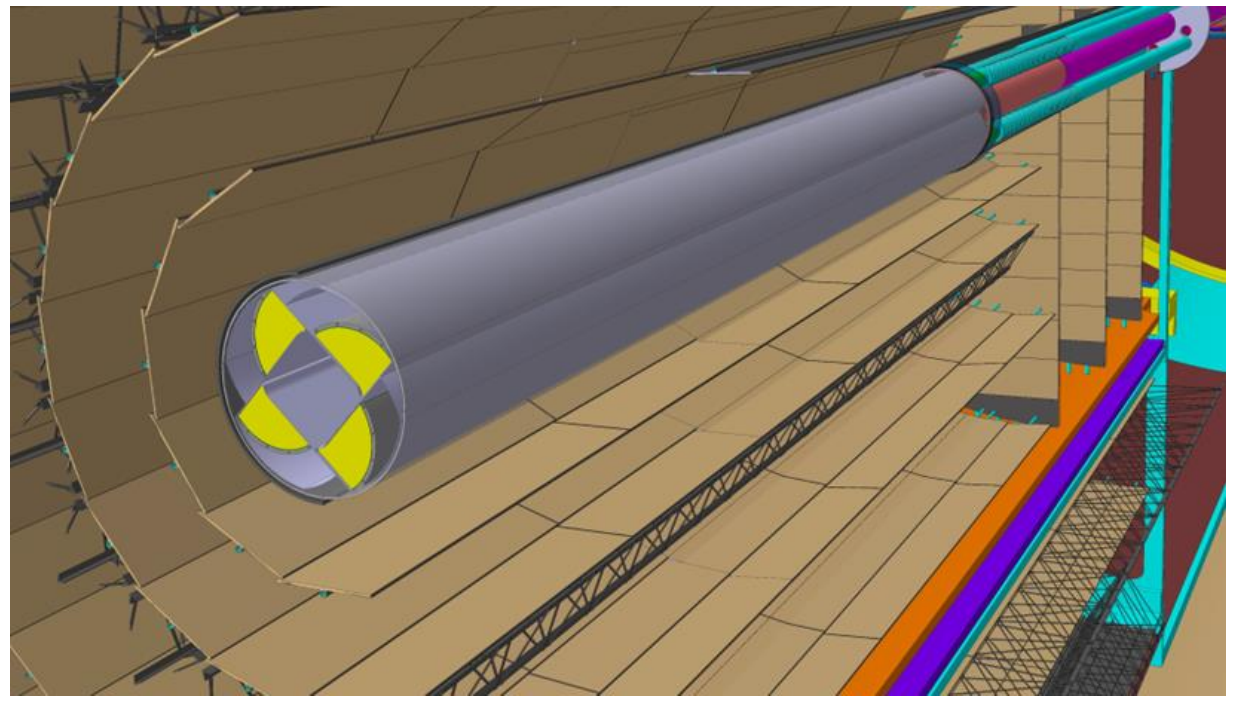
- High-resolution vertex detector: **excellent pointing resolution**
- **Particle Identification over large acceptance**: muons, electrons, hadrons, photons
- Fast read-out and online processing

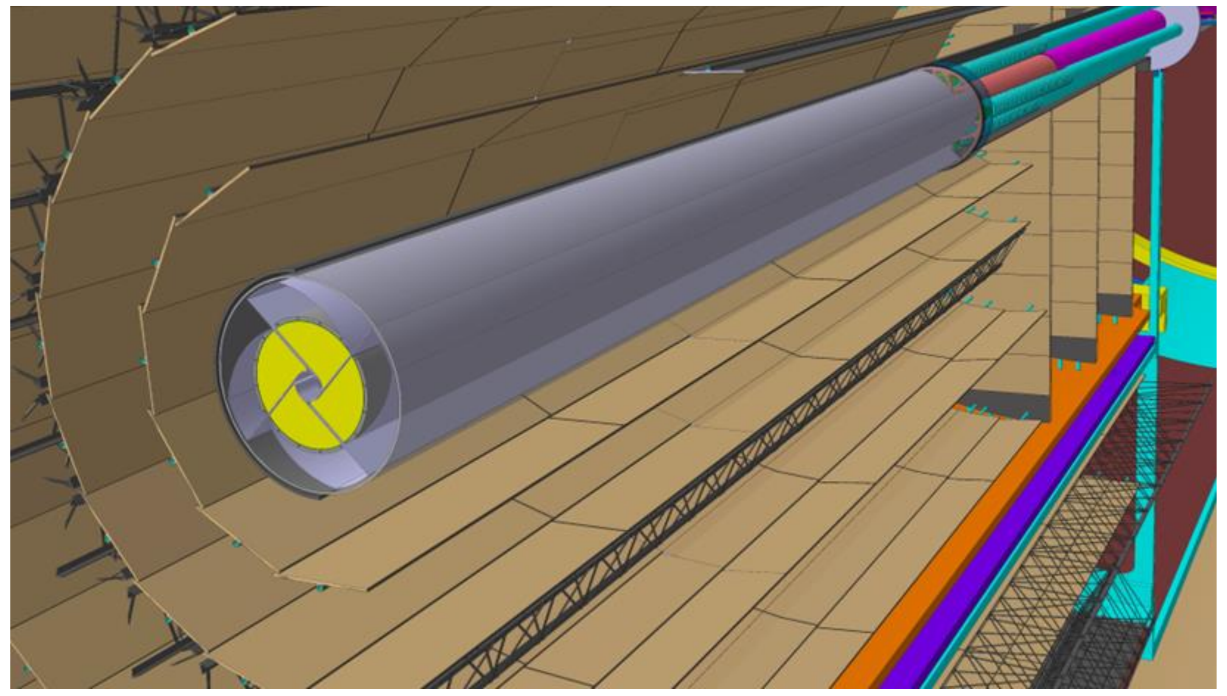




Improvements in precision, rate, acceptance

Retractable vertex tracker

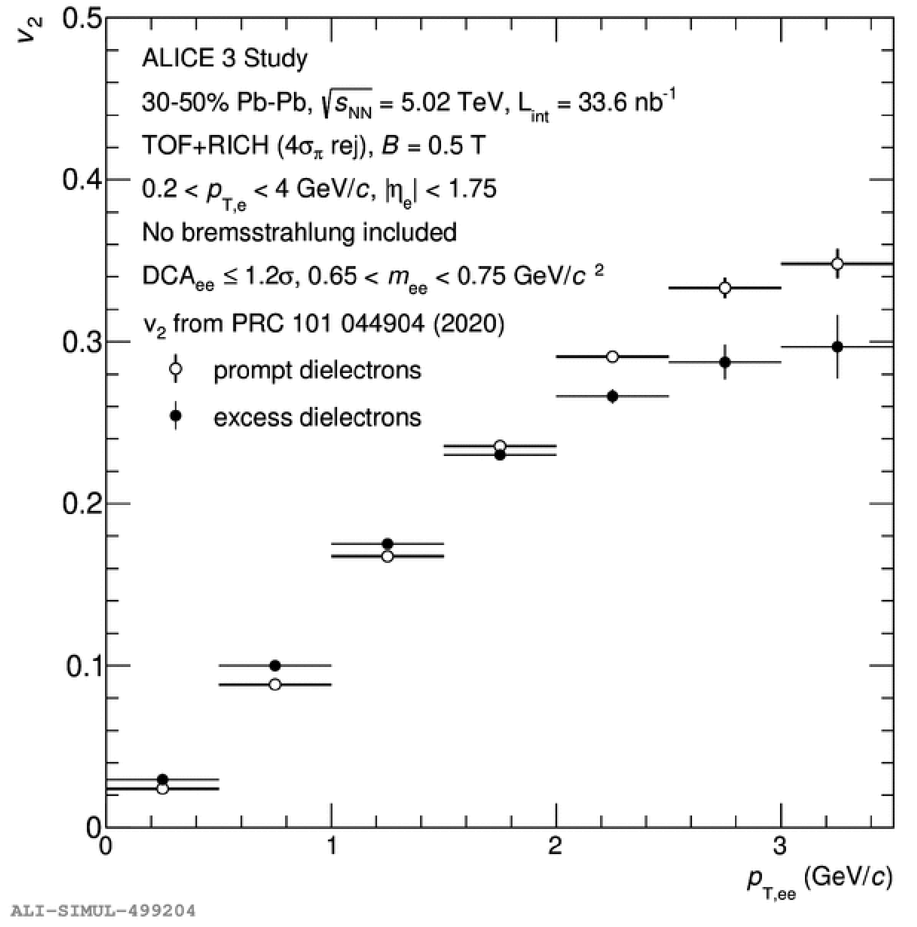




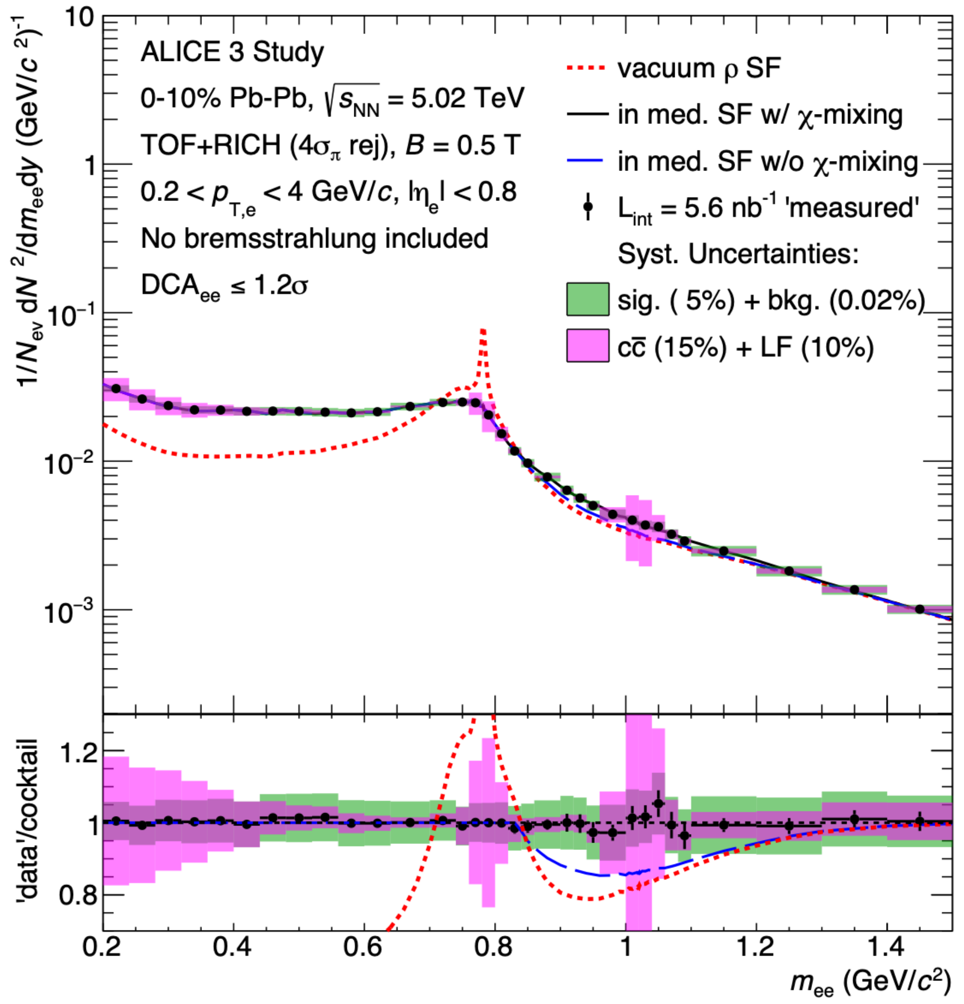
ALICE 3 Letter of Intent
(CDS: LHCC-2022-009)

ALICE 3: an ambitious physics program

Dielectrons: thermal radiation and chiral symmetry restoration

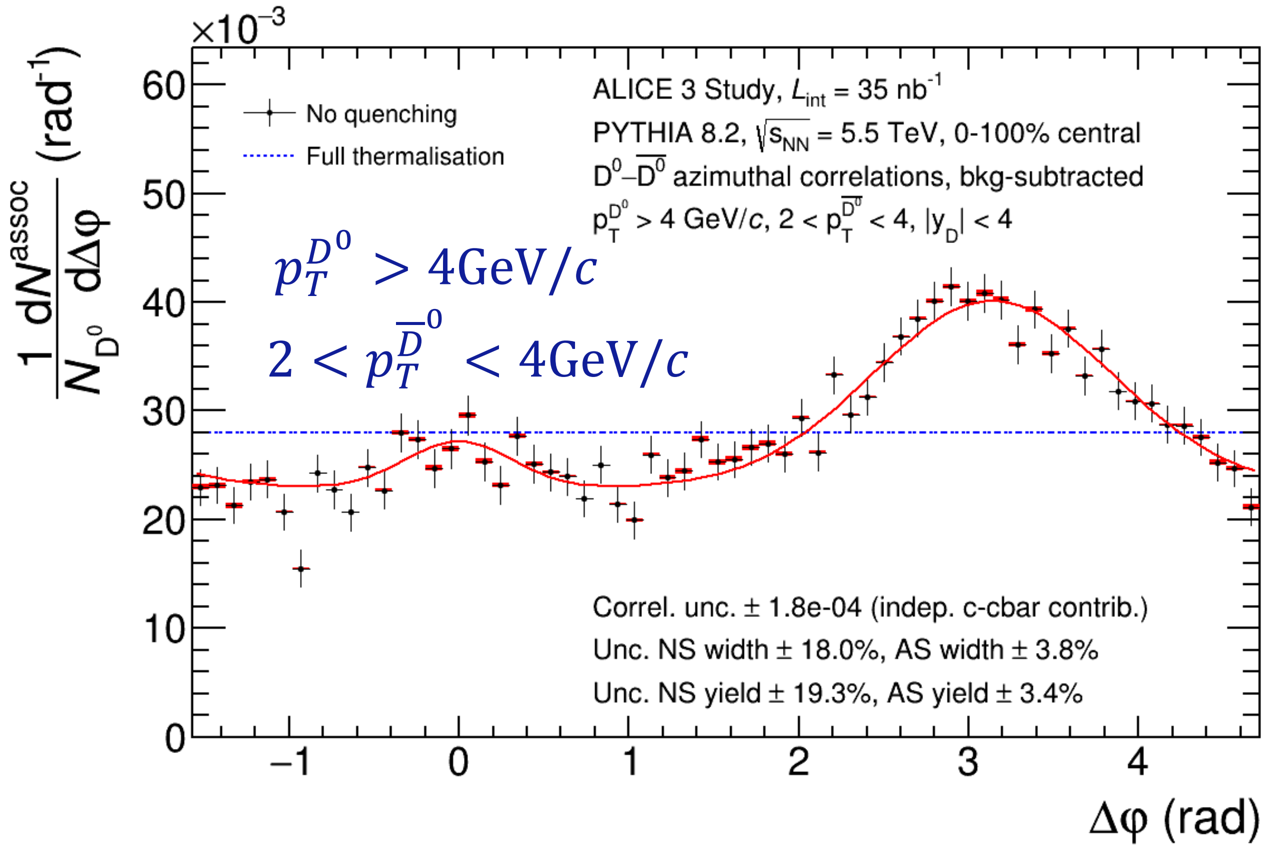


Direct measure of temperature and expansion of early stage

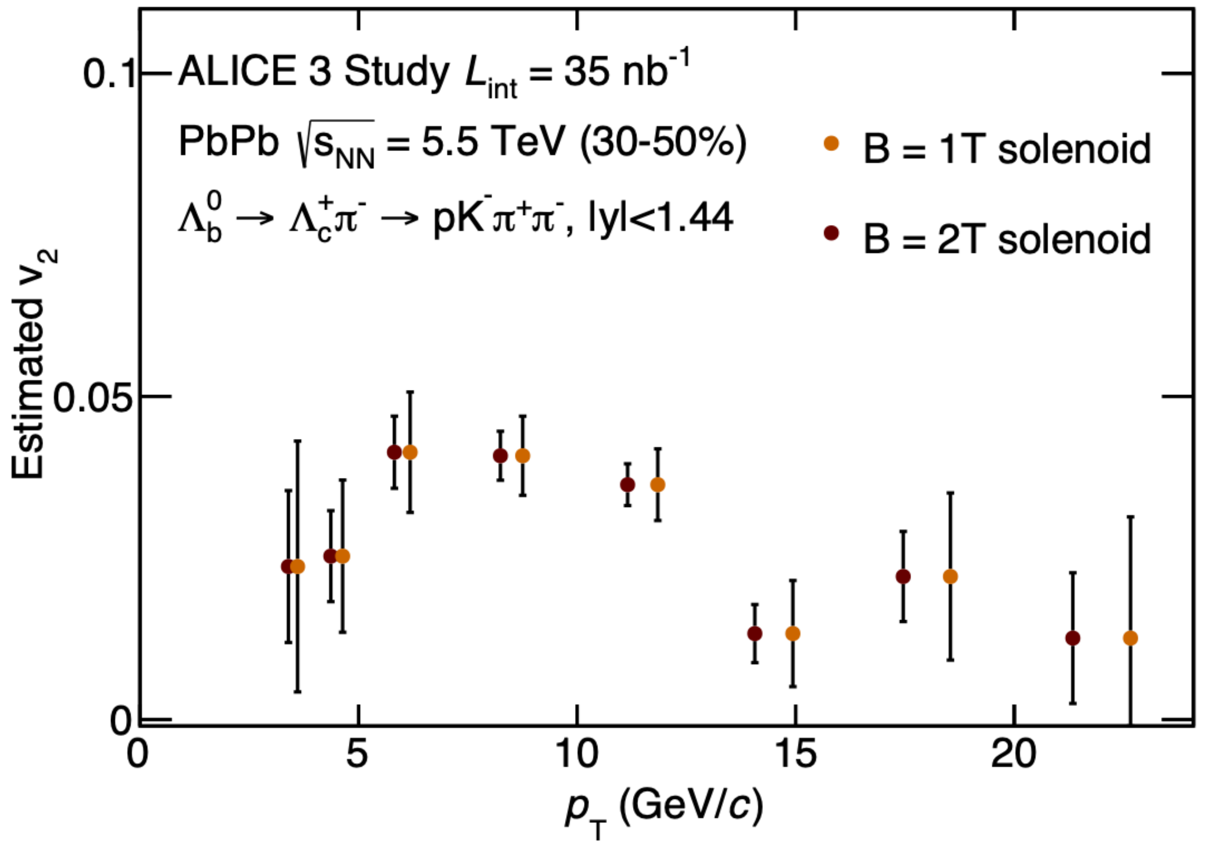


Chiral symmetry restoration

$D\overline{D}$ correlations: charm diffusion

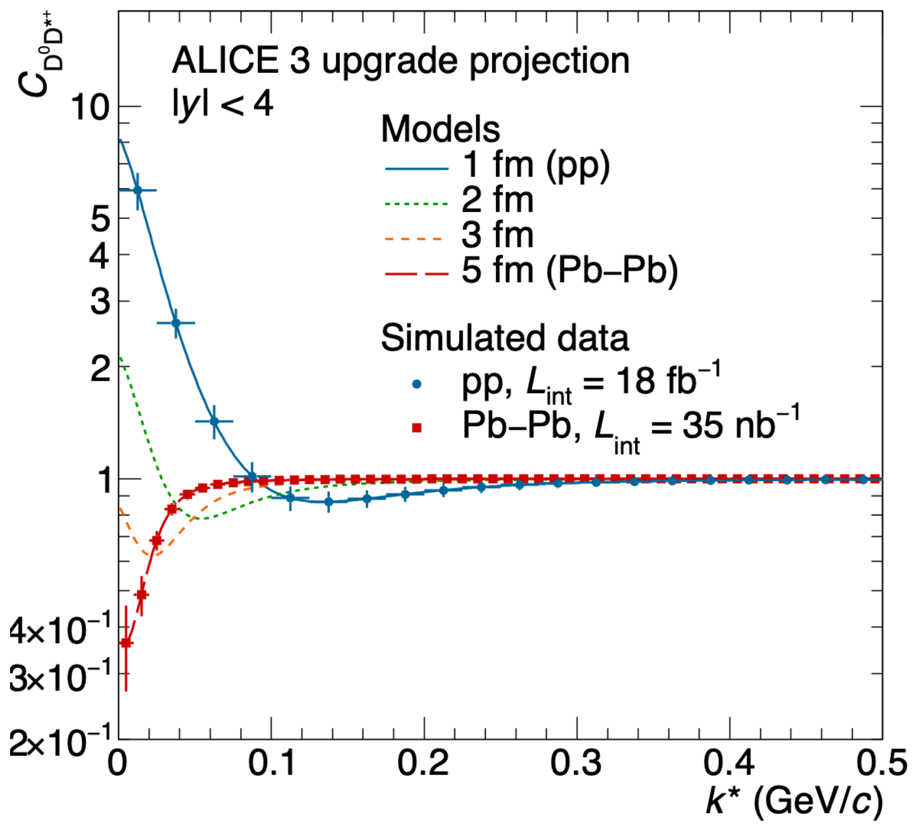


Heavy flavour v_2

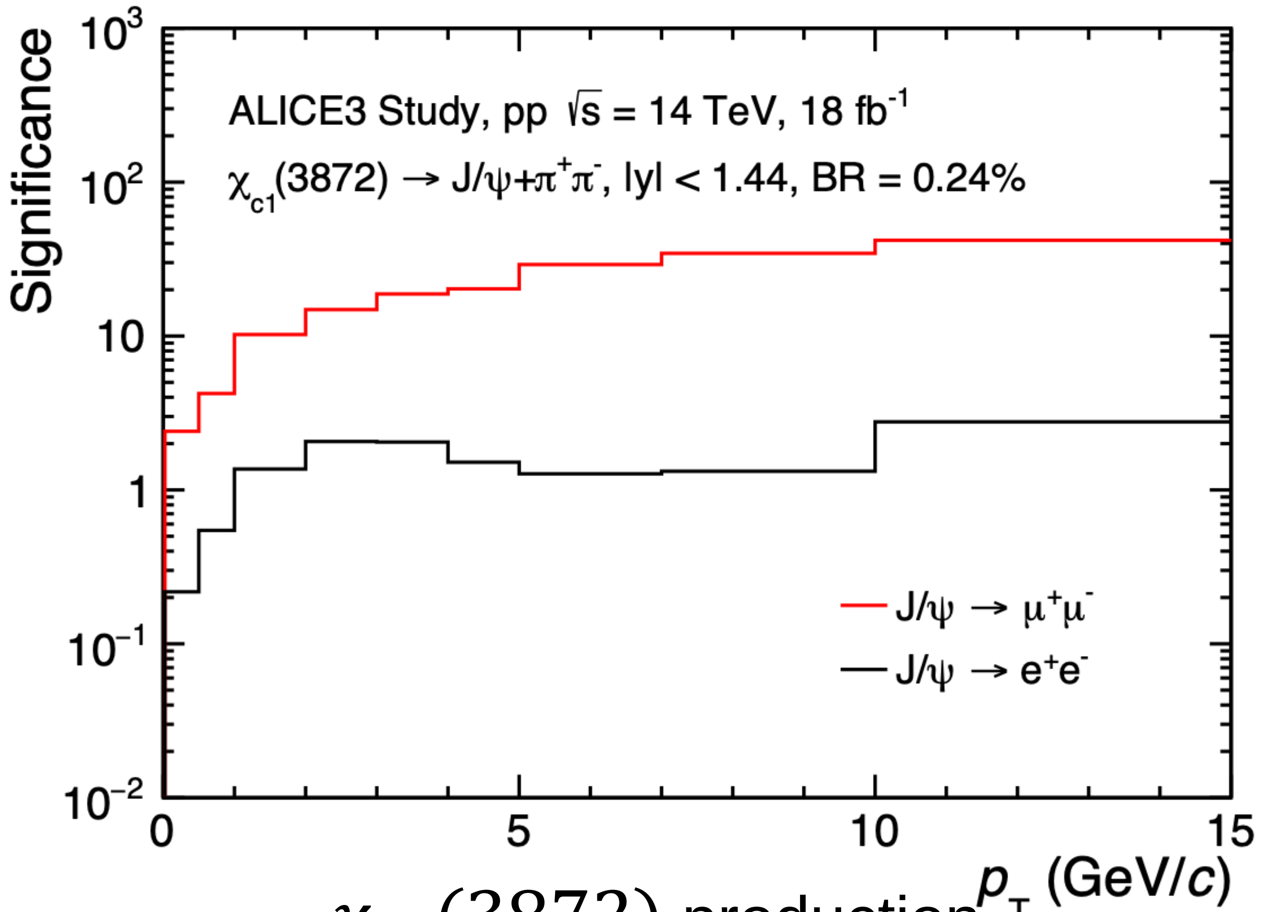


Thermalisation of heavy quarks

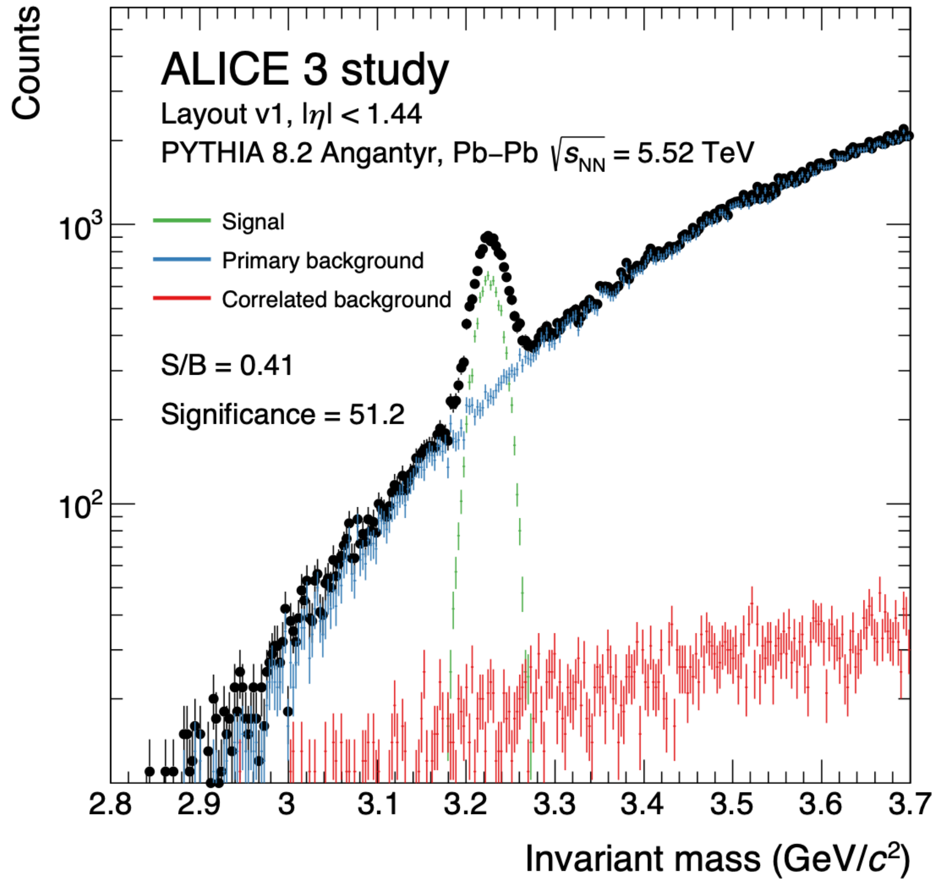
Exotic states and hadron interactions



D^0D^{*+} momentum correlations

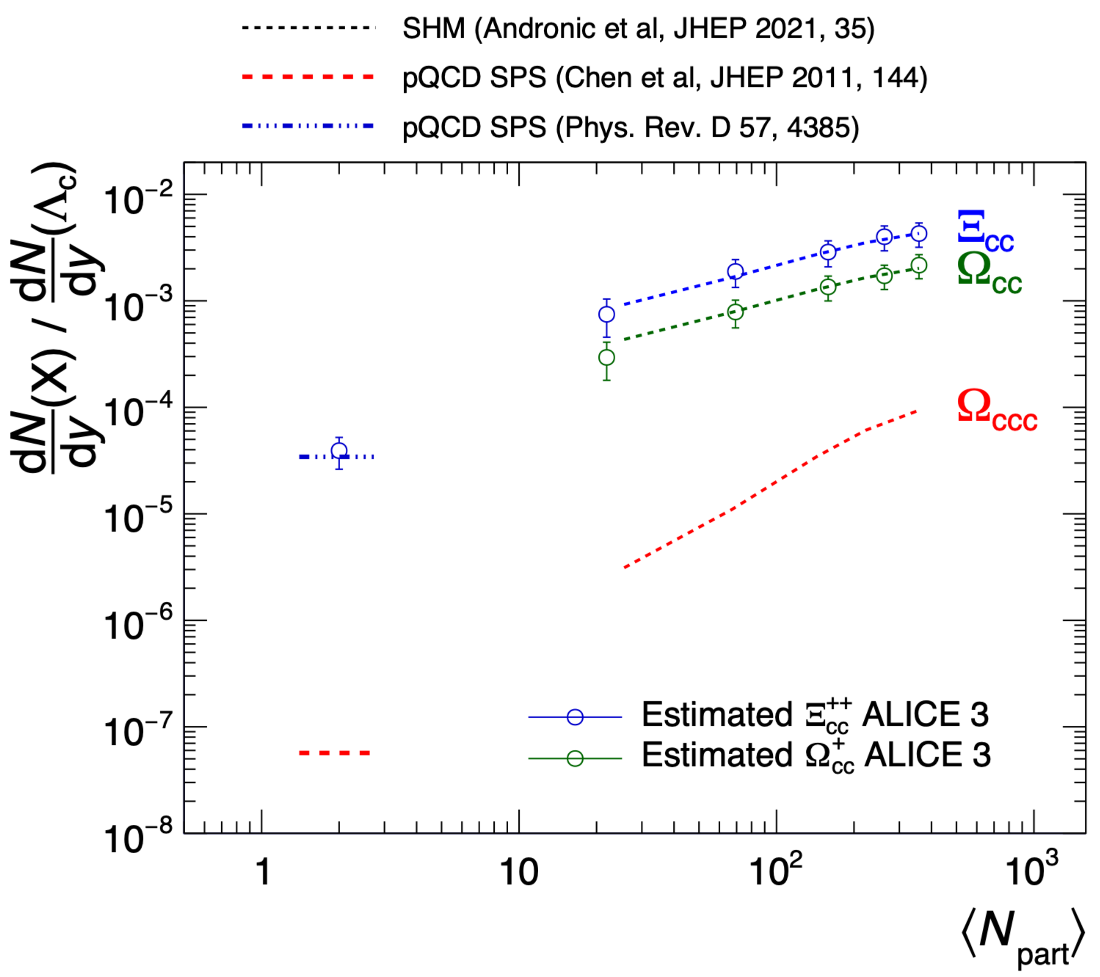


$\chi_{c1}(3872)$ production



c-deuteron

Multi-charm baryons



… and more

Conclusion

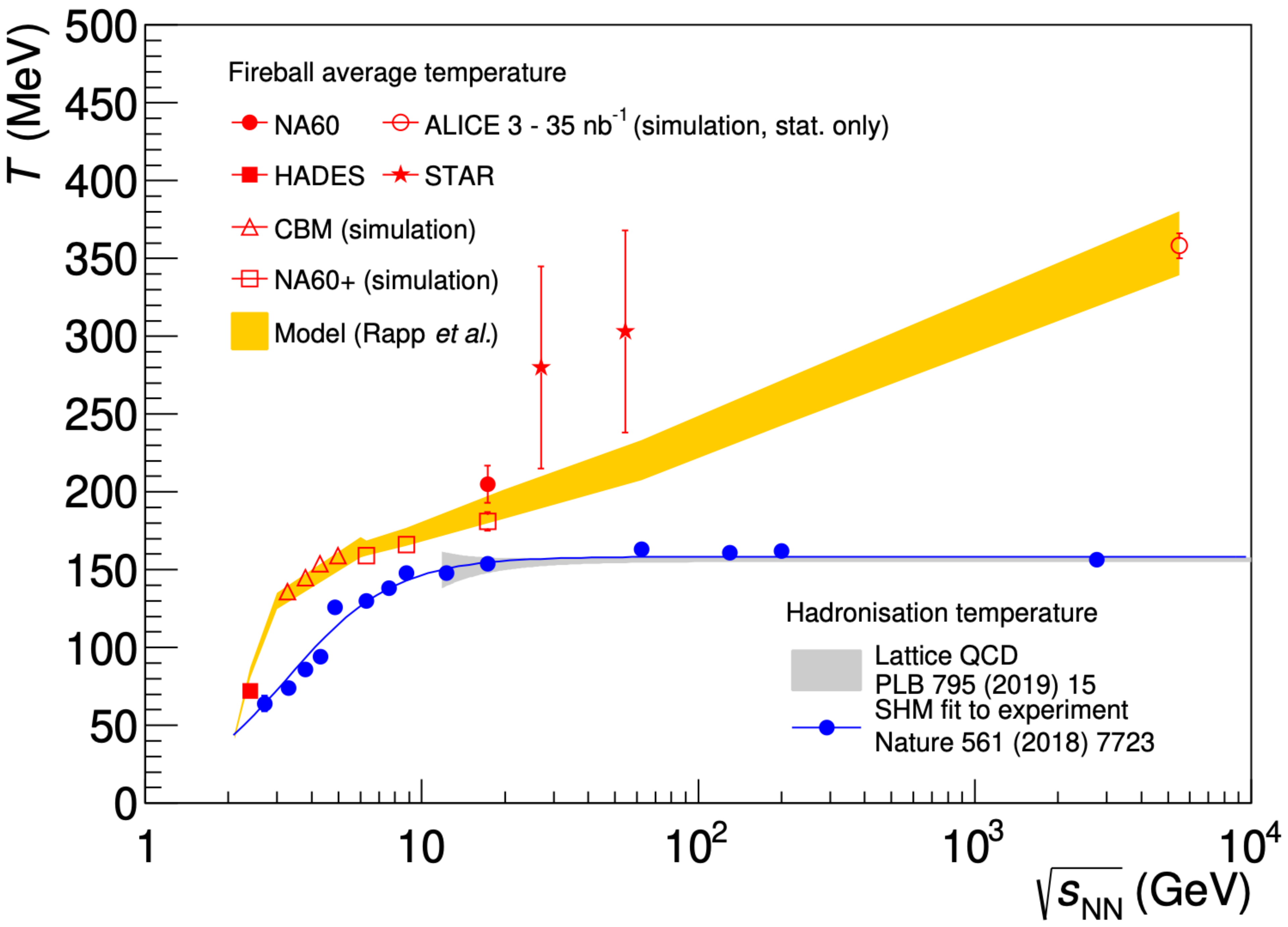
- Heavy-ion collisions at LHC provide unique laboratory to study strongly interaction matter
  - Hottest and densest matter available in the laboratory
  - Properties: low viscosity, short mean free path
  - Slower thermalisation for beauty than charm: mass dependence
- Large upgrade for Run 3: improved 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…

Temperature of the QGP: electromagnetic radiation

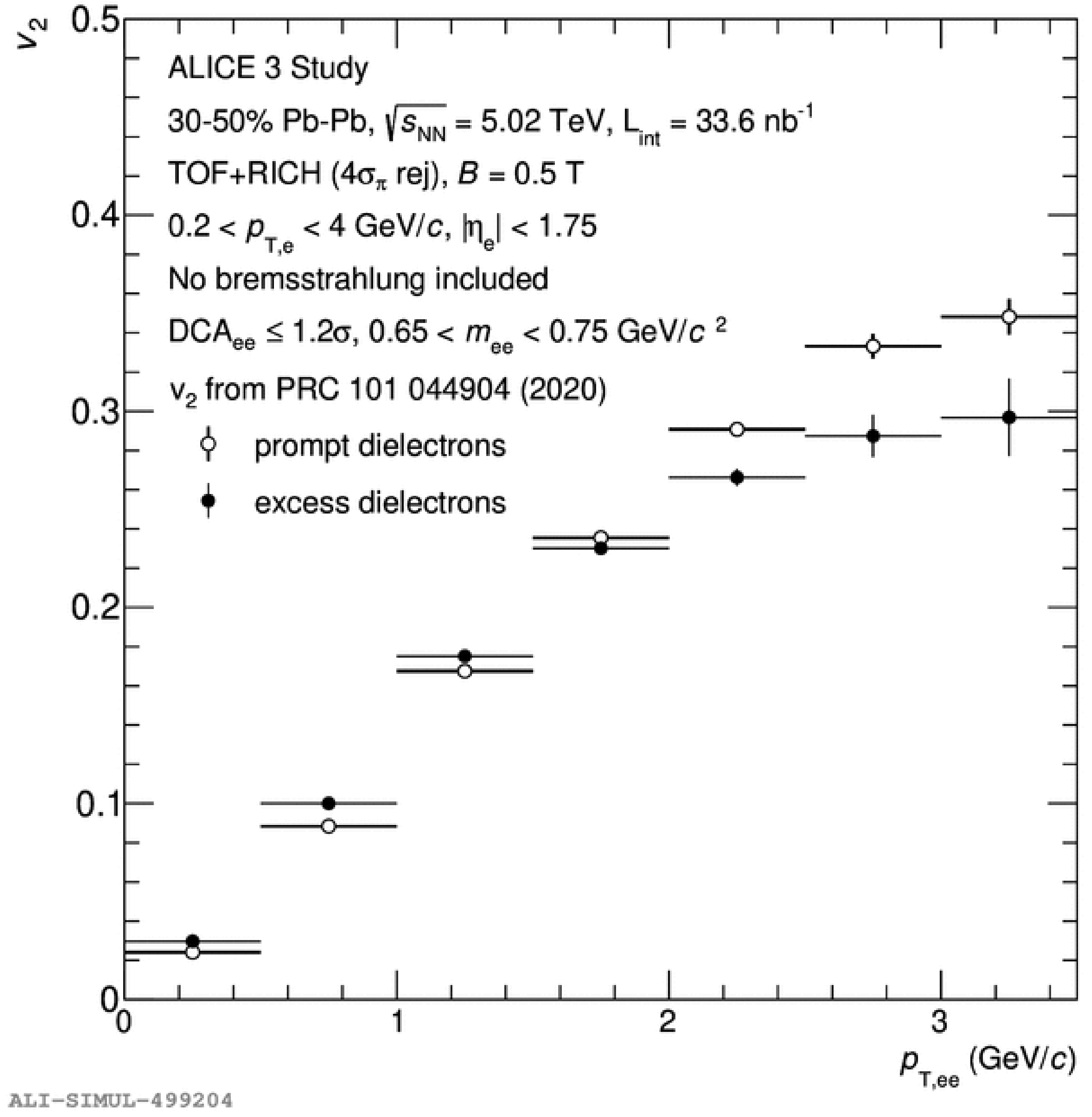
T vs energy



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

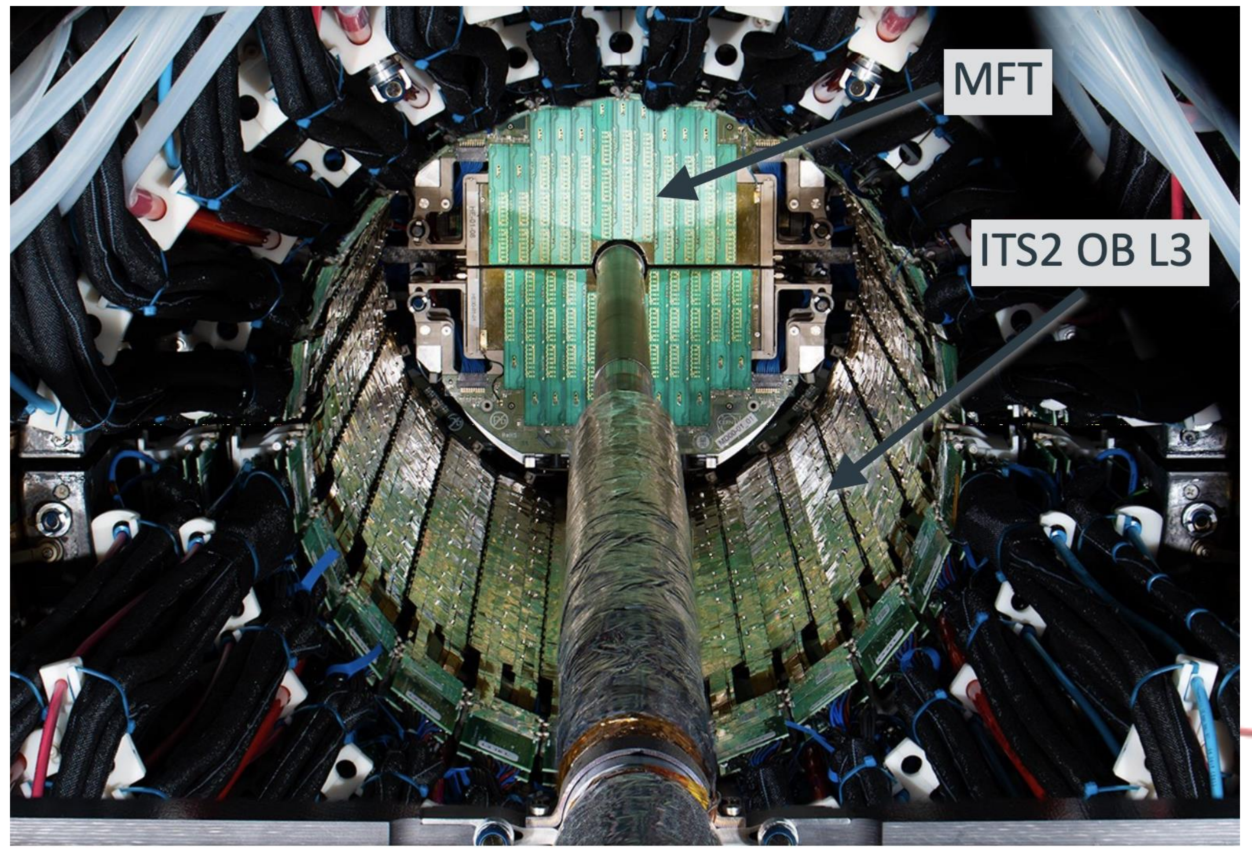
Electromagnetic radiation gives access to **temperature of QGP before hadronisa**

- 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

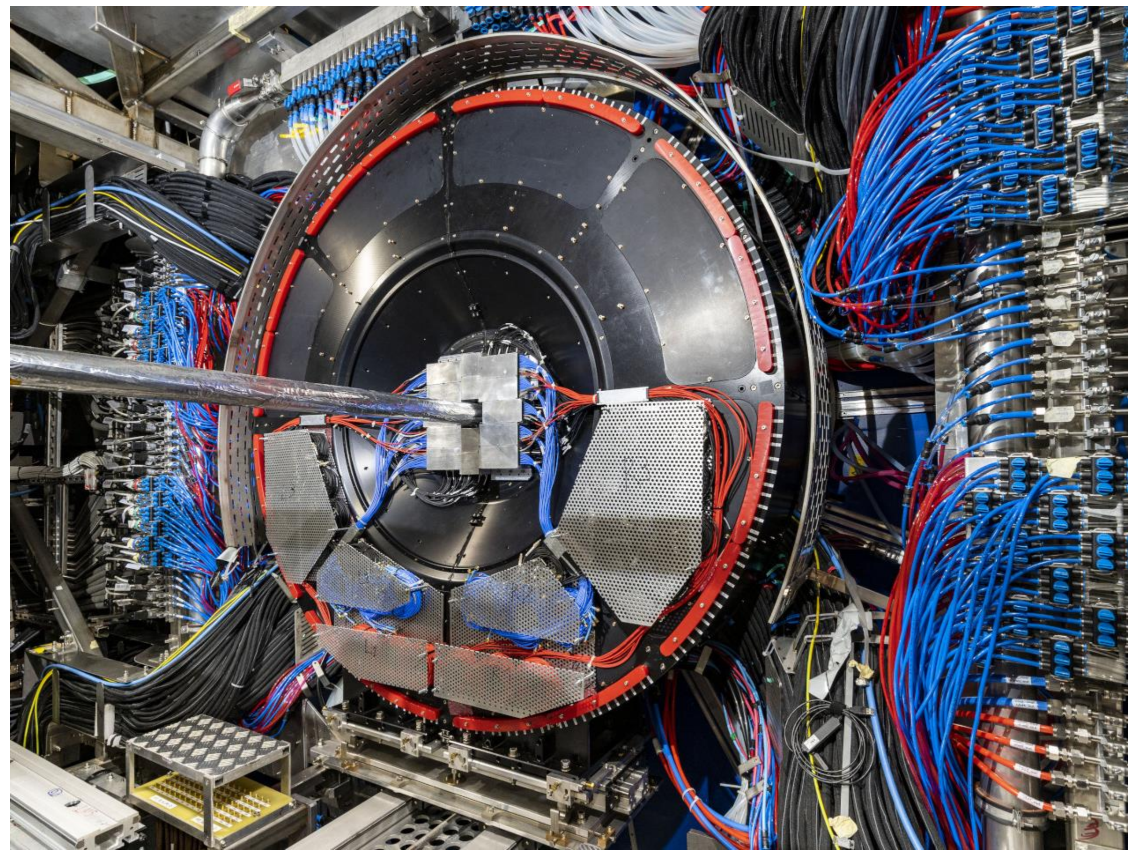
ALICE upgrades in Long Shutdown 2 (2019-2021)

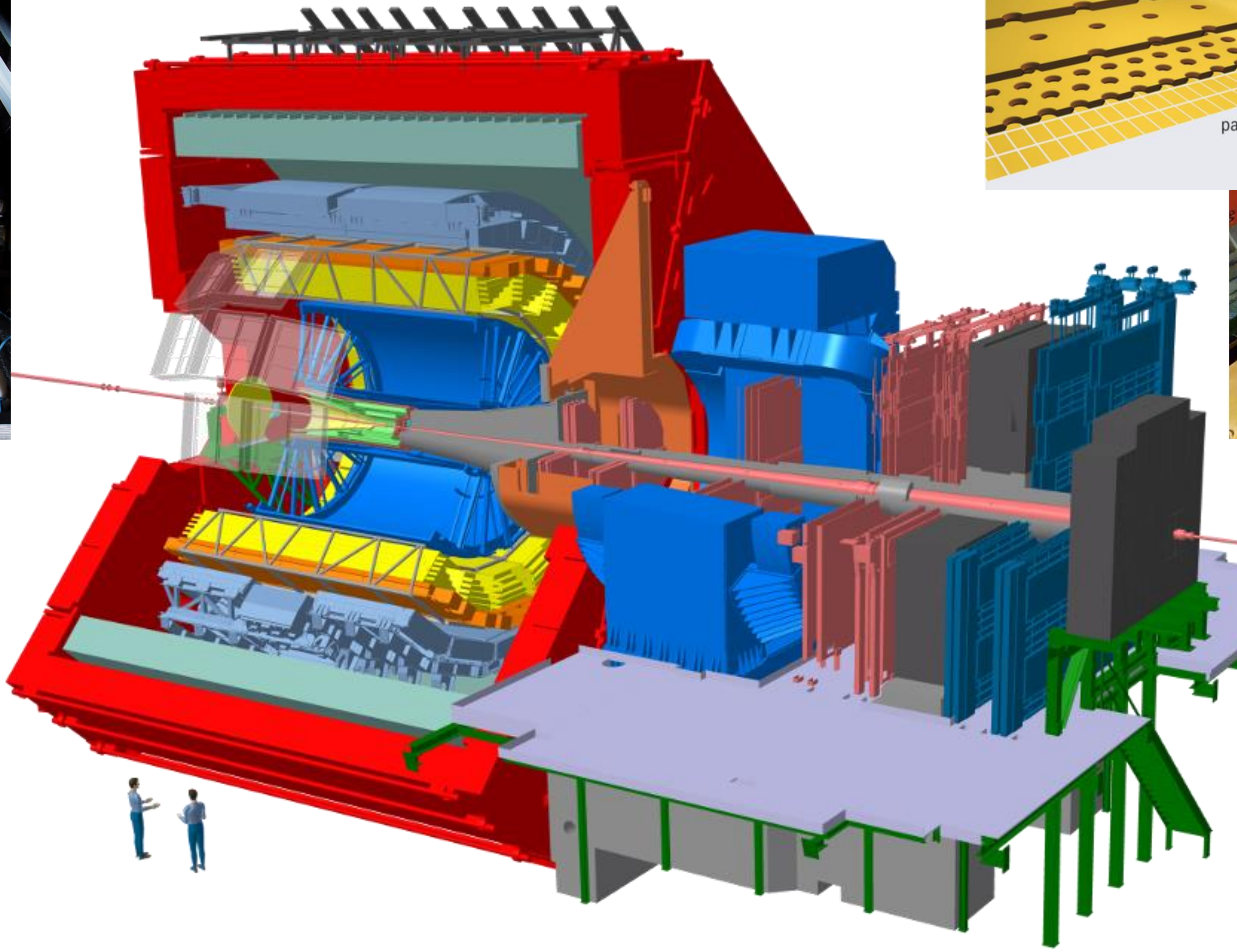
New ITS and MFT

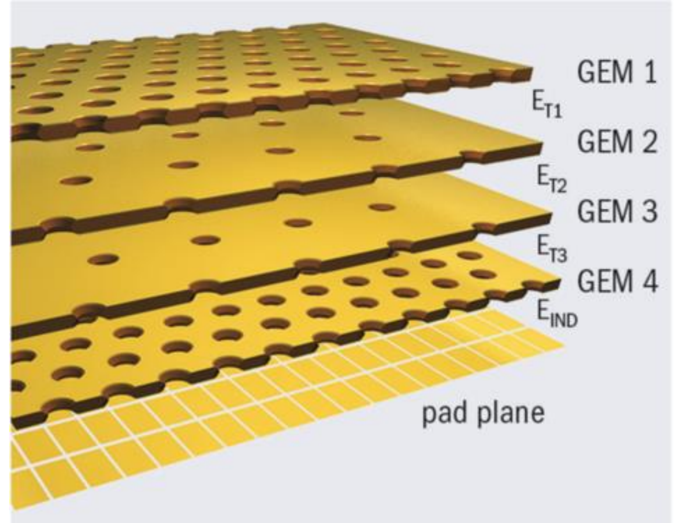


Full pixel detector
Improved spatial resolution

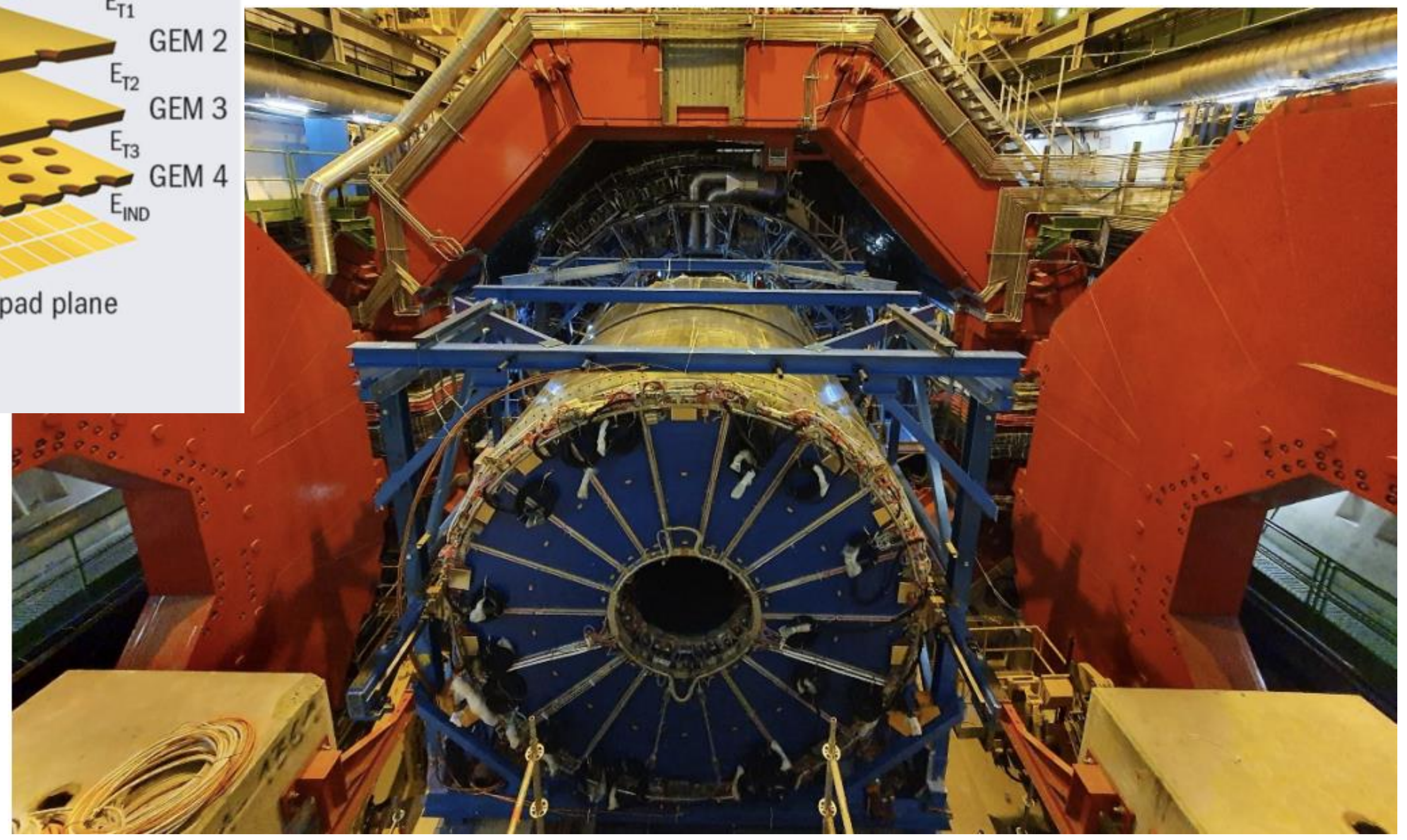
Fast Interaction Trigger







TPC: GEM readout



Continuous readout

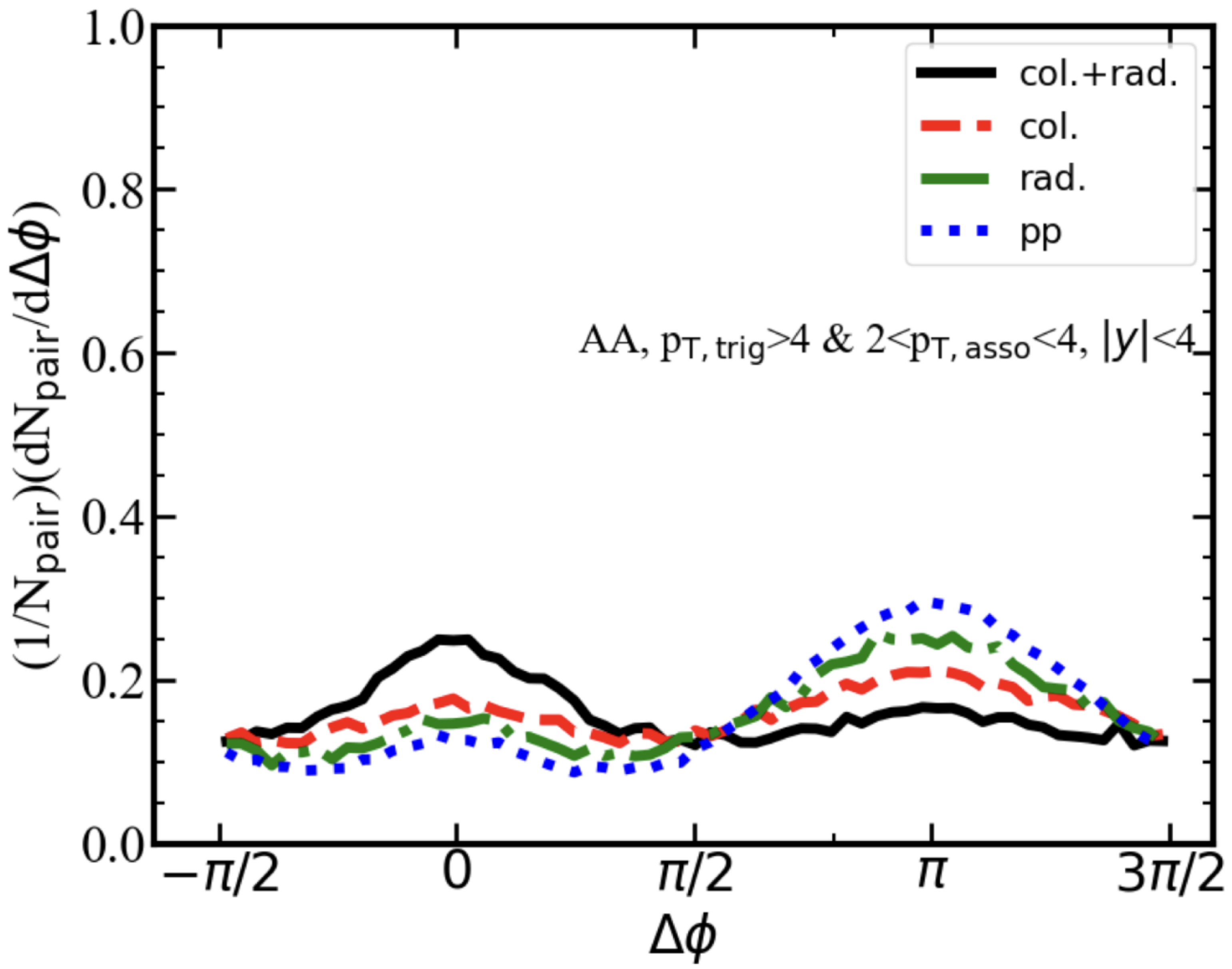
Online event processing

ALICE LS2 upgrade paper: arXiv:2302.01238

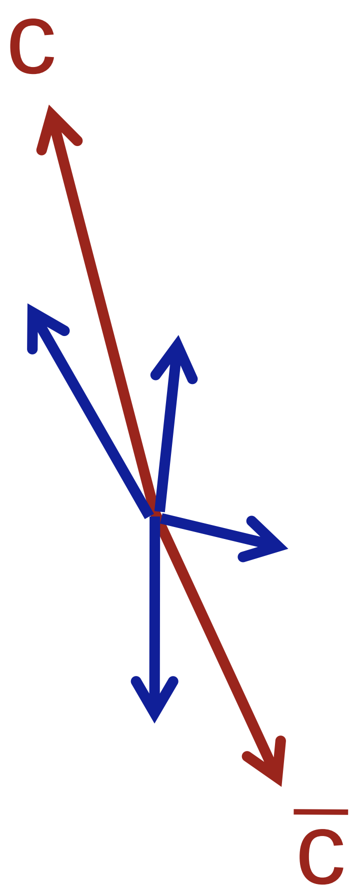
ALICE upgrade for Run 3, 4: improve pointing resolution, readout rate (50 kHz for HI events)

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

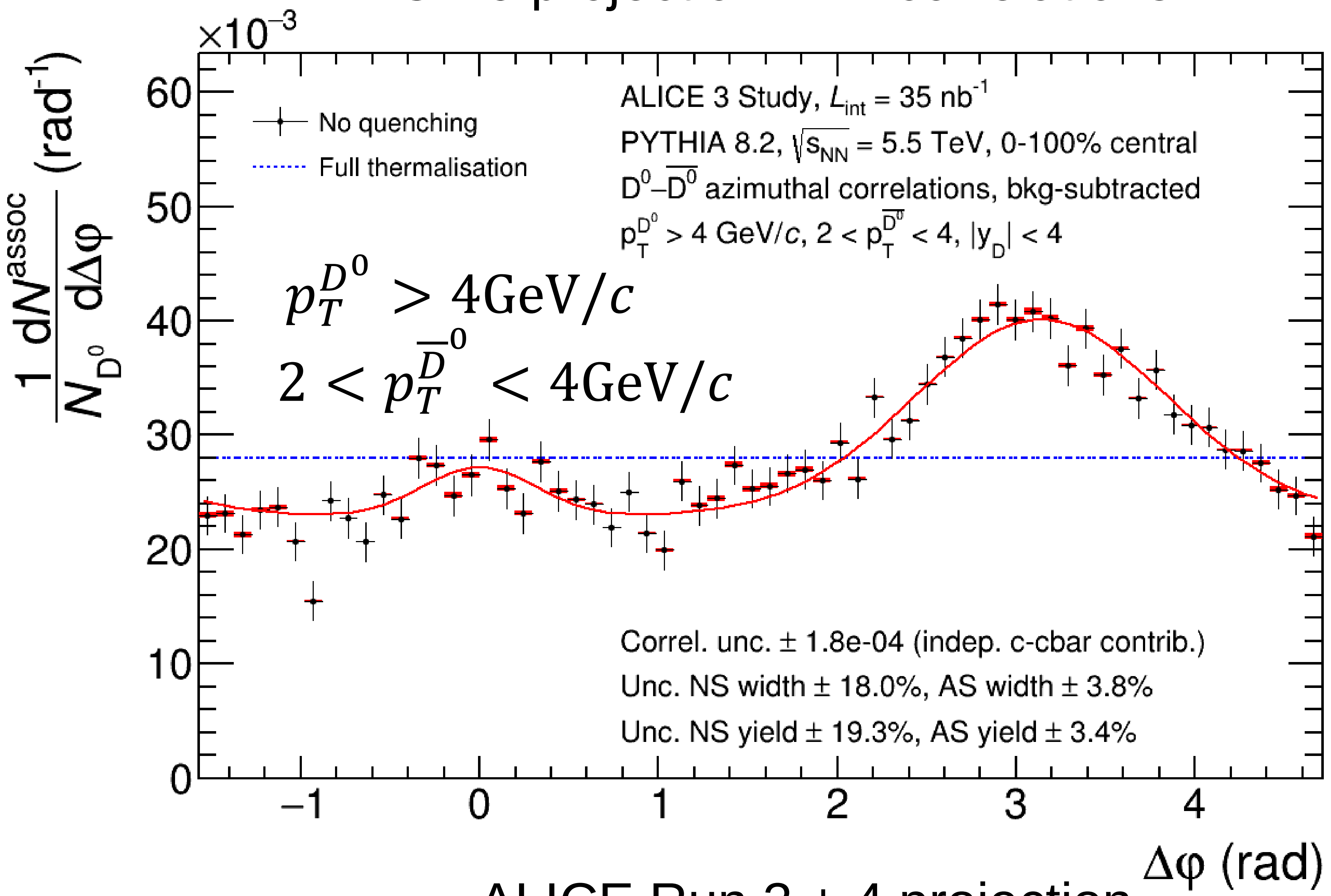
Charm azimuthal correlations



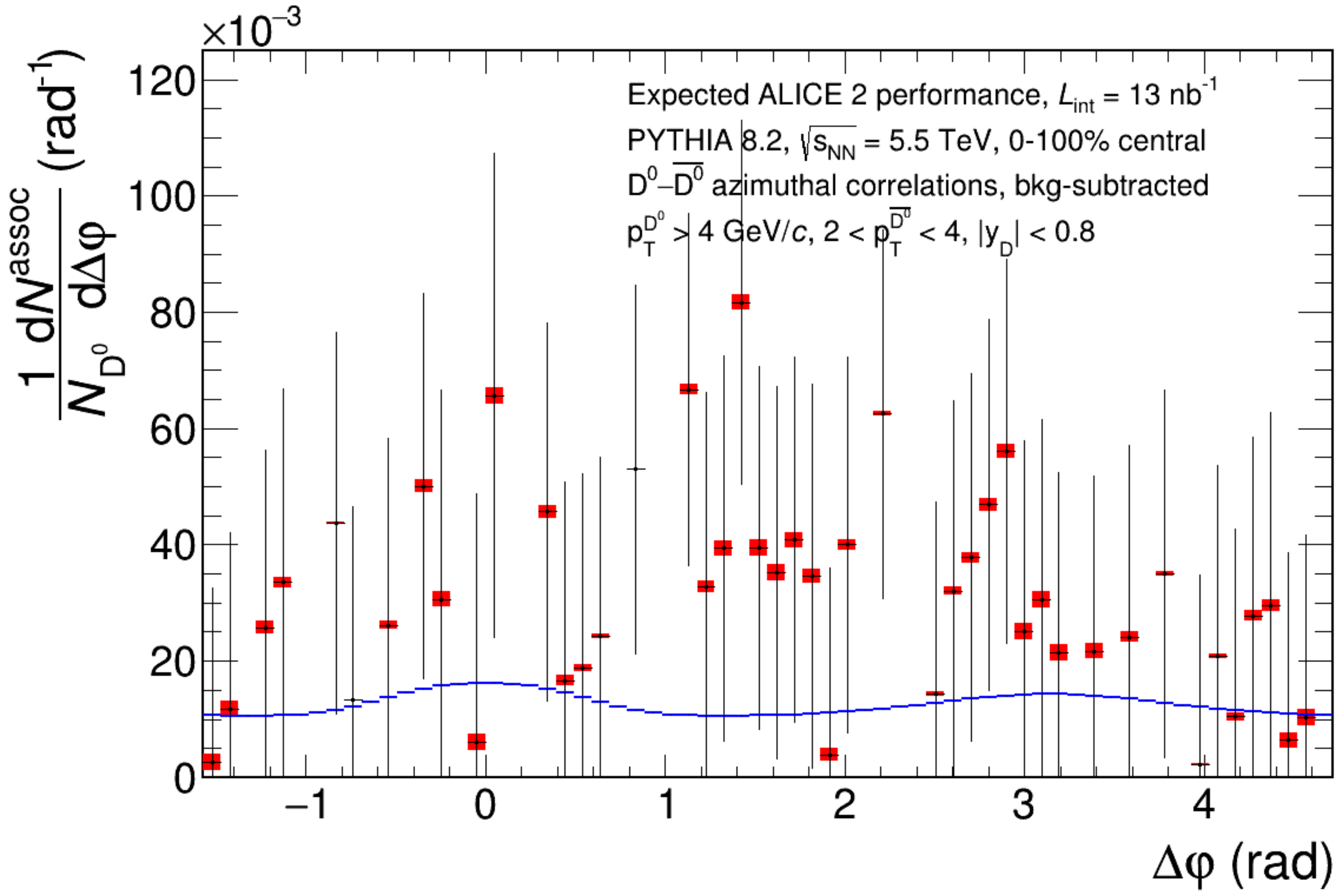
S. Cao et al., private comm., based on PLB 838 (2023) 137733



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



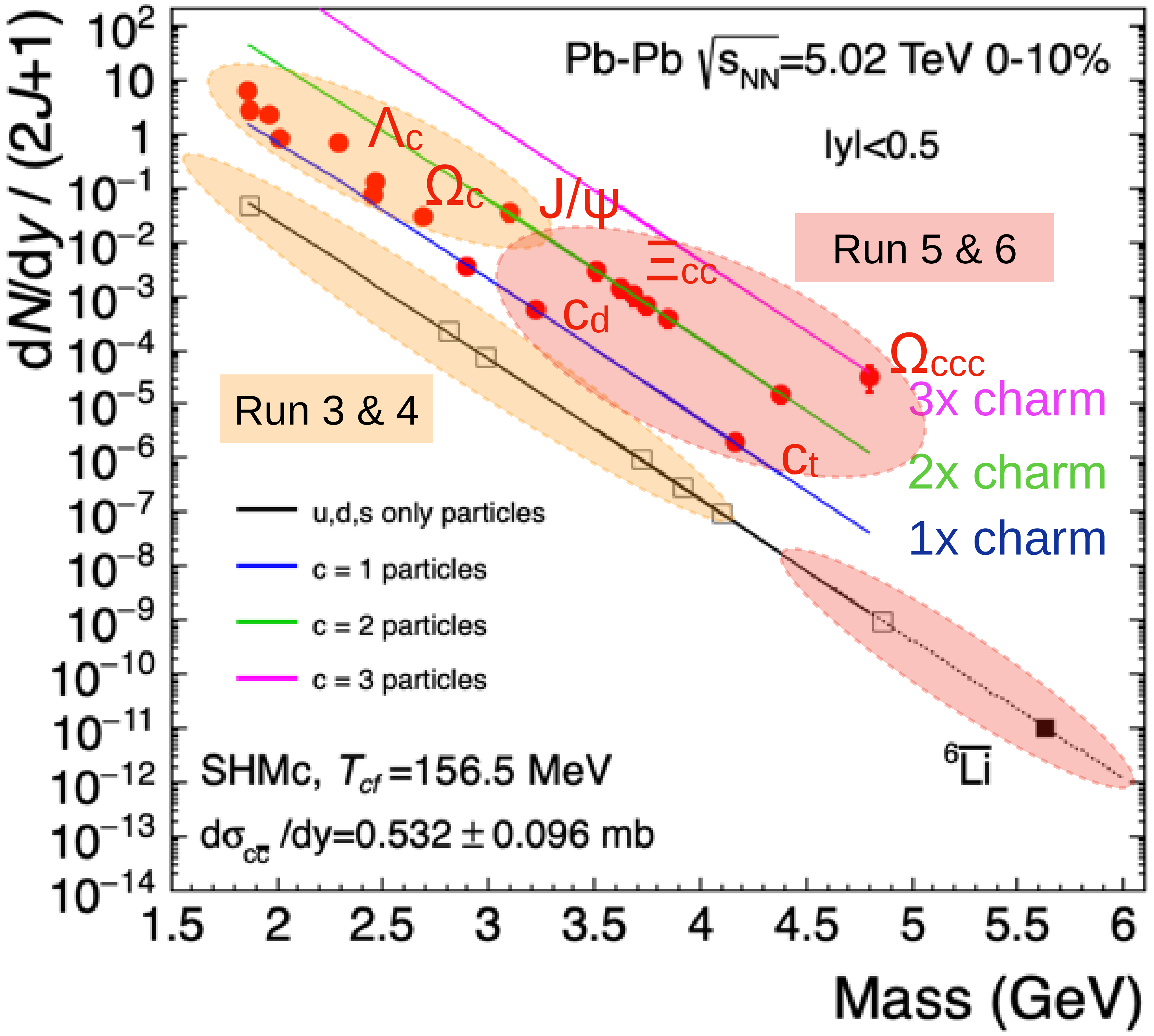
ALICE Run 3 + 4 projection



- Angular decorrelation **directly probes QGP scattering**
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → **heavy-ion measurement only possible with ALICE 3**

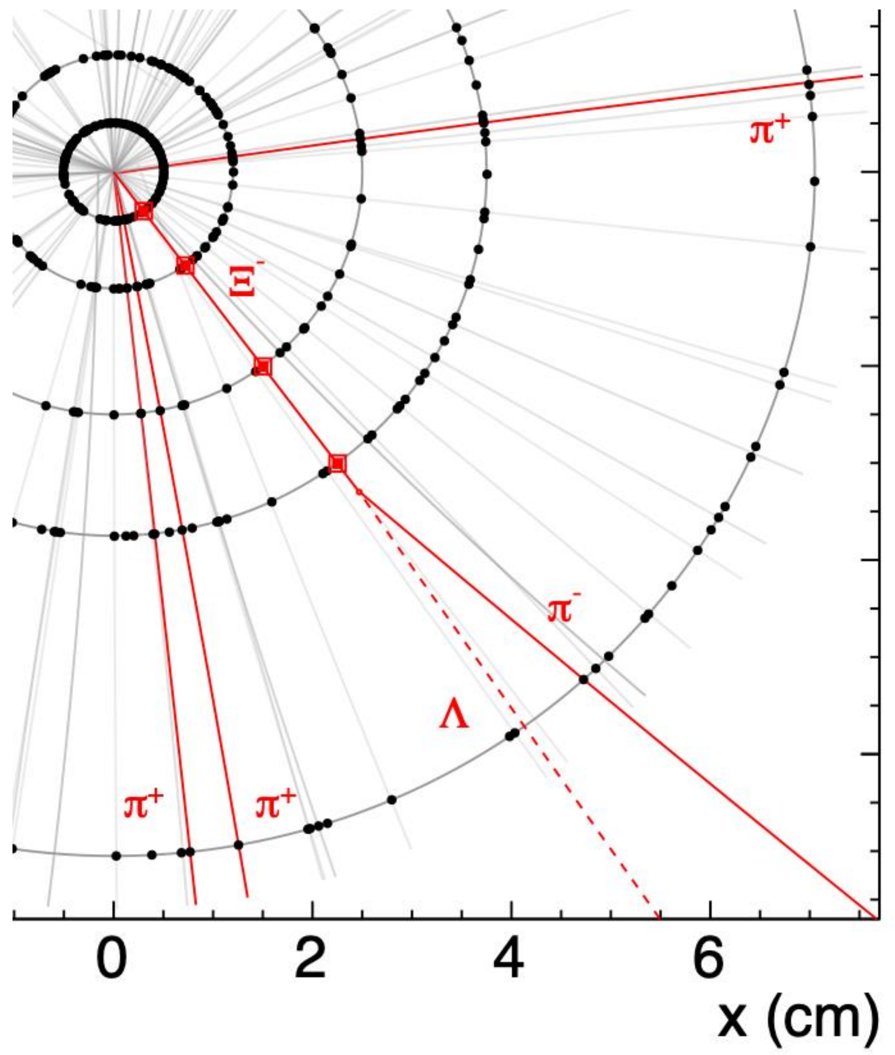
Hadron formation: multi-HF hadrons

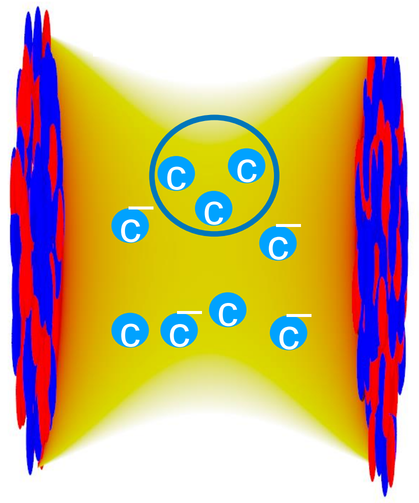
Yield vs mass



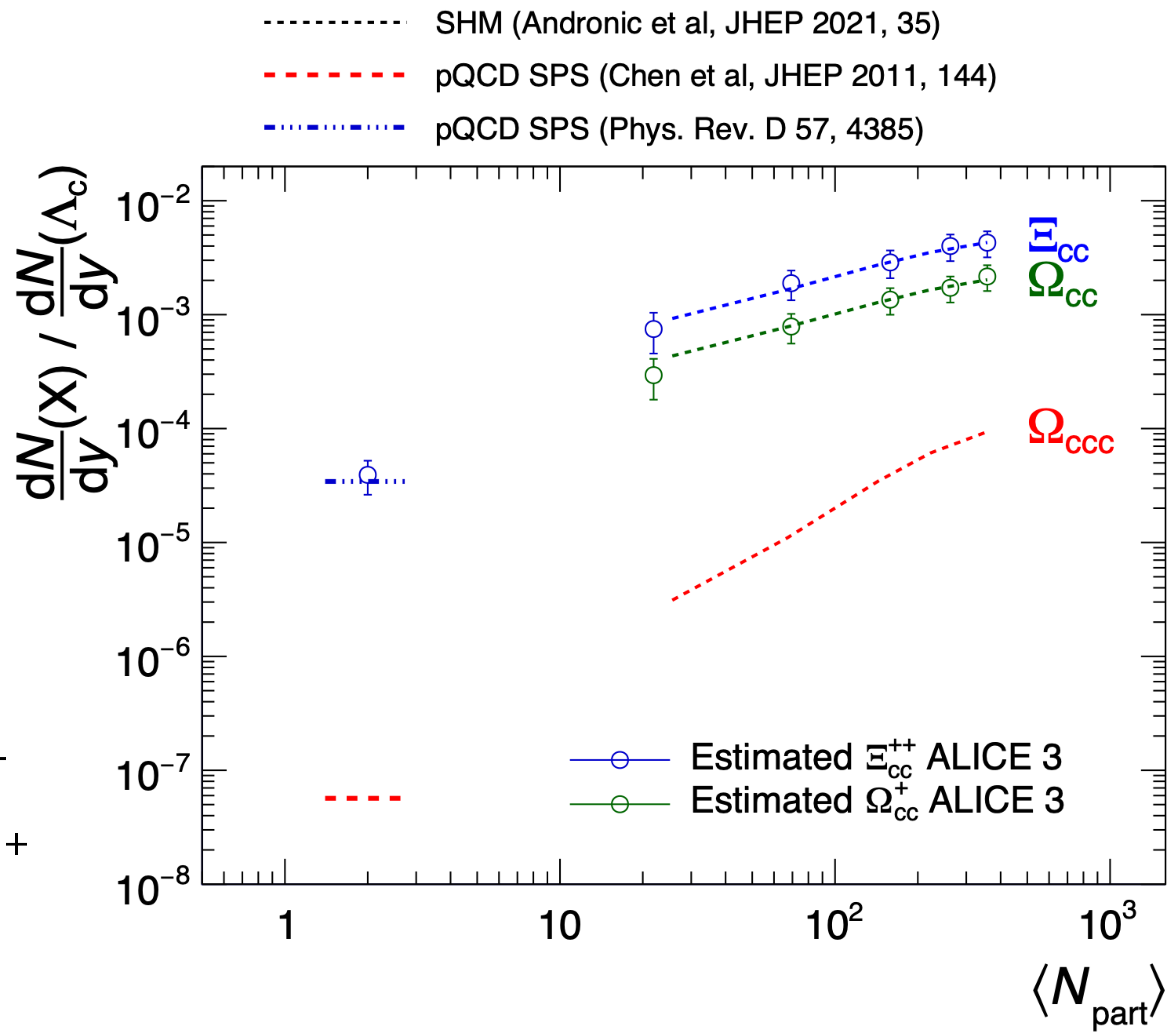
A Andronic et al, JHEP 07 (2021) 035

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

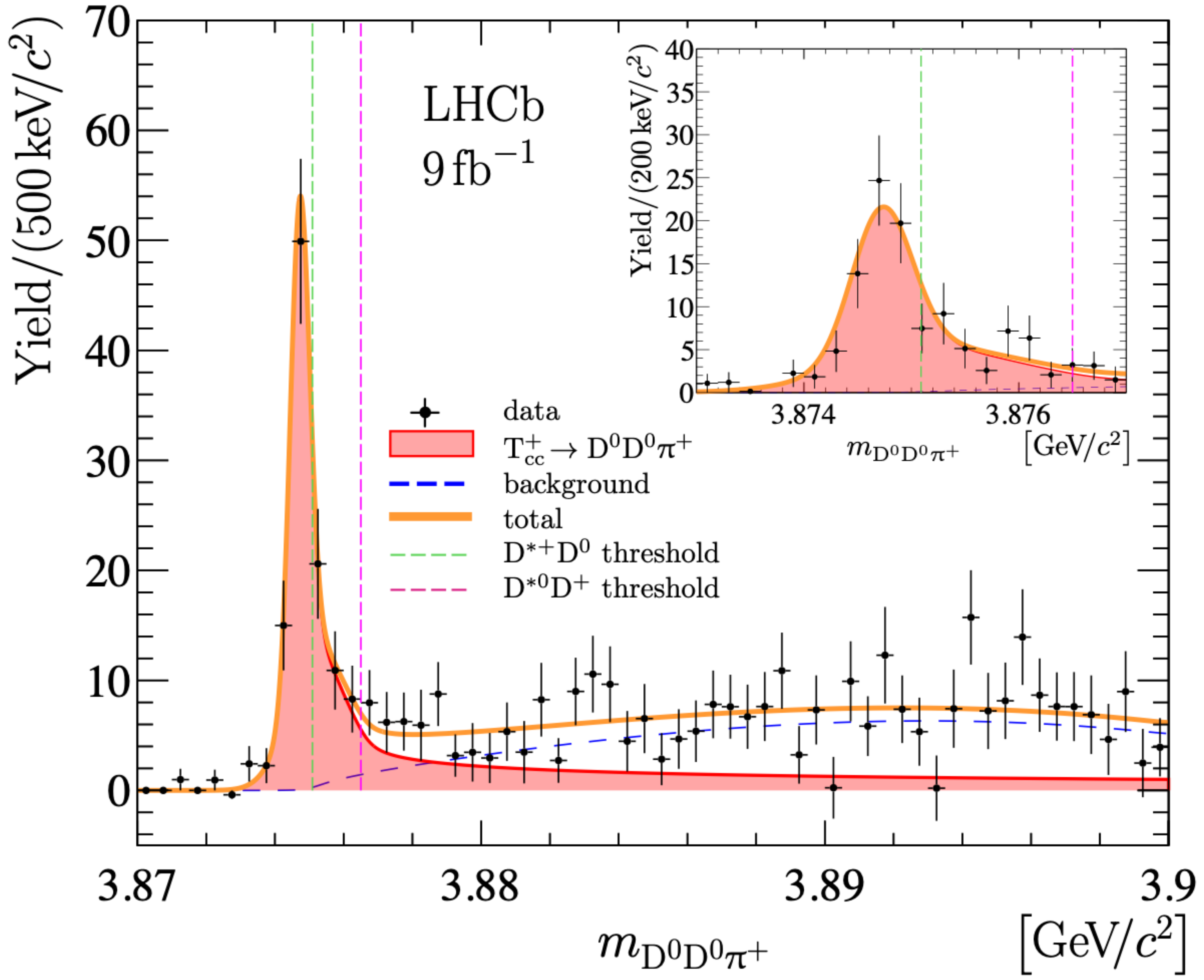
- Specific relation between yields: g_c^n for *n*-charm states

ALICE 3: unique experimental access to multi-charm baryons

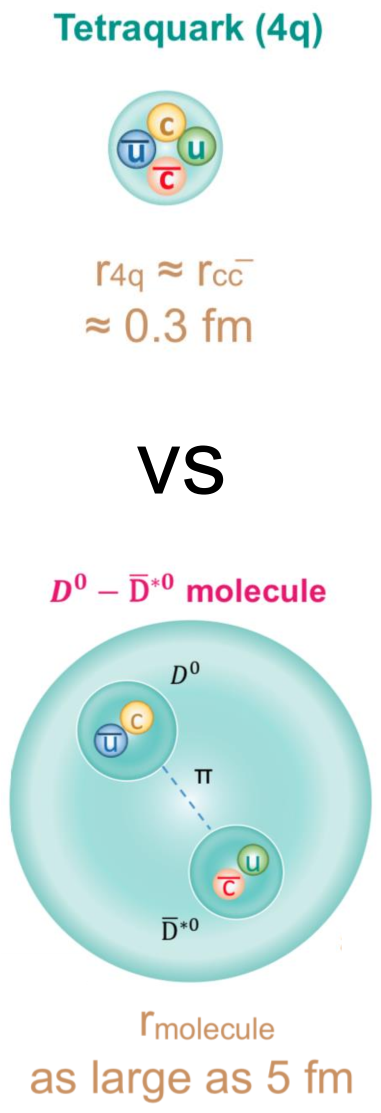
See also presentation by Antonin Maire

Heavy-ion collisions as a laboratory for hadron physics

T_{cc}^{+} discovery

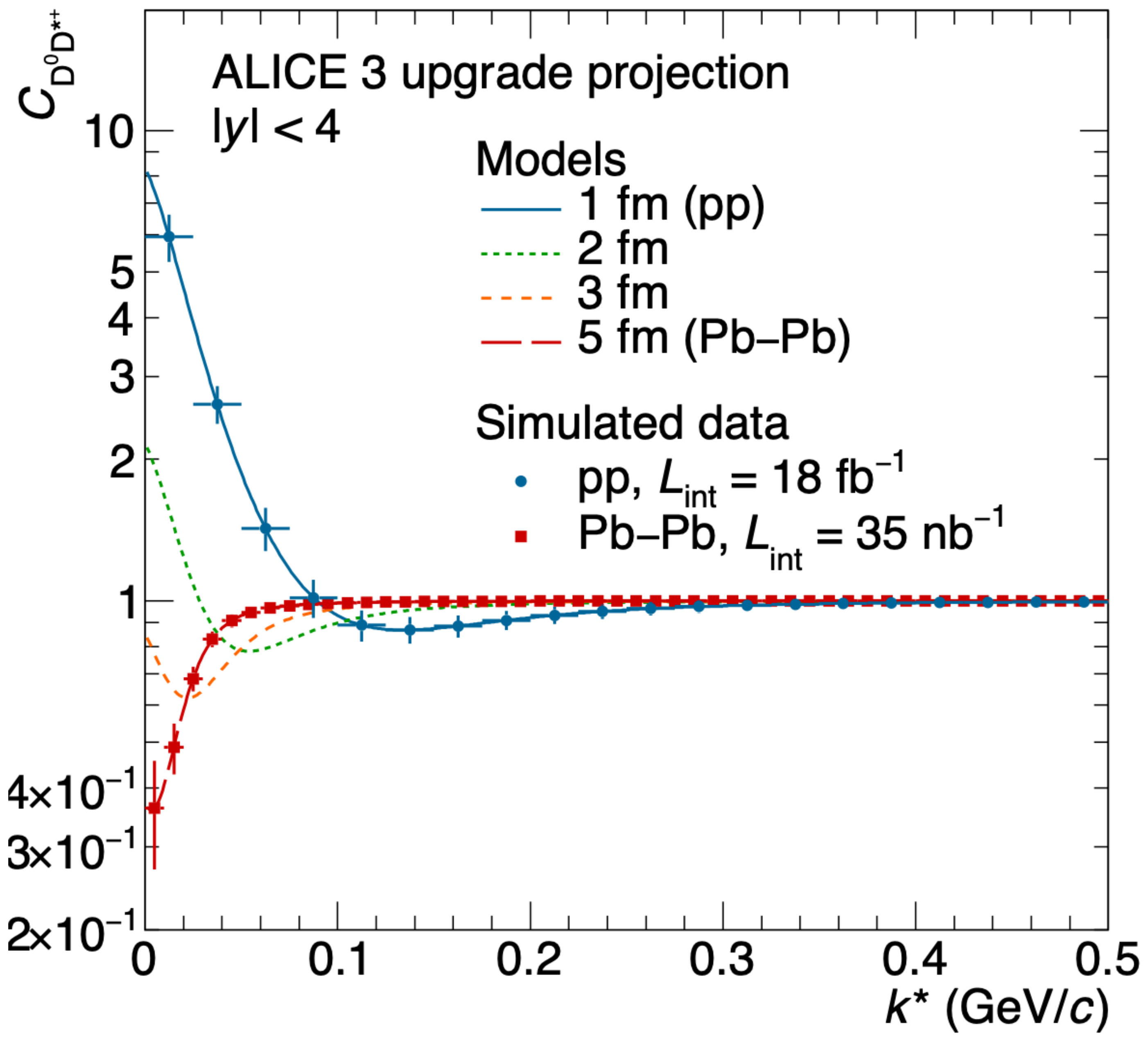


LHCb, Nat Phys 18 (2022) 7, 751

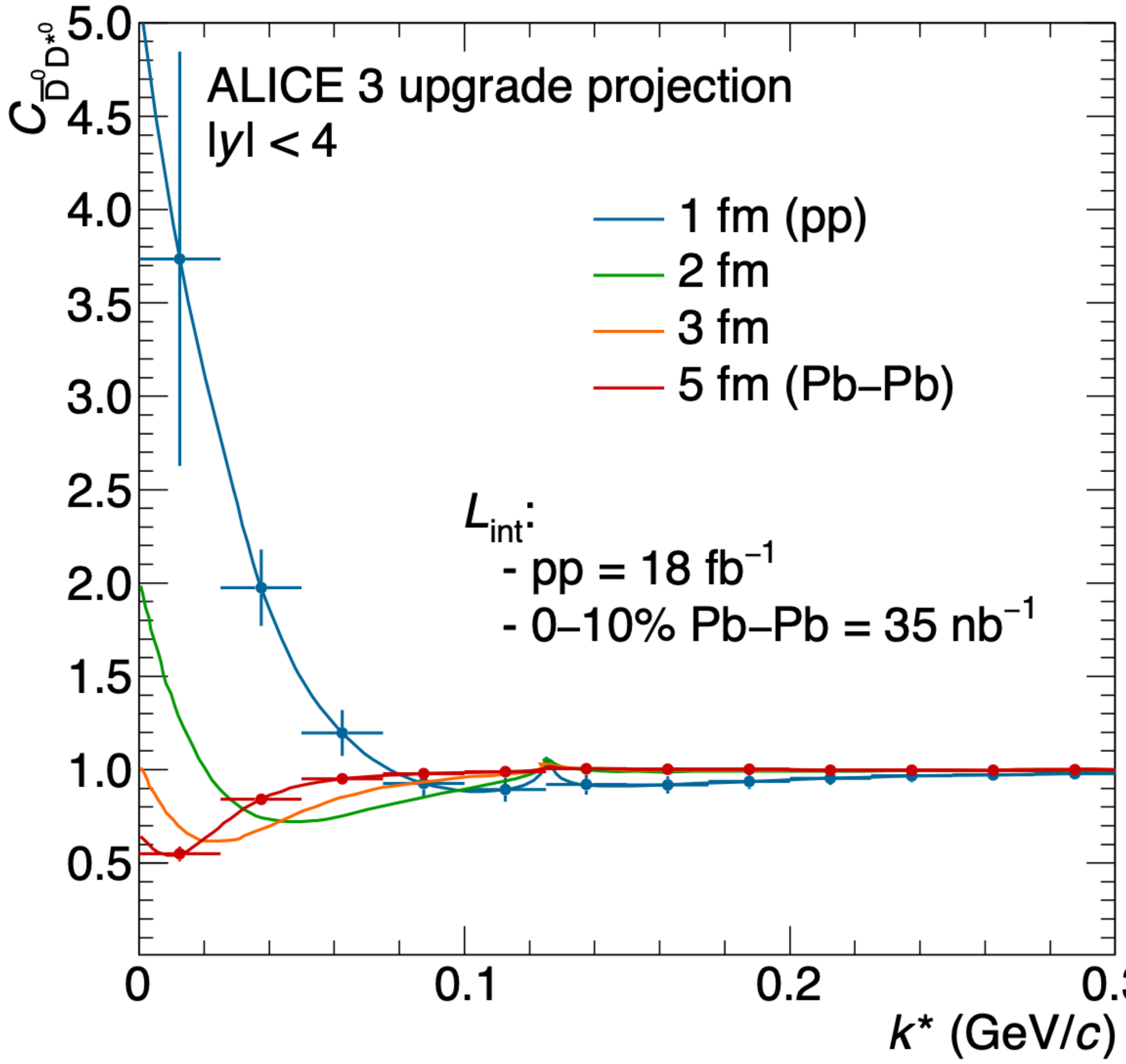


DD* momentum correlation

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