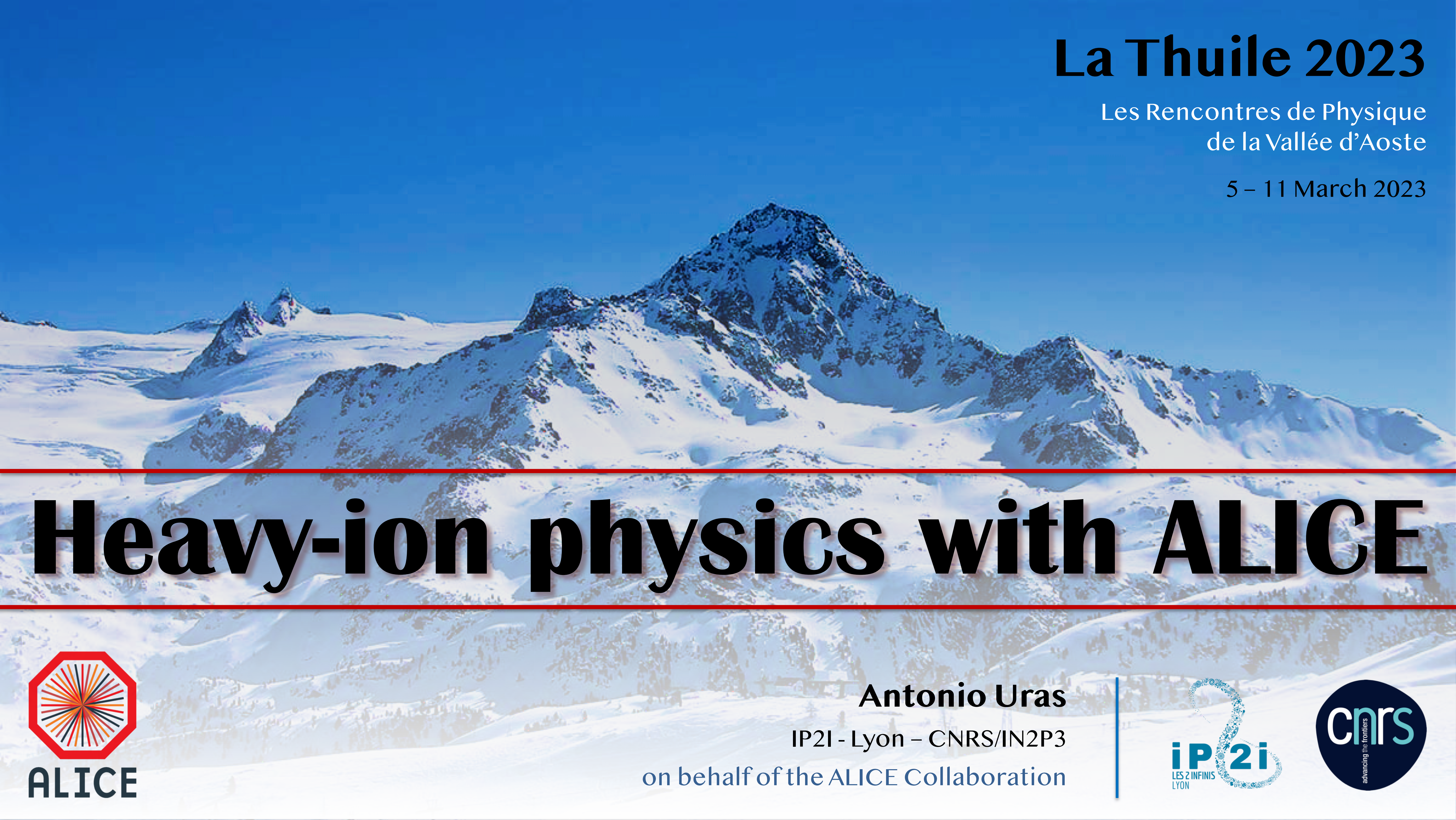


La Thuile 2023

Les Rencontres de Physique
de la Vallée d'Aoste

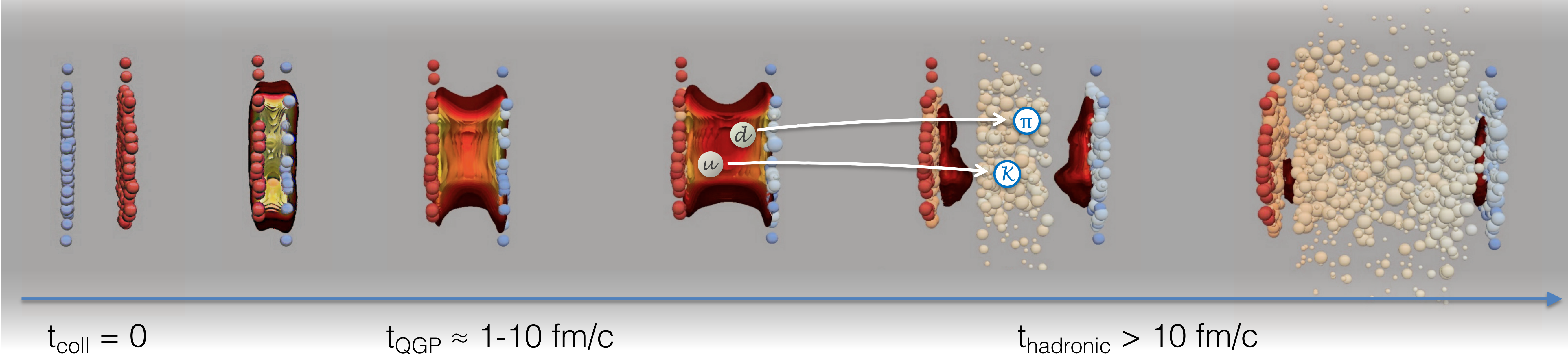
5 – 11 March 2023

Heavy-ion physics with ALICE

Antonio Uras
IP2I - Lyon – CNRS/IN2P3
on behalf of the ALICE Collaboration

ALICE physics program: current and future challenges

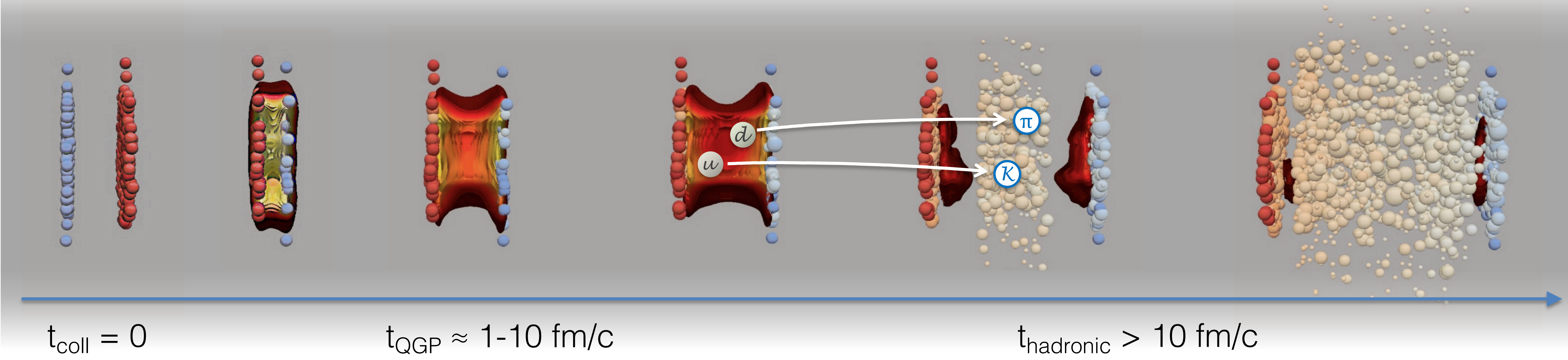
- **How is the equilibrium phase reached?**
- **What are the properties of the deconfined phase?** Viscosity, electromagnetic emission, diffusion coefficients for heavy quarks? Can they be estimated by the available theoretical models?
- **How do hadrons emerge from the deconfined phase?**
- **Is QGP produced in collisions involving a small number of nucleons?**



ALICE physics program: current and future challenges

- **Two main physics items driving the ALICE experimental approach:**
  - **Transport and hadronization of heavy flavors in the medium:** differential measurements of HF hadron production (suppression, enhancement, flow…) down to vanishing p_T
  - **Electromagnetic radiation from the medium:** dilepton measurements below J/ψ mass, down to zero p_T, to map the evolution of the collision

Light and high-granularity detector + continuous readout to access untriggerable probes with high S/B

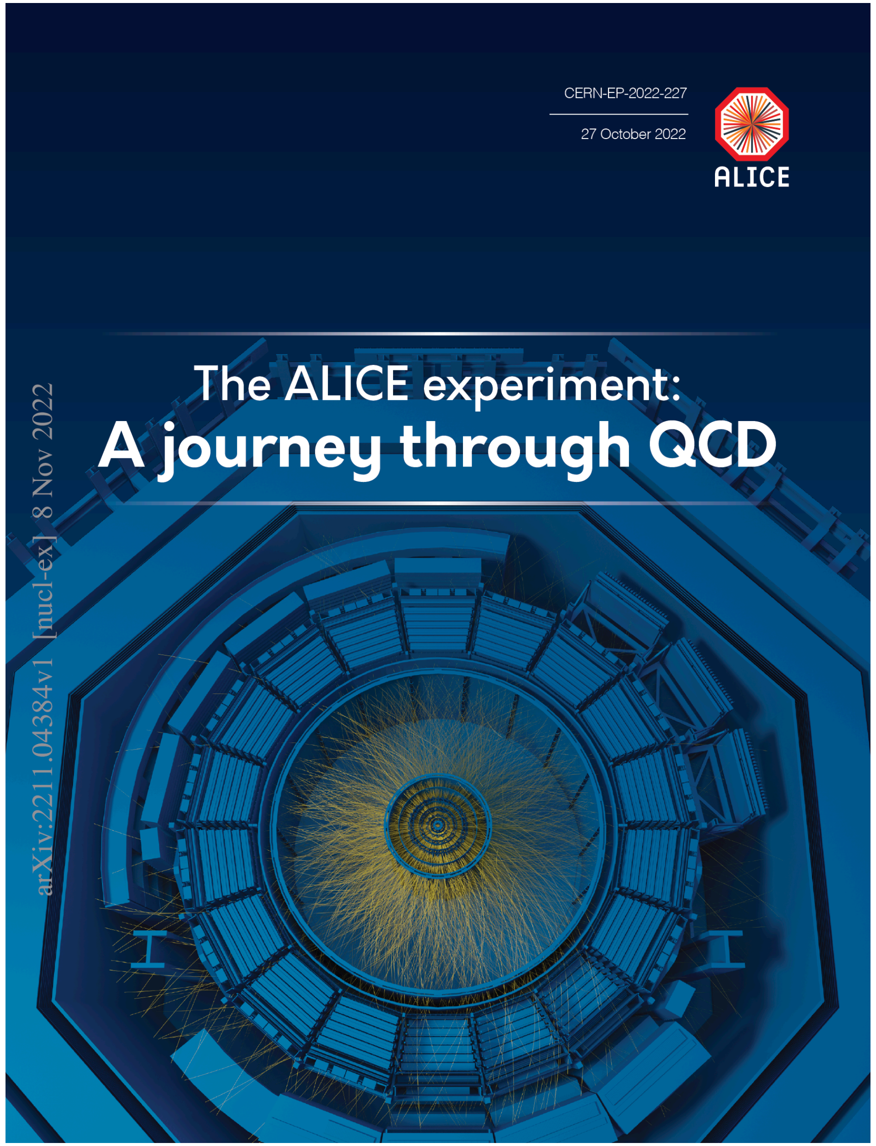


ALICE: a journey through QCD

ALICE review of Run 1-2 studies:

- Bulk properties and thermodynamics of the QGP
- QGP dynamics and evolution
- Interactions of partons with QGP medium
- Hadronization mechanisms in the QGP medium
- Electromagnetic properties and phenomena
- Initial state
- QGP-like effects in small systems
- Many other aspects of QCD and beyond…

arXiv:2211.04384



CERN-EP-2022-227

27 October 2022

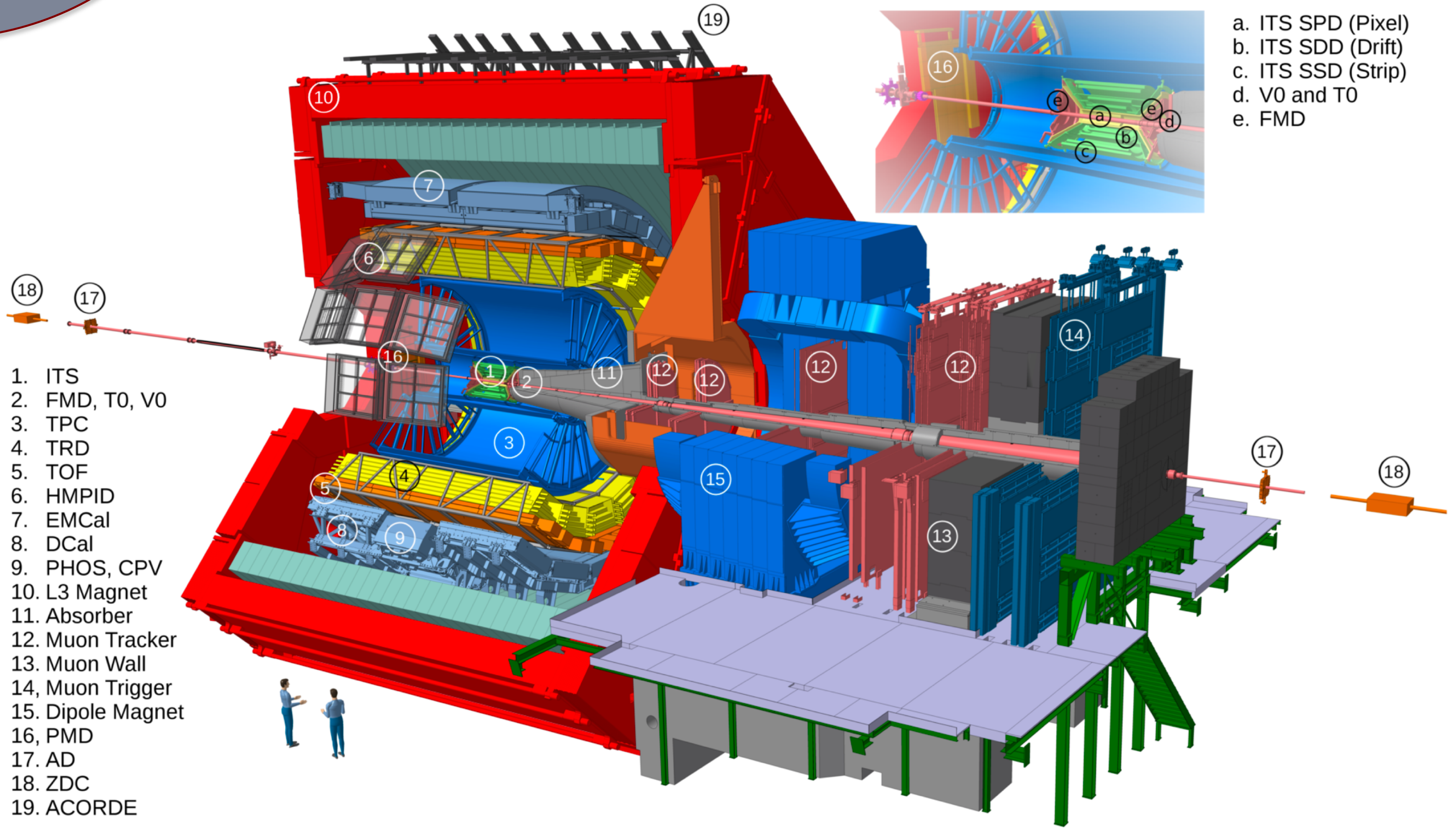
ALICE

The ALICE experiment:

A journey through QCD

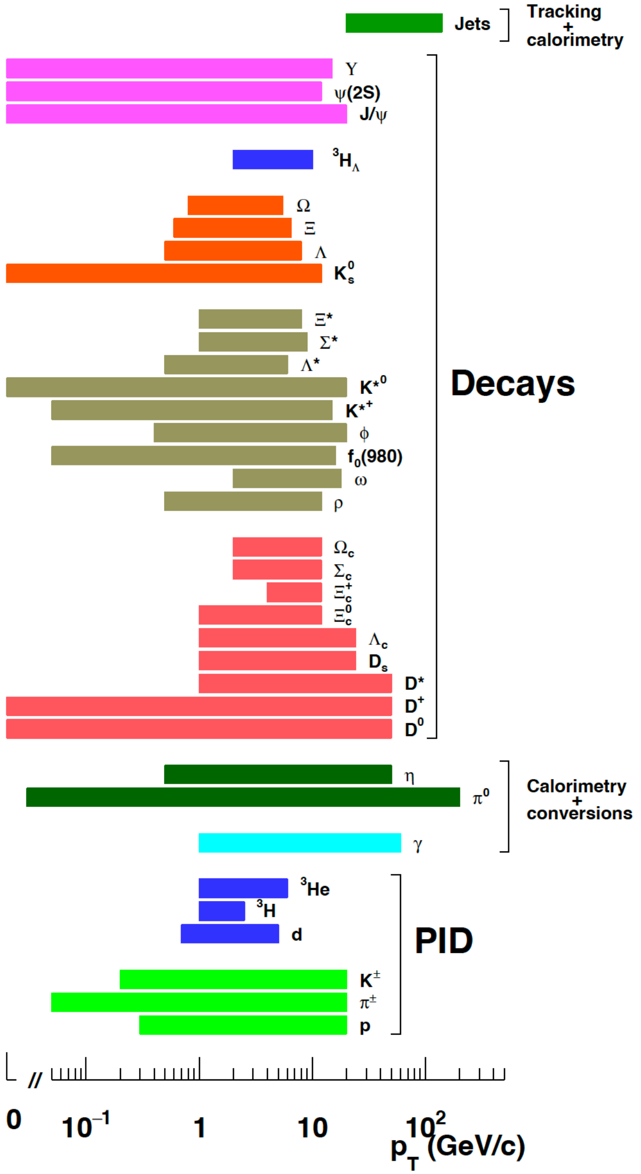
arXiv:2211.04384v1 [nucl-ex] 8 Nov 2022

The ALICE detector in Run1+2



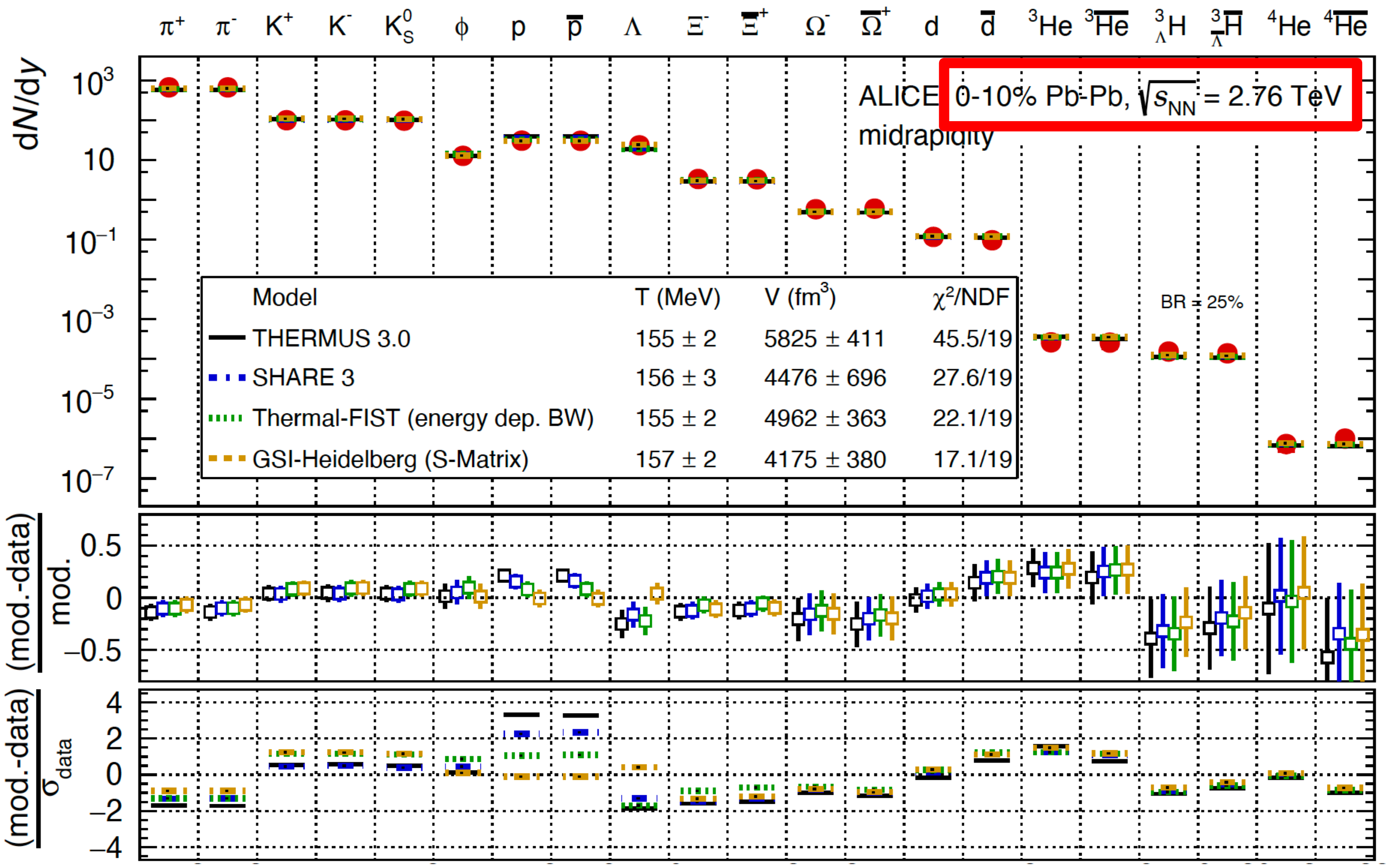
a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE



Light flavor production: chemical freeze-out

- **Hadron yields described by statistical hadronisation models over many orders of magnitude**



- **Chemical equilibrium** close to QGP transition temperature:

$T_{chem} \approx T_c \approx 156$ MeV

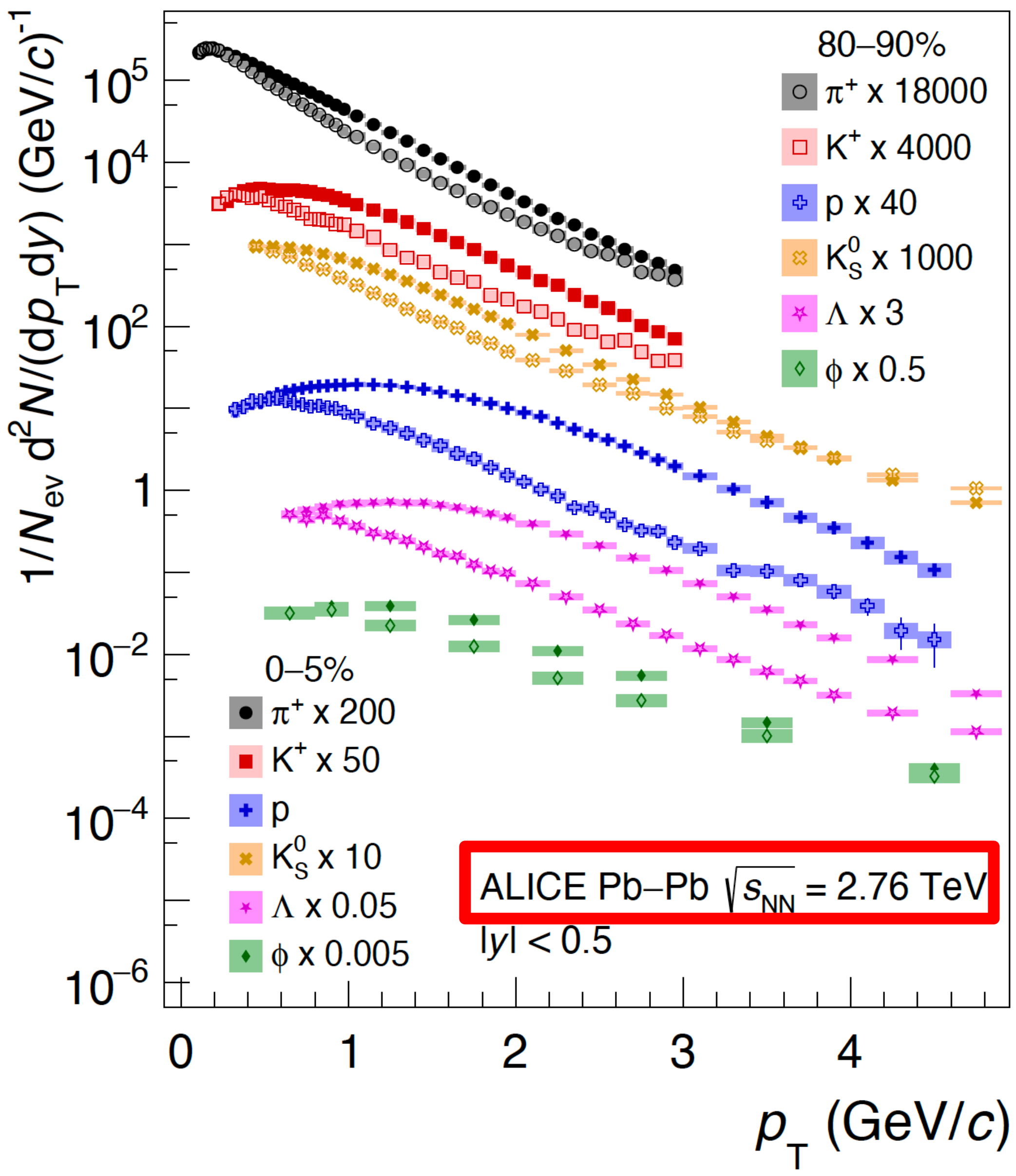
Chemical freeze-out happens near the hadronisation of the QGP itself

- **Volume of the fireball** for one unit of rapidity at the chemical freeze-out: ≈ **4500 fm^3**

arXiv:2211.04384

Light flavor production: kinetic freeze-out

arXiv:2211.04384

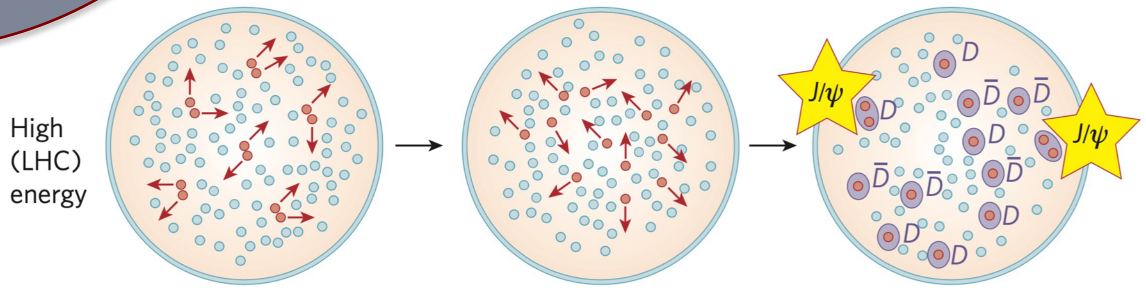


- Motion of final-state hadrons reflects the **hydrodynamic expansion of QGP** and the late, dissipative rescattering phase lasting until the kinetic freeze-out

- **Radial flow leads to flatter p_T distributions.** Mass-dependent effect: the additional p_T acquired by hadrons is given by their mass multiplied by the common radial flow velocity

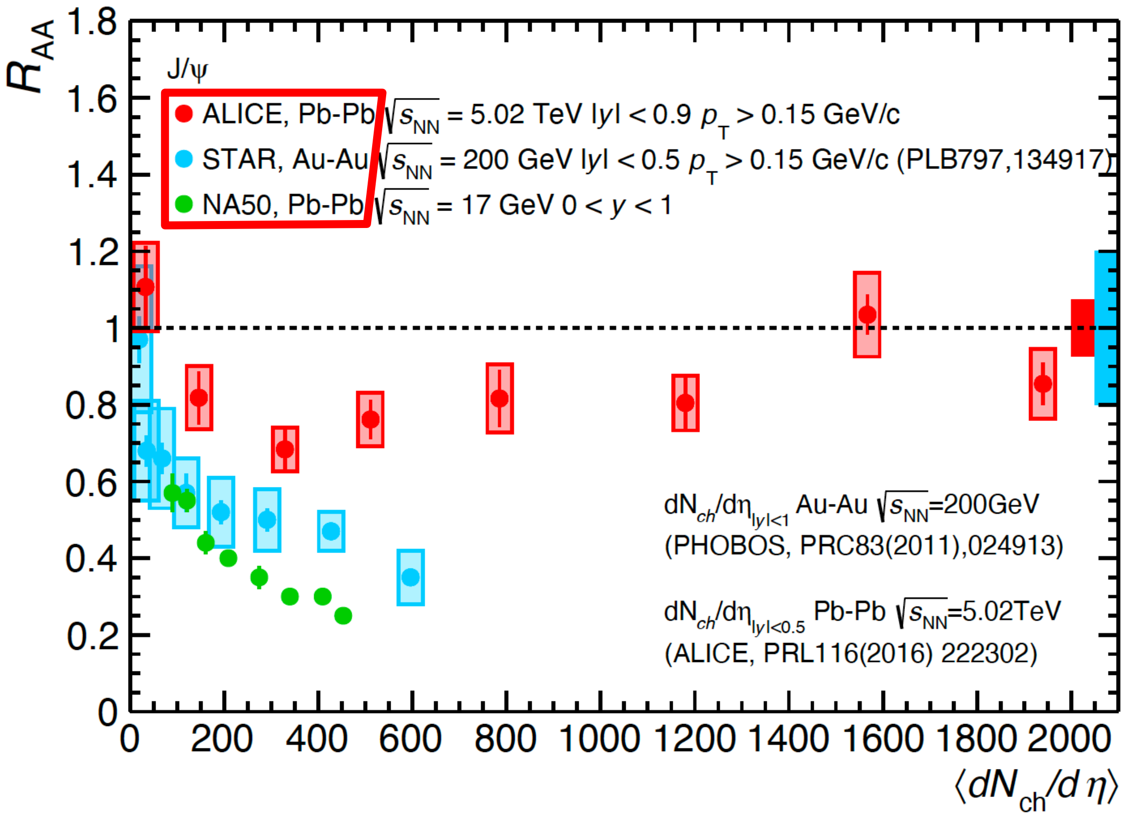
- The spectral shapes depend on centrality with the maxima shifted to higher p_T for more central collisions

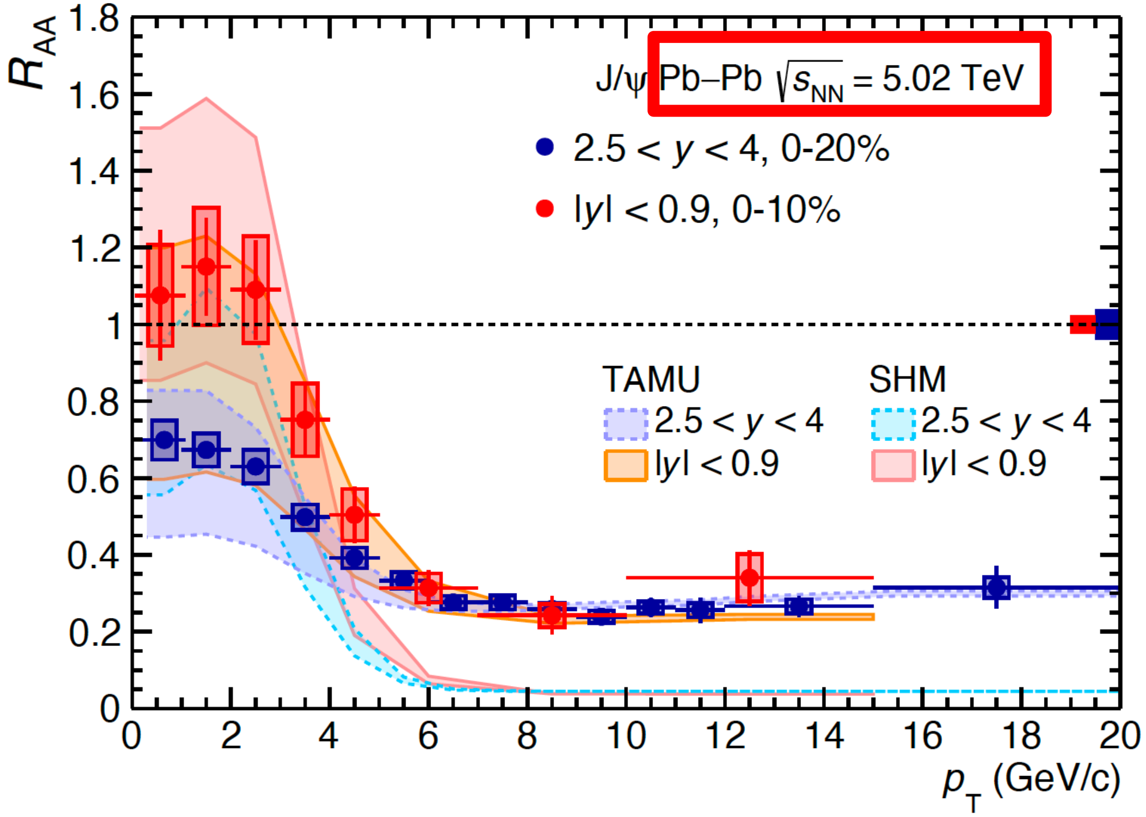
Quarkonium: dissociation and regeneration



- ❖ Interplay of melting and regeneration effects
- ❖ **Large regeneration effects at the LHC** due to much larger charm cross section w.r.t. to RHIC/SPS (lower energies)
- ❖ Larger regeneration effects at midrapidity and at low p_T

arXiv:2211.04384



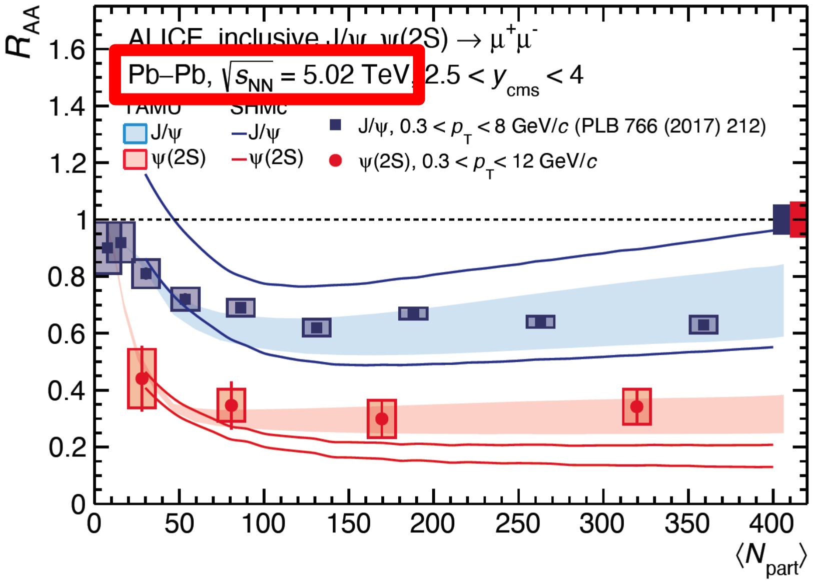


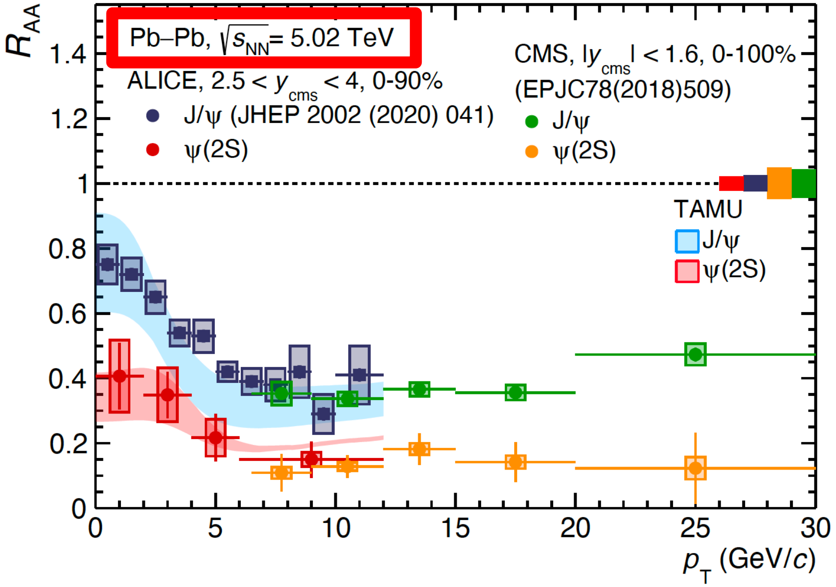
Quarkonium: dissociation and regeneration

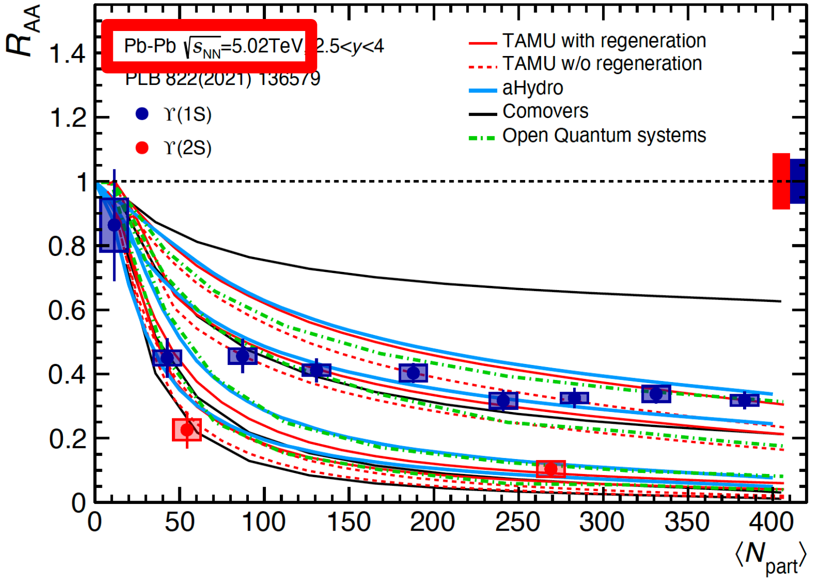
arXiv:2211.04384

- **Different states have different binding energies.** Loosely bound states melt first
- **Charmonium:** sequential suppression + regeneration effects especially at low p_T
- **Bottomonium:** sequential suppression only, even at the LHC energies

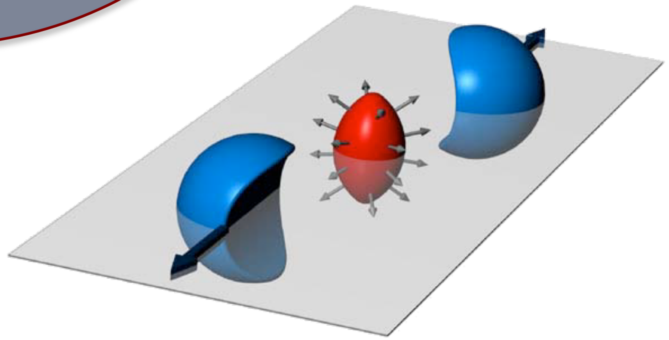
State	Binding energy (GeV)
ψ(2S)	≈ 0.05
ϒ(2S)	≈ 0.55
J/ψ	≈ 0.65
ϒ(1S)	≈ 1.10

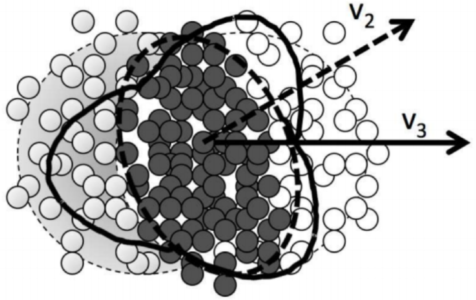


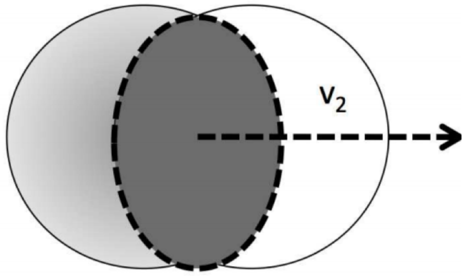




(Anisotropically) flowing with QGP



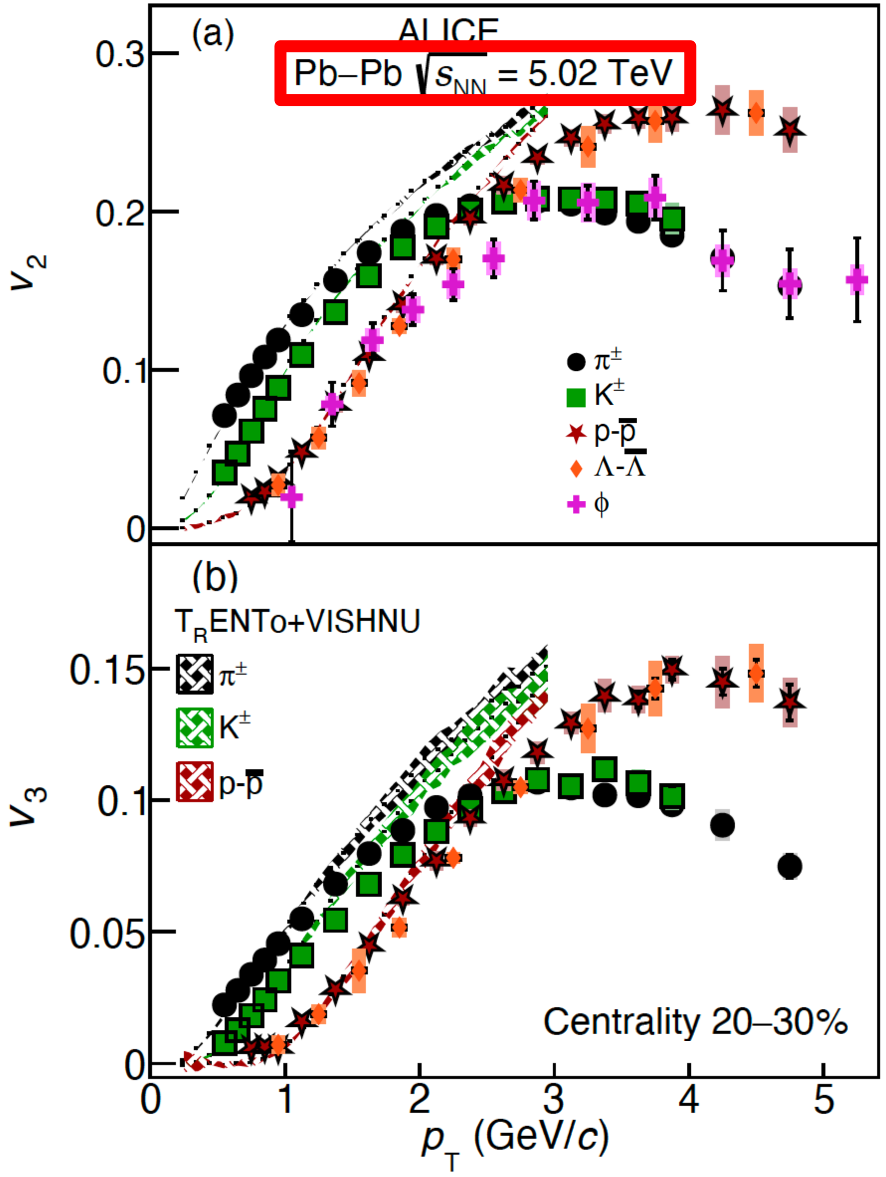




$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

- **Spatial anisotropy and density fluctuations** of the initial state induce momentum anisotropy **via QGP response**, characterized by anisotropic flow coefficients v_n
- A characteristic **mass ordering** develops due to an interplay between radial flow and the anisotropic expansion of the fireball, clearly visible for p_T < 2.5 GeV/c

arXiv:2211.04384

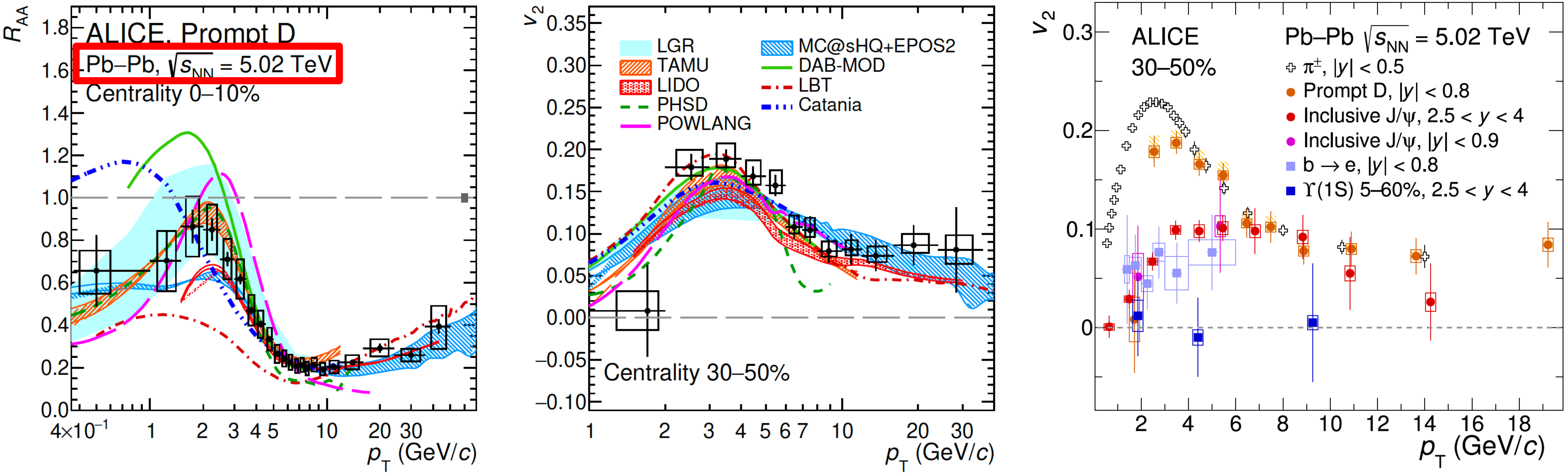


Heavy flavours: energy loss and flow

- **ALICE can access D-meson production down to zero p_T** from pp to Pb-Pb collisions: key asset to fully characterize energy loss mechanisms for charm, and its participation to the collective flow

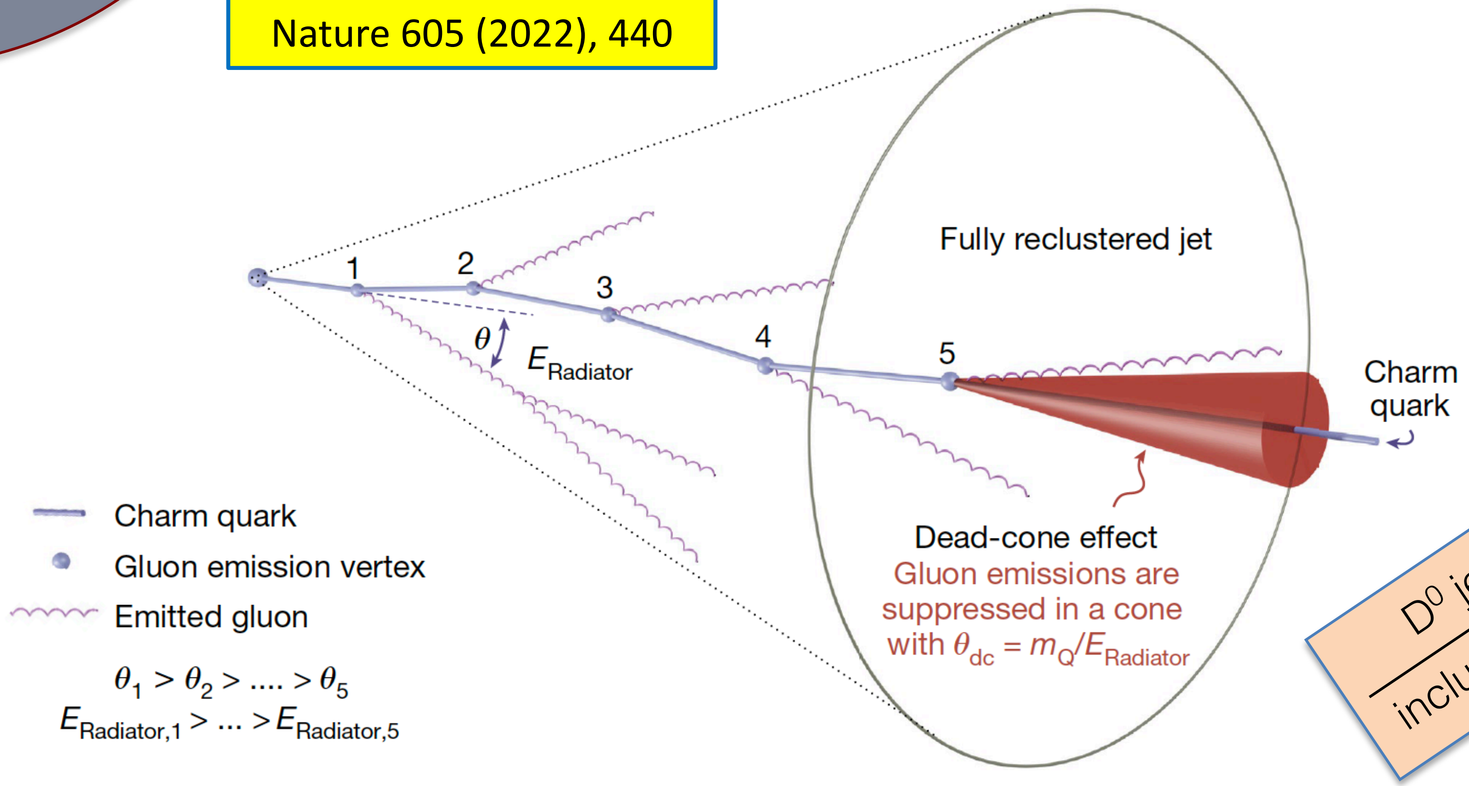
- Flow of charmonia and open charm mesons: **underlying charm-quark flow + partial thermalization** in the QGP. Smaller flow measured in the beauty sector, with hidden beauty compatible with zero flow

arXiv:2211.04384

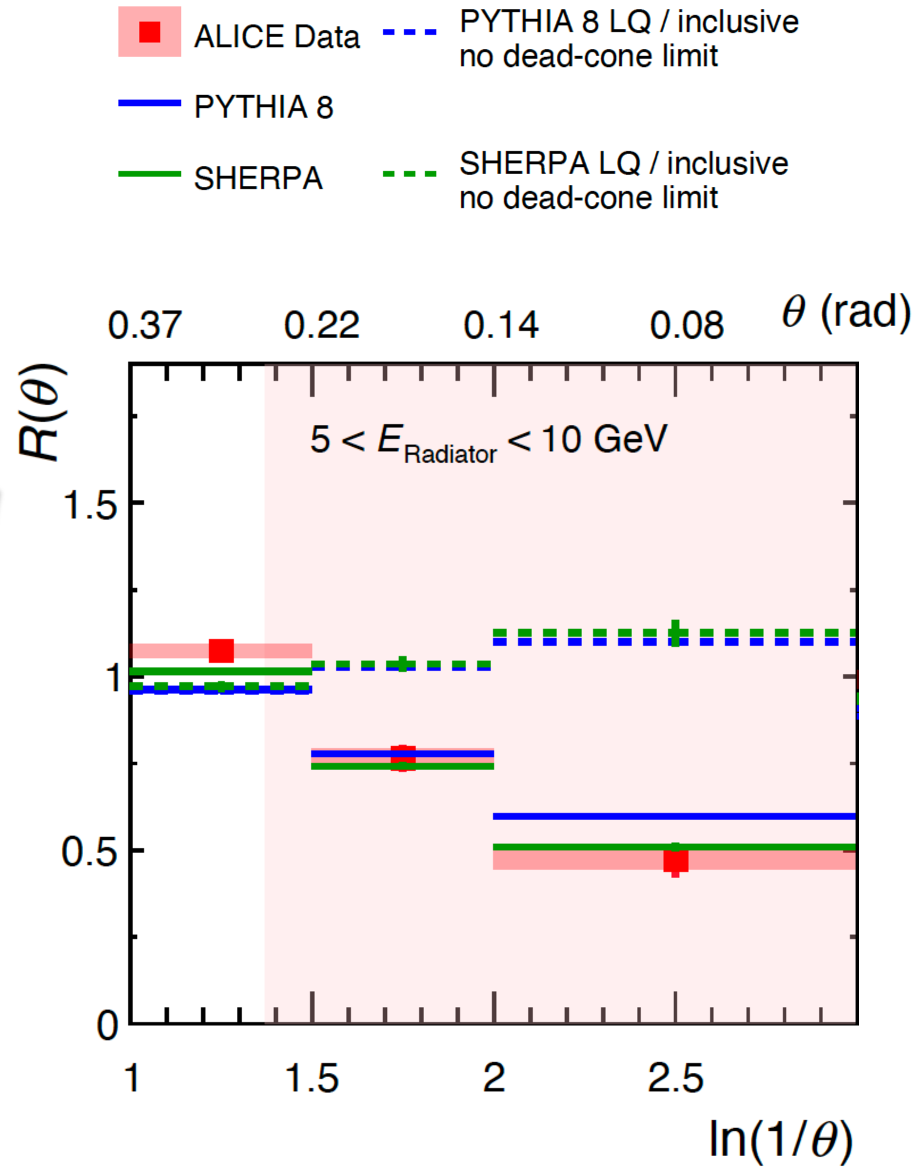


Heavy flavors: dead-cone effect

Nature 605 (2022), 440

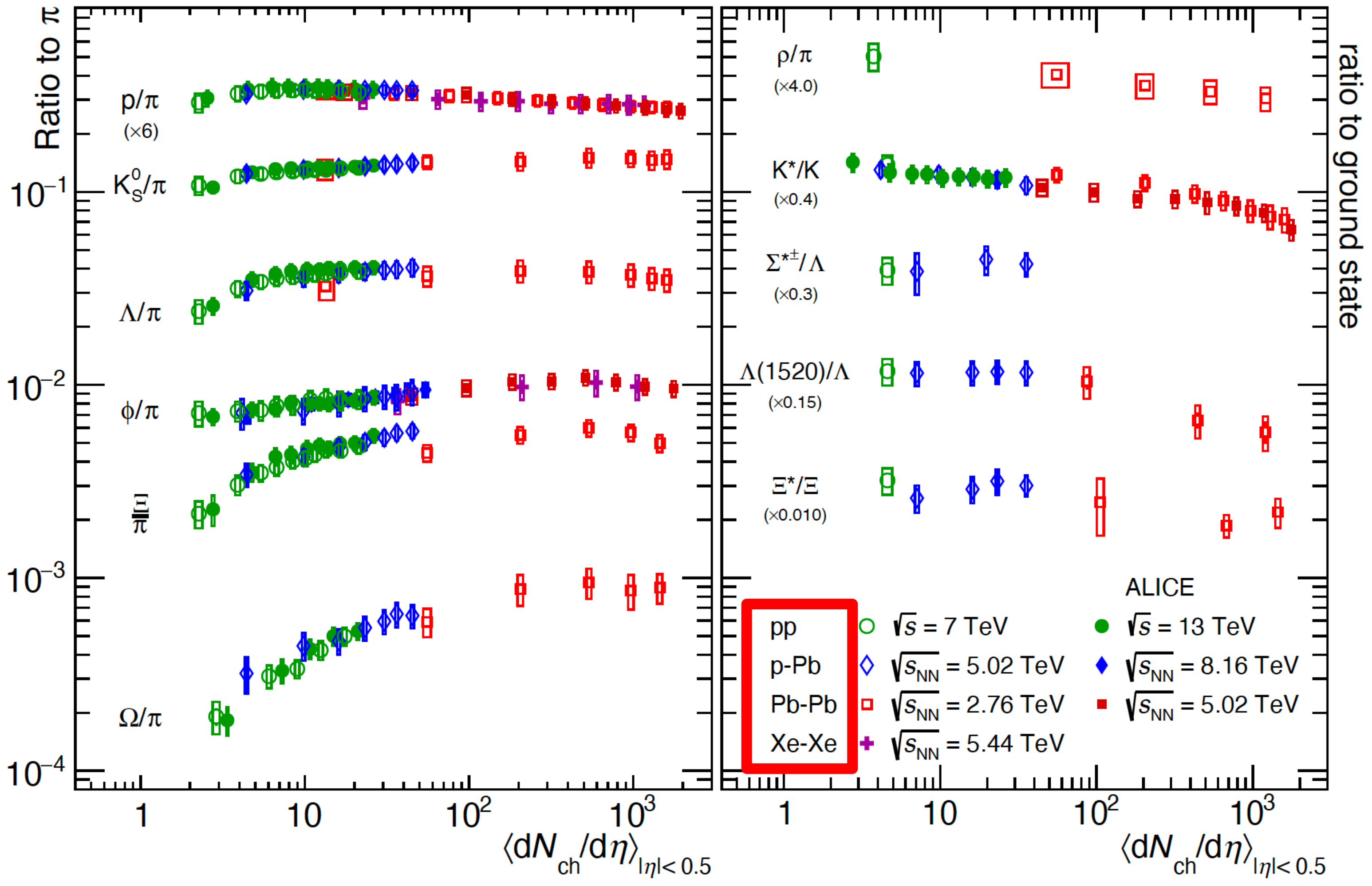


$\frac{D^0 \text{ jets}}{\text{inclusive jets}}$



- **Dead-cone effect:** gluon radiation off heavy quarks in jet fragmentation suppressed within a cone of m/E from the emitter
- **First direct observation with ALICE for charm quarks!**

Bridging small and large systems



increasing multiplicity

increasing multiplicity

- **Smooth increasing trend** of strange and charm particle yields relative to pions from pp to Pb-Pb, as a function of charged-particle multiplicity
- Is charged-particle multiplicity, more than collision system size, the **relevant scale parameter** for “strangeness enhancement” and other QGP-like effect?

arXiv:2211.04384

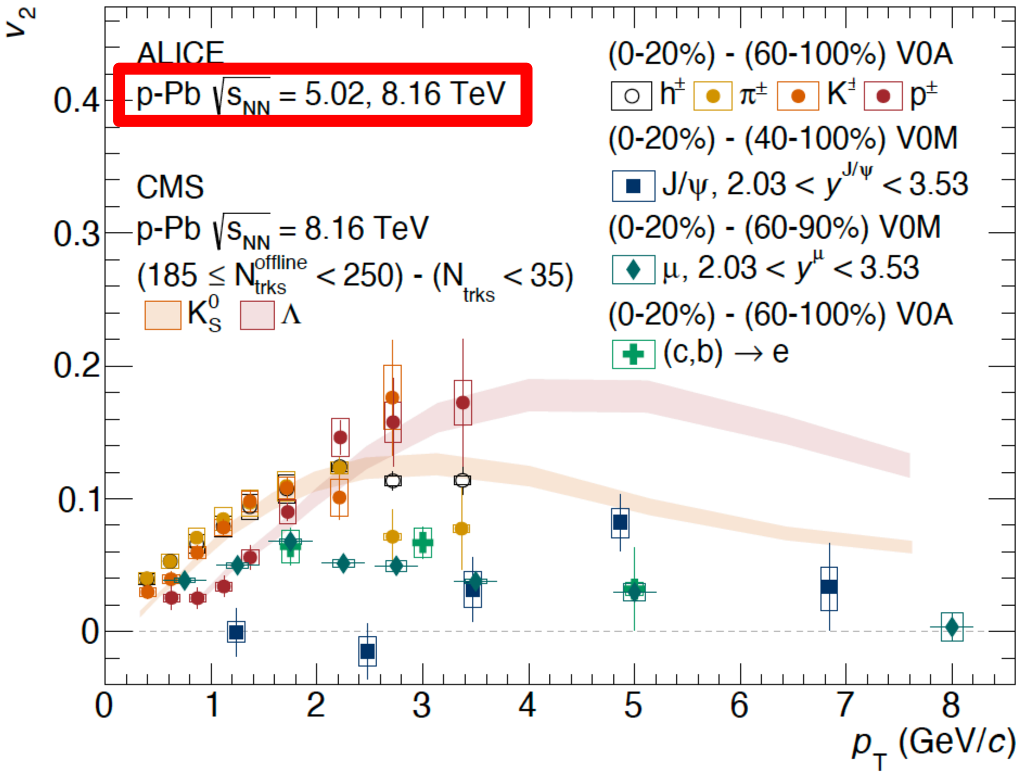
Bridging small and large systems

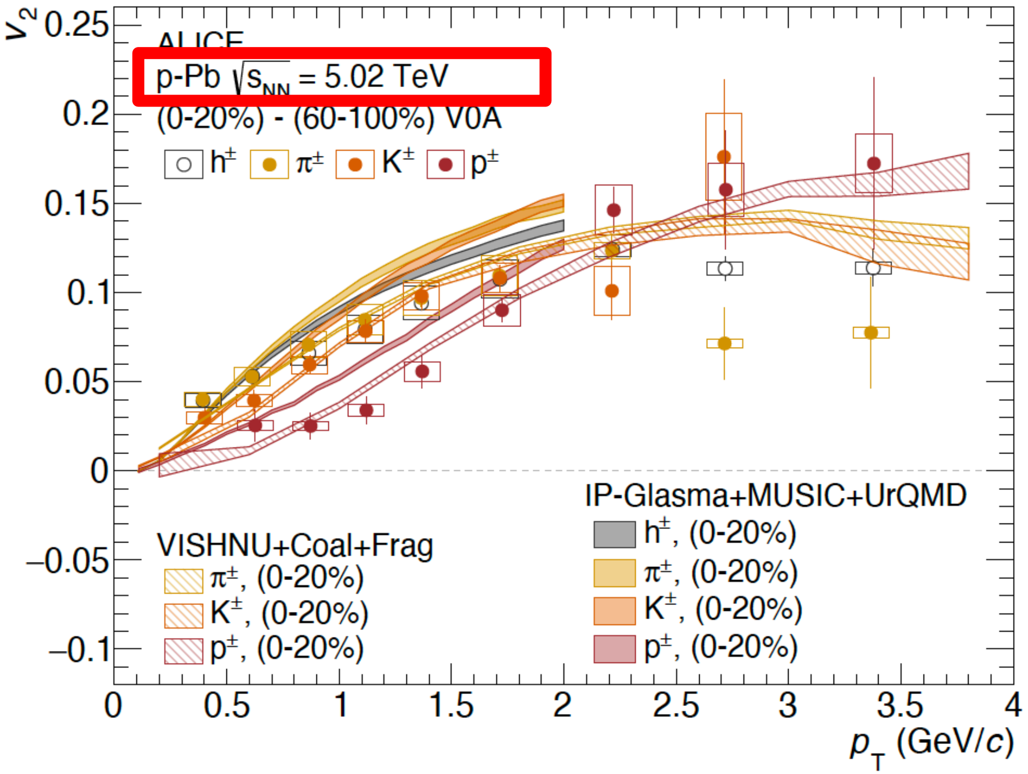
- Light and charmed hadrons exhibit **anisotropic (namely elliptic) flow in small systems** like proton-nucleus collisions

- Light sector described by hydrodynamics implementing a QGP equation of state

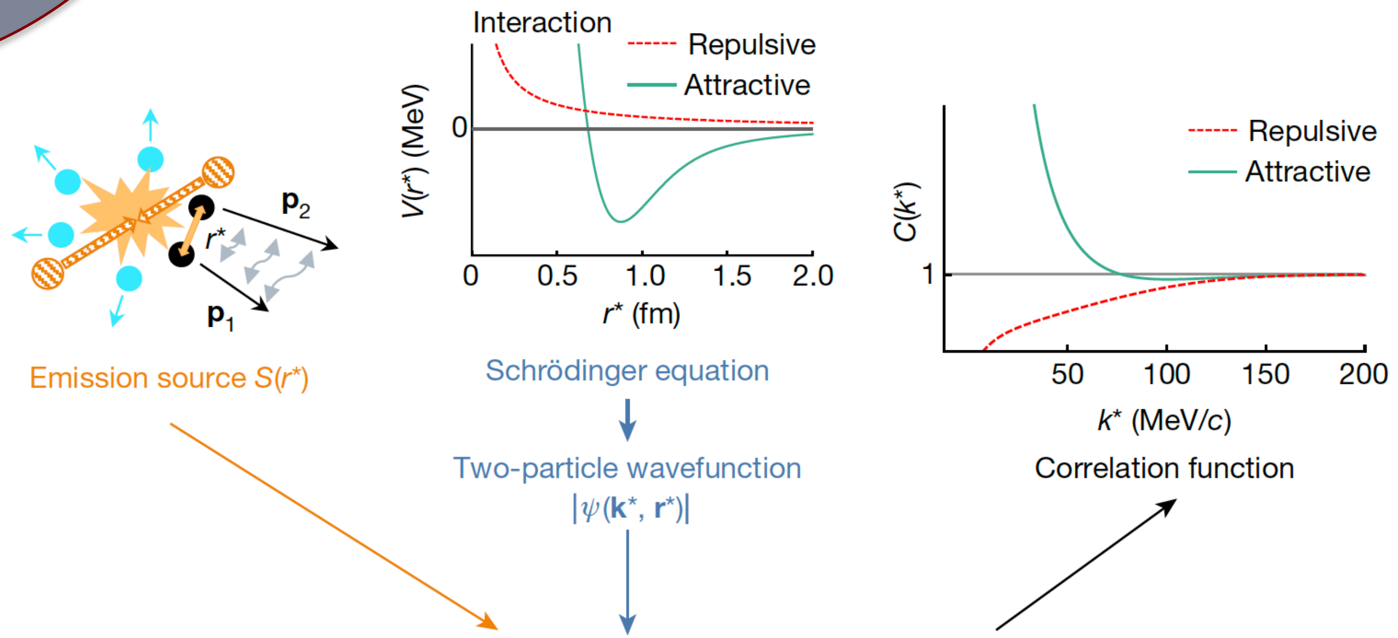
arXiv:2211.04384

- **Mass ordering** similar to the one caused by a collectively expanding medium in heavy-ion collisions



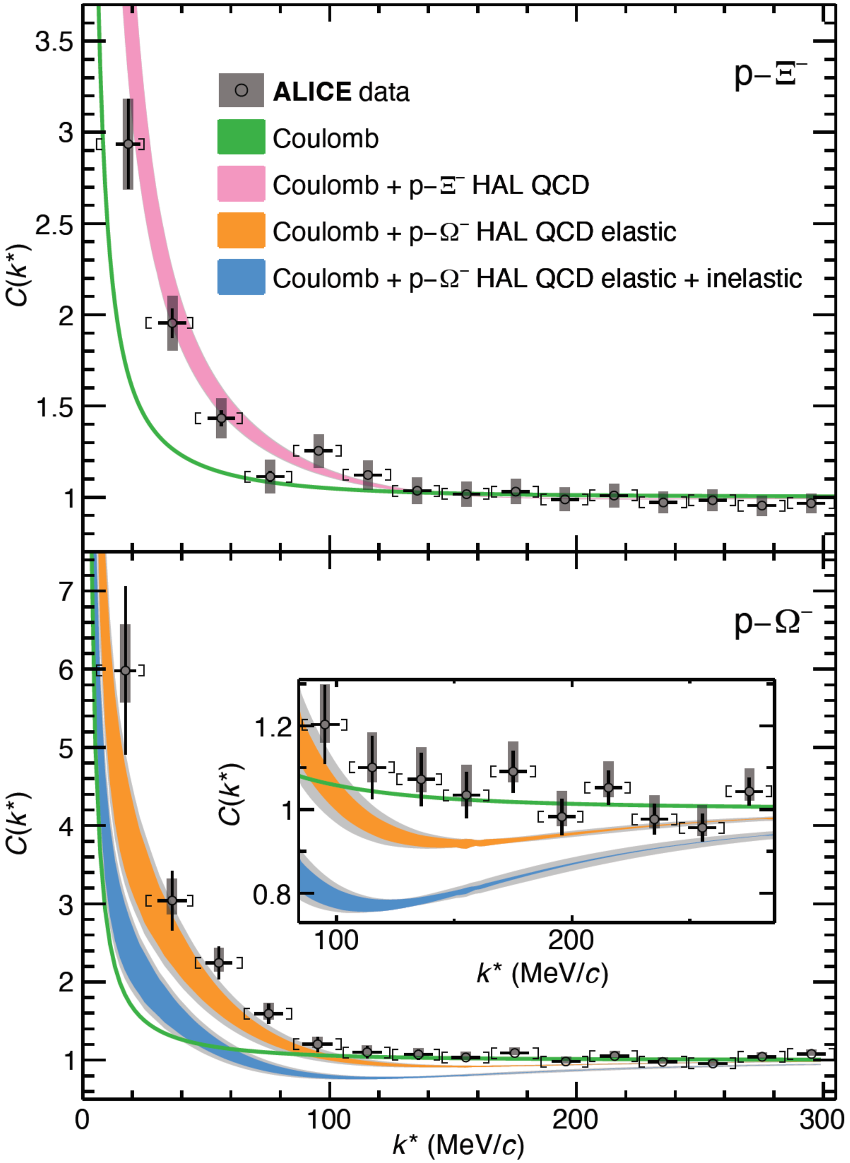


Beyond QGP: proton-hyperon potential



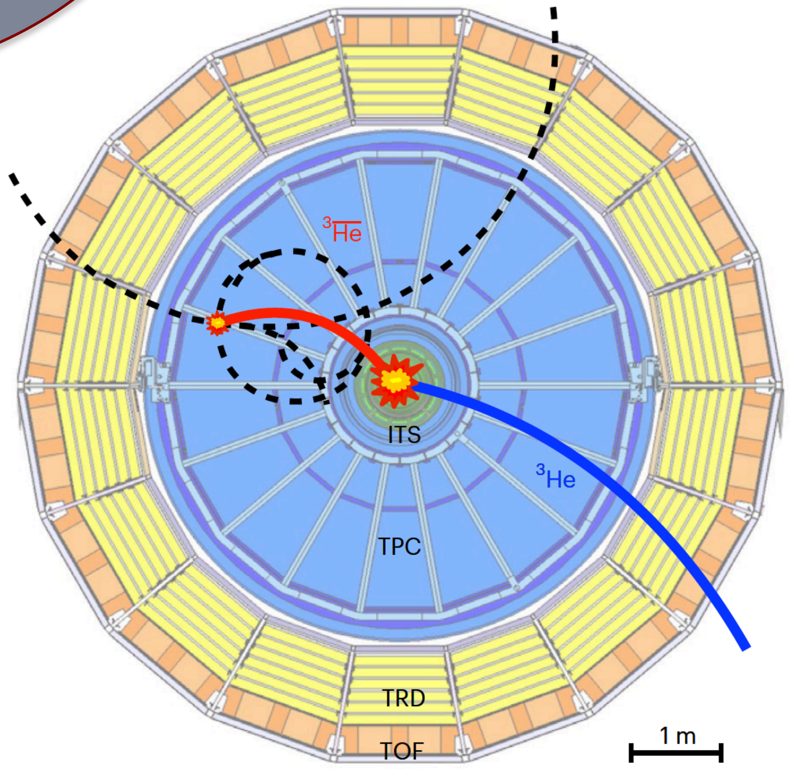
$$C(k^*) = \int S(r^*)|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2 d^3r^* = \xi(k^*)\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

Nature 588 (2020), 232



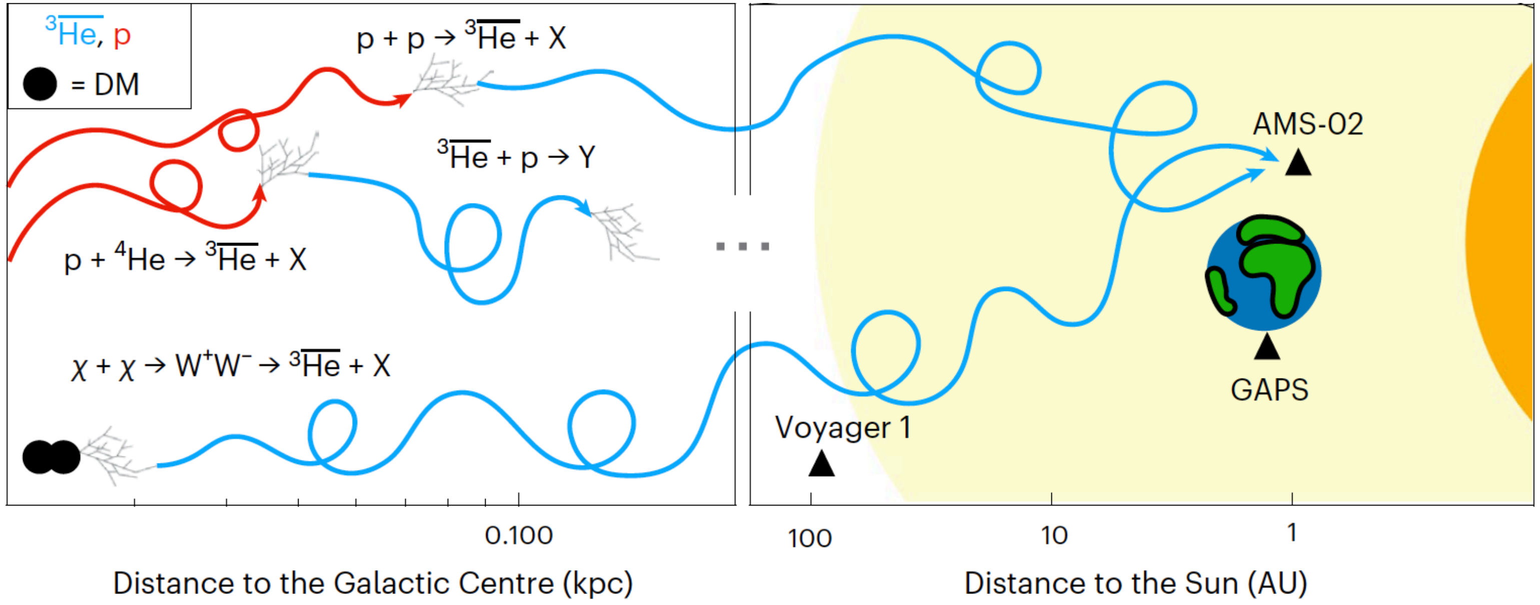
- Large production of hyperons at the LHC: unique opportunity to study **rare hadronic interactions via femtoscopy measurements**
- Proton-hyperon potential: important ingredient to establish the **EoS of hadronic matter at high density (core of neutron stars)**

Beyond QGP: contributing to dark matter searches



- Antinuclei are a valuable probe for indirect Dark Matter searches as a **final-state of dark matter annihilation processes**
  - Cross sections of antinuclei interaction with ordinary matter: key parameter to precisely model anti-nuclei propagation through the interstellar medium

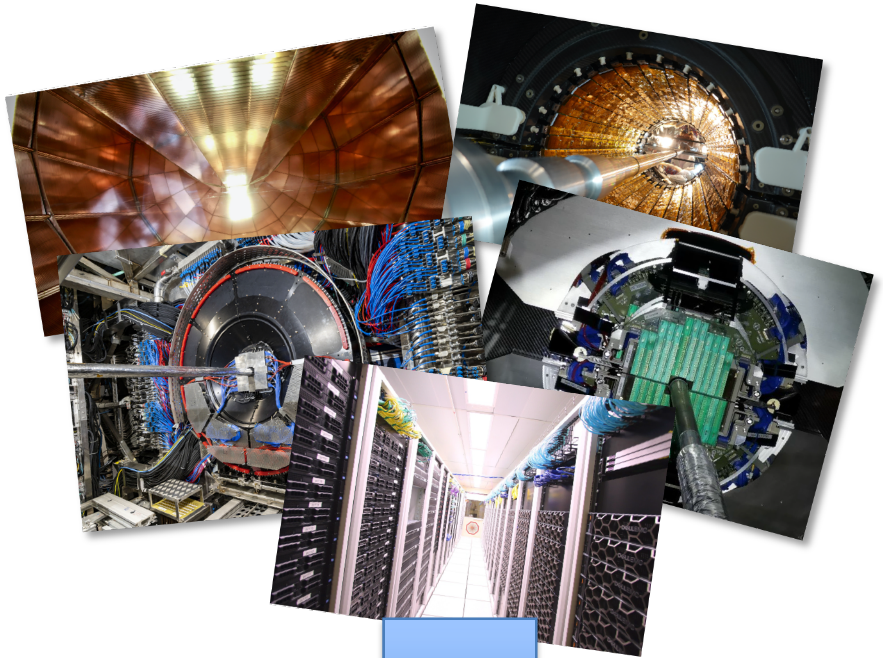
Nature Phys. 19 (2023), 61



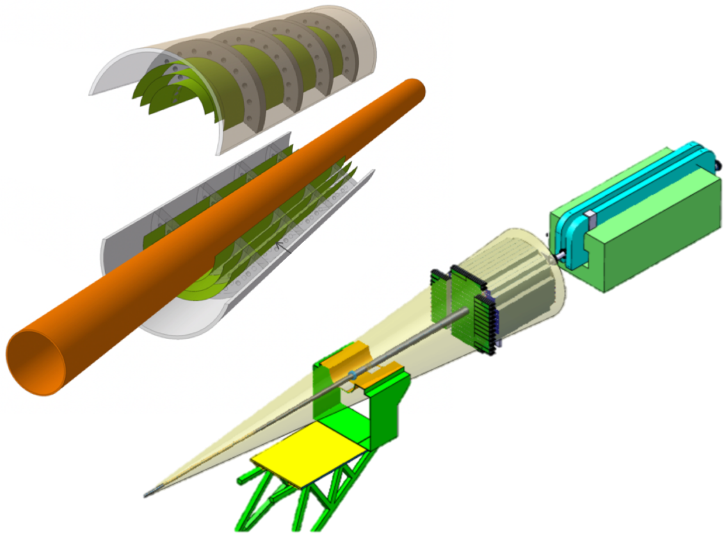
ALICE results indicate that **anti-^{3}He nuclei can travel long distances in the galaxy**, and can be used to study cosmic-ray interactions and dark-matter annihilation

ALICE upgrade timeline

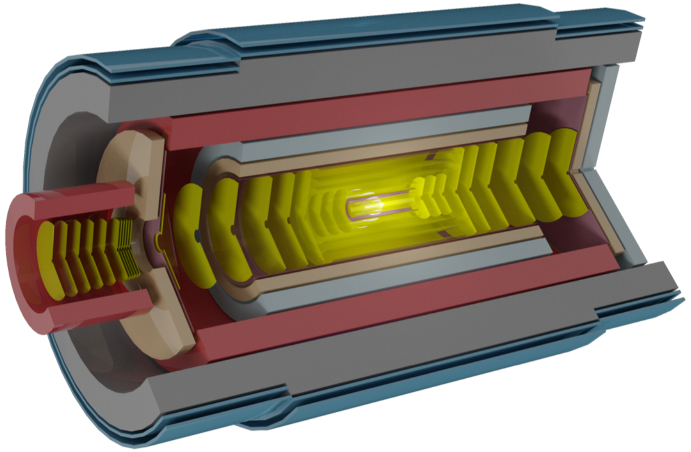
LS2: **ITS2, MFT, TPC, FIT, O^2**

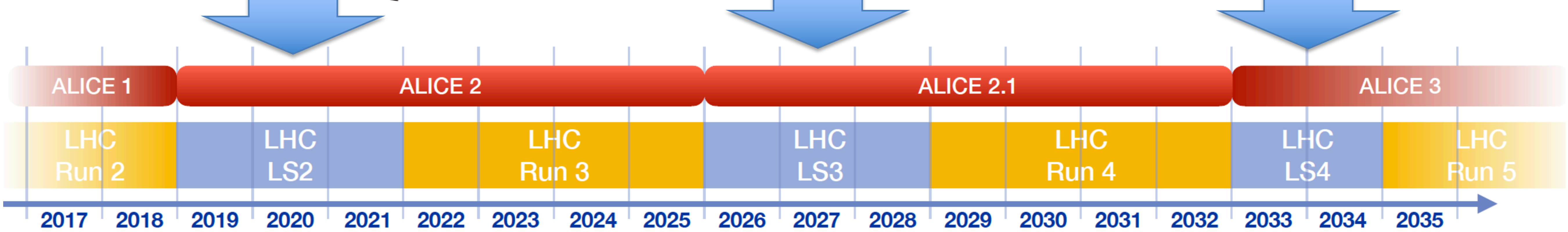


LS3: **ITS3, FoCal**



LS4: **ALICE 3**



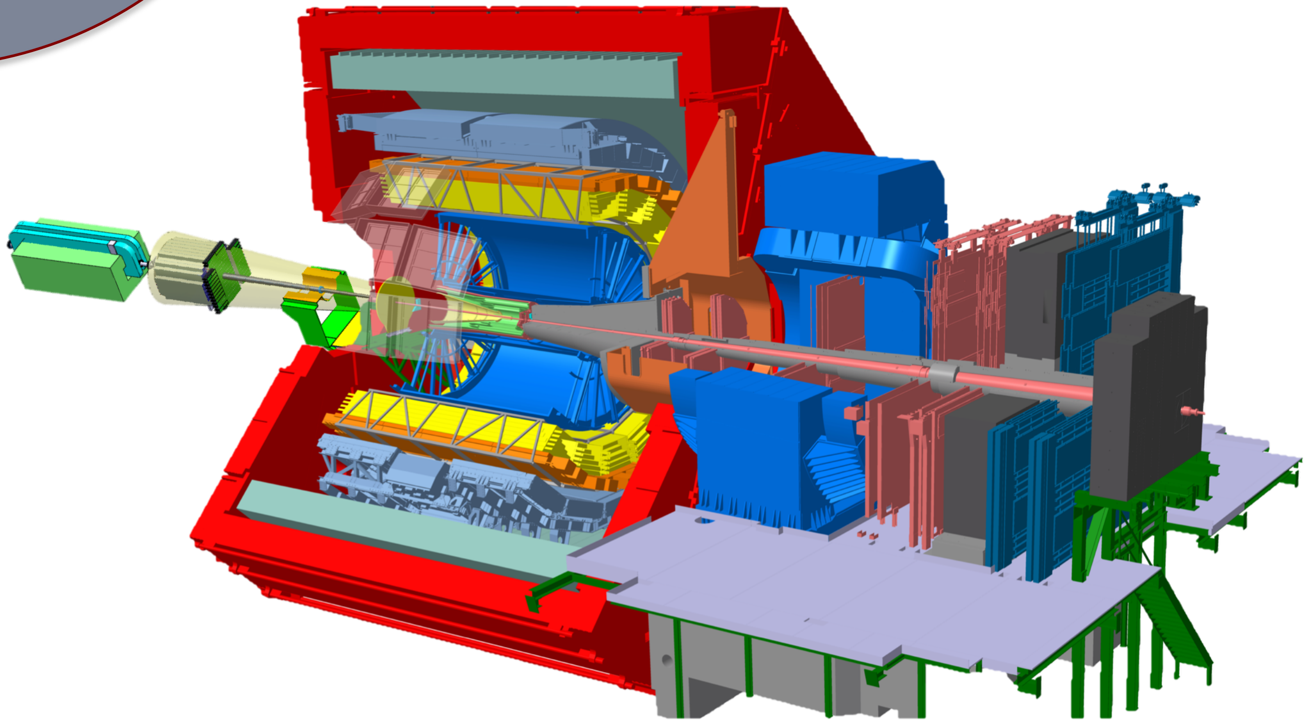


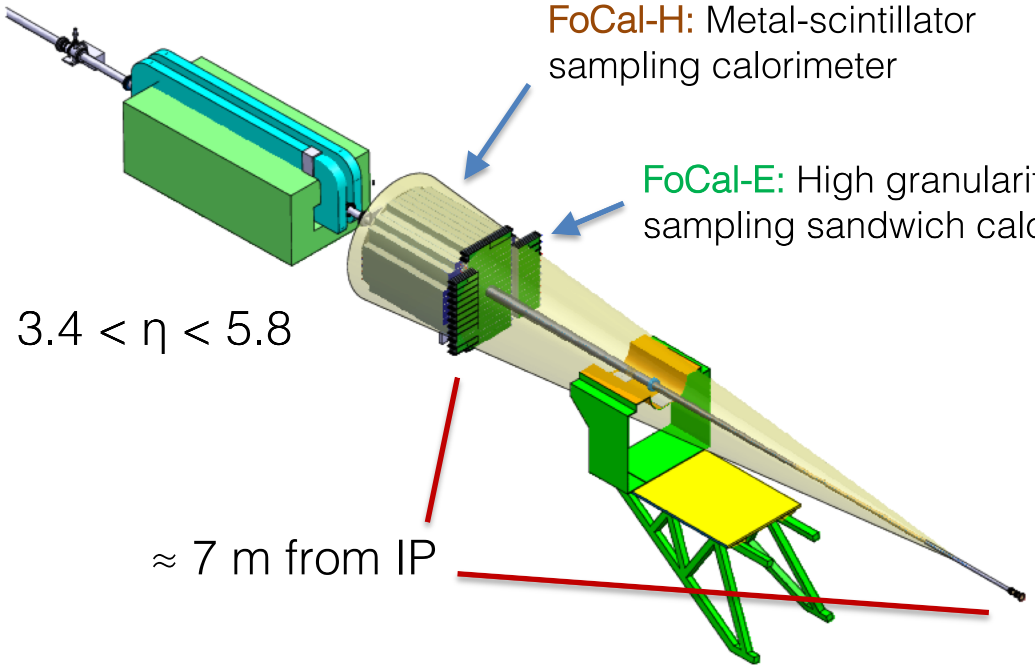
ALICE 1
ALICE 2
ALICE 2.1
ALICE 3

LHC Run 2
LHC LS2
LHC Run 3
LHC LS3
LHC Run 4
LHC LS4
LHC Run 5

2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

Run 4: glue at the smallest x with FoCal





FoCal-H: Metal-scintillator sampling calorimeter

FoCal-E: High granularity Si-W sampling sandwich calorimeter

$3.4 < \eta < 5.8$

≈ 7 m from IP

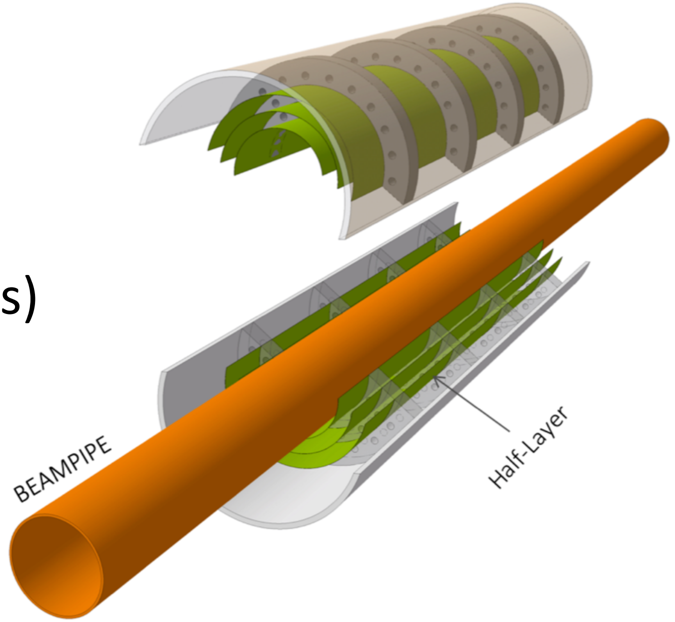
SOLID EDGE ACADEMIC COPY

Forward physics at LHC provides an opportunity to study the low-x region

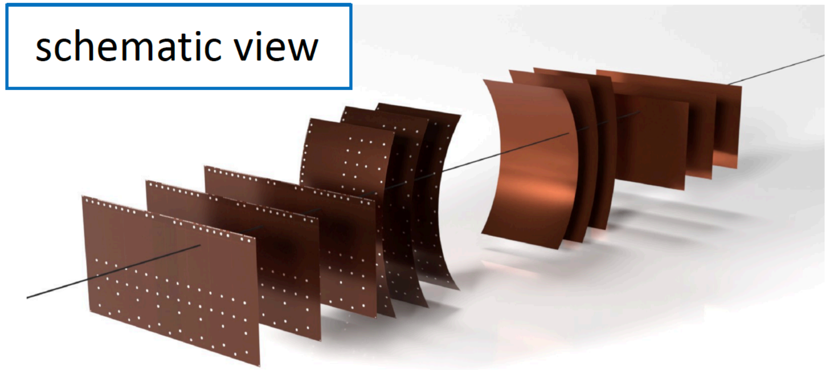
- Access to non-linear QCD mechanisms: investigate the onset of possible of gluon saturation (CGC)
- Quantify and constrain modifications of gluon (n)PDFs at small-x and Q^2
- Direct photons provide a more direct access to the low-x region (10^{-5})

Run 4: enhancing vertexing with ITS3

ITS3: replacing the 3 innermost layers of ITS2 with a next-generation vertex detector based on truly cylindrical layers (bent, wafer-scale CMOS sensors)



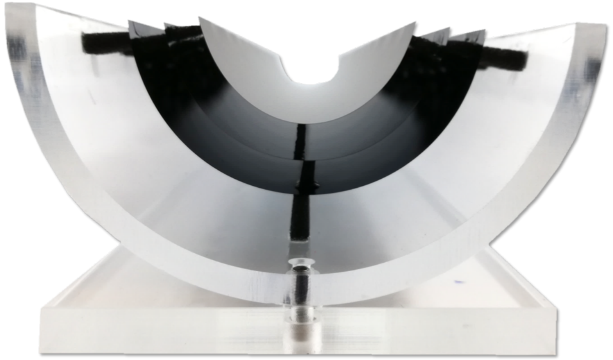
- Innermost layer from 22 mm to 18 mm (beam pipe to be replaced around the IP)
- 280 mm long sensor ASICs out of 300 mm long stitched wafers (2 halves × 3 layers)
- 20-40 µm (0.02 - 0.04% X_0), bent shape with R = 18/24/30 mm
- Carbon foam rib to hold ASICs in place + air cooling



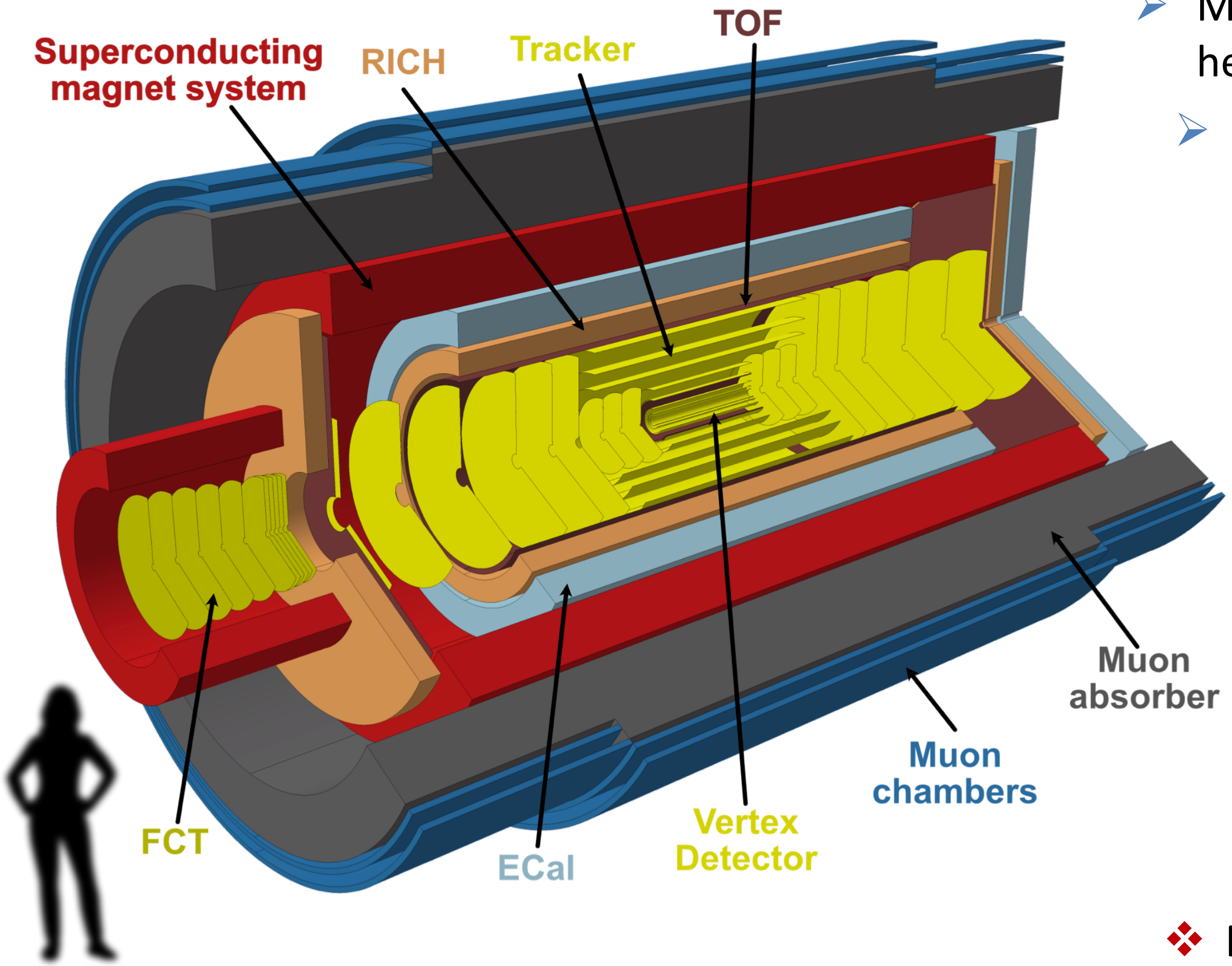
ALPIDE telescope used for the tests

- Bent ALPIDE efficiency > 99.9%
- Digital pixel test structure efficiency > 99 %

NIM A 1028 (2022), 166280



ALICE 3: a new experiment for Run 5 and beyond

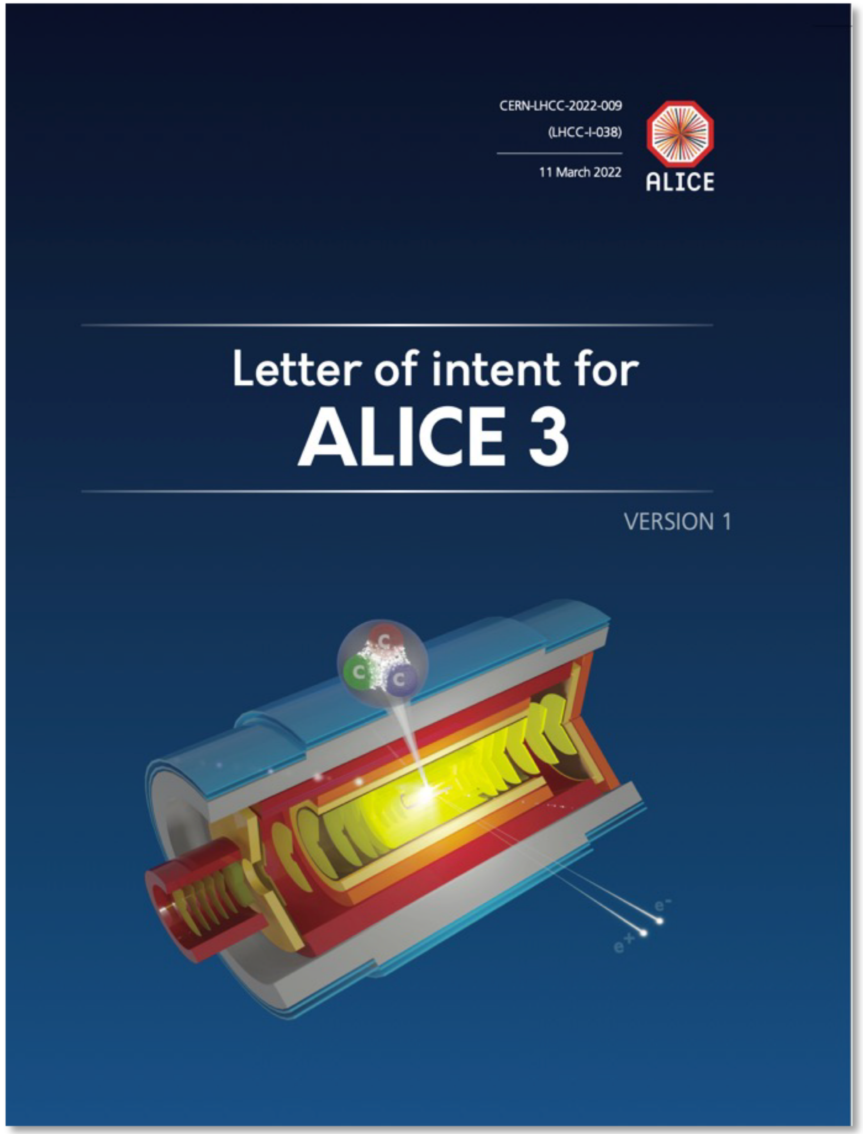


Selected physics case (CERN-LHCC-2022-009):

- Microscopic mechanisms of in-medium energy loss of heavy quarks
- HF hadronisation mechanisms
- Non-conventional hadronic structures
- Dilepton production: temperature of the QGP and pre-equilibrium phase
- Ultra-soft photons, BSM searches, …

- **Compact and ultra-light all-silicon tracker with large acceptance and high-resolution vertex detector**
- **Superconducting magnet system**
- **Particle identification down to vanishing p_T over 8 units of pseudorapidity**
- **Fast readout and online processing**

ALICE 3: costs and planning



CERN-LHCC-2022-009
(LHCC-I-038)
11 March 2022

ALICE

Letter of intent for
ALICE 3

VERSION 1

- **2023-25**: selection of technologies, small-scale proof of concept prototypes (≈ 25% of R&D funds)
- **2026-27**: large-scale engineered prototypes (≈ 75% of R&D funds) → Technical Design Reports
- **2028-31**: construction and testing
- **2032**: contingency
- **2033-34**: Preparation of the cavern and installation of ALICE 3

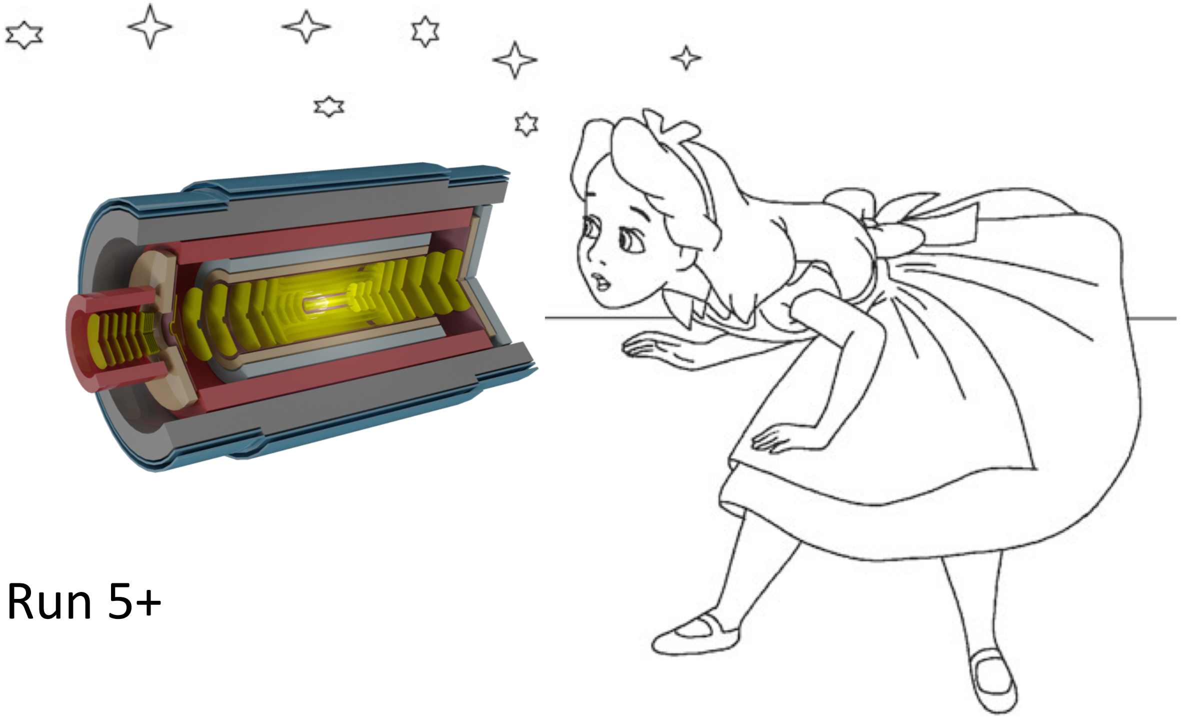
CERN-LHCC-2022-009

Summary

A wealth of physics results from Run 1 and 2, now collected in the ALICE review paper

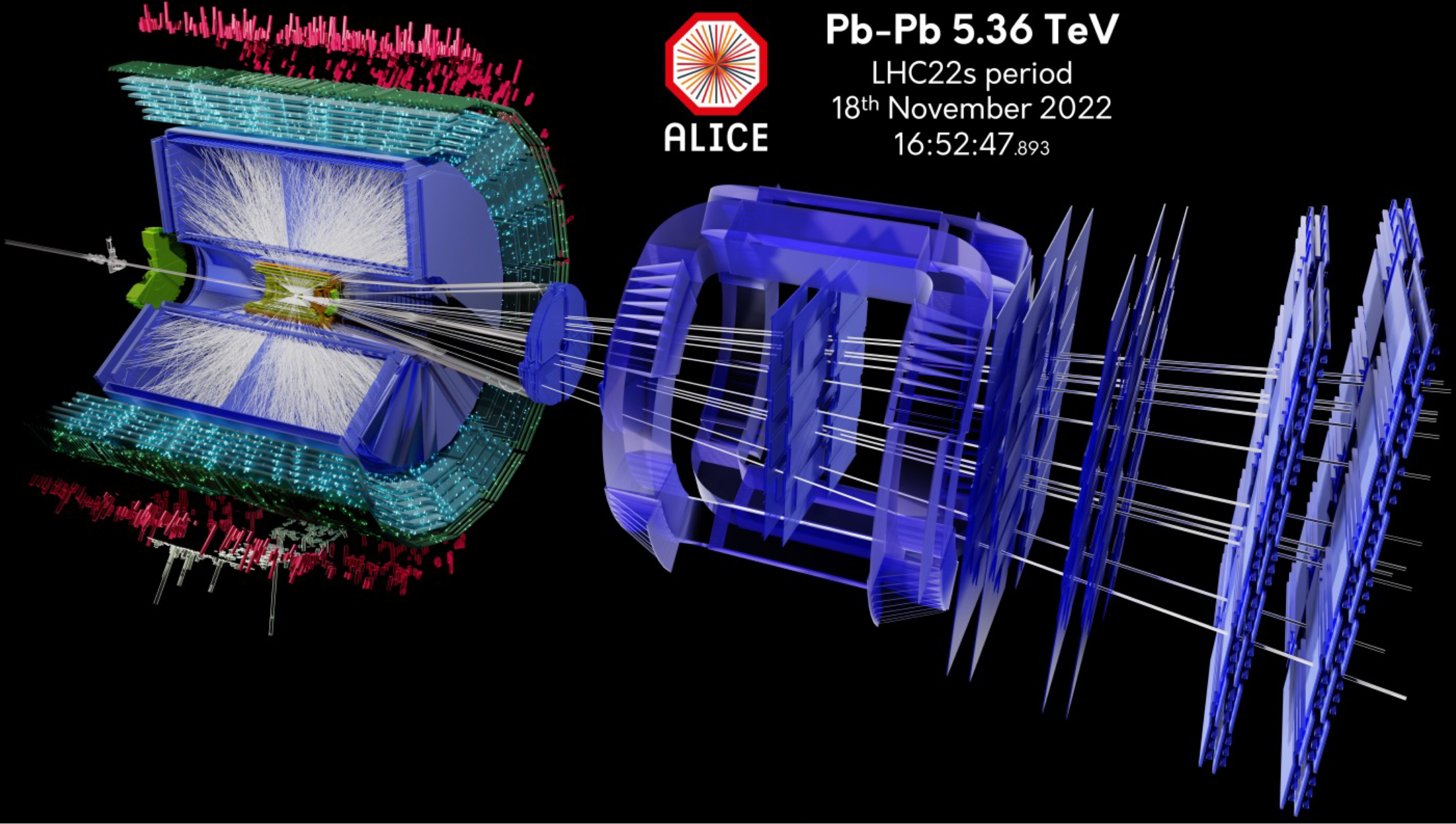
arXiv:2211.04384

- Detailed insights on QGP properties
- Identifying bridges between small and large collision systems
- Exciting results beyond QGP physics
- LHC Run 3 data taking just started, with continuous readout and improved tracking performance



Underway and coming up:

- New vertexing layers and forward calorimetry for Run 4
- ALICE 3: next-generation dedicated heavy-ion experiment for Run 5+



ALICE

Pb-Pb 5.36 TeV

LHC22s period

18th November 2022

16:52:47.893

Backup Slides

From the Heavy-Ion Physics Vocabulary: R_{AA}

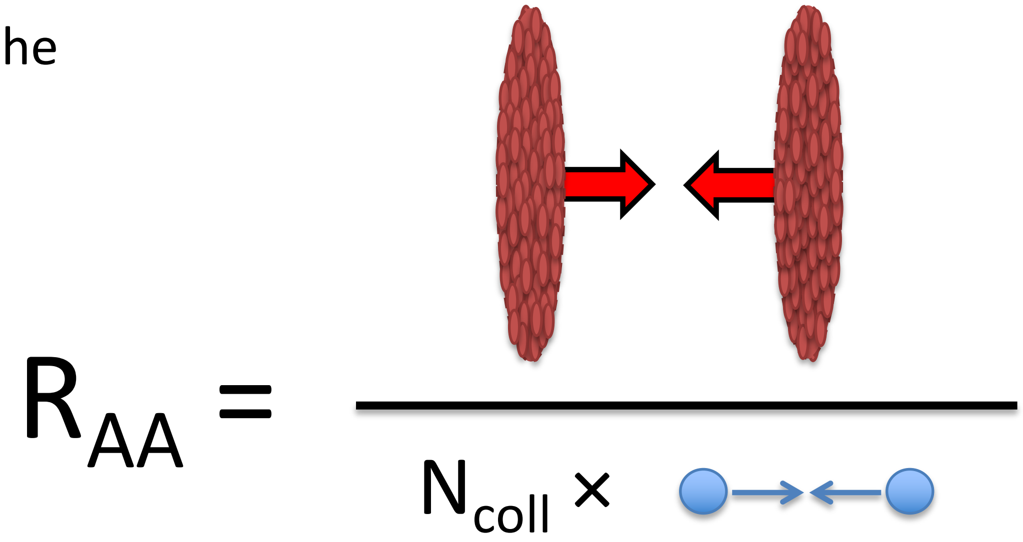
R_{AA} = nuclear modification factor (in A-A collisions w.r.t. pp collisions)

How is it built?

- Take the outcome of a measurement in pp (e.g. J/ψ yield)
- Evaluate the expected outcome of the same measurement in A-A in the hypothesis that A-A is a simple superposition of N_{coll} nucleon-nucleon collisions
- Take the ratio between the real and the expected outcomes of the measurement in A-A, and you have the R_{AA}

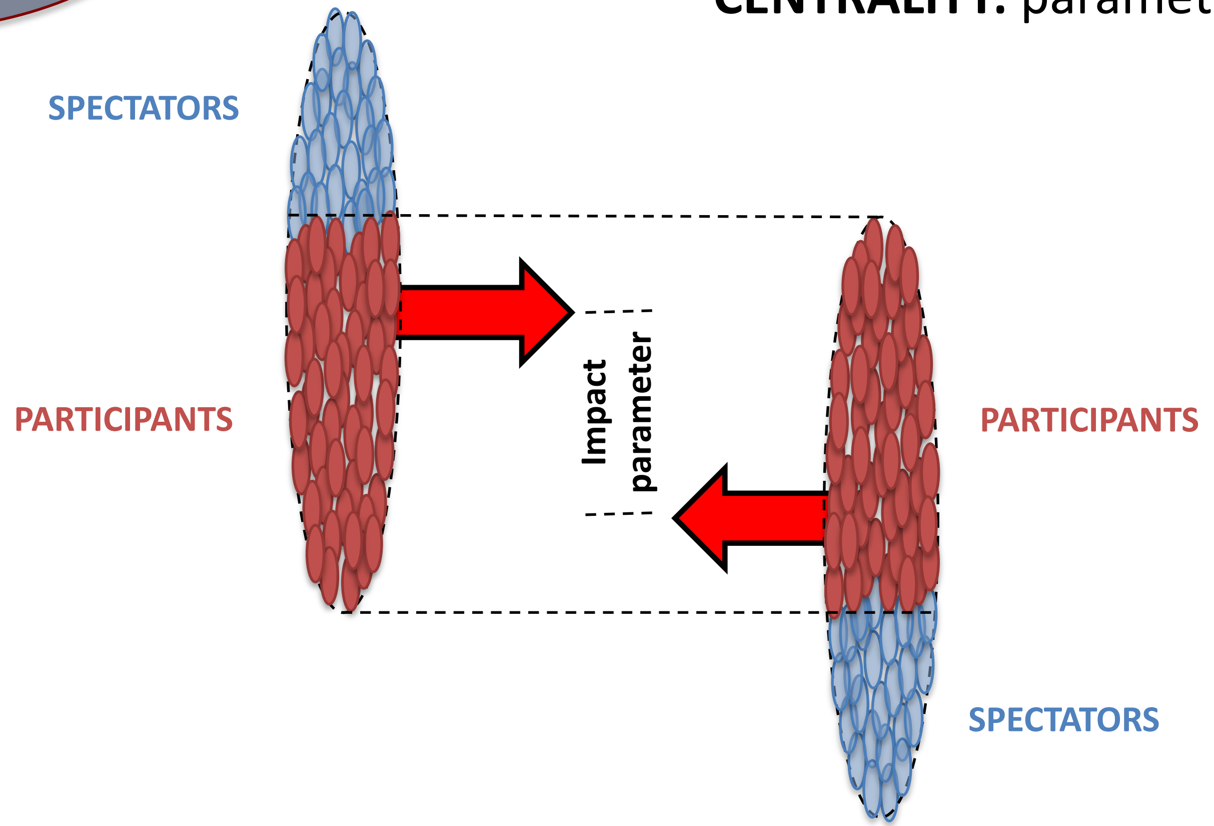
What does it mean?

- The R_{AA} quantifies the influence of the hot medium on the "vacuum" physics



From the Heavy-Ion Physics Vocabulary: Centrality

CENTRALITY: parameter characterizing each nucleus-nucleus collision

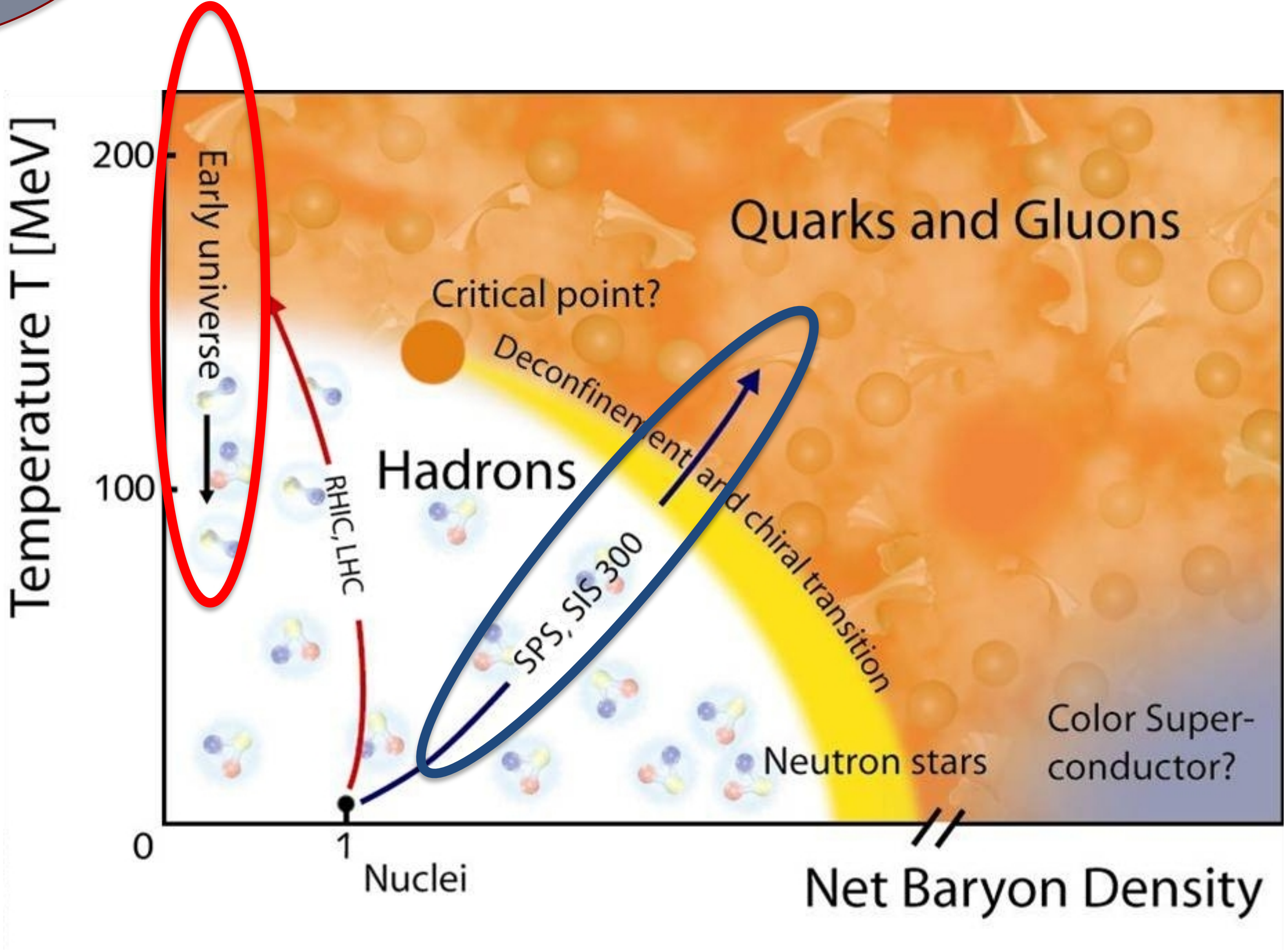


Linked to the collision geometry via the impact parameter (transverse distance between the nuclei centers)

Collision geometry implies collision dynamics: the smaller the impact parameter, the larger the number of nucleons participating to the collision

- Small impact parameter, large number of participating nucleons: **“central” collision, largest medium effects**
- Large impact parameter, small number of participating nucleons: **“peripheral” collision, smallest medium effects (possibly no medium effect at all)**

High- and Low-Energy Frontiers



- **The high-energy frontier:** large and long-living QGP, large cross-sections for heavy-flavors. Vanishing net baryon density: Early Universe conditions

- **The low-energy frontier:** focus on light-flavor observables. **Energy scan:** search of the critical point and characterization of the phase transition