Heavy ions beyond Run 4

Perspective from the ALICE Trieste group

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From the 2020 update

… The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

…Europe should maintain its capability to perform innovative experiments at the boundary between particle and nuclear physics, and CERN should continue to coordinate with NuPECC on topics of mutual interest

Inputs to the 2024 updates

- **Medium-term priorities:**
  - **Heavy ions at HL-LHC: new detector ALICE 3 for LHC Run 5 - 6**
    - First priority of NuPECC Long Range Plan 2024
    - Strong program, with participation of upgraded ATLAS, CMS, LHCb
  - Note: fixed targed HI experiments @CERN (NA60+)

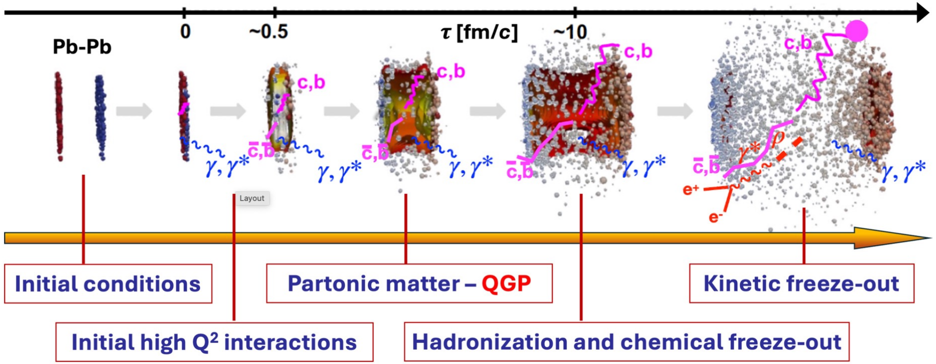
- **Long-term interest:**
  - **Heavy ions at FCC-hh: maintain the possibility to run ions in addition to pp**

- **The field is a driver of strong and innovative R&D:**
  - **Ultra-light pixel sensors, Silicon time-of-flight,…**

Major (expected) open questions after LHC Run4

Ultra-relativistic heavy ion collisions: produce and study **the quark-gluon plasma (QGP)**, which is a state of nuclear matter at extreme conditions of temperature and density.

- Equilibration reached in less than 1 fm/c
- Almost ‘’perfect liquid” with close to minimal dissipative properties
- Initial temperature well above the QCD transition temperature
- initial extreme transverse pressure gradients
- The system evolves close to equilibrium for more than 10 fm/c and expands into a volume of about 5000 fm3 per unit of rapidity



Major (expected) open questions after LHC Run4

Ultra-relativistic heavy ion collisions: produce and study **the quark-gluon plasma (QGP)**, which is a state of nuclear matter at extreme conditions of temperature and density.

In Run 3 + 4: expect an increased precision in the measurements of

- **Macroscopic** properties of the QGP (Temperature, heavy-quark diffusion coefficients)
- **Microscopic** structure of the QGP
- **Collective effects from small to large systems**

Important open questions will remain:

- **Time evolution of the QGP temperature**
- Mechanisms of the **chiral symmetry restoration**
- **Degree of thermalization of the charm and beauty quark** and the underlying microscopic mechanisms
- Hadronization in heavy-ion collisions

-> Requires high precision measurement of (multi-)charm hadrons and dileptons

ALICE future: pushing the frontiers of precision

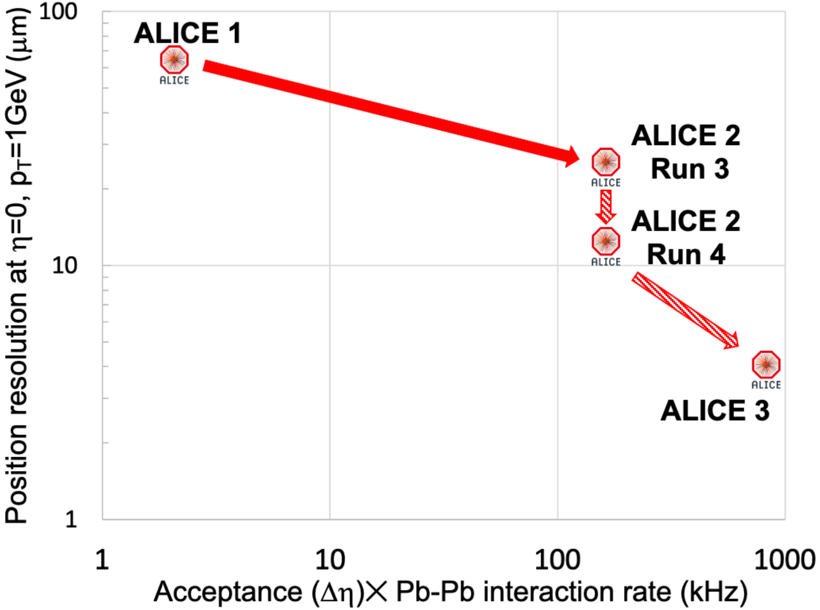
2010-2012		2015-2018		2022-2026		2030-2033		2036-2039		2040-2041
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

+ ITS3/FoCal

"ALICE 1" **Major upgrade** "ALICE 2" **New detector** "ALICE 3"

- **Enhance physics reach by improving:**
  - Rate capabilities & acceptance
  - Track precision

-> High precision, reduced background,
Access to rarer probes



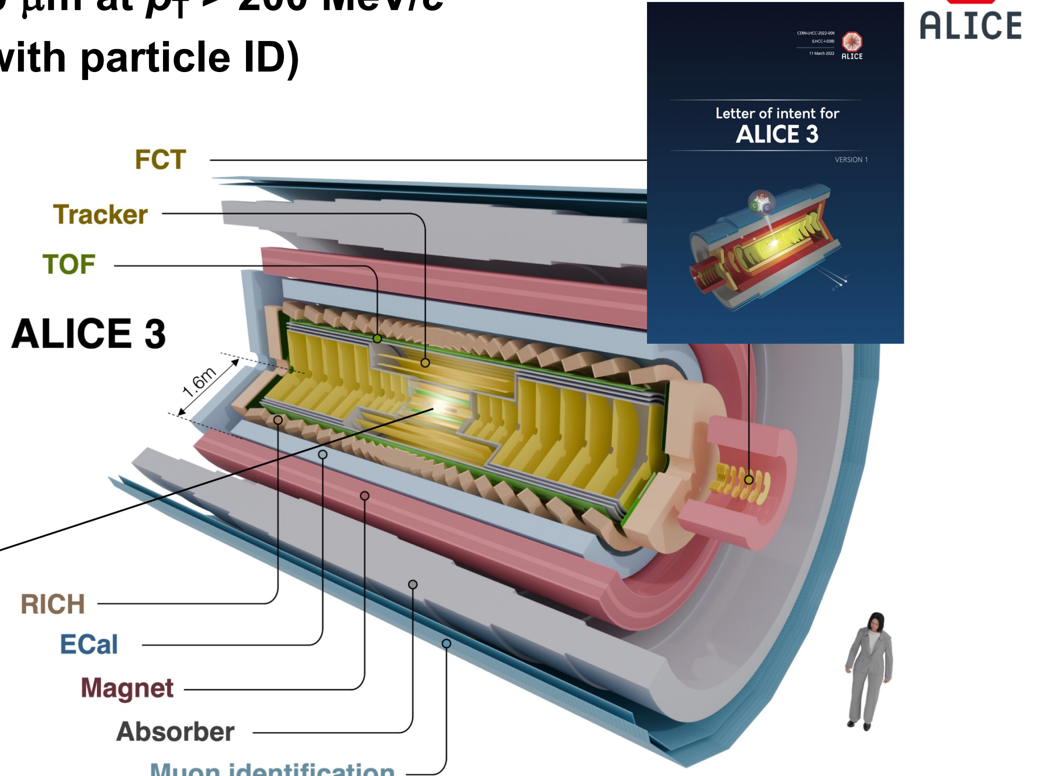
ALICE 3: next-generation heavy-ion detector

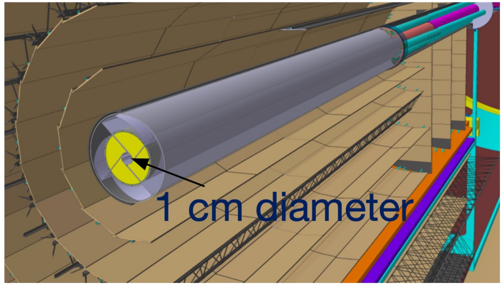
→ **Tracking precision × 3: <10 μm at p_T > 200 MeV/c**

→ **Acceptance × 4.5: |η| < 4 (with particle ID)**

→ **A-A rate × 5 (pp × 25)**

- Compact and light-weight all-pixel tracker
- Retractable vertex detector in vacuum
- Large acceptance with particle identification
- Superconducting solenoid (2T)
- Continuous readout and online processing

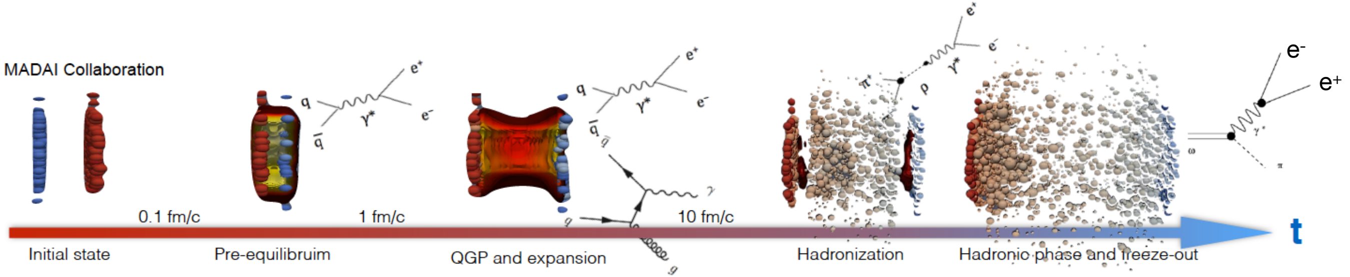




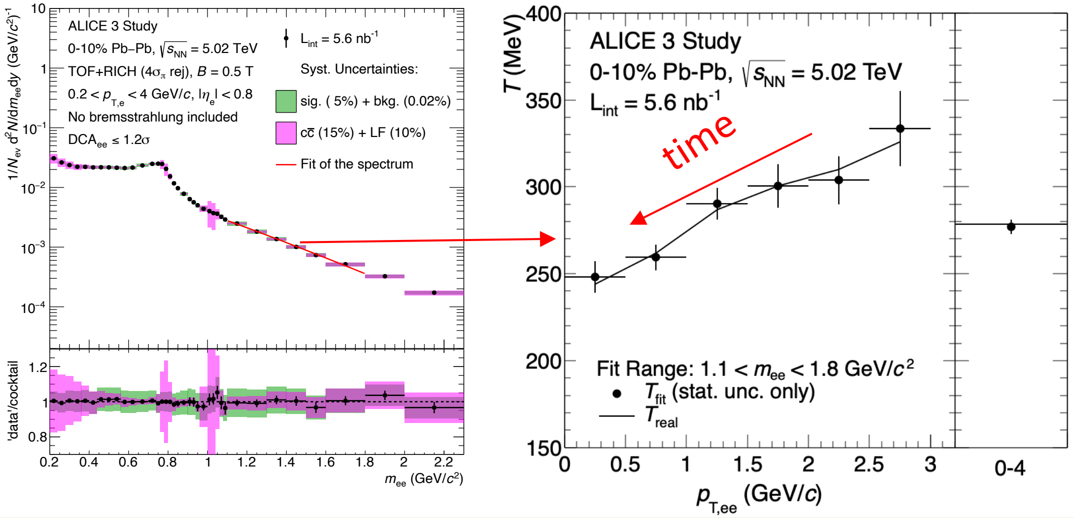
ALICE 3 LoI, CERN-LHCC-2022-009

Scoping Document submitted to LHCC

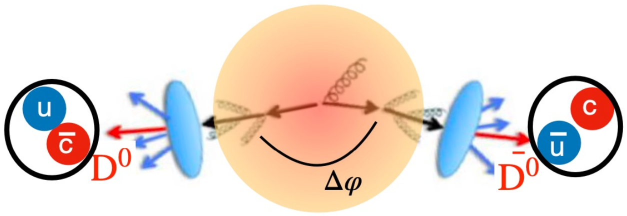
ALICE3: Quark-gluon plasma vs time



ALICE 3: access to time evolution of the temperature



ALICE3: Heavy-quark correlations



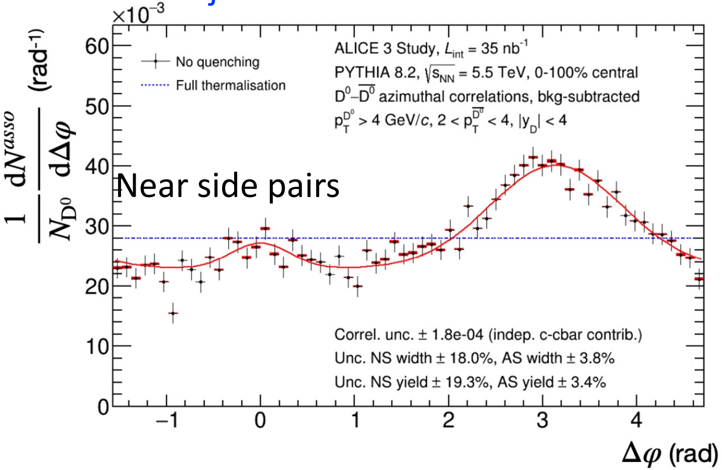
Angular decorrelation of heavy-flavour hadrons

Probe QGP scattering

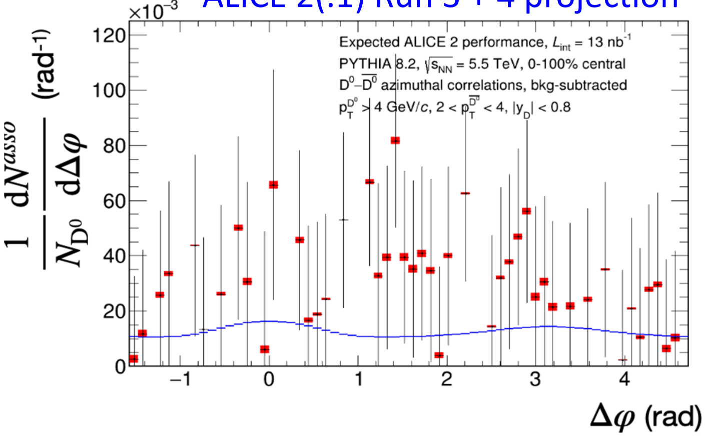
- Sensitive to energy loss and thermalization degree
- Requires high purity, efficiency and η coverage

<u>**Heavy-ion measurement only possible with ALICE 3**</u>

Projection for $D^0\overline{D}^0$ correlation



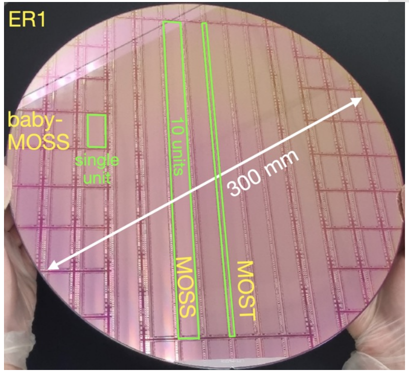
ALICE 2(.1) Run 3 + 4 projection

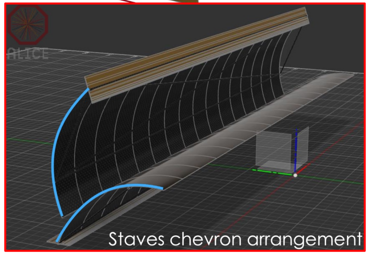


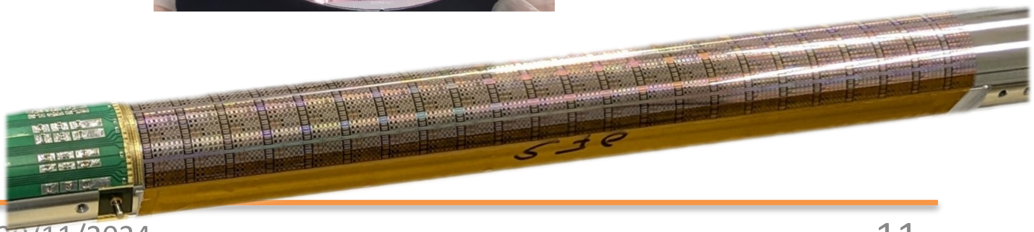
ALICE 3: R&D at TS and other INFN units

- **TS group involved in Inner Tracker:**
  - Vertex Detector + Middle Layers
- **Study of “ultra-light” Middle Layers:**
  - Material budget target ~0.2% per layer, compared to ~1% for traditional layout
  - Reduced number of modules and sensors, exploiting large, flexible, MAPS sensors
- Study of sensor, as evolution of ITS3 R&D

- **In general, strong involvement of INFN also in R&D for:**
  - Silicon timing layers (CMOS LGADs)
  - RICH with SiPM sensors
  - Superconducting magnet design

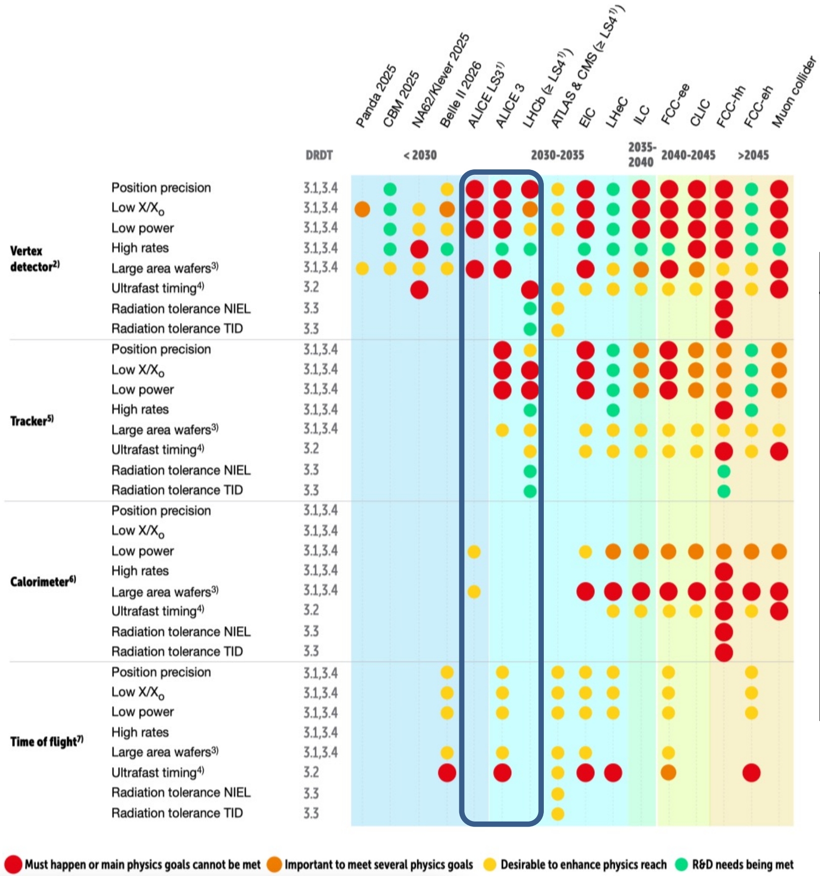






ALICE R&D paves the way for future HEP experiments

ECFA Detector R&D Roadmap:



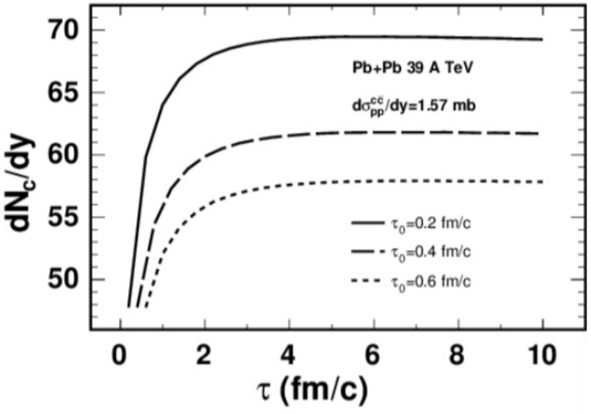
https://cds.cern.ch/record/2784893

→ **R&D for ALICE & LHCb phase II upgrades cover a significant part of the long-term strategic R&D lines defined by ECFA**

(Very) Far future: heavy ions at FCC-hh

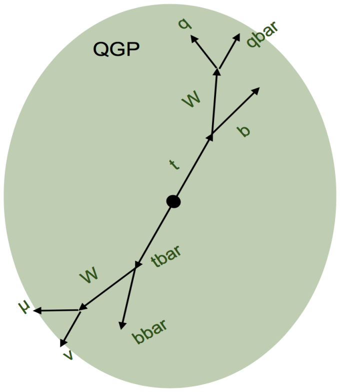
- **FCC-hh HI performance:** Pb-Pb $\sqrt{s_{NN}}$ = 39 TeV **~ 7 x LHC $\sqrt{s_{NN}}$**
- >100 nb^{-1}/month in “ultimate” luminosity scenario: **~ 20-30 x LHC L_{int}**
- QGP from LHC to FCC: volume x2, energy density x3, initial temperature ~1 GeV

Thermal charm-anticharm from QGP gluons



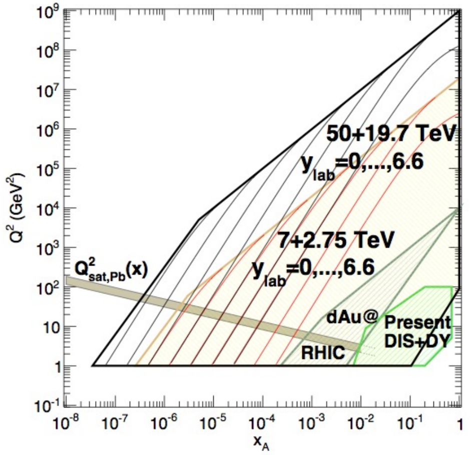
Ko, Liu, JPG43 (2016) 12, 125108

New hard probes of QGP



Apolinario et al., PRL120 (2018) 23, 232301

Smallest Bjorken-x ever for gluons in nuclei



Dainese et al., arXiv:1605.01389

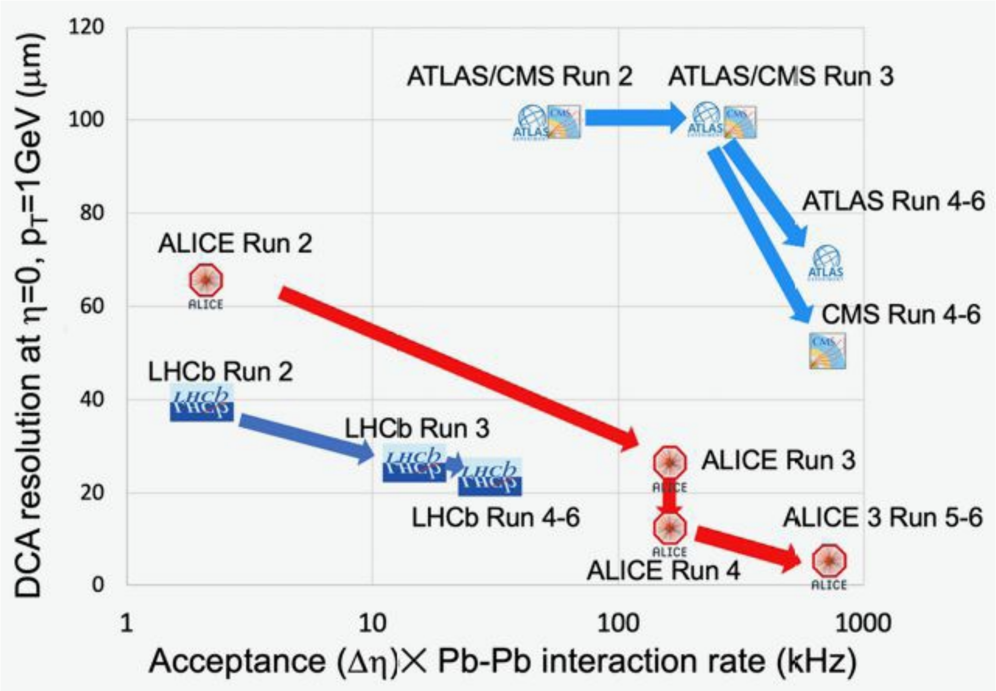
Input to the strategy update

Europe and CERN should support the continuation of heavy-ion programmes to pursue the exploration of the emergent properties of hot QCD matter and the measurement of its fundamental physics parameters

New detectors at LHC (ALICE 3, + upgraded other exps) and SPS (NA60+) can address the open fundamental questions, while ensuring a full exploitation of these accelerators, and a rich and diverse scientific environment

They also pave the way, with full-scale frontier detectors, for the sensors to be used in future HEP experiments

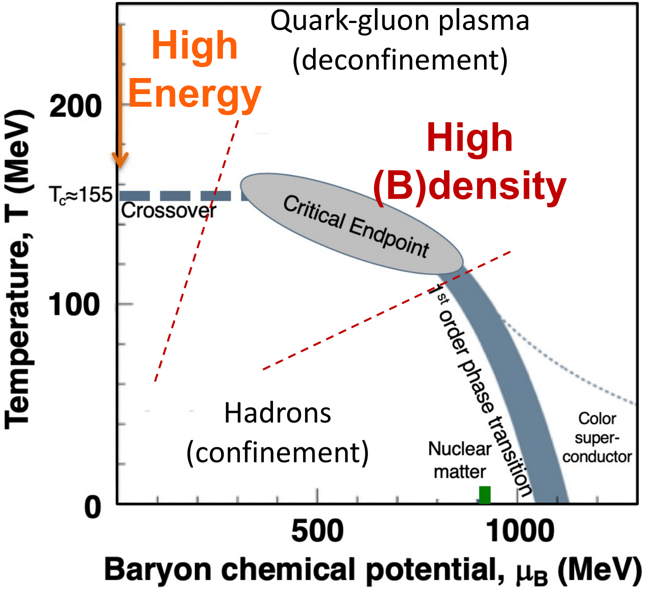
Back up



DCA resolution at η=0, p_T=1GeV (μm)
120
100
80
60
40
20
0
1
10
100
1000
Acceptance (Δη)× Pb-Pb interaction rate (kHz)
ATLAS/CMS Run 2
ATLAS/CMS Run 3
ATLAS Run 4-6
CMS Run 4-6
ALICE Run 2
LHCb Run 2
LHCb Run 3
LHCb Run 4-6
ALICE Run 3
ALICE 3 Run 5-6
ALICE Run 4

Quark-Gluon plasma: future research directions

Ultra-relativistic heavy ion collisions: produce and study **the quark-gluon plasma (QGP)**, which is a state of nuclear matter at extreme conditions of temperature and density.



High energy collisions (LHC, FCC-hh):

- Quantify properties of QGP and relate them to its constituents
- How are collectivity and thermalisation developed in QCD?
- Can they be developed also in small systems (pp, pA)?

High (B)density collisions (SPS, FAIR, …):

- Search for onset of deconfinement via energy scans
- Search for the Critical Endpoint (lQCD: $\mu_B > 300$, $T < 140$)
- QGP constituents at high μ_B → Neutron Star EoS

ALICE 3 main goals

Early stages: temperature, chiral symmetry restoration
- Dilepton and photon production, elliptic flow

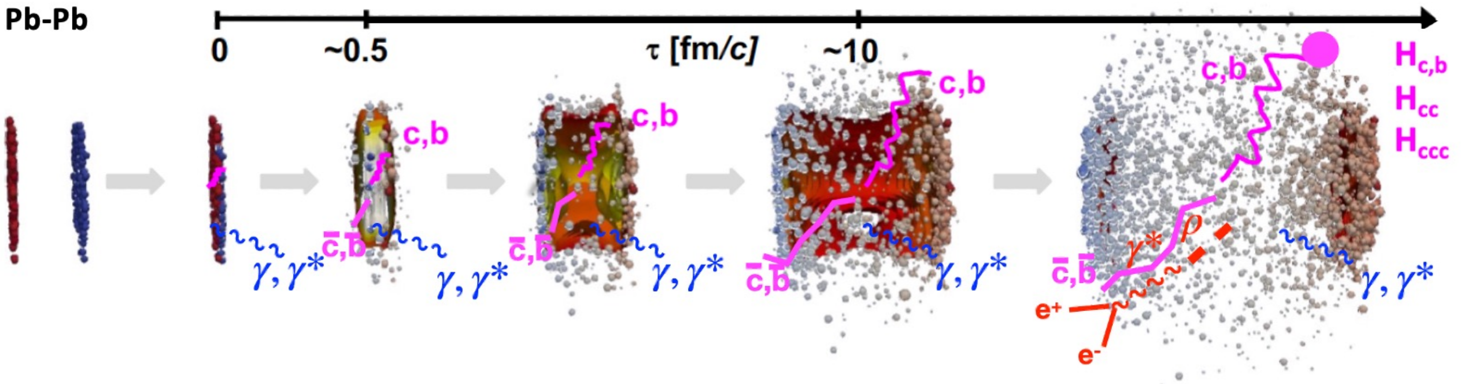
Heavy flavour diffusion and thermalization in the QGP
- Beauty and charm flow, charm hadron correlation

Hadronization in heavy-ion collisions
- Multi-charm baryon production: quark recombination
- Quarkonia,exotic mesons: dissociation and regeneration

Understanding fluctuations of conserved charges
- Hadron correlation and fluctuation measurements

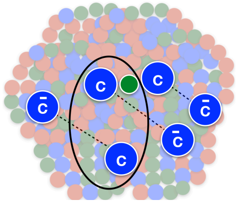
Nature of exotic hadrons
- Momentum correlations, production yields and dacays

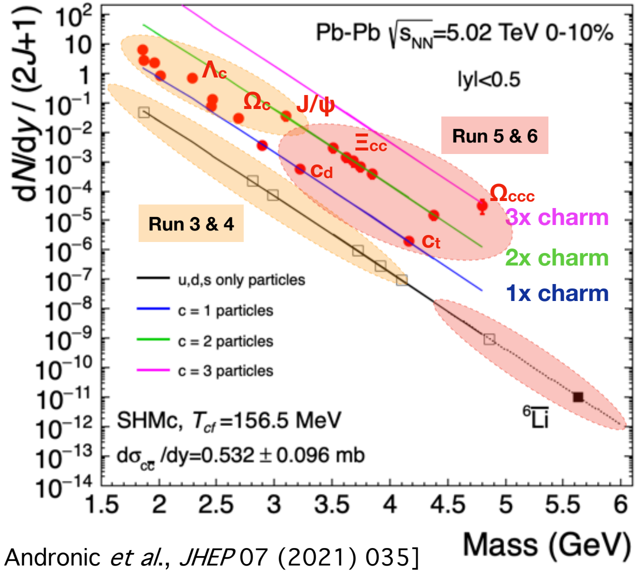
Beyond QGP physics
- Ultra-soft photon production: test of Low's theorem
- Search for axion-like particles in ultra-peripheral Pb-Pb
- Search for super-nuclei (c-deuteron, c-triton)



Multi-charm baryons

- Multi-charm baryon yields are powerful probes of the hadron formation mechanisms since produced by combination of uncorrelated charm quarks produced in the collision
- negligible same-scattering production (unlike e.g. J/ψ)





[A. Andronic *et al.*, *JHEP* 07 (2021) 035]