Emergence of quark-gluon plasma phenomena

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ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare

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The QGP is a state of strongly-interacting matter

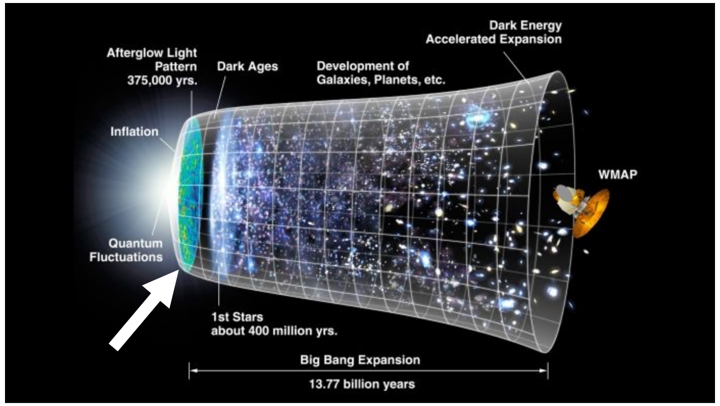
The Quark-Gluon Plasma is a **state of strongly-interacting (colored) matter** resulting from the **phase transition** of hadronic (color-neutral) matter under extreme conditions of pressure or temperature

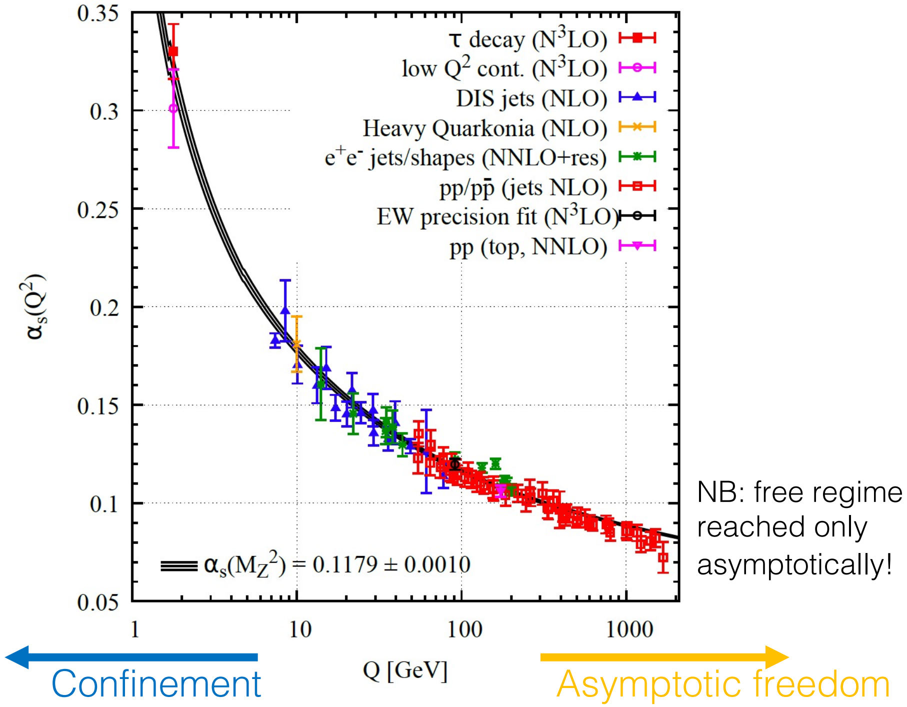
→ the **Universe O(1-10μs) after the Big Bang**

→ the properties of the **QGP emerge from the fundamental properties of the strong interaction**

→ **physics of condensed QCD matter**

→ a quest towards a **quantitative characterization of the QGP**





NB: free regime is reached only asymptotically!

QCD in extreme conditions in the laboratory

A QGP can be formed by compressing large amount of energy in a small volume

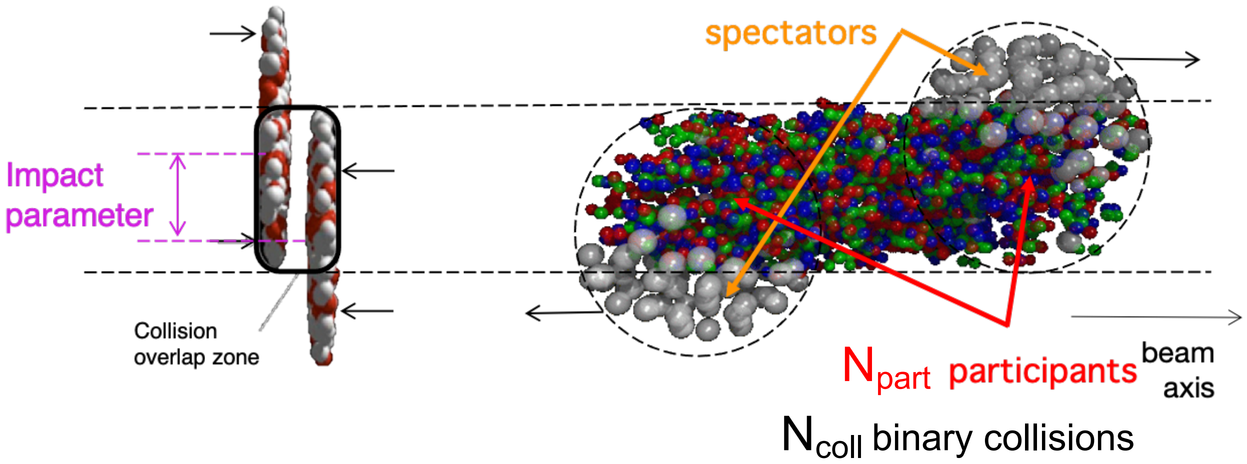
→ collide **heavy nuclei** (multiple, ~simultaneous nucleon-nucleon collisions)

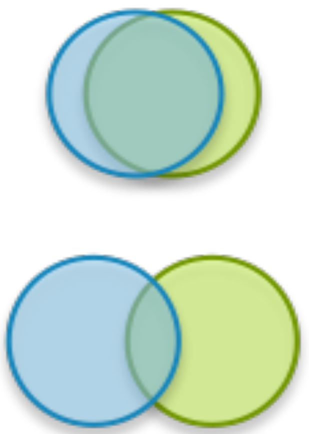
→ **control/vary the energy deposited** in the collision region by varying the collision system

- impact parameter/centrality, nuclear species, p-Pb, pp
- Classify events based on final-state charged particle multiplicity (good scaling observable? YES!)

→ **no direct observation** of the QGP is possible → rely on emerging particles as **probes**

Centrality = percentile of the total hadronic cross section





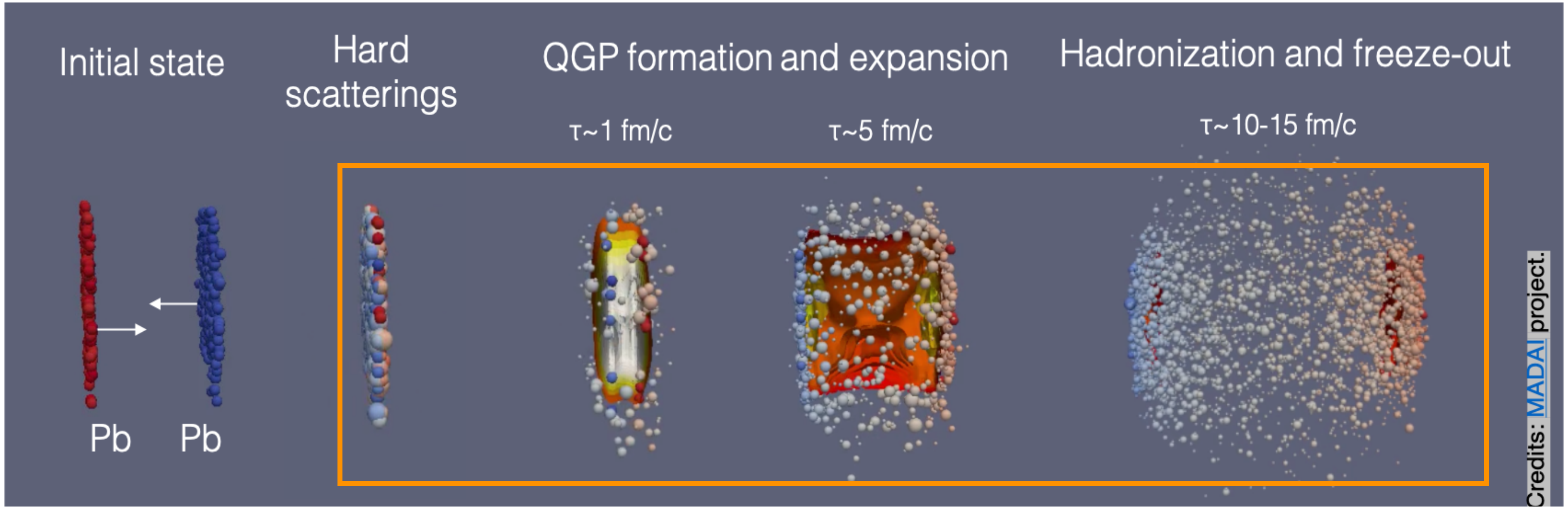
Central collisions (e.g. 0-10%)

→ Small impact parameter
→ Large N_{coll} and N_{part}
→ High particle multiplicity, N_{ch} or $dN_{ch}/d\eta$

Peripheral collisions (e.g. 70-80%)

→ Large impact parameter
→ Low N_{coll} and N_{part}
→ Low N_{ch} or $dN_{ch}/d\eta$

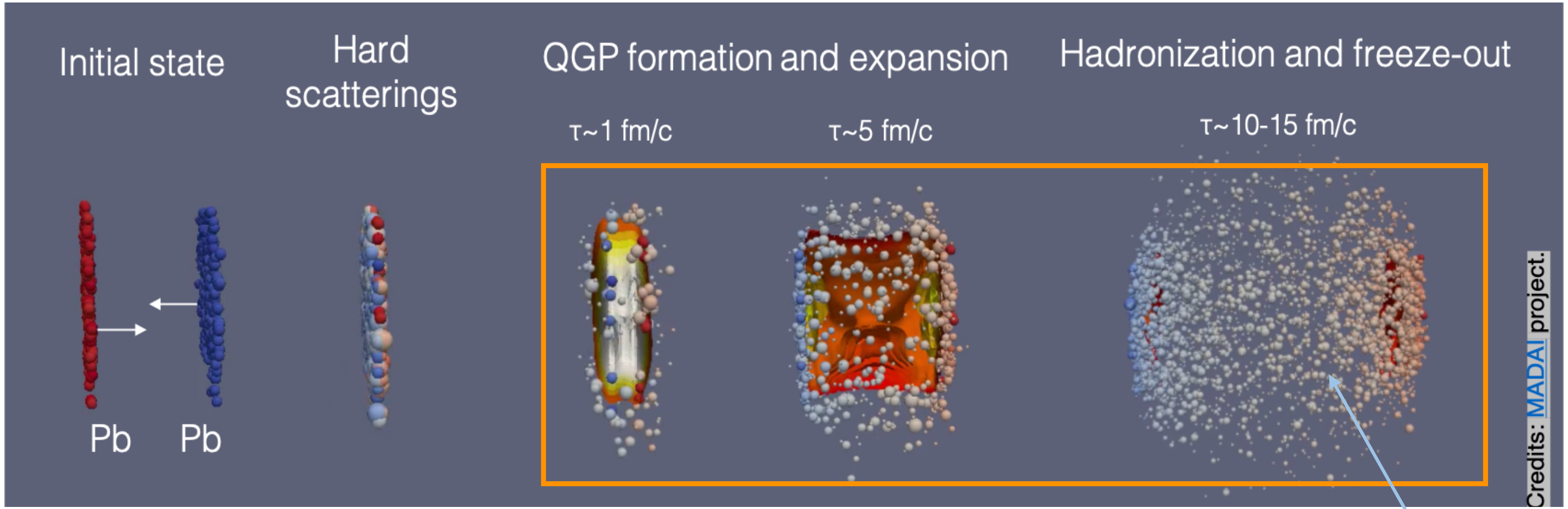
Access to all stages of the evolution



1 fm/c = 3×10^{-24} s, 1 MeV ~ 10^{10} K

Charm and beauty quarks (→ open HF, quarkonia), high-p_T partons (→ jets)
produced in the early stages in hard processes,
traverse the QGP interacting with its constituents
→ rare, calibrated probes, pQCD
→ in-medium interaction (energy loss) and transport properties
→ in-medium modification of the strong force and of fragmentation

Access to all stages of the evolution

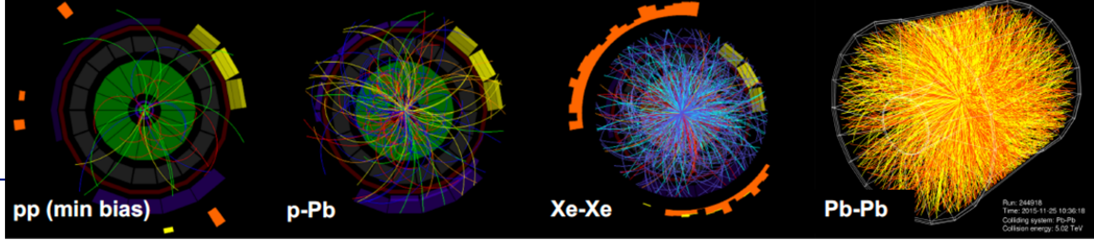


1 fm/c = 3×10^{-24} s, 1 MeV ~ 10^{10} K

Low-p_T particles, light flavour hadrons (u,d,s, +nuclei)
produced from hadronization of the strongly-interacting, thermalized QGP constitute the bulk of the system
→ non-perturbative regime
→ **thermodynamical, hydrodynamical and transport properties**

>2k charged particles per unit of rapidity in 5% most central Pb-Pb: 98% with p_T < 2 GeV/c, 90% pions

Outline



A **selection of results** from a broad experimental programme:

1. nuclear modification of high p_T particles, open charm and beauty hadrons
2. nuclear modification of quarkonium → **in medium energy loss and trasport**
3. particle abundances and strangeness enhancement
4. formation of nuclear clusters and hadron-hadron interaction → **hadronisation**
5. radial flow
6. elliptic flow of light flavour, beauty and charm hadrons → **collectivity**

A brief outlook to the physics with ion beams in the **near and far future at the LHC**:

1. LHC detector upgrades and physics in Runs 3 and 4
2. Run 5 and beyond: ALICE 3 as a new HI dedicated detector

See more in the next talk by A. Mazeliauskas for recent development of theory and quantitative characterizaton of the QGP properties

The nuclear modification factor, R_{AA}

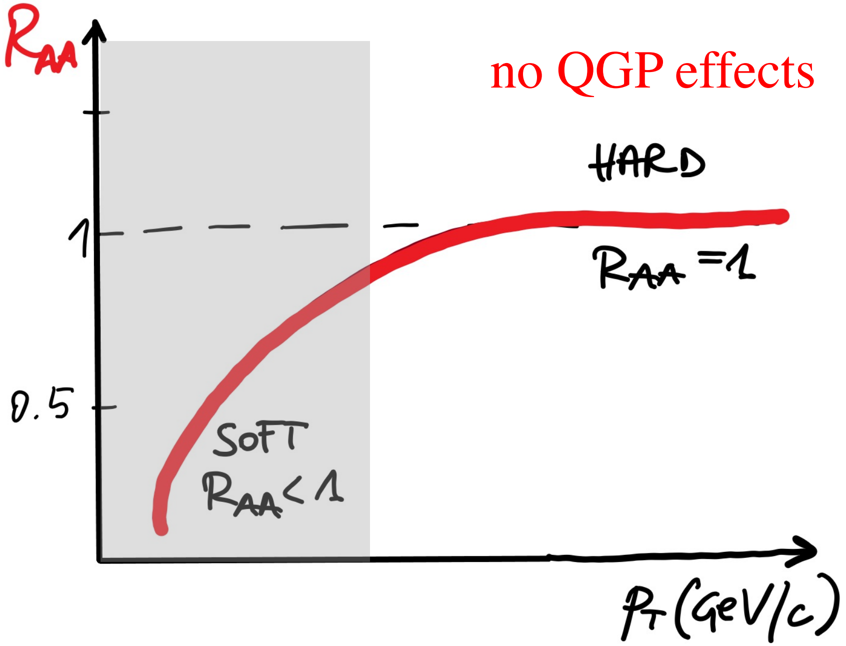
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

If a AA collision is a superposition of independent pp collisions, binary scaling holds for hard scattering processes:

$$\mathrm{d}N_{AA}/\mathrm{d}p_T = N_{coll} \times \mathrm{d}N_{pp}/\mathrm{d}p_T$$

and $R_{AA} = 1$ at high p_T
→ the medium is transparent to the passage of partons

NB: at low p_T, soft, non perturbative regime → R_{AA} not a good observable



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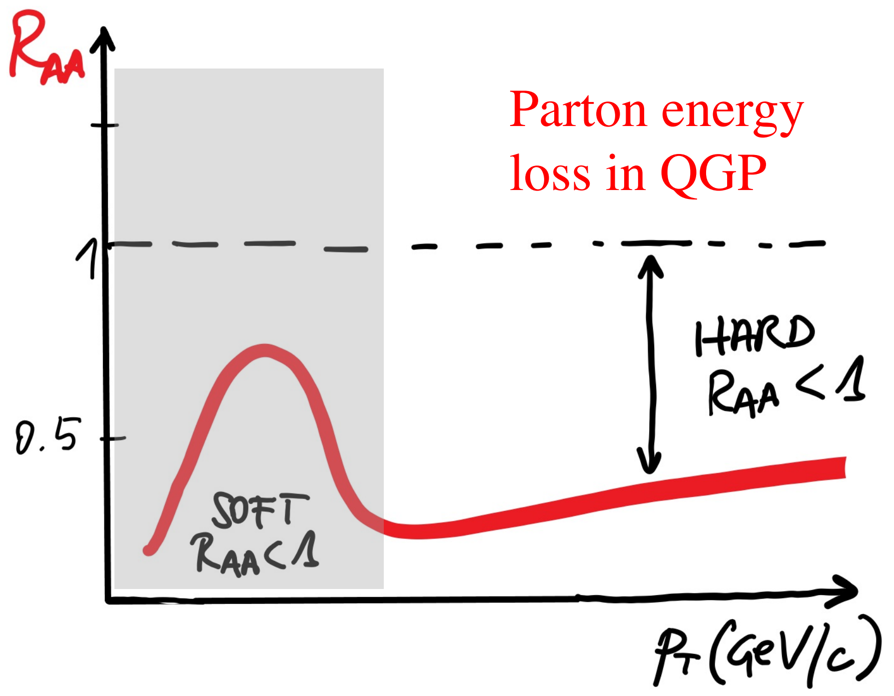
If R_{AA}< 1 at high p_T

→ the medium is **opaque** to the passage of partons

→ parton-medium final state interactions, energy loss, modification of FFs in the medium

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$$



Hard probes: QCD factorization extended to AA

$$\sigma_{AA\to hX} = \underbrace{NPDF(x_a, Q^2) NPDF(x_b, Q^2)} \otimes \underbrace{\sigma_{ab\to q}} \otimes \underbrace{P(\Delta E)} \otimes \underbrace{D_{q\to h}(z_q, Q^2)}$$

Cross section in AA collisions

Nuclear Parton Distribution Functions (nPDFs)
From proton to nuclear projectile/target
→ constrain with pA

cross section in vacuum

Parton interaction with medium

Fragmentation Functions (FFs)

Evidence of parton energy loss in QGP in central Pb-Pb

High precision measurements in a broad p_T range and vs centrality

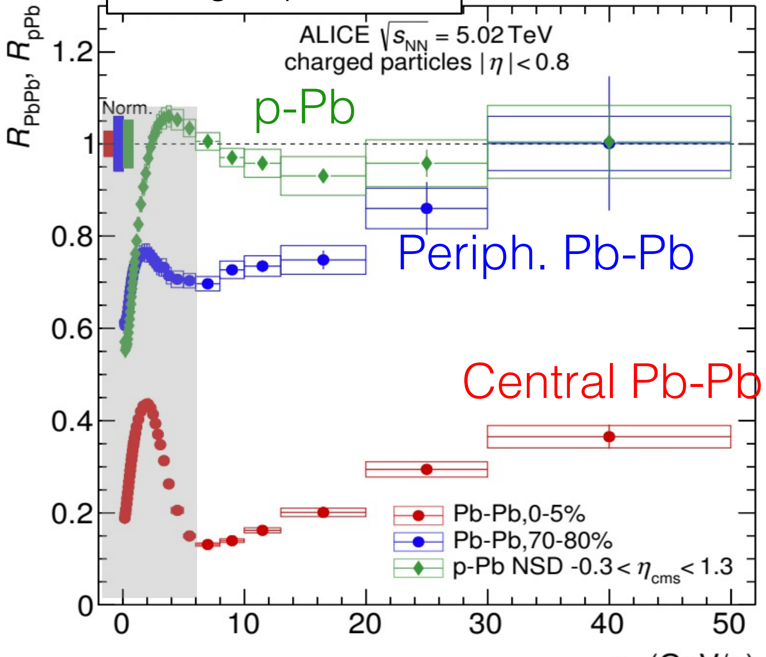
Strong suppression observed in central heavy-ion collisions up to very high p_T

No suppression for colorless Z bosons and photons, nor in p-Pb collisions

→ suppression due to parton energy loss

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

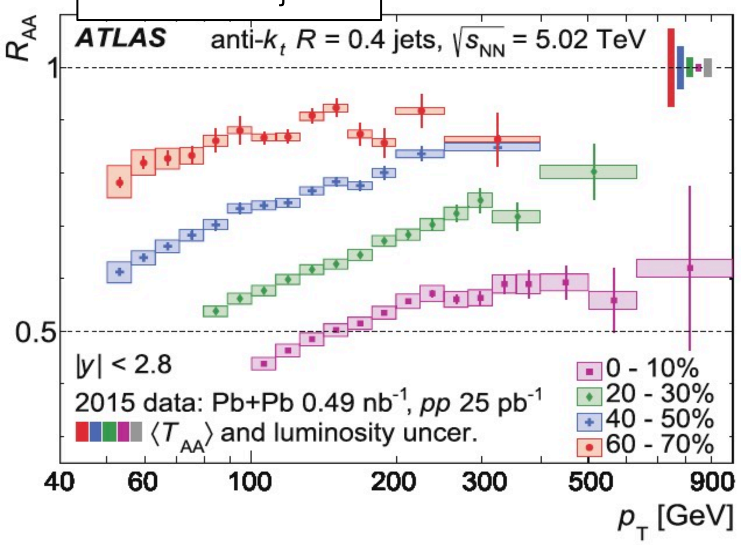
Charged particles



JHEP 11 (2018) 013

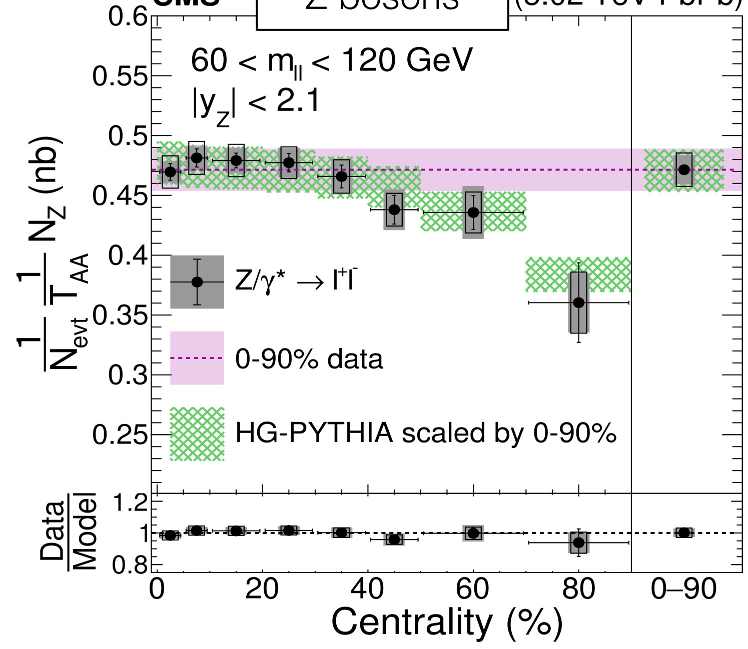
Run 2 data

Inclusive jets



PLB 790 (2019) 108

Z bosons



arXiv:2103.14089

No energy loss in small systems?

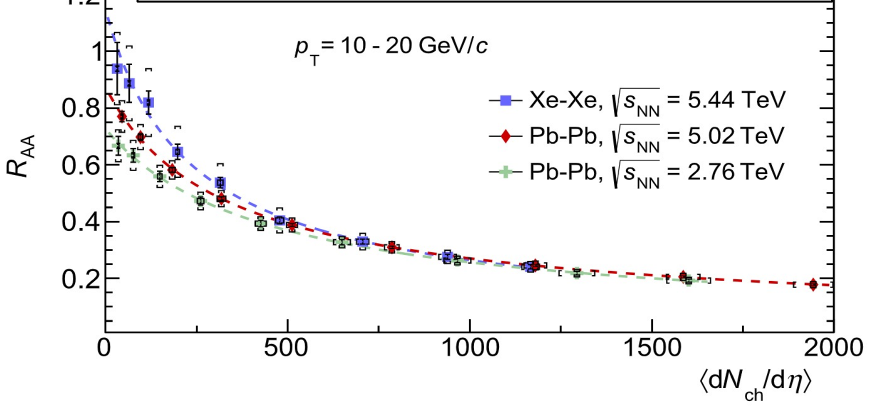
In Xe-Xe and in Pb-Pb, similar R_{AA} at similar final state charged particle multiplicity

Suppression in peripheral AA (similar multiplicity as p-Pb) from selection and collision geometry biases

→ no parton energy loss in peripheral Pb-Pb

OPEN QUESTION: **when does energy loss sets in?**

Compare $\sqrt{s_{NN}}$ and w/ Xe-Xe



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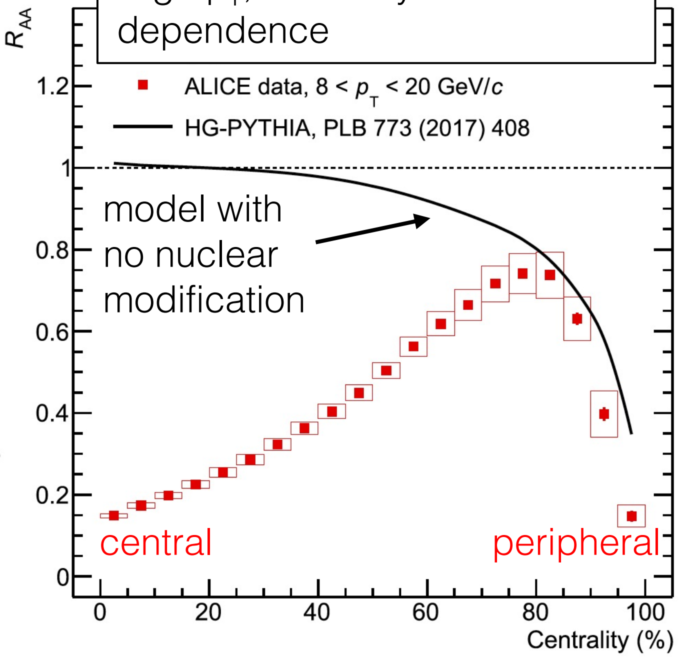
High p_T, centrality dependence



PLB 793 (2019) 420

Outlook to Runs 3 and 4:
→ Search for energy loss effects with light ion collisions (e.g. O-O, Ar-Ar, low $N_{part,}$ multiplicity similar to p-Pb, known geometry)

Energy loss of charm and beauty

Charm and beauty, produced in initial hard scatterings quarks loose energy via **gluon radiation** and **elastic collisions**

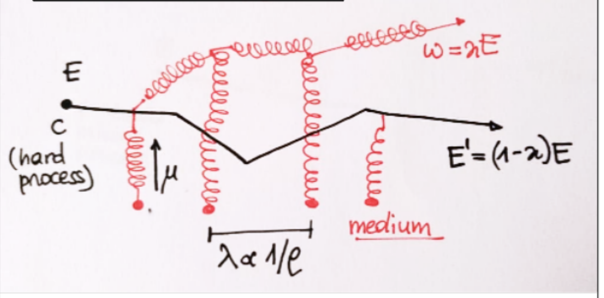
→ depend on color charge (C_r), mass, path length (L) and medium density (ρ)

→ provides information about the **nature of the energy loss mechanism** and the **properties of the medium**

Dead cone effect = suppression of the gluon radiation emitted by a (slow) heavy quark at small angles, $\vartheta < \vartheta_{DC} \sim m_q/E_q$

→ hierarchy in energy loss: $\Delta E_g > \Delta E_c > \Delta E_b$

In-medium E_{loss}



Baier-Dokshitzer-Mueller-Peigné-Schiff, Nucl. Phys. B. 483 (1997) 291

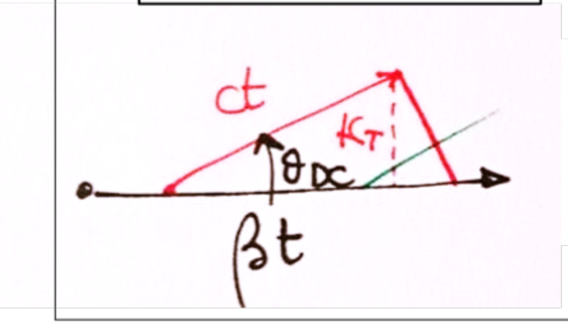
$$\langle \Delta E \rangle \propto \alpha_s C_r \hat{q} L^2$$

$$\hat{q} = \frac{\mu^2}{\lambda}$$

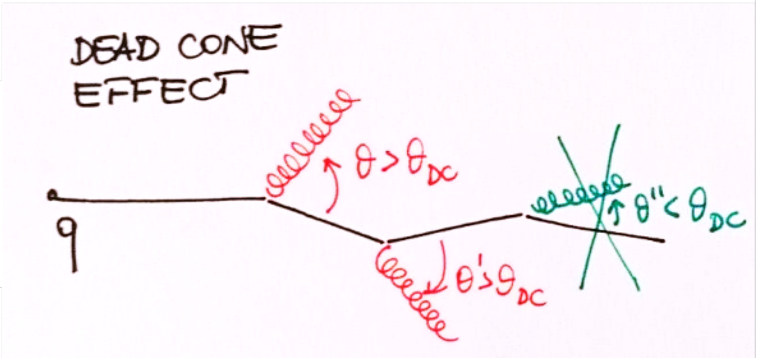
Average transverse momentum transfer

Mean free path ~1/density

Dead cone effect



$$\sin\theta_{DC} = 1 - \beta^2 = \left(\frac{M}{E}\right)^2$$

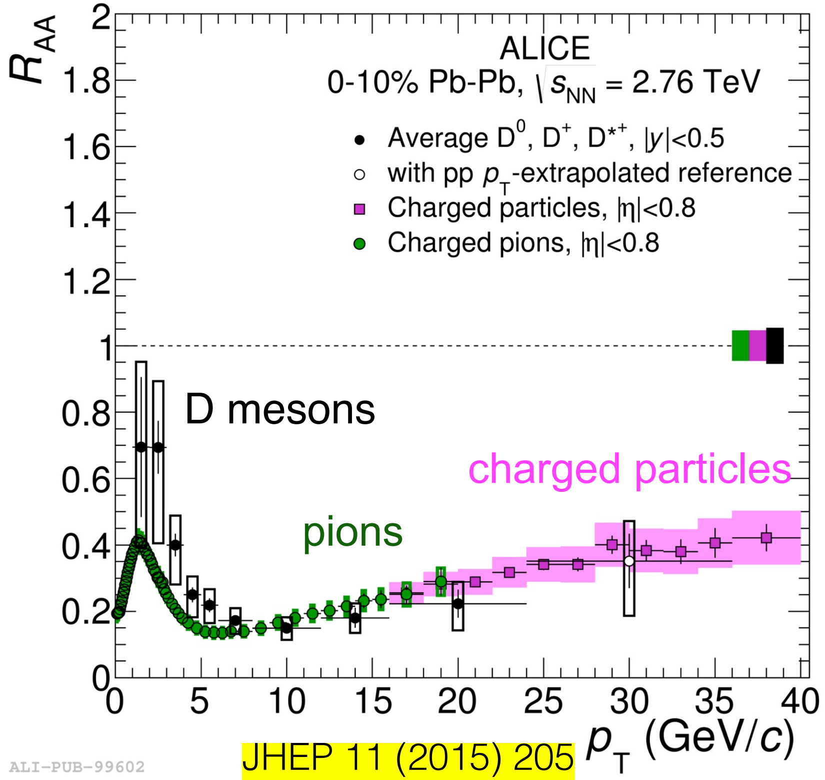


R_{AA} of heavy flavours

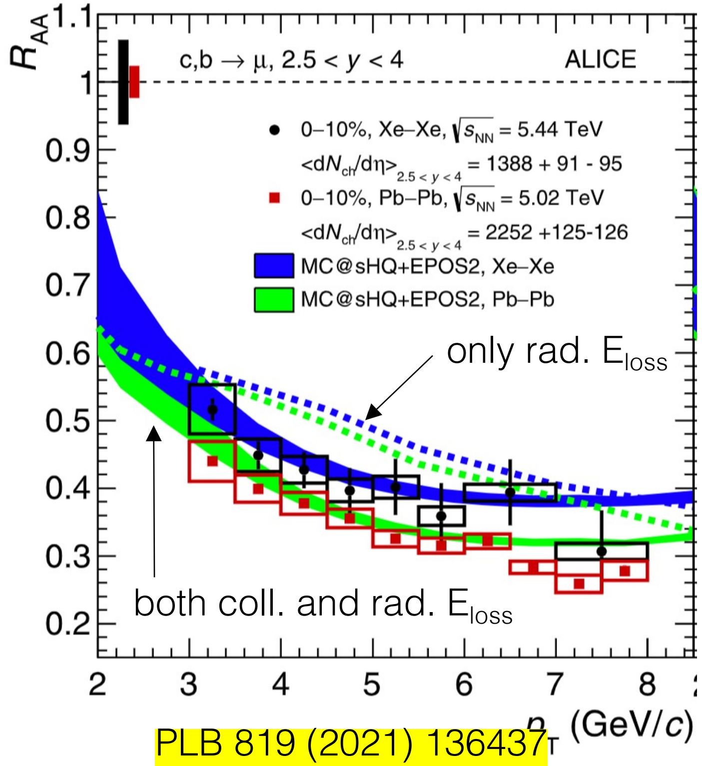
Strong suppression observed for charm and beauty via open charm mesons and leptons from c and b decay

Similar suppression for D and pions, less suppression for J/ψ from beauty than for D mesons → $\Delta E_c > \Delta E_b$

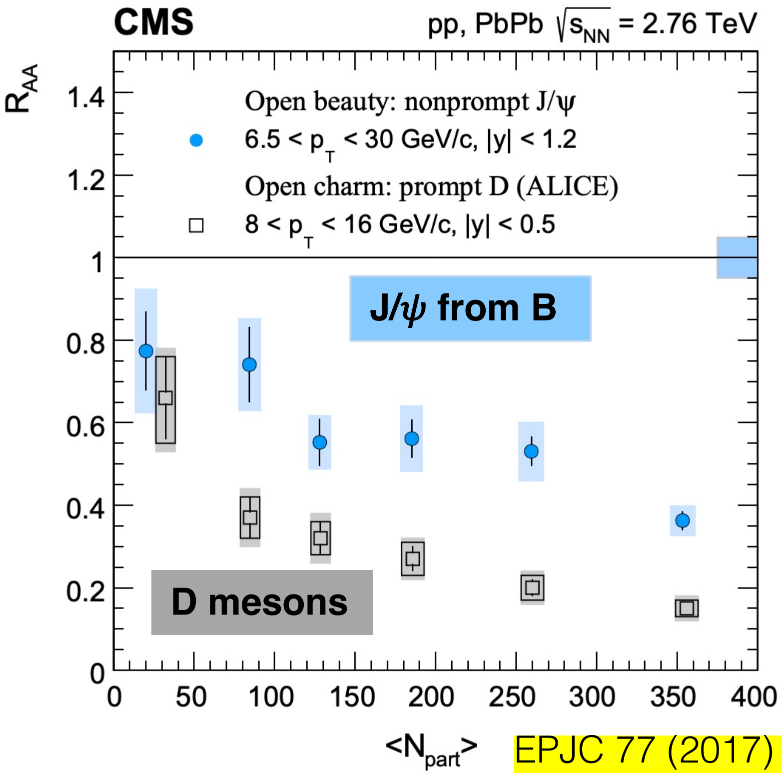
Results well described by models with both collisional and radiative E_{loss}



JHEP 11 (2015) 205



PLB 819 (2021) 136437



EPJC 77 (2017) 252

Intermezzo: first observation of the dead-cone effect in pp

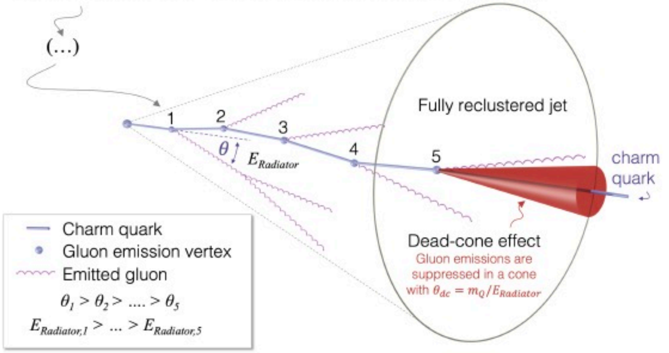
The pattern of the parton shower in vaccum is expected to depend on the mass of the initiating parton

First direct observation of the dead cone effect in QCD in hadronic collisions (pp 13 TeV) using D⁰-meson tagged jets

- new iterative declustering techniques used to reconstruct the parton shower of charm quarks
  Frye et al., JHEP 09 (2017) 083,
  Dreyer et al., JHEP 12 (2018) 064

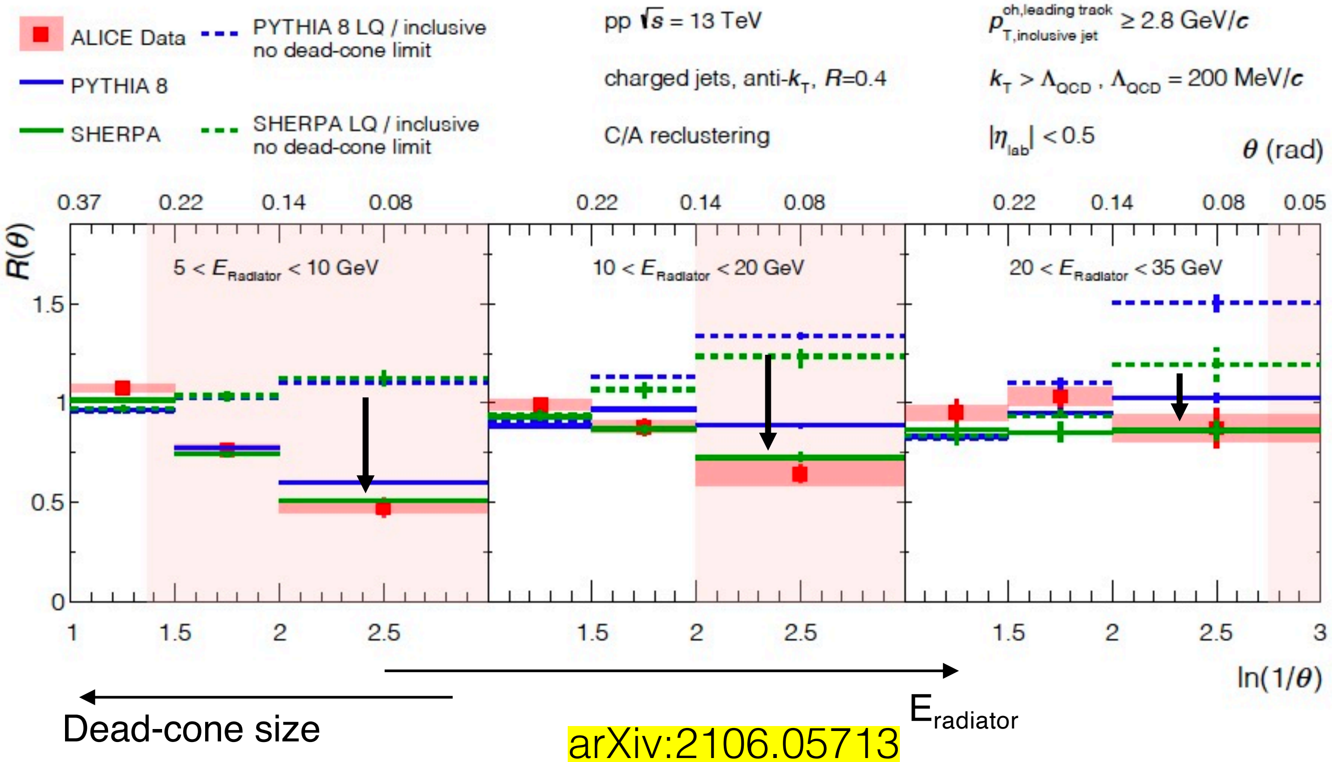
Prospects:

- beauty quark > mass dependence
- AA collisions > in-medium vs in-vacuum



Ratio of the splitting angle (θ) distributions for D^0-meson tagged jets and inclusive jets, in bins of $E_{Radiator}$

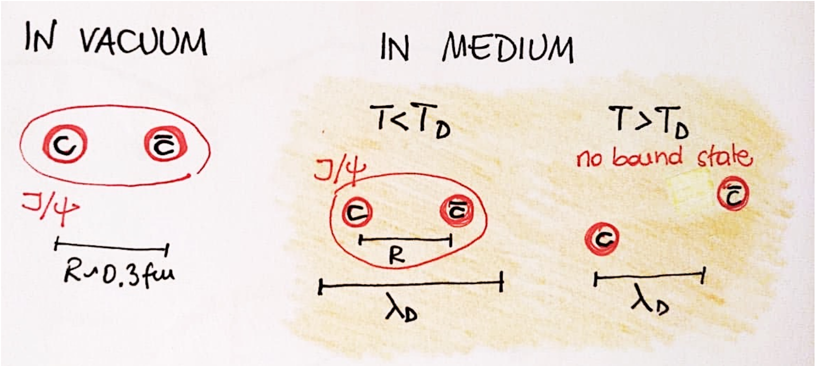
$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}}\frac{dn^{D^0\,\text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}}\frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)}\Bigg|_{k_T, E_{Radiator}}$$



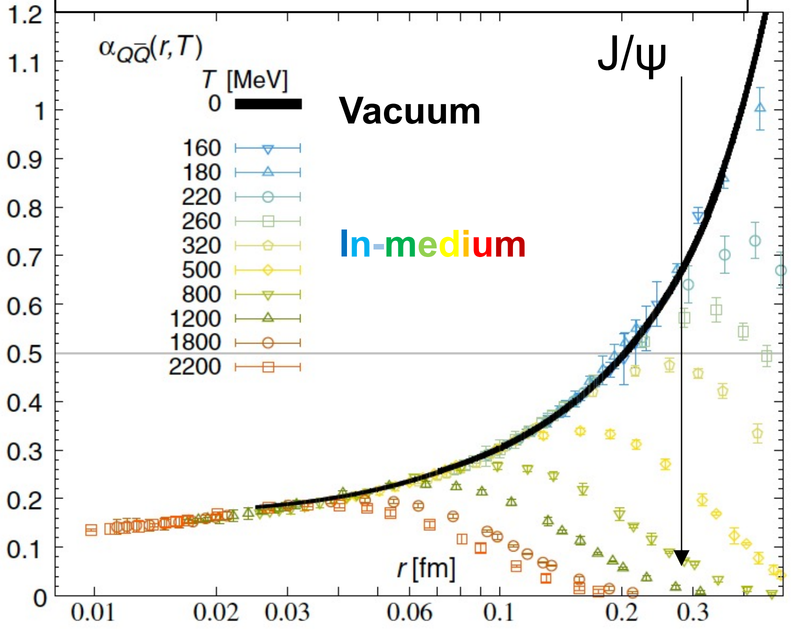
arXiv:2106.05713

Quarkonia at the LHC

Suppression of quarkonium suggested in the 1980's as QGP signature:
→ $q\bar{q}$ pairs are suppressed due to **color screening in the QGP**
→ lattice QCD predicts the effective $q\bar{q}$ coupling to decrease in medium with increasing T



Effective $q\bar{q}$ strong coupling from lQCD



A.Bazavov et al., Phys. Rev. D 98 (2018) 054511

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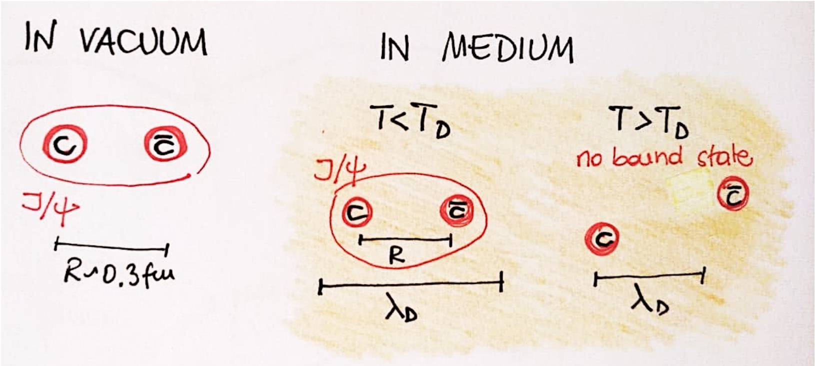
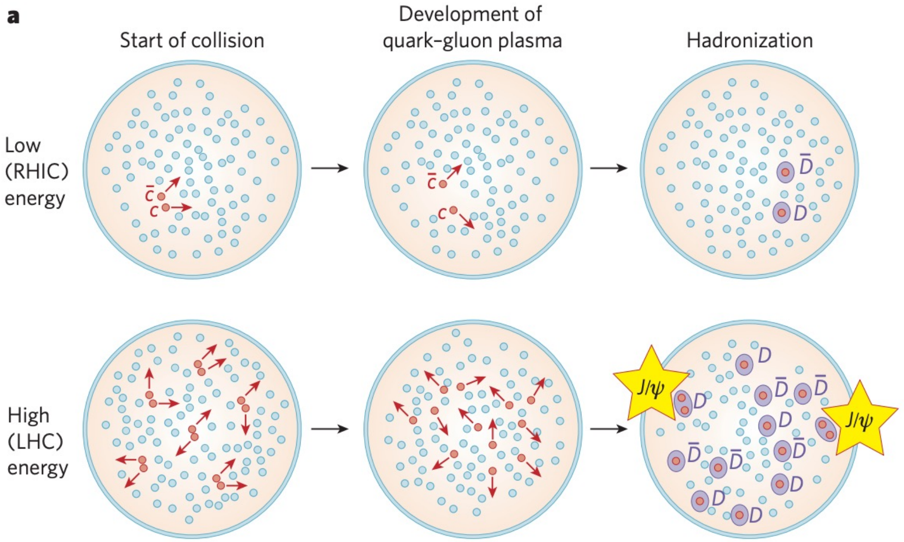
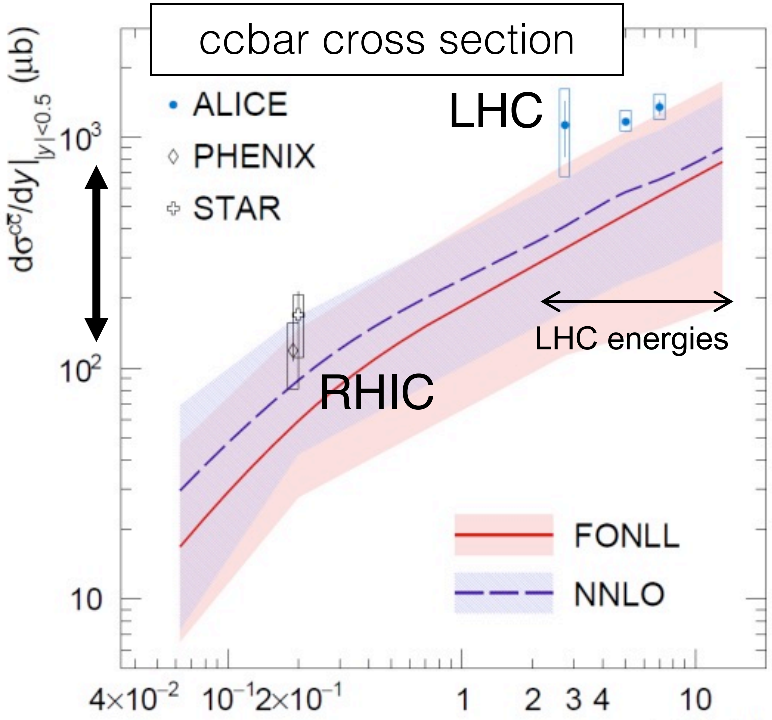
→ $q\bar{q}$ pairs are suppressed due to **color screening in the QGP**
→ lattice QCD predicts the effective $q\bar{q}$ coupling to decrease in medium with increasing T

$c\bar{c}$ cross section increase with $\sqrt{s}$:
~100 $c\bar{c}$ per central Pb-Pb event at the LHC vs ~10 $c\bar{c}$ at RHIC
→ **(re)generation of charmonium** and charmed hadron production take place at the phase boundary or in QGP





P. Braun-Munzinger, J. Stachel., Nature 448, 302–309 (2007)



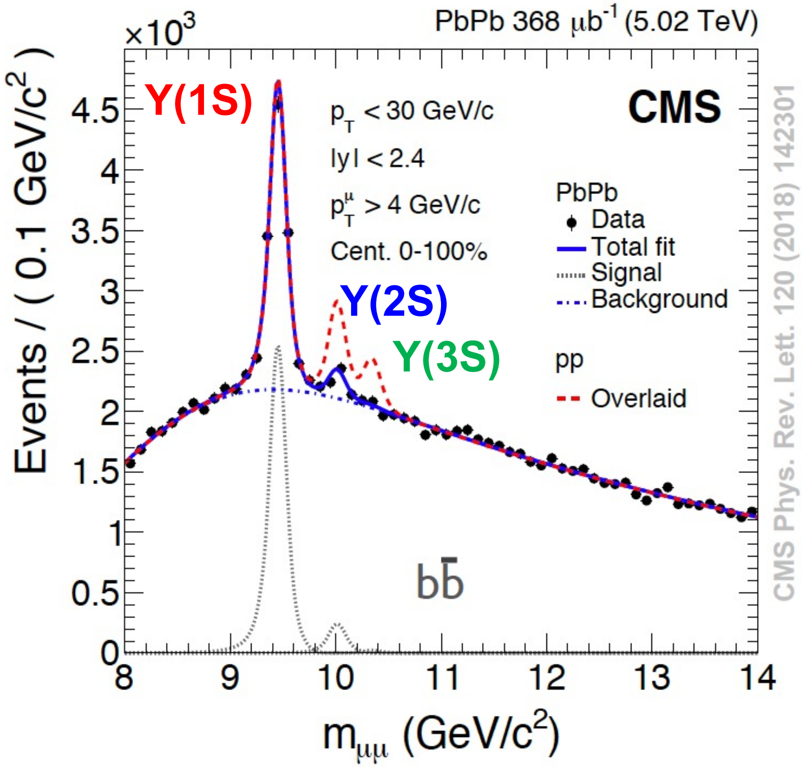
arXiv:2105.06335

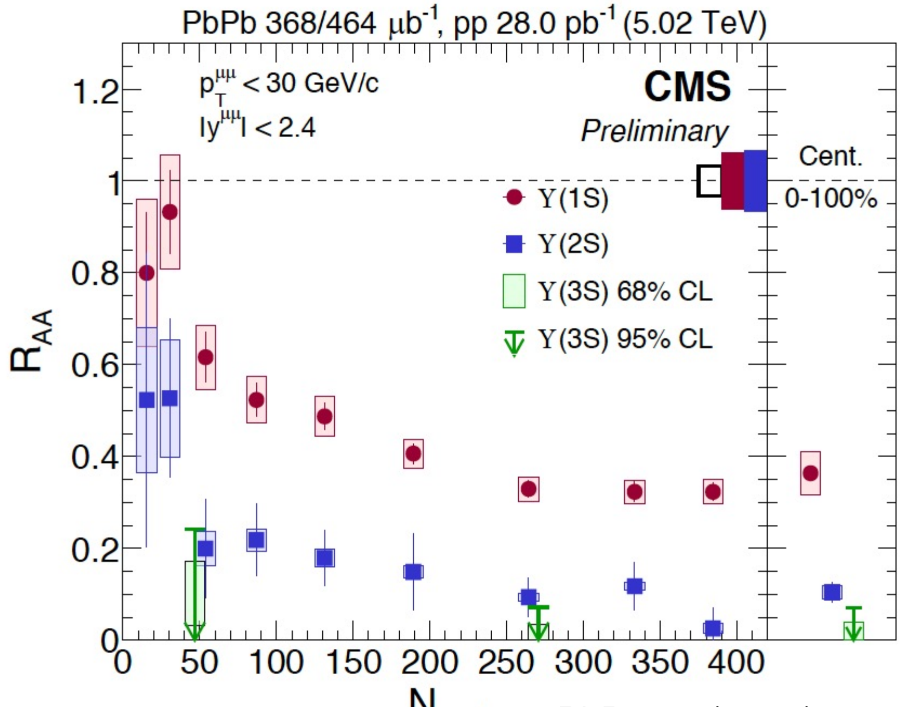
Sequential suppression of bottomonium states

Sequential suppression of excited bottomonium states observed

→ Centrality dependence consistent with **progressive suppression in a hotter medium**

→ Quarkonium as a **thermometer** for QGP





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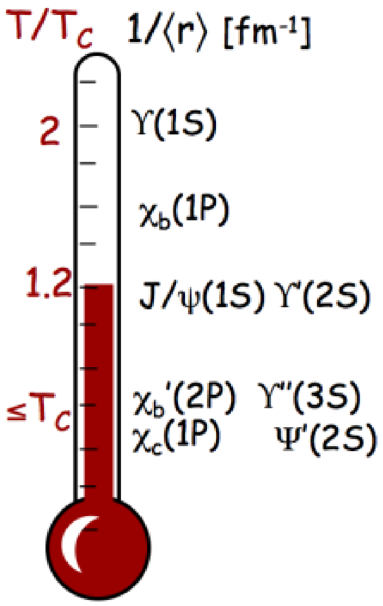


Figure: A. Mocsy
arxiv:0811.0337

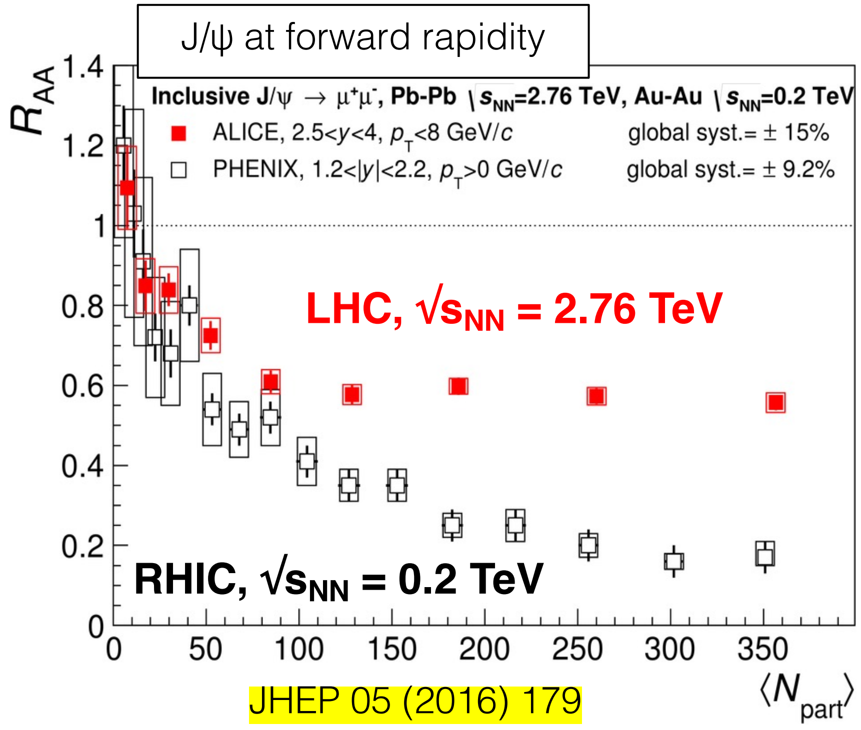
J/ψ dissociation and recombination at the LHC

R_{AA}(LHC) > R_{AA}(RHIC), R_{AA}at midrapidity > R_{AA} at forward rapidity

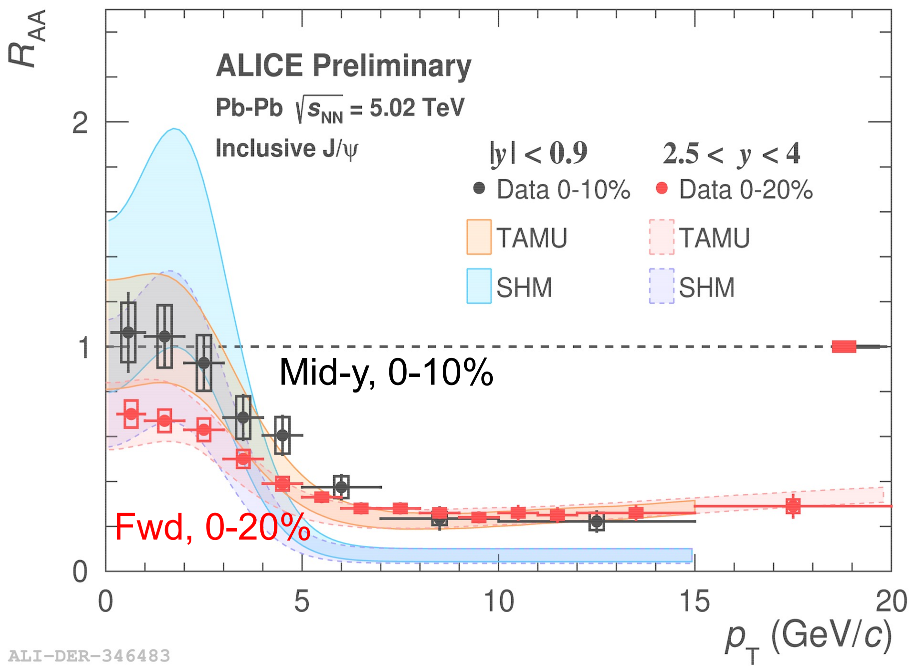
Statistical hadronization (SHM) and transport models based on the recombination picture describe data

→ **The J/ψ recombination picture is confirmed by LHC data** → signature of de-confinement

Not covered in this talk:
Fundamental measurements in p-Pb collisions constrain nPDFs and initial state effects
Coherent photoproduction of J/ψ plays a role in peripheral and ultra-peripheral Pb-Pb



JHEP 05 (2016) 179



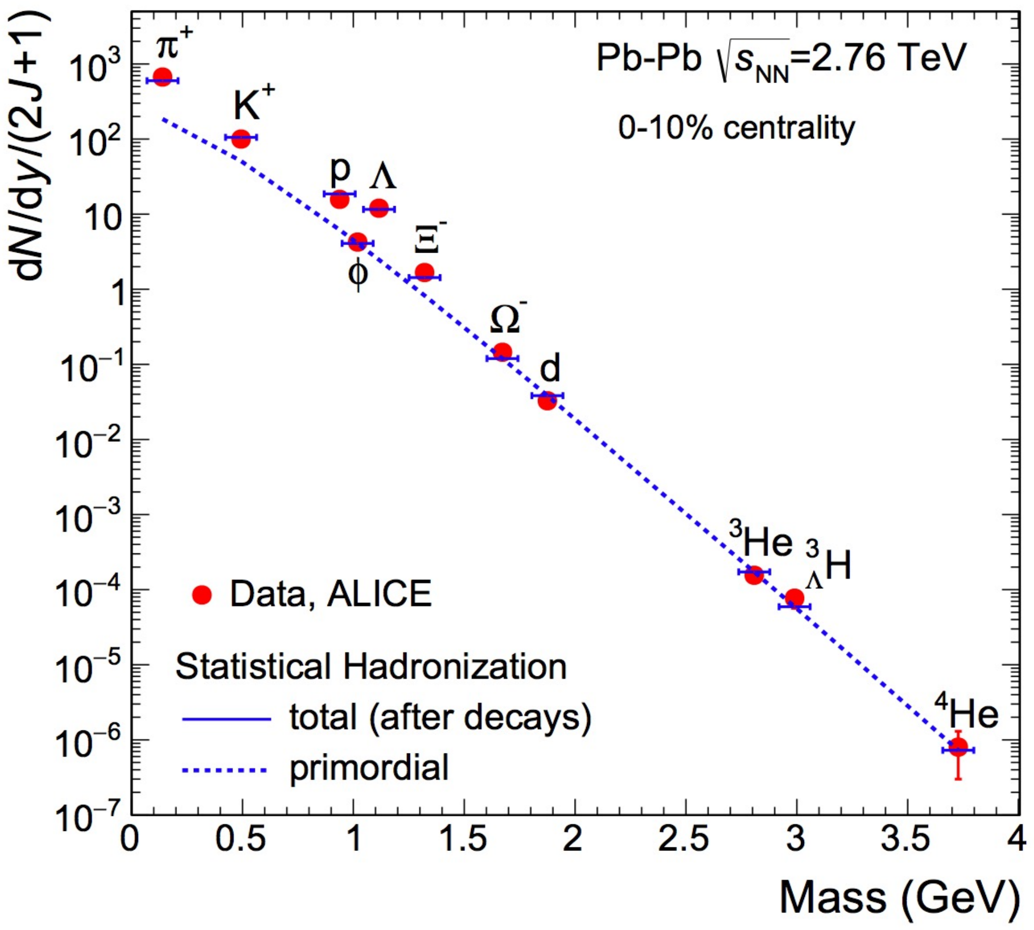
Light flavour hadrons from QGP hadronization

Success of the statistical hadronization model (chemical equilibrium) in describing yields of light flavour hadron species over 10 orders of magnitude in central AA collisions

(including strangeness, light nuclei and hypernuclei)

→ **bulk produced from the hadronization of a QGP in thermodynamical equilibrium**

$T_{chemical} \sim 155$ MeV



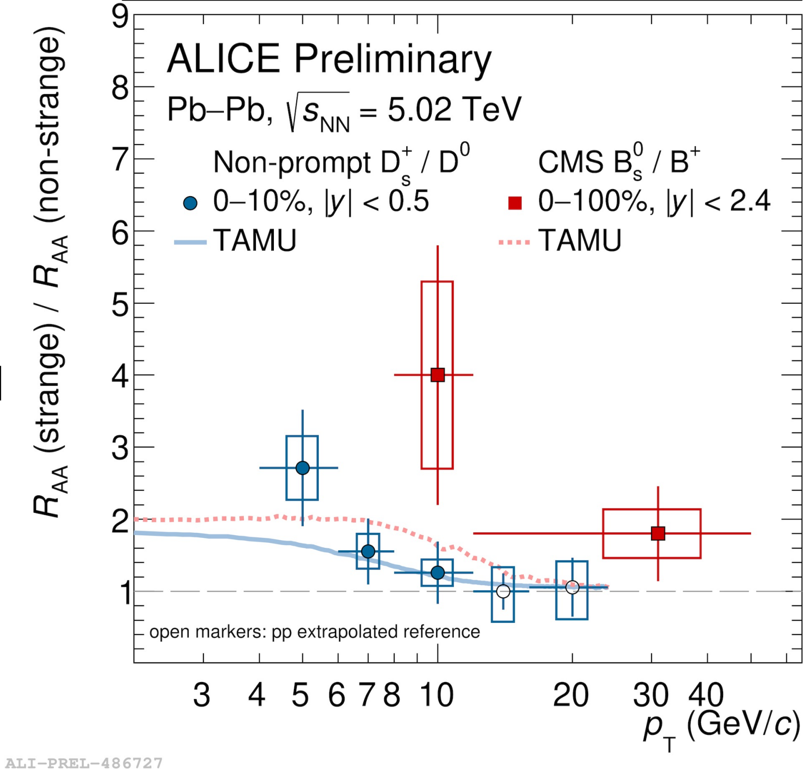
A. Andronic et al., Nature 561, 321 (2018)

Heavy flavour hadronization in heavy-ion collisions

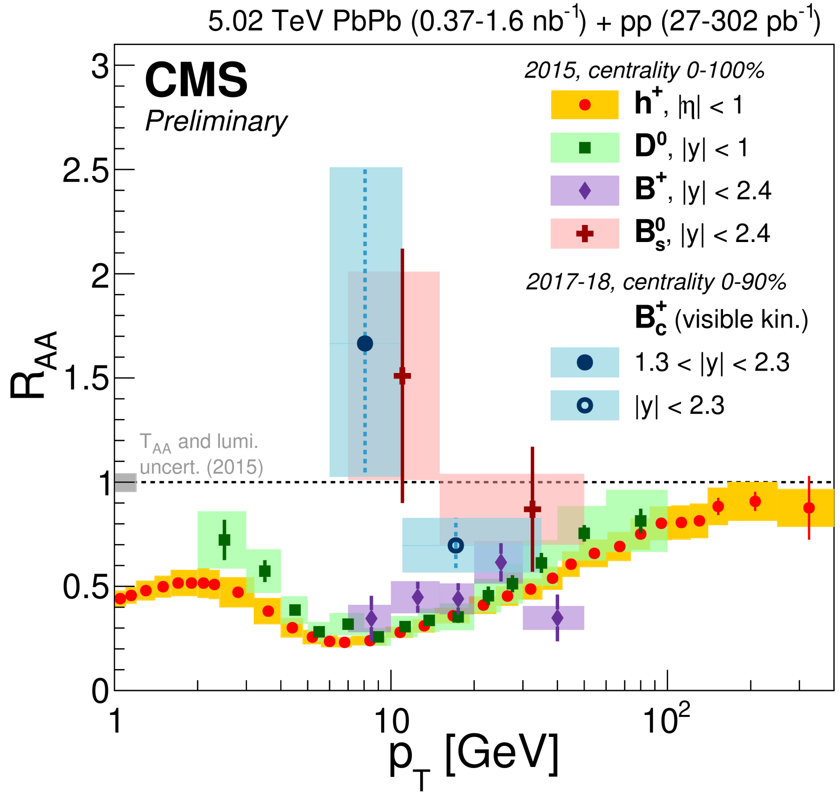
At low p_T, enhanced production of open heavy-flavour (D_s^+, B_s^0) with strangeness
→ **hadronisation via recombination in a strangeness-rich medium**

At mid p_T, B_s^0 and B_c^+ less suppresed than D, B, bottomonia and light hadrons
→ additional evidence that **recombination is at play?**

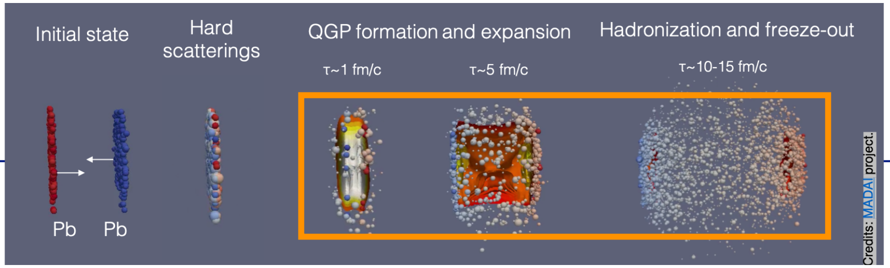
First measurement of non-prompt D_s^+/D^0 in central HI



First measurement of $B^+_c \rightarrow J/\psi + \mu + \nu_\mu$



Hydrodynamics at play: flow

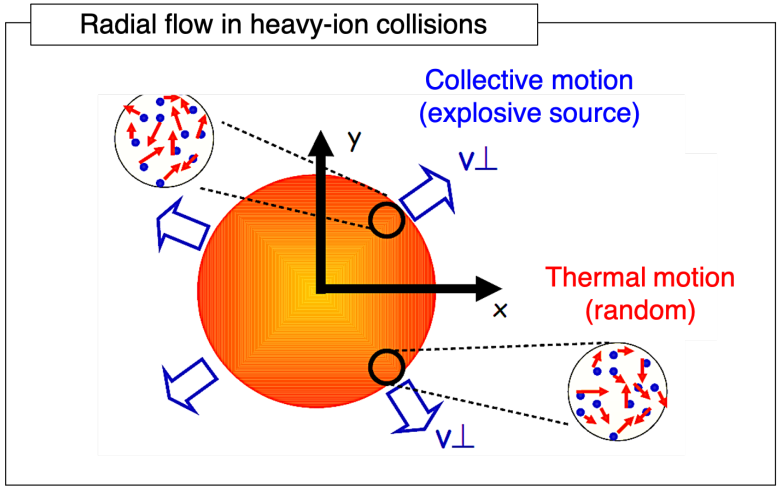


A collective motion of particles superimposed to the thermal motion → the system as a medium

Radial flow

radial expansion of a medium in the vacuum under a common velocity field

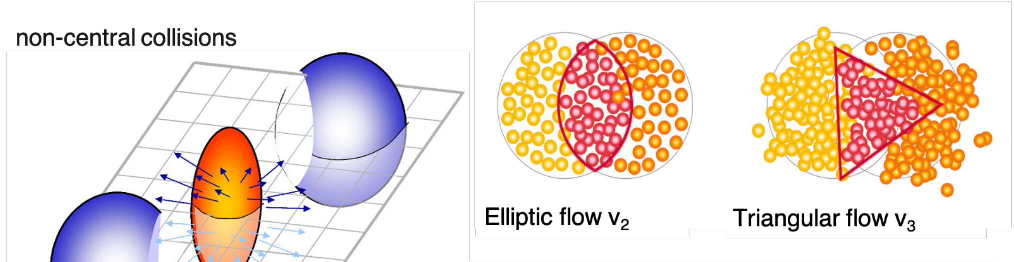
- Affects transverse momentum distribution of hadrons and their ratios, …



Anisotropic flow

pressure gradients convert spatial anisotropy into observable momentum anisotropies

- anisotropy in azimuthal angle described by a Fourier series
- v_n describe how initial fluctuations propagate in a viscous fluid



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

Radial and elliptic flow in AA collisions

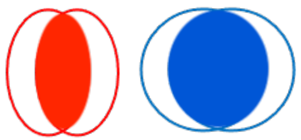
The presence of a **strong radial flow** is observed measuring light flavour hadron spectra and baryon/meson ratios

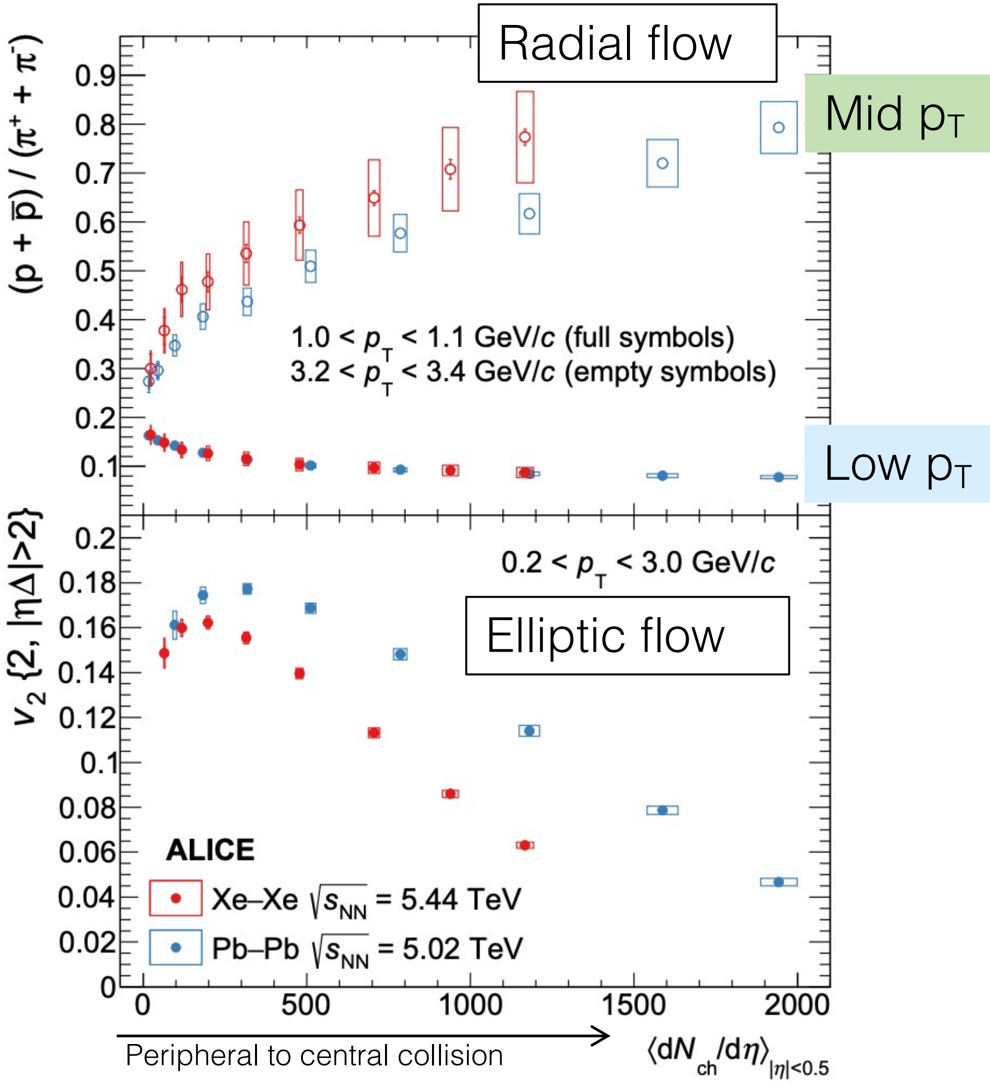
→ gets stronger with increasing centrality and pushes heavier particles to higher p_T

→ behaviour close to the **hydrodynamics** limit

Radial flow depends **only on the final-state charged particle multiplicity** (system size)

Elliptic flow depends on multiplicity and on the eccentricity (initial **geometry**)



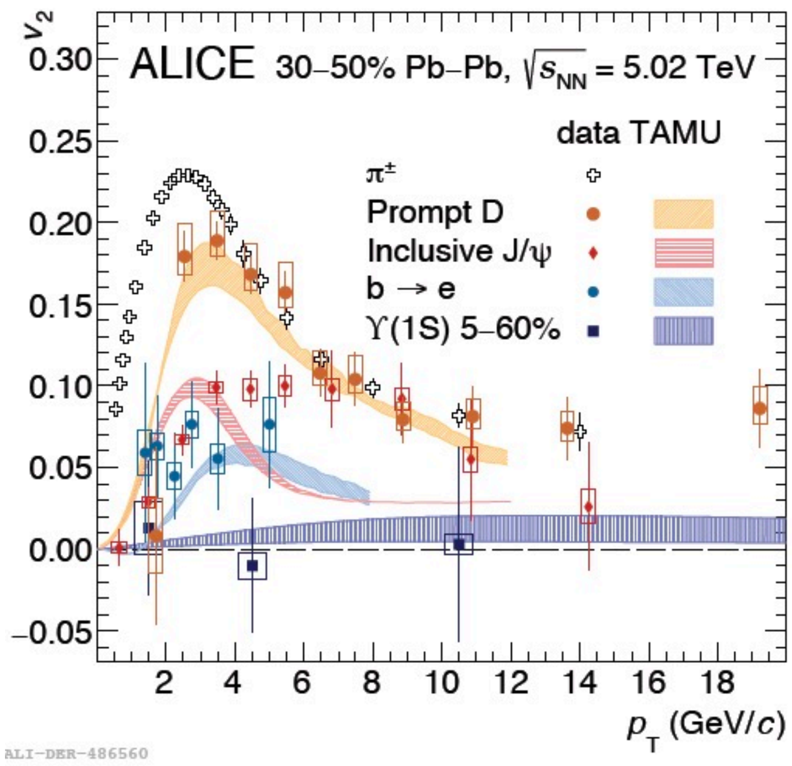


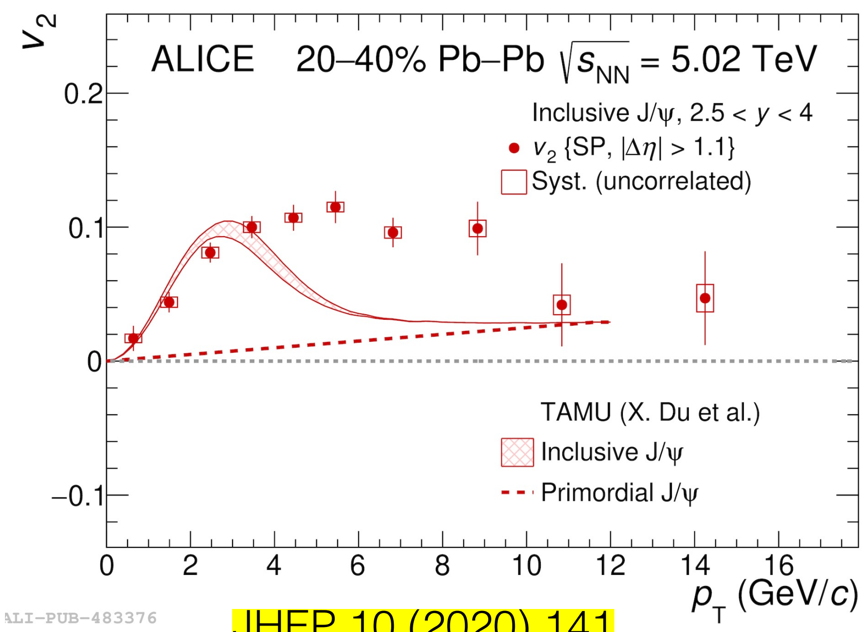
EPJC 81 (2021) 7, 584

Charm and beauty: to flow or not to flow

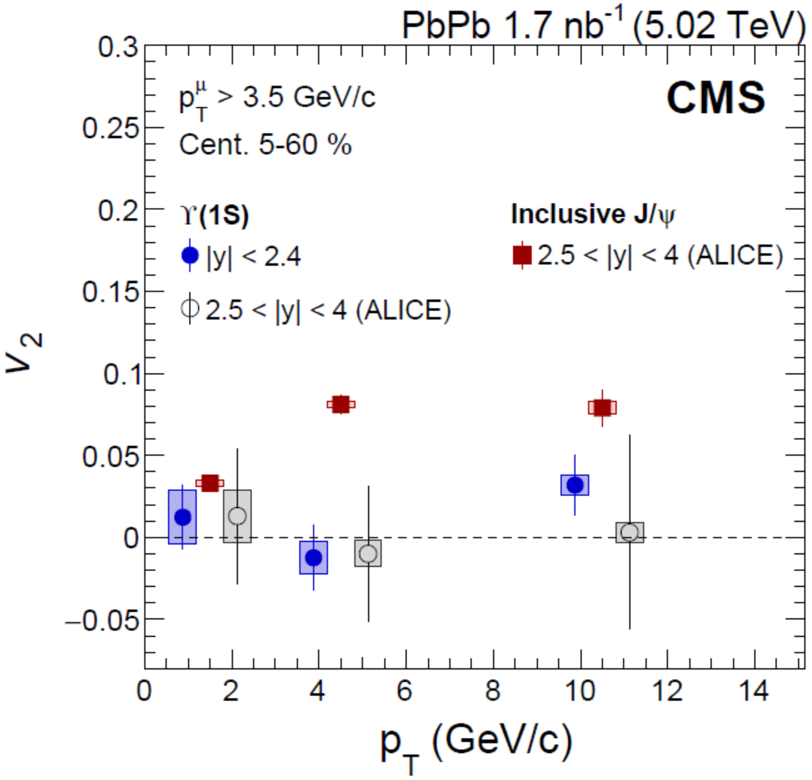
Charm hadron flow and R_{AA} at low p_T suggest that **charm is partially thermalized at the LHC**
→ a **partially-equilibrated probe** of the late hadronization stages

Beauty seems to experiences significantly less collectivity (if any) compared to charm
→ no significant evidence that **beauty** is even partially equilibrated with the medium → **non-equilibrium probe**





JHEP 10 (2020) 141

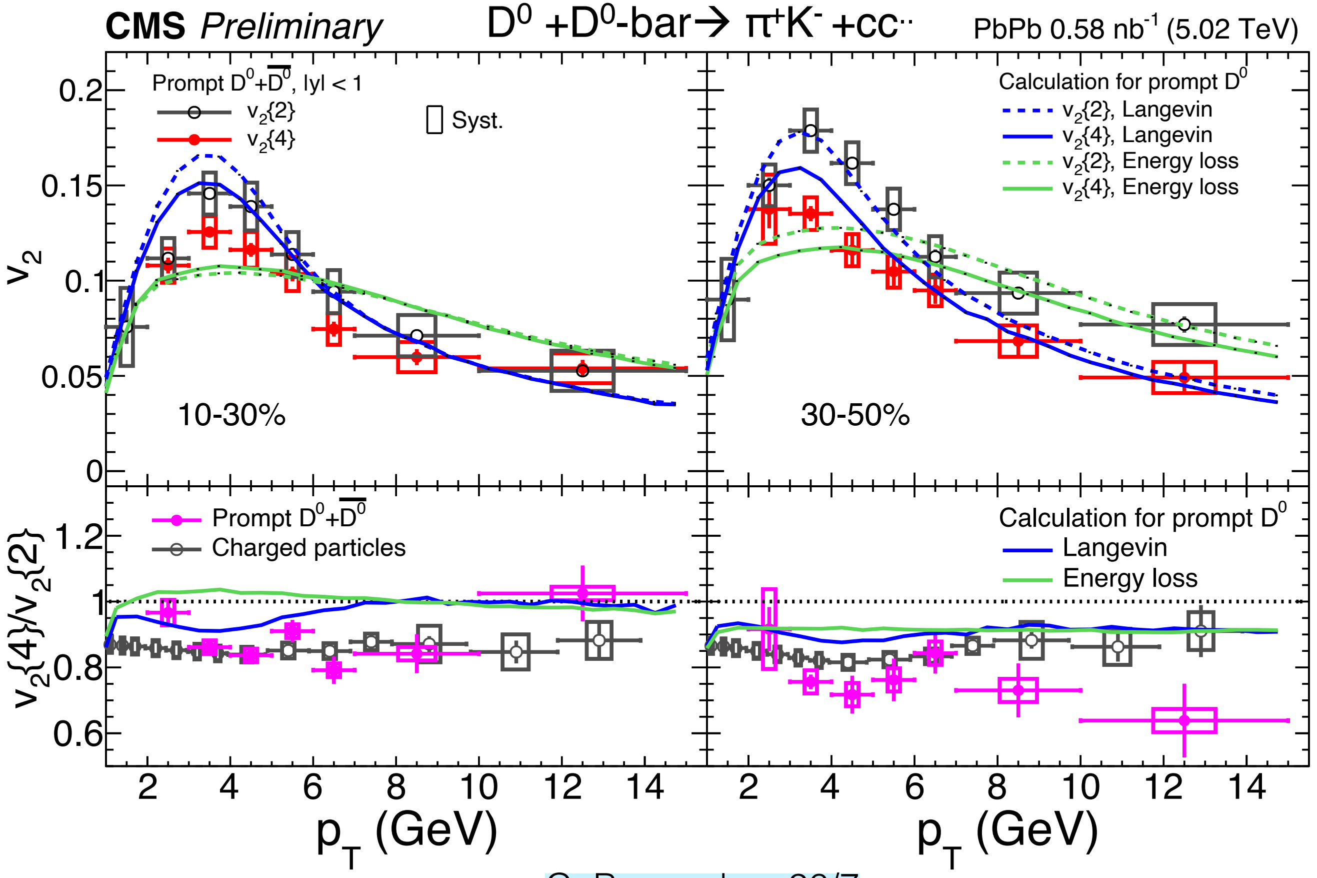


Prompt D^0 v_2 with 4-particle cumulants

Correlations of a D^0 meson with one (v2{2}) or three (v2{4}) other charged particles found in the detector.

→ Low-p_T charm quarks are strongly coupled to the QGP medium

At high-p_T, energy loss is expected to dominate.



C. Bernardes, 26/7

Collectivity correlates many particles over a wide η range

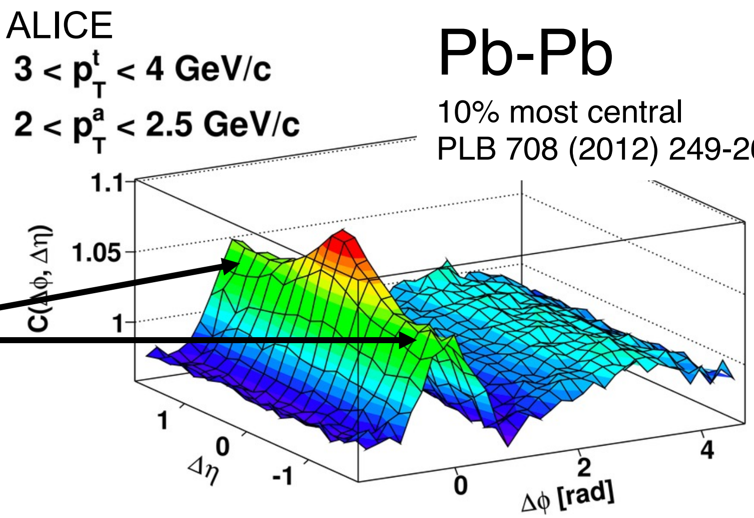
Observable: two-particle correlations vs $\Delta\eta$ (difference in rapidity) and $\Delta\varphi$ (difference in azimuthal angle)

The **ridge** spanning a large range in $\Delta\eta$ is due to long-range correlations emerging from early times (causality)

The azimuthal structure is due to the **medium response to the initial transverse geometry** (elliptic flow)

Discovered at the LHC

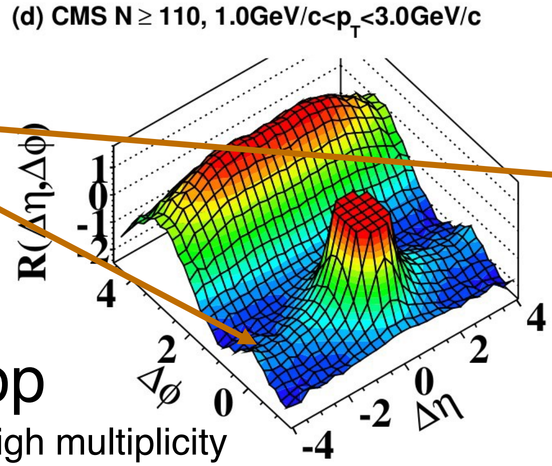
in high-multiplicity pp and p-Pb



Pb-Pb

10% most central

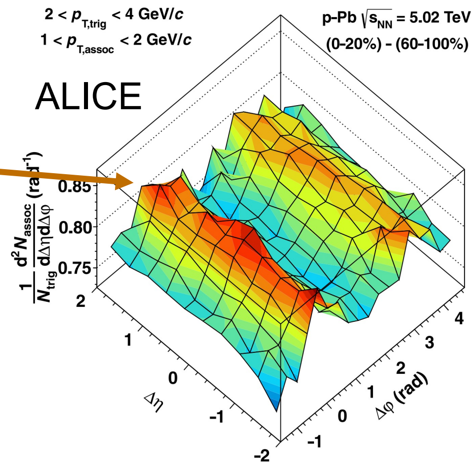
PLB 708 (2012) 249-264



pp

high multiplicity

JHEP 09 (2010) 091



p-Pb

Low-multiplicity subtracted

PLB 719 (2013) 29

Collectivity correlates many particles over a wide η range

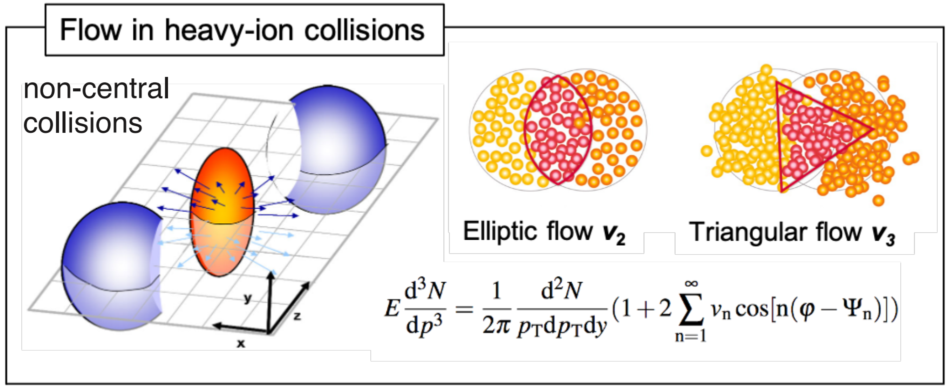
Elliptic flow from multi-particle correlations:

$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} > 0$

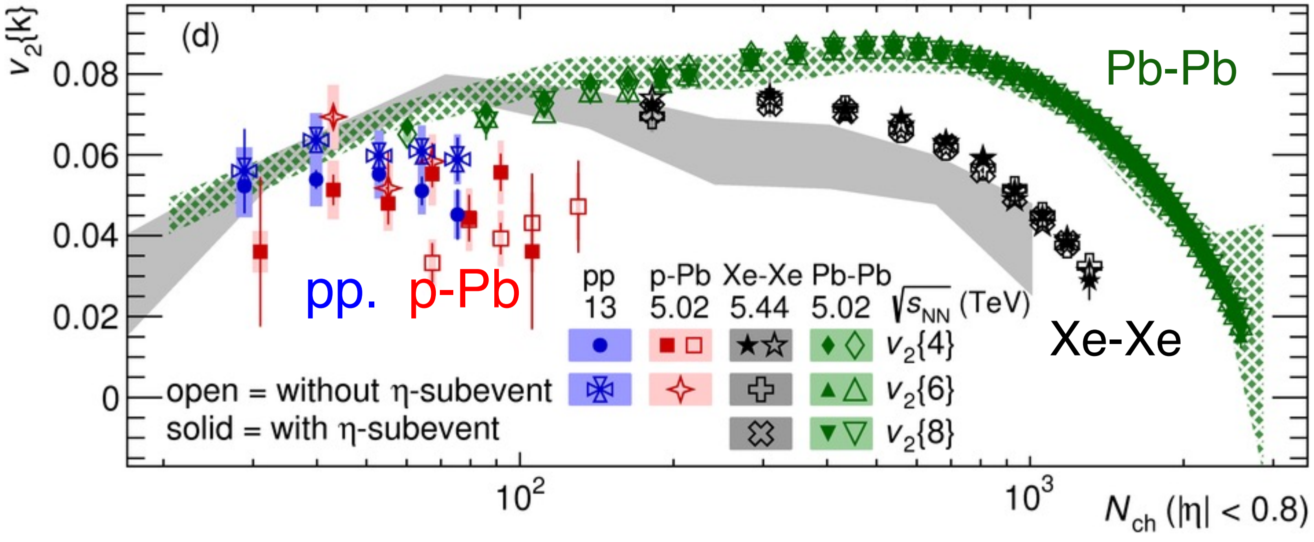
- subtract jets and other physical 2-particle correlations due to non-flow
- measure with rapidity gap

In AA collisions, collectivity originates from the presence of a strongly-interacting QGP: anisotropies and correlations in space converted into anisotropies in momentum space.

OPEN QUESTION: **what is the origin of the emerging collectivity in pp, p-Pb collisions?**



Elliptic flow from multi-particle correlations in all systems



PRL 123, 142301 (2019)

Discovery of strangeness increase with multiplicity in pp, p-Pb

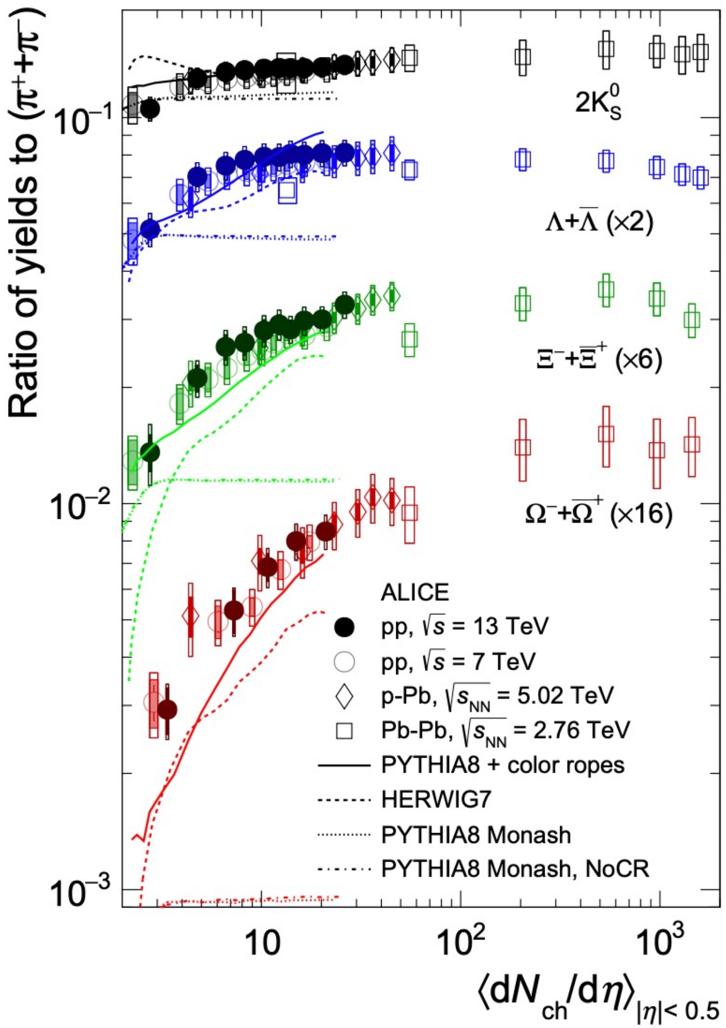
Multi-strange to non-strange yield ratios increase significantly and smoothly with multiplicity in pp and p-Pb collisions until saturation in Pb-Pb

- strangeness enhancement relative to pp suggested in the 1980's as QGP signature

→ **Particle composition evolves smoothly across collision systems, depending only on final-state multiplicity**

OPEN QUESTION: "**emergence**" in hadron production mechanism, **from microscopical hadron production mechanisms** (string overlap, color reconnection) **to the onset of a QGP** (thermalization, equilibration)**?**

→ A challenge for models!



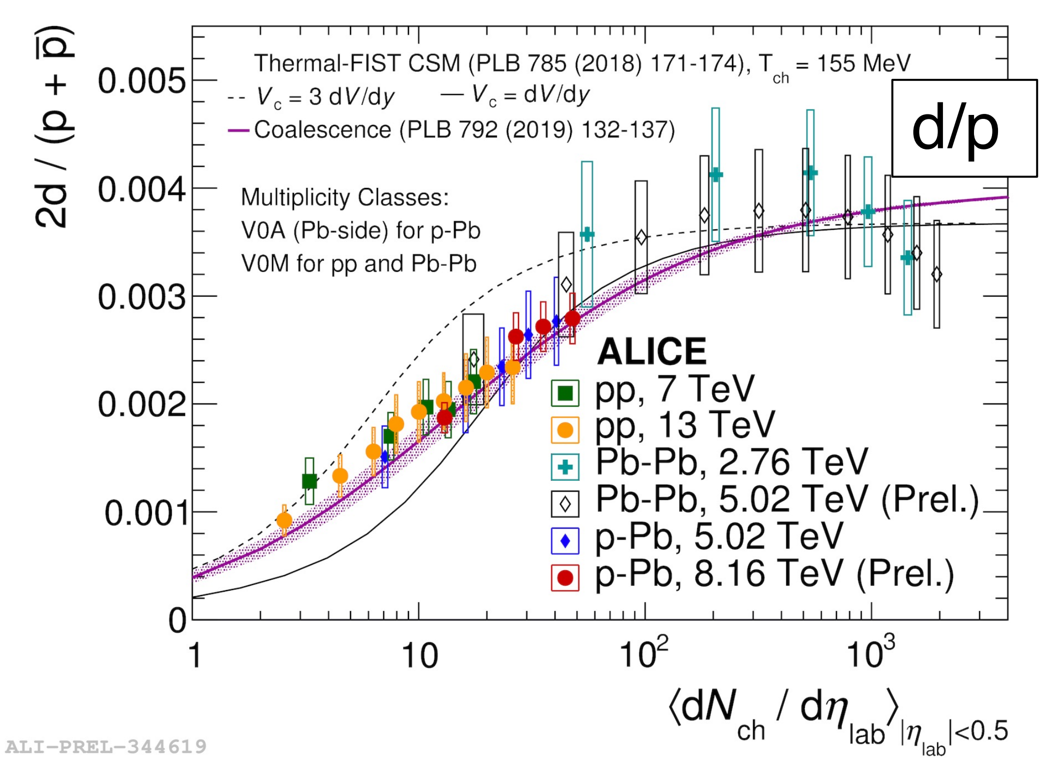
Nature Physics 13 (2017) 535-539, EPJC 80, (2020) 167 and 693

From hadrons to light (anti)nuclei

Smooth evolution of production of rare light nuclei as a function of the system size from pp to Pb-Pb

→ puzzle of the **survival of loosely bound states** (E_B ~ 2 MeV) in the hot hadron gas (T ~ 150-100 MeV) produced in heavy ion collisions

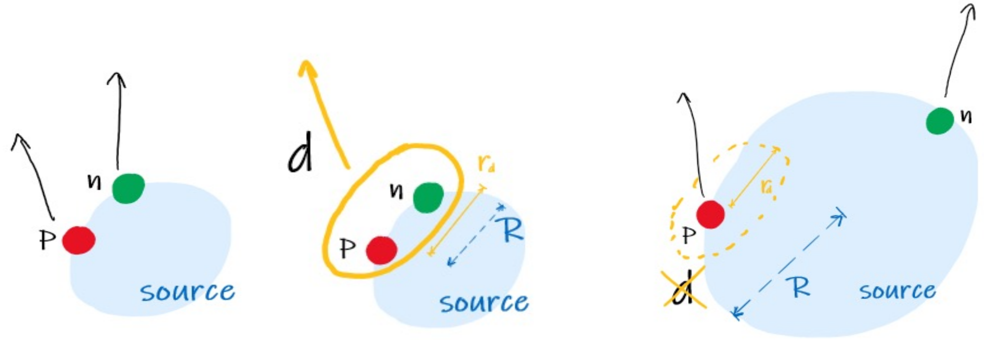
→ **nucleosynthesis in hadronic collisions**: statistical hadronization vs coalescence



Coalescence:

- cluster forms when nucleons are close in phase space
- dependence on the source size
- dependence on the nucleus internal structure

→ **test with hypertriton** (Λpn): loosely bound (B_Λ~ 130 keV) and large (r ~ 10-14 fm)



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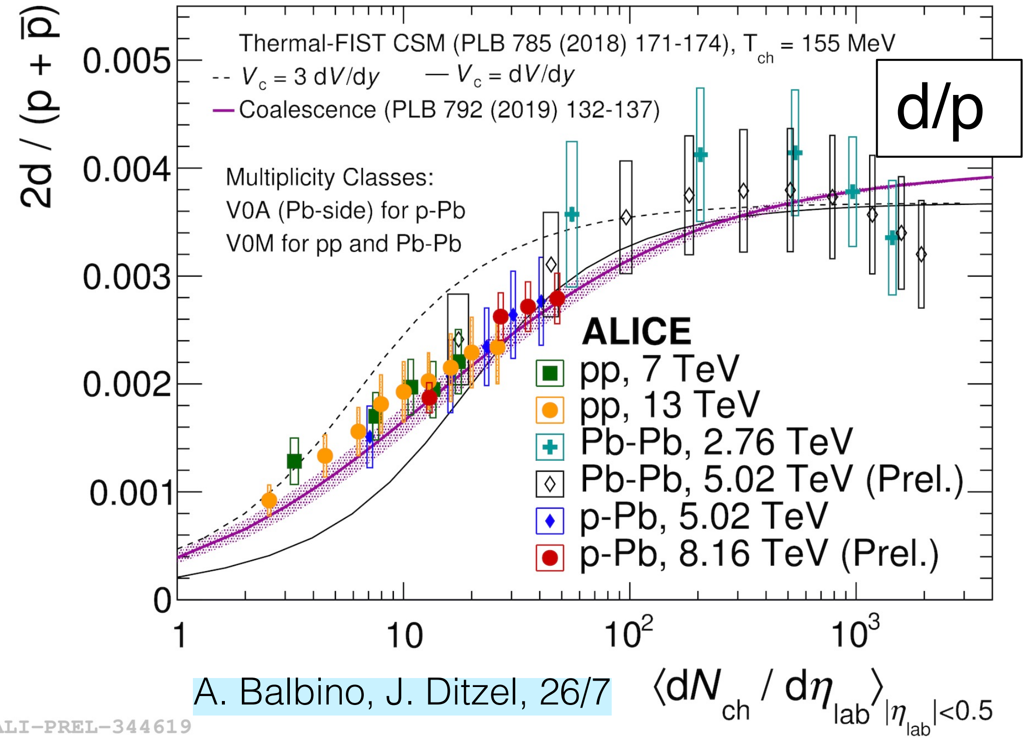
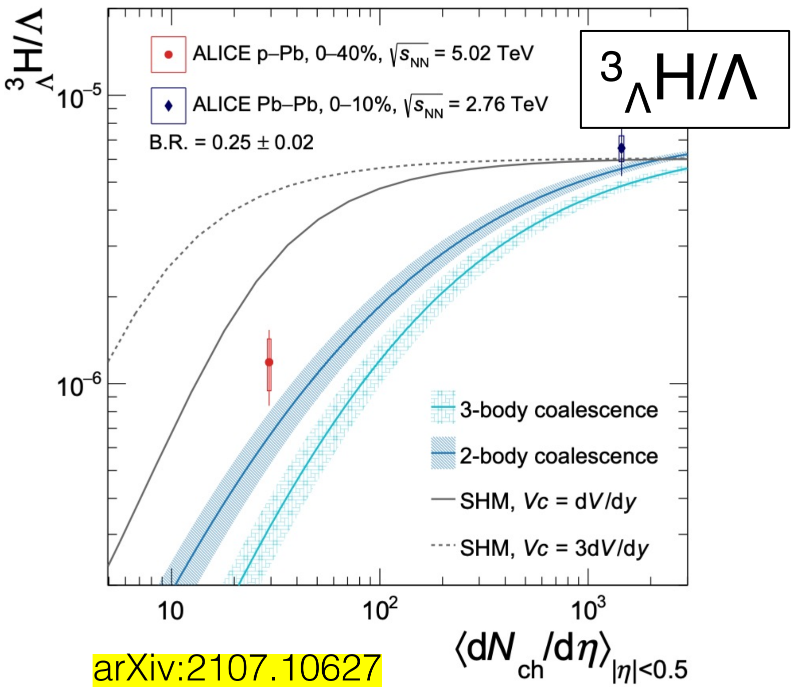
→ **nucleosynthesis in hadronic collisions**: statistical hadronization vs coalescence

→ applications to cosmic ray physics and indirect dark matter searches



A. Balbino, J. Ditzel, 26/7



arXiv:2107.10627

→ opens the way for systematic and precise measurements as a function of system size and momentum in Runs 3 and 4

Accessing the strong potential among hadrons

Two-particle femtoscopic correlations provide information about

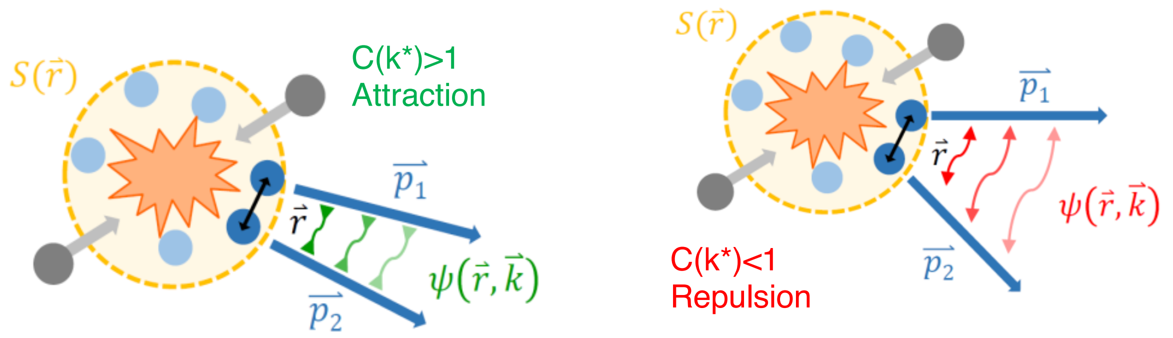
⟶ final-state interactions among hadrons

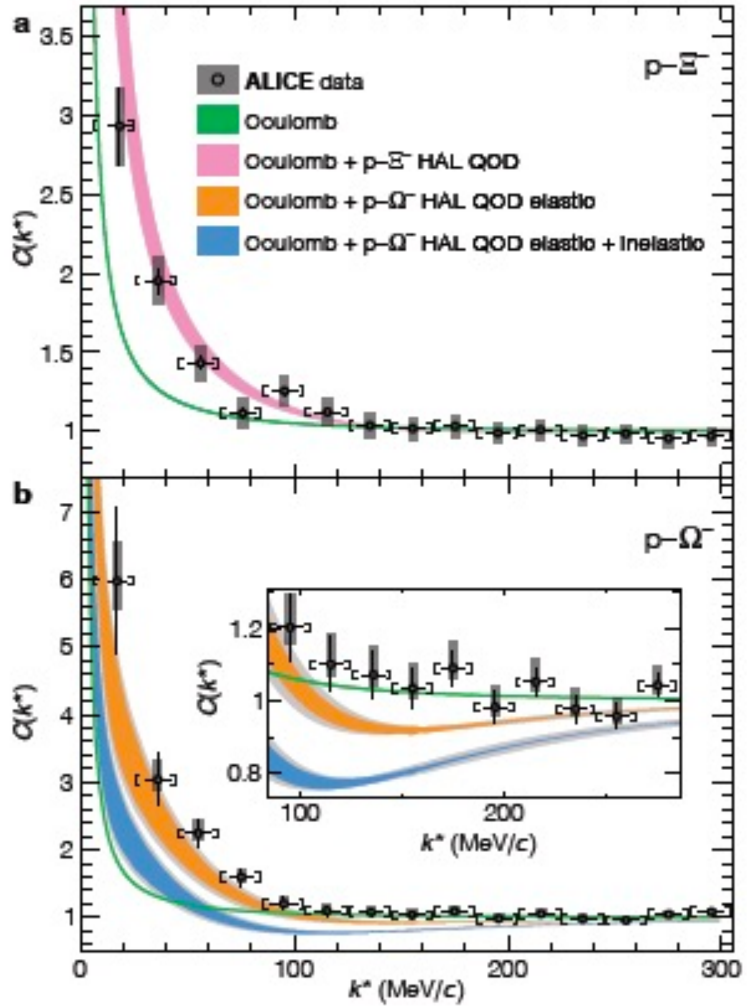
- direct comparison to ab initio **QCD calculations**

⟶ **source** (continuum) size and lifetime

⟶ **coalescence** (discrete bound state solutions)

A new and comprehensive programme of measurements in pp, p-A, AA at the LHC to **study of the residual strong interaction among (strange) hadrons and Y-N interaction** (relevant for neutron stars EoS)





Nature 588 (2020) 232–238

Physics with ion beams at the LHC in the near and far future

Physics in Run 3 and 4 with the upgraded detectors > arXiv:1812.06772

Run 5 and beyond > arXiv:1902.01211

Input to the European Particle Physics Strategy Update > website

The near and far future of HI at the LHC

2010-2012		2015-2018		2022-2024		2028-2030		2032-2034		2036-2039
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

High luminosity LHC

We are here

Major upgrades during LS2 for ALICE and LHCb

ATLAS and CMS phase II

- Replace inner tracking systems to increase coverage
- Timing layers: e.g. CMS MIP Timing Detector
- Calorimeters, muon system upgrades, etc…

ALICE ITS3 and FoCal

ALICE 3: a whole new dedicated HI experiment!

LHCb upgrade II
(CERN-LHCC-2018-027)

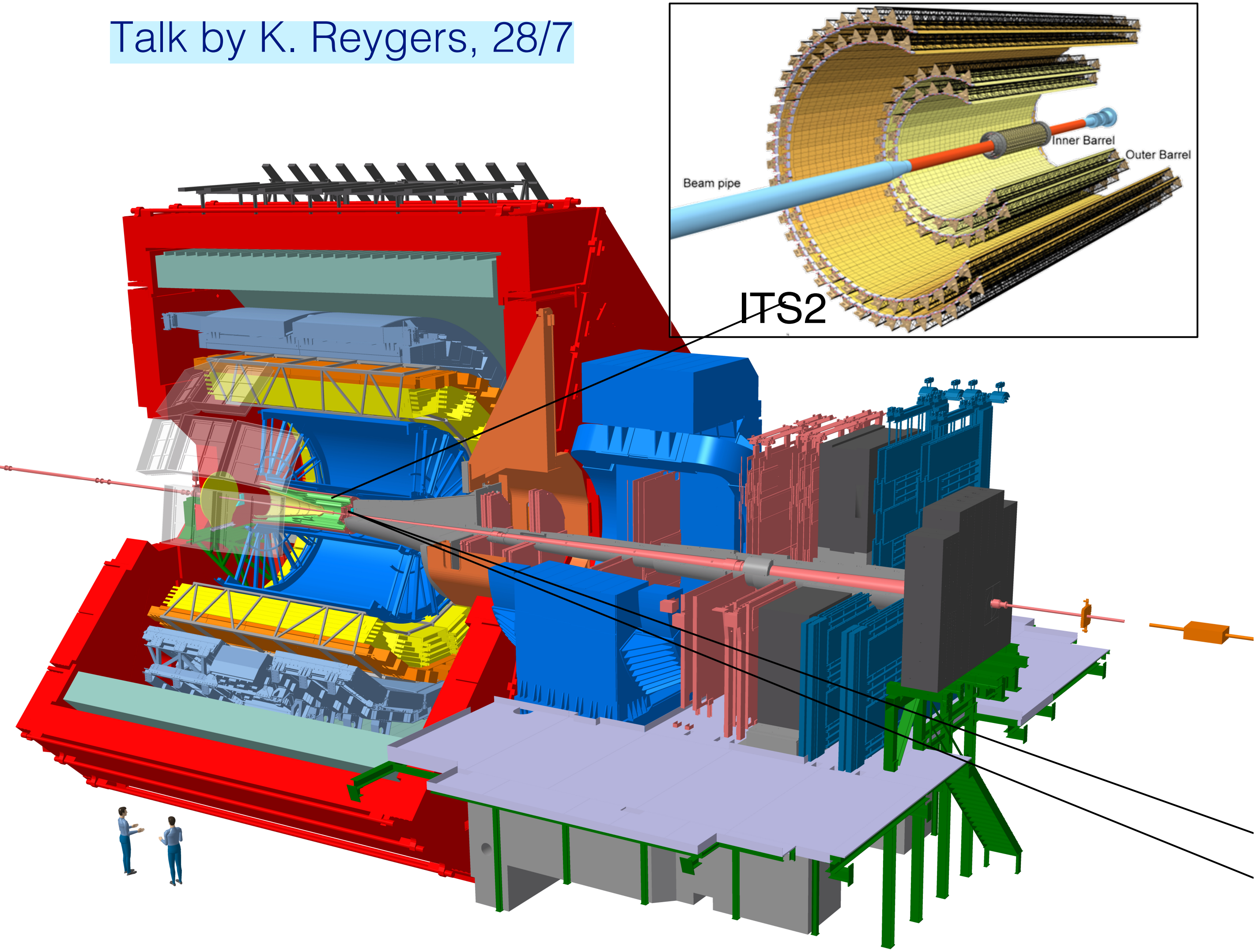
A precision era for flagship observables!

Much more in the Detector R&D and Data Handling parallel sessions…
Link to LHC schedule
Runs 3 and 4 expected lumi for heavy-ion programme: arXiv:1812.06772

ALICE upgraded for the LHC Run 3

Talk by K. Reygers, 28/7

ALICE-TDR-017 J.Phys.G 41 (2014) 087002



New Inner Tracking system (ITS2)
- 7 layers of Monolithic Active Pixel Sensors
- Innermost layer closer to the IP (r = 23 mm)
- Reduced material thickness

New TPC Readout Chambers
- Continuous readout on GEMs
- Read out at maximum Pb-Pb collision rate of 50 kHz (x50 for non triggerable observables)
- cont. readout also in pp w/ event filtering at full reco level

Update of readout
- The main PID detectors consolidated and speed-up (e.g., TOF readout update) to preserve PID capabilities

Integrated Online-Offline system (O2)
New Muon Forward Tracker (MFT)
New Fast Interaction Trigger (FIT) Detector

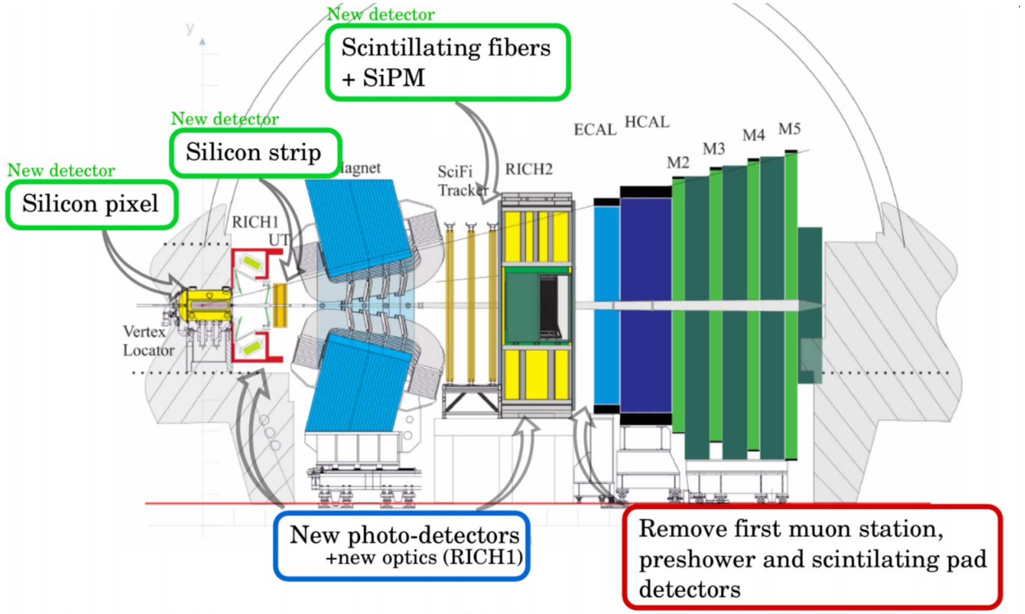
LHCb upgraded for the LHC Run 3

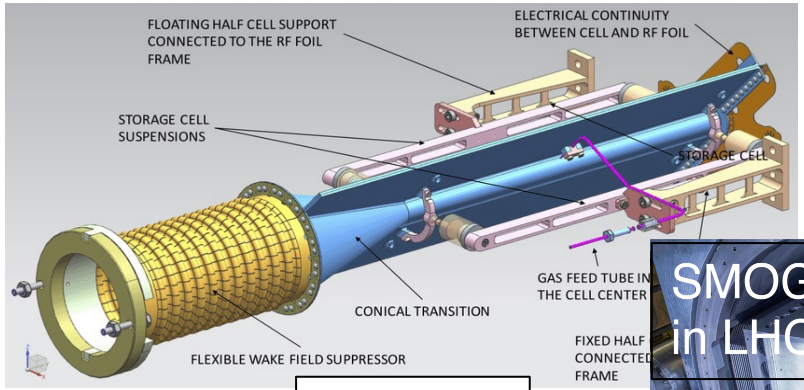
Total **replacement of the LHCb tracker**

Pb-Pb collision study enabled up to 30% central Pb-Pb instead of current limit at 60%

SMOG2 upgrade (LHCb-TDR-020)

- fixed-target mode enabled by injecting noble gas into the vacuum vessel of the LHCb VELO
- effective areal densities (luminosities) ~8-35x SMOG1, at the same flow rate
- variable target types and at different $\sqrt{s}$
- cold nuclear matter effects, search for charm in proton at low x, antiproton cross section in p-He for cosmic ray physics





SMOG2

Upgrades in LS3: ALICE ITS3 and FoCal, CMS and ATLAS

ALICE ITS3: a new ultra-light inner barrel based on bent ultra-thin, wafer-scale sensors

→ low momentum charmed hadrons

→ low-mass dielectrons

LoI: CERN-LHCC-2019-018

Talk by F. Krizek, 29/7

ALICE Forward Calorimeter

A new high-granularity Si-W sampling Em calorimeter combined with a sampling Hadronic calorimeter

→ gluon PDFs (small-x)

→ π^0,jets (and di-jets), J/ψ, Υ in UPC, W, Z, event plane and centrality

LoI: CERN-LHCC-2020-009

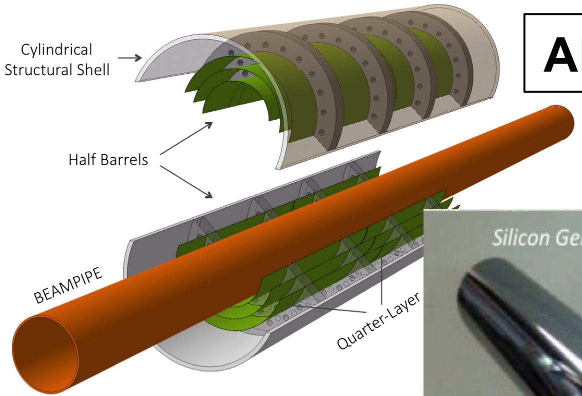
Major upgrades for ATLAS and CMS

→ Highlight for HI: timing detectors

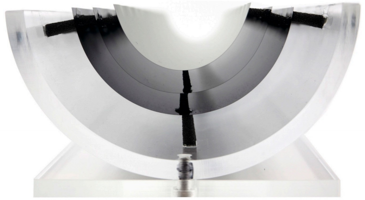
CMS MIP Timing Detector

→ precision timing on single charged tracks (σ ~ 30-40 ps) → PID in |y|<2

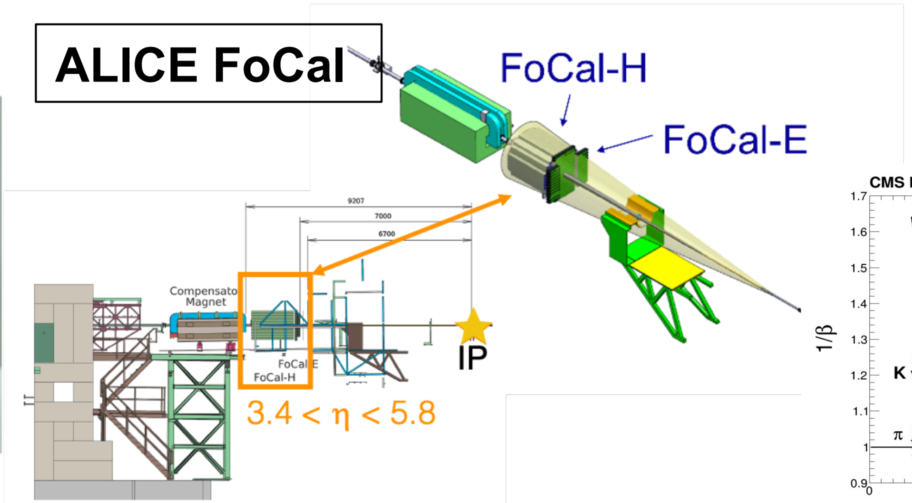
- Barrel (BTL): LYSO crystals + SiPMs
- Endcaps (ETL): Low Gain Avalanche Diodes



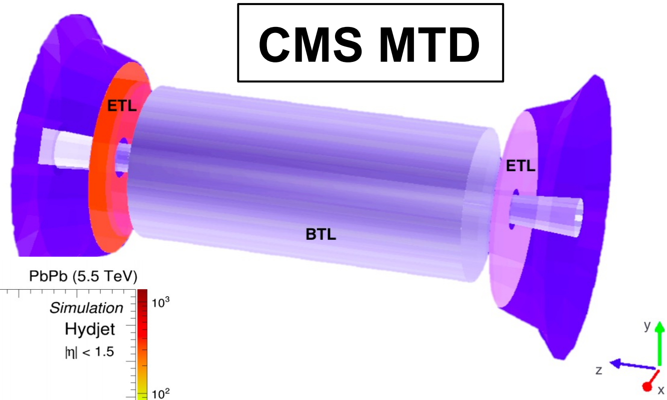
ALICE ITS3

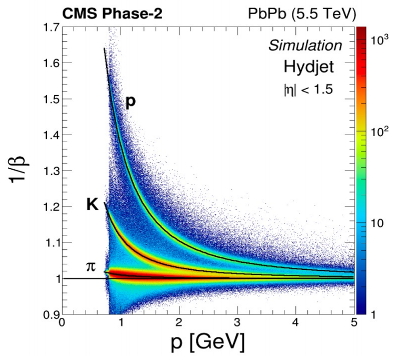


ALICE FoCal



CMS MTD





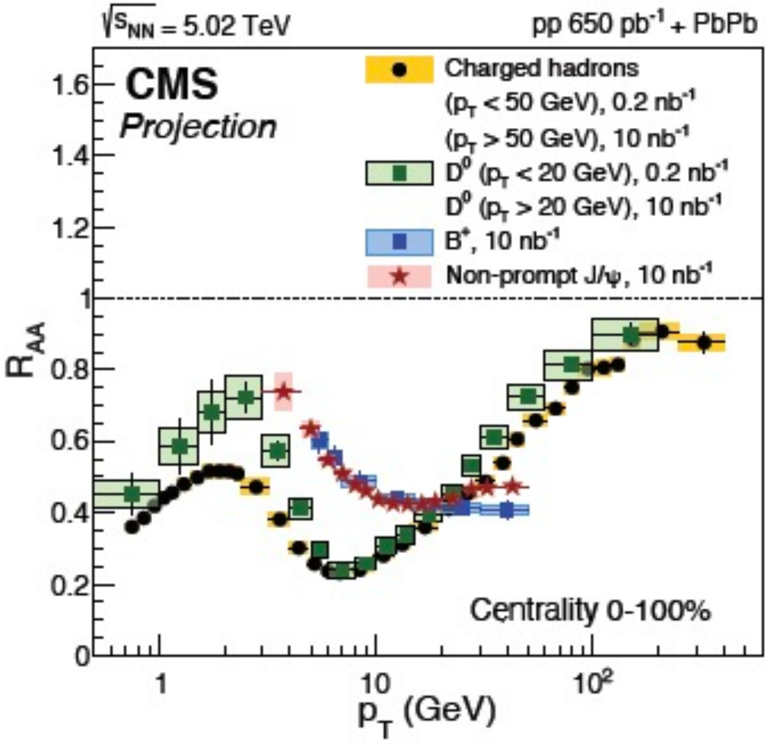
TDR: CMS-TDR-020

Talk by B. Marzocchi, 27/7

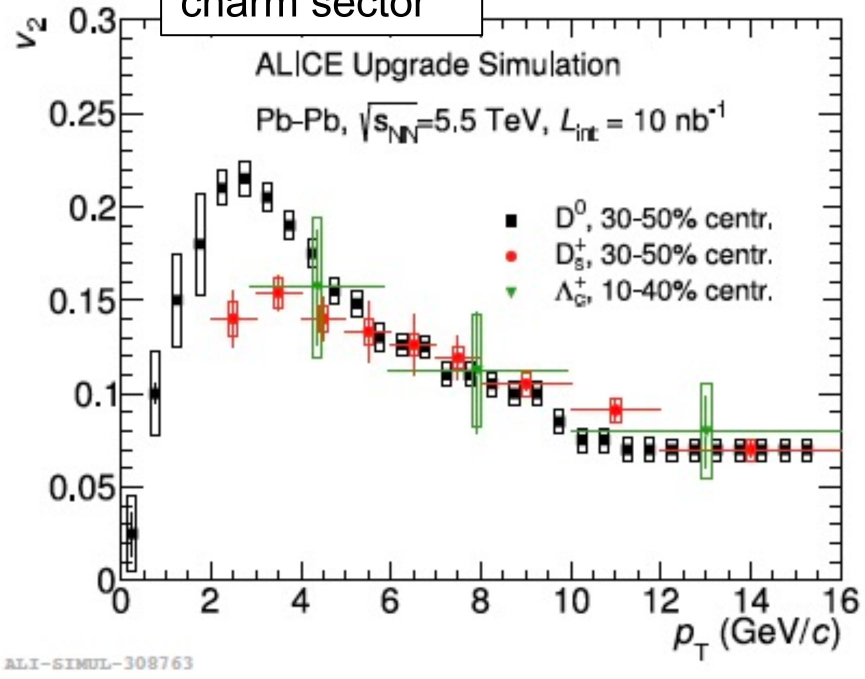
Open heavy-flavour: energy loss and hadronization

Study mass dependence of energy loss, in-medium thermalization of heavy-flavours and their hadronization as a probe of the medium transport properties (e.g. charm spatial diffusion coefficient)

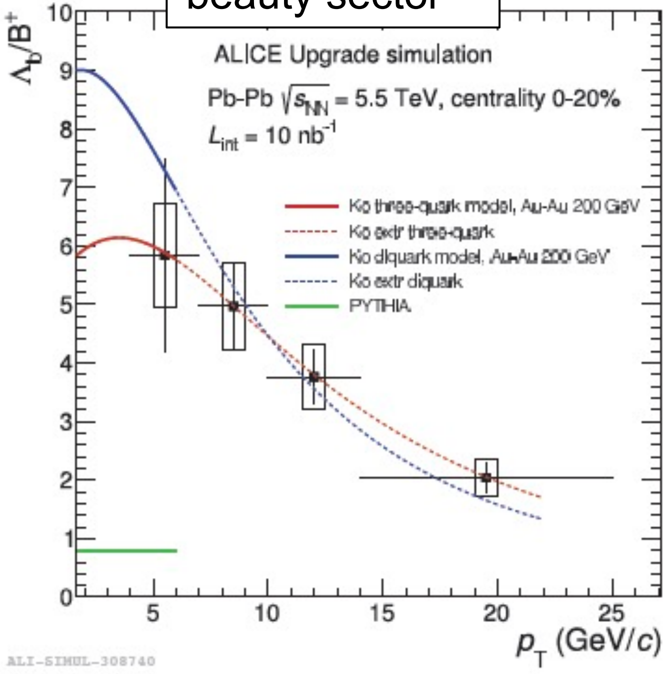
High-precision elliptic-flow and R_{AA} measurement at mid- and forward rapidity for both c and b sectors



charm sector



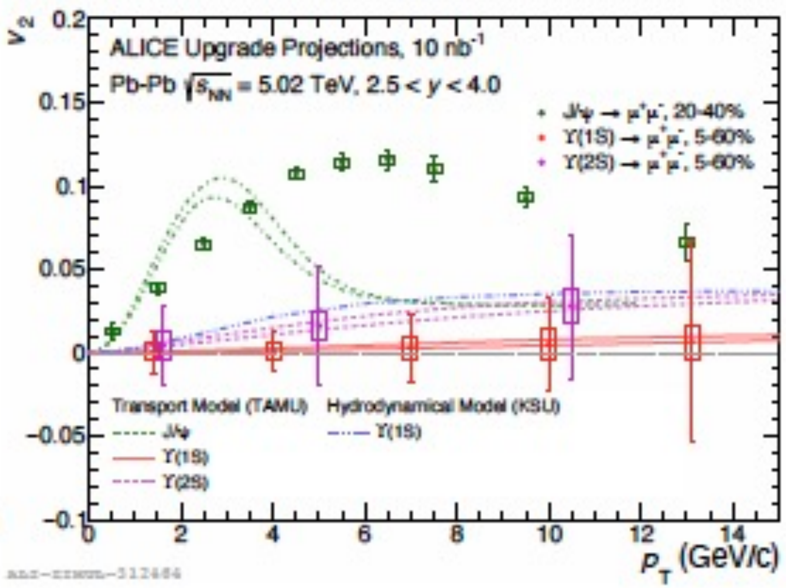
beauty sector

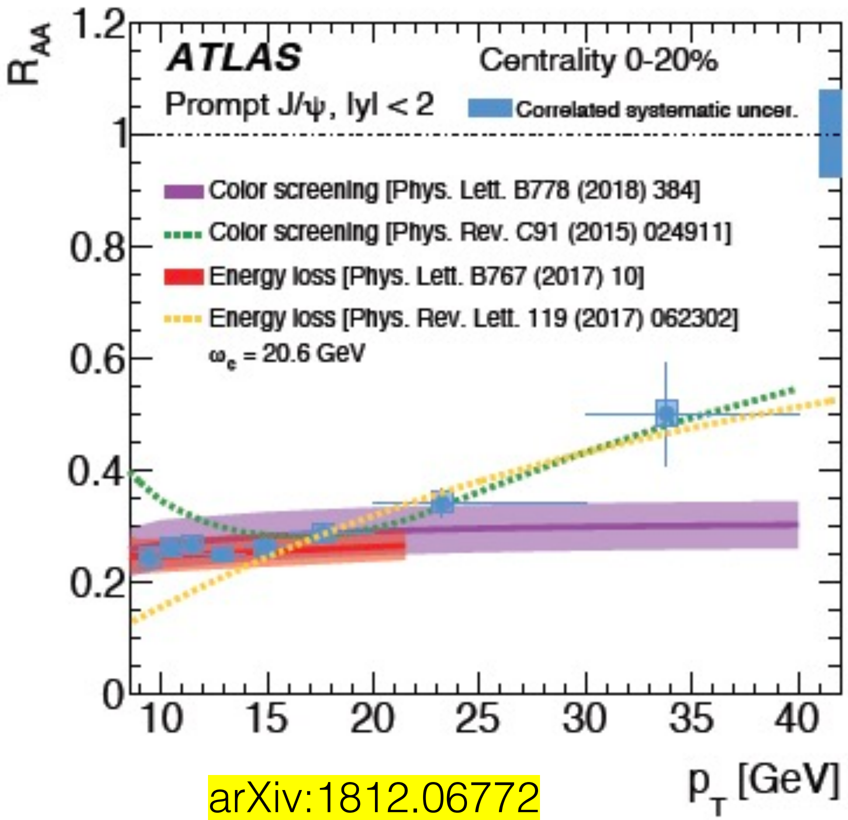


arXiv:1812.06772

Quarkonia: melting vs regeneration vs energy loss

Study regeneration and thermalization of heavy flavours with precision measurements of charmonia flow, RAA and ψ(2S)/J/ψ, explore feeddown





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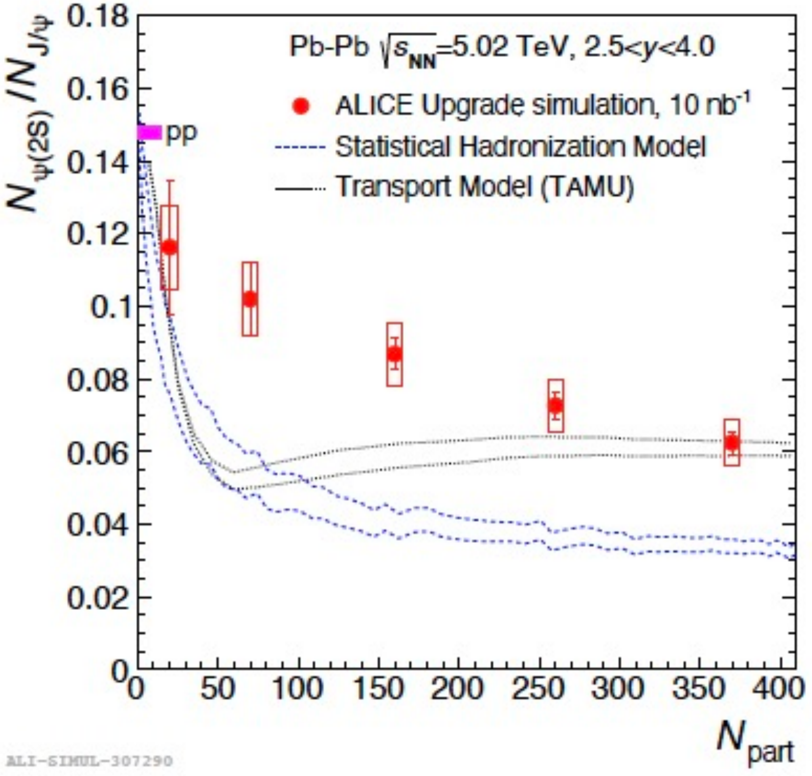
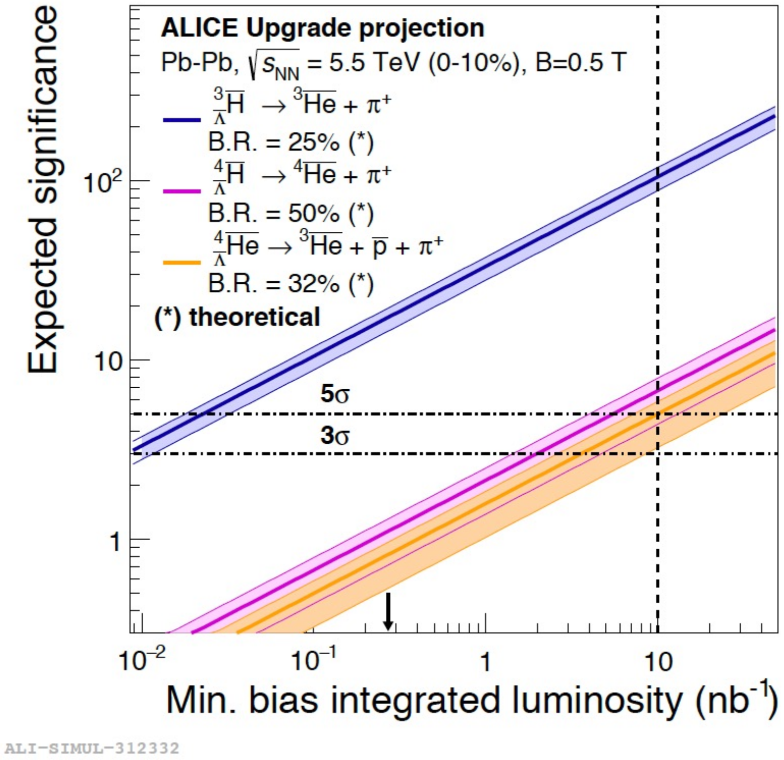
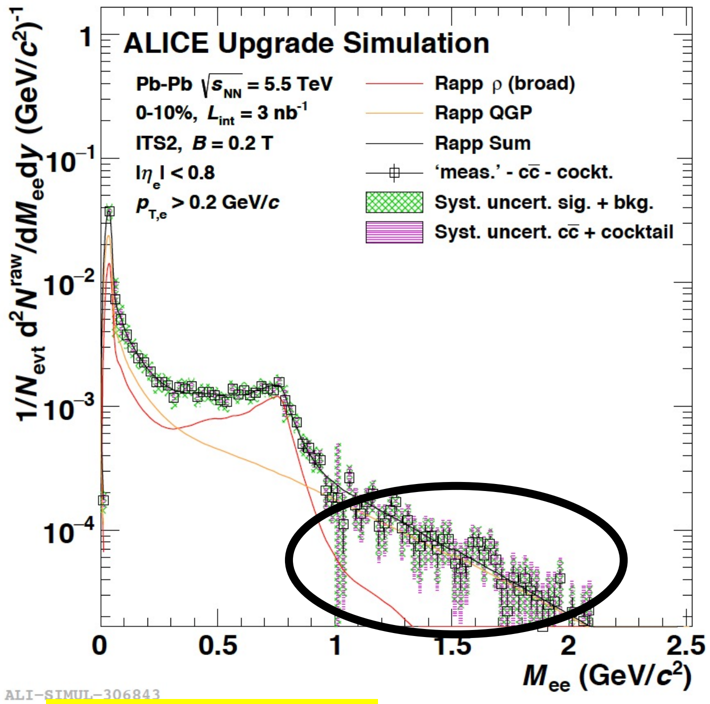


Nuclei, dileptons, small systems and more…

Clarify formation mechanisms of nuclear bound states from a dense partonic state: (anti-)nuclei and (anti-)(hyper-)nuclei up to A = 4

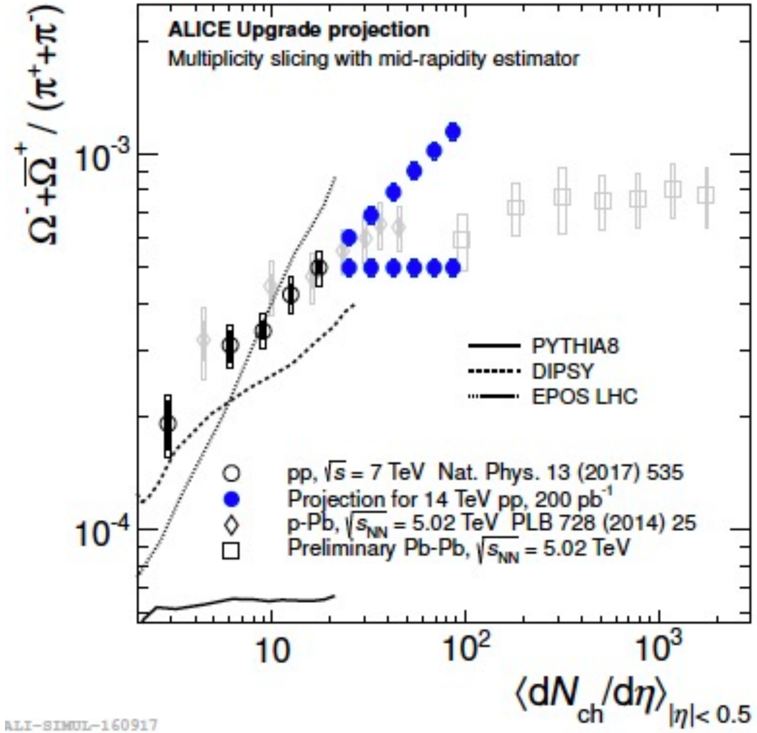


Access to the thermal dilepton excess after subtraction of light hadron decay and charm



arXiv:1812.06772

A "small systems" programme to study collectivity, strangeness production, the onset of QGP like features



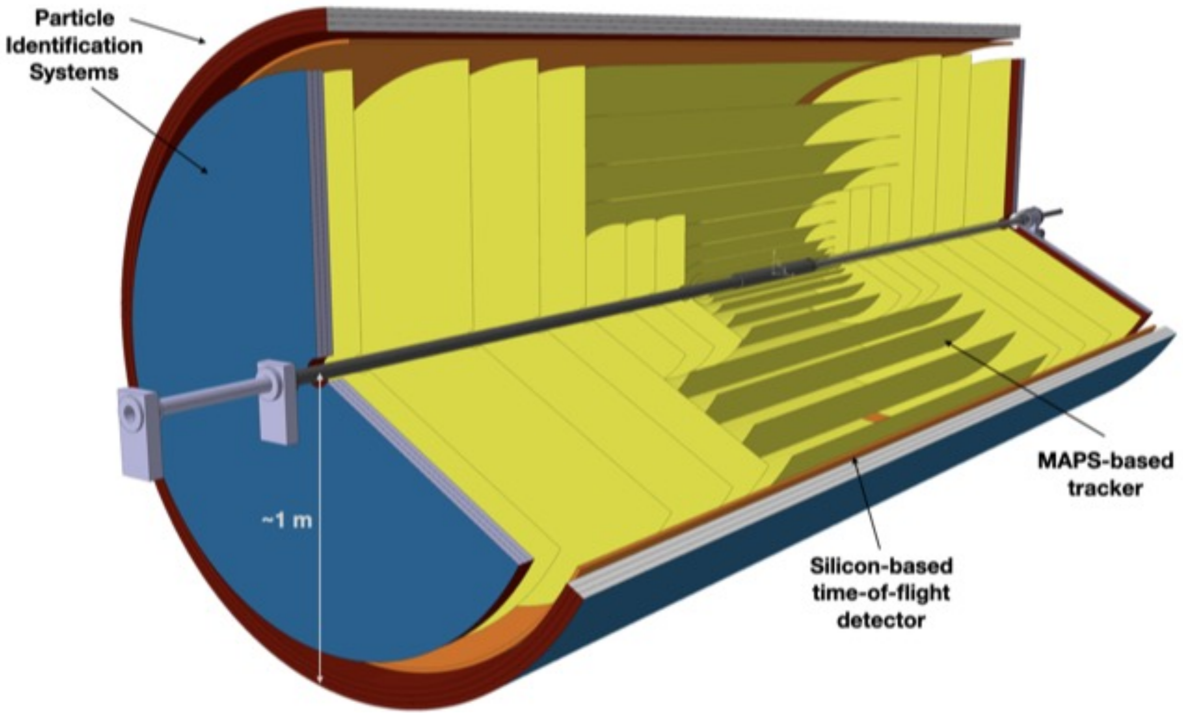
+ net-charge fluctuations, jets (the QCD objects!), heavy-quark jets, light ions, nPDFs, low-x physics,…

ALICE 3: a new dedicated HI experiment in Run 5 and beyond

ALICE 3: a new dedicated heavy-ion experiment at the LHC

- replace ALICE between Run 4 and Run 5
- Expression of Interest submitted in 2019 (ESPPU), arXiv:1902.01211
- Open ALICE 3 workshop in October 2021
- **Letter of Intent to be submitted to the LHCC by end of 2021**

ALICE 3 detector concept



Physics from pp to Pb-Pb:

- Vertexing accuracy and tracking down to $p_T = 0$ (w/ retractable inner tracking layers)
- Particle identification
- Wide rapidity coverage
- Extreme acquisition rates for soft probes

Talk by G.M. Innocenti, 29/7

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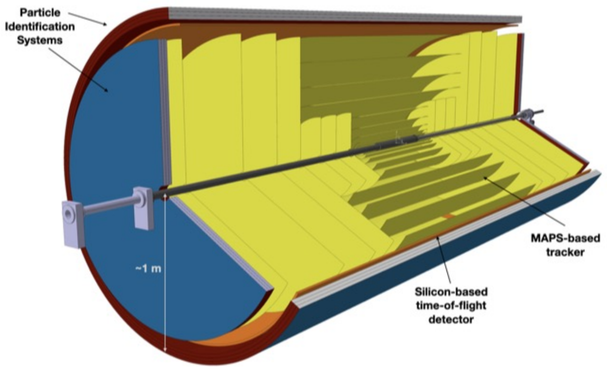

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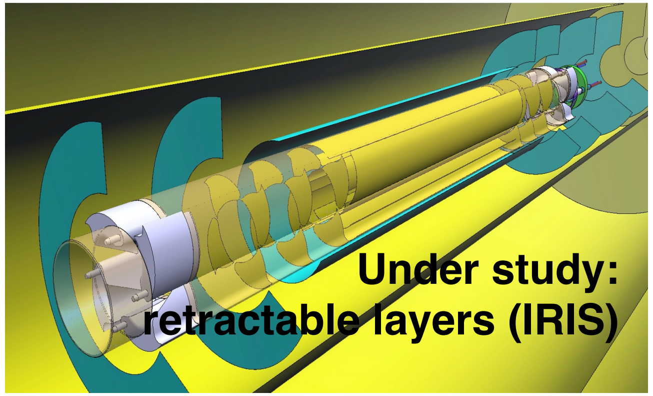
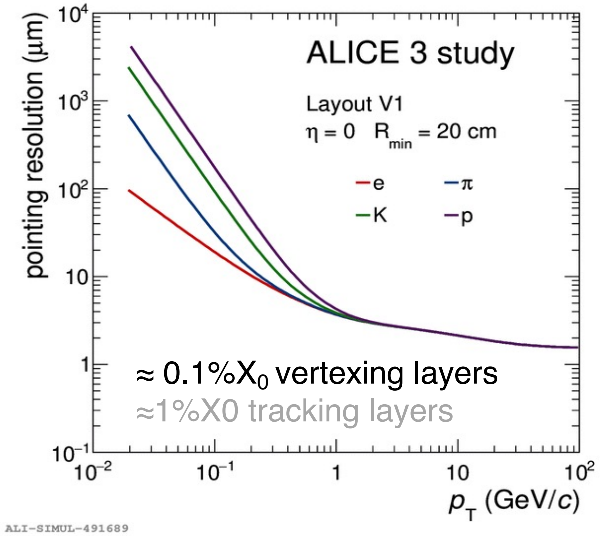
Silicon tracker: large acceptance, ultra-light, IB based on large bended MAPS





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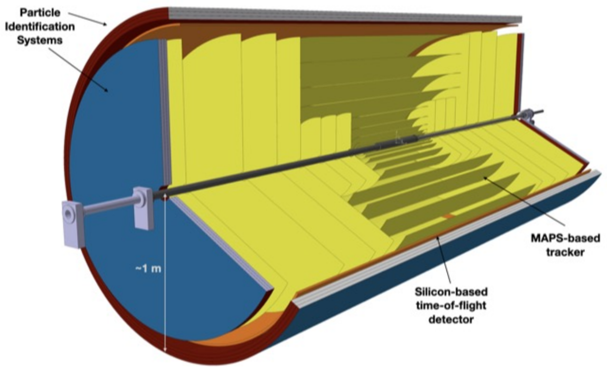

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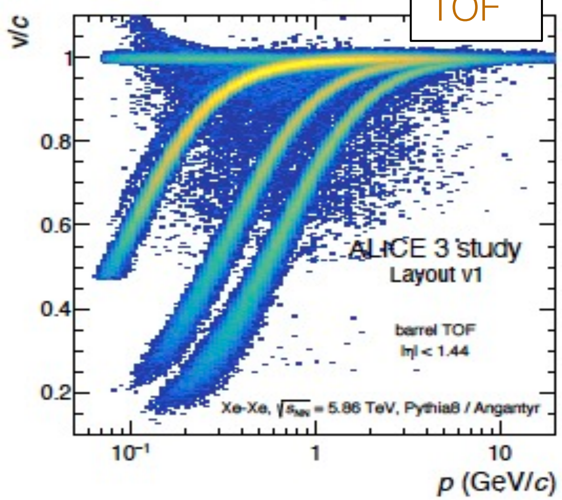
Silicon tracker: large acceptance, ultra-light, IB based on large bended MAPS

Options for PID:

Silicon-based TOF detector outside the tracker, σ = 20 ps

Aerogel-RICH detector, outside of TOF

TOF

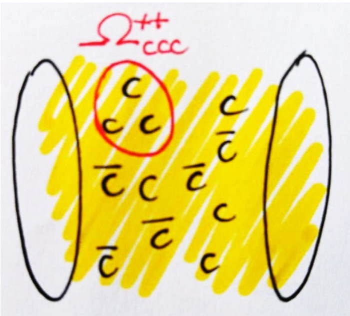


Unique physics with a fast ultra-light detector

Multi-HF states production to investigate hadronization from the QGP

- Multi-charm baryon production expected to be enhanced by 10^2-10^3x
- low p_T B, χ_c, X, …

$$\Omega^{++}_{ccc} \to \Omega^{+}_{cc} + \pi^{+}$$
$$\Omega^{+}_{cc} \to \Omega^{0}_{c} + \pi^{+}$$
$$\Omega^{0}_{c} \to \Omega^{-} + \pi^{+}$$
$$\Omega^{-} \to \Lambda + K^{-}$$
$$\Lambda \to p + \pi^{-}$$



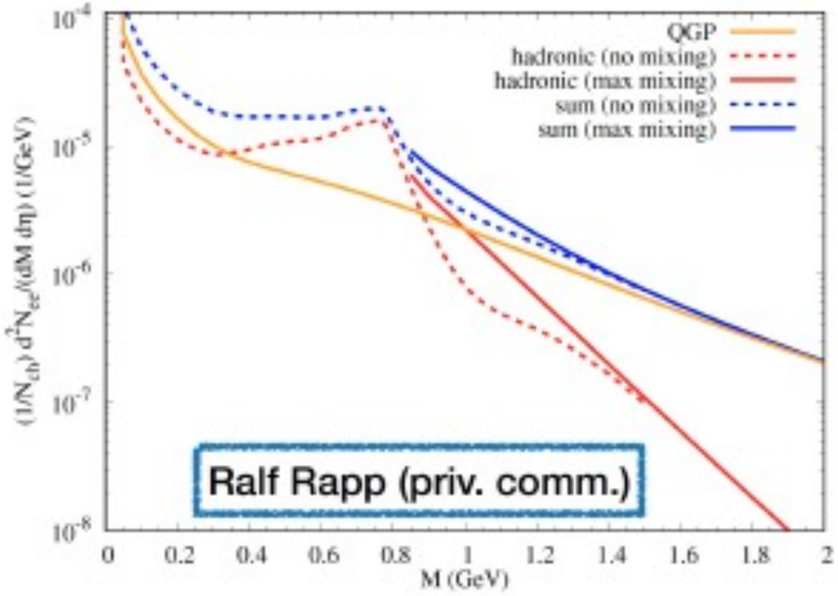
Dilepton radiation from various phases of the collision

Effect of **chiral symmetry restoration** (predicted by lattice QCD) on the dielectron spectrum

QGP parameters (diffusion coefficients, conductivity properties, …) with unprecedented precision

Ultra-soft (p_T ~ 10 MeV) **photon** production relative to hadron production (Low's theorem, non-pert. QCD)

…and more new unique windows opened at the LHC!



Conclusions

We have reached a **precision era** in the quest for the **quantitative characterization of QGP properties** and the study of **QGP phenomena emerging from QCD** in extreme conditions

A broad physics programme with heavy ions at the LHC has brought **new discoveries and new tools** (observables, analysis techniques, …), and opened **new roads**

- collectivity in small systems
- smooth evolution of hadrochemistry from small to large systems
- role of charm as probe of mechanisms of hadronization from the QGP
- study the nature of the hadron-hadron interaction
- understand nucleosynthesis in hadronic and nuclear collisions
- …

We are sharpening our plans and our tools for a **bright future** of the field!

Thank you!

DARK UNIVERSE | FEATURE

CERN Courier 30.10.2020

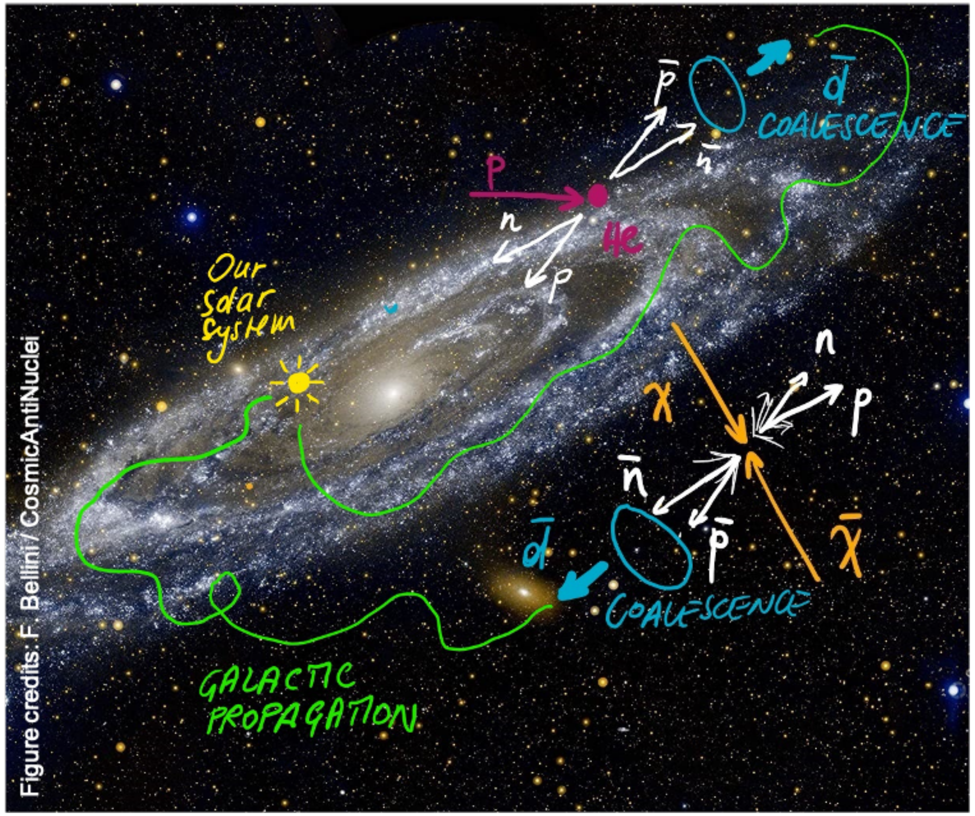
ALICE's dark side

Precision measurements of the production and annihilation of light antinuclei are sharpening the search for dark matter.

European Research Council
Established by the European Commission

If found in cosmic rays (AMS-02, GAPS), light antinuclei (antideuterons, antihelions) may be originated from interactions of

- dark matter (WIMP) particles
- primary CR with the galactic interstellar matter (pp, p-He…)



Ingredients needed to predict rates:

- antimatter cluster formation mechanisms
  → decisively constrain with measurements in ALICE

  H2020-ERC-STG CosmicAntiNuclei

- model of cosmic ray propagation in the Galaxy and the heliosphere
- annihilation cross section of antinuclei
  → measured with ALICE at low p_T

Inelastic cross section of anti-^{3}He

First measurement of the anti-^{3}He inelastic cross section using pp, Pb-Pb data and ALICE as a target

→ new information on interaction with the detector material (compare to Geant)

Application to the propagation of cosmic ray antinuclei through the Galaxy, show **high transparency of the Galaxy to anti-^{3}He fluxes**

→ relevant application to **indirect dark matter searches** with space-borne experiments as AMS-02, GAPS