CERN Summer Student Lectures 2024

Heavy Ions 3/3

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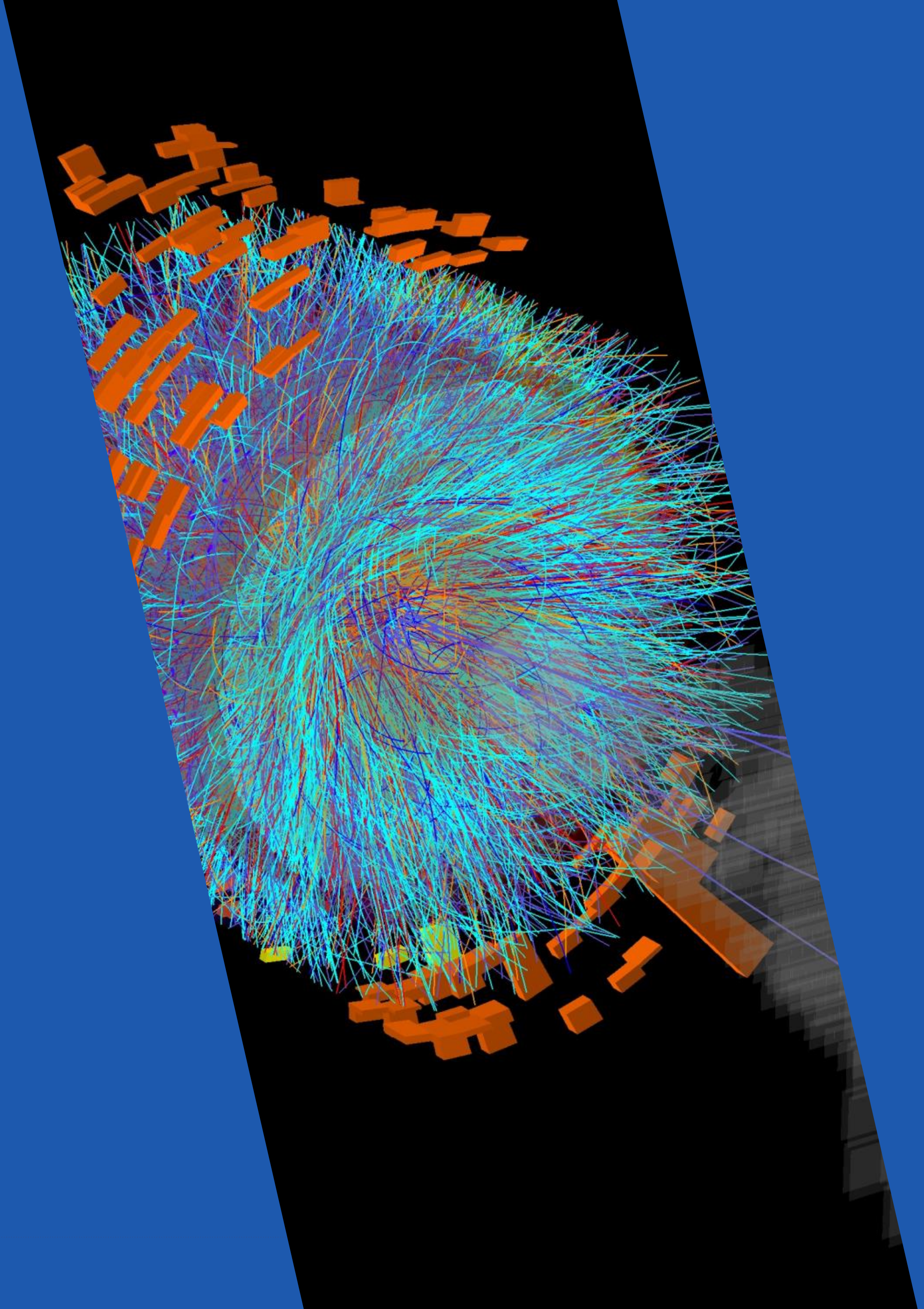
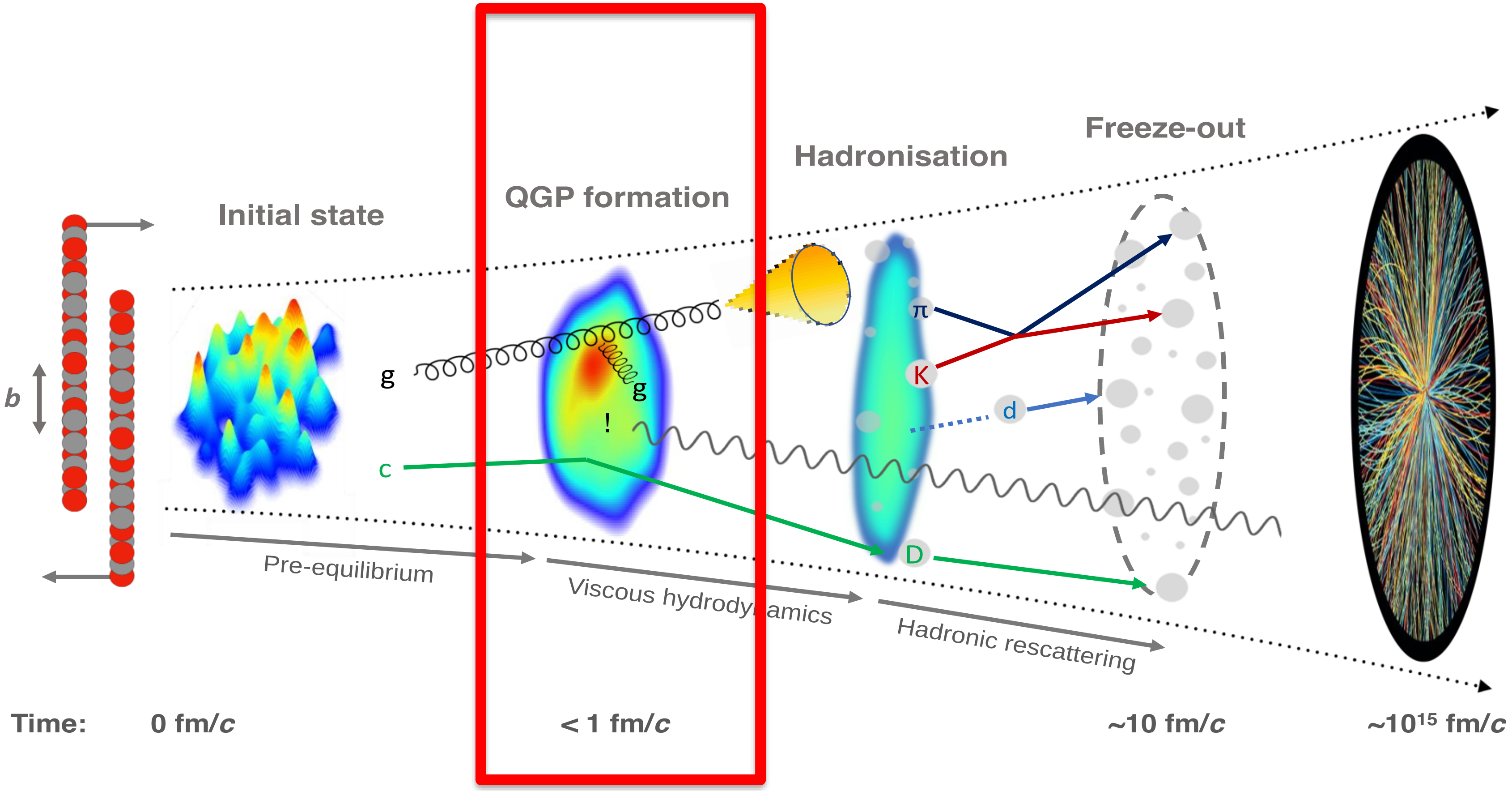


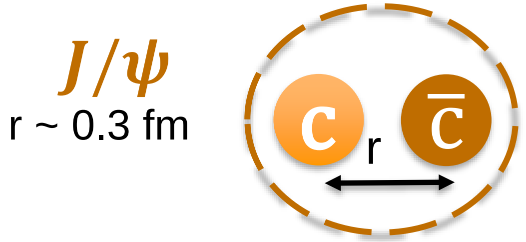
How does the presence of a colored QGP affect hadron formation?



Quarkonium ($q\bar{q}$) as a thermometer for QGP

In vacuum, at T=0, a $q\bar{q}$ pair is bound by the Cornell potential

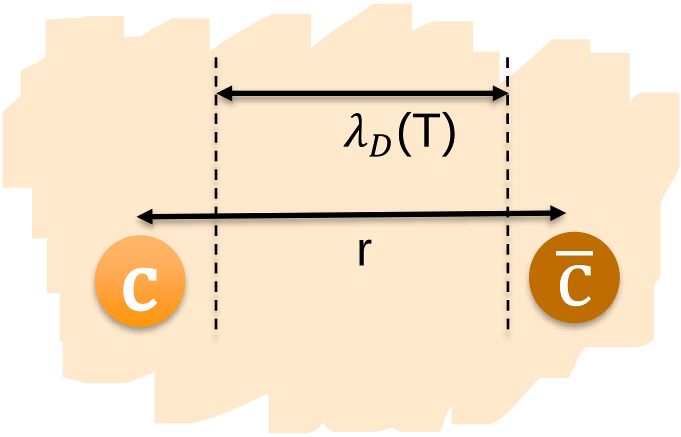
$$V(r) = \underbrace{-\frac{\alpha}{r}}_{\text{Coulomb term}} + \underbrace{kr}_{\text{Confinement term}}$$



In vacuum
T = 0
Bound state

When the $q\bar{q}$ is immersed in the hot deconfined QGP (T>0), the “confinement term” vanishes.
The surrounding color charges screen the binding potentials (Debye color screening), resulting in

$$V(r) = -\frac{\alpha}{r} e^{-r/\underbrace{\lambda_D}_{\text{Debye lenght T-dependent!}}}$$



In QGP
T > 0
No bound state if
$r > \lambda_D$ or
$T > T_D$

A bound state can be found by minimizing the energy

$$E = \frac{p^2}{2\mu} - \frac{\alpha}{r} e^{-r/\lambda_D}$$

→

It does NOT admit bound solutions if $\boldsymbol{\lambda_D \lesssim 0.6}$ **fm**

Quarkonium as a thermometer for QGP

Charmonium suppression (J/ψ, ψ',…) suggested as ''smoking gun'' signatures for the QGP back in the 1980's. *[Matsui, Satz, Phys. Lett. B 178 (1986) 416]*

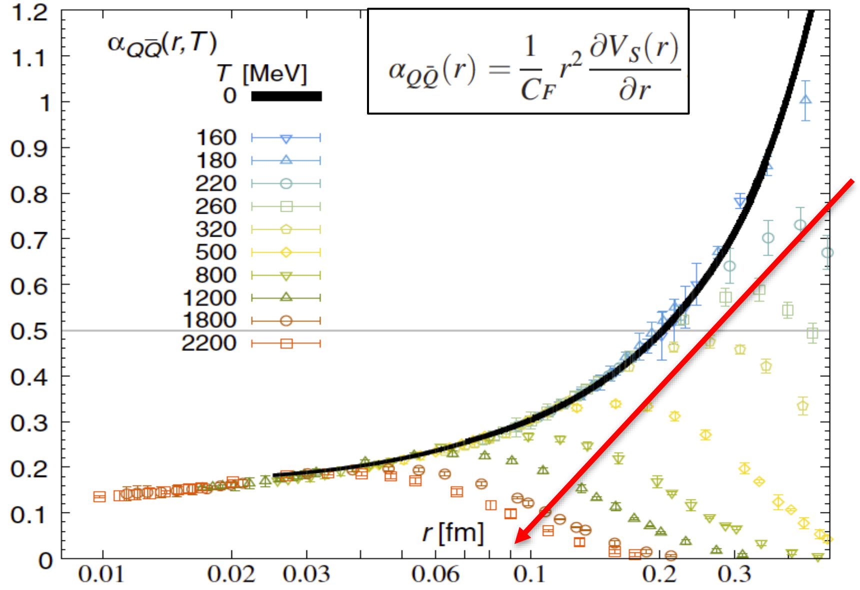
Modern lattice QCD calculations show that the strenght of the interaction (coupling $\alpha_{Q\bar{Q}}$) between q and $\bar{q}$ at large distances gets progressively reduced as temperature of the medium increases.

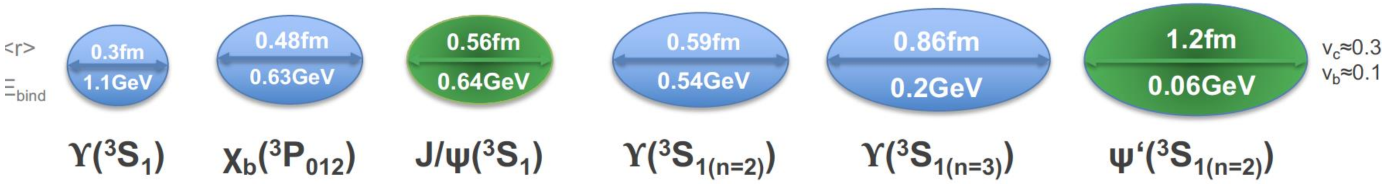
→ $q\bar{q}$ melting, depending on temperature
→ quarkonium as a thermometer for QGP

Key observables:

- $q\bar{q}$ R_{AA}
- ground and excited $q\bar{q}$ states

Effective coupling from lattice QCD vs T





To larger radius →
To lower binding energy →

J/ψ ($c\bar{c}$) suppression

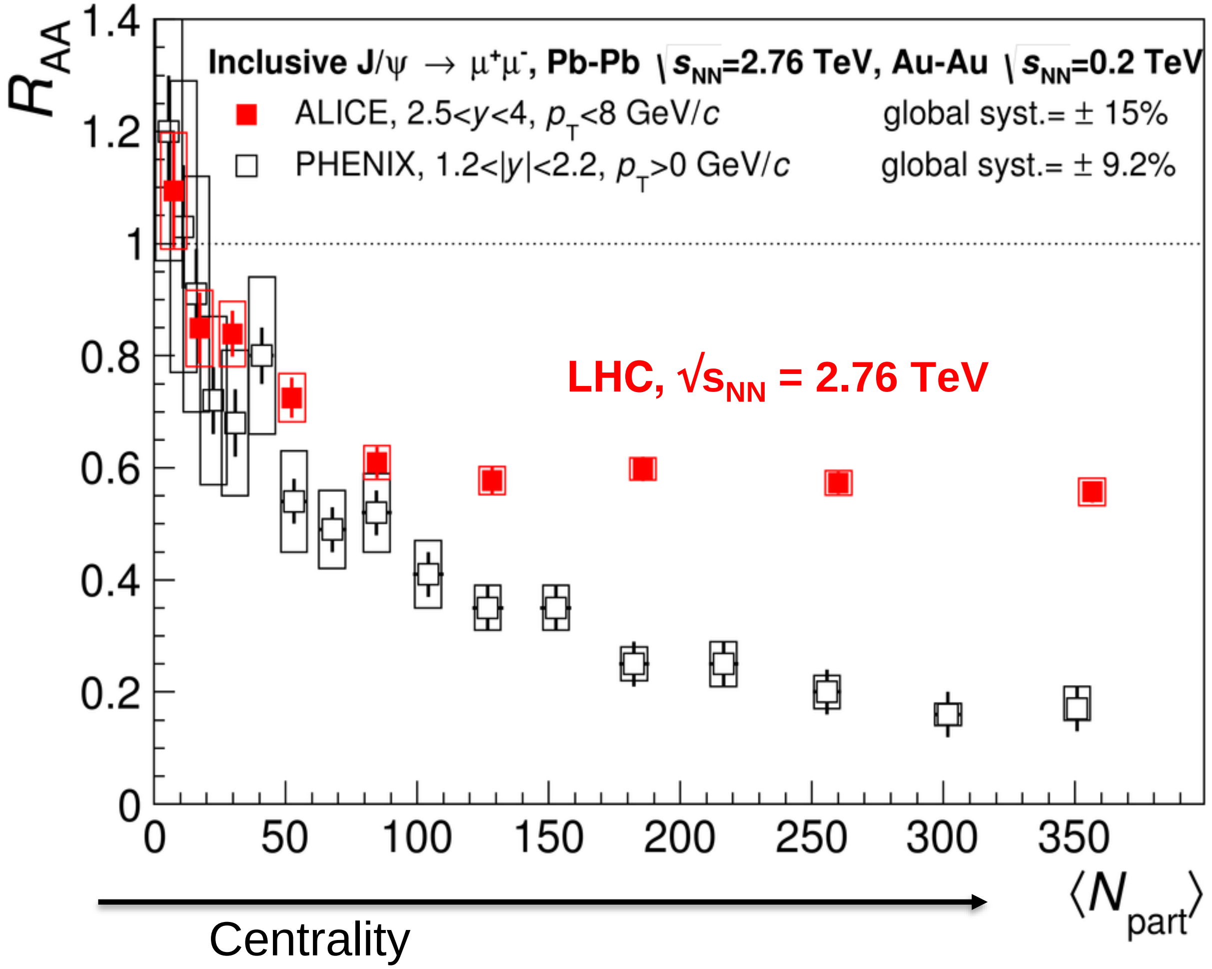
- observed at the SPS ($\sqrt{s_{NN}}$ = 17 GeV)
- later measured at RHIC ($\sqrt{s_{NN}}$=200 GeV) up to very high multiplicities

For similar multiplicities the suppression at SPS is similar to that at RHIC despite the energy difference (not shown)

At the LHC, J/ψ is less suppressed than at RHIC

→ larger charm cross section

→ regeneration

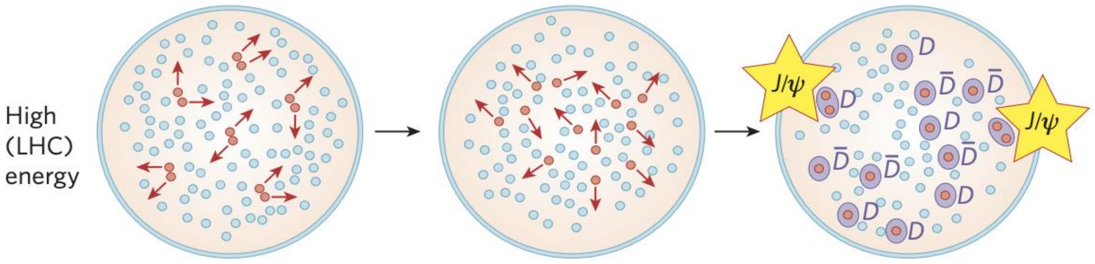


$c\bar{c}$ cross section vs energy

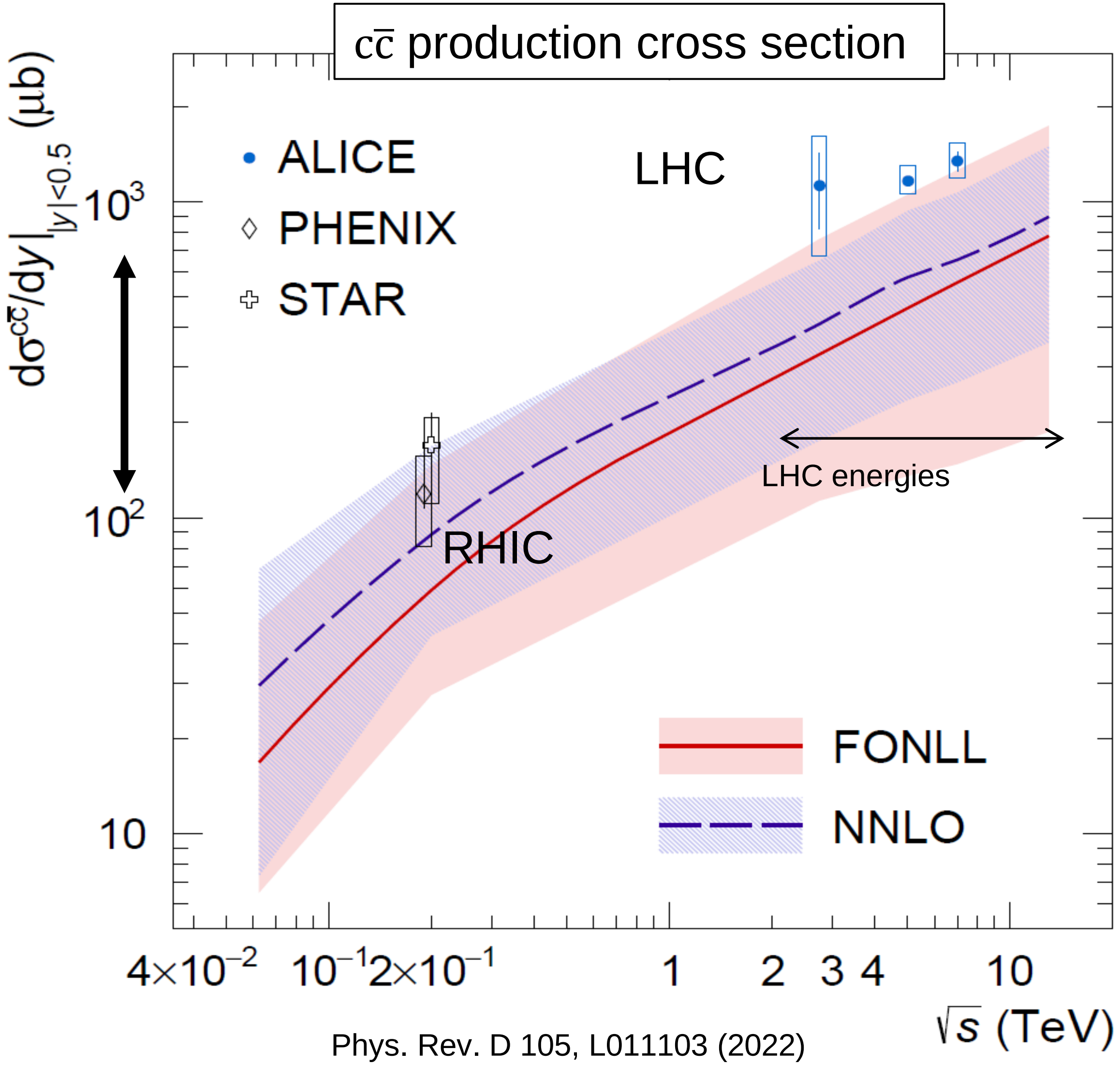
The cross section for producing a $c\bar{c}$ pair increases with √s

In a central event
At SPS ~0.1 $c\bar{c}$
At RHIC ~10 $c\bar{c}$
At LHC ~100 $c\bar{c}$

c from one $c\bar{c}$ pair may combine with $\bar{c}$ from another $c\bar{c}$ pair at hadronization to form a J/ψ
→ **regeneration!**



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



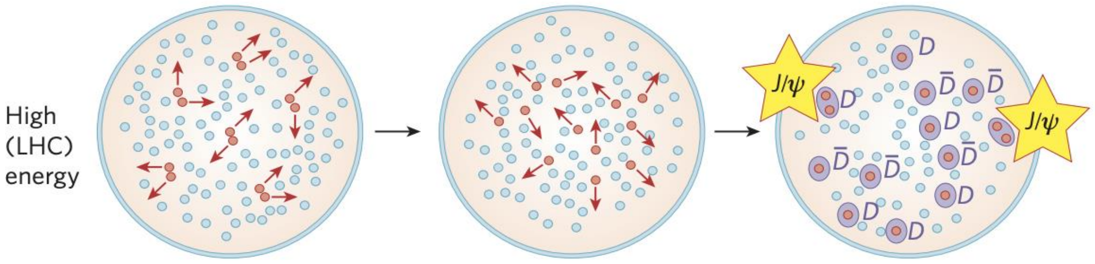
Phys. Rev. D 105, L011103 (2022)

J/ψ regeneration

R_{AA} midrapidity > R_{AA} forward rapidity

- **Regeneration of charmonium** and charmed hadrons take place in QGP or at the phase boundary.
- R_{AA} depends on the local charm quark density in the medium

→ **Signature of de-confinement.**



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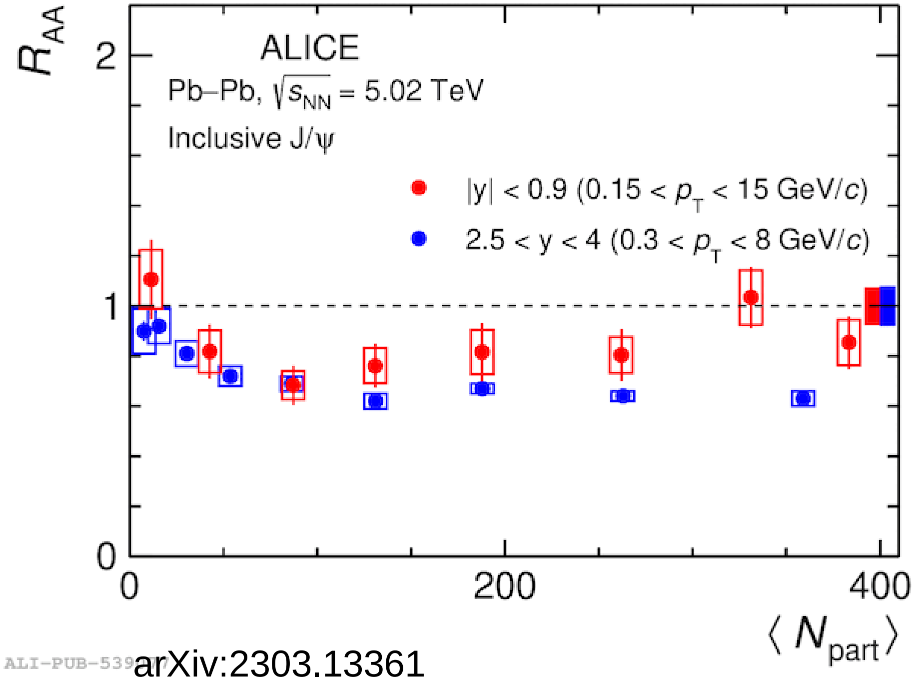
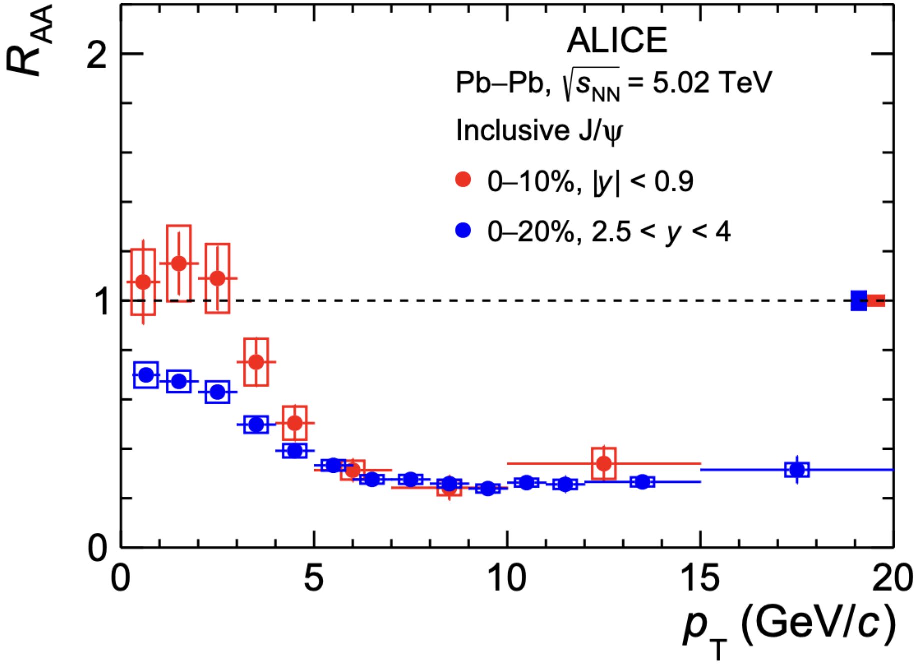


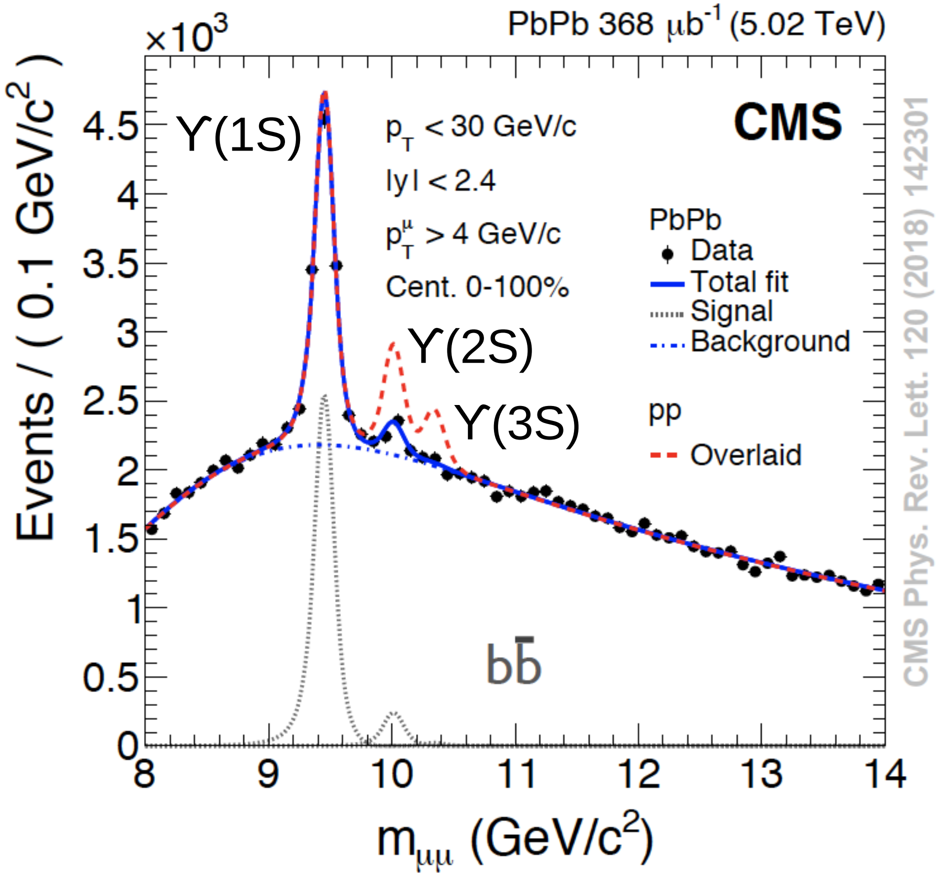
arXiv:2303.13361

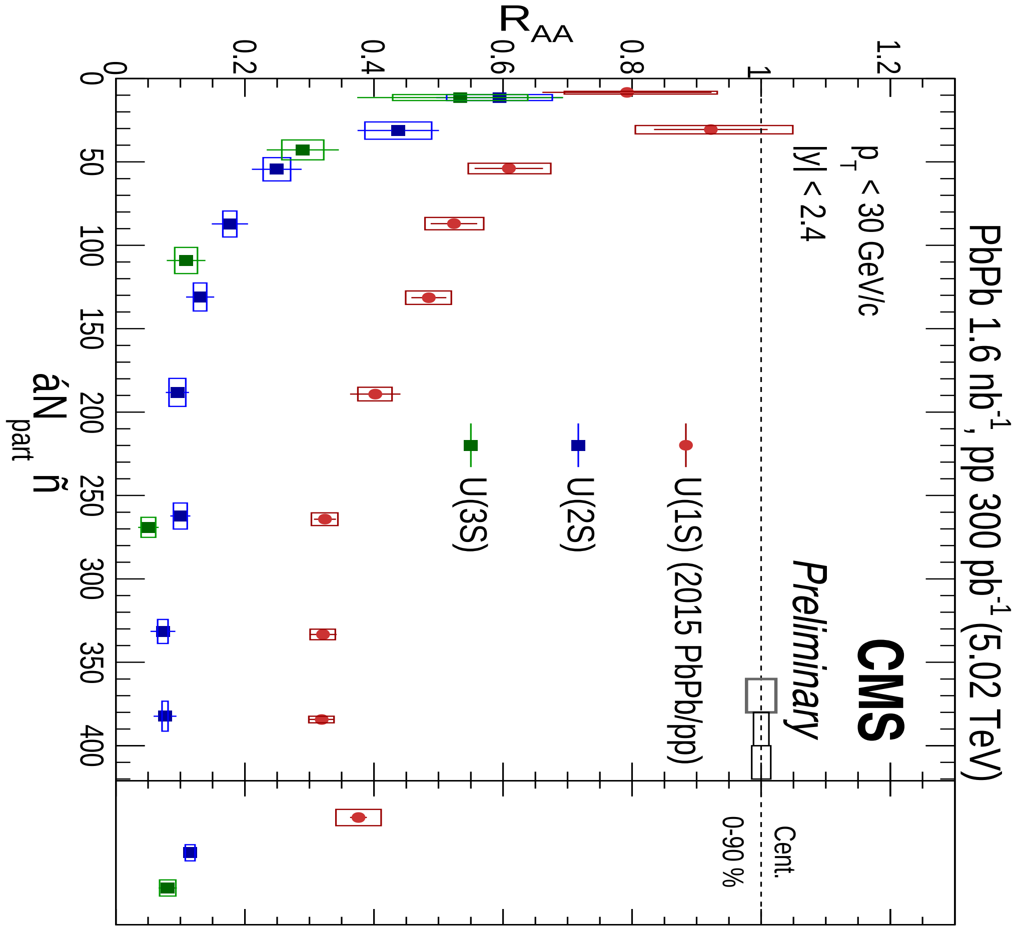


Sequential melting of b$\bar{b}$ states

Measurements reveal a sequential suppression of high mass b$\bar{b}$ states (bottomonium).

- The centrality dependence is consistent with progressive suppression in a hotter medium.

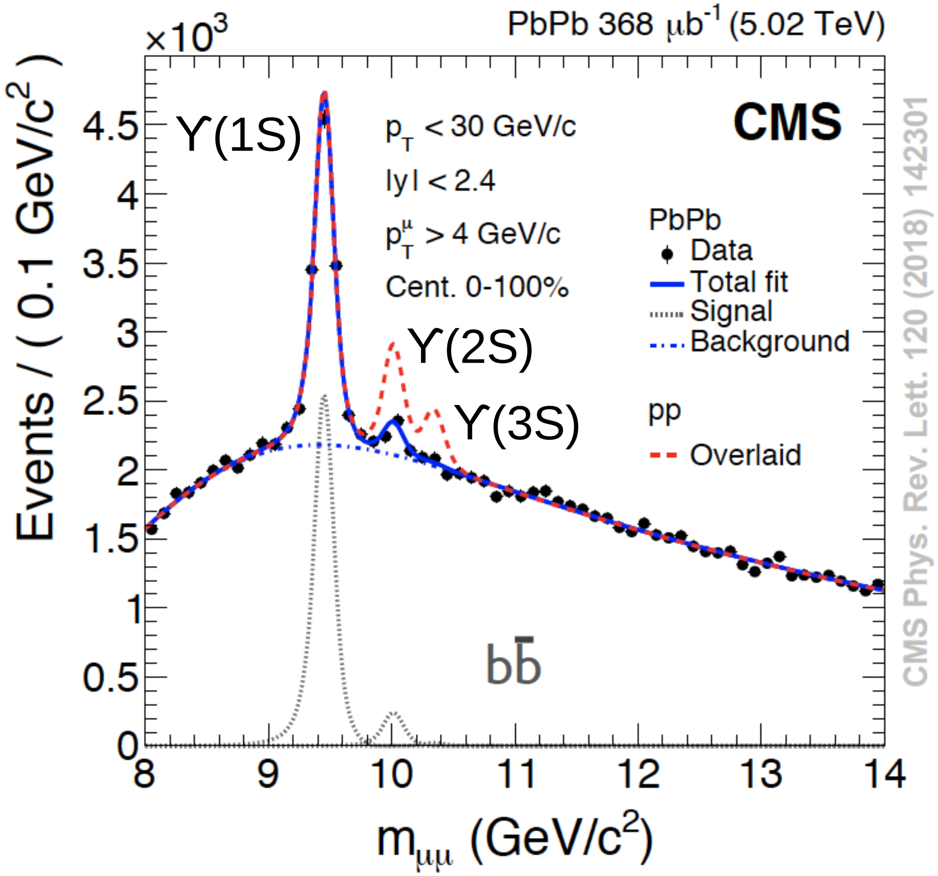


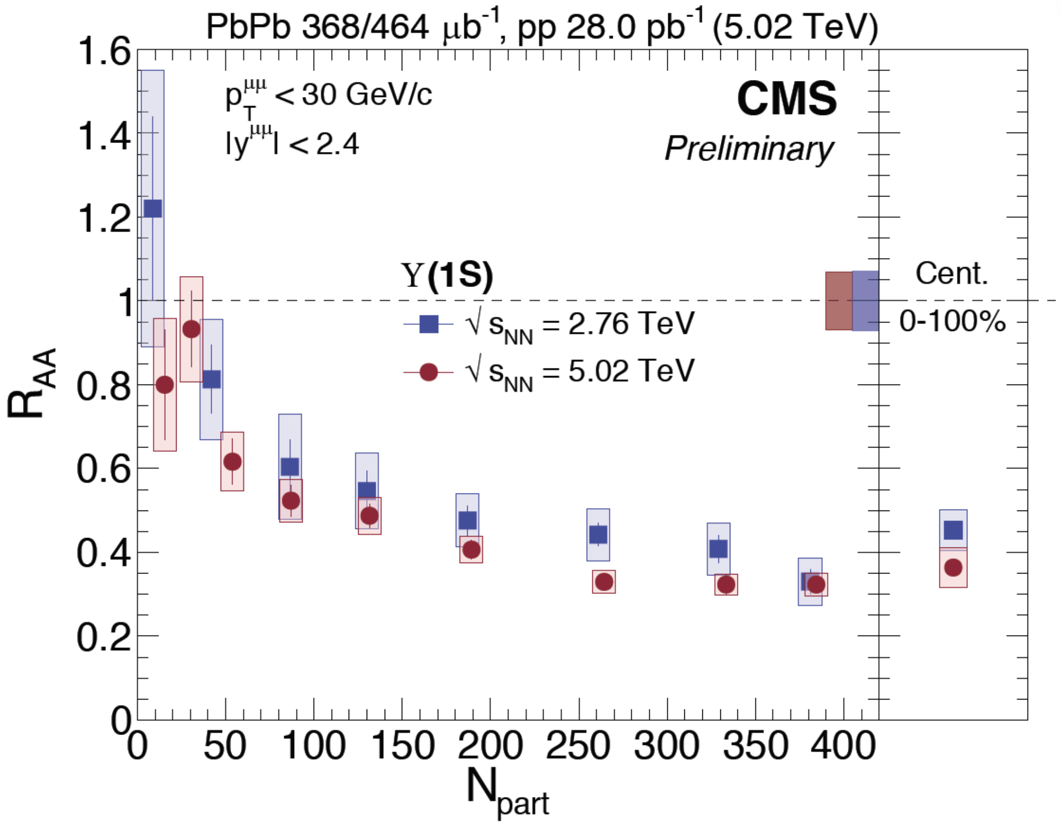


Sequential melting of $b\bar{b}$ states

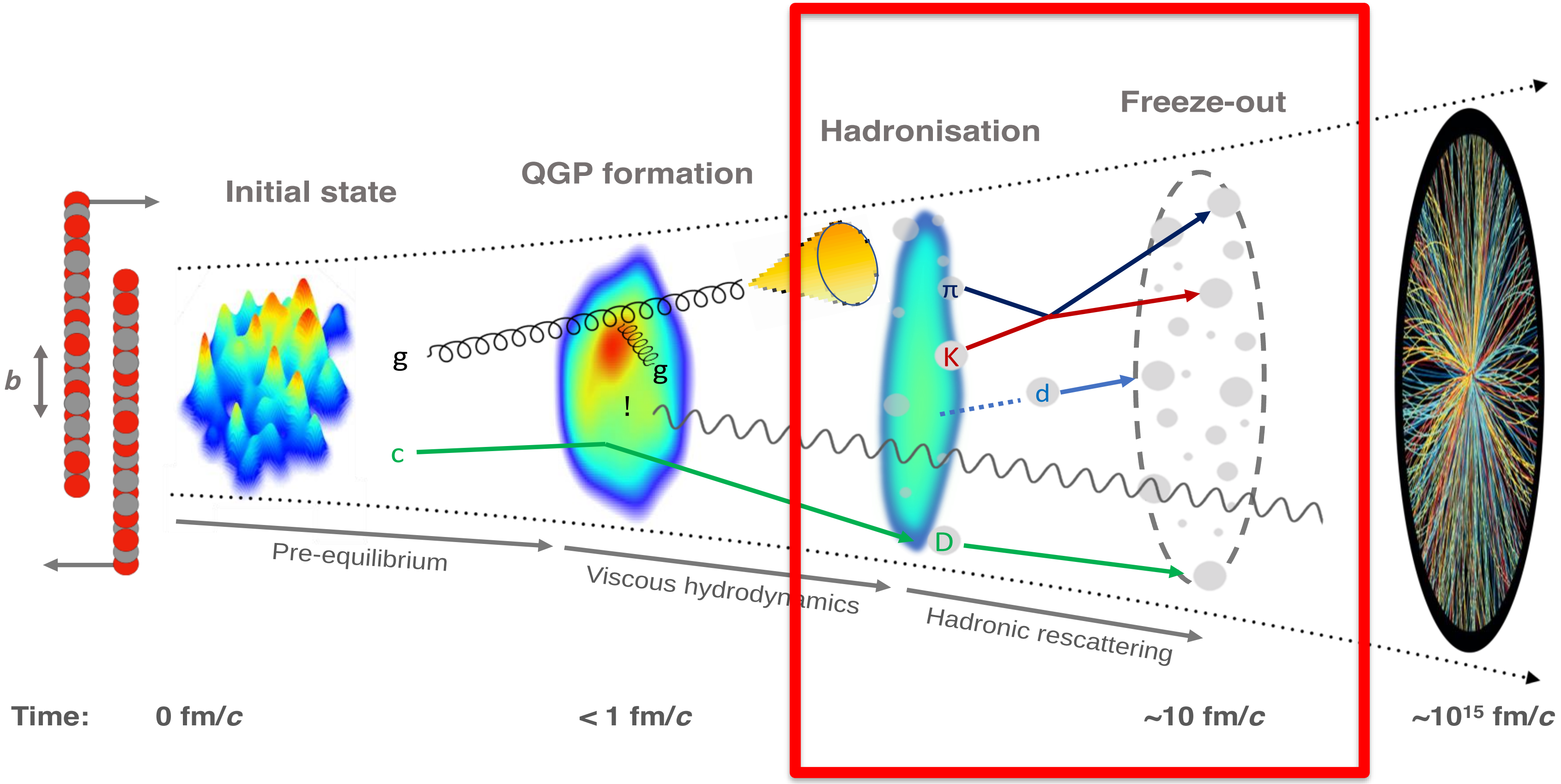
Measurements reveal a sequential suppression of high mass $b\bar{b}$ states (bottomonium).

- The centrality dependence is consistent with progressive suppression in a hotter medium.
- Increased suppression with increased collision energy → no recombination at hadronisation





What about the bulk of hadrons formed by hadronisation of the QGP?

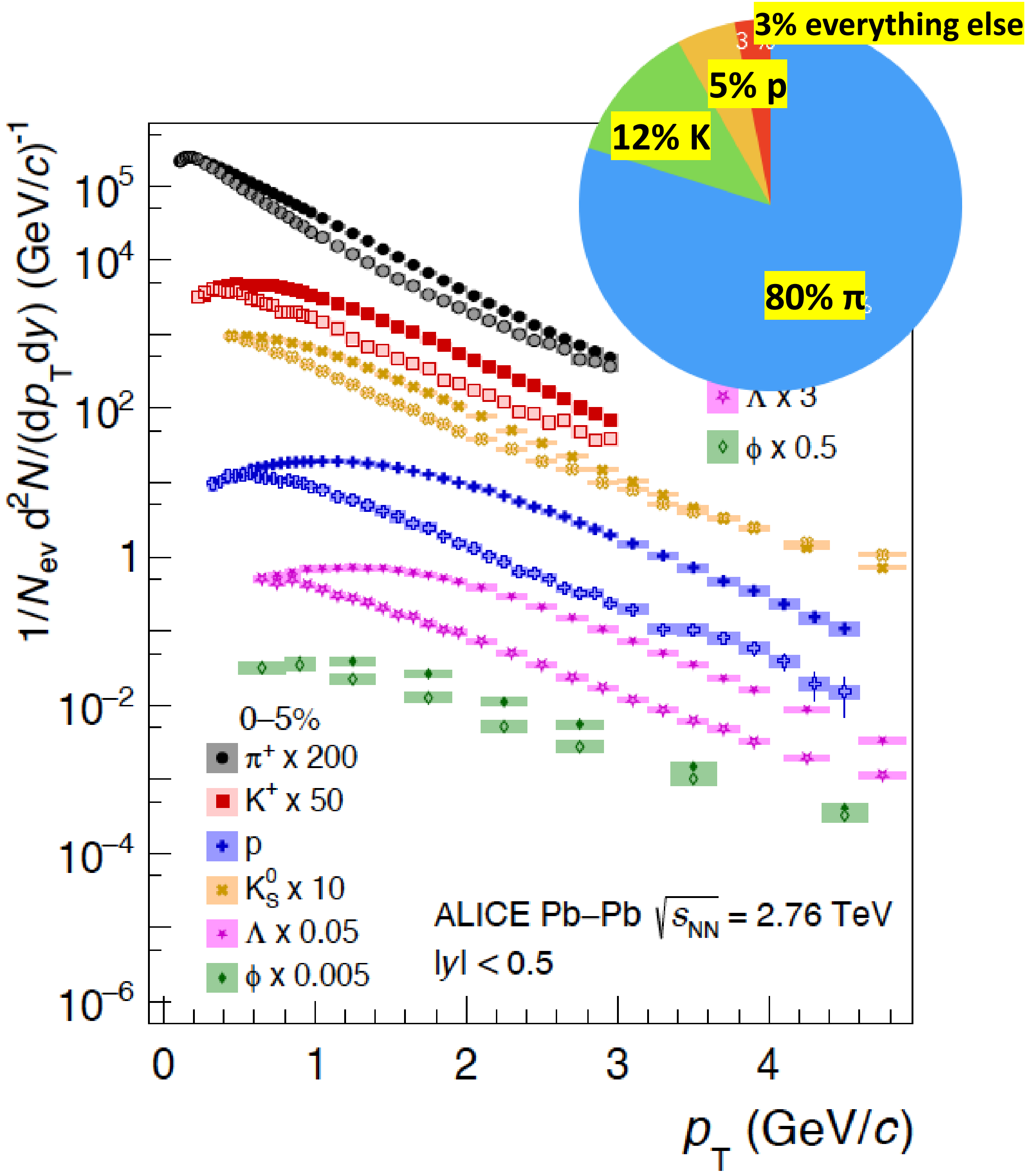


Bulk particle production

The bulk of particles is **soft** and composed by **light flavour** hadrons that are produced when the **QGP transitions** into a hot (T< 155 MeV) and dense gas of hadrons.

A **collective motion** is observed: the **dynamic and thermodynamic properties of the QGP** are studied by measuring p_T distributions azimuthal angle (φ) distributions.

Keep in mind: **π,K, p are the most abundant** hadronic species produced in the collision!



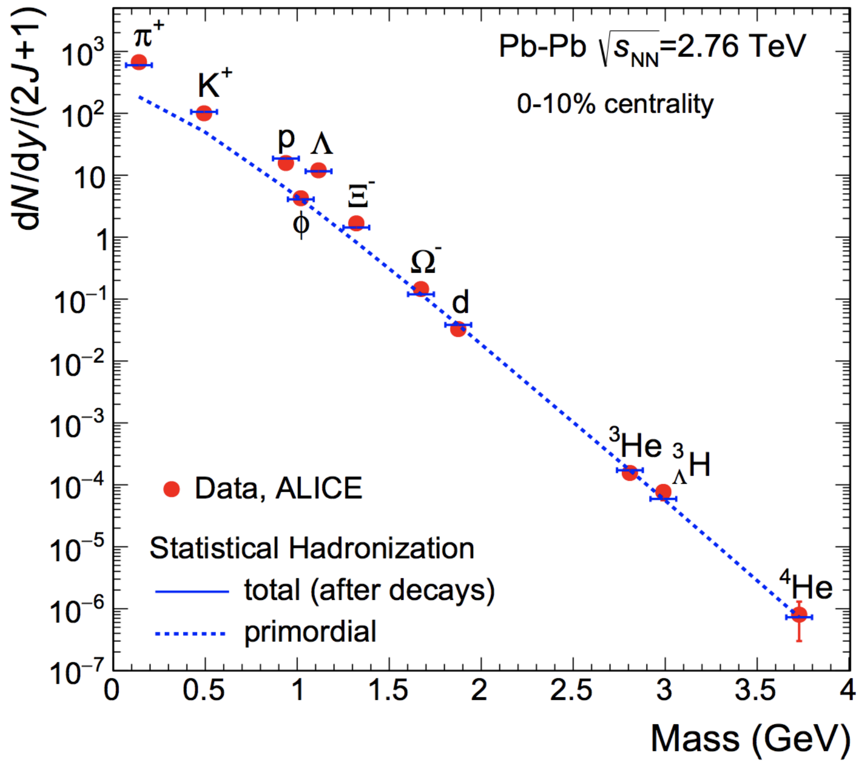
Chemical equilibrium temperature from SHM

Statistical hadronization model (SHM) describes an ideal relativistic gas of hadrons and resonances in **chemical equilibrium** (as the result of the hadronization of a QGP in thermodynamical equilibrium.

Particle abundances are obtained from the partition function of a Grand Canonical (GC) ensemble

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T] \pm 1}$$

where chemical potential for quantum numbers are constrained with conservation laws.

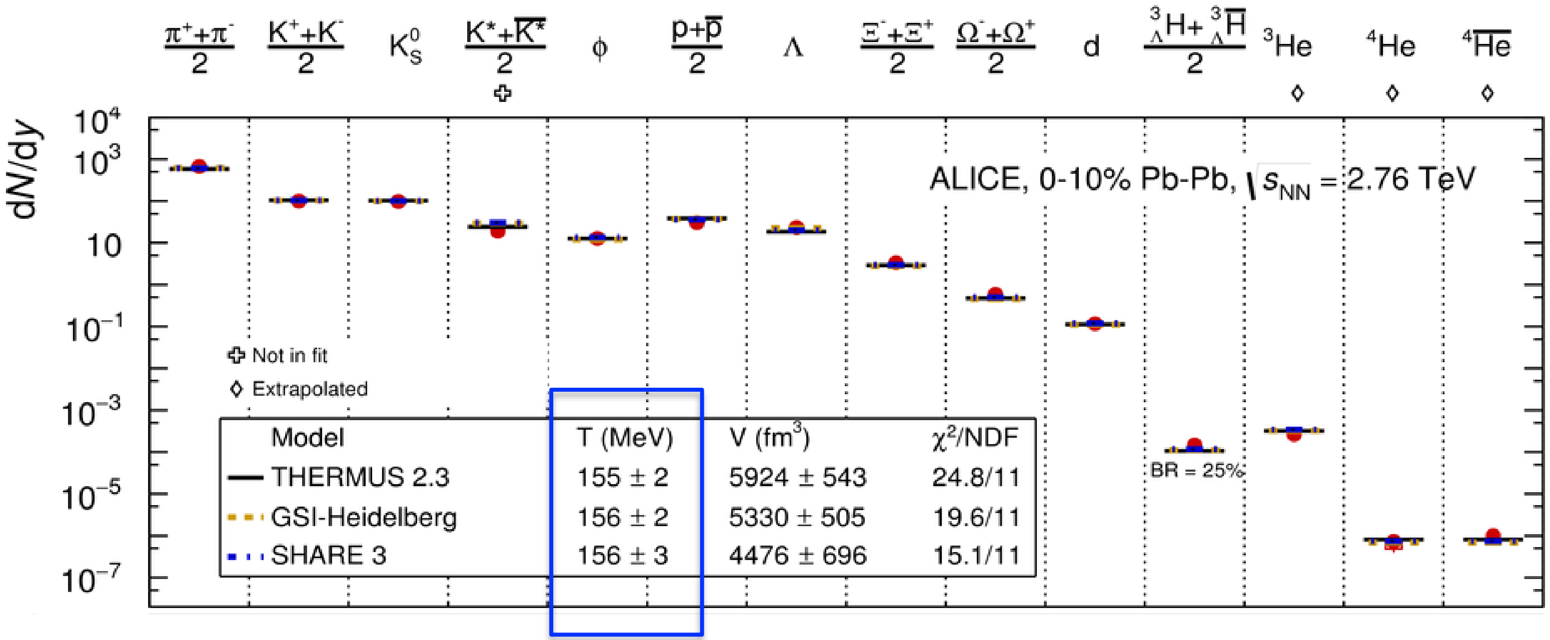


A. Andronic et al., Nature 561, 321 (2018

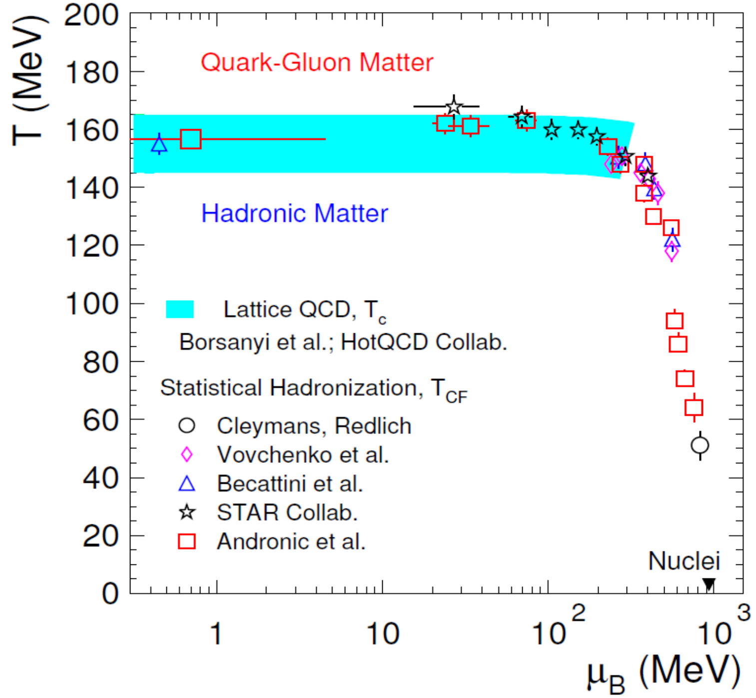
How to use it:

- ☐ **Predict yields** (see right figure) at a given temperature
- ☐ **Fit measured particle yields (or ratios)** to extract μ_B, T_{ch}, V.

Chemical freeze-out temperature



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	24.8/11
GSI-Heidelberg	156 ± 2	5330 ± 505	19.6/11
SHARE 3	156 ± 3	4476 ± 696	15.1/11



Production of (most) light-flavour hadrons (and anti-nuclei) is described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out** temperature, **T_{ch} ≈ 156 MeV**

⟶ Approaches the critical temperature roof from lattice QCD: **limiting temperature** for hadrons!

→ the success of the model in fitting yields over 10 orders of magnitude supports the picture of a system in **local thermodynamical equilibrium**

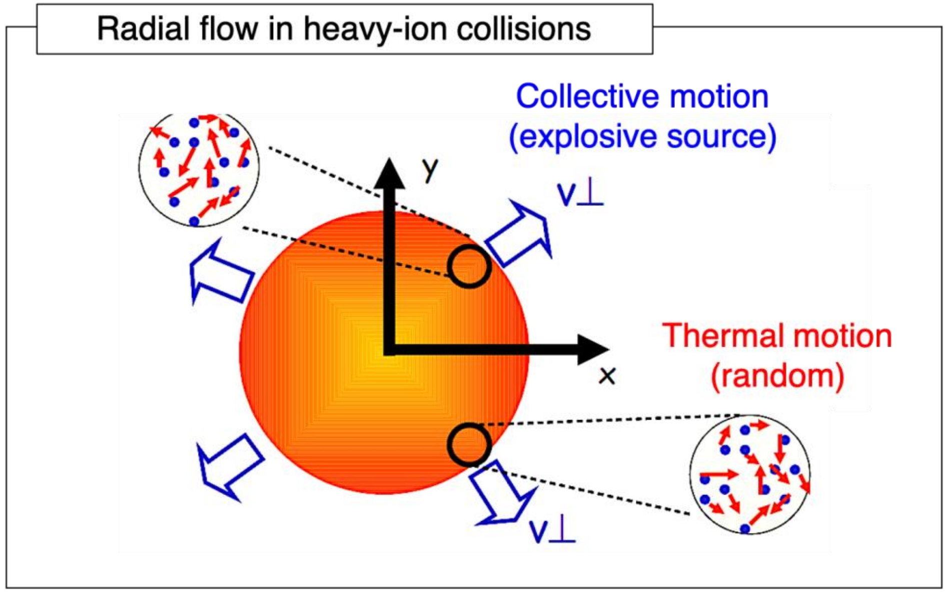
Hydrodynamics at play: radial flow (1/2)

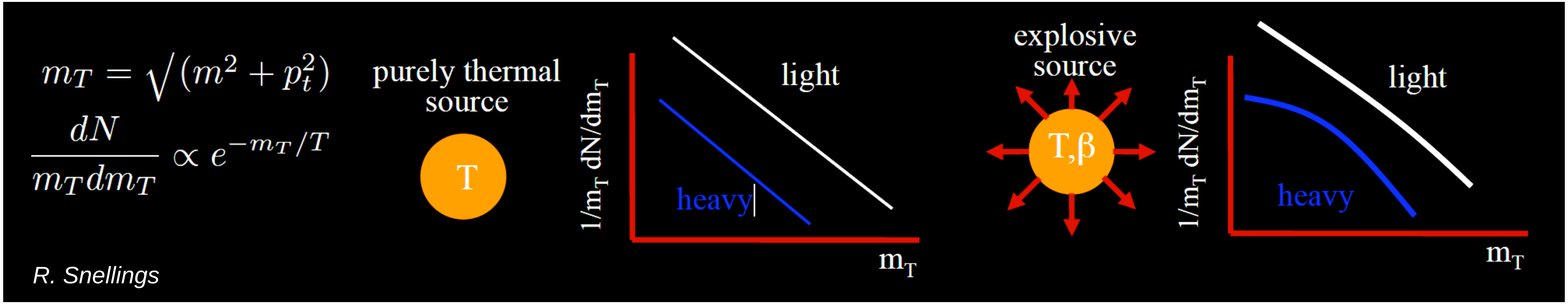
A **collective motion** is superimposed to the thermal motion of particles → the system as a **medium**

Radial flow

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

→ Affects the low p_T distribution of hadrons and their ratios depending on their mass

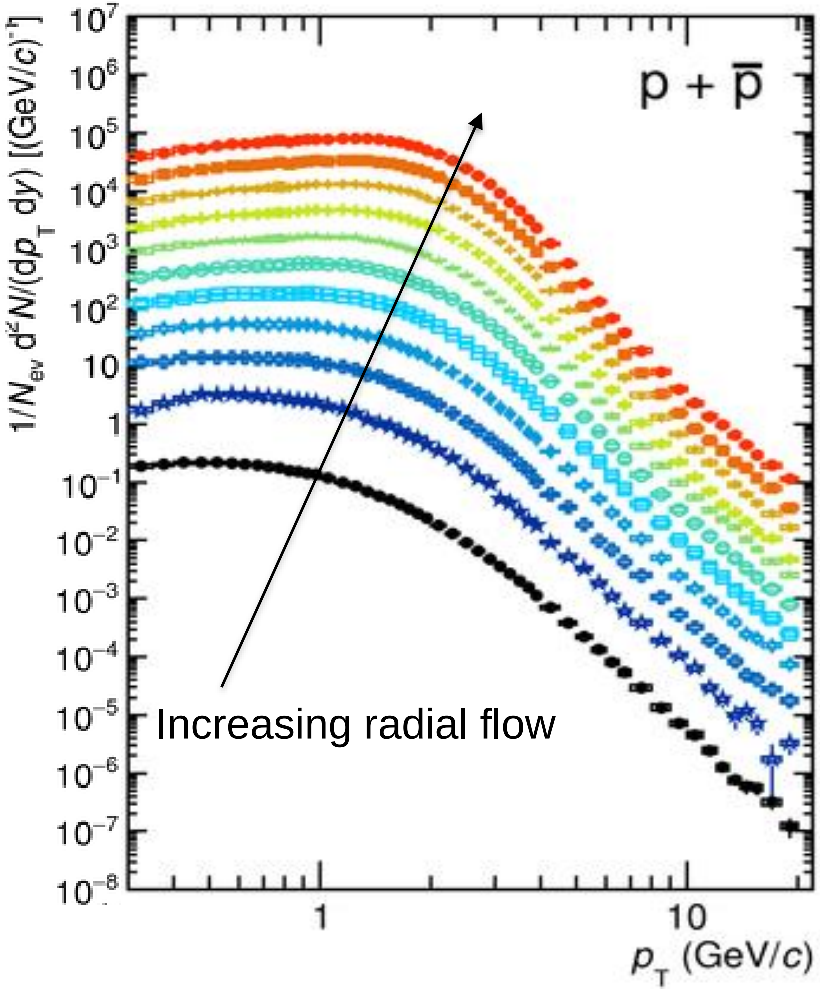

Radial flow in heavy-ion collisions


$$m_T = \sqrt{(m^2 + p_t^2)}$$

$$\frac{dN}{m_T dm_T} \propto e^{-m_T/T}$$

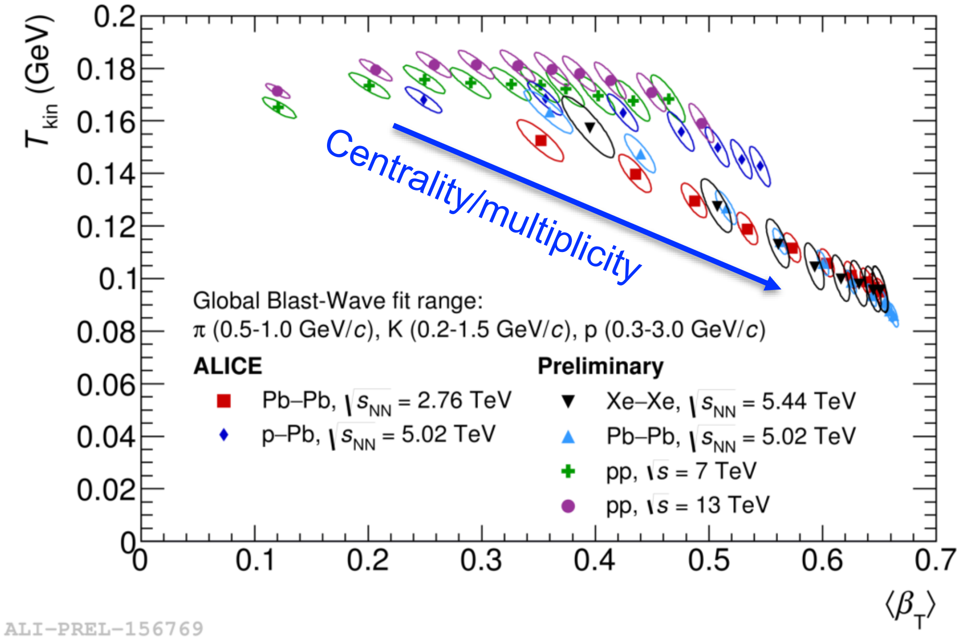
R. Snellings

Hydrodynamics at play: radial flow (2/2)



At low $p_{T,}$ the radial flow "pushes" particles to higher momenta
→ spectra get "harder" for more central collisions
→ mass dependence

A simplified hydrodynamical model, the Boltzmann-Gibbs blast-wave model is used to **quantify radial flow and the kinetic freeze-out temperature.**



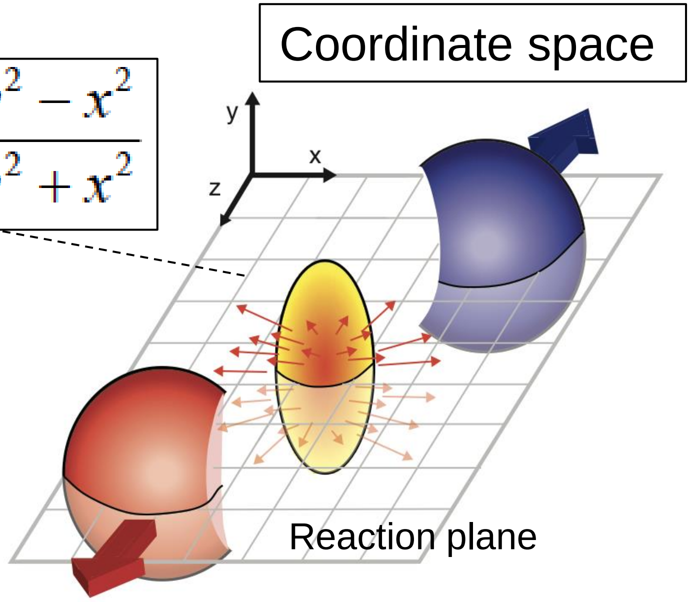
More central (higher multiplicity) events have lower T_{kin} and higher flow velocity

T_{kin} ~ 100-140 MeV

Hydrodynamics at play: anisotropic flow (1/2)

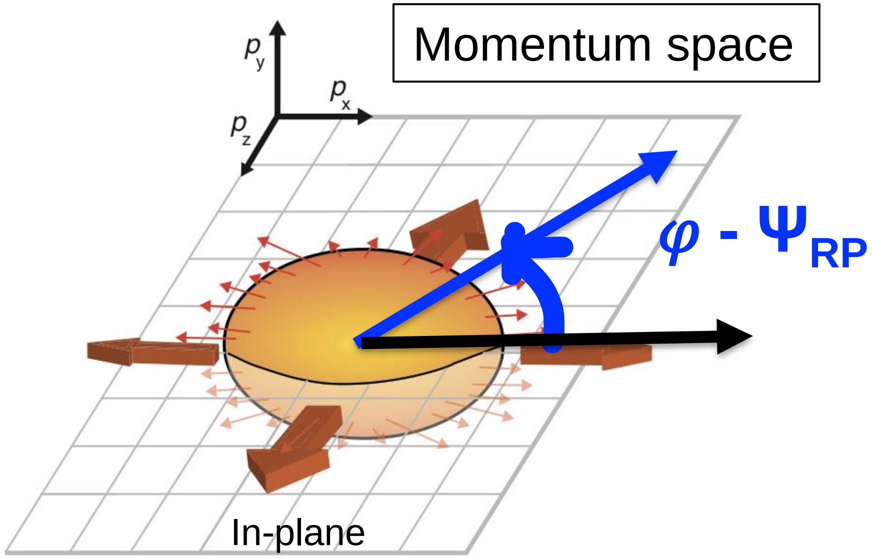
Initial geometrical anisotropy (”almond” shape) in non-central HI collisions → eccentricity

$$\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$$



Pressure gradients develop → more and faster particles along the reaction plane than out-of-plane

Scatterings among produced particles convert **anisotropy** in coordinate space into an observable momentum anisotropy
→ **anisotropic flow**
→ quantified by a Fourier expansion in azimuthal angle φ



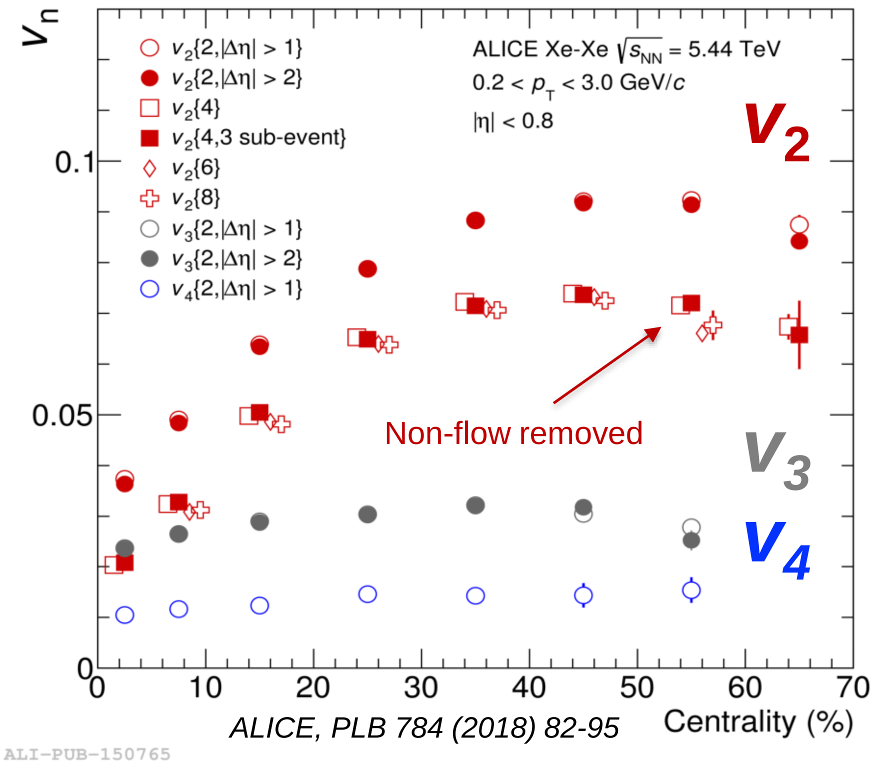
v_n = **harmonics**

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right),$$

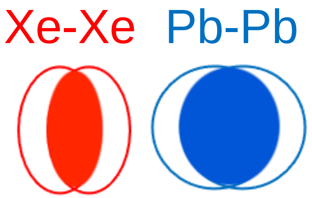
Hydrodynamics at play: anisotropic flow (2/2)

The **strong centrality dependence** of v_2 reflects the degree of “anisotropy” in initial geometry.

Fluctuations of the initial state energy-density lead to different shapes of the overlap region
→ **non-zero higher-order flow** coefficients (“harmonics”)



ALICE, PLB 784 (2018) 82-95



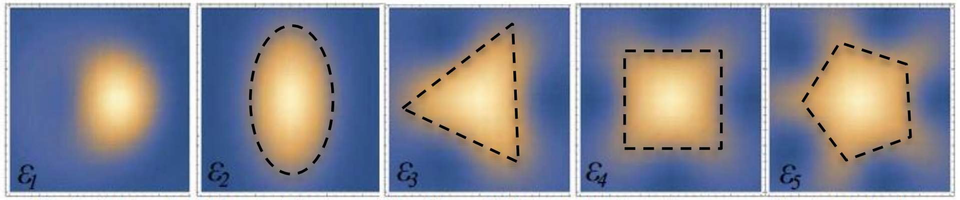
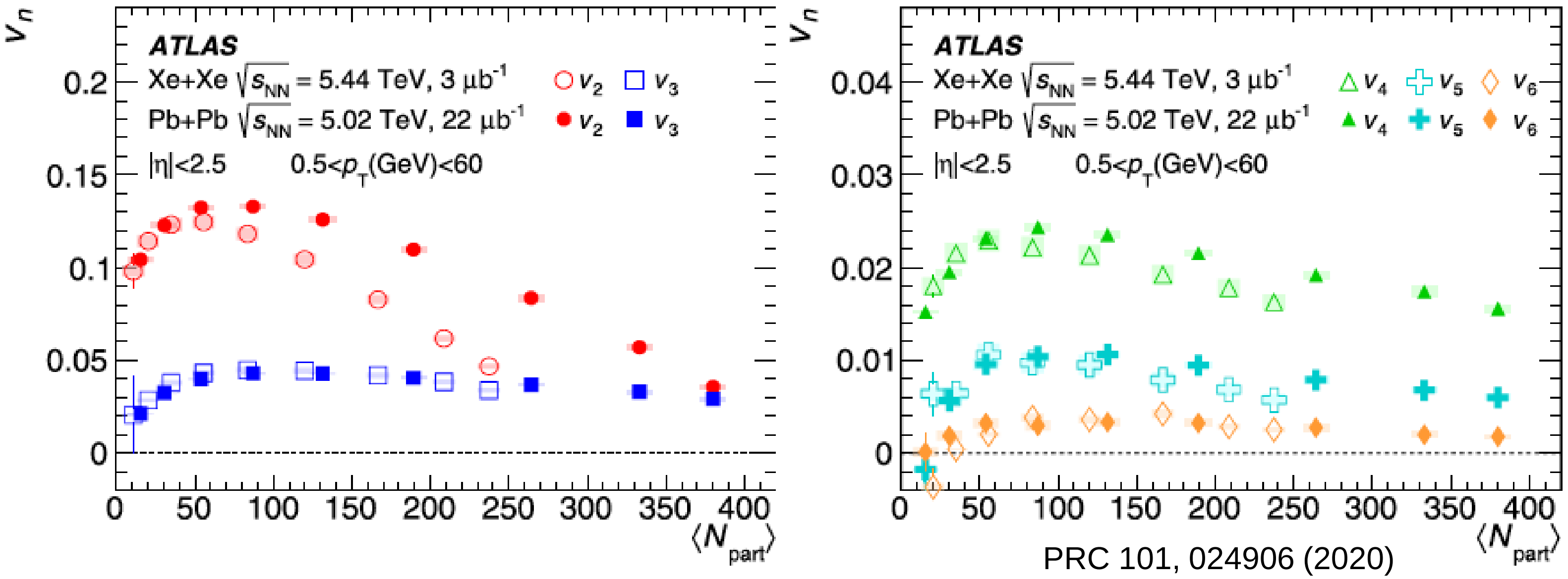


Fig. 2. (color online) Characteristic shapes of the deformed initial state density profile, corresponding to anisotropies of $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, $\mathcal{E}_4$ and $\mathcal{E}_5$ (from left to right).

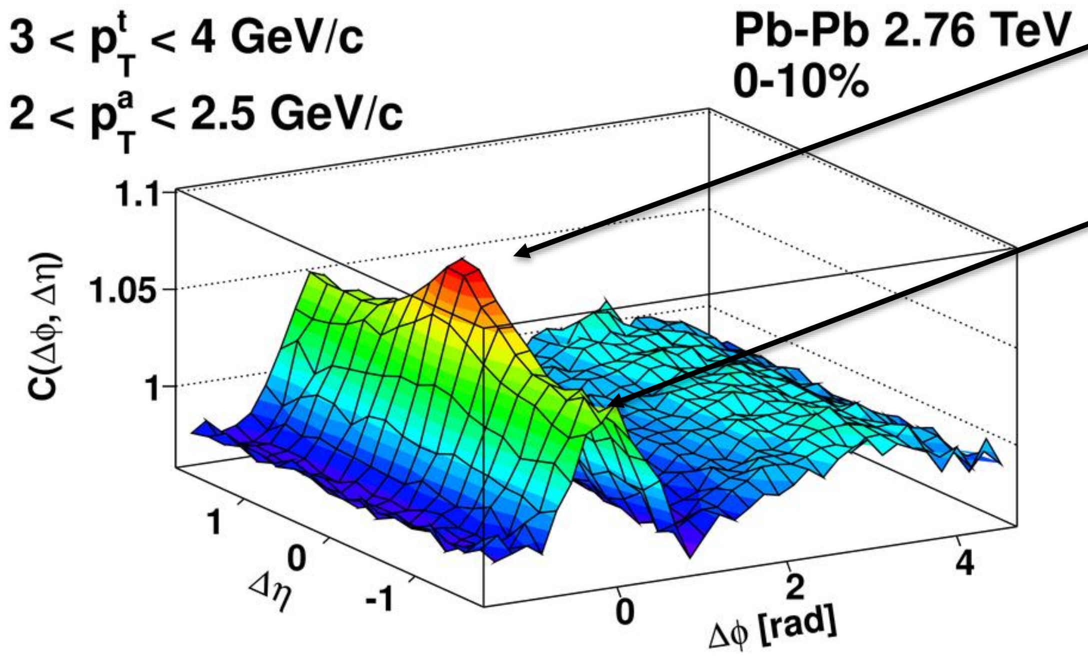
Li Yan 2018 Chin. Phys. C 42 042001



PRC 101, 024906 (2020)

Two-particle correlations in Pb-Pb collisions

Collectivity can also be studied by looking at correlations of two particles vs $\Delta\eta$ (difference in rapidity) and $\Delta\varphi$ (difference in azimuthal angle).



ALICE, Phys.Lett. B 708 (2012) 249-264

Peak at $\Delta\eta \sim 0$:
short-range correlations □ **jets**

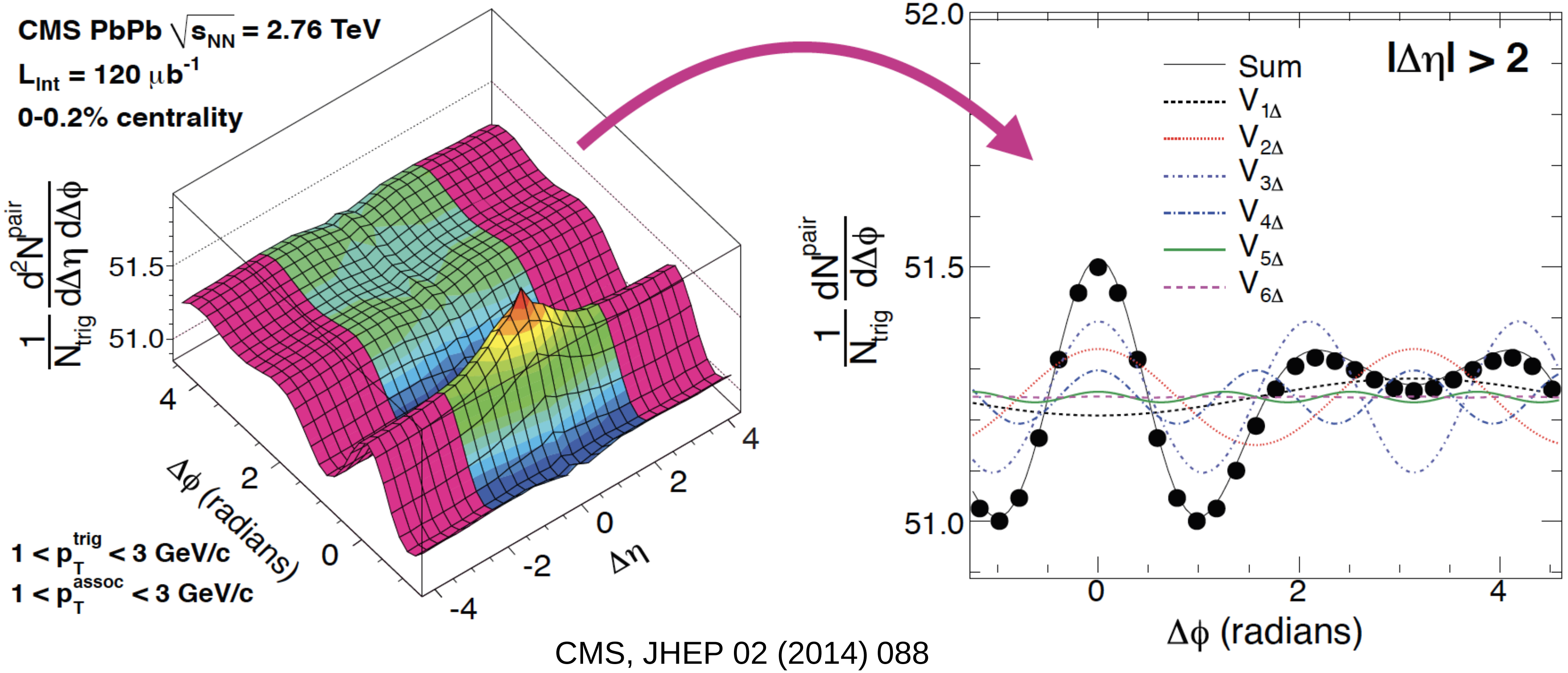
Broad **”ridge”** in a wide $\Delta\eta$ range:
long-range correlations emerging from early times (causality) □ **anisotropic flow**

In azimuth: structure determined by the medium response to the initial transverse geometry

Two-particle correlations in Pb-Pb collisions

Collectivity can also be studied by looking at correlations of two particles vs $\Delta\eta$ (difference in rapidity) and $\Delta\varphi$ (difference in azimuthal angle).

→ Decomposition in Fourier series of the azimuthal distribution at large η.



CMS, JHEP 02 (2014) 088

Hydrodynamical modeling

Ideal hydrodynamics

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu J^\mu_B = 0$$

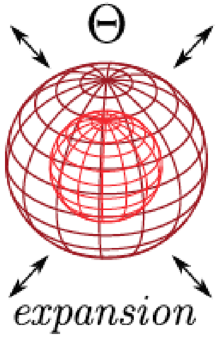
- applies to a system in local equilibrium (e.g. thermodynamical)
- requires energy and charge conservation
- system is described by energy density ε, pressure P, velocity u^ν, and charge n and by 5 equation of motion, closed by one equation-of-state (EOS) $\varepsilon = \varepsilon(P)$
- The response of the system to external solicitation is controlled by the EOS

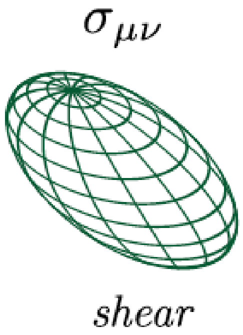
Viscous hydrodynamics

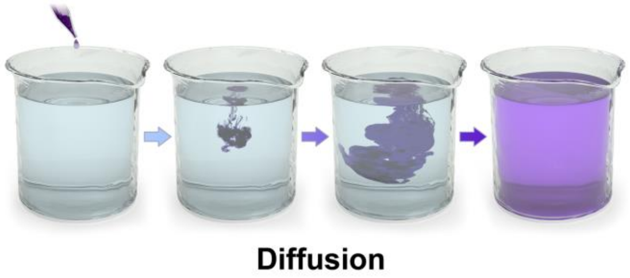
- Includes corrections for dissipative effects:
  bulk ζ and shear viscosity η, charge diffusion, κ

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P - \zeta\Theta)\Delta^{\mu\nu} - 2\eta\sigma^{\mu\nu}$$

$$J^\mu = q u^\mu + \kappa \nabla^\mu_\perp (\mu/T)$$





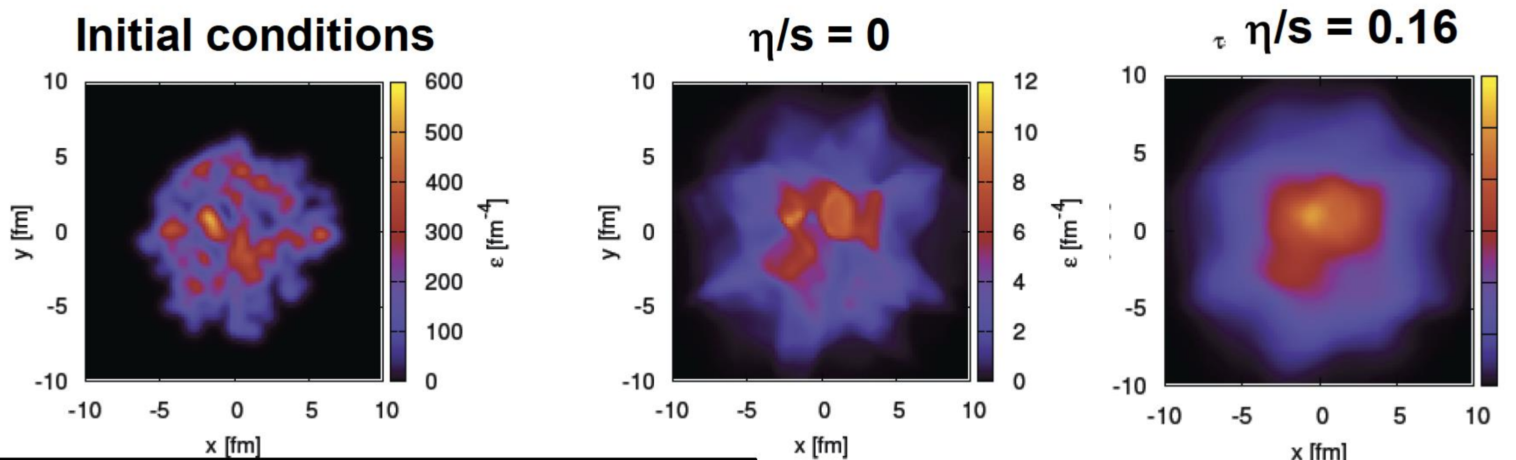


Figs. from Rezzolla and Zanotti, 2013

Shear viscosity

Shear viscosity (expressed as viscosity over entropy, η/s) washes out initial-state anisotropies

- Larger consequences on higher-order harmonics
- Larger η/s reduces flow

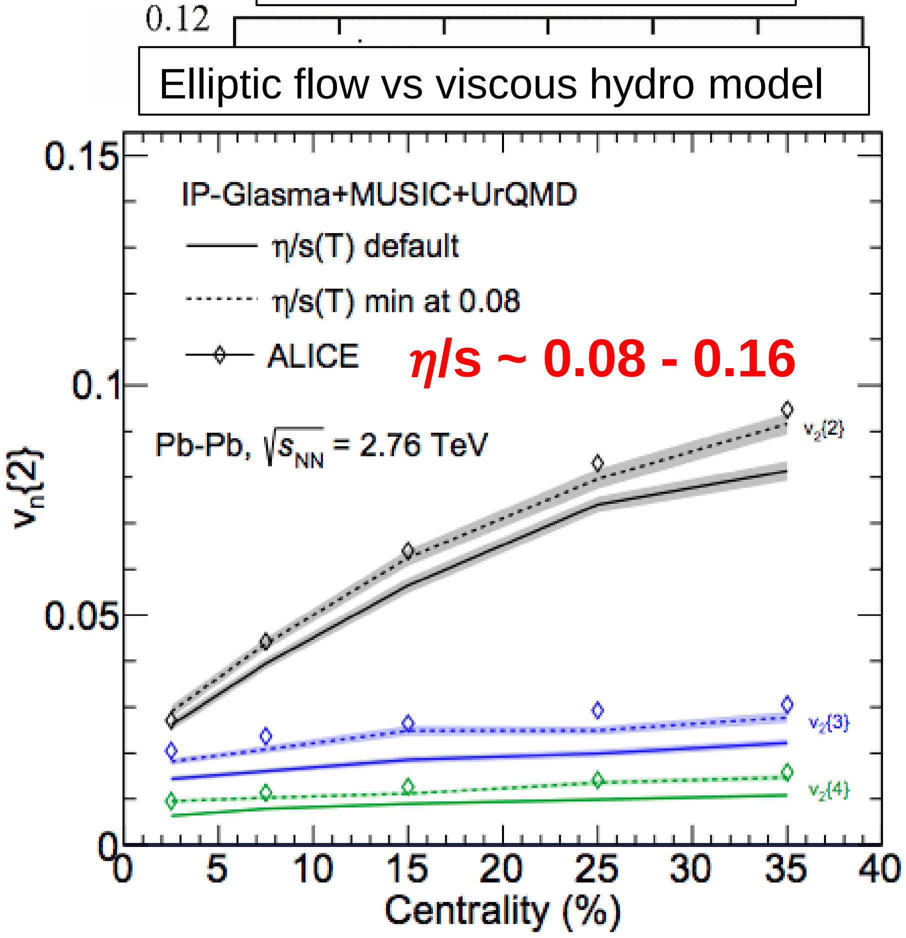


Water: $\eta/s \sim 30$ | Olive oil $\eta/s \sim 240$

MUSIC, Sangyo

Larger η/s reduces flow

Elliptic flow vs viscous hydro model



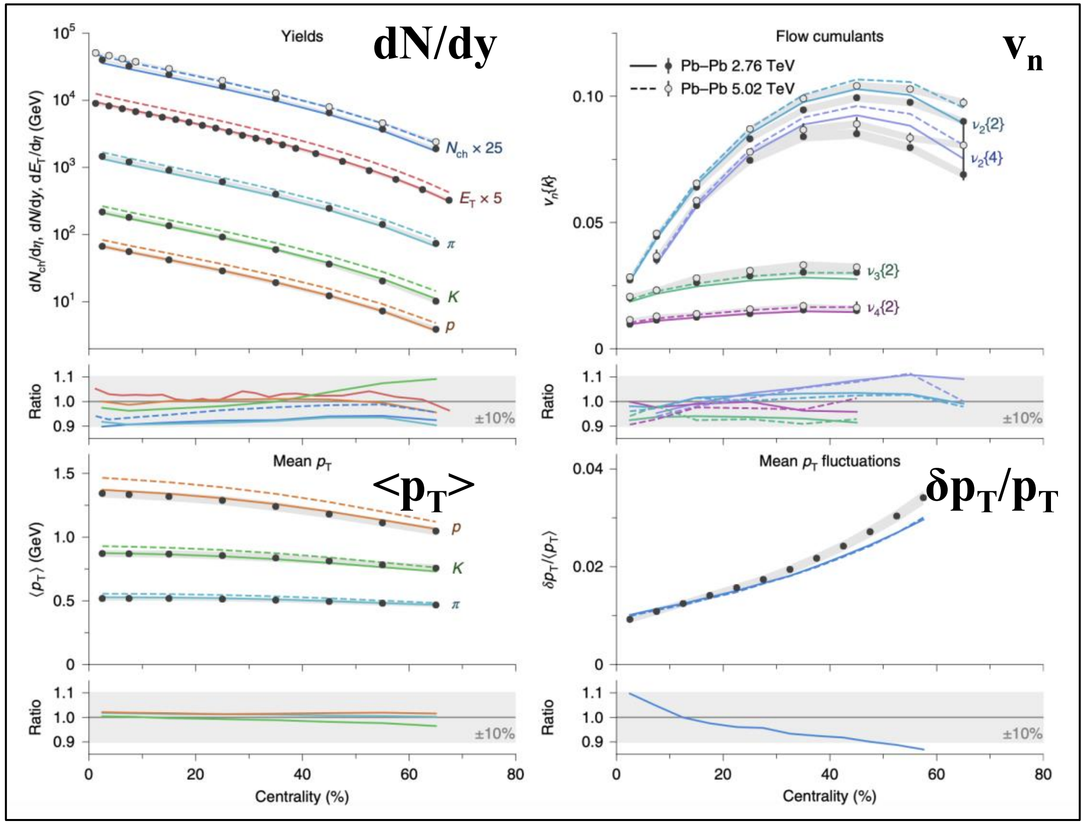
$\eta/s \sim 0.08 - 0.16$

Kovtun, Son, and Starinets

Measured v_2 is described very well by hydrodynamic models
→ **QGP behaves as a ~perfect liquid!**

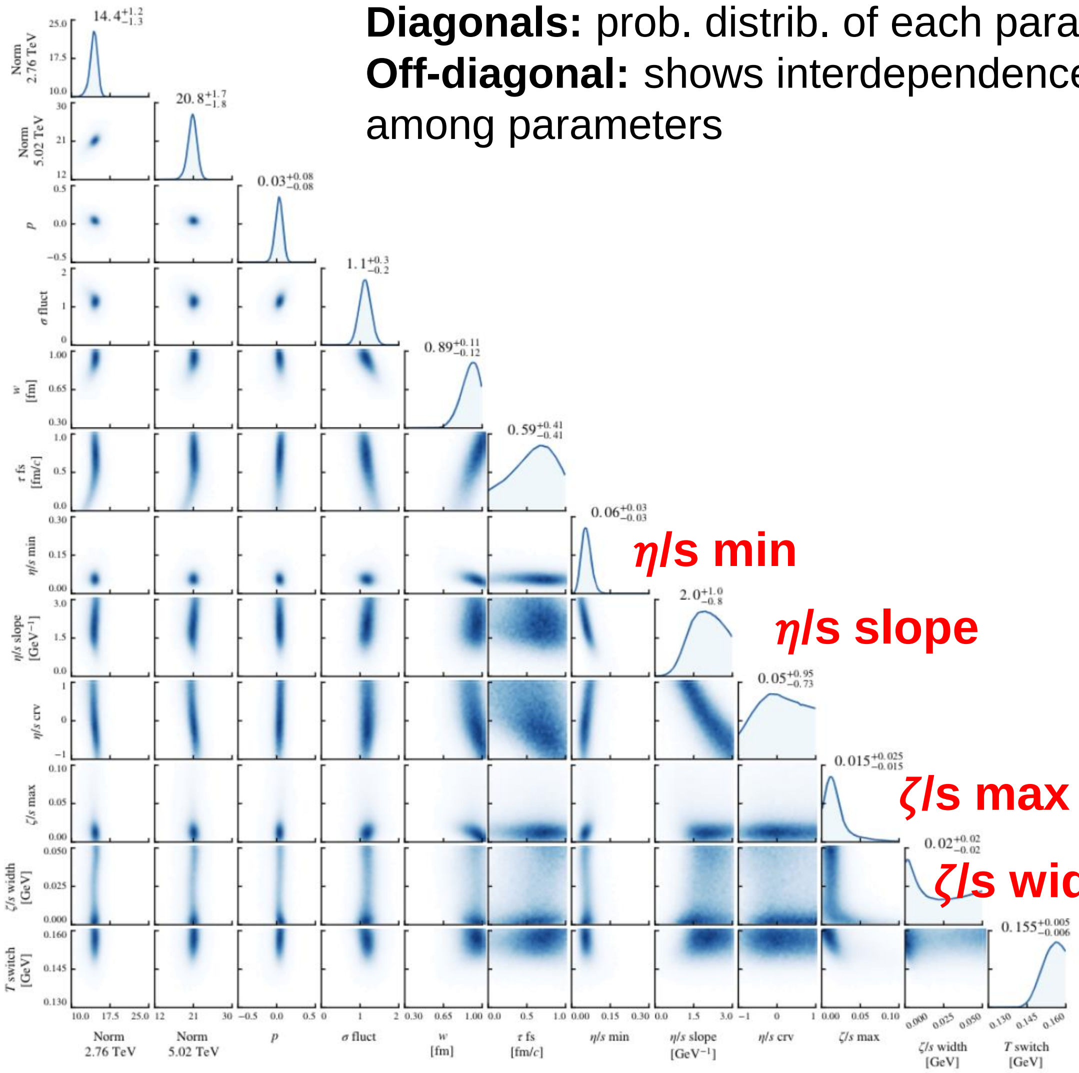
QGP properties from flow 1/2

Bayesian analysis of yields, mean p_T, flow harmonics measured by ALICE has been used to extract the QGP properties.



J. E. Bernhard et al, Nature Physics 15 (2019) 1113

S.A. Bass et al. / Nuclear Physics A 967 (2017) 67–73



Diagonals: prob. distrib. of each param.
Off-diagonal: shows interdependence among parameters

η/s min

η/s slope

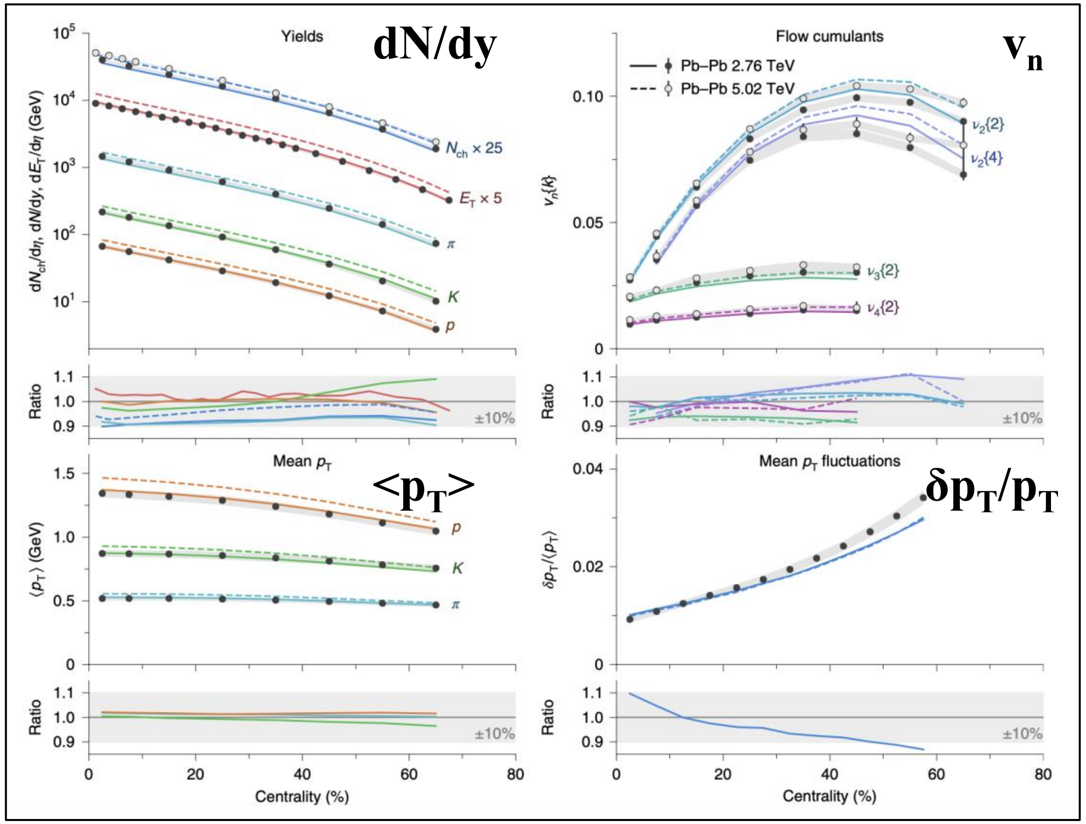
ζ/s max

ζ/s width

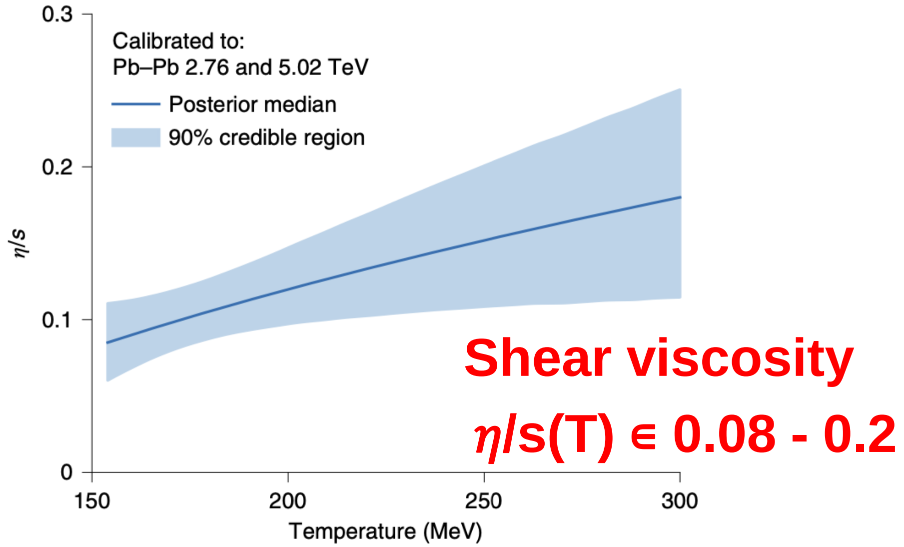
Tc

QGP properties from flow 2/2

Bayesian analysis of yields, mean p_T, flow harmonics measured by ALICE has been used to extract the QGP properties.

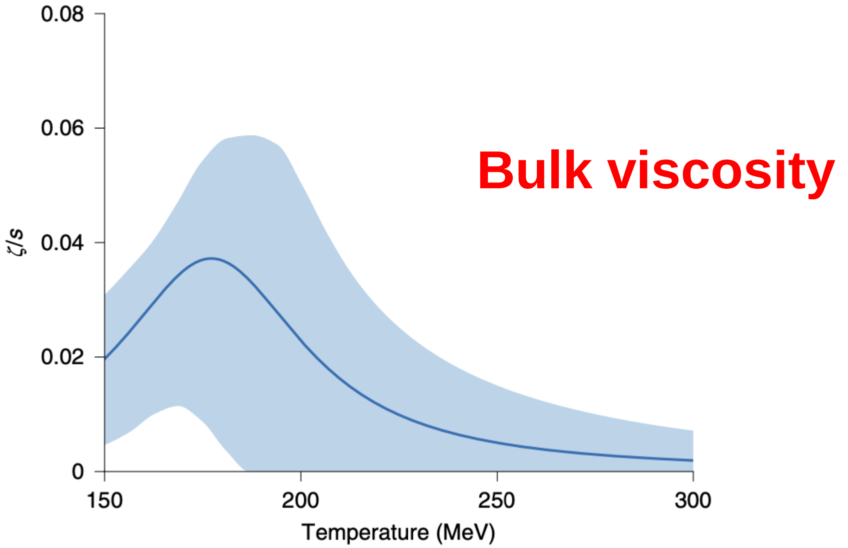


J. E. Bernhard et al, Nature Physics 15 (2019) 1113



Shear viscosity

$\eta/s(T) \in 0.08 - 0.2$



Bulk viscosity

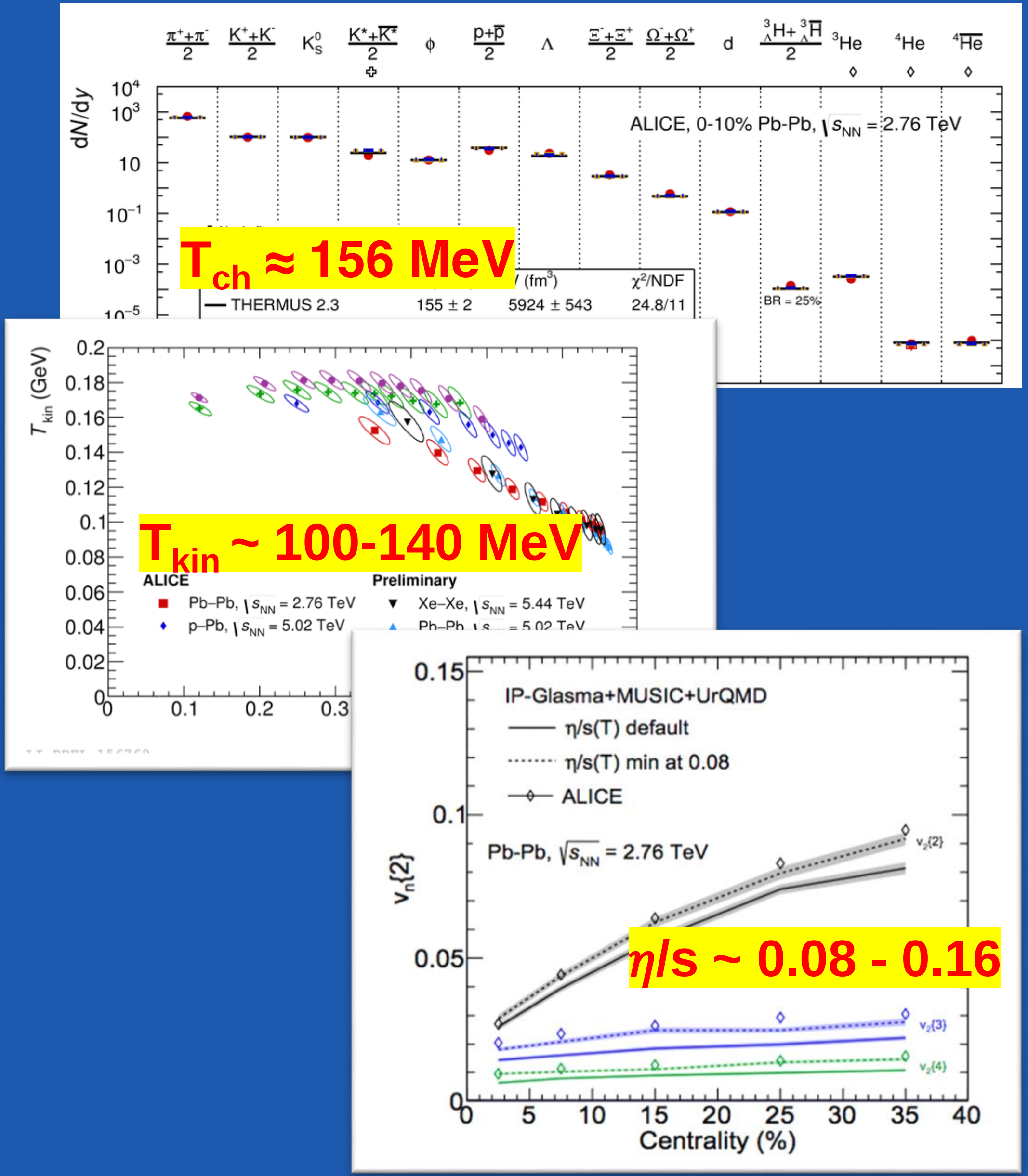
Bulk particle abundances are described by the statistical hadronization model assuming chemical equilibrium and with **Tch ~ 156 MeV**

The QGP expands rapidly under **radial flow**.

Spatial anisotropy of the initial collision region causes **anisotropic flow.**

Spectra and flow coefficients are well described by viscous hydrodynamics with a very low shear viscosity (**η/s ~ 0.08 –0.16**) → "perfect liquid"

The **success of SHM and hydrodynamic** description also supports the idea of a medium in local **thermodynamical equilibrium.**



Formation of quark-gluon plasma at the LHC

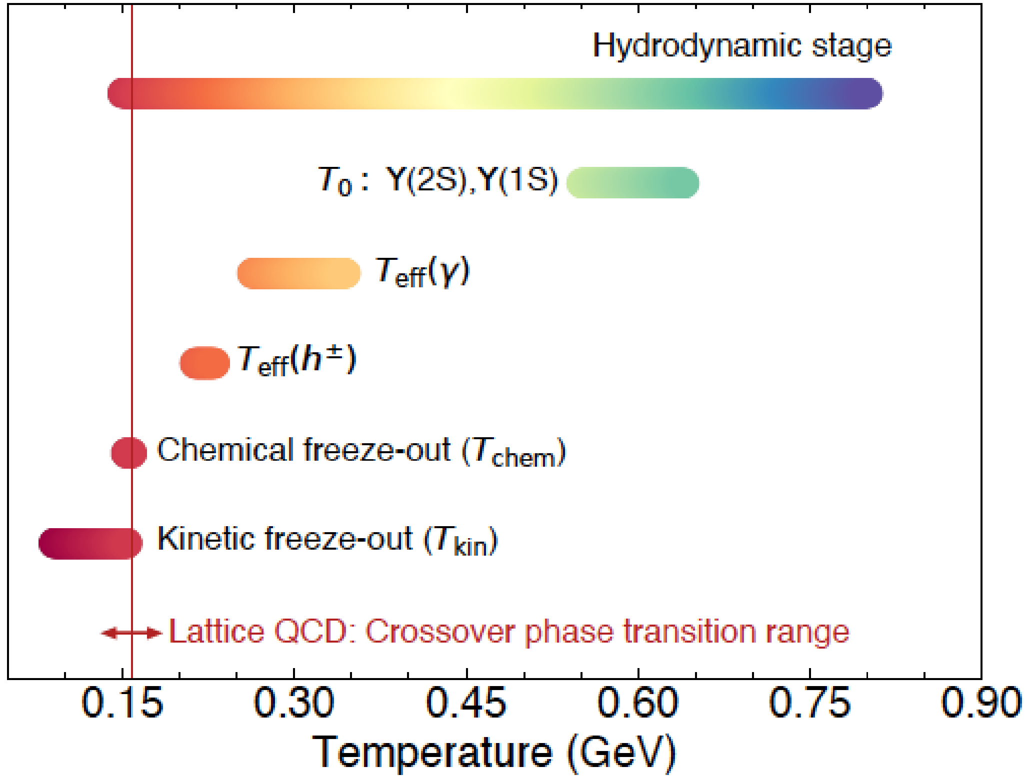
The conditions to form a QGP are met and exceeded in heavy-ion collisions at the LHC.

The **initial energy density** estimated in central collisions is ~12 GeV/fm^3 at the early time of 1 fm/c

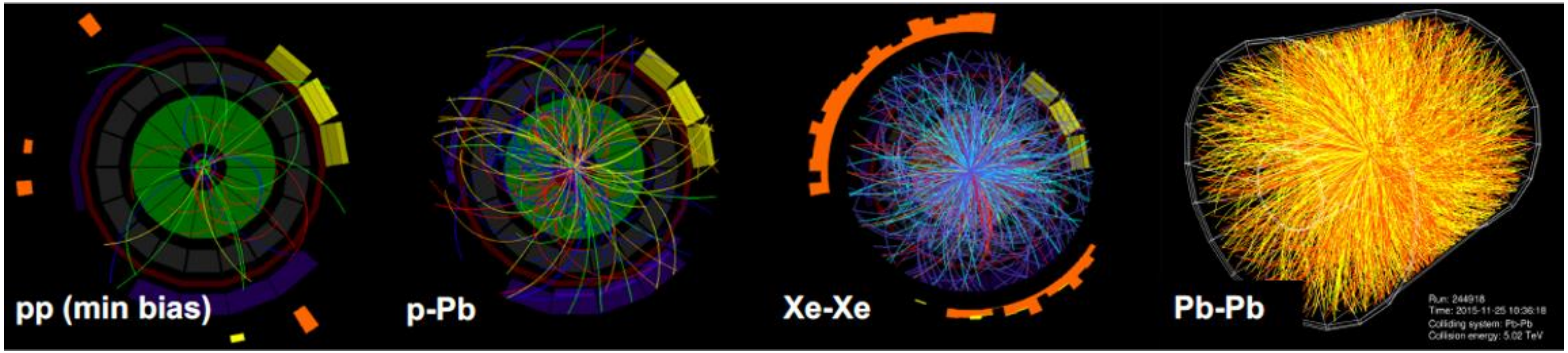
The **initial QGP temperature** is up to 5 times higher than the QCD decofinement temperature predicted by ab-initio lattice QCD calculations, T_{pc} = 155–159 MeV

The matter created has the largest temperature and energy density ever observed!

ALICE, arXiv:2211.04384



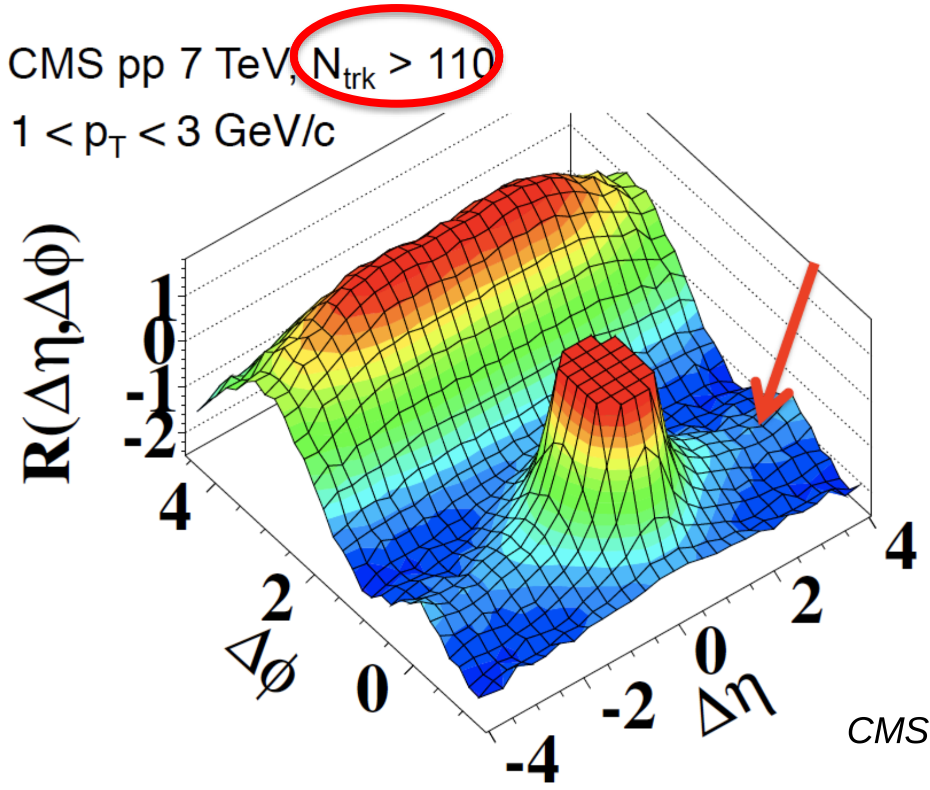
Can we produce a QGP in pp collisions?

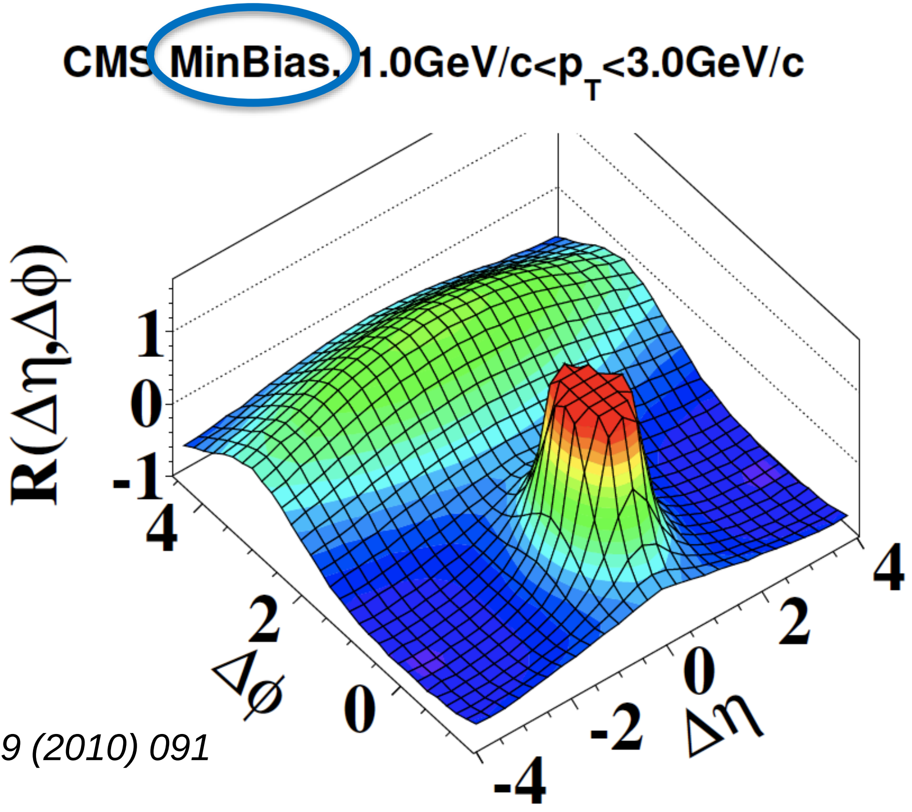


Discovery of collectivity in small systems

The first indication of the presence of collective phenomena in high-multiplicity pp collisions came from the study of two-particle correlations vs $\Delta\eta$ and $\Delta\varphi$.

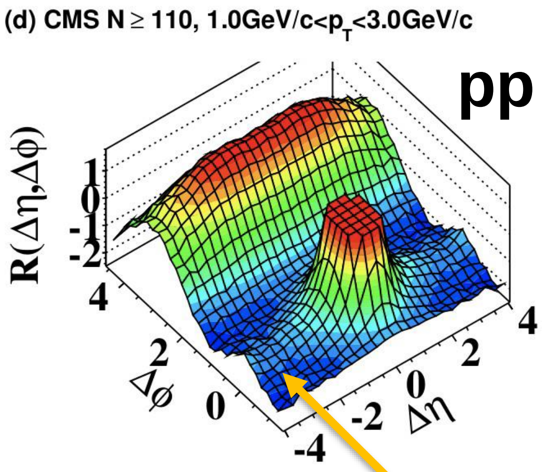
A **ridge** is observed in high multiplicity pp but not in minimum bias pp collisions!
The ridge is not reproduced by pp Monte Carlo generators, e.g. PYTHIA.





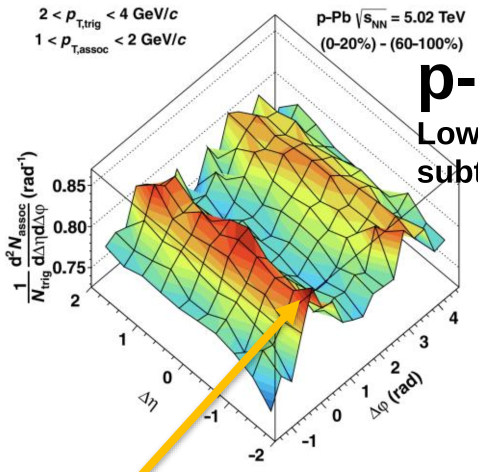
CMS, JHEP 09 (2010) 091

The “ridge” in pp, p-Pb collisions



pp

CMS, JHEP 09 (2010) 091

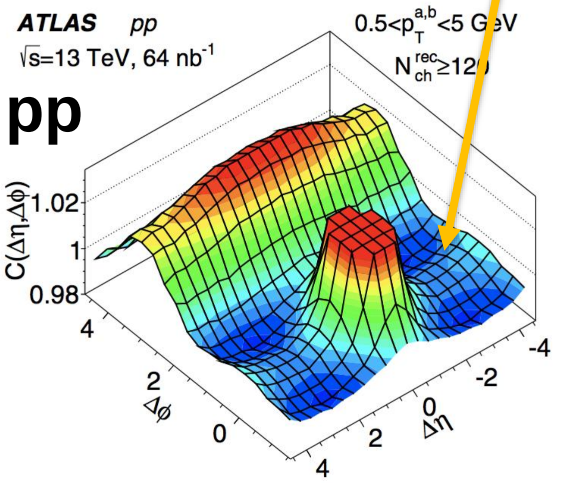


p-Pb

Low-multiplicity subtracted

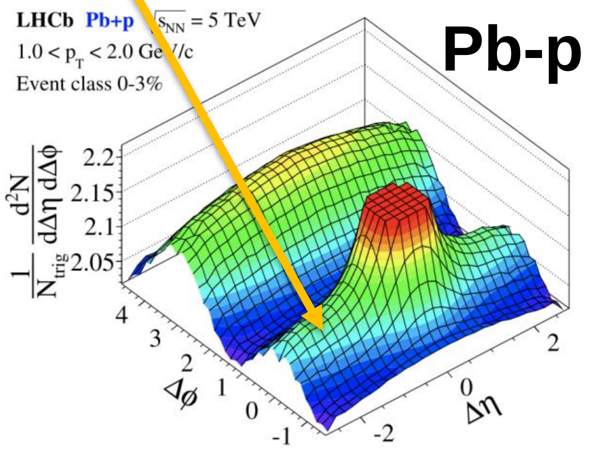
ALICE, PLB 719 (2013) 29

Near side ridge



pp

ATLAS, PRC 96, (2017) 024908



Pb-p

LHCb, PLB 762 (2016) 473–483

Signs of collectivity in **small systems** “discovered” at the LHC in terms of long-range ($2 < |\Delta\eta| < 4$) near-side ($\Delta\phi = 0$) “ridge” in 2-particle correlations, visible in **high multiplicity** pp, p-Pb, Pb-p collisions

Are the long-range correlations in high-multiplicity pp coming from (hydrodynamic) flow?

Collectivity correlates many particles over a wide η range

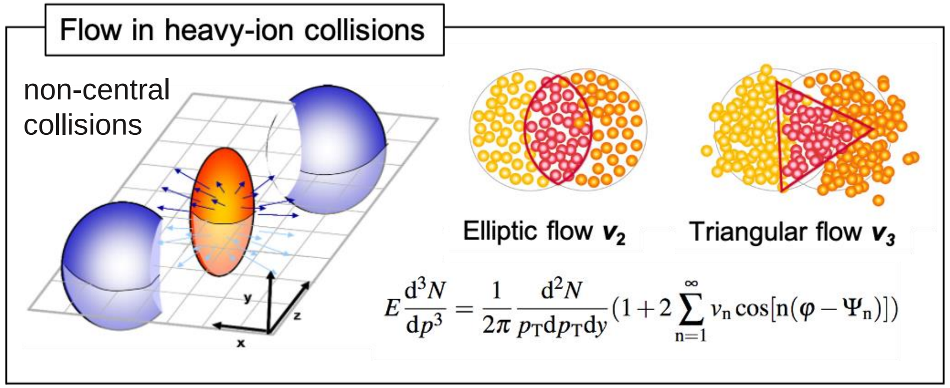
Elliptic flow from multi-particle correlations:

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

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

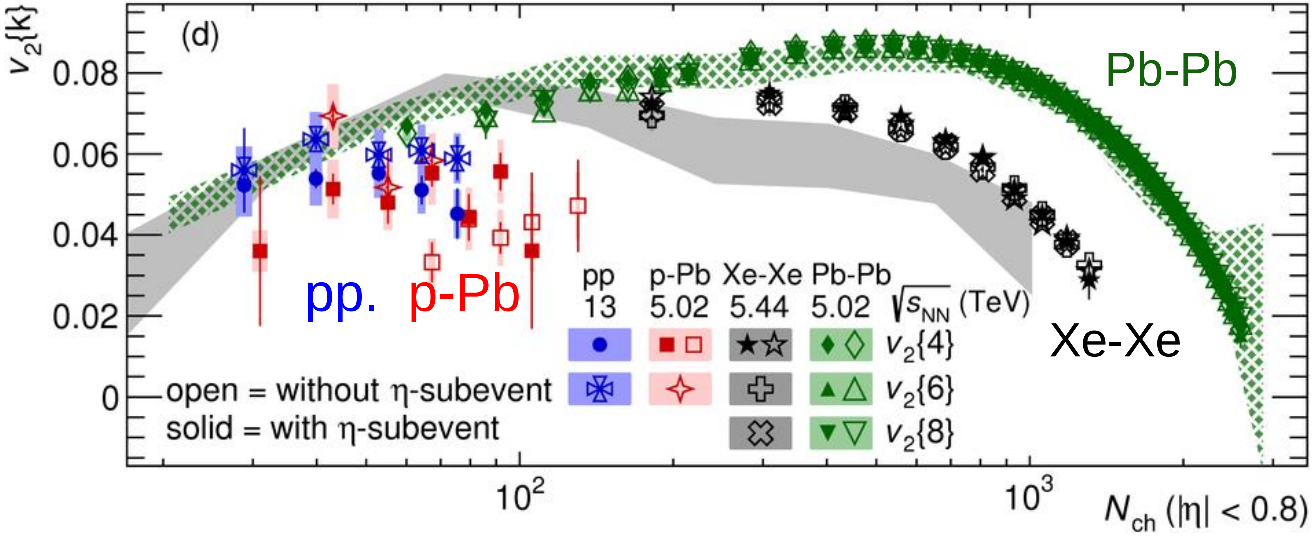
In AA collisions, collectivity originates from the presence of a strongly-interacting QGP

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



$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos[n(\varphi-\Psi_n)]\right)$$

Elliptic flow from multi-particle correlations in all systems



PRL 123, 142301 (2019)

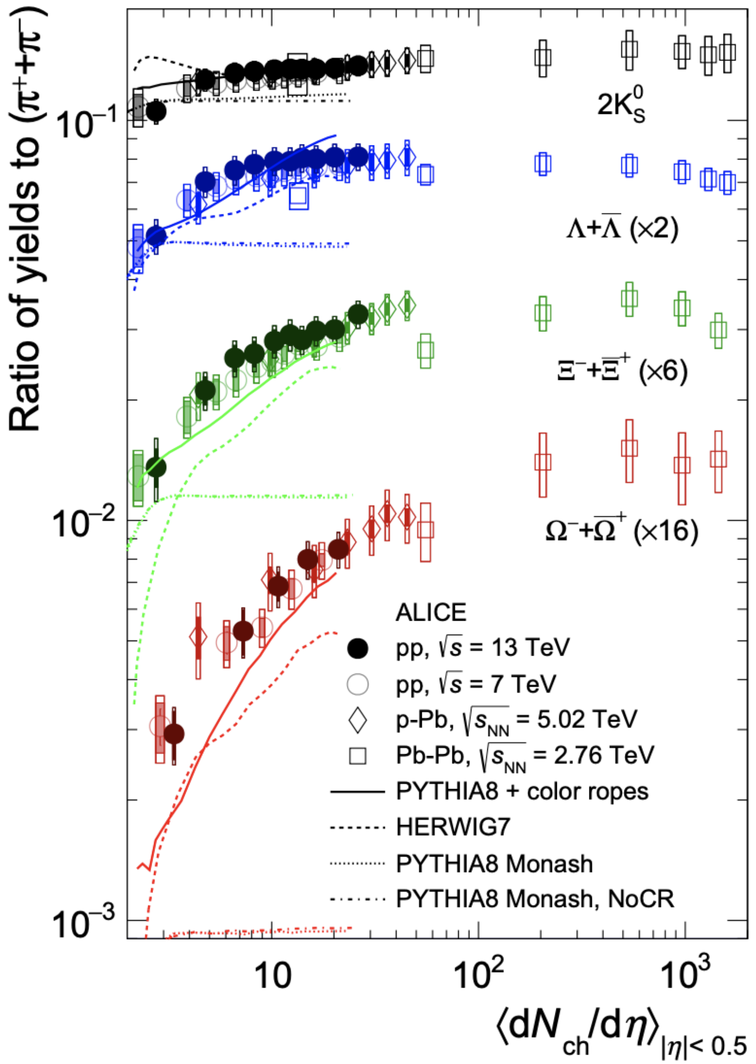
Discovery of strangeness enhancement in small systems

Strangeness enhancement relative to pp suggested in the 1980’s as QGP smoking gun.

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

→ **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

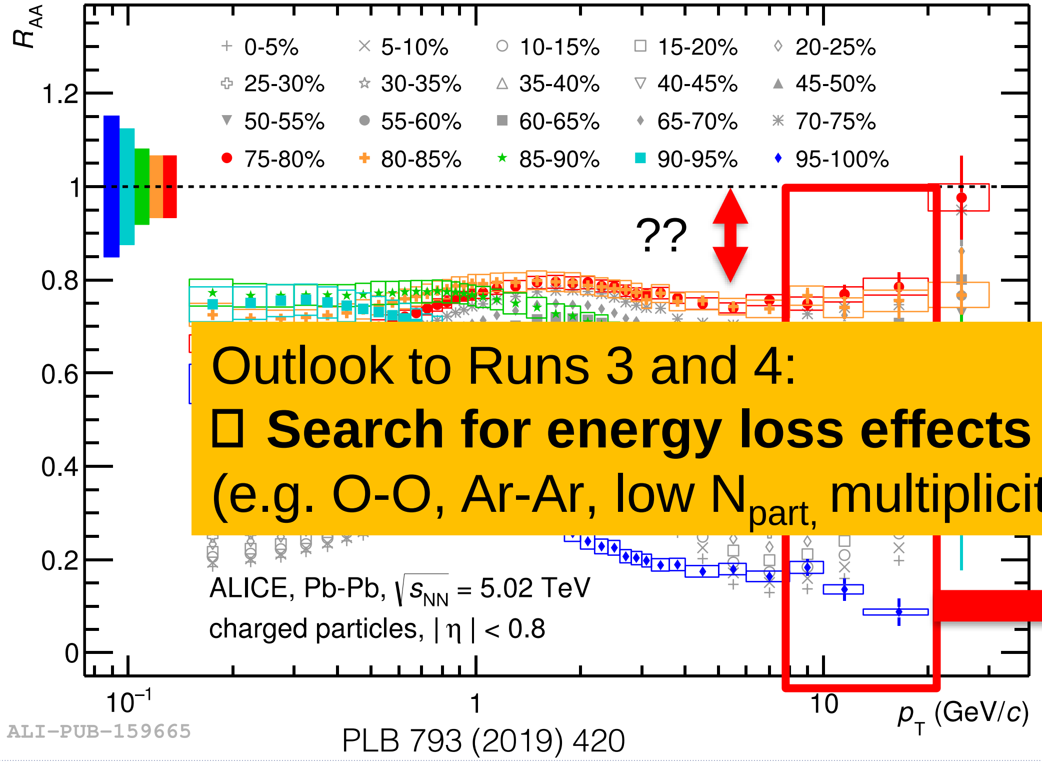
No energy loss in small systems?

Not observed so far.

- Strong change of behaviour of R_{AA} beyond 80% centrality is reproduced considering **biases in event selection and collision geometry**, and no nuclear modification → **not a medium effect!**

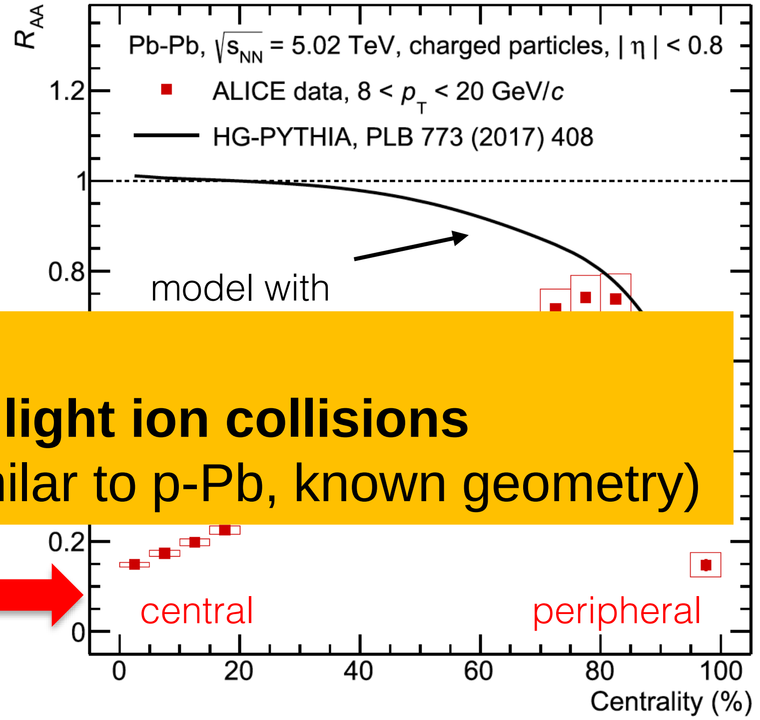
OPEN QUESTION: when (which system “size”) does energy loss sets in?

Charged particle nuclear modification factor vs p_T



PLB 793 (2019) 420

High pT, centrality dependence



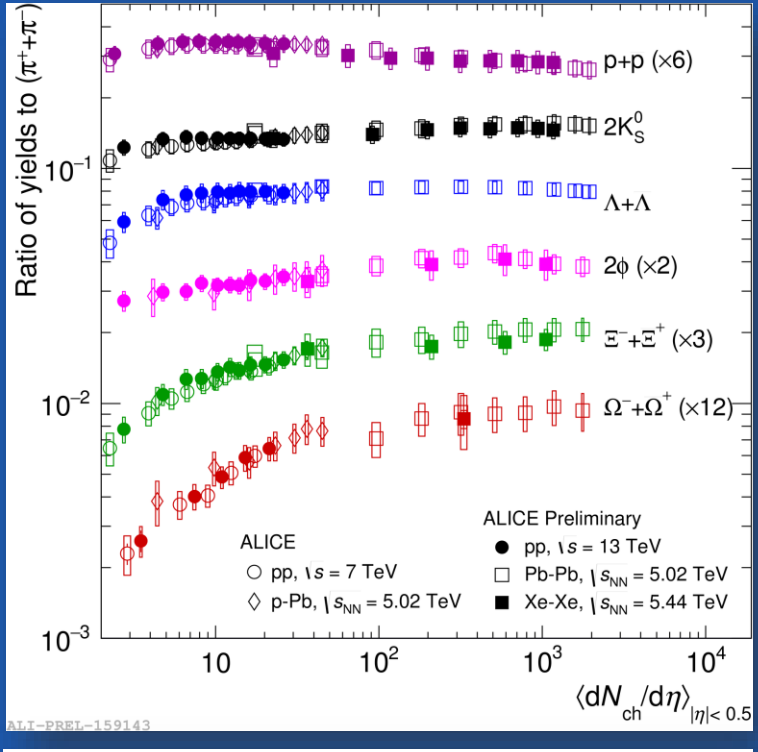
Outlook to Runs 3 and 4:

☐ **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)

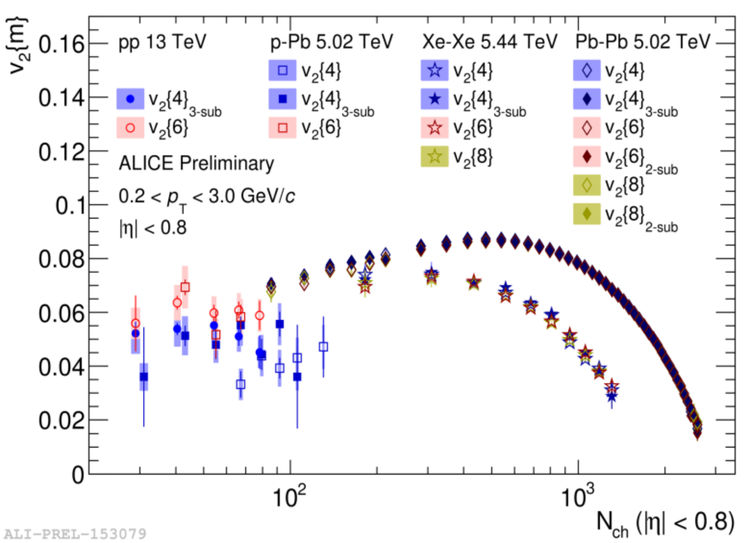
Particle chemistry:

- **continuity** observed across collision systems
- depends on charged particle multiplicity
- Strangeness production in enhanced in presence of a QGP in AA collisions (established)
- In small systems, **strangeness enhancement** observed with increasing multiplicity (to be understood!)



Collective dynamics

- **Radial and anisotropic flow**
- Flow up to higher harmonics in heav-ion collisions
- Discovery of **collective phenomena in small systems** at the LHC, whose origin is to be understood.



Any energy loss in small systems?

Summary and outlook

Experimental probes and evidence for a QGP formed in heavy-ion collisions

- Strong jet quenching and medium-induced modification
- Quarkonium suppression → Melting of states as a function of temperature
- Regeneration and partial thermalisation of charm
- Radial and anisotropic flow → Collective behavior of a QGP with very low shear viscosity (η/s),
- High temperatures, mostly statistical particle production (Tchem, Tkin)
- Heavy-ion-like effects observed in pp and p-Pb collisions

A new frontier

- Is there QGP in small systems?
- Can we explain these effects without a QGP?
- Can we describe these emerging phenomena in one unified picture across systems?

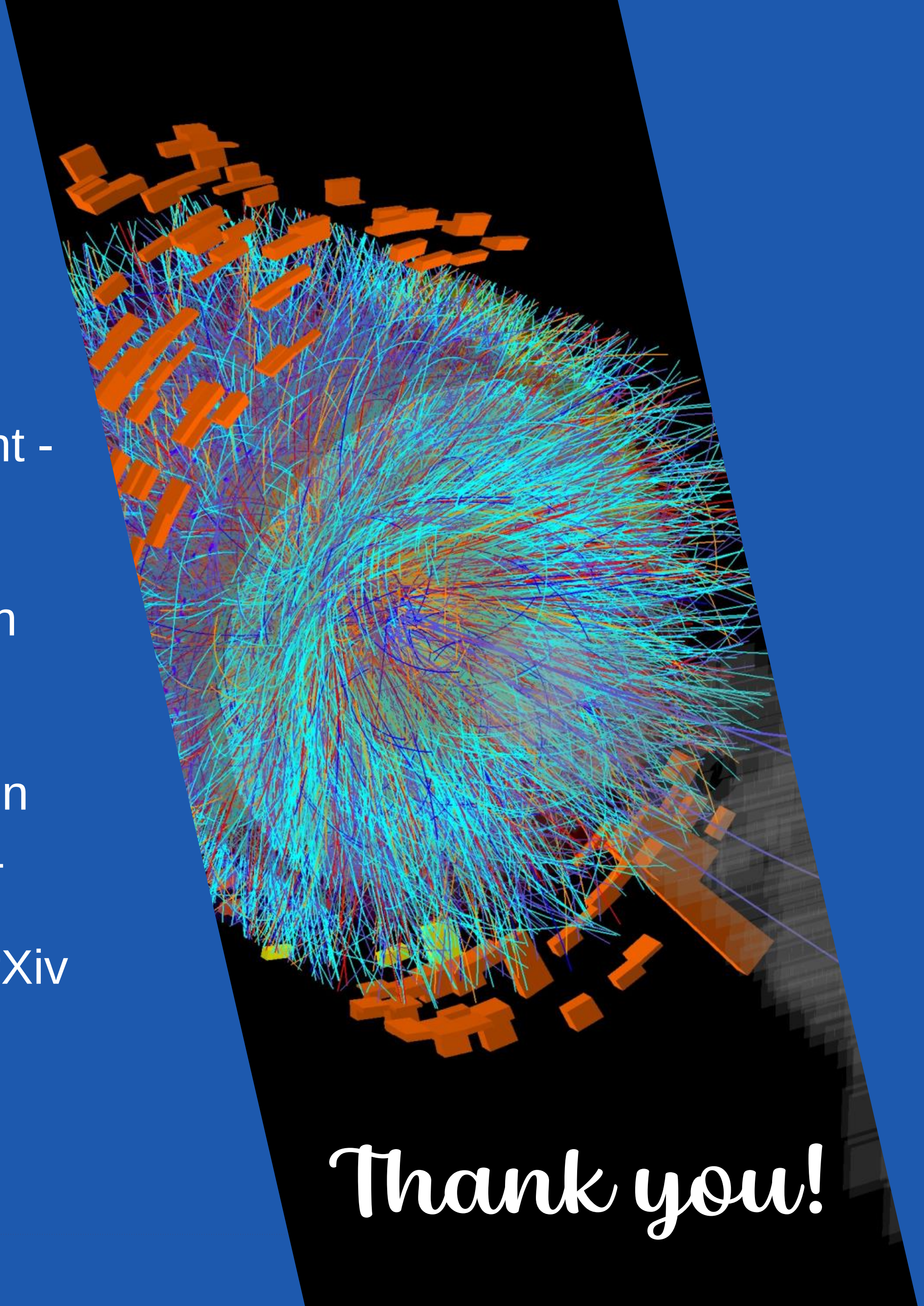
Big progress towards a quantitative characterisation of the properties of the QGP with still open questions to be addressed in Run3 and beyond.

Further readings:

- [review] ALICE Collaboration, The ALICE experiment -- A journey through QCD, arXiv:2211.04384
- [future] CERN Yellow Report on QCD with heavy-ion beams at the HL-LHC, arXiv:1812.06772
- [future] Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC, arXiv:2211.02491

+ many more reviews on specific topics available on arXiv

Contact: francesca.bellini@cern.ch



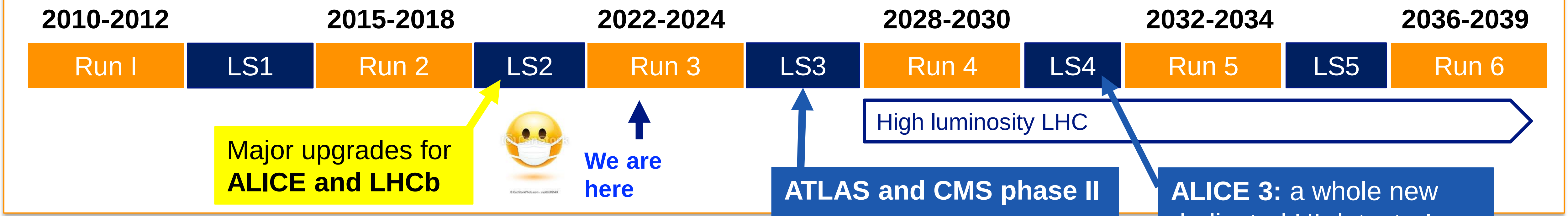
Thank you!

Bonus material

What’s next?

Heavy-ion program at the LHC in Runs 3+4 – An appetizer

Recall: Heavy-ion physics at the LHC

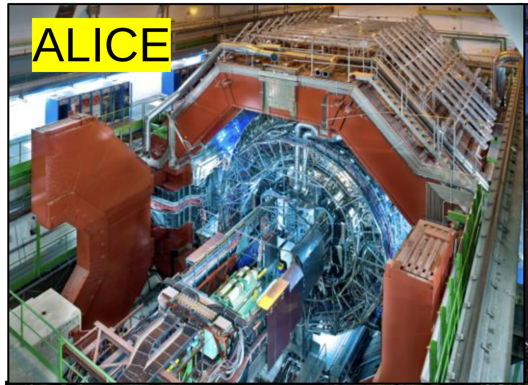


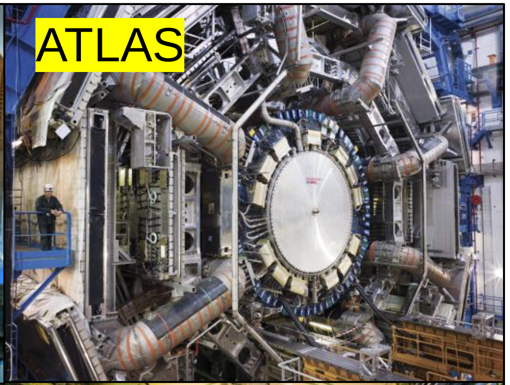
Major upgrades for ALICE and LHCb

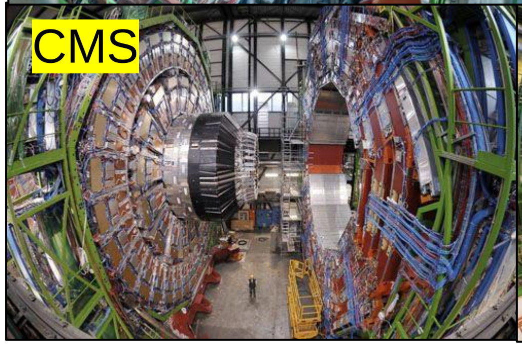
We are here

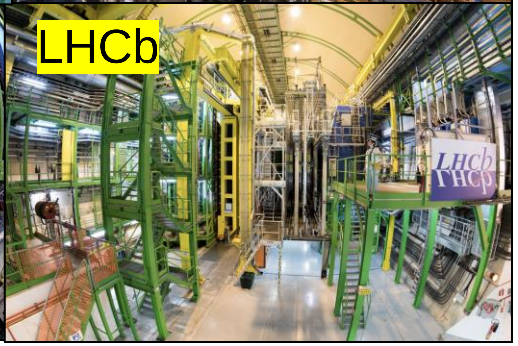
ATLAS and CMS phase II
ALICE ITS3 and FoCal

ALICE 3: a whole new dedicated HI detector!
LHCb upgrade II





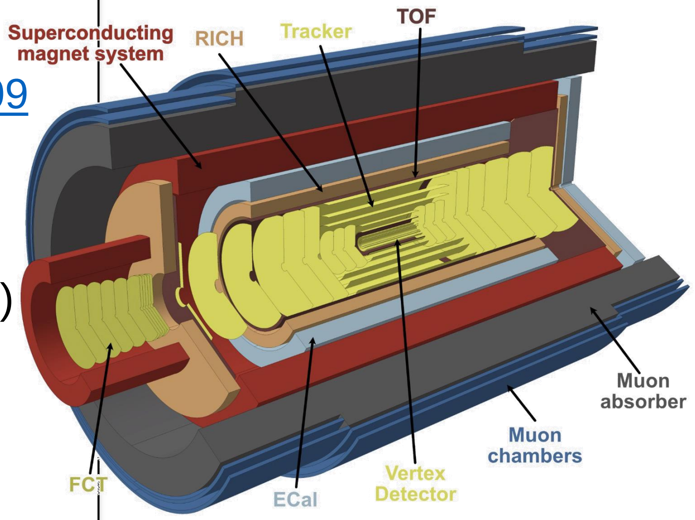




ALICE 3

- Letter of Intent: CERN-LHCC-2022-009
- next-generation HI experiment
- all-Si MAPS tracker
- ultimate vertex detector
- minimal mass (essentially only sensor)
- 5 mm from beam (LHC aperture)

Physics focus:
- low-p_T heavy-flavour
- electromagnetic radiation from QGP



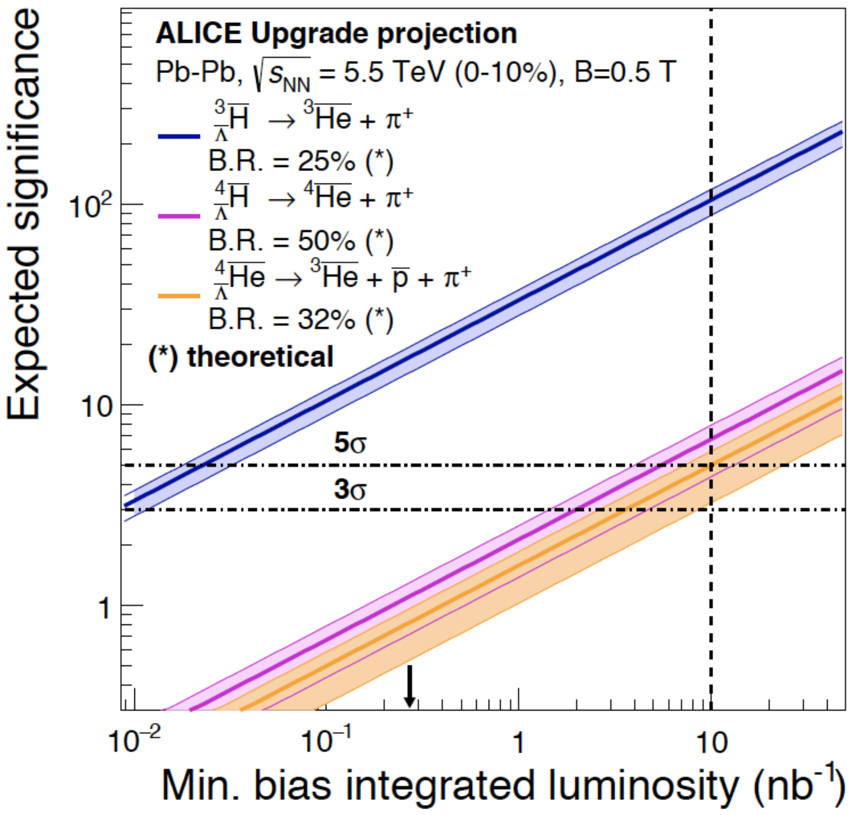
Runs 3+4 - Nuclei and small systems

(anti-)nuclei and (anti-)(hyper-)nuclei up to A = 4

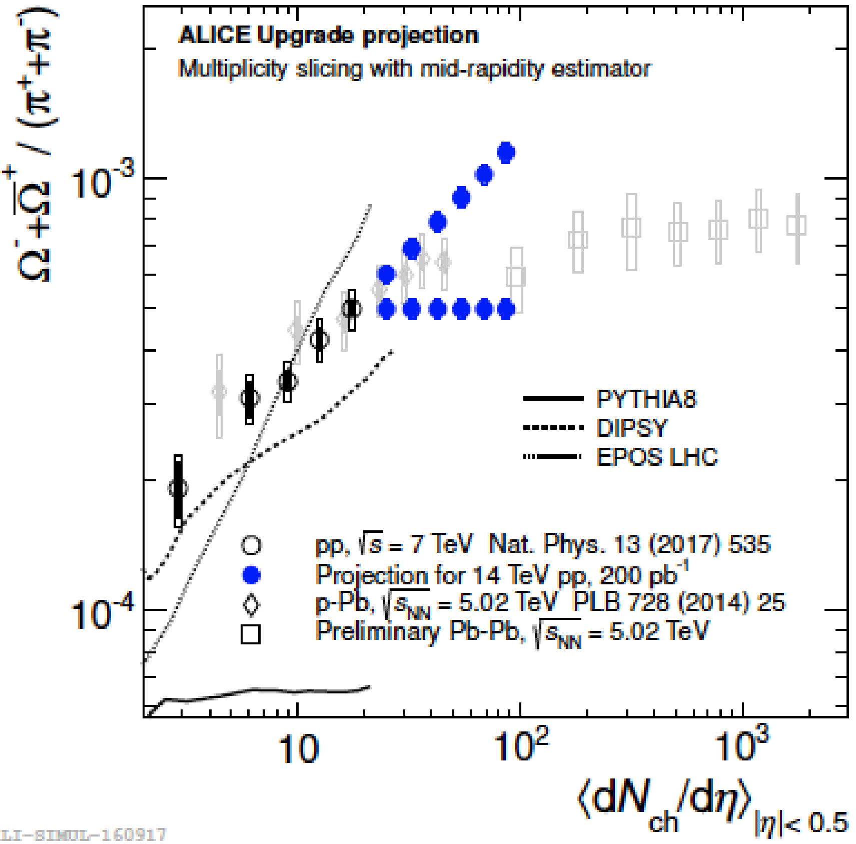
- Clarify formation mechanisms of nuclear bound states from a dense partonic state
- Determine T_{ch} even more precisely

A “small systems” programme to study collectivity, strangeness/chemistry, hadronisation

- Investigate the onset of QGP like features



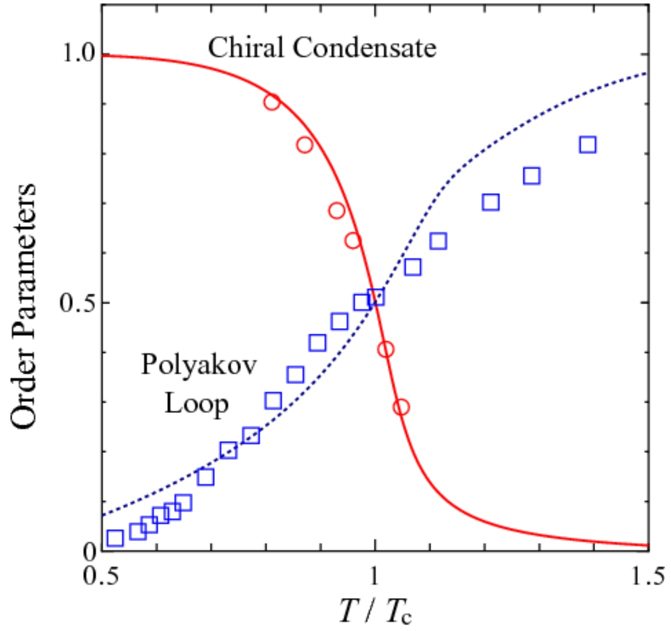
ALI-SIMUL-312332



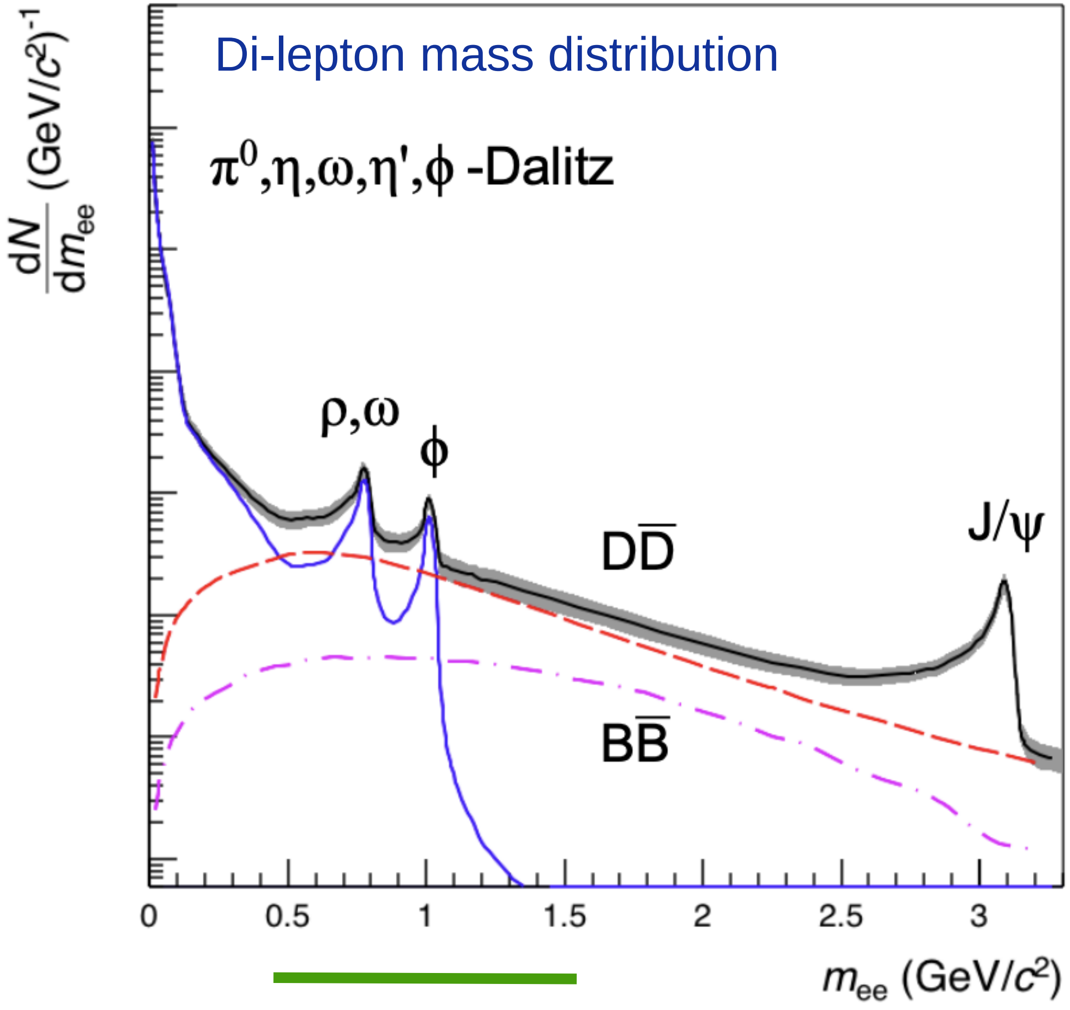
ALI-SIMUL-160917

Runs 3+4 – Dileptons and chiral symmetry

Lattice QCD predicts chiral symmetry restoration to occur around the same temperature as the confined/deconfined transition
→ **but no experimental observation yet!**



☐ **Search for signatures of chiral symmetry restoration** at the QCD phase boundary by measuring intermediate mass dilepton spectrum



omega/phi region:
chiral symmetry and
rho-a_1 mixing

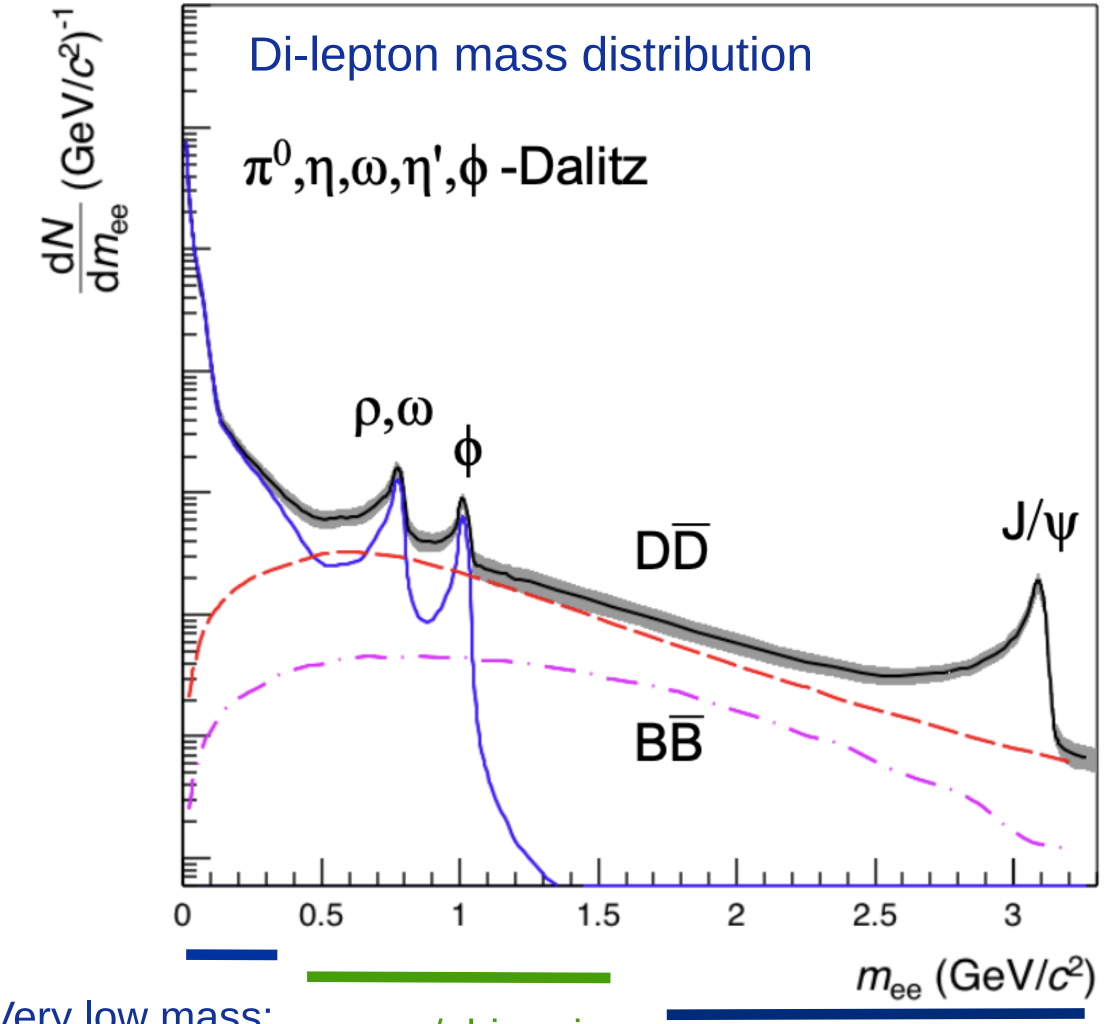
Runs 3+4 – Dileptons and early QGP temperature

Measurements of dilepton spectrum:

☐ **Search for signatures of chiral symmetry restoration** at the QCD phase boundary by measuring intermediate mass dilepton spectrum

☐ **Access the temperature of QGP in the early stages** by measuring the mass spectrum of dileptons in the large mass range and dilepton excess due to electromagnetic radiation emitted by the QGP

Bonus in Runs 3 and 4:
- statistics
- reduced, well-known material
- heavy-flavour rejection



Very low mass:
conductivity

omega/phi region:
chiral symmetry and
rho-a_1 mixing

Large mass:
very early times

Runs 3+4 – Dileptons

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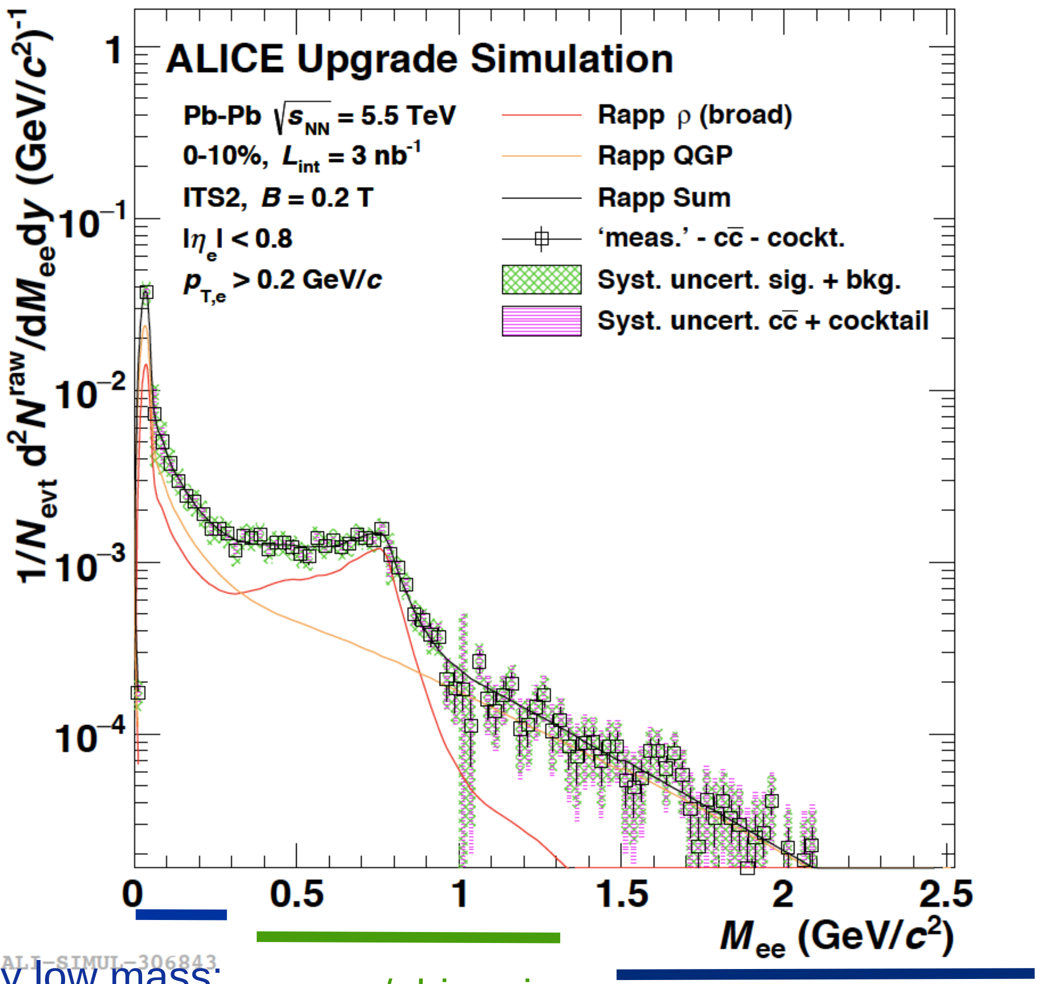

Very low mass:
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omega/phi region:
chiral symmetry and
rho-a1 mixing

Large mass:
very early times

Runs 3+4 - More charm

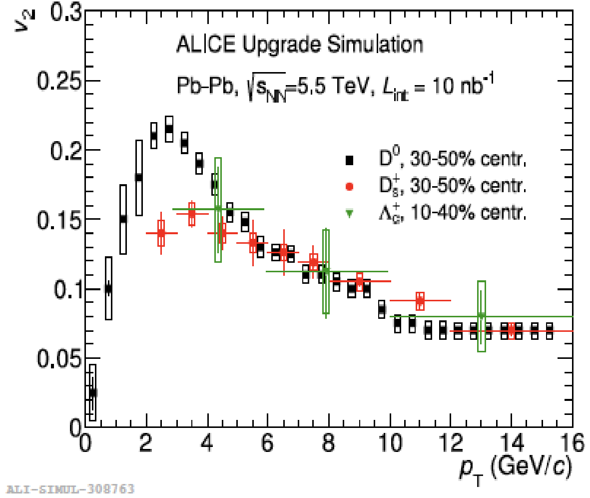
Higher precision for rarer probes in the HF sector

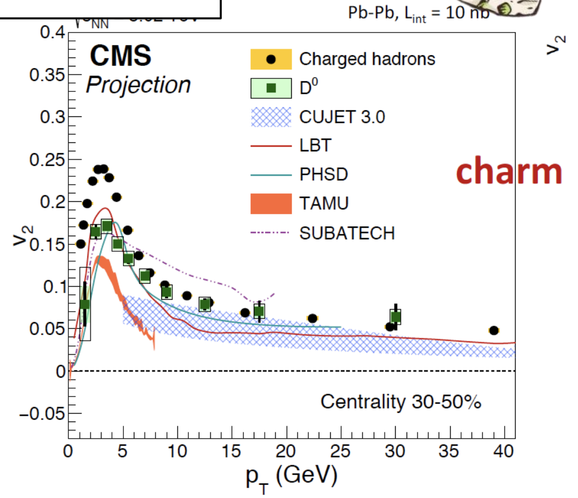
- Low-p_T production and v_2 of several HF hadron species
- first measurements of b at forward y down to zero p_T (main focus of ALICE)
- B hadrons and b-jets (main focus of ATLAS and CMS)

☐ Study mass dependence of **energy loss**, in-medium **thermalization** of heavy-flavours

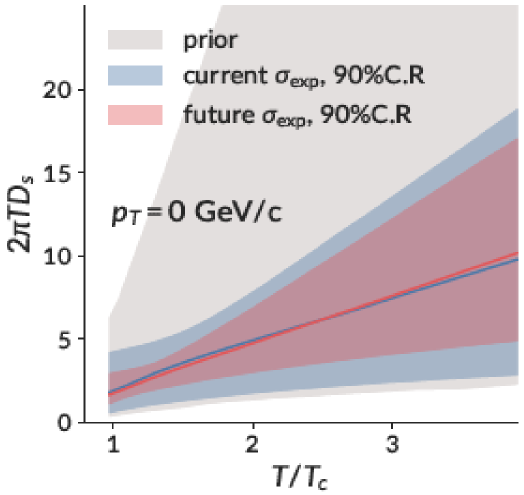
☐ Access to the **medium transport properties,** e.g. charm diffusion coefficient

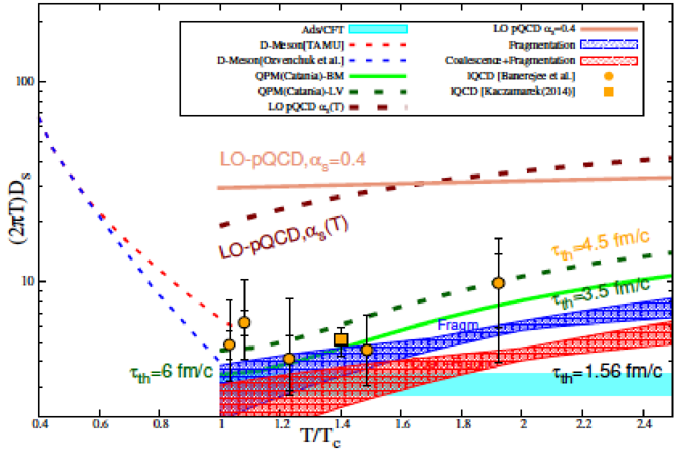
v_2 in charm sector





Projections for extraction of charm diffusion coefficient





Runs 3+4 - More beauty

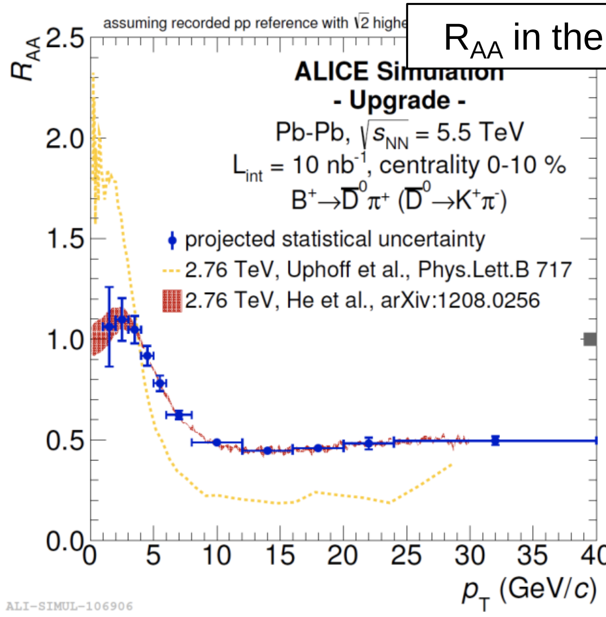
Higher precision for rarer probes in the HF sector

- Low-p_T production and v_2 of several HF hadron species
- first measurements of b at forward y down to zero p_T (main focus of ALICE)
- B hadrons and b-jets (main focus of ATLAS and CMS)

□ Study mass dependence of **energy loss**, in-medium **thermalization** of heavy-flavours

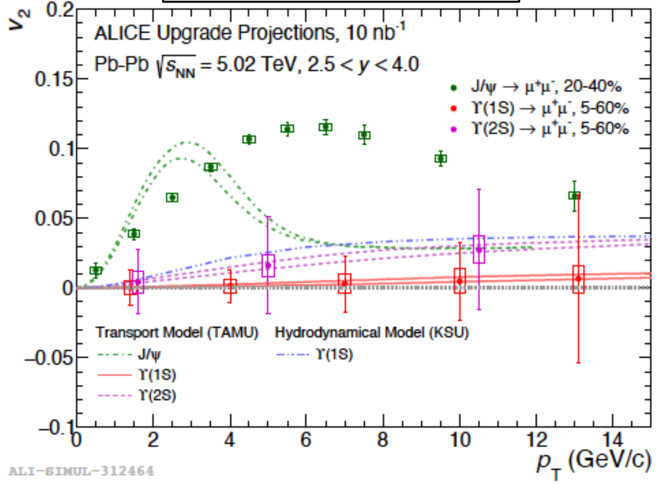
□ Access flavor-dependence of in-medium fragmentation functions with jet measurements

R_{AA} in the beauty sector

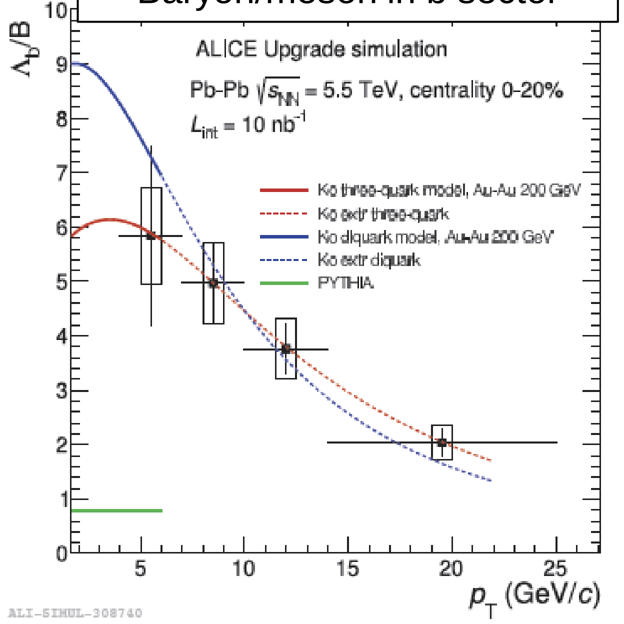


Example: B^+ □ $D^0\pi^+$ (displaced) channel down to low p_T accessible in the ALICE central barrel thanks to the upgraded ITS

v_2 in beauty sector



Baryon/meson in b sector



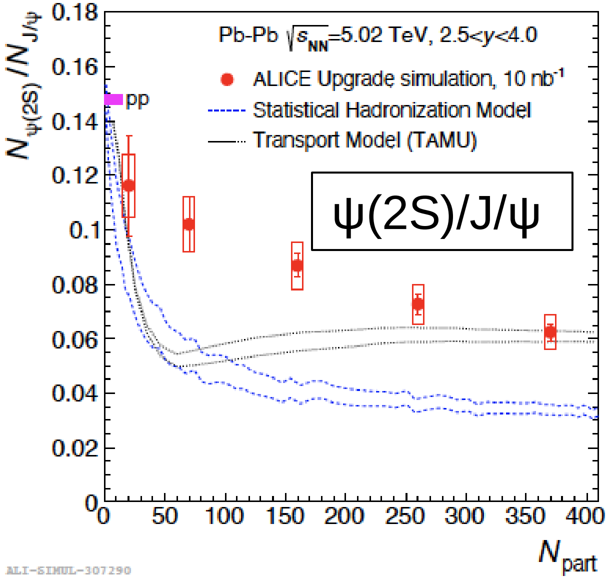
Runs 3+4 – More quarkonia

Measure charmonium and bottomonium spectrum with **increased precision**

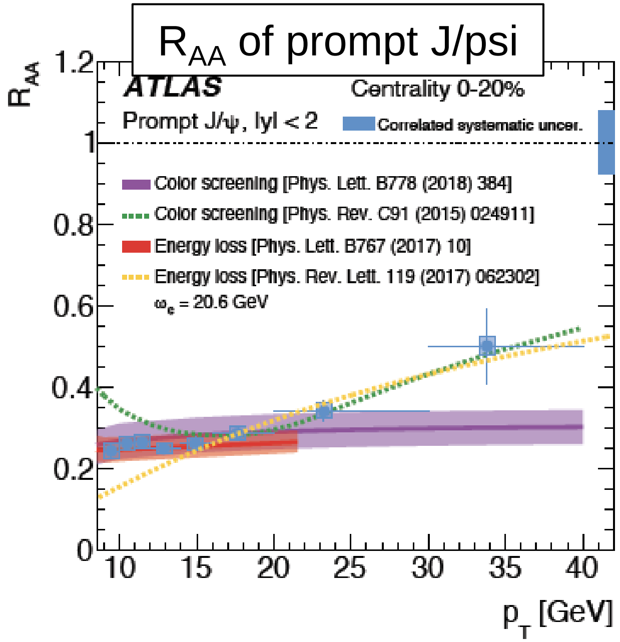
- Nuclear modification R_{AA}
- ψ(2S)/J/ψ, Υ(2S)/Υ(1S)
- explore feeddown

☐ constrain models
☐ probe melting and regeneration of quarkonia
☐ probe deconfinement
☐ access the medium temperature

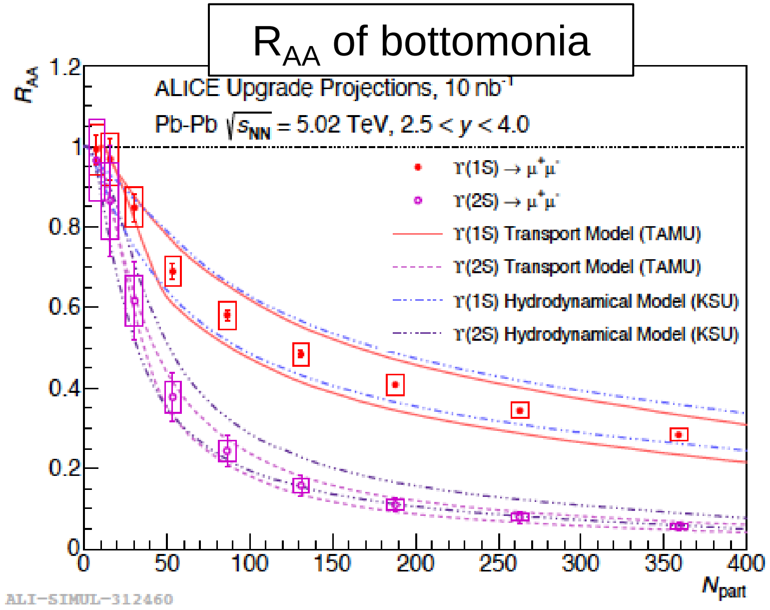
Further reading: CERN Yellow Report on QCD with heavy-ion beams at the HL-LHC arXiv:1812.06772



ψ(2S)/J/ψ



R_{AA} of prompt J/psi



R_{AA} of bottomonia

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

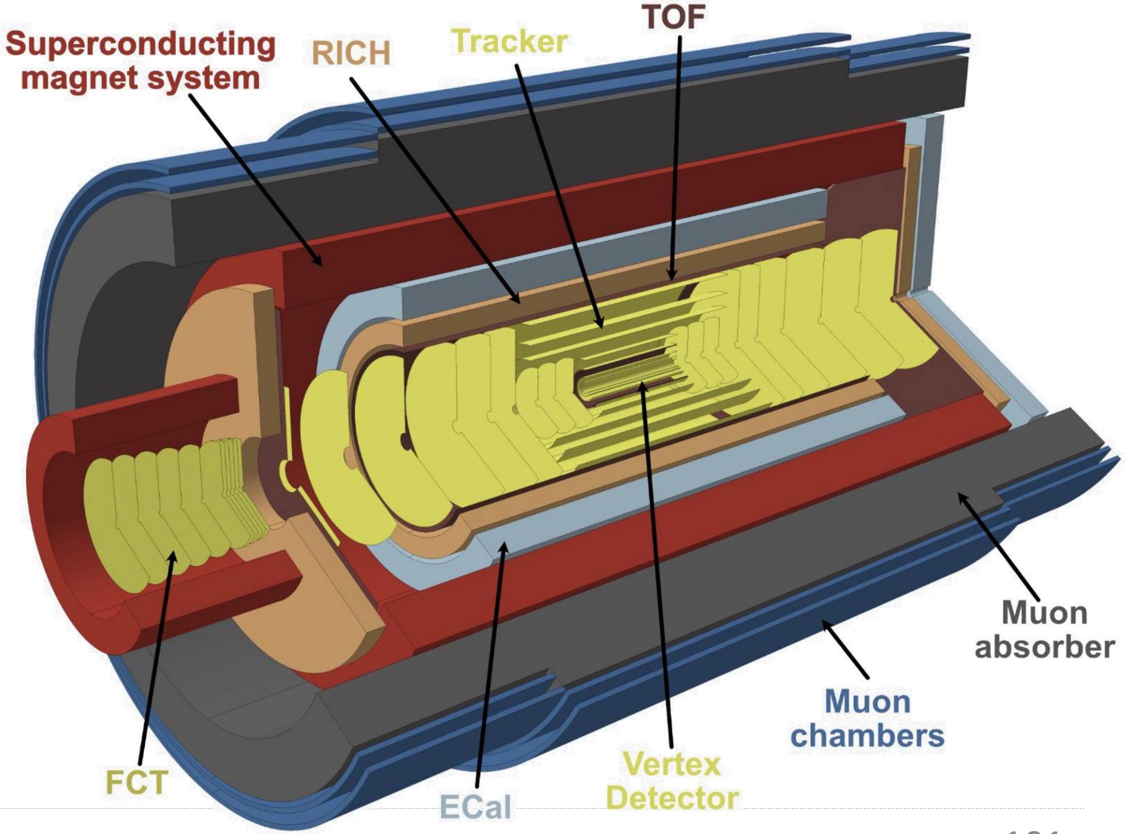
ALICE 3: a new dedicated heavy-ion experiment at the LHC

- replace ALICE between Run 4 and Run 5
- Expression of Interest submitted in 2019 (ESPPU), arXiv:1902.01211
- Letter of Intent submitted to the LHCC: CERN-LHCC-2022-009

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

ALICE 3 detector concept



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 a factor of 10^2-10^3, low p_T B, $\chi_{c,}$ X, …

- **Dilepton radiation** from various phases of the collision

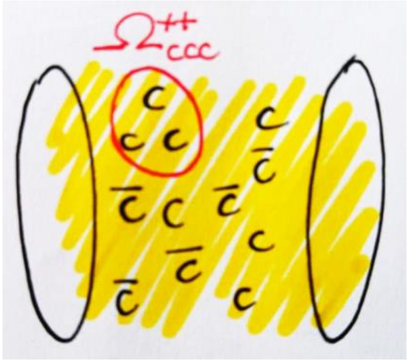
- Effect of **chiral symmetry restoration** (predicted by lattice QCD) on the dielectron spectrum

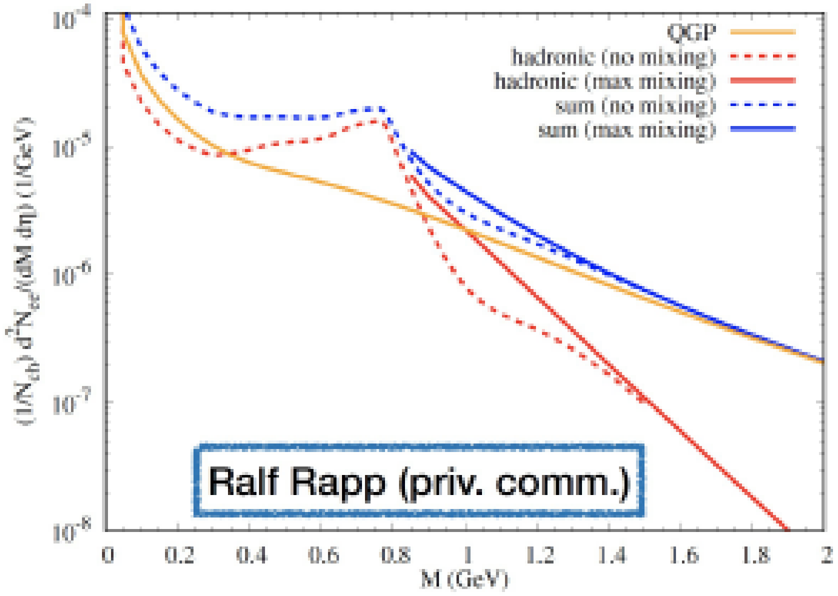
- **QGP parameters** (diffusion coefficients, conductivity properties, …) with unprecedented precision

- **Ultra-soft** (p_T ~ 10 MeV) **photon** production relative to hadron production (non-pert. QCD)

…and more new unique windows opened at the LHC!

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





Ralf Rapp (priv. comm.)

Characteristics of a heavy-ion detector: ALICE

ALICE is the dedicated heavy-ion detector at the LHC, designed and built specifically for this purpose.

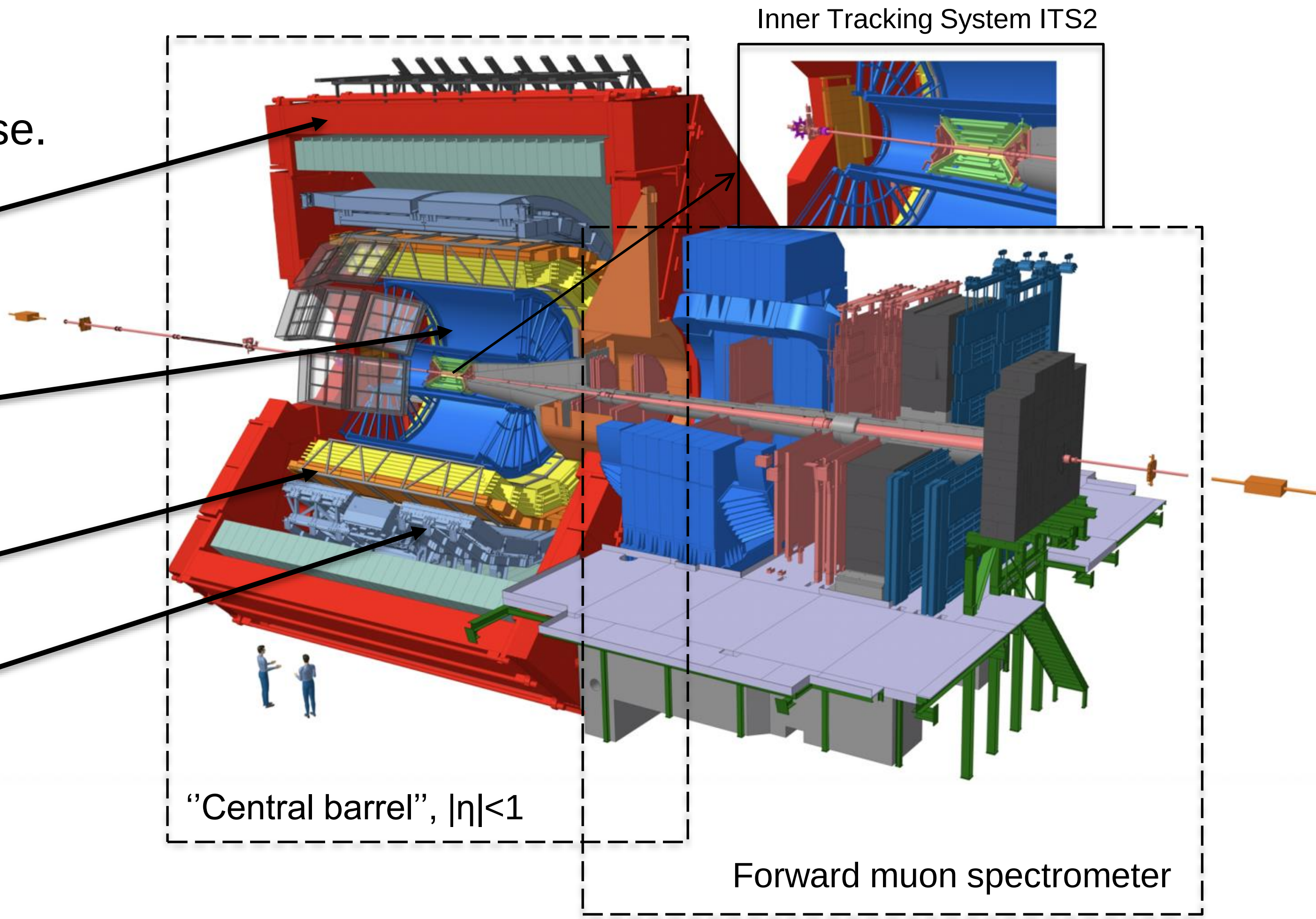
Solenoid: magnetic field B = 0.5 T

Inner Tracking System + Time Projection Chamber: vertexing and tracking + identification (TPC) down to very low p_T ~ 0.1 GeV/*c*

Time-Of-Flight, TRD, HMPID, etc.: Particle identification detectors

Electromagnetic calorimeters

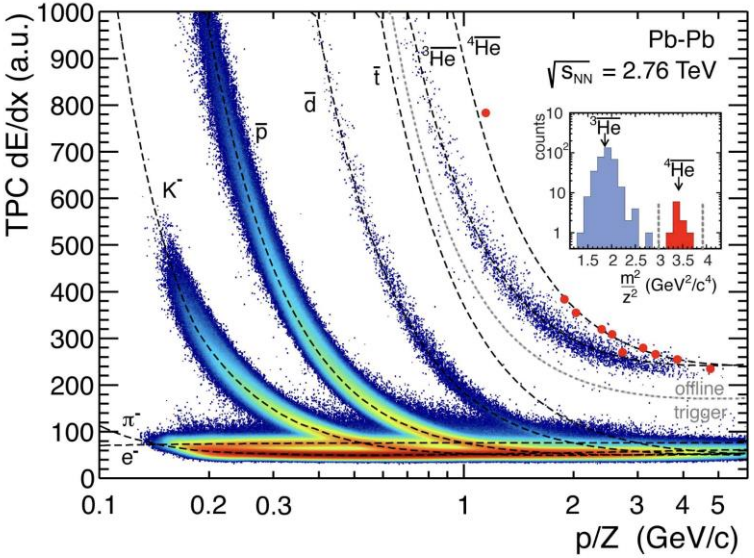
+ Forward rapidity detectors and ZDC: trigger, centrality, event time determination, …



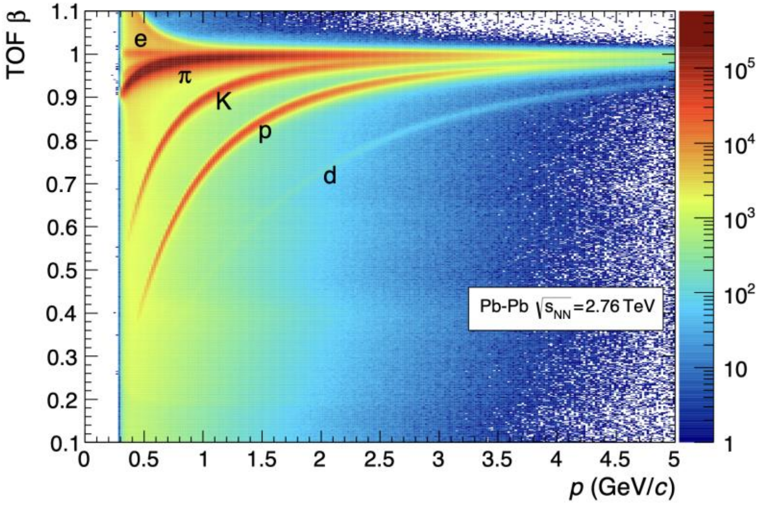
Particle identification

- Direct identification: π, K, p, light (anti)nuclei
- Electron identification using calorimeters and transition radiation detectors
- Strange and heavy-flavour hadrons:
    - reconstruction of secondary vertex and weak decay topology + PID + invariant mass reconstruction
- Photons detected in calorimeters and through pair production
- Quarkonia through leptonic decays

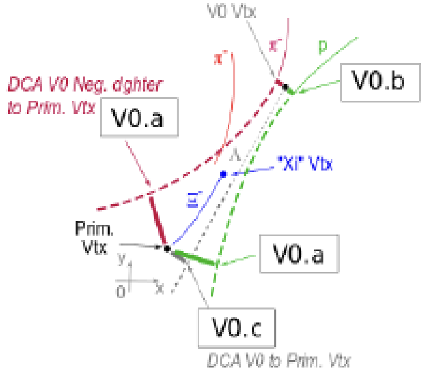
Energy loss of long lived particles in TPC



Particle velocity from TOF measurement and momentum



Ξ→Λπ⁻
(similarly for Ω→ΛK⁻)



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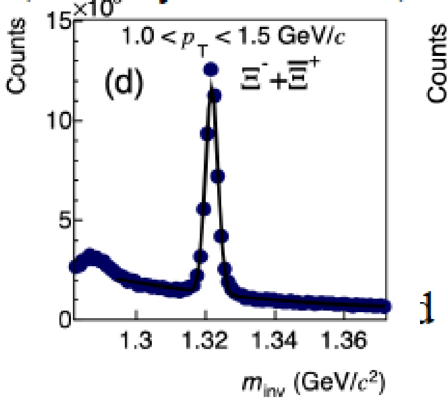
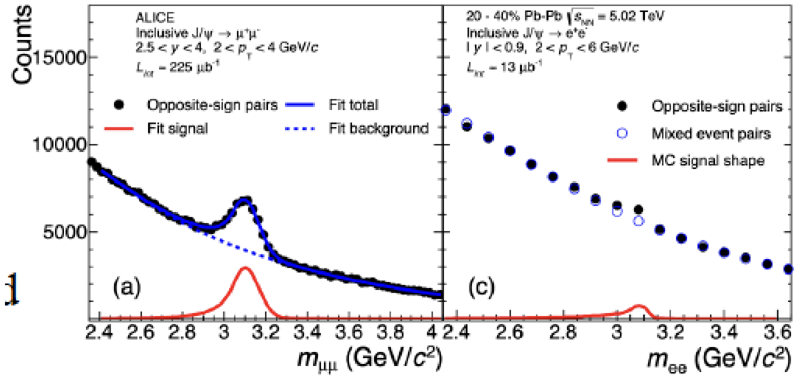


J/ψ→μ⁺μ⁻ J/ψ→e⁺e⁻



Glauber model

Nucleus-nucleus interaction as **incoherent** superposition of nucleon-nucleon collisions calculated in a probabilistic approach

[M. L. Miller et al., An. Rev. Nucl. Part. Sci. 57 (2007) 205-243]

- nucleons in nuclei are considered as point-like and non-interacting
- nuclei (and nucleons) have straight-line trajectories (no deflection)

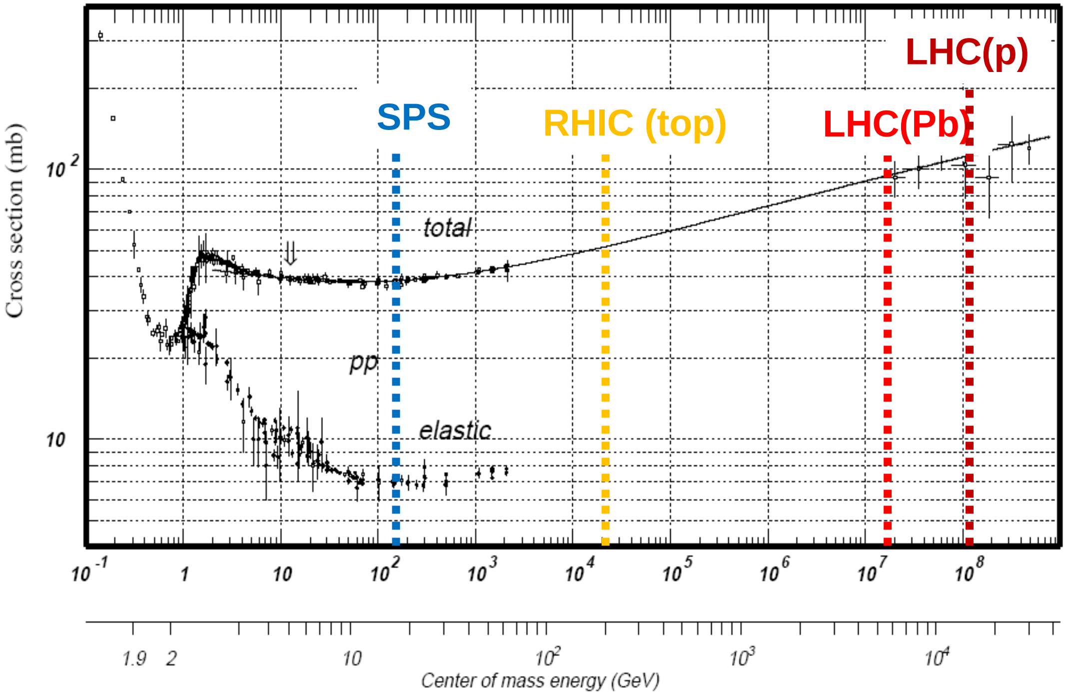
Input:

- Nucleon-nucleon inelastic cross section
- Nuclear density distribution, e.g. Fermi

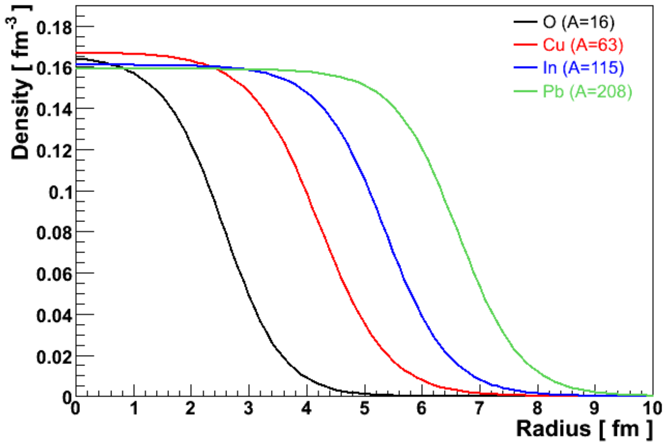
$$\rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}$$

ρ^0 = density in the nucleus center
R = nucleus radius
a = skin depth
w = deviations from spherical shape

Proton-proton cross section (from PDG)



Examples of density distributions of nuclei



Glauber model (2)

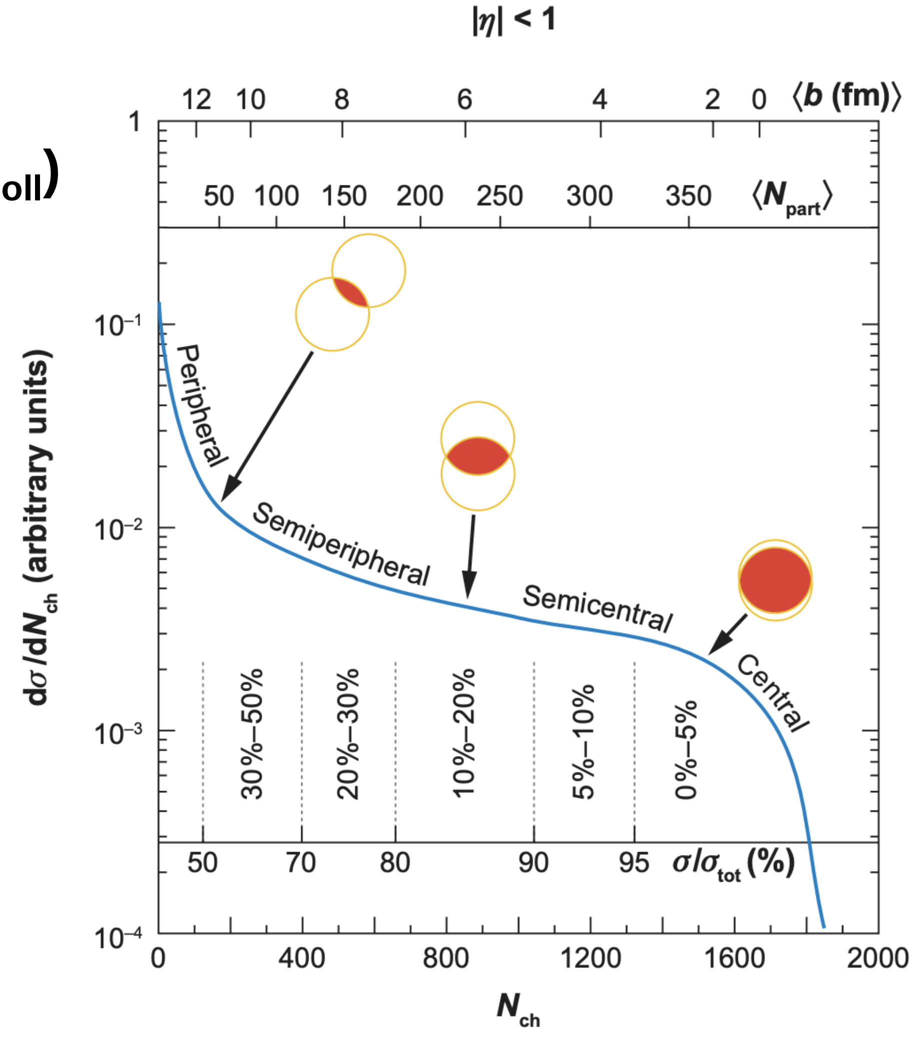
Output:

- Interaction probability
- **Number of elementary nucleon-nucleon collisions (N_{coll})**
- **Number of participant nucleons (N_{part})**
- **Number of spectator nucleons**
- Size of the nuclei overlap region

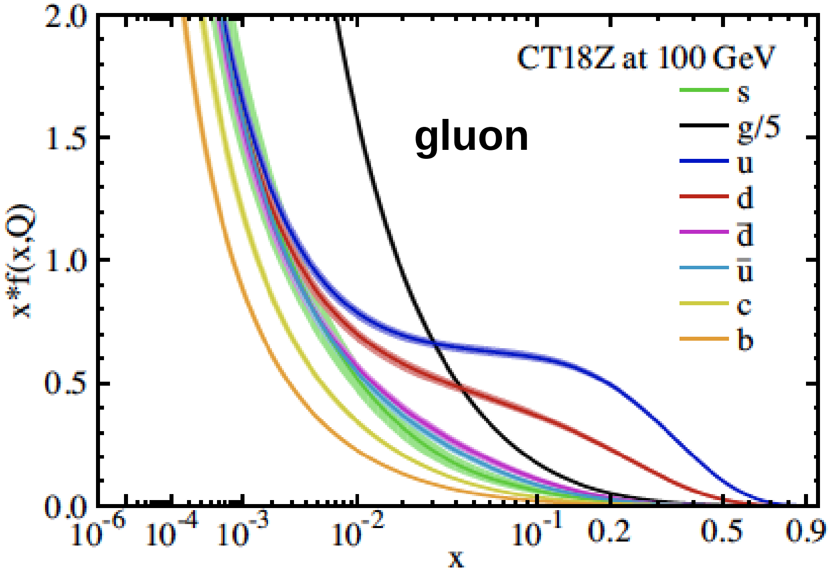
These variables are fundamental to study the scaling properties of observables in HIC – **Rule of thumb**:

- ***N_{part}*** scaling of soft particle production
  → bulk of the system

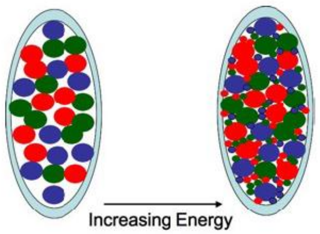
- ***N_{coll}*** scaling of high p_T particle production
  → hard partons produced early in the collision



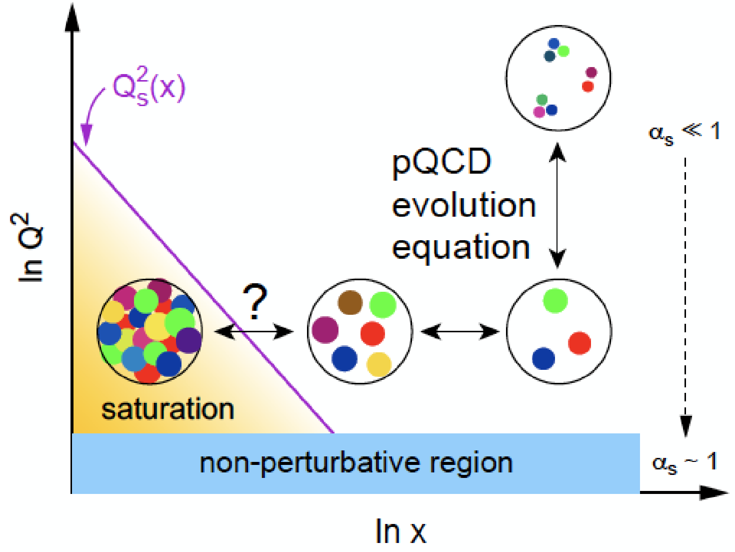
Initial stage of heavy ion collisions

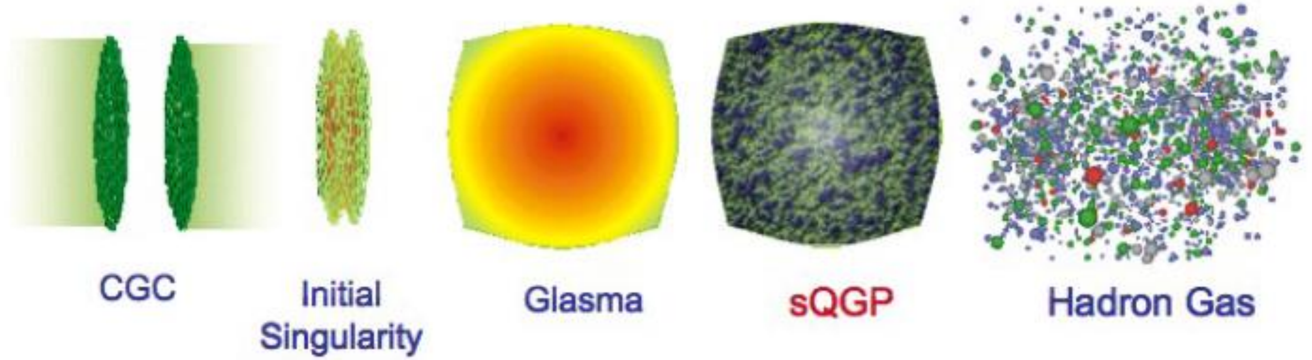


Color Glass Condensate: at high energy and small x, the hadron content is dominated by gluonic matter “packed” into high density



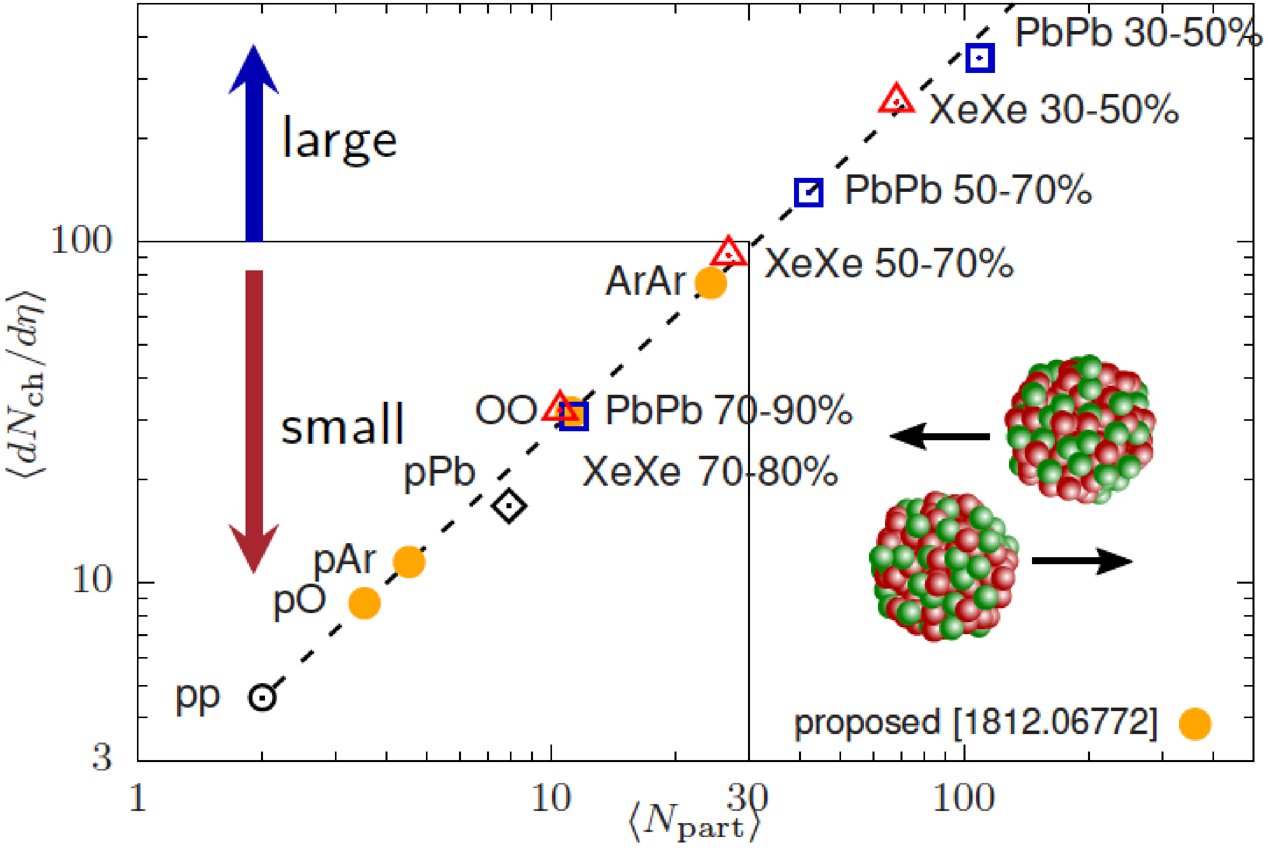
Saturation (momentum) scale Q_{sat} = inverse size scale of smallest gluons which are closely packed
→ gluons of size larger than $1/Q_{sat}$ no longer fit



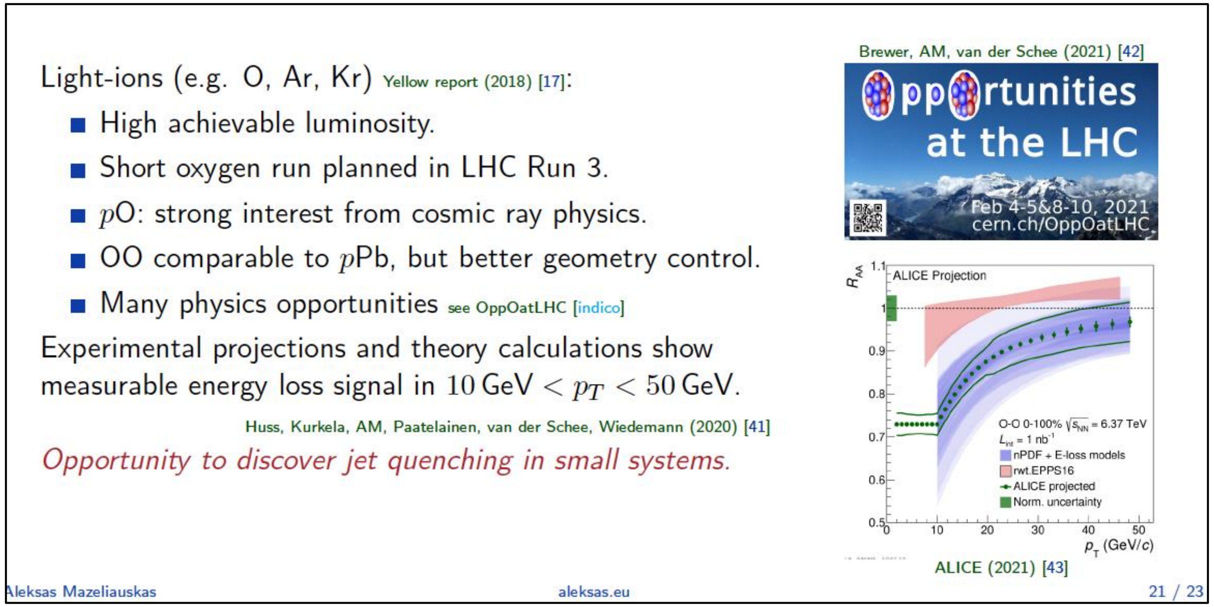


L. McLerran, https://bib-pubdb1.desy.de/record/296833/files/ismd08_mcl_intro-corr.pdf
+ more reviews in literature,

Light ions at the LHC



From A. Mazeliauskas, EPS-HEP 2021:



Light-ions (e.g. O, Ar, Kr) Yellow report (2018) [17]:

- High achievable luminosity.
- Short oxygen run planned in LHC Run 3.
- pO: strong interest from cosmic ray physics.
- OO comparable to pPb, but better geometry control.
- Many physics opportunities see OppOatLHC [indico]

Experimental projections and theory calculations show measurable energy loss signal in $10\,\text{GeV} < p_T < 50\,\text{GeV}$.

Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann (2020) [41]

Opportunity to discover jet quenching in small systems.

Brewer, AM, van der Schee (2021) [42]

ALICE (2021) [43]

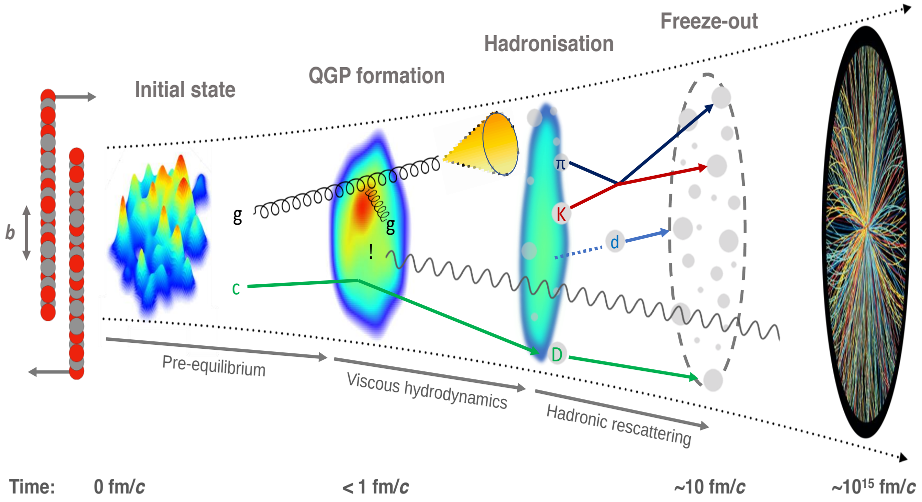
Aleksas Mazeliauskas aleksas.eu 21 / 23

Determination of the initial temperature with photons

Direct photons

= photons <u>not</u> originating from hadron decays

→ Produced at every stage, they do not interact with the QGP nor the hadrons



Prompt: produced in hard scatterings of incoming partons

- provide information on parton distributions in nuclei
- follow a power law spectrum
- dominate at high transverse momentum, $p_T \gtrsim 5$ GeV/*c*

Thermal: emitted by deconfined quark–gluon matter as well as hadronic matter, rate $\propto T^2 \exp(-E_\gamma/T)$

- carry information about the temperature, collective flow and space-time evolution of the medium
- follow an approximately exponential spectrum
- dominate at lower transverse momenta, $p_T \lesssim 4$ GeV/*c*

From **jet-photon conversion**, ie. from the interaction of hard scattered partons with the medium

- important for $p_T \lesssim 10$ GeV/c.

Thermal photon excess in central Pb-Pb collisions

Direct photon fraction quantified by

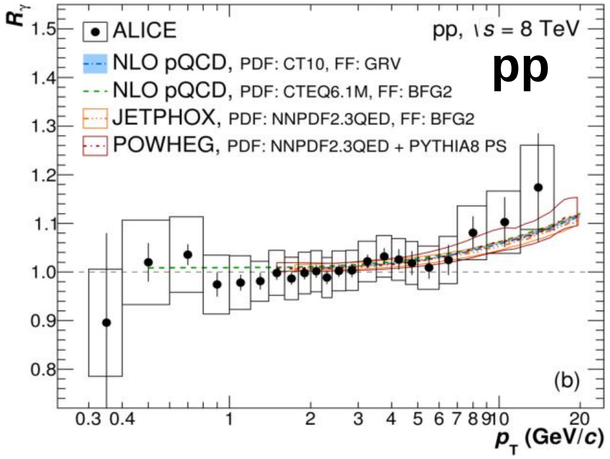
$$R_\gamma \equiv \frac{\gamma_{,\mathrm{inc}}}{\pi^0_{\mathrm{param}}} \Big/ \frac{\gamma_{,\mathrm{dec}}}{\pi^0_{\mathrm{param}}} = \frac{\gamma_{,\mathrm{inc}}}{\gamma_{,\mathrm{dec}}}$$

Excess in thermal photon region ($p_T < 3$ GeV/c) observed in central Pb-Pb collisions wrt pQCD expectations
(2.6σ for 0-20% and 1.5σ in 20-40%)

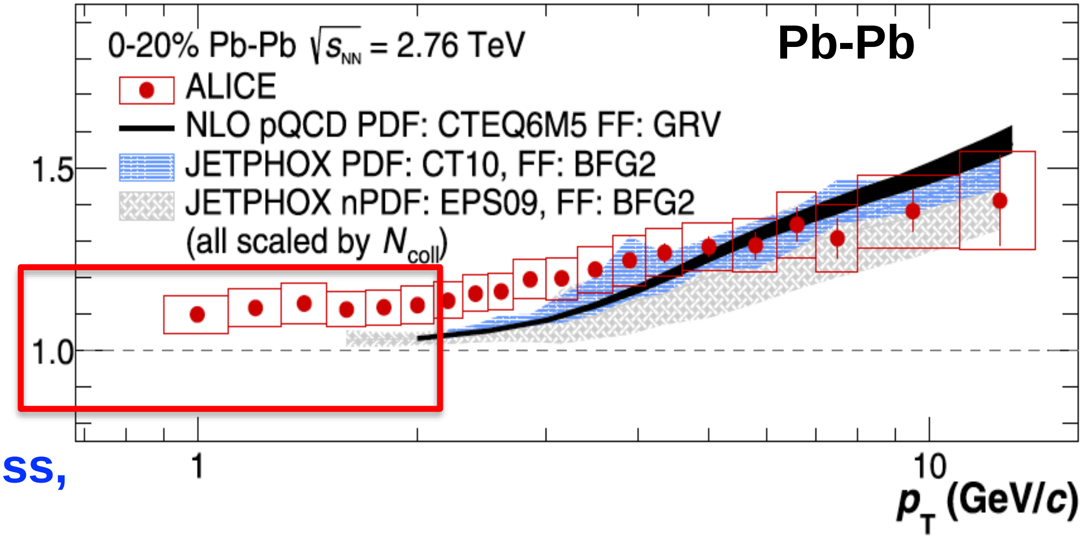
Spectrum consistent with NLO pQCD calculations at high p_T in all systems;

No excess observed in pp, p-Pb.

Phys. Rev. C 99, 024912 (2019)

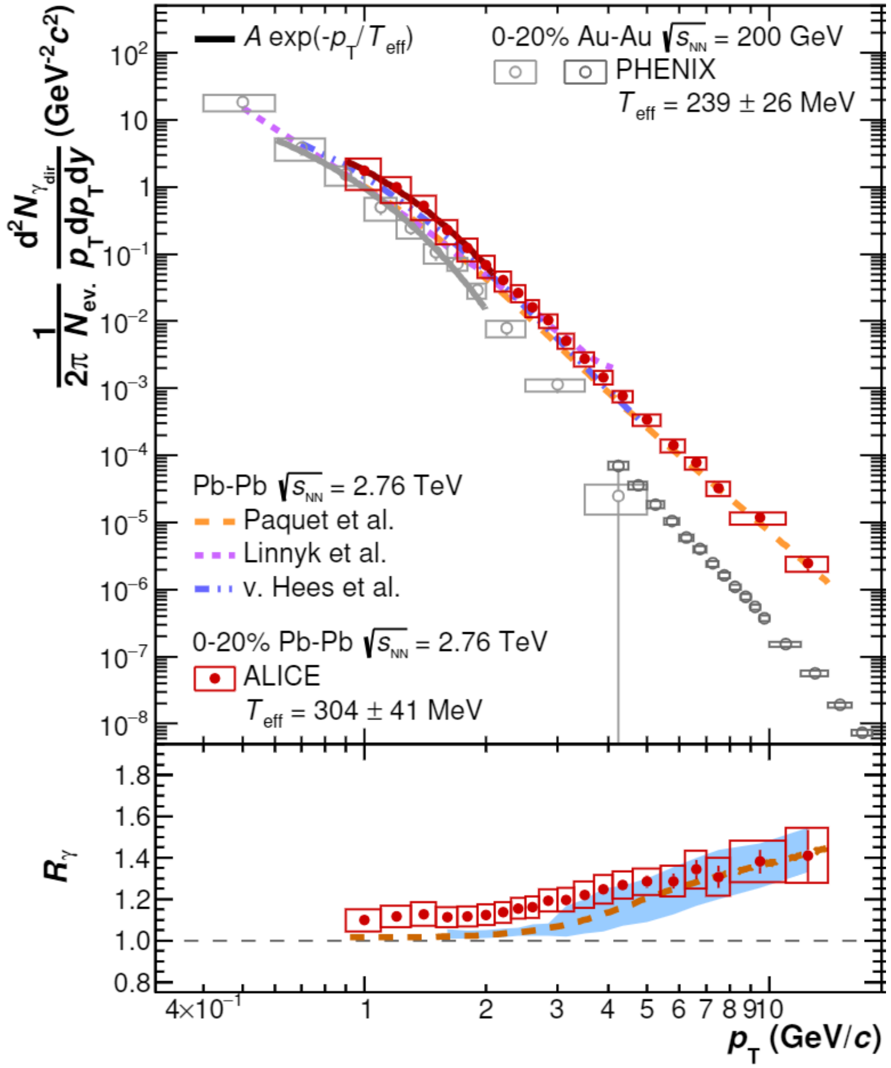


Phys. Lett. B 754 (2016) 235-248



Thermal excess, from QGP

Effective temperature from direct photons



ALICE, Phys. Lett. B 754 (2016) 235-248

After subtraction of the pQCD expectation, spectra at low p_T are fitted with an exponential distribution

$$d^2N_{\gamma_{dir}}/(p_T dp_T dy) \propto e^{-p_T/T_{eff}}$$

T_{eff} = (304 ± 41) MeV in 0-20% Pb-Pb
larger than the lQCD critical temperature!

compared to RHIC:
T_{eff} = (239 ± 26) MeV in 0-20% Au-Au

NB: This represents an **effective temperature** of the fireball and can be related to the “true” temperature by accounting for the radial expansion of the system, which causes a blue-shift of the emitted photons.

Dead-cone effect in pp

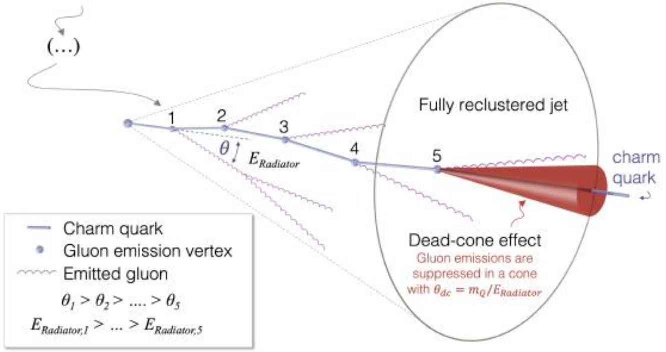
The pattern of the parton shower in vacuum is expected to depend on the mass of the initiating parton

First direct observation of the dead cone effect in QCD in hadronic collisions (pp 13 TeV) using D^0-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]

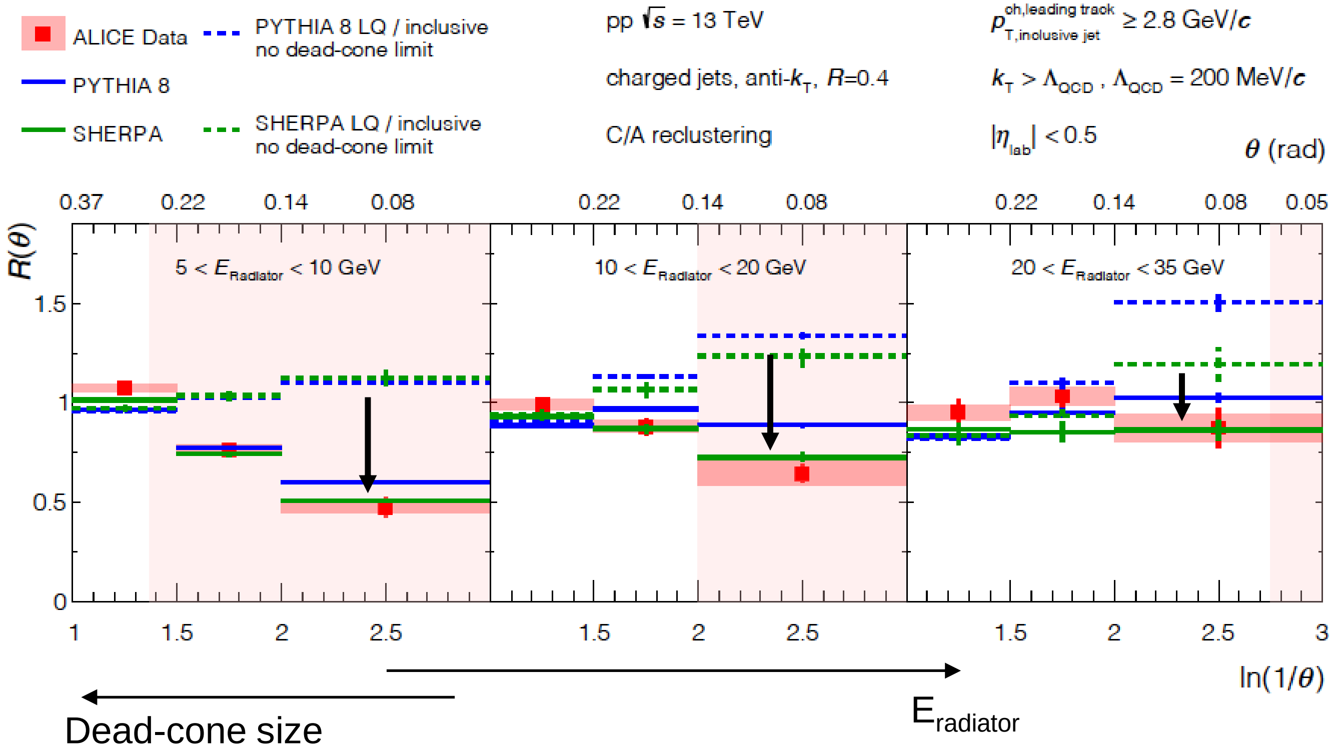
To be measured next:

- In beauty sector → mass dependence
- In 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}

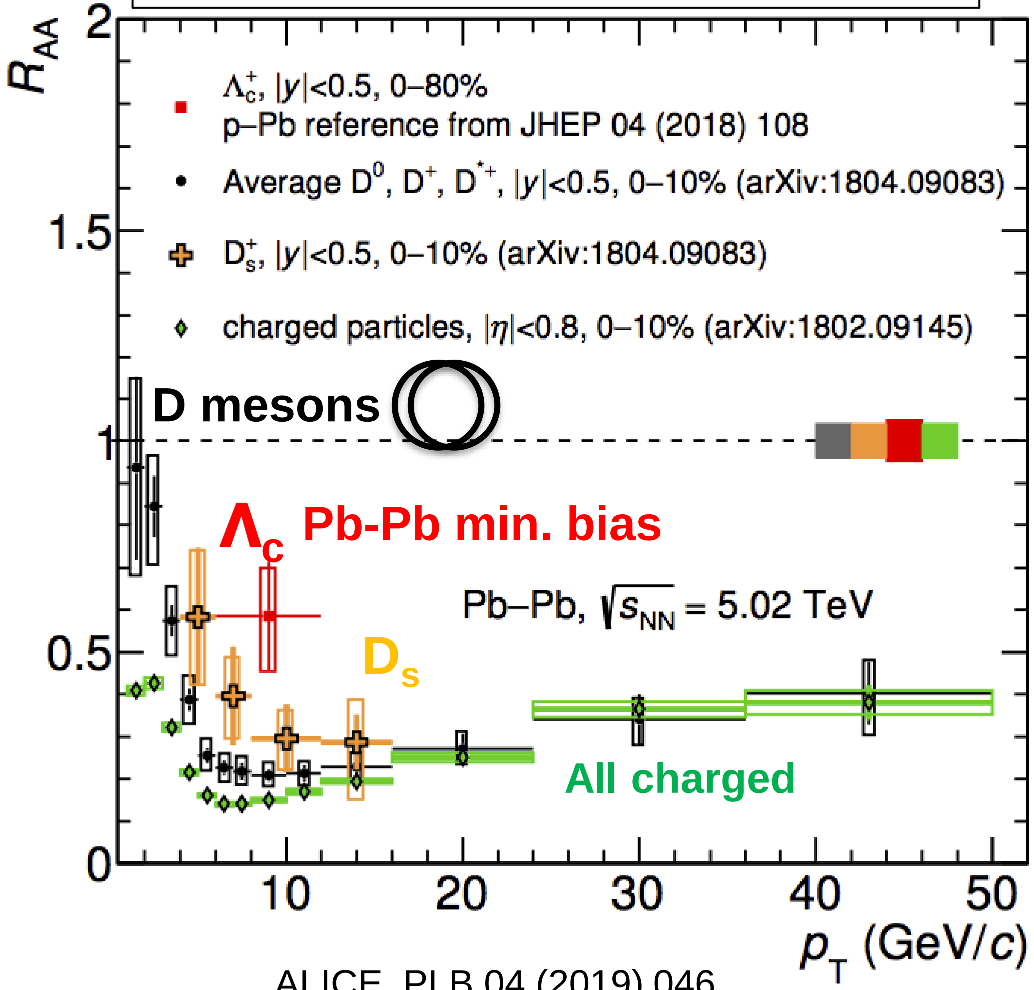
$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$



ALICE, Nature 605 (2022) 7910, 440-446

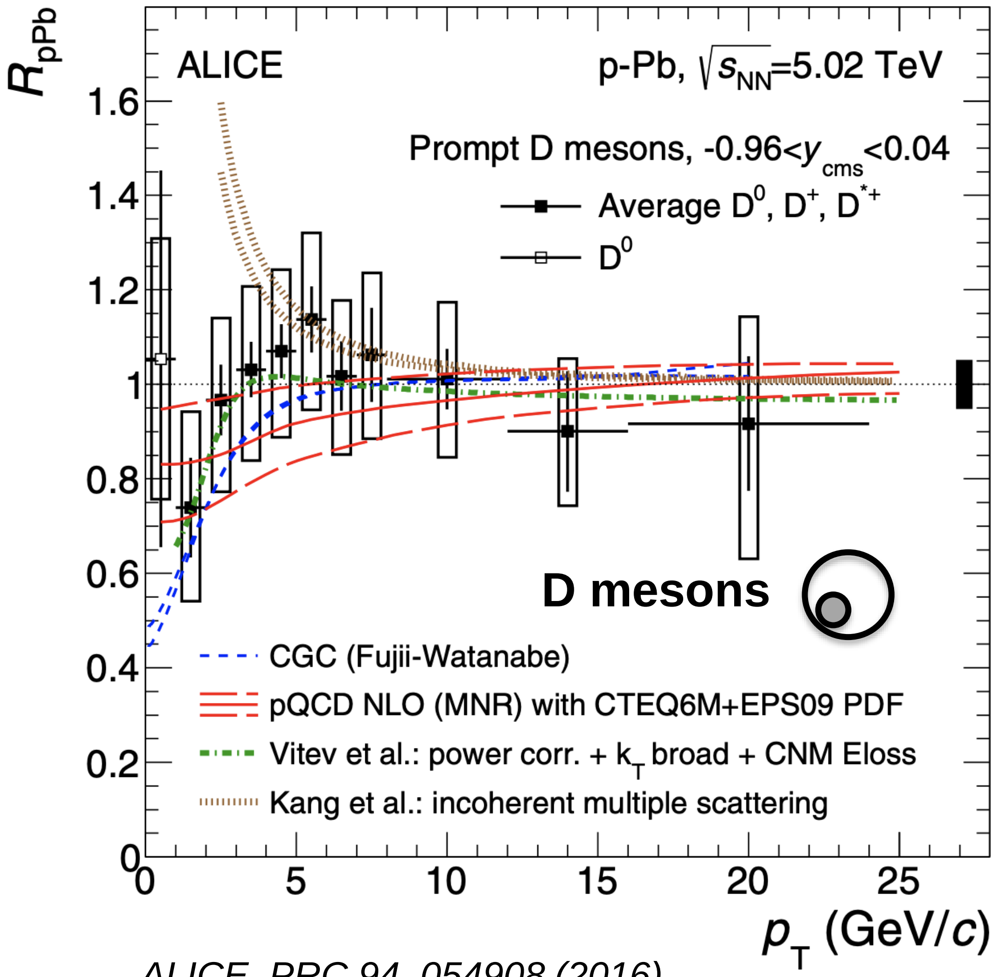
Nuclear modification in the charm sector

Nuclear modification factor of light and charmed hadrons vs p_T



ALICE, PLB 04 (2019) 046

HF nuclear modification factor in p-Pb



ALICE, PRC 94, 054908 (2016)

In-medium jets: main questions

Related to the nature and properties of the medium

- Density of the medium and transport properties
- Nature of the scattering centers
- Distribution of the radiated energy
- …

Related to the nature of the energy loss mechanism

- Path length dependence
- Broadening effects
- Microscopic mechanism for energy loss
  → Study the **shape and structure of jets** for insight into the details of jet modification mechanisms due to interactions with the plasma

- Flavour dependence
  → **measure charm and beauty R_{AA}**