CERN Summer Student Lectures 2023

Heavy Ions 3/3

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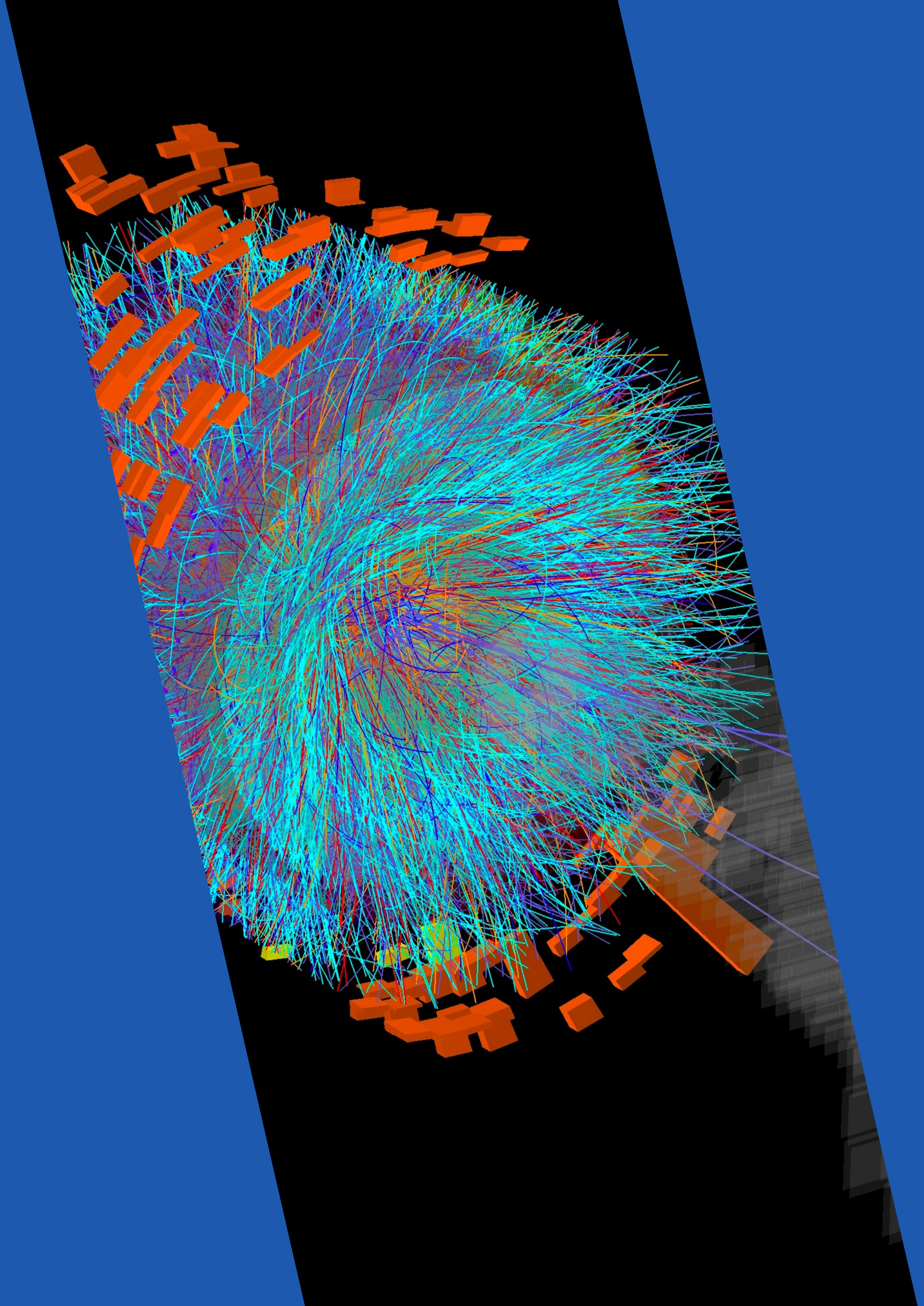
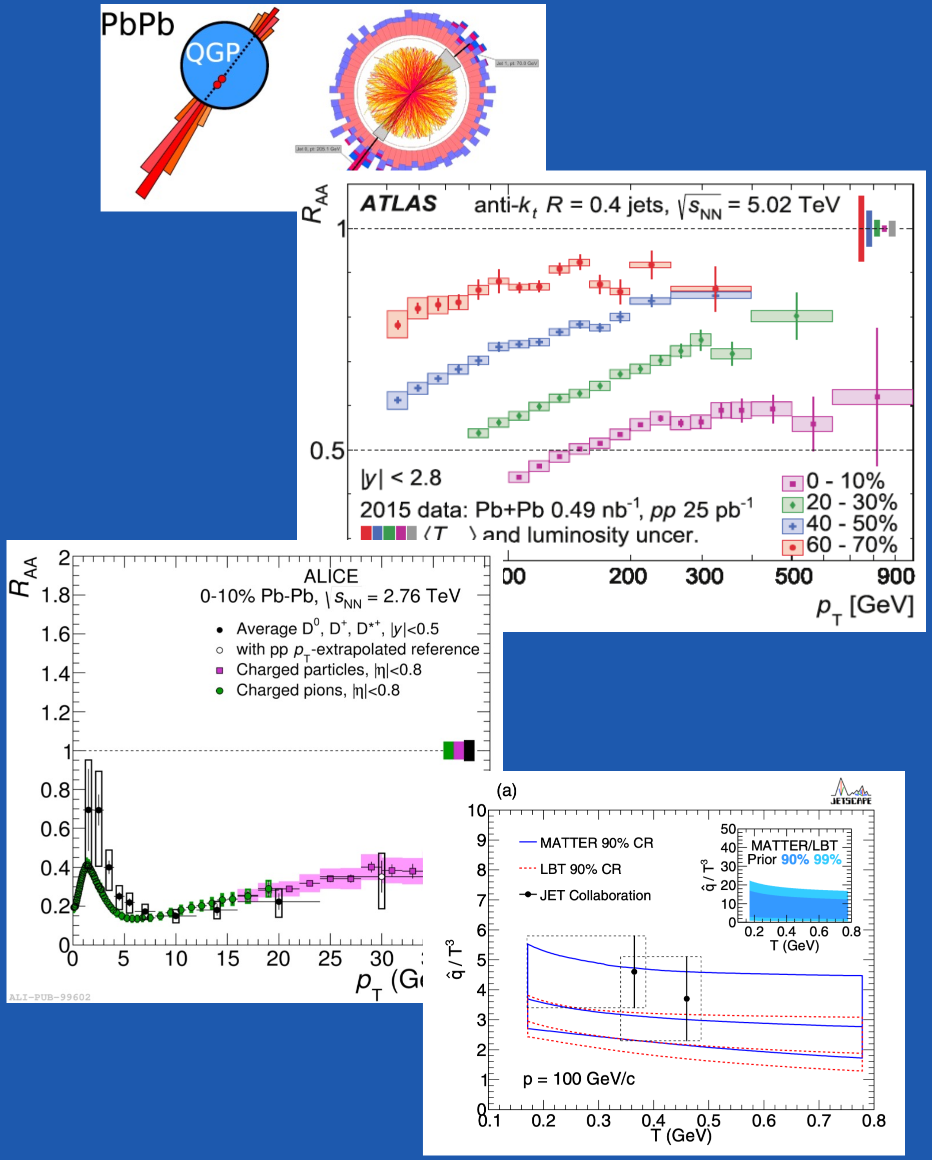


Yesterday’s summary – take home 1/4

Evidence of the creation of a strongly-interacting medium in central heavy ion collisions comes from the observed strong suppression of particle production, explained by the energy loss of colored partons in the colored QGP.

- Radiative energy loss dominates at high p_T for light flavours, gluons and charm
- c and b also affected by dead cone effect and collisional energy loss

A **quantitative characterization** of the properties of the medium (e.g. transport coefficient, …) requires **models**.



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

Quarkonium as a thermometer for QGP

Charmonium suppression (J/ψ, ψ',…) was suggested as ''smoking gun'' signature for the QGP back in the 1980's *[Matsui, Satz, PLB178 (1986) 416-422]*

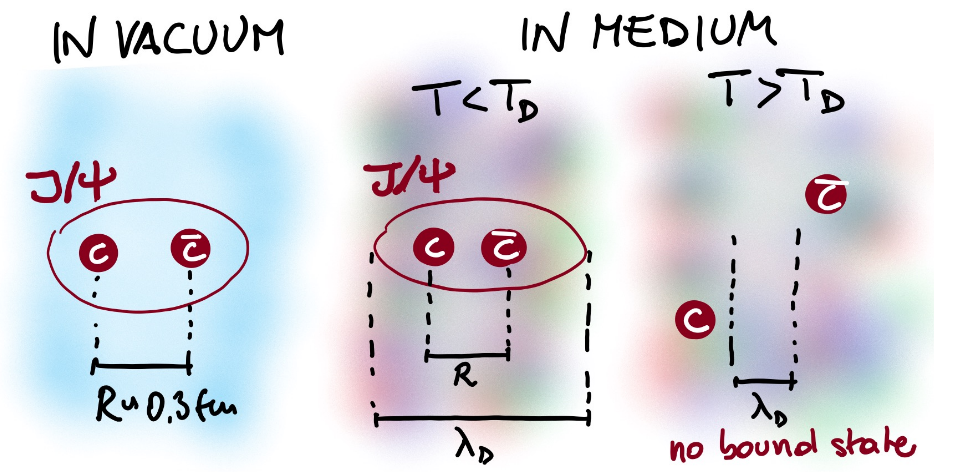
In vacuum (T=0), $q\bar{q}$ is bound by the Cornell potential.

$$V(r) = -\frac{\alpha}{r} + kr$$

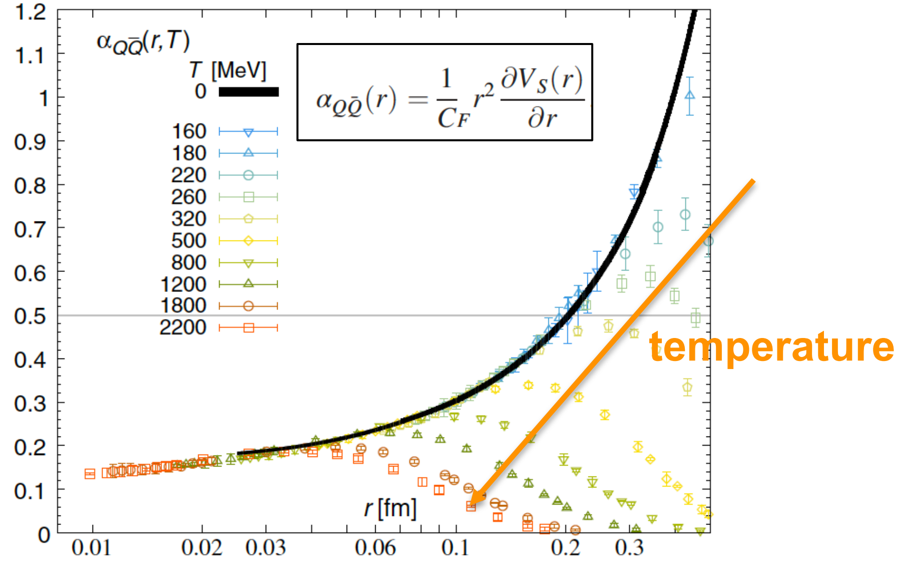
In the dense and hot QGP (**T>0**), the binding potential is modified by color-charge (Debye) screening effects

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

The effective coupling between q and $\bar{q}$ at large distances gets reduced → **$q\bar{q}$ melting**



Effective coupling from (2+1) QCD at various T

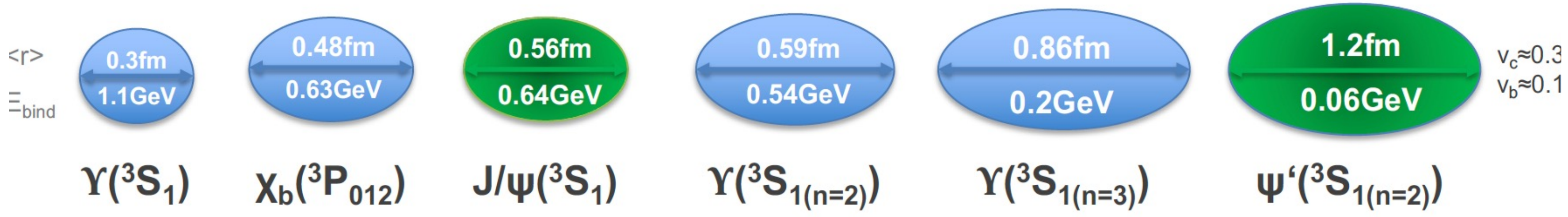


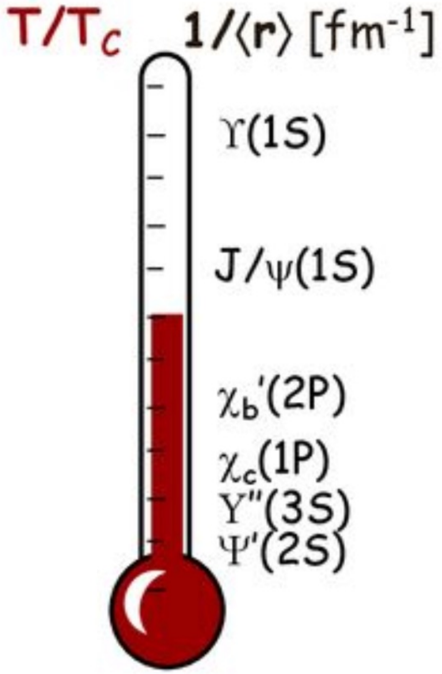
Distance between $q\bar{q}$ (fm)

Quarkonium as a thermometer for QGP

$c\bar{c}$ (J/Ψ, Ψ',..) and $b\bar{b}$ (ϒ', ϒ'', ϒ''') states are a laboratory for QCD:

- Small decay width (~keV), significant BR into dileptons
- Intrinsic separation of energy scales: $m_Q >> \Lambda_{QCD}$ and $m_Q >> B_E$
- A variety of states characterized by different binding energies





To larger radius →

To lower binding energy →

→ Goal: understand mechanisms of **dissociation and regeneration** in QGP

J/ψ ($c\bar{c}$) suppression

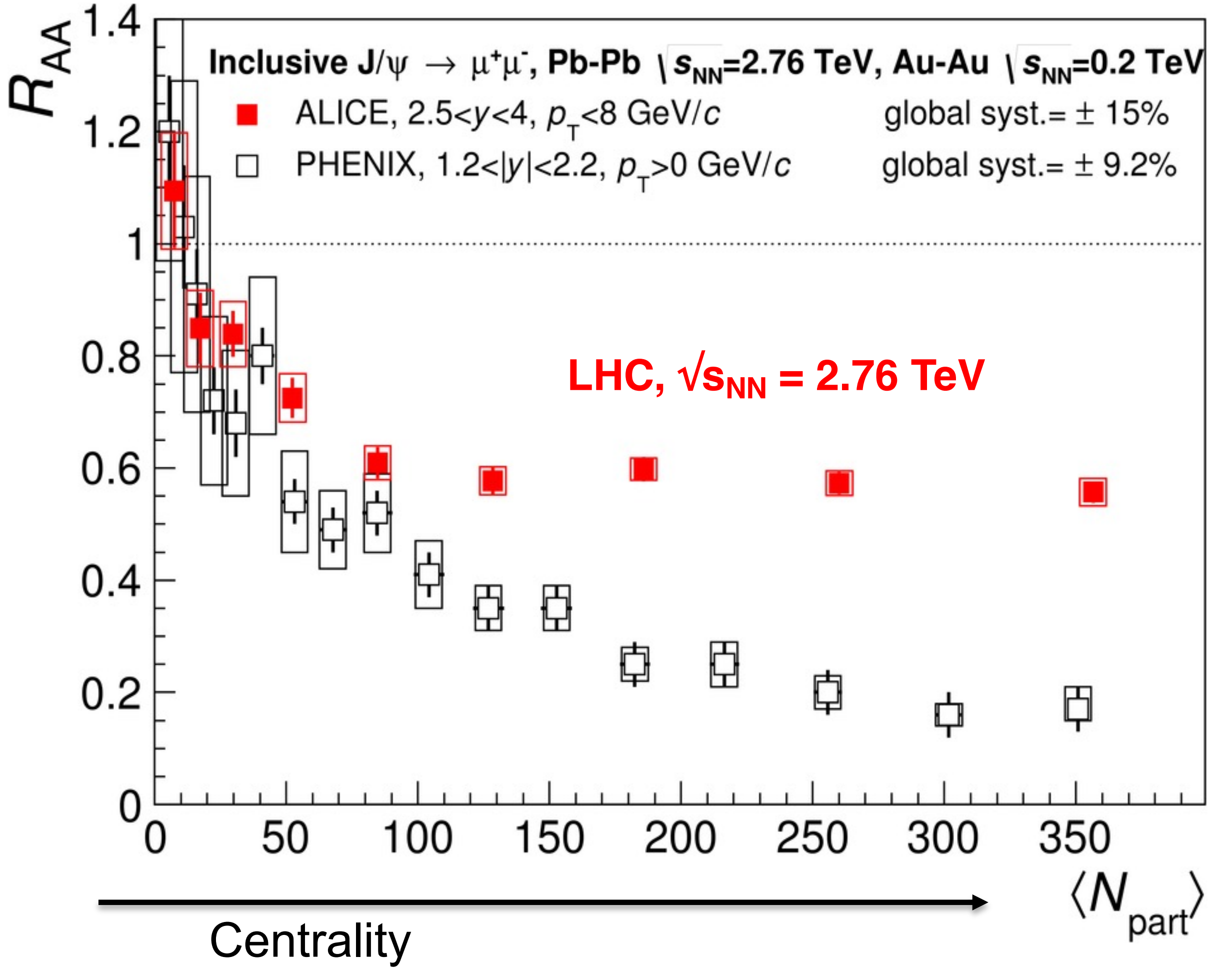
- observed at the SPS ($\sqrt{s_{NN}}$ = 17 GeV)
- later measured at RHIC ($\sqrt{s_{NN}}$=200 GeV) up to very high multiplicities

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

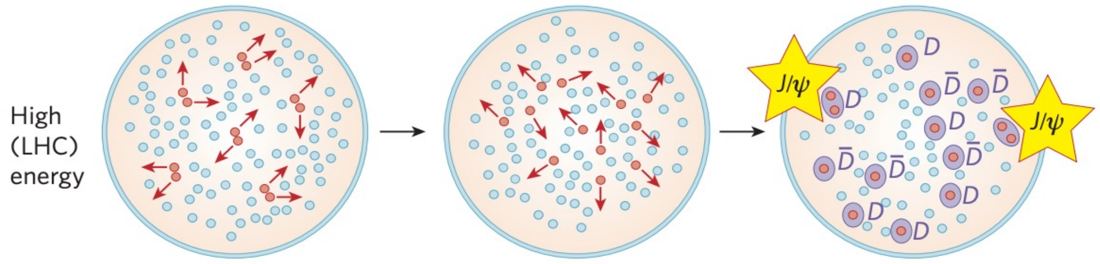


$c\bar{c}$ cross section vs energy

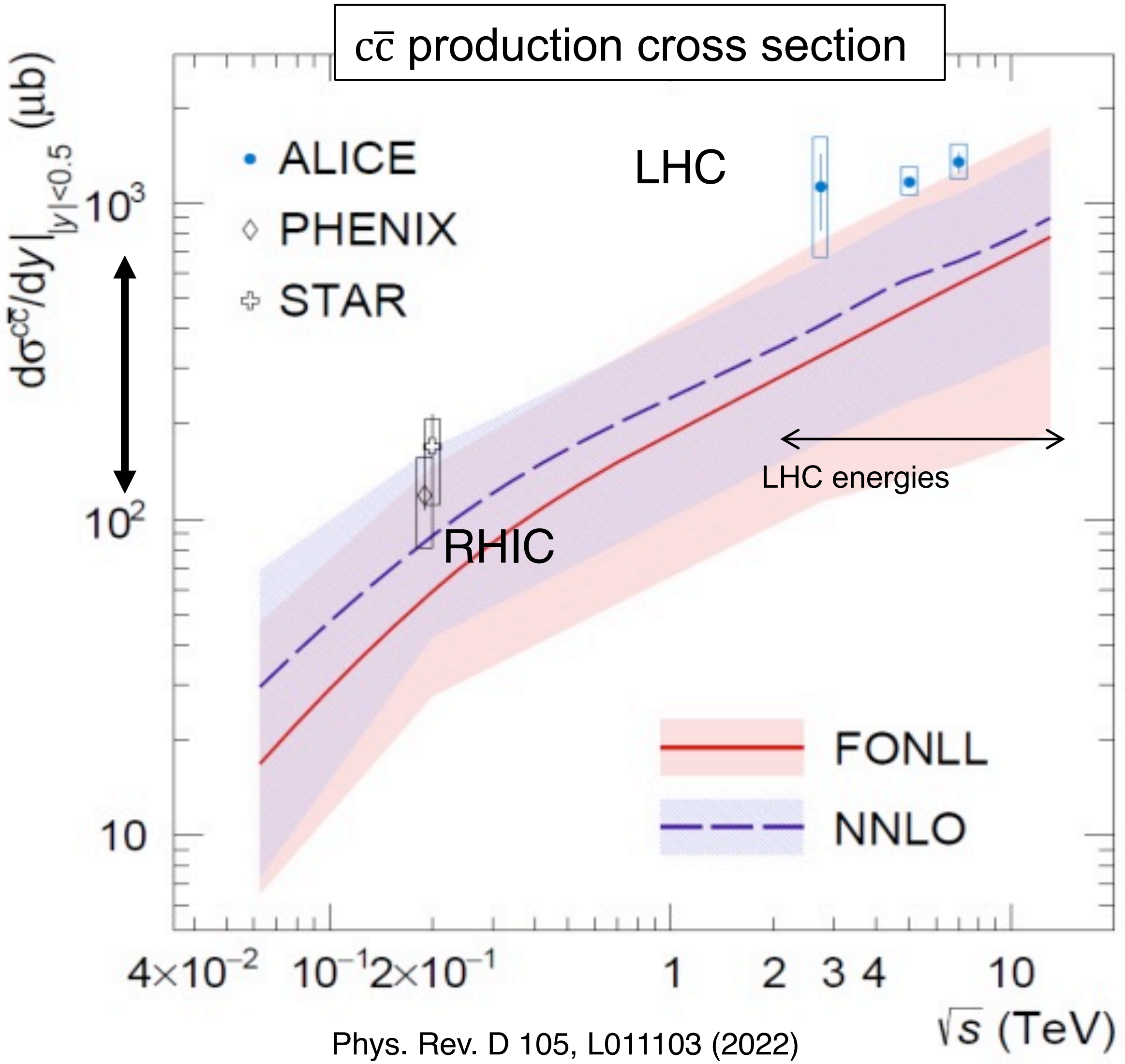
The cross section for producing a $c\bar{c}$ pair increases with $\sqrt{s}$

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)



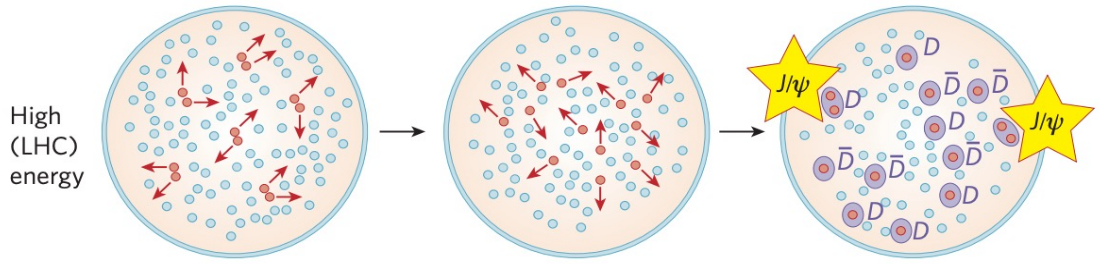
Phys. Rev. D 105, L011103 (2022)

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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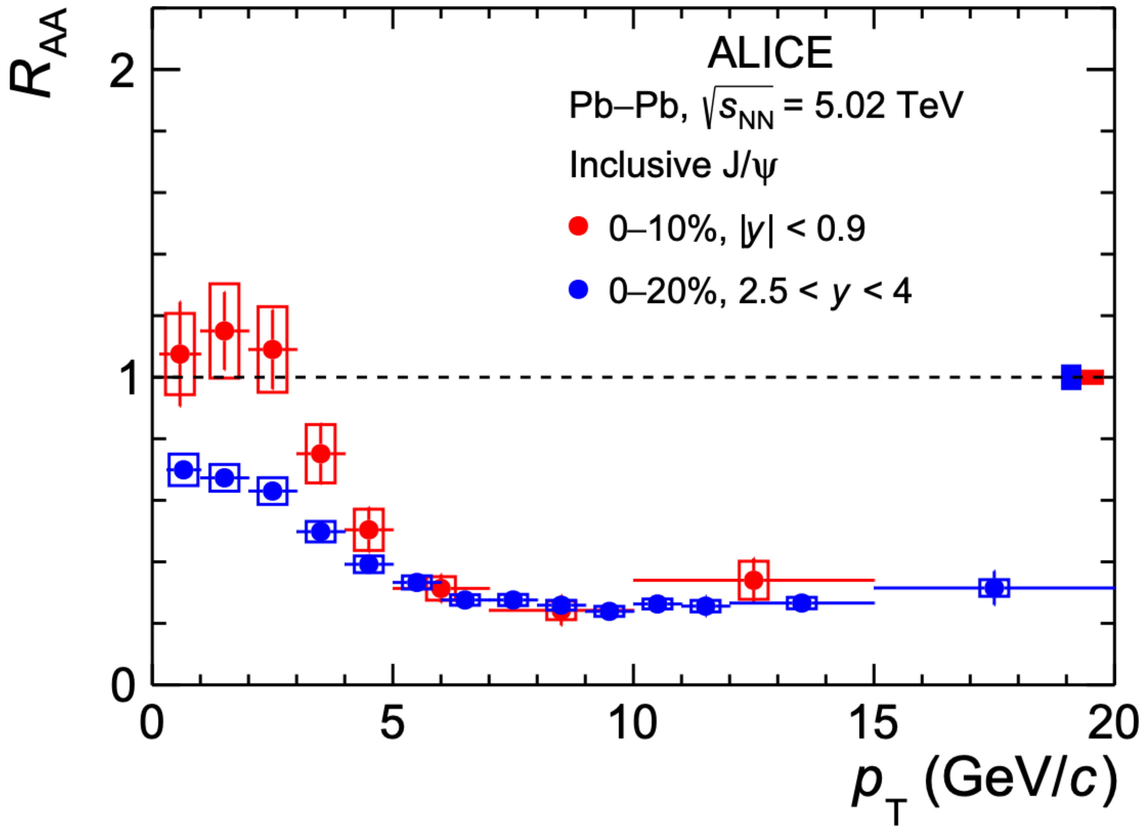
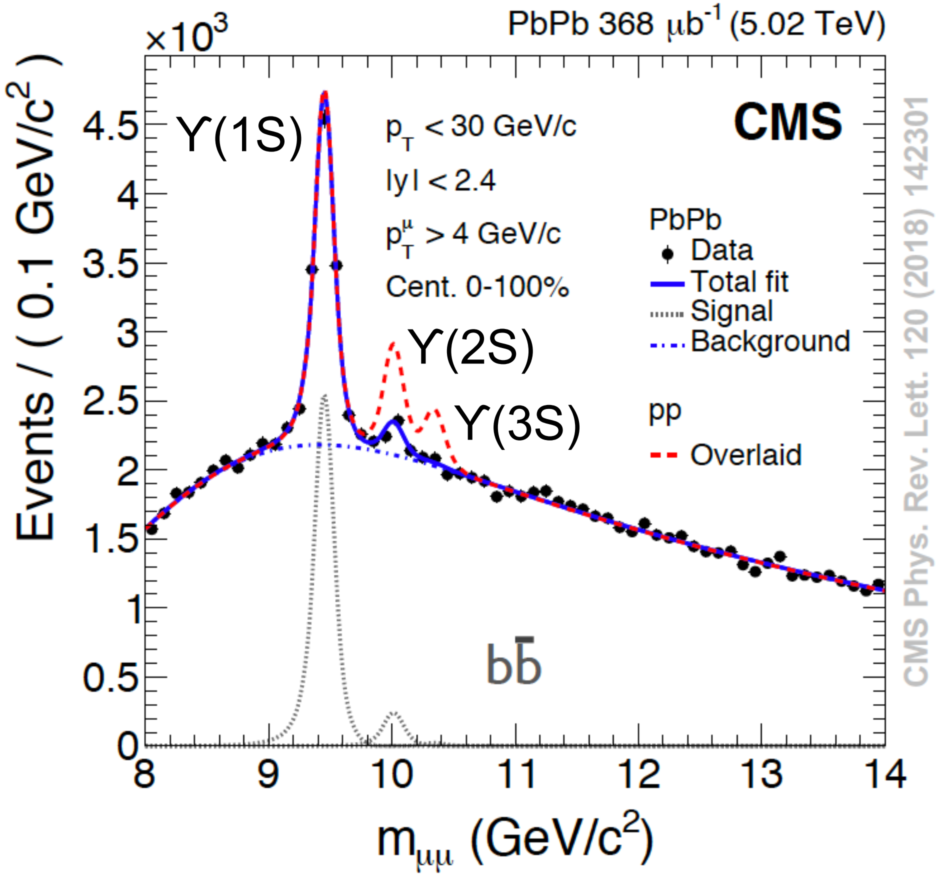


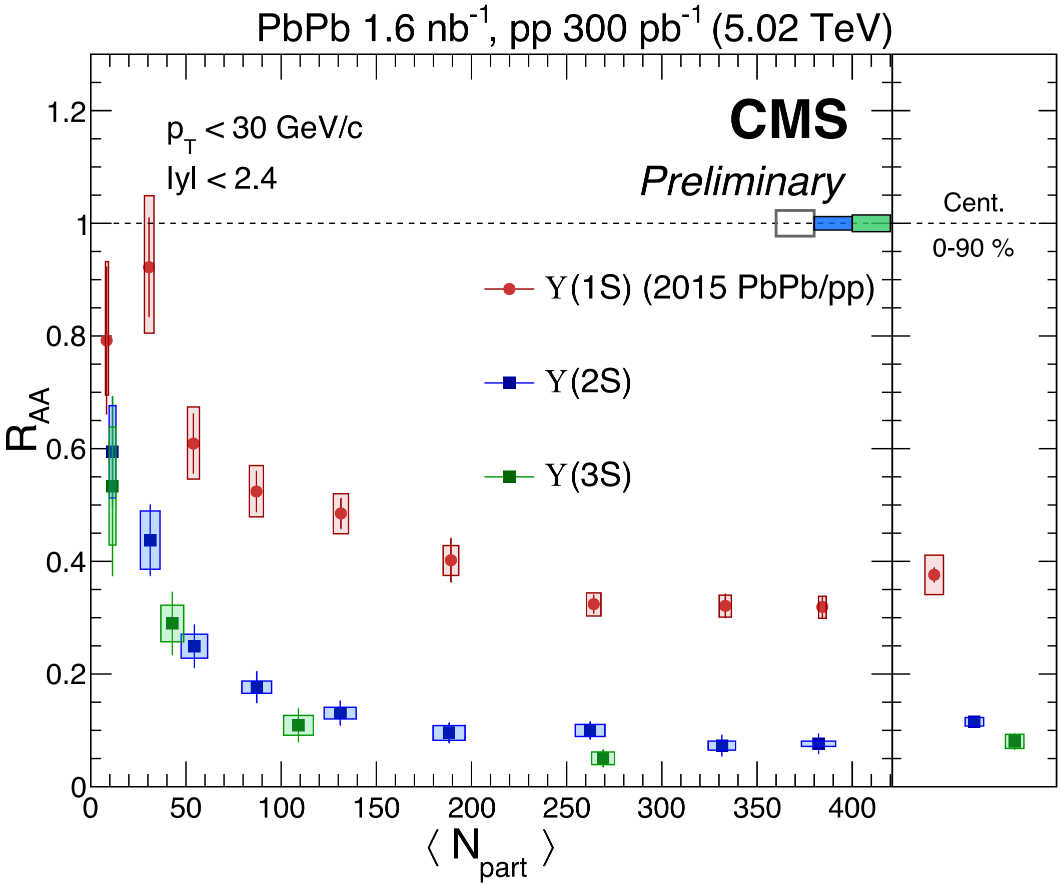
ALICE, arXiv:2303.13361

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.

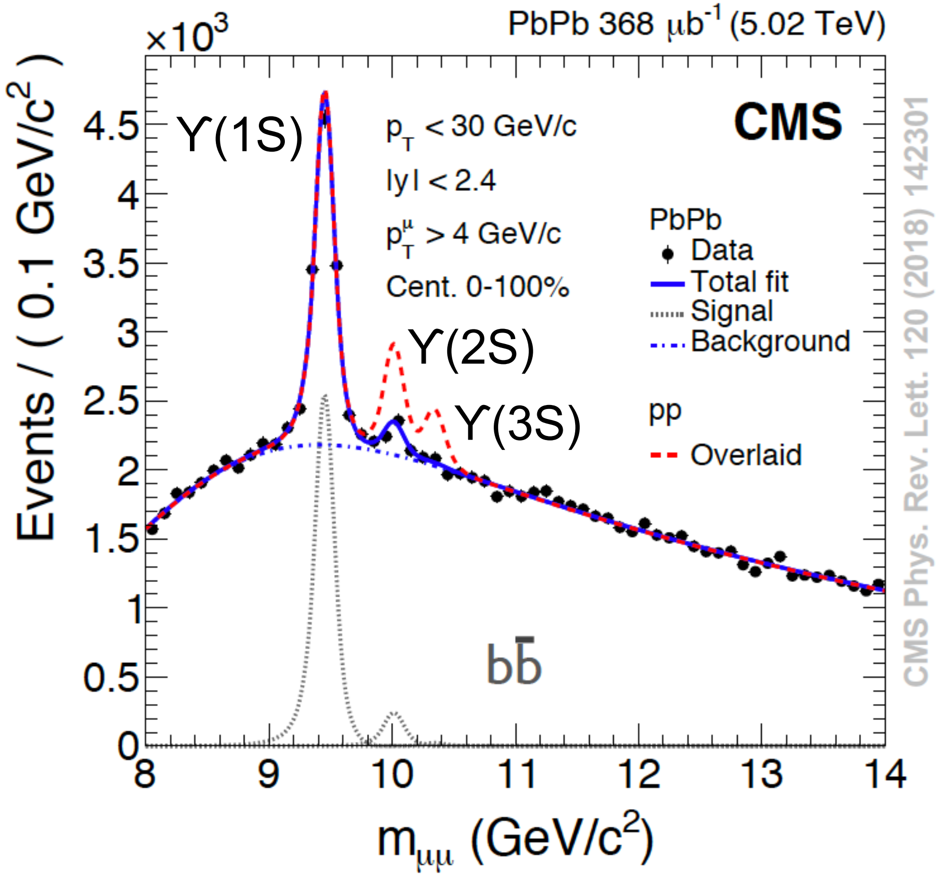


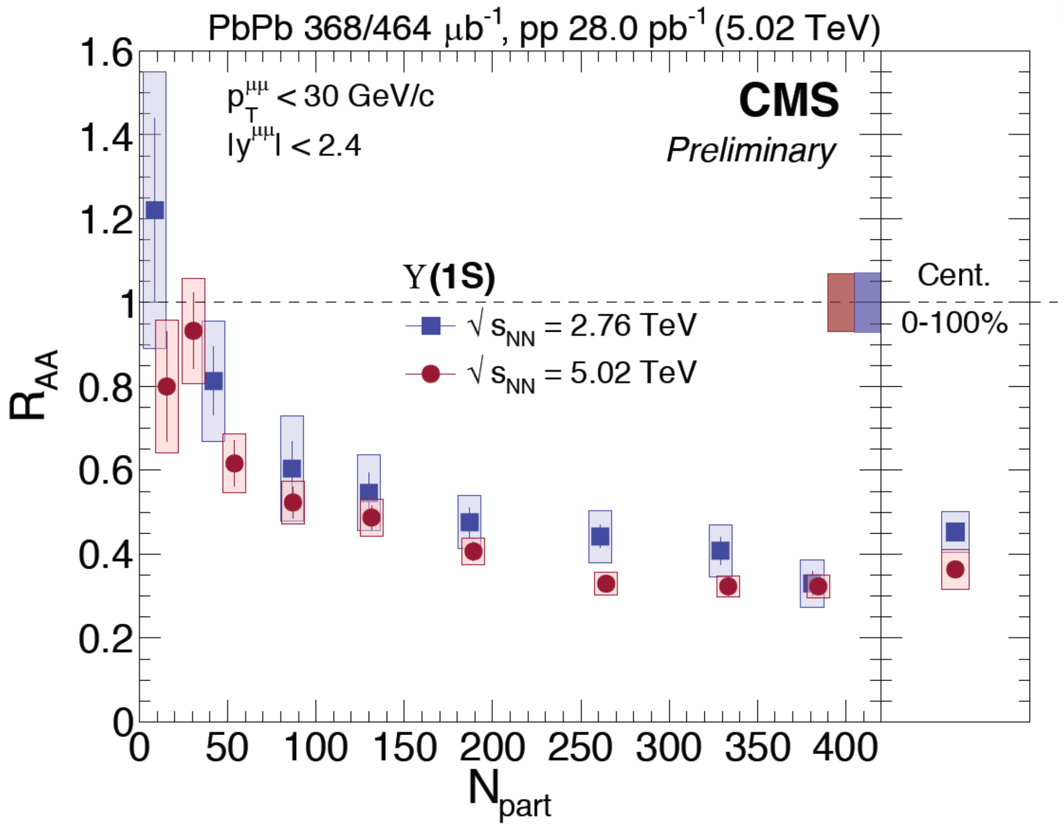


Sequential melting of $b\bar{b}$ states

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

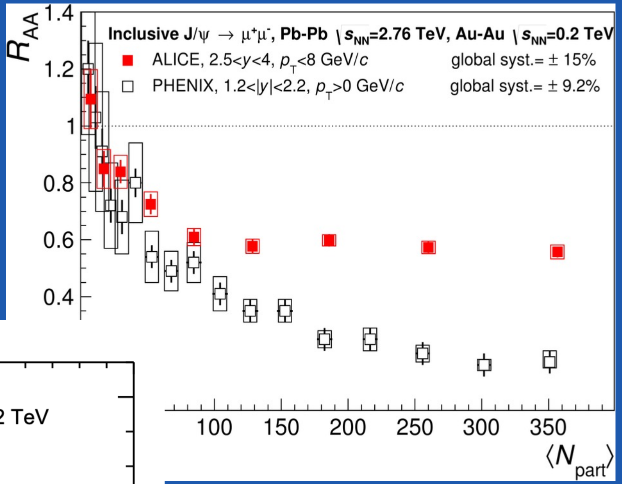


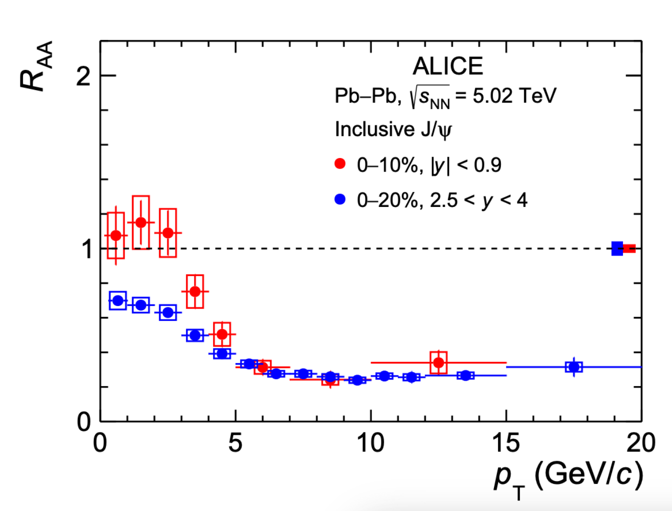


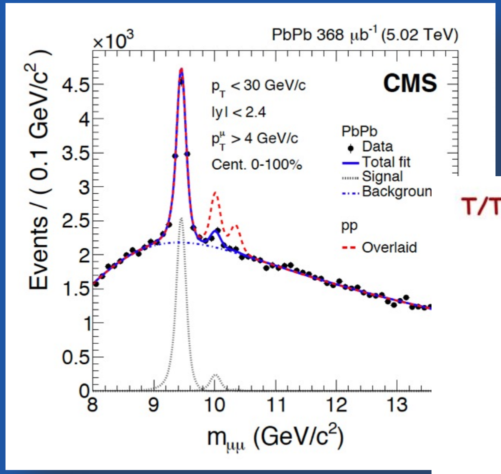
Take home 2/4

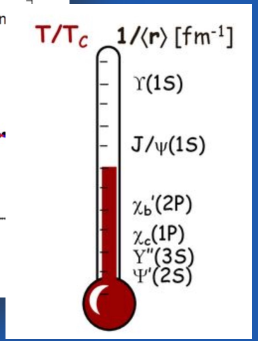
The study of quarkonium ($c\bar{c}$, $b\bar{b}$) states provides information on the mechanisms of **dissociation and regeneration** of strongly-bound state in a medium (T>0).

- The high density of color charges in the QGP leads to melting of quarkonia
- The large abundance of charm quarks at LHC results in regeneration of the amount of J/ψ
- States with smaller binding energies are more suppressed



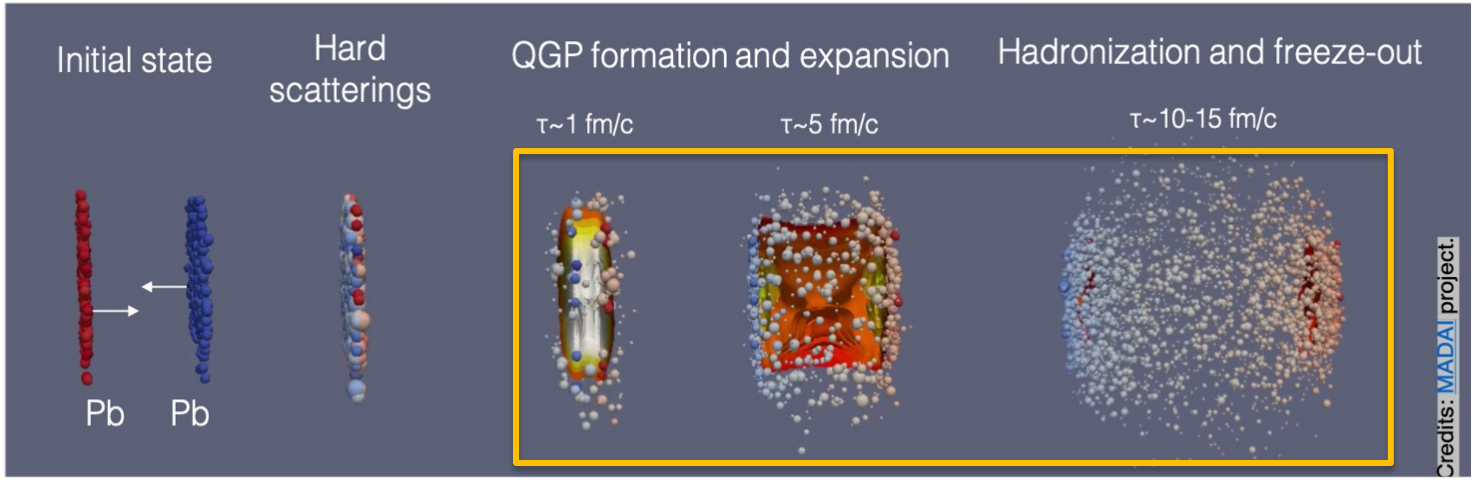


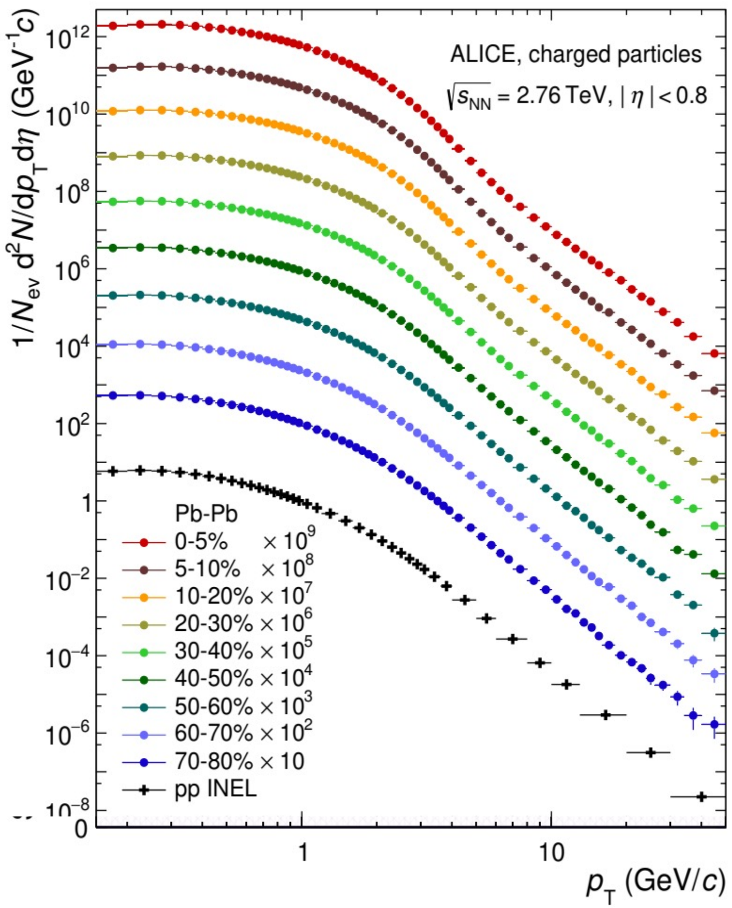




How does the QGP affect production of hadrons?

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 and resonances.

A **collective motion** is observed: the **dynamic and thermodynamic properties of the QGP** are studied by measuring p_T and azimutal distributions of particles produced in the bulk

The hadron-gas phase and freeze-outs

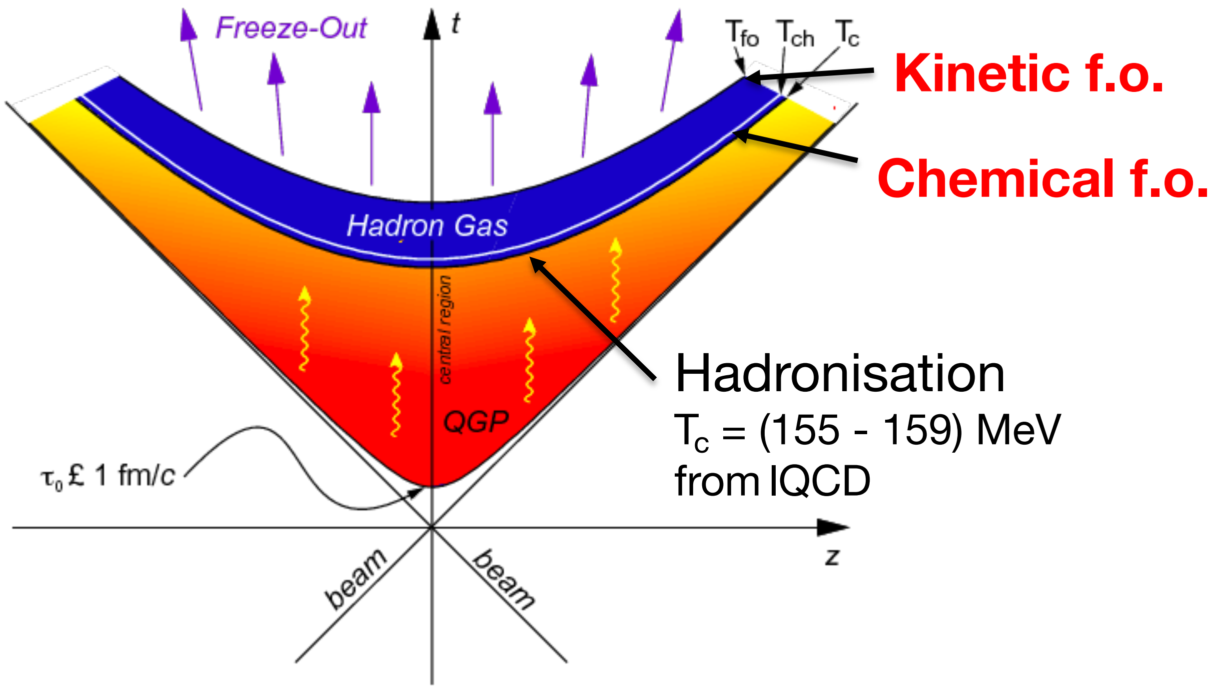
After hadronisation, the system is a hot ($T < 155$ MeV) and dense gas of hadrons and resonances.

Chemical freeze-out

- Inelastic collisions stop
- Relative particle abundances are fixed

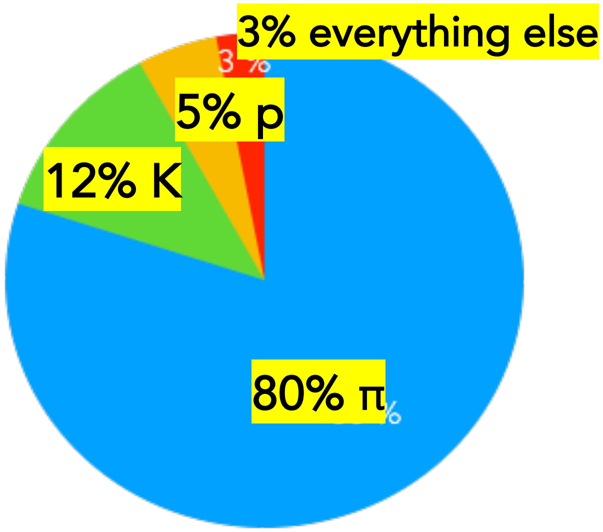
Kinetic freeze-out

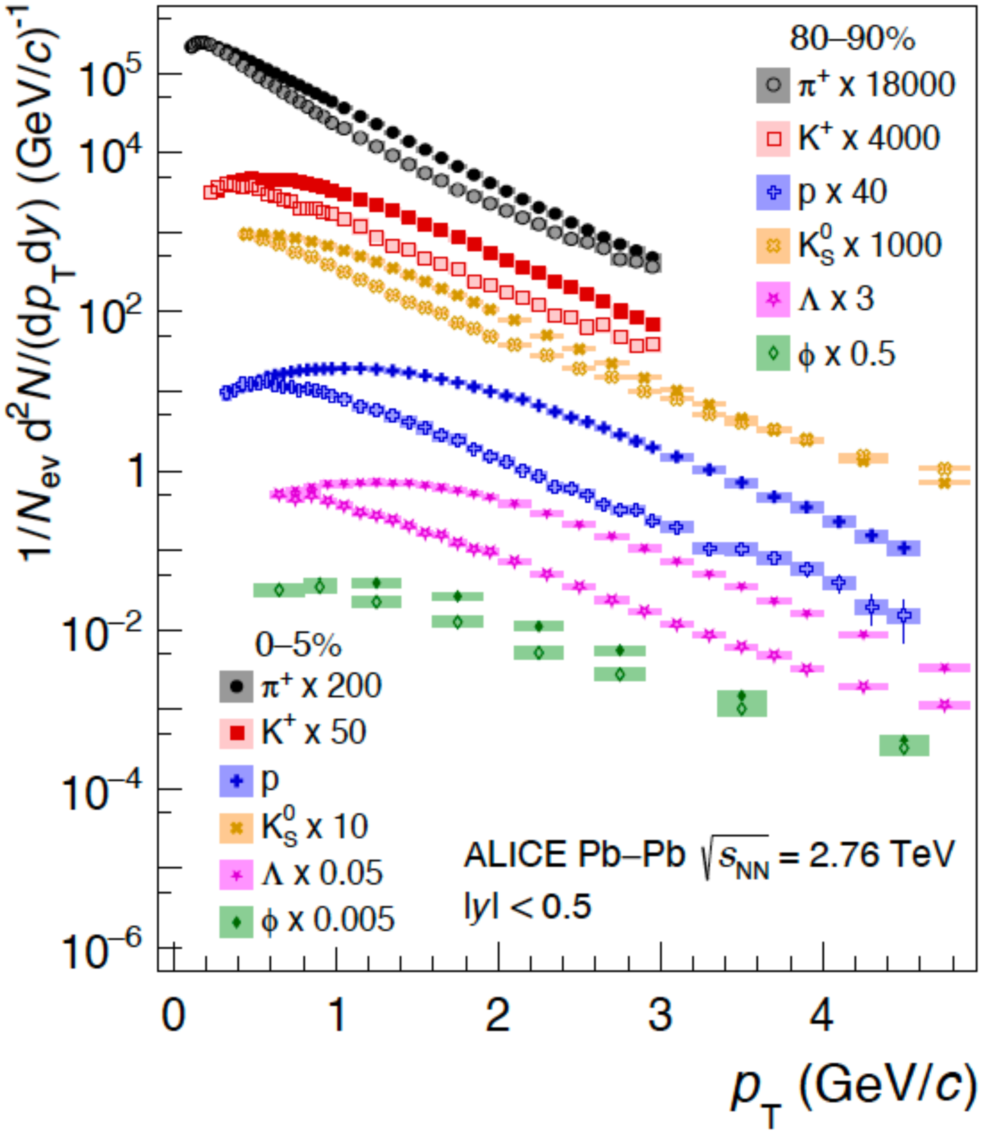
- (pseudo)elastic collisions stop
- Momentum distributions are fixed



→ Fit abundance of identified hadrons: probe chemical equilibrium at **chemical freeze-out**
→ Fit shape of p_T spectra: probe final hadron kinematics at **kinetic freeze-out**

Identified particle production





πKp are the most abundant hadronic species produced in the collision
→ Integrate $d^2N/(dy dp_T)$ spectra over p_T to extract yields, dN/dy.

Statistical hadronisation model in a nutshell

It models an ideal relativistic gas of hadrons and resonances in **chemical equilibrium**
(as the result of the hadronization of a QGP in thermodynamical equilibrium.

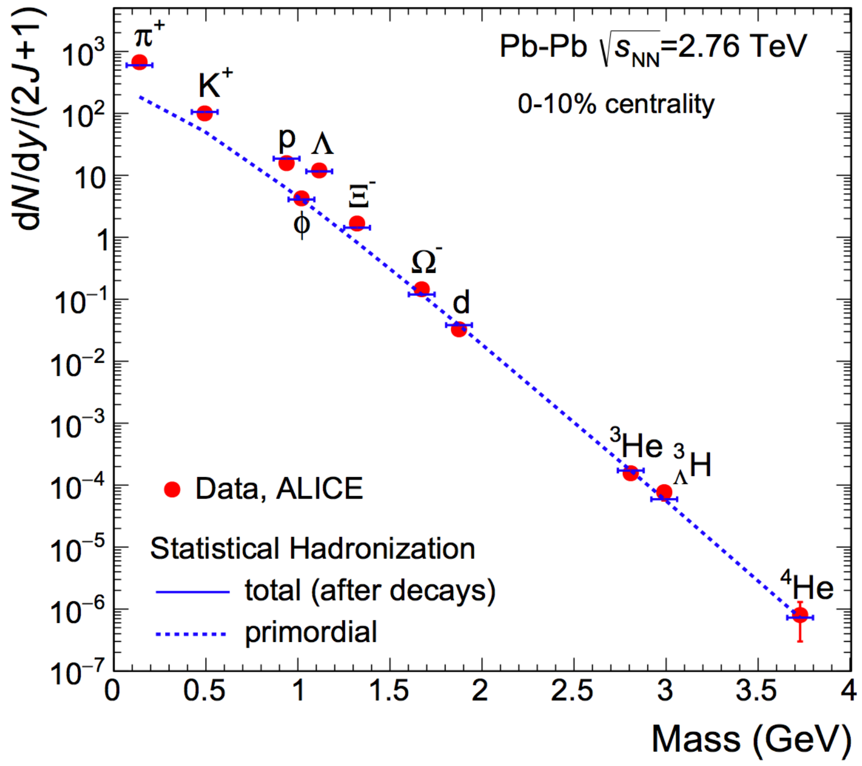
Particle abundances are obtained from the partition function of a Grand Canonical (GC) ensemble

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

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

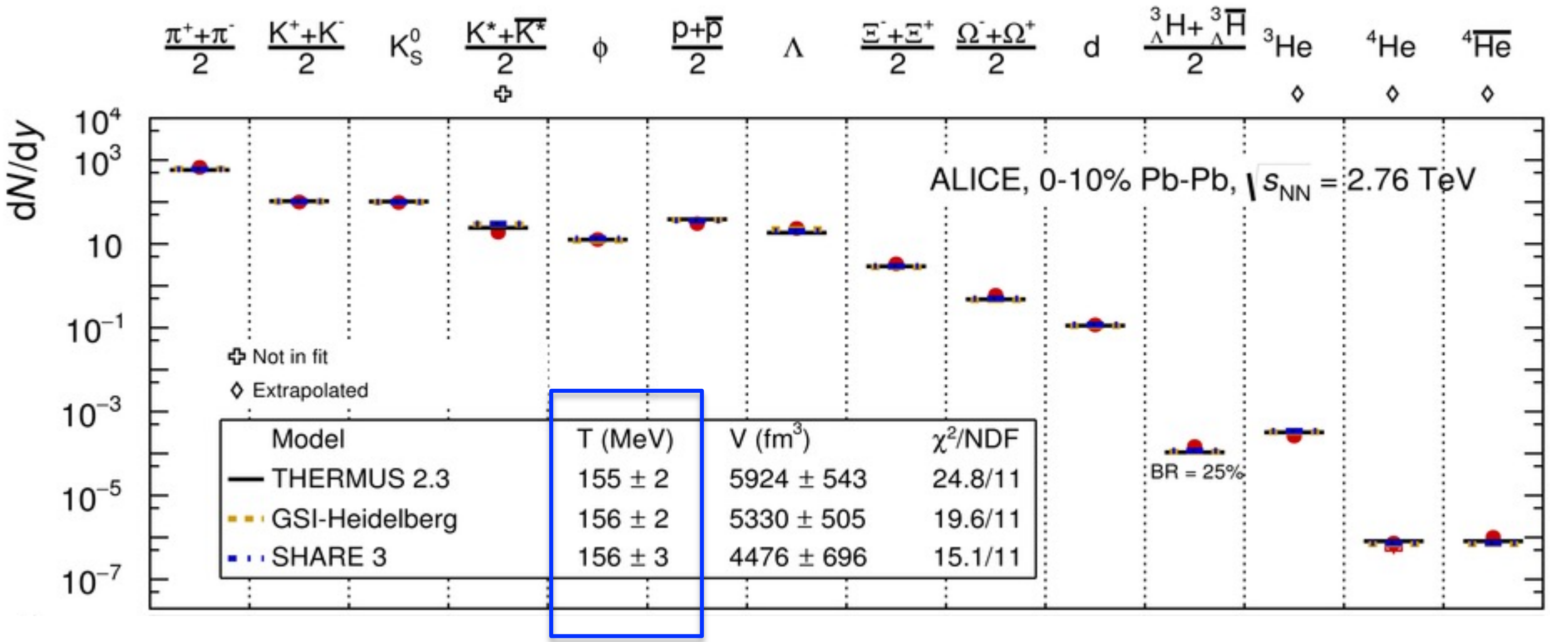
$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i$$

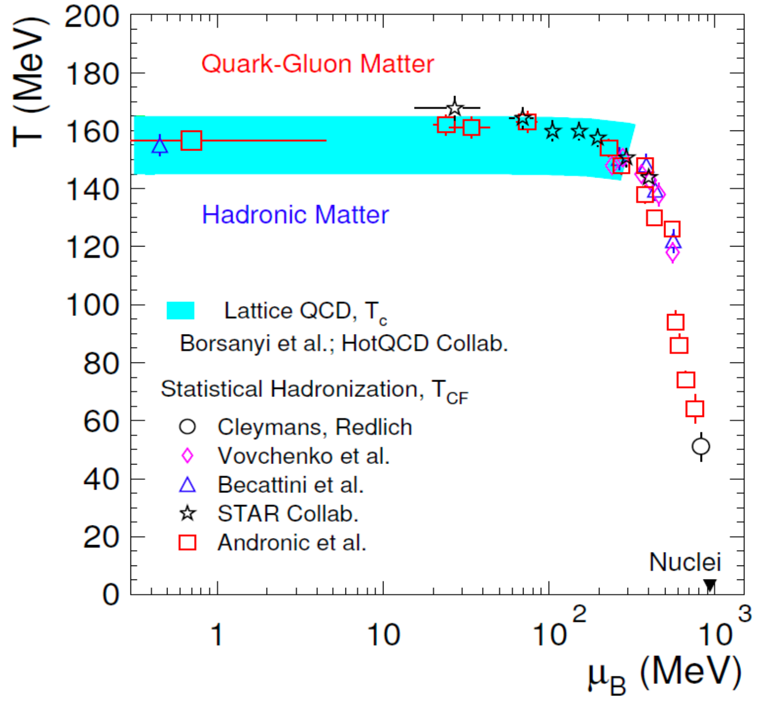
- ❑ Predict yields (see right figure) at a given temperature
- ❑ Fit measured particle yields (or ratios) to extract μ_B, T_{ch}, V.



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

Chemical freeze-out temperature





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**

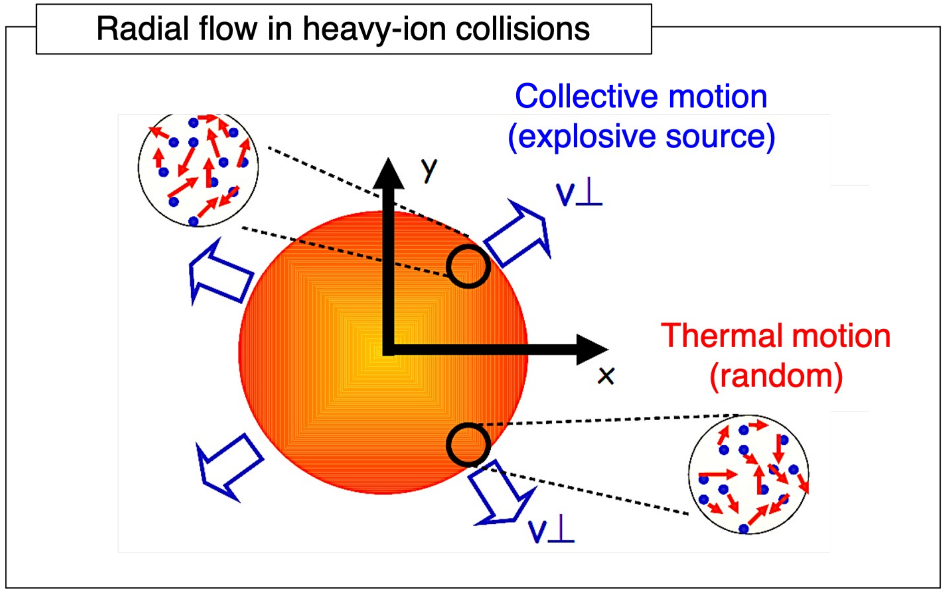
Hydrodynamics at play: radial flow (1/2)

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

Radial flow

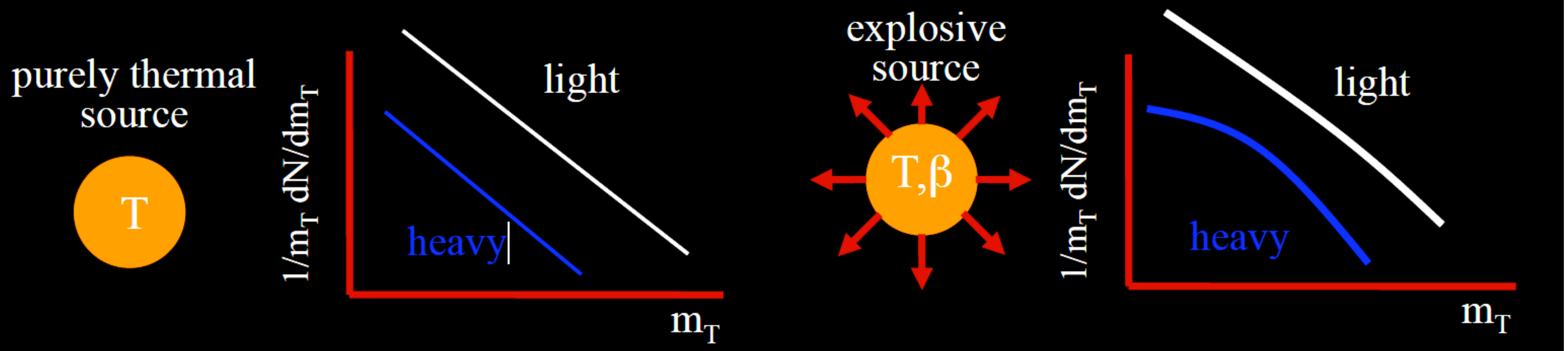
radial expansion of a medium in the vacuum under a common velocity field

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



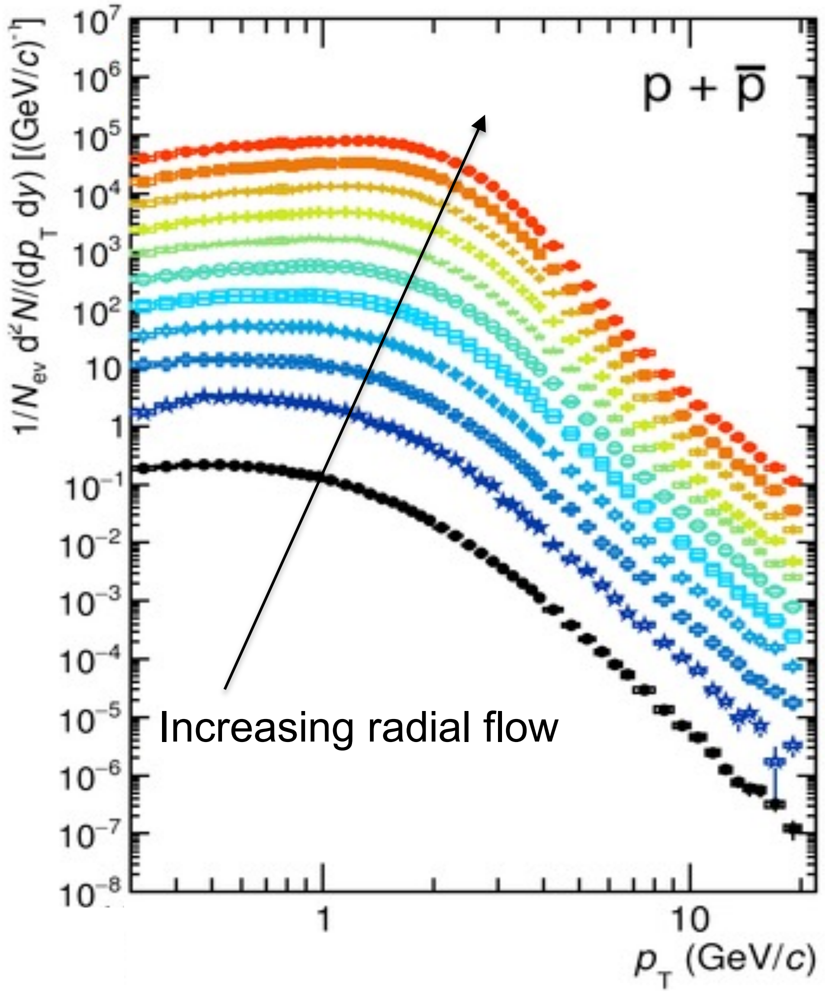
$$m_T = \sqrt{(m^2 + p_t^2)}$$

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



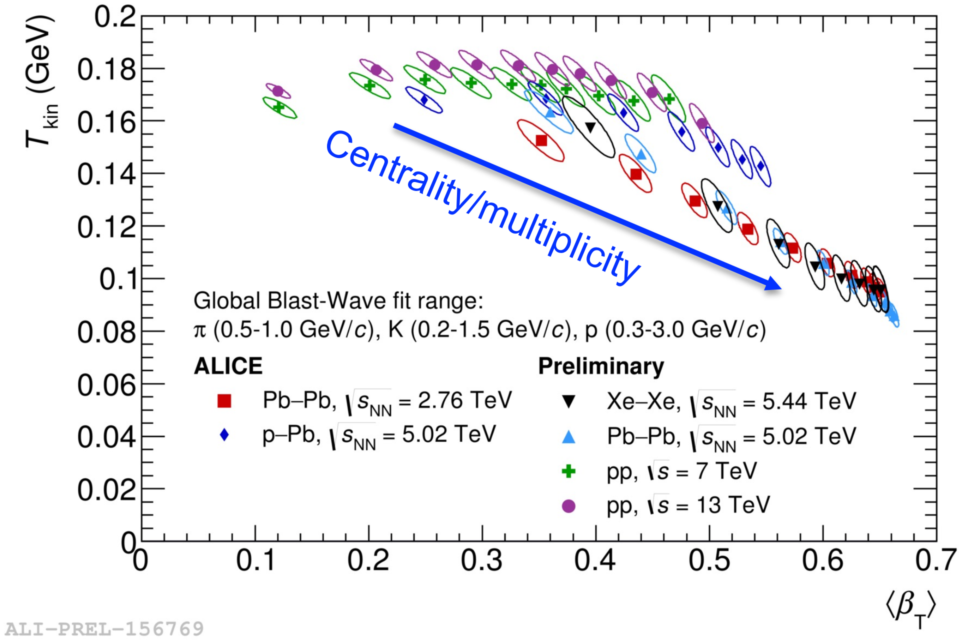
R. Snellings

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.**



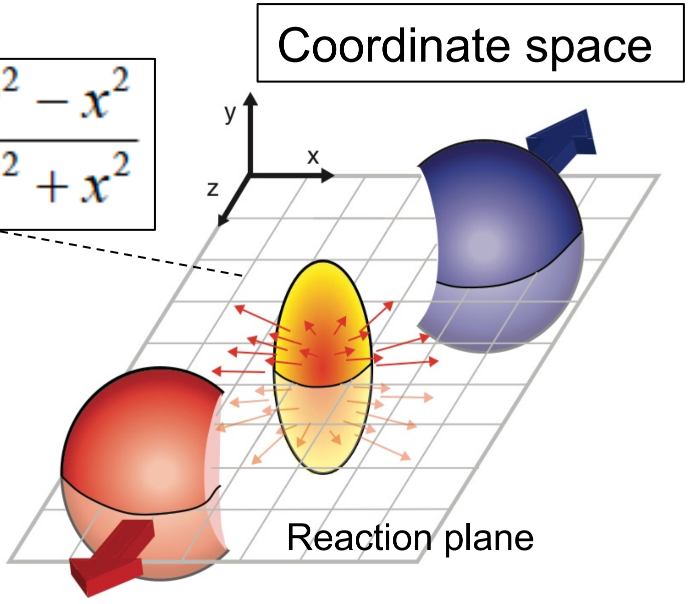
More central (higher multiplicity) events have lower T_{kin} and higher flow velocity

T_{kin} ~ 100-140 MeV

Hydrodynamics at play: anisotropic flow (1/2)

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

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

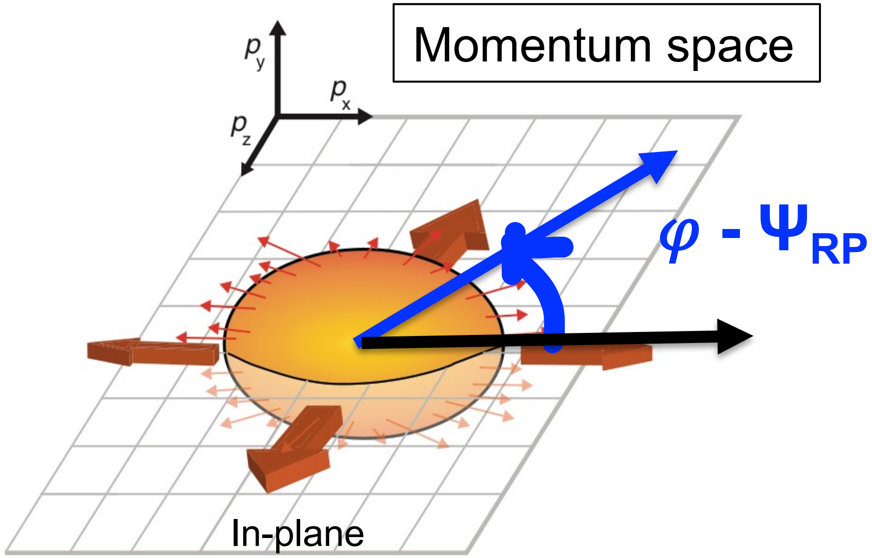


Pressure gradients develop → more and faster particles along the reaction plane than out-of-plane

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**

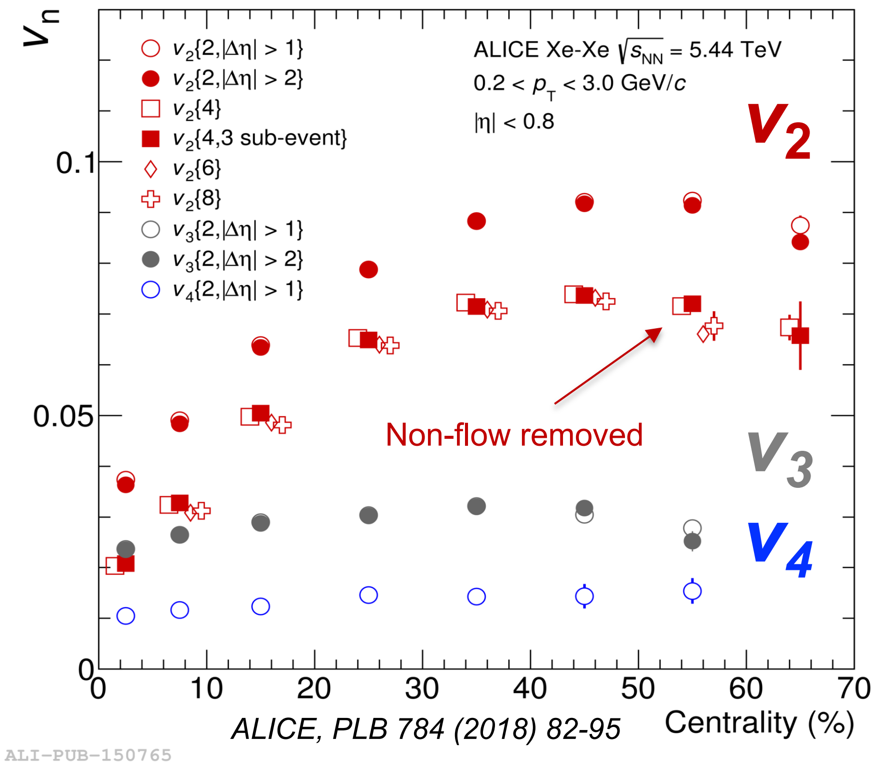
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right),$$



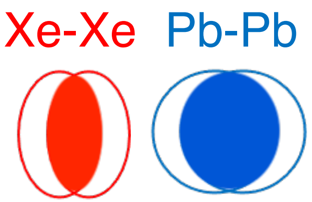
Hydrodynamics at play: anisotropic flow (2/2)

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



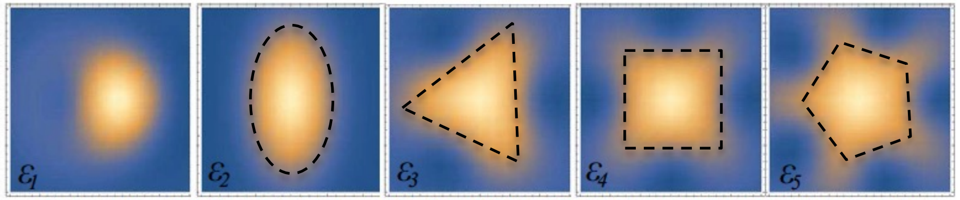
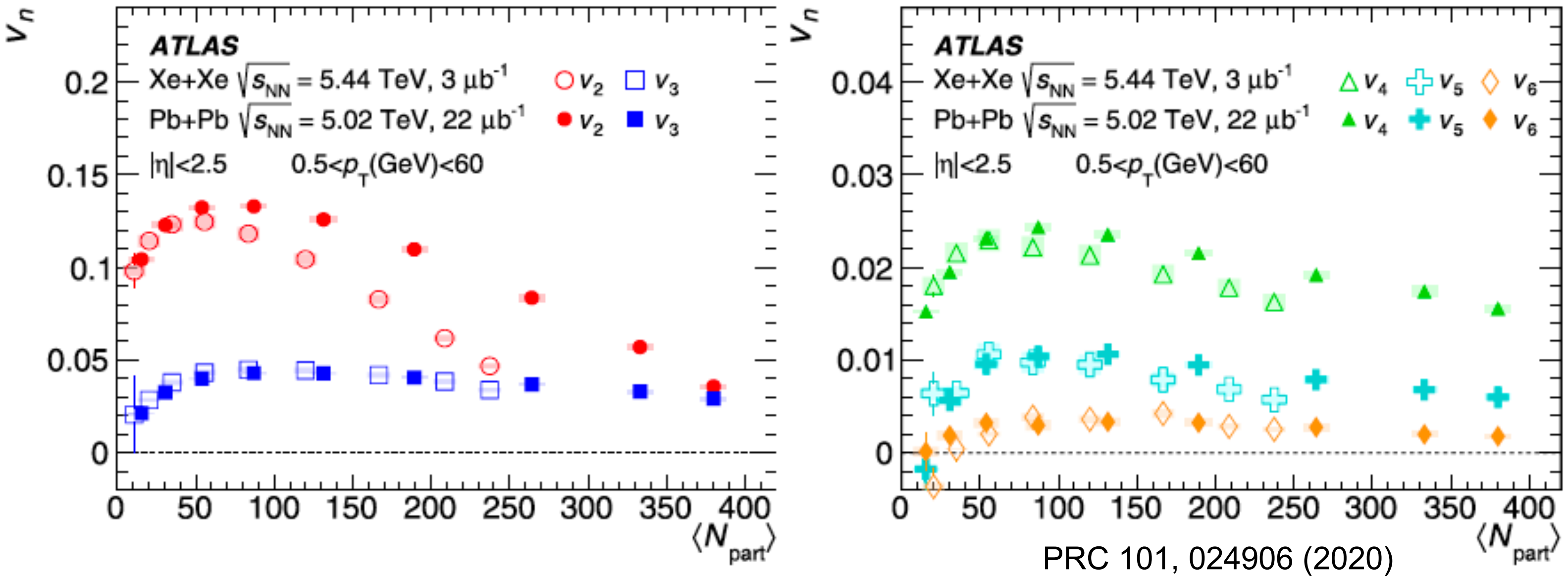


Fig. 2. (color online) Characteristic shapes of the deformed initial state density profile, corresponding to anisotropies of $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, $\mathcal{E}_4$ and $\mathcal{E}_5$ (from left to right).

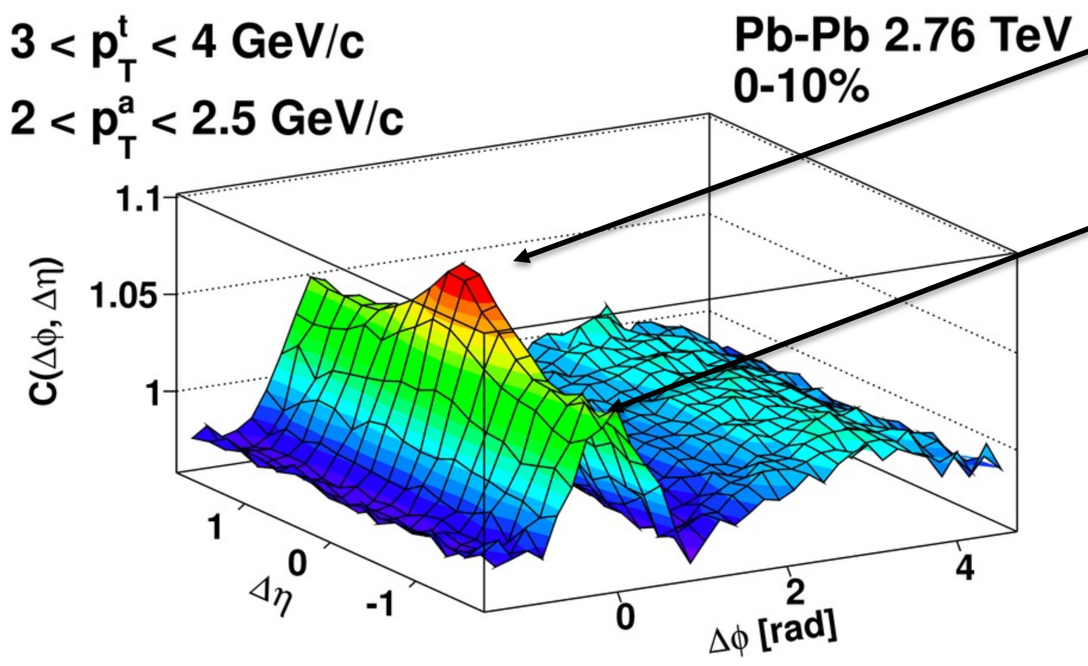
Li Yan 2018 Chin. Phys. C 42 042001



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**

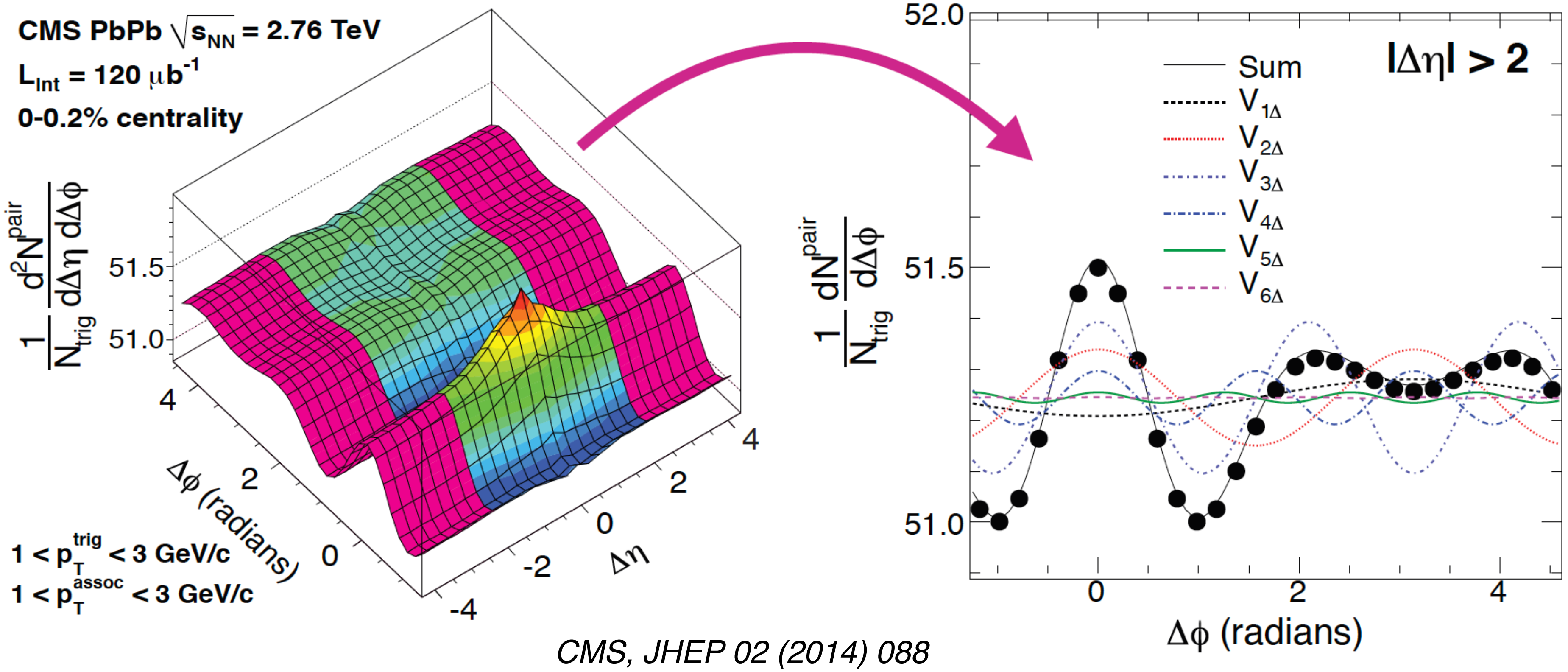
Broad **"ridge"** in a wide $\Delta\eta$ range:
long-range correlations emerging from early times (causality) → **anisotropic flow**

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

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

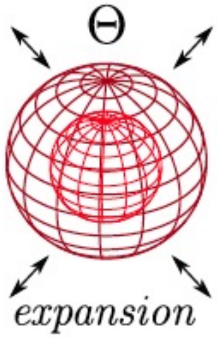
- applies to a system in local equilibrium (e.g. thermodynamical)
- requires energy and charge conservation
- system is described by energy density ε, pressure P, velocity u^ν, and charge n and by 5 equation of motion, closed by one equation-of-state (EOS) $\varepsilon = \varepsilon(P)$
- The response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

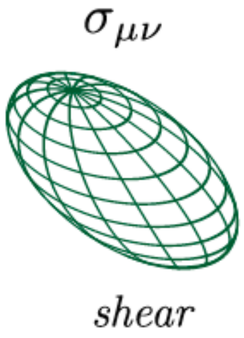
Viscous hydrodynamics

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

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

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



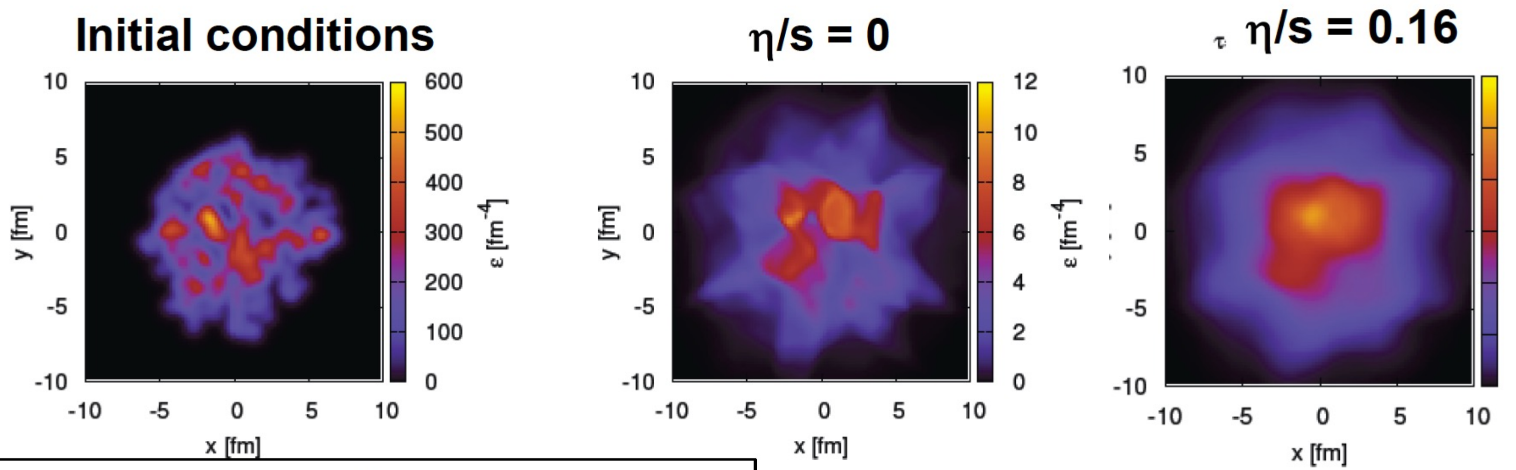


Figs. from Rezzolla and Zanotti, 2013

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

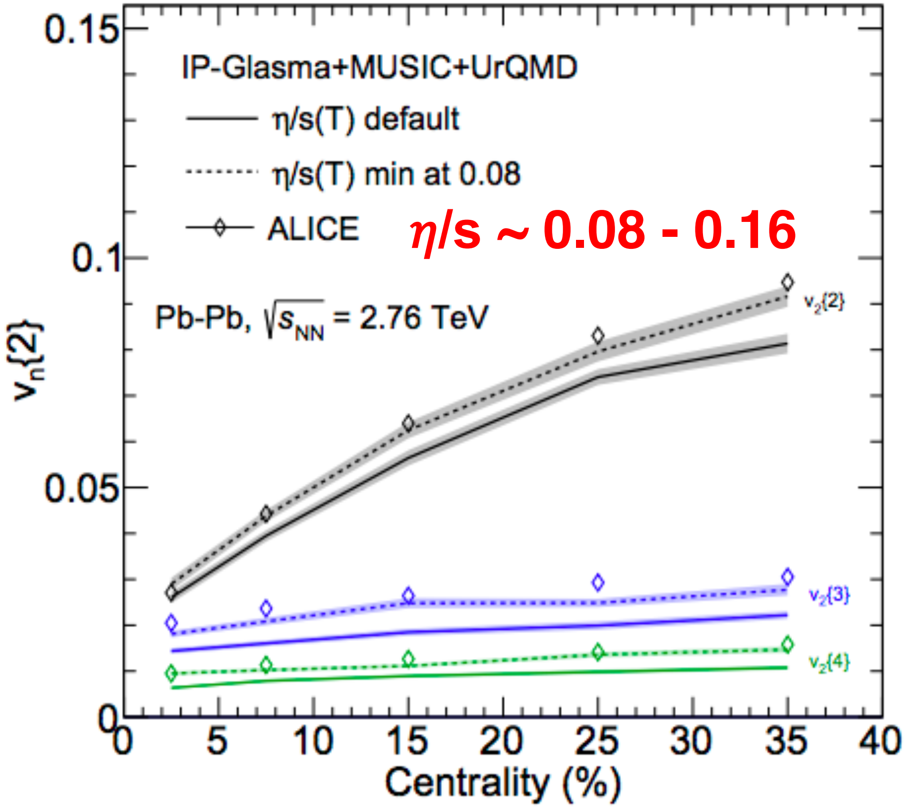


Water: η/s ~ 30 | Olive oil η/s ~ 240

MUSIC, Sangyo

Larger η/s reduces flow

Elliptic flow vs viscous hydro model

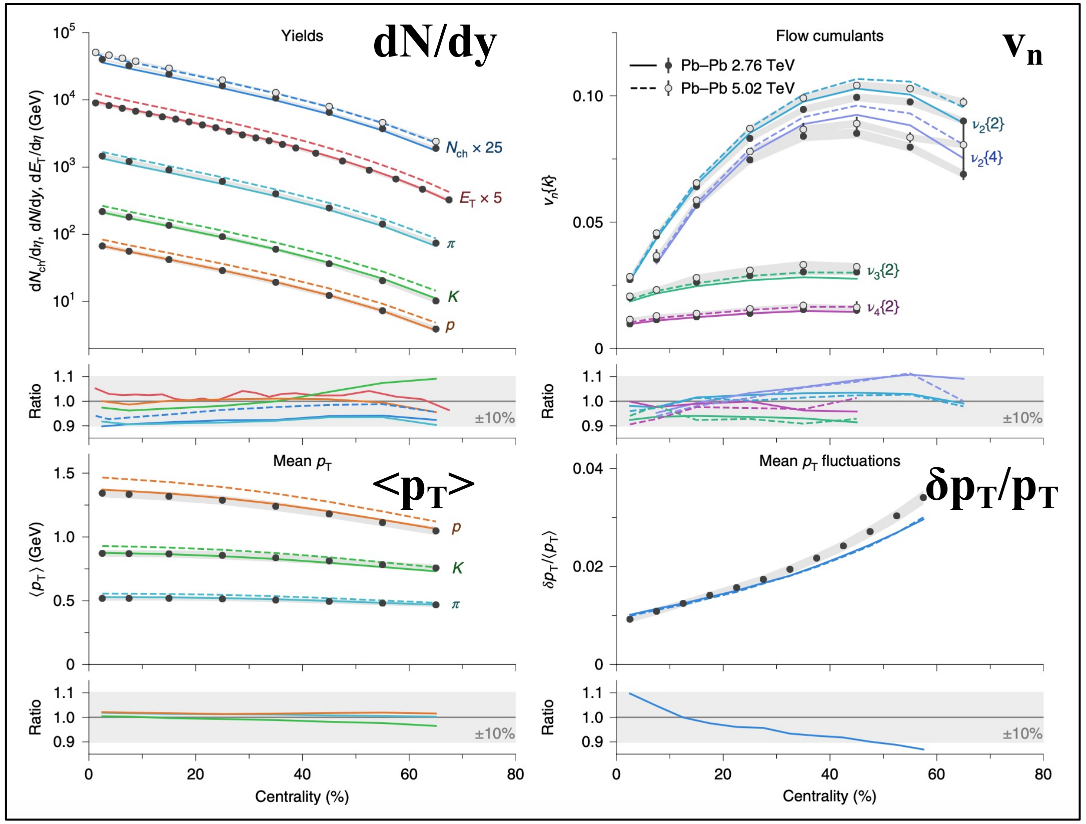


Kovtun, Son, and Starinets

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

QGP properties from flow 1/2

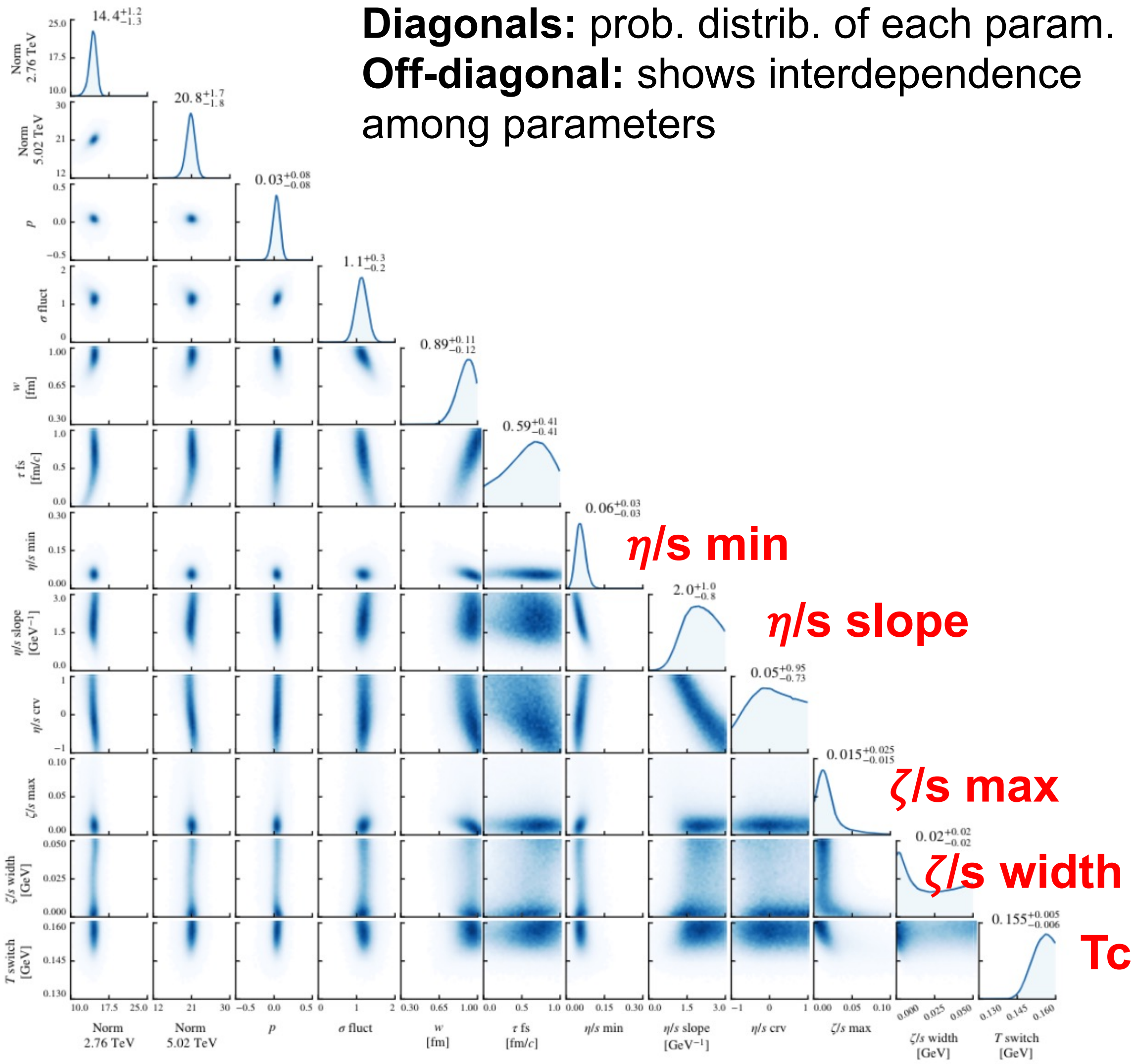
Bayesian analysis of yields, mean p_T, flow harmonics measured by ALICE has been used to extract the QGP properties.



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

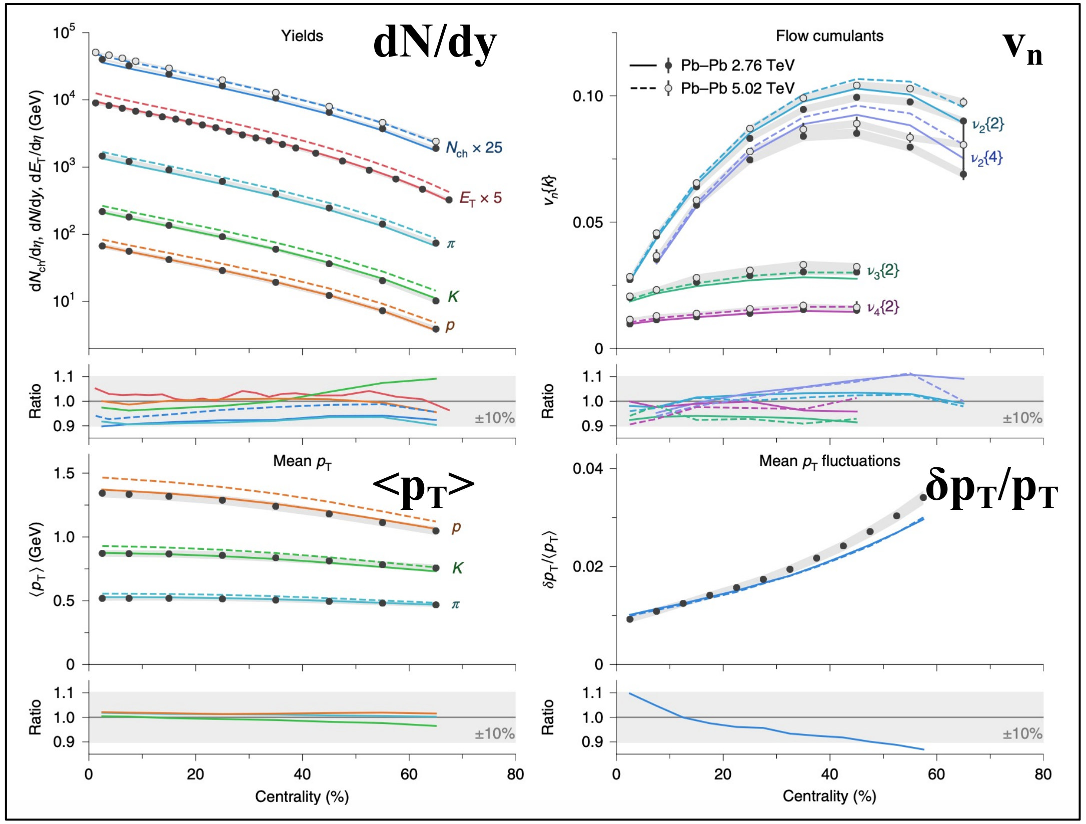
S.A. Bass et al. / Nuclear Physics A 967 (2017) 67–73

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

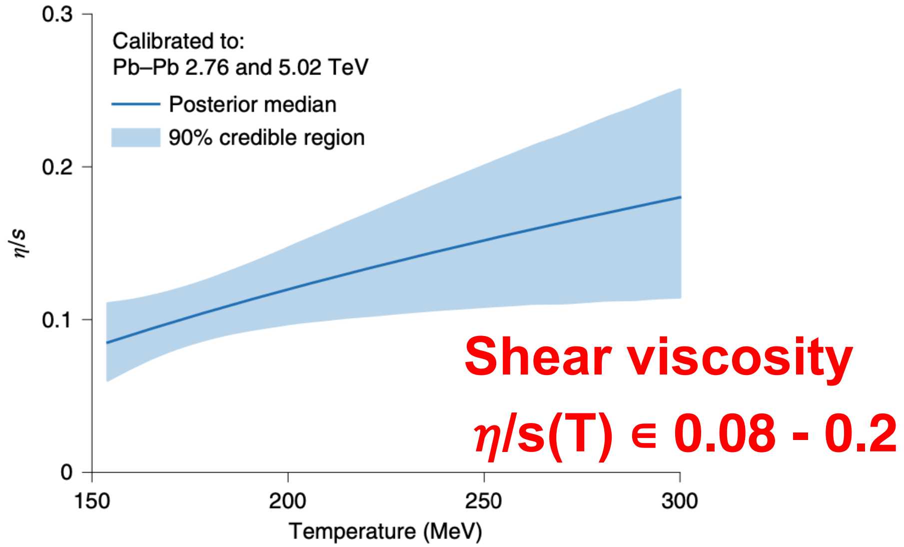


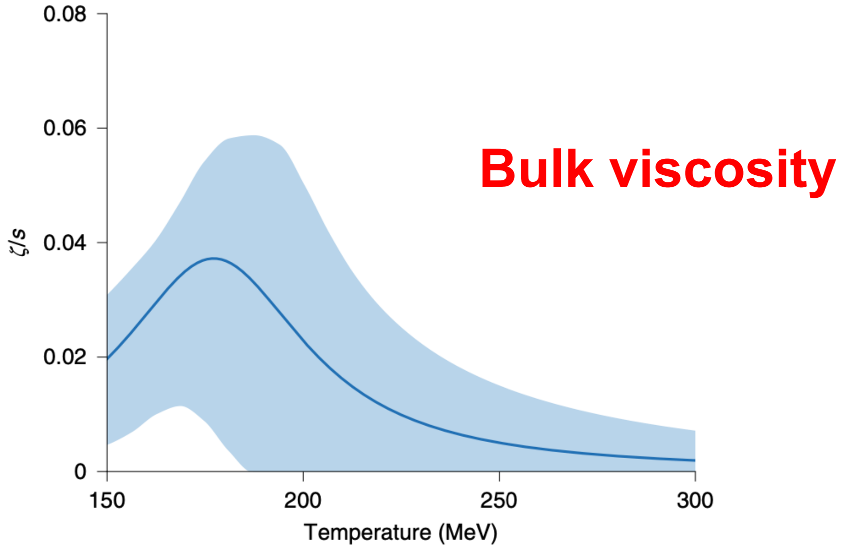
QGP properties from flow 2/2

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





Take home 3/4

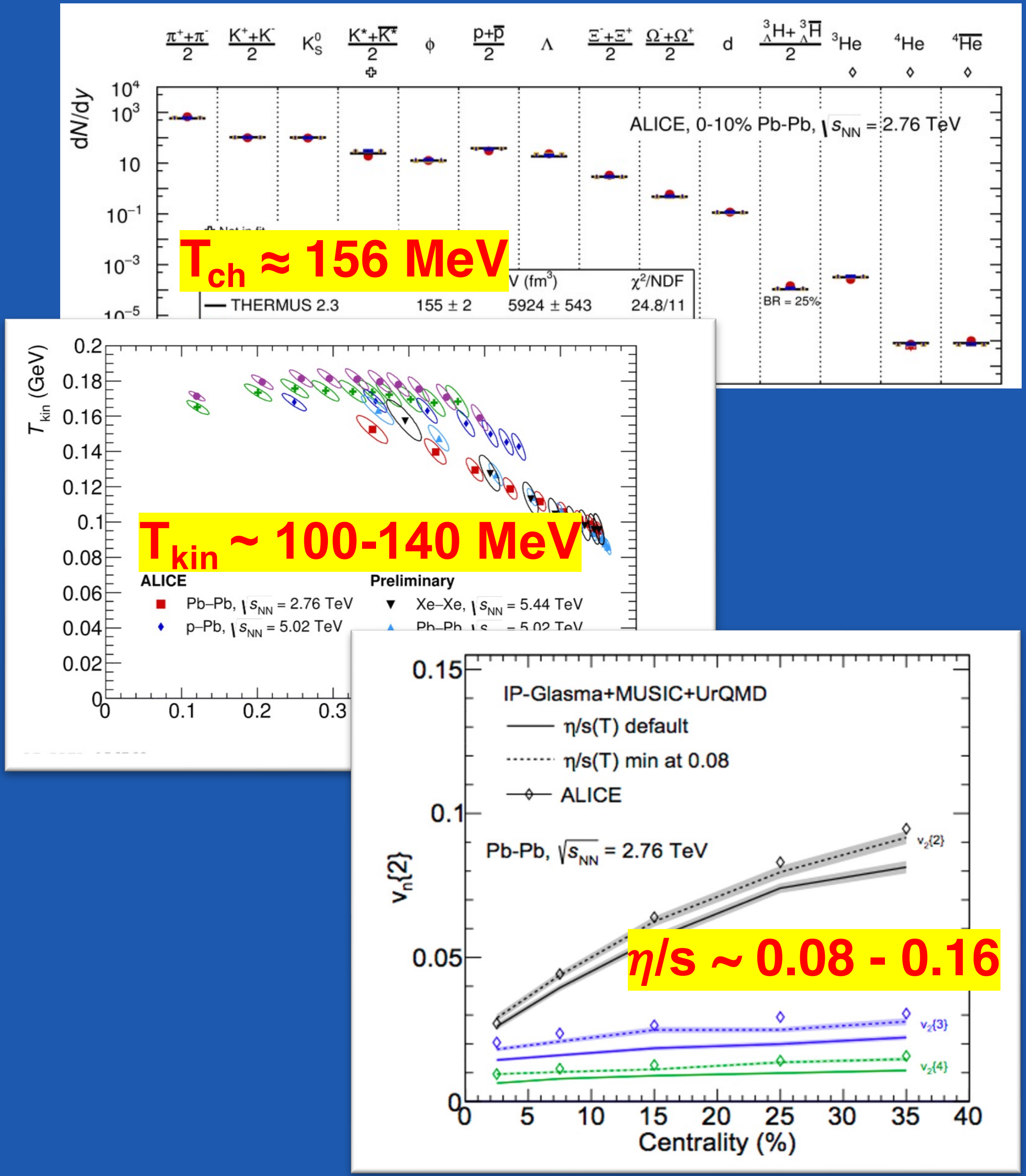
Bulk particle abundances are described by the statistical hadronization model assuming chemical equilibrium and with **Tch ~ 156 MeV**

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

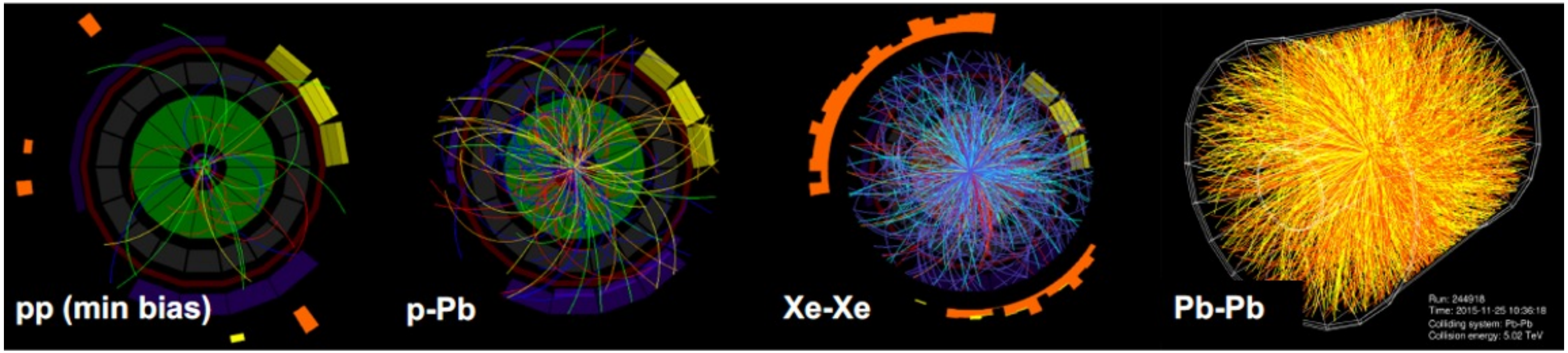
Spatial anisotropy of the initial collision region causes **anisotropic flow**.

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.**



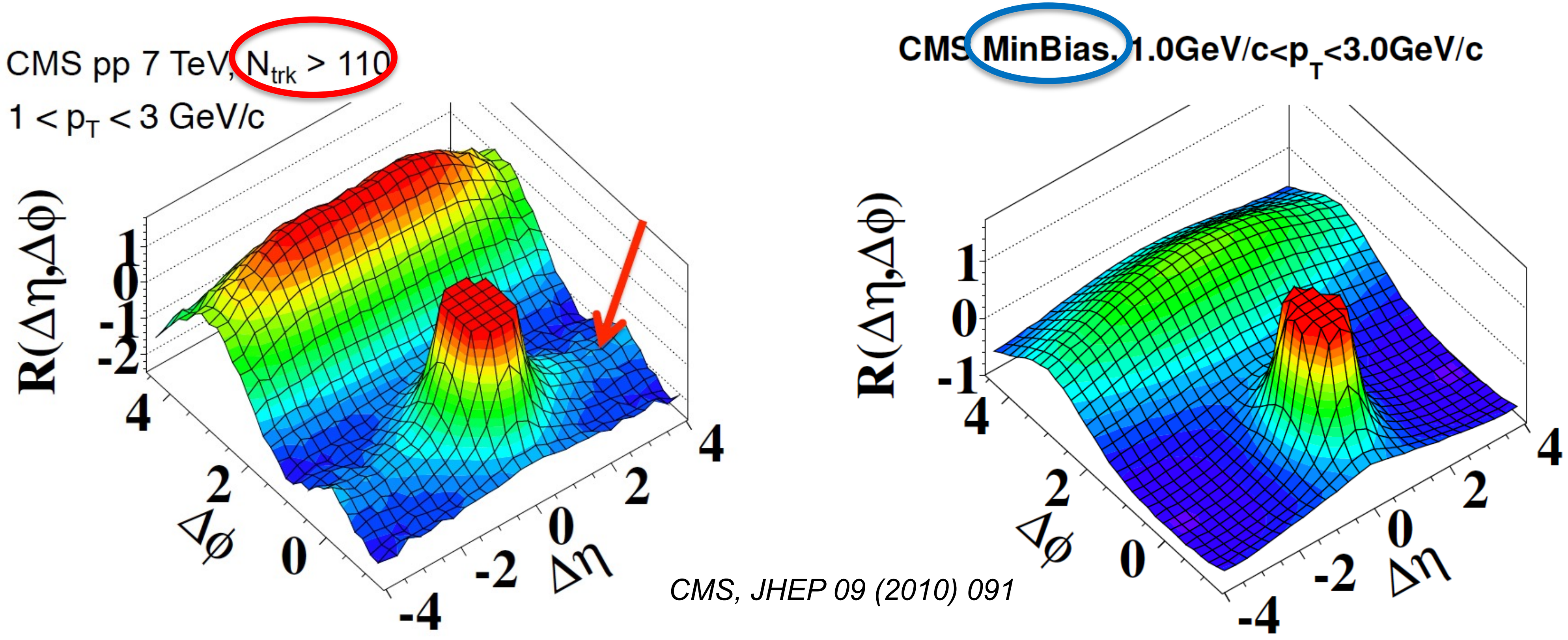
Can we produce a QGP also in pp collisions?



Discovery of collectivity in small systems

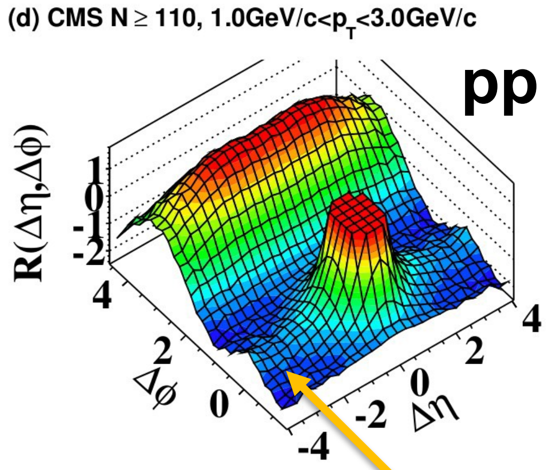
The first indication of the presence of collective phenomena in high-multiplicity pp collisions came from the study of two-particle correlations vs $\Delta\eta$ and $\Delta\varphi$.

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.

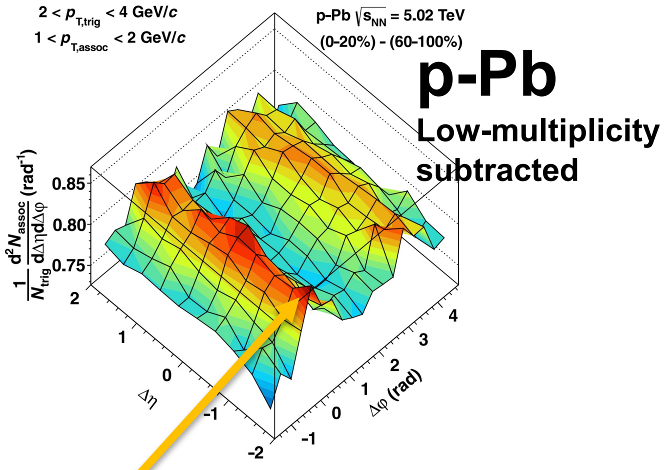


CMS, JHEP 09 (2010) 091

The “ridge” in pp, p-Pb collisions

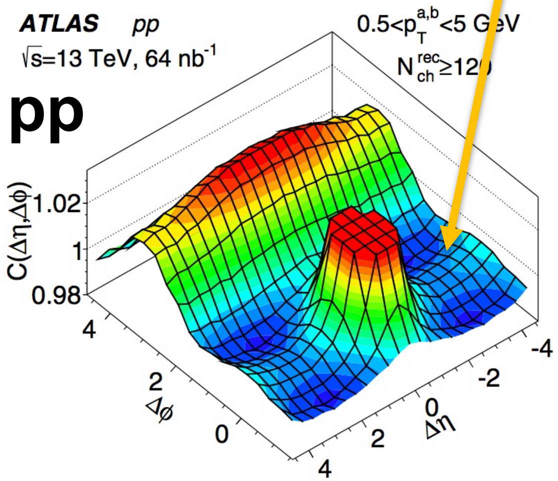


CMS, JHEP 09 (2010) 091

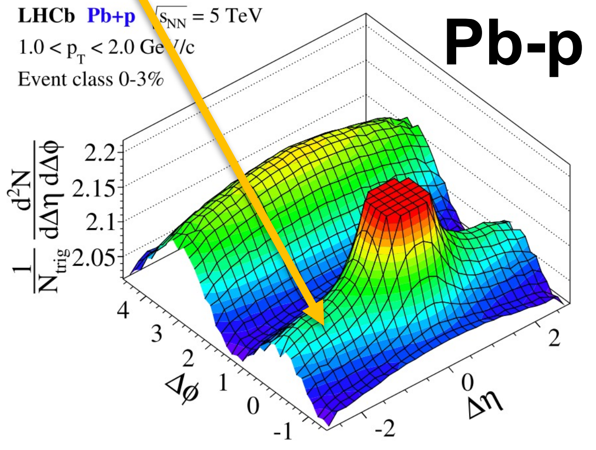


ALICE, PLB 719 (2013) 29

Near side ridge



ATLAS, PRC 96, (2017) 024908



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

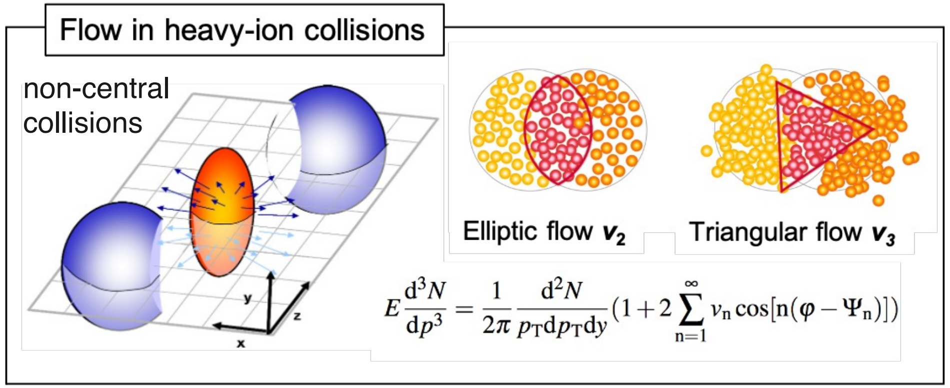
Elliptic flow from multi-particle correlations:

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

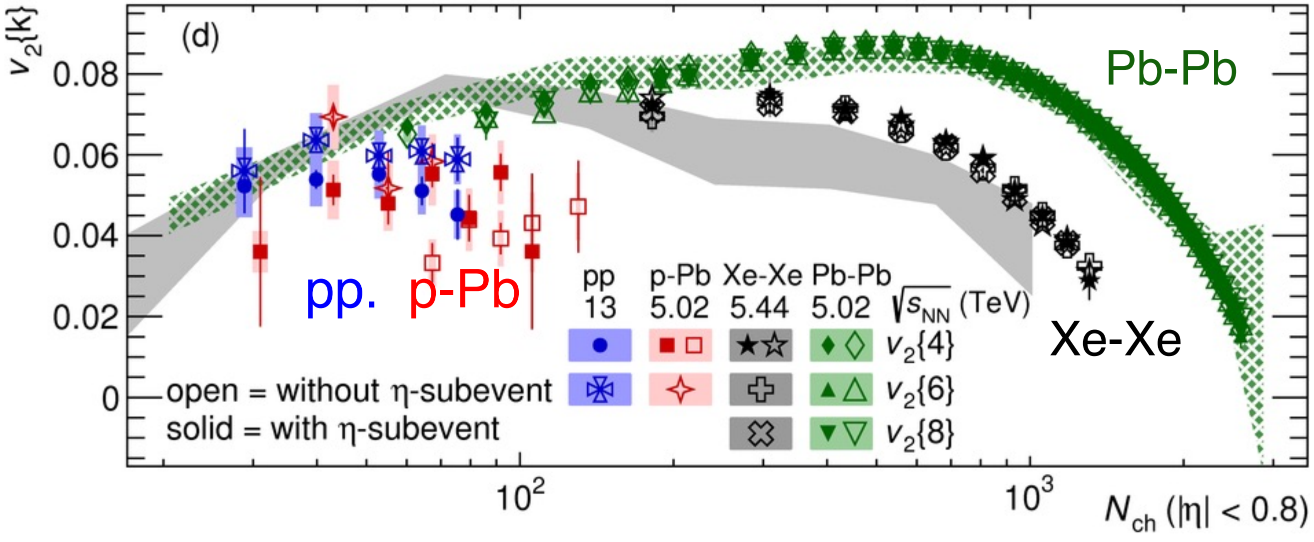
- subtract jets and other physical 2-particle correlations due to non-flow
- measure with rapidity gap

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?**



Elliptic flow from multi-particle correlations in all systems



PRL 123, 142301 (2019)

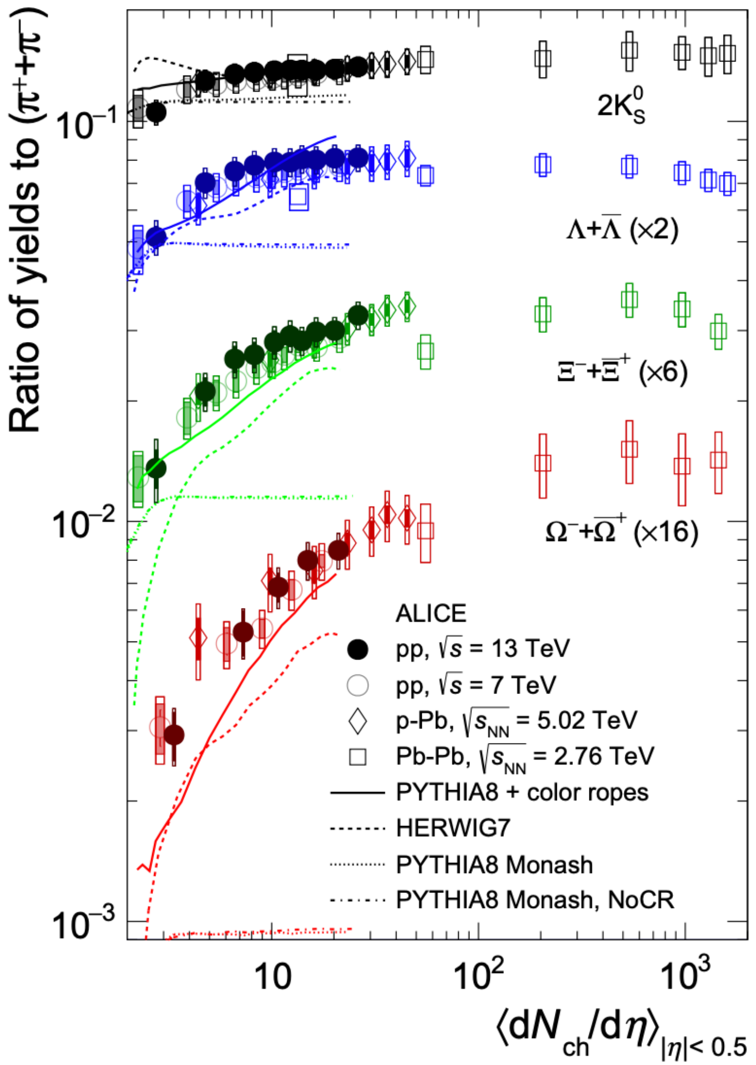
Chemistry from small to large systems

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

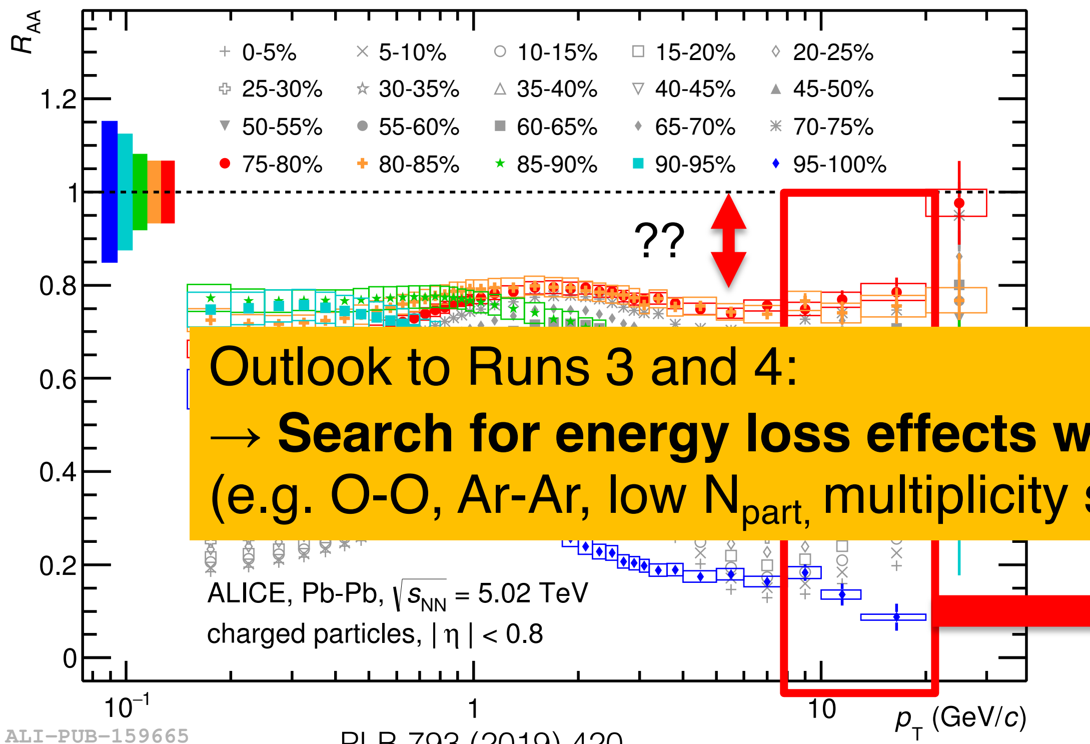
No energy loss in small systems?

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!**

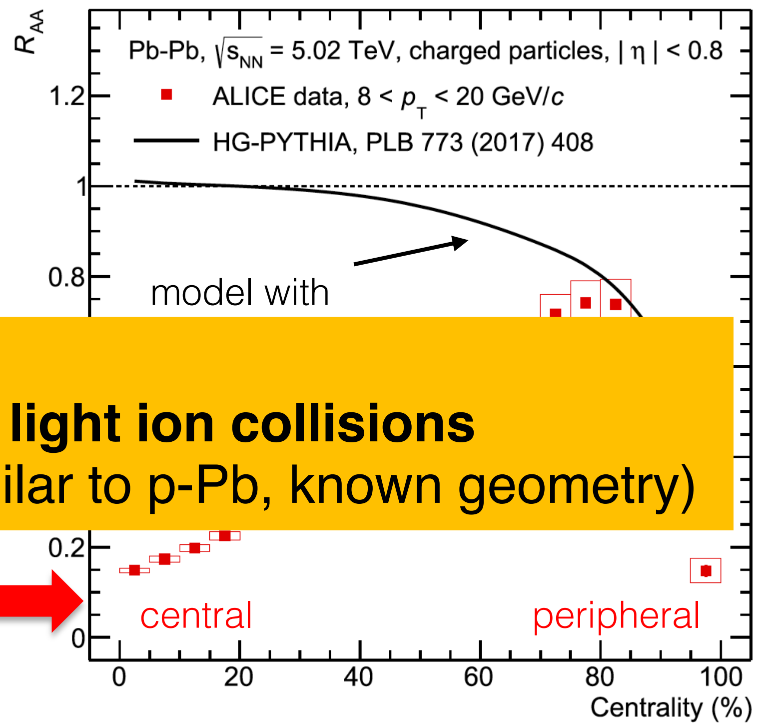
OPEN QUESTION: when (which system "size") does energy loss sets in?

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)

Take home 3/4

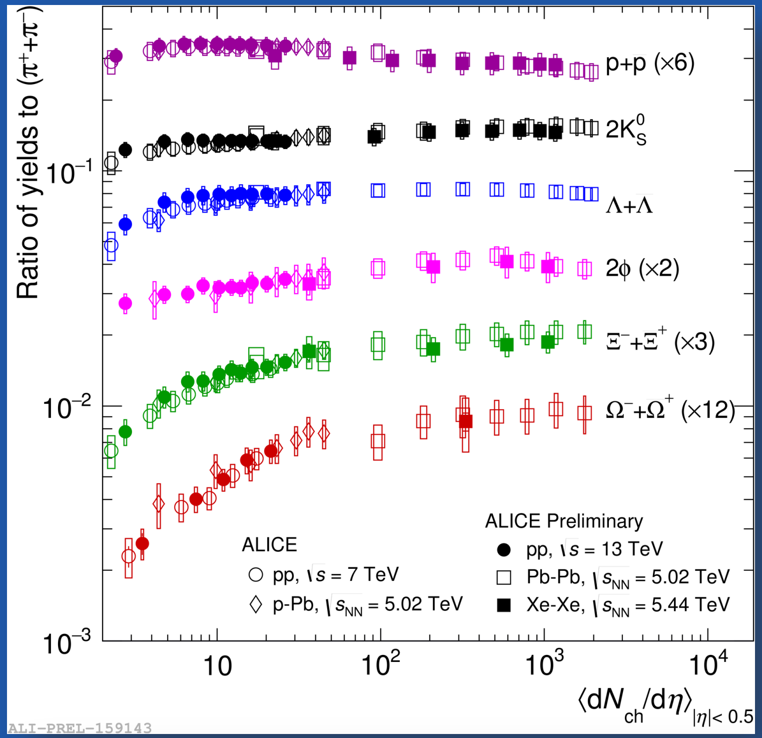
Soft probes probe the bulk of the system as a whole.

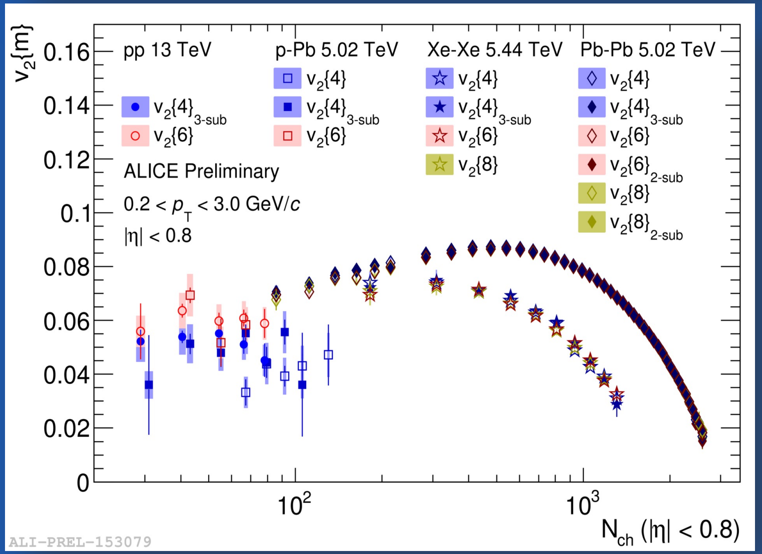
Particle chemistry:

- continuity observed across collision systems
- depends on charged particle multiplicity
- Strangeness production in enhanced in presence of a QGP in AA collisions
- In small systems, strangeness enhancement observed with increasing multiplicity

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.





Summary and outlook - take home 4/4

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?

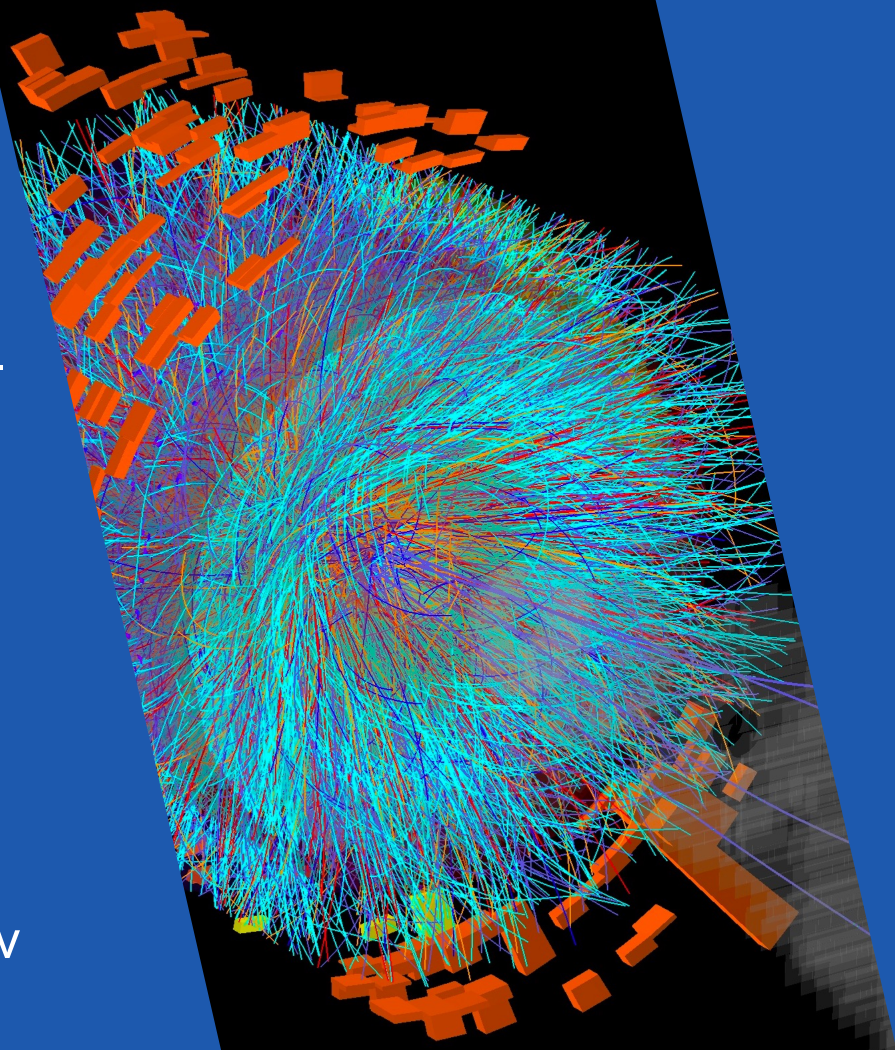
Big progress towards a quantitative characterisation of the properties of the QGP with still open questions to be addressed in Run3 and beyond.

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!

What’s next?

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

Recall: Heavy-ion physics 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

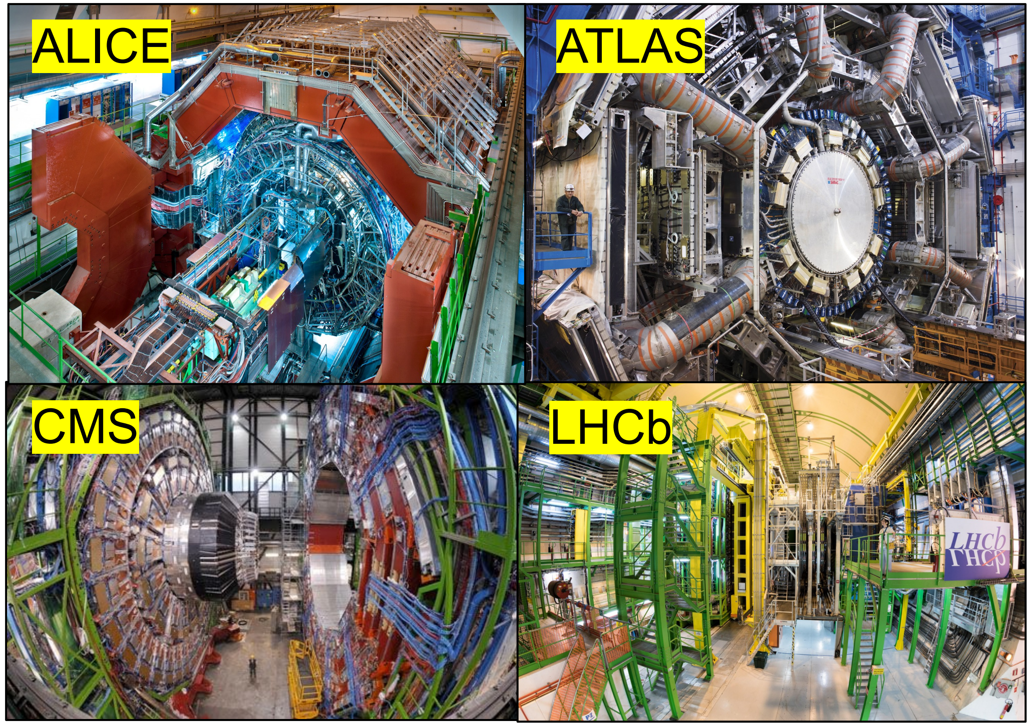
High luminosity LHC

Major upgrades for **ALICE and LHCb**

We are here

ATLAS and CMS phase II
ALICE ITS3 and FoCal

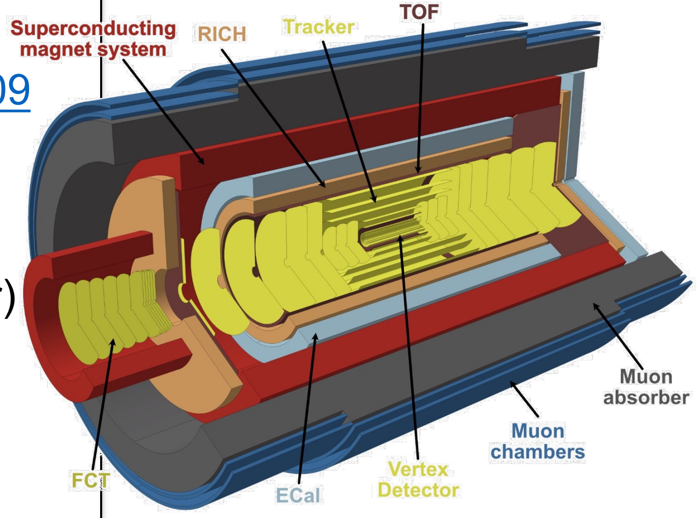
ALICE 3: a whole new dedicated HI detector!
LHCb upgrade II



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



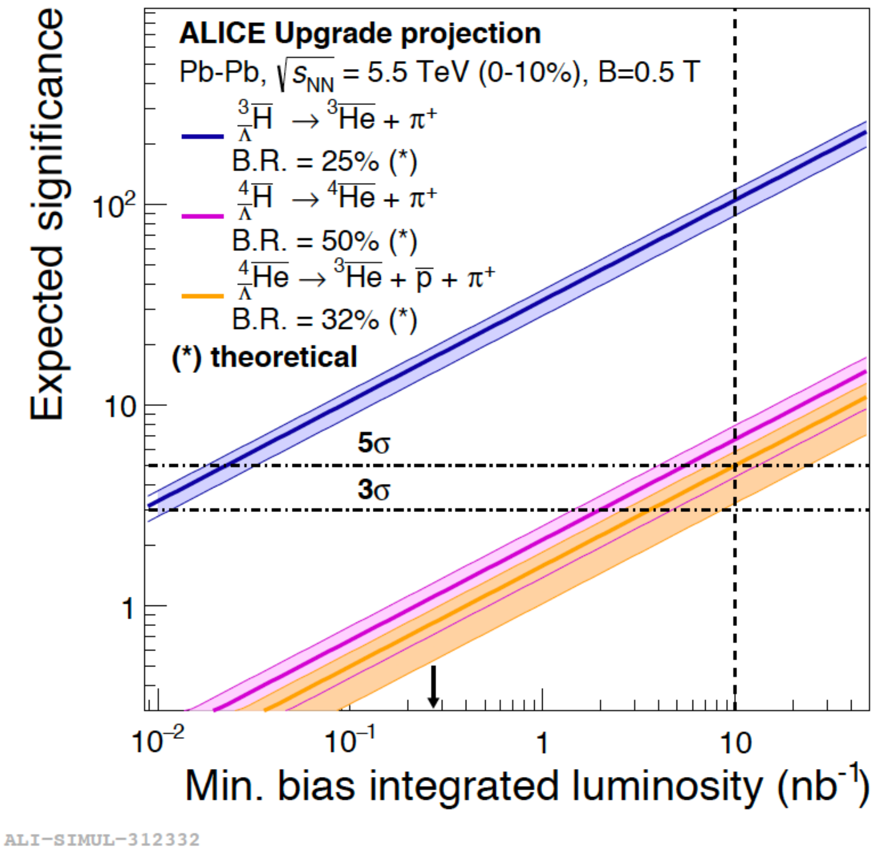
Runs 3+4 - Nuclei and small systems

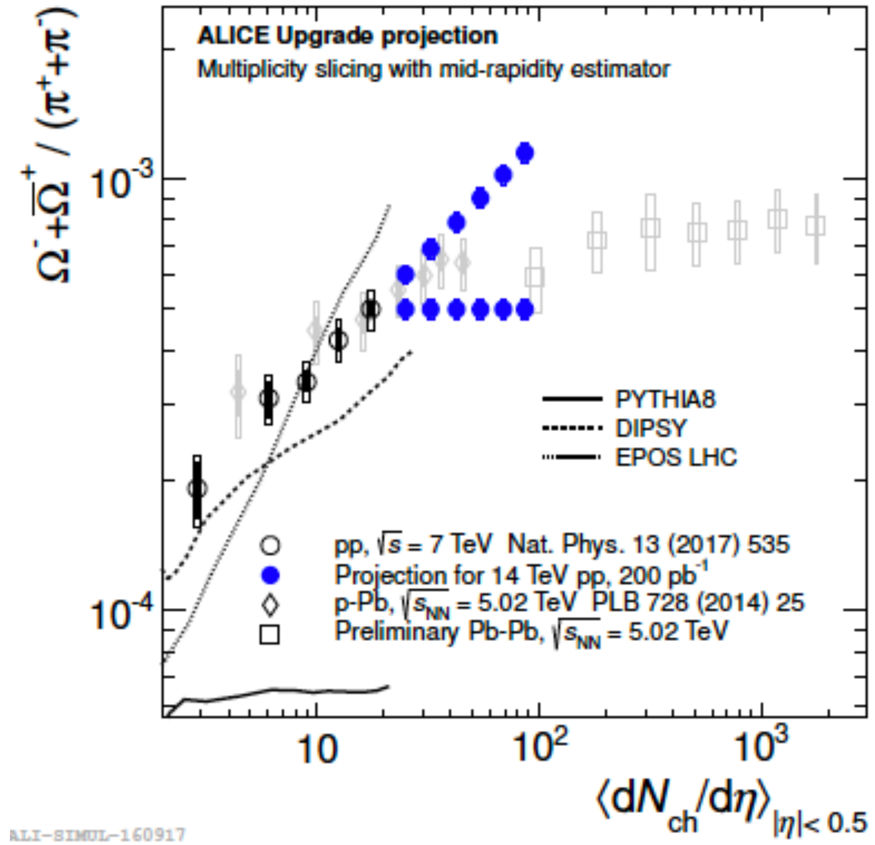
(anti-)nuclei and (anti-)(hyper-)nuclei up to A = 4

- 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

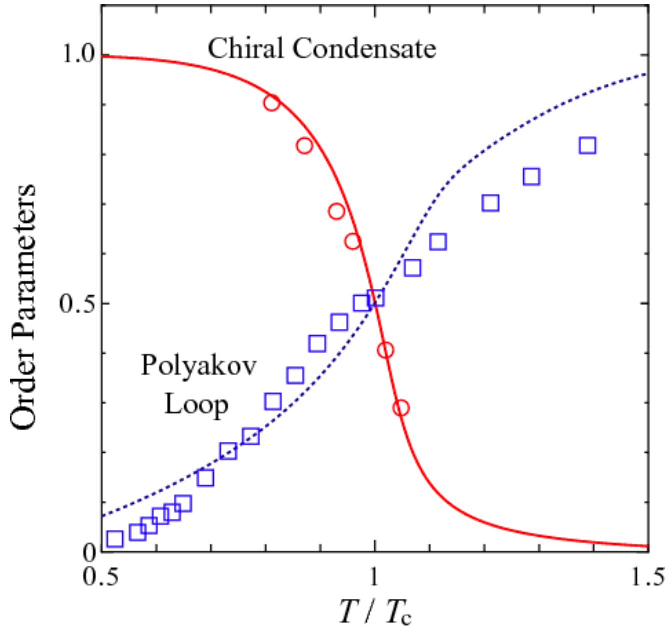
- Investigate the onset of QGP like features



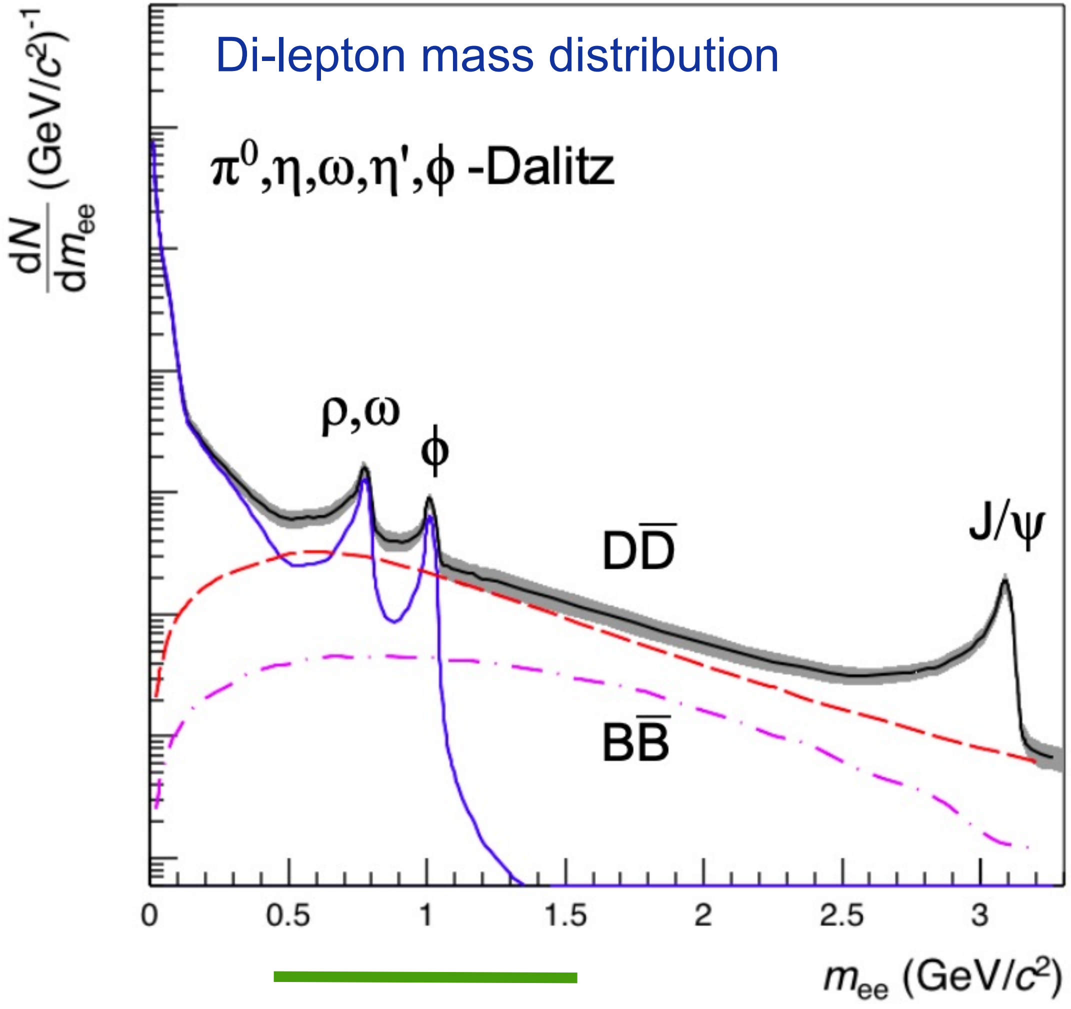


Runs 3+4 – Dileptons and chiral symmetry

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-a1 mixing

Runs 3+4 – Dileptons and early QGP temperature

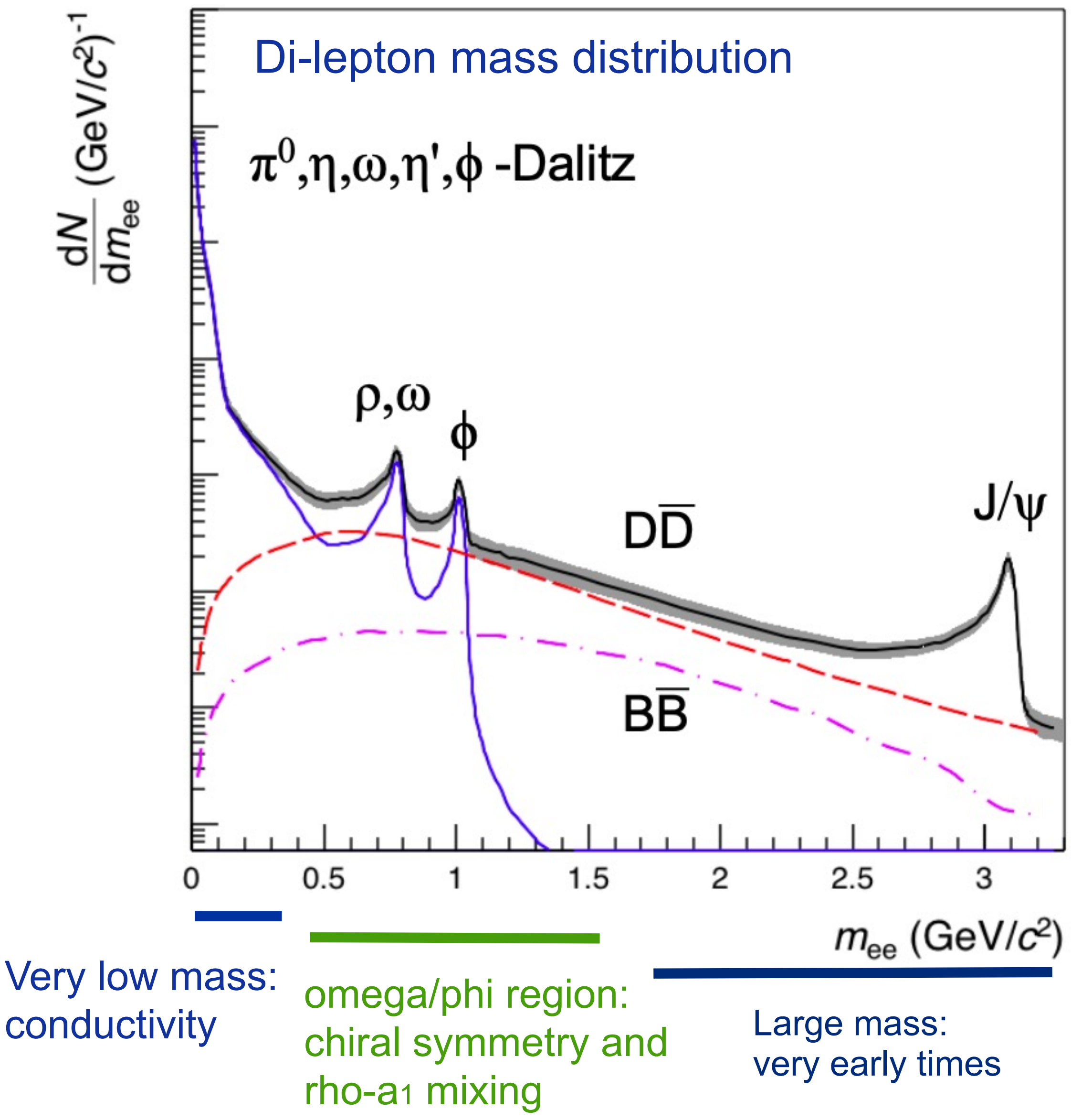
Measurements of dilepton spectrum:

→ **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



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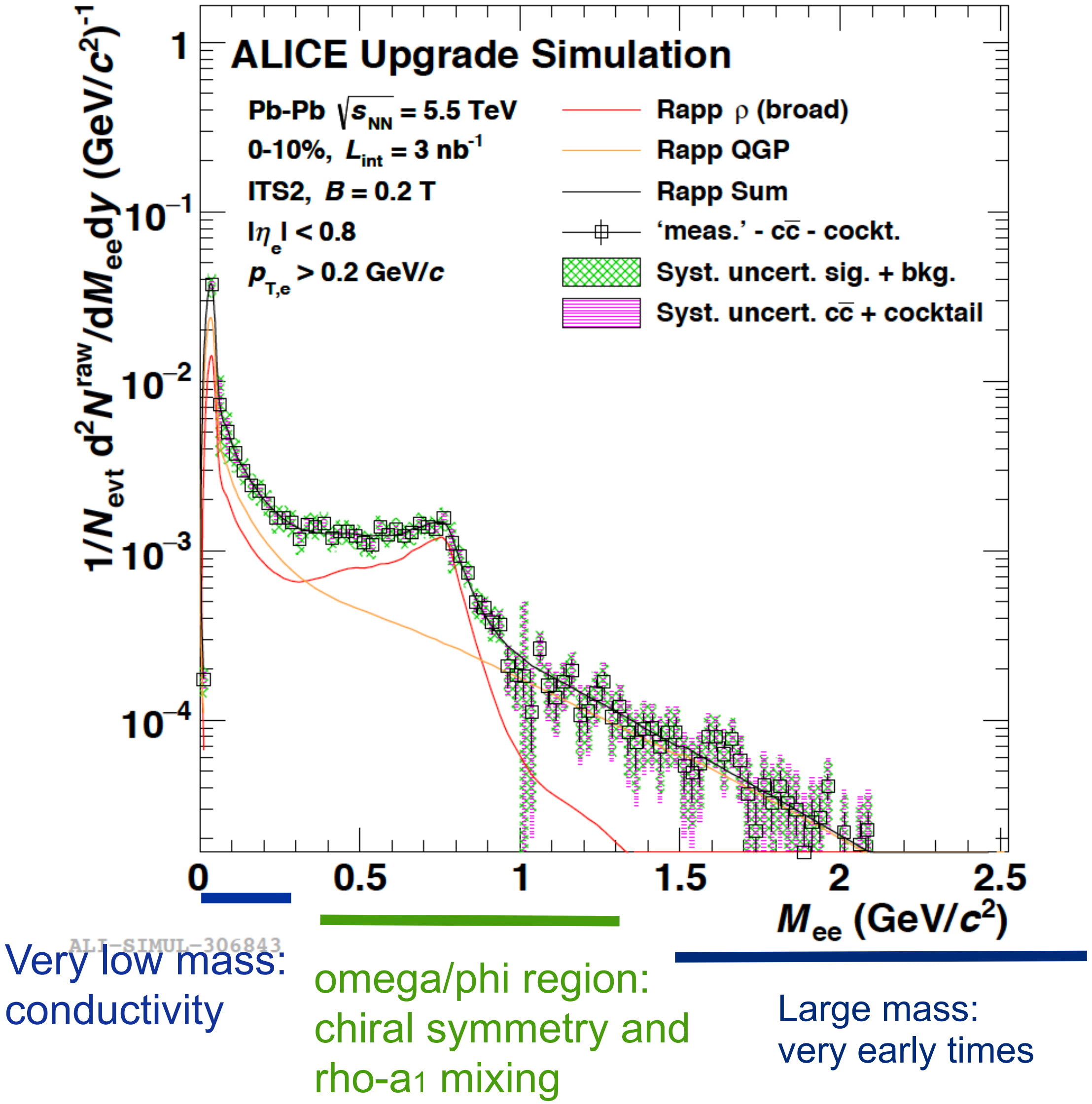


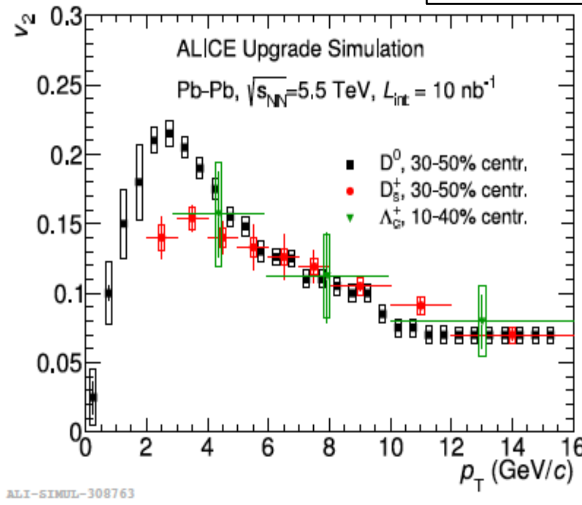
Runs 3+4 - More charm

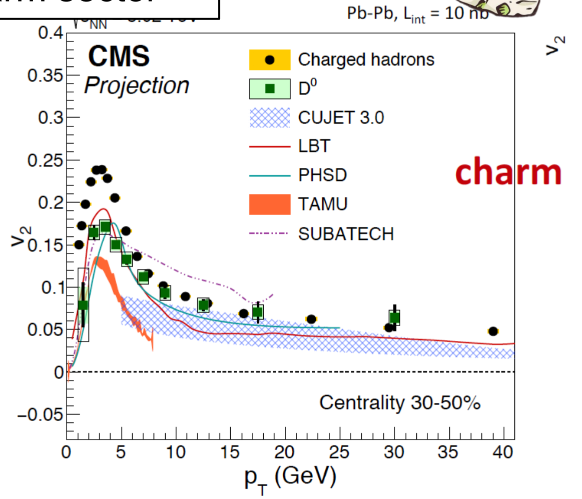
Higher precision for rarer probes in the HF sector

- 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)

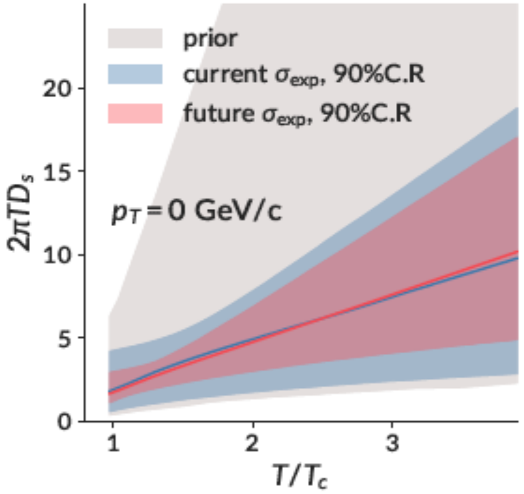
→ Study mass dependence of **energy loss**, in-medium **thermalization** of heavy-flavours
→ Access to the **medium transport properties,** e.g. charm diffusion coefficient

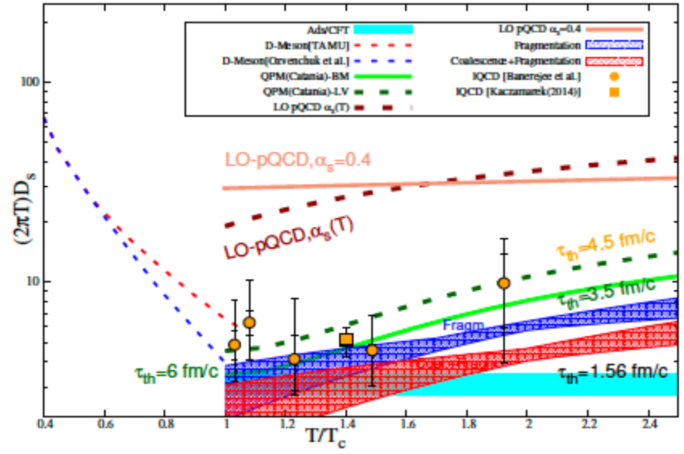
v_2 in charm sector





Projections for extraction of charm diffusion coefficient





Runs 3+4 - More beauty

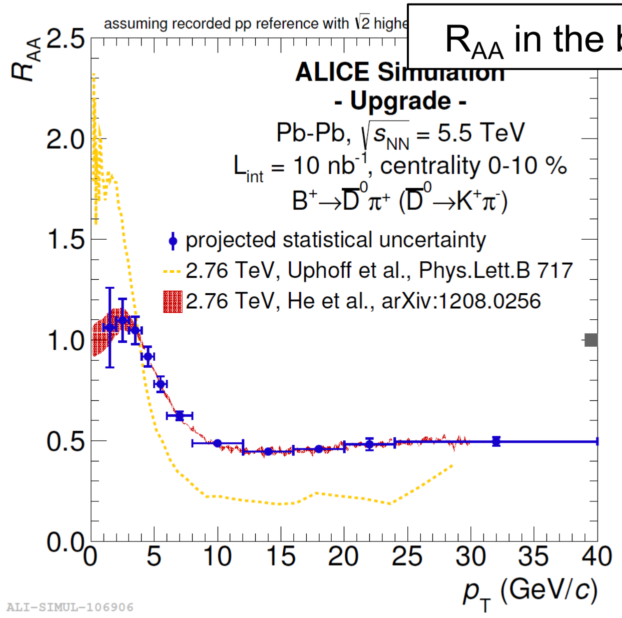
Higher precision for rarer probes in the HF sector

- 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

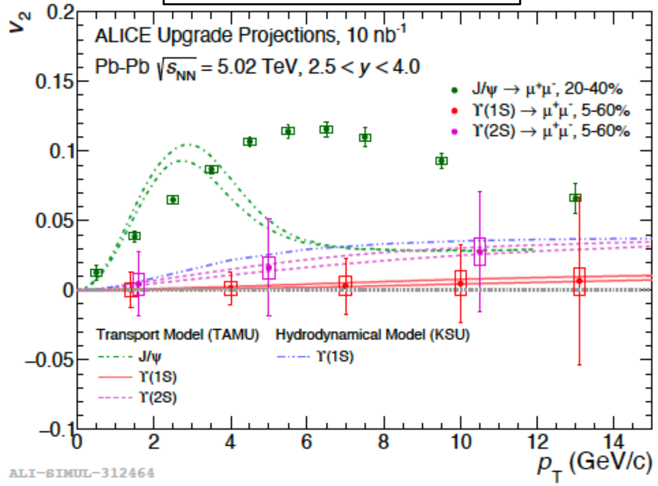
→ Access flavor-dependence of in-medium fragmentation functions with jet measurements

R_{AA} in the beauty sector

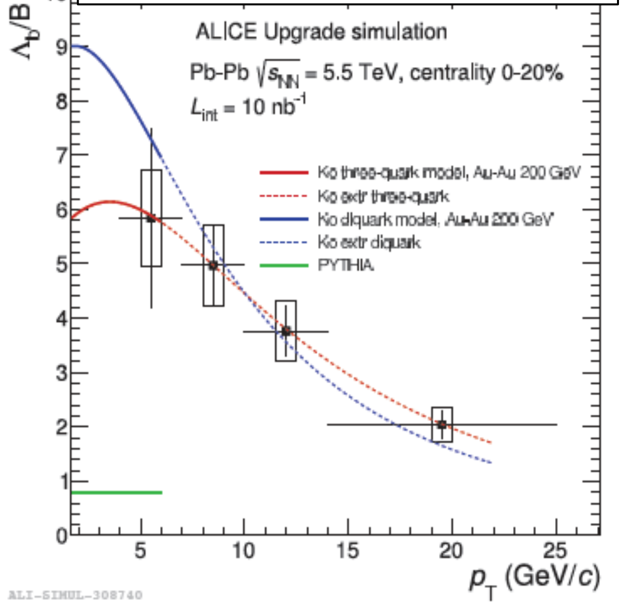


Example: $B^+ \rightarrow D^0\pi^+$ (displaced) channel down to low p_T accessible in the ALICE central barrel thanks to the upgraded ITS

v_2 in beauty sector



Baryon/meson in b sector



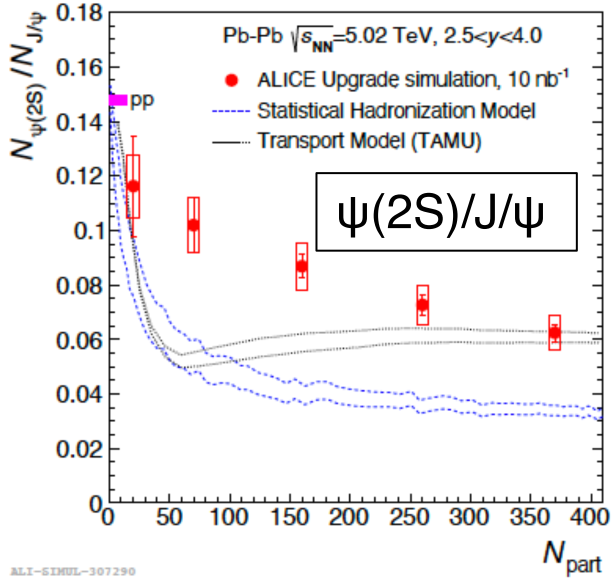
Runs 3+4 – More quarkonia

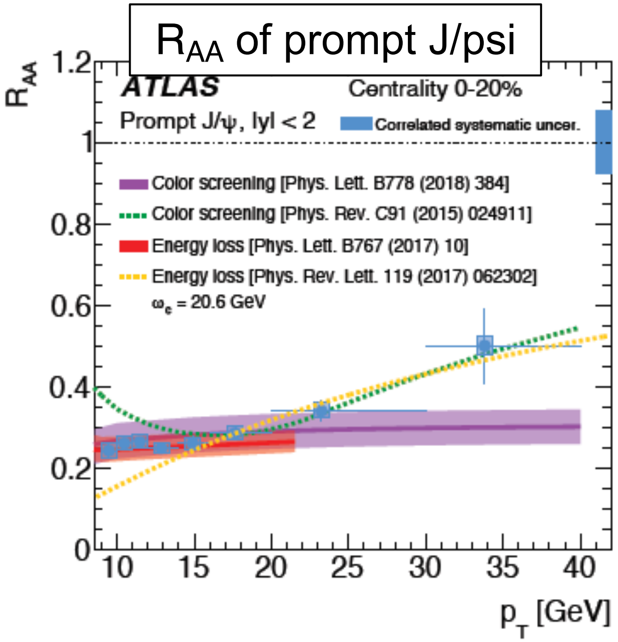
Measure charmonium and bottomonium spectrum with **increased precision**

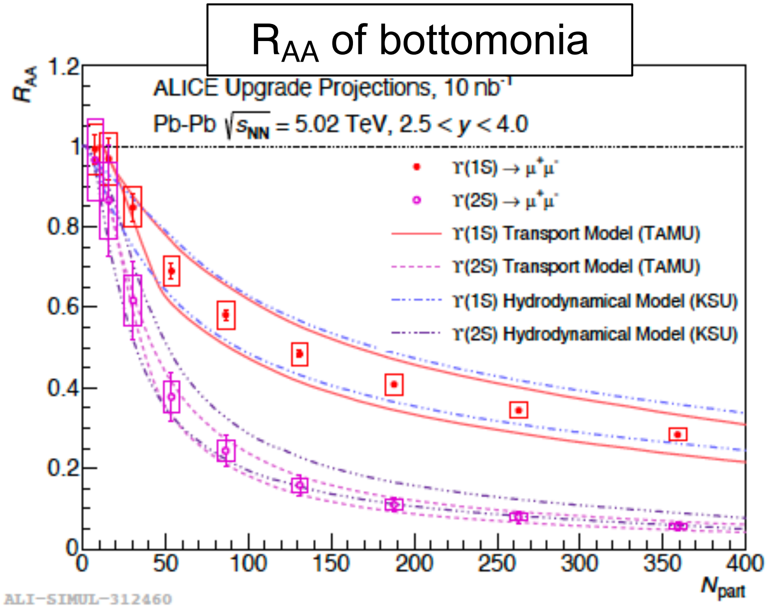
- Nuclear modification R_{AA}
- ψ(2S)/J/ψ, Υ(2S)/Υ(1S)
- explore feeddown

→ 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



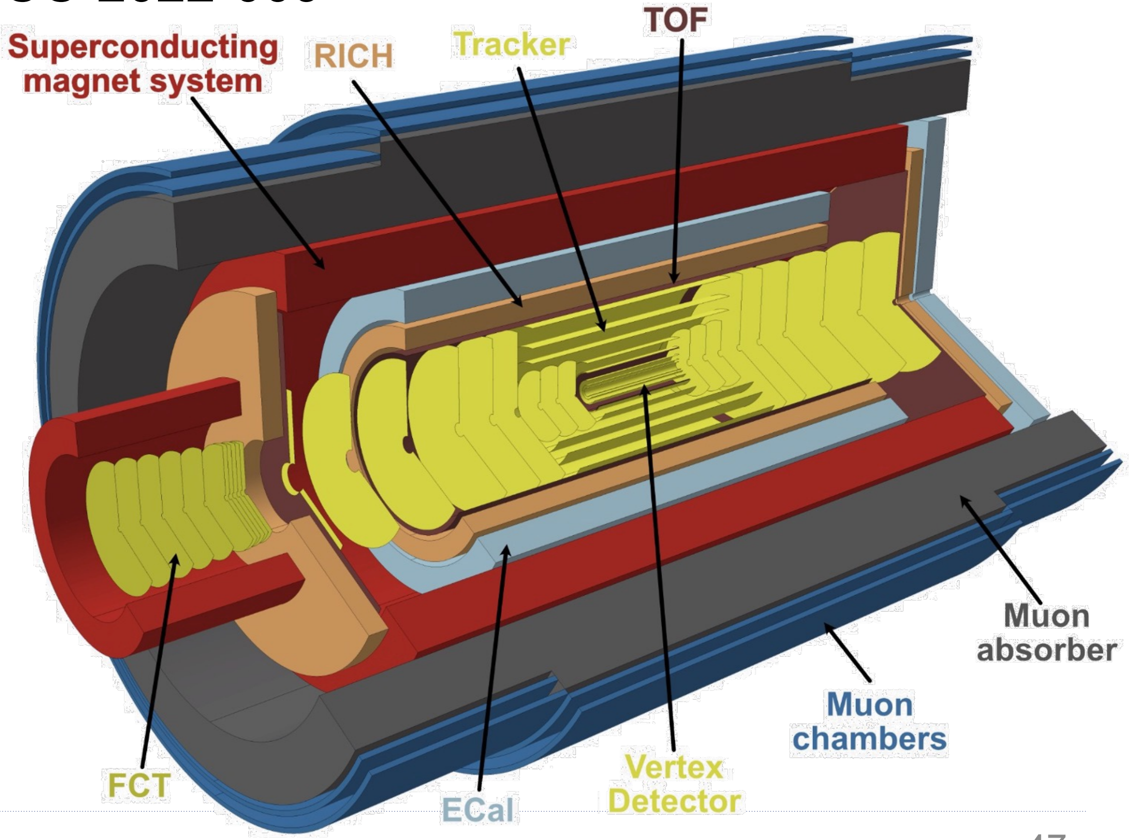




ALICE 3: a new dedicated HI experiment in Run 5 and beyond

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

ALICE 3 detector concept

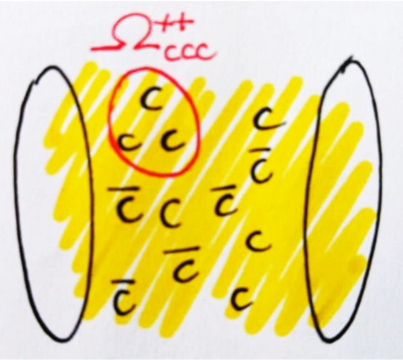


Physics from pp to Pb-Pb:
- Vertexing accuracy and tracking down to $p_T = 0$ (w/ retractable inner tracking layers)
- Particle identification
- Wide rapidity coverage
- Extreme acquisition rates for soft probes

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, χ_c, X, …

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



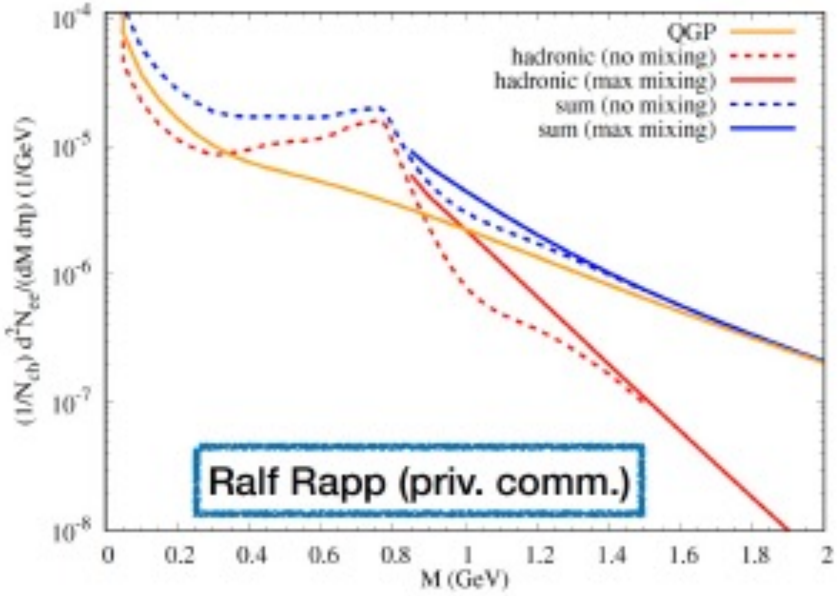
- **Dilepton radiation** from various phases of the collision

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

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

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

…and more new unique windows opened at the LHC!



Bonus material

Characteristics of a heavy-ion detector: ALICE

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

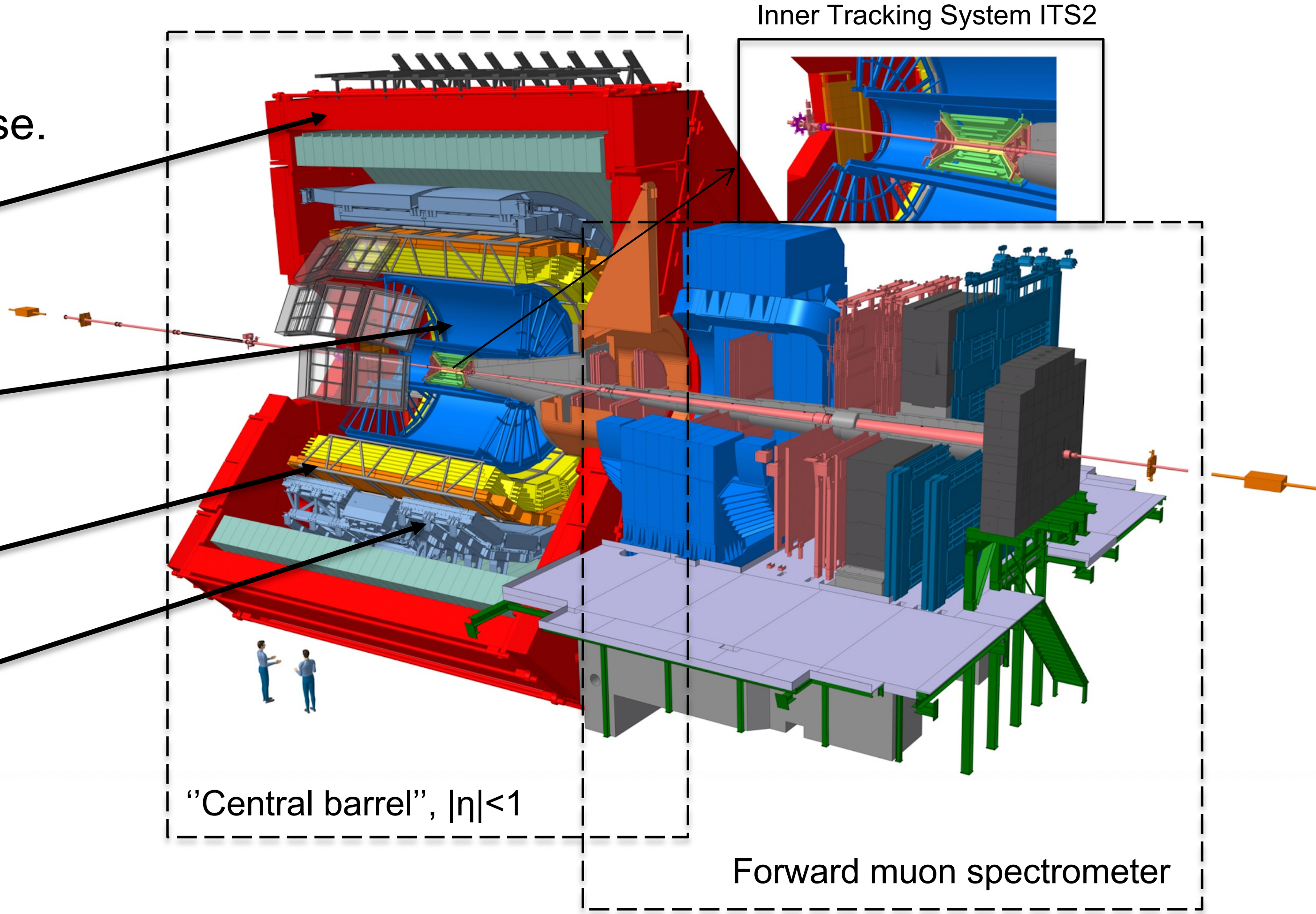
Solenoid: magnetic field B = 0.5 T

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

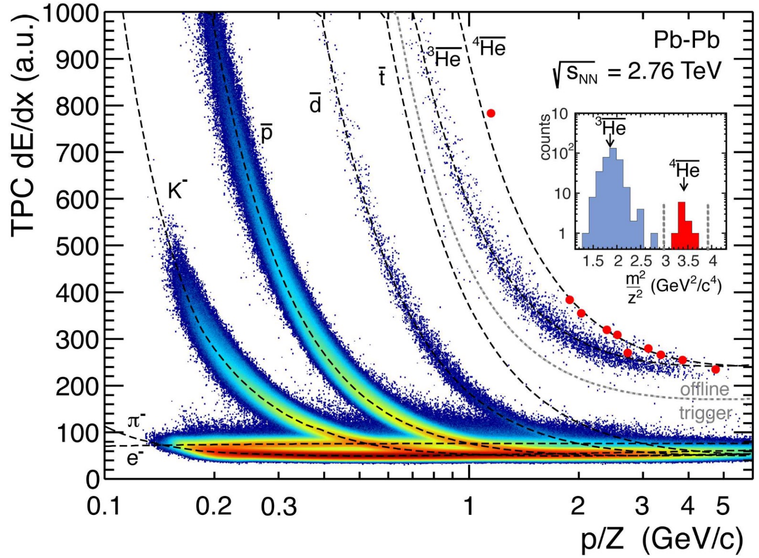
+ Forward rapidity detectors and ZDC: trigger, centrality, event time determination, …



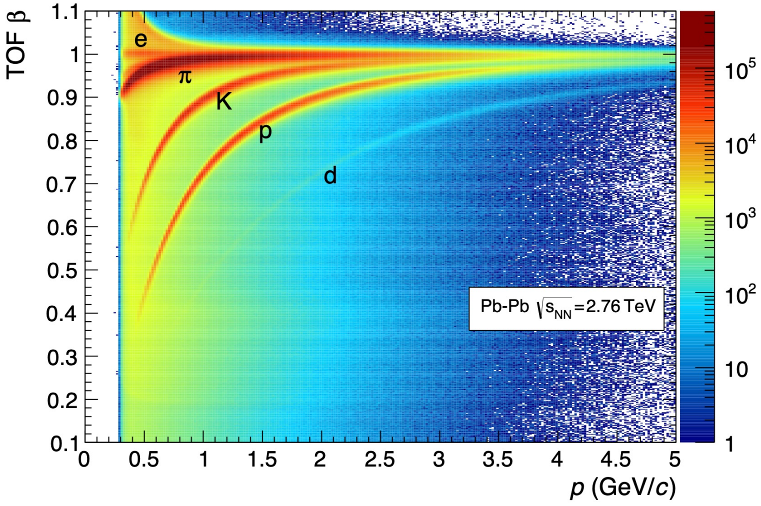
Particle identification

- 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

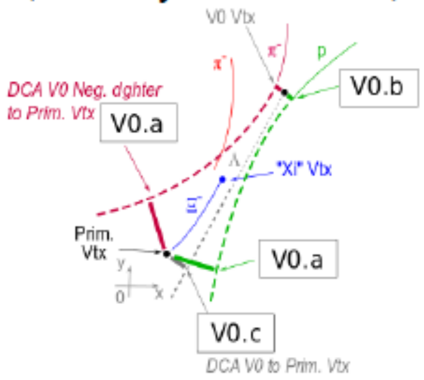
Energy loss of long lived particles in TPC



Particle velocity from TOF measurement and momentum



$\Xi \rightarrow \Lambda\pi^-$ (similarly for $\Omega \rightarrow \Lambda K^-$)



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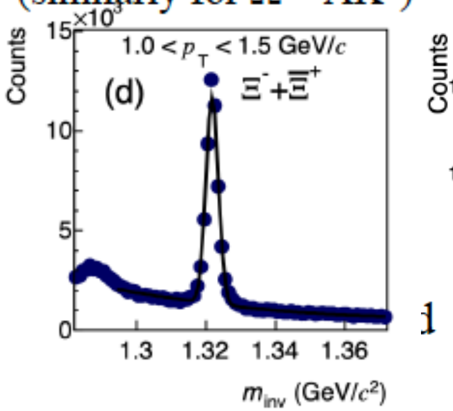
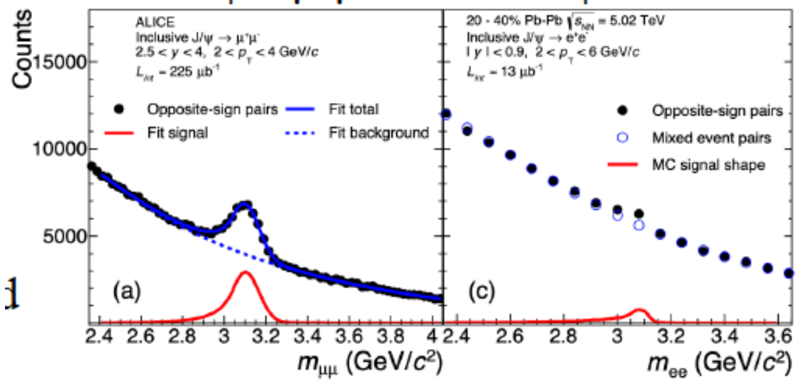
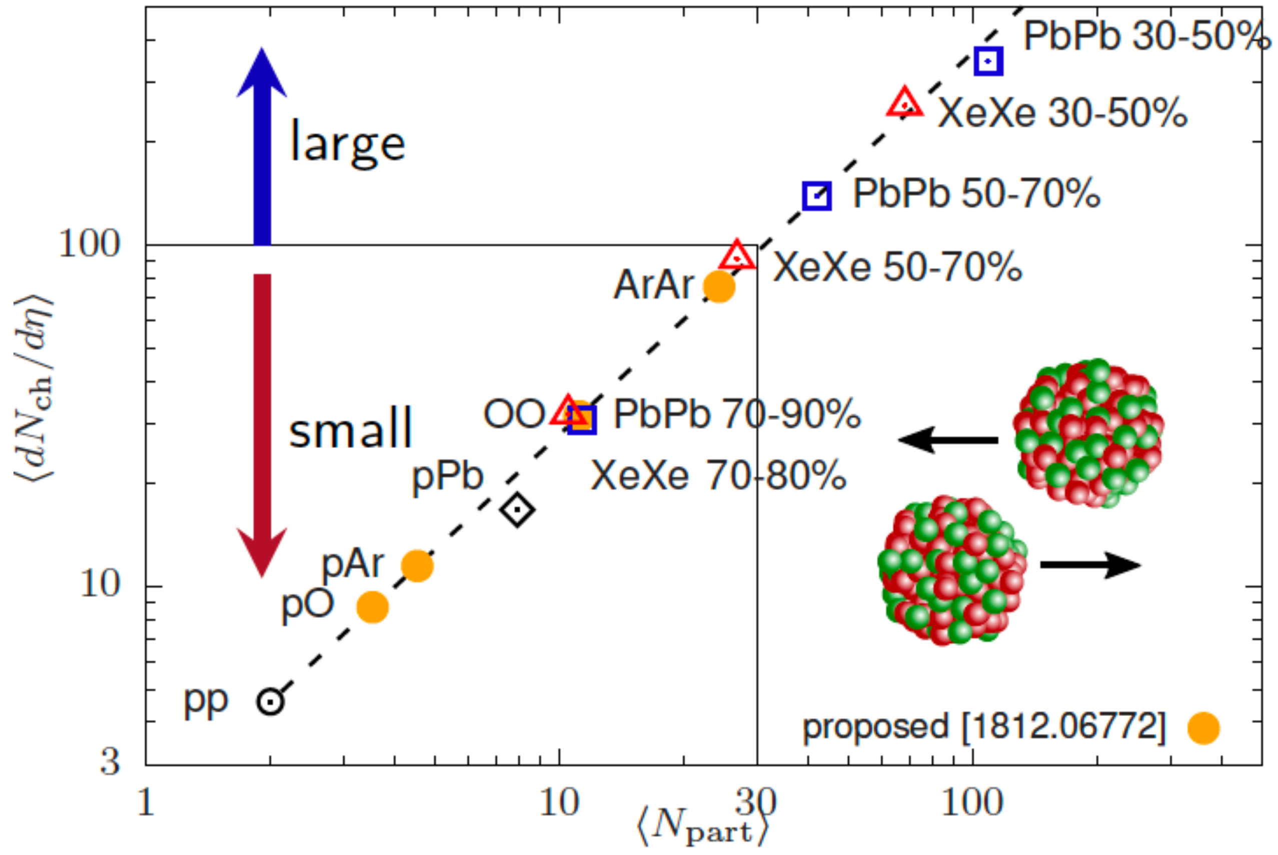


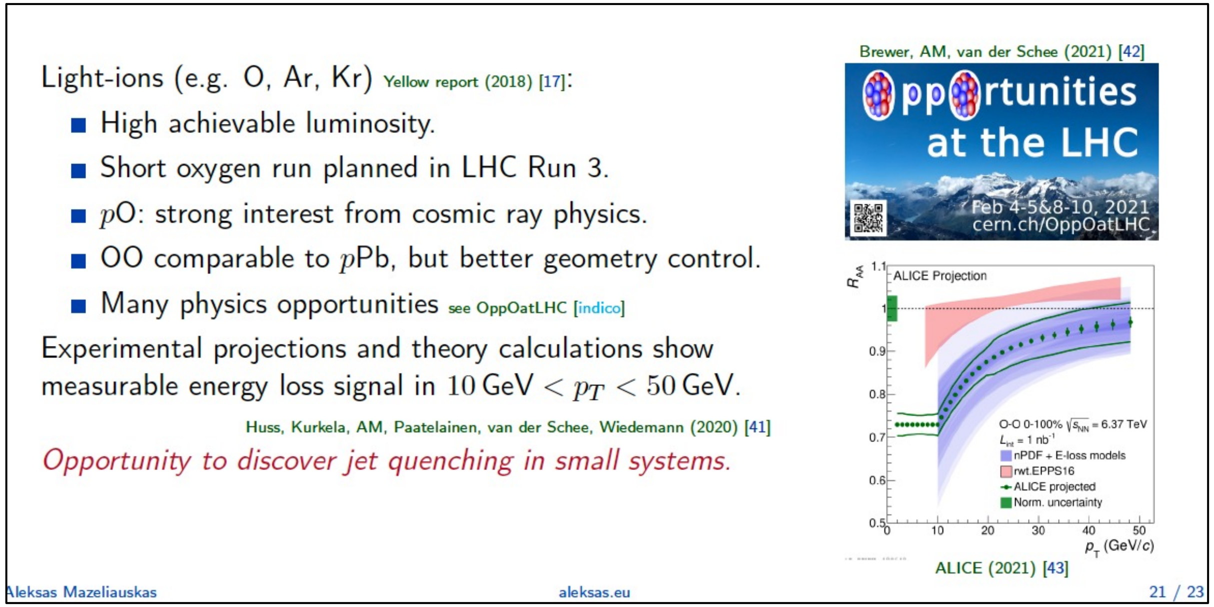
$J/\psi \rightarrow \mu^+\mu^-$ $J/\psi \rightarrow e^+e^-$



Light ions at the LHC



From A. Mazeliauskas, EPS-HEP 2021:



Hydrodynamical modeling (details)

Describe the expanding medium macroscopically.

Input

- Initial conditions
- equation-of-state (EOS) $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}(P)$ from latticeQCD
- bulk ζ and shear viscosity η, charge diffusion, κ

Output

- Any other relevant observable, e.g. spectra, jet quenching, …

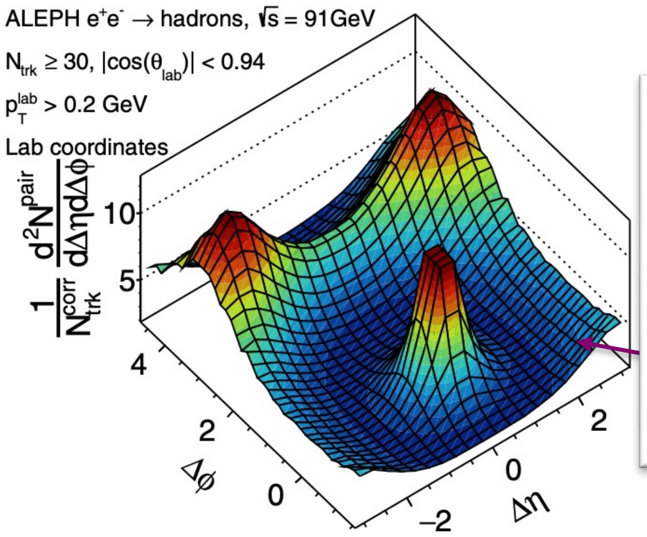
arXiv:1712.05815

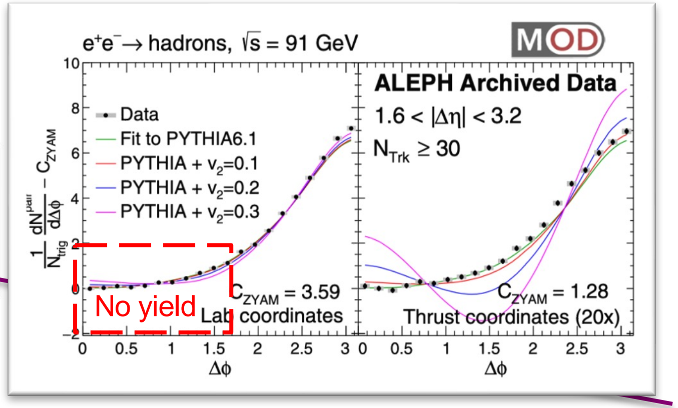
	Gauge/Gravity	Kinetic (BGK)	pQCD	Lattice QCD
$\epsilon(P)$	3 P	Eq. (3.30)	3 P	Eq. (3.125)
η	$\frac{\epsilon+P}{4\pi T}$	$\frac{(\epsilon+P)\tau_R}{5}$	$\frac{3.85(\epsilon+P)}{g^4 \ln(2.765 g^{-1})T}$	$0.10(6)\frac{\epsilon+P}{T}$
τ_π	$\frac{2-\ln 2}{2\pi T}$	τ_R	$\frac{5.9\eta}{\epsilon+P}$	
λ_1	$\frac{\eta}{2\pi T}$	$\frac{5}{7}\eta\tau_R$	$\frac{5.2\eta^2}{\epsilon+P}$	
λ_2	$2\eta\tau_\pi - 4\lambda_1$	$-2\eta\tau_R$	$-2\eta\tau_\pi$	
λ_3	0	0	$\frac{30(\epsilon+P)}{8\pi^2 T^2}$	
κ	$\frac{\epsilon+P}{4\pi^2 T^2}$	0	$\frac{5(\epsilon+P)}{8\pi^2 T^2}$	$0.36(15)T^2$
Refs.	[19, 28, 29] [128, 129]	[28, 119, 120]	[121–123] [130]	[124–127] [131, 132]

Table 2.1: Compilation of leading-order results for transport coefficients in various calculational approaches, see text for details.

Flow observables are related to the response of the system to the initial spatial anisotropies
→ Can be used to deduce conclusions on initial conditions, EoS and transport coefficients **by data comparison**

Searching for the “ridge” in the smallest systems

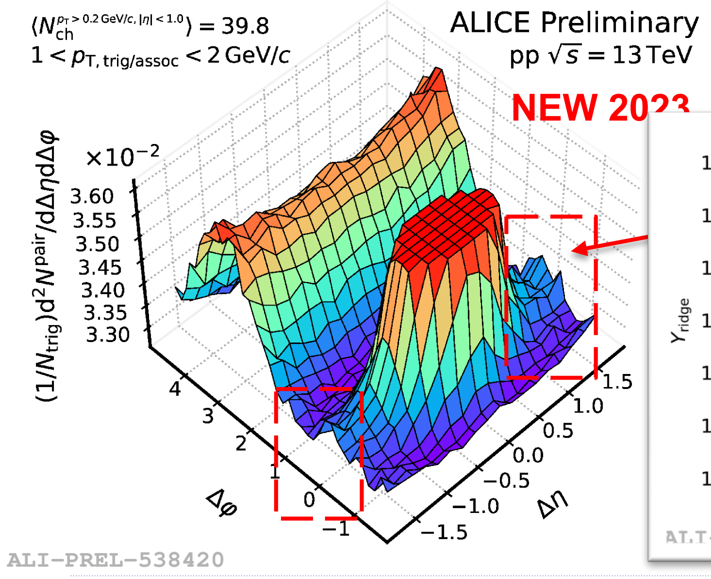


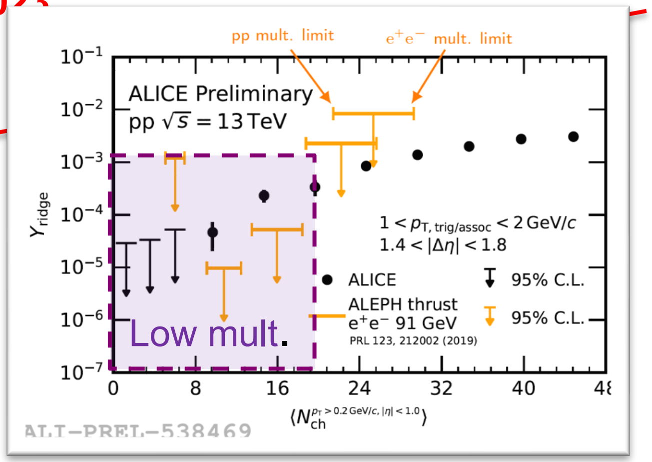


Y.J.Lee et al, PRL 123, 212002 (2019)

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

Checked in e+e- using ALEPH archived data:
→ No ridge observed





Latest result:
→ ridge observed in low-multiplicity pp collisions

Are these long-range correlations in pp coming from (hydrodynamic) flow?

Hadronisation by fragmentation and recombination

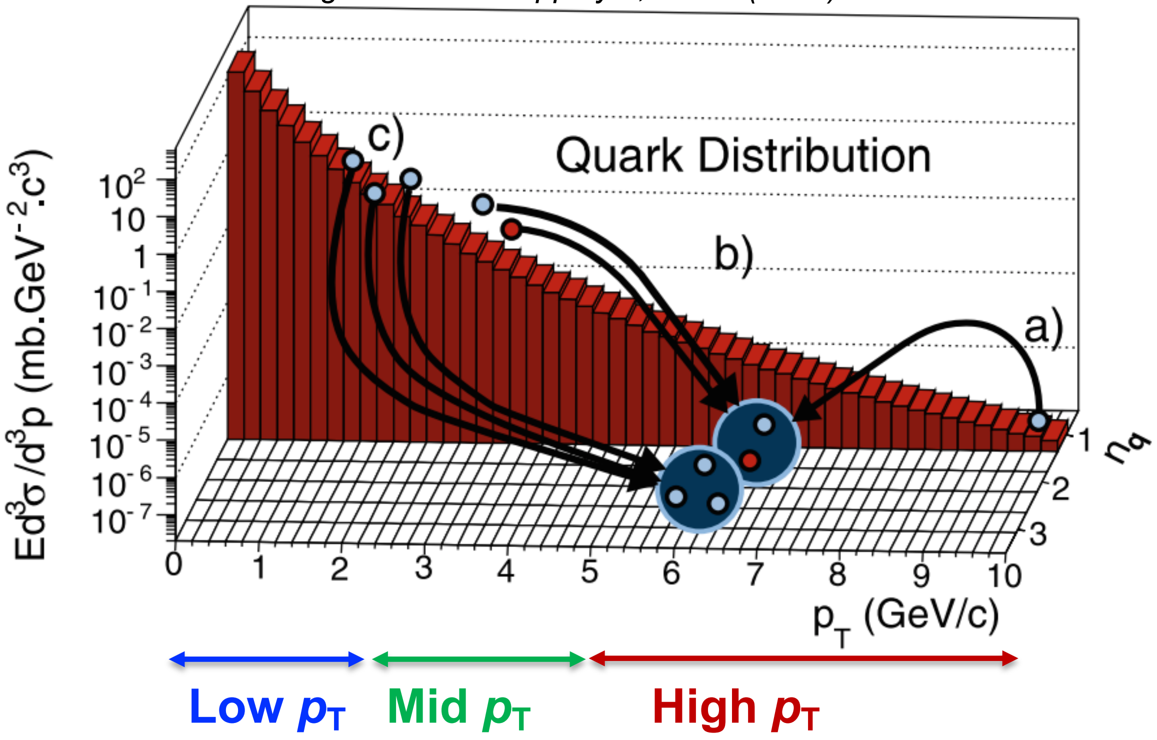
Ratios of baryon to meson production spectra are sensitive to competing particle production mechanisms, depending on transverse momentum

Fragmentation (a) of high-p_T partons into mid-p_T hadrons

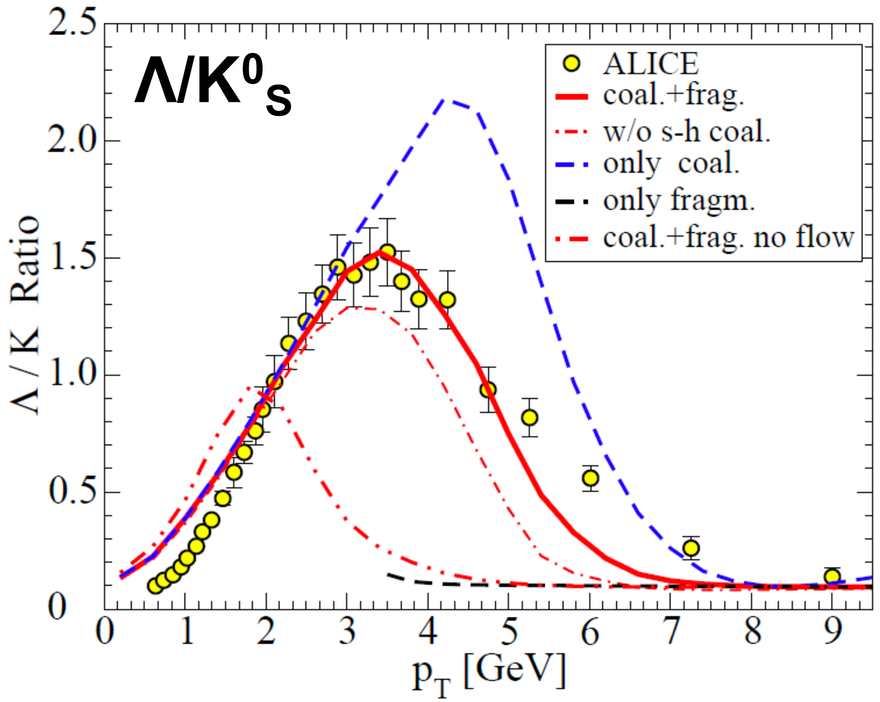
Recombination (b,c) of low-p_T partons close in phase space into mid-p_T hadrons via coalescence

+ influence of **collective flow**

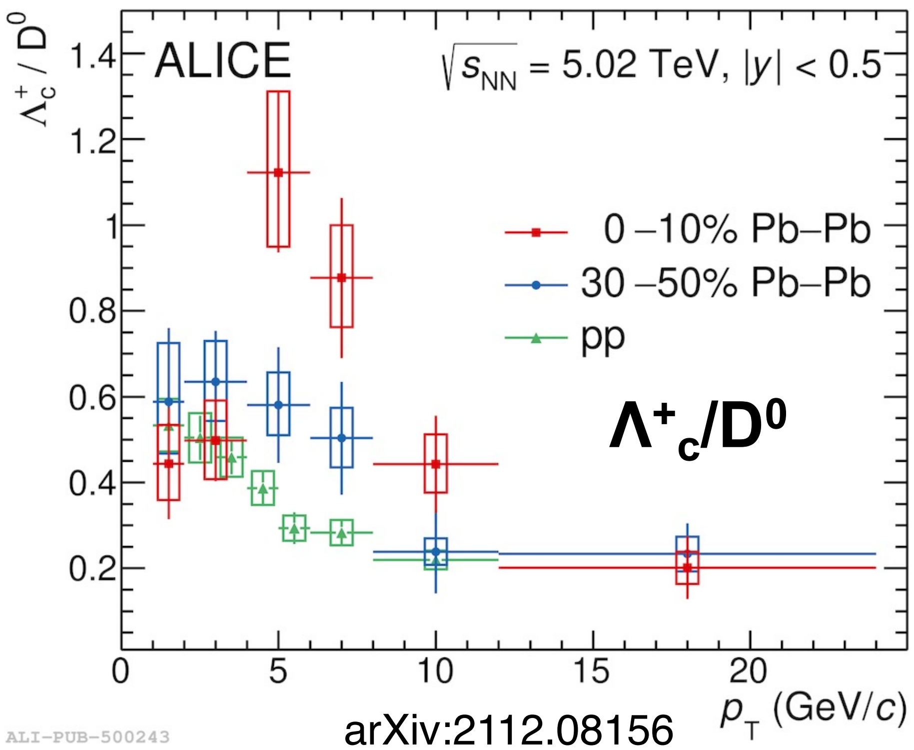
Figure from B. Hippolyte, EPJC (2009) 62: 237–242



Investigating hadronization mechanisms



V. Minissale et al., PRC 92 (2015) 054904



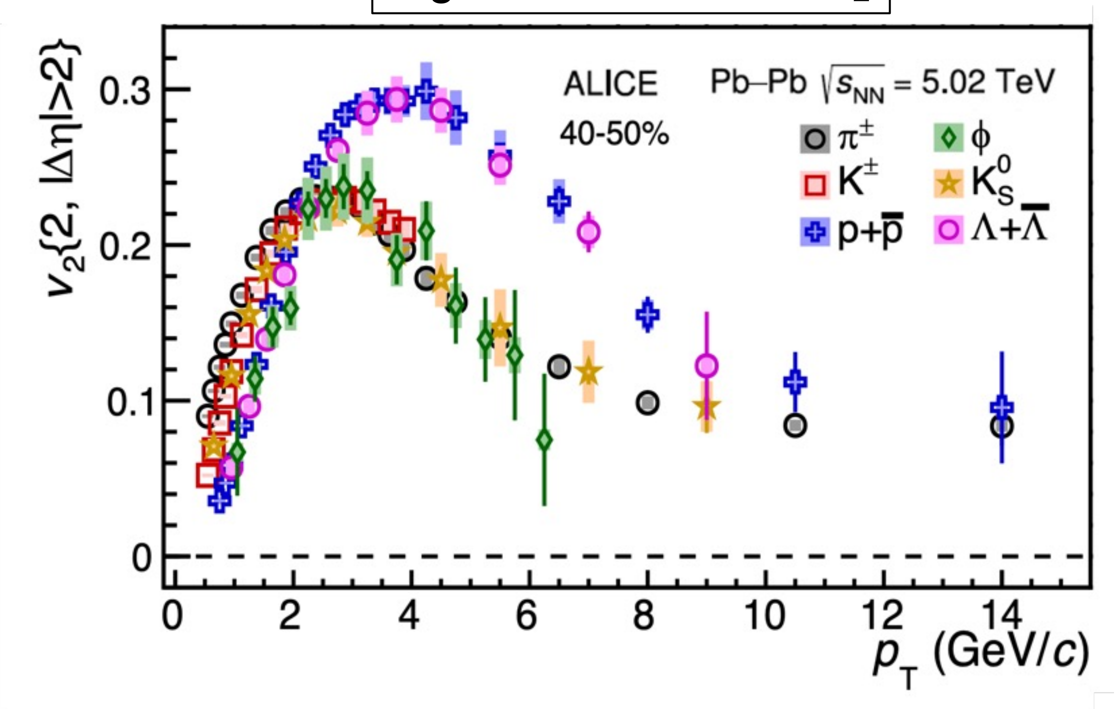
arXiv:2112.08156

At intermediate p_T, a **baryon/meson enhancement** is observed for p/π, Λ/K^0_S
→ interplay of **radial flow** and **recombination**

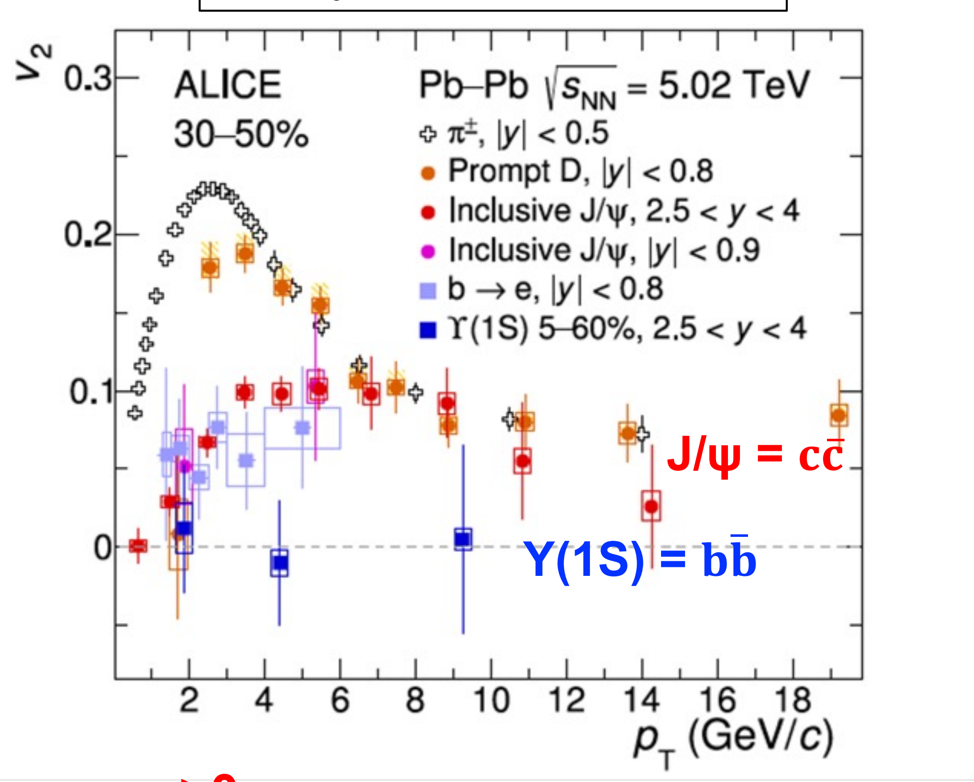
Λ_c/D^0 enhancement possibly due to the **recombination of charm** quarks traveling through the QGP **with light quarks** from the QGP.

Flow of identified hadrons

Light flavour hadron v_2



Heavy flavour hadron v_2



Light flavour hadrons exibit ''textbook'' flow

- Mass dependence at low p_T
- Interplay of production mechanisms at mid-p_T (baryon/meson separation → recombination)

Charm v_2>0

- charm partially thermalised with the QGP
- recombination with LF at hadronisation

No significant evidence of flow of beauty

Strangeness production in a hadron gas

In a **hadron gas at high temperature** (e.g. **hadronic phase of HIC**, T = 150 MeV < T_c), (multi-)strange hadron production is an **energy threshold problem**

By **multi-step hadronic processes**

e.g. $\pi + n \rightarrow K + \Lambda$, $E_{th} \sim 540$ MeV

$\pi + \Lambda \rightarrow K + \Xi$, $E_{th} \sim 560$ MeV

- Requires longer medium lifetime
- under-saturation of strangeness

By **direct production**

e.g. $\pi + \pi \rightarrow \pi + \pi + \Lambda + \Lambda$-bar, $E_{th} \sim 2200$ MeV

$\pi + \pi \rightarrow \pi + \pi + \Xi^- + \Xi^+$-bar, $E_{th} \sim 2600$ MeV

- Have to happen very early
- By non-thermalised hadrons

The strangeness quantum number has to be conserved locally and exactly in a **finite system** (e.g. **pp**), which reduces the phase space available for particle production.

[K. Redlich, A. Tounsi, Eur. Phys. J. C 24, 589–594 (2002)]

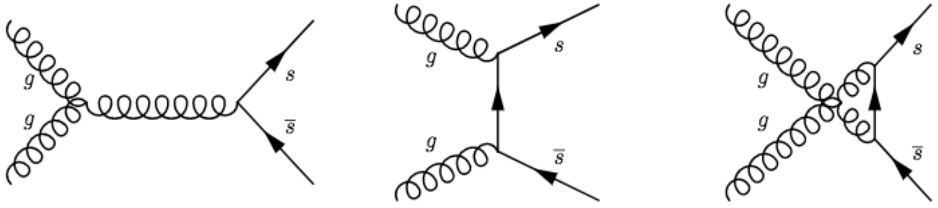
→ **canonical suppression** due to **quantum number conservation**

→ Relaxation of canonical suppression with increasing √s (and number of particles)

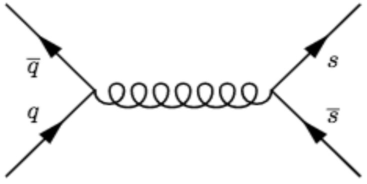
Strangeness production in a QGP

Strangeness is produced dominantly by fusion of thermalized gluons (a) in the QGP.
Energy threshold for s-sbar: ~200 MeV (if $m_s^{QCD} \longrightarrow m_s^{Higgs}$ by restoration of chiral symmetry)

(a) $gg \rightarrow s\bar{s}$

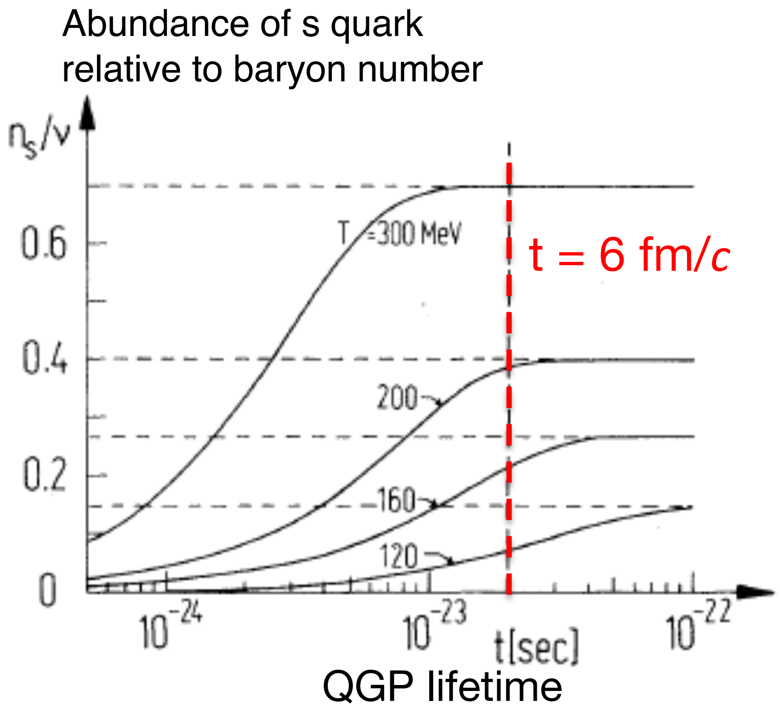


(b) $q\bar{q} \rightarrow s\bar{s}$



The backward reaction of (b) depends on the s quark density, thus on the QGP lifetime.
⇢ saturation of strangeness abundance reached on the time scale of ~ 1-few fm/c

Strangeness enhancement in HIC relative to pp was historically proposed as a signature of the presence of a deconfined Quark--Gluon Plasma.



J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066

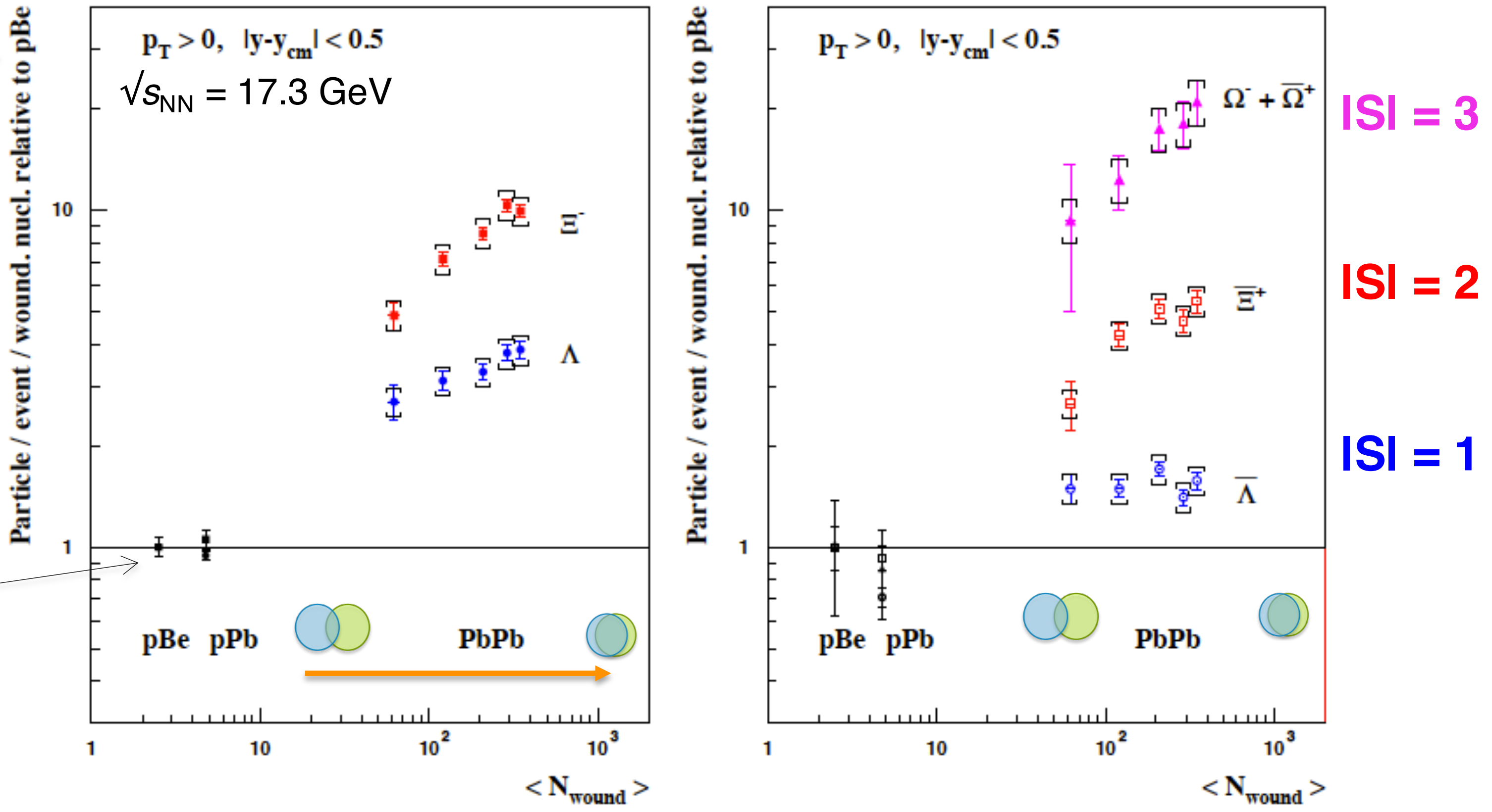
Observation of strangeness enhancement at SPS

NA57, J.Phys. G32 (2006) 427-442

Yields normalised to N_{wound} relative to p-Be

=> Not just an effect of having more participants in Pb-Pb!

p-Be used as a proxy for pp since N_{wound} is close to 2 (as in pp)



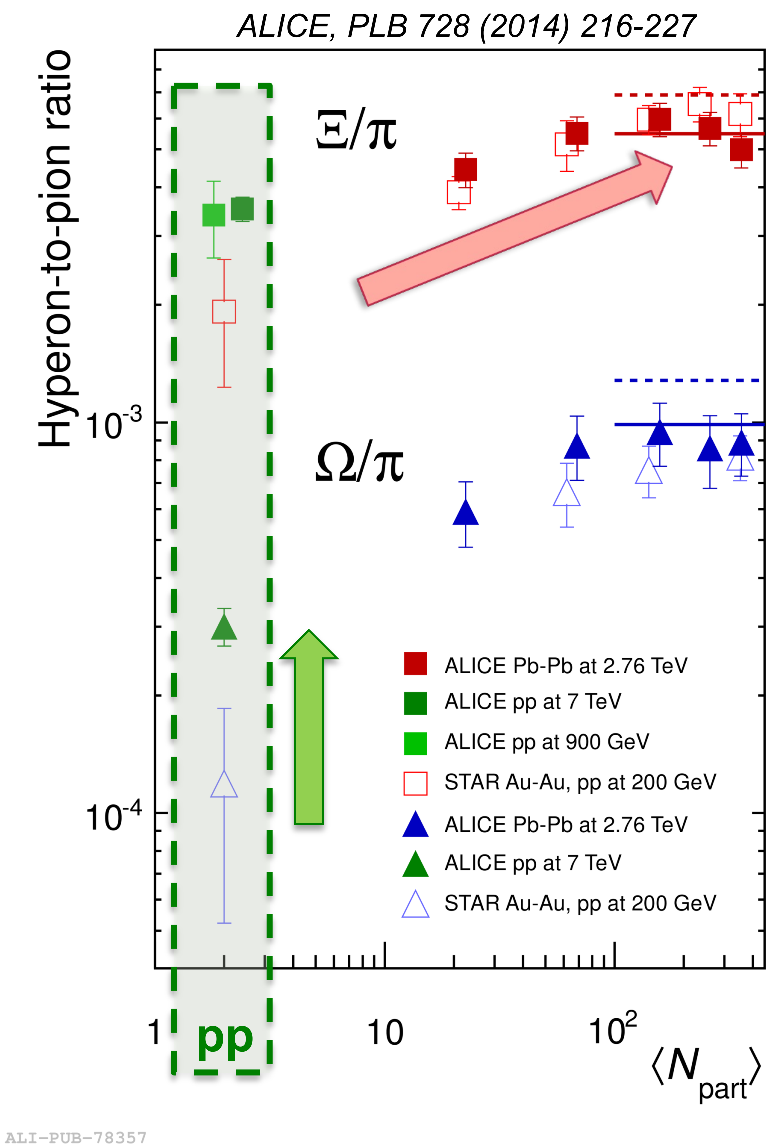
Enhancement observed in Pb-Pb collisions wrt p-Pb, p-Pb for multi-strange (anti)baryons

⇢ Anti-baryons less enhanced than baryons ⇢ quarks (not anti-quarks!) in the initial stage

⇢ **Hierarchy** of the enhancement with the strangeness content

⇢ **Increase** of the enhancement with the **centrality** of the collision

Strangeness production from RHIC to LHC



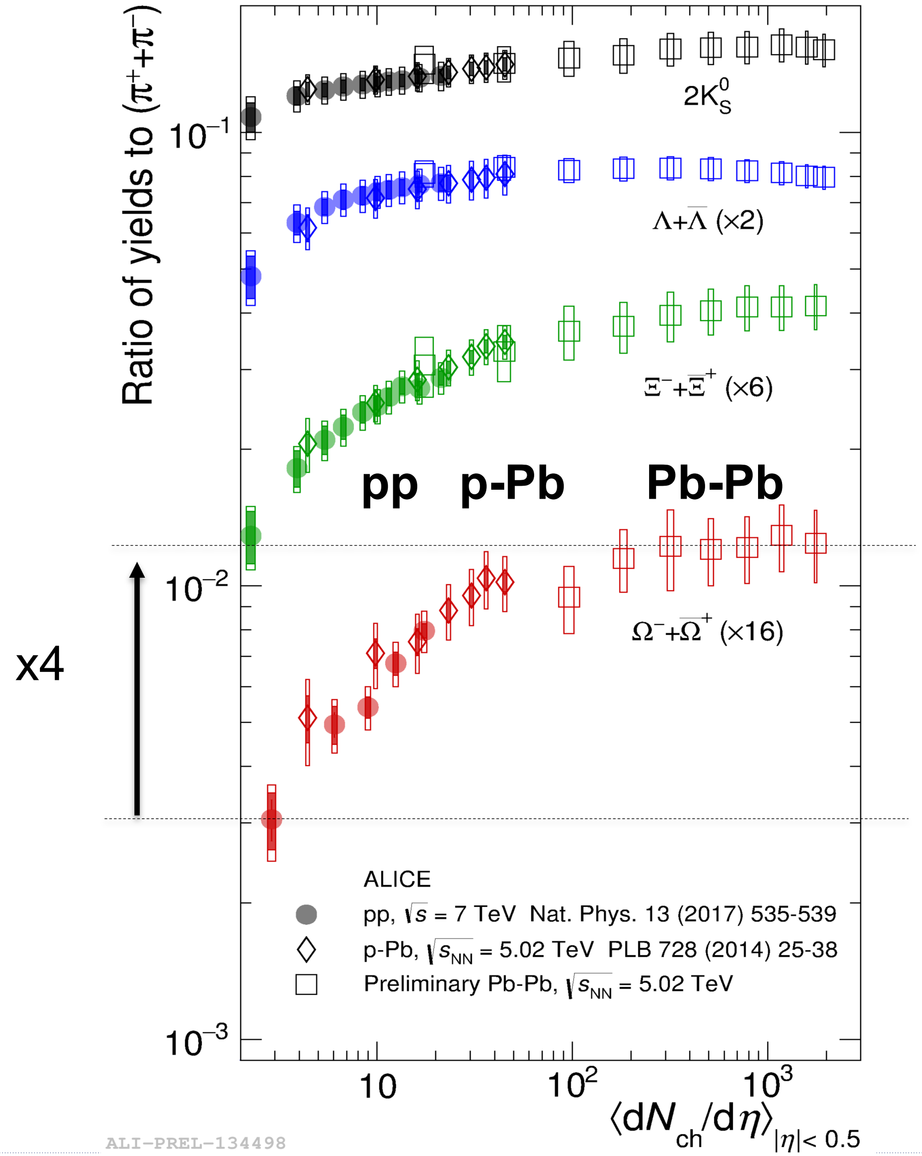
RHIC: $\sqrt{s_{NN}}$ = 200 GeV (empty markers)
LHC: $\sqrt{s_{NN}}$ = 2.76 TeV (full markers)

Observation of

- increase of strangeness production relative to strange-less π in pp collisions with increasing √s
- strangeness enhancement in HIC relative to minimum bias pp collisions
- saturation of strangeness from peripheral to central Pb-Pb

→ Prompted more differential studies in pp collisions as a function of charged particle multiplicity

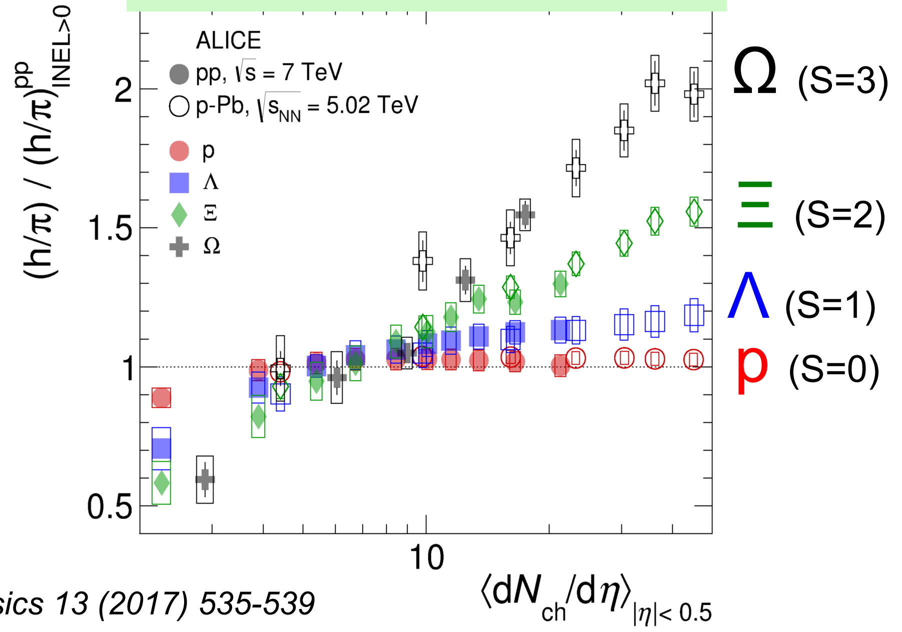
Discovery of strangeness enhancement in pp collisions



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

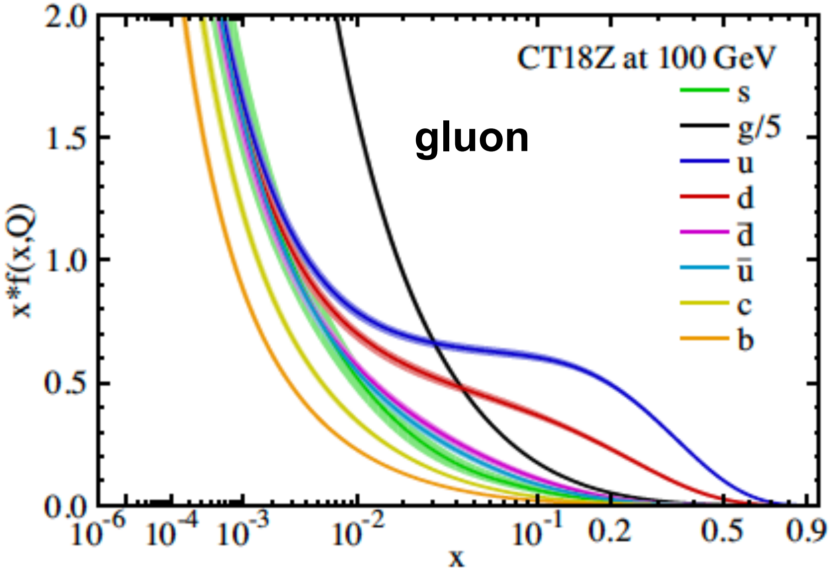
Enhancement in pp is larger for hadrons with larger strangeness content

Double ratio = enhancement relative to min bias pp

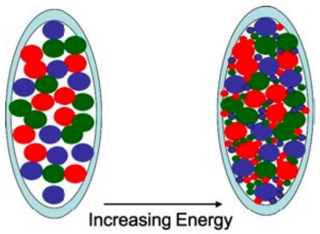


Nature Physics 13 (2017) 535-539

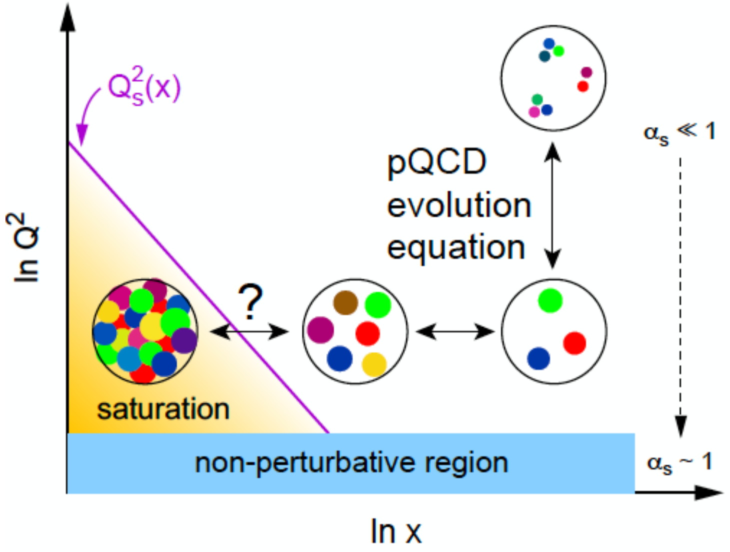
Initial stage of heavy ion collisions

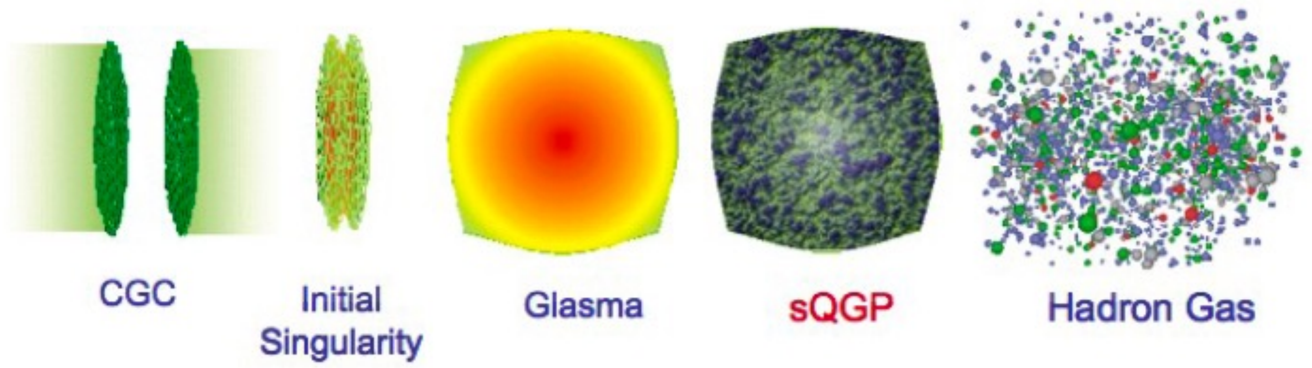


Color Glass Condensate: at high energy and small x, the hadron content is dominated by gluonic matter "packed" into high density



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,