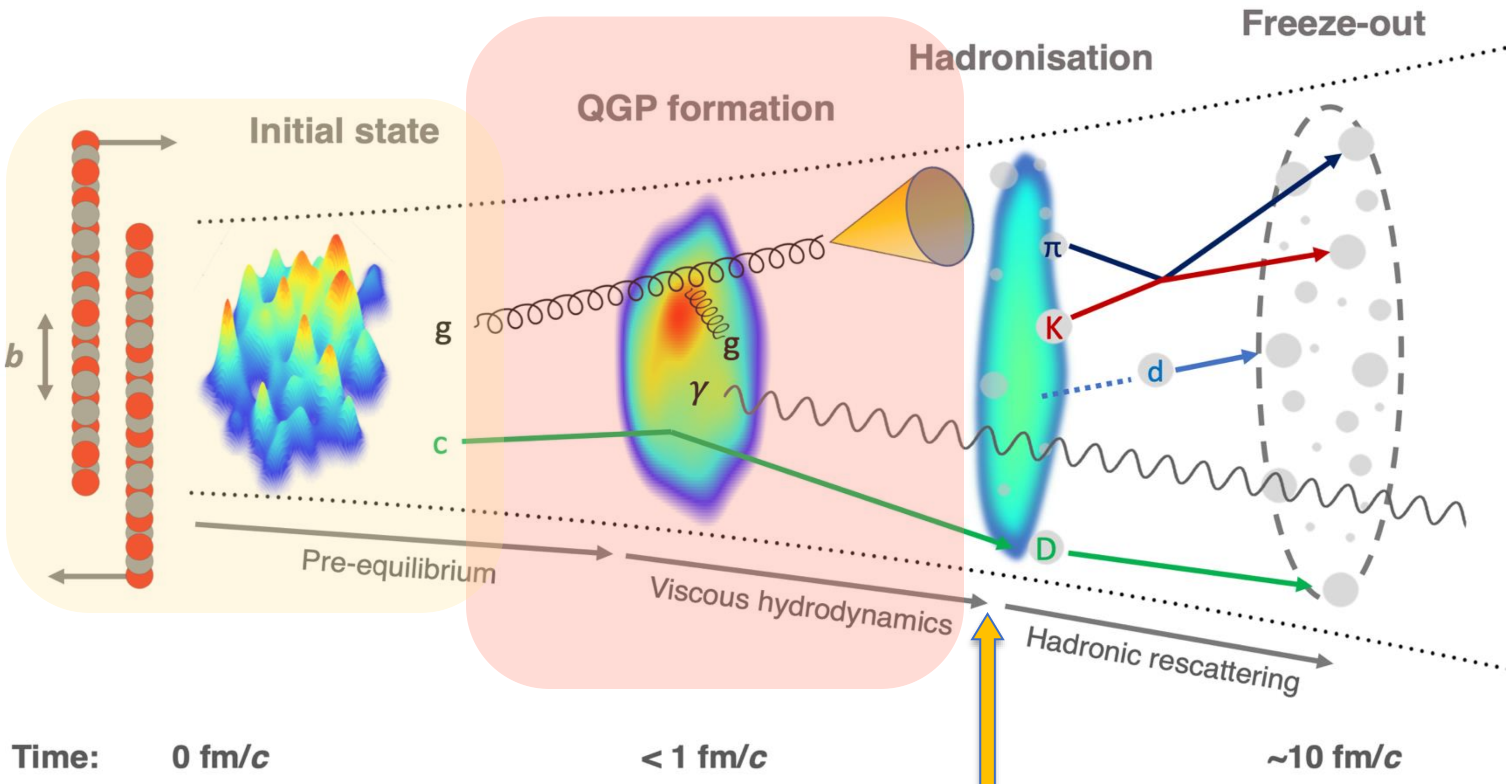
Collective effects in particle production from small to large colliding systems: status and future prospects

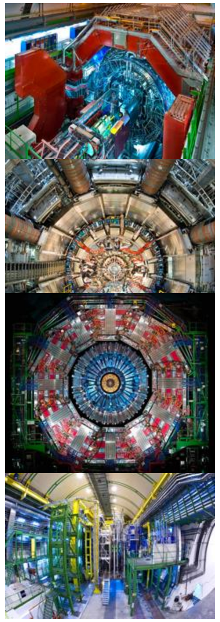
F. Bellini (Università e INFN, Bologna)
Workshop on High Luminosity LHC and Hadron Colliders
LNF, 3rd October 2024

INFN

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Collective effects in particle production





What are the macroscopic properties of the QGP? Temperature? Viscosity?

Collectivity of QCD across system sizes?

Can we have QGP in small systems?

Phase transition (crossover) to hadron gas
at T_{pc} = (156.5 ± 1.5) MeV
P. Steinbrecher et al. NPA 982 (2019) 847

Hadron gas phase
$T \sim 155 \rightarrow 100$ MeV

Collectivity – a definition

Common behavior exhibited by a **group of entities** associated with a phenomenon of an **underlying complex many-body system** for which the basic interactions may be well understood.

E.g. "Loose" definition:

- **correlations** of many particles
- across a **long range in rapidity**
- due to a **common source**

Photo: Daniel Biber [link]

Long-range correlations in particle emission

Collective expansion translates into **long η-range modulation** of particle emission **in azimuth.**

Observed in Pb-Pb collisions → **collectivity expected**

Broad **''ridge''** in a wide $\Delta\eta$ range:
long-range correlations
emerging from early times

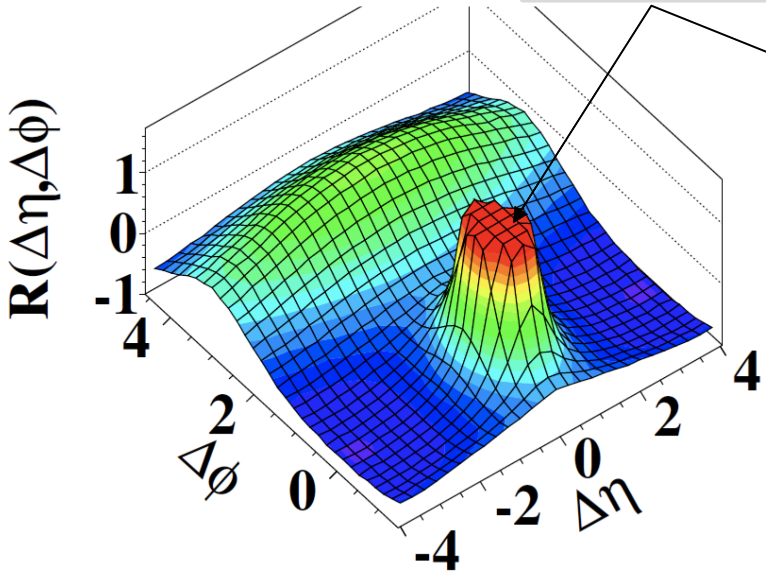
Modulation in azimuth
determined by the medium **response** to the initial transverse geometry

→ **anisotropic flow**
→ decomposition in Fourier series of the azimuthal distribution at large η

No ridge nor modulation in pp min bias

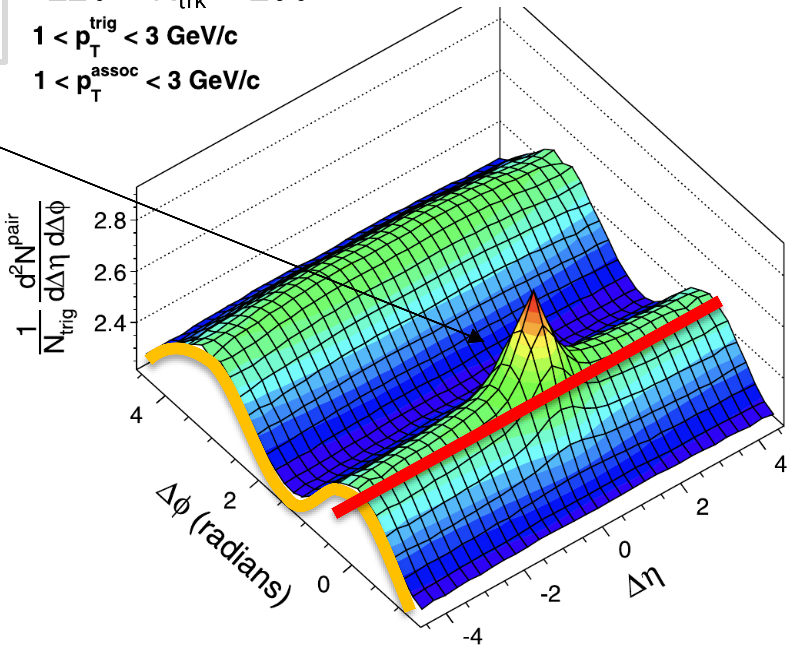
CMS, pp $\sqrt{s}$ = 7 TeV
minimum bias
1.0 GeV/c < p_T < 3.0 GeV/c

Peak at $\Delta\eta$ ~ 0:
short-range correlations
→ **jets**



CMS, JHEP 1009:091 (2010)

CMS, PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
220 < N_{trk} < 260
$1 < p_T^{trig} < 3$ GeV/c
$1 < p_T^{assoc} < 3$ GeV/c



CMS, JHEP 02 (2014) 088

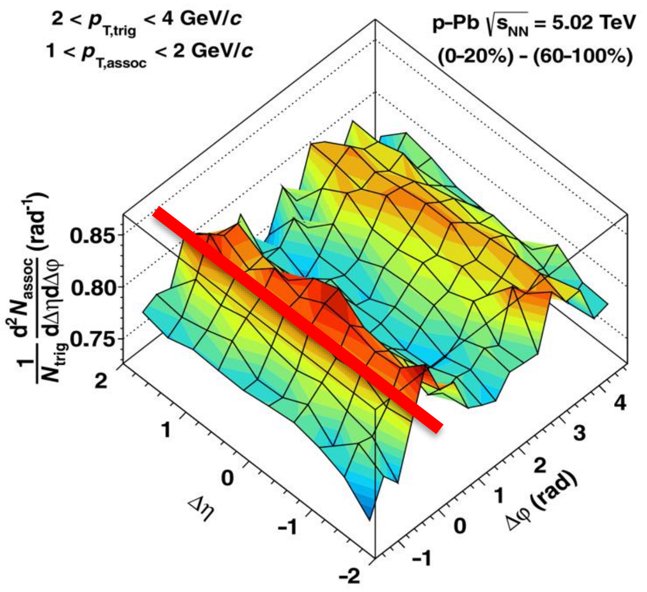
... down to p-Pb and pp collisions

discovery at the LHC!

...**observed** also in defined-multiplicity p-Pb and pp collisions → **collectivity? Unexpected!**
→ **"small systems"** are born!

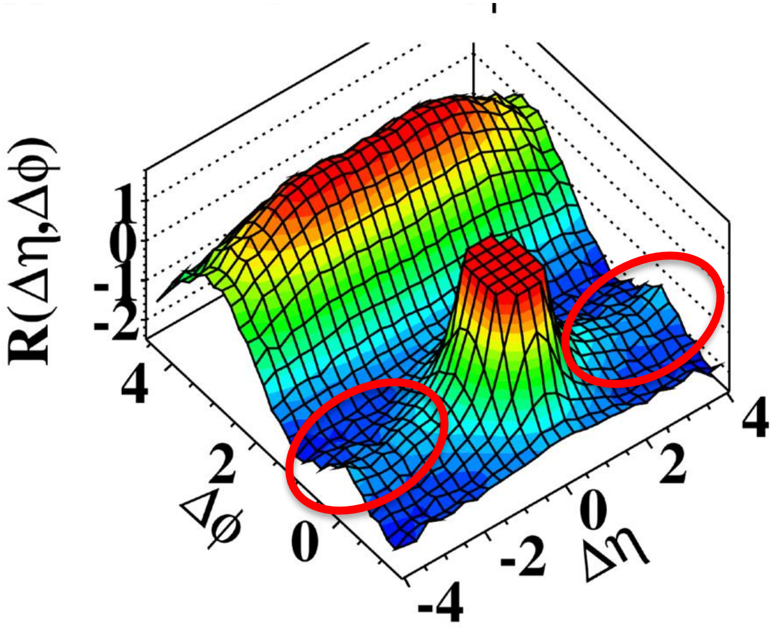
Decreasing final-state multiplicity / system size →

ALICE, p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Low-multiplicity subtracted



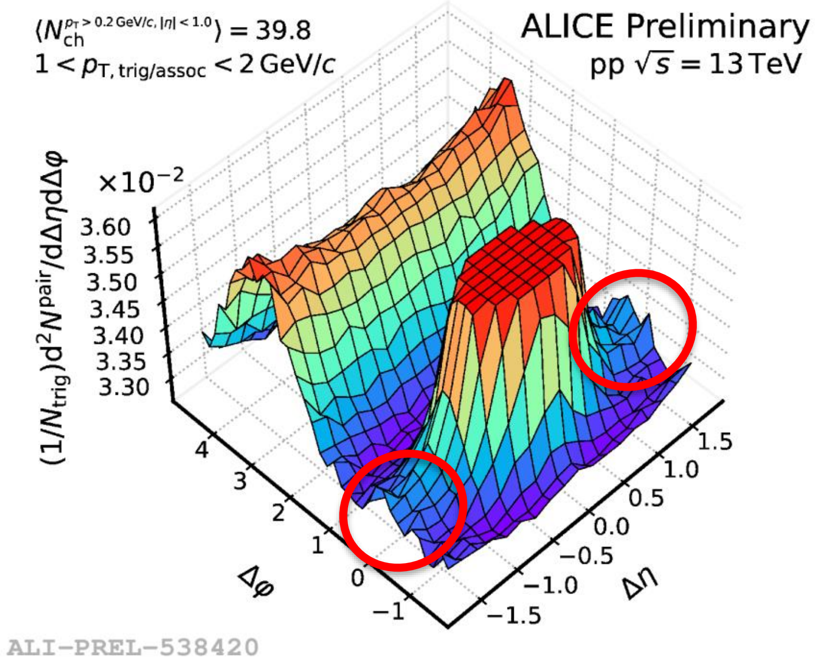
ALICE, PLB 719 (2013) 29

CMS, pp $\sqrt{s}$ = 7 TeV
high-multiplicity $N_{trk} \geq 110$



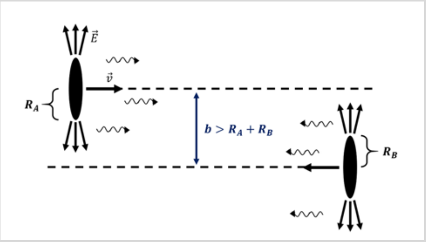
CMS, JHEP 1009:091 (2010)

ALICE, pp $\sqrt{s}$ = 13 TeV
low-multiplicity, N_{ch} ~ 40



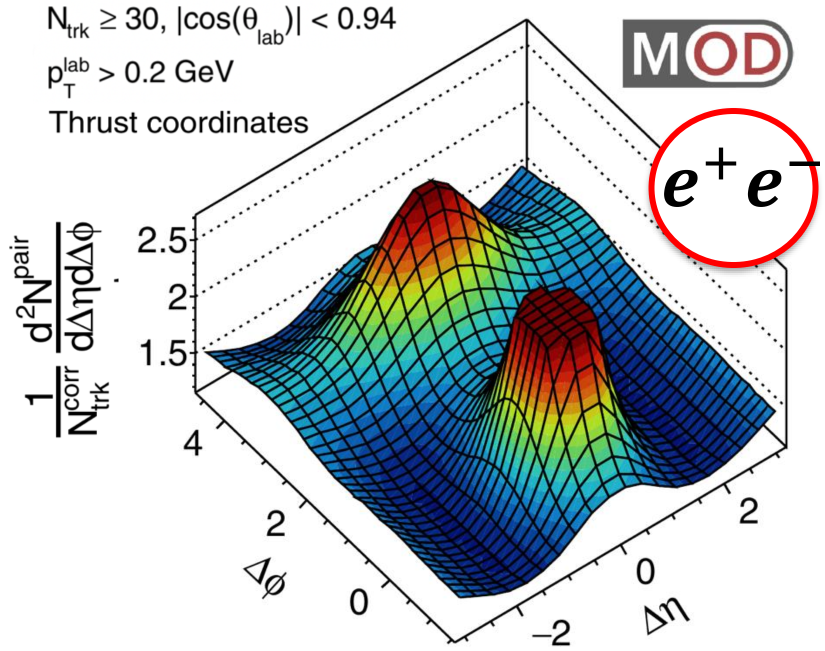
What about other (smaller) systems?

No significant long range correlation found!



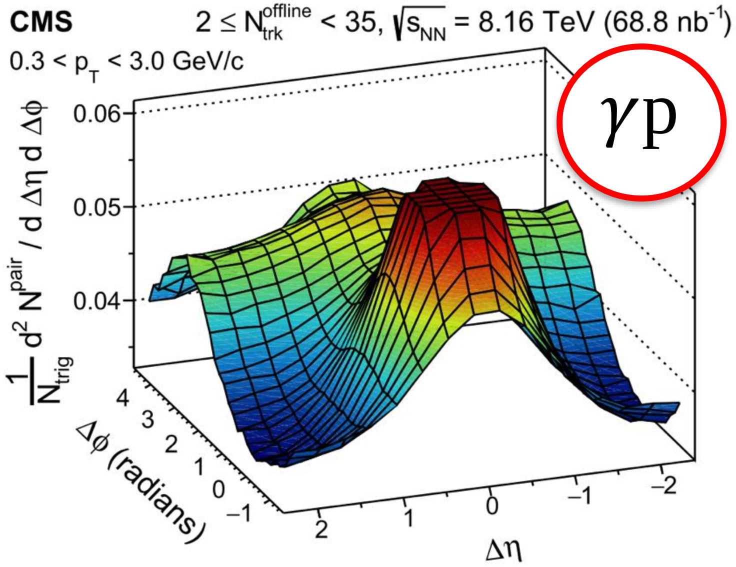
Coulomb fields of moving charges equivalent to a flux of photons boosted to high energies:
γ up to of ~10s GeV with a ~few TeV Pb beam

ALEPH, $e^+e^- \rightarrow hadrons$, $\sqrt{s}$ = 91 GeV



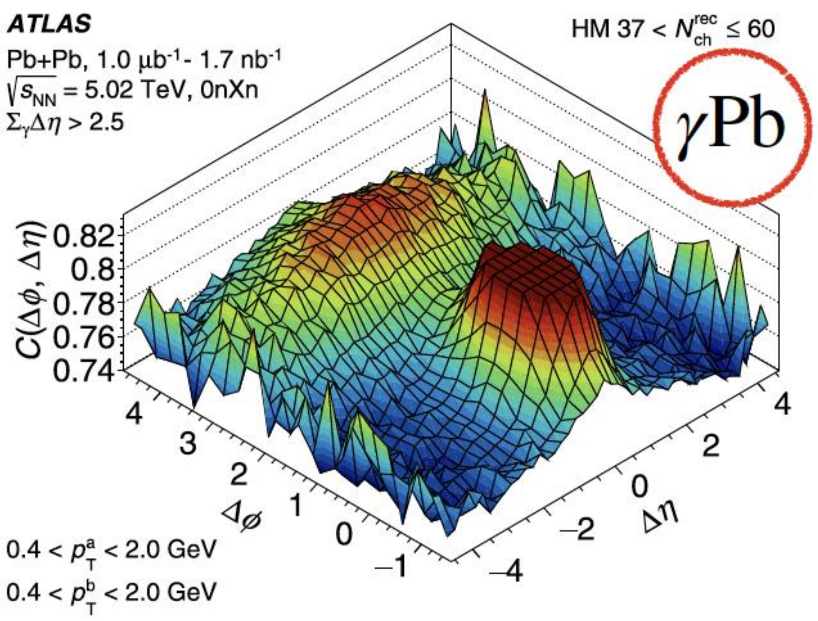
A. Badea et al. PRL 123 (2019) 212002

CMS, Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
γp-enhanced



CMS, Phys. Lett. B 844 (2023) 137905

ATLAS, Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV UPC



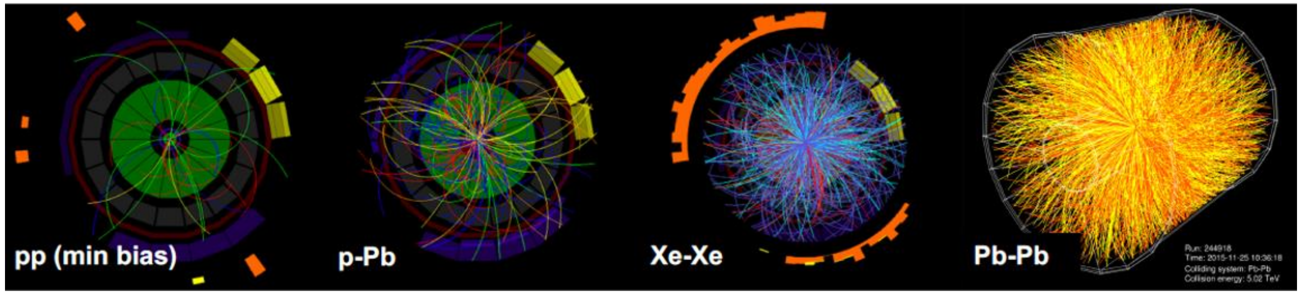
ATLAS, PRC 104, (2021) 014903

Small and large systems – a definition

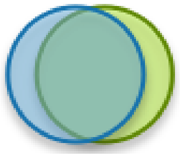
We form a QGP by compressing a large amount of energy in a small volume in heavy-ion collisions.

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

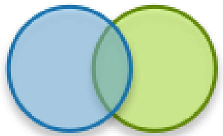
- impact parameter / **centrality**
- nuclear **species** (p-Pb, pp, XeXe, OO, pO...)
- classify events based on final-state charged particle **multiplicity**



Centrality = % of the total hadronic cross section

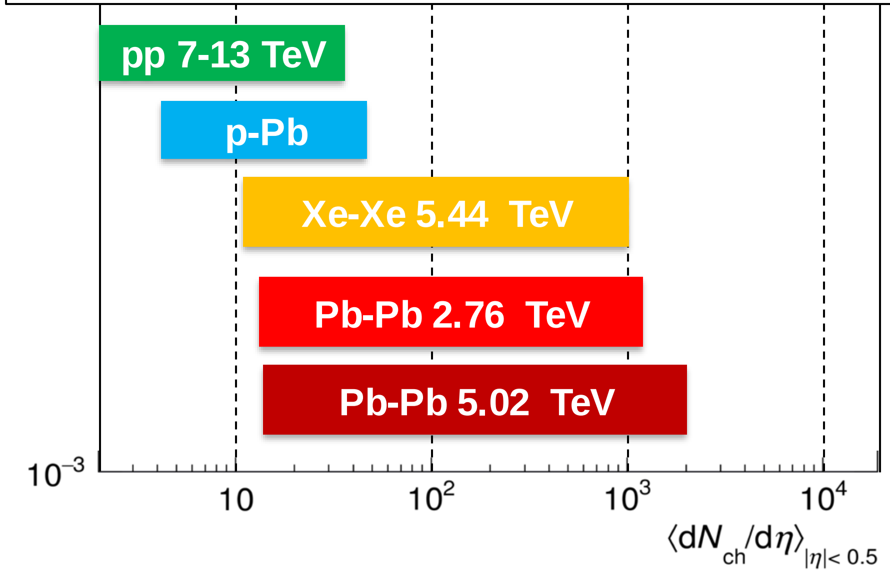


Central collisions (e.g. 0-10%)
→ Small impact parameter
→ High particle multiplicity, N_{ch} or $dN_{ch}/d\eta$



Peripheral collisions (e.g. 70-80%)
→ Large impact parameter
→ Low N_{ch} or $dN_{ch}/d\eta$

Final-state charged particle **multiplicity** at mid-y

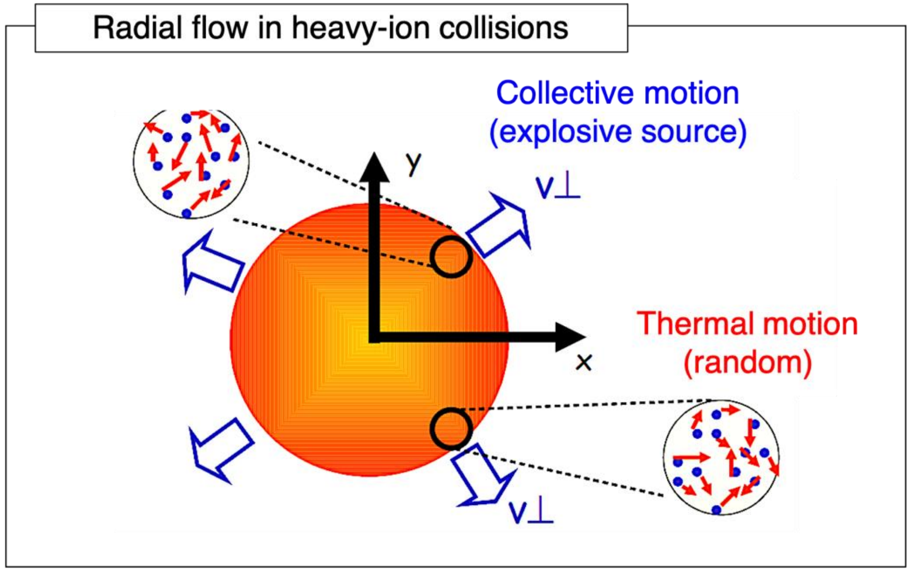


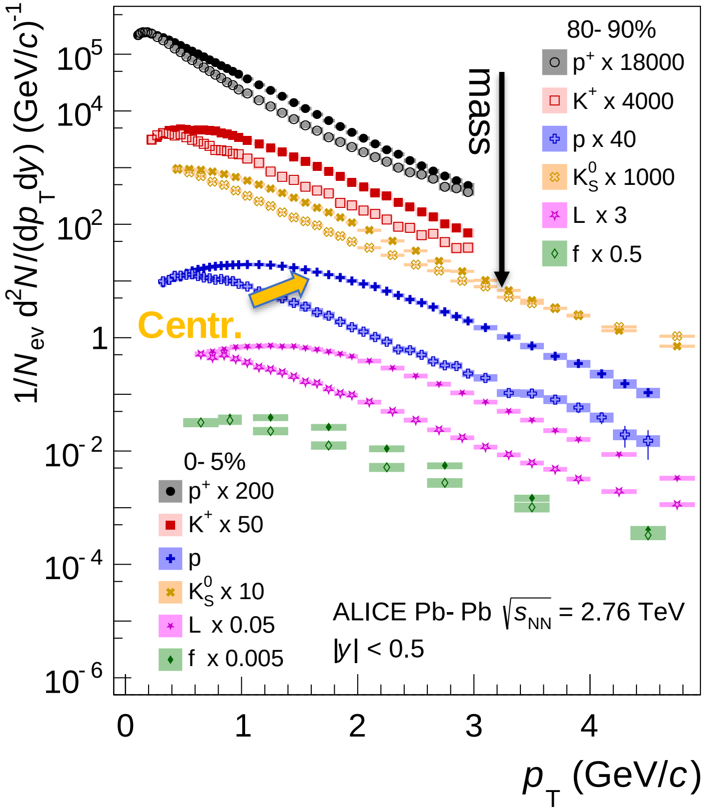
Collectivity: a cornerstone of HI collisions

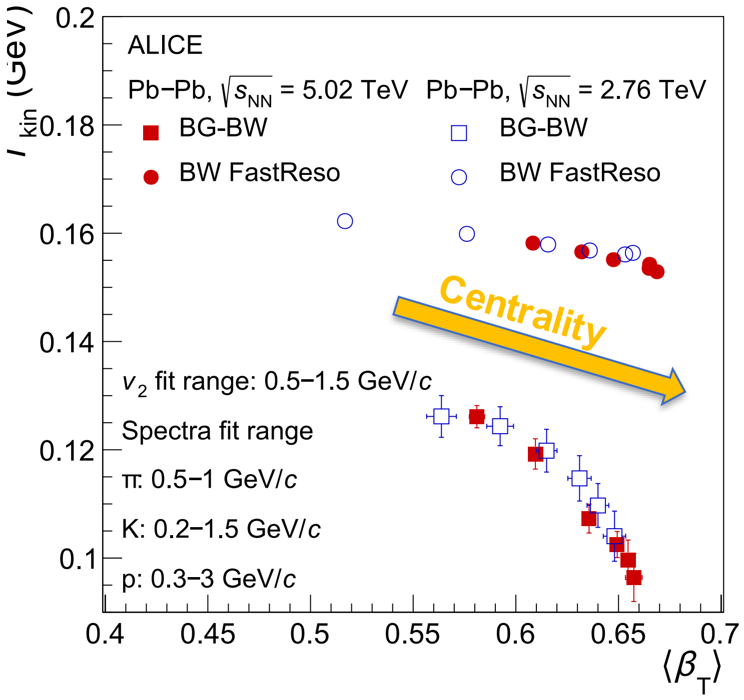
A collective motion of particles superimposed to the thermal motion → a **medium**

Radial flow: radial **expansion** of a medium in the vacuum under a common velocity ($\beta = v/c$)

- Affects transverse momentum distribution of hadrons and their ratios (mass dependence)
- Increasing from peripheral to central collisions







ALICE, EPJC 84 (2024) 813

Collectivity: a cornerstone of HI collisions

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

Scatterings convert anisotropy in coordinate space into an observable momentum anisotropy → **anisotropic flow**

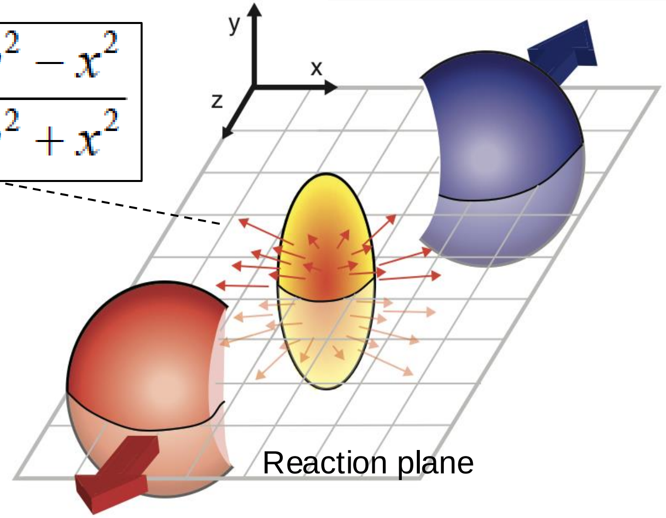
→ anisotropy in azimuthal angle described by a Fourier series
→ v_n describe how initial fluctuations propagate in a **viscous fluid**

v_n = **flow coefficients** *(harmonics)*

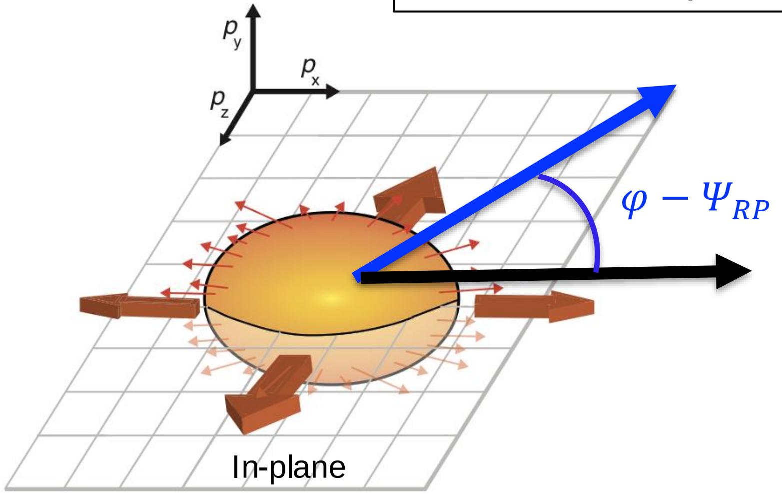
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos[n(\varphi-\Psi_n)]\right),$$

Coordinate space

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



Momentum space



Anisotropic flow

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

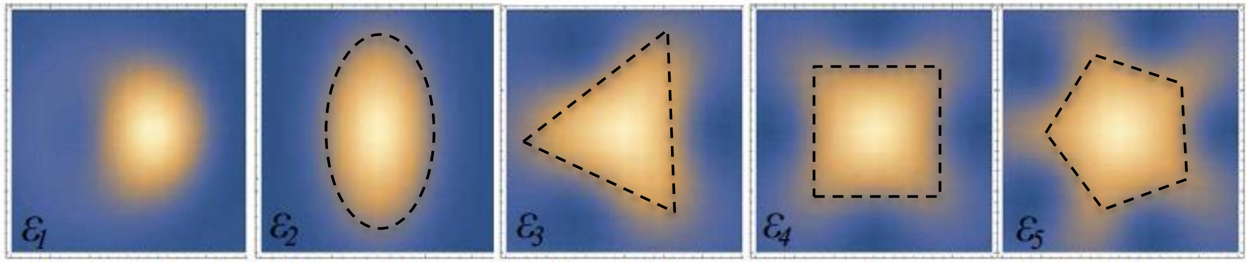
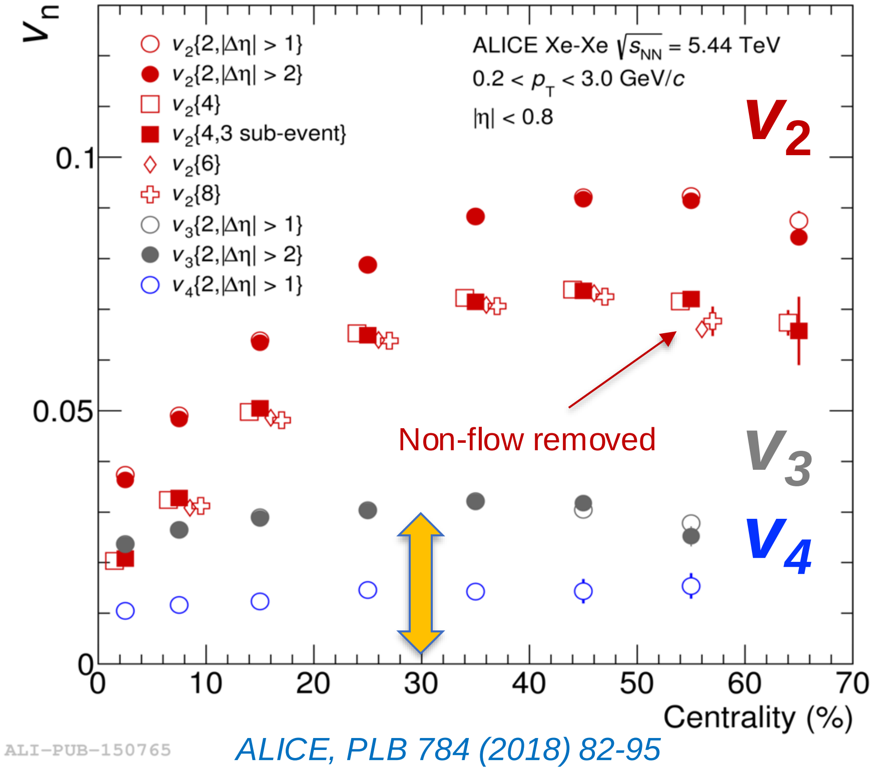
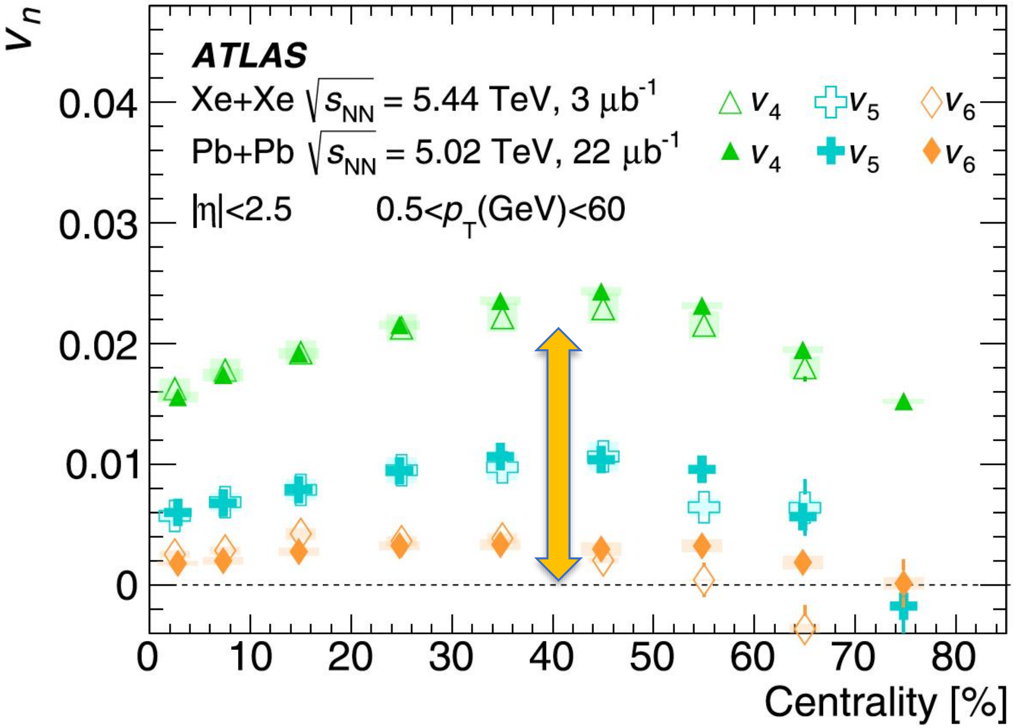


Fig. 2. (color online) Characteristic shapes of the deformed initial state density profile, corresponding to anisotropies of $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, $\mathcal{E}_4$ and $\mathcal{E}_5$ (from left to right).

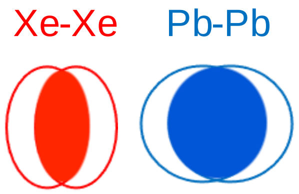
Li Yan 2018 Chin. Phys. C 42 042001



ALICE, PLB 784 (2018) 82-95



ATLAS, PRC 101, 024906 (2020)



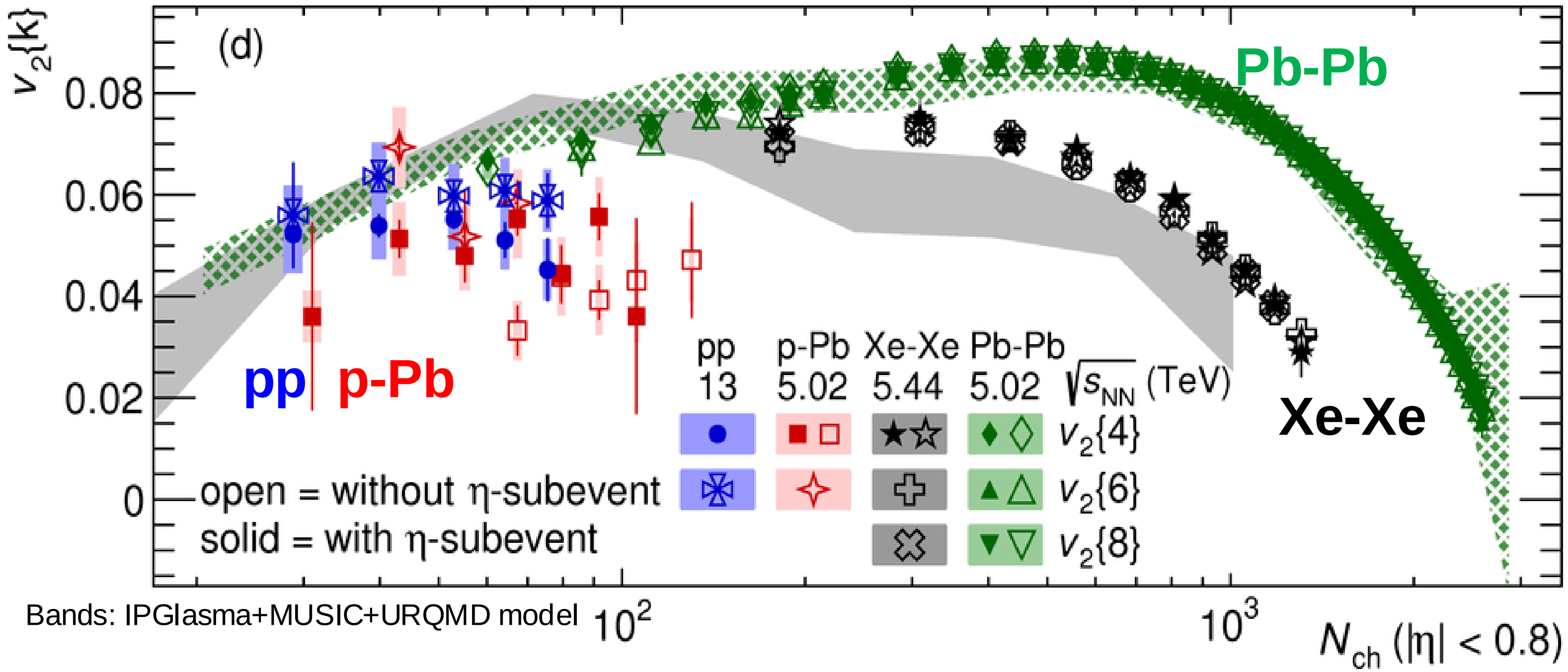
True collectivity correlates many particles

Elliptic flow by correlating multiplets of particles: $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} > 0$

- **subtract non-flow** phenomena as jets and other physical 2-particle correlations
- measure with **rapidity gap** (long η-range!)

  → *nota bene:* importance of broad η coverage!

Elliptic flow from multi-particle correlations in all systems



Bands: IPGlasma+MUSIC+URQMD model

ALICE, PRL 123, 142301 (2019)

OPEN QUESTION:
what is the origin of the observed collectivity in small systems?

Final state? Anisotropies, correlations via **multiple scatterings**
→ hydrodynamic flow [established in Pb-Pb collisions]

Initial state? From **momentum correlations** at partonic level [gluon saturation, Color Glass Condensate, ...]
E.g. Venugopalan, PRD 87, 094034 (2013) + ...

Characterization of fluid behaviour

Long wavelenghts ⇔ *long range correlations*
strong evidence of **fluid-like response**

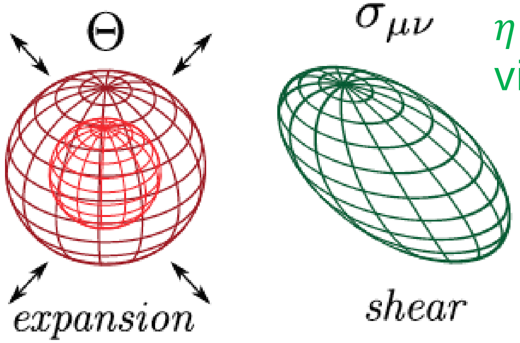
Theory: ***Relativistic viscous fluid dynamics***
accounts for collective dynamics in terms of QGP properties (EOS, transport coefficients) that are calculable from first principles in QFT.

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

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

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

ζ = Bulk viscosity



η = shear viscosity

κ = charge diffusion

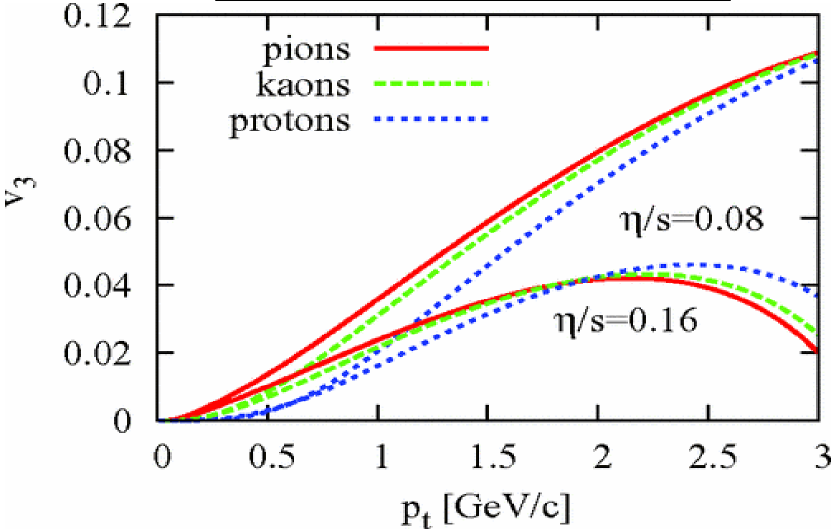
Figs. from Rezzolla and Zanotti, 2013

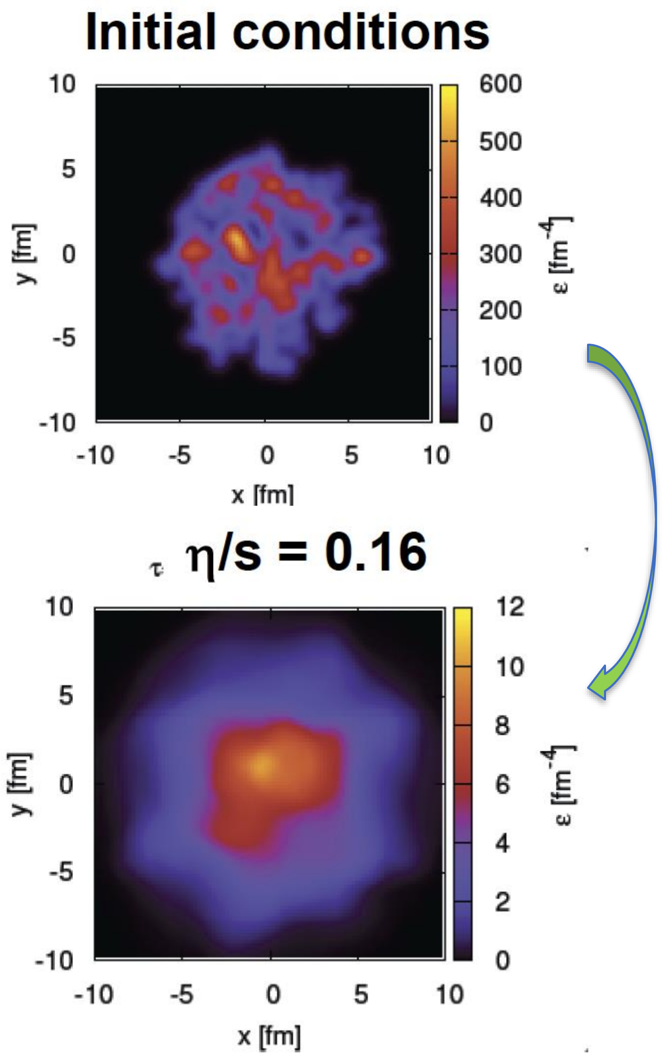
Characterization of fluid behaviour

Long wavelenghts ⇔ long range correlations
strong evidence of **fluid-like response**

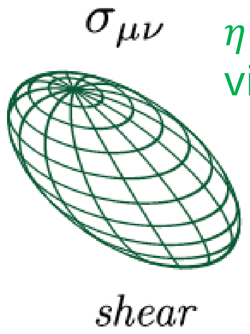
Theory: ***Relativistic viscous fluid dynamics*** accounts for collective dynamics in terms of QGP properties (EOS, transport coefficients) that are calculable from first principles in QFT.

Larger η/s reduces flow





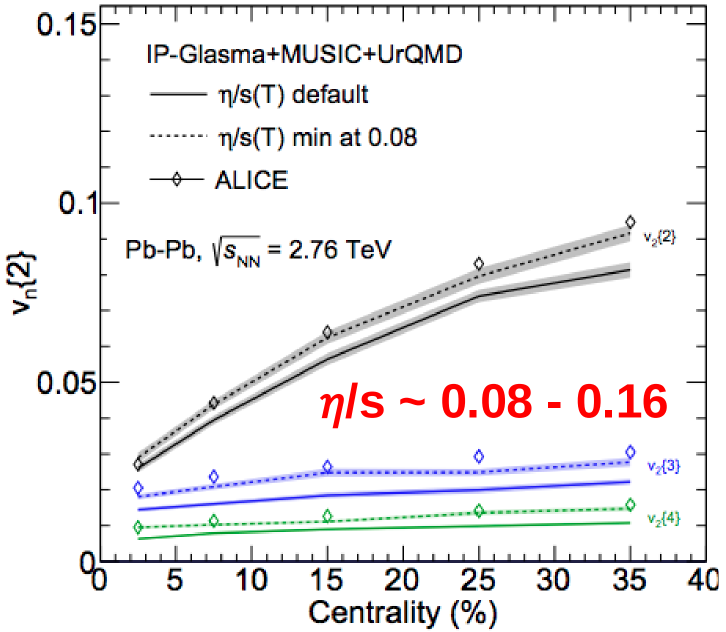
MUSIC, Sangyong Jeon



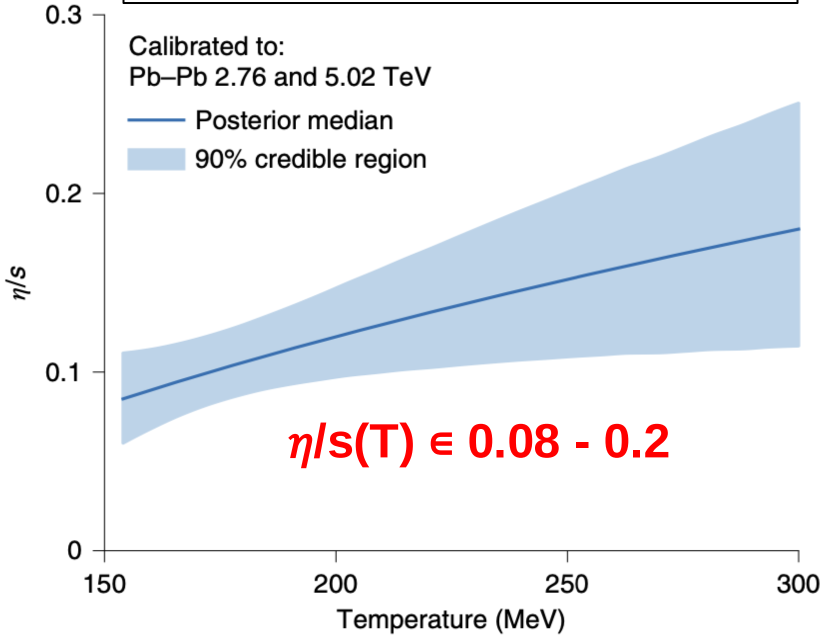
η = shear viscosity

What is the viscosity of QGP?

Hydro modelling

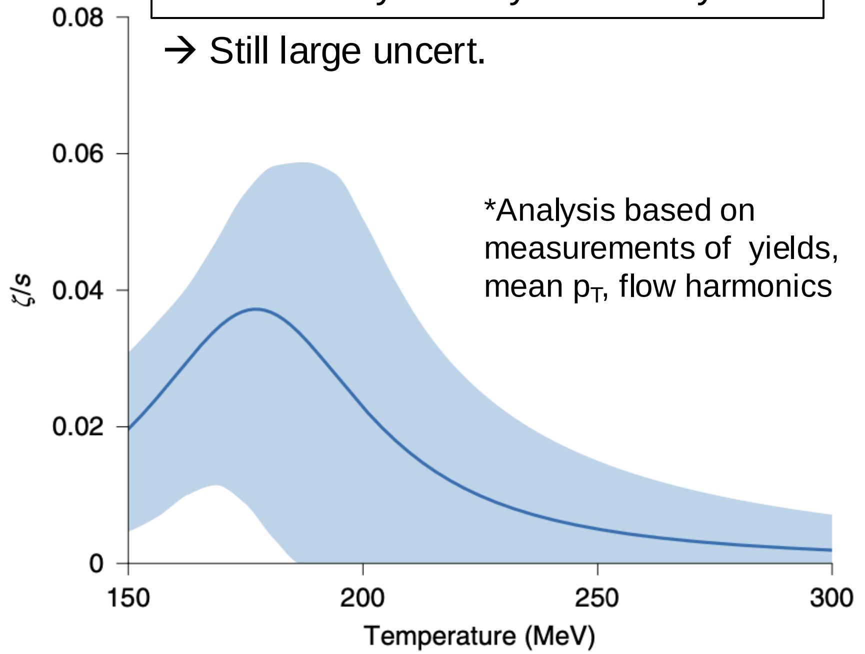


Shear viscosity via Bayesian analysis*



Bulk viscosity via Bayesian analysis*

→ Still large uncert.



*Analysis based on measurements of yields, mean p_T, flow harmonics

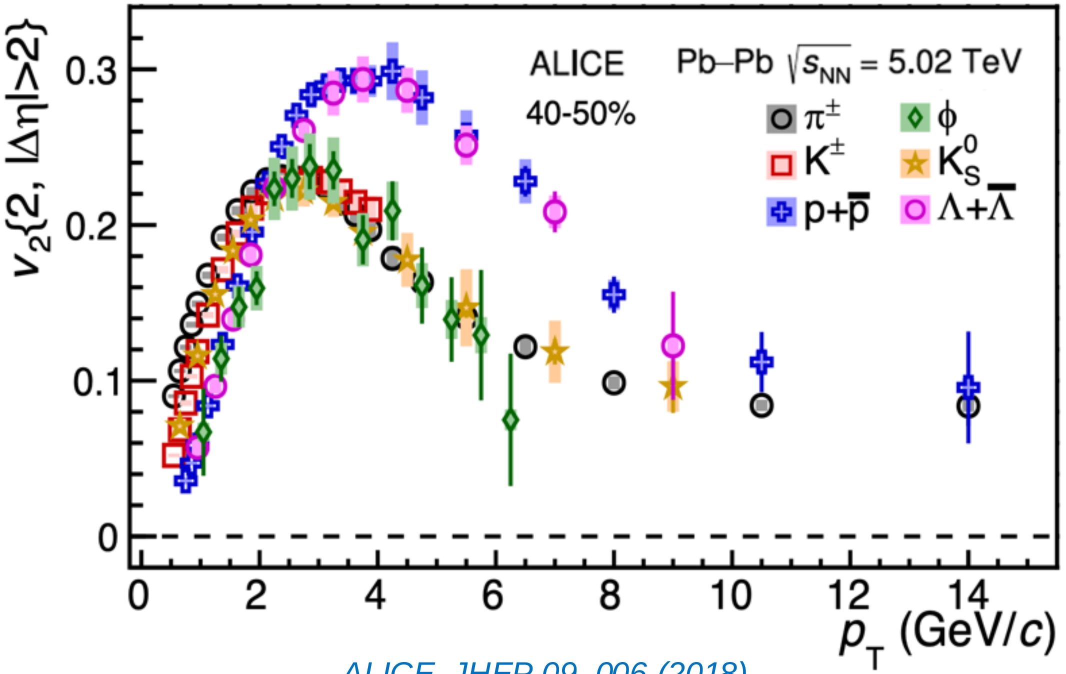
J. E. Bernhard et al, Nature Physics 15 (2019) 1113

Spectra and flow coefficients are well described by viscous hydrodynamics with a very low shear viscosity (**η/s ~ 0.08 – 0.16**), minimally dissipative effects

QGP close to a perfect fluid

Flow of identified hadrons in large systems

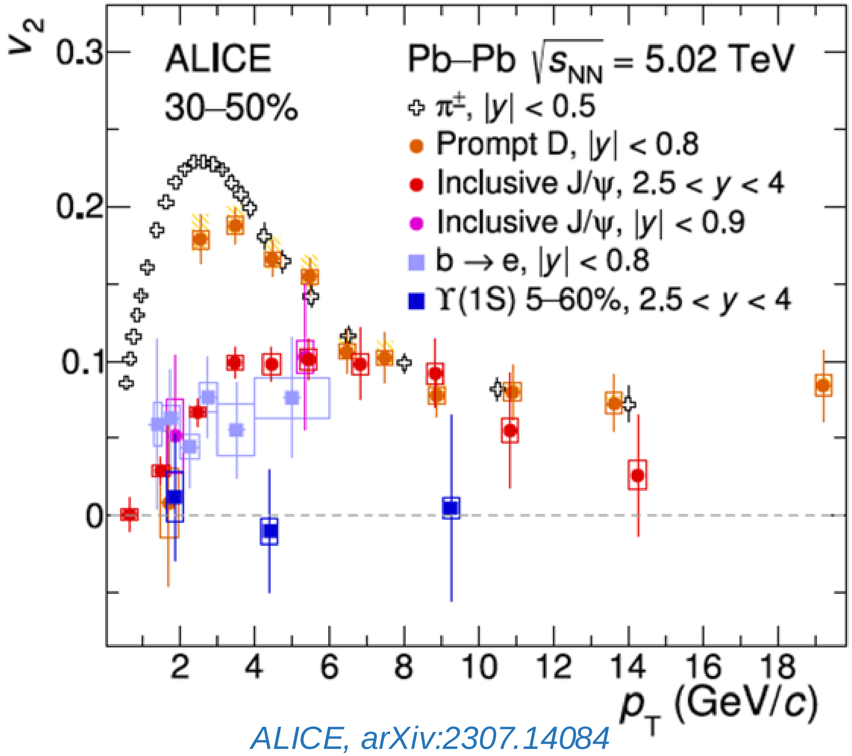
Light flavour hadrons exibit ''textbook'' flow
- Mass dependence at low p_T
- Interplay of production mechanisms at mid-p_T (baryon/meson splitting → recombination)



ALICE, JHEP 09, 006 (2018)

Charm $v_2 > 0$
- **charm partially thermalised** with the QGP
- recombination with LF at hadronisation

No significant evidence of flow of beauty



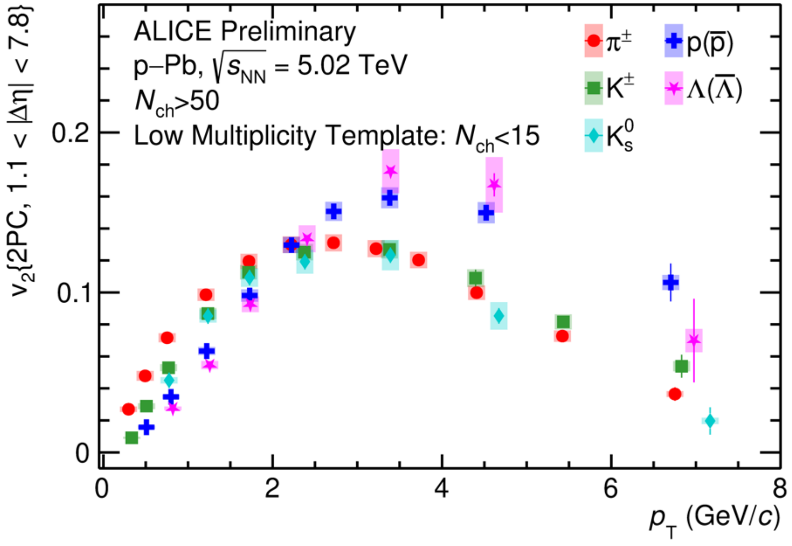
ALICE, arXiv:2307.14084

Identified particle flow v_2 in small systems

v_2>0 for LF and HF hadrons, with features reminding of Pb-Pb collisions

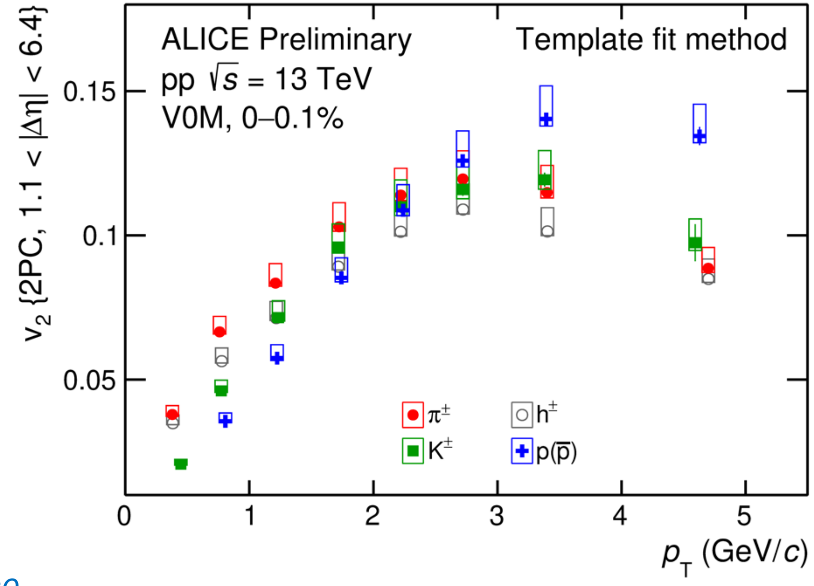
- mass scaling at low p_T
- consistency with hydrodynamics *(though worse than in Pb-Pb → Devil's in the details: bulk viscosity, initial stage…)*

Light and strange in p-Pb

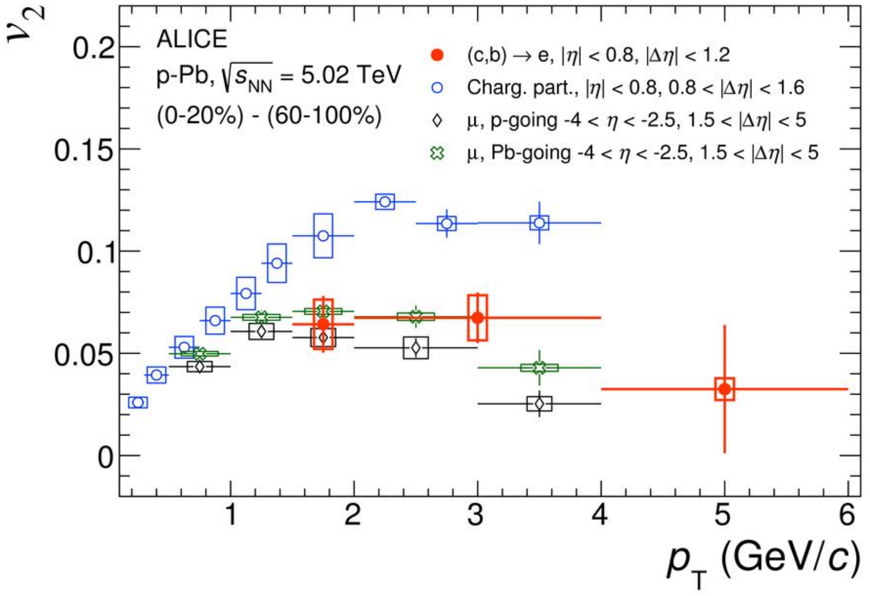


+ ALICE, PLB 726 (2013) 164-177, PLB 780 (2018) 7-20

Light and strange in pp HM



charm and beauty in p-Pb



ALICE, PRL122, 072301 (2019)

Runs 3+4 - More charm and beauty

High-lumi

Higher precision for rarer probes

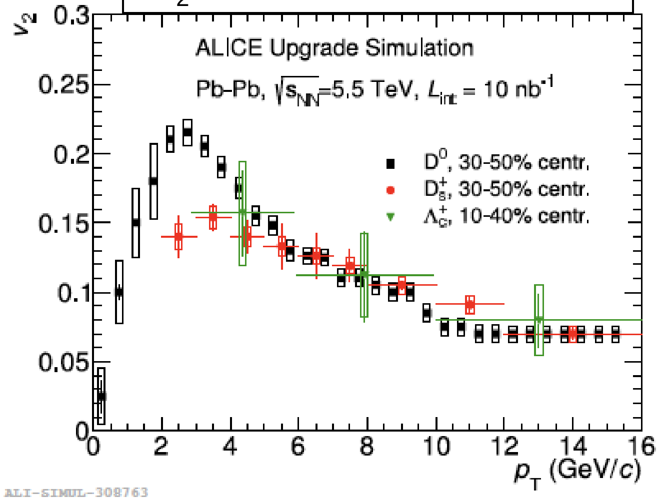
- Low-p_T production
- v_2 of several HF hadron species
- b at fwd-y down to zero p_T (mainly ALICE)
- B hadrons and b-jets (mainly ATLAS, CMS)

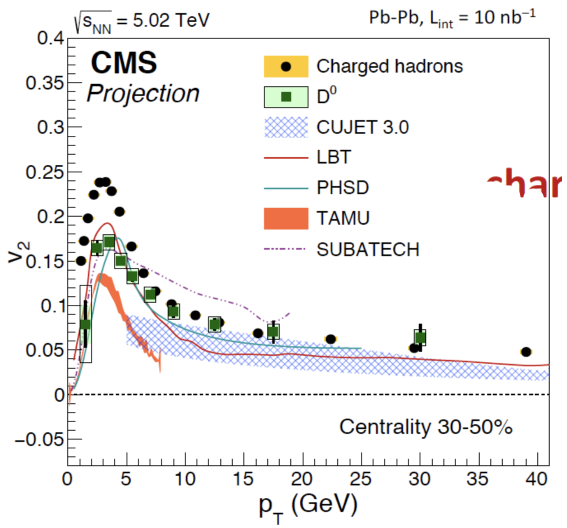
→ Study mass dependence of **energy loss**, in-medium **thermalization** of heavy-flavours

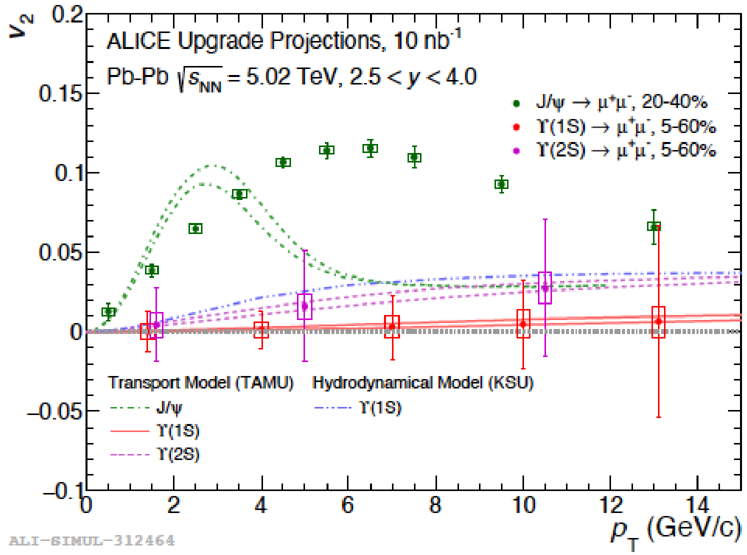
→ Access to the **medium transport properties,** e.g. charm diffusion coefficient, linked to charm equilibration time

$$\tau_Q = \frac{m_Q}{T} D_s$$

v_2 in charm sector – Pb-Pb







v_2 in beauty sector

High-lumi

Runs 3+4 - More charm and beauty

Higher precision for rarer probes

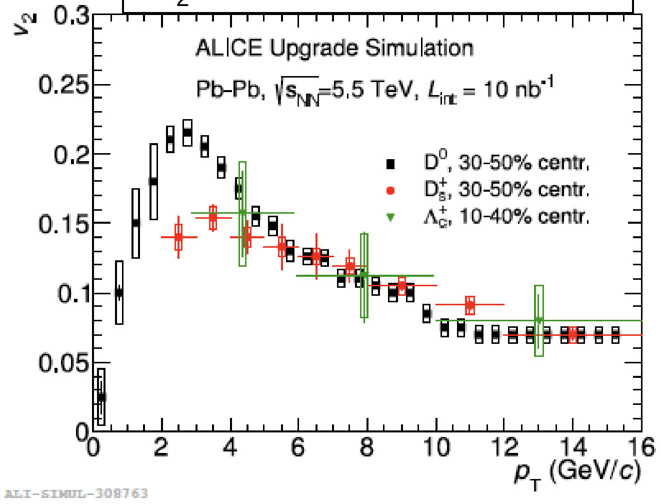
- Low-p_T production
- v_2 of several HF hadron species
- b at fwd-y down to zero p_T (mainly ALICE)
- B hadrons and b-jets (mainly ATLAS, CMS)

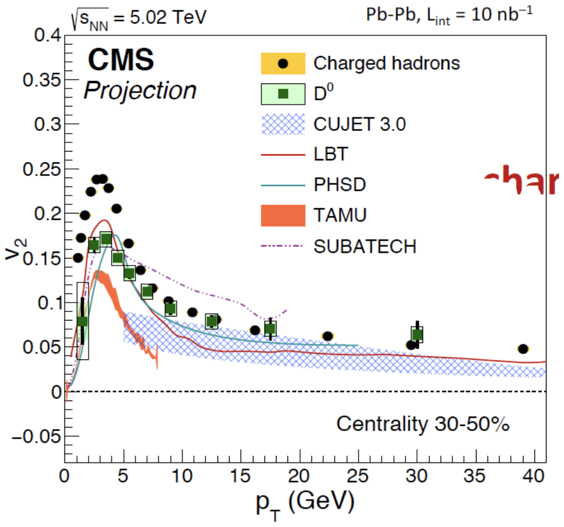
→ Study mass dependence of **energy loss**, in-medium **thermalization** of heavy-flavours

→ Access to the **medium transport properties,** e.g. charm diffusion coefficient, linked to charm equilibration time

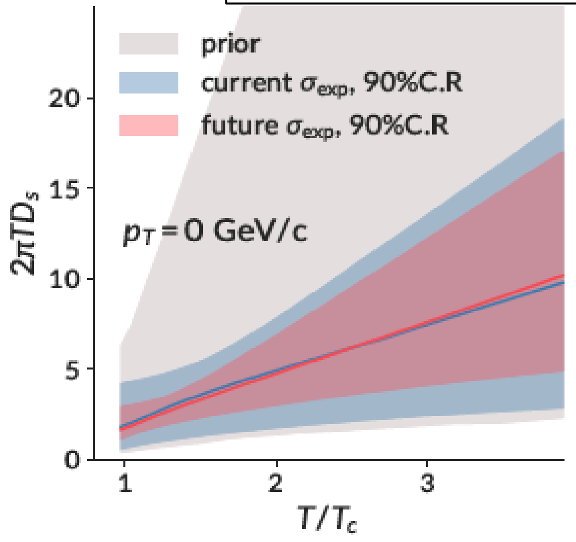
$$\tau_Q = \frac{m_Q}{T} D_s$$

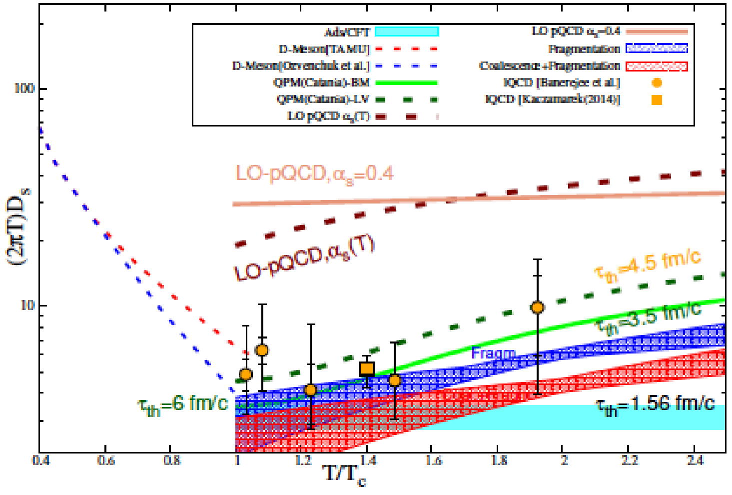
v_2 in charm sector – Pb-Pb





Projections for extraction of charm diffusion coefficient



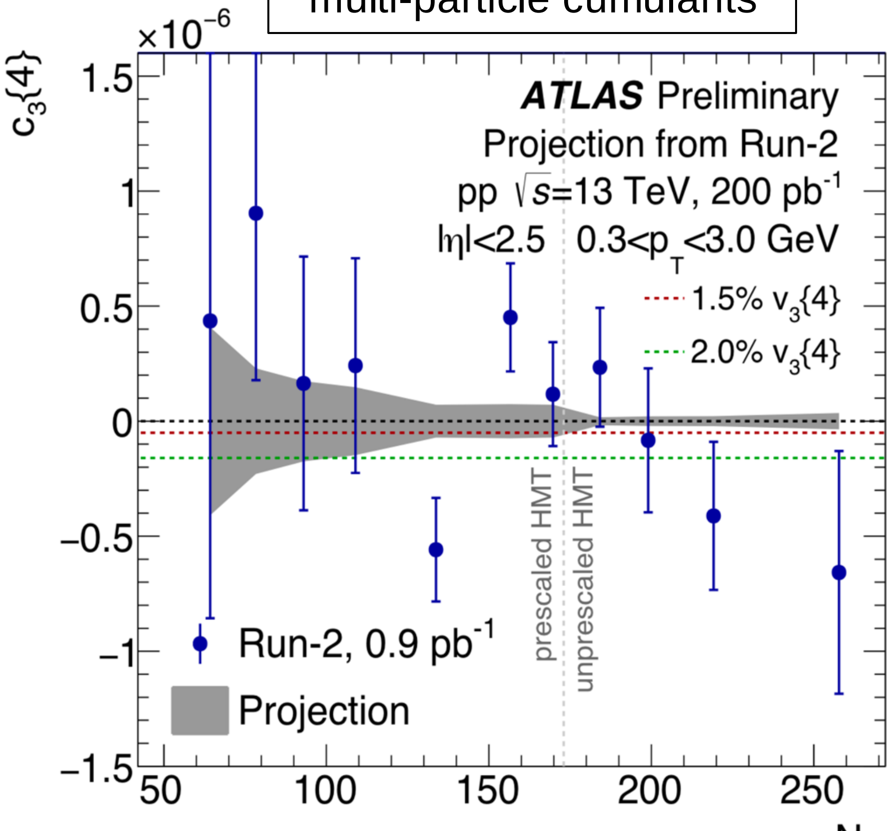


Runs 3+4 - More flow

High-lumi

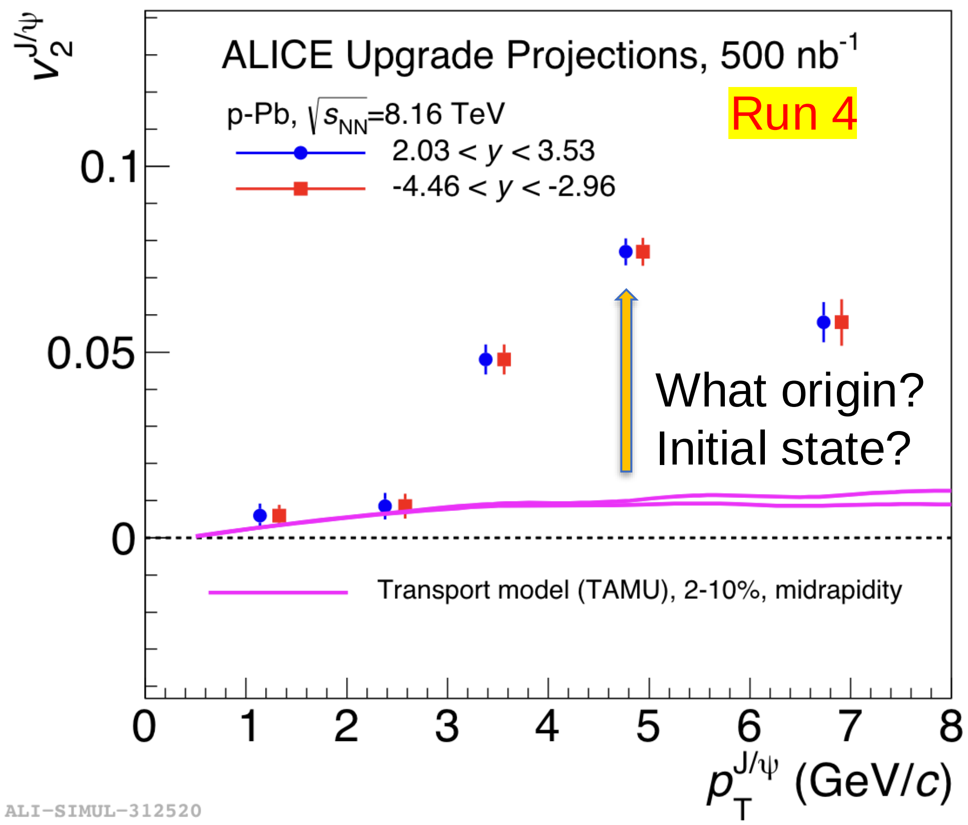
- v_2 of HF in small systems
- flow from multi-particle cumulants

multi-particle cumulants



ATL-PHYS-PUB-2018-020

v₂ of charm - small systems



Light flavour hadrons from QGP hadronisation

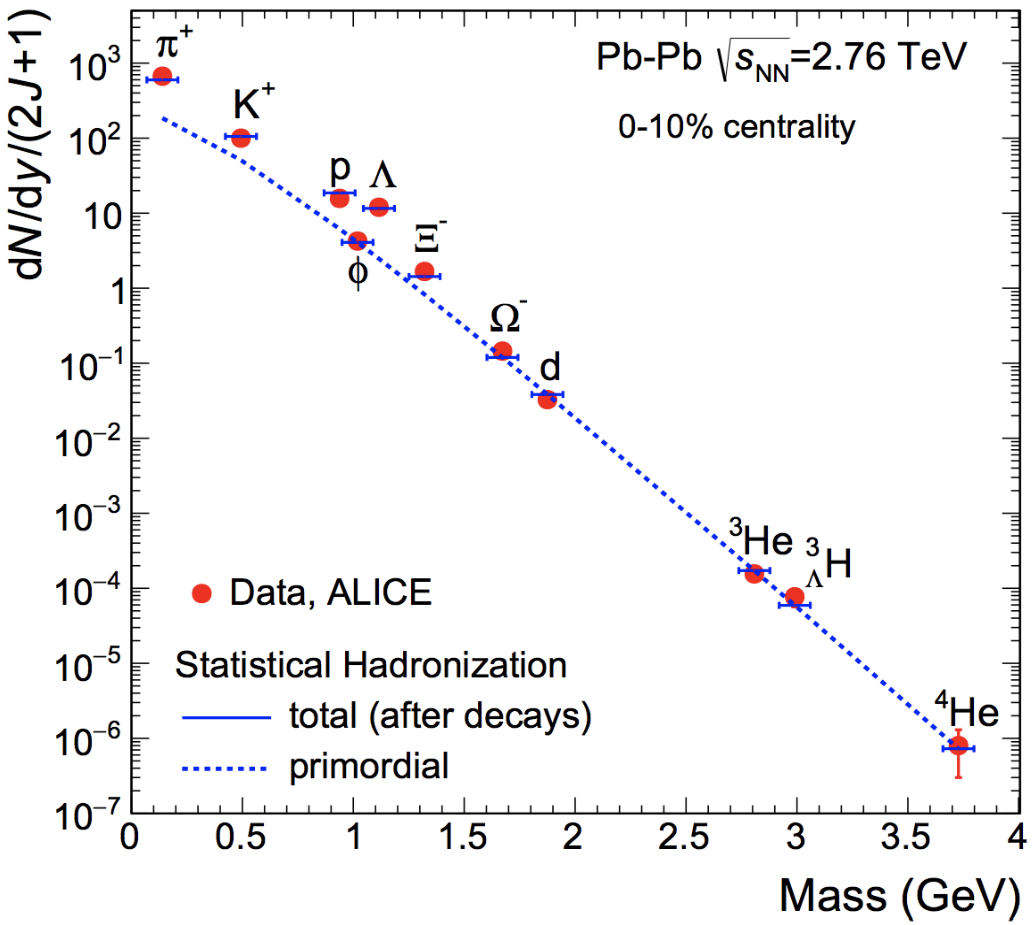
Success of the statistical hadronization model (chemical equilibrium) in describing yields of light flavour hadron species over 10 orders of magnitude in central Pb-Pb collisions

(including strangeness, light nuclei and hypernuclei)

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

$T_{\text{chemical}} \sim 155$ MeV

Nota bene: Close to the limiting temperature for hadrons to exist:
T_{pc} = (156.5 ± 1.5) MeV predicted by lattice QCD



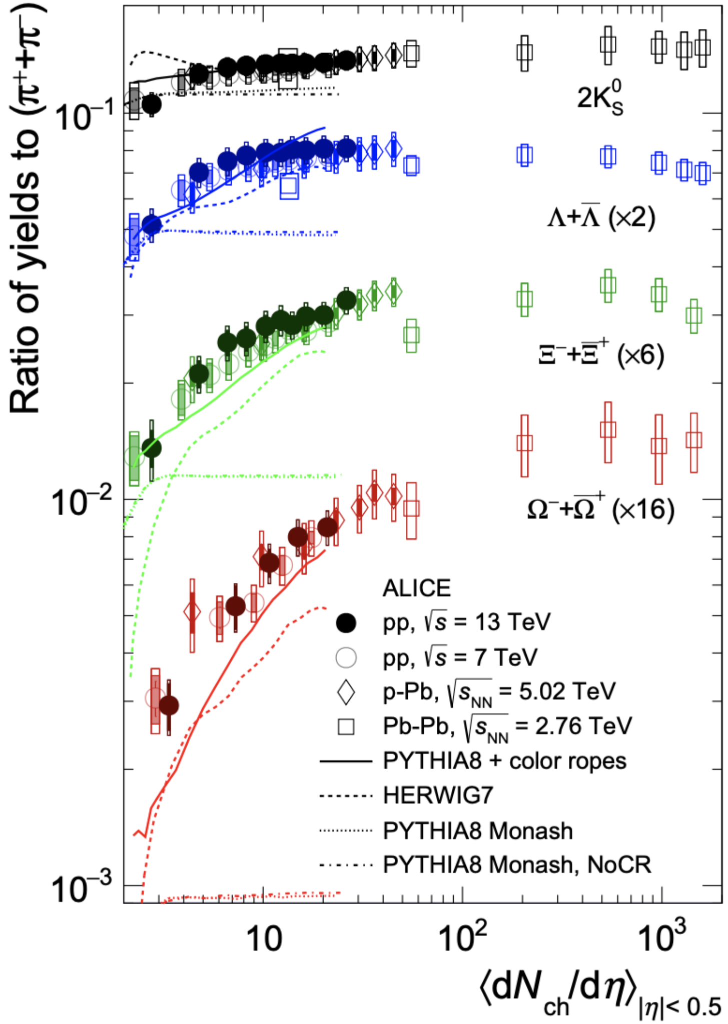
Andronic et al., Nature 561, 321 (2018)
Data from ALICE, see also ALICE, EPJC 84 (2024) 813

Strangeness production in pp, p-Pb

discovery at the LHC!

Increase of (multi)strange to non-strange yield ratios 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 (production by thermalised gluon fusion in QGP)



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

Strangeness production in pp, p-Pb

Increase of (multi)strange to non-strange yield ratios with multiplicity in pp and p-Pb collisions until saturation in Pb-Pb

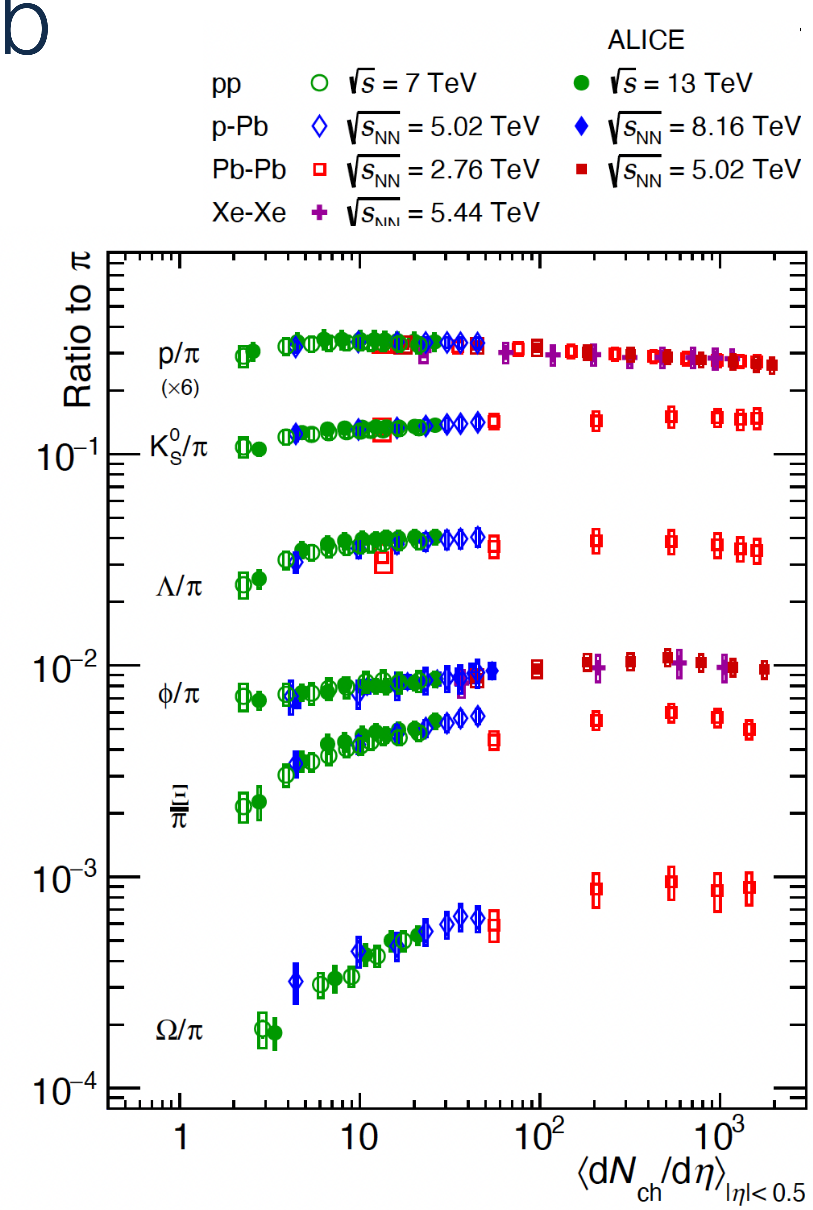
- strangeness enhancement relative to pp suggested in the 1980's as QGP signature (production by thermalised gluon fusion in QGP)

→ **Smooth evolution of hadrochemistry** across collision systems, chiefly **driven by multiplicity**

Similarities (collective behaviour) across systems
→ **common hadron production mechanism?**

Advocates for a unification of the theoretical description under a "small-to-large" or "large-to-small" paradigm.

A point of no return (?)



ALICE, EPJC 84 (2024) 813

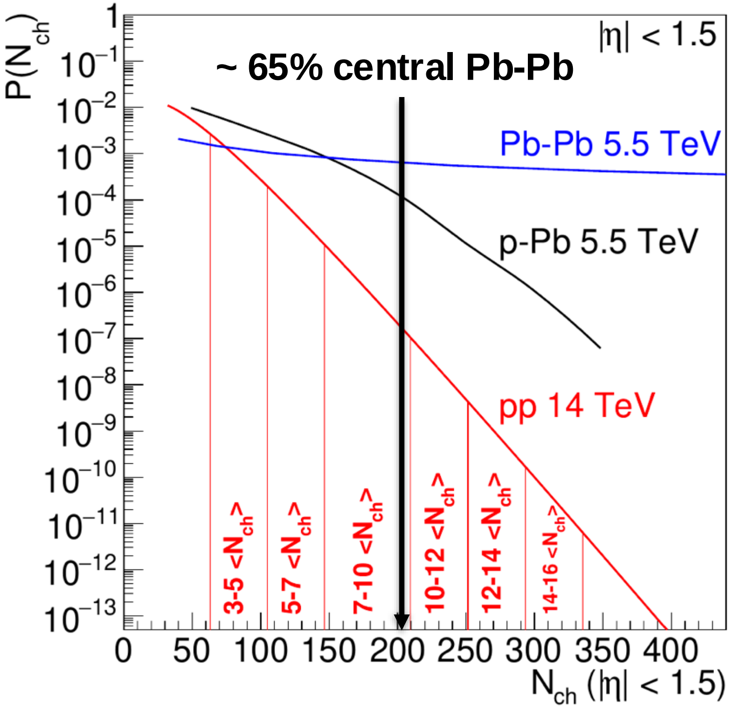
Runs 3+4 - A "small systems" programme

High-lumi

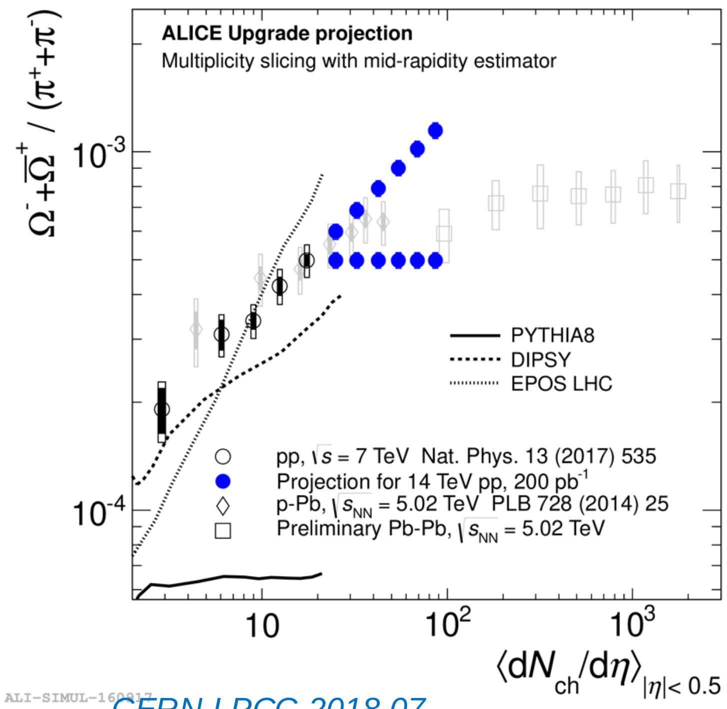
- systematic study of "QGP signals" in pp, p-Pb and Pb-Pb, p-O and O-O
- **Very high multiplicity pp overlap with up to 65% central Pb-Pb collisions!**
- study collectivity, strangeness/chemistry, hadronisation

→ search for the **onset of QGP-like features**

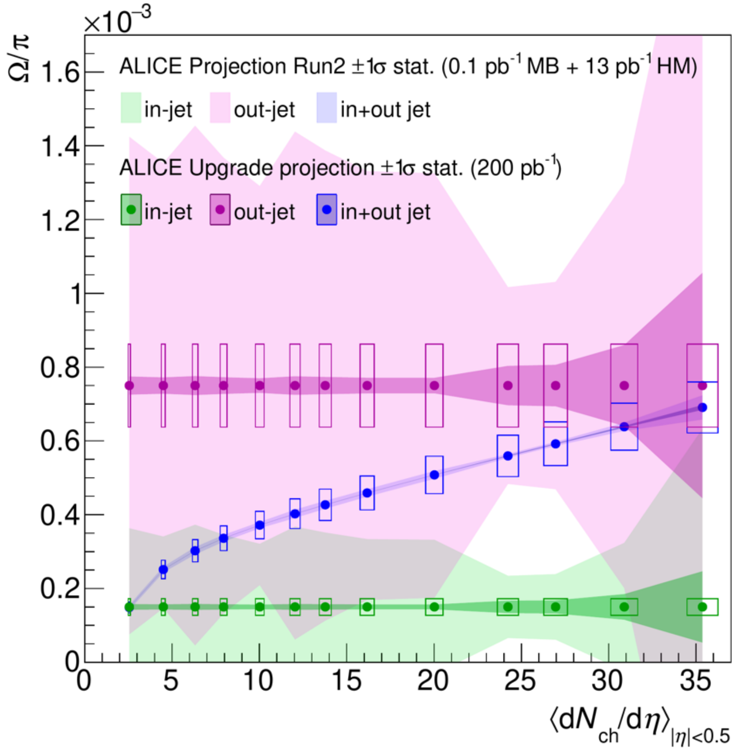
Beware of selection biases!!!
→ ALICE 3 (wider acceptance) > Run4



CERN-LHCC-2020-018



CERN-LPCC-2018-07

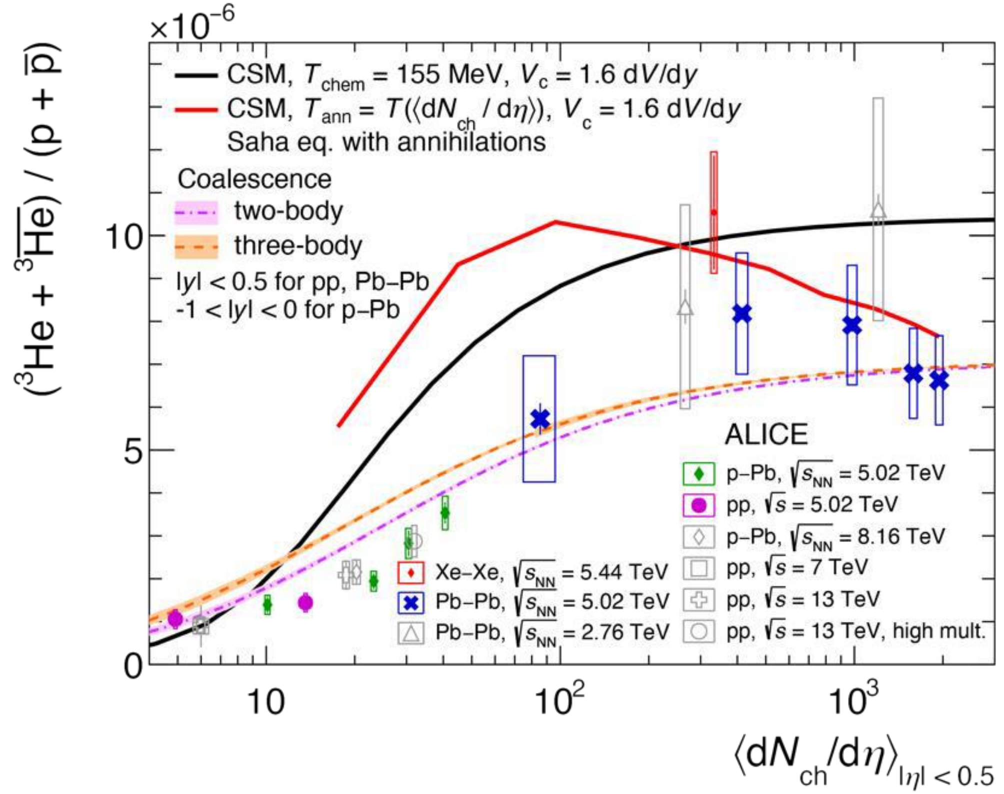


Production of loosely-bound light (anti)nuclei

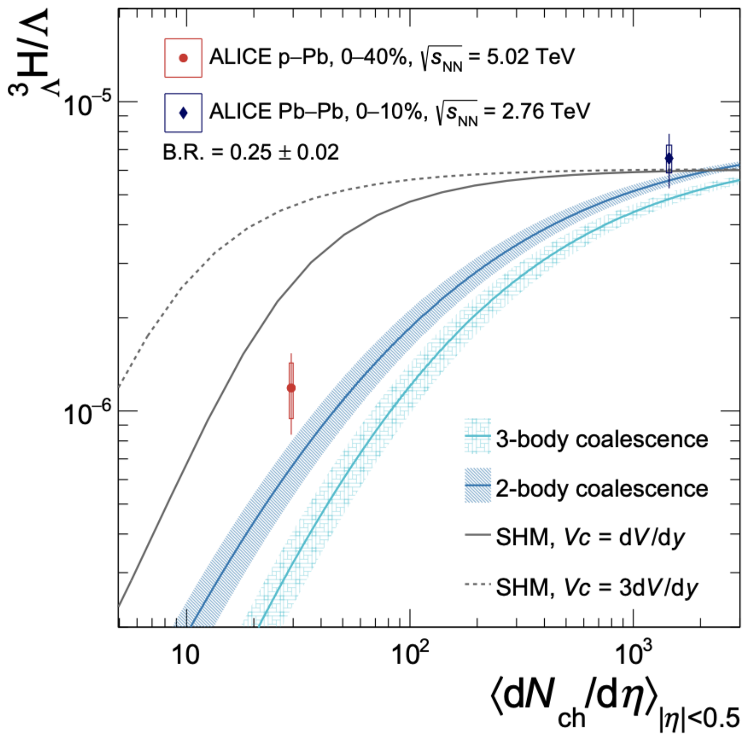
Smooth evolution as a function of the system size from pp to Pb-Pb

→ puzzle of the **survival of loosely bound states** (E_B ~ 2 MeV) in HIC hadron gas (T ~ 150-100 MeV)

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



ALICE, arXiv:2405.19826



ALICE, PRL 128 (2022) 252003

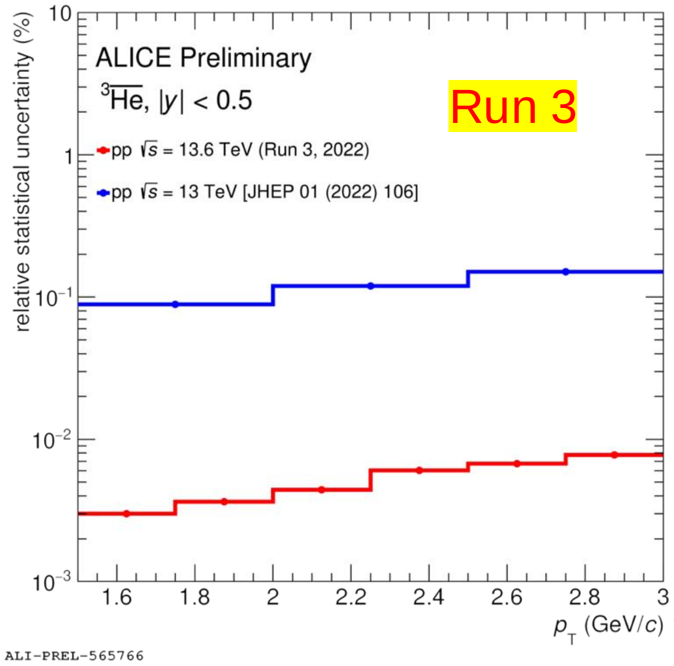
key test with hypertriton (Λpn): loosely bound (B_Λ~ 130 keV) and large (r ~ 10-14 fm)

Runs 3+4: (anti)(hyper)nuclei

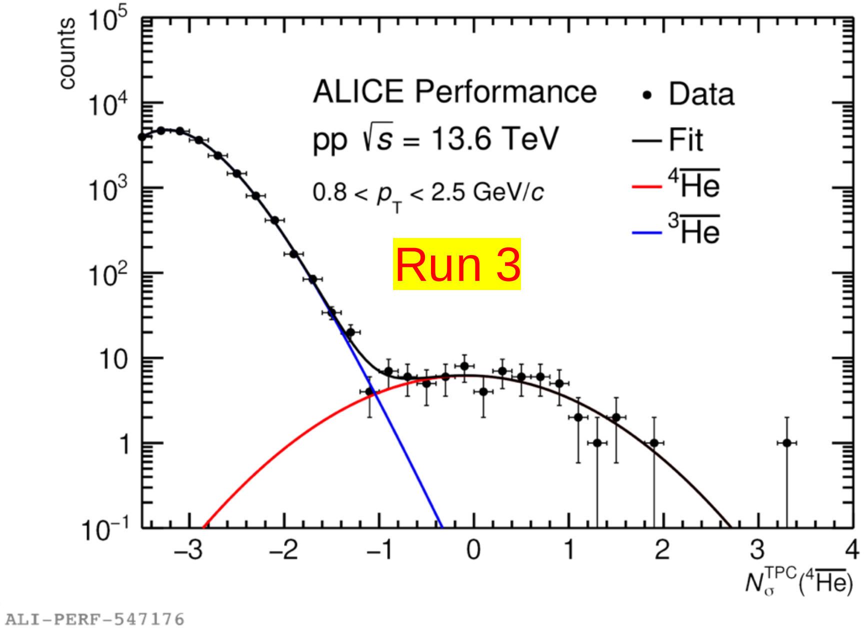
High-lumi

- More A=3 and A=4 states from **small to large** systems + discovery of A=4,5 anti-hypernuclei
- Clarify **formation mechanisms** of nuclear bound states from a dense partonic state
- Determine $\boldsymbol{T_{ch}}$ even more precisely

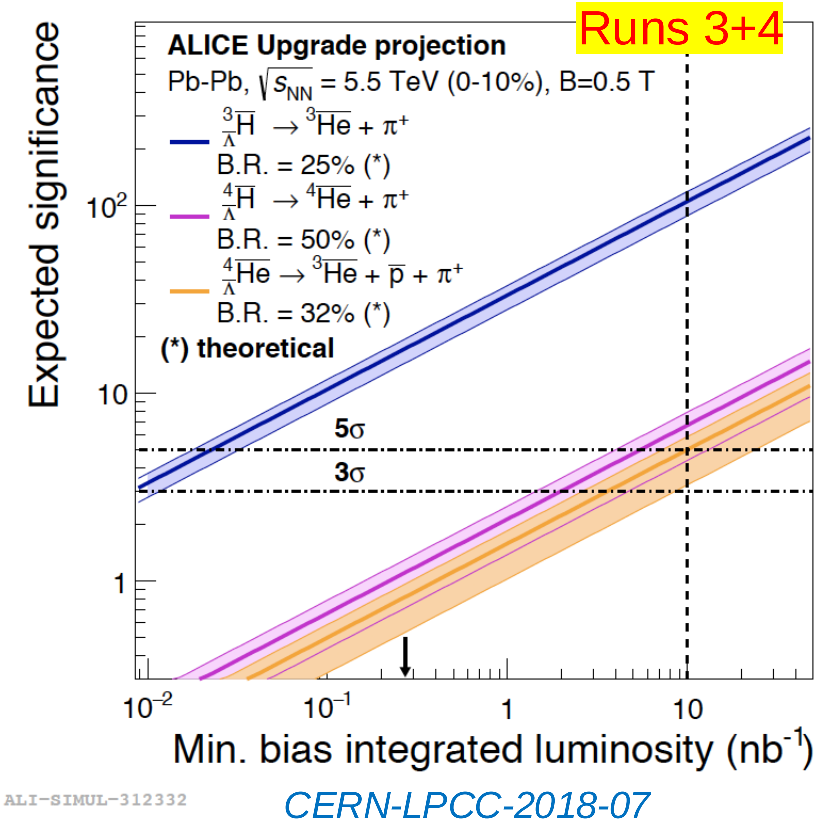
+ Beyond HIC: astrophysics and hadron physics



A=3 in Run 3 pp with similar stat. precison as A=2 in Run 2



First anti-alpha in pp in Run 3



CERN-LPCC-2018-07

Instead of a full summary, the open questions…

We have entered the **precision era** for the **quantitative** characterization of QGP properties
and the study of **QGP phenomena emerging from QCD at high densities.**

The study of **collectivity from large to small systems is a central topic in Runs 3+4** and HL phase
→ will have a strong impact on the future programme beyond Run4!!!

What is the origin of the observed emerging collectivity from small to large systems?

What are the limits of QGP formation?

How do collective phenomena and macroscopic properties of matter arise from the fundamental interaction of QCD?

Thank you!

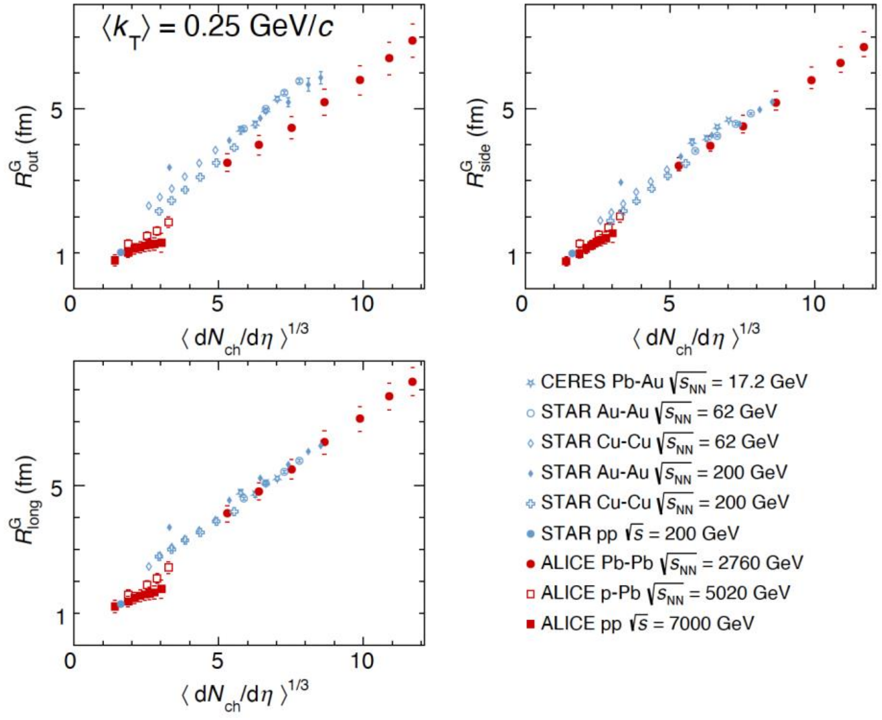
Contact: francesca.bellini@bo.infn.it

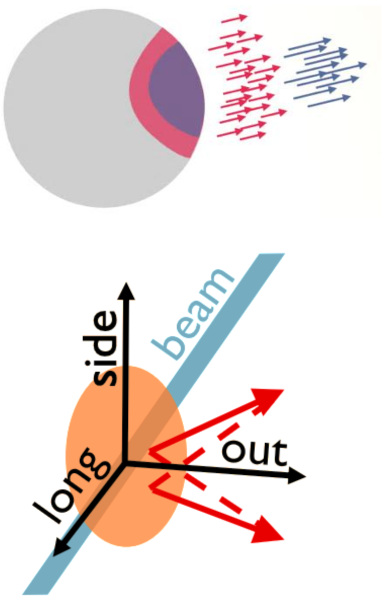
Space-time extension of the heavy-ion source

2- and 3-particle correlations allows to ‘’measure’’ the particle-emitting source size **at freeze-out**

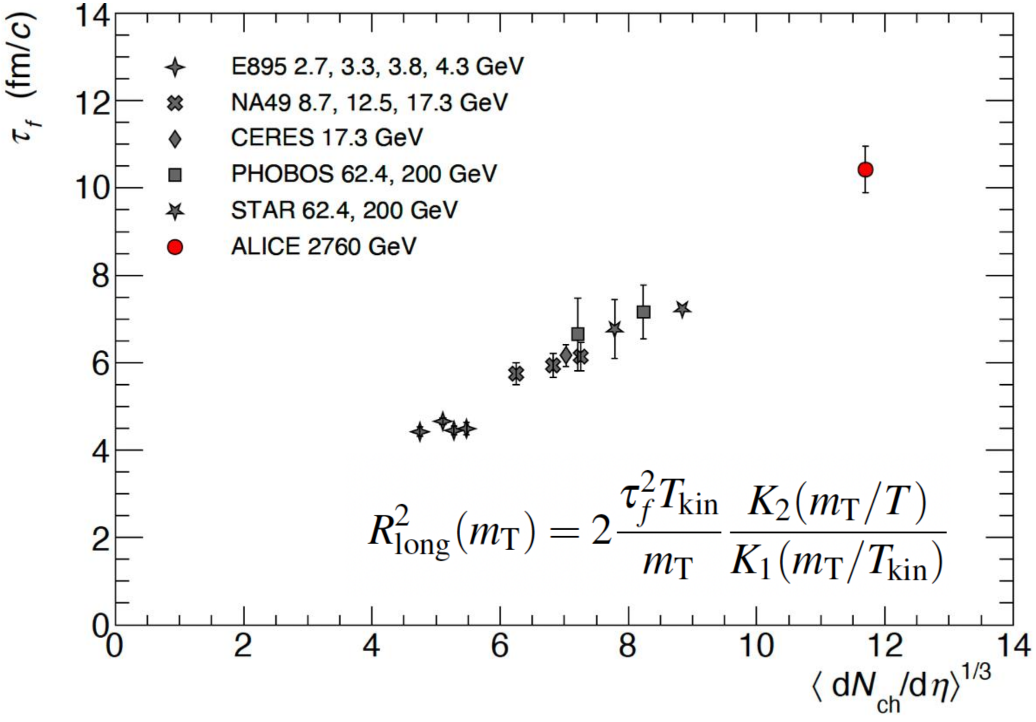
- Requires theoretical modelling of the h-h interaction (not available for all particle species!)
- Needs to account for collective effects → k_T and m_T dependence
- From 1D to 3D → requires large statistics

3D radii from Two-pion femtoscopy





Decoupling time from two-pion femtoscopy



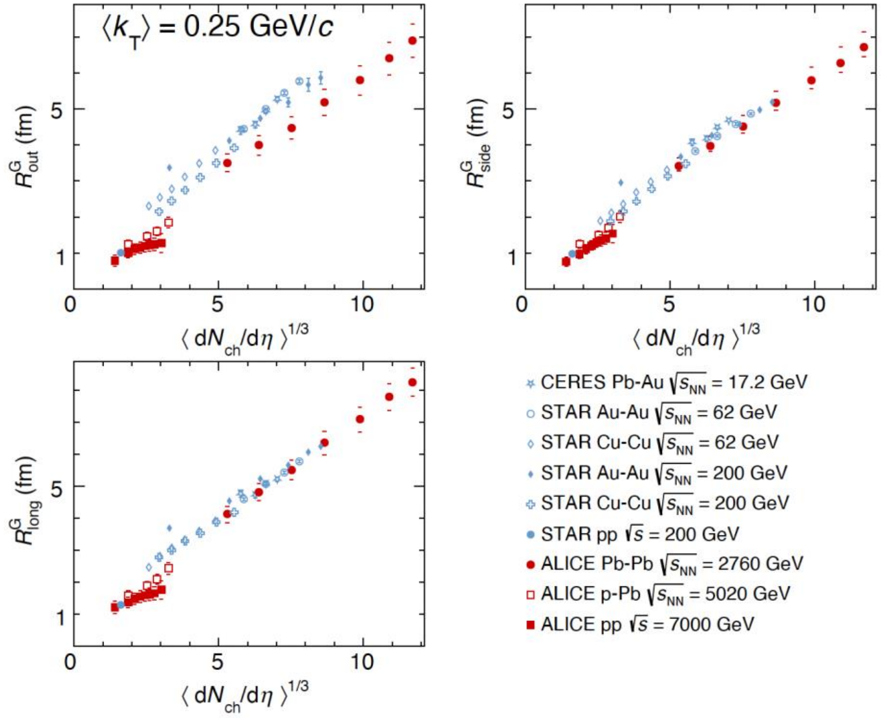
$$R^2_{\mathrm{long}}(m_{\mathrm{T}}) = 2\frac{\tau_f^2 T_{\mathrm{kin}}}{m_{\mathrm{T}}}\frac{K_2(m_{\mathrm{T}}/T)}{K_1(m_{\mathrm{T}}/T_{\mathrm{kin}})}$$

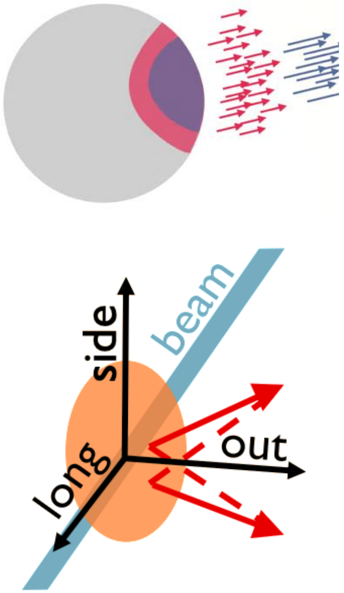
Space-time extension of the heavy-ion source

2- and 3-particle correlations allows to ‘’measure’’ the particle-emitting source size **at freeze-out**

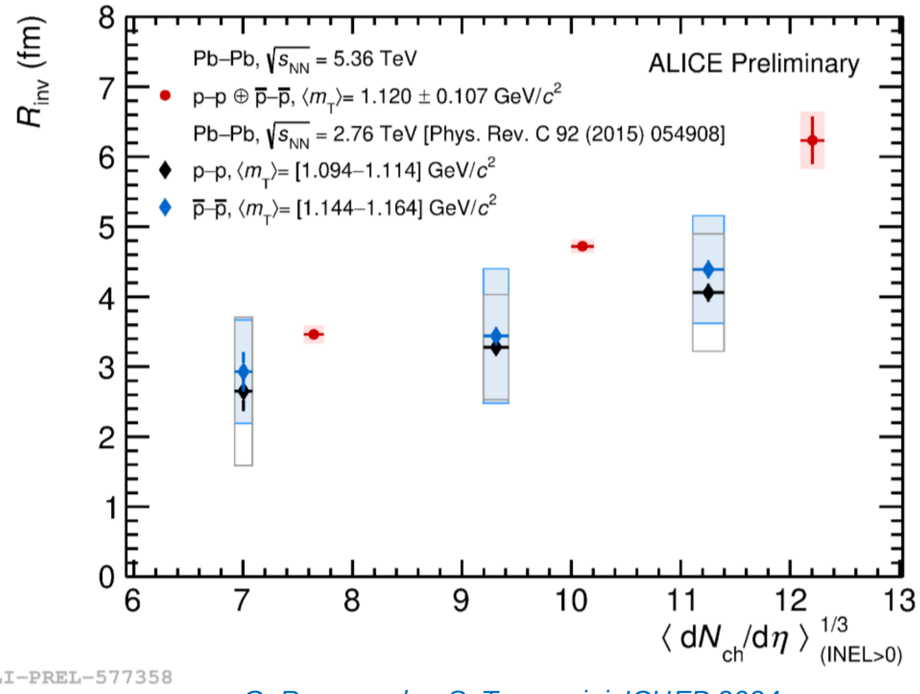
- Requires theoretical modelling of the h-h interaction (not available for all particle species!)
- Needs to account for collective effects → k_T and m_T dependence
- From 1D to 3D → requires large statistics

3D radii from Two-pion femtoscopy





Run 3: proton source



G. Romanenko, S. Tomassini, ICHEP 2024

Accessing the strong potential among hadrons

Two-particle femtoscopic correlations provide information about

⟶ final-state interactions among hadrons

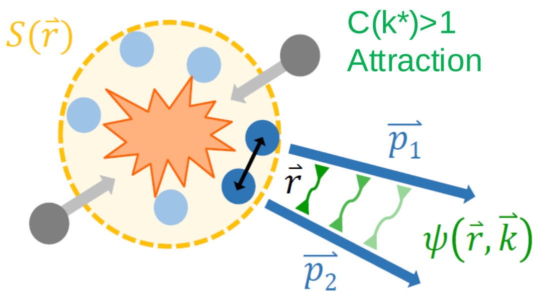
⟶ direct comparison to ab initio **QCD calculations**

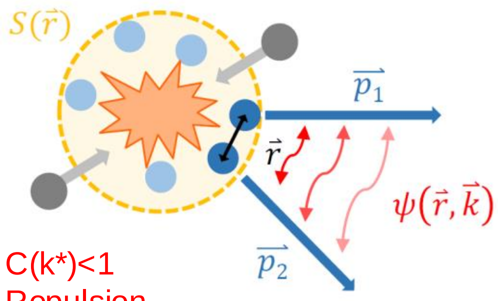
⟶ **source** size and lifetime

⟶ **bound states** (e.g. light nuclei, hypernuclei)

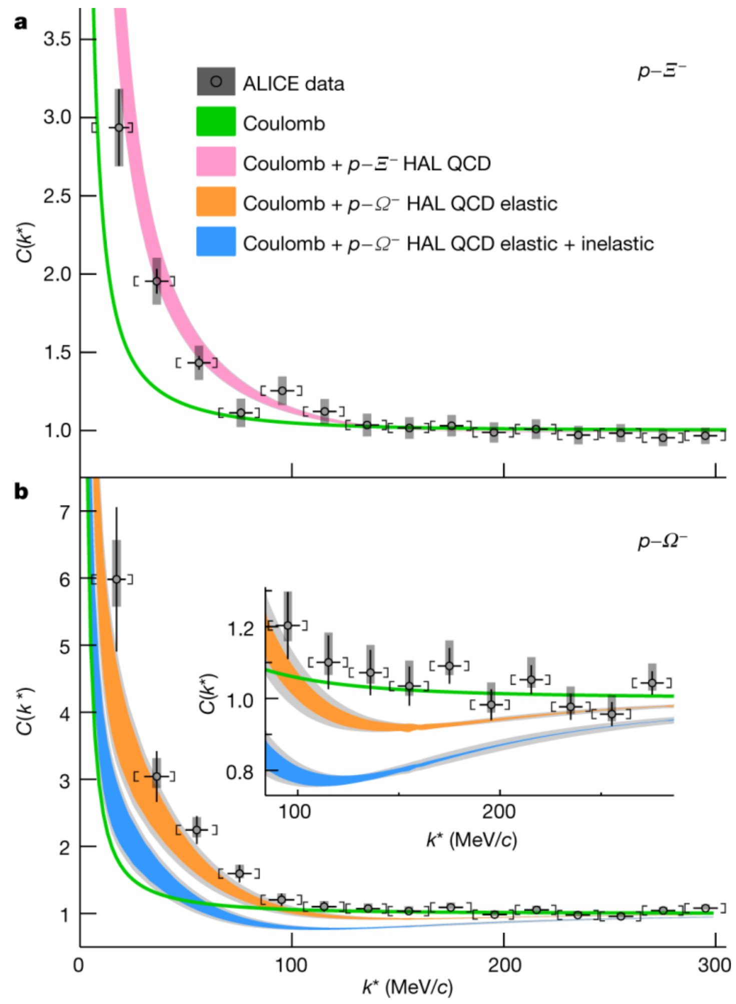
A new and comprehensive programme of measurements in pp, p-A, AA at the LHC to **study of the residual strong interaction among (strange) hadrons and Y-N interaction**

+ Beyond HIC: neutron stars and hadron physics



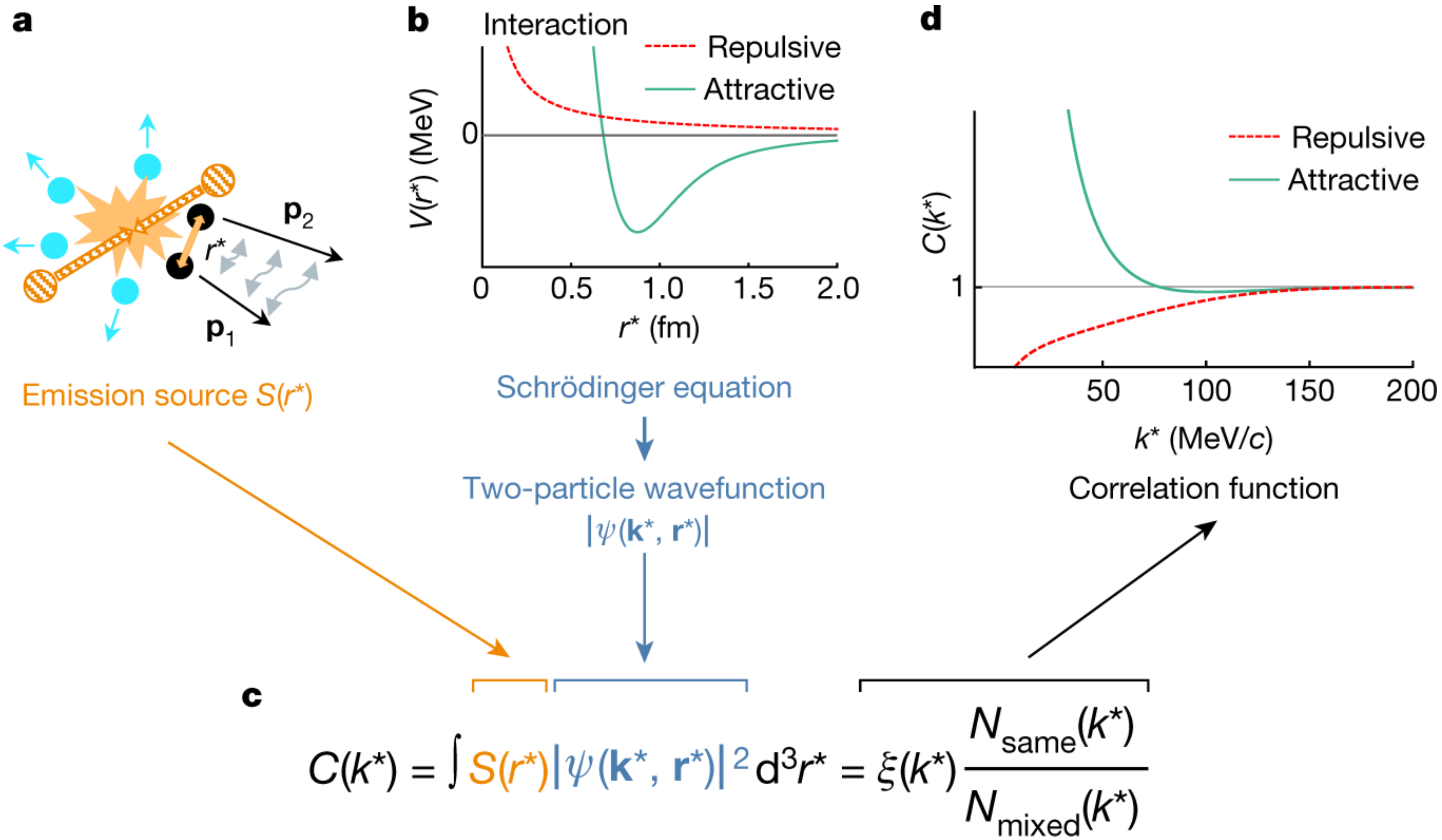


p–Ξ⁻ and p–Ω⁻ correlation functions



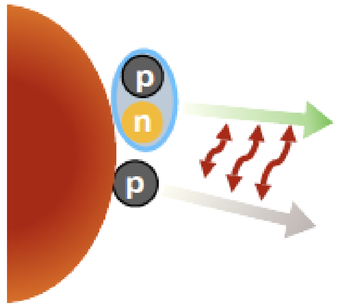
ALICE, Nature 588 (2020) 232–238

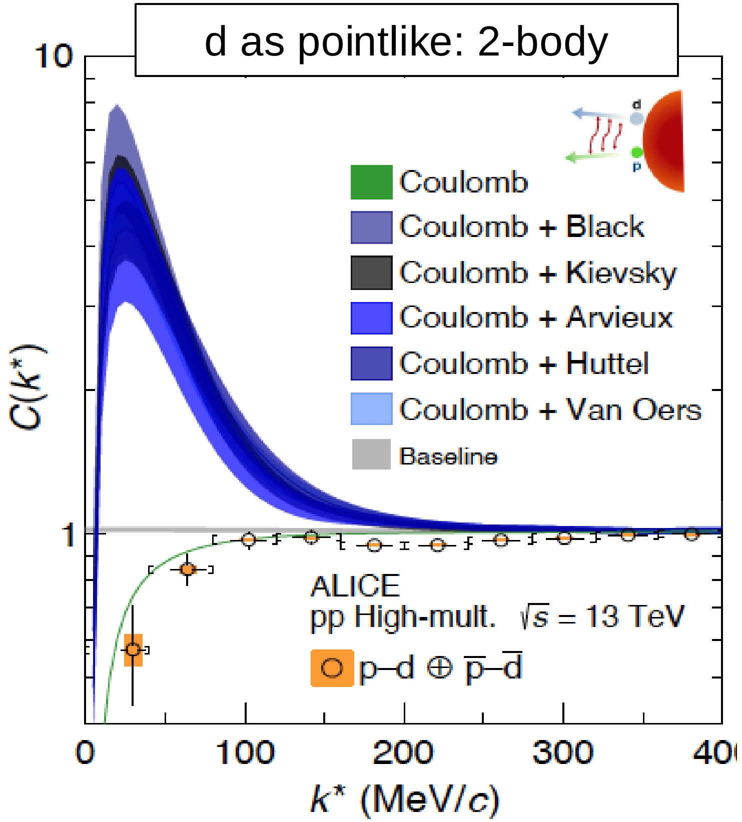
Femtoscopy technique

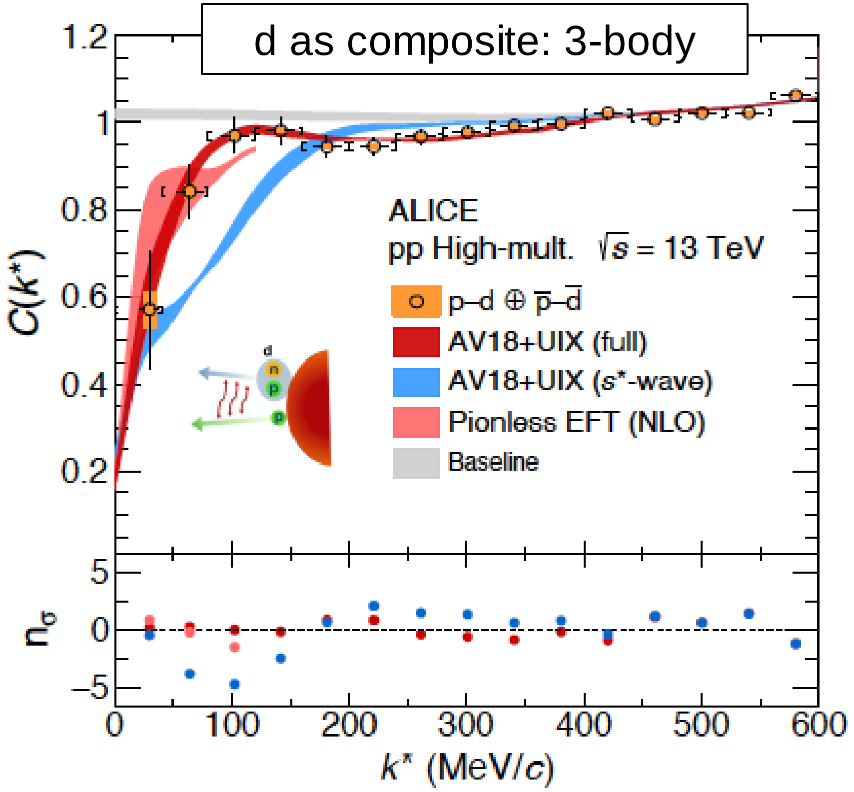


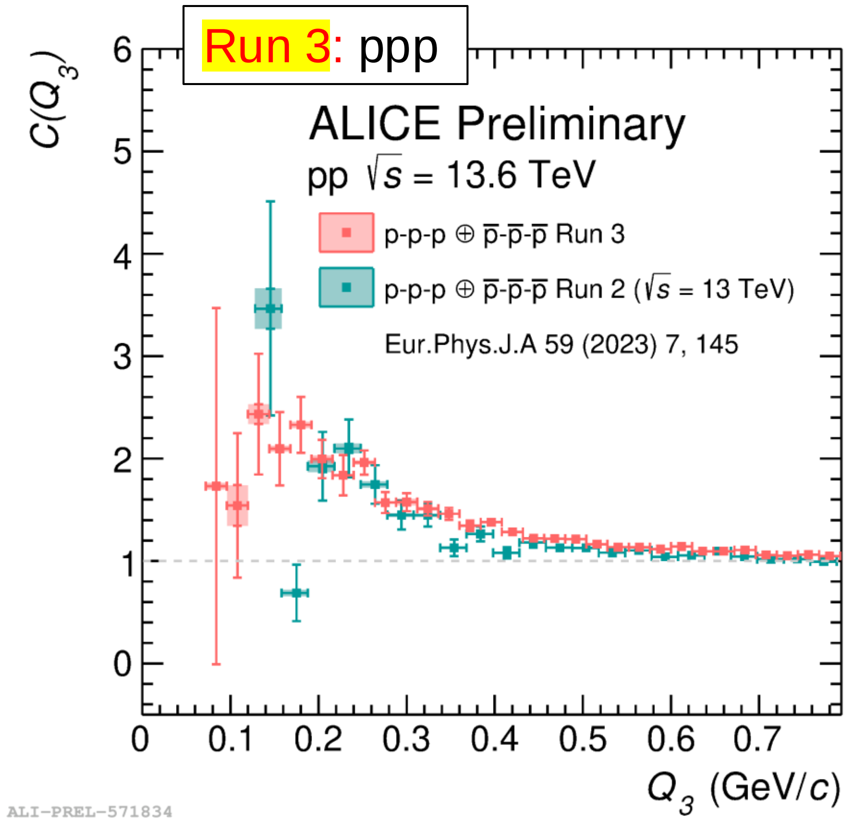
p-d as a three-body system

The p-d correlations is reproduced by treating the deuteron as a composite particle
→ access to the genuine three-body interaction!



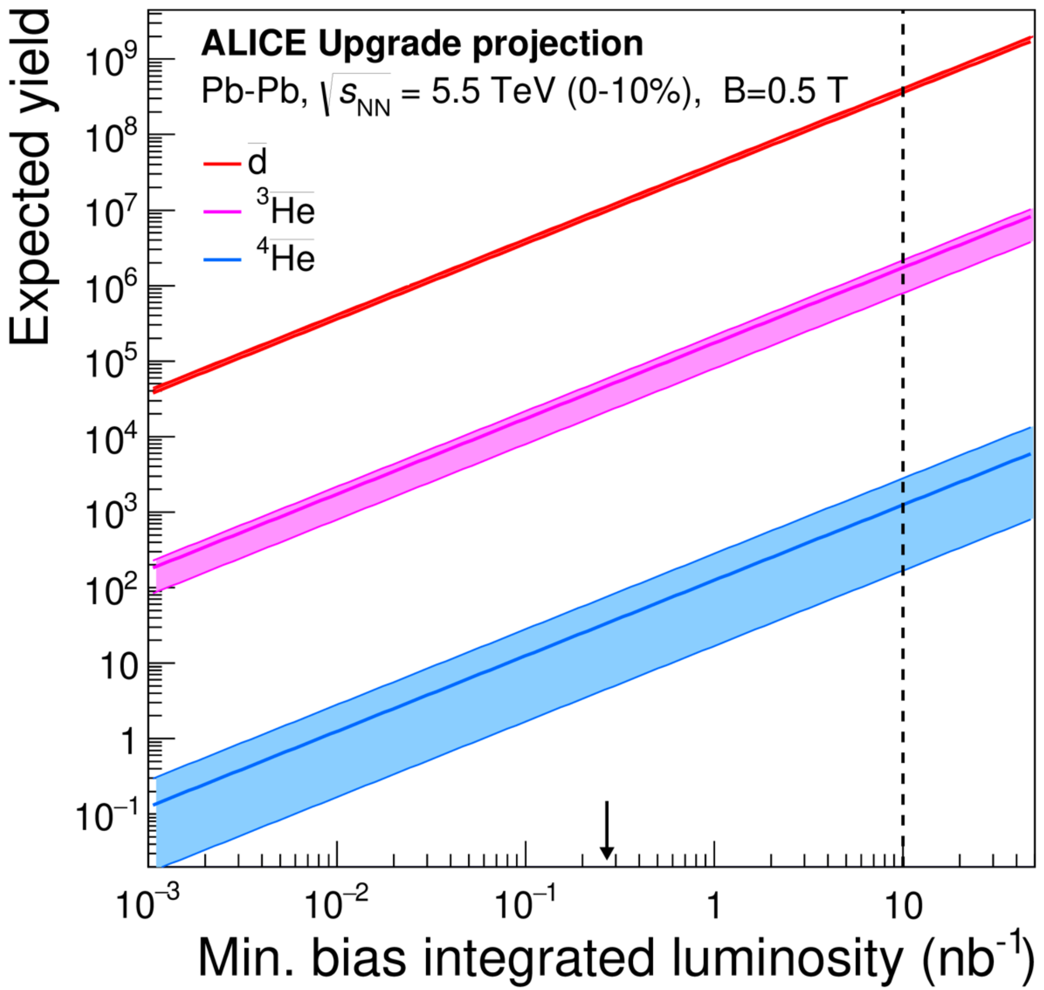




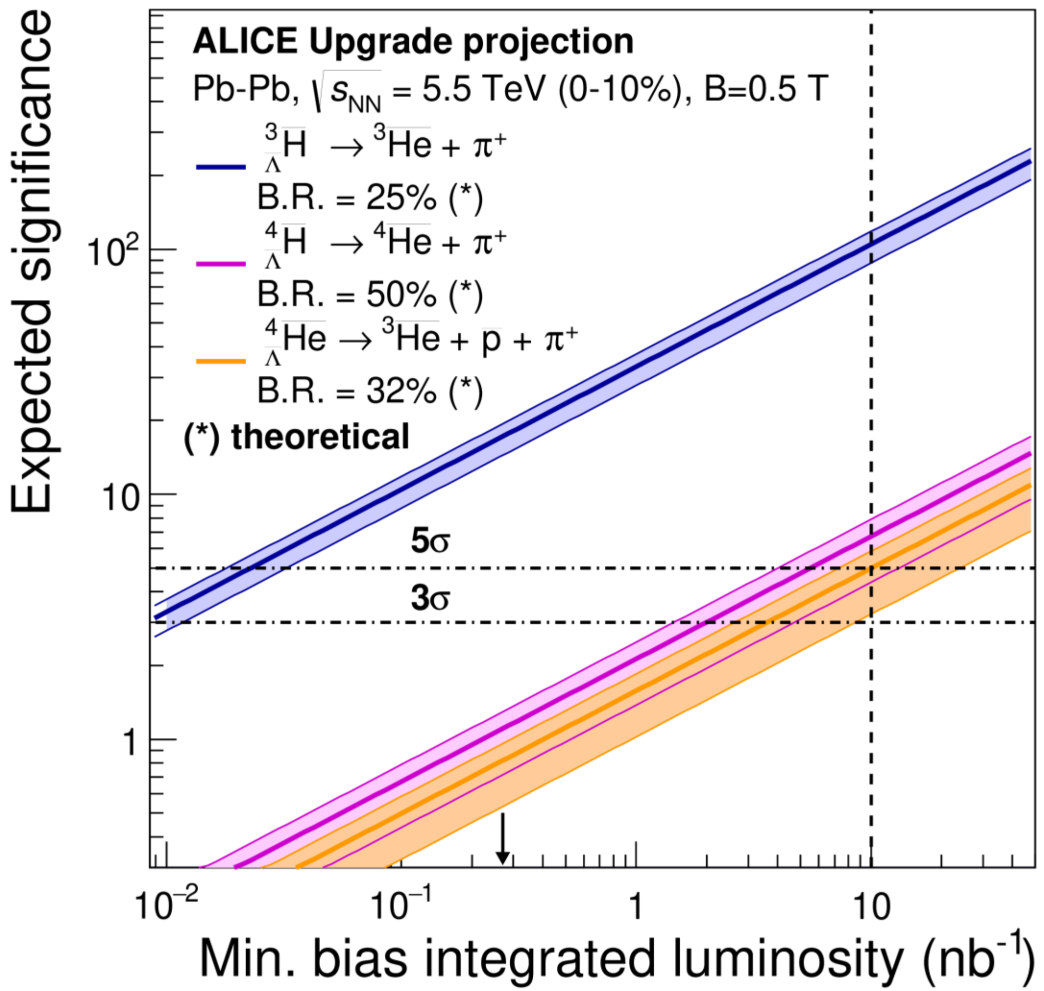


ALICE, PRX 14 (2024) 031051, Theory: M. Viviani, at al., arXiv:2306.02478

More (anti)(hyper)nuclei with high-lumi

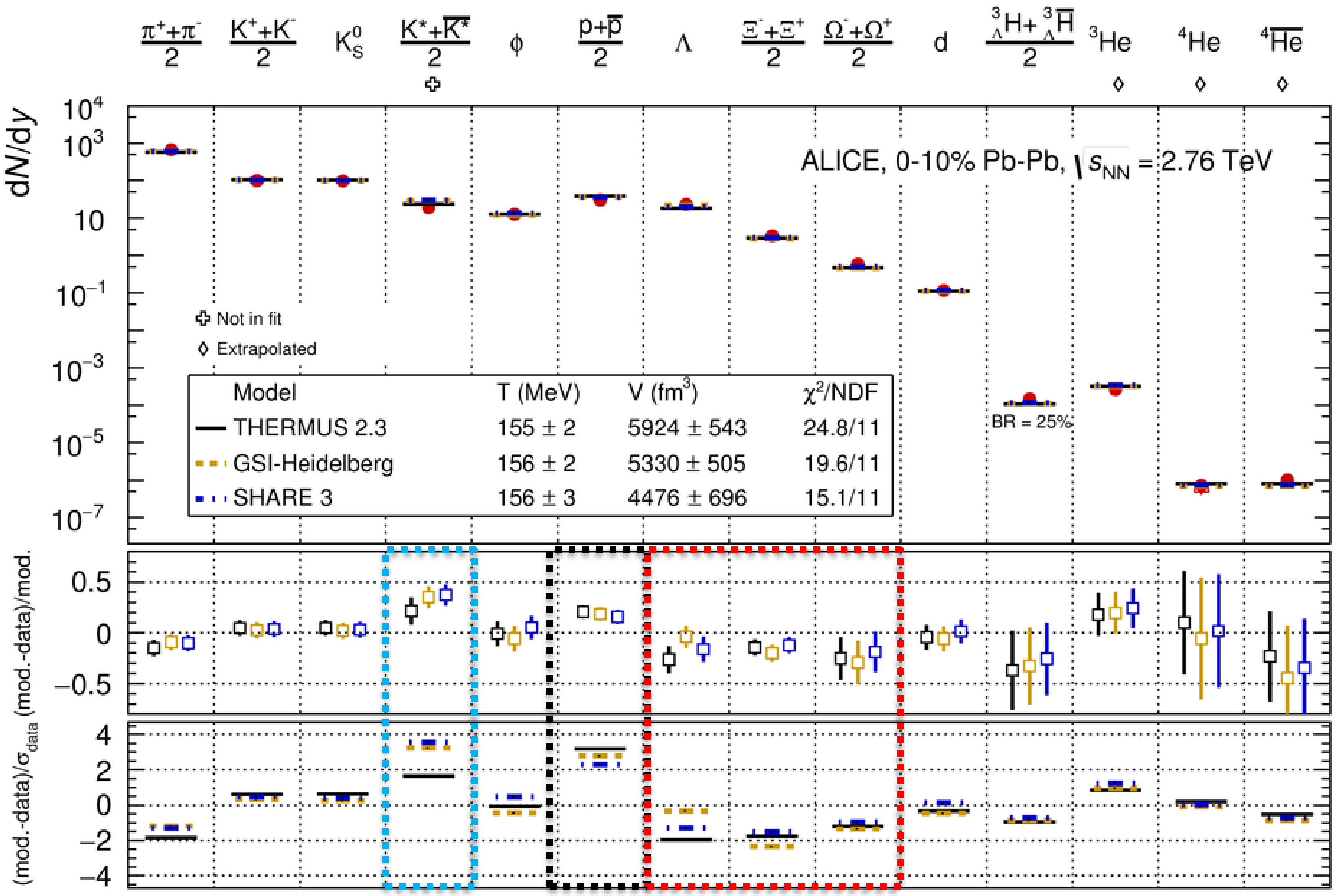


ALI-SIMUL-312336



ALI-SIMUL-312332

Hadrons from a thermal medium



ALICE, Nucl. Phys. A 971 (2018) 1-20

Production of (most) light-flavour hadrons in Pb-Pb at 2.76 TeV is described (χ^2/ndf ~ 2) by thermal models with a single chemical freeze-out temperature

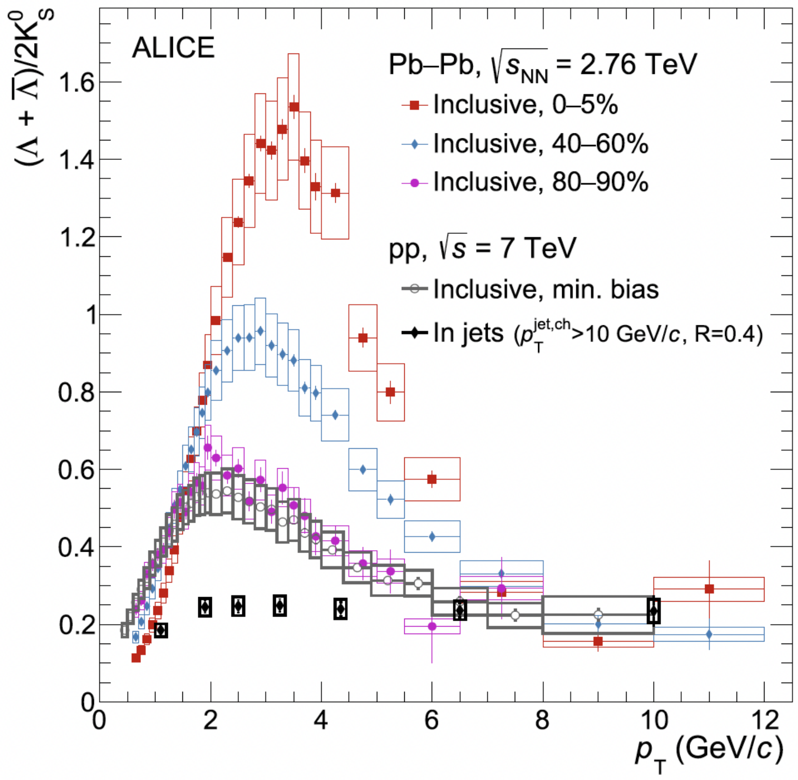
T_{ch} ≈ 156 MeV at 2.76 TeV

Deviation for short-lived **K^{*0}**

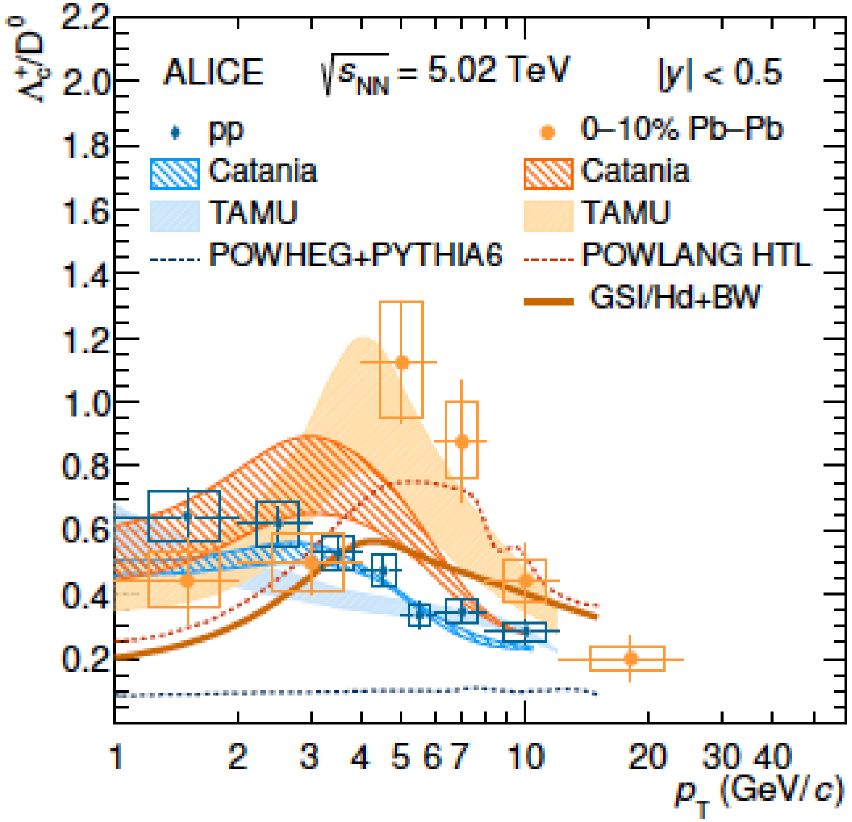
Tensions between **protons** and **multi-strange baryons**

Baryon-to-meson

Baryon/meson in LF sector



Baryon/meson in c sector



Baryon/meson in b sector