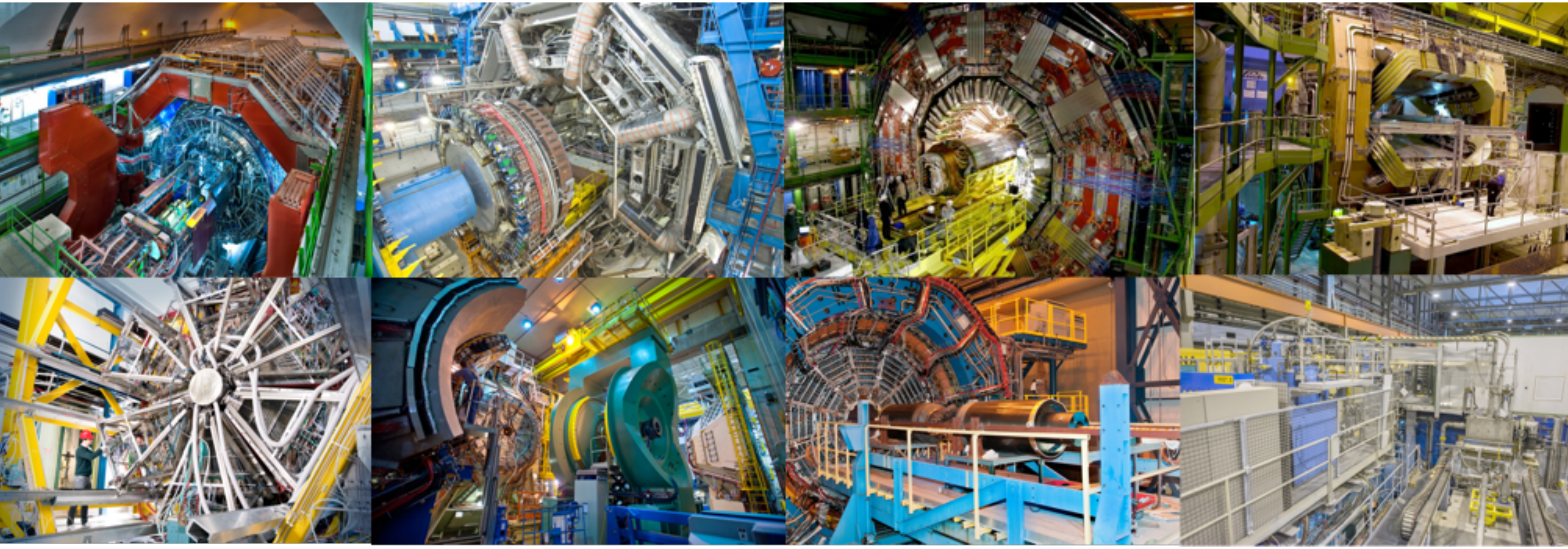
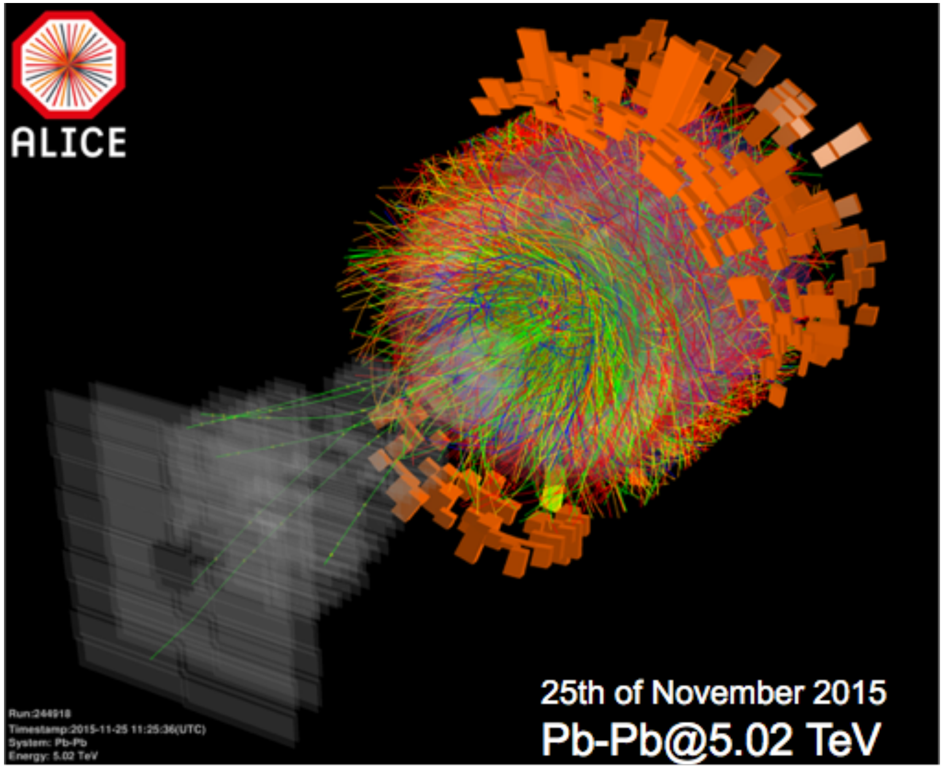
Recent experimental highlights in heavy-ion physics



Alexander Kalweit, *CERN*

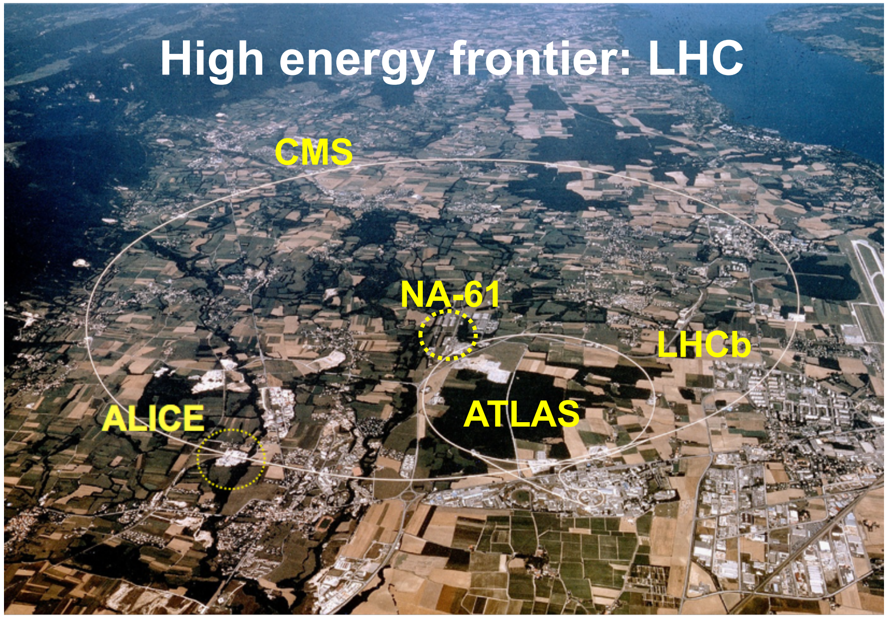
Outline

- A brief introduction to (ultra-relativistic) heavy-ion physics
- The production of light flavor hadrons from Pb-Pb to pp collisions ("**soft probes**")
- Search for the **QCD critical point** and onset of de-confinement
- Heavy-flavor production and jets ("**hard probes**")
- Summary and outlook



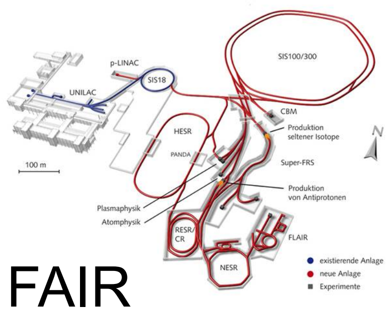
A brief introduction to (ultra-relativistic) heavy-ion physics

Heavy-ion experiments

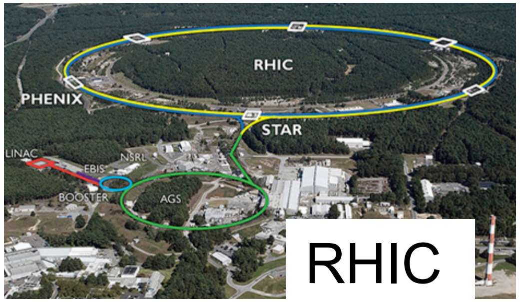


→ By now **all major LHC experiments have a heavy-ion program**: LHCb took Pb-Pb data for the first time in November 2015.

Low energy frontier: RHIC (BES), SPS
→ future facilities: FAIR (GSI), NICA



FAIR



LHC Run 2

- LHC Run 2 data taking and analysis is now in full swing.
- Significant increase in integrated luminosity (approx. 4 times in Pb-Pb) allow more **precise investigation of rare probes**.
- Various collision systems at different center-of-mass energies are ideally suited for **systematic studies of particle production**.

→ Heavy-ion physics is a huge field with many observables and experiments: impossible to cover all topics! I will present a personally biased selection of results.

Run 1(2009-2013)	Run 2 (2015-now)
Pb-Pb 2.76 TeV	**Pb-Pb** 5.02 TeV
p-Pb 5.02 TeV	**p-Pb** 5.02 TeV, 8.16 TeV
pp 0.9, 2.76, 7, 8 TeV	**pp** 5.02, 13 TeV

Heavy-ions & Quantum Chromodynamics (QCD)

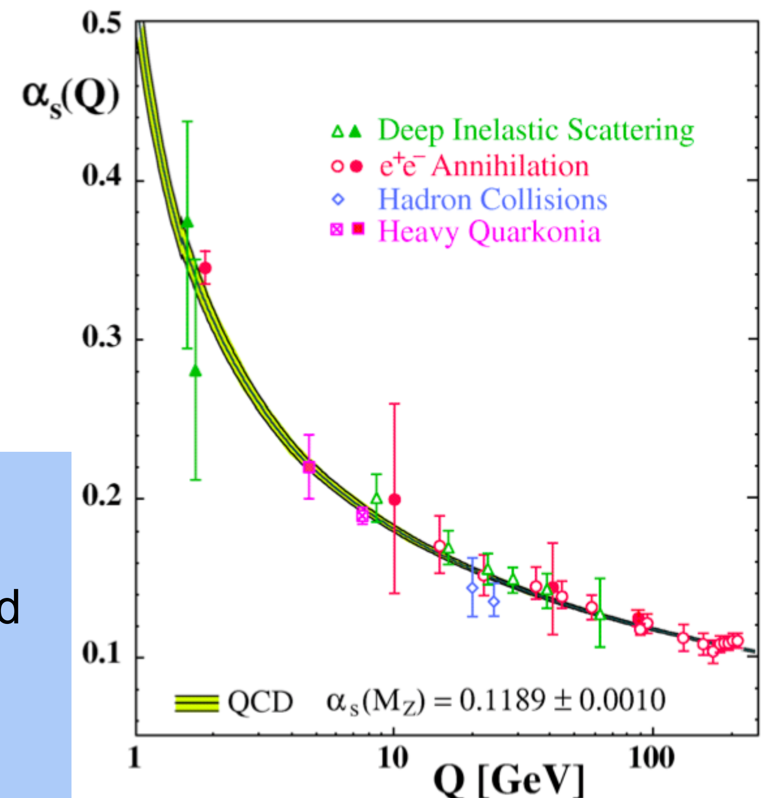
Heavy-ion physics is the physics of *high energy density QCD:*

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(i\gamma^{\mu}D_{\mu} - m)q - \frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a}$$

Quark-field

Quark-mass

Gluon field strength tensor



[Prog.Part.Nucl.Phys. 58 (2007) 351-386]

Properties of QCD relevant for heavy-ions:

(a.) *Confinement*: Quarks and gluons are bound in color neutral mesons ($q\bar{q}$) or baryons (qqq).

(b.) *Asymptotic freedom*: Interaction strength decreases with increasing momentum transfer ($\alpha_S \rightarrow 0$ for $Q^2 \rightarrow \infty$).

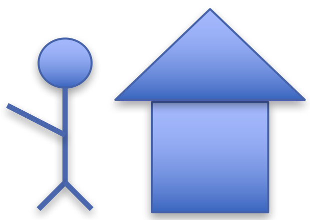
(c.) *Chiral symmetry*: Interaction between left- and right handed quarks disappears for massless quarks.

Remarkable confirmation of the standard model in the last years at the LHC.
→ Discovery potential in **many body phenomena** (as in QED and solid state physics)!

QGP as the asymptotic state of QCD

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

bound quarks & gluons



Where is the phase transition?
→ Lattice QCD

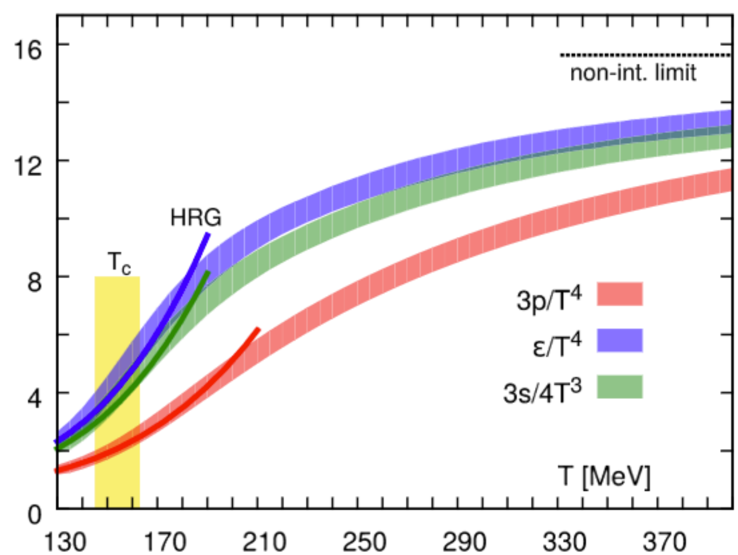
Asymptotic freedom: *free quarks & gluons*

$T_0 \approx 1/40$ eV

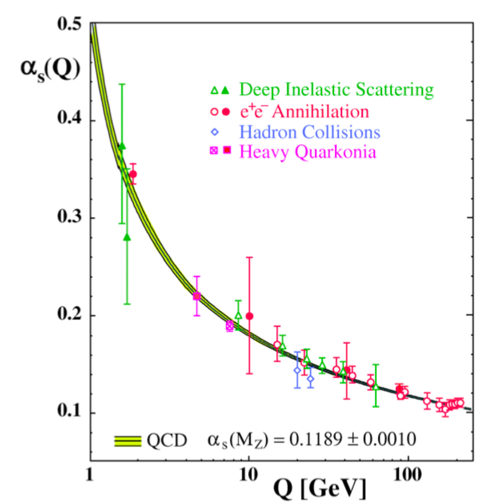
Critical temperature
$T_c \approx$ **156 MeV**

$T \rightarrow \infty$ Temperature T

→Are such extreme temperatures reached in the experiment?
Yes..
→Is it for all quark flavors the same?
Not clear yet..
→…

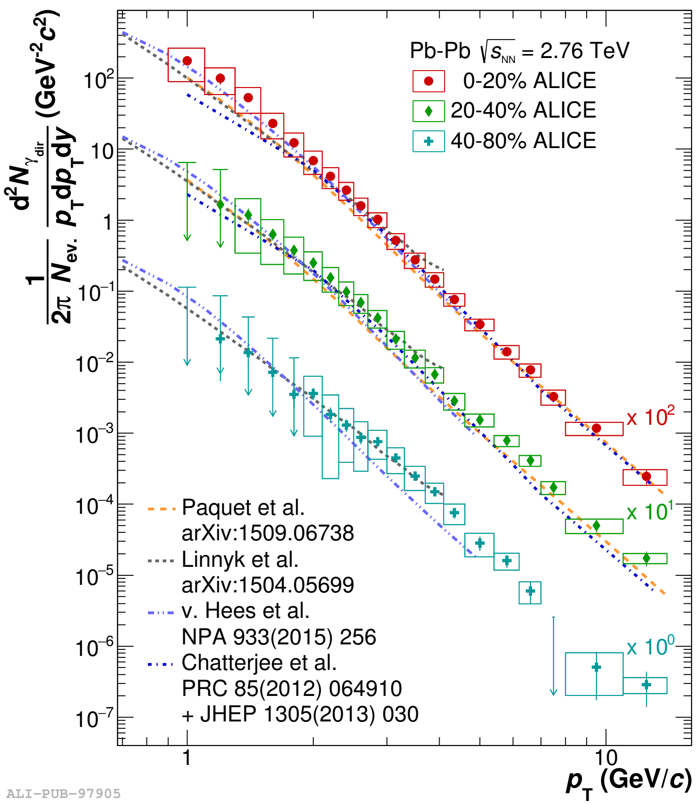


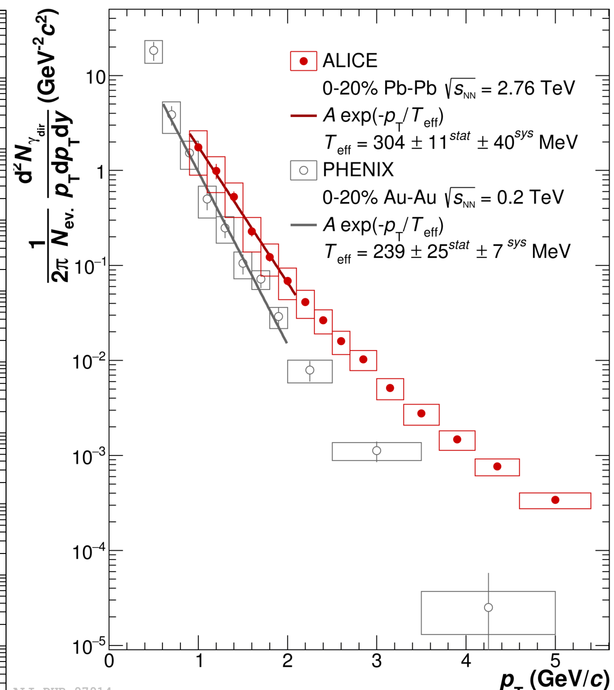
[PRD 90 094503 (2014)]



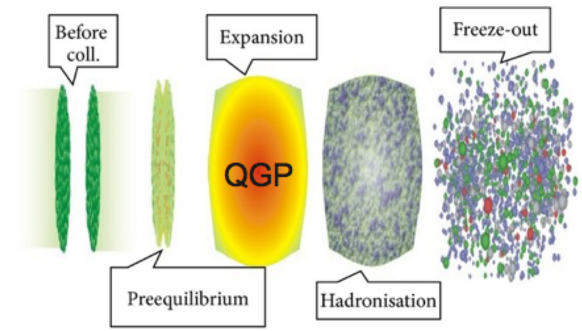
Direct photons – black body radiation from the QGP

- The challenging measurement of direct (subtract decays such as $\pi^0 \rightarrow \gamma\gamma$) photons gives access to the initial temperature of the system created in heavy-ion collisions.
- However, model comparisons are needed as direct photons are also emitted at later stages of the collision.





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

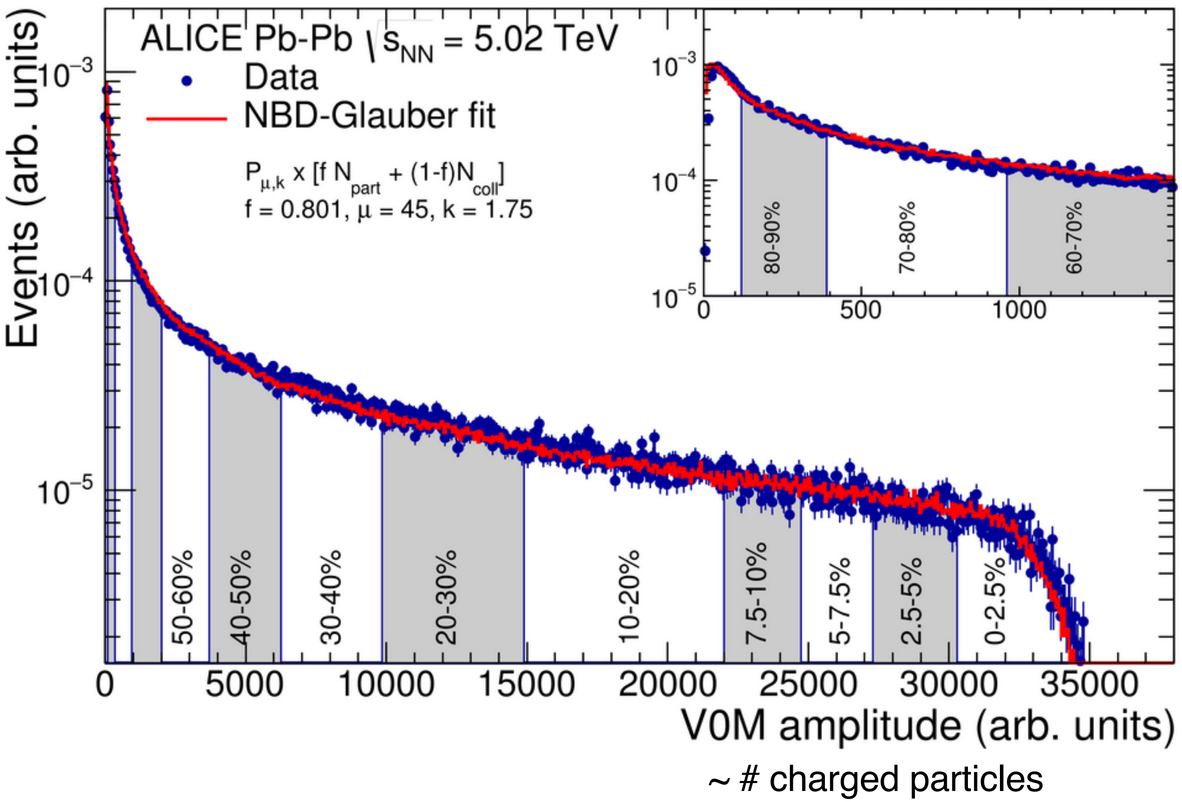


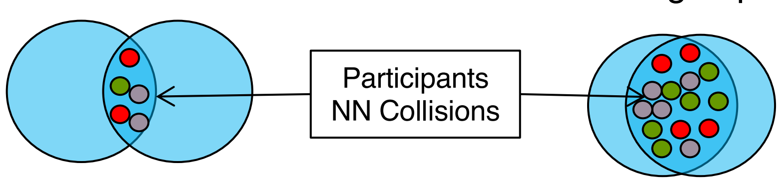
[arXiv:1207.702]

T_{eff} = 304 ± 11 ± 40 MeV

→ Effective temperature of approx. 300 MeV is observed as a result of a high initial temperature and the blue-shift due to the radial expansion of the system.

Geometry of heavy ion collisions





Centrality Variables:

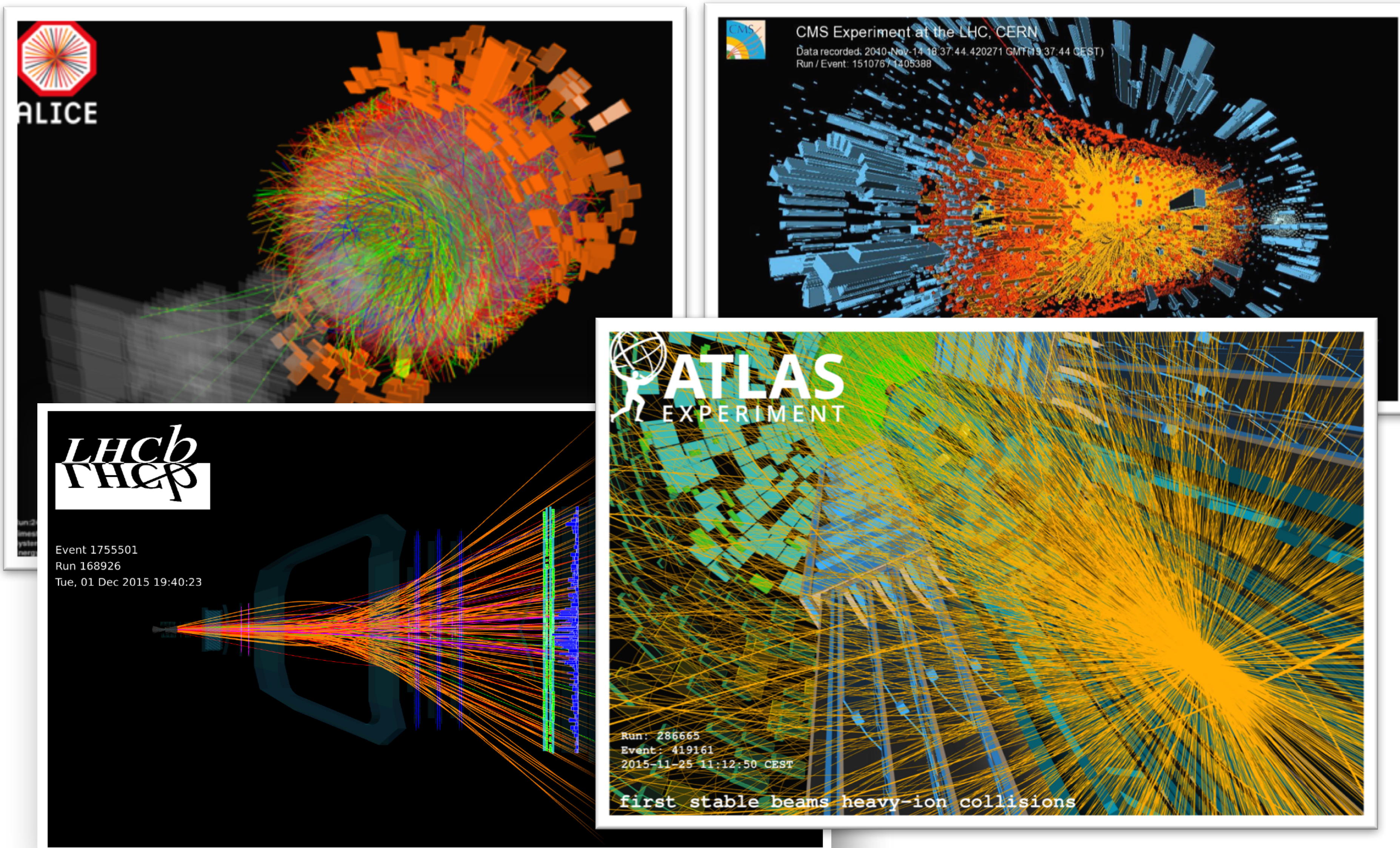
- ***N_{coll}***: Number of nucleon-nucleon collisions
- ***N_{part}***: Number of participating nucleons
- Percentile of hadronic cross-section:

0-5% => central ("many particles")

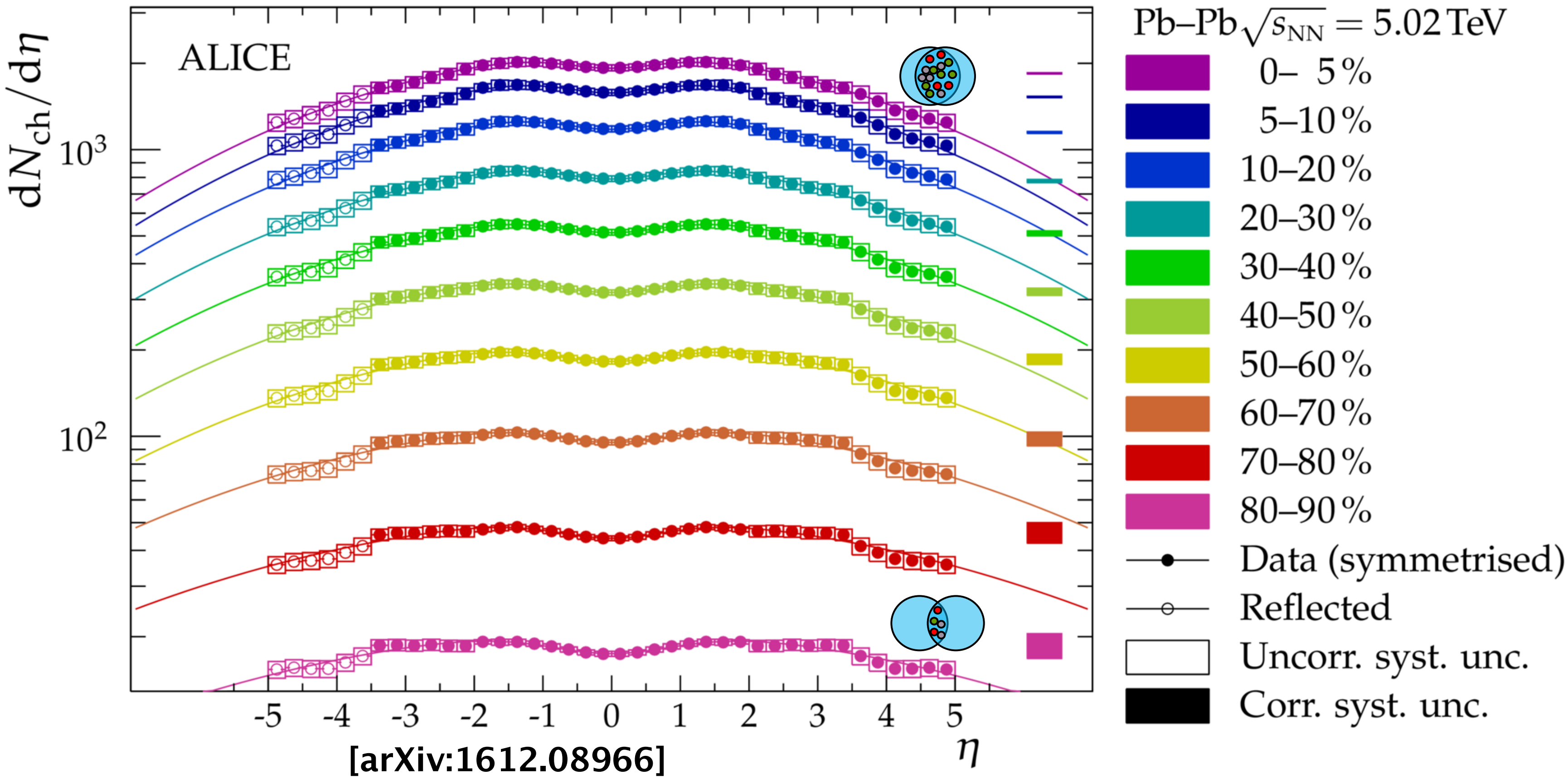
80-90% => peripheral ("few particles")

→ We can determine (a posteriori) the geometry of heavy ion collisions.

How many particles are created in such a collision?



$dN_{ch}/d\eta$ in 5.02 TeV Pb-Pb collisions at the LHC



[arXiv:1612.08966]

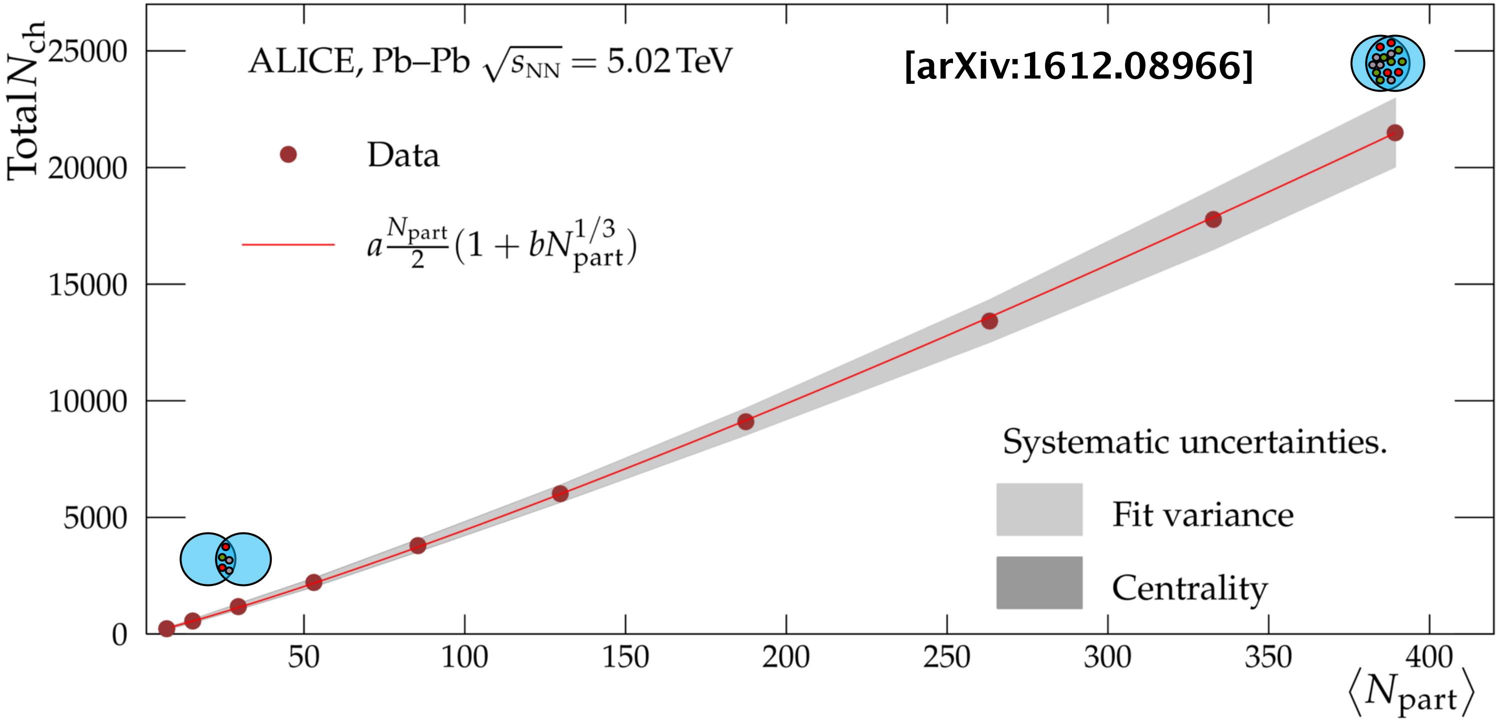
ALI-PUB-115086

dN_{ch}/dη ≈ 1943 ± 54 at midrapidity 0-10%.

→ Even at LHC energies, 95% of all particles are produced at p_T < 2 GeV/c in pp and Pb-Pb collisions.

→ Bulk particle production and the study of collective phenomena are associated with ***"soft" physics*** in the non-perturbative regime of QCD.

Total number of charged hadrons in Pb-Pb



→ Collisions of heavy-ions at high energy accelerators allow the creation of several tens of thousands of hadrons (1 << *N* << 1mol) **in local thermodynamic equilibrium** in the laboratory.

Success of **thermal models** describing **yields of hadrons composed of up, down, and strange quarks** supports idea of matter in local thermal equilibrium (*chemical*).

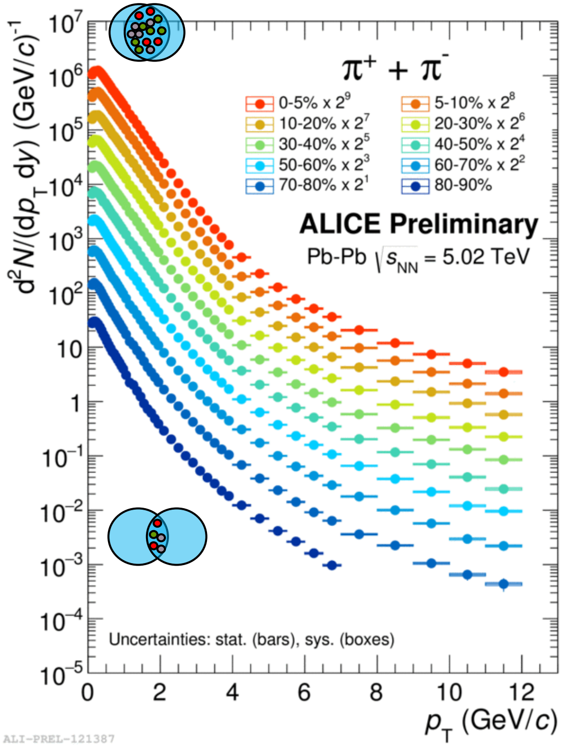
Success of **hydro models** describing **spectral shapes and azimuthal anisotropies** supports idea of matter in local thermal equilibrium (*kinetic*).

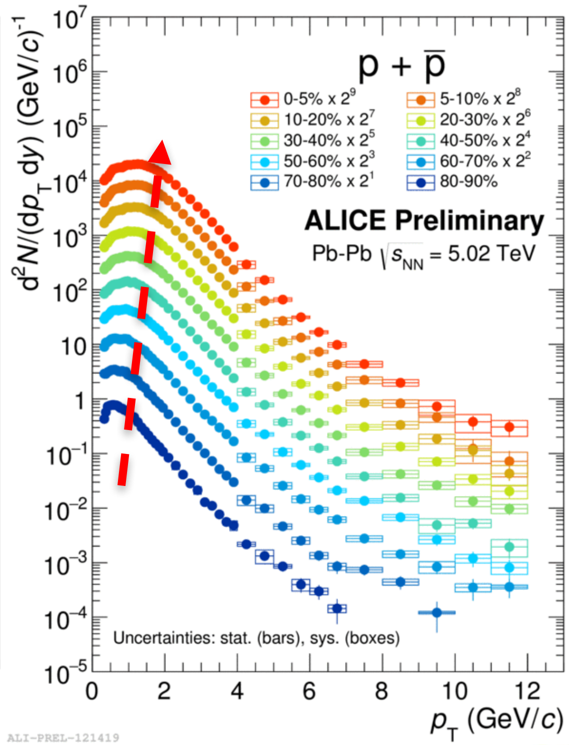
Equilibrium models such as hydro typically need 5-6 interactions to work. Where does this picture break down? Does it work in pp and pPb? → **What is the smallest possible QGP droplet?**

Soft probes

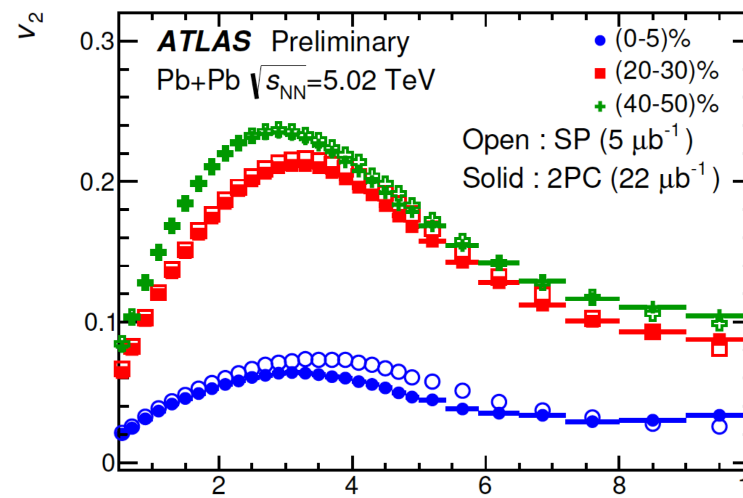
Hydrodynamics – spectral shapes and v_2

Radial flow

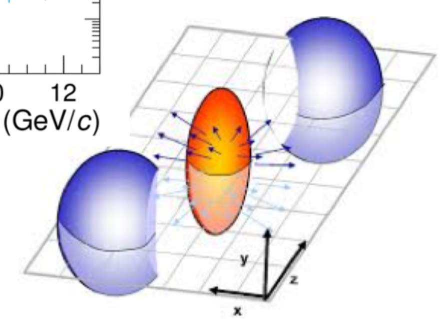




Elliptic flow



[ATLAS-CONF-2016-105]



→ Initial **spatial anisotropy** is converted by scatterings into an **anisotropy in momentum space**.

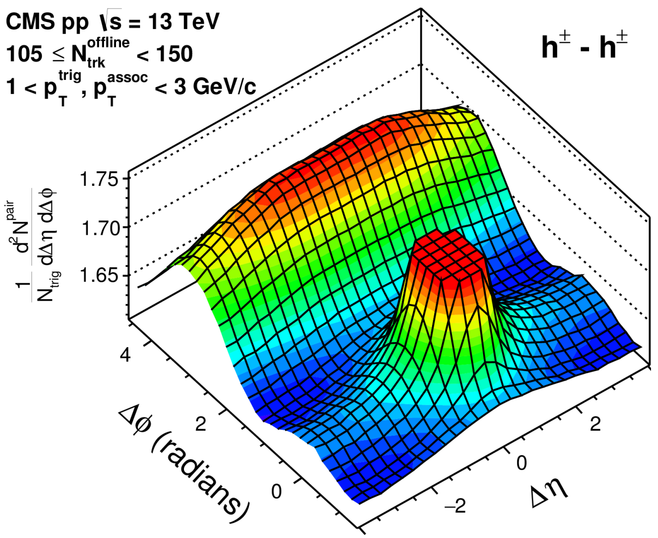
Textbook-like hardening of p_T-spectra as expected in hydro:

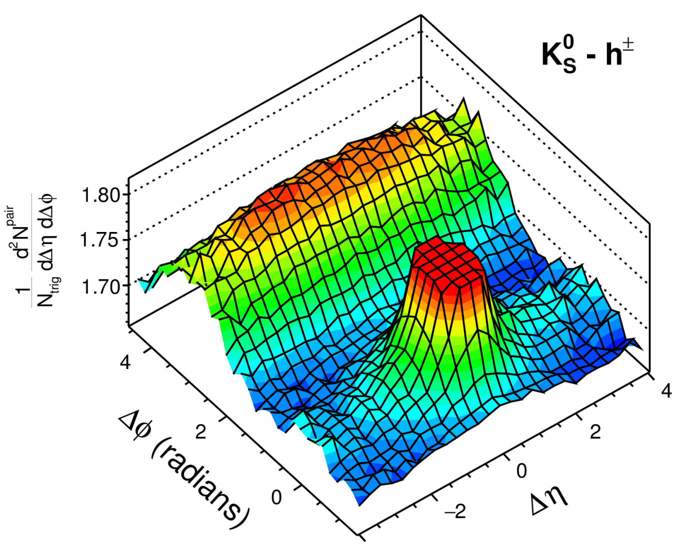
- With centrality
- With the particle mass: $p = \beta\gamma \cdot m$

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

Radial flow $\quad$ v_1 – direct flow, $\quad$ **v_2- elliptic flow**

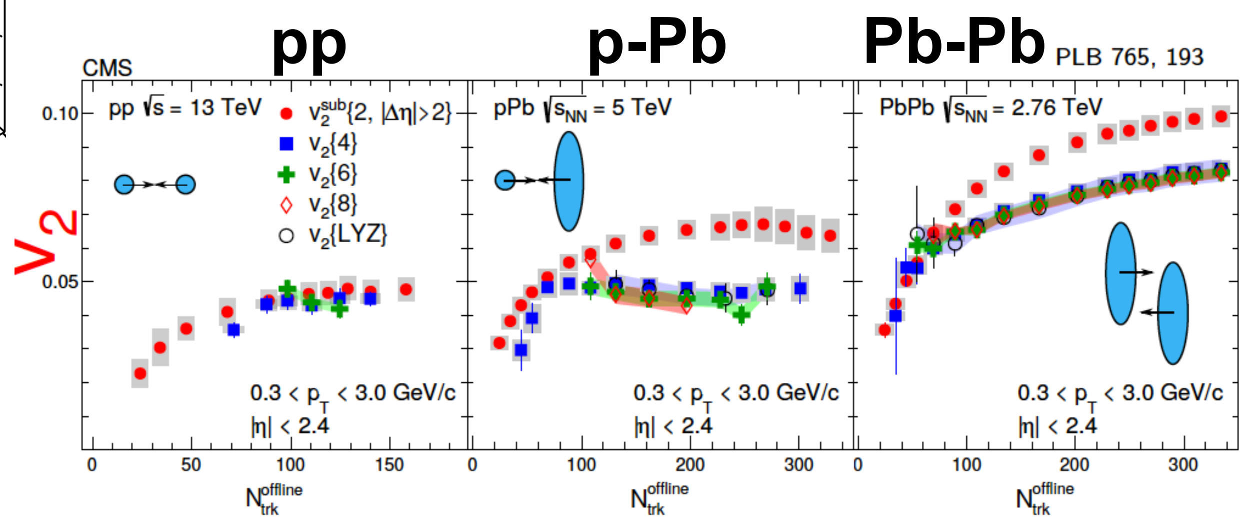
(Double) ridges





[Phys. Lett. B 765 (2017) 193]

- Long-range azimuthal correlations (as originating from elliptic flow) are also observed in small systems: double ridges.



- Similar observations hold true for many other typical *kinetic* heavy-ion observables measured in high multiplicity pp and pPb collsions → clear indication for collectivity in small systems.

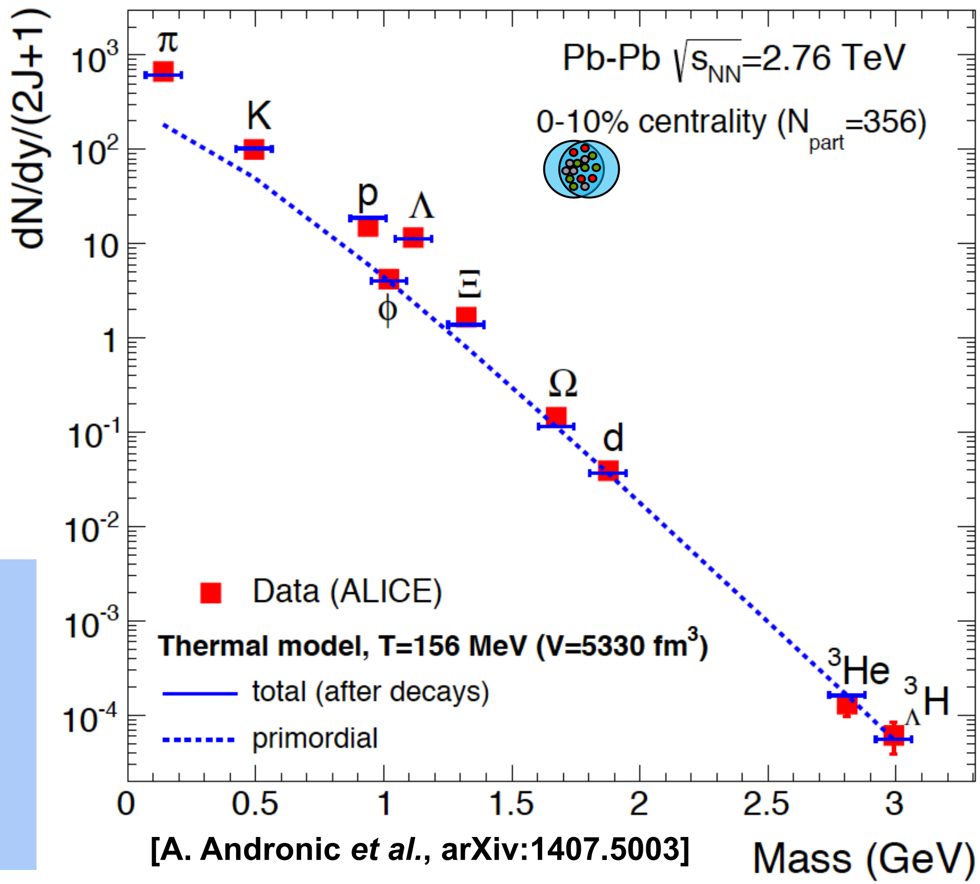
Hadrochemistry

$$\frac{dN}{dy} = \int \frac{d^3N}{dp_T dy d\varphi} \, d\varphi dp_T$$

Production yields of light flavour hadrons from a chemically equilibrated fireball can be calculated by statistical-thermal models (roughly $dN/dy \sim \exp\{-m/T_{ch}\}$)

→ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 7 orders of magnitude with a common chemical freeze-out temperature of **$T_{ch} \approx 156$ MeV**.

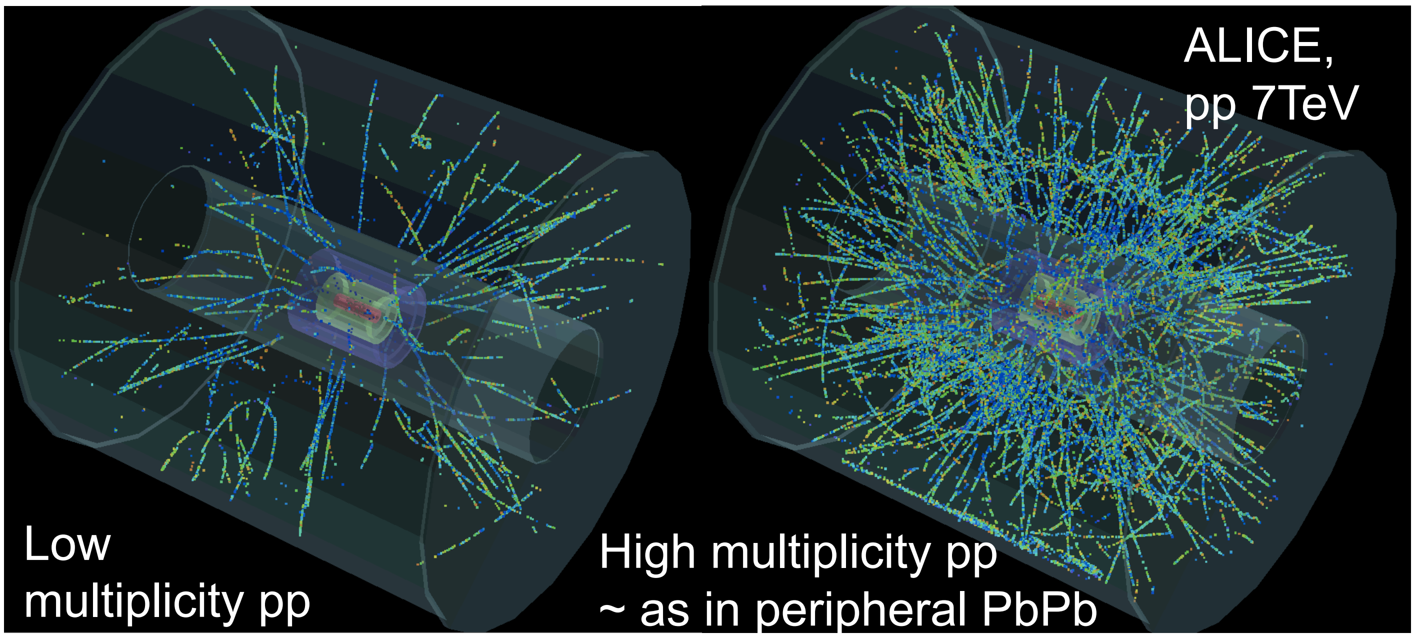
→ This includes **strange hadrons** which are rarer than u,d quarks. Approx. every fourth to fifth quark (every tenth) is a strange quark in Pb-Pb collisions (in pp collisions).

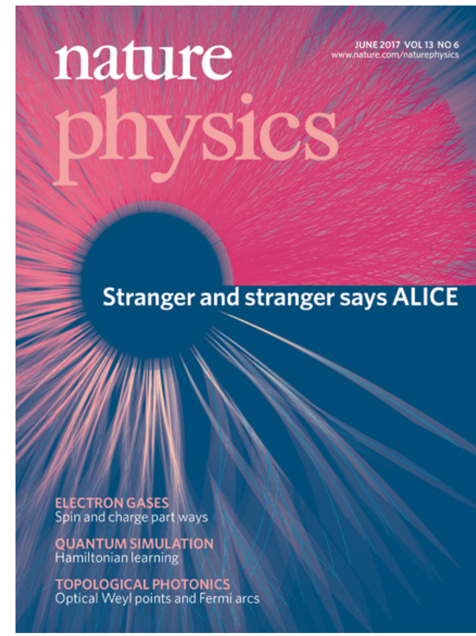


[A. Andronic *et al.*, arXiv:1407.5003]

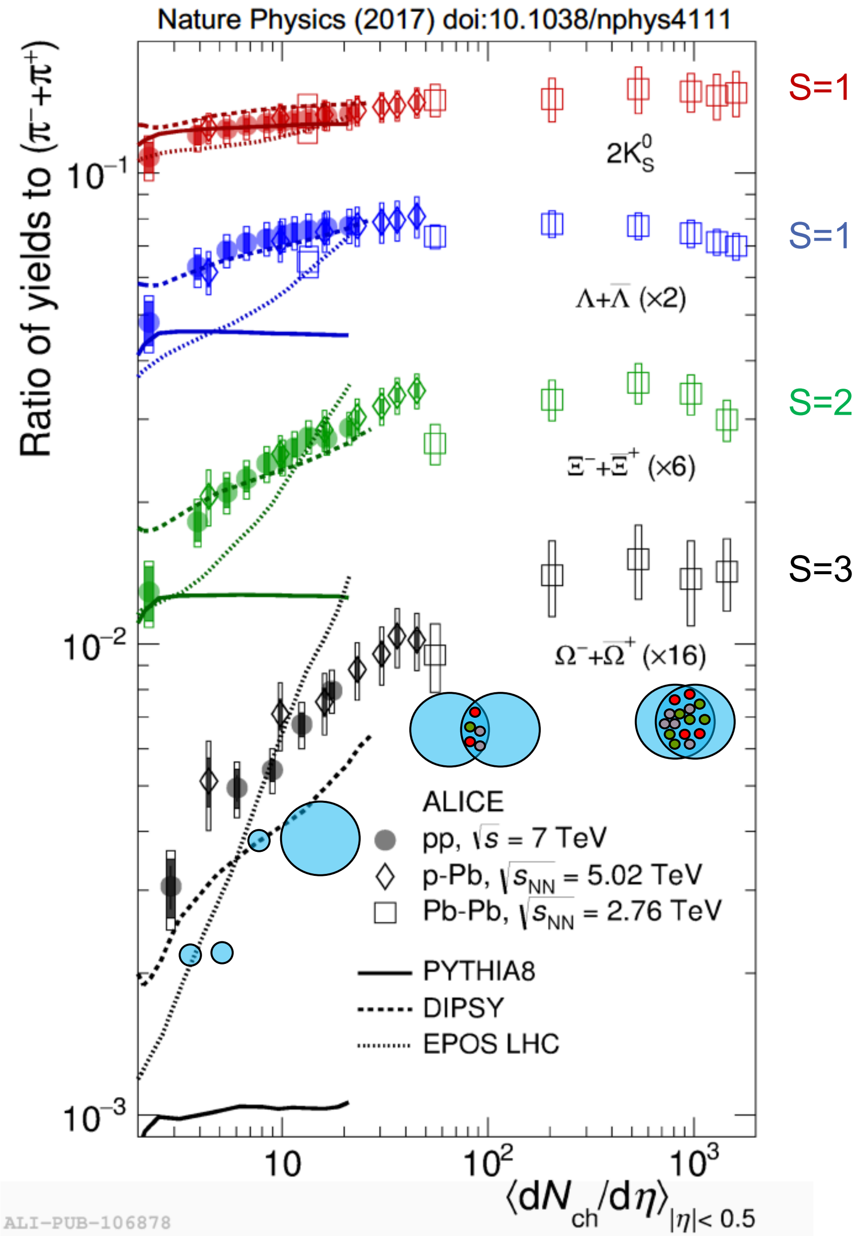
→ Light (anti-)nuclei are also well described despite their low binding energy ($E_b << T_{ch}$).

How does hadrochemistry evolve with system size?



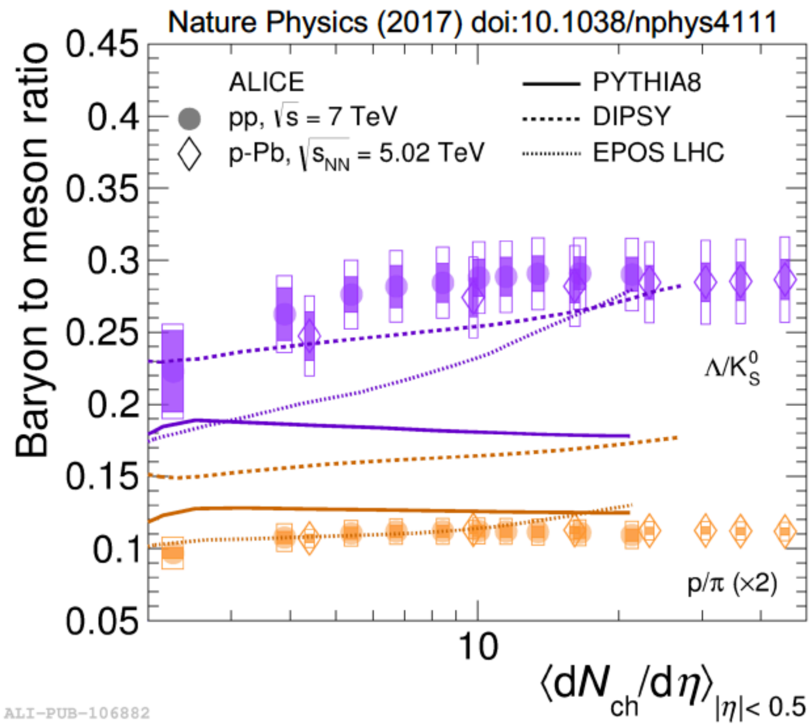


Strangeness enhancement



- Smooth evolution of hadrochemistry observed from pp to pPb to Pb-Pb collisions as a function of charged particle multiplicity.
- Significant enhancement of strange to non-strange particle production observed in pp collisions.
- pp collision data allows to compare to a plethora of QCD inspired event generators:
  - **PYTHIA8** completely **misses** the behavior of the data (independent of switching ON/OFF color reconnection)
  - **DIPSY** (color ropes) describes the increase in strangeness production qualitatively but fails to predict protons correctly in its original version..
  - **EPOS-LHC** (core-corona) only qualitatively describes the trend.

Strangeness enhancement



→ Hyperon-to-pion enhancement is strangeness related and not mass or baryon number related.

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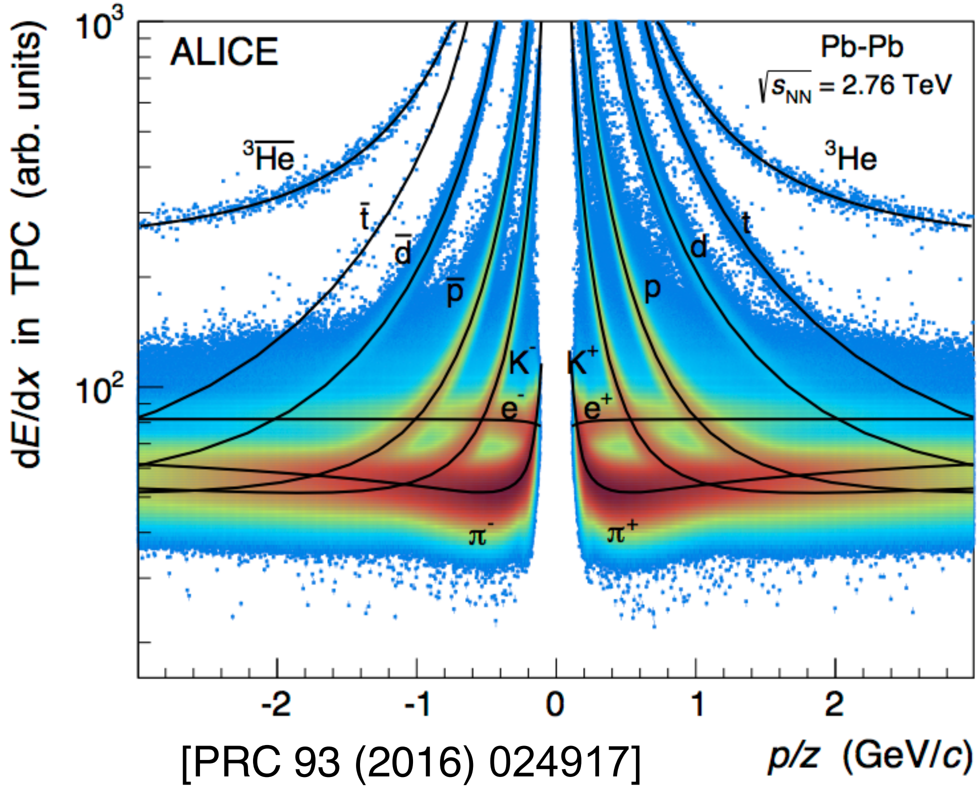
Measurements of (anti-)(hyper-)nuclei

- Collisions at the LHC produce a large amount of (anti-)(hyper-)nuclei.
  - Matter and anti-matter are produced in equal abundance at LHC energies.
  - Puzzle: production yields are in agreement with thermal model prediction even though light (anti-)nuclei should be dissolved in such a hot medium.



[PRC 93 (2016) 024917]

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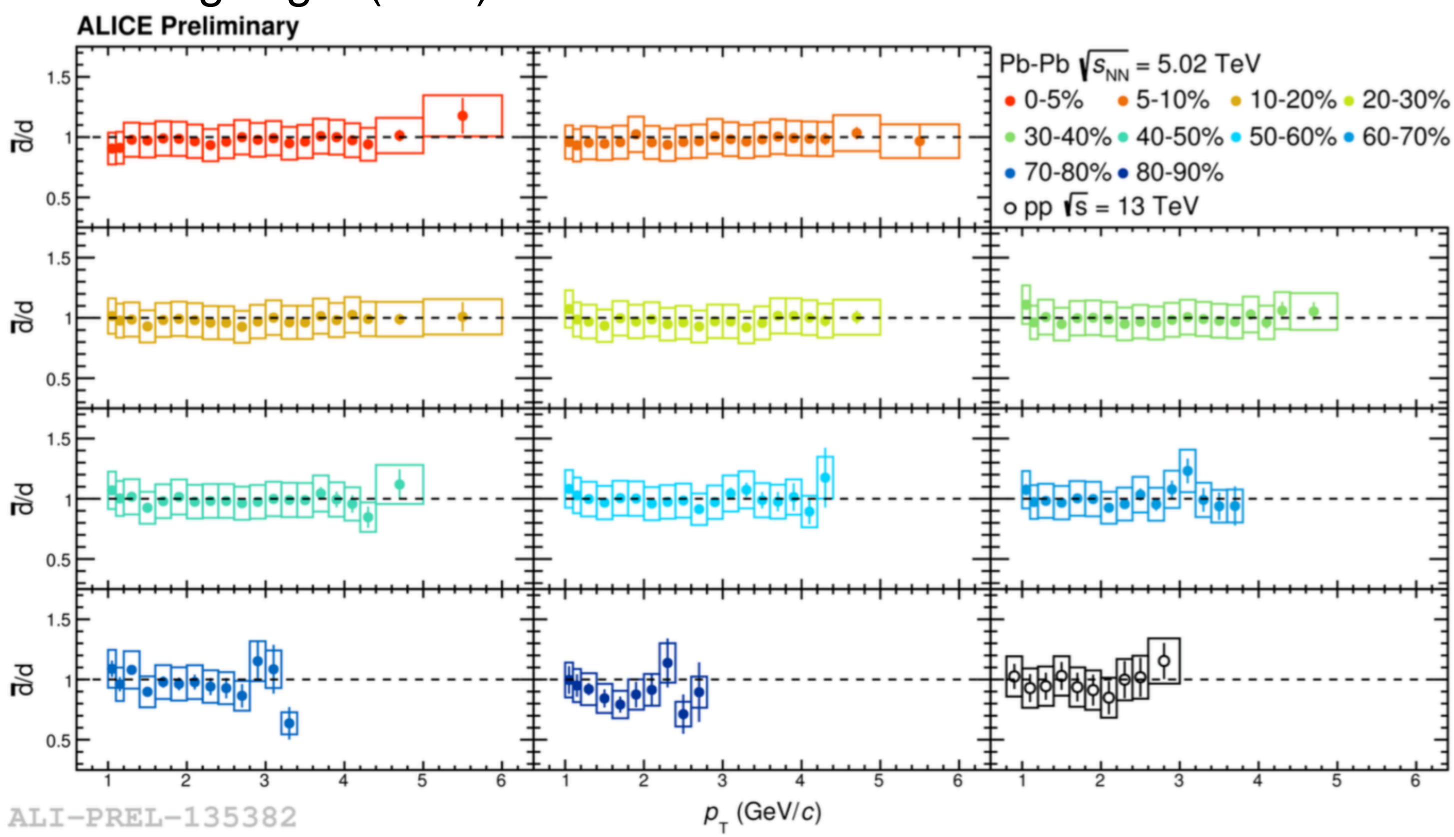


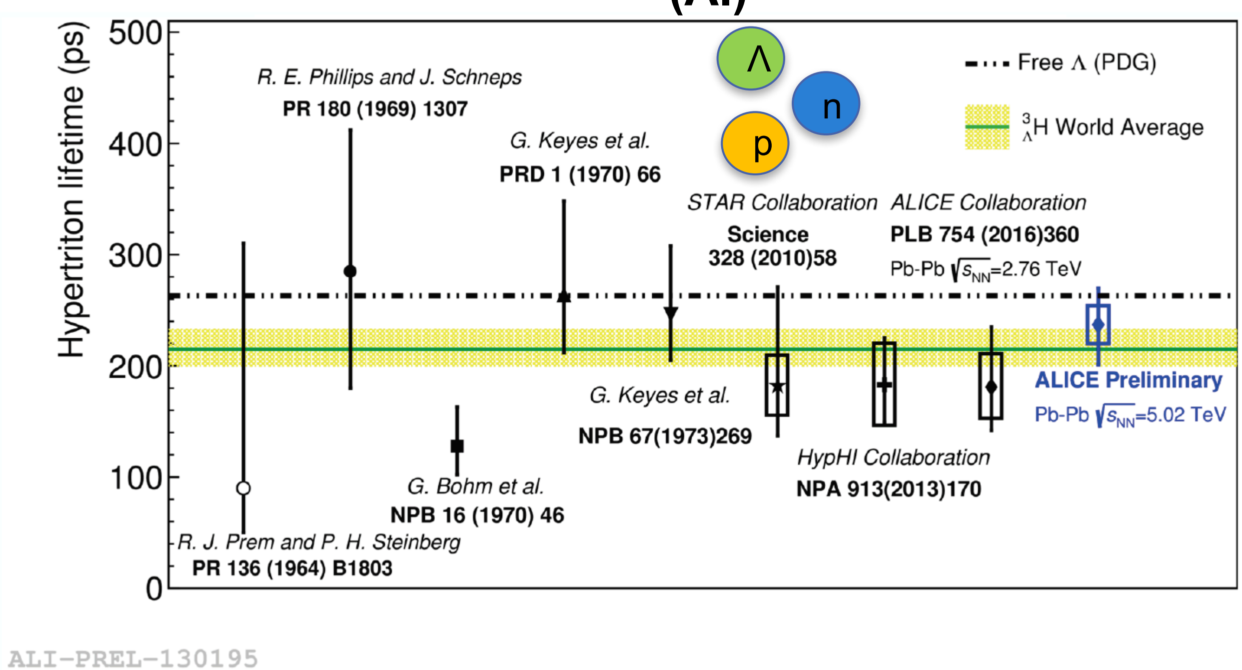
[ALICE-PUBLIC-2017-006]

(anti-)(hyper-)nuclei – impact beyond heavy-ion physics

A. Heavy-ion measurements may help in constraining the not well known lifetime of the hyper-triton (sensitive to the hyperon-nucleon interaction potential in nuclear physics).

B. Collider measurements are used for background estimations in the searches for (anti-)nuclei of galactic/dark matter origin (such as in AMS).

(A.)



(B.)

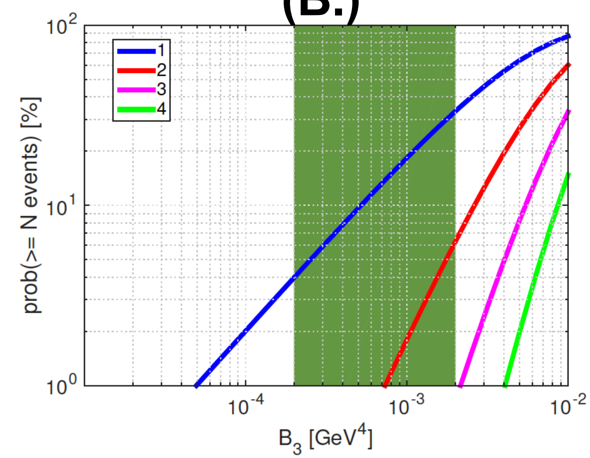


FIG. 5: Poisson probability for detecting $N \geq 1, 2, 3, 4$ $\overline{^3\mathrm{He}}$ events in a 5-yr analysis of AMS02, assuming the same exposure as in the $\bar{p}$ analysis [28]. Eq. (14) shown as green band.

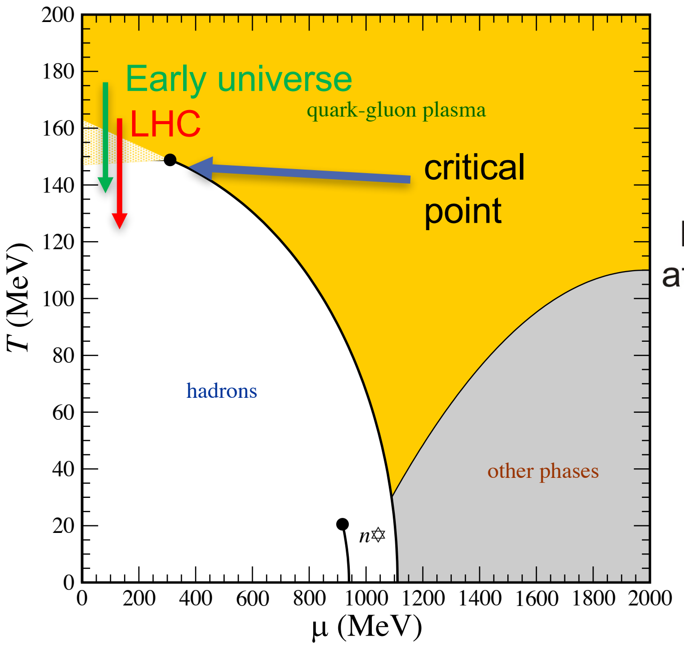
[K. Blum *et al.*, arXiv:1704.05431]

Search for QCD critical point and onset of de-confinement

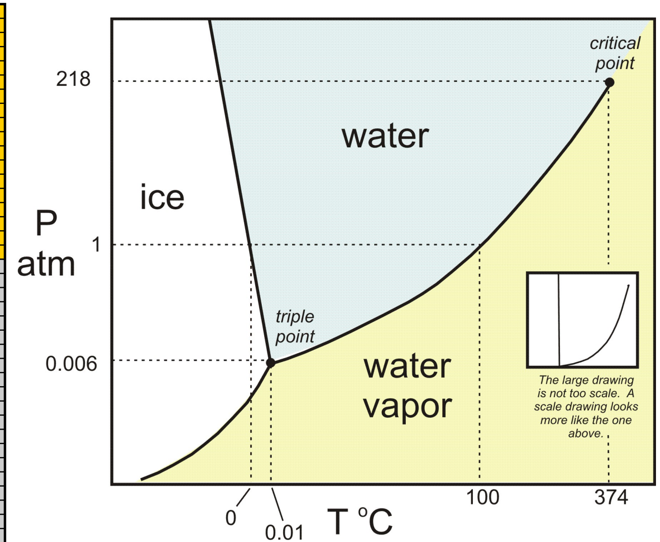
The phase diagram of QCD

- The thermodynamics of QCD can be summarized in the following (schematic) phase diagram.

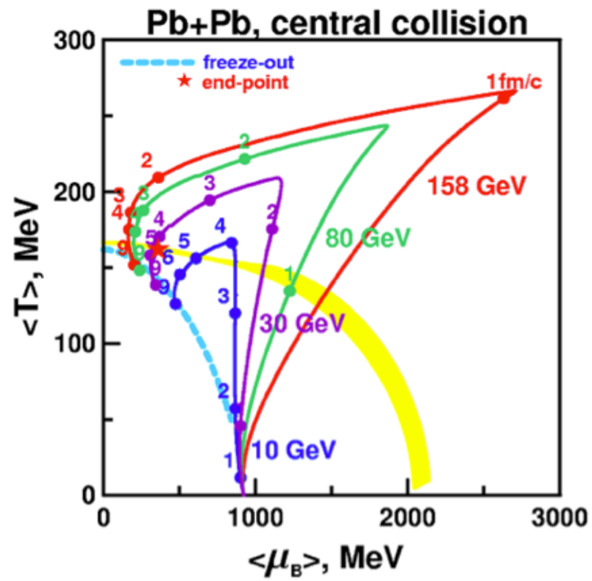
- Control parameters: temperature T and baryo-chemical potential μ_B.



[Ann. Rev. Nucl. Part. Sci. 62 (2012) 265]



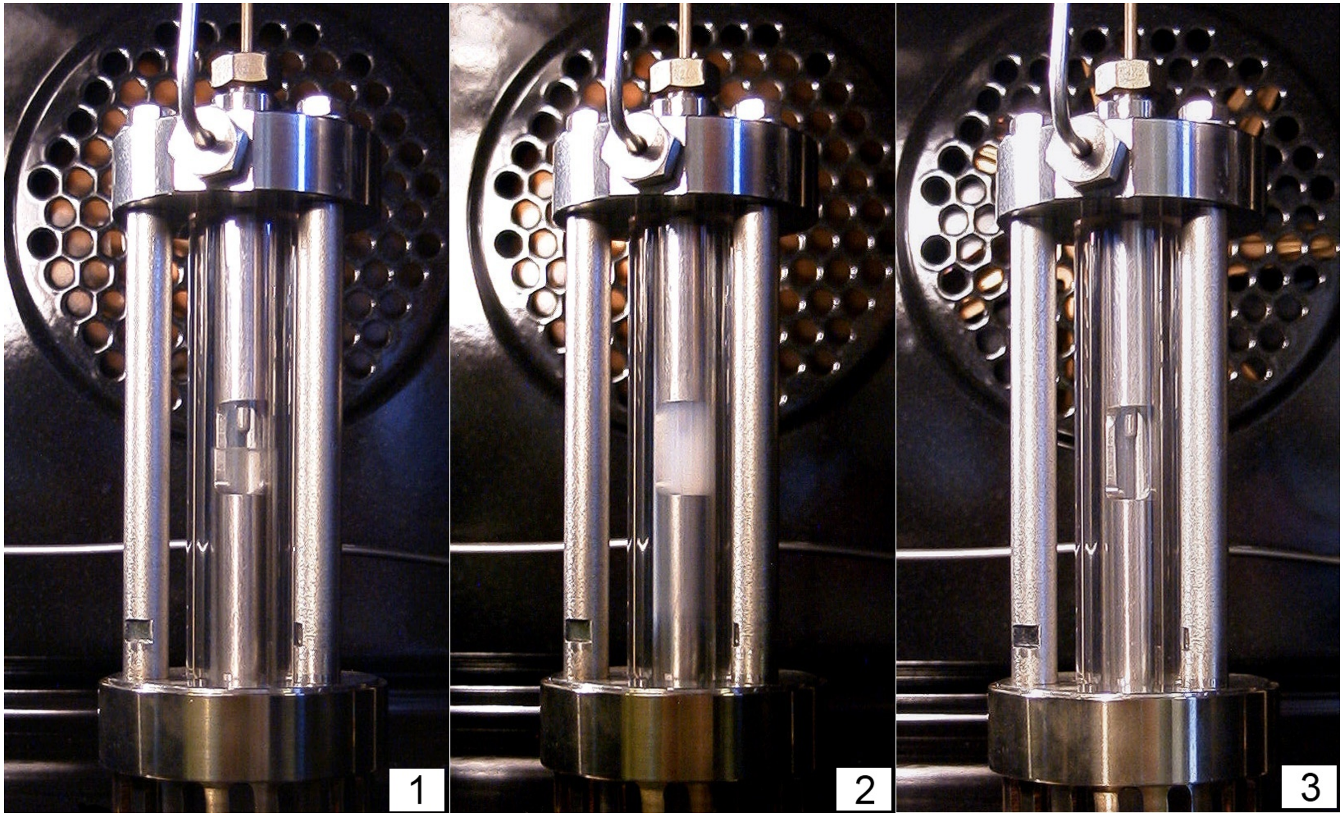
[http://serc.carleton.edu/research_education/equilibria/phaserule.html]



Y.B. Ivanov et al., Phys. Rev. C 73 (2006) 30.

→ Different regions of the phase diagram are probed with different $\sqrt{s_{NN}}$.
=> beam energy scan (BES) at RHIC.

Critical fluctuations – in ordinary matter

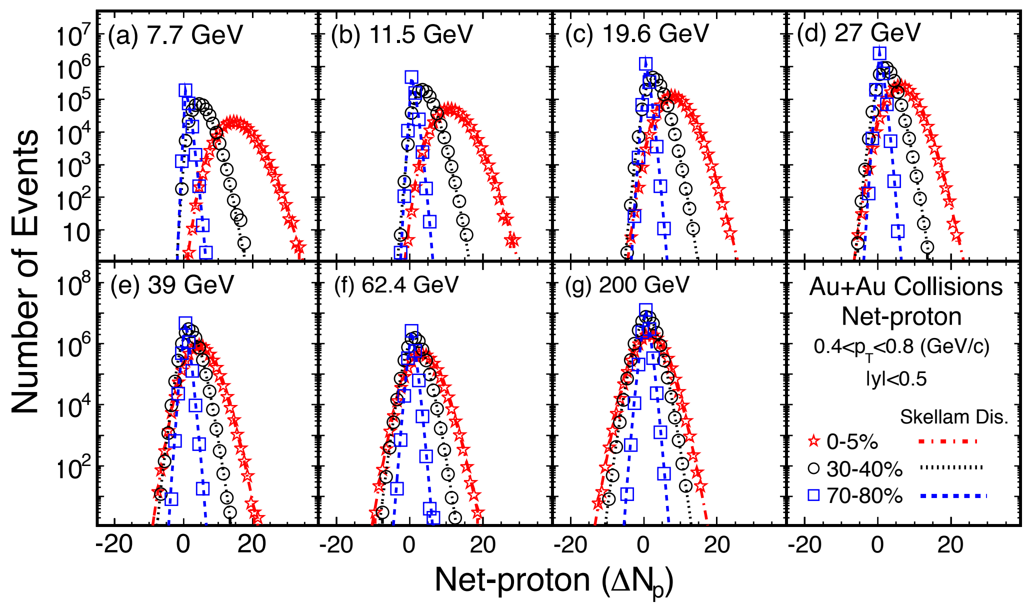


[S. Horstmann, Ph.D. Thesis University Oldenburg]

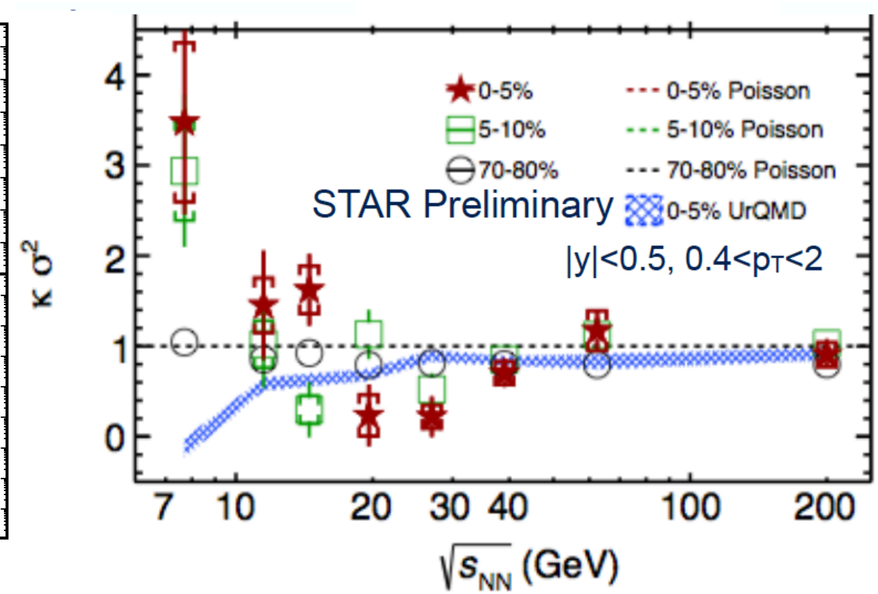
- Phase transitions are often connected to critical phenomena.
- Example: Opalescence of Ethene at the critical point (divergence of correlation lengths).

Critical fluctuations – in quark matter

- In the QCD case, **event-by-event fluctuations** in the conserved charges of QCD (Baryon number *B*, Strangeness *S*, electric charge *Q*).
- Key observable: baryon number fluctuations quantified as the higher moments χ_B of the net-proton (N_p-$N_{anti\text{-}p}$) distribution.



[PRL 112 (2014) 032302]



→ Hint for deviation from Poisson baseline in kurtosis around $\sqrt{s_{NN}} \approx 20$ GeV?

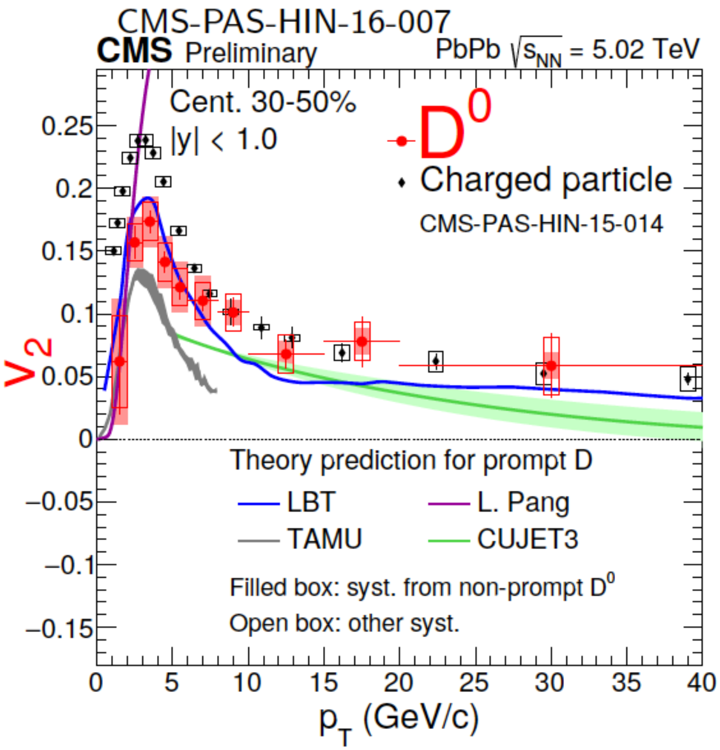
Hard probes

Heavy flavor

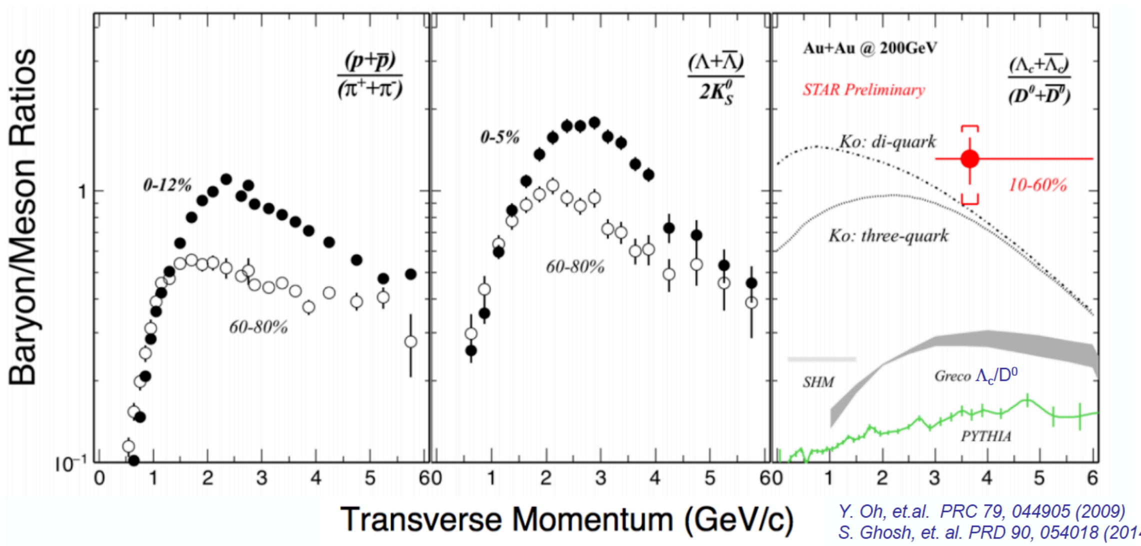
- Heavy quark flavors (*c*,*b*) are dominantly produced in initial hard scatterings (calculable in pQCD) and then interact with the medium.

- There is strong evidence that **charm quarks *thermalize*** in the medium.

(A.) Elliptic flow of D mesons:



(B.) Baryon-to-meson enhancement seen in Λ_C:

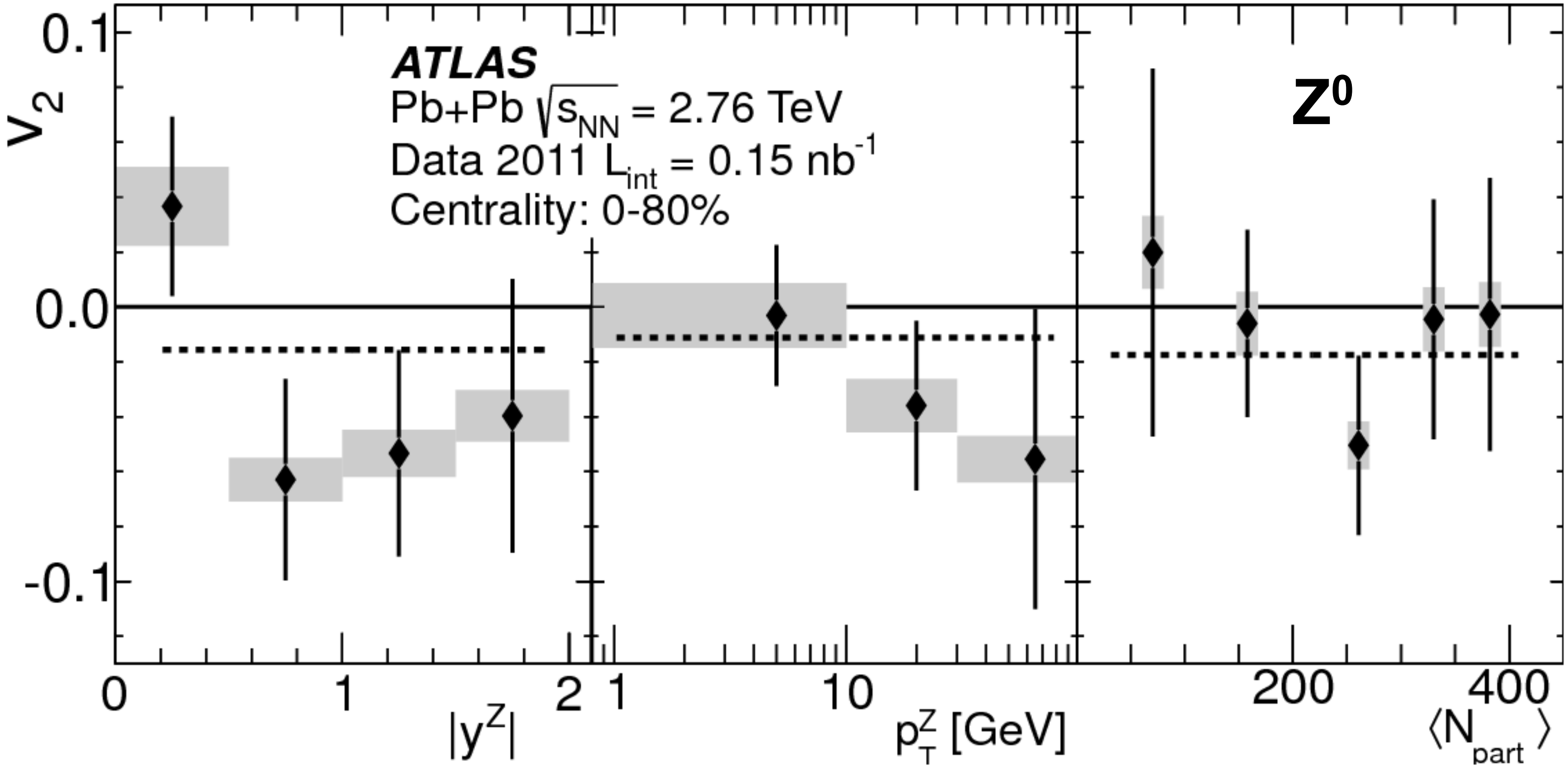


Y. Oh, et.al. PRC 79, 044905 (2009)
S. Ghosh, et. al. PRD 90, 054018 (2014)

Heavy flavor

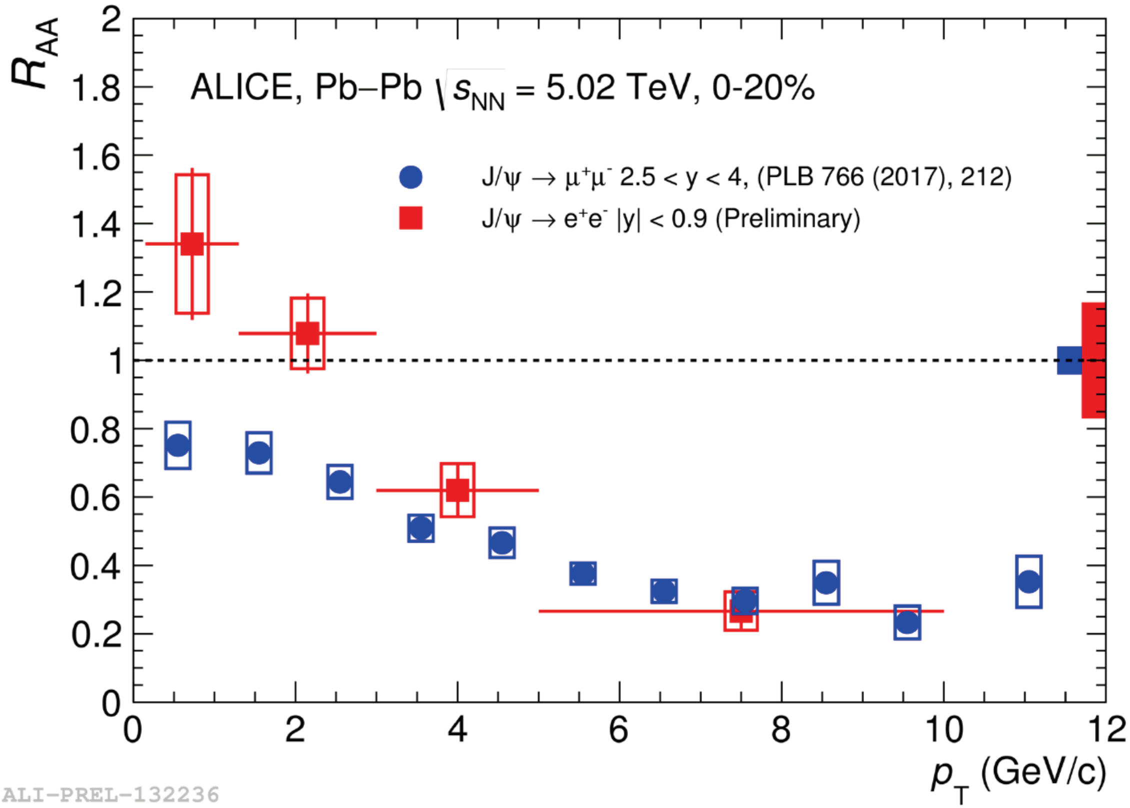
- Heavy quark flavors (*c*,*b*) are dominantly produced in initial hard scatterings (calculable in pQCD) and then interact with the medium.

- N.B.: **electroweak probes do not show any interaction with the medium**.



[PRL 110, 022301 (2013)]

J/ψ recombination



→ As $c\bar{c}$ bound state, the J/ψ is expected not to be bound in the QGP phase (*Matsui/Satz*, 1986), but it can re-generate at the phase boundary.

→ 5.02 TeV Pb-Pb data strongly confirms J/ψ recombination picture:

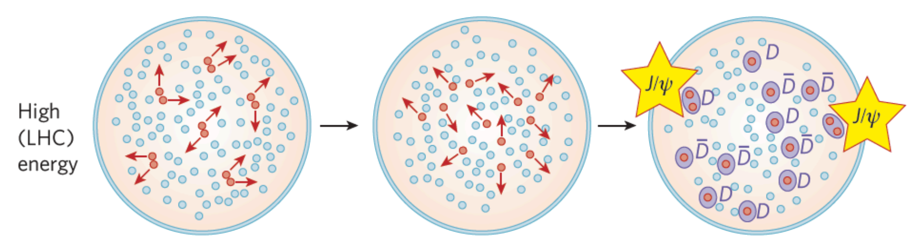
- R_{AA}(LHC) > R_{AA}(RHIC)
- R_{AA} midrapidity > R_{AA} forward rap.

→ Signature of de-confinement.

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \cdot dN_{pp}/dp_T}$$

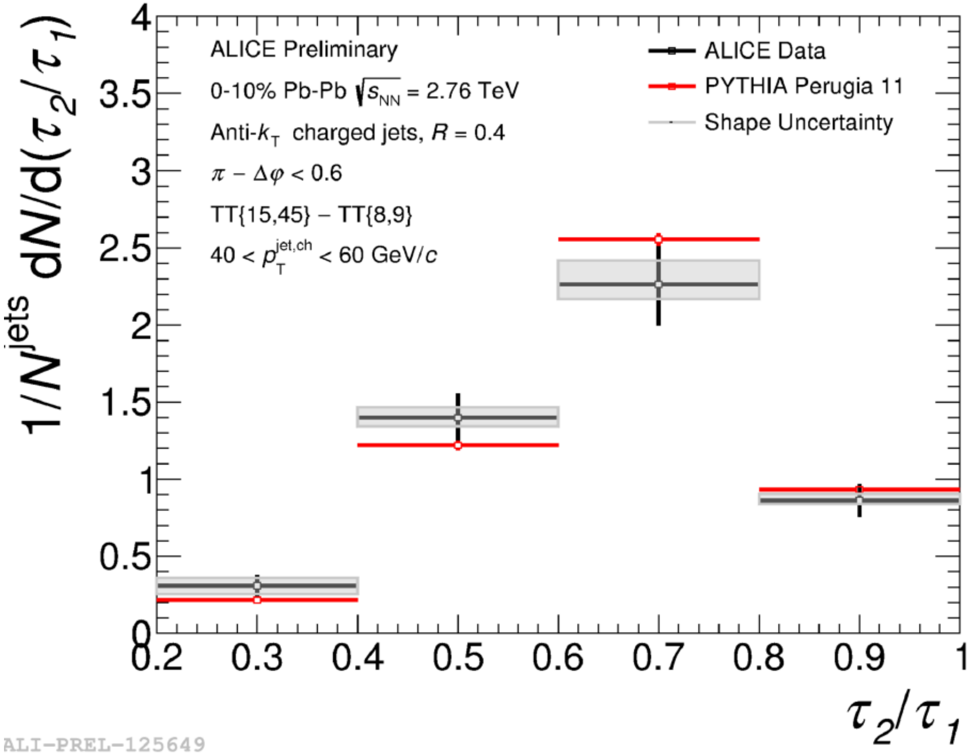
R_{AA} < 1 → suppression w.r.t pp coll.
R_{AA} > 1 → enhancement w.r.t to pp coll.

[P. Braun-Munzinger, J. Stachel, Nature doi:10.1038/nature06080]

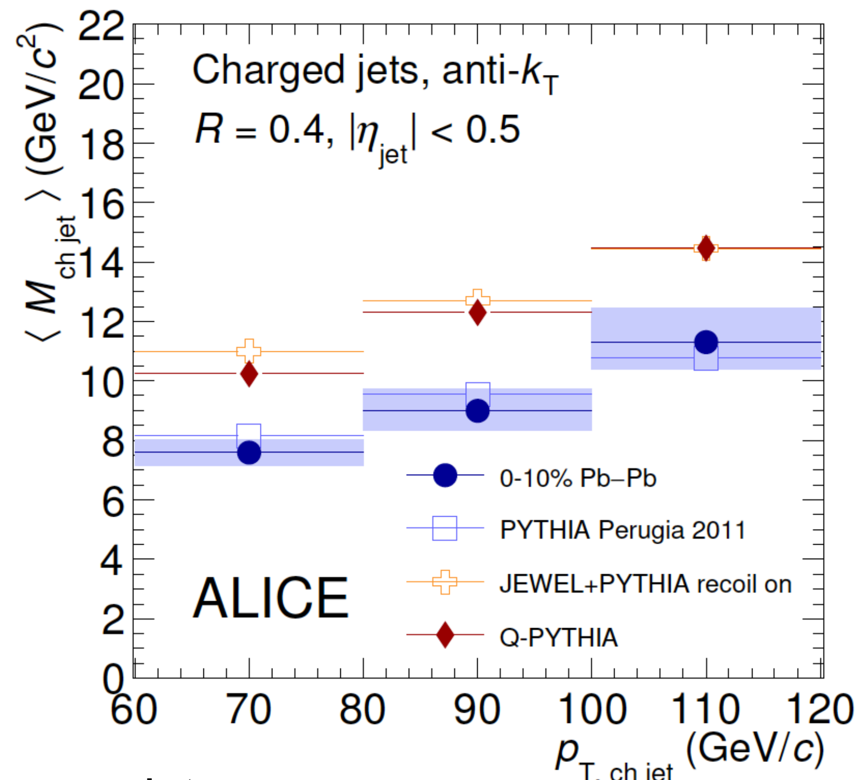


Jet substructure in heavy-ions

- Several state-of-the-art jet substructure measurements are carried out as well in the heavy-ion environment.
- Interestingly, jets lose energy in the medium, but their structure seems unmodified.



N-subjettiness
(sensitive to two-prongness)



Jet mass
(sensitive to broadening)

Summary and outlook

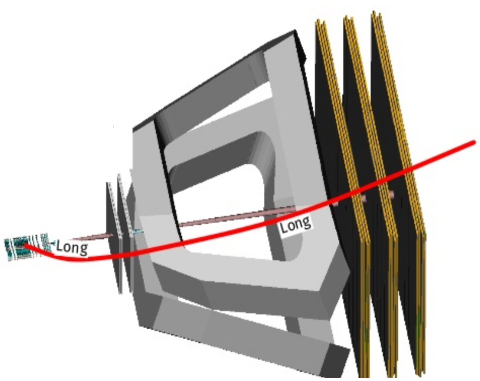
Summary

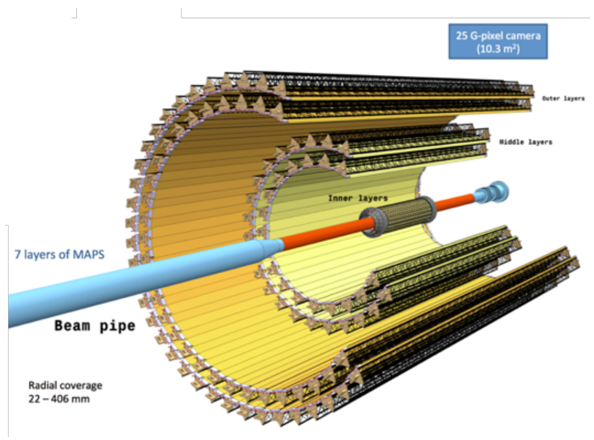
- The field of (ultra-relativistic) heavy-ion physics has seen a wealth of beautiful new results in the last years from LHC and the beam energy scan at RHIC.
- New facilities are coming up at the high net-baryon density frontier at lower center-of-mass energies: NICA and FAIR.
- LHC Run2 data analysis is in full swing.
- Change of paradigm: pp and p-Pb data samples are not only reference samples anymore, but show at high multiplicities similar features to Pb-Pb collisions.

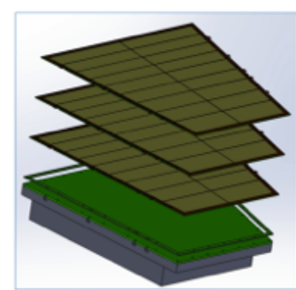
Preparations for LHC Run 3 and 4

Major detector upgrades in long shutdown 2 (2019-2020) will open a new era for heavy-ion physics:

- New pixel Inner Tracker System (ITS) for ALICE
- GEM readout for ALICE TPC => continuous readout
- SciFi tracker for LHCb
- 50 kHz Pb-Pb interaction rate



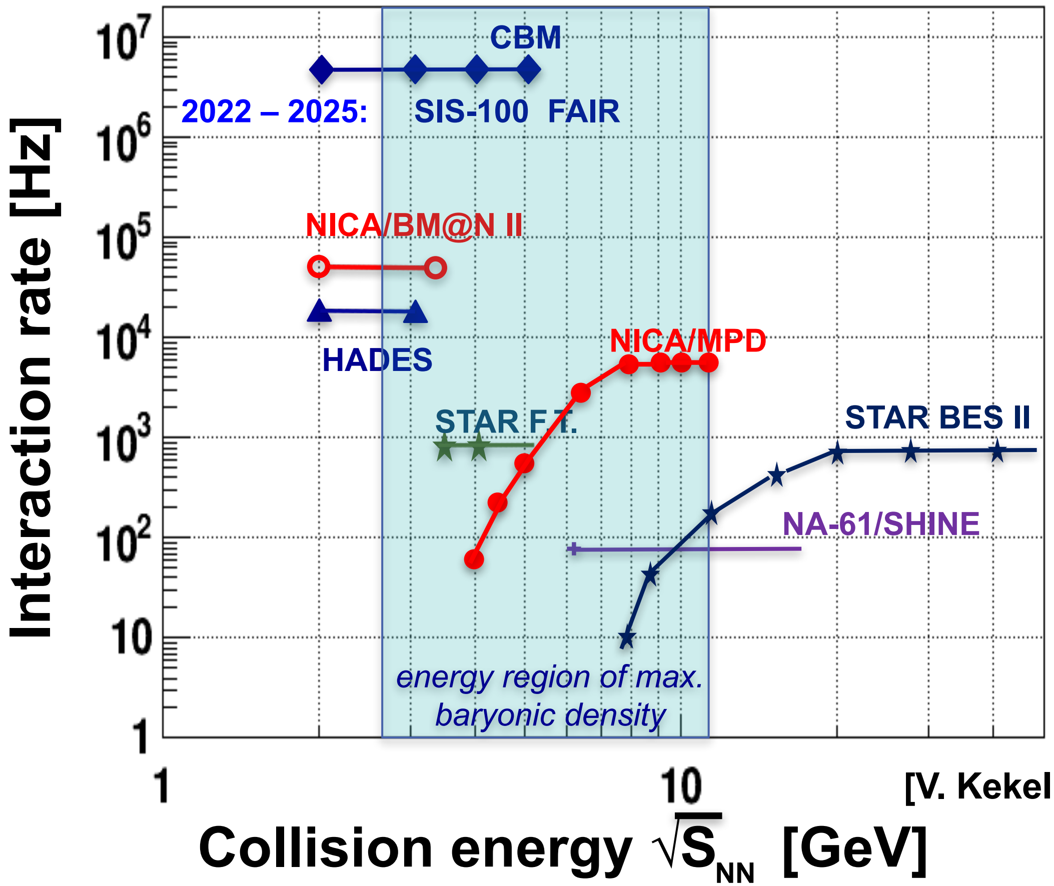




Replace wire chambers with GEMs

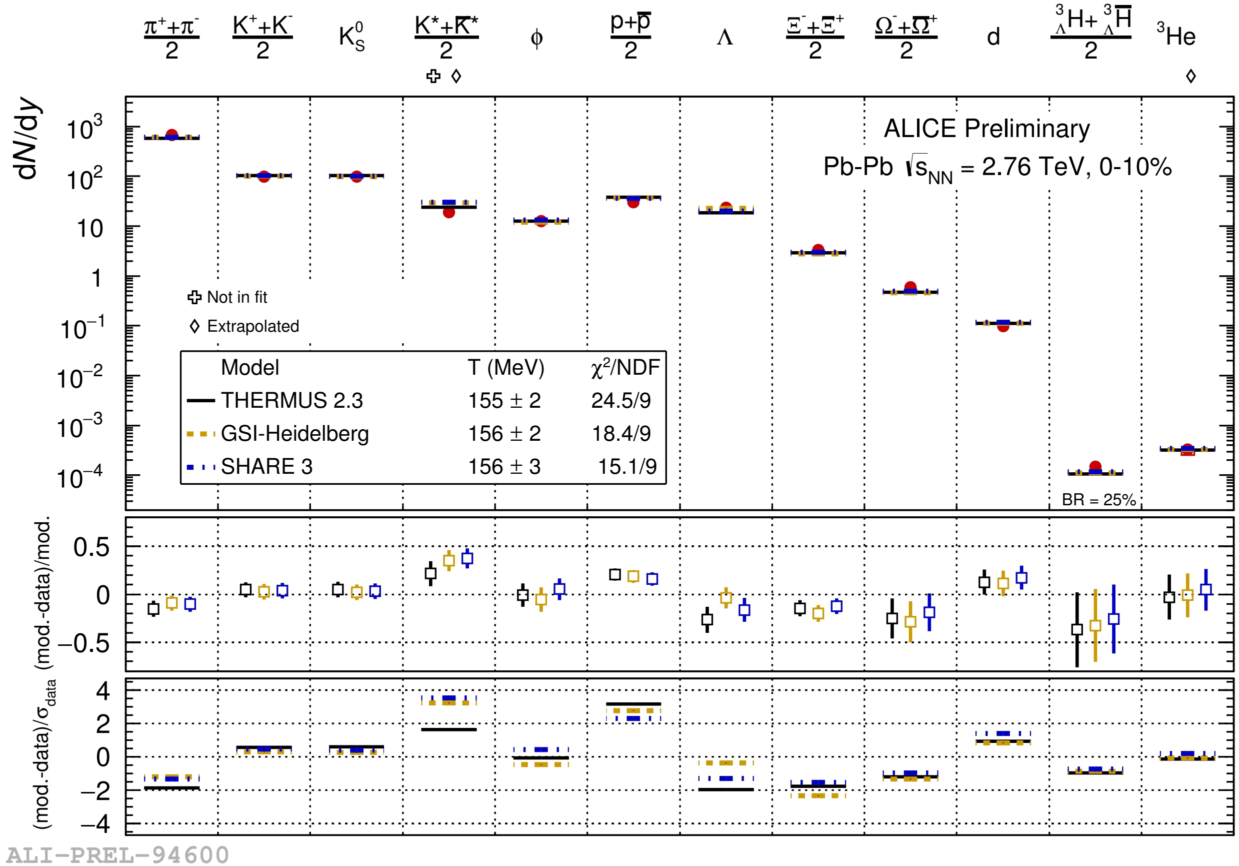
ADDITIONAL SLIDES

Energy ranges covered by different accelerators

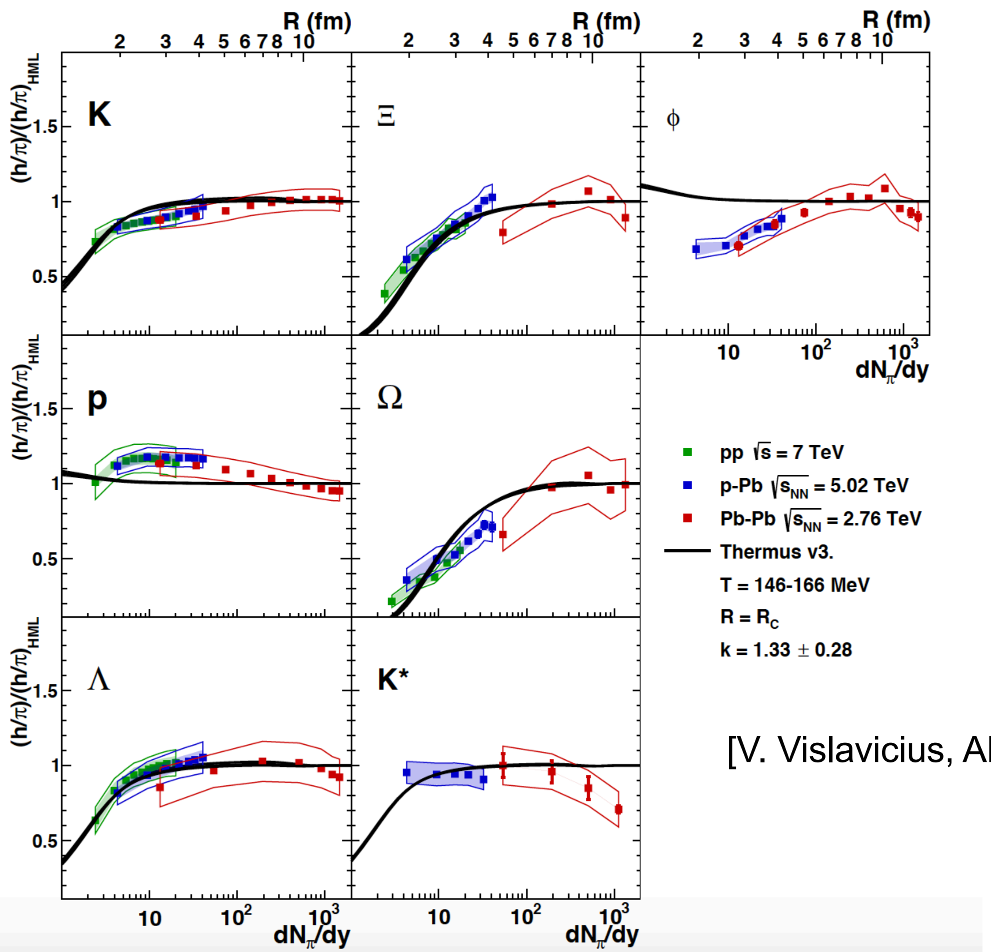


[V. Kekelidze, SQM2017 talk]

Thermal model fit



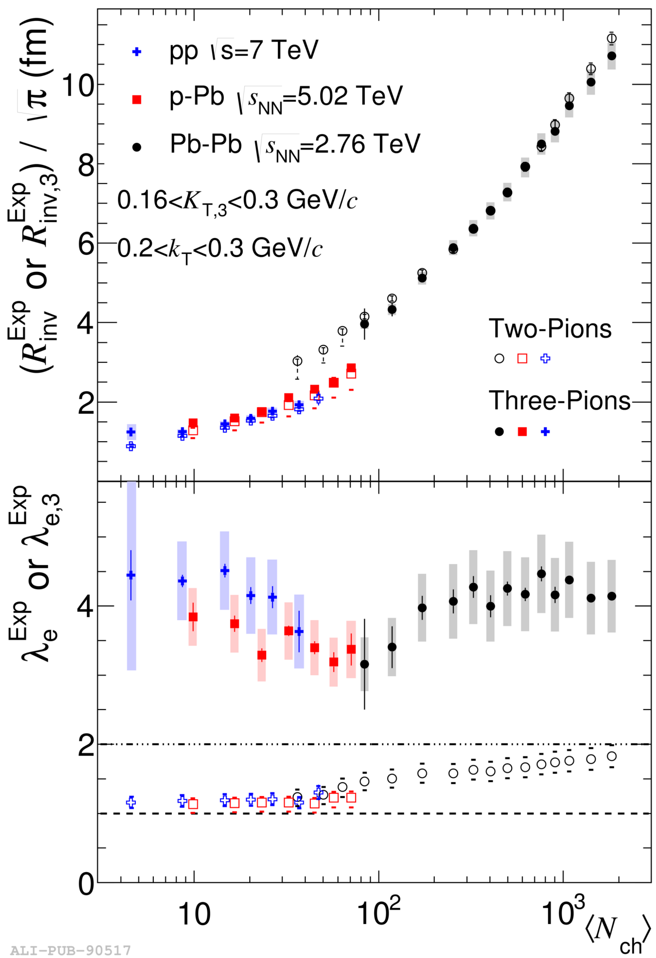
Strangeness canonical suppression



[V. Vislavicius, AK, arXiv:1610.03001]

System size

- Charged particle event multiplicity is taken as a measure of the system size.
- Such an approach is supported by interferometry analysis (HBT).

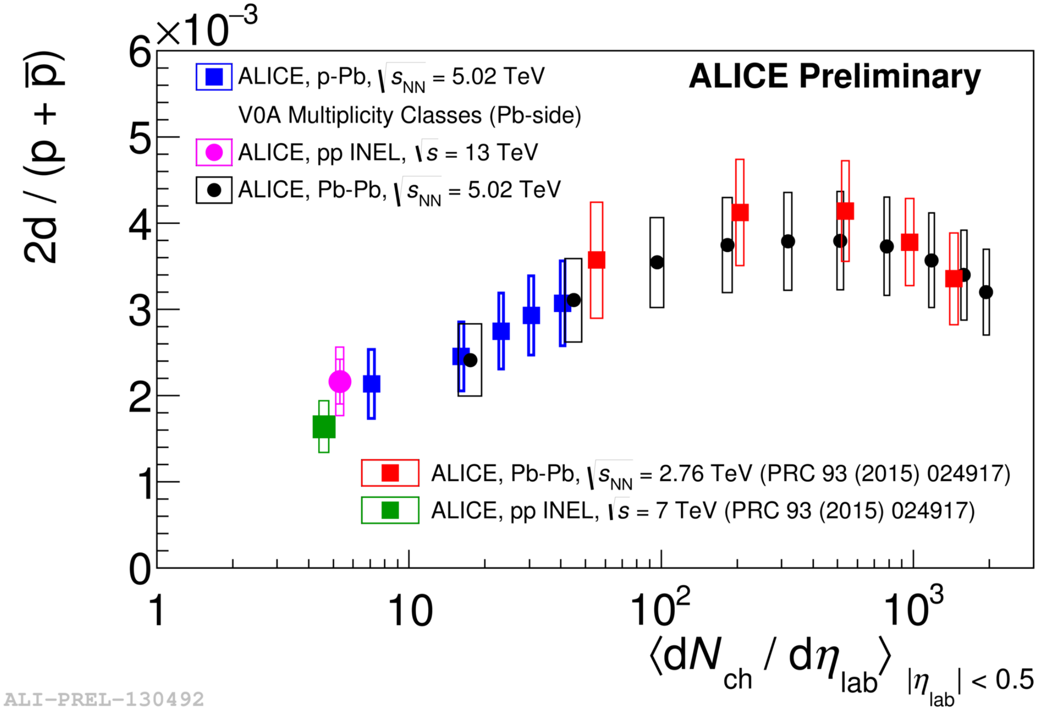


Production of (anti-)nuclei

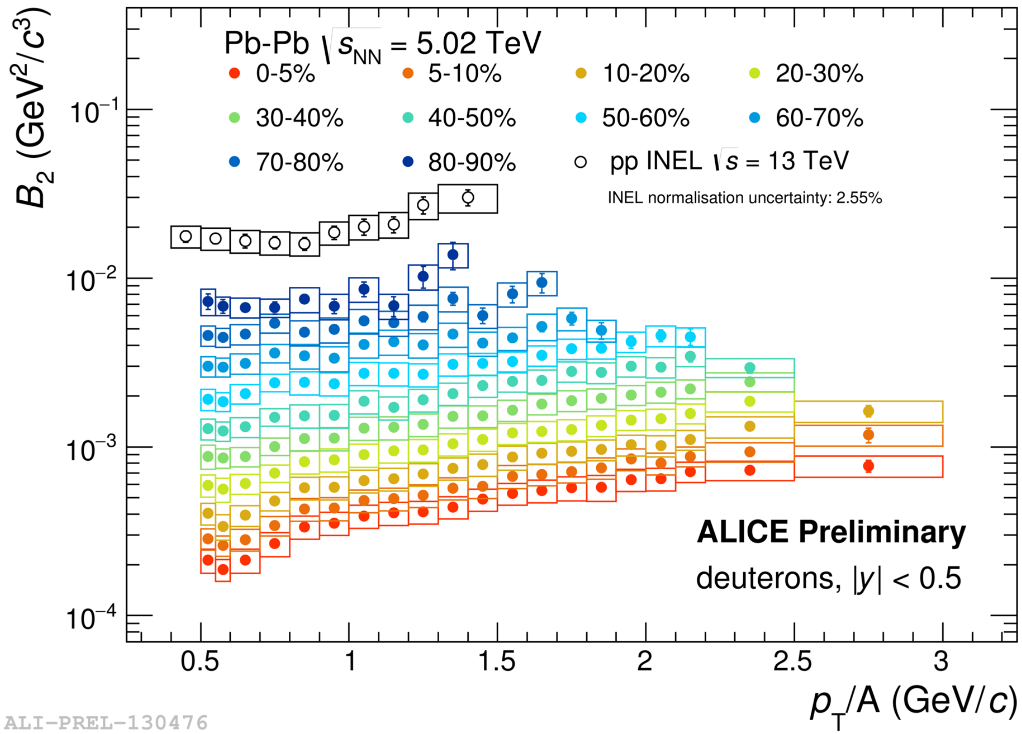
- Coalescence model naturally describes the increase from low to high multiplicity, but not the saturation at the thermal model expectation.

- Idea for such a mechanism: *d*/*p* ratio is determined by the entropy per baryon which is fixed at chemical freeze-out and not changed by the isentropic expansion thereafter.

[J. Kapusta, P. Siemens, PRL 43 (1979) 1486]
[A. Andronic *et al.*, PLB697 (2011) 203]



Thermal and coalescence production of (anti-)nuclei



$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A \qquad B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{(A-1)} \frac{1}{A!} \frac{M}{m^A}$$

- p_T-integrated particle yields of light nuclei are well described by thermal-statistical models with chemical freeze-out temperatures much larger than their binding energy: $T_{ch} \approx 156$ MeV $\gg E_{B,deut} \approx 2.2$ MeV
- Such a difference of scales is not present in the coalescence approach.
- The coalescence model in its simplest form cannot predict p_T-integrated yields in Pb-Pb collisions:
  → Strong dependence on p_T and on centrality.
  → Needs detailed modeling of expansion and source volume.

Chemical freeze-out line

- By colliding nuclei with different center of mass energies, different regions of the phase diagram are explored.

- Thermal model fits to the experimental data define the chemical freeze-out line in the QCD phase diagram.