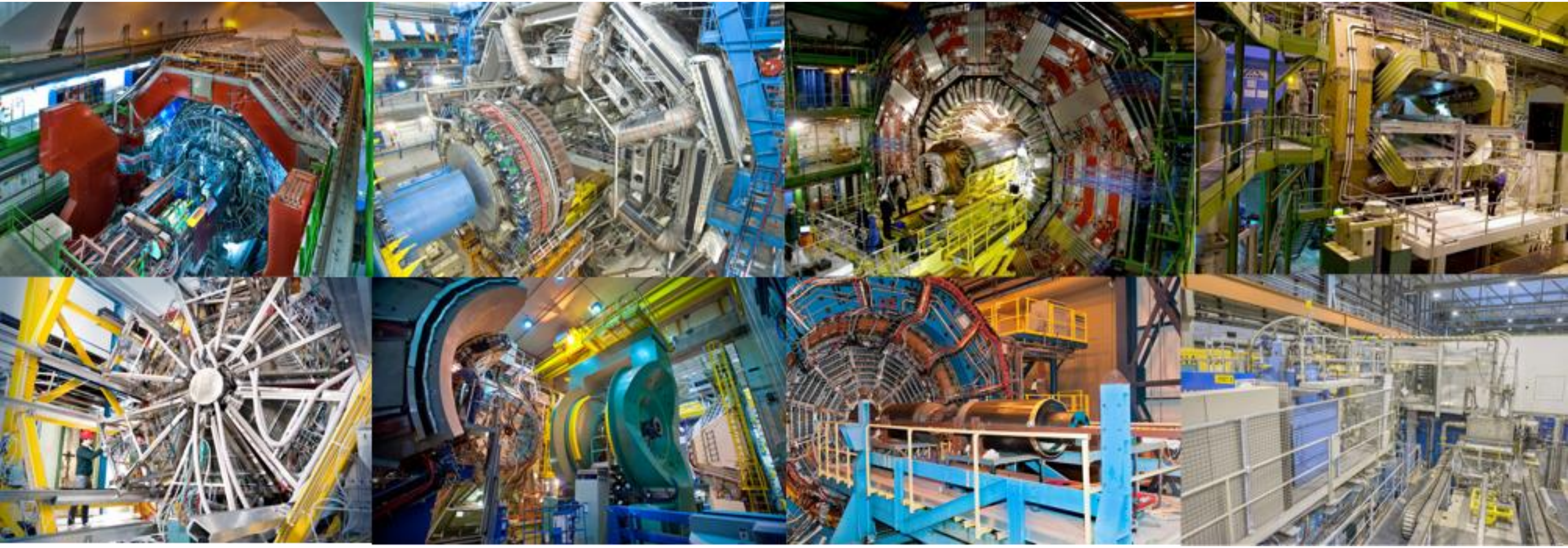
The physics of heavy-ion collisions



Alexander Kalweit, *CERN*

Overview

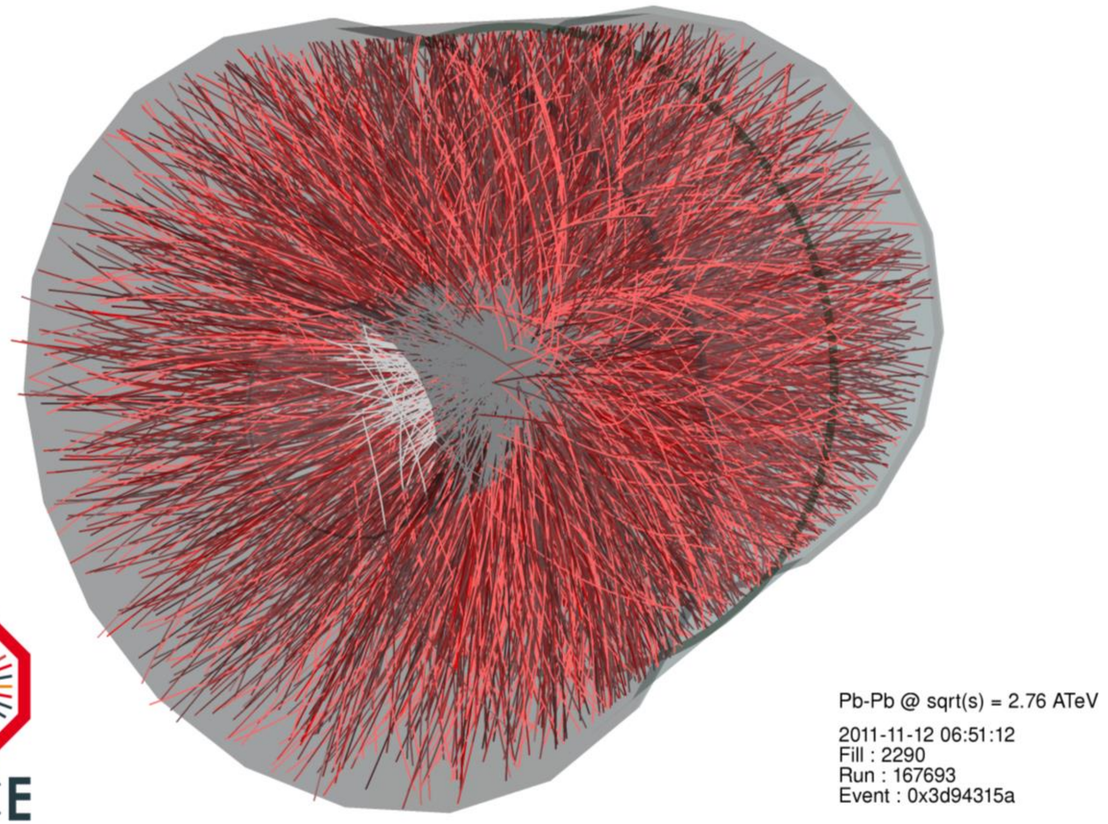
- Three lectures (one hour each):
  - Friday, 10:30h-11:30h (Prevessin)
  - Saturday, 11:30h-12:30h (Meyrin)
  - Monday, 10:30h-11:30h (Prevessin)

- Specialized discussion sessions with **heavy-ion experts** in the afternoons on Friday and Monday.

- Feel free to contact me for any questions regarding the lecture: Alexander.Philipp.Kalweit@cern.ch

- Many slides, figures, and input taken from:

  Jan Fiete Grosse-Oetringhaus, Constantin Loizides, Federico Antinori, Roman Lietava



ALICE
A JOURNEY OF DISCOVERY

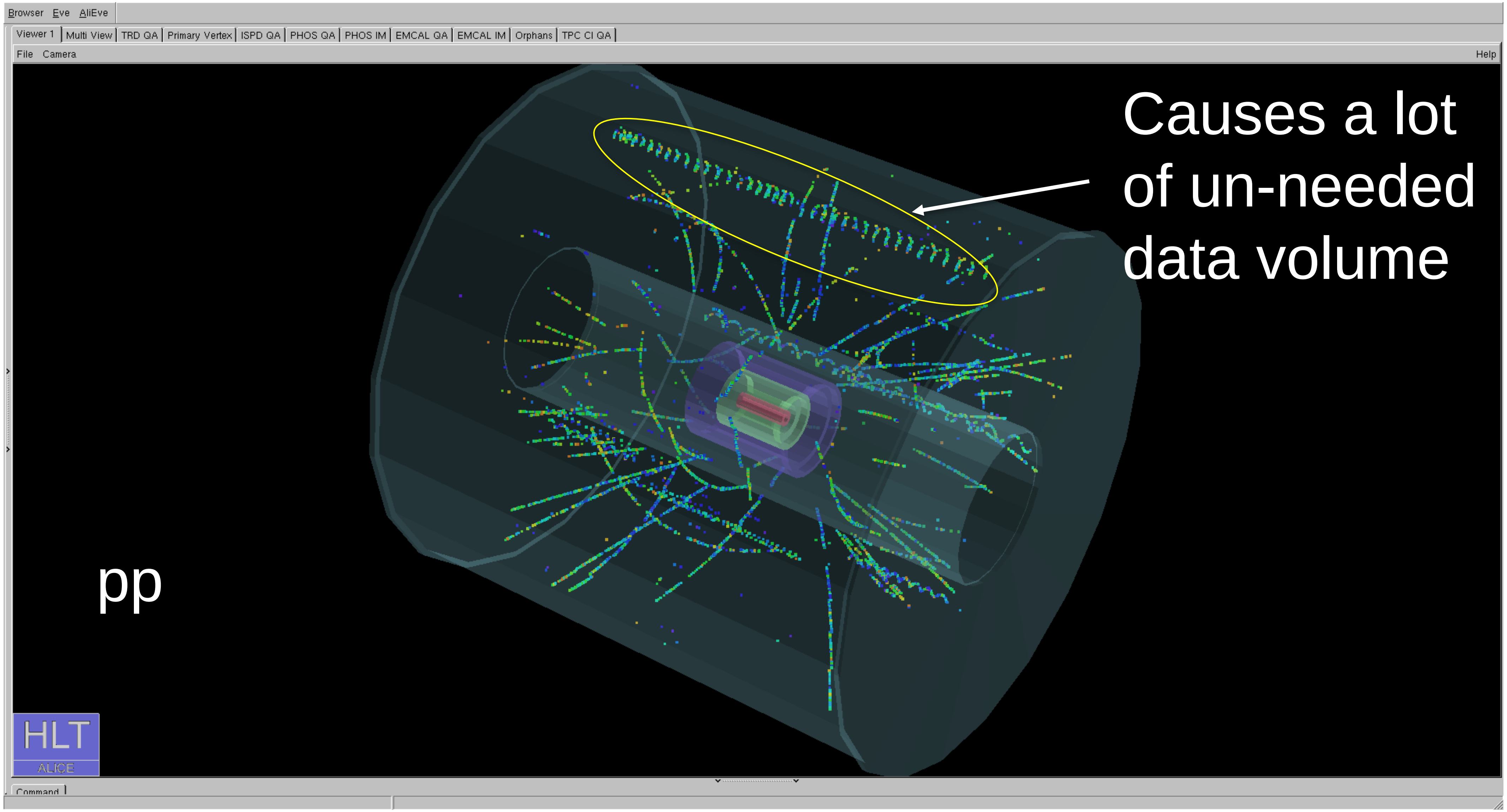
FAQ (1)

- How many bunches are in the LHC during heavy-ion operation?
  - During last run typically 518.

Run#	Bunches	Scheme	Fill #	Energy per beam	Intensity per bunch	Mu	B B	B A	B C	MB Interaction	Rate (Hz)
246994 L	268	100_150ns_518Pb_516Pb_492_444_24_22inj	4,720	6,369		0	444	74	72	1,462,567	292.10
246991 L	268	100_150ns_518Pb_516Pb_492_444_24_22inj	4,720	6,369		0.0005	444	74	72	379,251	238.67
246989 L	268	100_150ns_518Pb_516Pb_492_444_24_22inj	4,720	6,369		0.0007	444	74	72	2,551,035	253.61
246984 L	268	100_150ns_518Pb_516Pb_492_444_24_22inj	4,720	6,370		0.0011	444	74	72	1,757,655	240.84
246982 L	268	100_150ns_518Pb_516Pb_492_444_24_22inj	4,720	6,369		0.0014	444	74	72	145,502	174.88

- What are average event sizes?
  - In pp up to 1-2 MegaByte, in Pb-Pb up to 50 MegaByte.
  - Strong online compression (raw amplitudes -> clusters [lossy], cluster position with respect to the helix).

FAQ (2)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pp
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ALICE
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Outline and discussion leaders

- Introduction
- The QCD phase transition
- QGP thermodynamics and soft probes (Francesca)
  - Particle chemistry
  - QCD critical point and onset of de-confinement
  - (anti-)(hyper-)nuclei
  - Radial and elliptic flow
  - Small systems
- Hard scatterings (Leticia, Marta)
  - Nuclear modification factor
  - Jets
- Heavy flavor in heavy-ions
  - Open charm and beauty
  - Quarkonia
- Di-leptons

Francesca Bellini

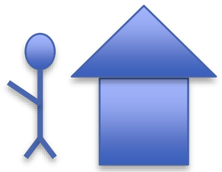
Leticia Cunqueiro

Marta Verweij

Reminder: 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

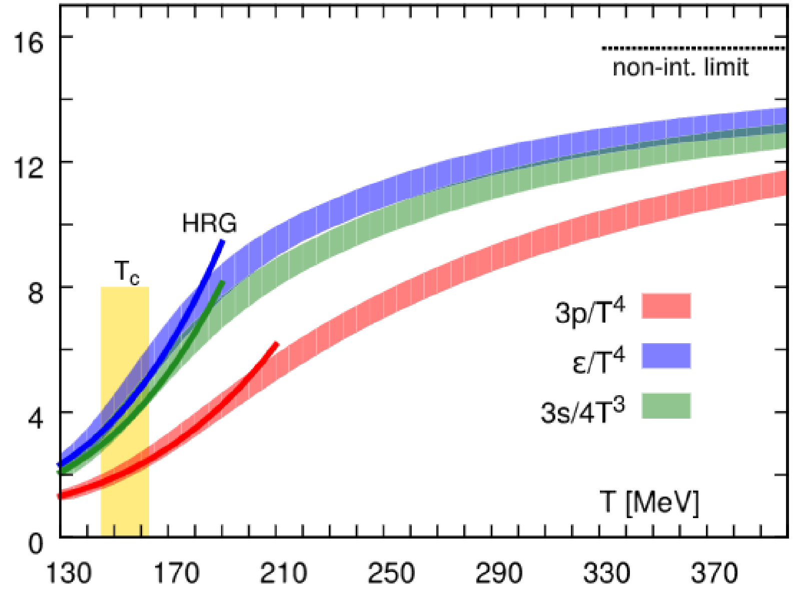
Critical temperature
$T_c \approx 156$ MeV

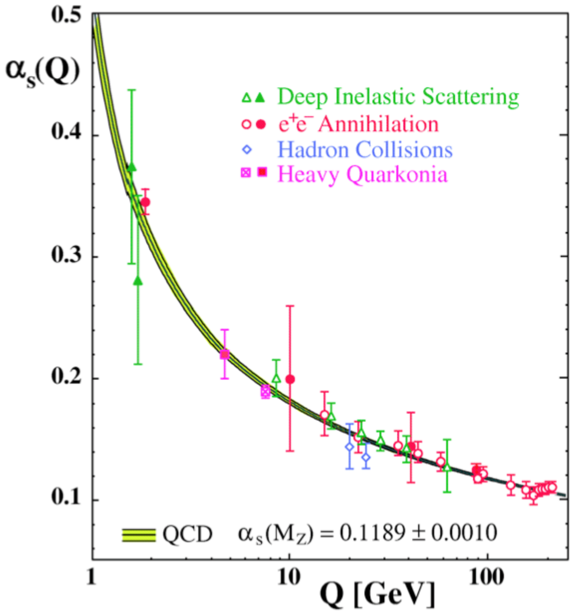
$T \rightarrow \infty$

Temperature T

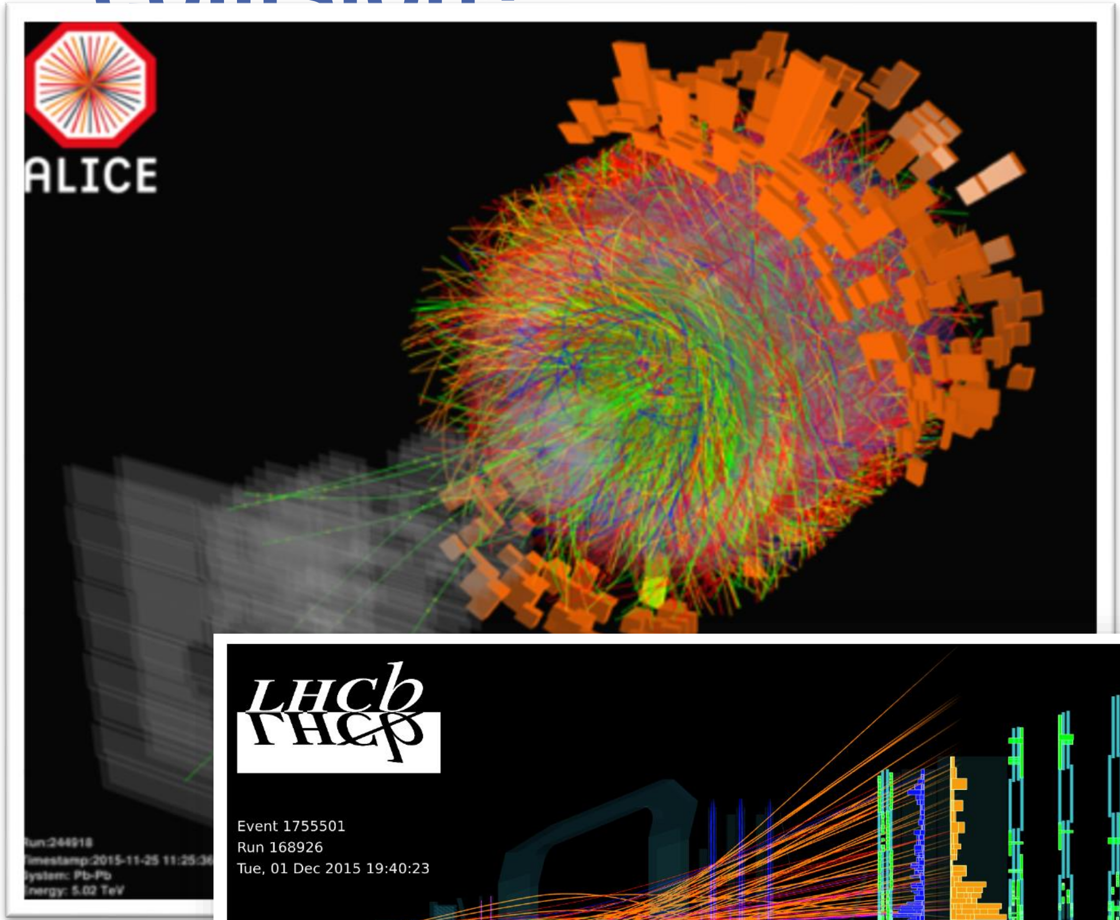
- → Are such extreme temperatures reached in the experiment?
  Yes..
- → Is it for all quark flavors the same?
  Not clear yet..
- → …

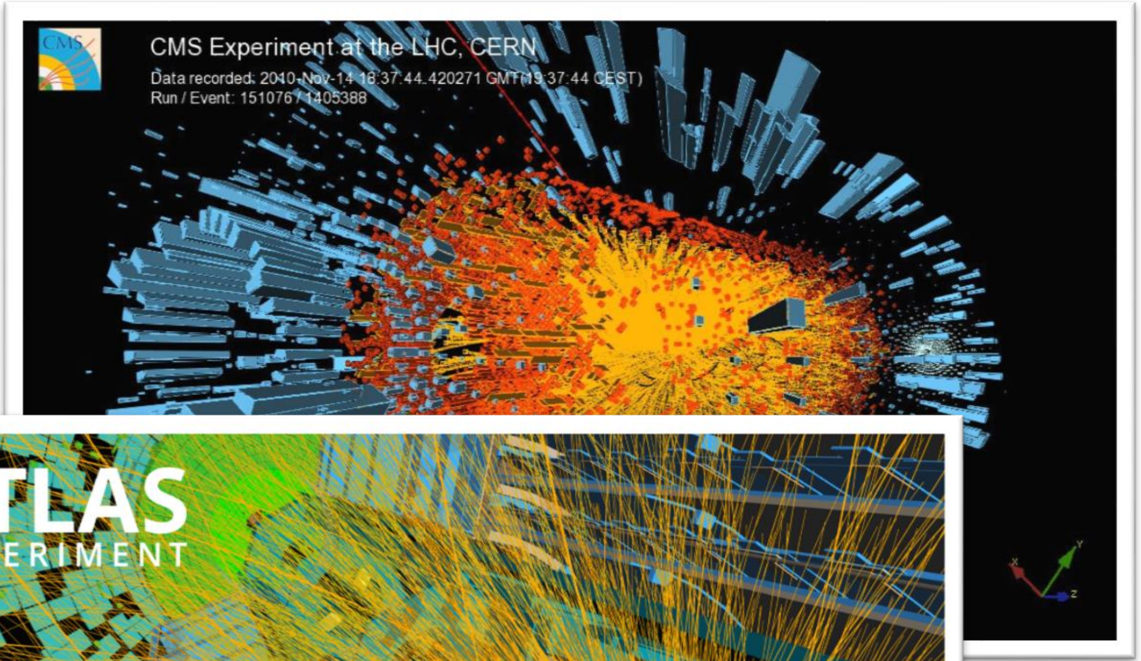
[PRD 90 094503 (2014)]

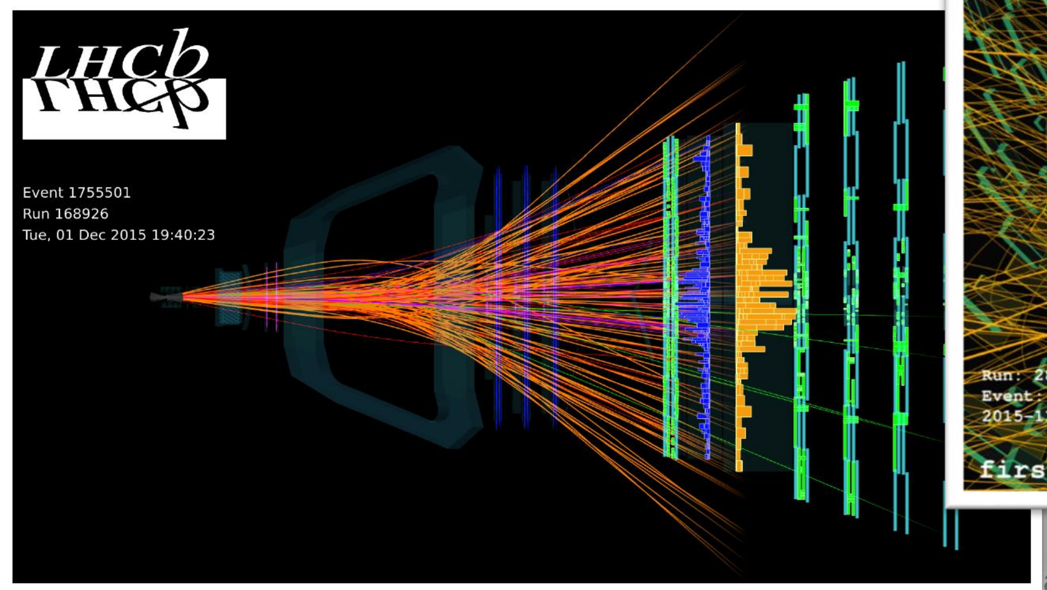


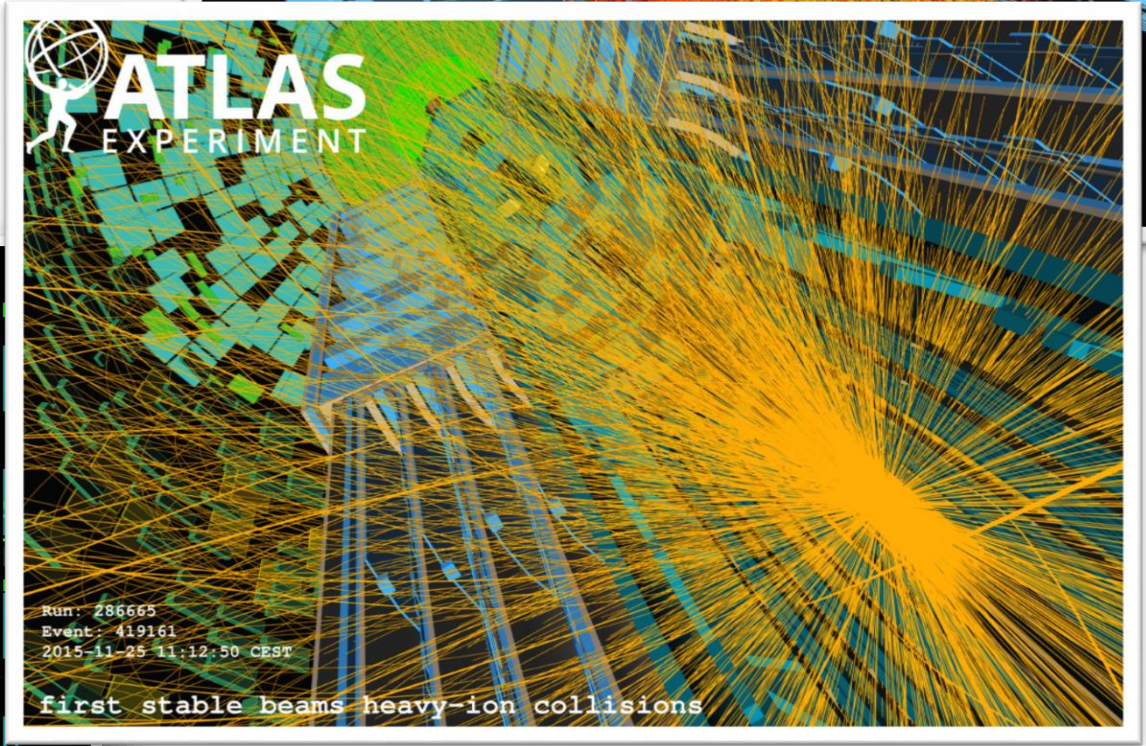


How many particles are created in such a collision?

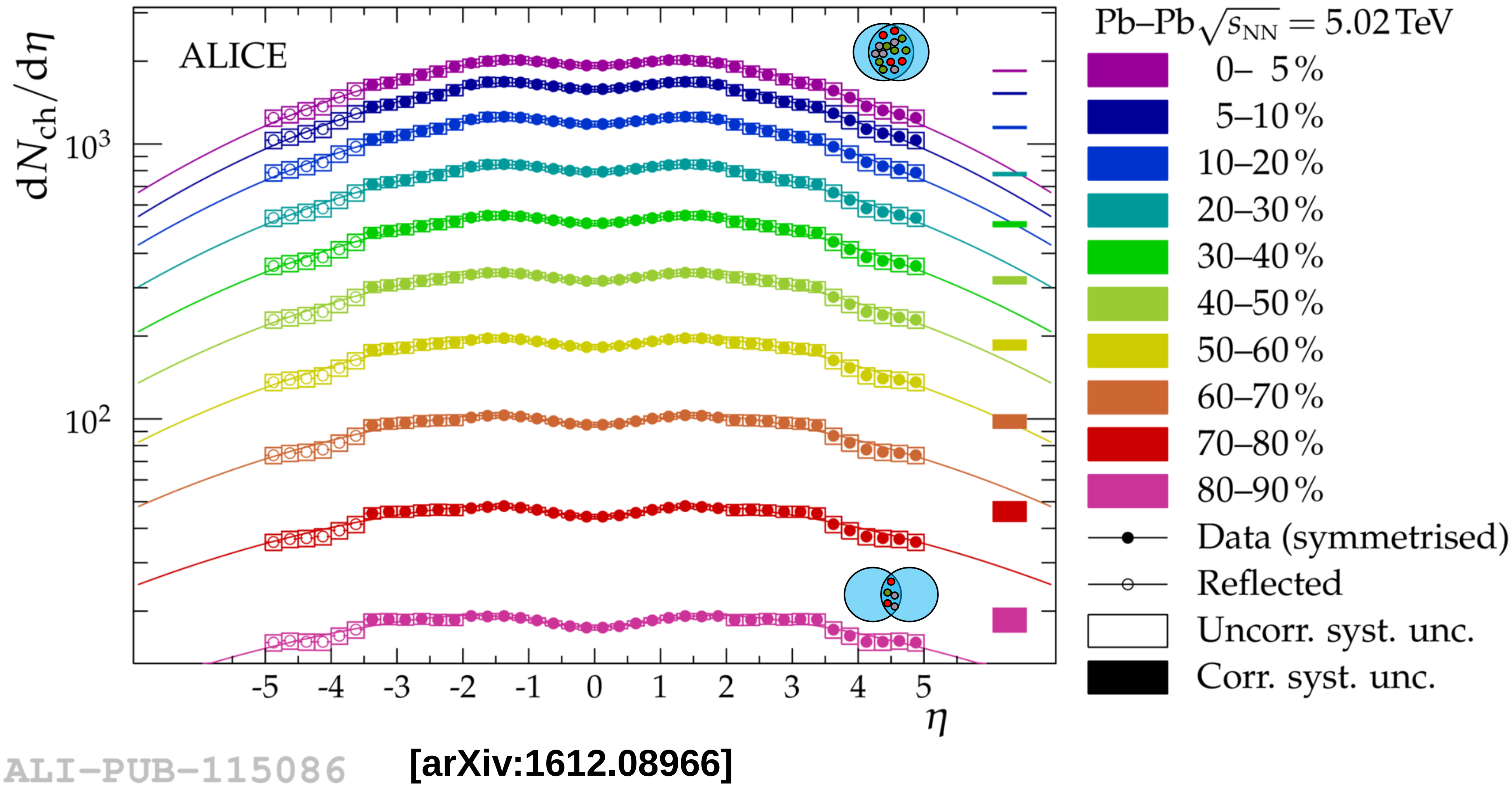








$dN_{ch}/d\eta$ in 5.02 TeV Pb-Pb collisions at the LHC



[arXiv:1612.08966]

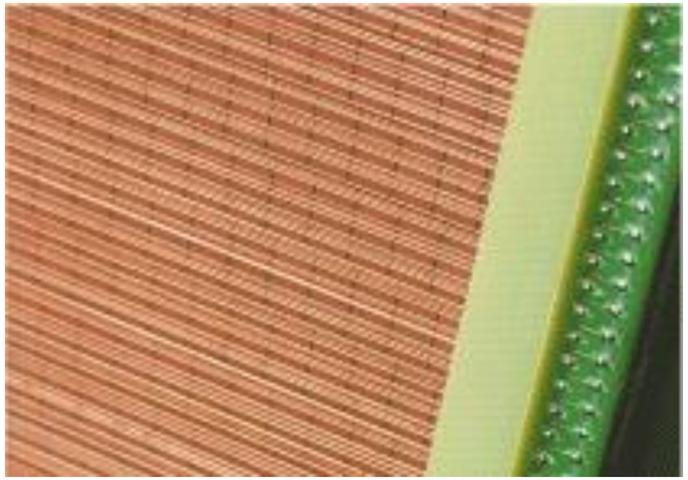
$dN_{ch}/d\eta \approx$ 1943 ± 54 at midrapidity.

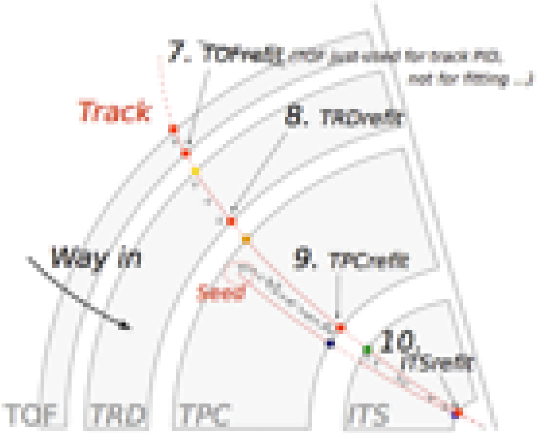
→ Even at LHC energies, 95% of all particles are produced with p_T < 2 GeV/c in pp and Pb-Pb collisions.

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

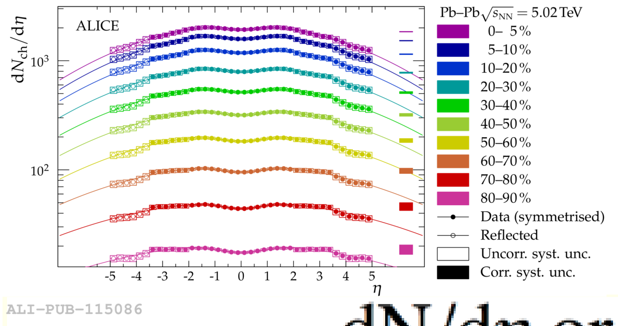
Instrumentation for heavy-ion experiments: granularity

- In order to cope with the high density of particles, heavy-ion detectors have to be very granular (e.g. large TPC with small read-out pads).
- Track seeding typically in outer detectors (where track density is lower) and then Kalman filter propagation to the primary vertex.



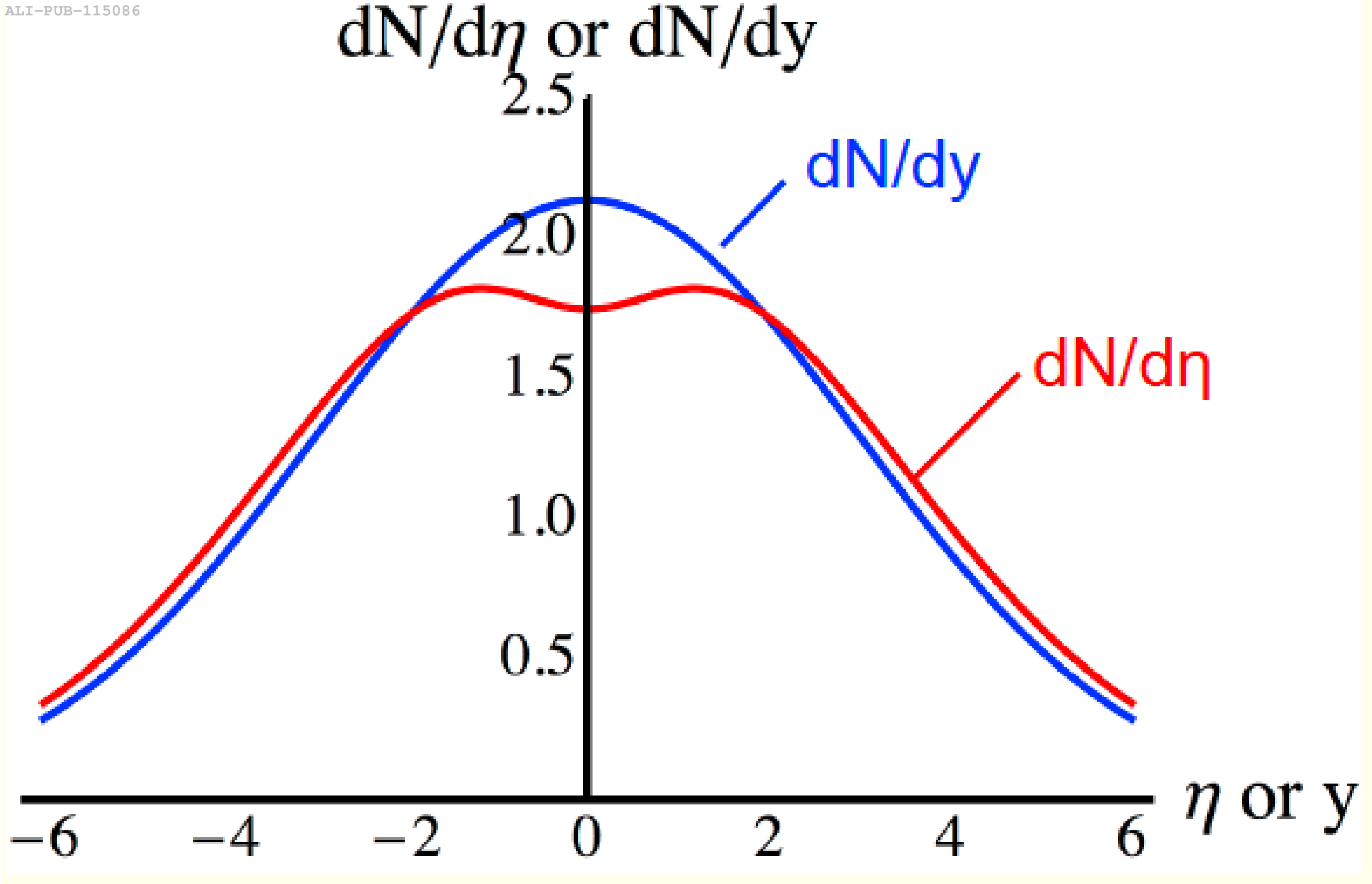


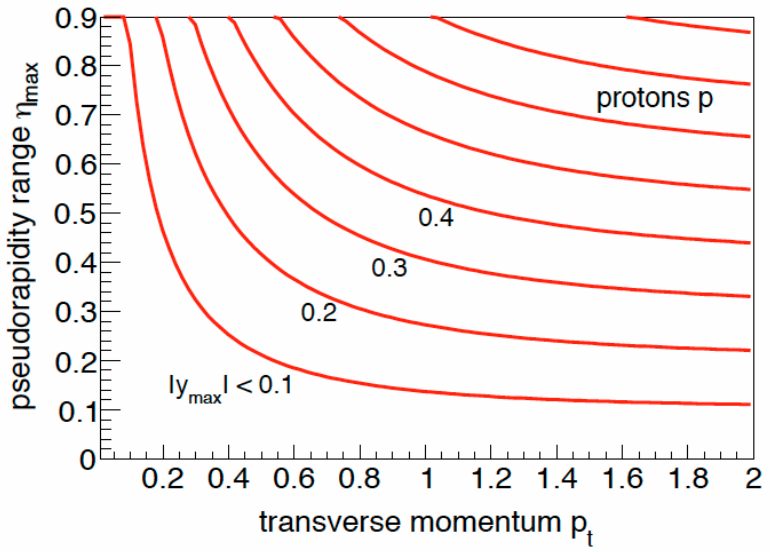
Short reminder: (Pseudo-)rapidity



$$\frac{dN}{d\eta} = \sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}}\, \frac{dN}{dy}$$

→ Always keep in mind: Rapidity and pseudo-rapidity are not the same, especially at low transverse momenta!

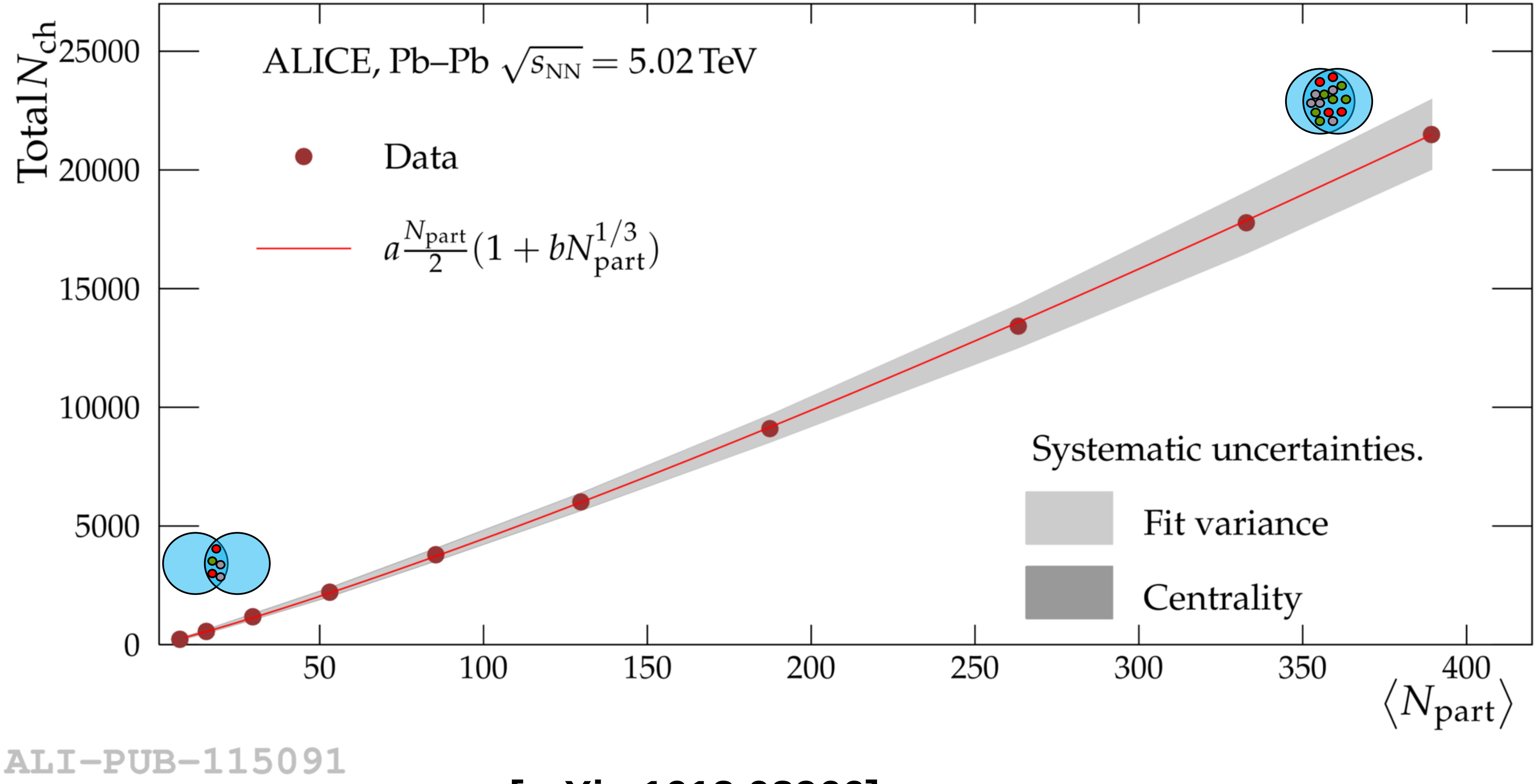




From: K. Reygers

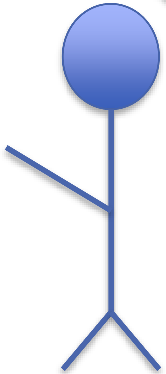
Total number of charged hadrons in Pb-Pb collisions

→ 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.



[arXiv:1612.08966]

So, we have enough particles, but are they in local thermodynamic equilibrium? How can we test that?



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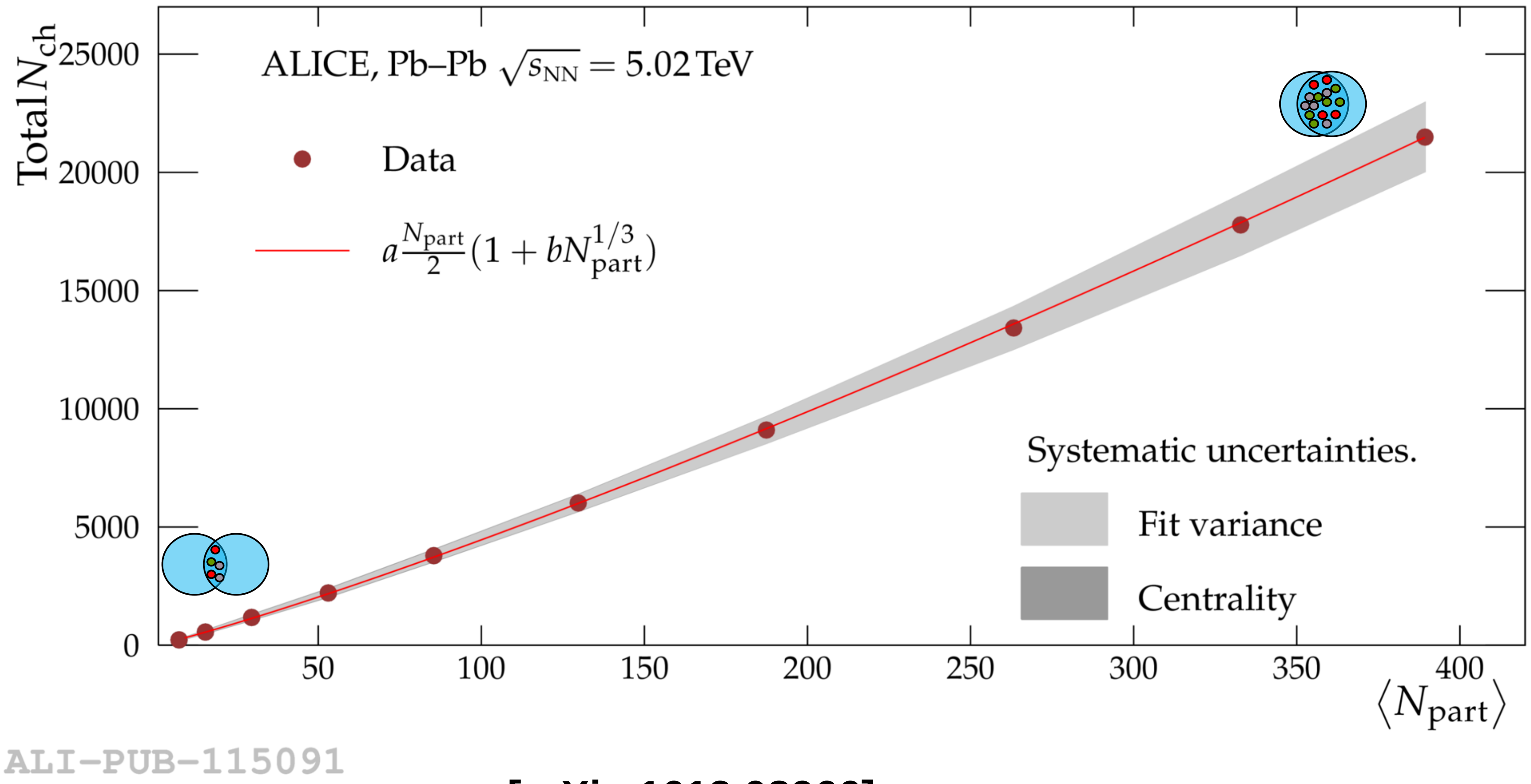
Success of **hydro models** describing **spectral shapes and azimuthal anisotropies** supports idea of matter in local thermal equilibrium (*kinetic*).

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



[arXiv:1612.08966]

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?**

A short introduction to statistical thermodynamics (1)

- The **maximum entropy principle** leads to the thermal most likely distribution of particle species.

- Entropy: the number of possible micro-states Ω being compatible with a macro-state for a given set of macroscopic variables (*E*, *V*, *N*):

$$S = k_B \cdot \ln\Omega$$

- Compatibility to a given macroscopic state can be realized *exactly* or *only in the statistical mean*.

L. Boltzmann

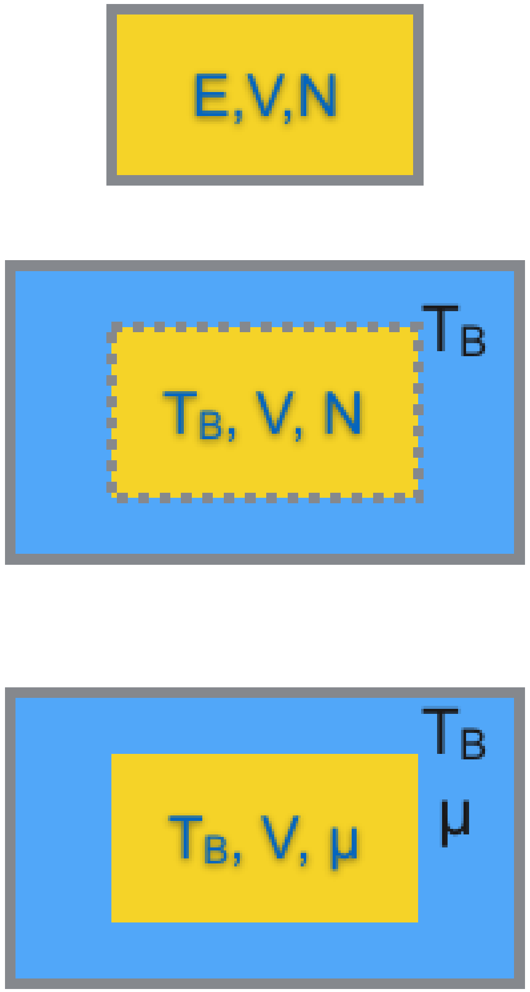
A short introduction to statistical thermodynamics (2)

- We therefore distinguish three different *statistical ensembles*:

  (i) micro-canonical: *E*, *V*, *N* fix

  (ii) canonical: *T*, *V*, *N* fix
  ➔ given volume element is coupled to a heat bath

  (iii) grand-canonical: *T*, *V*, μ fix
  ➔ given volume element can also exchange particles with its surrounding (heat bath and particle reservoir)



Statistical model for e^+e^- collisions.

Strangeness conservation in peripheral HI collisions.

Central relativistic heavy-ion collisions.

A short introduction to statistical thermodynamics (3)

- A small example: barometric formula (density of the atmosphere at a fixed temperature as a function of the altitude *h*).

- Probability to find a particle on a given energy level *j*:

$$P_j = \frac{\exp\left(-\frac{E_j}{k_B T}\right)}{Z}$$

Boltzmann factor

Partition function *Z*
(*Zustandssumme* = *“sum over states”*)

- Energy on a given level is simply the potential energy: $E_{pot} = mgh$. This implies for the density n (pressure p):

$$\frac{p(h_1)}{p(h_0)} = \frac{n(h_1)}{n(h_0)} = \frac{N \cdot P(h_1)}{N \cdot P(h_0)} = \exp\left(-\frac{\Delta E_{pot}}{k_B T}\right) = \exp\left(-\frac{mg}{RT}\Delta h\right)$$

QGP thermodynamics and soft probes

Particle chemistry

Statistical-thermal model for heavy-ion collisions

- Starting point: grand-canonical partition function for an *relativistic ideal quantum gas of hadrons* of particle type i (i = pion, proton,… → full PDG!):

(-) for bosons, (+) for fermions (quantum gas)

$\beta = \frac{1}{kT}$

$E_i = \sqrt{p^2 + m_i^2}$ *dispersion relation (relativistic)*

$$\ln Z_{GK_i} = \pm g_i \frac{V}{2\pi^2\hbar^3} \int_0^\infty dp\; p^2 \ln\left(1 \pm e^{-\beta(\epsilon(p)-\mu_i)}\right)$$

spin degeneracy

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

chemical potential representing each conserved quantity

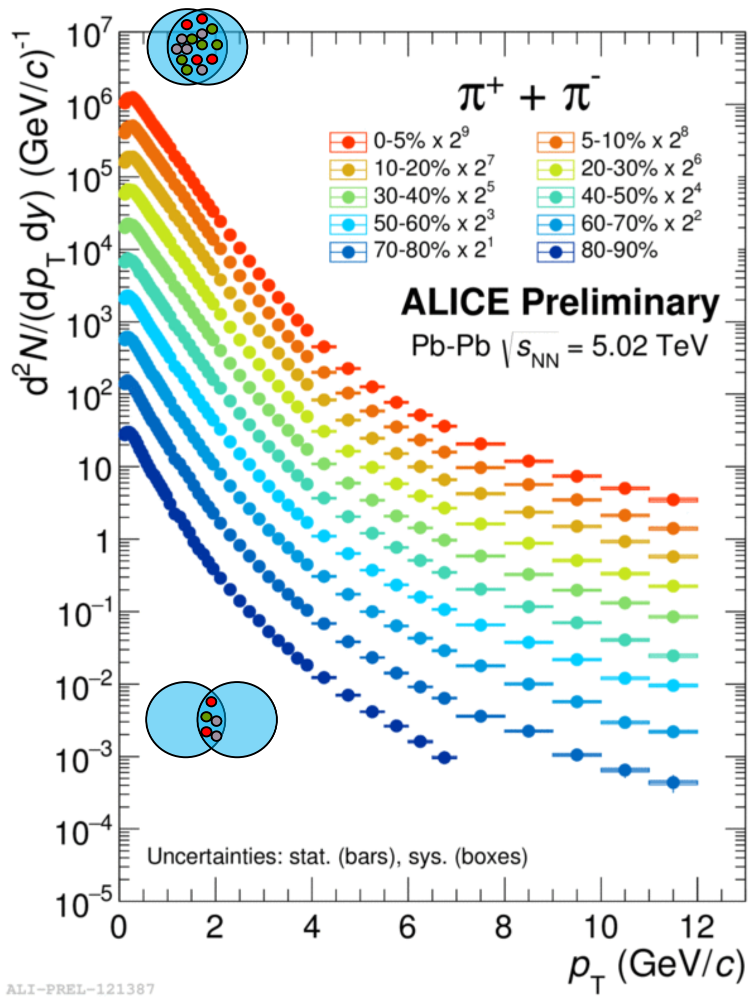
Only two free parameters are needed: **(T,μ_B)**. Volume cancels if particle ratios n_i/n_j are calculated. If yields are fitted, it acts as the third free parameter.

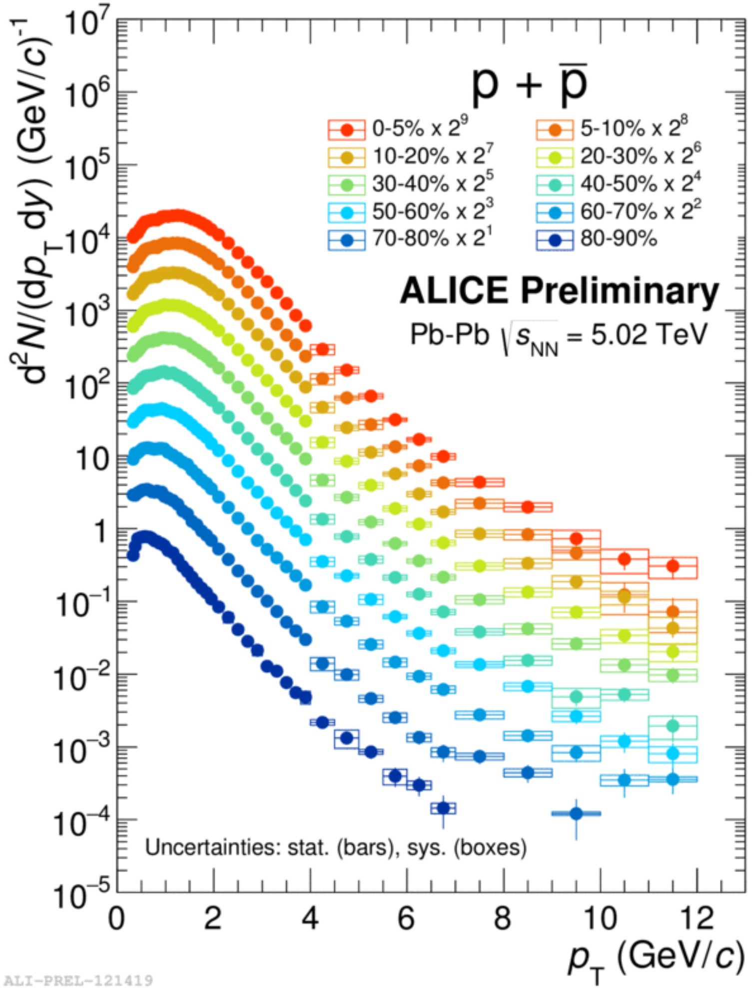
- Once the partition function is known, we can calculate all other thermodynamic quantities:

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} \qquad P = \frac{\partial(T\ln Z)}{\partial V} \qquad s = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial T}$$

Partition function shown here is only valid in the resonance gas limit (HRG), i.e. relevant interactions are mediated via resonances, and thus the non-interacting hadron resonance gas can be used as a good approximation for an interacting hadron gas.

p_T-spectra of identified particles

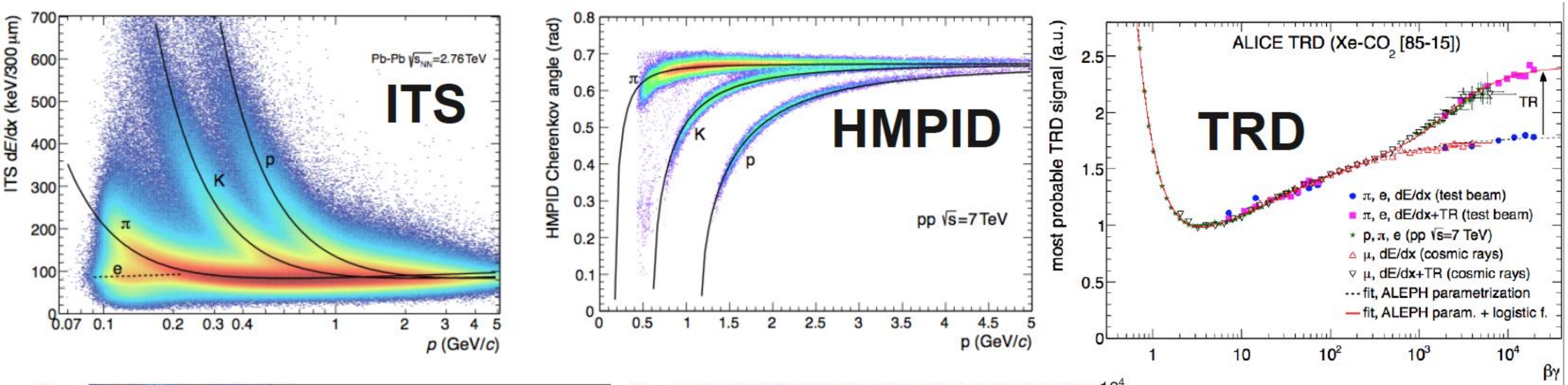


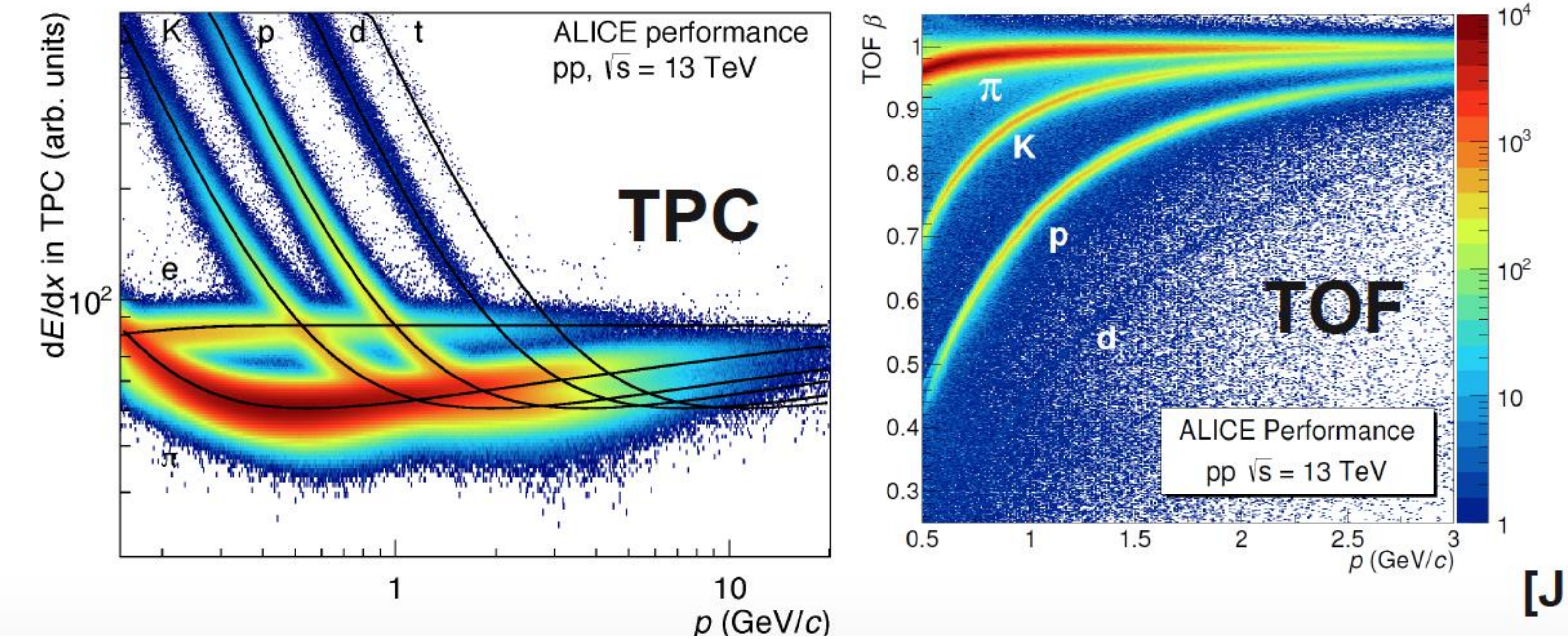


1. Identify particle in the detector (pion, kaon, proton, Lambda, Xi, Omega, anti-deuteron…)
2. Fill p_T-spectrum
3. Interpolate unmeasured region at low p_T (at high p_T negligible)
4. Integrate:

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

Instrumentation for heavy-ion experiments: PID





→ In order to measure as many different particle species directly, heavy-ion experiments typically have a lot of particle identification (PID) detectors.

[JMP A29 (2014) 1430044]

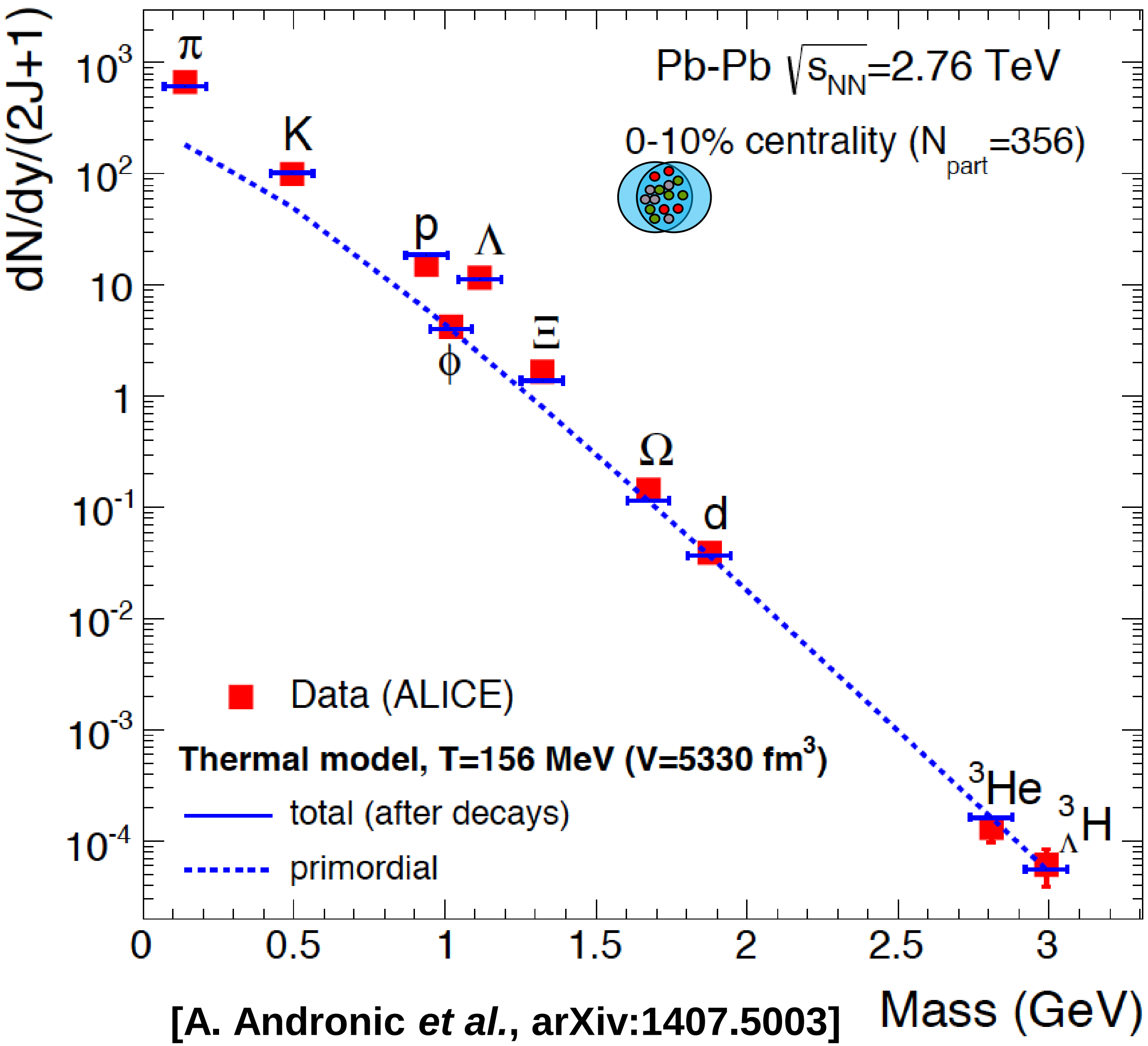
Chemical equilibrium at the LHC (1)

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 detail derived from partition function)

→ 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**.

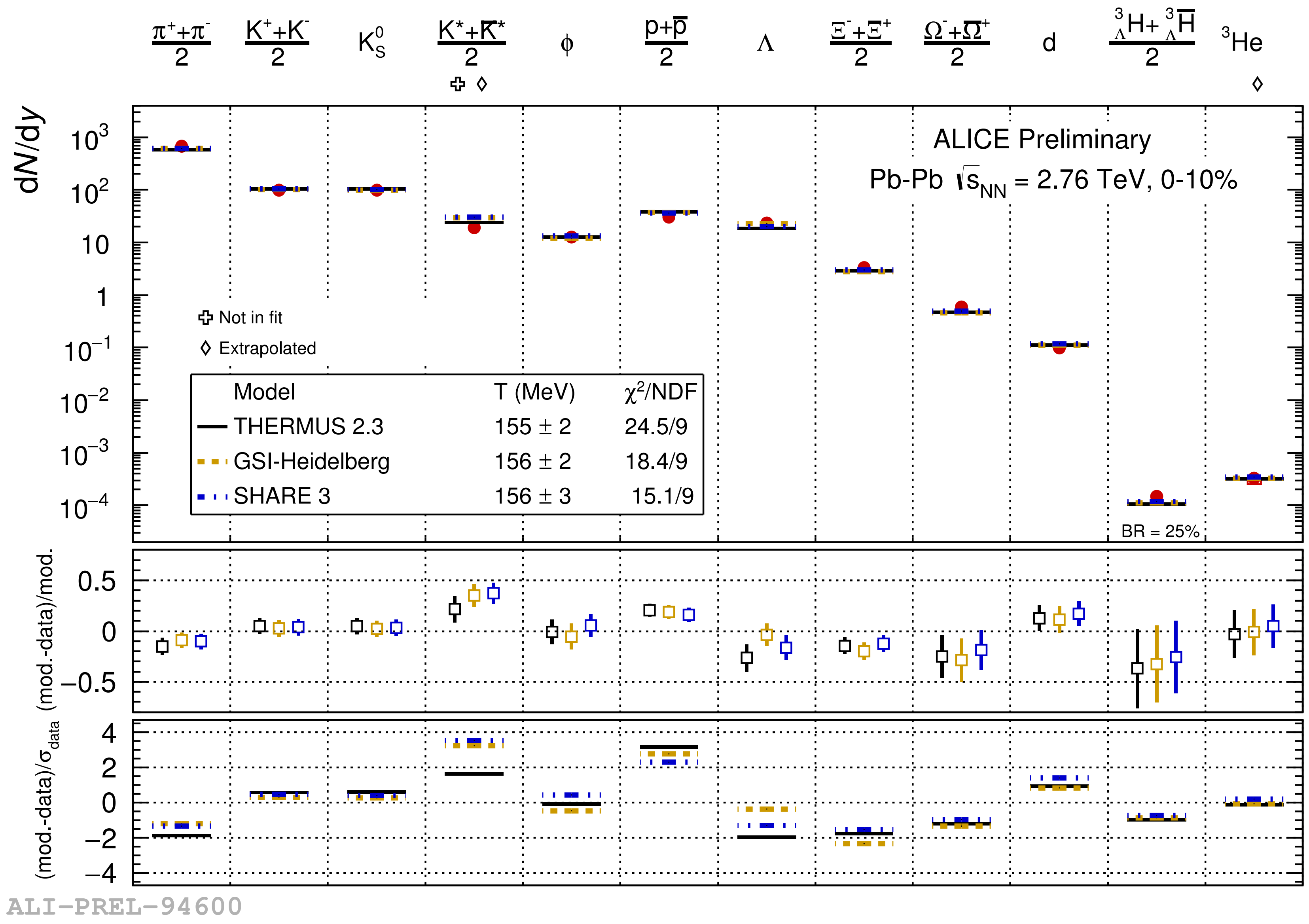
→ This includes **strange hadrons** which are rarer than u,d quarks. Approx. every fourth to fifth quark (every tenth) is a strange quark in Pb-Pb collisions (in pp collisions).

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



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

Chemical equilibrium at the LHC (2



Particle yields of light flavor hadrons are described over 7 orders of magnitude within 20% (except K*0) with a common chemical freeze-out temperature of Tch ≈ 156 MeV (prediction from RHIC extrapolation was ≈ 164 MeV).

Hadrons are produced in apparent chemical equilibrium in Pb-Pb collisions at LHC energies.

Largest deviations observed for protons (incomplete hadron spectrum, baryon annihilation in hadronic phase,..?) and for K*0.

Three different versions of thermal model implementations give similar results.

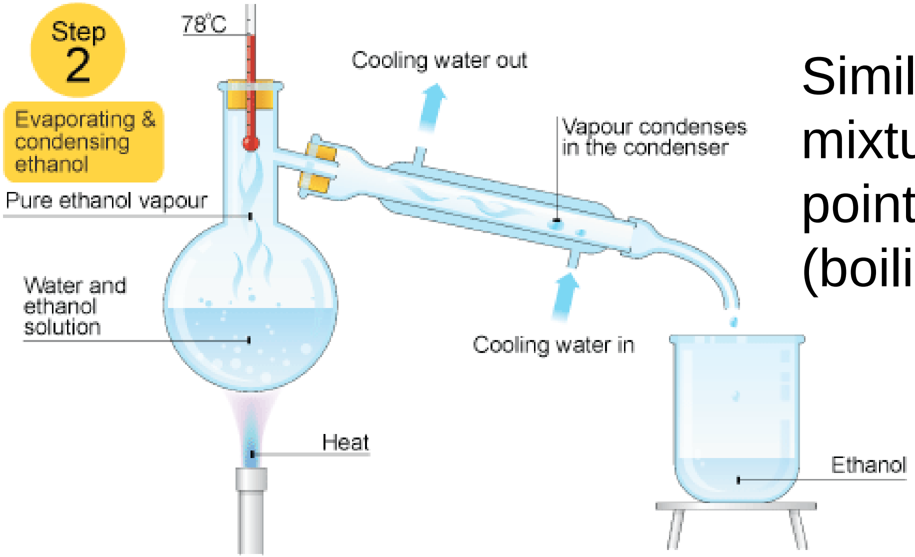
[Wheaton et al, Comput.Phys.Commun, 18084]
[Petran et al, arXiv:1310.5108]
[Andronic et al, PLB 673 142]

Sequential freeze-out?

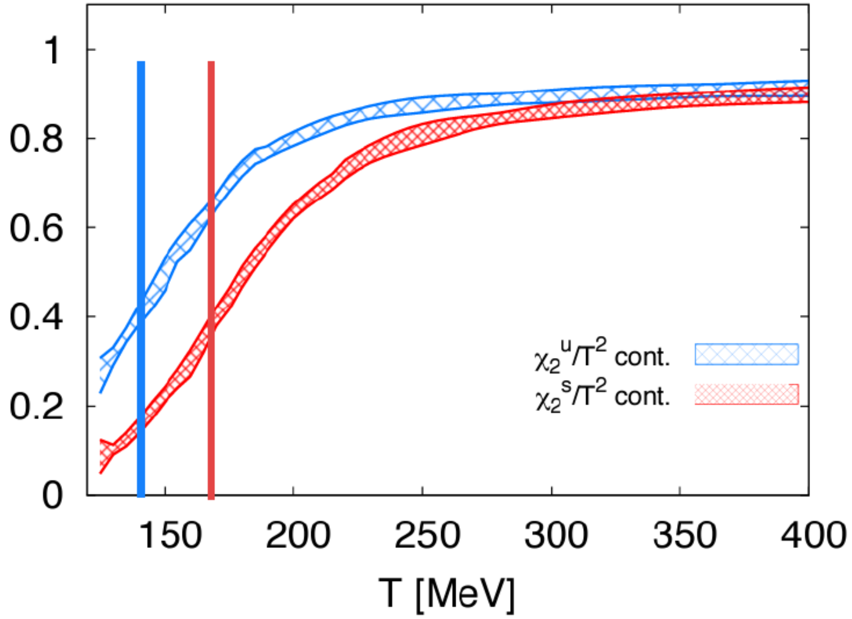
- Are the deviations observed in the thermal model fit for p and Ξ due to physics?

- Two main ideas on the market:

(1.) Different chemical freeze-out temperatures for *s* w.r.t. to *u,d* quarks.
→ motivated by LQCD



Similar to heating a mixture of alcohol (boiling point 78,32 °C) and water (boiling point 100 °C).



C. Ratti et al., PRD 85, 014004 (2012)

(2.) Inelastic collisions in the hadronic phase.

→ Was this previously overlooked, because the difference is "only" about 10 MeV? Interesting research topic for the next years.

Chemical equilibrium vs collision energy

[A. Andronic et al., NPA 834 (2010) 237]

- Hadron yields from SIS up to RHIC and LHC can be described in a hadro-chemical model applying thermal fits.

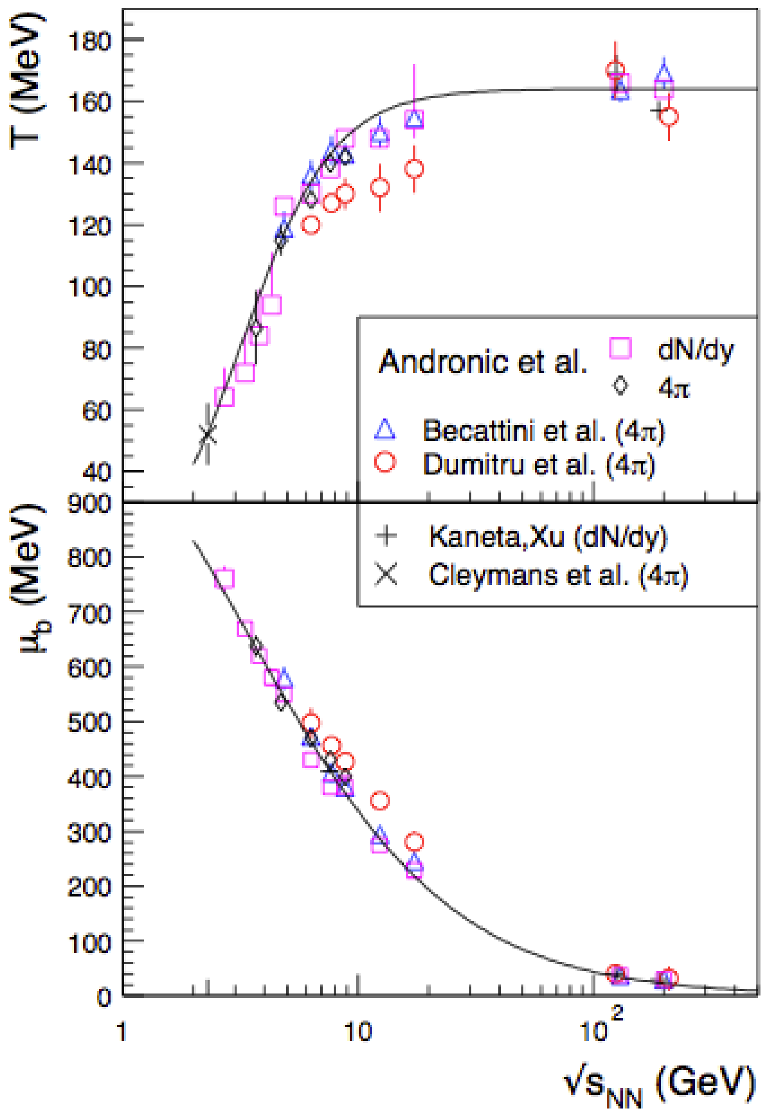
- Effective parameterization of (T, μ_B) as a function of collision energy:

$$T[\mathrm{MeV}] = T_{lim}\left(1 - \frac{1}{0.7 + (\exp(\sqrt{s_{NN}}(\mathrm{GeV})) - 2.9)/1.5}\right)$$

$$\mu_b[\mathrm{MeV}] = \frac{a}{1 + b\sqrt{s_{NN}}(\mathrm{GeV})},$$

- Particle ratios can be calculated (or predicted) at any collision energy….

→ One observes a *limiting temperature of hadron production* around T≈160MeV.



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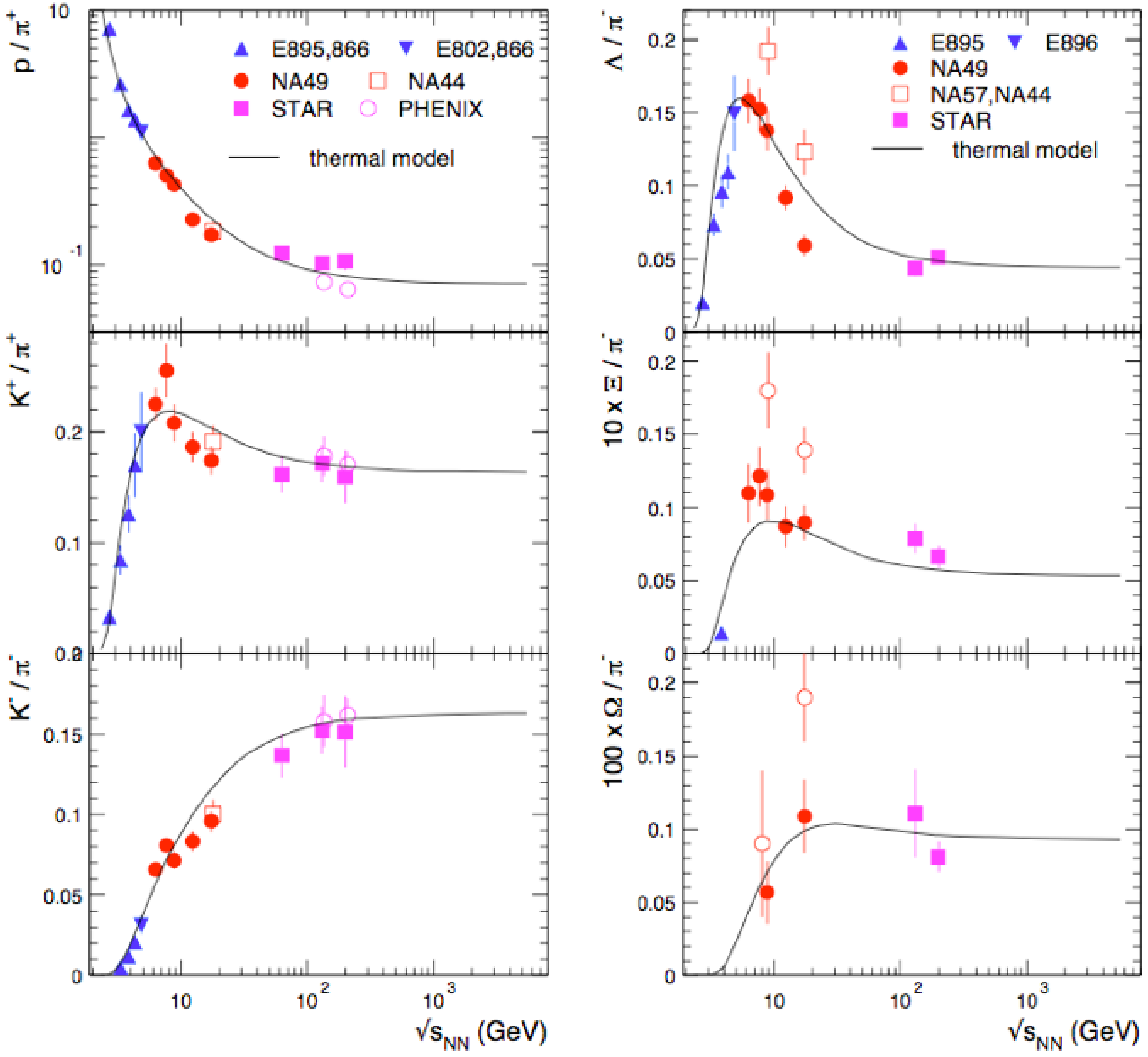
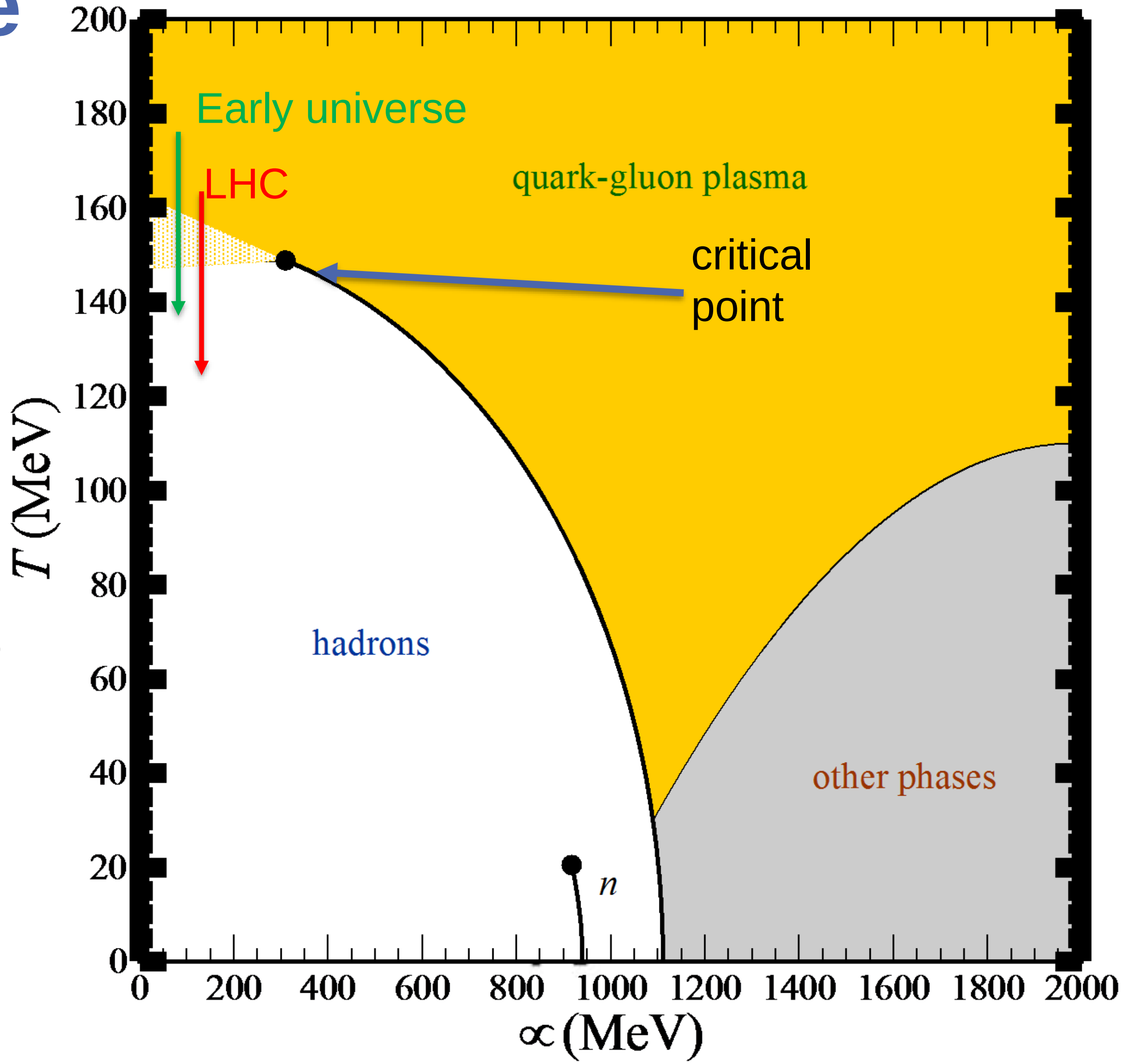


Chemical freeze-out line

- 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.
- The previously schematic phase diagram becomes one which is actually measured.



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

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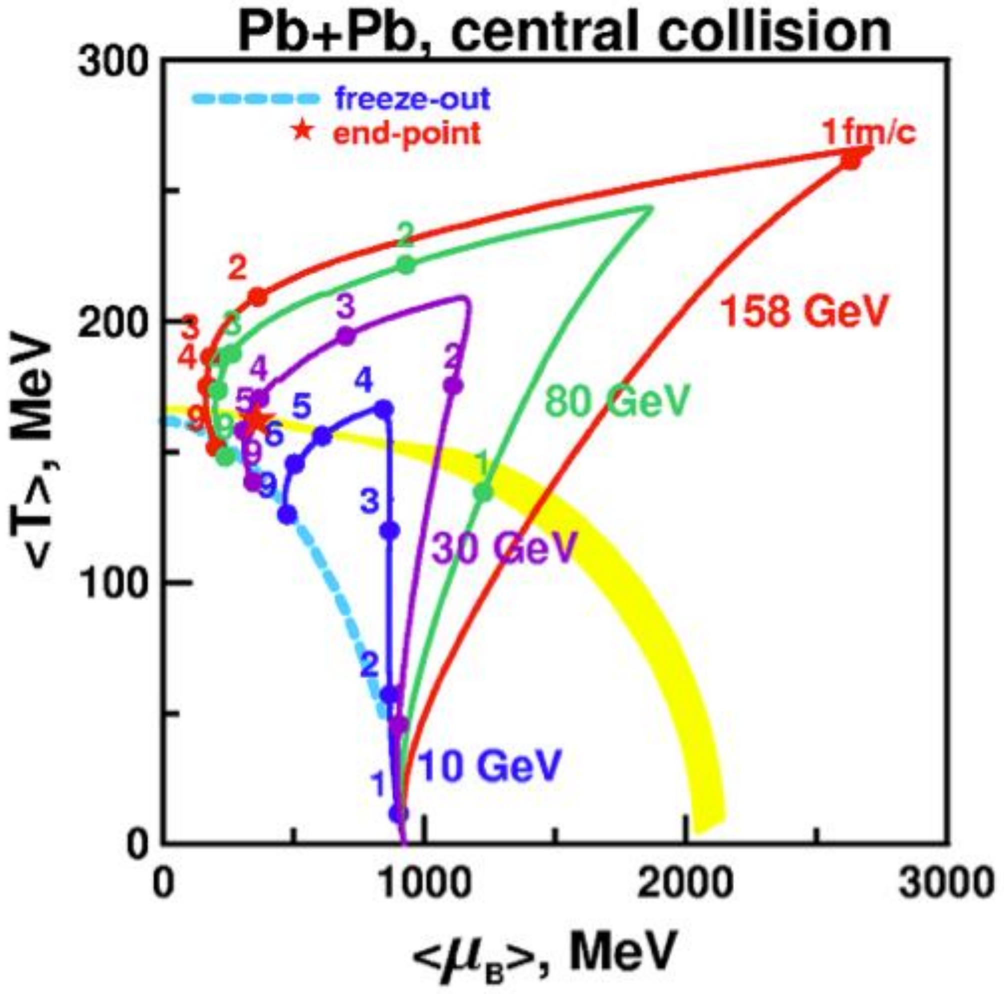

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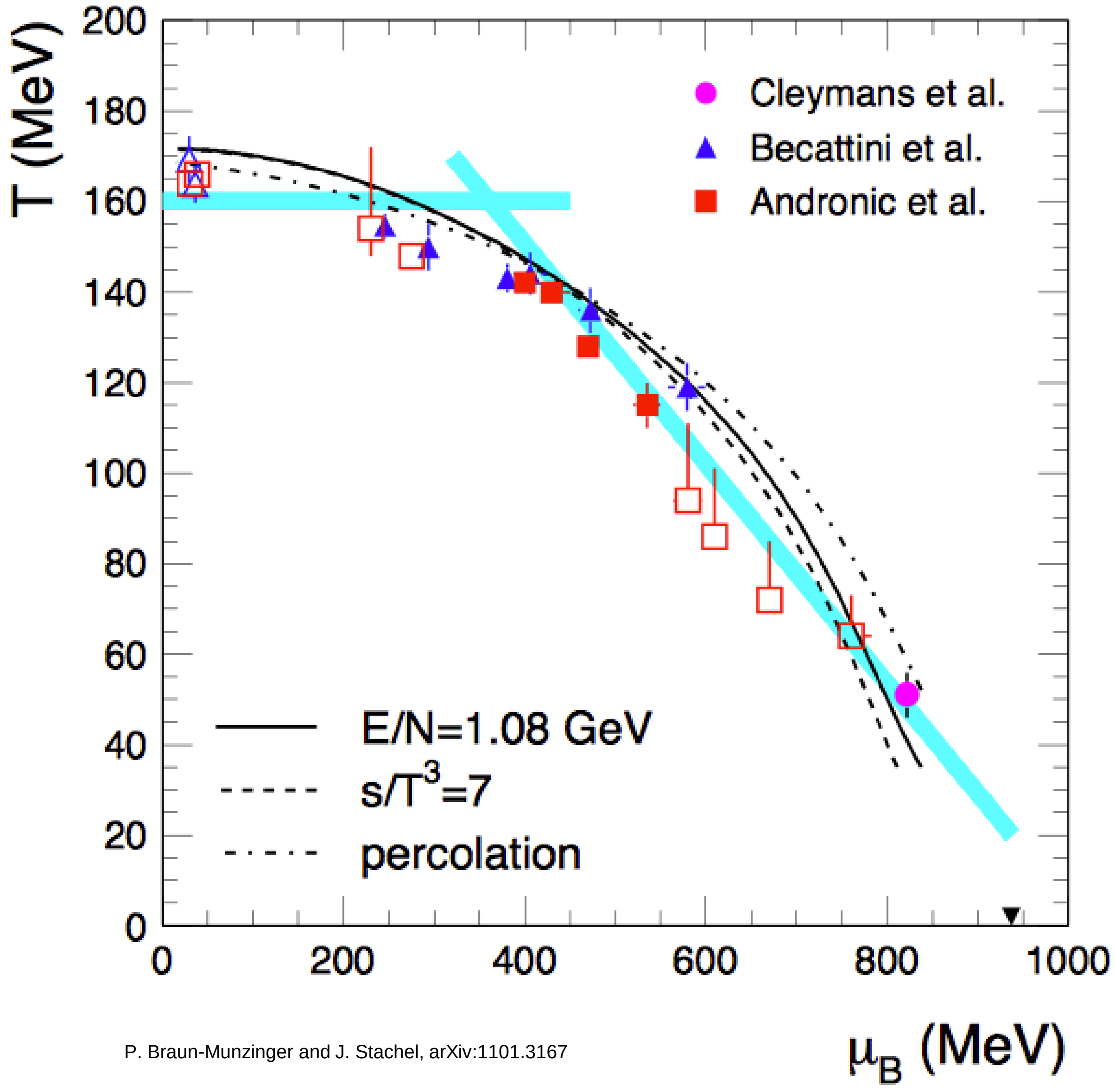
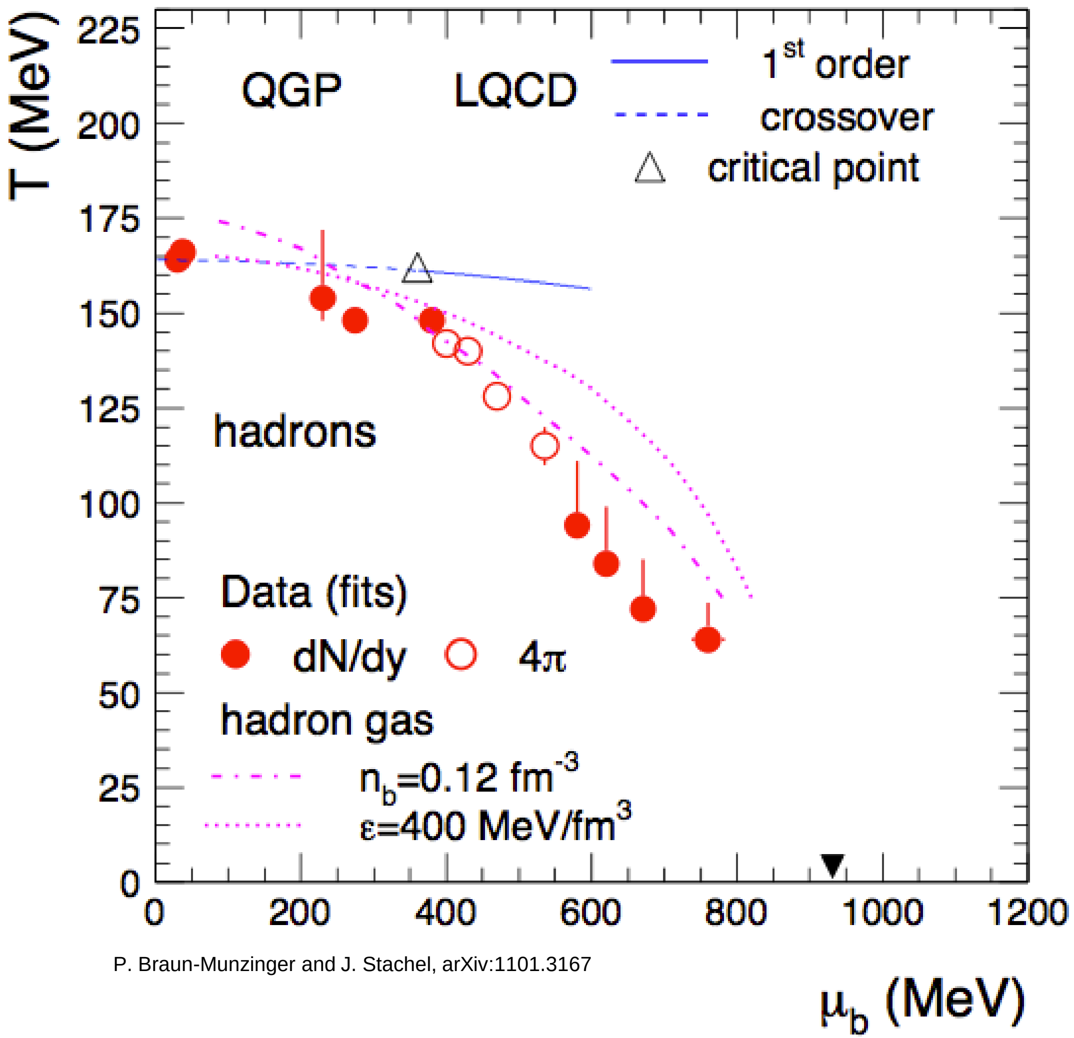


P. Braun-Munzinger and J. Stachel, arXiv:1101.3167

Chemical freeze-out as a proof of QGP existence?



P. Braun-Munzinger and J. Stachel, arXiv:1101.3167

A priori, a thermal model description is not related to the QGP itself. It describes a *hadron gas and not a parton gas*.

However, the *chemical freeze-out line* determined by thermal fits coincides with the phase boundary calculated by lattice QCD above top SPS energies!

However, a detailed study of collision rates and timescales of fireball expansion imply that equilibrium cannot be reached in the hadronic phase…

Do multi-particle collisions near TC equilibrate the system? A rapid change in density near the **phase transition** can explain this [1].

Alternatively, the system is 'born into equilibrium' by the filling of phase space during hadronization [2].

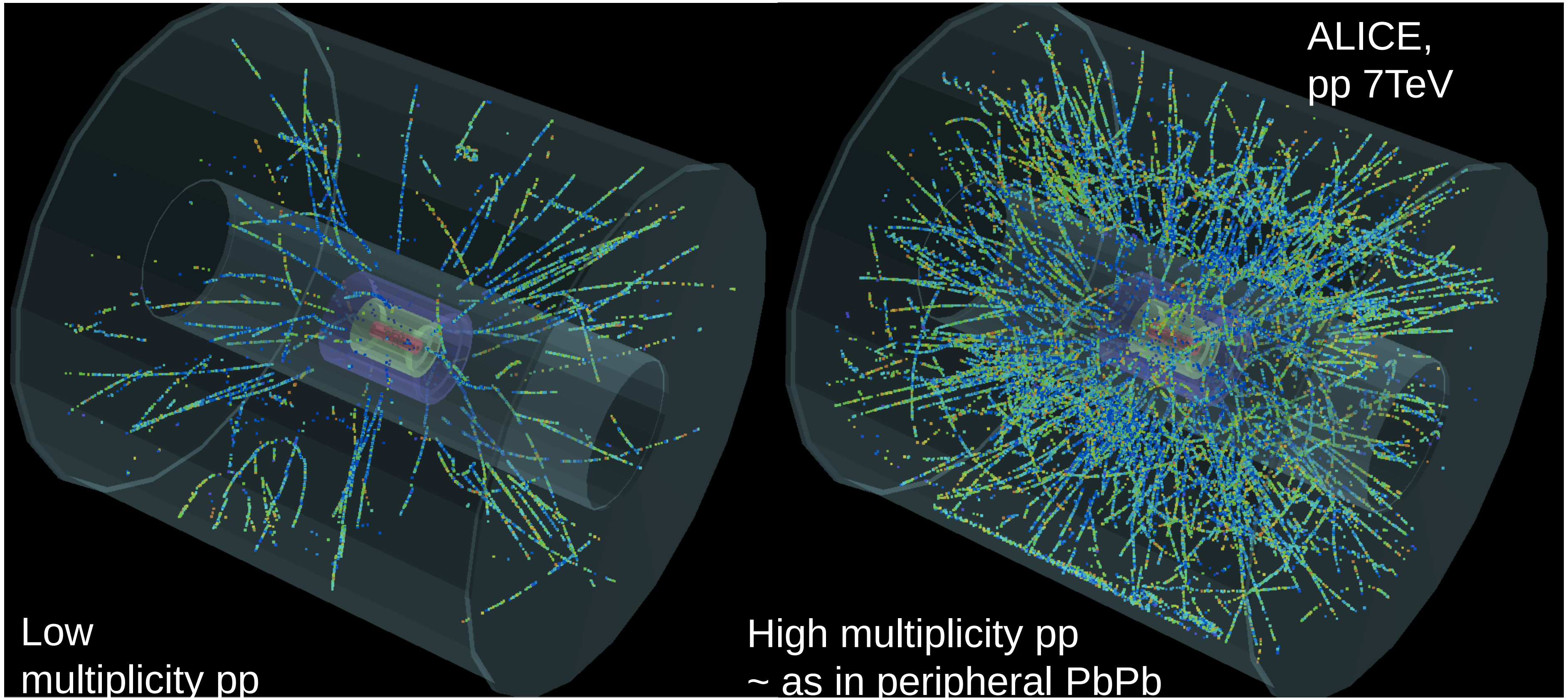
[1] Braun-Munzinger, P., Stachel, J. & Wetterich, C., Phys. Lett. B. 596, 61–69 (2004).

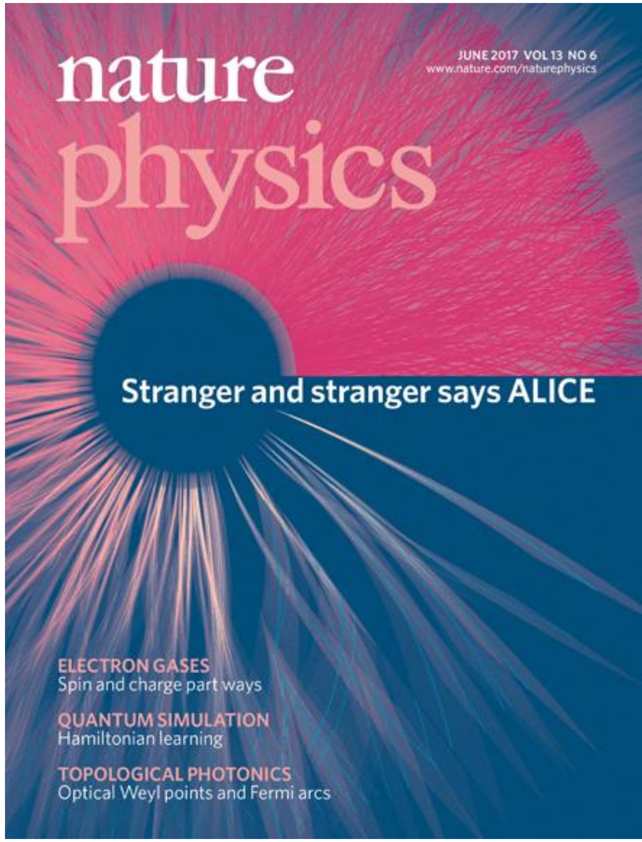
[2] Stock, R. Phys. Lett. B 456, 277–282 (1999).

Small systems: high multiplicity pp and pPb

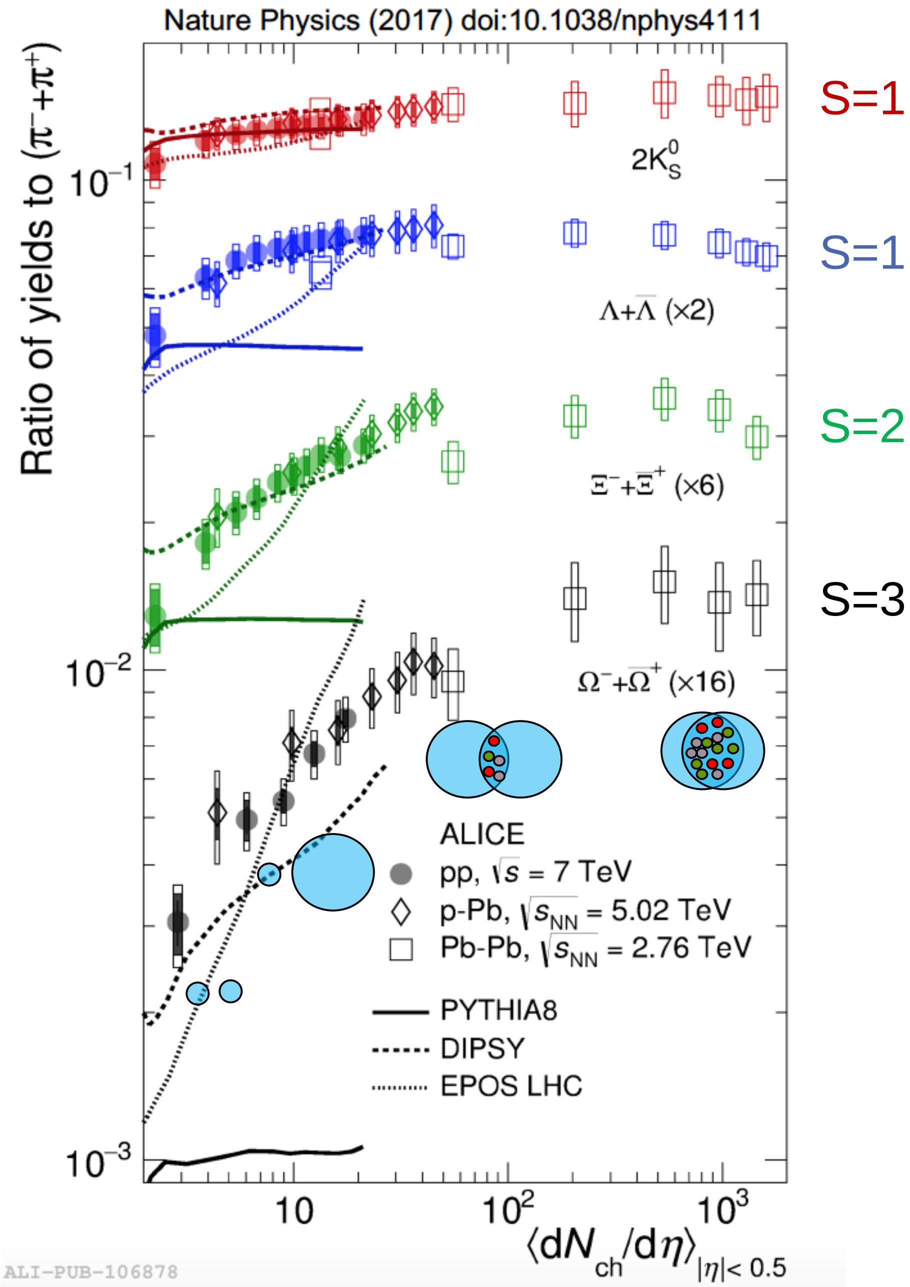
Particle chemistry

How does hadrochemistry evolve with system size?



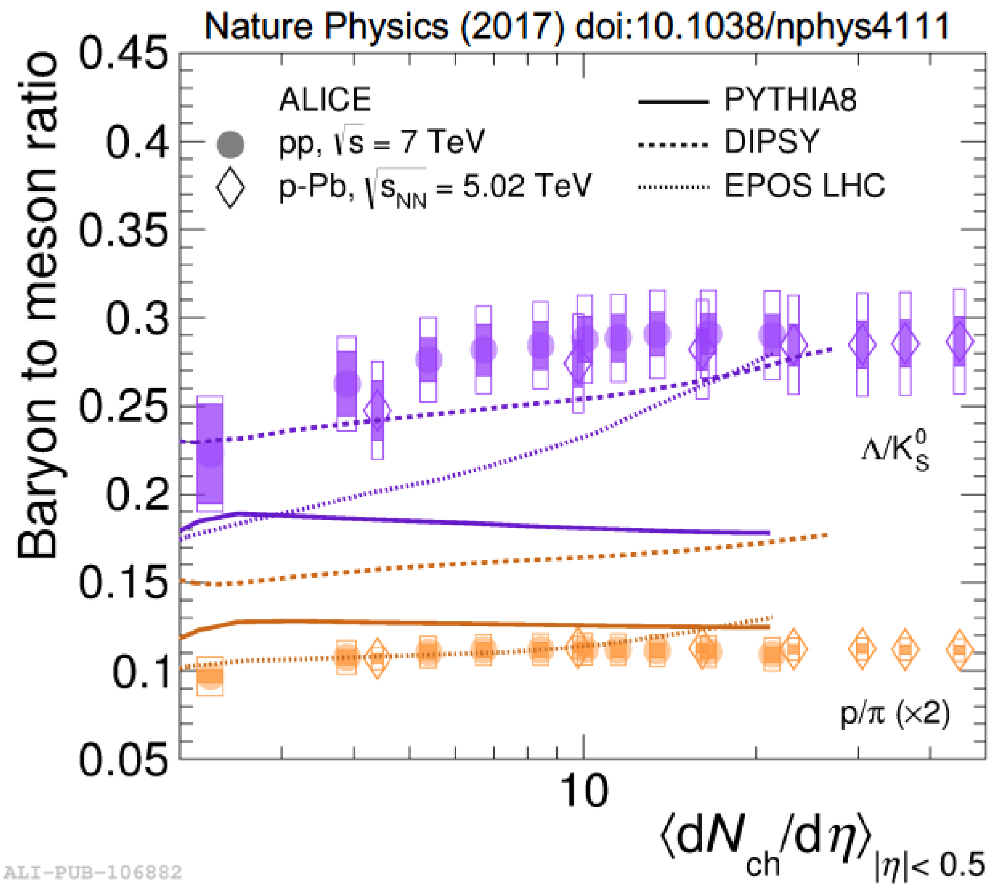


Chemical equilibrium in small systems



- 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.

Chemical equilibrium in small systems

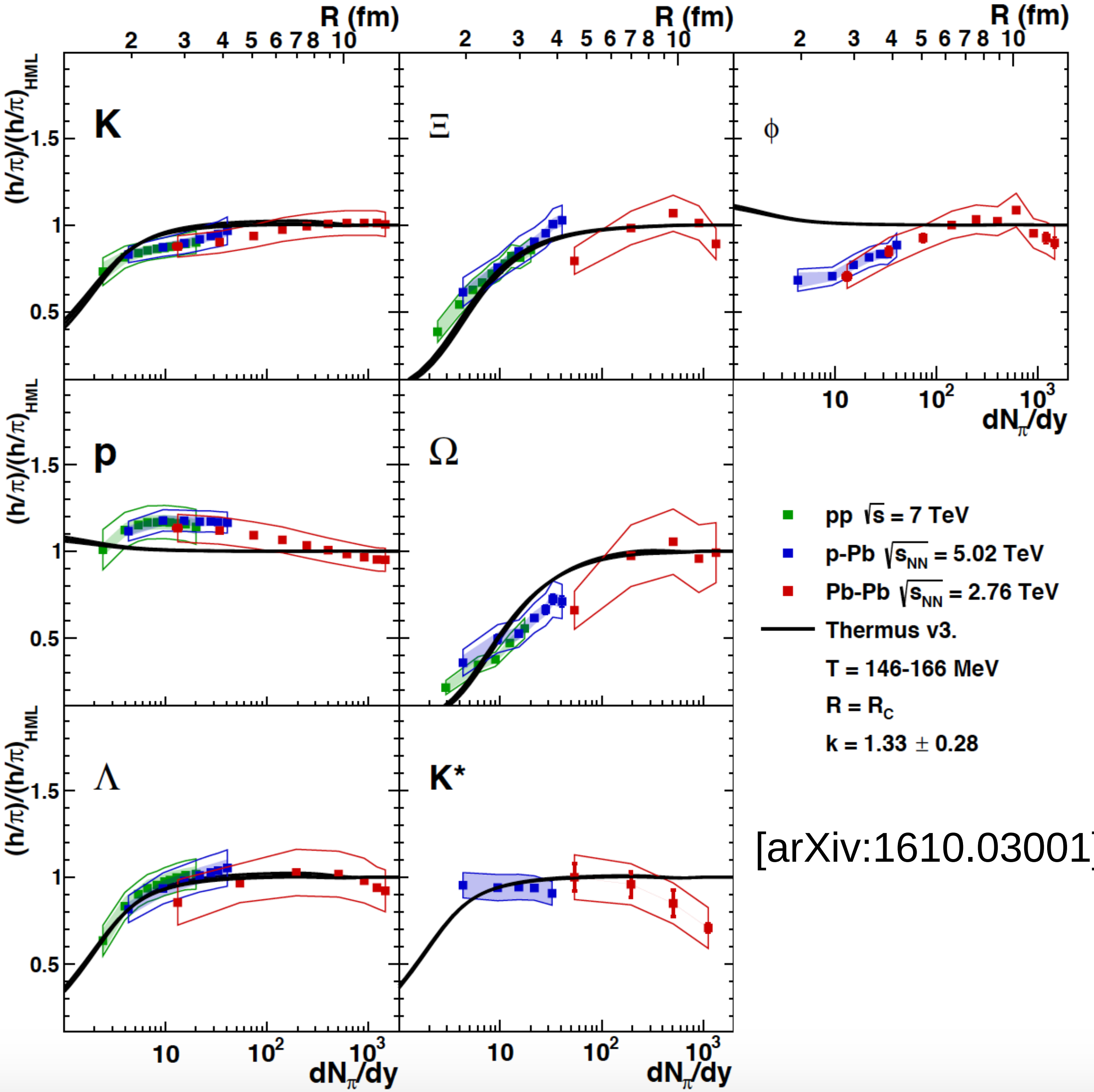


→ Hyperon-to-pion enhancement is strangeness related and not mass or baryon number related.

- The chemical equilibrium picture holds also in small collision systems such as high multiplicity pp and pPb collisions.

→ Currently one of the hottest topics in heavy-ion research!

Strangeness canonical suppression



[arXiv:1610.03001]

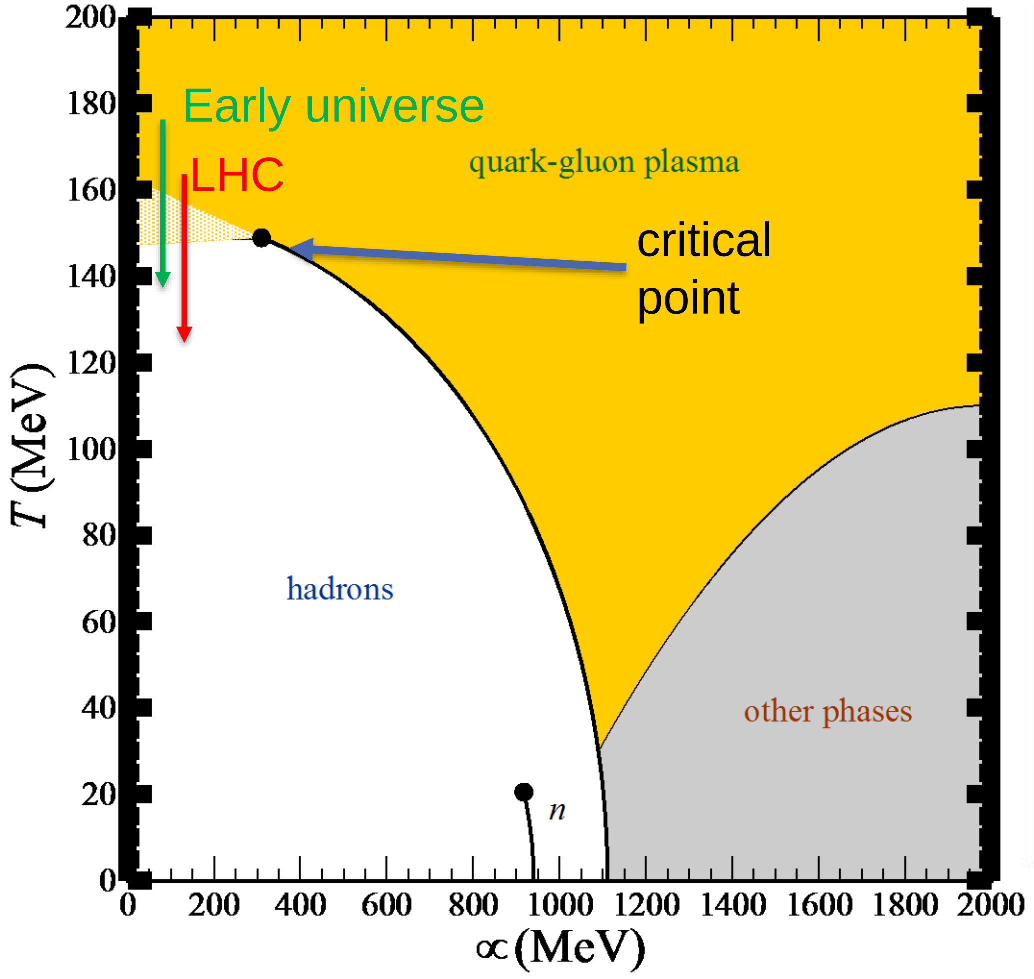
- From a thermal-statistical point of view strangeness production is very sensitive to the system size, i.e. the total number of produced particles.
- As *it is rare (w.r.t to u,d), but not so rare (w.r.t c,b,t)*, its thermal production rate is influenced by the explicit conservation of the strangeness quantum number.
- Simplified picture: explicit conservation of strangeness limits the phase-space for strange particle production and leads to a suppression in small systems (<-> ***strangeness enhancement in large systems***).

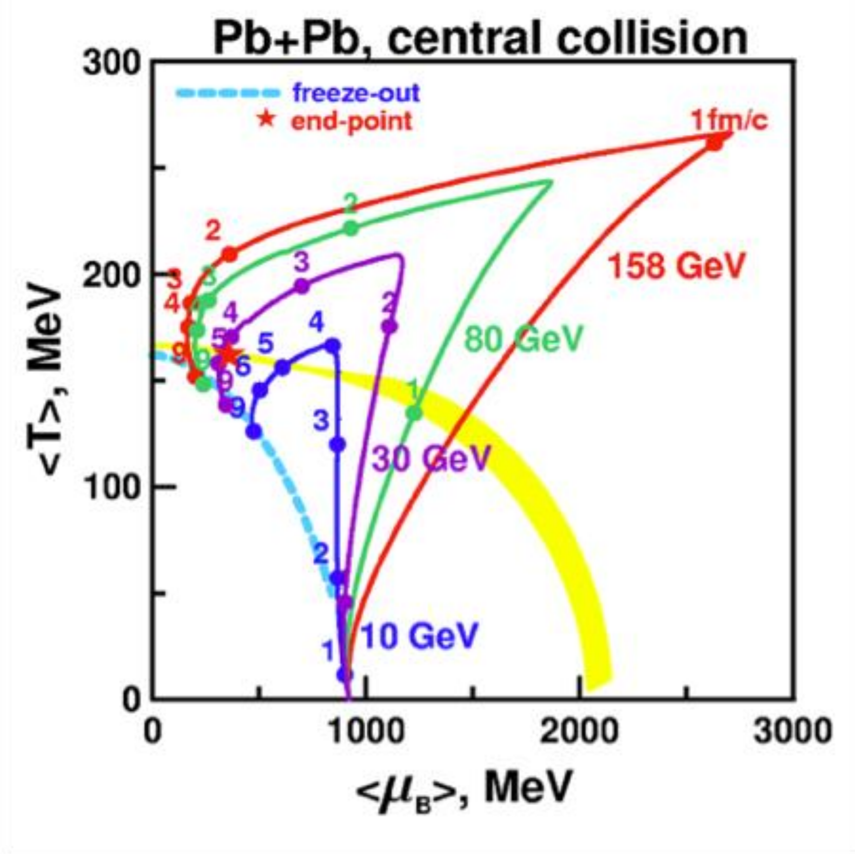
QGP thermodynamics and soft probes

Search for QCD critical point and onset of de-confinement

The QCD critical point

- By a variation of beam energies, one might hit the critical point in the QCD phase diagram => ***critical chiral dynamics***.





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

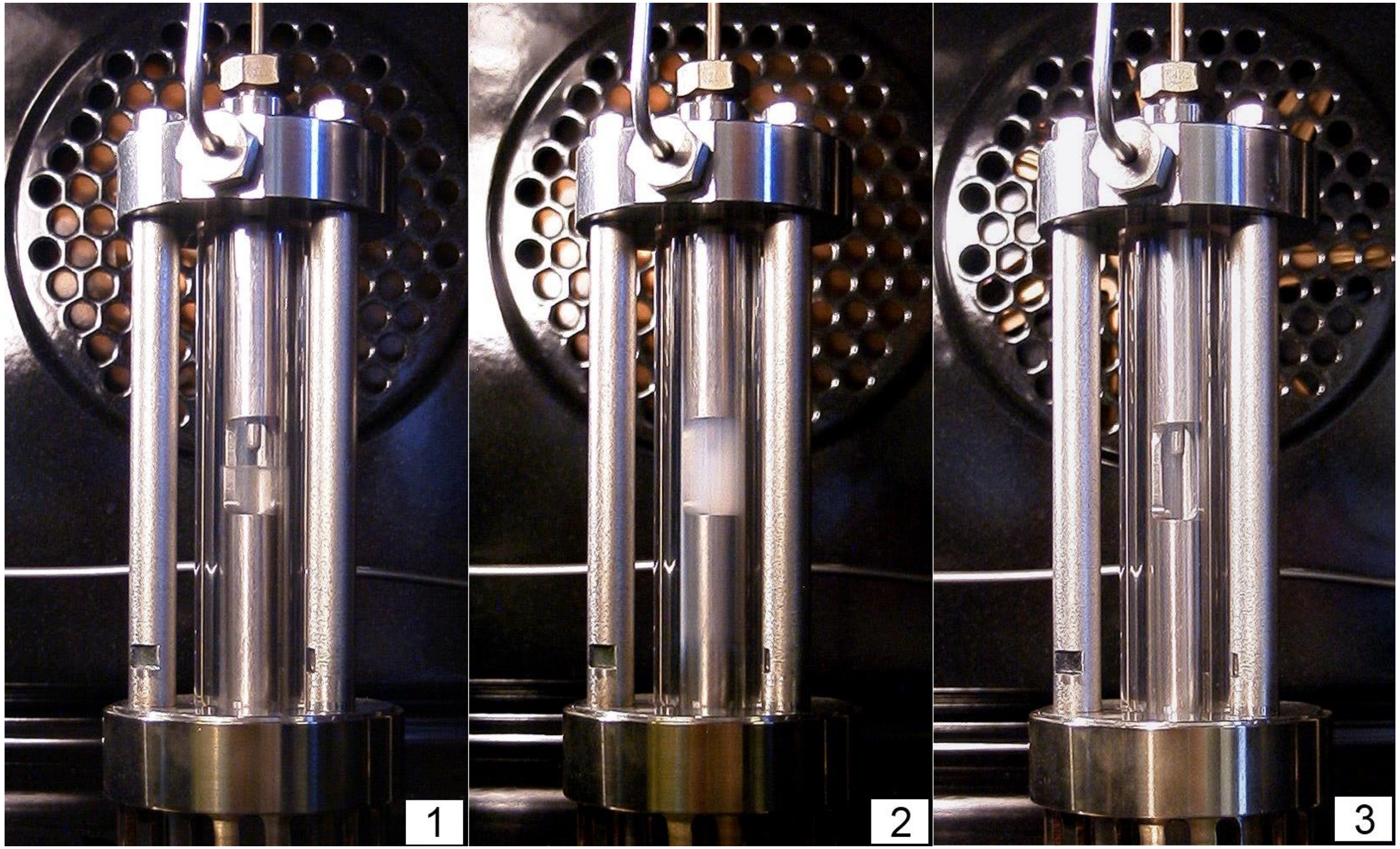
→ Different regions of the phase diagram are probed with different $\sqrt{s_{NN}}$.

=> Beam energy scan (BES) at RHIC.

Critical fluctuations – in ordinary matter

- Phase transitions are often connected to critical phenomena.

- Example: Opalescence of Ethene at the critical point (divergence of correlation lengths).



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

Fluctuations in QCD

- QCD phase transitions: the thermodynamic susceptibilities χ of the conserved quantities of QCD (**electric charge *Q*, baryon number *B*, Strangeness *S***) correspond to (event-by-event) fluctuations in the particle production.

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n}(P/T^4)}{\partial(\mu_B/T)^l \, \partial(\mu_S/T)^m \, \partial(\mu_S/T)^n}$$

- Fluctuations are quantified as moments (mean, variance, skewness, kurtosis) or cumulants ***K*** of the event-by-event distributions:

$$\begin{array}{ccccccccc} M & = & K_1 & = & \mu & = & \langle N \rangle & = & VT^3 \cdot \chi_1 \\ \sigma^2 & = & K_2 & = & \mu_2 & = & \langle (\delta N)^2 \rangle & = & VT^3 \cdot \chi_2 \\ S & = & K_3/\sigma^3 & = & \mu_3/\sigma^3 & = & \langle (\delta N)^3 \rangle/\sigma^3 & = & VT^3 \cdot \chi_3/(VT^3 \cdot \chi_2)^{3/2} \\ \kappa & = & K_4/\sigma^4 & = & (\mu_4 - 3\mu_2^2)/\mu_2^2 & = & \langle (\delta N)^4 \rangle/\sigma^4 - 3 & = & (VT^3 \cdot \chi_4)/(VT^3 \cdot \chi_2)^2 \end{array}$$

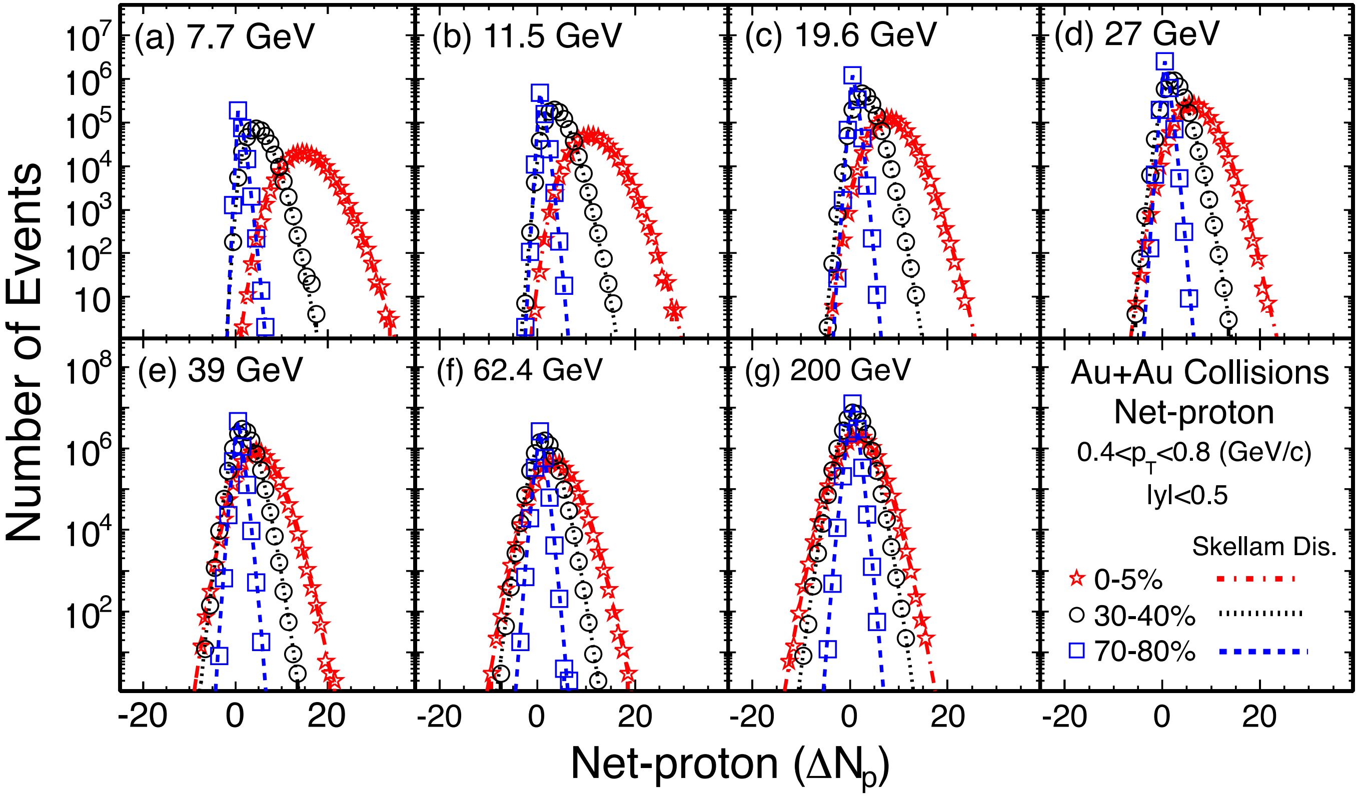
$$\mu_i = \langle (\delta N)^i \rangle$$

$$\delta N = N - \langle N \rangle$$

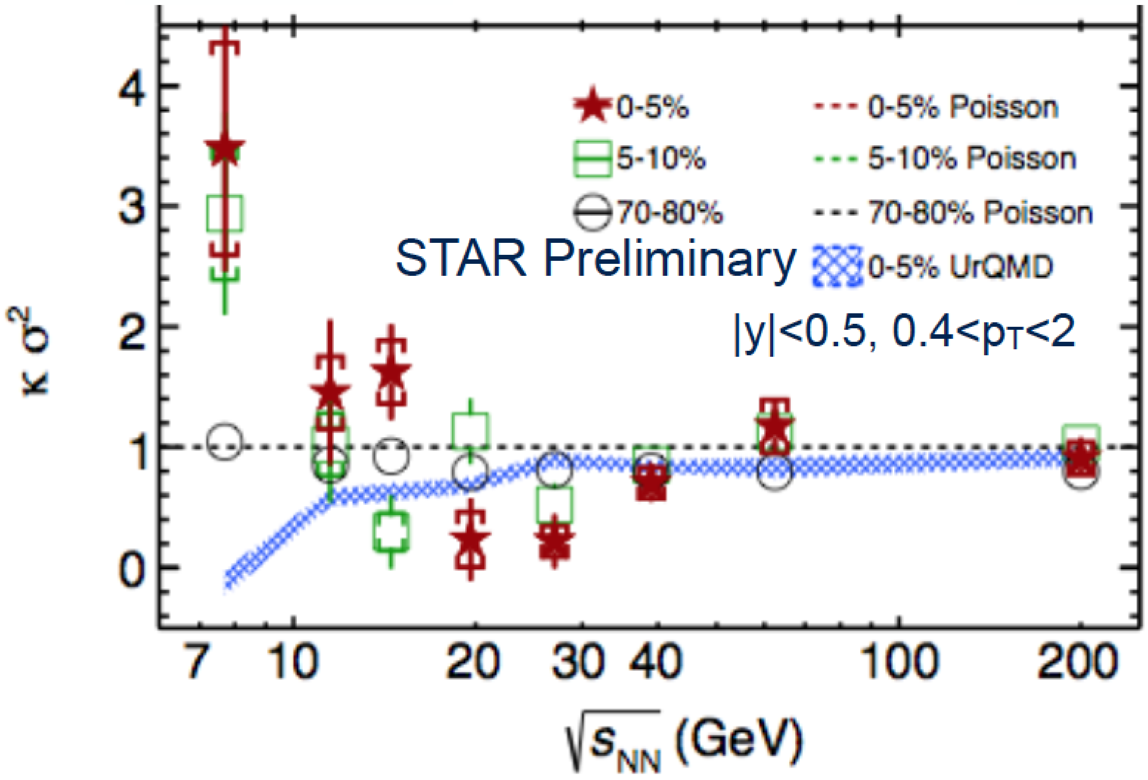
Critical fluctuations – in quark matter

- 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 => fixed at chemical freeze-out

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



[PRL 112 (2014) 032302]

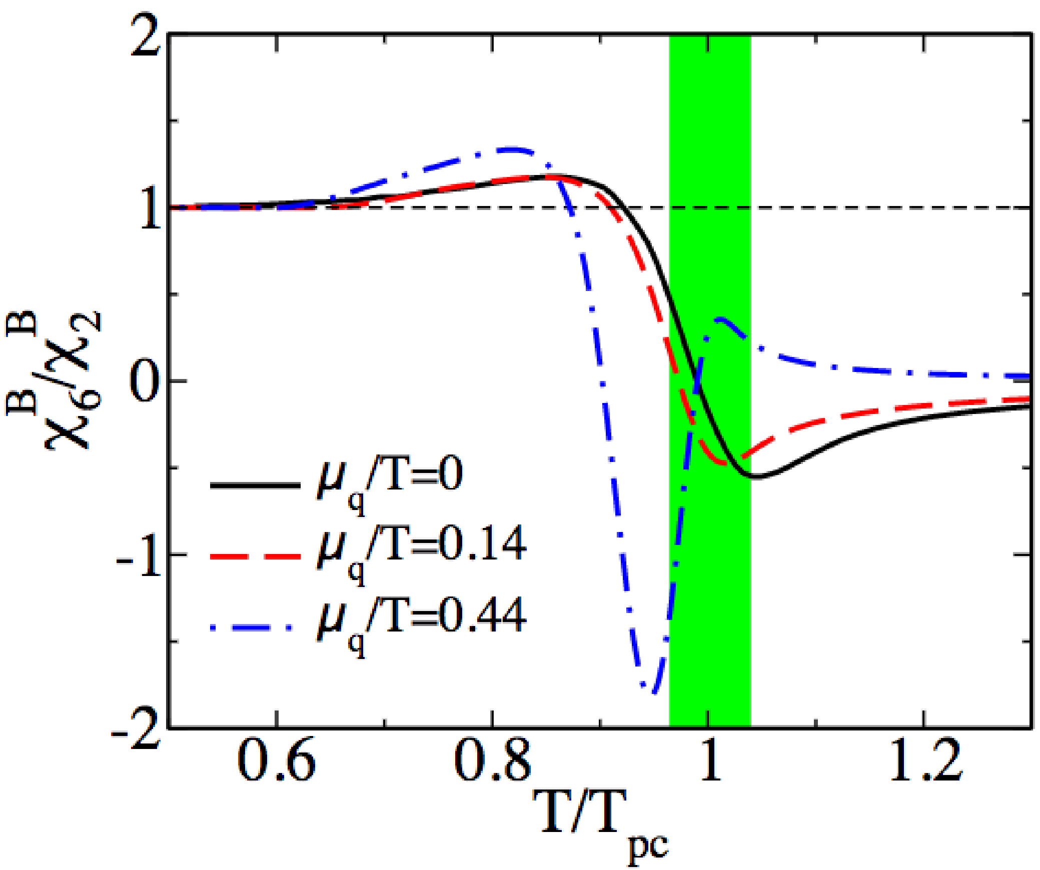


Chiral critical dynamics at LHC energies

- Even though LHC energies are far away from the critical point, remnants of the critical chiral dynamics might still be measurable in higher order net-charge fluctuations at the LHC.

→ Test of a Lattice QCD prediction.

→ Experimental proof that chiral and de-confinement phase transition occur indeed at the same temperature.

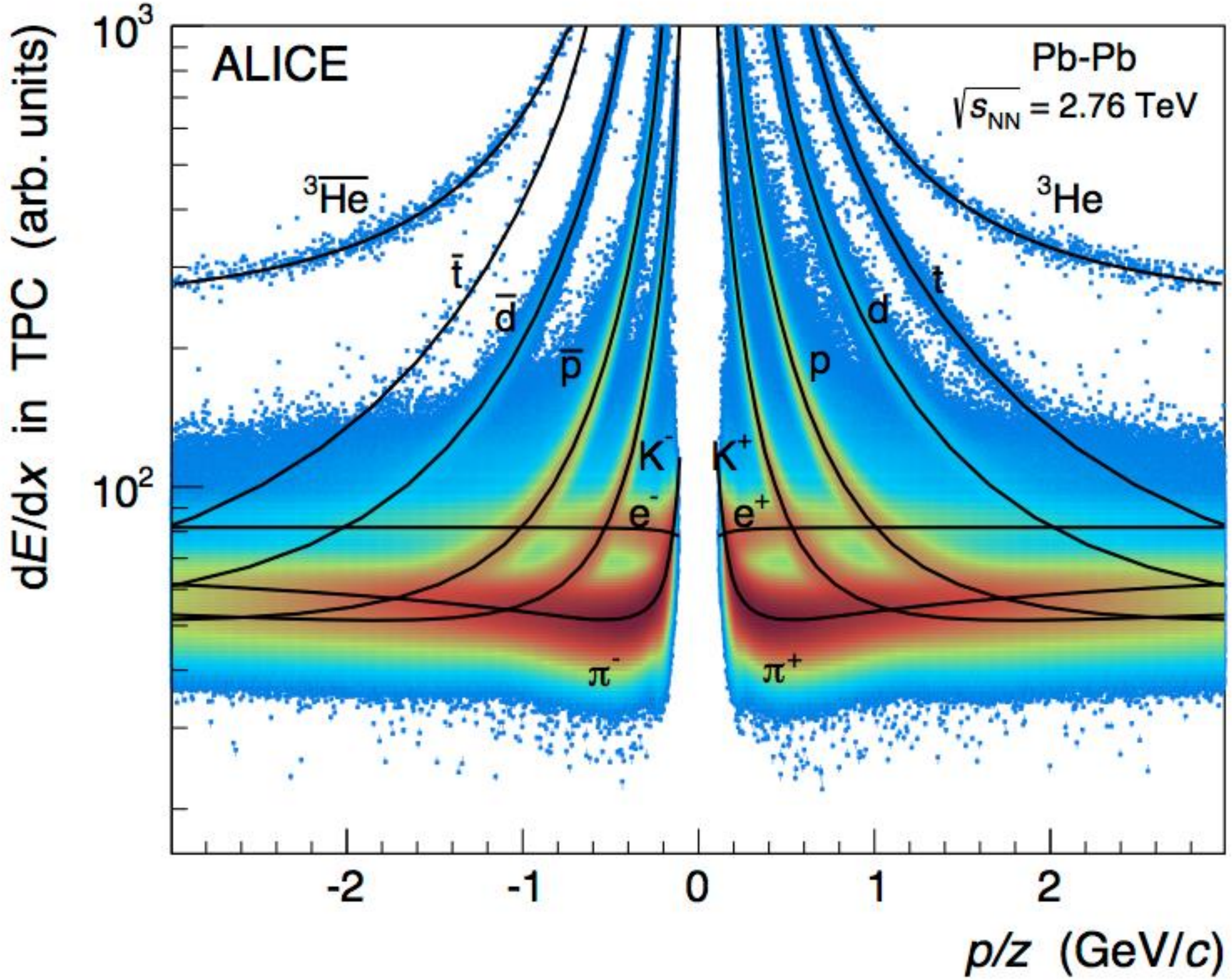


[Eur. Phys. J. C 71 (2011) 1694]

QGP thermodynamics and soft probes

(anti-)(hyper-)nuclei

Particle identification via d*E*/dx



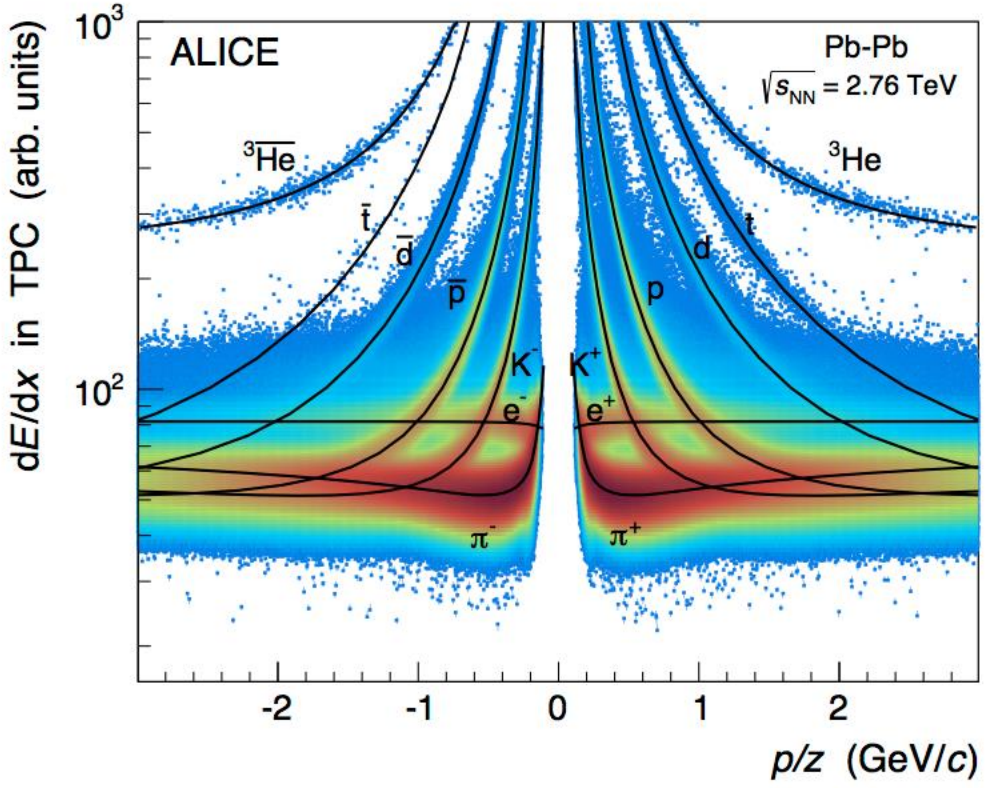
$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Separation of z = 1 and z = 2 via dE/dx is also very important for the correct determination of the momentum via the track curvature: $p_T \sim 0.3\ B \cdot r \cdot z$

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.
  - Open puzzle: production yields are in agreement with thermal model prediction even though light (anti-)nuclei should be dissolved in such a hot medium.

[ALICE-PUBLIC-2017-006]



[PRC 93 (2016) 024917]

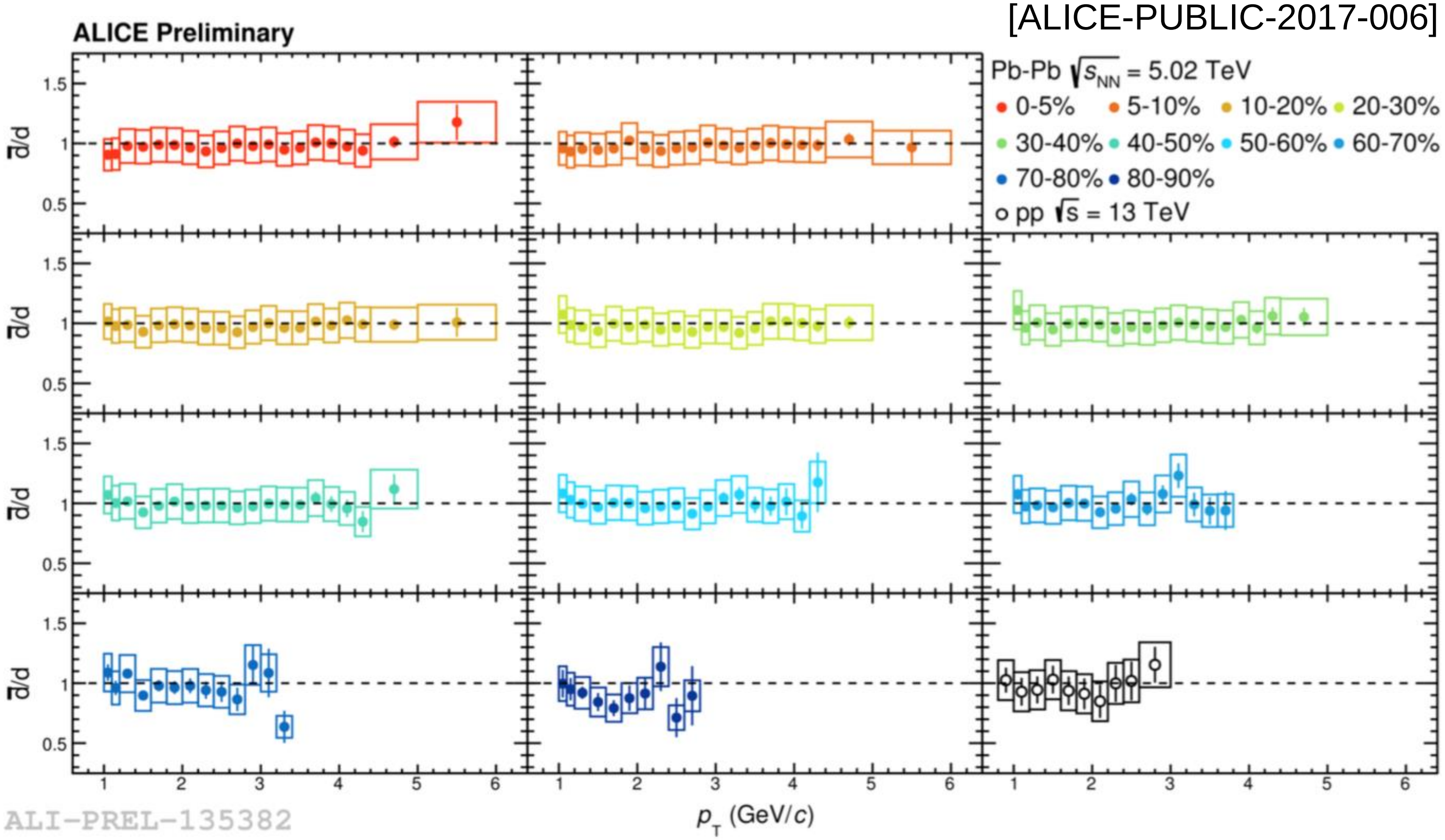
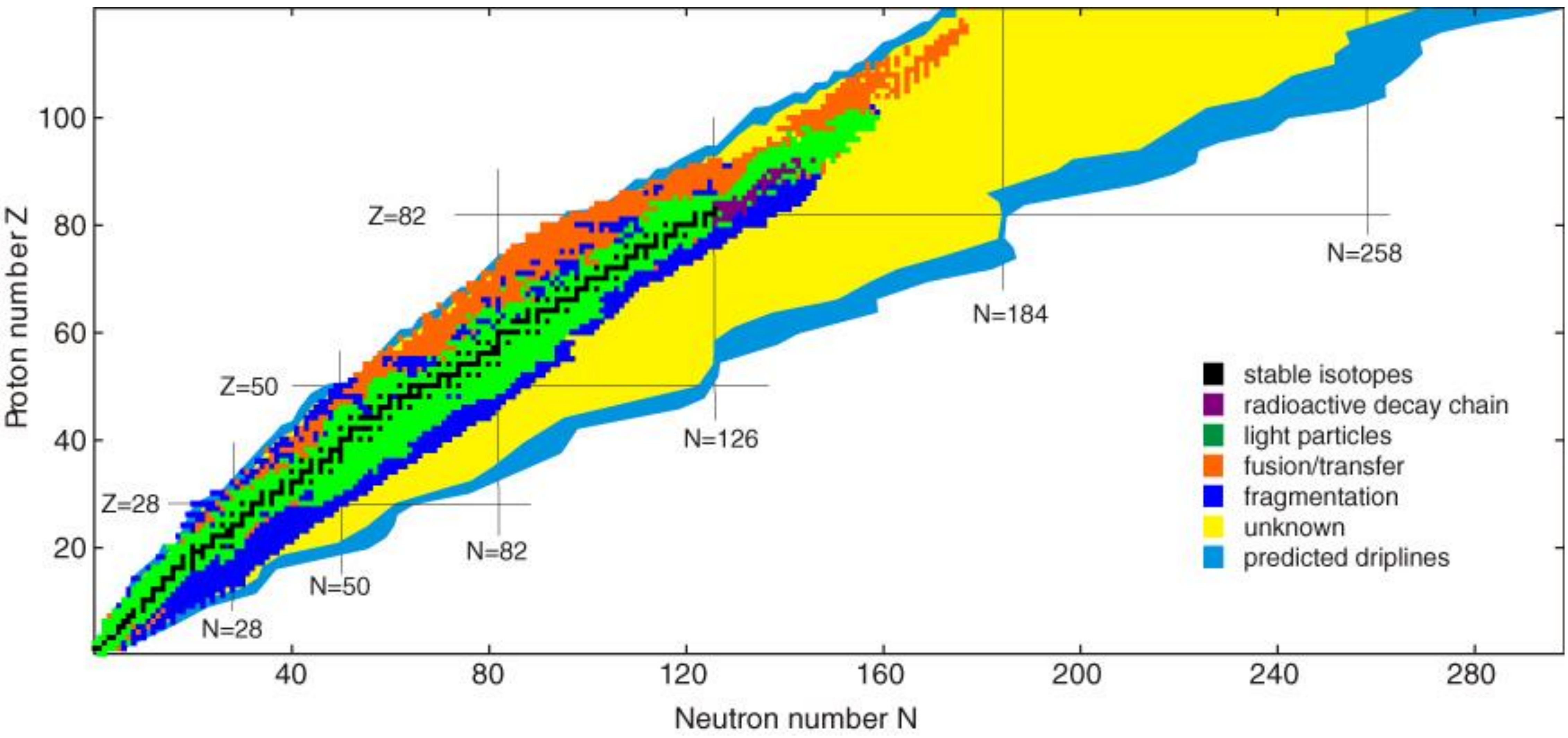


Table of nuclides

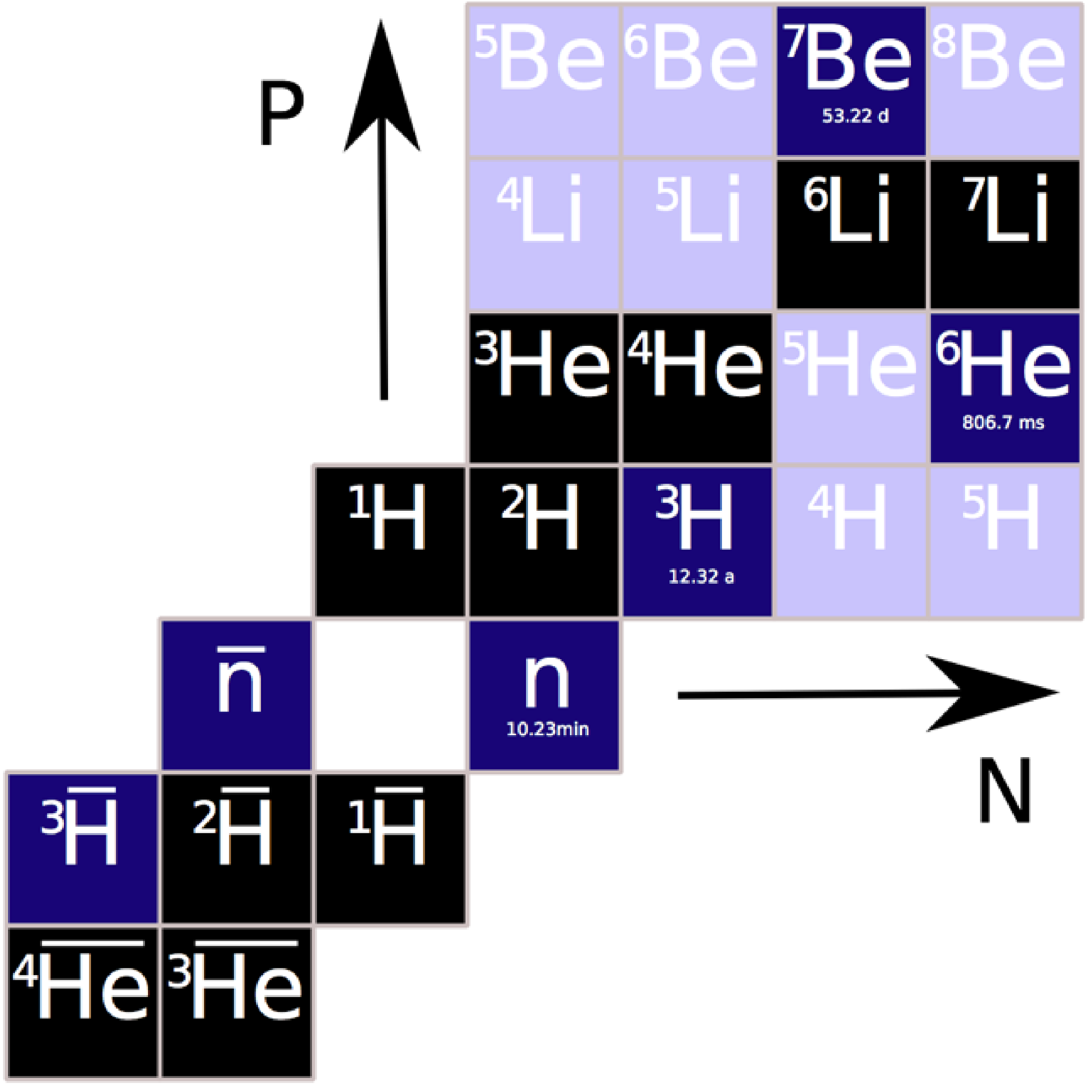


Light (anti-)nuclei

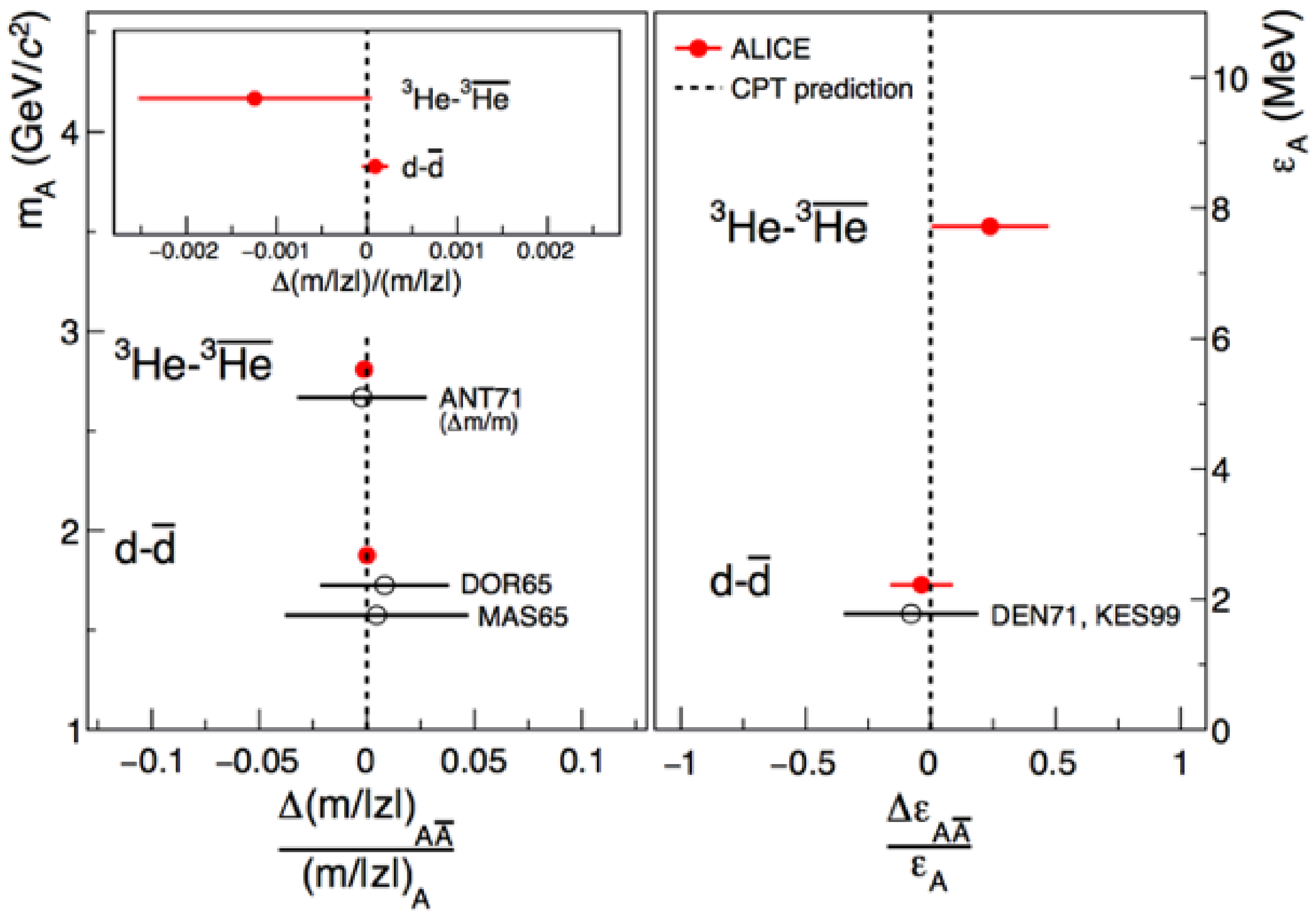
- Even in Pb-Pb collisions at LHC energies, light anti-nuclei are rarely produced.

- (Anti-)nuclei up to the (anti-)alpha are in reach (1st observation of the anti-alpha by the STAR experiment at RHIC in 2011).

→ A very good and very stable particle identification is needed to separate these rare particles from the background.



Testing CPT with anti-nuclei



[Nature Physics 11 (2015) 811-814]

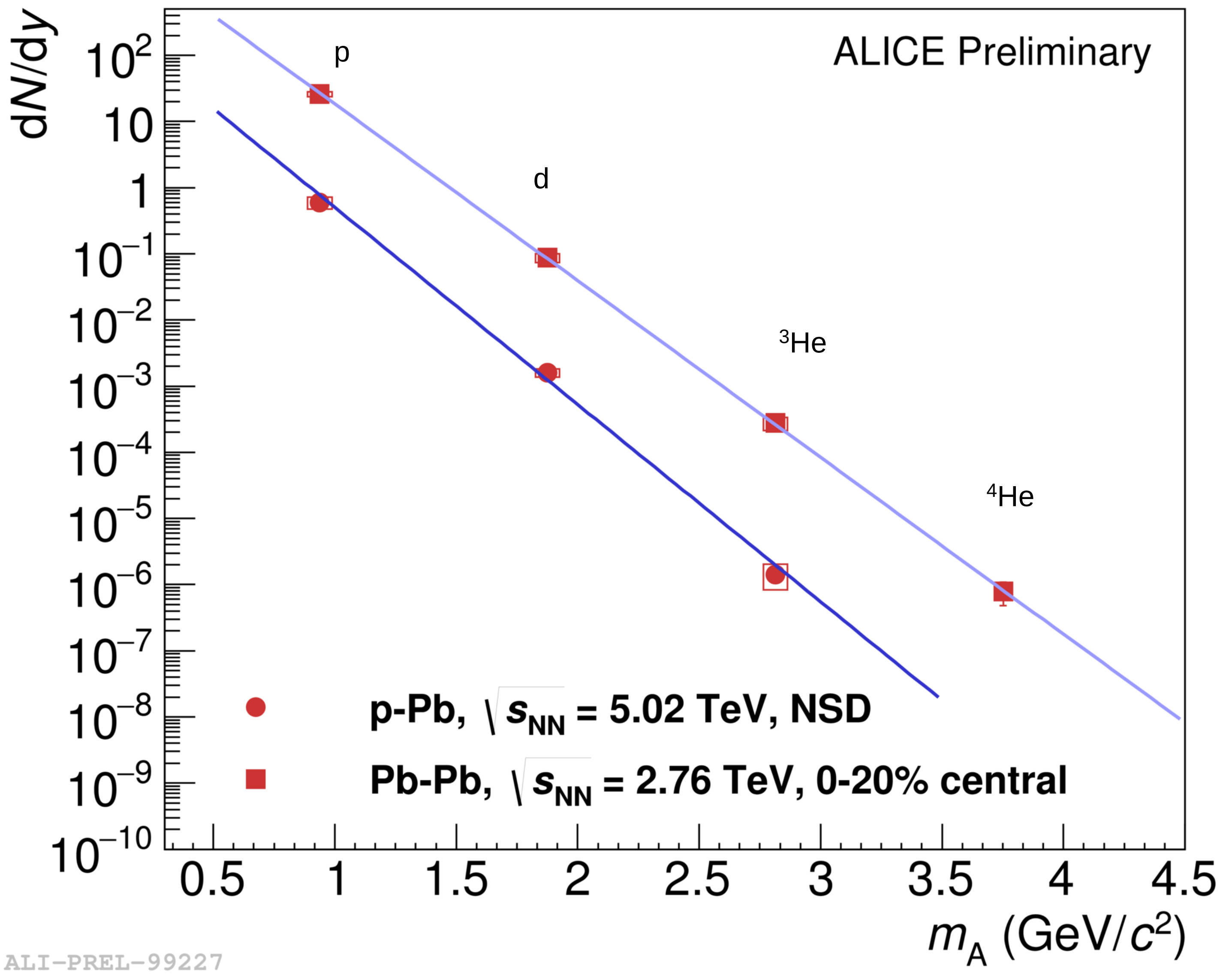
The ALICE collaboration performed a test of the CPT invariance looking at the mass difference between nuclei and anti-nuclei.

This test shows that the masses of nuclei and anti-nuclei are compatible within the uncertainties. The binding energies are compatible in nuclei and anti-nuclei as well.

Mass ordering

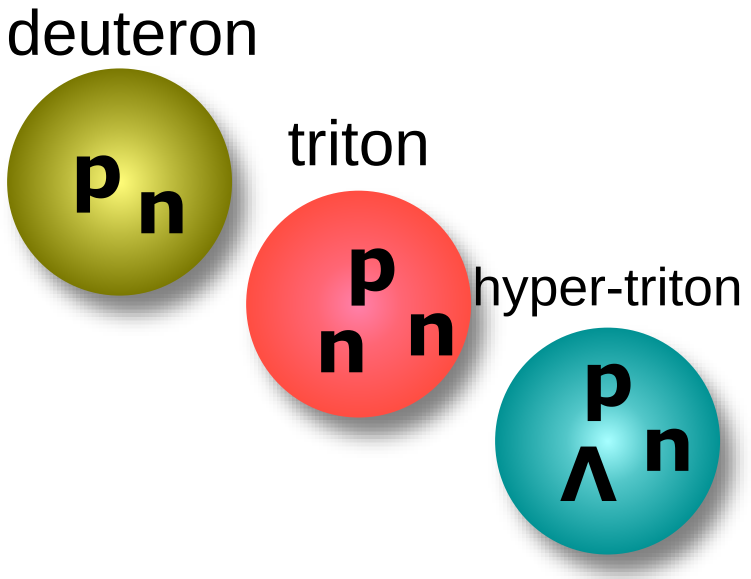
→ For each additional nucleon the production yield decreases by a factor of about 300!

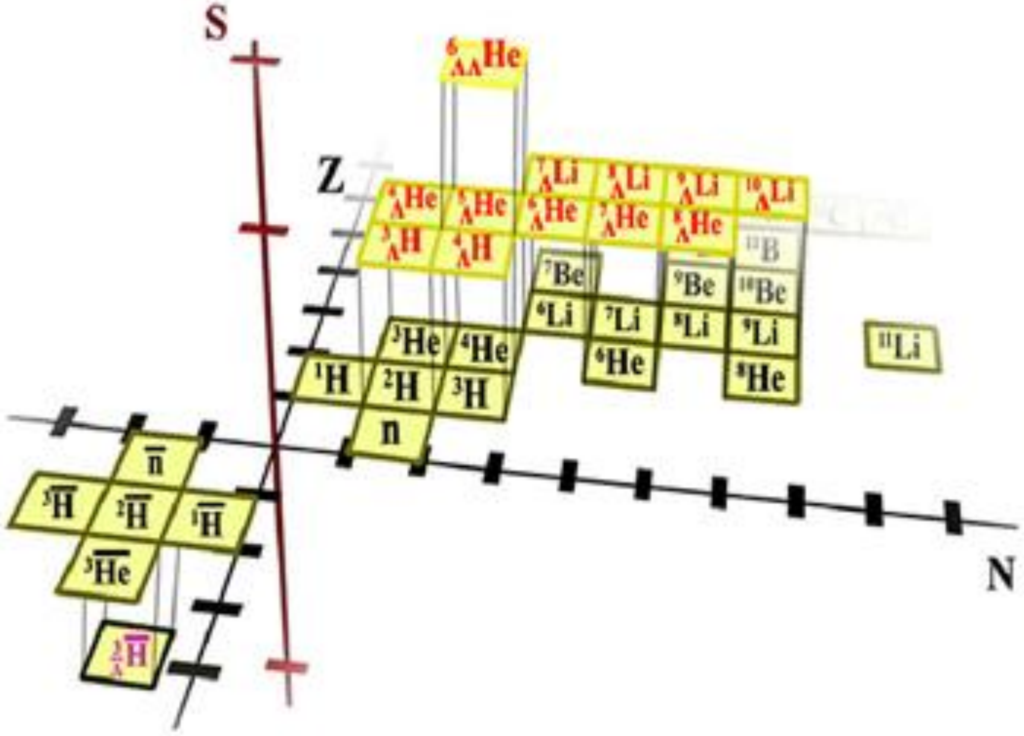
→ Such a behaviour can be directly derived from the thermal model which predicts in first order dN/dy ~ exp(-m/T)



Hyper-nuclei (1)

- By ‘replacing’ one nucleon by one hyperon, the table of nuclides can be extended in a third dimension.
- Hyper-nuclei have a long tradition in nuclear physics: discovery in the 1950s by M. Danysz and J. Pniewski in a nuclear emulsion exposed to cosmic rays.





The STAR Collaboration, **Science 328, 58 (2010)**

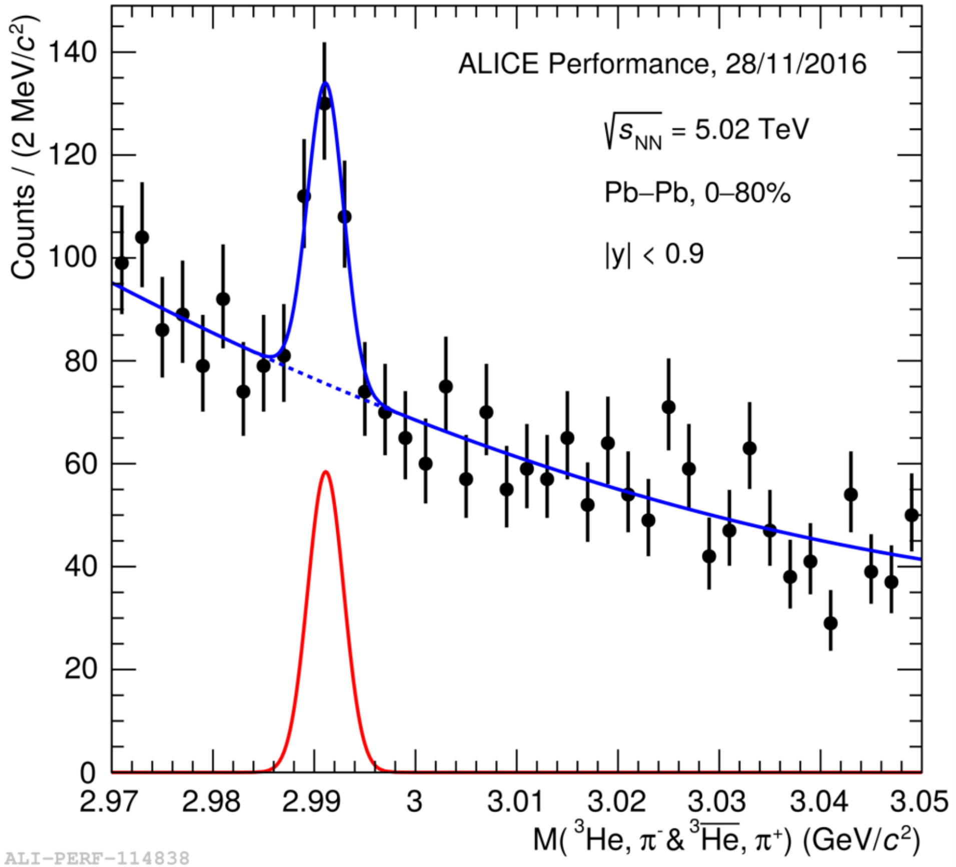
Hyper-nuclei (2)

- Reconstruction of hyper-nuclei can be based on well established techniques for Λ and other weakly decaying light flavor hadrons as lifetimes and decay topologies are similar.

$$\Lambda \longrightarrow p + \pi^- \ (63.9\%)$$

- Experimentally one searches for (anti-)nuclei from displaced vertices:

$$^{3}_{\Lambda}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \pi^-$$
$$^{3}_{\Lambda}\mathrm{H} \longrightarrow \mathrm{d} + \mathrm{p} + \pi^-$$
$$^{4}_{\Lambda}\mathrm{H} \longrightarrow {}^{4}\mathrm{He} + \pi^-$$
$$^{4}_{\Lambda}\mathrm{He} \longrightarrow {}^{3}\mathrm{He} + p + \pi^-$$
$$^{5}_{\Lambda}\mathrm{He} \longrightarrow {}^{4}\mathrm{He} + p + \pi^-$$

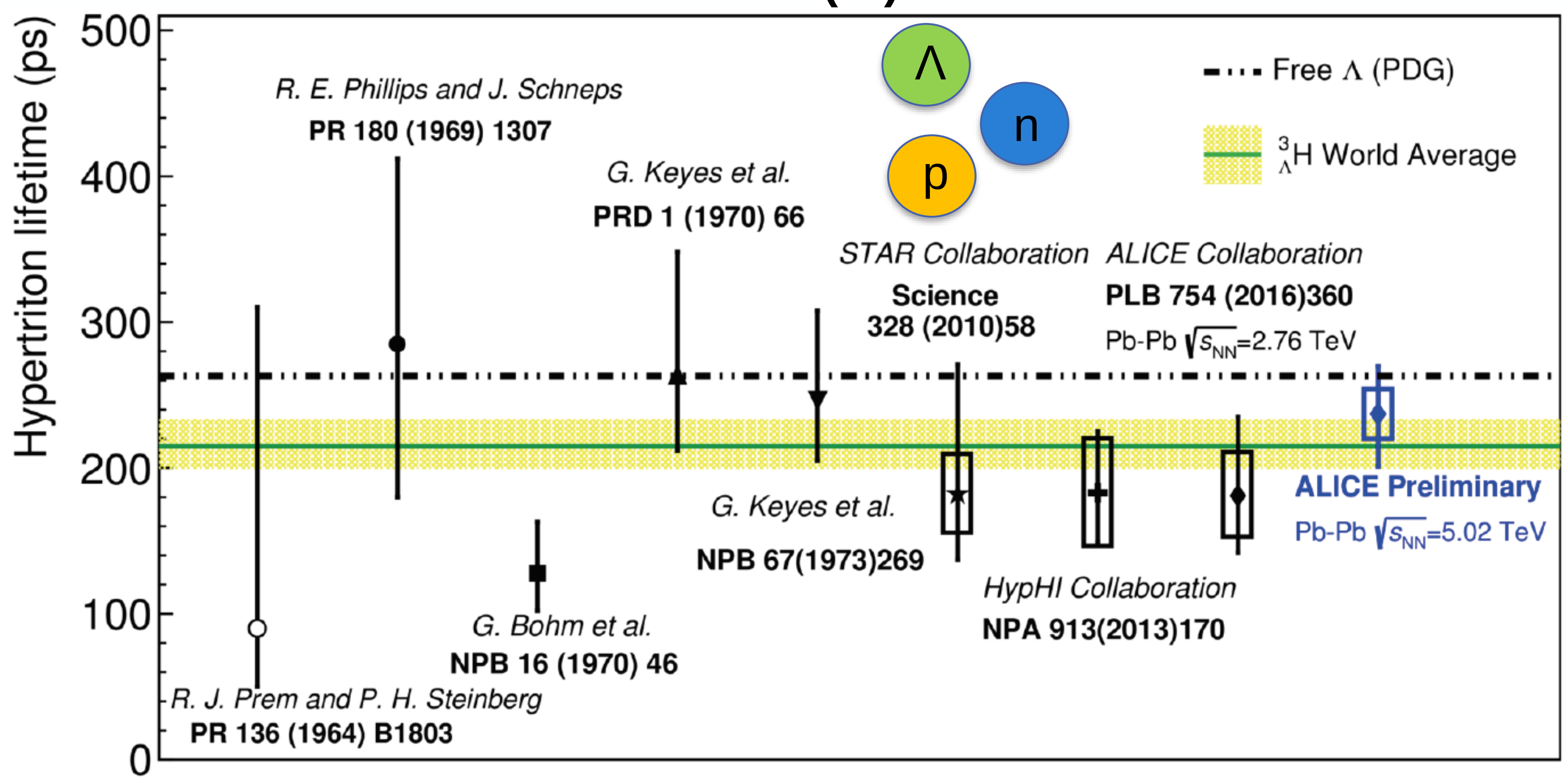


- Branching ratios are only partially constrained by measurements.

(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.)



ALI-PREL-130195

(B.)

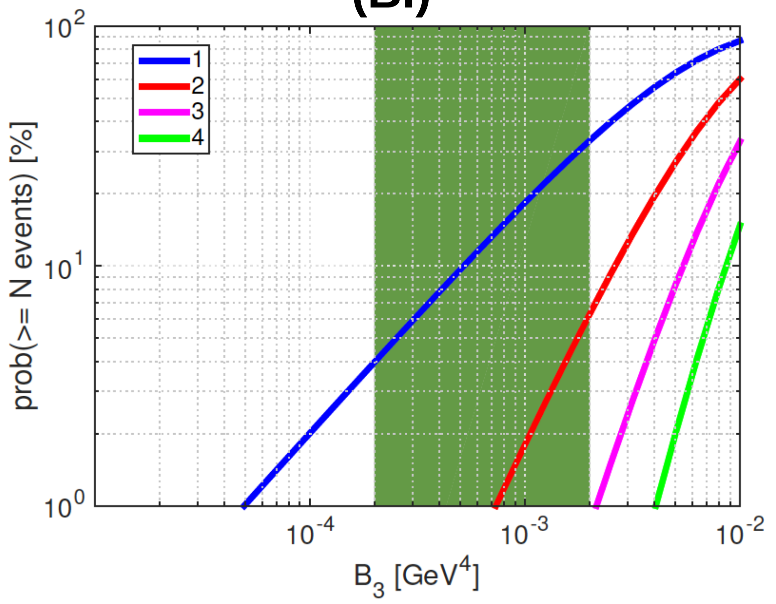


FIG. 5: Poisson probability for detecting $N \geq 1, 2, 3, 4$ $\overline{^3\mathrm{He}}$ events in a 5-yr analysis of AMS02, assuming the same exposure as in the $\bar{p}$ analysis [28]. Eq. (14) shown as green band.

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

QGP thermodynamics and soft probes

Radial and elliptic flow

Bulk particle production and collectivity

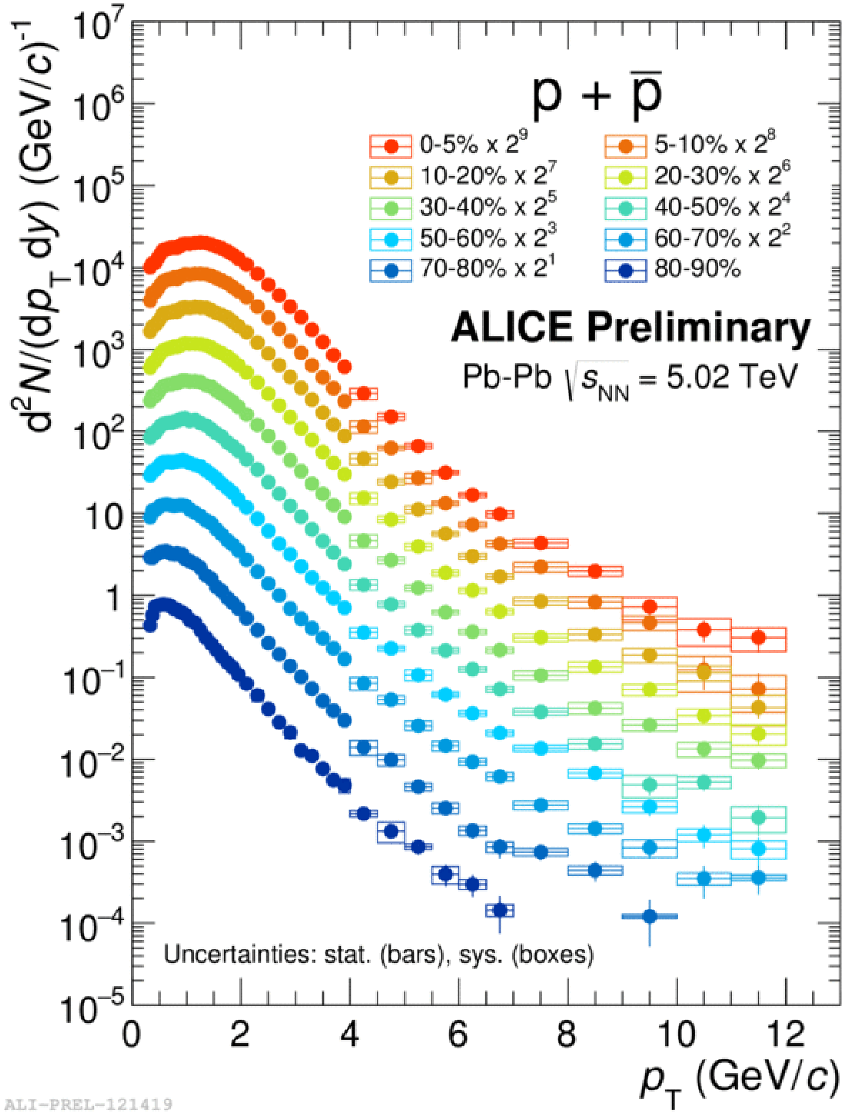
- Low p_T hadrons composed of (u,d,s) valence quarks define the collective behaviour of the fireball.

- “Basline model of ultra-relativistic heavy-ion physics”

A fireball in *local thermodynamic equilibrium*:

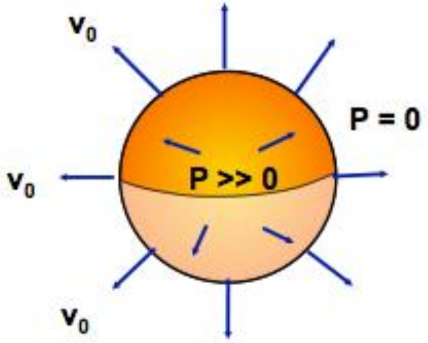
- particle chemistry in agreement with thermal model predictions
- p_T-spectra and v_2 measurements show patterns of radial and elliptic hydrodynamic flow.

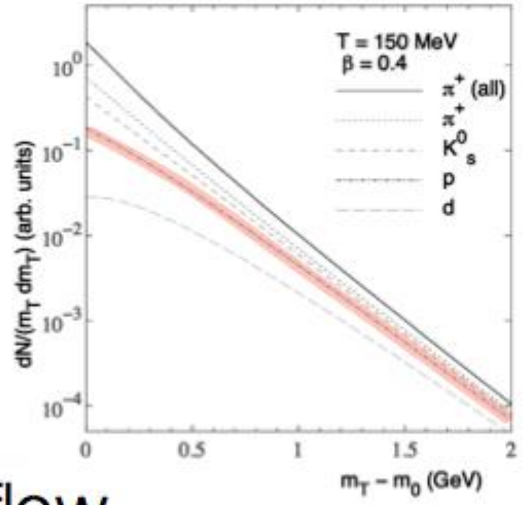
N.B.: Collective flow has nothing to do with the particle flow method to reconstruct tracks and jets in ATLAS/CMS

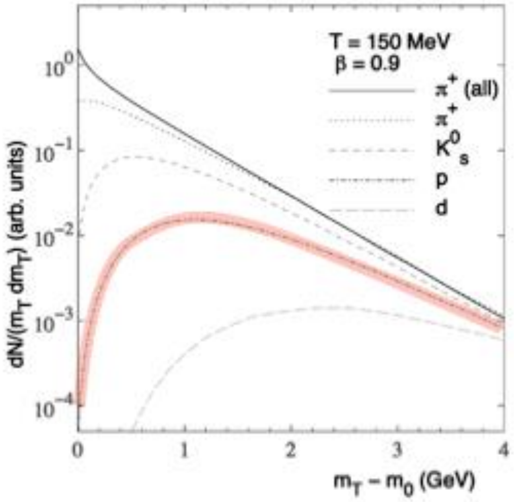


Radial and elliptic flow

Isotropic radial flow

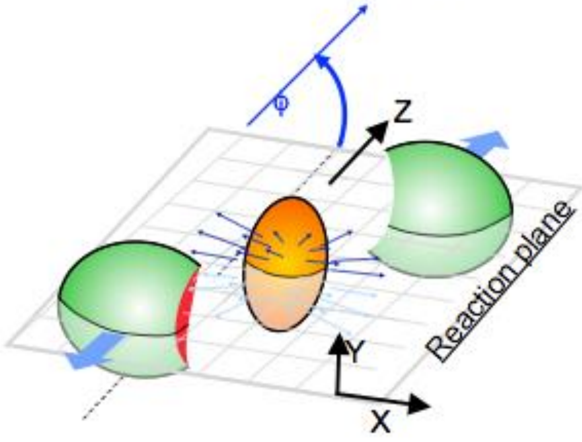




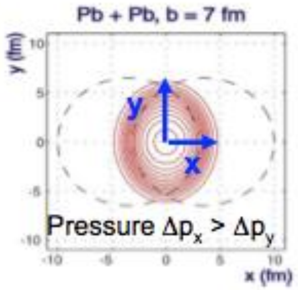


Anisotropic (elliptic) flow

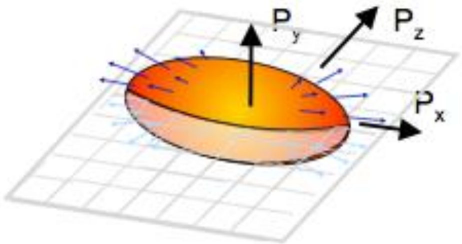
Spatial deformation



Azimuthal (φ) pressure gradients



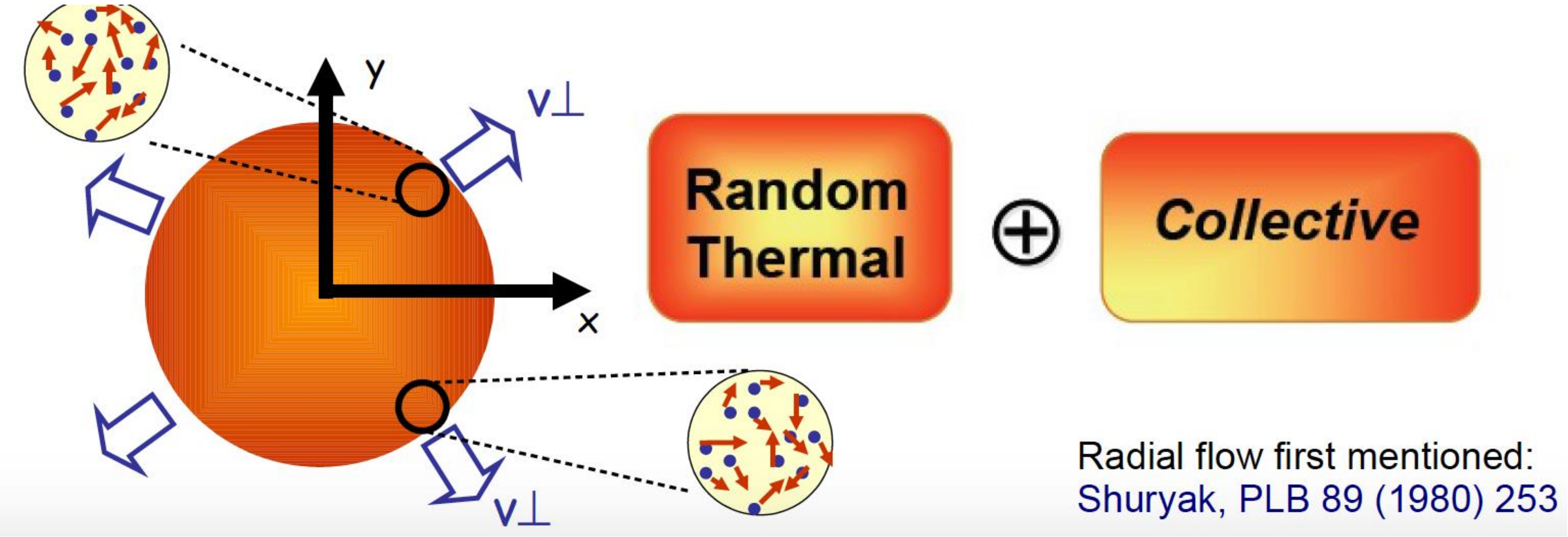
Anisotropic particle density



$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

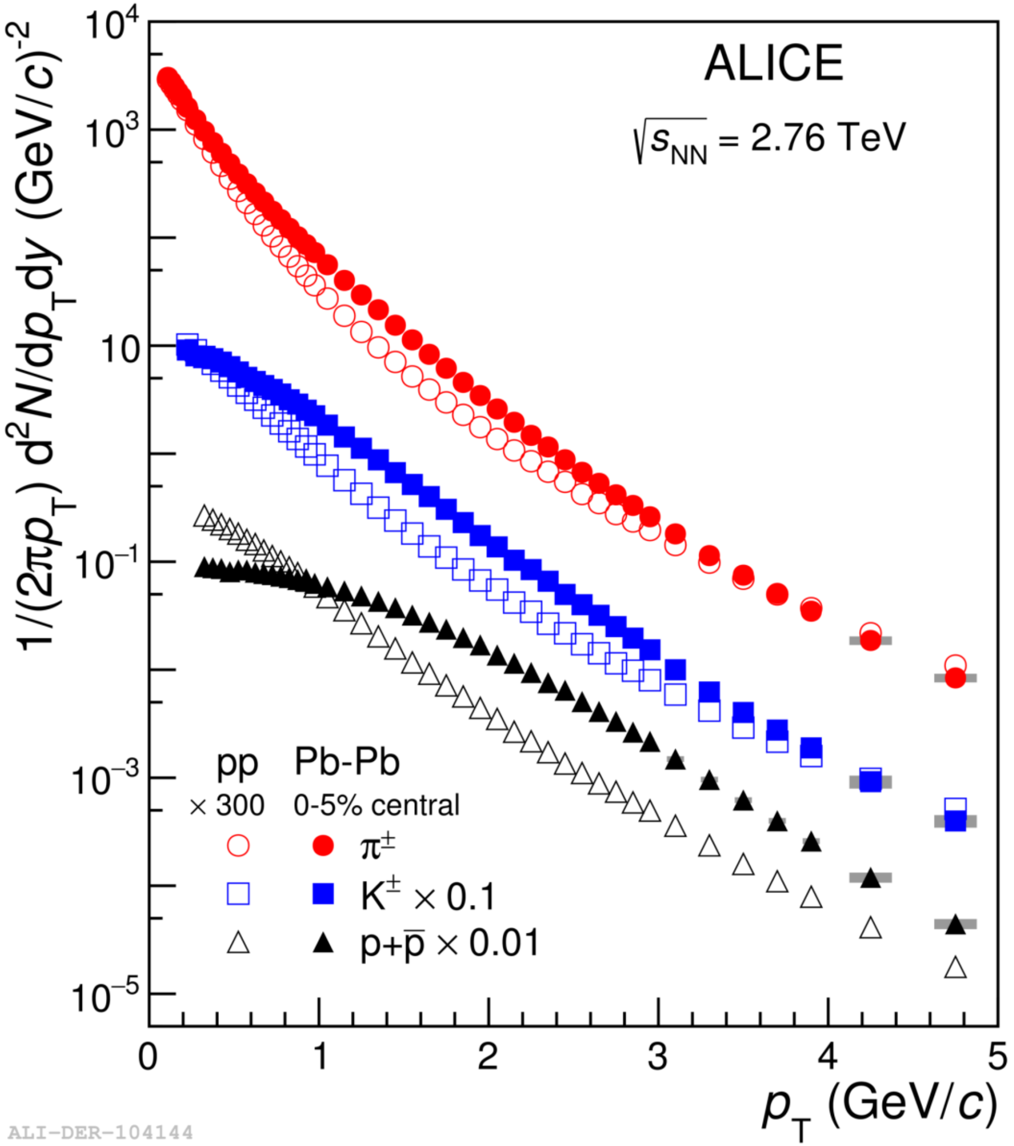
Flow in AA collisions

- Flow picture: Collective motion of particles superimposed to the thermal motion.
- Radial flow is a natural consequence of any interacting system expanding into the vacuum.



From: C. Loizides

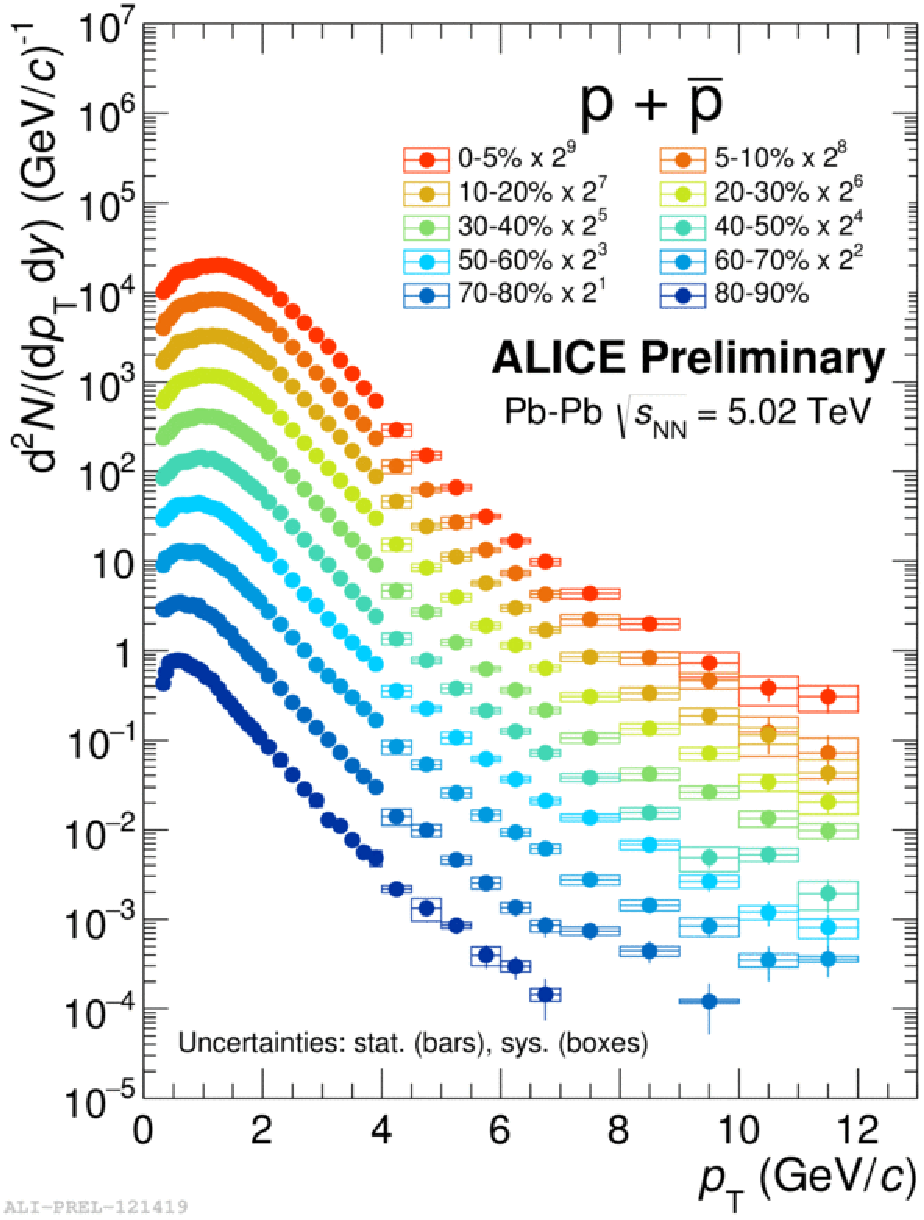
Radial flow (1)



Common radial hydrodynamic expansion leads to a modification of the spectral shape: mass dependent *boost.*

→ p_T-spectra harden with centrality.
→ More pronounced for heavier particles(e.g.: $p > K > \pi$) as *velocities* become equalized in the flow field
 (p = βγ·m).
→ Hydrodynamic models show a good agreement with the data.

Radial flow (2)



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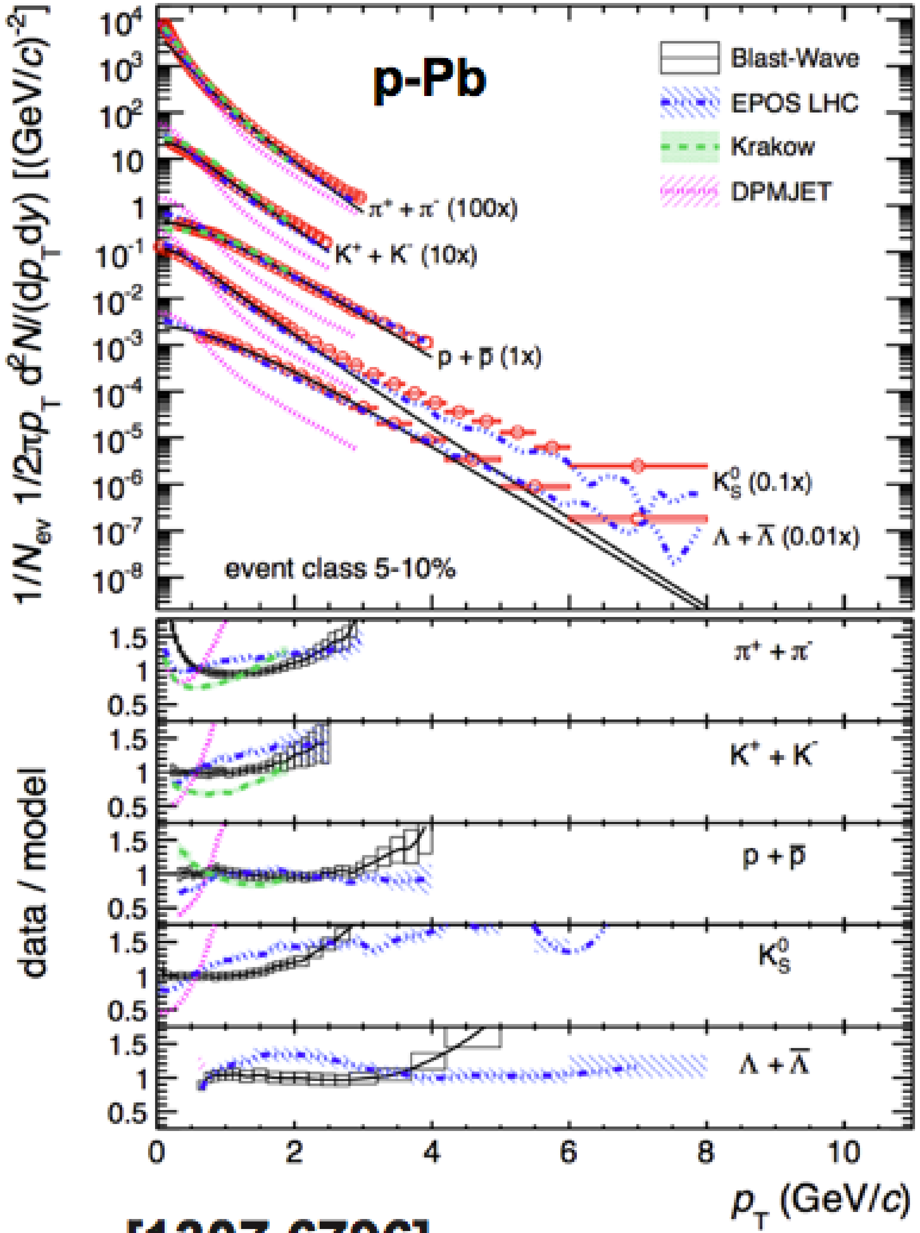
Radial flow (3)



[1307.6796]

Common radial hydrodynamic expansion leads to a modification of the spectral shape: mass dependent *boost.*

→ p_T-spectra harden with centrality.

→ More pronounced for heavier particles(e.g.: *p* > *K* > *π*) as *velocities* become equalized in the flow field (p = βγ·m).

→ Hydrodynamic models show a good agreement with the data.

Blast-wave model (1)

- How fast is the expansion velocity? Estimate in a simplified hydro model:
  - Consider a thermal source (Boltzmann type p_{T}-spectrum) of particles:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} \propto E\,e^{-E/T} \qquad E = m_{\mathrm{T}}\cosh(y)$$

  - Boost source radially with velocity β and evaluate at y=0:

$$\frac{1}{m_{\mathrm{T}}}\frac{\mathrm{d}N}{\mathrm{d}m_{\mathrm{T}}} \propto m_{\mathrm{T}}\,I_0\left(\frac{p_{\mathrm{T}}\sinh(\rho)}{T}\right)K_1\left(\frac{m_{\mathrm{T}}\cosh(\rho)}{T}\right) \qquad \rho = \tanh^{-1}(\beta)$$

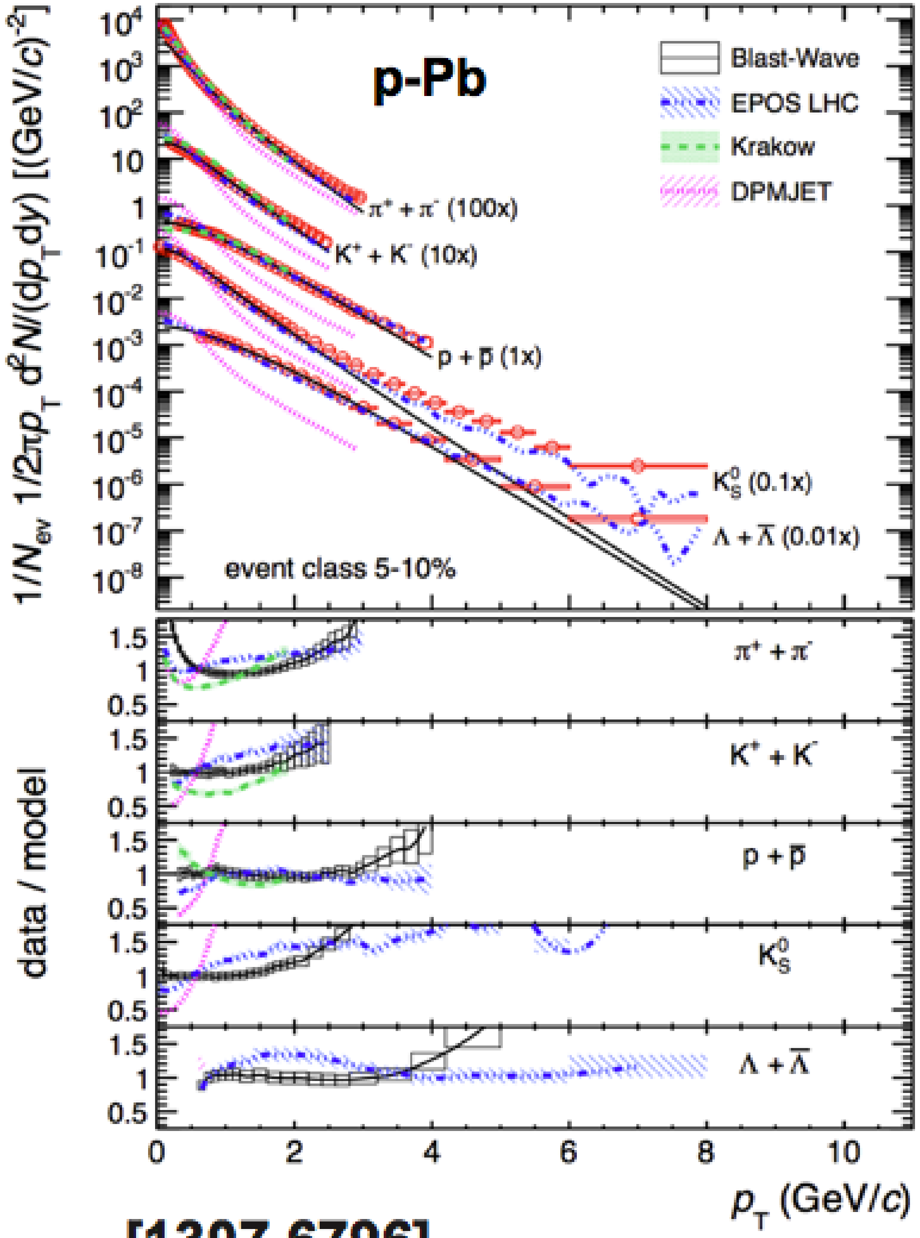
  - Simple assumption: consider uniform sphere of radius *R*

$$\frac{1}{m_{\mathrm{T}}}\frac{\mathrm{d}N}{\mathrm{d}m_{\mathrm{T}}} \propto \int_0^R r\mathrm{d}r\, m_{\mathrm{T}}\,I_0\left(\frac{p_{\mathrm{T}}\sinh(\rho(r))}{T}\right)K_1\left(\frac{m_{\mathrm{T}}\cosh(\rho(r))}{T}\right)$$

    and parameterize velocity profile as $\beta(r) = \beta_{\mathrm{s}}\,(r/R)^n$

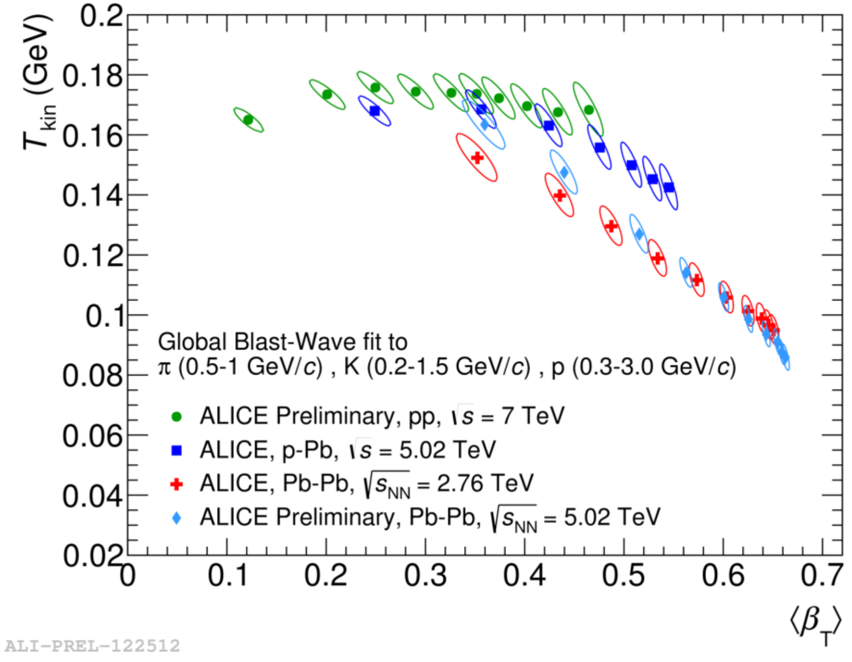
- Three free parameters: kinetic freeze-out temperature T_{kin}, surface expansion velocity β_{S}, exponent *n* of velocity profile.

Blast-wave model (2)



[1307.6796]

- Common blast-wave fit gives a good description of the data at low transverse momenta.
- Average expansion velocity: ~ 0.65c
- Kinetic freeze-out temperature: ~ 80 MeV



End of lecture 2

- Now we know the temperature of the system at the final decoupling.
- Tomorrow: elliptic flow and why the QGP is an *ideal liquid*.

Particle detection
($t \approx 10^{15}$fm/c)

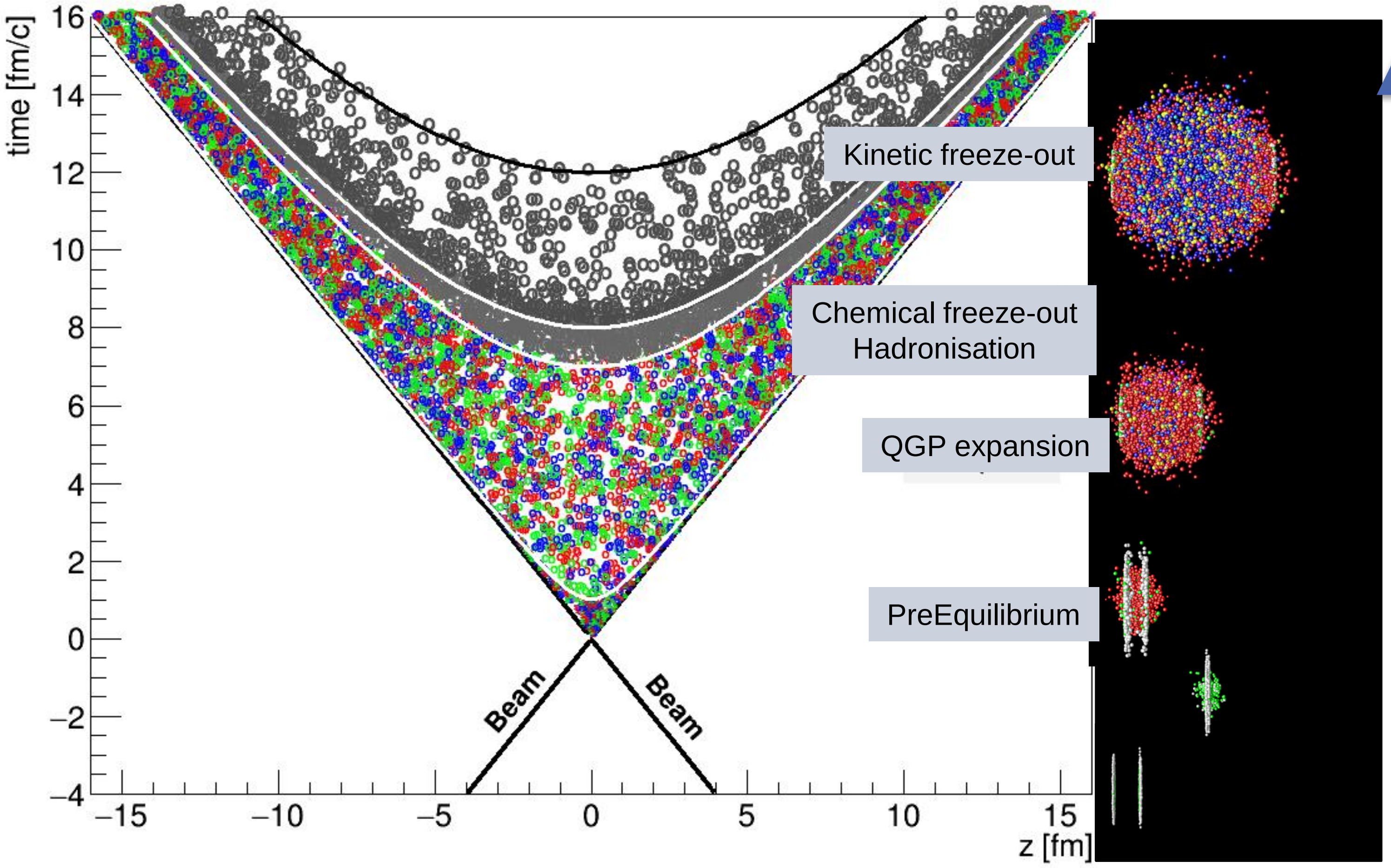
Kinetic freeze-out
(t=10fm/c)

Chemical freeze-out

Hydrodynamic
evolution (t~0.5fm/c)

Pre-equilibrium

Collision (t=0fm/c)



T ~ 90 MeV

System
cools dow
by
(isentropic
expansion

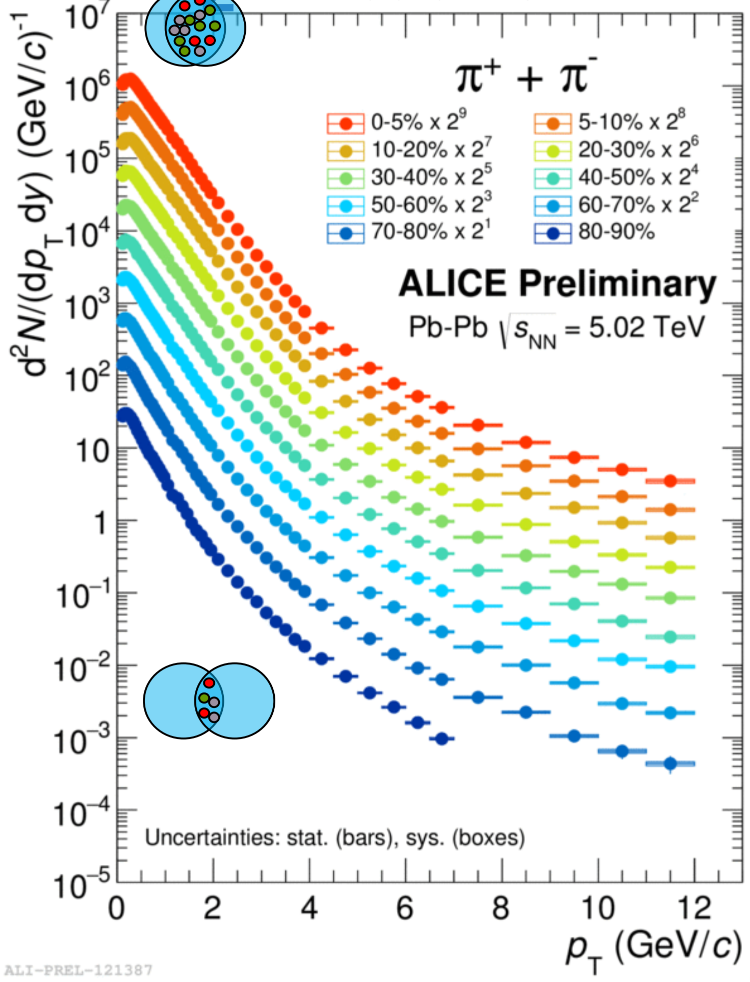
T > 300 Me

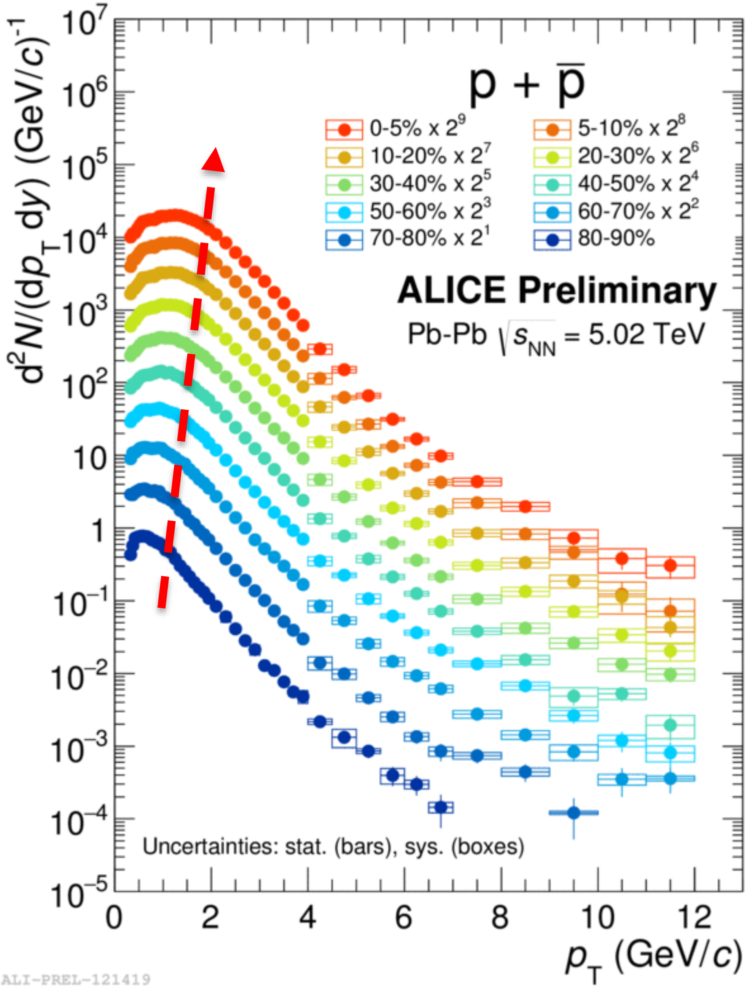
Small systems: high multiplicity pp and pPb

Radial and elliptic flow

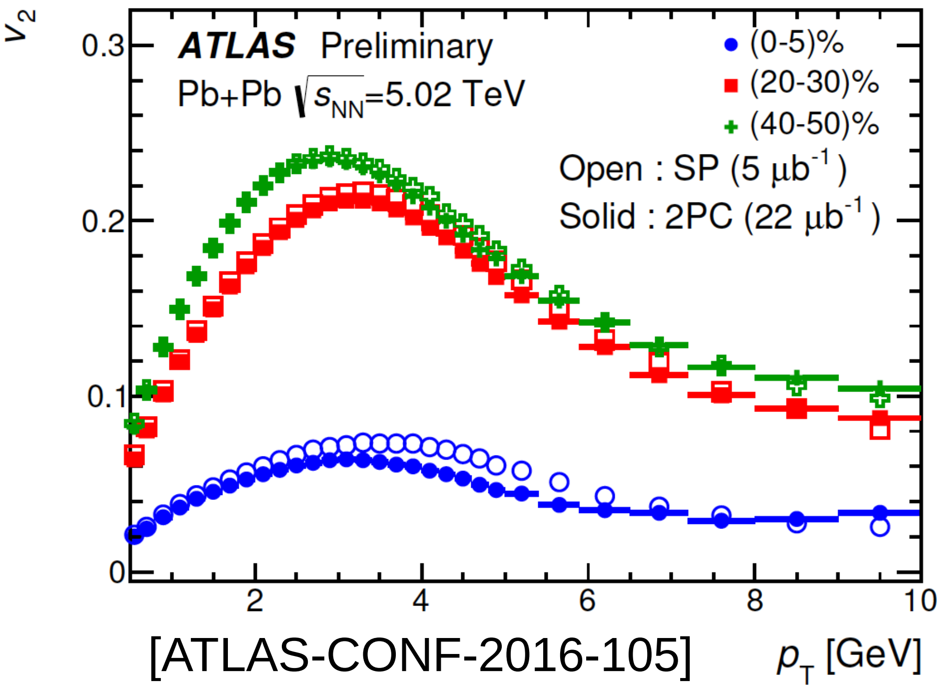
Hydrodynamic expansion – spectral shapes and v_2

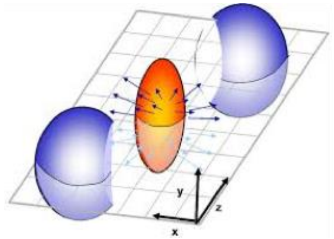
Radial flow





Elliptic flow





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

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

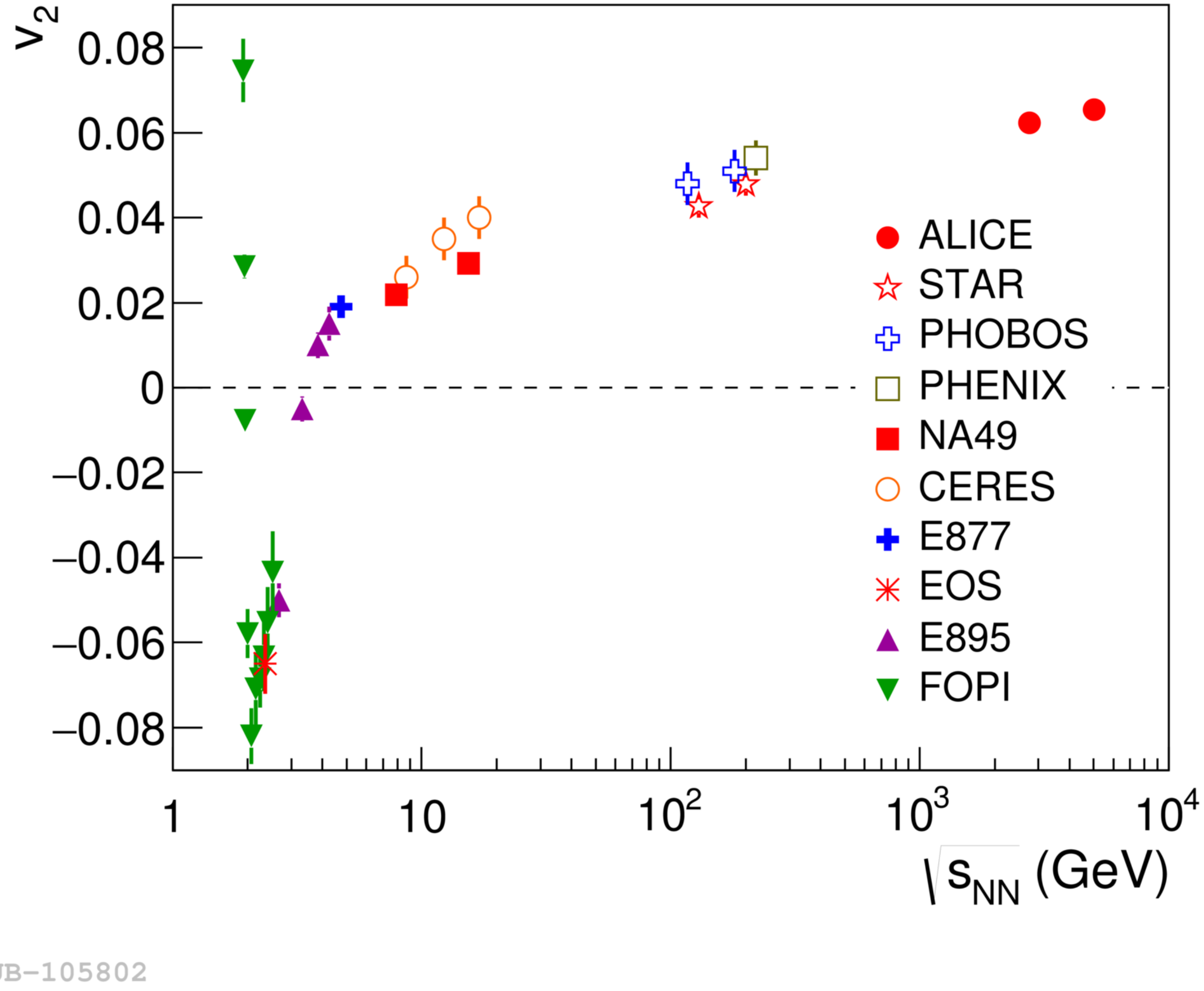
Radial flow v_1 – direct flow, $\mathbf{v_2}$**- elliptic flow**

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

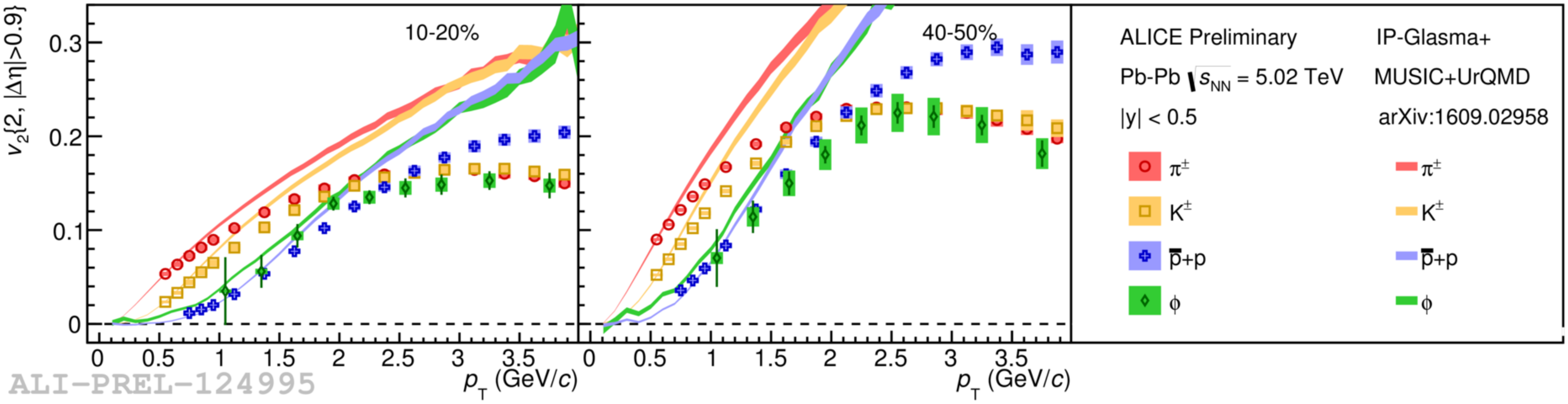
- With centrality
- With the particle mass: p = βγ·m

Elliptic flow (heavy-ion physics)

[PRL 116, 132302 (2016)]



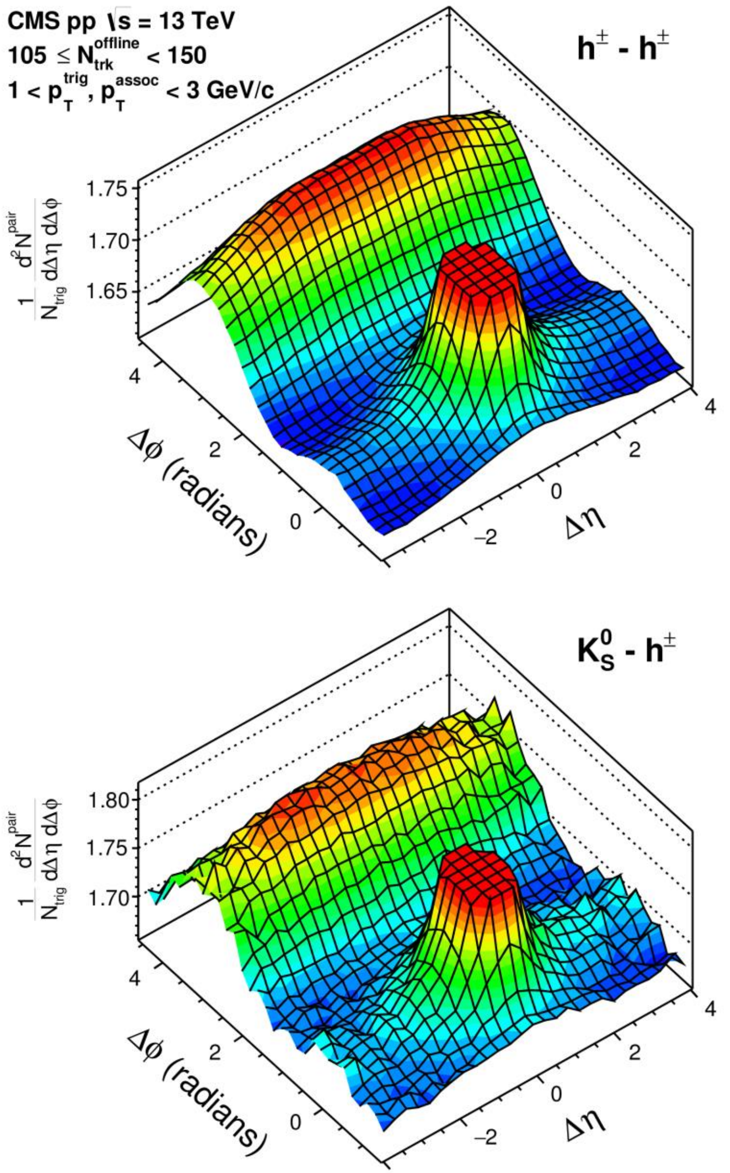
Elliptic flow (ALICE)



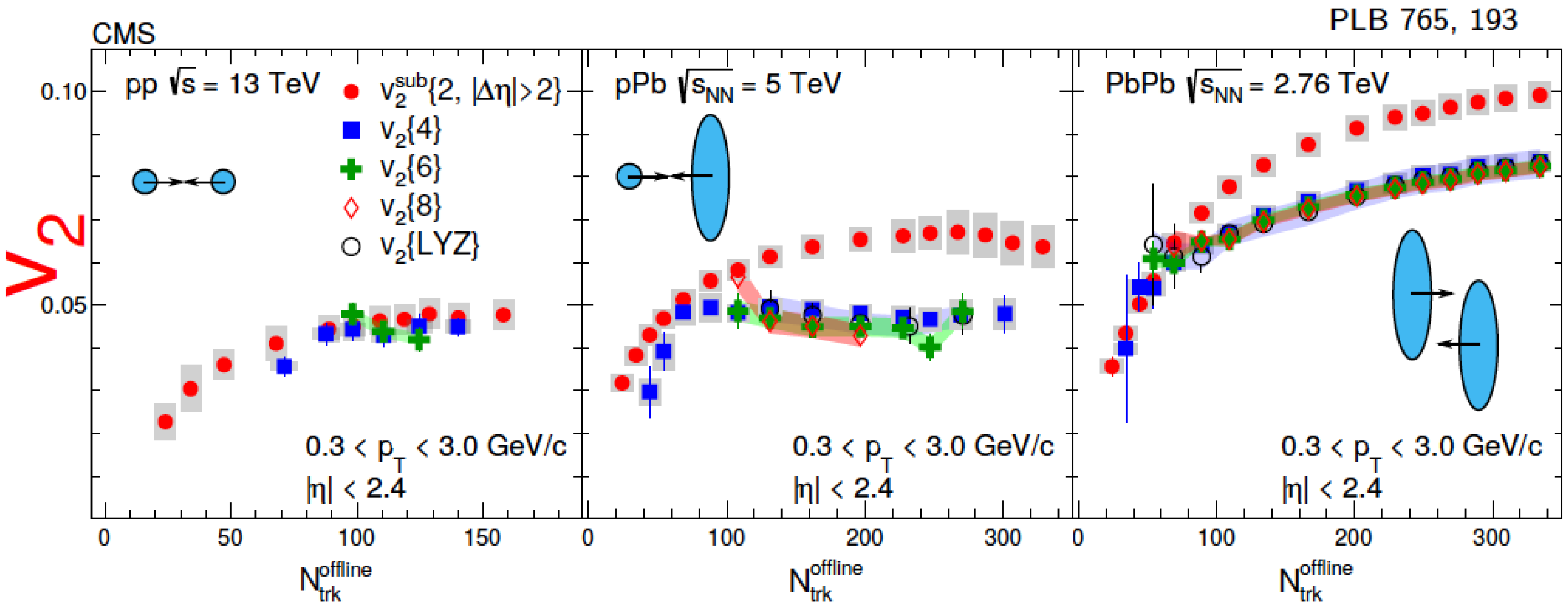
Validity of hydrodynamic description confirmed at the highest centre-of-mass energies available.

Expected mass ordering
(p = βγ·m) observed.

(Double) ridges



- 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.

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