Light flavour production in pp and heavy ion collisions at the LHC

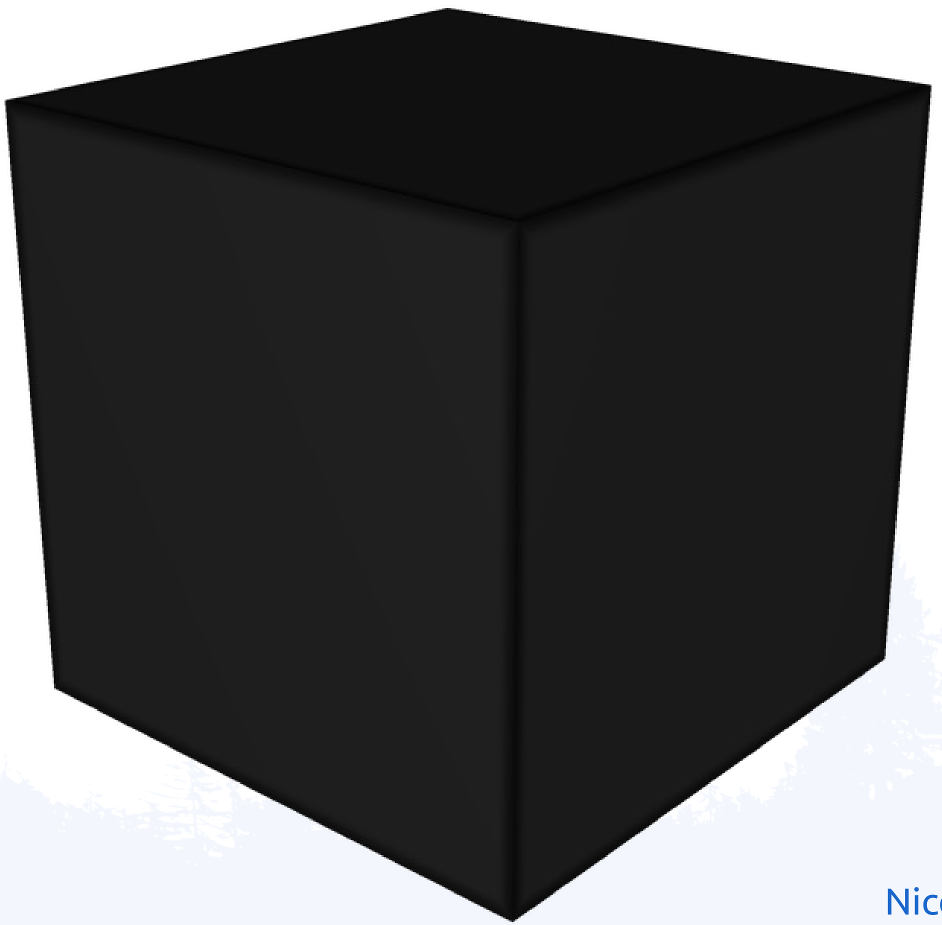
Aperitivi scientifici @ INFN Bologna

03/07/2020

Nicolò Jacazio (CERN)

What's in the box?

- Imagine having a black box with water inside
- How to know what's really inside?



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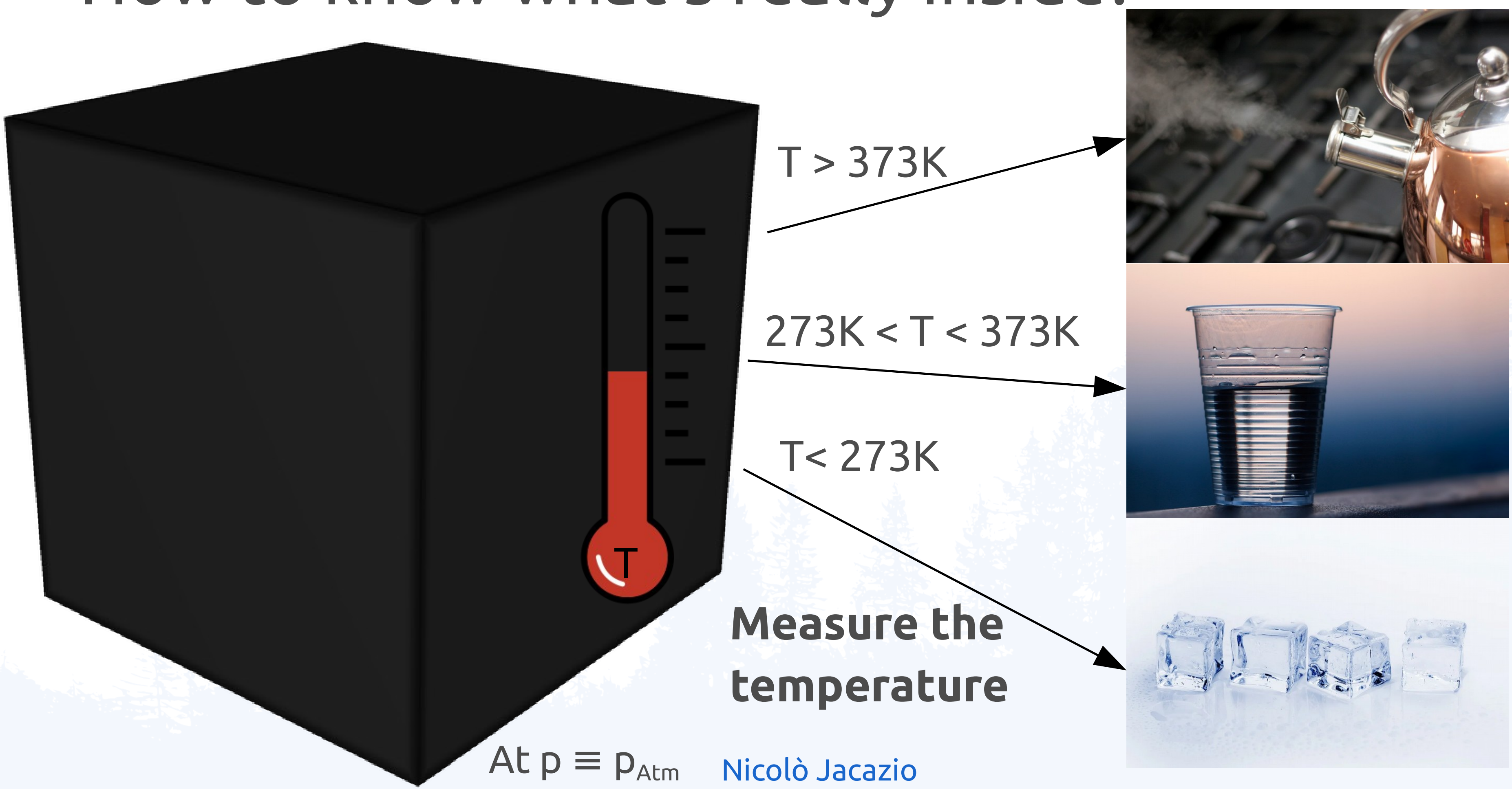

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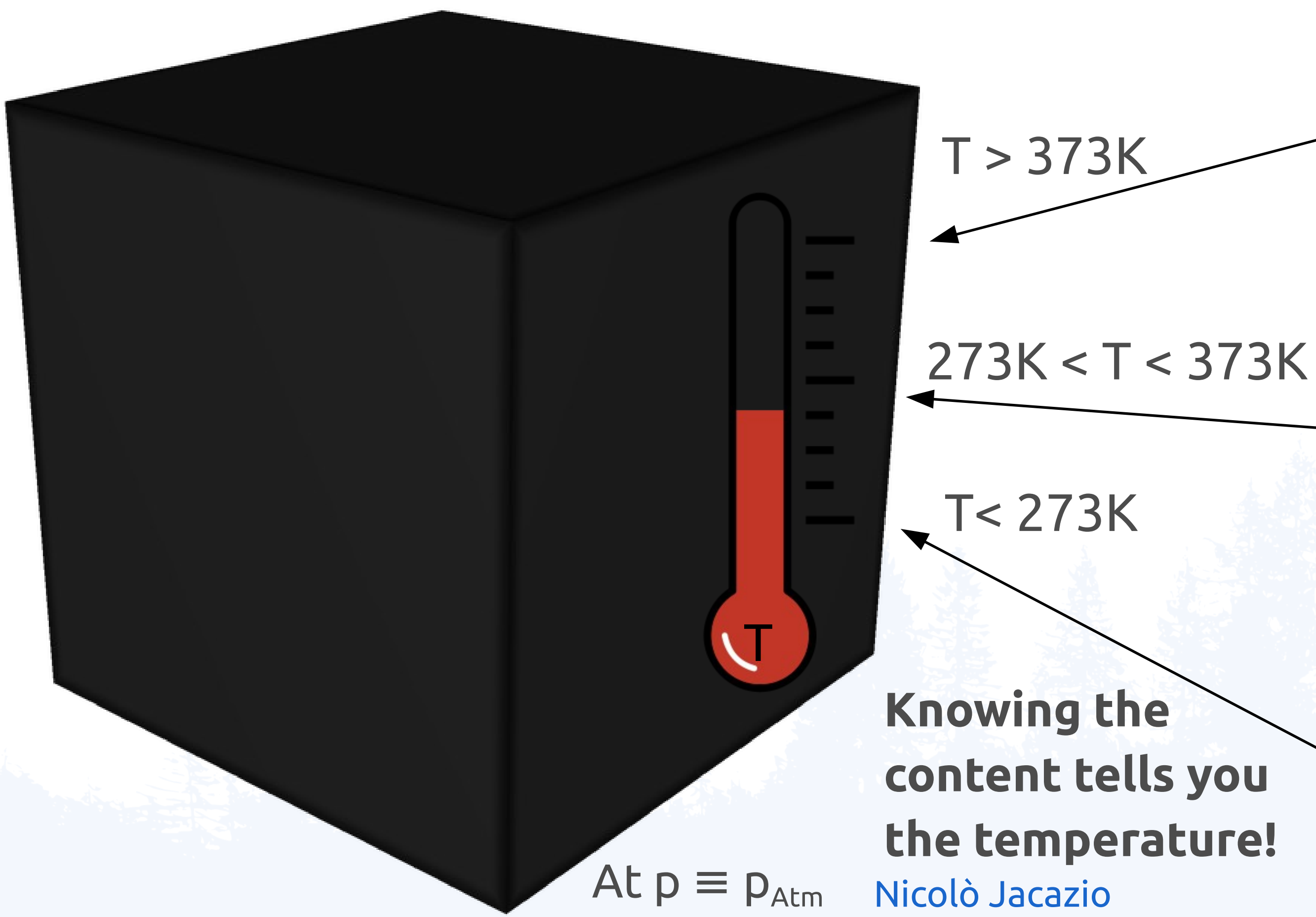
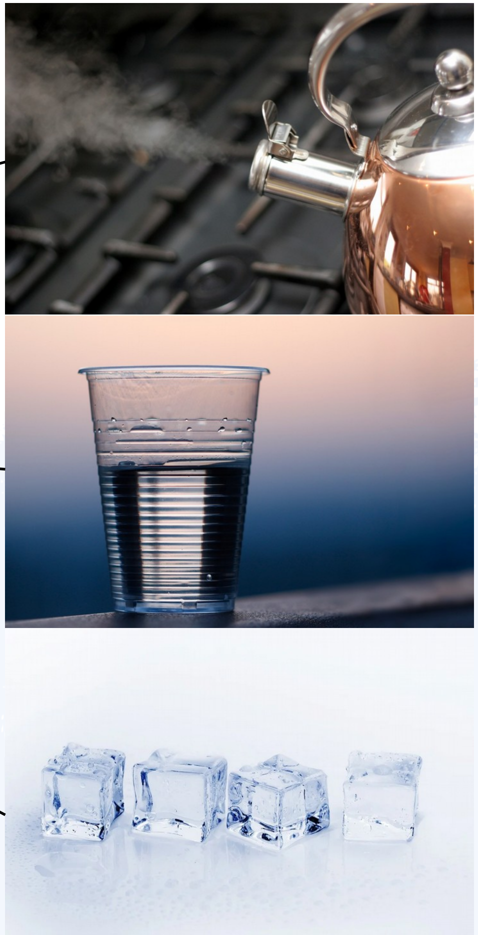


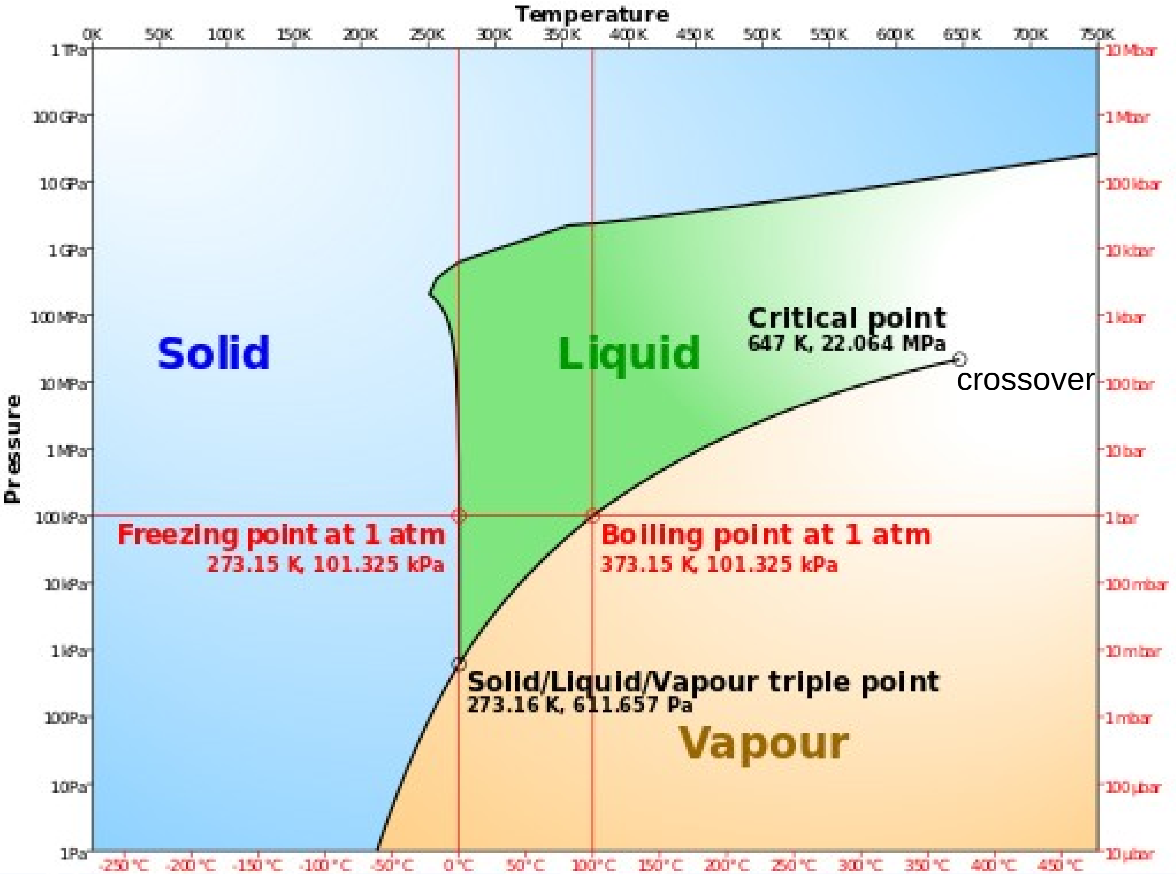


Knowing the content tells you the temperature!

At $p \equiv p_{Atm}$

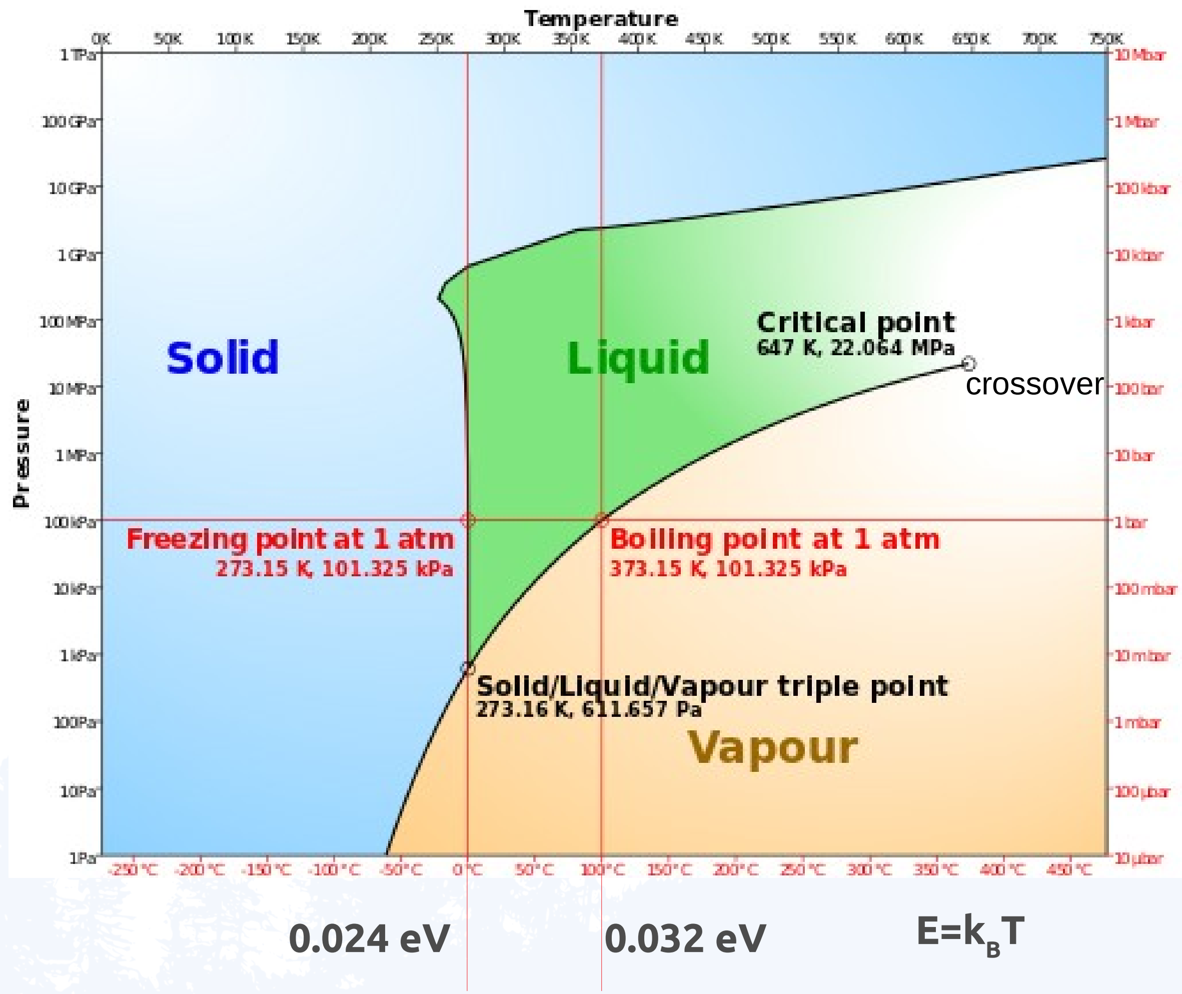
Water phase diagram

- The phase of the matter in the box depends on its thermodynamic state
- Three phases are available in the case of water
- Phase diagram investigated by varying pressure and temperature



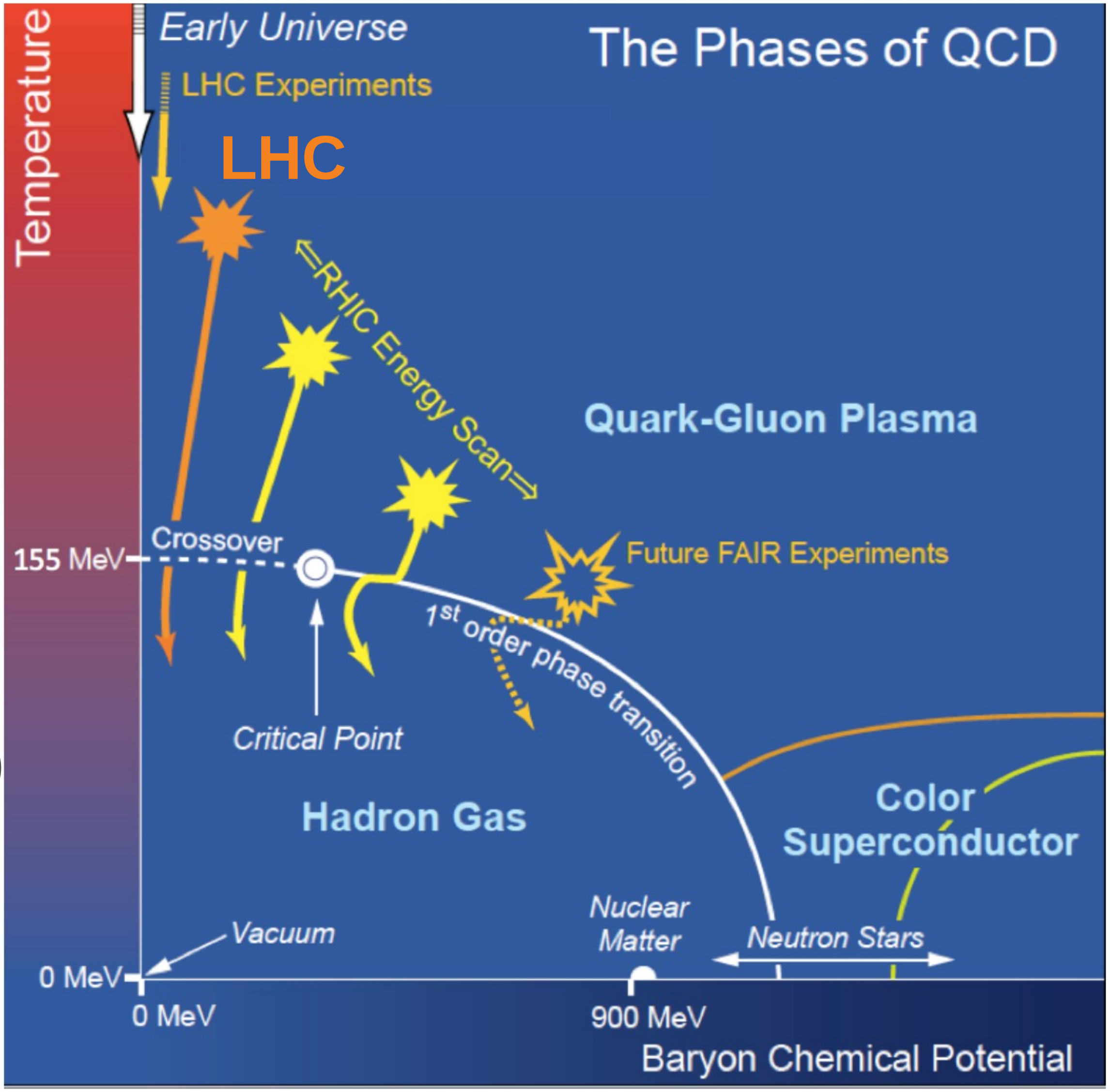
Water phase diagram

- The phase of the matter in the box depends on its thermodynamic state
- Three phases are available in the case of water
- Phase diagram investigated by varying pressure and temperature
- Temperature measurements can be expressed in particle physics units



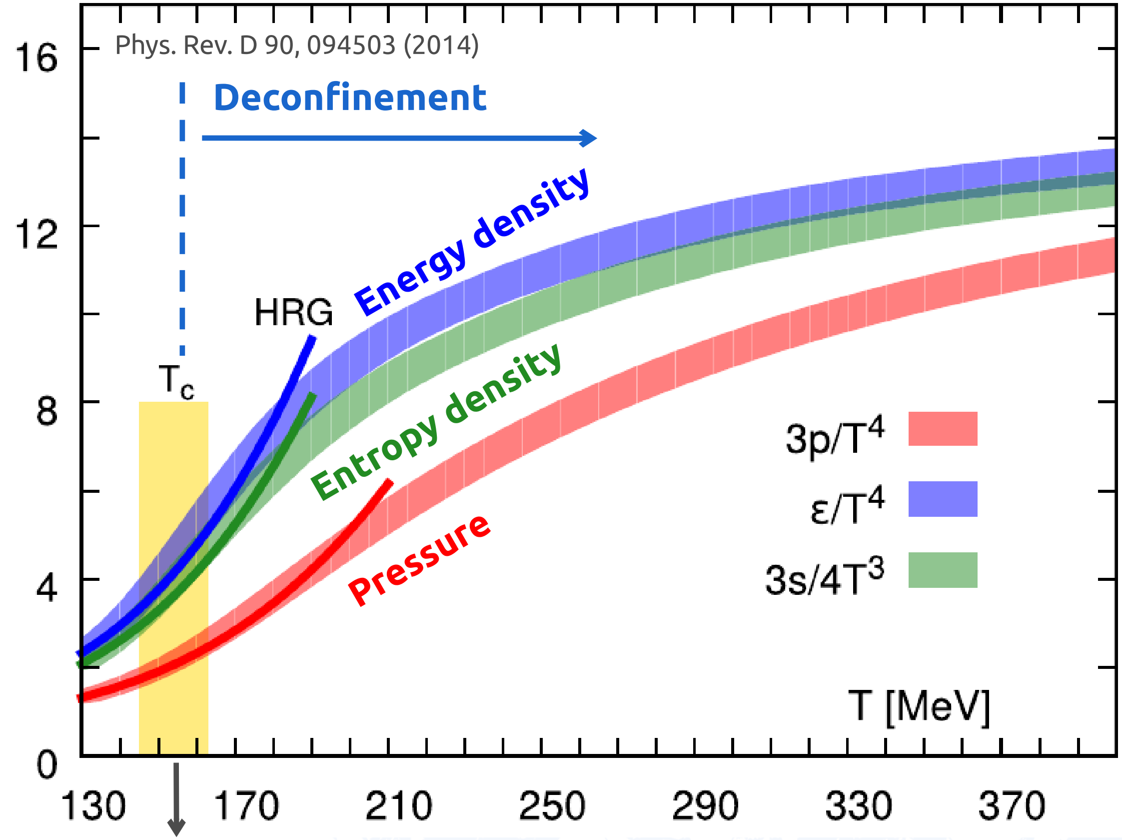
QCD phase diagram

- The QCD phase diagram can be investigated in the same way
- Temperatures at play are order of magnitudes higher than what we are used to
- High temperatures and low net baryon density are reached in heavy-ion collisions at the LHC
- Deconfined (strongly interacting) quark and gluons
  -> the **Quark-Gluon Plasma**
- Free partons moving over distances larger than the typical size of hadrons



Heavy-ion collisions

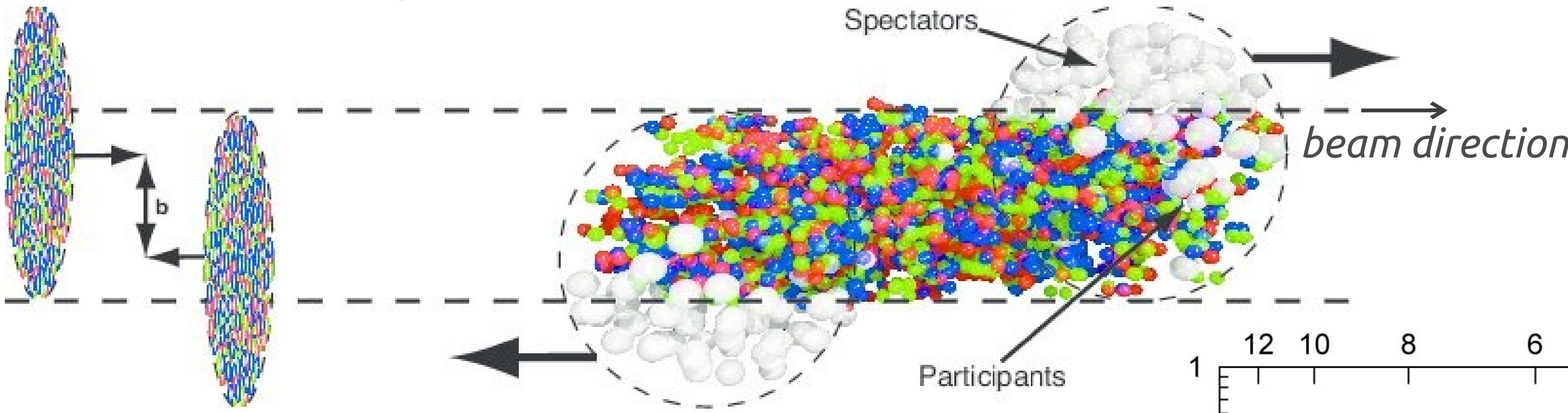
- Computations from lattice QCD identify a critical temperature T_c
- $T > T_c$: deconfined phase, quarks and gluons are the degrees of freedom
- $T < T_c$: confined phase, hadrons are the degrees of freedom
- Energy densities > 1GeV/fm^3 produce a deconfined medium



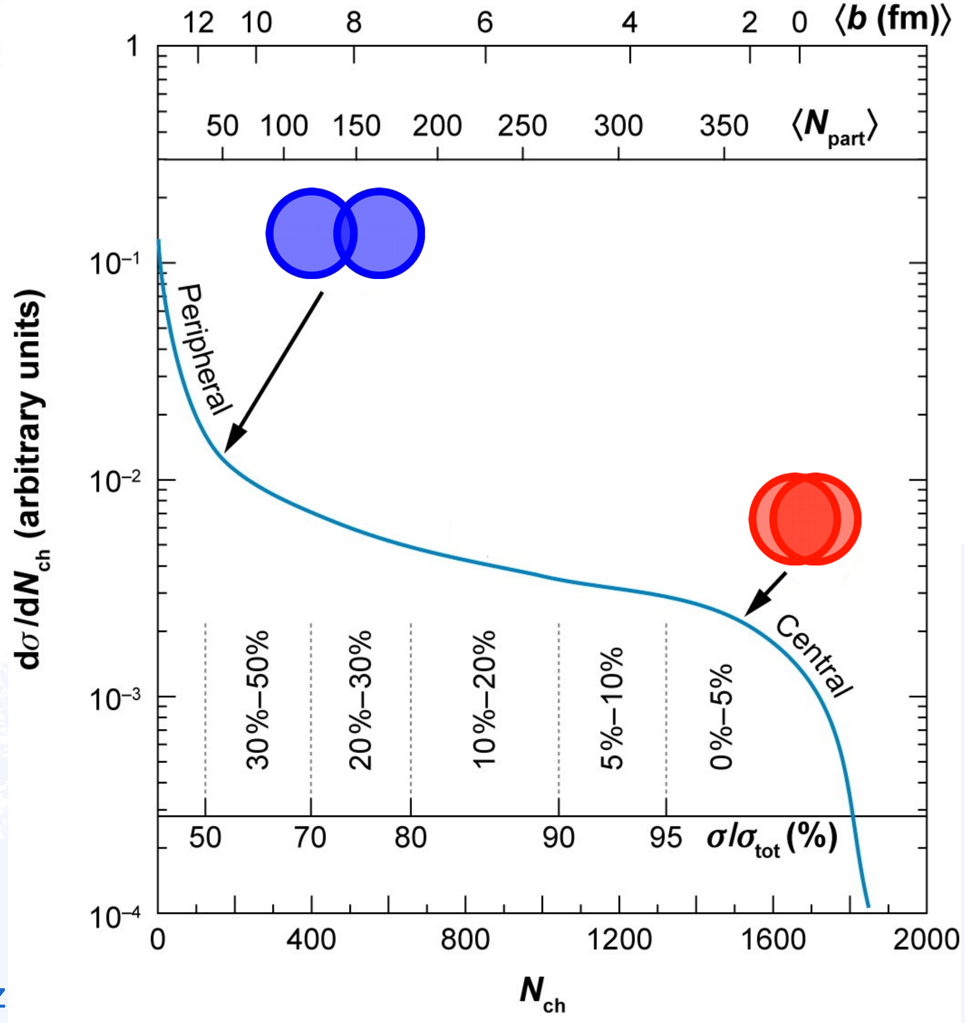
T_c = 154 ± 9 MeV $\mu_{B=0}$

The thermodynamic properties of the medium can be derived from the measurement of final state particles (π, K, p, ...)

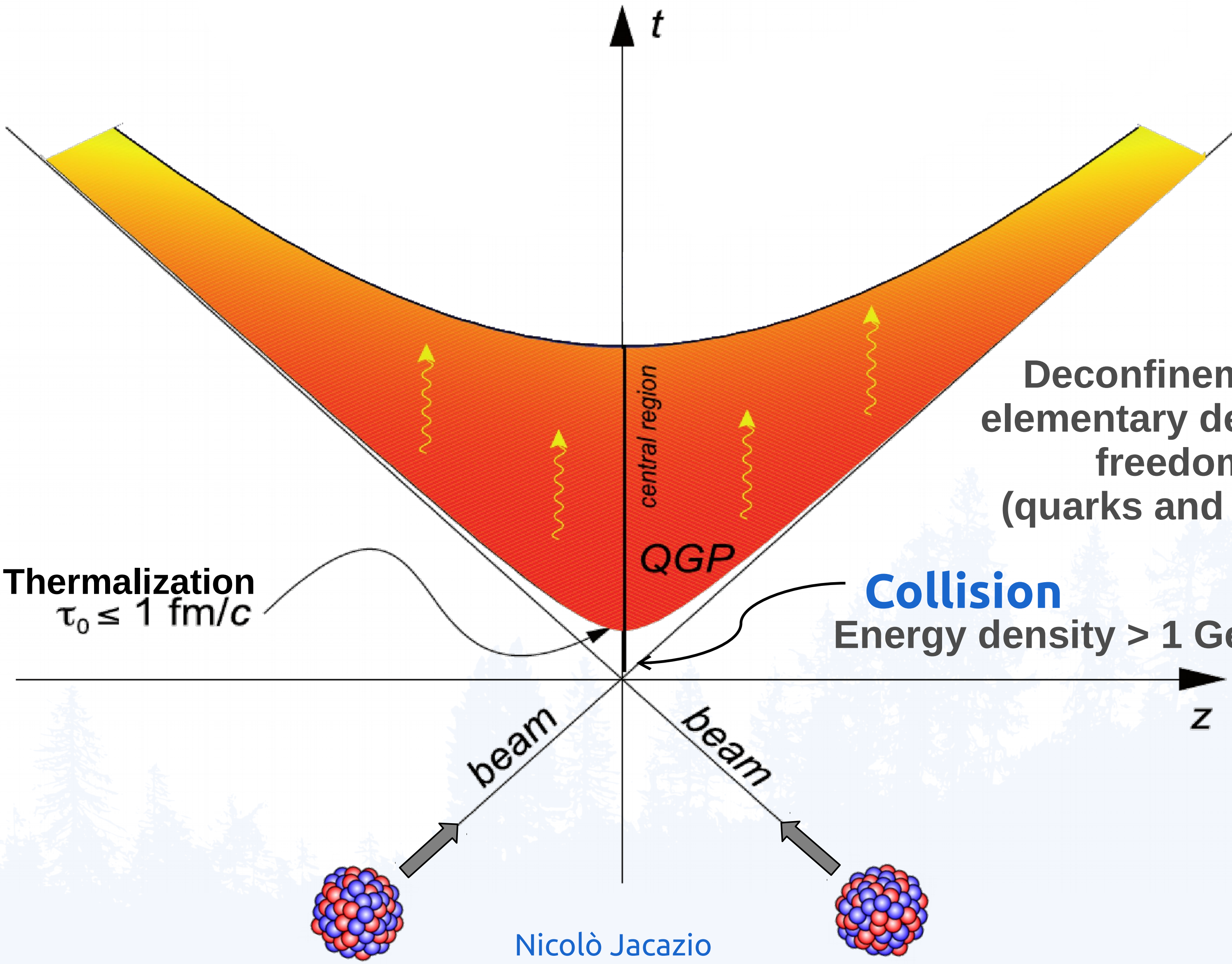
Heavy-ion collisions



- The impact parameter of the collision defines how many nucleons interact (N_{part}) and how many are not involved in the collision
- Centrality is expressed in fraction of the total inelastic cross section (σ_{tot})
- The largest energy density is achieved in the most central collisions



Evolution of a heavy ion collision



Deconfinement of elementary degrees of freedoms (quarks and gluons)

Collision

Energy density > 1 GeV/fm^3

Evolution of a heavy ion collision

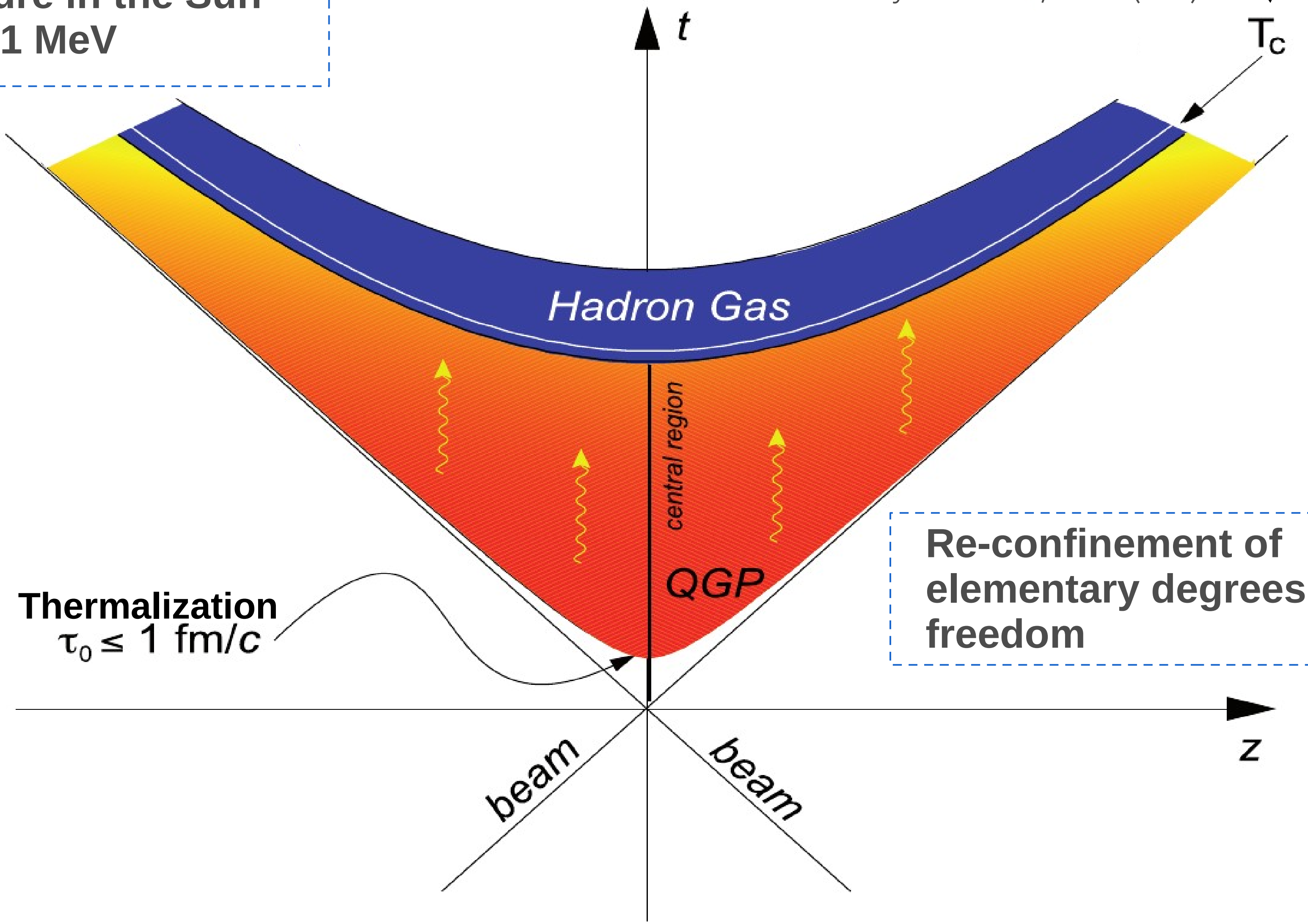
For comparison

Temperature in the Sun core ~ 0.01 MeV

Critical temperature

From lattice QCD: T_c = 154 MeV
Phys. Rev. D 90, 094503 (2014)

Thermalization
$\tau_0 \leq 1$ fm/c

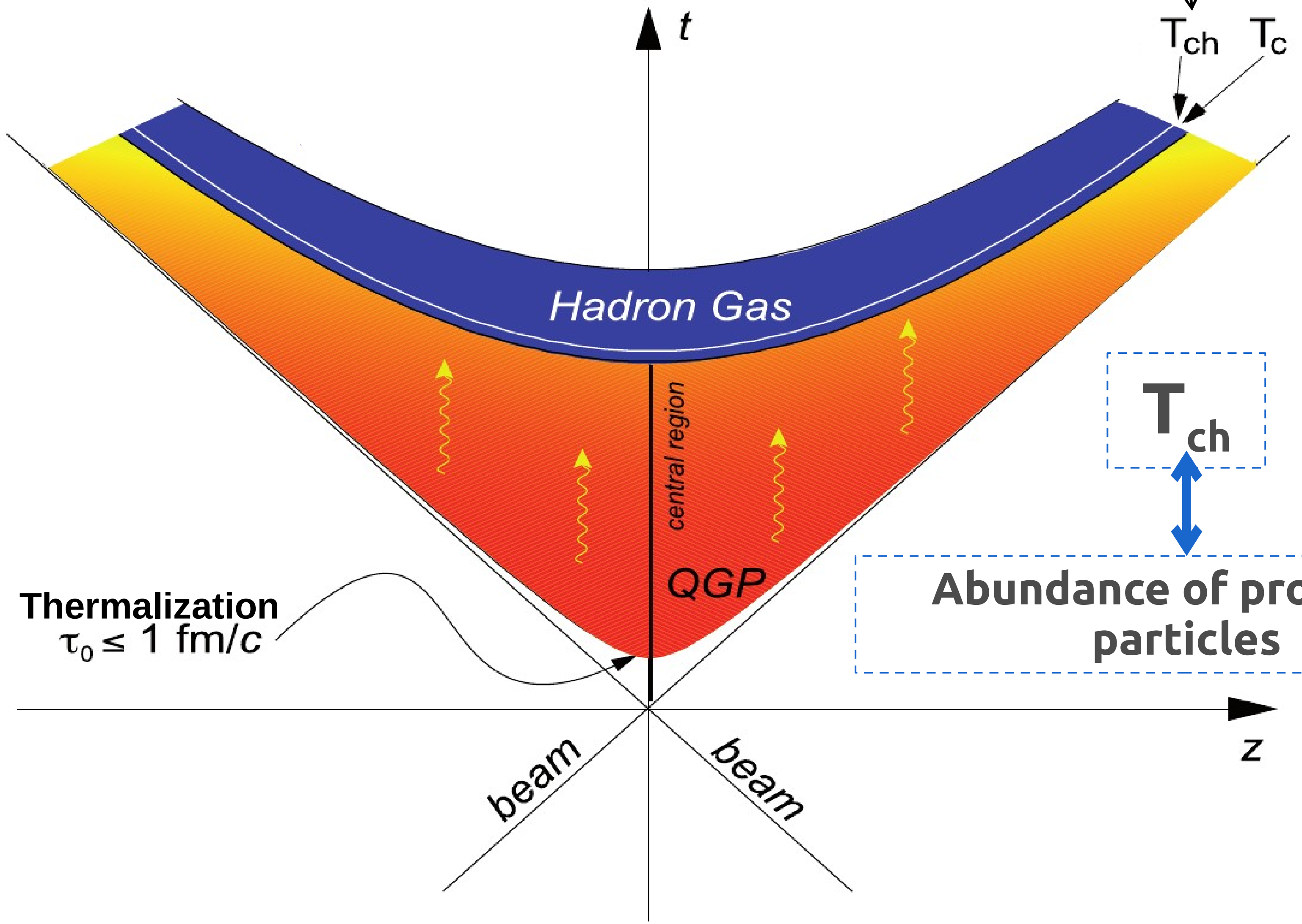


Re-confinement of elementary degrees of freedom

Evolution of a heavy ion collision

Chemical freeze-out

Hadron abundances are fixed

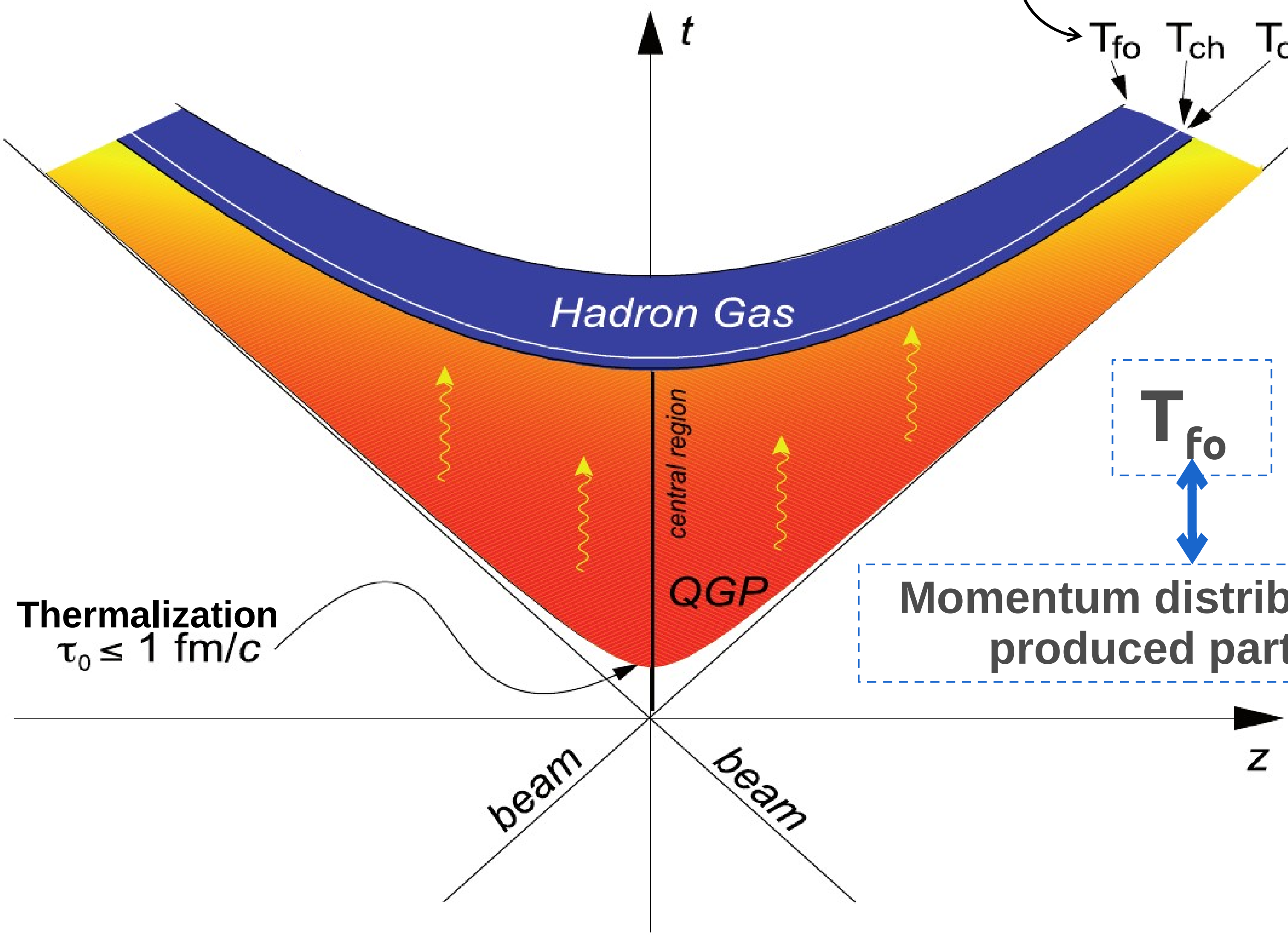


T_{ch} ↔ Abundance of produced particles

Evolution of a heavy ion collision

Kinetic freeze-out

Hadrons decouple from the medium

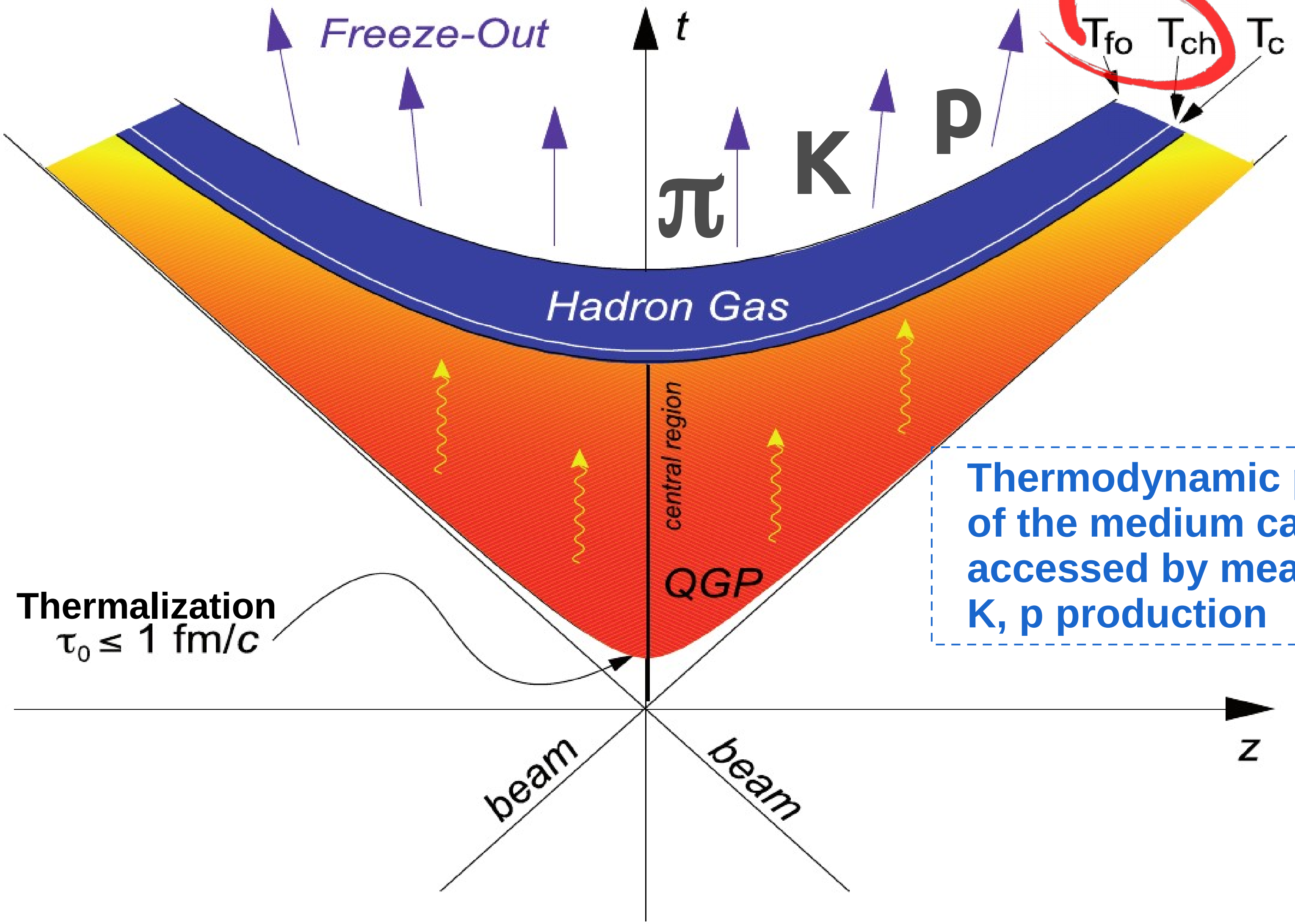


T_{fo}

Momentum distributions of produced particles

Evolution of a heavy ion collision

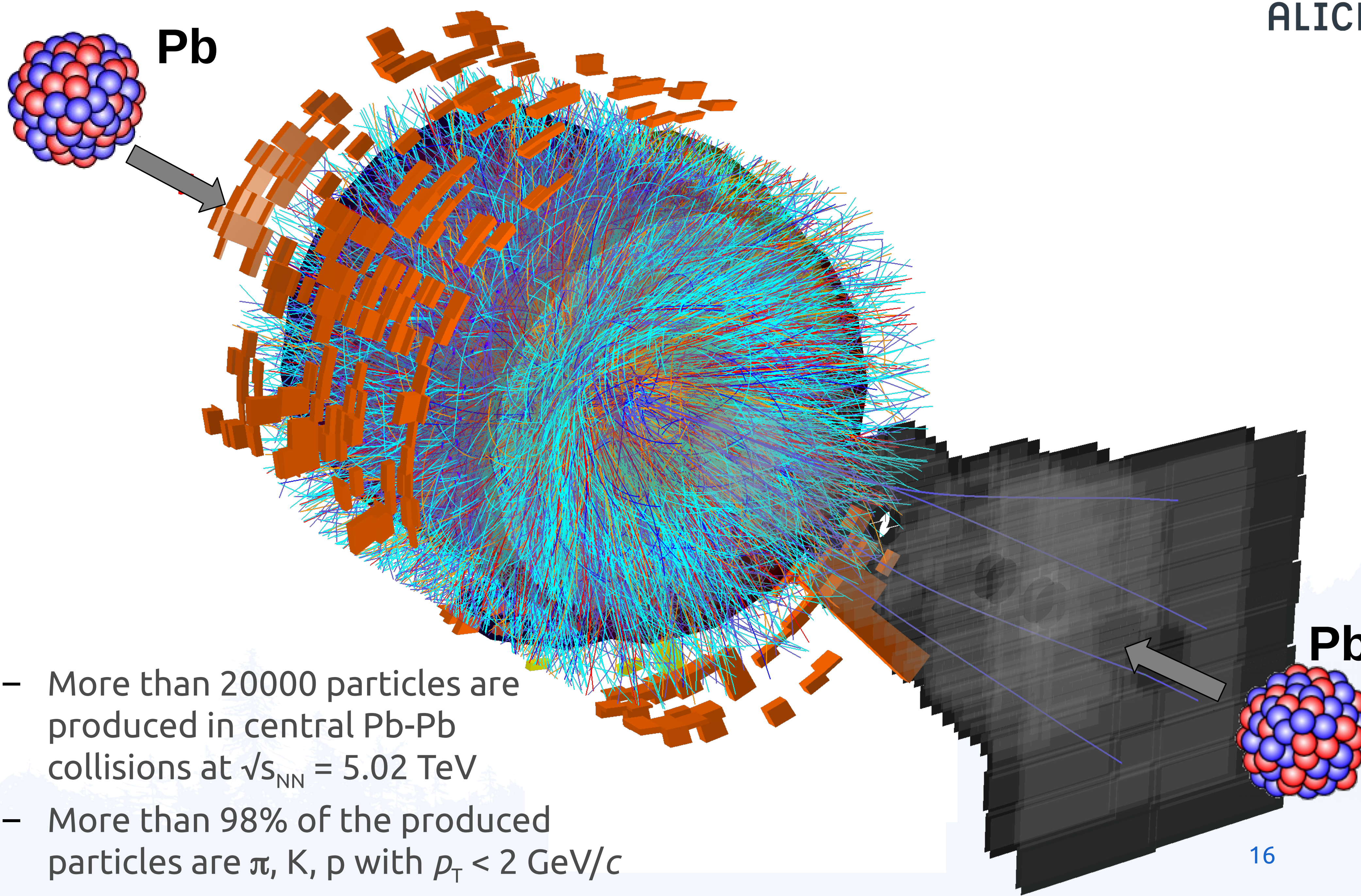
Produced particles leave the collision area and can be detected



Thermodynamic properties of the medium can be accessed by measuring π, K, p production

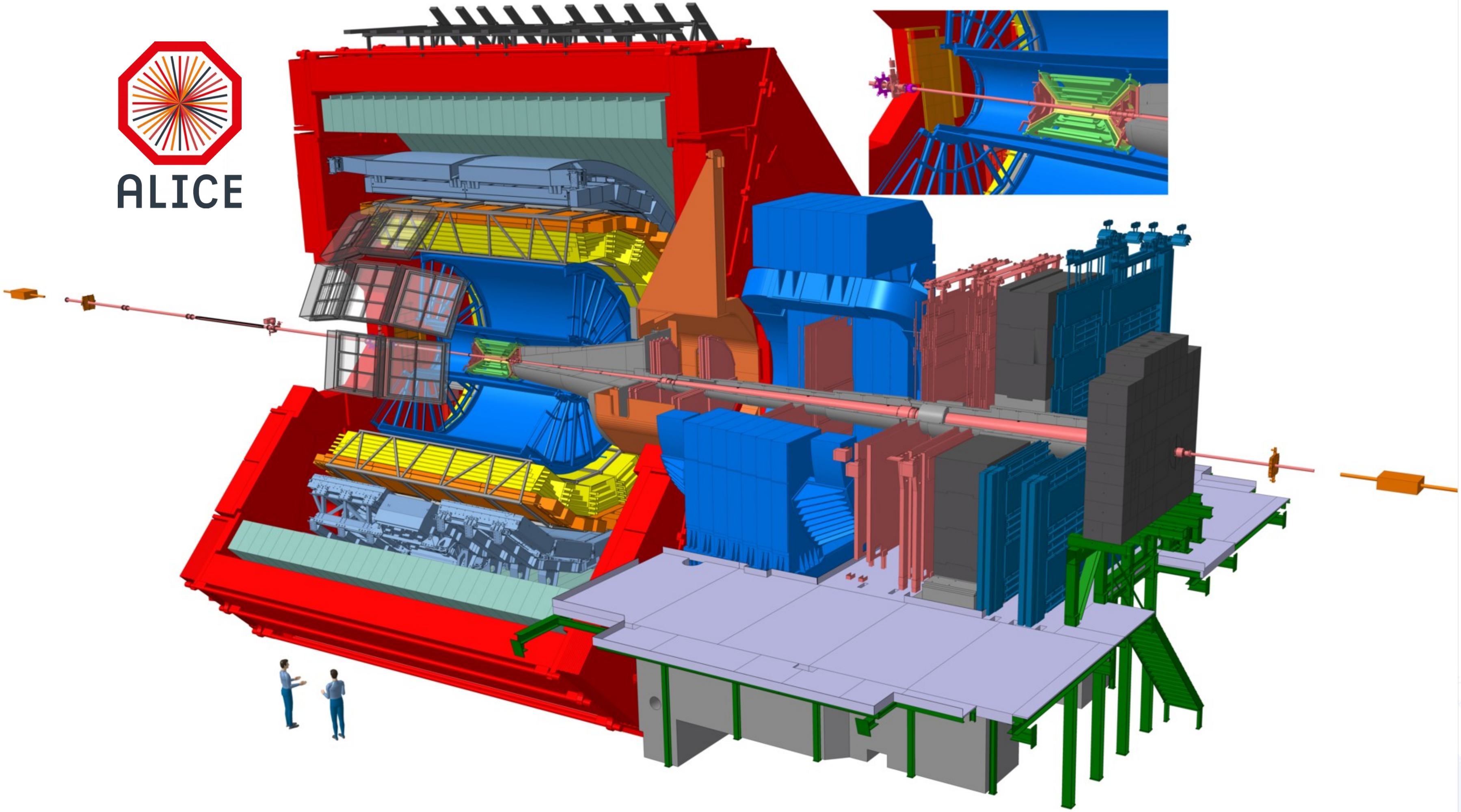

The ALICE detector
A Large Ion Collider Experiment

A Large Ion Collider Experiment



- More than 20000 particles are produced in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- More than 98% of the produced particles are π, K, p with p_T < 2 GeV/c

A Large Ion Collider Experiment



- Moderate magnetic field (B = 0.5 T) in the mid-rapidity region $|\eta| < 0.9$
- Tracking down to $p_T \sim 100$ MeV/c
- Extensive particle identification (PID) by several techniques
- High granularity to cope with the high occupancy in Pb-Pb collisions

Particle identification with ALICE

Inner Tracking System (ITS)

- dE/dx in silicon
- 4 layers with analogue readout

Time Projection Chamber (TPC)

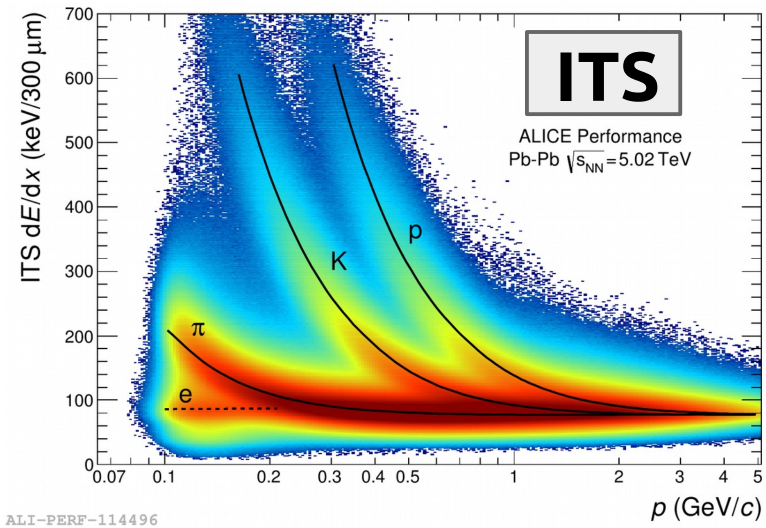
- dE/dx in gas (Ar–CO_2)
- $\sigma_{dE/dx}$ ~ 5%

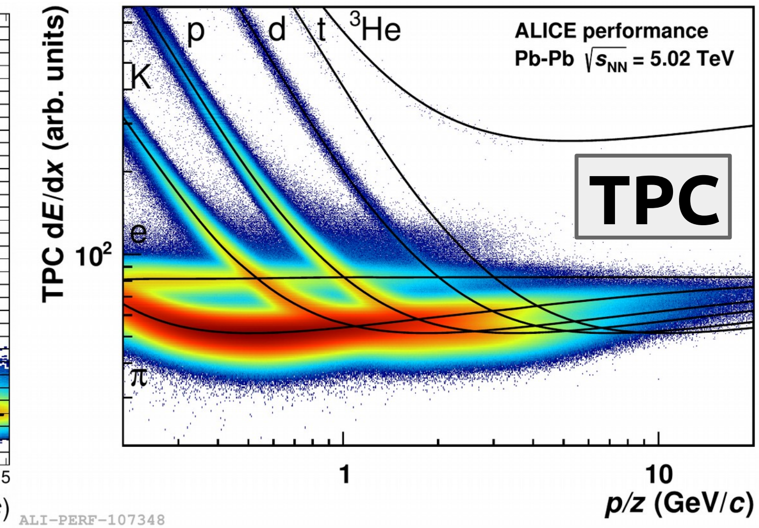
Time Of Flight (TOF)

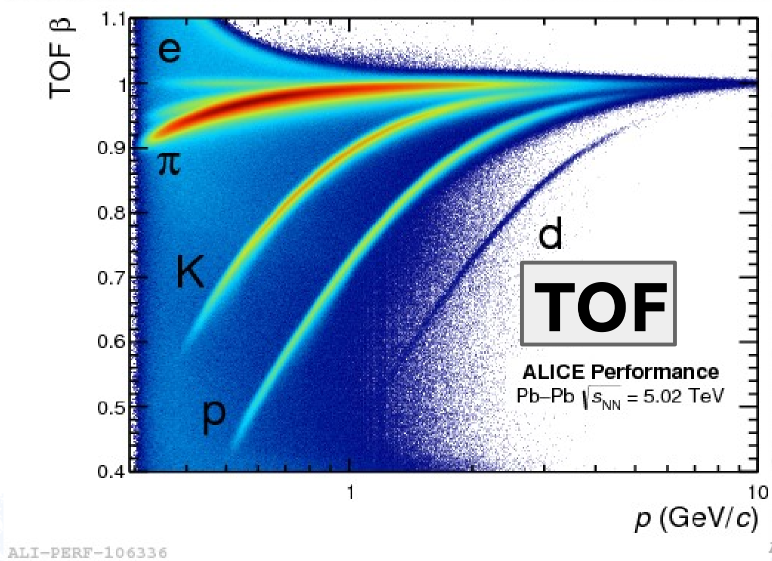
- Time-of-flight measurement
- σ_{TOF} ~ 60 ps

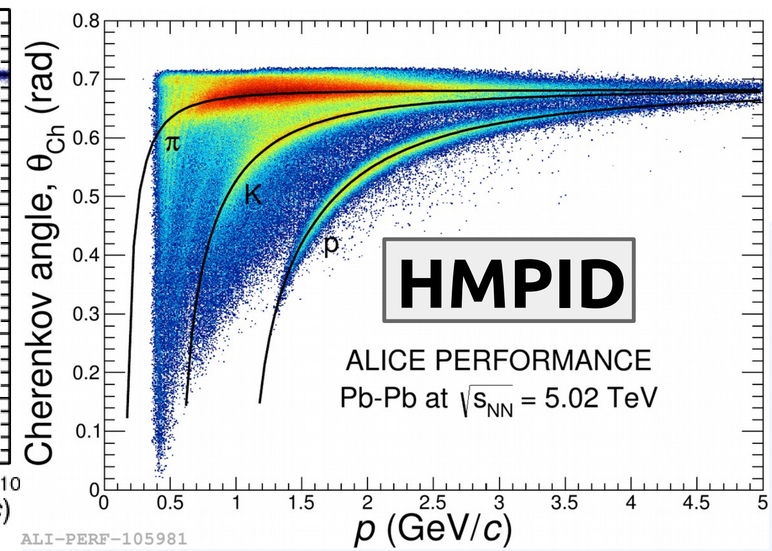
High Momentum Particle IDentification (HMPID)

- Cherenkov angle measurement



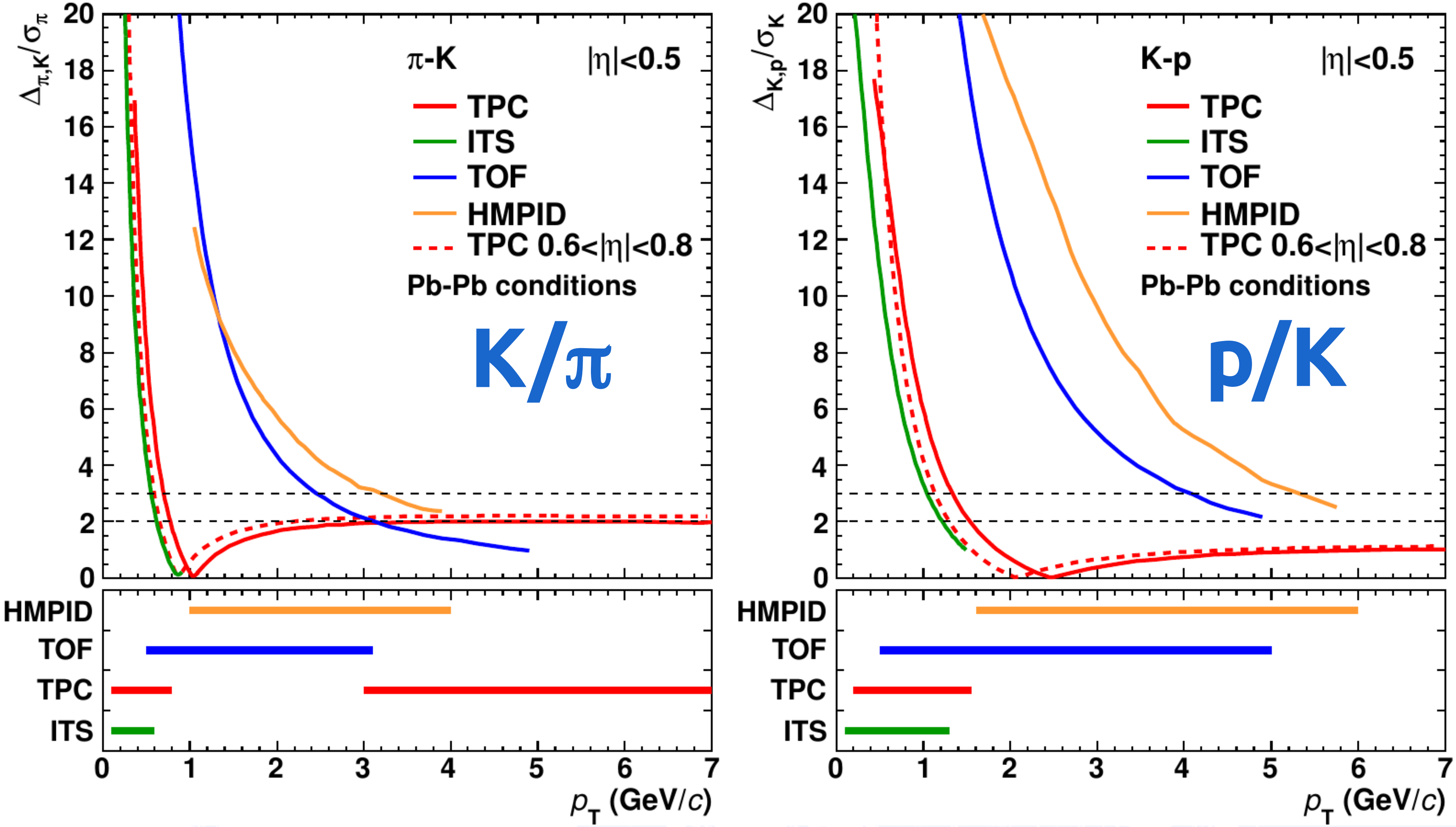






Excellent signal separation for pions, kaons, protons in the mid-rapidity region

Particle identification with ALICE



A continuous K/π and p/K separation is possible by combining the information of **ITS**, **TPC**, **TOF**, **HMPID** over different p_T intervals

Run1 and Run2 are now over!

- ALICE recorded collisions with all the systems available at the LHC, data taking will resume with the start of Run3!

Run 1 (2009-2013)	Run 2 (2015-2018)
pp 0.9, 2.76, 7, 8 TeV	pp 5.02, 13 TeV
p-Pb 5.02	p-Pb 5.02, 8.16 TeV
Pb-Pb 2.76 TeV	Pb-Pb 5.02 TeV Xe-Xe 5.44 TeV

Nucleus-nucleus (AA)

- Deconfinement, QGP formation
- Testing QCD phase diagram
- Particle production ruled by thermodynamics and collectivity

Proton-nucleus (pA)

- Control experiment for AA
- Used to disentangle cold/hot nuclear matter effects
- Surprising features in high-multiplicity events

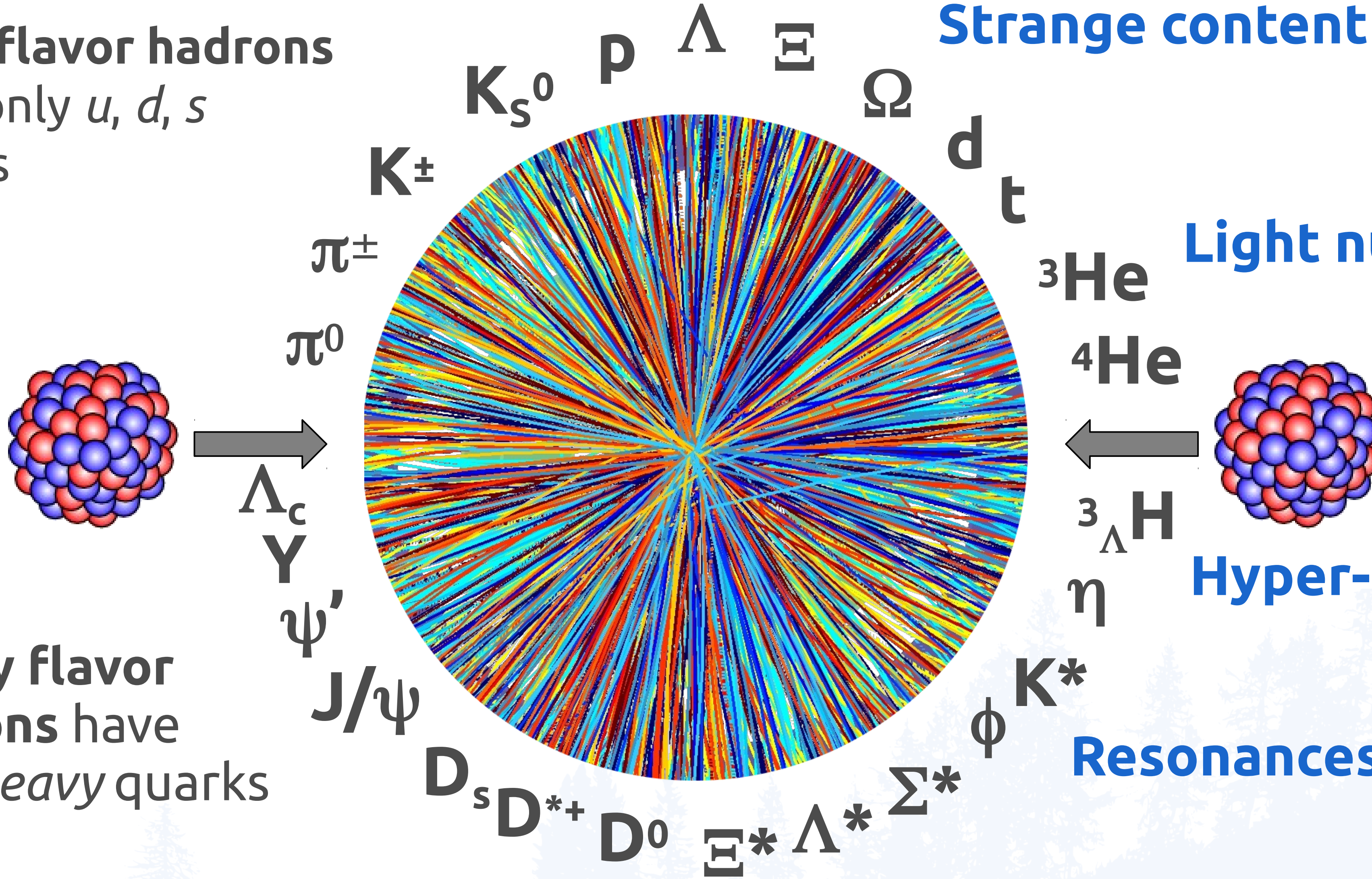
Proton-proton (pp)

- Baseline for both pA and AA collisions
- Similarities to AA in high-multiplicity event

Whole-lotta particles to measure

Light flavor hadrons have only *u*, *d*, *s* quarks

Heavy flavor hadrons have also *heavy* quarks

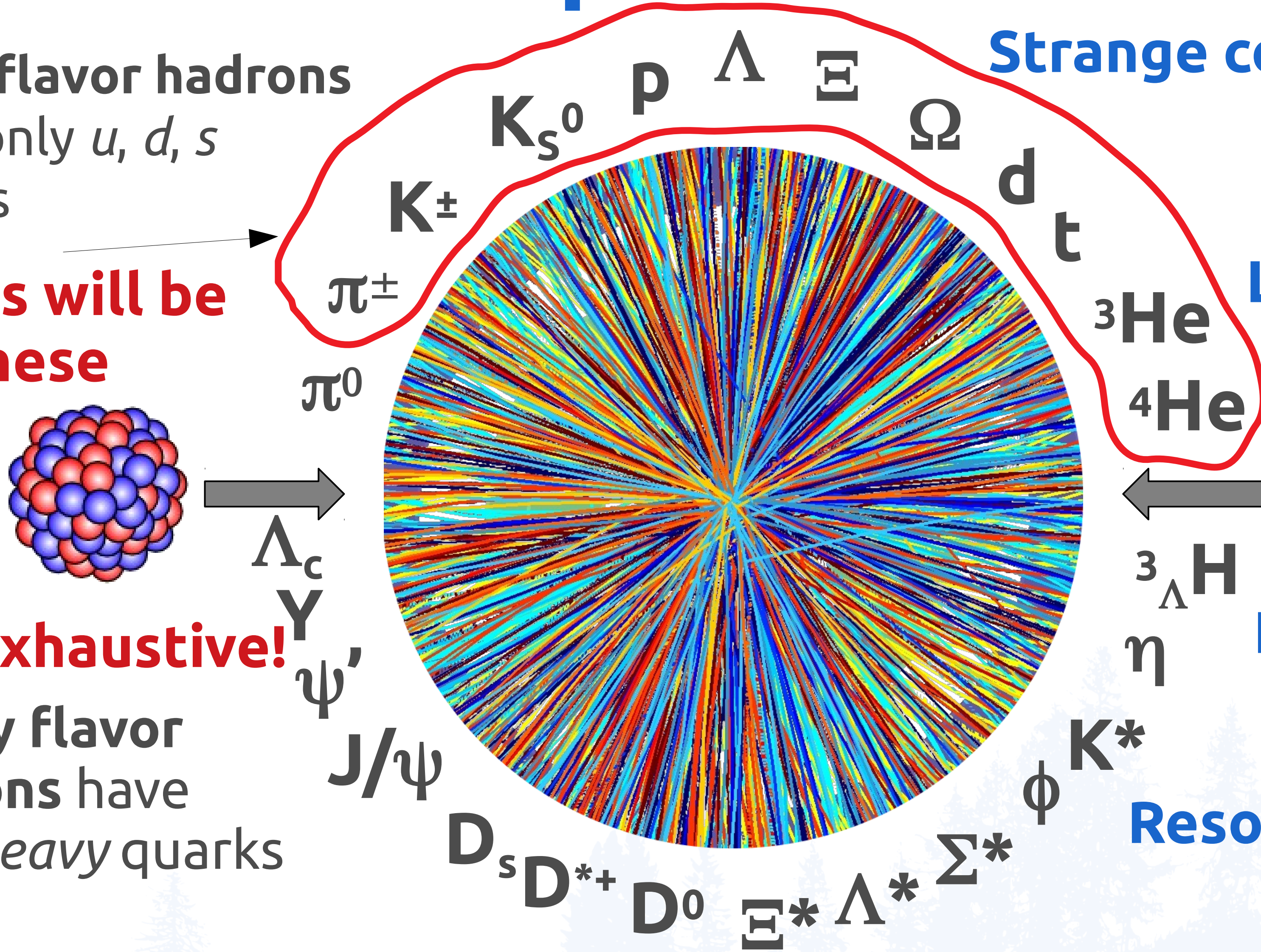


– All measured by ALICE in several collision systems (pp, p-Pb, Pb-Pb, Xe-Xe) and energies

Whole-lotta particles to measure

Light flavor hadrons have only *u*, *d*, *s* quarks

Focus will be on these



Strange content

Light nuclei

Hyper-nuclei

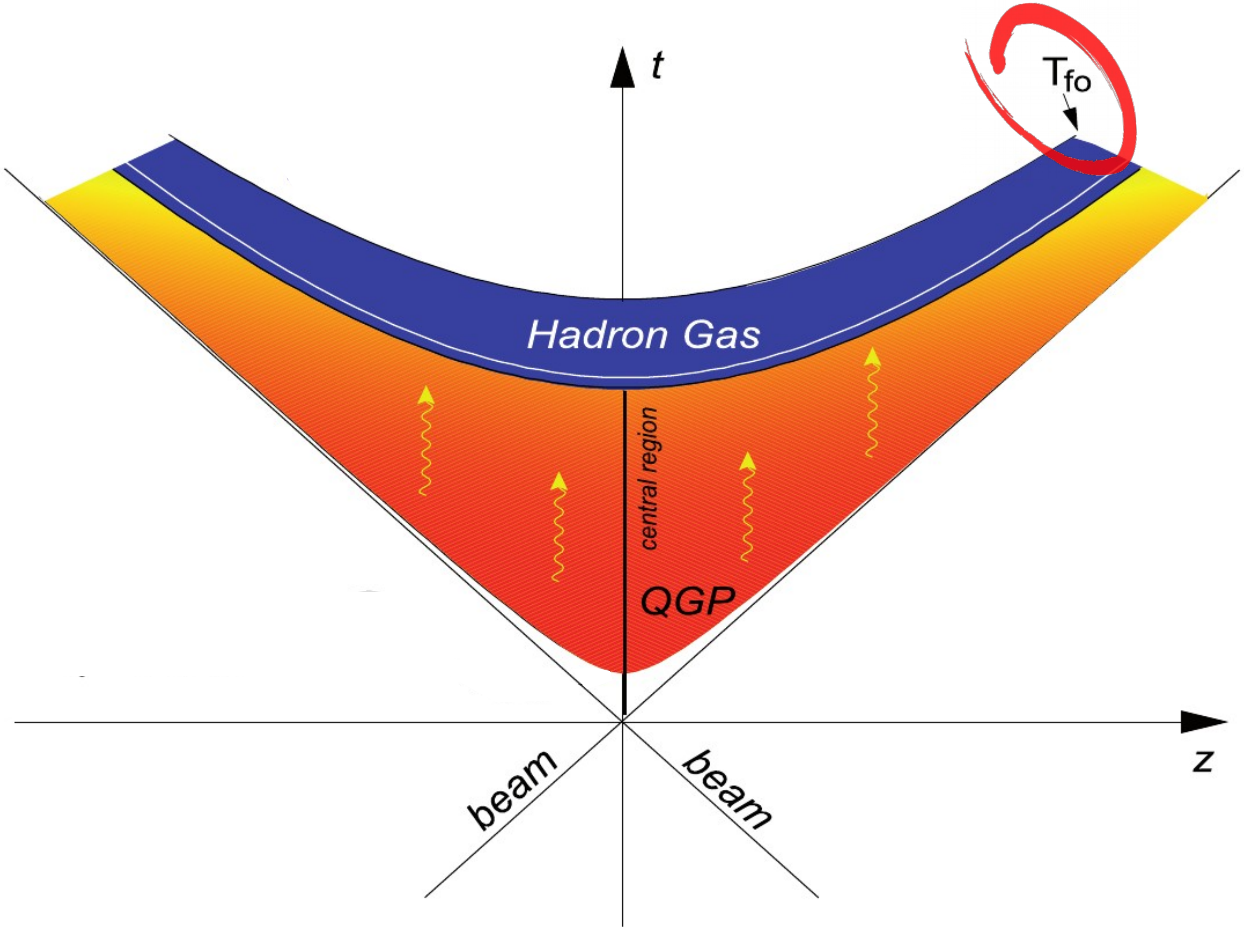
Resonances

Not exhaustive!

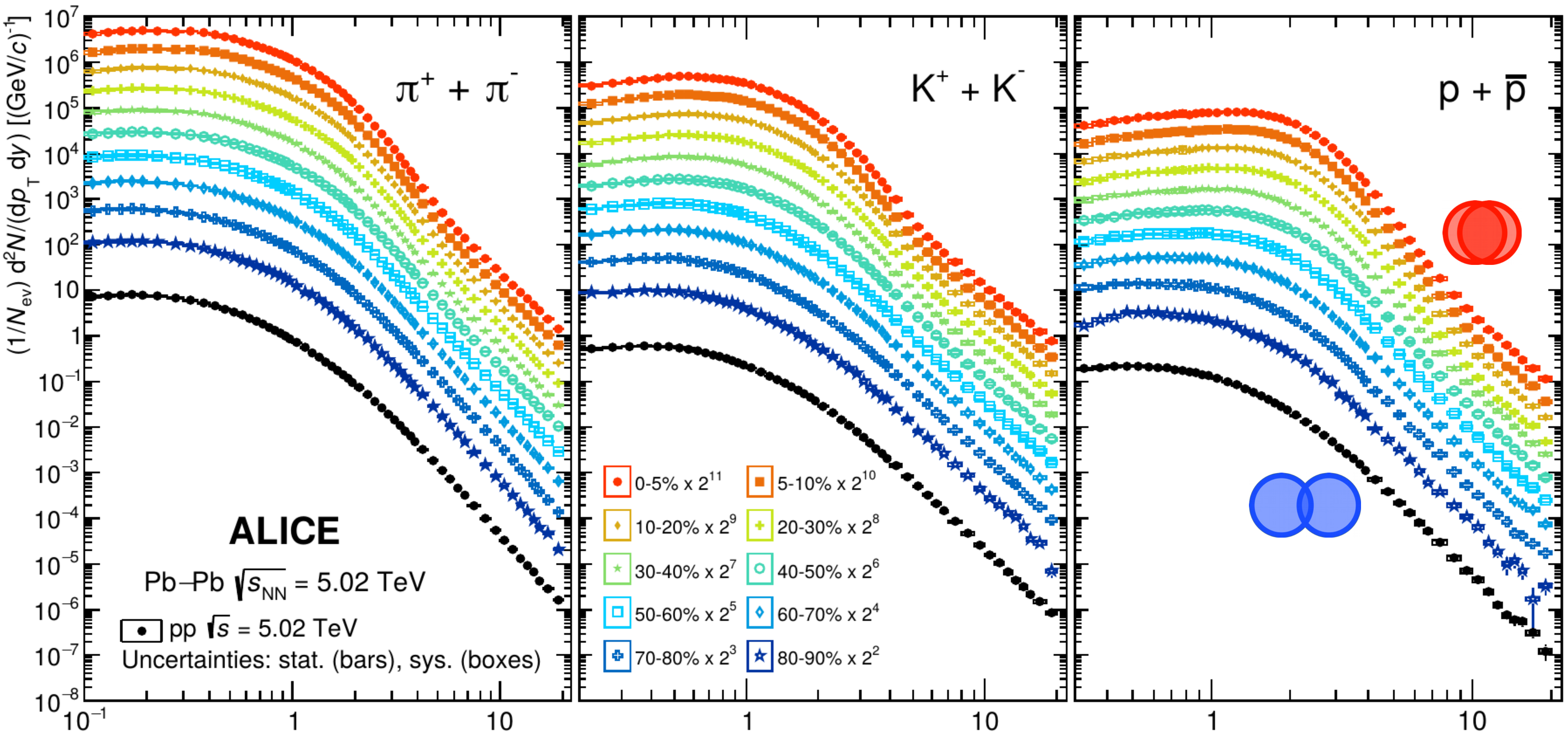
Heavy flavor hadrons have also *heavy* quarks

– All measured by ALICE in several collision systems (pp, p-Pb, Pb-Pb, Xe-Xe) and energies

Measuring the system at the kinetic freeze-out



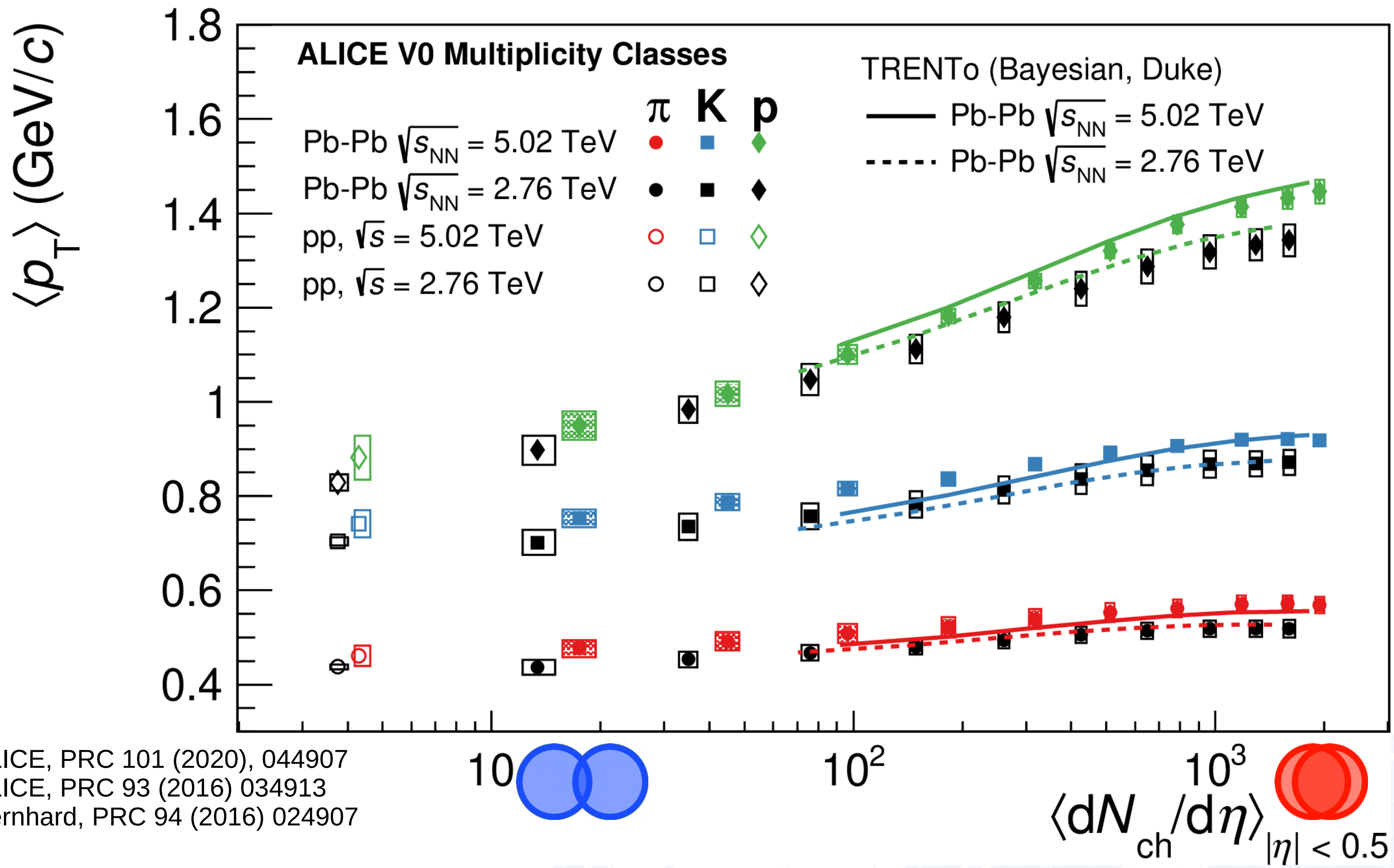
π/K/p in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



ALICE, PRC 101 (2020), 044907

- **Mass-dependent hardening** of the soft part with increasing centrality due to the **collective expansion (*radial flow*)**
- **Depletion at low p_T and enhancement at intermediate p_T**

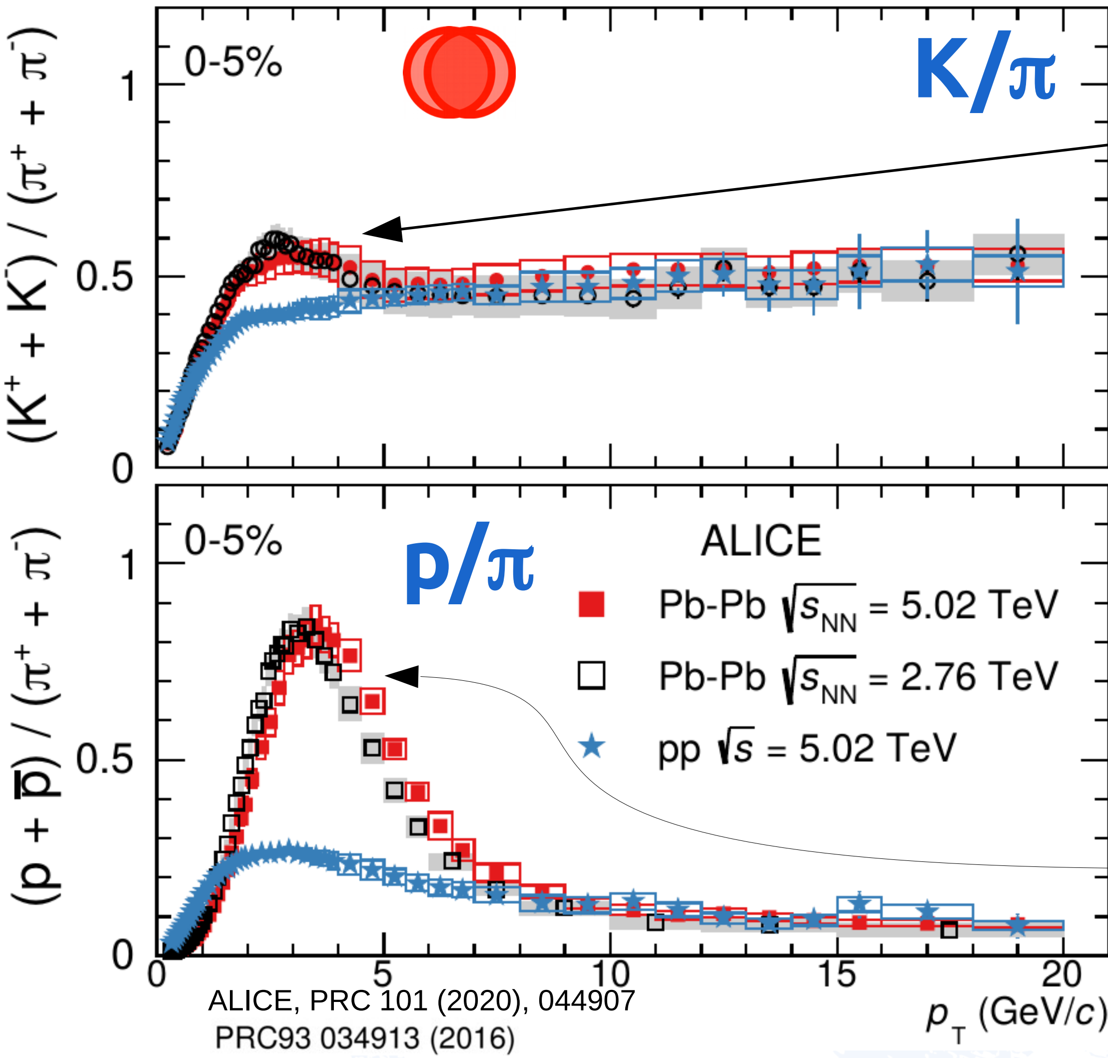
Average transverse momentum



ALICE, PRC 101 (2020), 044907
ALICE, PRC 93 (2016) 034913
Bernhard, PRC 94 (2016) 024907

- **Higher $\langle p_T \rangle$ at higher energies** (both pp and PbPb)
- Predictions based on QGP parameters extracted at 2.76 TeV with a bayesian analysis of heavy-ion measurements is able to reproduce the increase with multiplicity

Spectra ratios: central

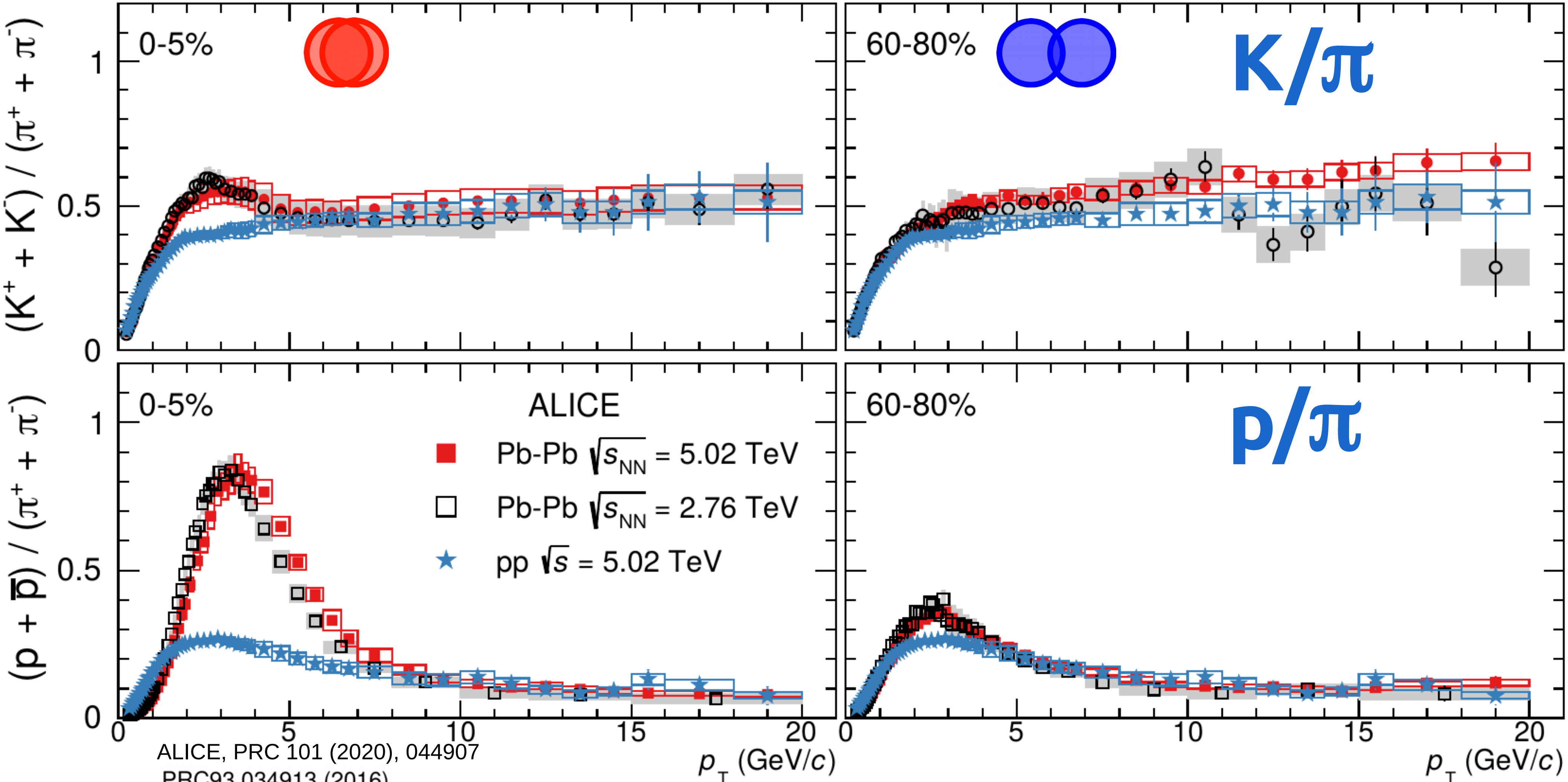


Saturation of the ratio for $p_T > 2$ GeV/c

Peak at $\sqrt{s_{NN}}$ =5.02 TeV shifted at higher p_T w.r.t. 2.76 TeV (larger radial flow)

- **Peak at 2-4 GeV/*c* due to radial flow**
- **No significant change at different $\sqrt{s_{NN}}$ (2.76 and 5.02 TeV)**
- No large peak in pp collisions

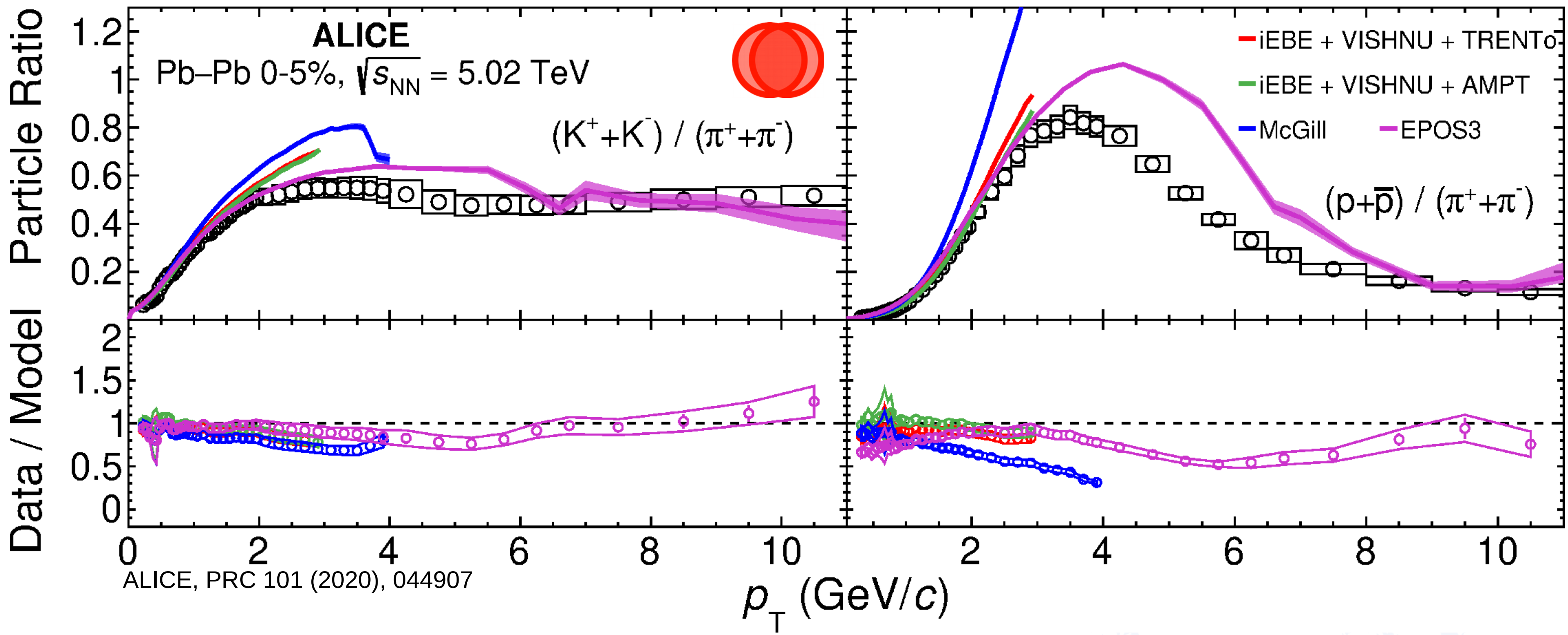
Spectra ratios: peripheral



ALICE, PRC 101 (2020), 044907
PRC93 034913 (2016)

- **Peak at 2-4 GeV/*c* due to radial flow**
- **No significant change at different $\sqrt{s_{NN}}$ (2.76 and 5.02 TeV)**
- Peripheral collision are more similar to pp collisions

Spectra ratios: model comparison

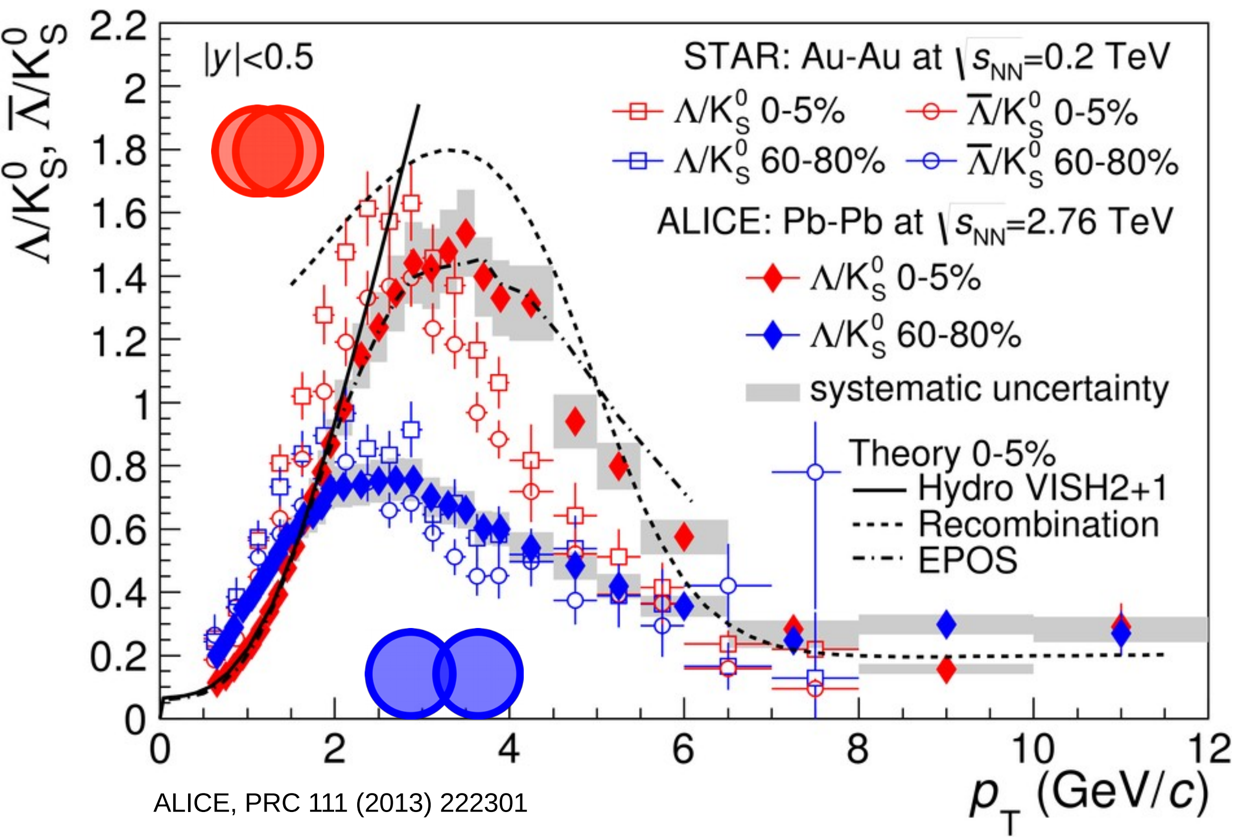


iEBE-VISHNU: Viscous hydrodynamics (QGP expansion) + Hadron cascade model (UrQMD) to simulate the evolution of the hadron resonance gas - Phys.Rev. C92, 014903 (2015) & 011901(R) (2015)

EPOS: Non uniform fireball divided in the core (high density) and corona (lower density) - Phys. Rev. C89 no. 6, (2014) 064903

McGill: IP-Glasma initial condition matched to hydrodynamic variables and evolved using viscous hydrodynamic model (MUSIC) - Phys. Rev. C 95, 064913 (2017)

Spectra ratios: Λ/K_s^0

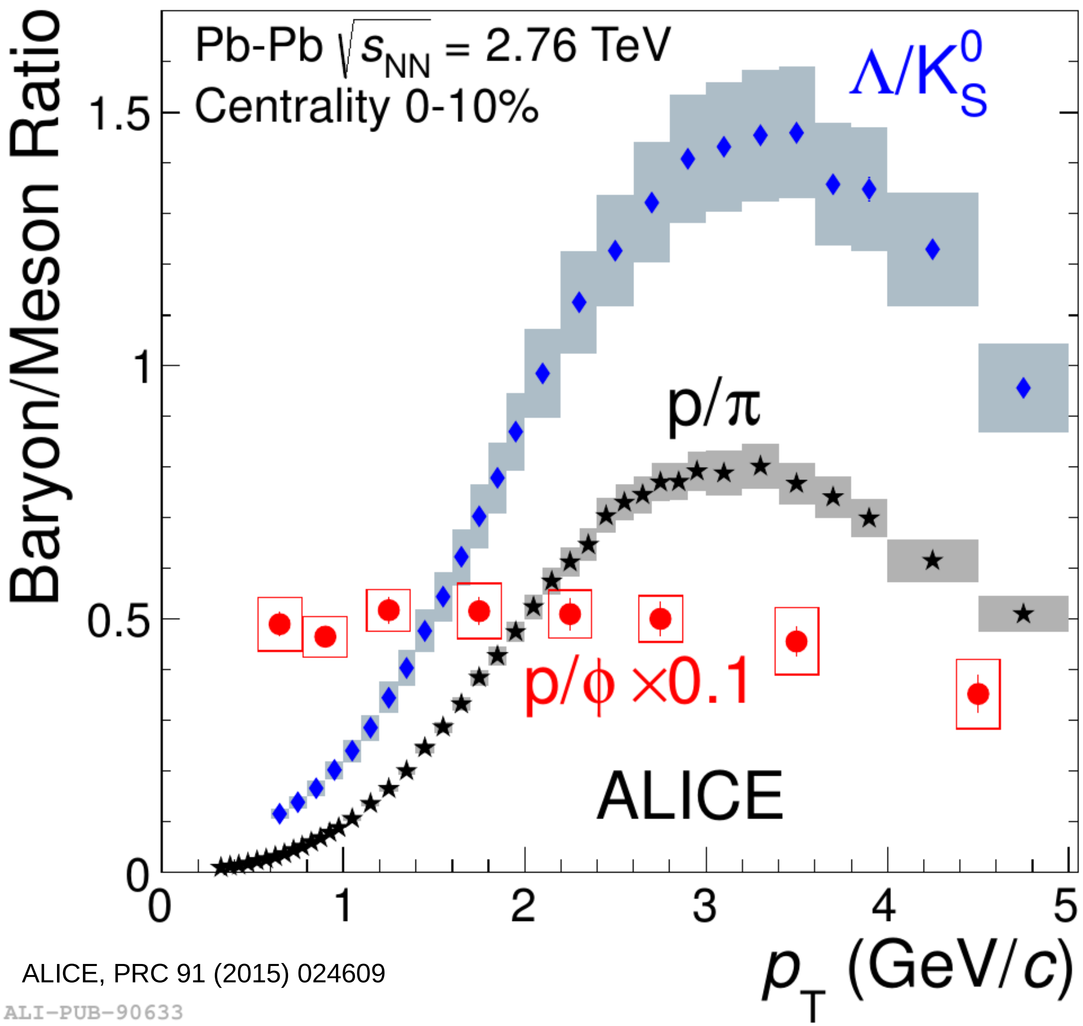


ALICE, PRC 111 (2013) 222301

- **Hydro:** good agreement with the deta for p_T < 2 GeV/c, deviations for higher p_T
  - Song, PLB 658 (2008) 279
- **Recombination:** reproducing only approximately the shape
  - Fries, Ann.Rev.Nucl.Part.Sci. 58 (2008) 177
- **EPOS:** overall good description of the data
  - Werner, PRL 109 (2012) 102301

- **Peak at 2-4 GeV/*c* due to radial flow also present for other particles**
- **Stronger radial flow at higher energies**
- **Same centrality dependence**

Spectra ratios: p/ϕ vs p/π



Using baryons and mesons with similar mass allows us to test if the enhancement is due to mass or quark content

- **Baryon**: proton
  m_p = 938 MeV/c^2
- **Meson**: ϕ
  m_ϕ = 1018 MeV/c^2
- Similar masses, different constituent quarks

- **Scaling p/ϕ → enhancement due to mass difference!**

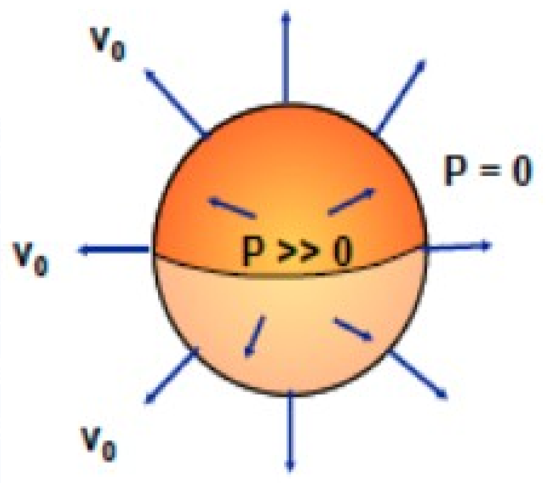
Blast-Wave model

- The Blast-Wave model describes the particle distribution at the kinetic freeze-out as a result of the expansion of a thermalized source
- The Boltzmann-Gibbs statistics is used as an initial thermal distribution
- The expanding source causes a mass dependent hardening
- The expansion velocity and decoupling temperature are free parameters of the model

$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{Kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{Kin}}\right) r\,dr$$

$$m_T = \sqrt{m^2 + p_T^2} \qquad \rho = \tanh^{-1}(\beta_T) \qquad \beta_T = \beta_s \left(\frac{r}{R}\right)^n$$

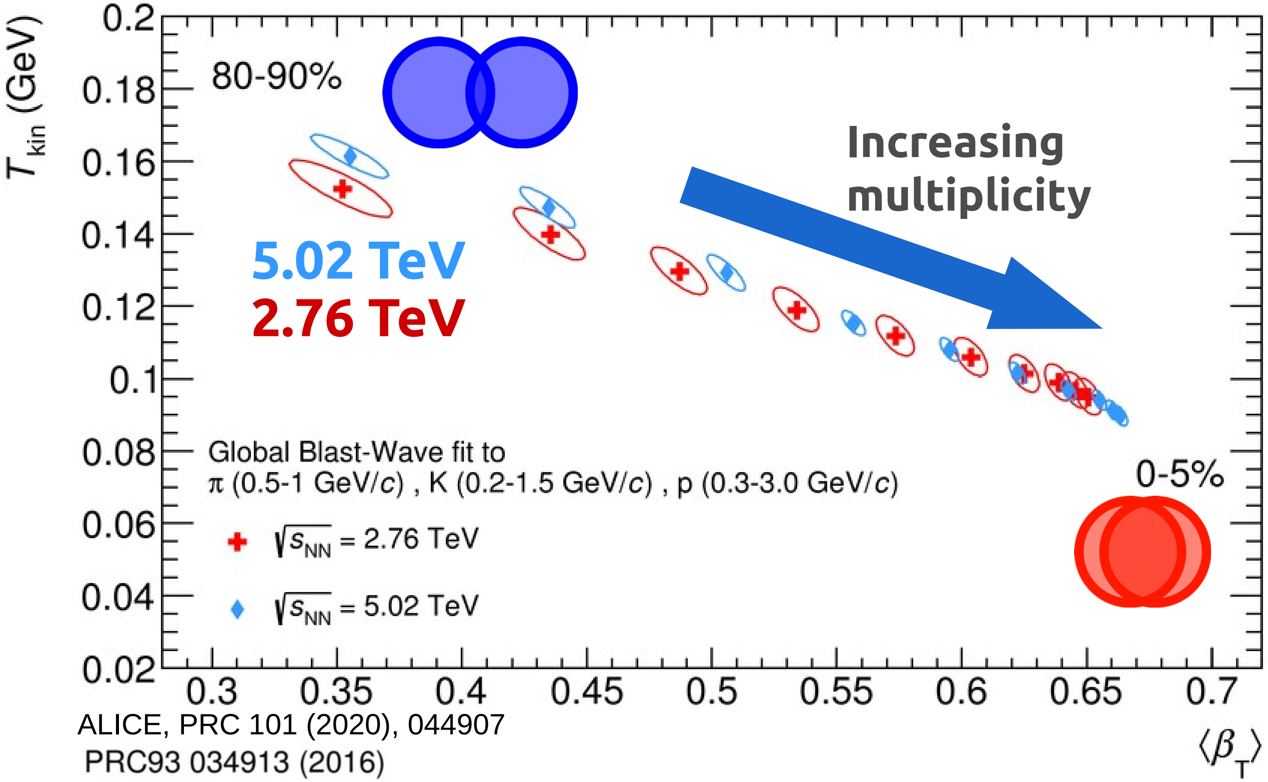
Schnedermann, Sollfrank and Heinz Phys. Rev. C 48, 2462



» β_T → radial expansion velocity

» T_{Kin} → kinetic freeze-out

Blast-Wave model: β_T vs T_{kin}



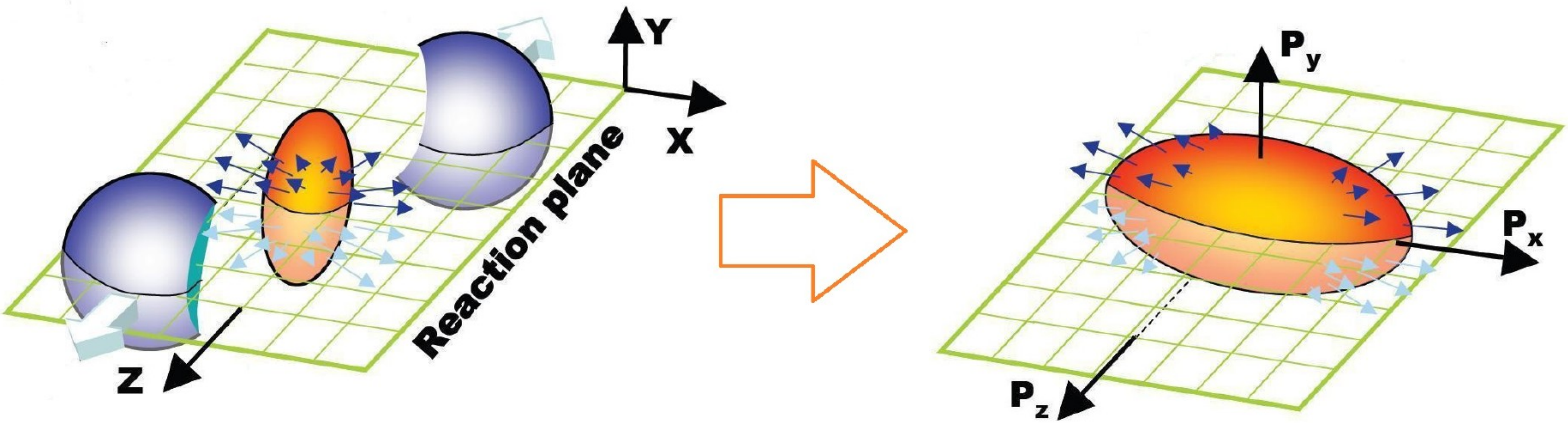
ALICE, PRC 101 (2020), 044907
PRC93 034913 (2016)

- The free parameters of the BW model are obtained with a simultaneous fit to the π, K, p p_T-distributions

- Central collisions exhibit the lowest kinetic freeze-out temperature (~85 MeV)
- The temperature decreases with increasing collision energy
- Longer lived system?

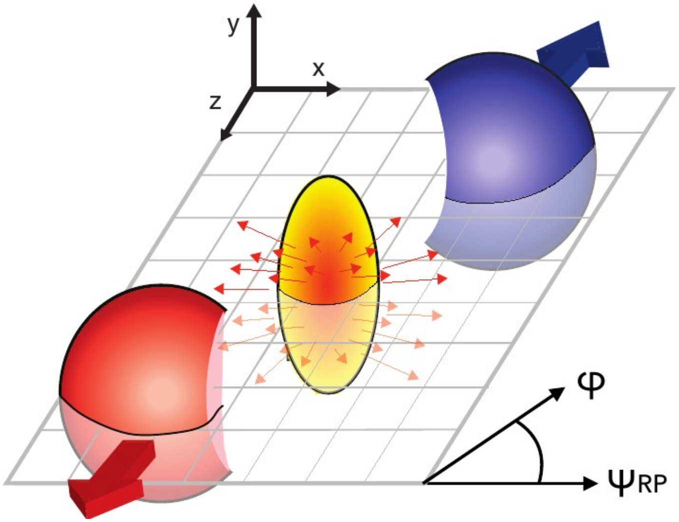
- The maximum expansion velocity is reached in the most central collisions
- The expansion velocity slightly increases with the collision energy

Collective flow: anisotropies



- Particle production in heavy-ion collisions can be described by hydro models
- Initial hot and dense partonic matter rapidly expands with common velocities (collective flow) as the system cools down
- Dependence of the shape of the p_T distribution on the particle mass
- Non-spherical strongly interacting systems convert spatial anisotropies to momentum anisotropies: azimuthal anisotropic flow patterns

Anisotropic flow coefficients

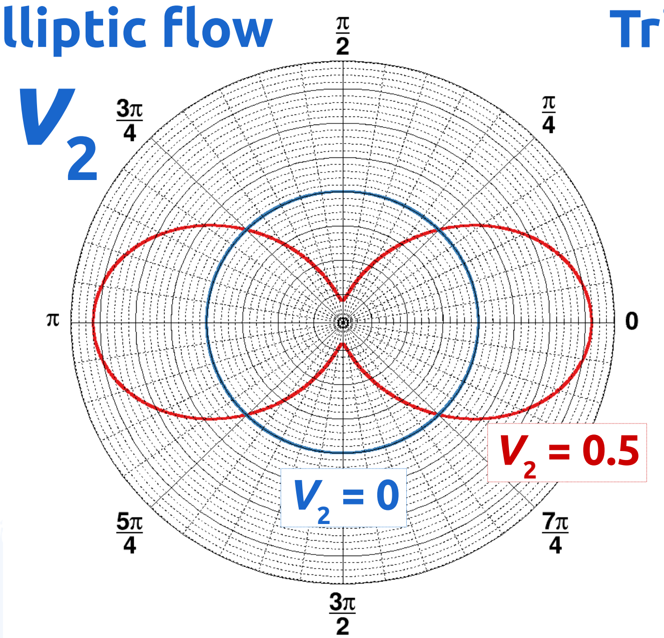


- Non-spherical strongly interacting systems convert spatial anisotropies to momentum anisotropies → **anisotropic flow**
- Quantified with Fourier coefficients

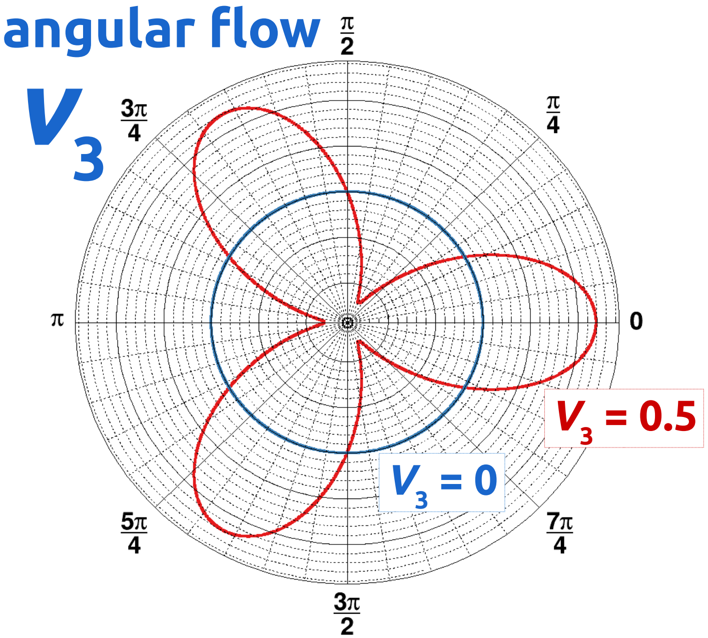
$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+2\sum_{n=1}^{\infty}v_n\cos\left[\left(\varphi-\Psi_n\right)\right]\right)$$

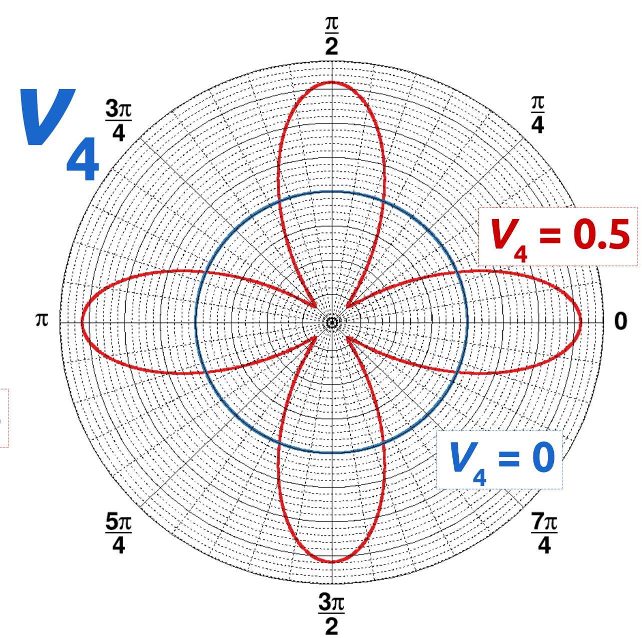
$$v_n(p_T,y)=\left\langle\cos\left[n\left(\varphi-\Psi_n\right)\right]\right\rangle$$

Elliptic flow



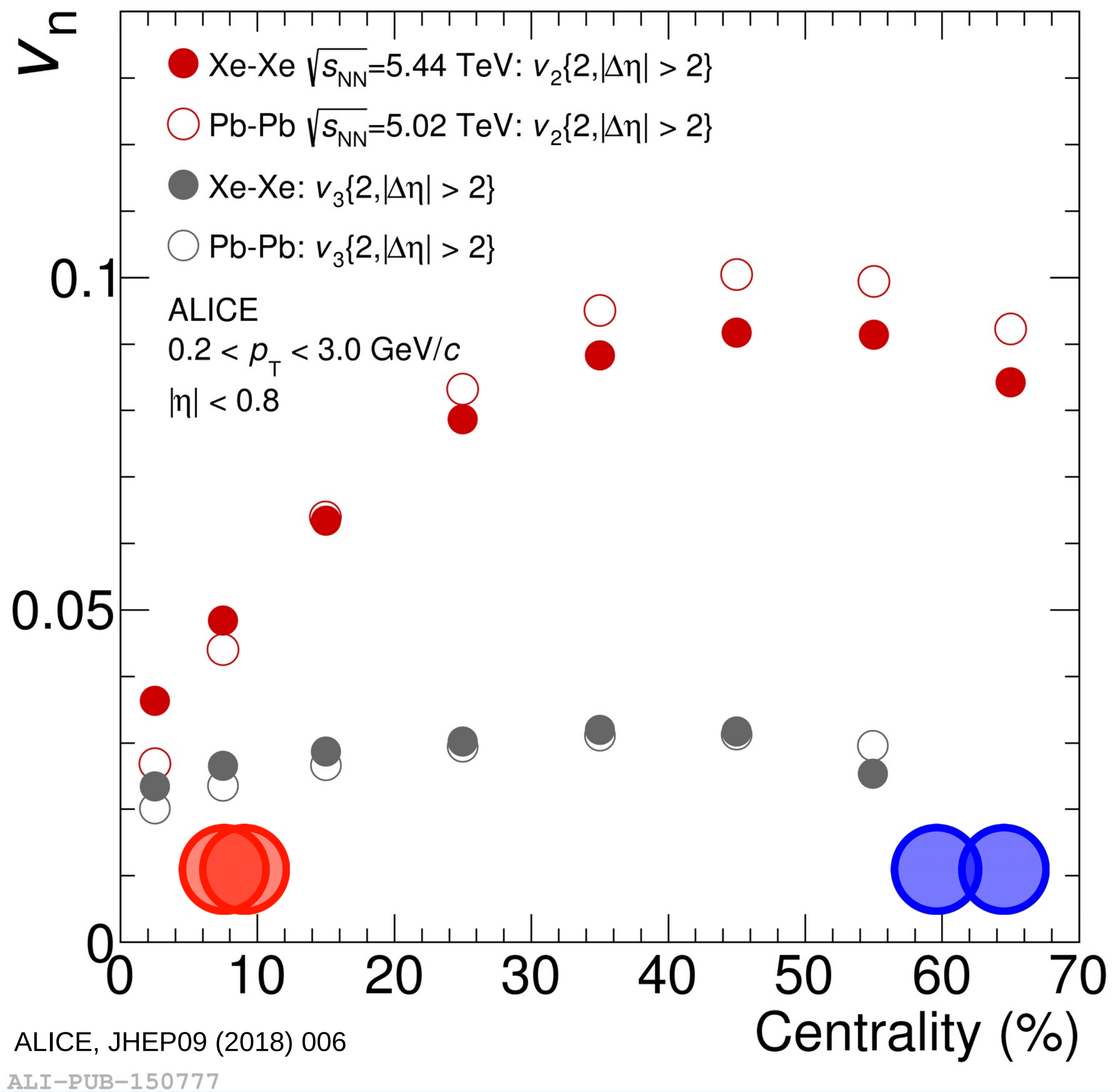
Triangular flow



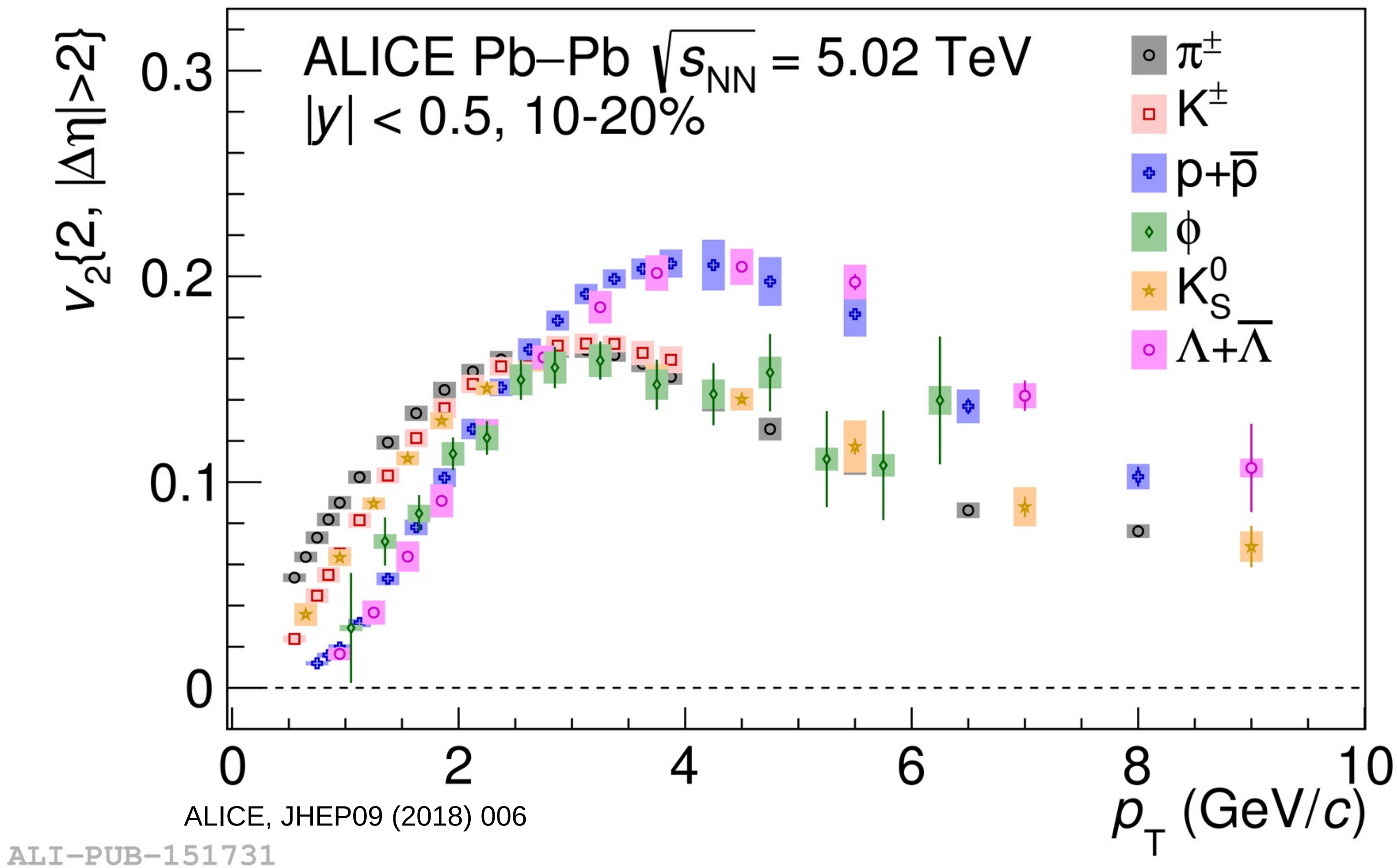


v_2 and v_3 across different systems

- The anisotropic flow in heavy-ion collisions at the LHC depends only weakly on the size of the collision system (Pb-Pb vs Xe-Xe)
- Centrality dependence of v_2 and v_3 shows similar trends in both Pb-Pb and Xe-Xe collisions (different charged particle multiplicities)
- Increase in v_2 is larger than for v_3



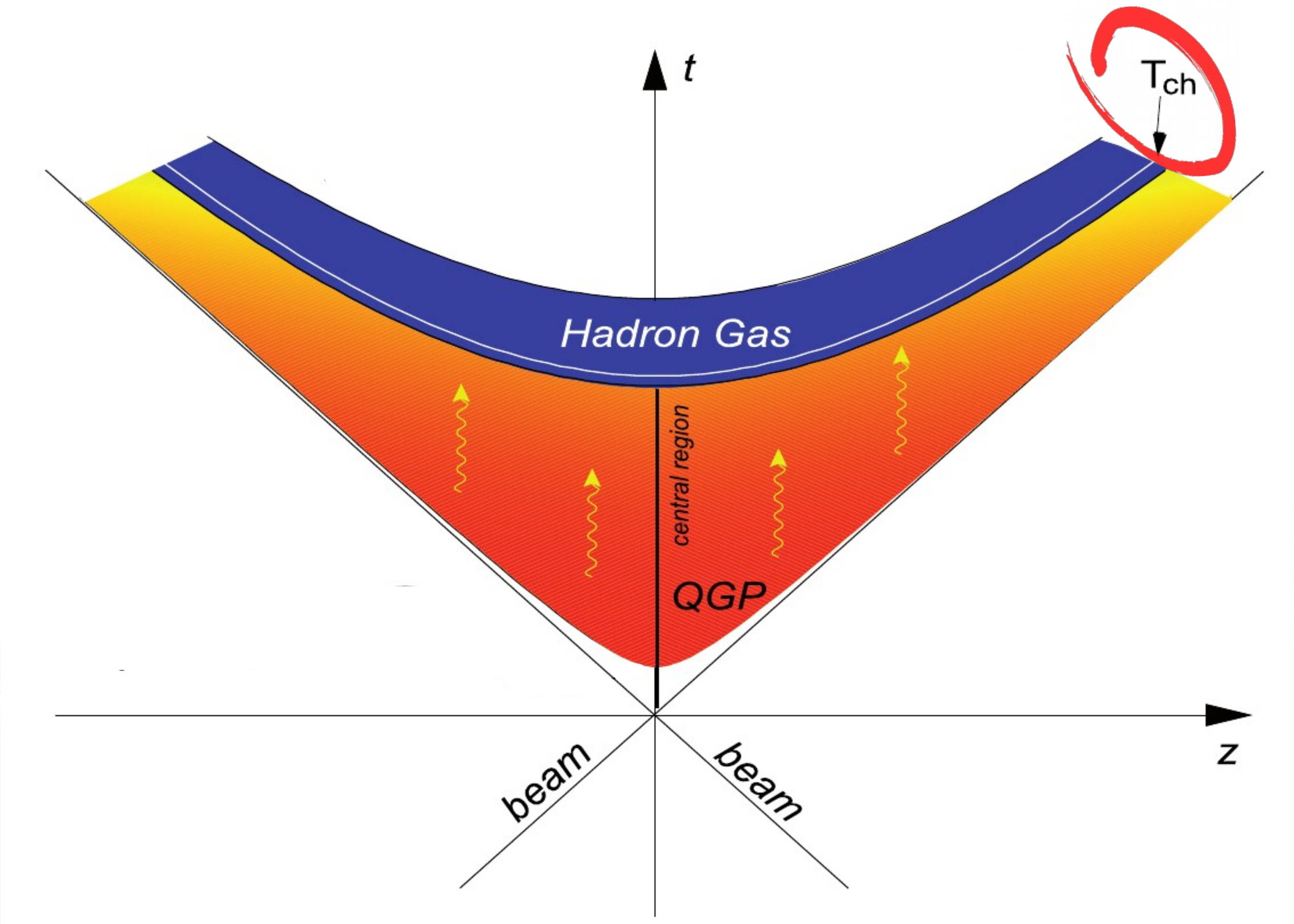
Identified particle v_2



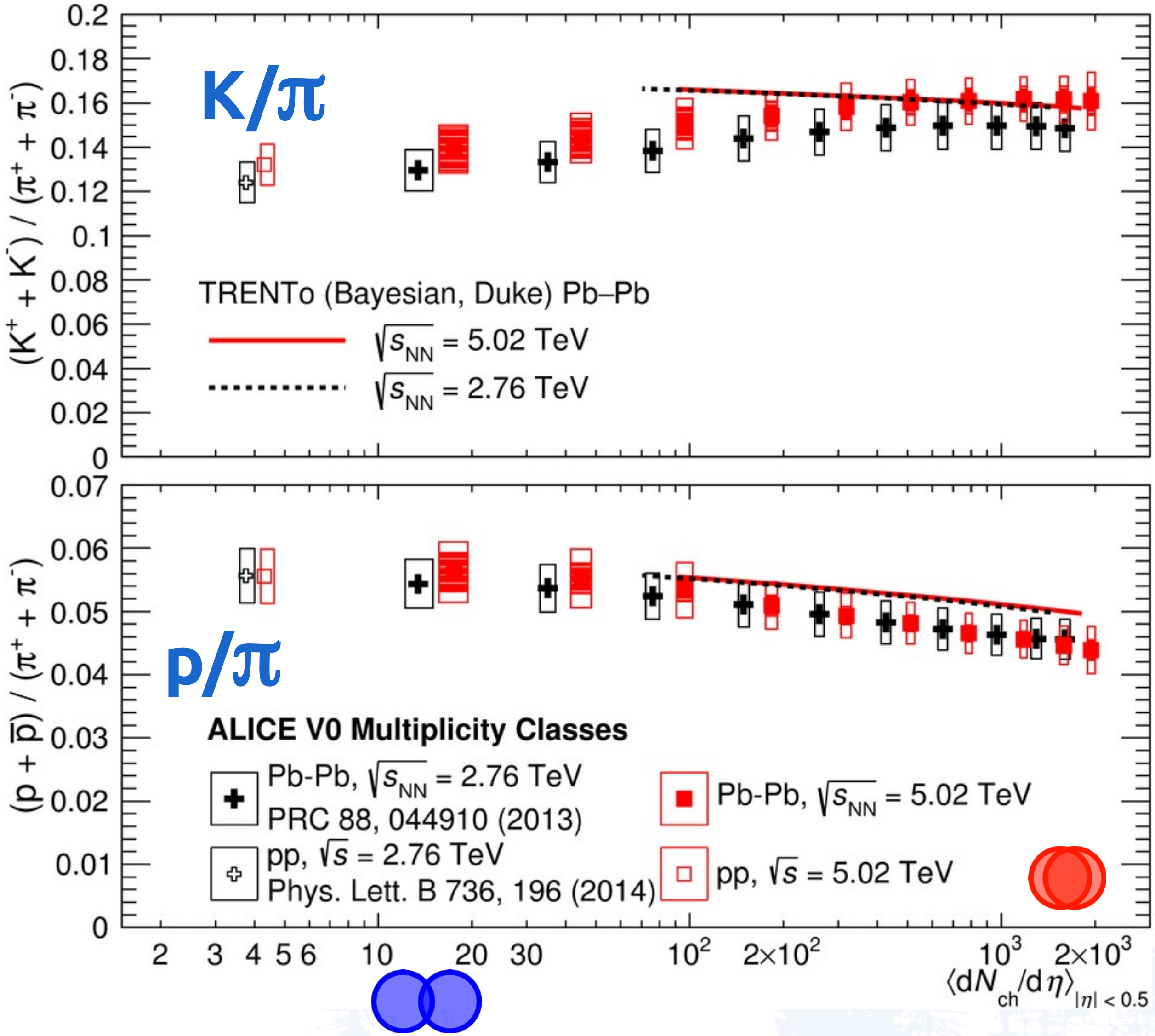
ϕ follows **mass ordering** at low p_T (proton v_2) and **quark content** at intermediate p_T

- p_T < 2 GeV/c → **mass ordering** indicative of radial flow
- p_T ~2.5 GeV/c → crossing between v_2 of baryons and mesons
- p_T > 3 GeV/c → v_2 baryons > v_2 mesons up to p_T ≈ 10 GeV/c **quark content scaling**

Measuring the system at the chemical freeze-out



Ratios of p_T-integrated particle yields



ALICE, PRC 101 (2020), 044907
Bernhard, PRC 94 (2016) 024907

- K/π increases as a function of multiplicity while p/π shows a moderate decrease in Pb-Pb collisions (baryon annihilation in hadronic phase?)
- K/π and p/π measured in **peripheral Pb–Pb collisions are consistent with the pp values**
- **No significant energy dependence is observed** for p/π and K/π
- **Bayesian model describes the trend**

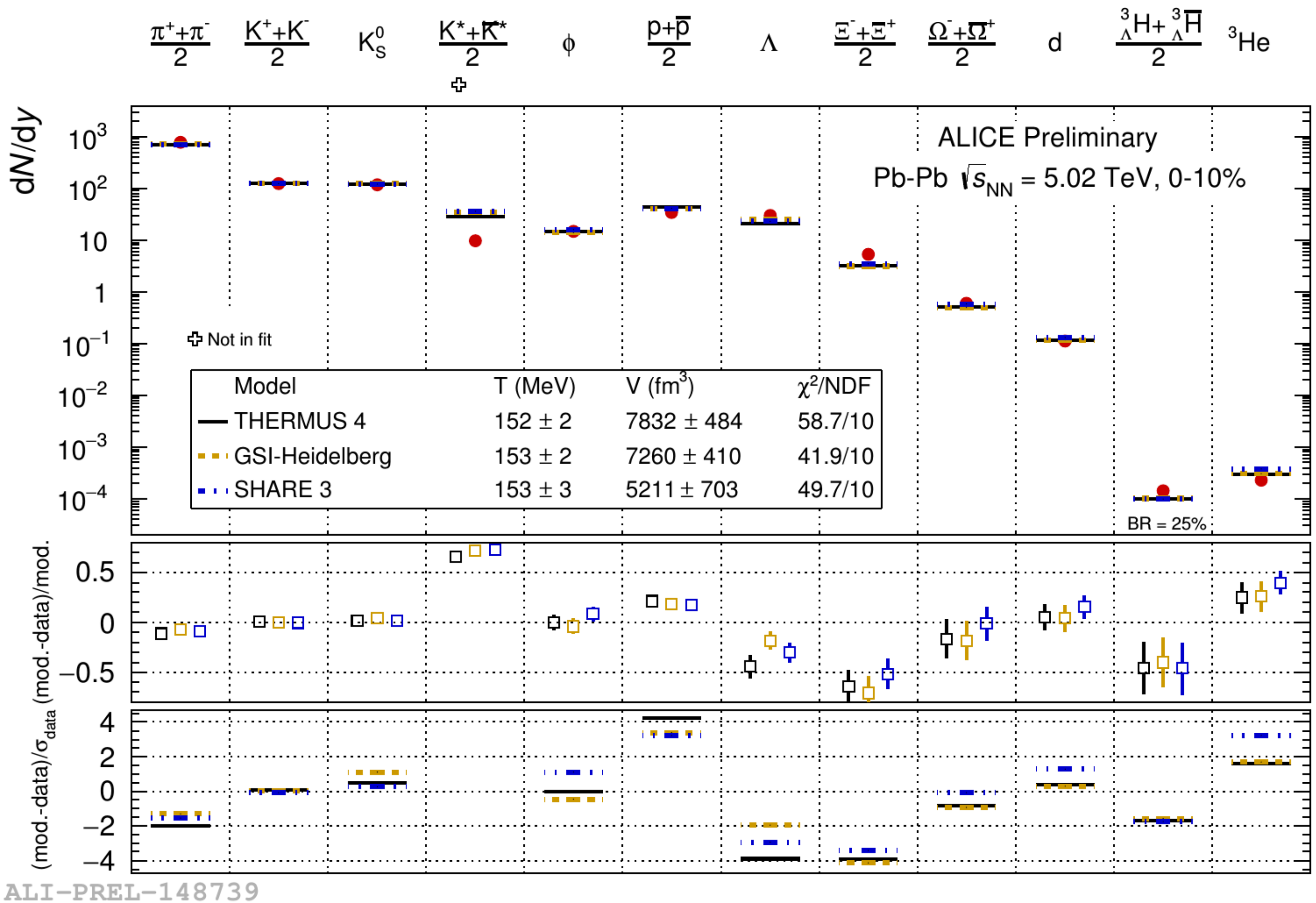
Thermal model

- At the chemical freeze-out, the system (hadron resonance gas) is in thermal and chemical equilibrium
- The particle abundances in a thermalized medium can be derived as a function of its thermodynamic properties (temperature and volume) by writing the system's partition function
- In heavy-ion collisions the grand-canonical ensemble is used

$$\ln Z^{GC}(T, V, \{\mu_i\}) = \sum_{\text{species } i} \frac{g_i V}{(2\pi)^3} \int d^3p \ln\left(1 \pm e^{-\beta(E_i - \mu_i)}\right)^{\pm 1} \Rightarrow N_i^{GC} = T \frac{\partial \ln Z^{GC}}{\partial \mu_i}$$

- The quantum number conservation (baryon number, strangess, electric charge) in the reaction is ensured by chemical potential $\boldsymbol{\mu}_i$ that can be fixed from the quantum number of the initial stage

Thermal model



- A single chemical freeze-out temperature for all particle species (common source)

- The chemical freeze-out temperature in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV is **153 ± 2 MeV**
- This value is in close to the critical temperature T_c obtained from lattice QCD→**phase transition is close to chemical freeze-out**

What we learn so far

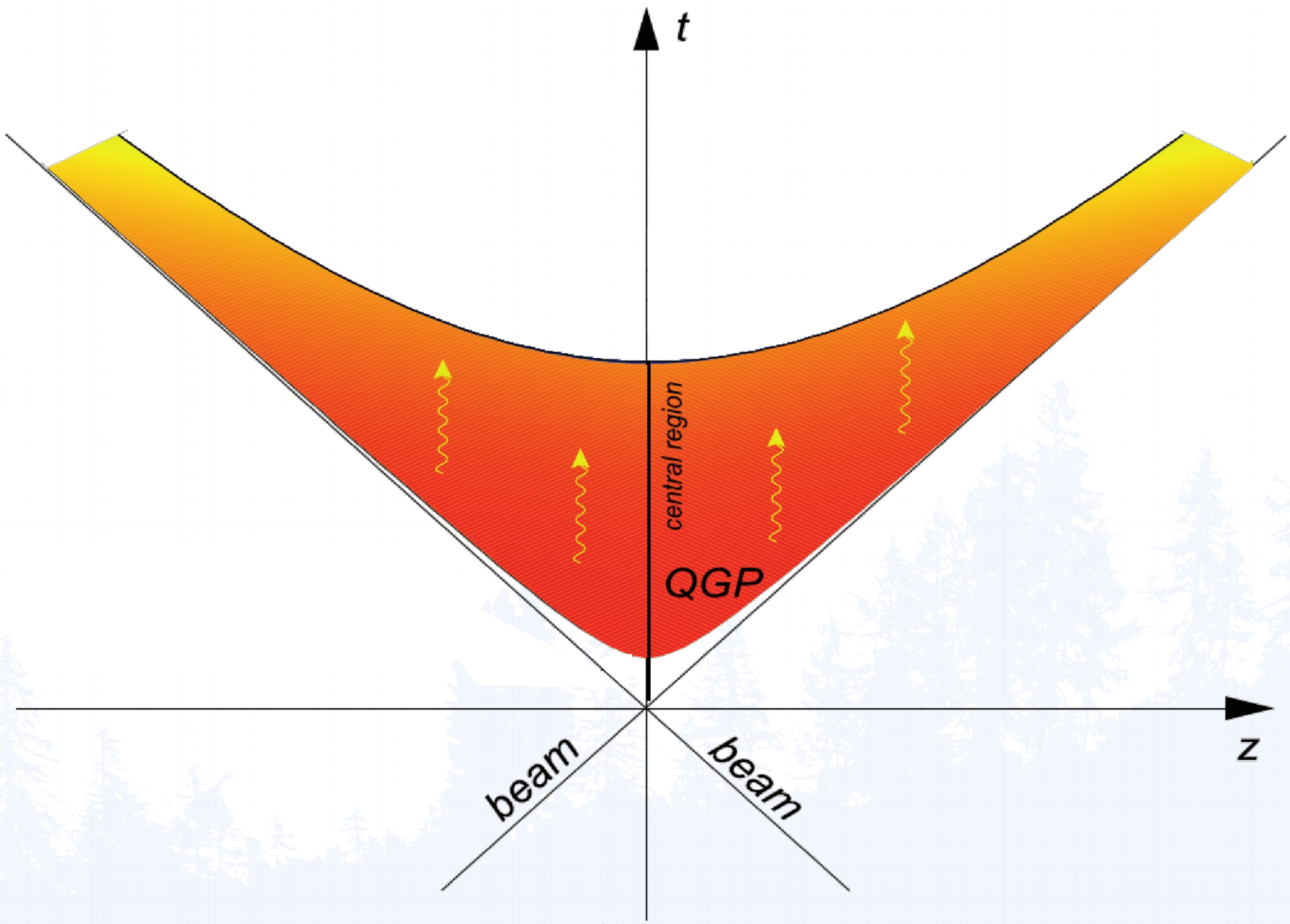
Kinetic freeze-out:

- Significant mass dependent hardening of the particle spectra is observed in central collisions
  - » Radial flow is larger at 5.02 TeV w.r.t. 2.76 TeV
- **Blast-Wave model analysis**
  ⇒ Higher expansion velocity in central collisions at 5.02 TeV w.r.t. 2.76 TeV
  - » Lower decoupling temperature T_{kin} ~85 MeV

Chemical freeze-out:

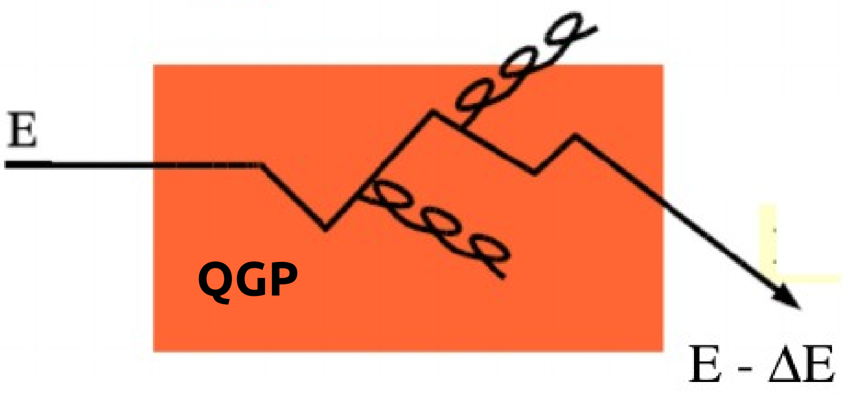
- **Thermal model analysis**
  ⇒ Describes the yield of produced particles with a single freeze-out temperature T_{ch} ~ 153 MeV
  - » Chemical freeze-out is close to phase transition (T_c ~154 MeV)

Investigating the QGP phase



Nuclear modification factor R_{AA}

- Useful information on the QGP can be obtained from hard probes i.e. highly energetic partons produced in hard scatterings



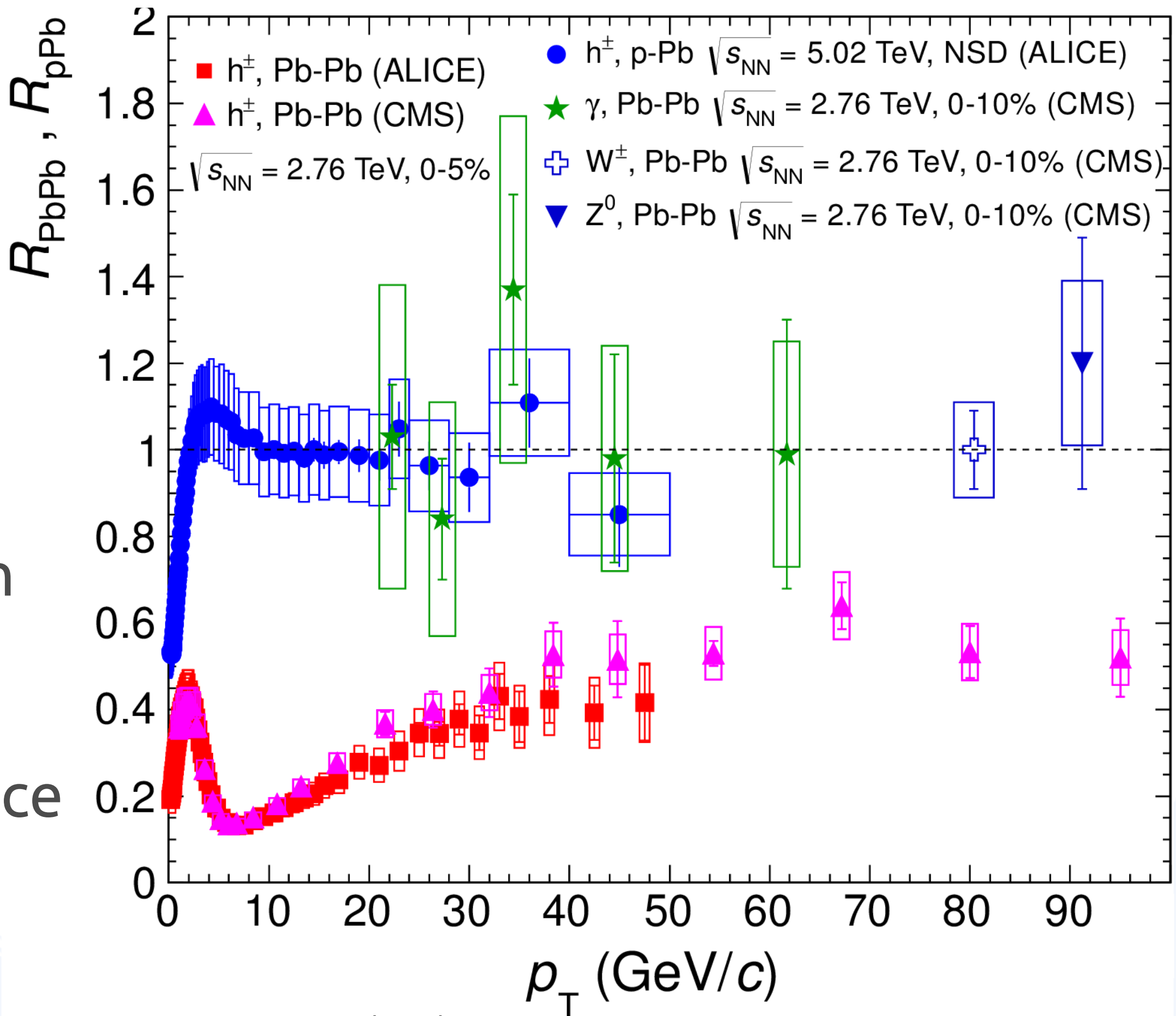
Partonic energy loss in the medium due to **gluon radiation** and **collisions** with the medium partons

$$R_{AA} = \frac{(d^2N/dydp_T)_{AA}}{\langle N_{coll}\rangle\,(d^2N/dydp_T)_{pp}}$$

- No QGP is expected to form in pp collisions
- R_{AA} quantifies the difference between Pb-Pb collisions and the sum of $\langle N_{coll}\rangle$ incoherent collisions i.e. quantifies the effect of the presence of the medium

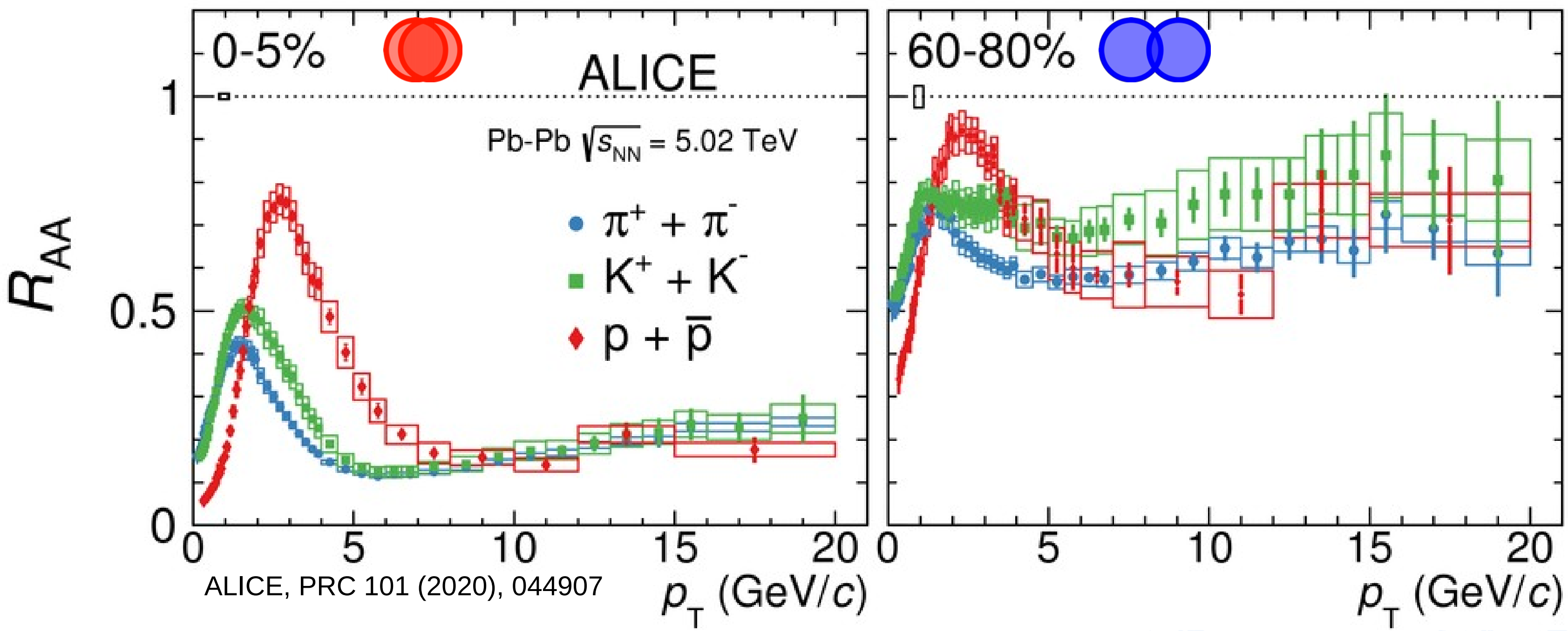
Nuclear modification factor R_{AA}

- **$R_{AA} < 1$:**
  particles are absorbed or lose their energy in a medium opaque to the color charge (QGP)
- **$R_{AA} = 1$:**
  the presence of a dense medium cannot be seen on the produced particles
- Only color charged probes are affected by the presence of the medium
- γ, W and Z bosons are unaffected by the medium as they cannot lose energy via gluon radiation



CMS, PLB 710 (2012) 256
CMS, PLB 715 (2012) 66
CMS, PRL 106 (2011) 212301
ALICE, PRL 110 (2013) 082302
ALICE, PLB 720 (2013) 52-62

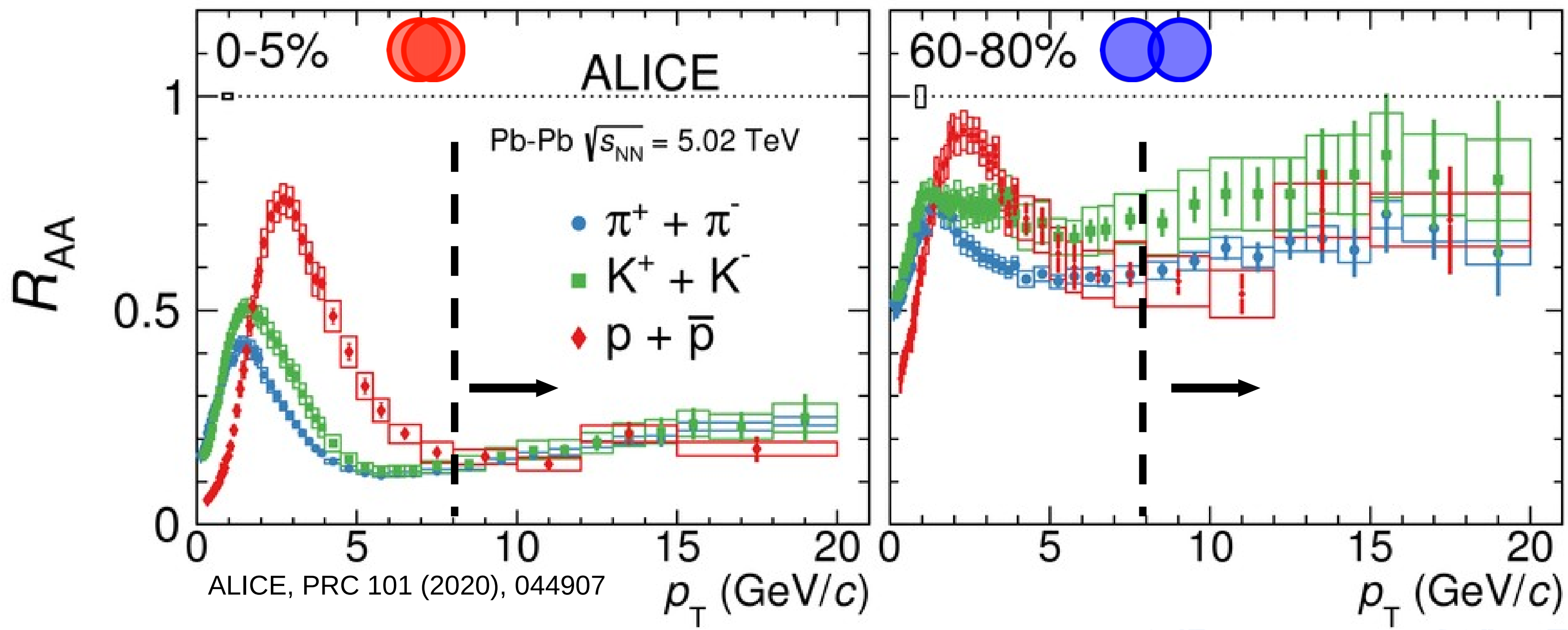
Nuclear modification factor R_{AA}



ALICE, PRC 101 (2020), 044907

- Low momenta partons are created in soft QCD processes and are subject to different effects in pp and Pb-Pb (e.g. collective flow)
- High momenta partons are created in hard scatterings (perturbative QCD) at the early stage of the collision and should scale with $<N_{coll}>$

Nuclear modification factor R_{AA}



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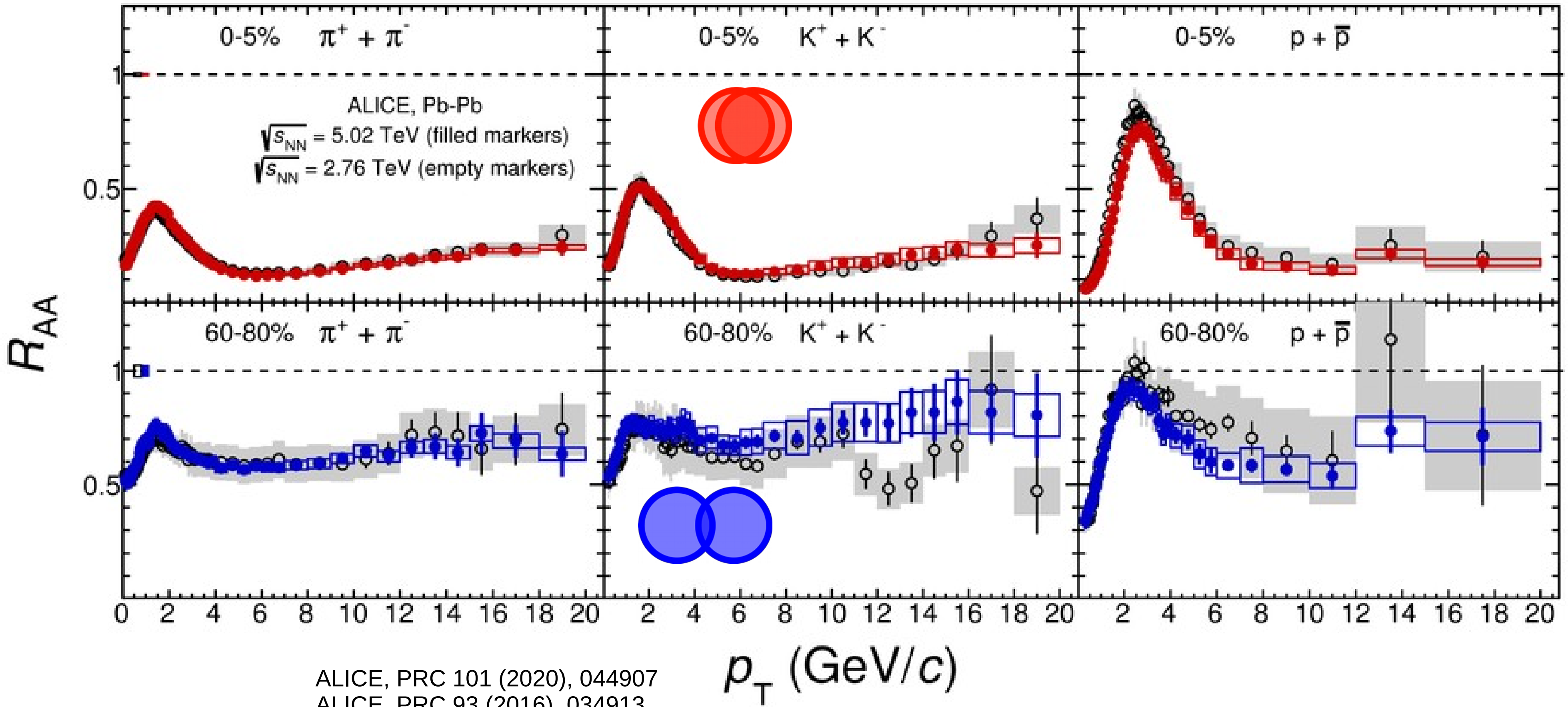
- All three species are equally suppressed for all centralities at high p_T (> 8 GeV/c)
- Similar parton fragmentation into baryon and mesons
- The suppression decreases in peripheral events

Energy dependence of the R_{AA}



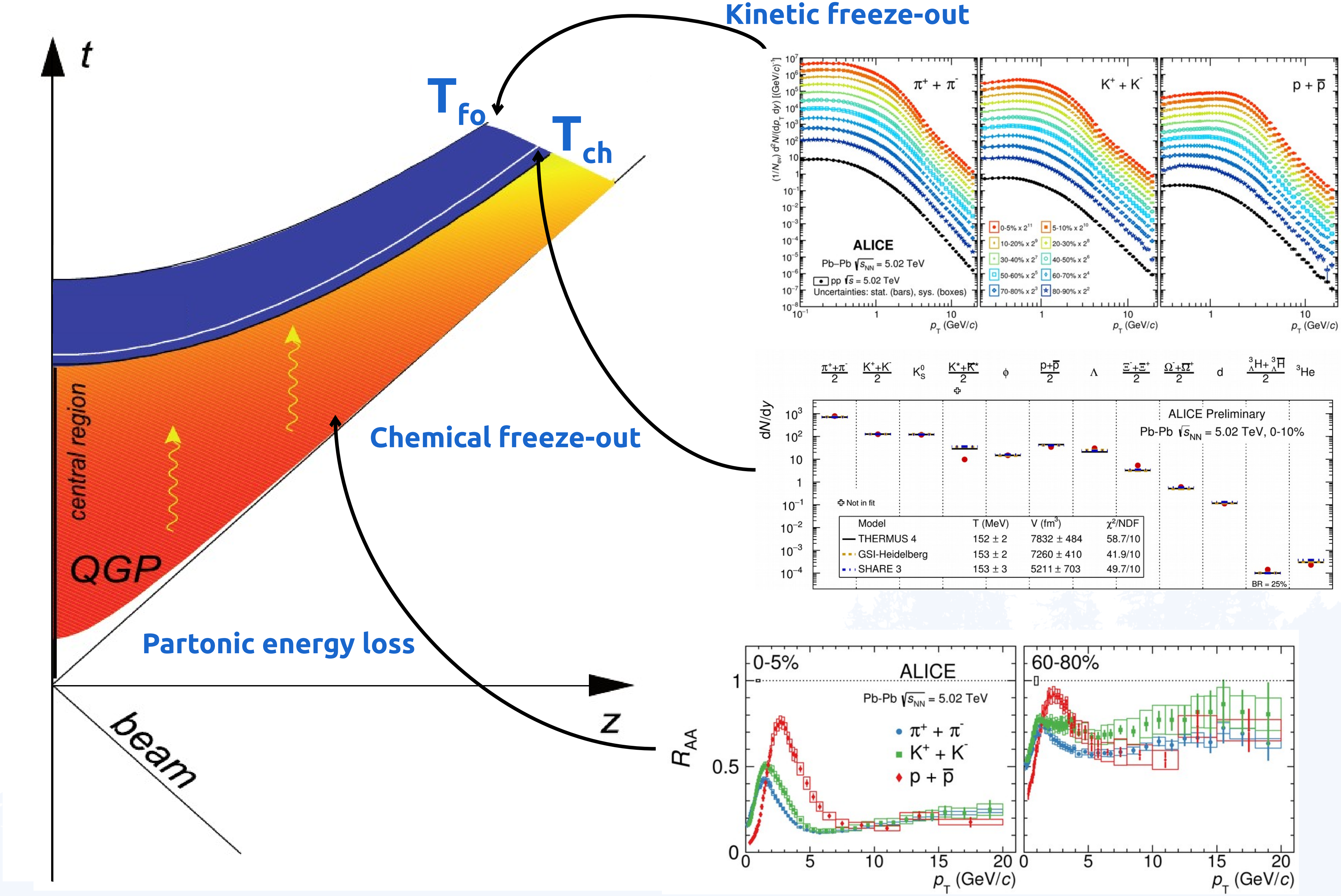
ALICE, PRC 101 (2020), 044907
ALICE, PRC 93 (2016), 034913

- **No significant evolution with collision energy is found**
- Similar observations for pions and kaons
- This suggests that the specific energy loss of partons is similar between the two collision systems

What we learn from the R_{AA}

- In central collisions the nuclear modification factor is significantly suppressed at large momenta (p_T > 8 GeV/c) **this indicates the presence of a medium opaque to the color charge**
- The suppression decreases in peripheral events
- All light-flavor hadrons are equally suppressed
- ***R_{AA}* has no significant evolution** with the collision energy

Investigating



Latest results from ALICE

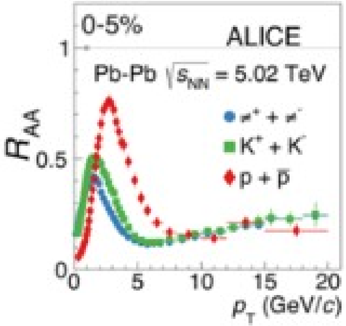
- Most of the results shown in this presentation are taken from

Editors' Suggestion

Production of charged pions, kaons, and (anti-)protons in Pb-Pb and inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV

S. Acharya *et al.* (ALICE Collaboration)

Phys. Rev. C **101**, 044907 (2020) – Published 29 April 2020



The ALICE Collaboration reports unique data on particle production in Pb-Pb and inelastic p-p collisions at the LHC at 5.02 TeV. The measurements range from very peripheral to the most central collisions, and cover particles with transverse momenta from hundreds of MeV/c to 20 GeV/c. The precision and breadth of the data provide tight constraints on our understanding of particle production mechanisms in these collisions.

Show Abstract +

Conclusions and outlook

- List of results presented here is far from behing exhaustive
- AA, pA, pp are fundamental for any heavy-ion experiment as much interpretative power is lost without any of them
- The evolution of heavy-ion collisions is already very well studied
- In the future of LHC, upgraded detectors will collect data at higher luminosities
- Focus will be on hard probes (charm and beauty quarks) and on light nuclei and hypernuclei
- However, there is plenty of room for precision measurements that will put tight constrains to models and provide better insight to better understand the QGP

Time for peanuts!