Heavy ion collisions as a tool: which physics can be explored?

The XVth Quark confinement and the Hadron spectrum conference in Stavenger

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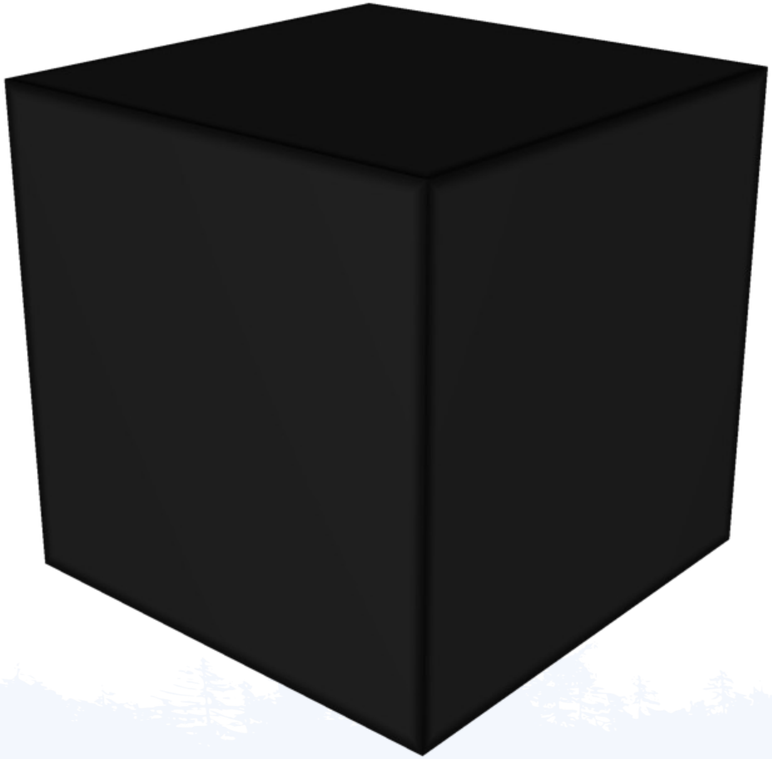
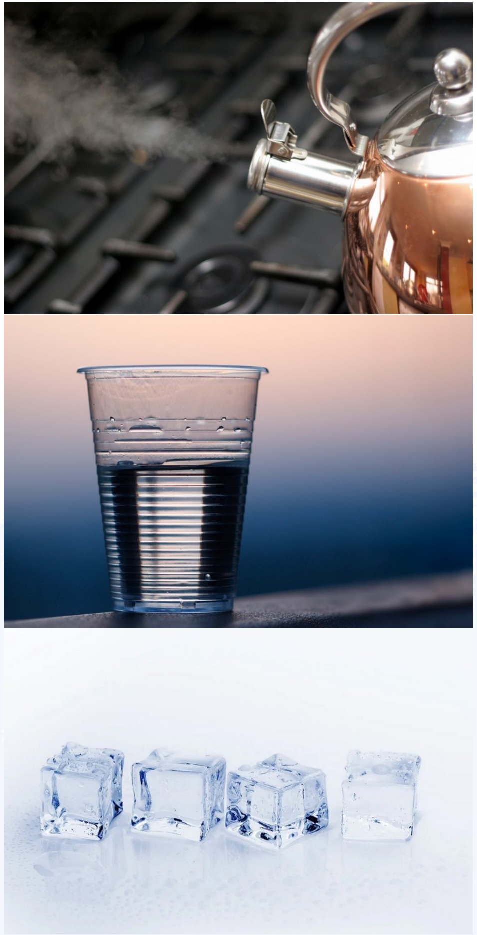
XVth Quark Confinement and the Hadron Spectrum Conference

2022 - University of Stavanger

What's in the box?

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





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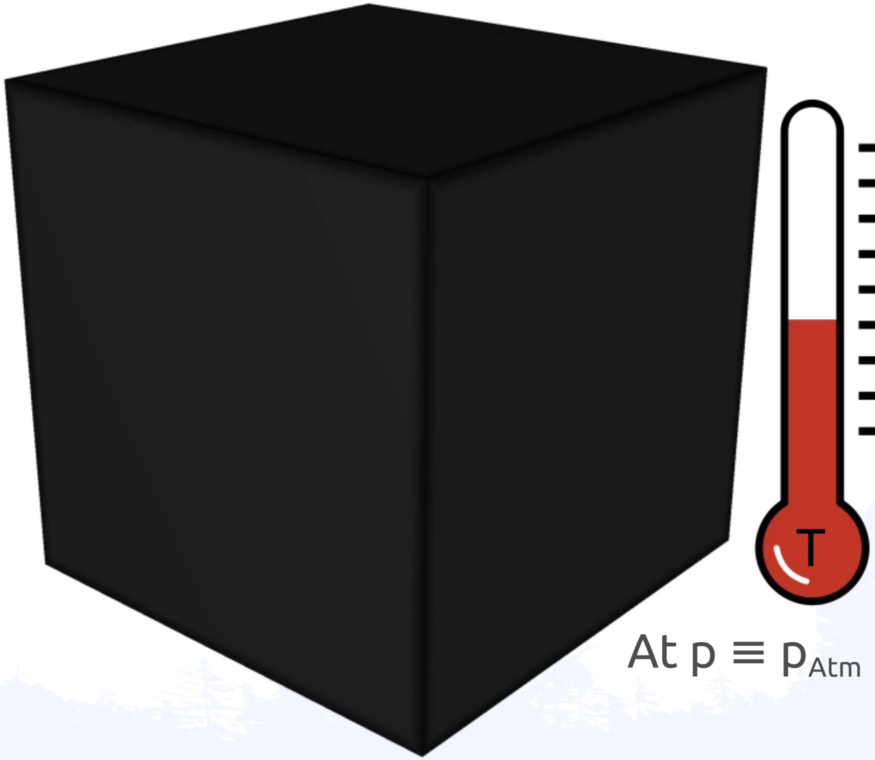

$T > 373K$

$273K < T < 373K$

$T < 273K$

To know the state measure the temperature!

What's in the box?

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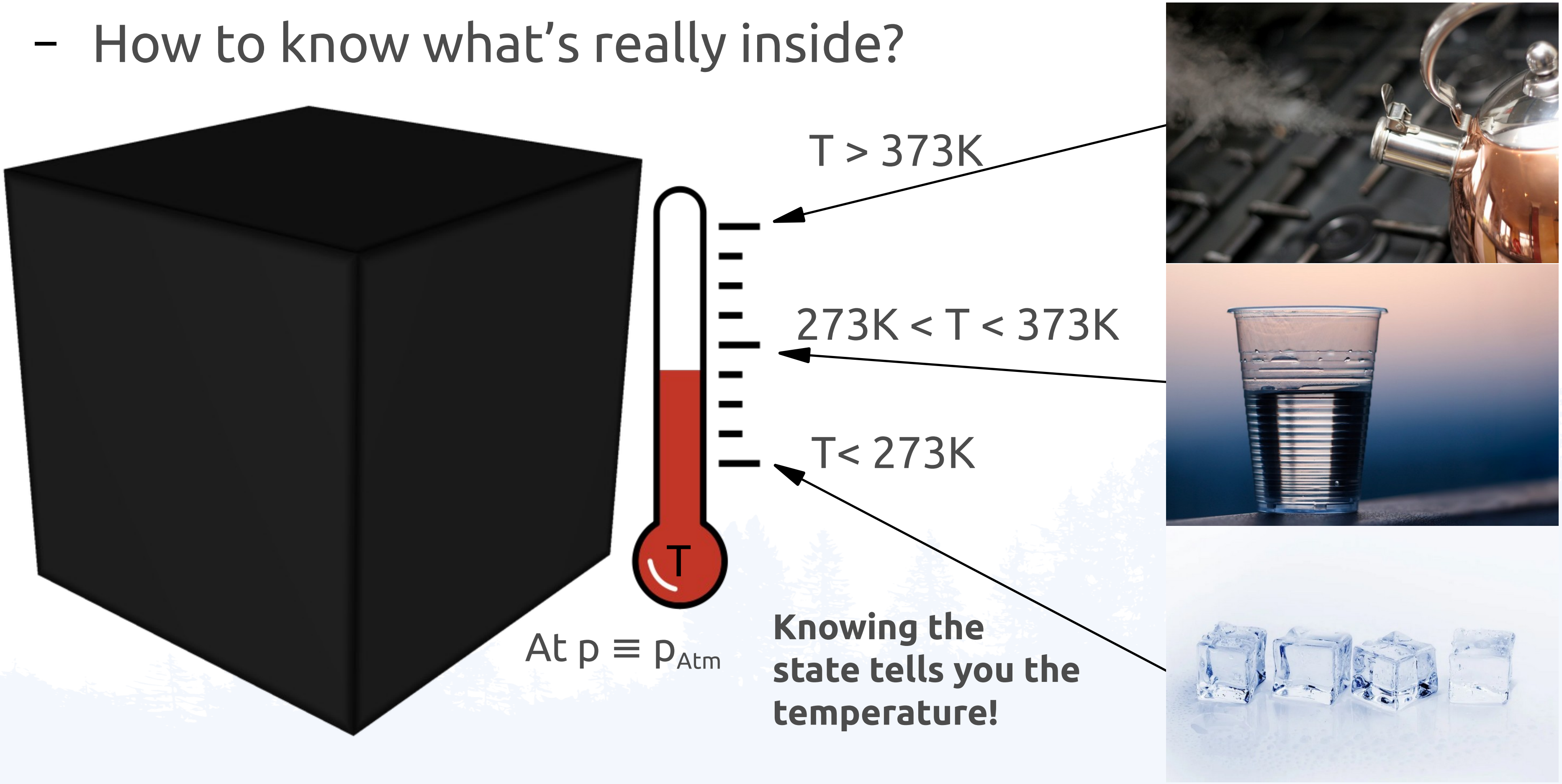
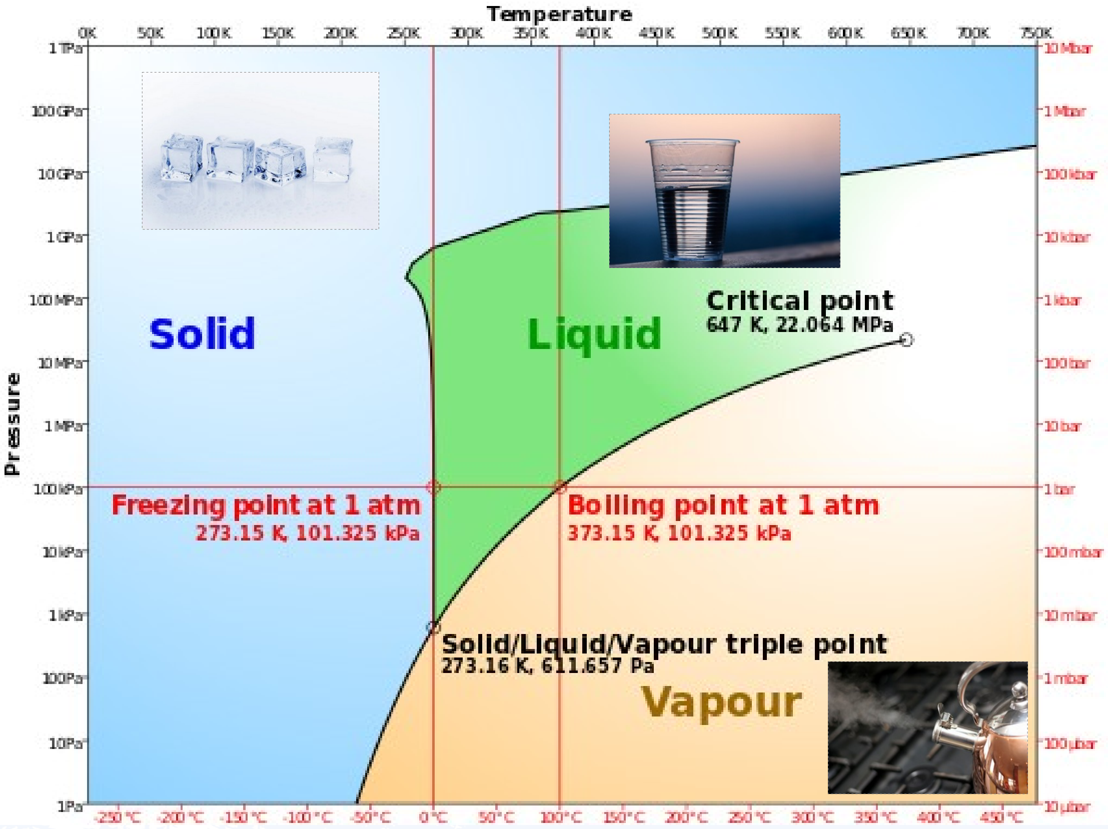


Water phase diagram

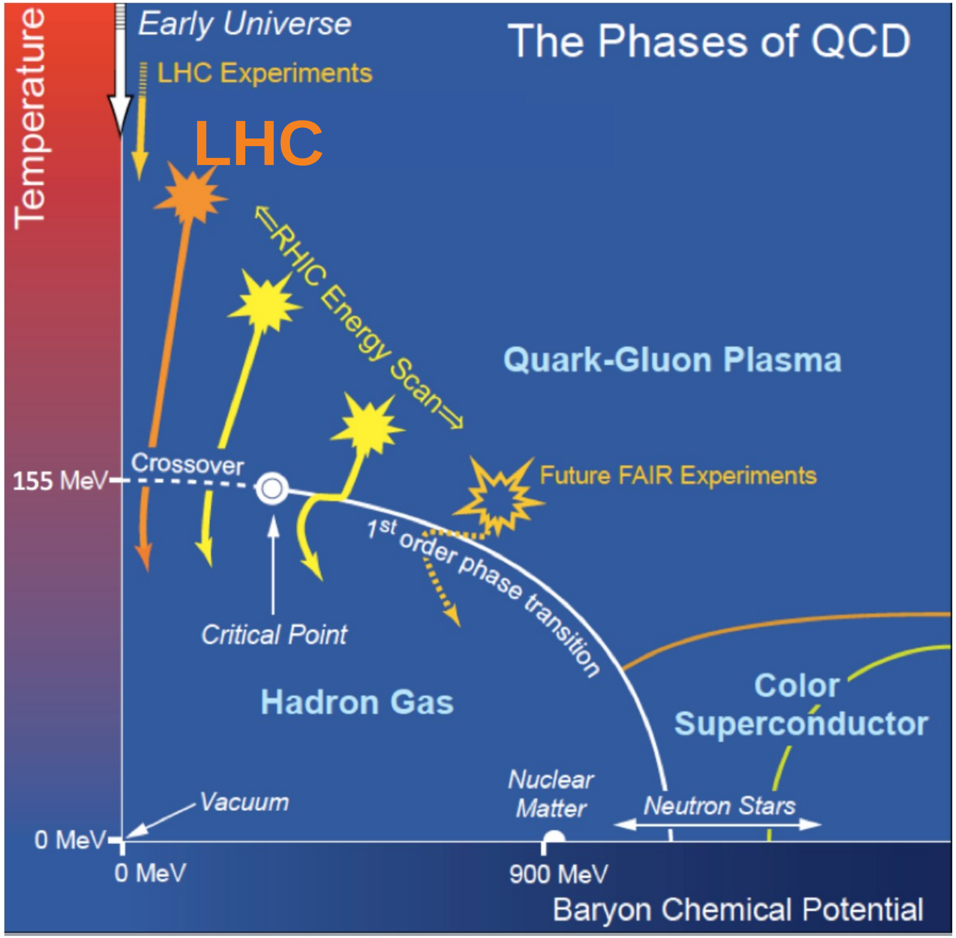
- The phase of the matter in the box depends on its thermodynamic state
- Three phases (at least) are available in the case of water
- Phase diagram investigated by varying pressure and temperature



QCD phase diagram

- The QCD phase diagram can be investigated in the same way
- 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**
- Partons moving over distances larger than the typical size of hadrons

Main physics goal in heavy ion physics!

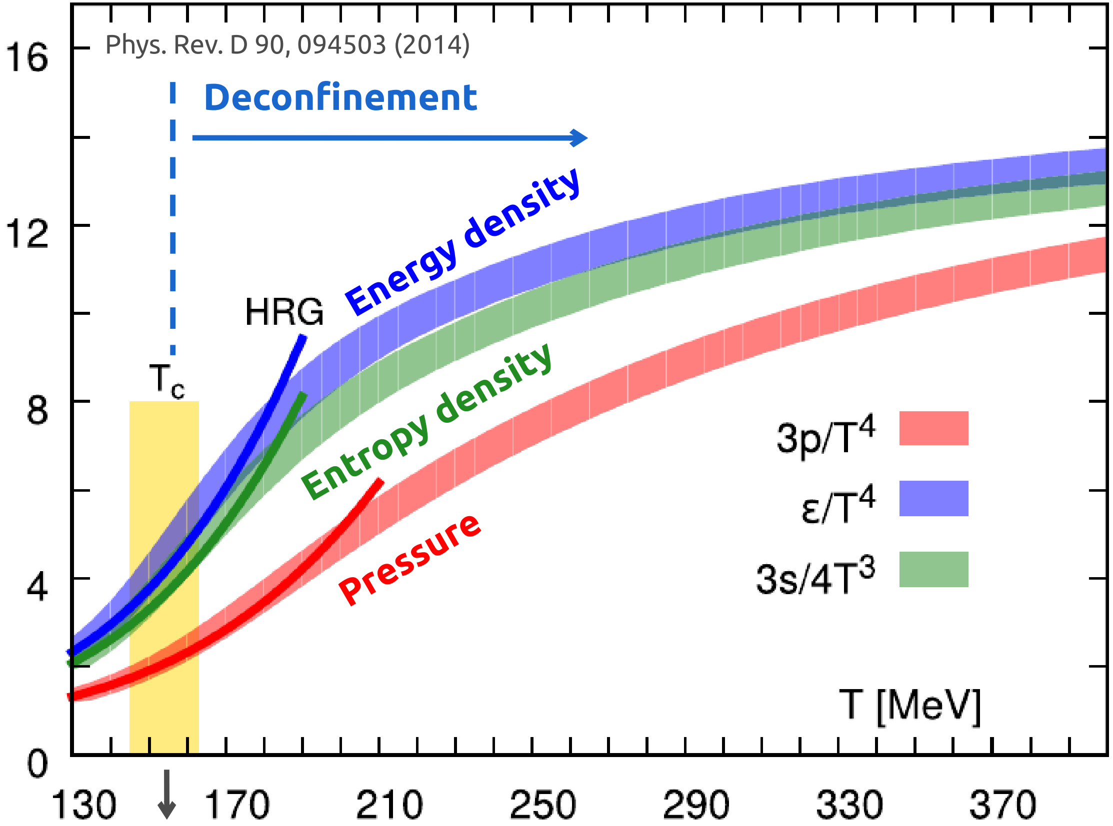


Heavy-ion collisions

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

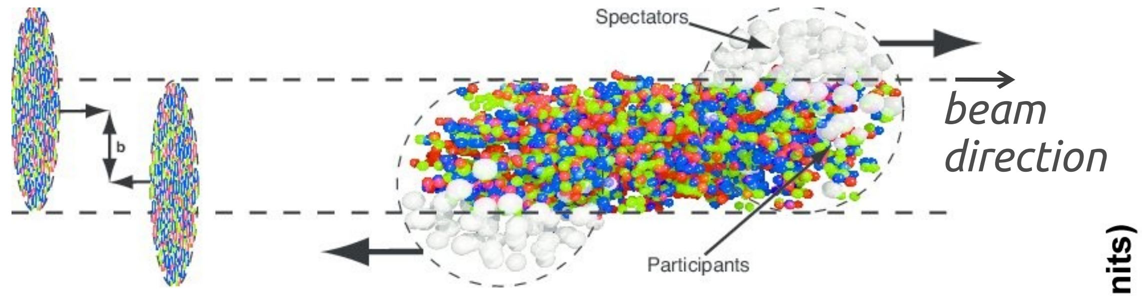
Systems with energy densities > 1GeV/fm³ produce a deconfined medium



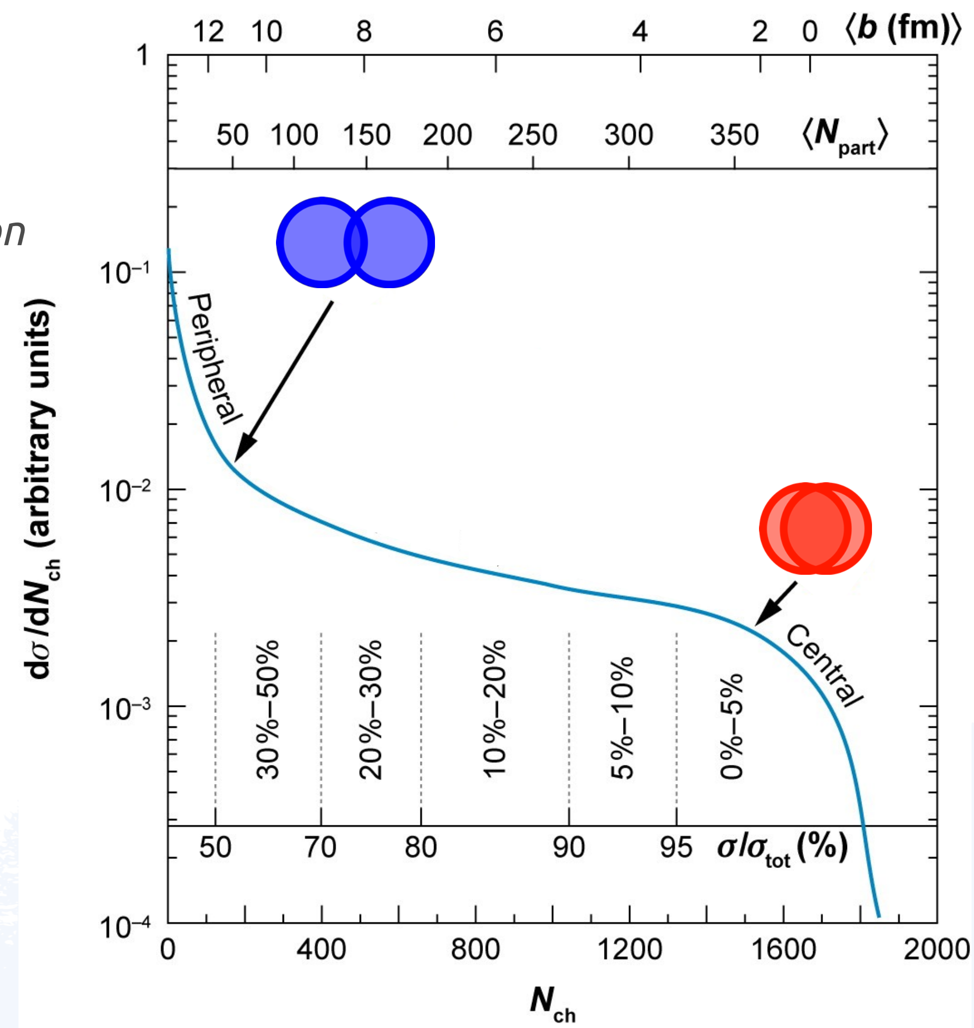
$T_c = 154 \pm 9$ MeV $\mu_{B=0}$

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

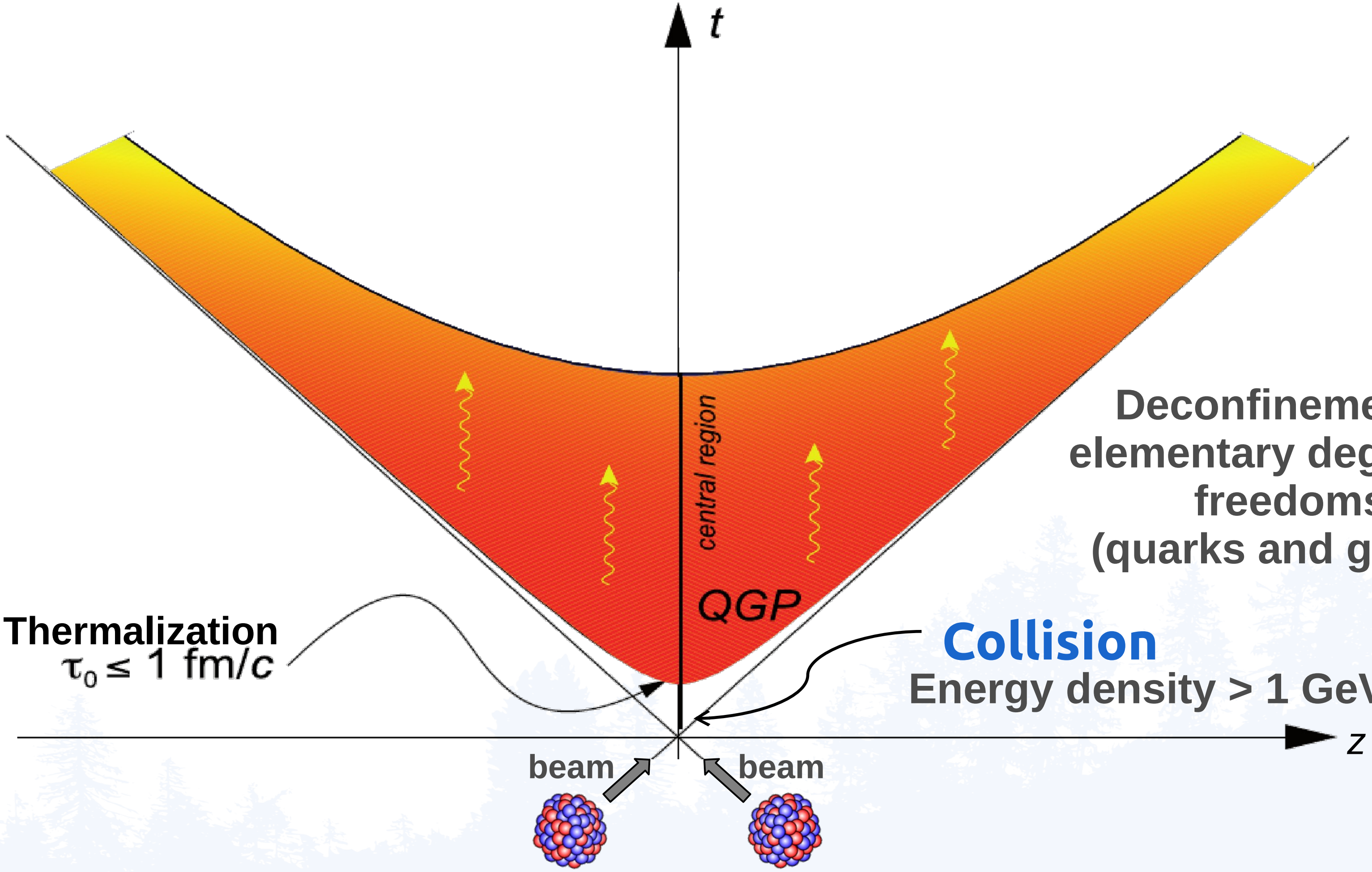
Heavy-ion collisions



- 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 ($\boldsymbol{\sigma}_{tot}$)
- **The largest energy density is achieved in the most central collisions**



Evolution of a heavy ion collision

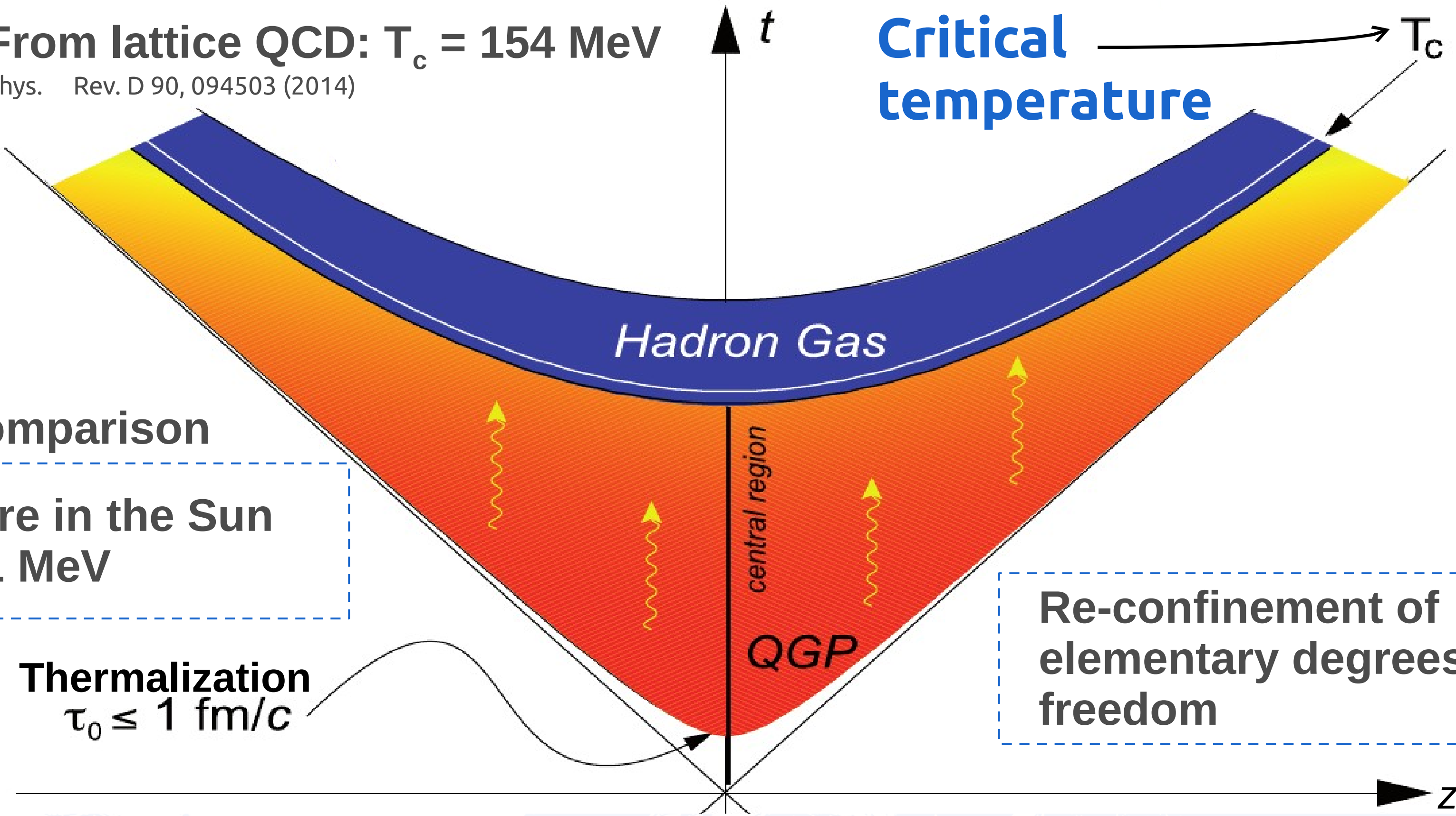


Deconfinement of elementary degrees of freedoms (quarks and gluons)

Evolution of a heavy ion collision

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

Critical temperature

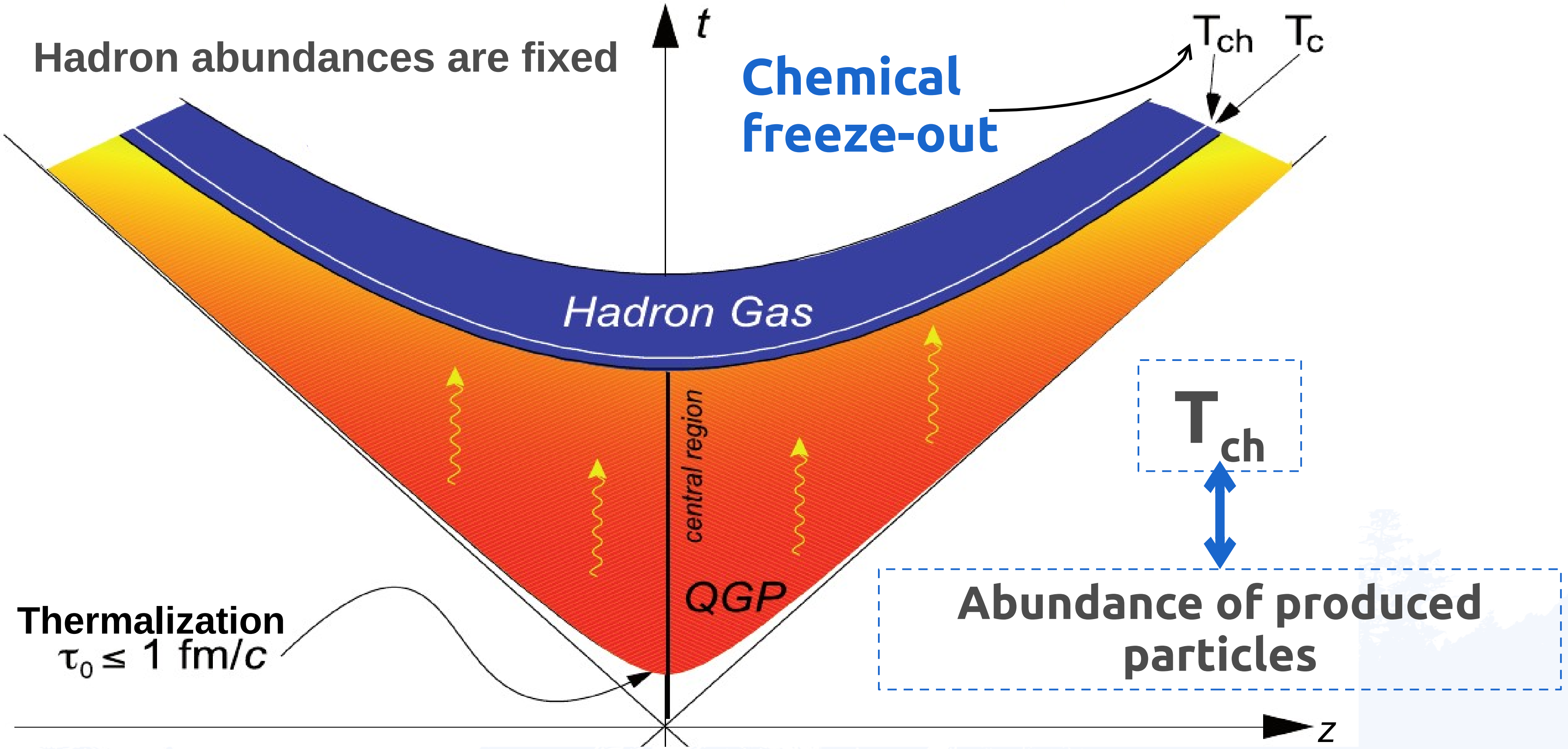


For comparison

Temperature in the Sun core ~ 0.01 MeV

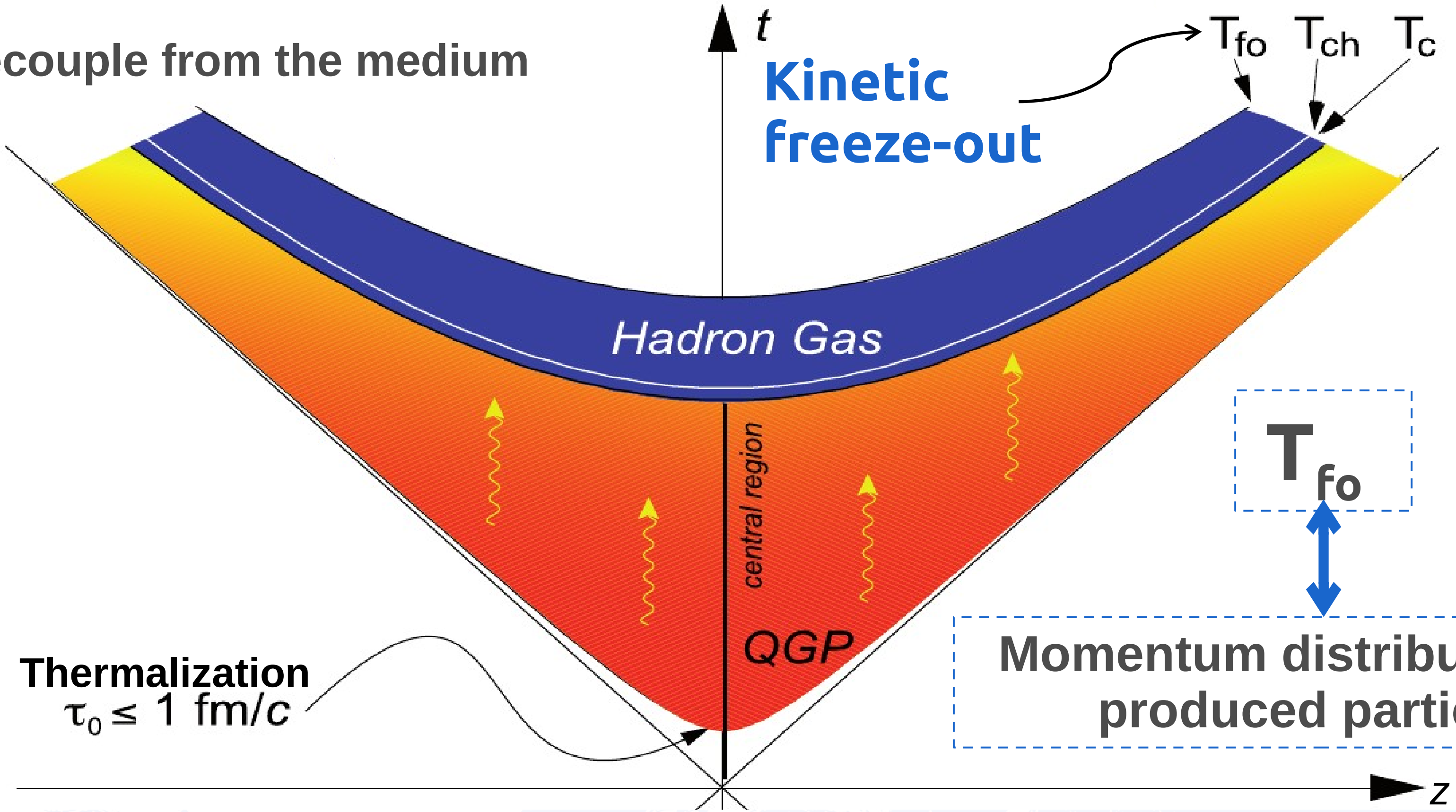
Re-confinement of elementary degrees of freedom

Evolution of a heavy ion collision



Evolution of a heavy ion collision

Hadrons decouple from the medium

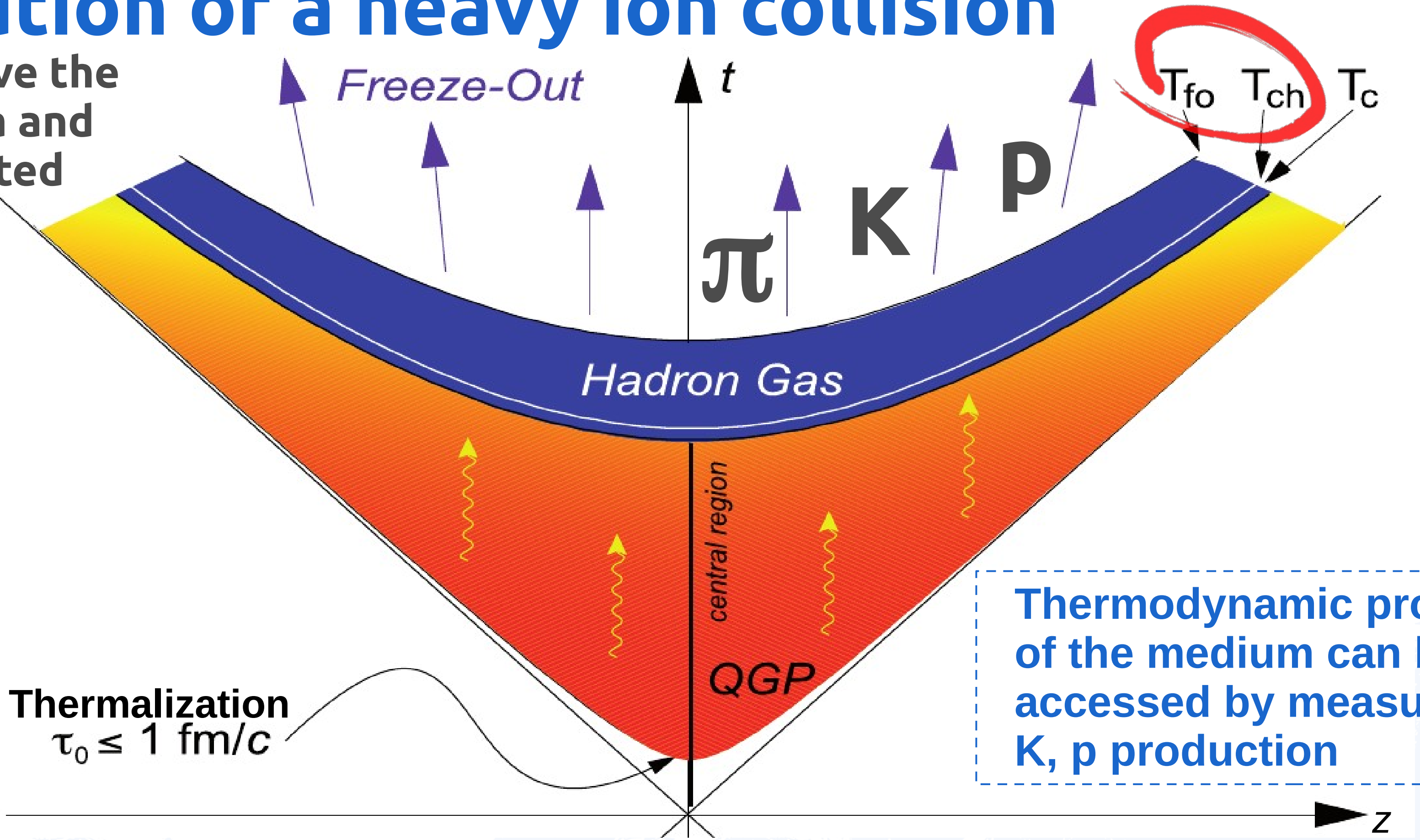


T_{fo}

Momentum distributions of produced particles

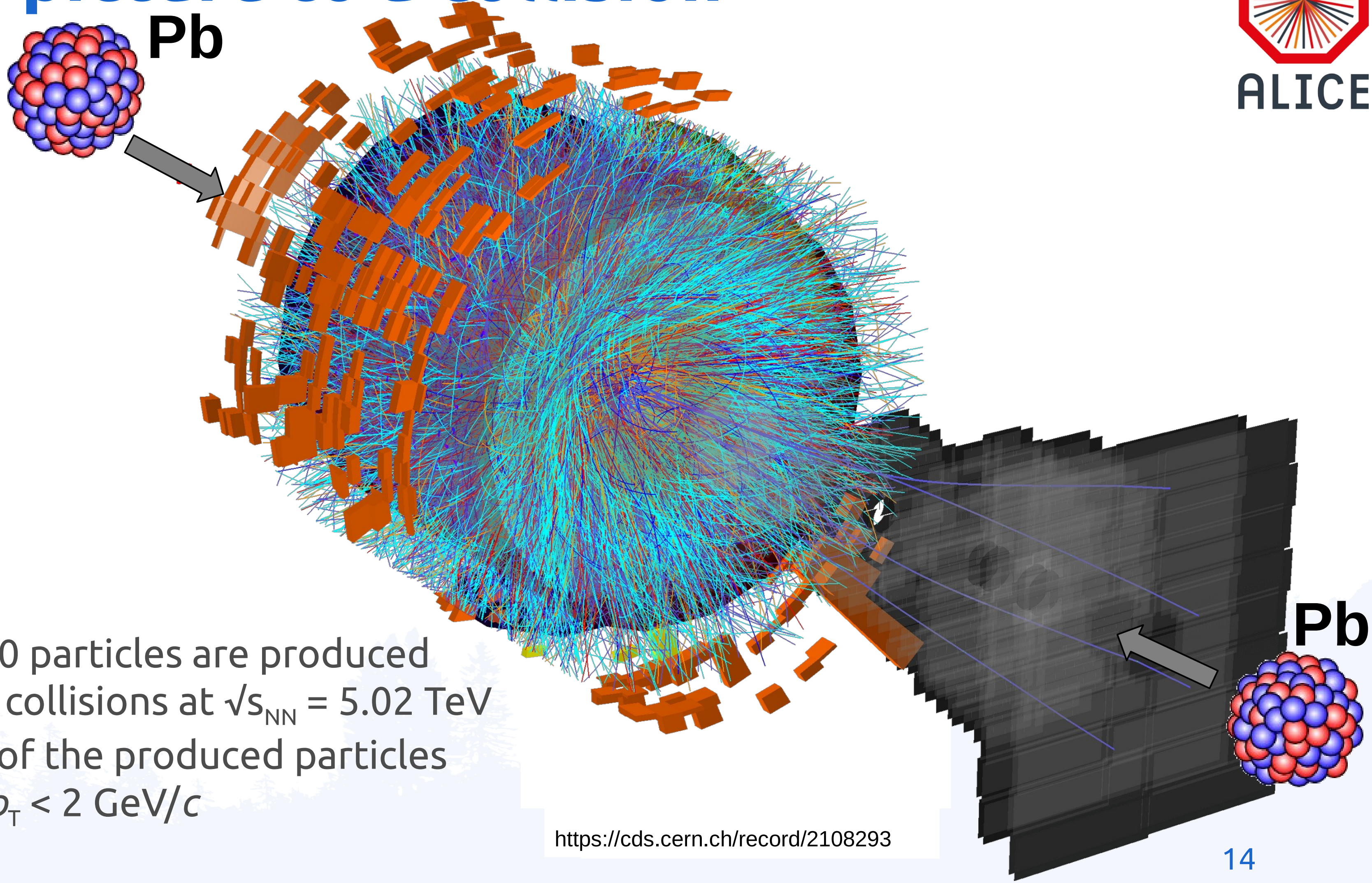
Evolution of a heavy ion collision

Particles leave the collision area and can be detected



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

Taking a picture to a collision



- 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

https://cds.cern.ch/record/2108293

From large to small systems

Heavy ion collisions complemented by smaller collision systems

At the LHC:

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
- First pp collisions (900 GeV) of Run 3 at the end of last October

Whole-lotta particles to measure

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

Strange content

K_S^0 p Λ Ξ Ω

$K^\pm$

$\pi^\pm$

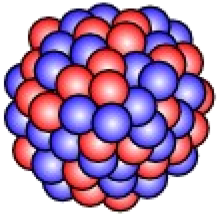
π^0

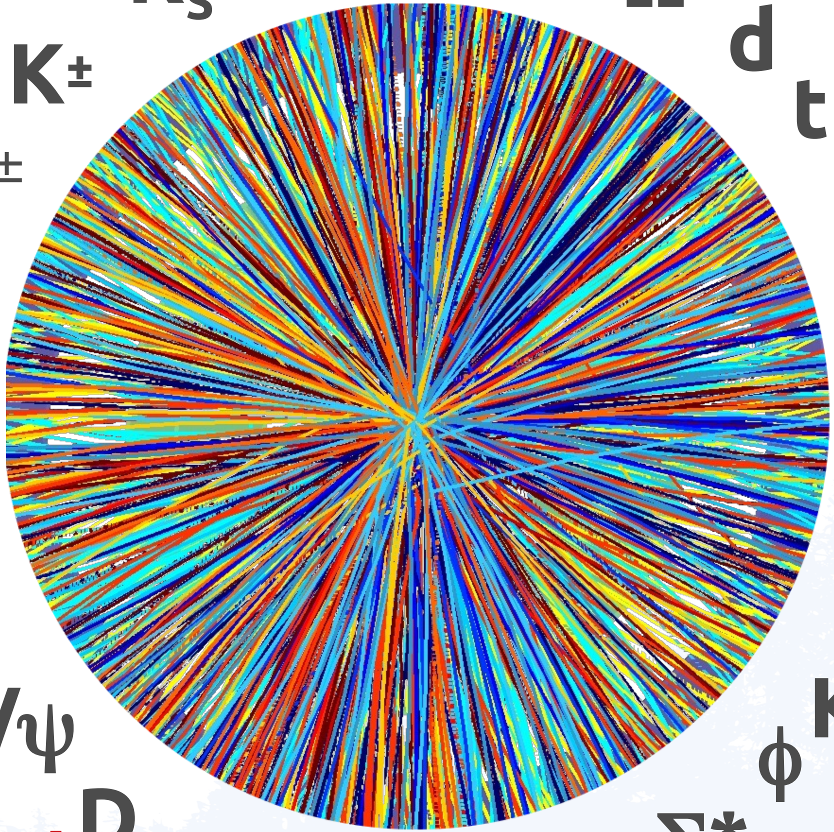
d t

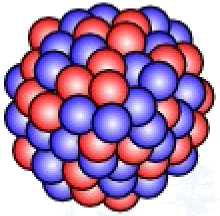
Light nuclei

^3He

^4He







Λ_c

Υ

ψ'

J/ψ

$^3_\Lambda H$

Hyper-nuclei

η

K^*

ϕ

Resonances

Σ^*

Λ^*

Ξ^*

D^0

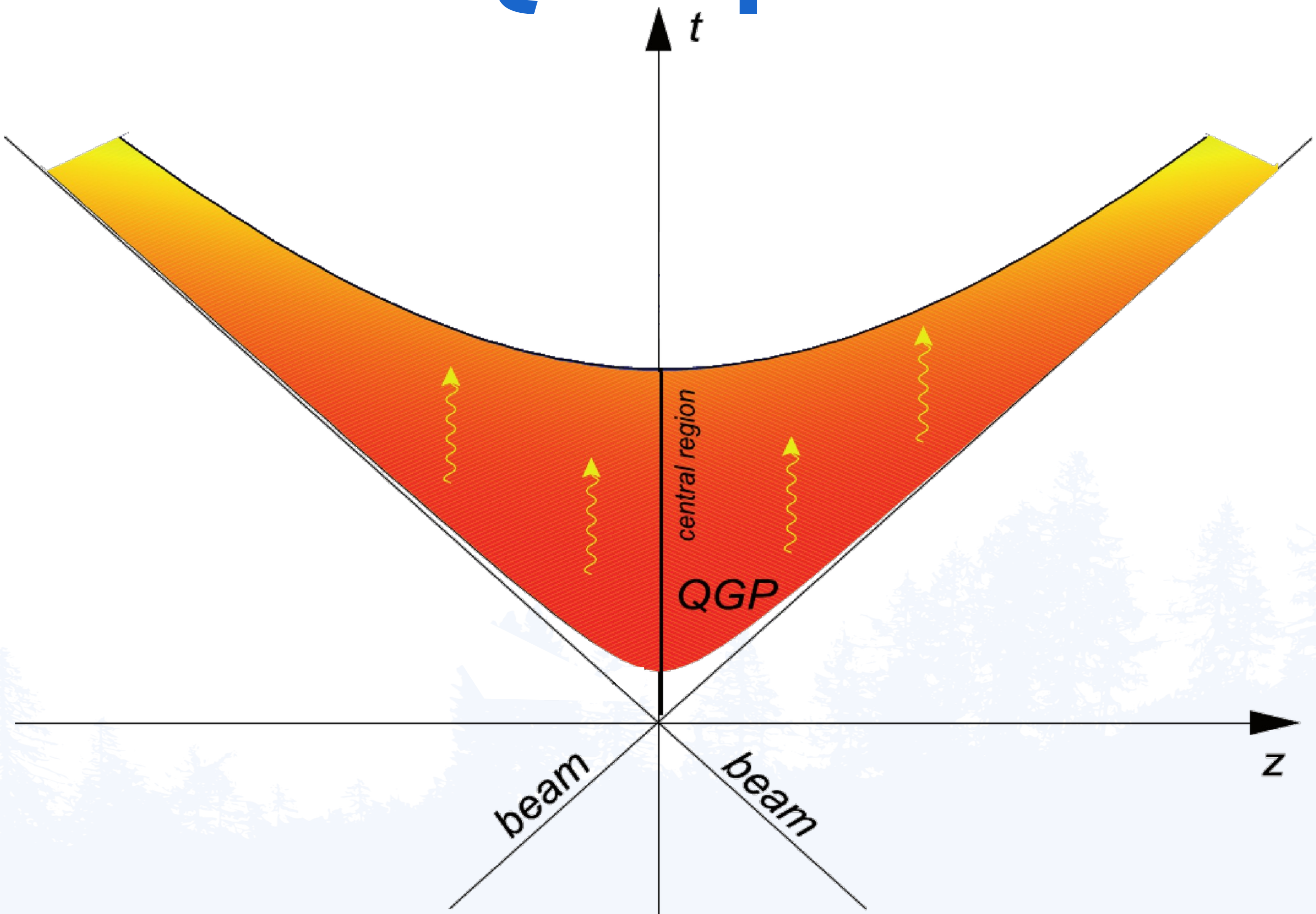
D^{*+}

D_s

Heavy flavor hadrons have also *heavy* quarks

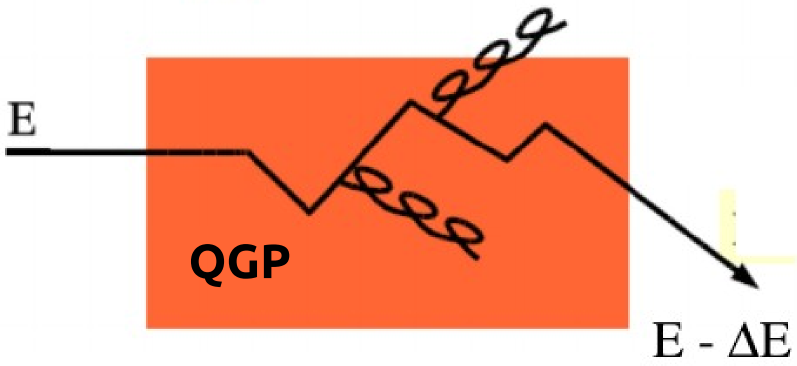
Not exhaustive!

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

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

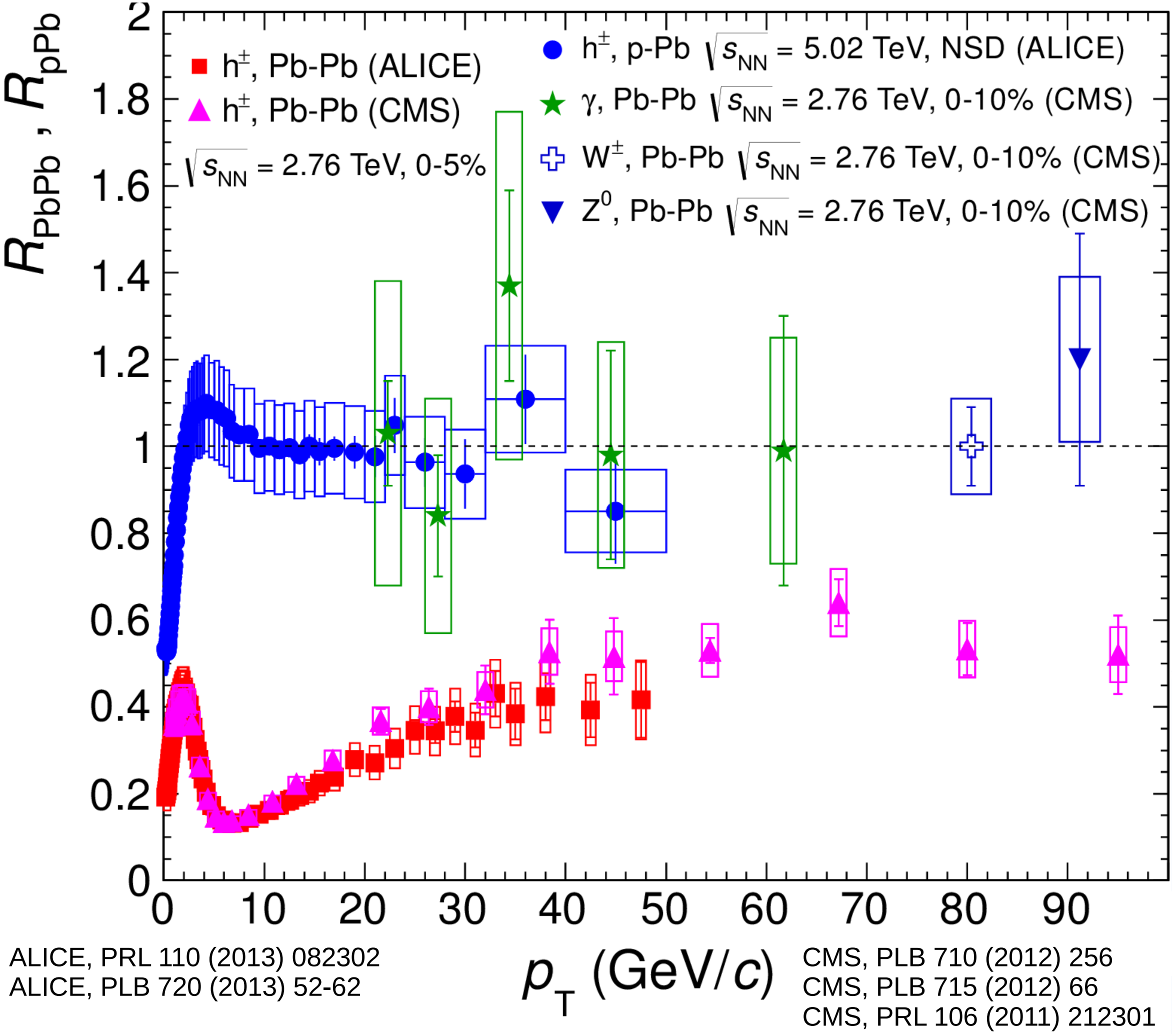
- No QGP is expected to form in pp collisions
- R_{AA} quantifies the difference between Pb-Pb collisions and the sum of $\langle N_{coll}\rangle$ incoherent collisions i.e. quantifies the effect of the presence of the medium

Nuclear modification factor: R_{AA}

R_{AA} accounts for the modification of the medium on the particle spectrum

- **$R_{AA} < 1$:**
  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

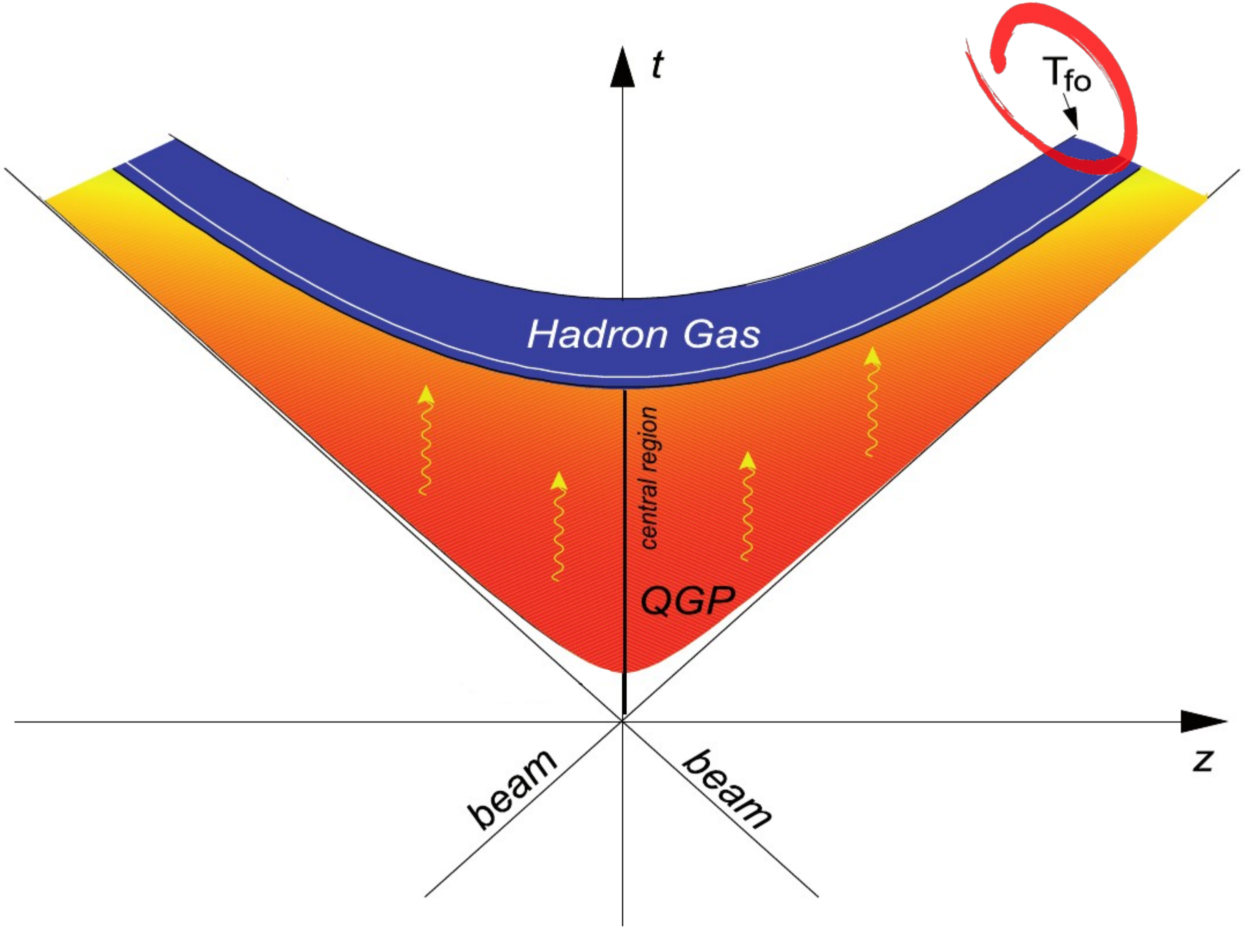
Different hadrons gives information of quark interaction with medium



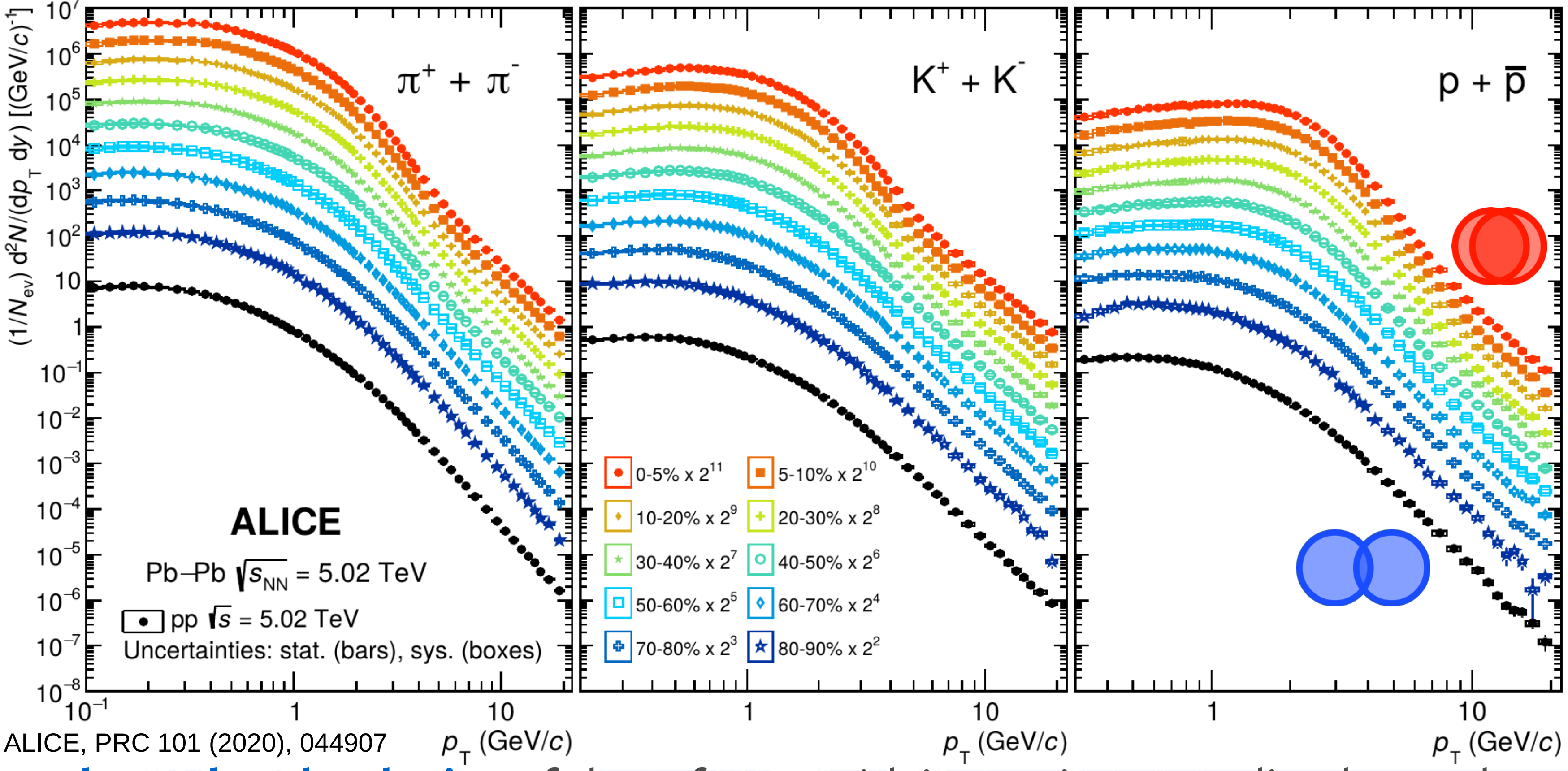
ALICE, PRL 110 (2013) 082302
ALICE, PLB 720 (2013) 52-62

CMS, PLB 710 (2012) 256
CMS, PLB 715 (2012) 66
CMS, PRL 106 (2011) 212301

Measuring the system at the kinetic freeze-out



Light flavor hadron spectra



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**

Blast-Wave model

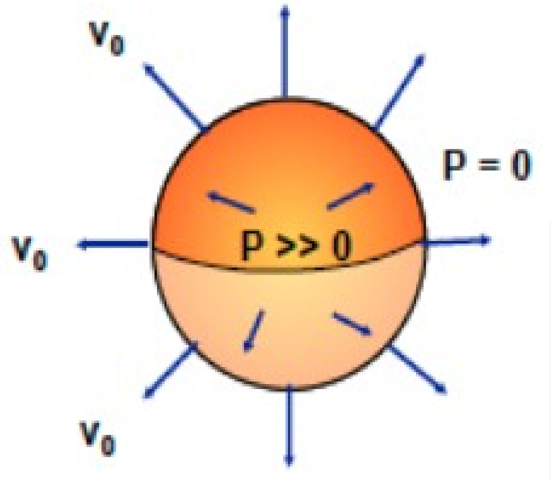
The Blast-Wave model describes the particle distribution at the kinetic freeze-out as a result of the expansion of a thermalized source

- 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

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

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

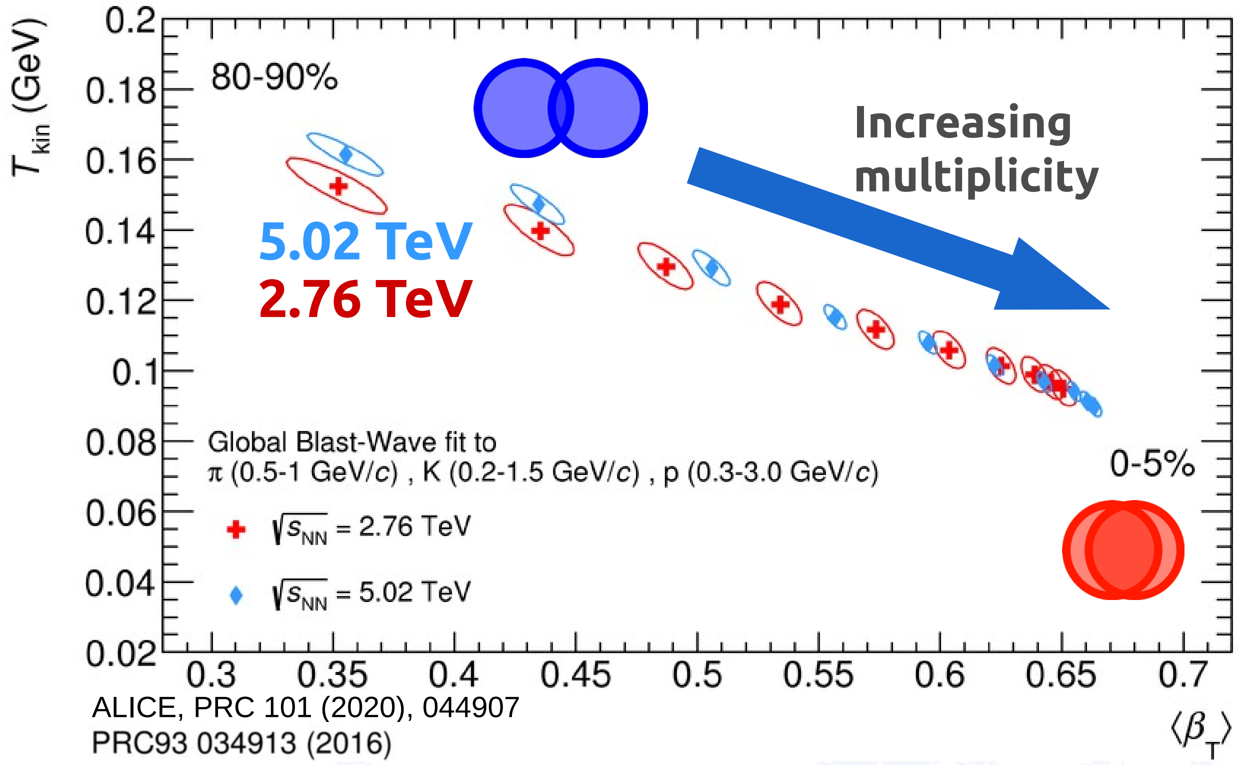
Schnedermann, Sollfrank and Heinz Phys. Rev. C 48, 2462



» β_T → radial expansion velocity

» T_{Kin} → kinetic freeze-out

Blast-Wave model: β_T vs T_{kin}



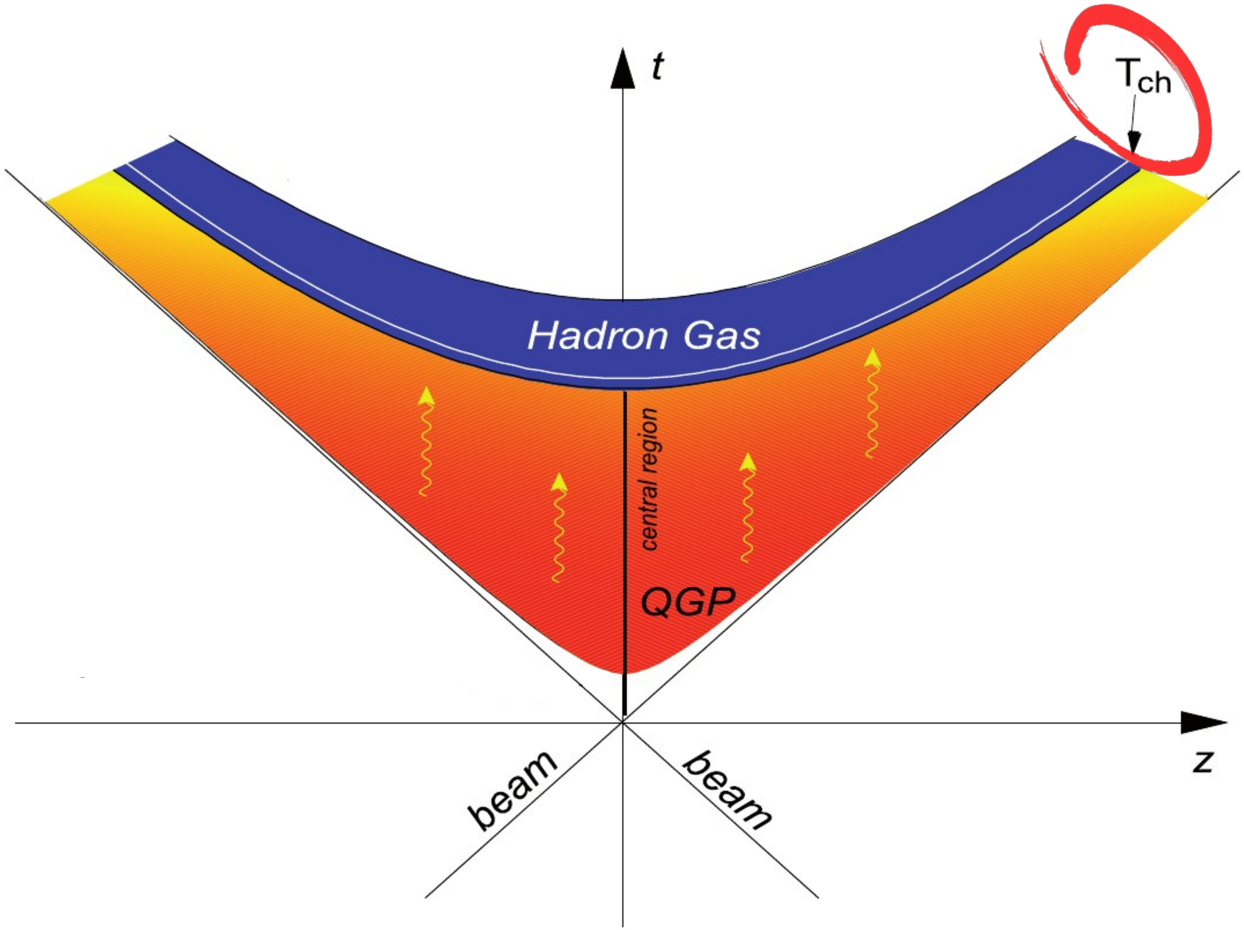
ALICE, PRC 101 (2020), 044907
PRC93 034913 (2016)

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

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

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

Measuring the system at the chemical freeze-out



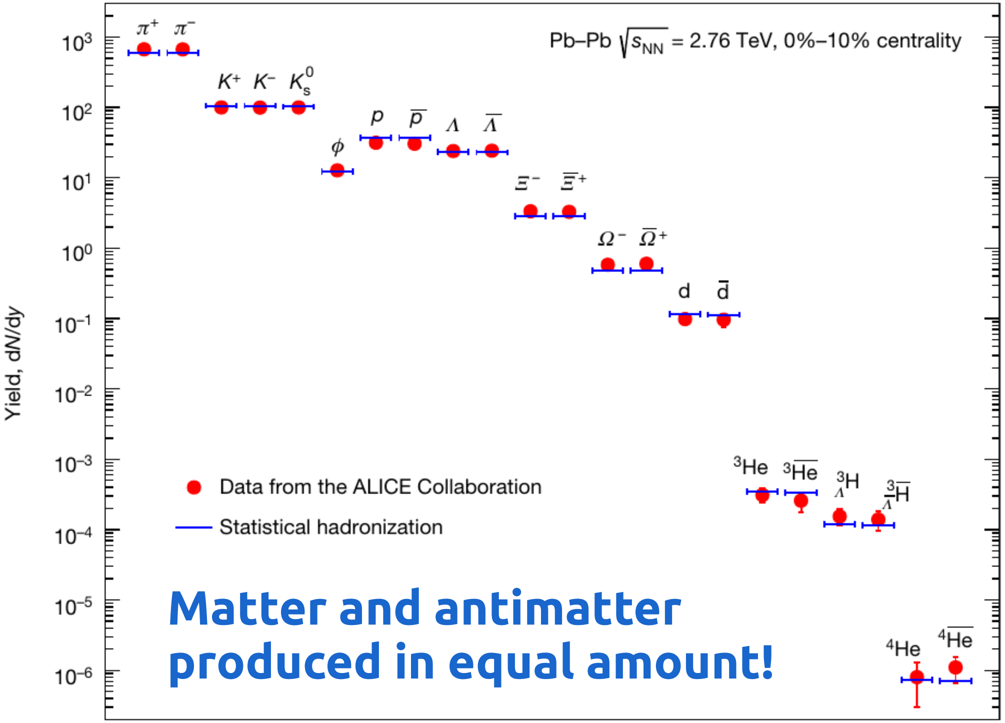
Thermal model

- 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

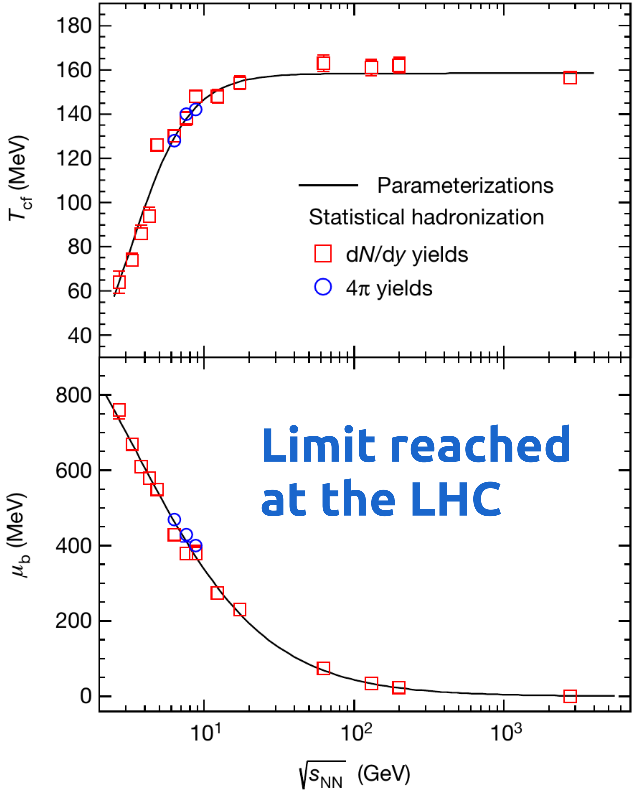
$$\ln Z^{GC}(T, V, \{\mu_i\}) = \sum_{\text{species } i} \frac{g_i V}{(2\pi)^3} \int d^3p \ln\left(1 \pm e^{-\beta(E_i - \mu_i)}\right)^{\pm 1} \Rightarrow N_i^{GC} = T \frac{\partial \ln Z^{GC}}{\partial \mu_i}$$

- The quantum number conservation (baryon number, strangeness, 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 to describe particle yields

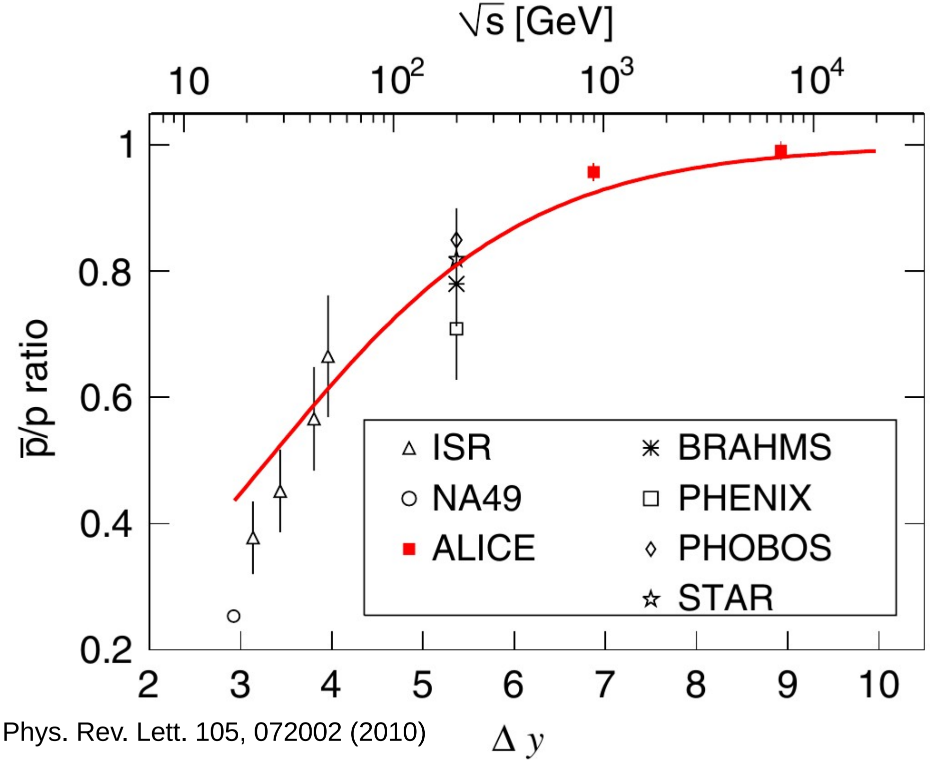


Andronic et al., Nature volume 561, pages 321–330 (2018)

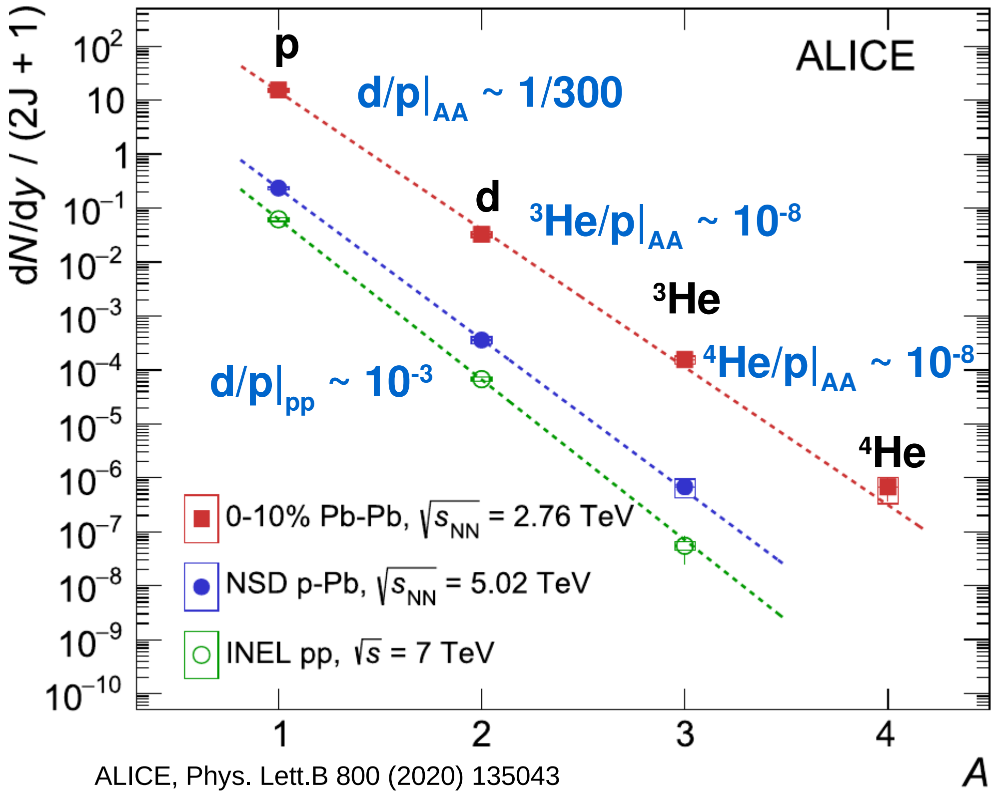


- Single chemical freeze-out temperature for all particle species (common source) in central Pb-Pb collisions $\mathbf{T_{ch}}$**~156 ± 1.5 MeV**
- This value is in close to the critical temperature T_c (~154 MeV) obtained from lattice QCD → **phase transition is close to chemical freeze-out**

Antimatter factories with heavy ions



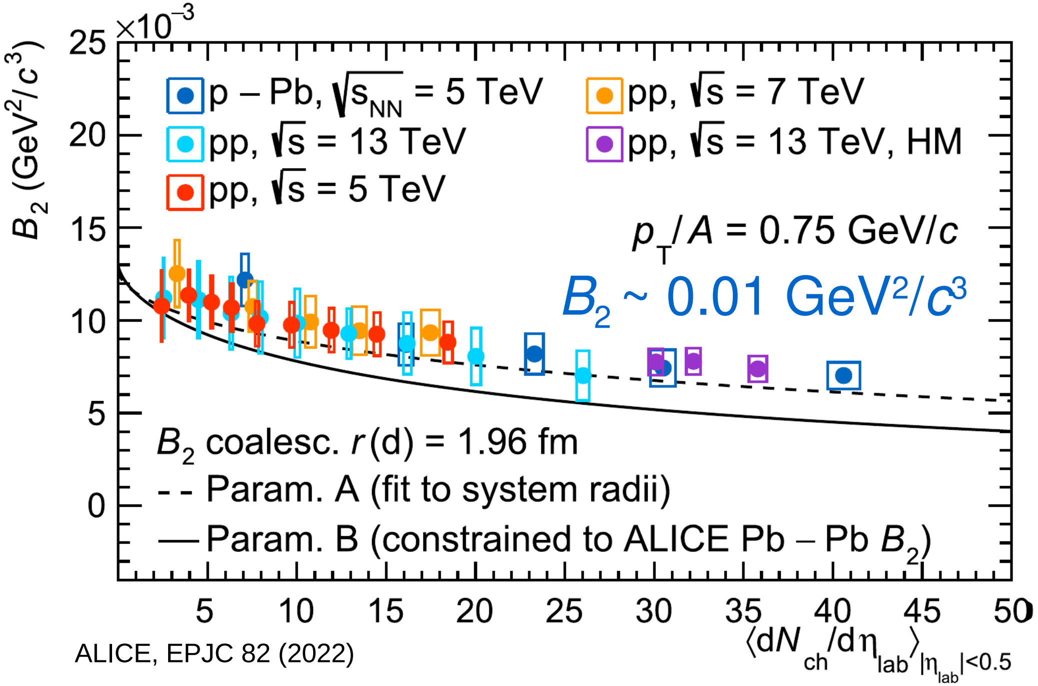
Phys. Rev. Lett. 105, 072002 (2010)



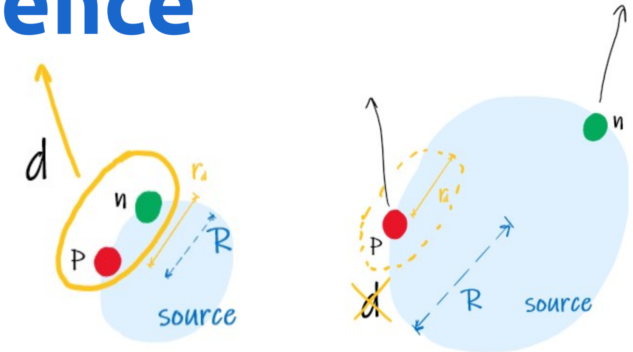
ALICE, Phys. Lett.B 800 (2020) 135043

- Matter-antimatter ratio at LHC ~ 1 **independently on the collision system**
- Production rates strongly depend on the mass number and collision system

Nuclei formation by coalescence



ALICE, EPJC 82 (2022)



$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$

For a nucleus large w.r.t. the source
→ “simple” coalescence models

$$B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{(A-1)} \frac{1}{A!} \frac{M}{m^A}$$

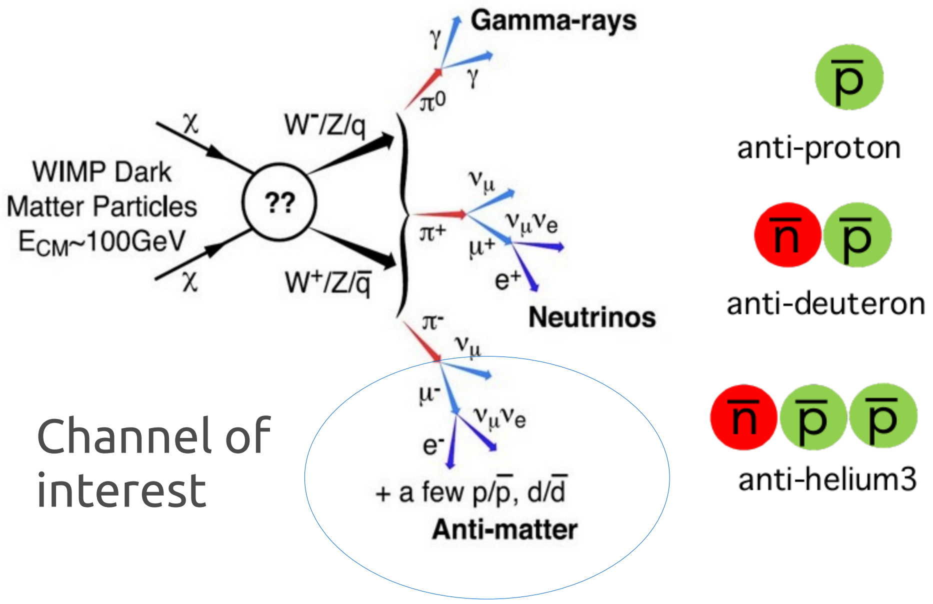
Nucleus mass (M)

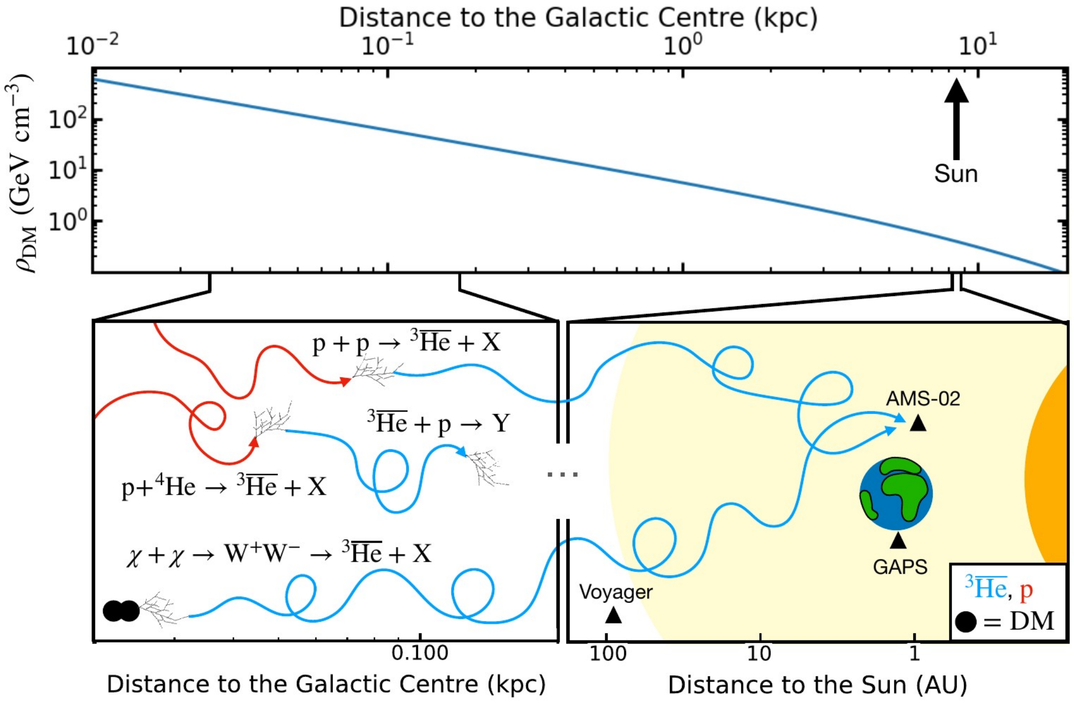
Nucleon mass (m)

Coalescence momentum (p_0)

- (Anti-)nuclei can be formed at kinetic freeze-out by coalescence of nucleons close enough in phase space
- Production depends on the **coalescence probability B_A**
- **B_A measured extensively in small and large systems**

Antimatter as dark matter “smoking gun”





ALICE, arXiv:2202.01549

- **Anti-p and anti-n are produced** by WIMP annihilation into SM channels
- Anti-deuterons and anti-^{3}He are produced via coalescence of anti-nucleons
- **No anti-nuclei as primary cosmic rays (only nuclei → mostly protons and helium)**
- Secondary anti-p, anti-d, anti-^{3}He produced by interaction of primary CR with the InterStellar Matter (pp, p-He, …) → **background for the DM signal**

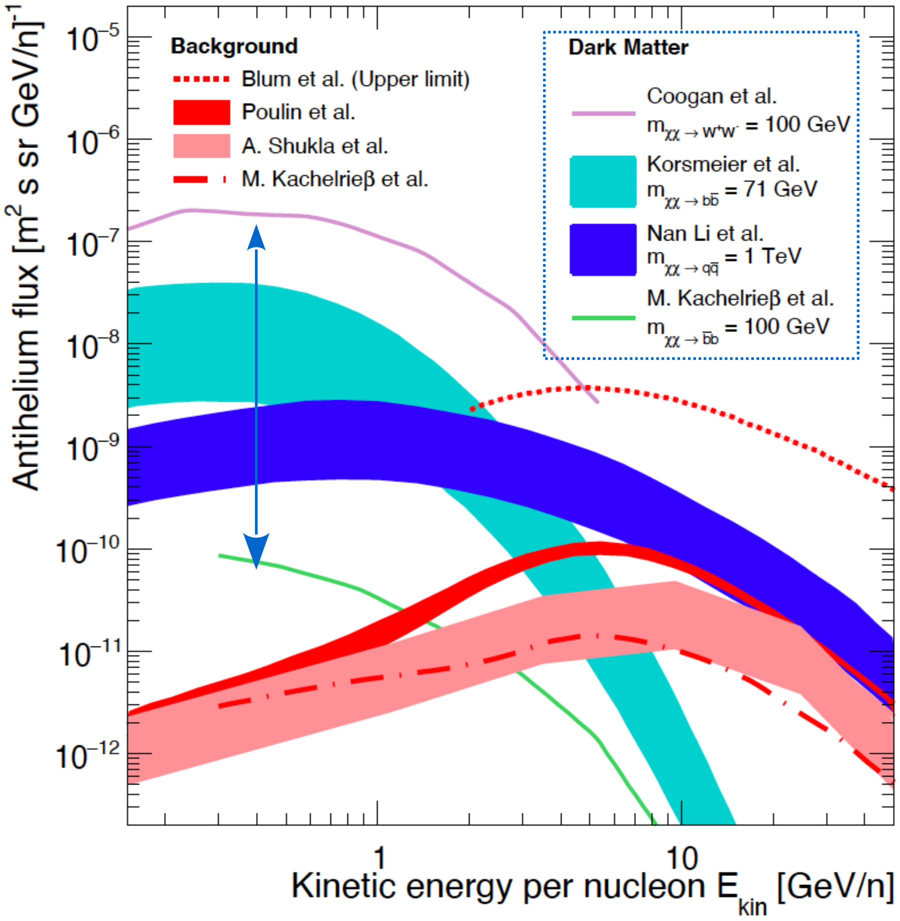
The dark matter source

Anti-nuclei flux from Dark Matter **depends on the details of the particle physics model** and the DM density in a given point of the Galaxy

In particular:

- thermally-averaged annihilation cross section into SM channel
- DM mass, e.g. $70 < m_{DM} < 100\ GeV/c^2$
- energy spectrum of the products
- DM density in the vicinity of the solar system

P. von Doentichem et al., JCAP08(2020)035



The background source

Secondary anti-nuclei can be produced by spallation reactions of primary CR with ISM, e.g.

$$\mathrm{p} + \mathrm{p} \to \bar{\mathrm{d}} + X \qquad \mathrm{p} + {}^{3}\mathrm{He} \to \bar{\mathrm{d}} + X$$

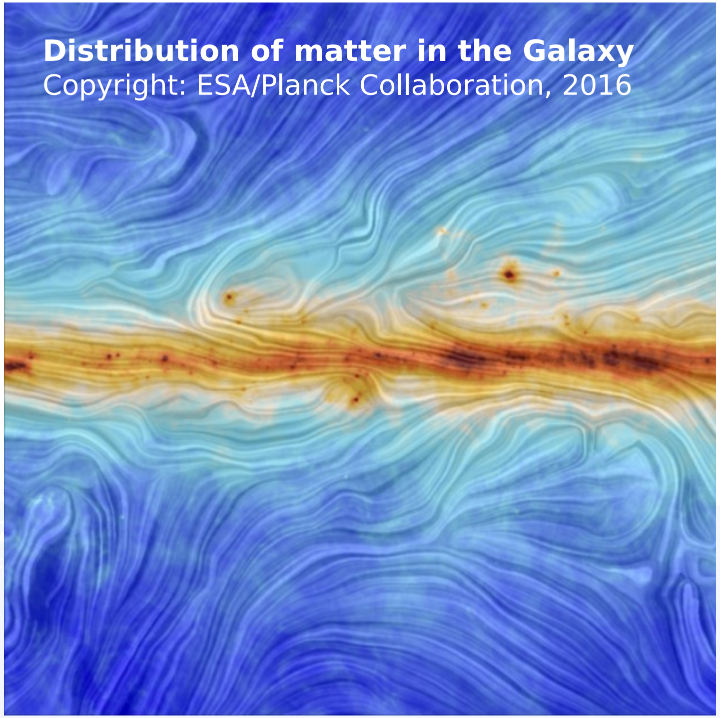
$$\bar{\mathrm{p}} + \mathrm{p} \to \bar{\mathrm{d}} + X \qquad \bar{\mathrm{p}} + {}^{3}\mathrm{He} \to \bar{\mathrm{d}} + X$$

- **Depends on the cross-sections for p̄ production in pp, p-He, p-A**
- Achieved via the coalescence mechanism (as for DM) → different anti-nucleon distributions coalescence momentum unknown

In addition, a tertiary CR component:

$$\bar{\mathrm{d}} + \mathrm{p} \to \bar{\mathrm{d}} + X$$

$$\bar{\mathrm{d}} + {}^{3}\mathrm{He} \to \bar{\mathrm{d}} + X$$



Towards precise estimate of anti-nuclei flux

Anti-matter flux predictions for signal from DM and background from secondary/tertiary CR require as input:

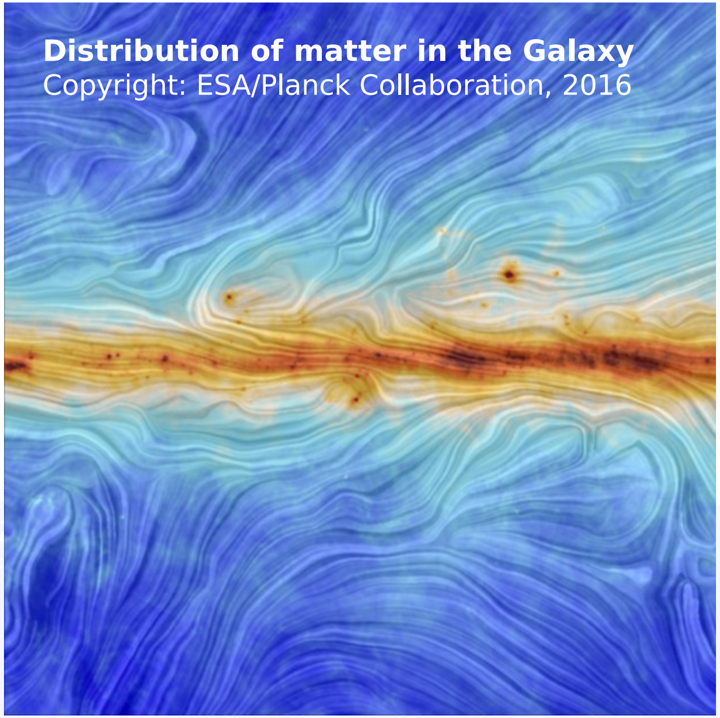
- **Coalescence mechanism**
- **Coalescence momentum**
- **Cross-sections for anti-p production in pp, p-He, p-A**

To measure at the collider!

Flux calculations sensitive to the astrophysical details, i.e. how particles propagate in the Galaxy:

- Acceleration by Super Novae remnants
- Diffusion in the galactic magnetic field (~*μGauss*)
- Energy loss / gain (*for loosely bound nuclei, break-up dominates*)
- Solar modulations (*matter mostly at low E, where DM signal prominent*)

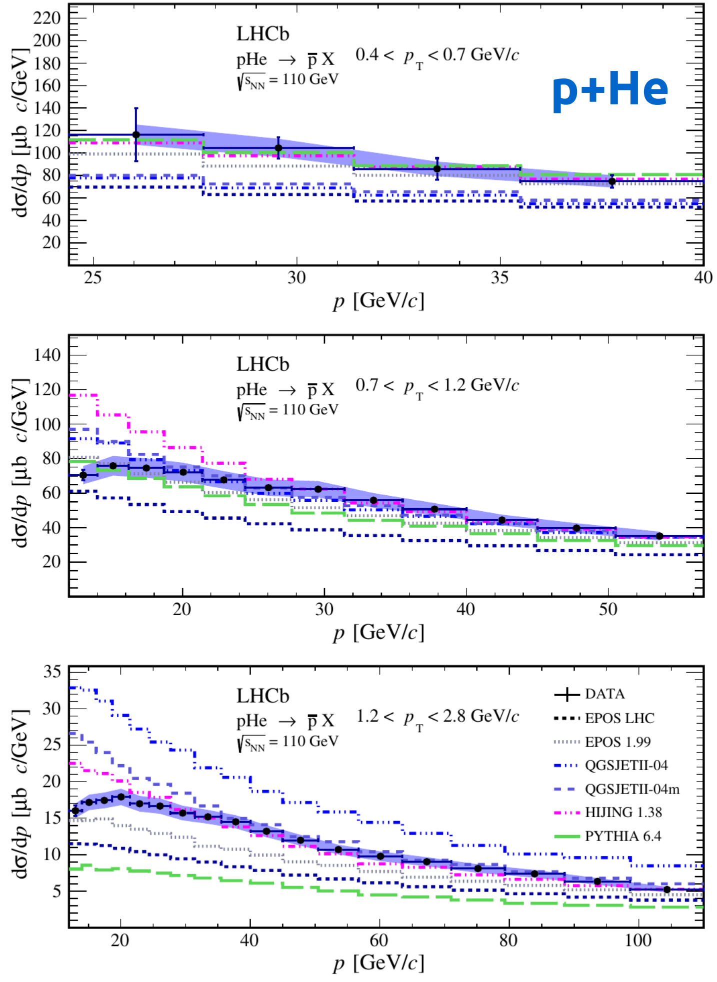
Tuned on astrophysical measurements



Constraining background to DM searches

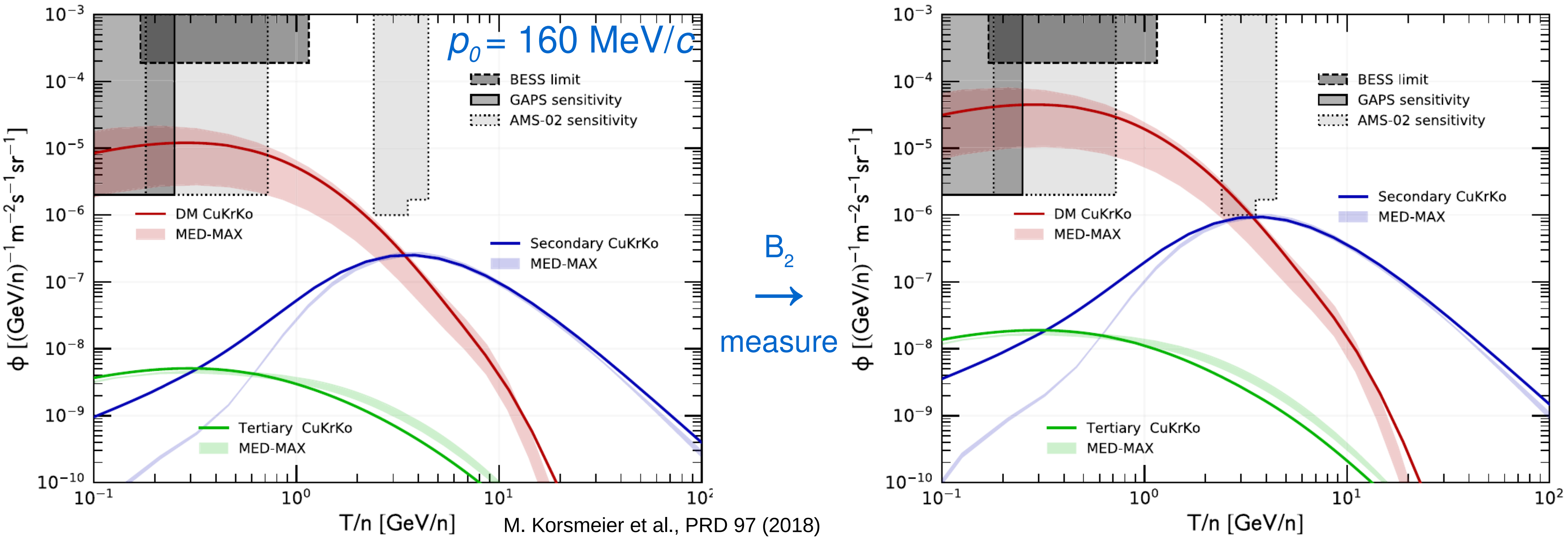
Fixed target experiment with the LHCb SMOG system

- Versatile collision system
- **Energy scale** $\sqrt{s_{NN}}$ = 110 GeV typical of the cosmic ray collisions with the InterStellar Matter
- Accessible range of the anti-proton kinematic spectrum of interest for cosmic processes
- **Crucial measurements** for improving the precision of the **secondary $\bar{p}$ cosmic ray flux** prediction
- Critical to interpret measurement of spaceborn experiments



LHCb, Phys. Rev. Lett. 121, 222001

B_2 measurement improving DM searches



M. Korsmeier et al., PRD 97 (2018)

- Predictions are updated with LHC coalescence parameter measurements
- Coalescence momentum p_0 constrained:
- Predictions for DM signal **increased by >10x**
- Predictions for background flux **increased by 2-3x**

$$B_2 = \frac{m_d}{m_p m_n}\frac{\pi p_0^3}{6}$$

B_2 ~ 0.01 → p_0 ~ 250 MeV/c

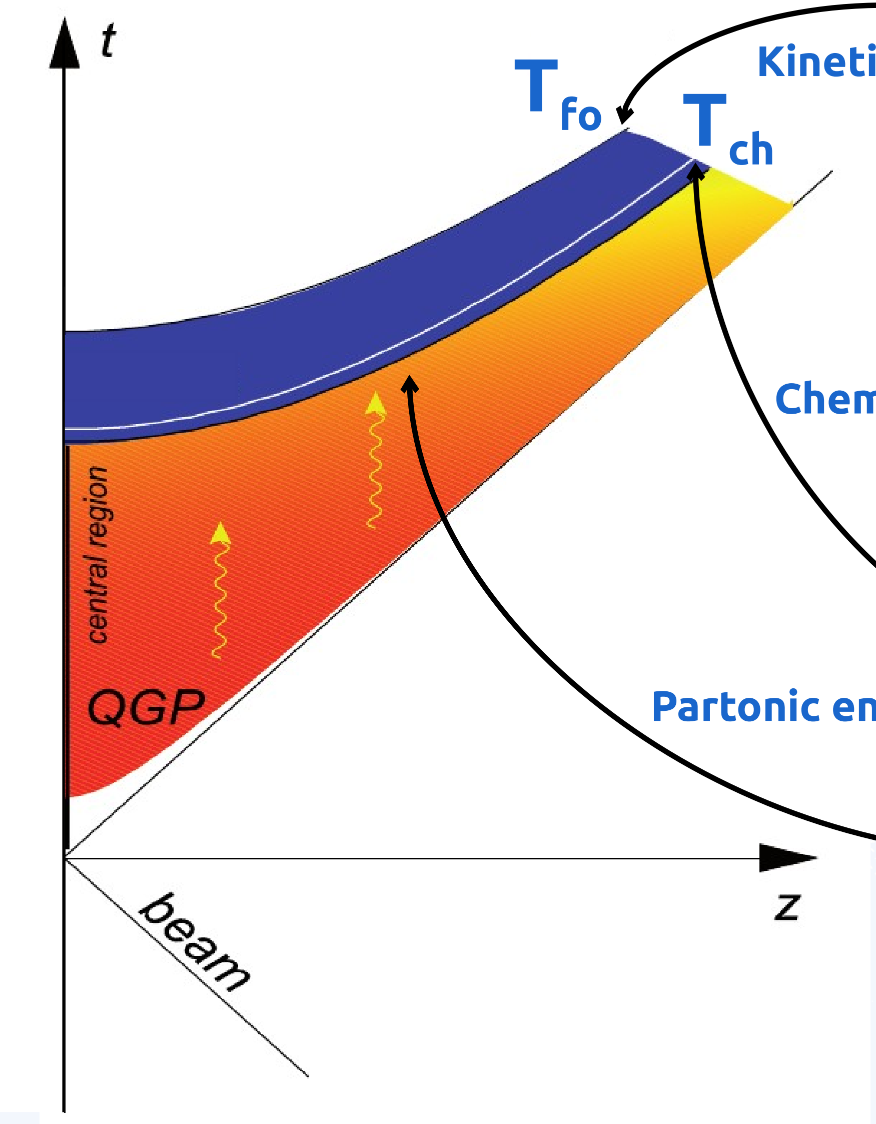
Conclusions and outlook

Heavy ion collisions can be used as a large set of ”tools”

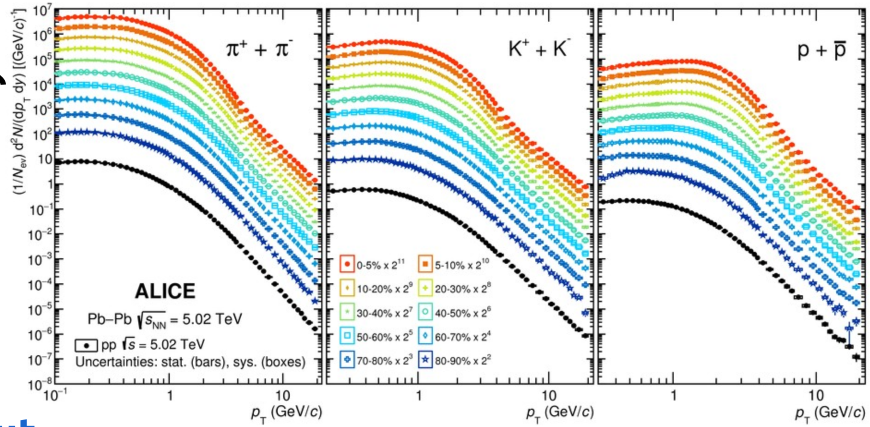
- Understanding of **soft and hard QCD** processes
  - AA, pA, pp are to be seen as a single block they are all needed to understand the underlying dynamics
- **Antimatter factories** to explore detector effects and contribute to **dark matter searches →** needed from experiments at the collider:
  - Understand antinuclei formation in DM decays
  - Understand antinuclei formation in background reactions
  - Understand interaction of antinuclei with matter to determine the transparency of the galaxy

Future experiments with upgraded detectors will collect data at higher luminosity and providing measurements with **unprecedented precision**!

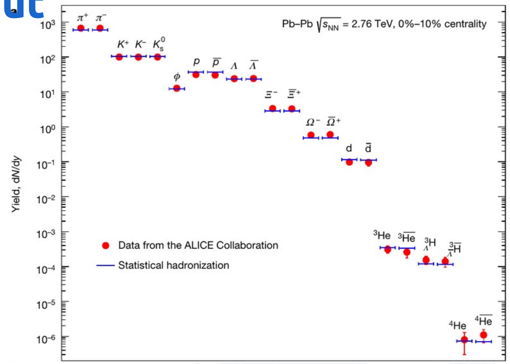
- Focus will be on **hard probes** (charm and beauty quarks) and on **rare probes** (light nuclei and hypernuclei)
- Impact will be more incisive also on dark matter searches!



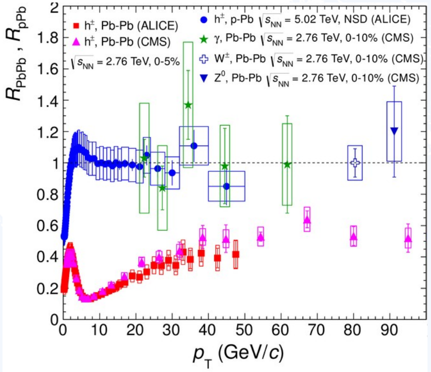
Kinetic freeze-out



Chemical freeze-out



Partonic energy loss



And way way more!