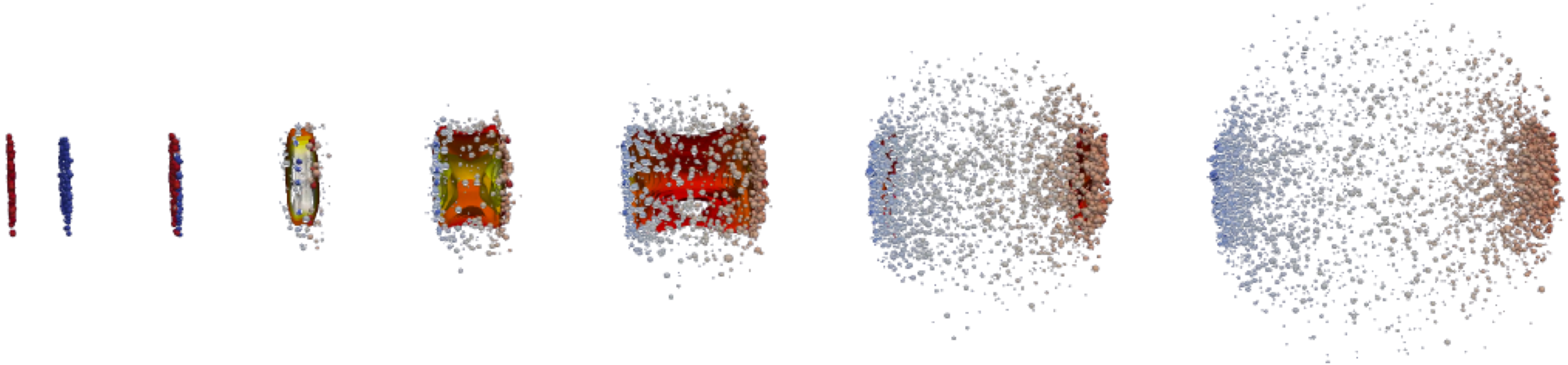
Ultra-relativistic heavy-ion physics



[MADAI collab.]

Alexander Kalweit, *CERN*

XXXII International seminar of nuclear and subnuclear physics "Francesco Romano", Otranto 2021

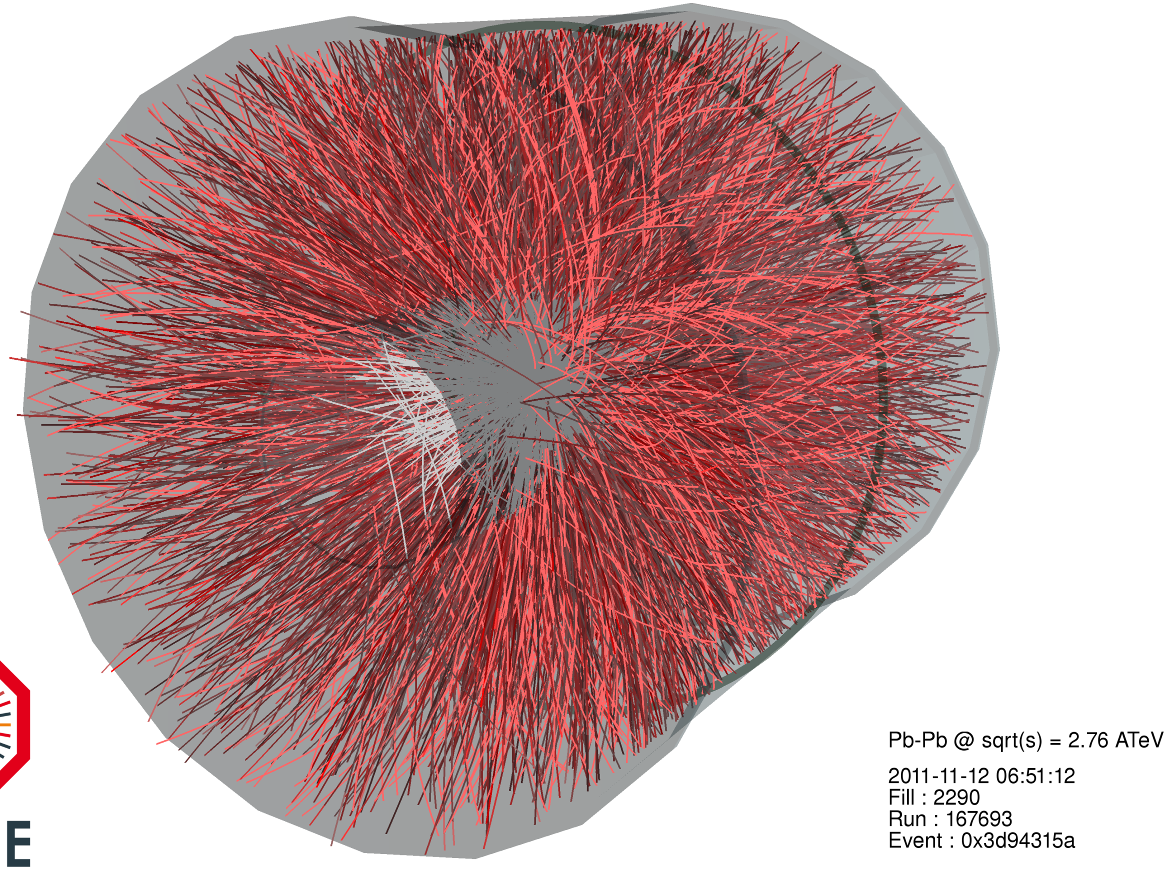
Overview

- Two lectures today:
  - **09:00h → 10:50h**
  - **15:00h → 16:00h**

- 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, Francesca Bellini



Outline of this lecture

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

"Soft" probes

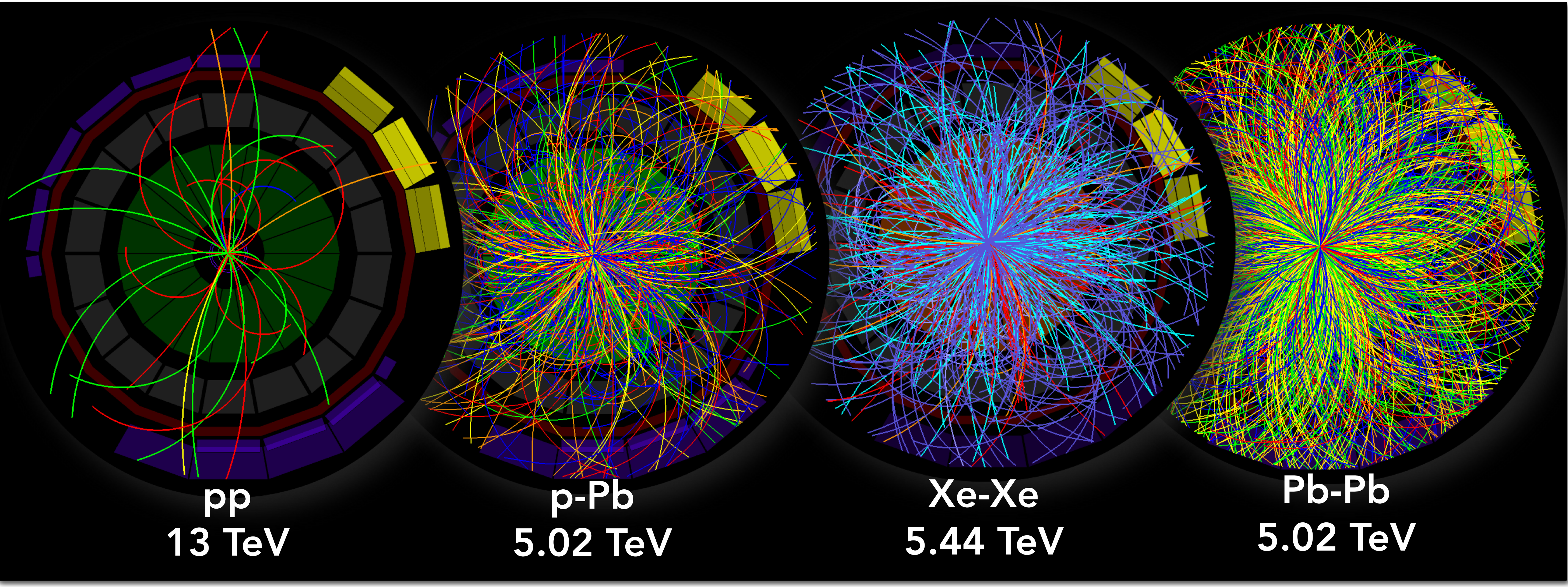
"Hard" probes

→ 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 topics.

Introduction

pp / p-Pb / Pb-Pb collisions

- The LHC can not only collide protons on protons, but also heavier ions.
- Approximately one month of running time is dedicated each year to heavy-ions.



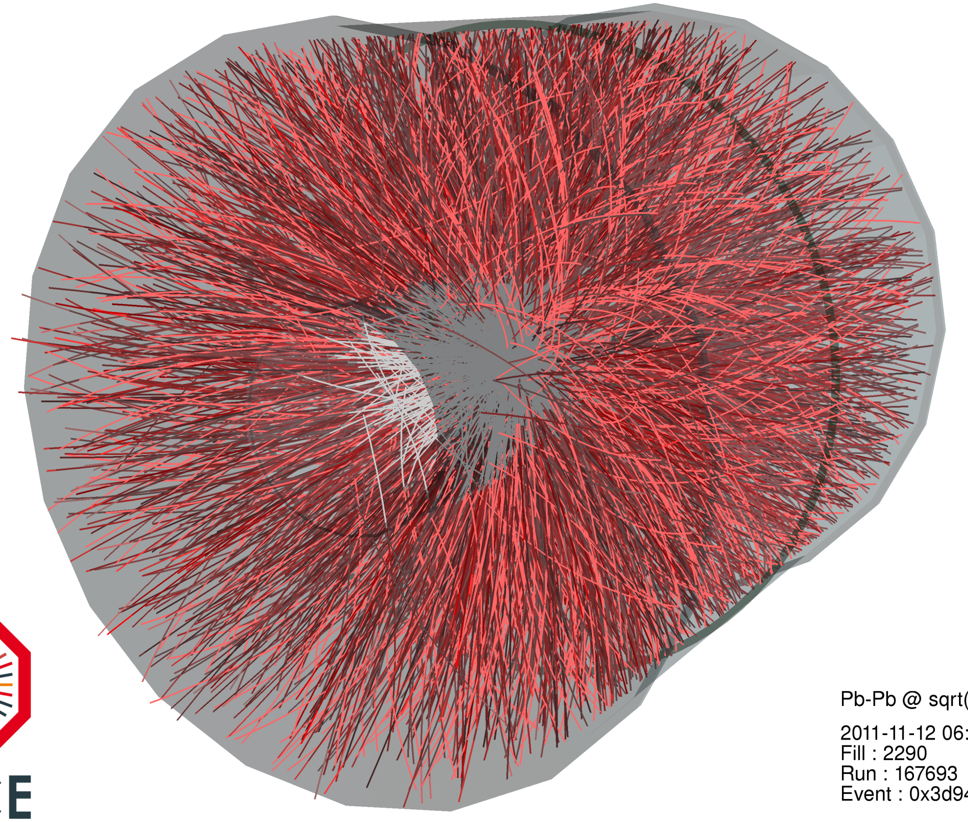
Heavy-ions at the LHC

Energy per nucleon in a ${}^{208}_{82}$Pb-Pb collision at the LHC (Run 1):

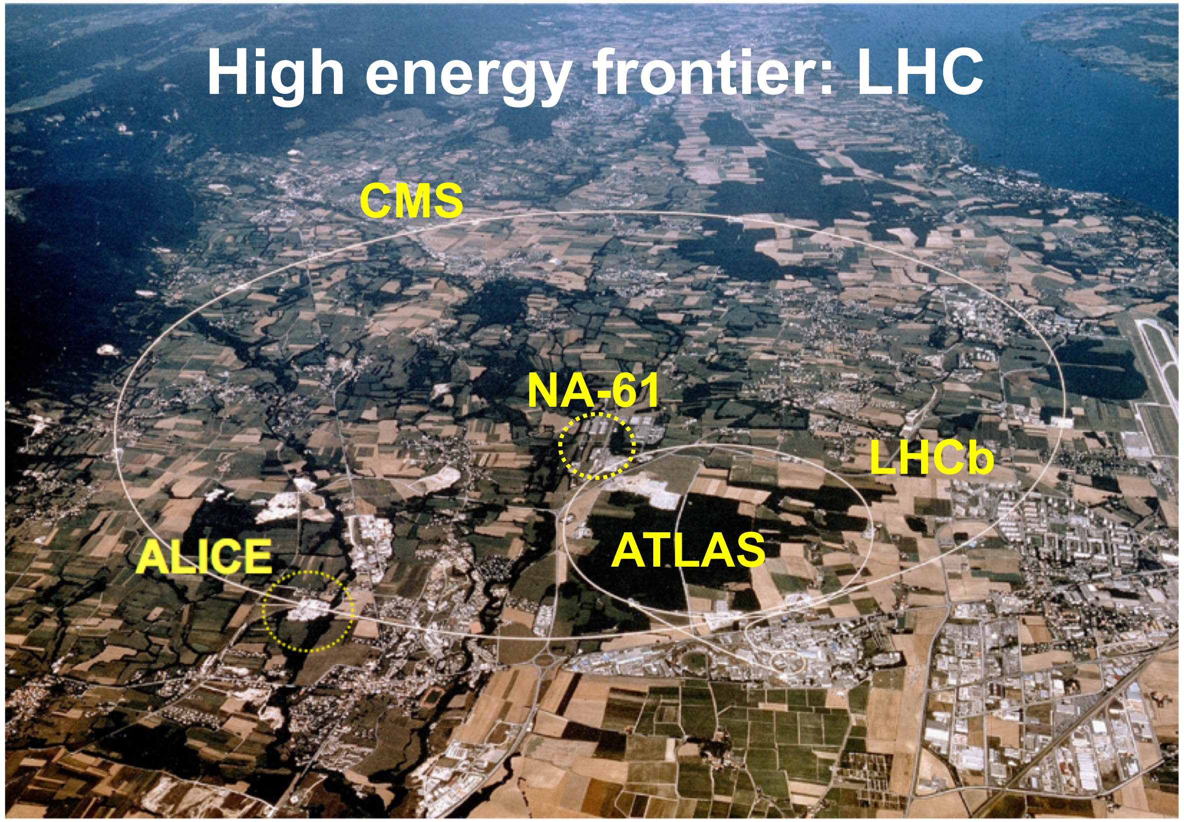
- pp collision energy $\sqrt{s}$ = 7 TeV
- beam energy in pp E_{beam} = 3.5 TeV
- Beam energy per nucleon in a Pb-Pb nucleus: $E_{beam,PbPb}$ = 82/208* 3.5 = 1.38 TeV
- Collision energy per nucleon in Pb-Pb: $\sqrt{s_{NN}}$ = 2.76 TeV
- Total collision energy in Pb-Pb: **$\sqrt{s}$ = 574 TeV**
- Run 2: $\sqrt{s_{NN}}$ = 5.02 TeV and thus **$\sqrt{s}$ = 1.04 PeV**

→ What can we learn from these massive interactions?

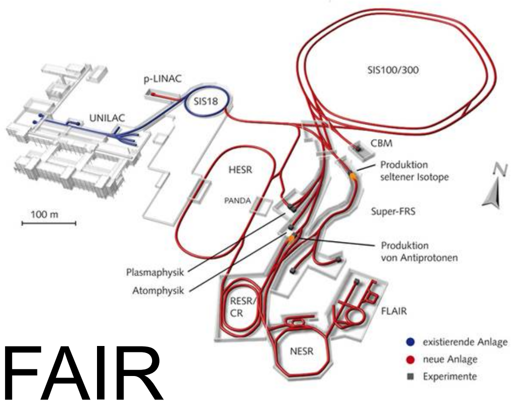
ALICE
A JOURNEY OF DISCOVERY



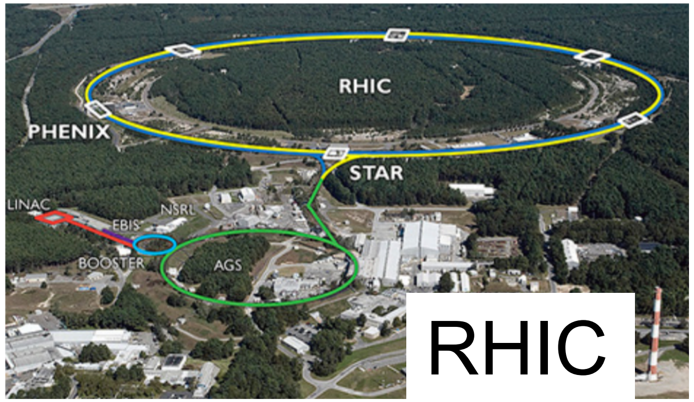
Heavy-ion experiments



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



FAIR



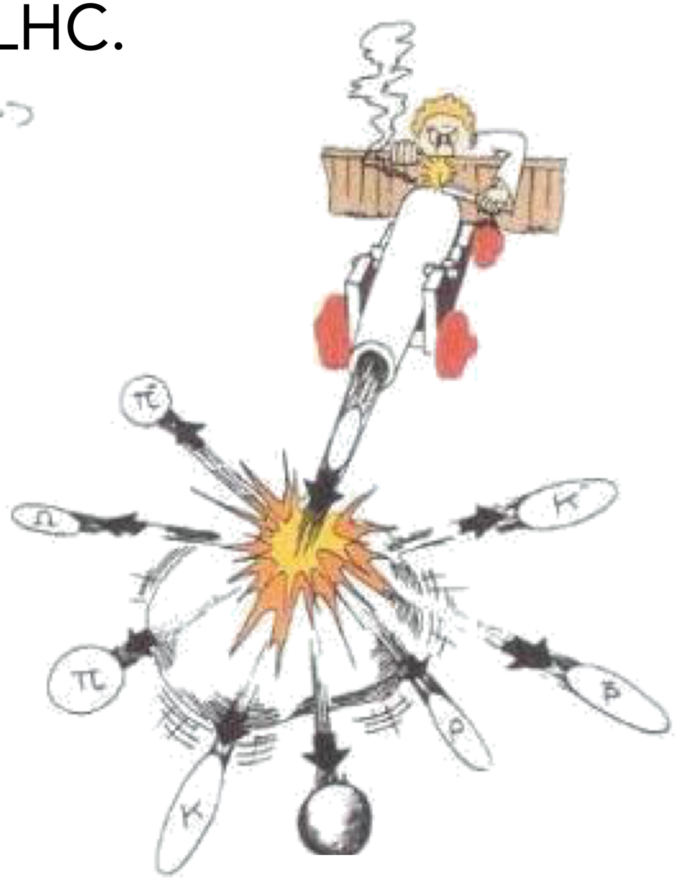
→ By now **all major LHC experiments have a heavy-ion program**: LHCb took Pb-Pb data for the first time in November 2015.

Increasing the beam energy over the last decades…

..from early fixed target experiments at GSI/Bevalac and SPS to collider experiments at RHIC and LHC.

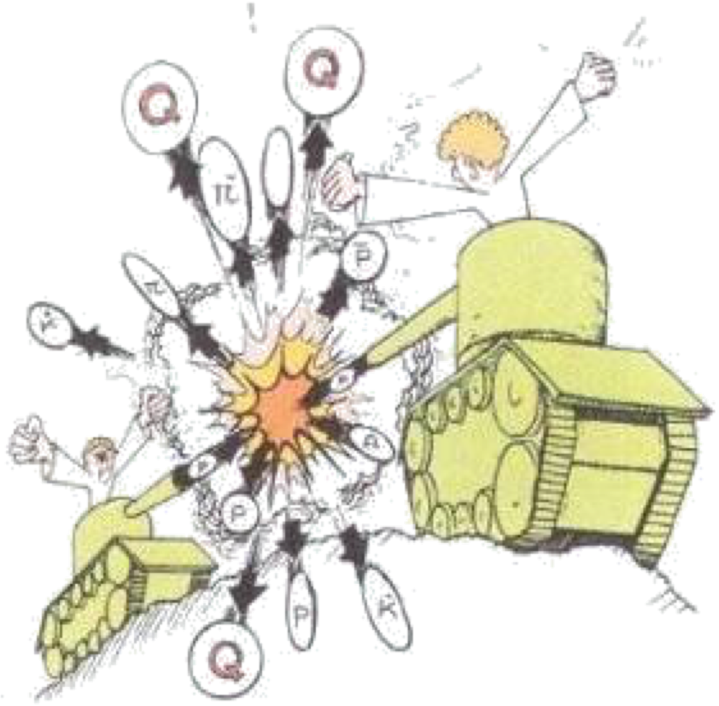
SIS

GSI Darmstadt, $\sqrt{s_{NN}}$~2.4 GeV



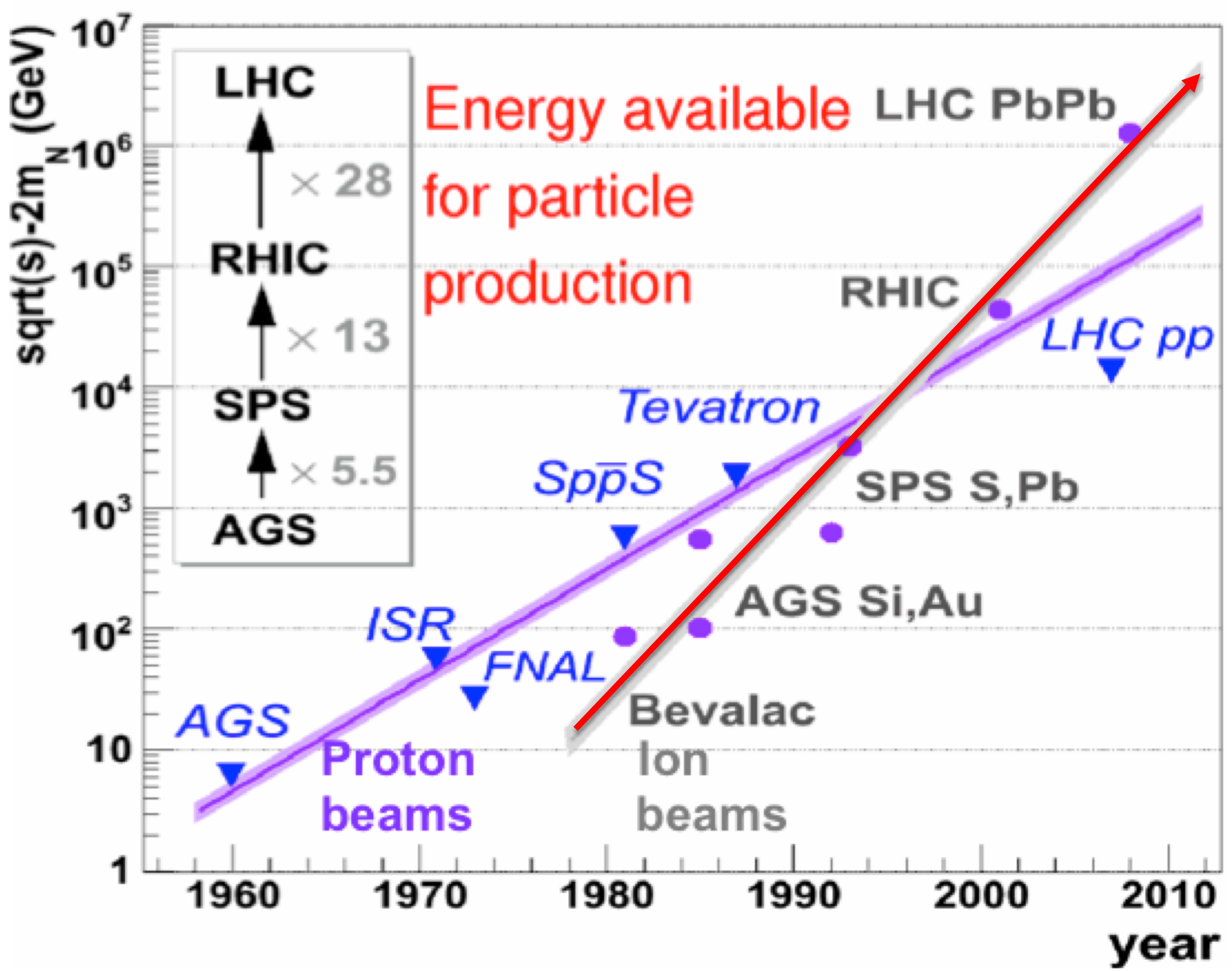
SPS

CERN, $\sqrt{s_{NN}}$~6-20 GeV



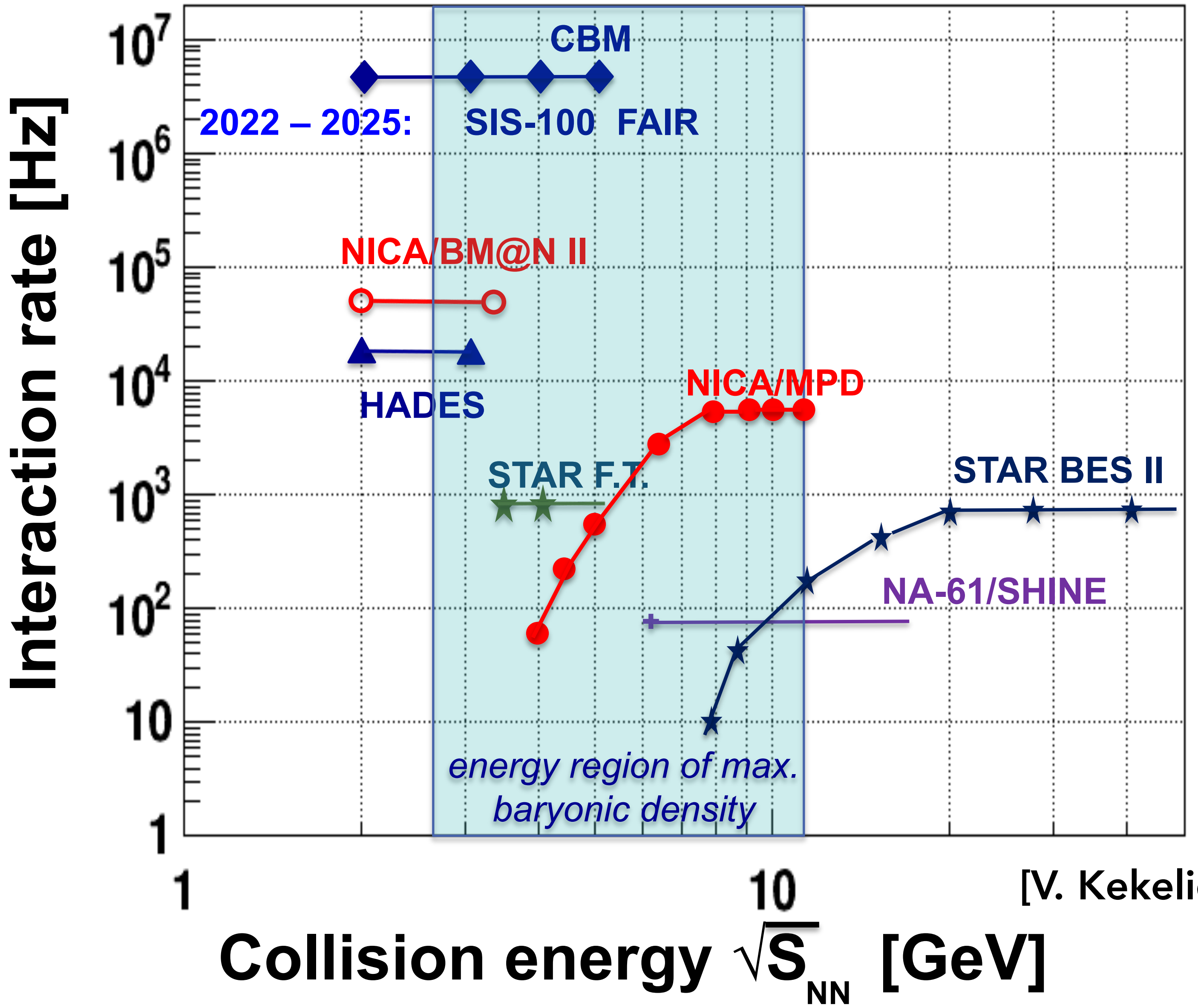
RHIC/LHC

Brookhaven → RHIC $\sqrt{s_{NN}}$~8-200 GeV (BES)
CERN → LHC $\sqrt{s_{NN}}$ = 5.02 TeV



Energy available for particle production
sqrt(s)-2m_N (GeV)
year
LHC
RHIC
SPS
AGS
× 28
× 13
× 5.5
LHC PbPb
RHIC
LHC pp
Tevatron
SPS S,Pb
SppS
AGS Si,Au
ISR
FNAL
AGS
Bevalac
Proton beams
Ion beams
1960
1970
1980
1990
2000
2010

Energy ranges covered by different non-LHC accelerators



[V. Kekelidze, SQM2017 talk]

→ Collider experiments allow for very high $\sqrt{s_{NN}}$ and fixed target experiments allow for very high interaction rates at lower $\sqrt{s_{NN}}$.

LHC Run 2

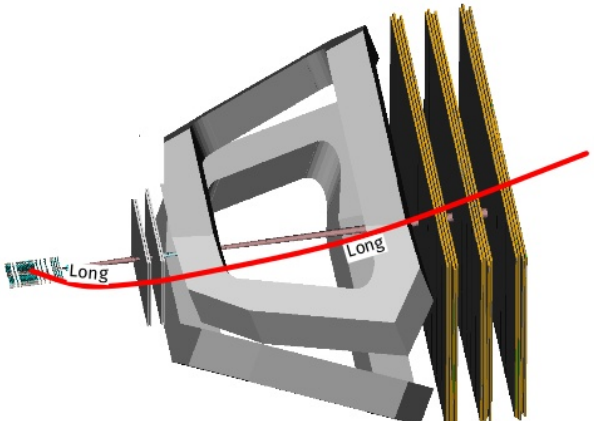
- LHC Run 2 data taking is now completed and the analysis is now in full swing.
- Significant increase in integrated luminosity (approx. 4 times in Pb-Pb) allow more **precise investigation of rare probes**.
- Various collision systems at different center-of-mass energies are ideally suited for **systematic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

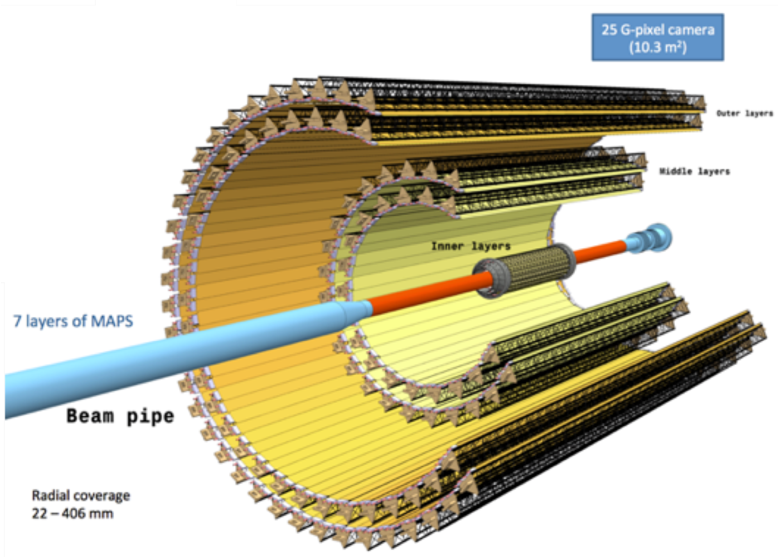
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	2018	5.02	~0.9 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}

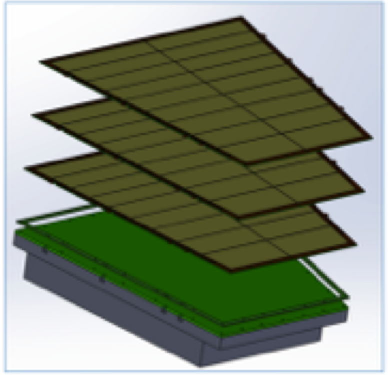
LHC Run 3 and 4

Major detector upgrades in long shutdown 2 (2019-2021) 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

The QCD phase transition

The standard model

The standard model describes the **fundamental** building blocks of matter (Quarks and Leptons) and their Interactions:

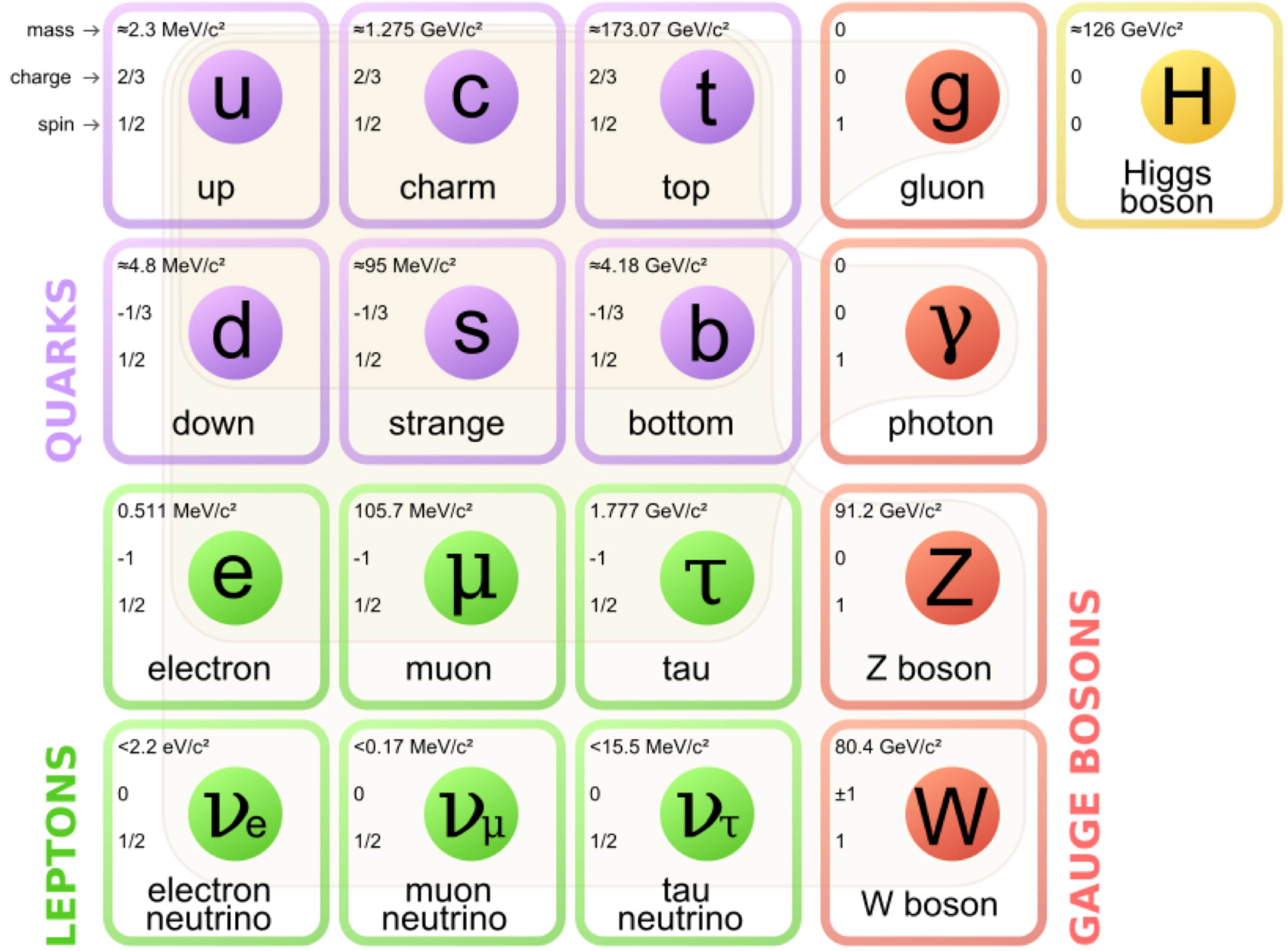
1. Elektromagnetic: γ
2. Weak interaction: W&Z
3. **Strong interaction: Gluons**
4. Gravitation: Graviton?

Dramatic confirmation of the standard model in the last years at the LHC: discovery and further investigation of the Higgs-Boson.

However, no signs of physics beyond the standard model were found so far (SUSY, dark matter..).

→ In heavy-ion physics, we investigate physics within the standard model and not beyond it.

→ Discovery potential in **many body phenomena of the strong interaction** (as in QED and solid state physics: magnetism, electric conductivity, viscosity,..)!



[https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg]

Heavy-ions and Quantum Chromodynamics

Heavy-ion physics is the physics of *high energy density Quantum Chromodynamics (QCD):*

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

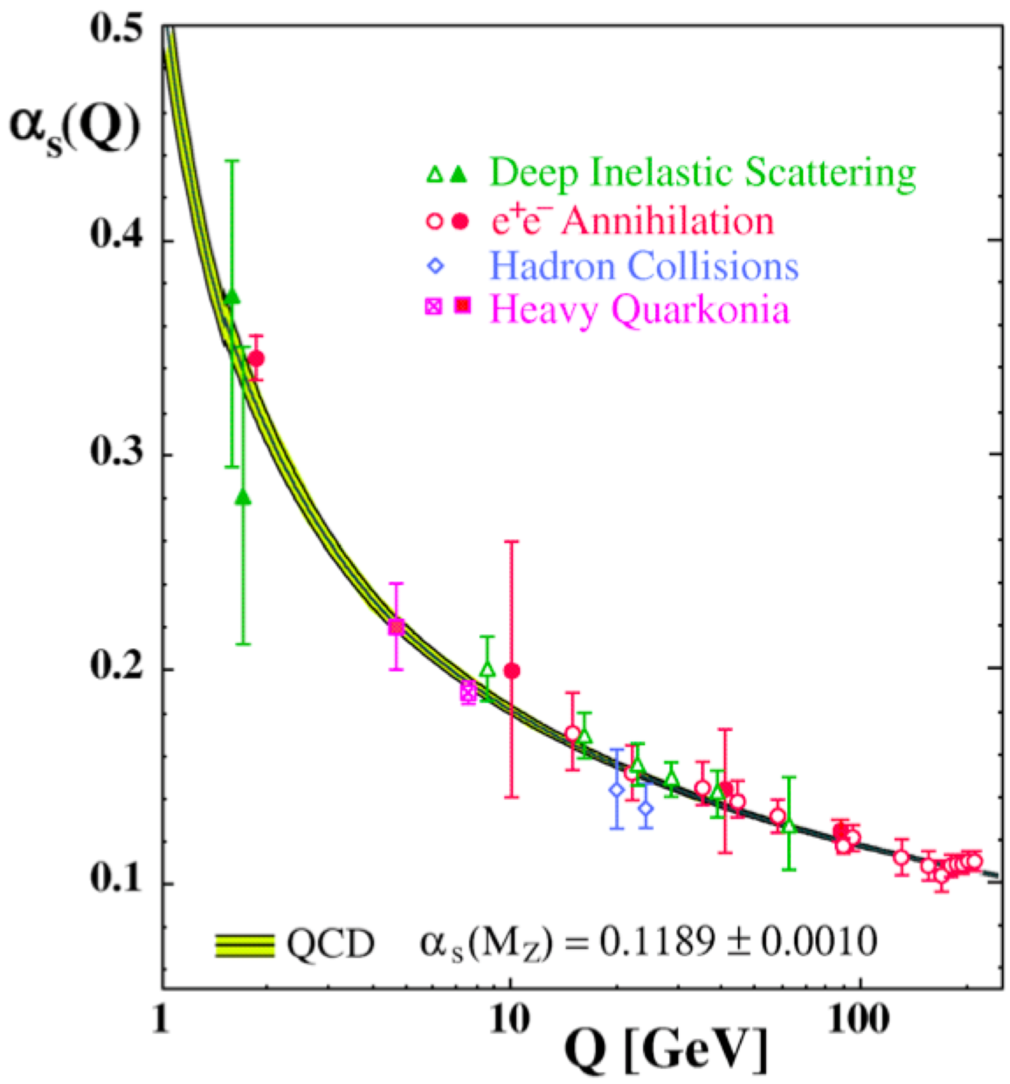
Quark-field | Quark-mass | Gluon field strength

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.

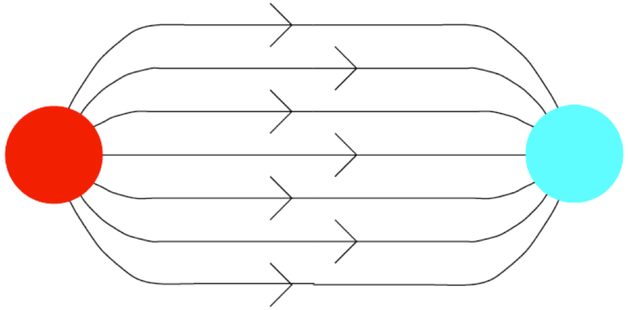


[Prog.Part.Nucl.Phys. 58 (2007) 351-386]

(De-)confinement (1)

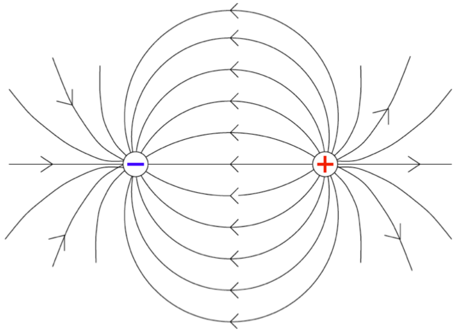
- QCD vacuum:
  - Gluon-gluon self-interaction (non abelian) → in contrast to QED
  - QCD field lines are compressed in a flux tube

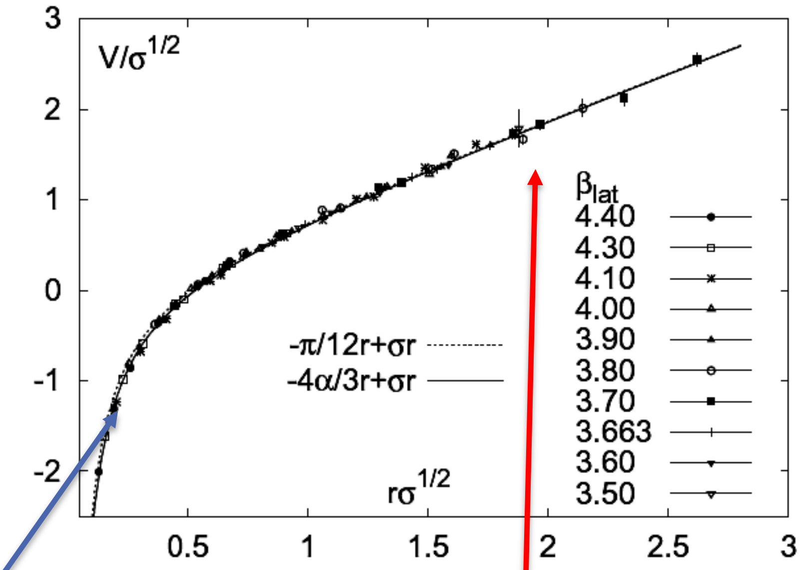
QCD q



$\bar{q}$

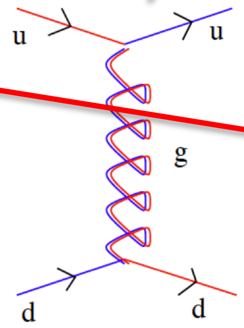
QED

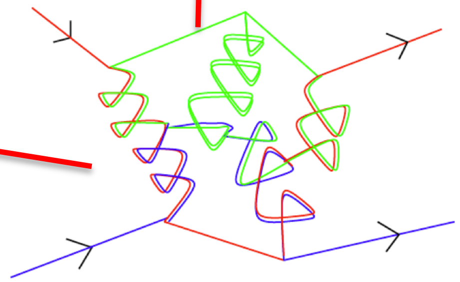




- Potential grows linearly with distance
  → ***Cornell potential:***

$$V(r) = -\frac{A(r)}{r} + Kr$$

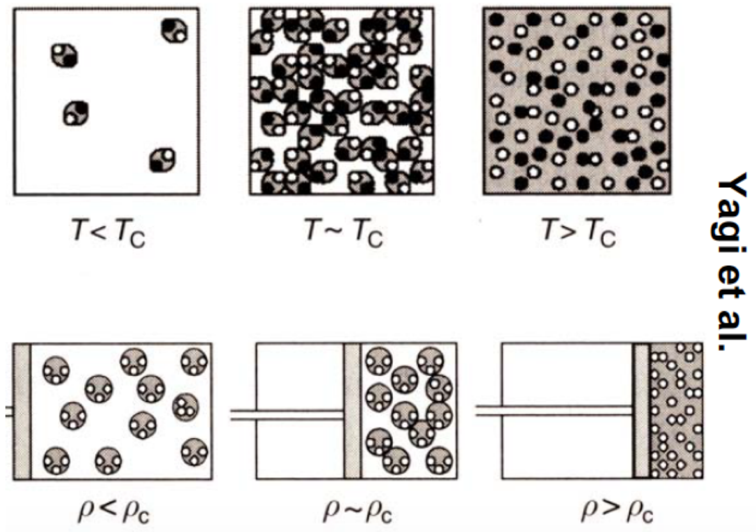


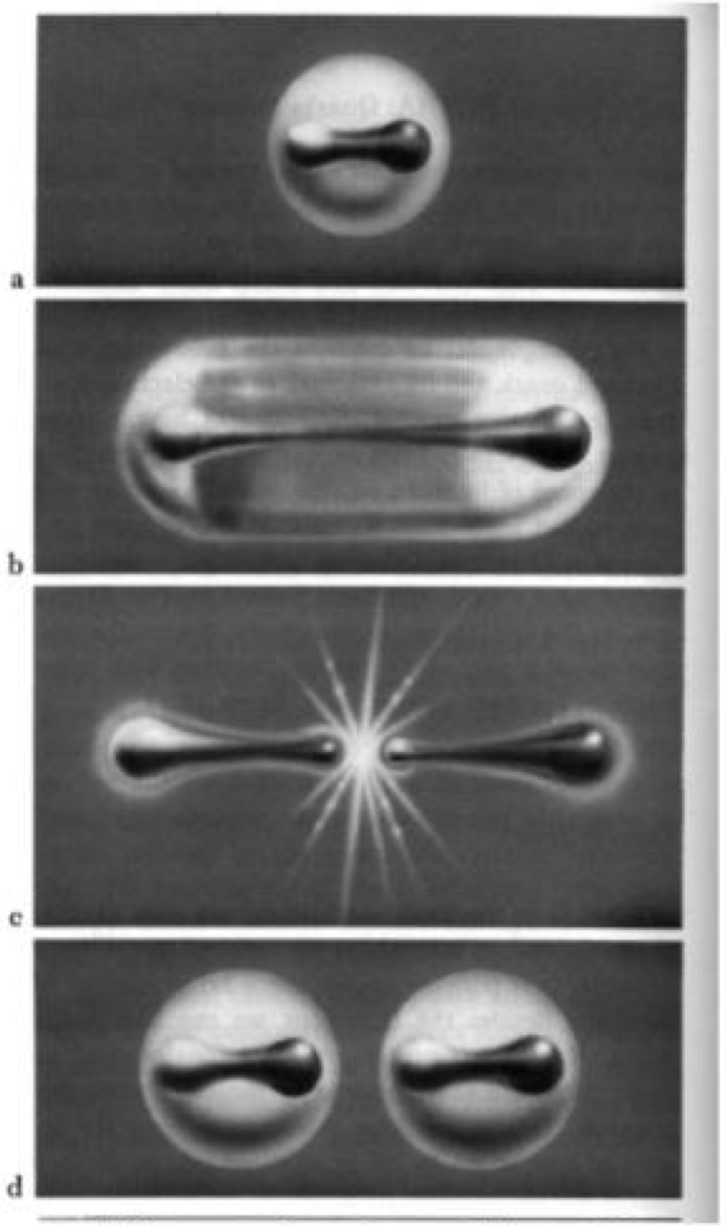


- "String tension" is huge:
  K ~ 880 MeV/fm

(De-)confinement (2)

- Pulled apart, the energy in the string increases.
- New q-qbar is created once the energy is above the production threshold as it is energetically more favorable than increasing the distance further.
- No free quark can be obtained → confinement.
- Percolation picture: at high densities / temperatures, quarks and gluons behave quasi-free and *color conductivity* can be achieved: Quark-Gluon-Plasma (QGP).





[illustration from Fritzsch]

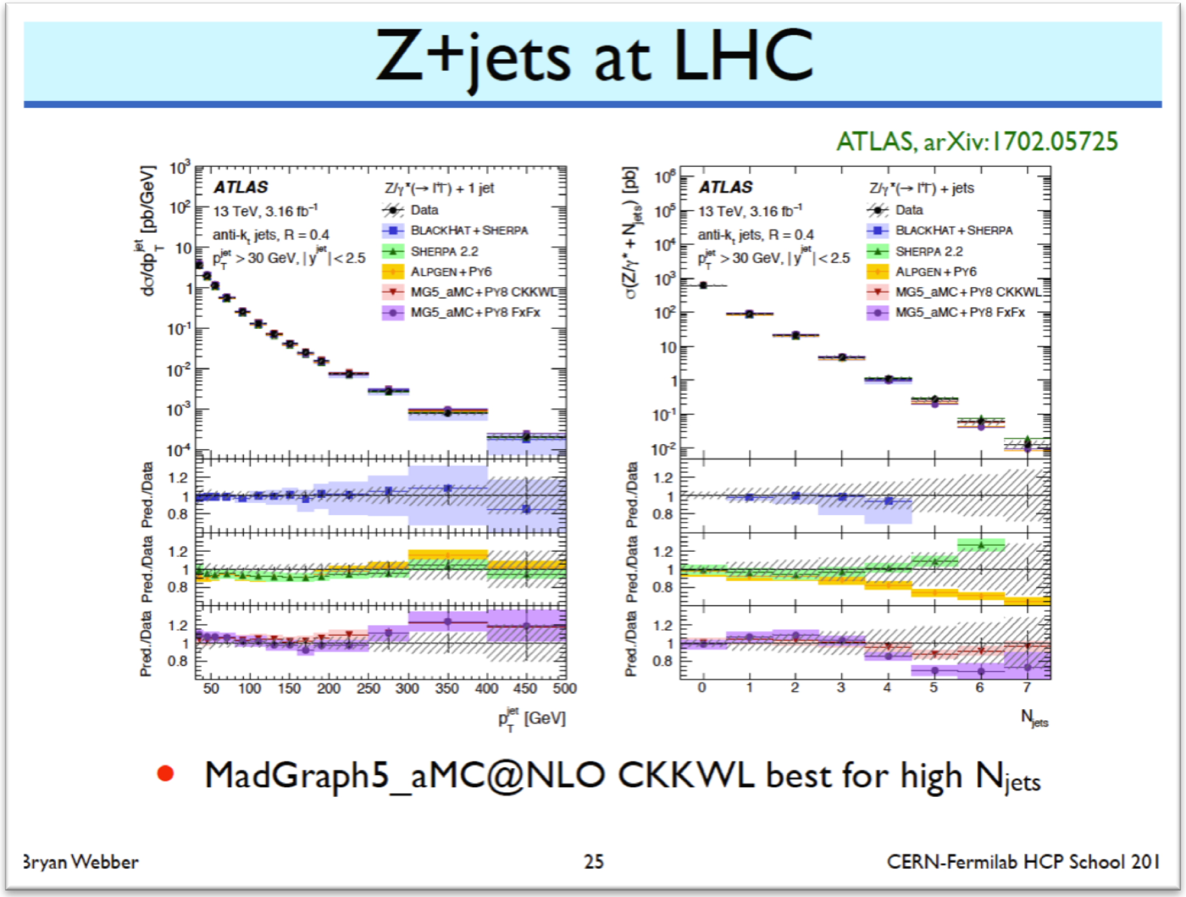
Ab-initio QCD calculations

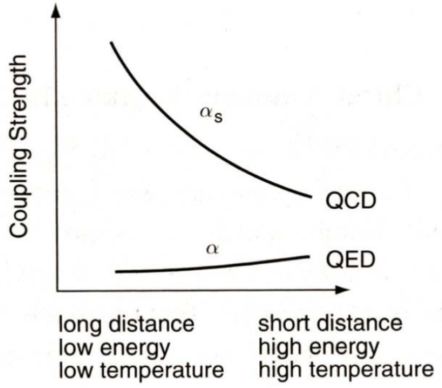
- *Ab-initio*: a calculation without modeling (and model parameters), but directly derived from the basic theory and only based on fundamental parameters.

- In QCD, there are two *ab-initio* approaches relevant for heavy-ion physics:
  - Perturbation theory: **pQCD**
  - Lattice QCD: **LQCD**

- Perturbation theory is only applicable for small values of α_S:
  → only possible for large momentum transfers as in jets.

- **(De-)confinement** cannot be described by pQCD, but with LQCD!





Soft and hard probes (1)

Phenomenologically, we can distinguish:

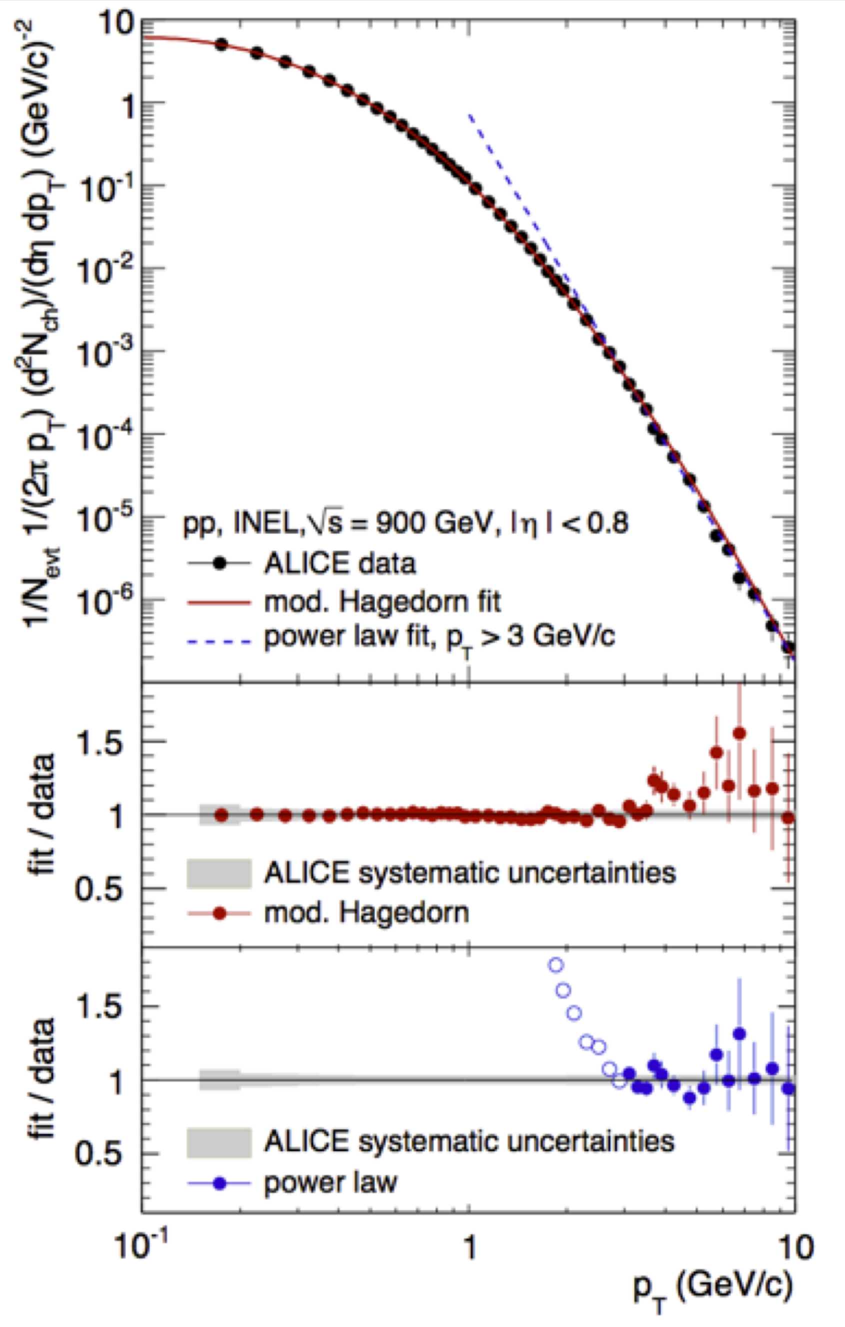
A *thermal* (*soft QCD*) part of the transverse momentum spectrum which **contains most of the yield** and shows roughly an exponential shape (thermal-statistical particle chemistry and flow).

A *hard part* (power-law shape, **pQCD**) which is studied in jet physics (energy loss mechanisms etc., R_{AA} in heavy-ion physics)

→ Even at LHC energies ~98% of all particles are produced at $p_T < 2$ GeV/c.

→ ~80% are pions, ~13% are kaons, ~4% are protons.

→ The ***bulk*** of the produced particles is not accessible with pQCD methods.



Soft and hard probes (2)

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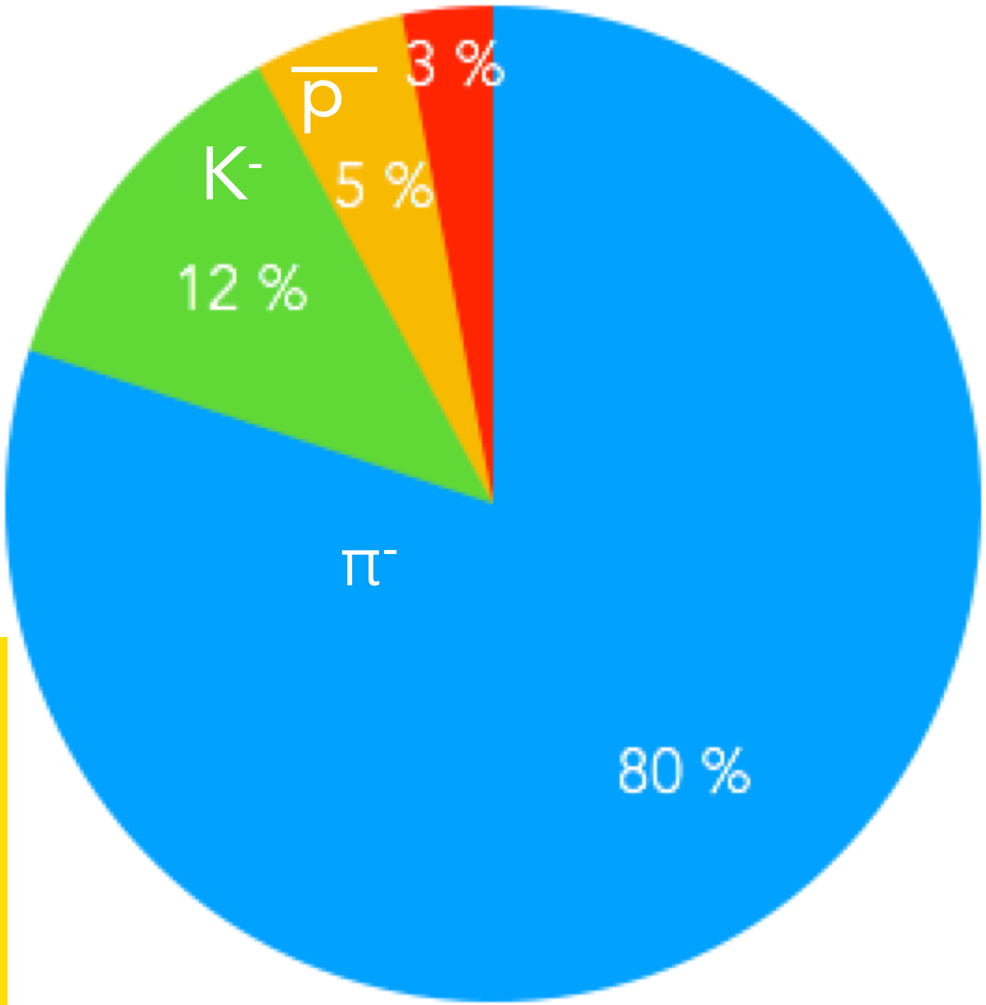
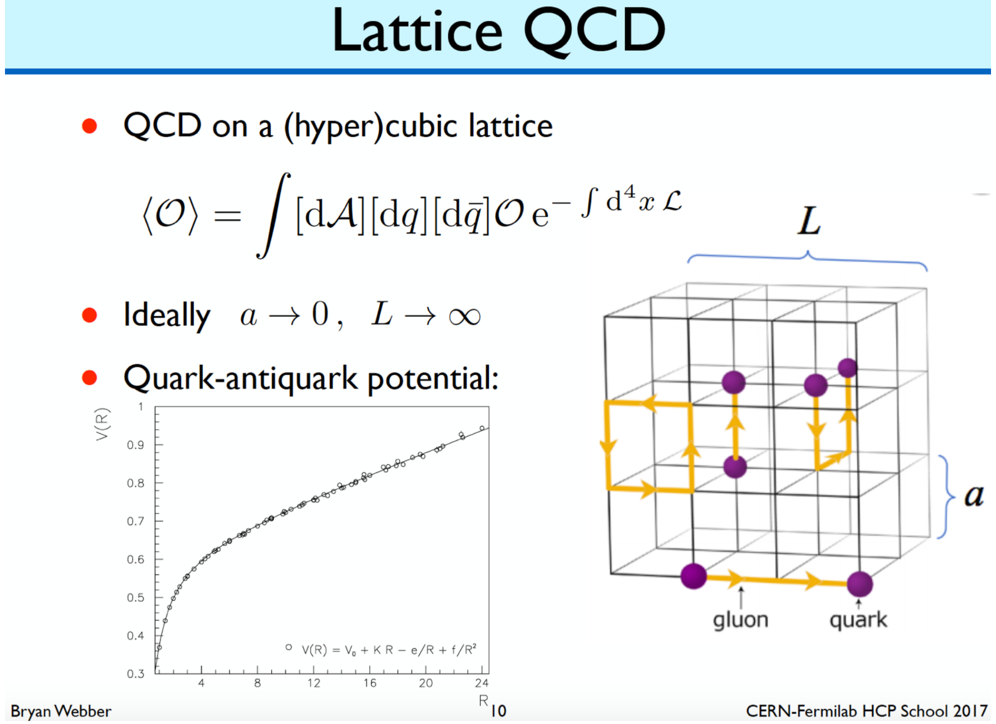
(negative particles)



Lattice QCD (LQCD)

- Solve QCD **numerically** by discretizing Lagrangian on a space-time grid.
- Static theory, no dynamical calculations possible as computations are done in imaginary time ($\tau \rightarrow i\tau$).
- Only directly applicable (extrapolation methods exist) to systems with no net-baryon content:
  number of baryons = number of anti-baryons
  (early universe, midrapidity LHC
  → $\mu_B \approx 0$ MeV)

- Computationally very demanding
  → dedicated supercomputers.

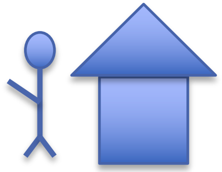


JUGENE in Jülich
(294,912 cores, ~ 1 PetaFLOPSS

QGP as the asymptotic state of QCD (1)

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

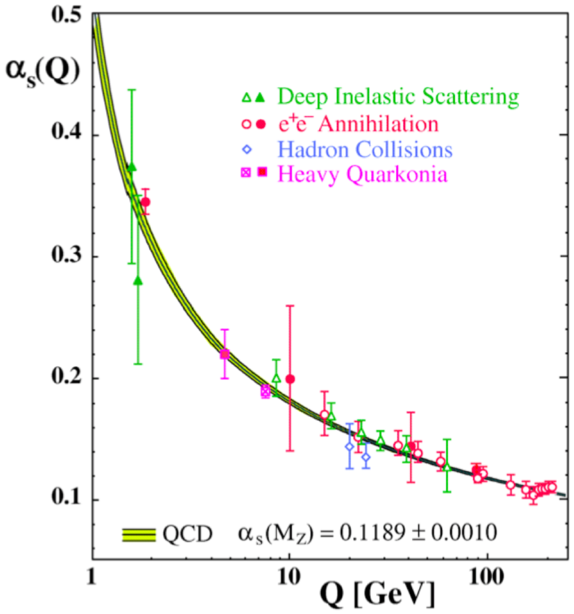
bound quarks & gluons



Asymptotic freedom: *free quarks & gluons*

$T \rightarrow \infty$

Temperature T



QGP as the asymptotic state of QCD (2)

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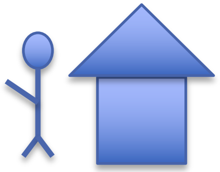


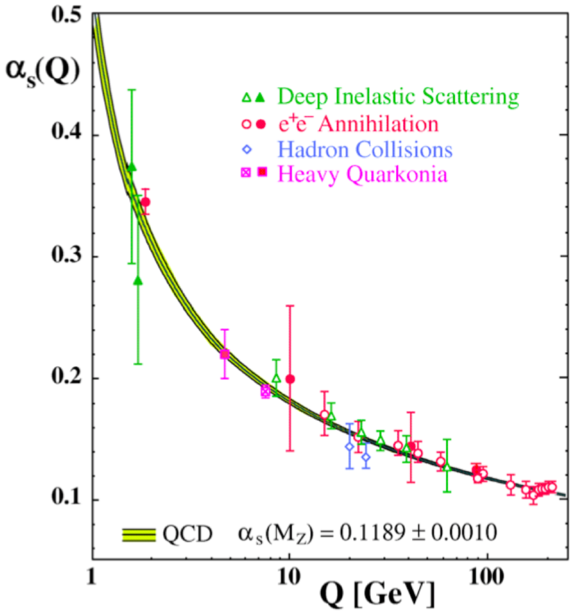
Where is the phase transition?
→ Lattice QCD

Asymptotic freedom: *free quarks & gluons*

$T_0 \approx 1/40$ eV

$T \to \infty$

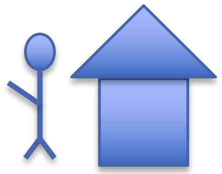
Temperature T



QGP as the asymptotic state of QCD (3)

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*

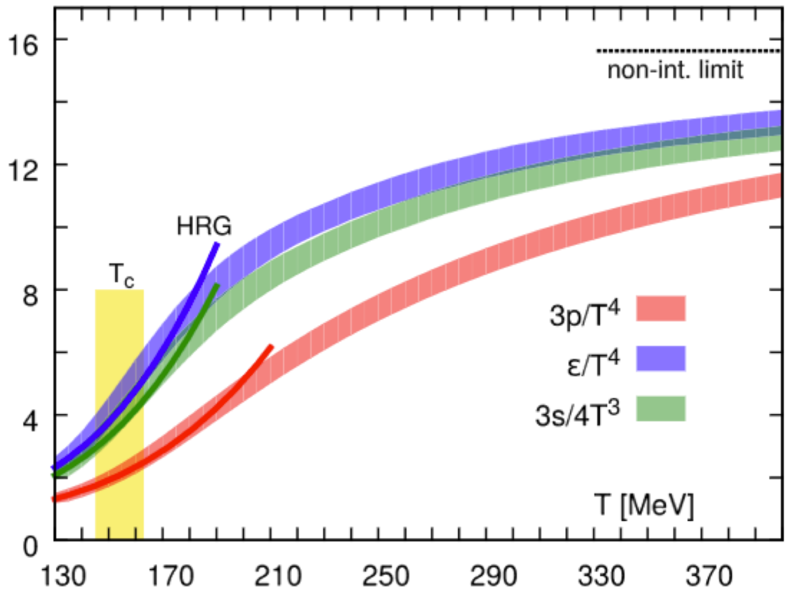
$T_0 \approx 1/40$ eV

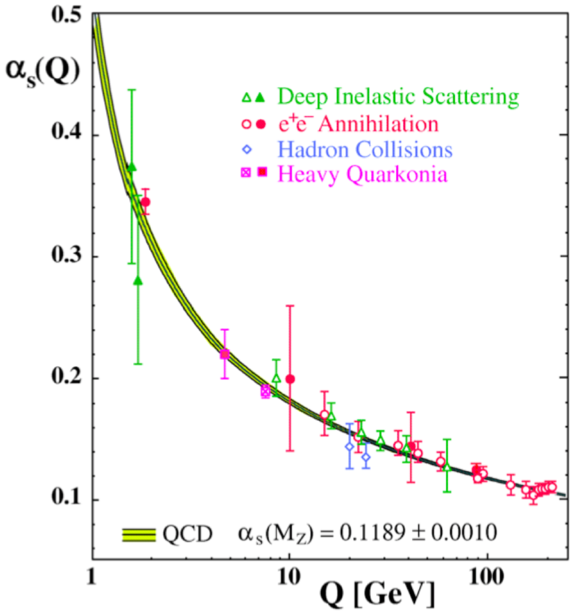
Critical temperature
$T_c \approx 156$ MeV

$T \rightarrow \infty$

Temperature T

[PRD 90 094503 (2014)]





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

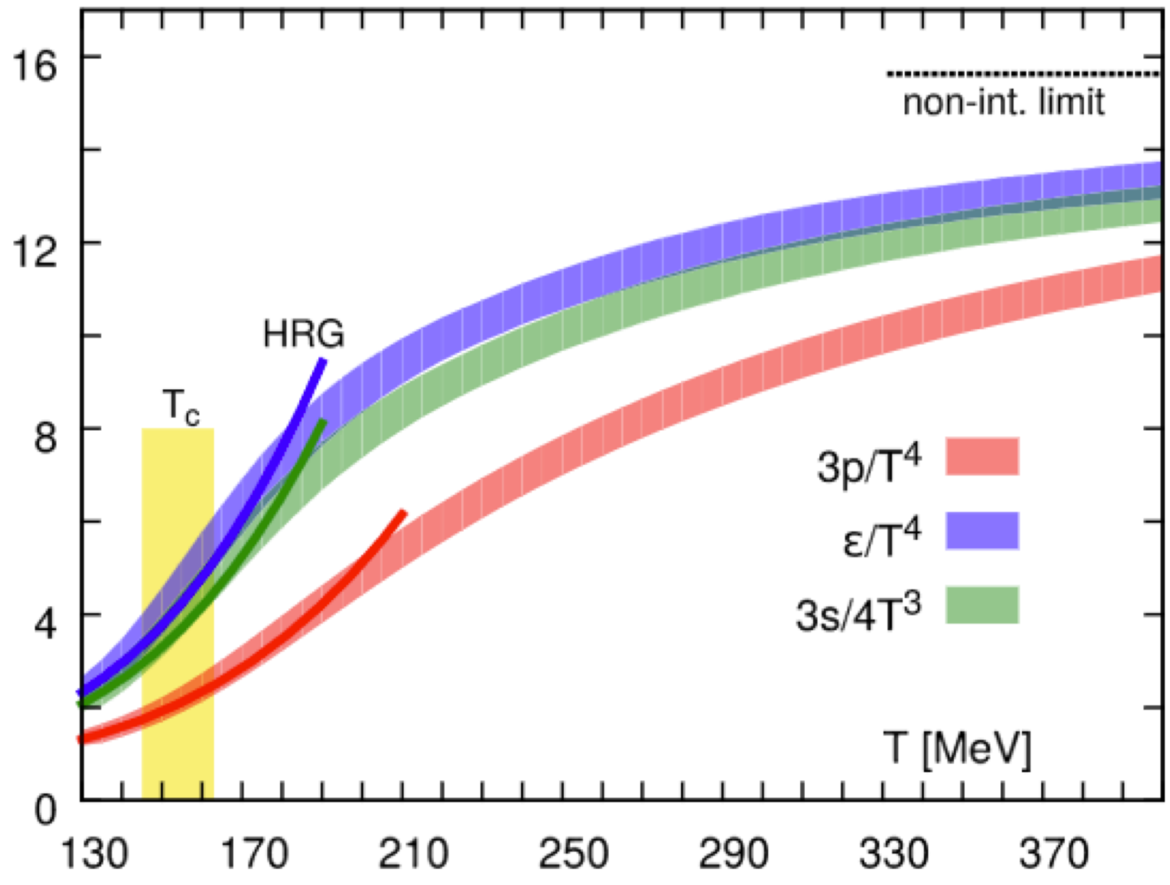
Phase transition in Lattice QCD

Critical temperature
$T_c \approx$ 156 +/- 9 MeV

[PRD 90 094503 (2014)]

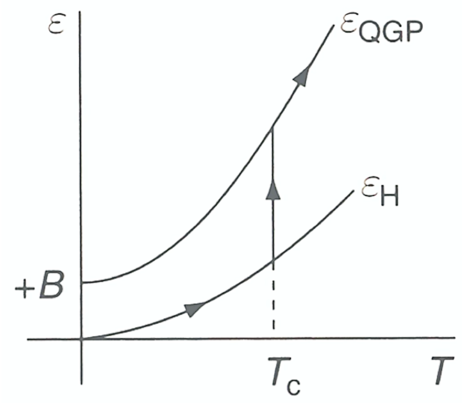
Steep rise in thermodynamic quantities due to change in number of degrees of freedom → phase transition from **hadronic to partonic** degrees of freedom.

Energy density ε
Pressure p
Entropy density s



For comparison:
T=156 MeV ≙ $1.8 \cdot 10^{12}$ K
Sun core: $1.5 \cdot 10^7$ K
Sun surface: 5778 K

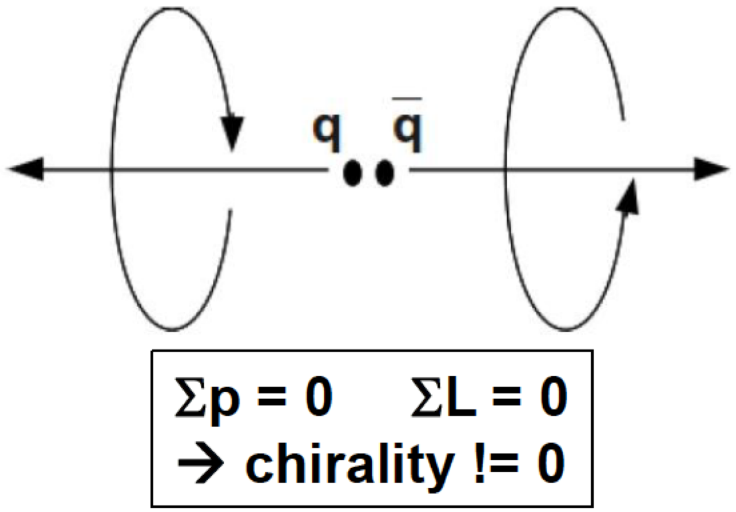
Smooth *crossover* for a system with net-baryon content equal 0. For a *first order phase transition*, the behavior would be not continuous.



Chiral symmetry

- QCD Lagrangian is symmetric under $SU(2)_L \times SU(2)_R$
  → In the dynamics of QCD, the interaction between right handed (spin parallel to momentum vector) and left handed (spin anti-parallel to momentum vector) quarks vanishes *in the case of massless quarks.*

- Light quarks have a finite small bare (current) mass
  → explicit breaking of chiral symmetry.



- Creation of coherent q-qbar pairs in QCD vacuum (as in cooper pairs in superconductivity).
  - Has a non-zero chiral charge
  - Not symmetric under $SU(2)_L \times SU(2)_R$
    → *spontaneous symmetry breaking in the QCD ground state* (pseudo-goldstone boson: pions)

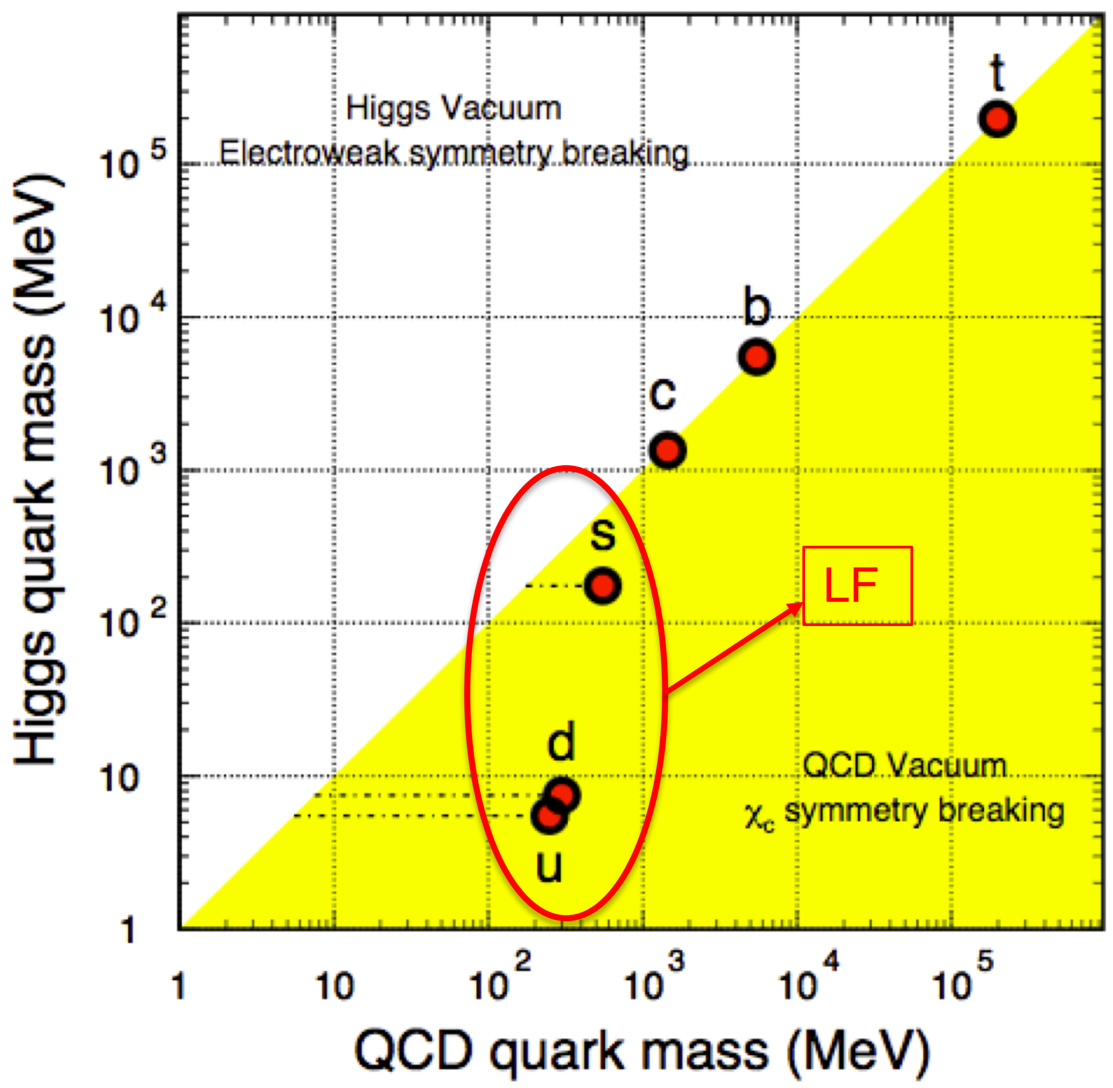
- Quarks acquire ~350 MeV additional (constituent) mass
  - Only relevant for the *light* u,d,s quarks.

Spontaneous breaking of chiral symmetry

- Consequences:
  - Isospin symmetry: constituent quark masses $m_u \approx m_d$ → isospin symmetry
  - Isospin symmetry is not based on a fundamental relation, but due to the fact that the acquired masses are much larger than the bare masses
  - m(nucleon) >> m(bare u+u+d)
    938 MeV >> ~10 MeV

- In the QGP, chiral symmetry is expected to be restored!

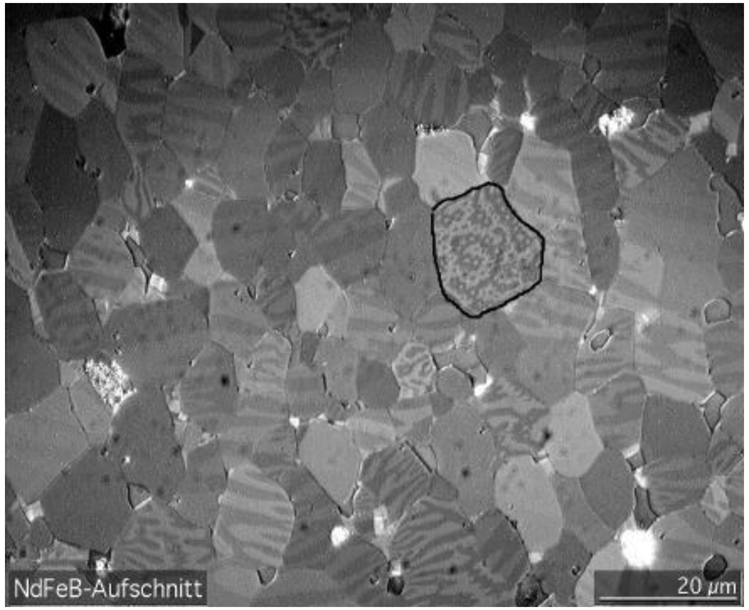
arXiv:nucl-ex/0610043

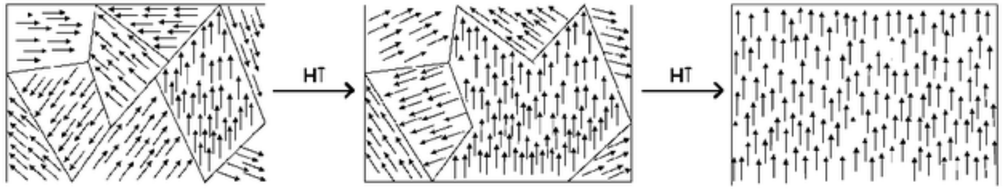


Spontaneous and explicit symmetry breaking

→ Best explained in an analogy to ferromagnetism:

QCD	Ferromagnetism
• chiral symmetry	• symmetry of $\hat{H}$ under rotations of spin axis
• quark-antiquark-condensate $<\overline{\psi}\psi>$	• magnetisation $M = <\uparrow>$
• *explicit symmetry breaking* by current mass m_{curr}	• *explicit symmetry breaking* by external magnetic field h
• *spontaneous symmetry breaking* by constituent mass m_{cons} for $T < T_C$	• *spontaneous symmetry breaking* by quantum mechanical exchange forces for $T < T_C$ (Curie temperature)





Magnetic domains

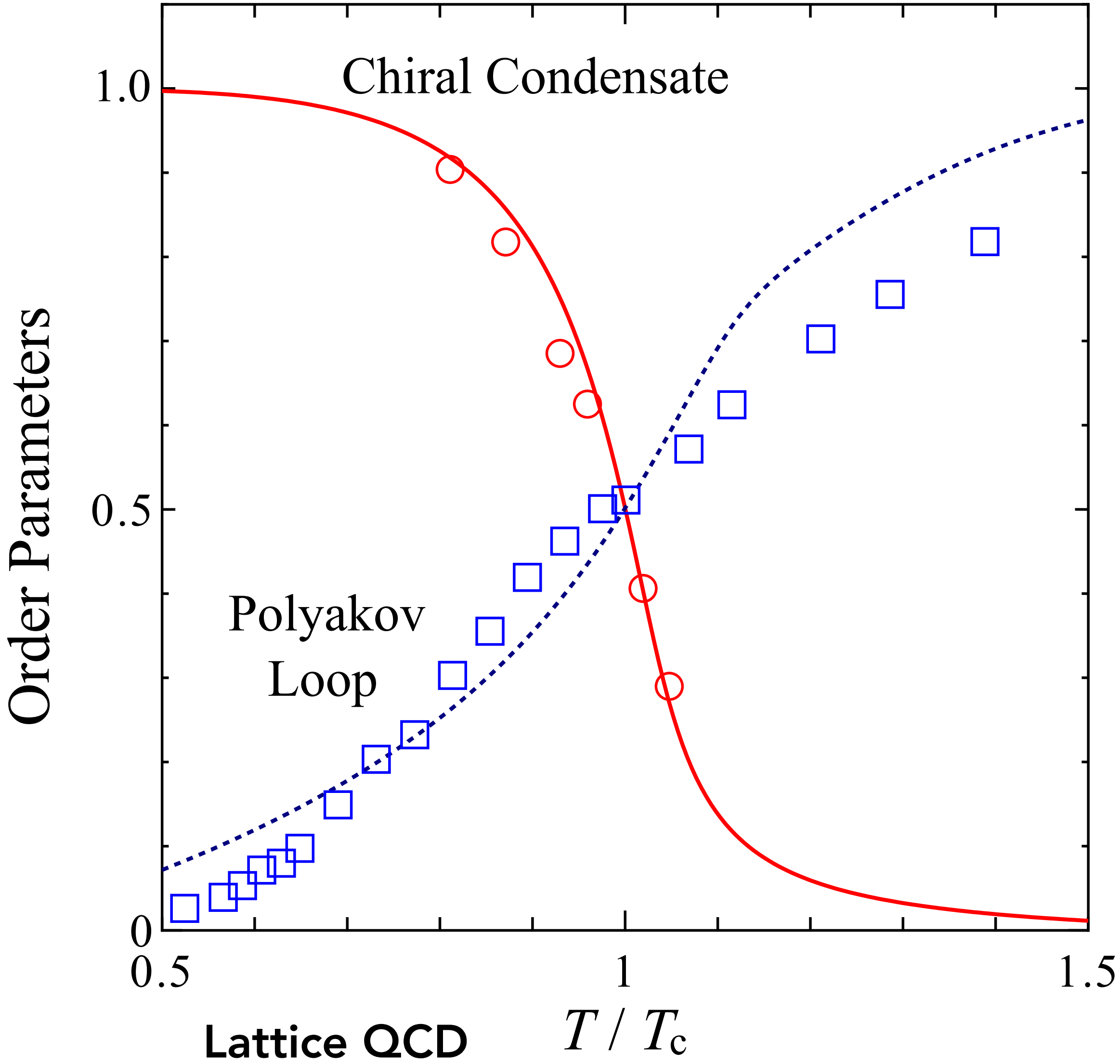
Chiral and de-confinement transition

- **Both phase transitions take place at the same temperature** in Lattice QCD (**de-confined ↔ confined** and **chiral symmetry restored ↔ chiral symmetry broken**).

- The fact that both phase transitions occur at the same temperature is not linked from first principles QCD!

  → Experimental verification: di-leptons and net-charge fluctuations (see later).

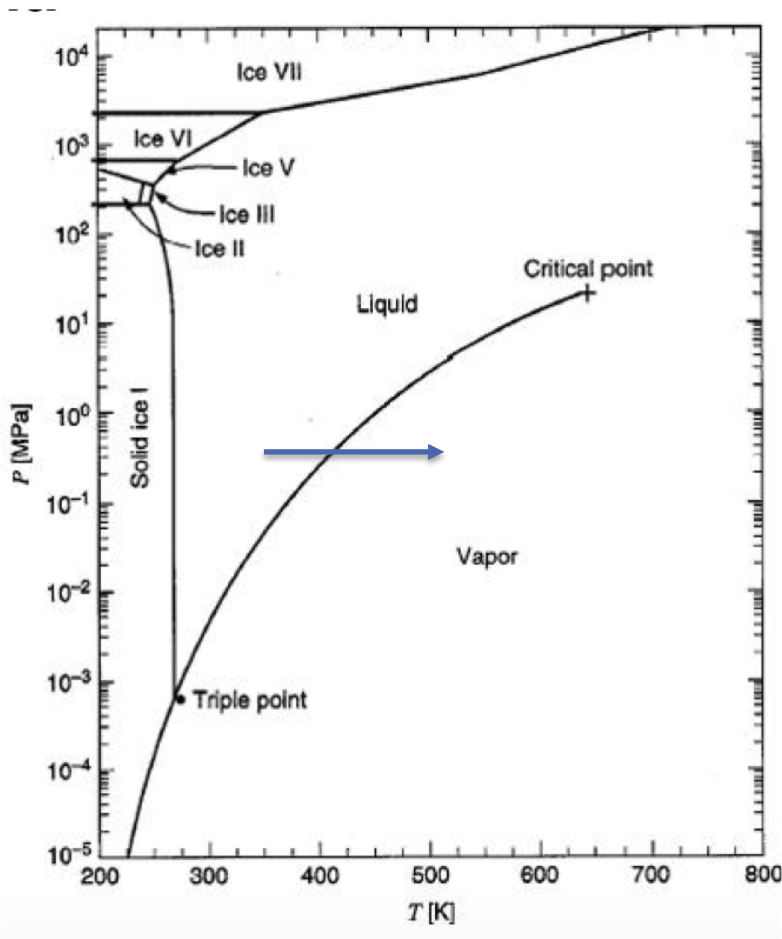
[PLB 723 (2013) 360]



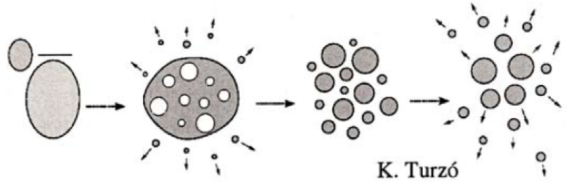
Lattice QCD

Summary: phase transitions from 0 to 10^{13} K

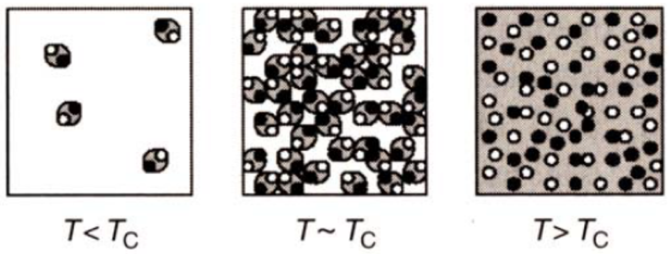
- Even in our everyday life we realise that matter comes in various forms:
  Solid → liquid → gas → plasma (*de-localisation*)
  ~0 K → ~ 273 K → ~ 373 K → ~2000K



- In our life as heavy-ion physicist, we continue further:
  - First, around T=10 MeV ($1.1 \cdot 10^{11}$K), the nucleons are not bound to nuclei anymore (low energy heavy-ion experiments at a few 100 MeV beam energy).



  - Then, at around T=156MeV ($1.8 \cdot 10^{12}$K) the (de-)confinement and chiral symmetry phase transition.

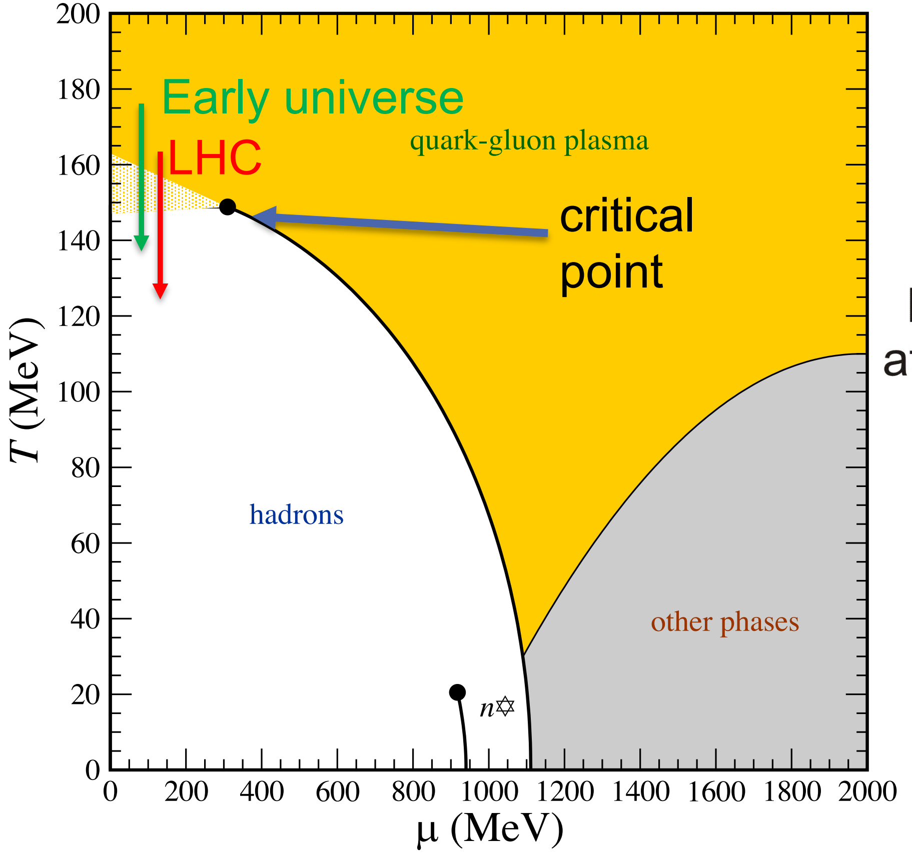


Phase transition: A phase transition is of n^{th} order if discontinuities in variations transverse to the coexistence curve occur for the first time in the n^{th} derivatives of the chemical potential (Ehrenfest defintion).

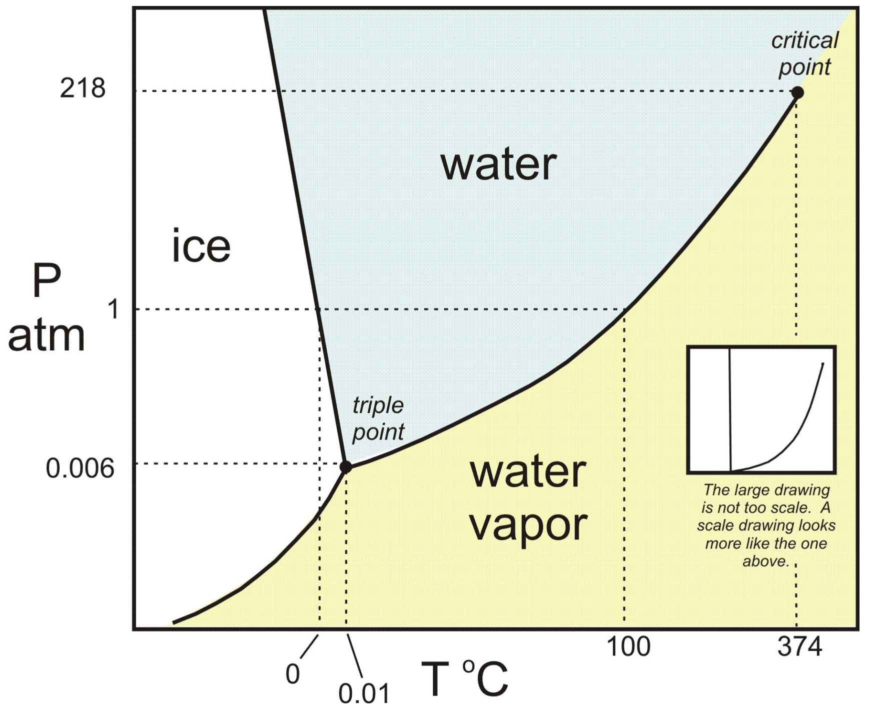
The phase diagram of QCD (1)

- The thermodynamics of QCD can be summarized in the following (schematic) phase diagram.
- Control parameters: temperature T and baryo-chemical potential μ_B.
- At LHC-energies ($\sqrt{s}$ = 5.02 TeV): $\mu_B \approx 0$ MeV << T_{ch}
- At SIS18: ($\sqrt{s}$ = 2.4 GeV): $\mu_B \approx 883$ MeV >> T_{ch}

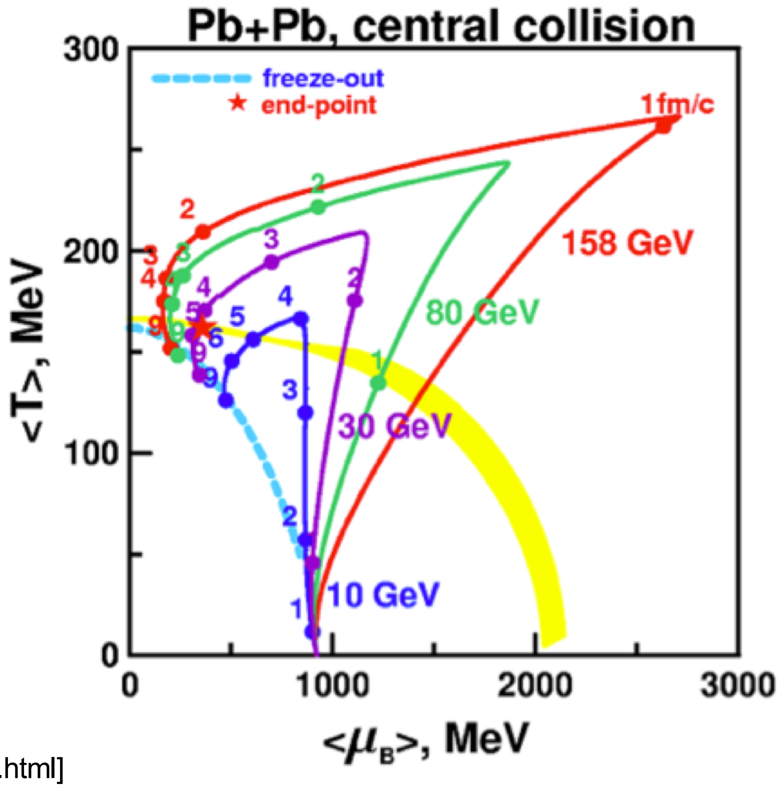
→ Different regions of the phase diagram are probed with different $\sqrt{s_{NN}}$.
=> beam energy scan (BES) at RHIC.



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



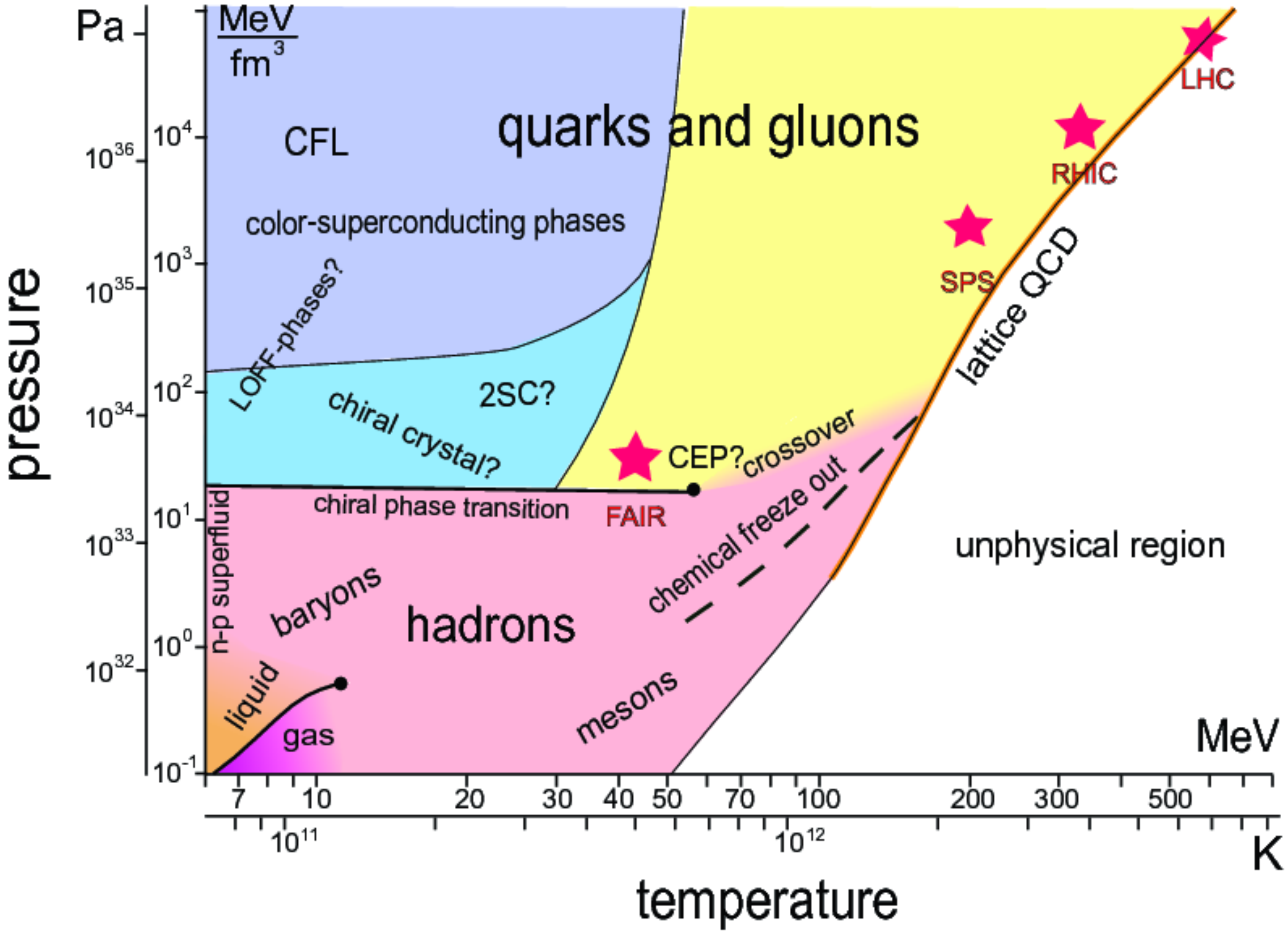
[http://serc.carleton.edu/research_education/equilibria/phaserule.html]



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

The phase diagram of QCD (2)

→ Alternative representation which is not used in practice, but to emphasize more the similarity to the phase diagram of water.



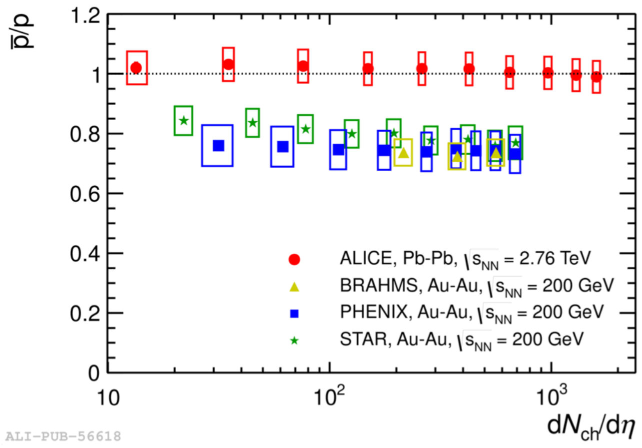
The baryochemical potential μ_B

- In contrast to the (chemical freeze-out) temperature *T*, the baryochemical potential is a less intuitive quantity…
- It quantifies the net-baryon content of the system (baryon number transport to midrapidity).

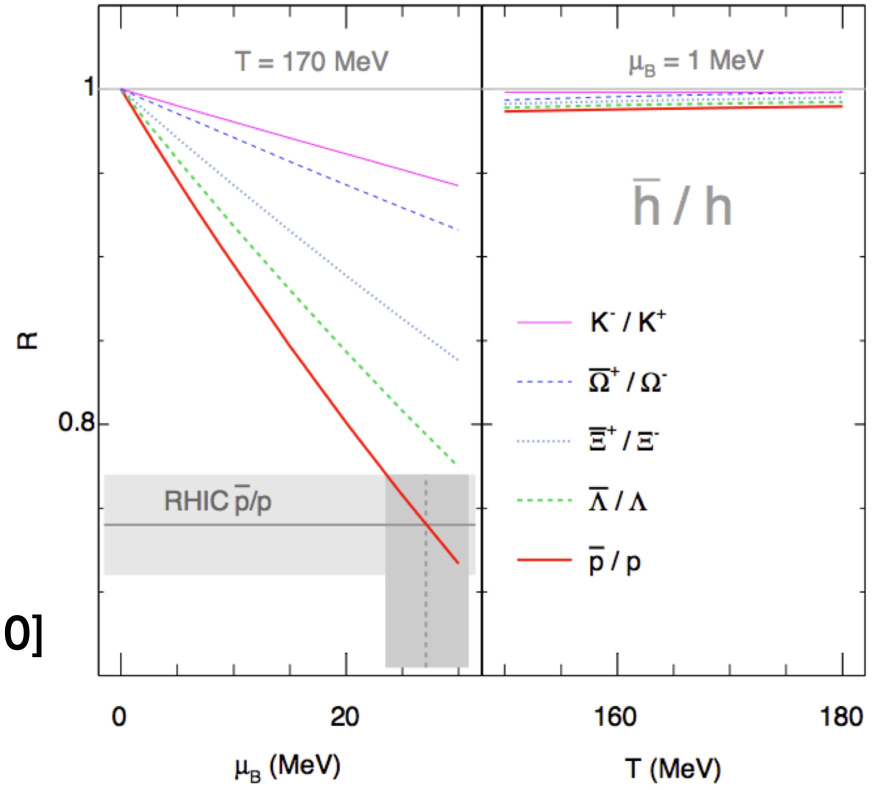
fundamental thermodynamic relation

$$dU = T\,dS - p\,dV + \Sigma\mu_i\,dn_i \quad .$$

$$\Rightarrow \mu_i := \left(\frac{\partial U(S,V,n_j)}{\partial n_i}\right)_{S,V,n_{j\neq i}}$$



[Phys.Rev. C88 (2013) 044910]



(I. Kraus)

$$\mu_B \approx 0 \quad => \quad \bar{p}/p \approx 1$$

However, (anti-)nuclei are more sensitive:

$$\frac{n_{\bar{p}}}{n_p} = e^{-(2\mu_B)/T} \qquad \frac{n_{\bar{d}}}{n_d} = e^{-(4\mu_B)/T}$$

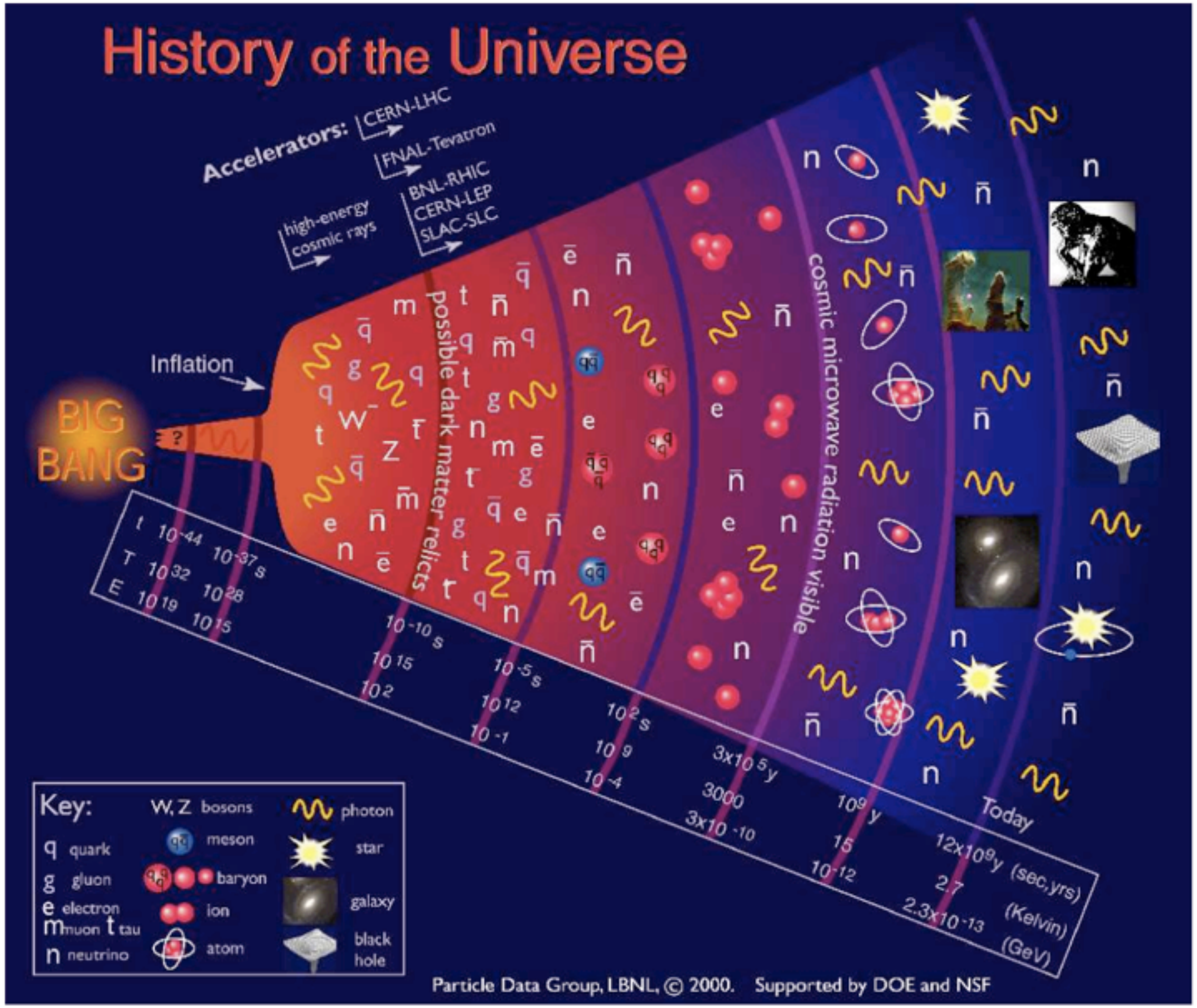
$$\frac{n_{^3\overline{He}}}{n_{^3He}} = e^{-(6\mu_B)/T}$$

QGP and the early universe (1)

- Big bang in the early universe and little bang in the laboratory.

- The Universe went through a QGP phase about 10ps after its creation and froze out into hadrons after about 10μs which later formed nuclei.

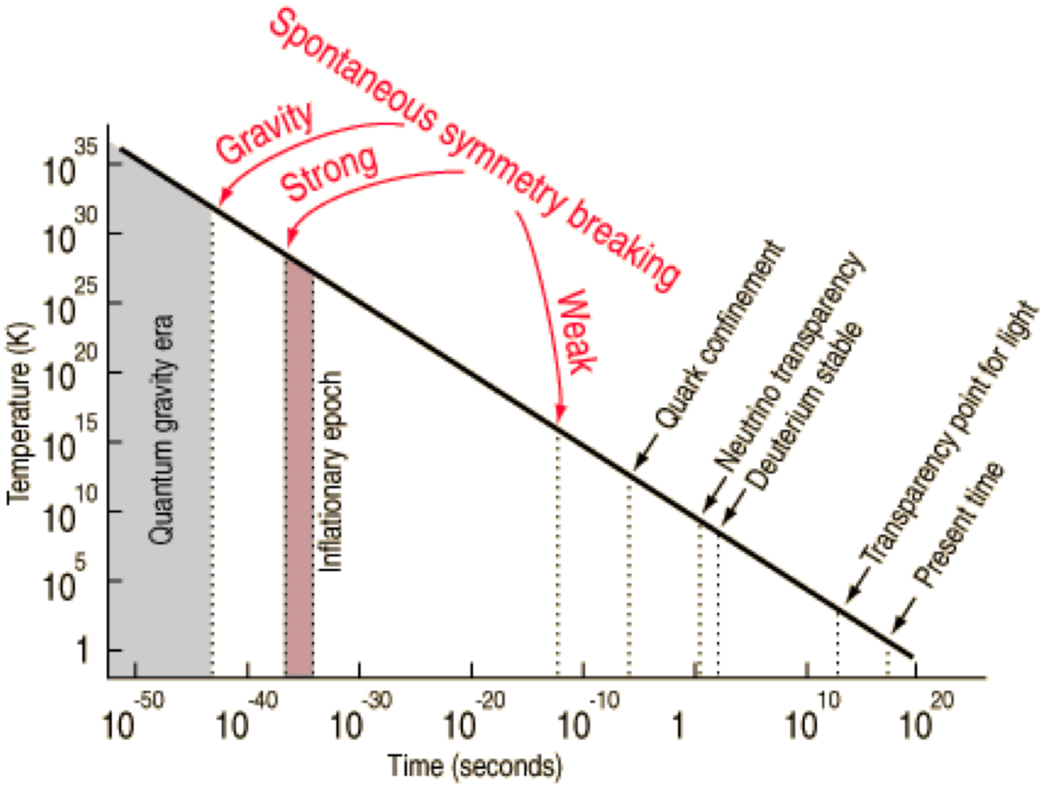
- In addition, there are similarities between the big bang (universe QGP) and the little bang (heavy-ions) concerning the **decoupling**.

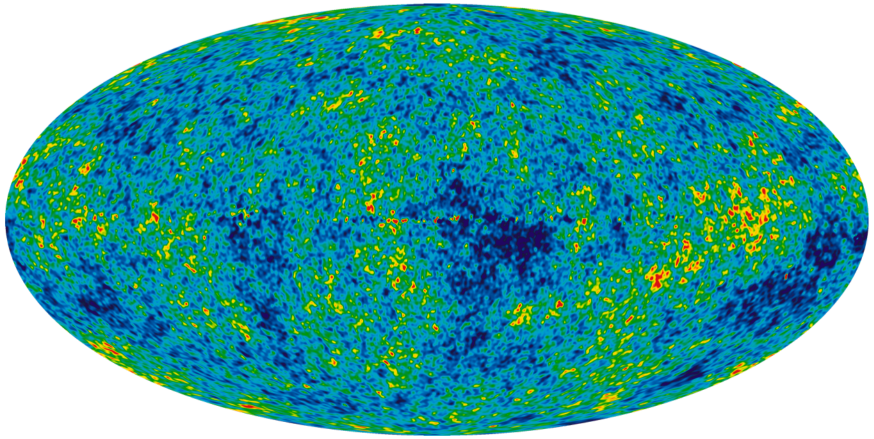


QGP and the early universe (2)

- Decoupling: different type of particles fall out of thermal equilibrium with each other and *freeze out* when the mean free path for interaction is comparable to the size of the expanding system.

- Examples of this analogy:
  - Early Universe: neutrinos decouple early as their interaction is weak.
  - Heavy-ions:
    - chemical freeze-out (inelastic interactions changing particle type) happens before kinetic freeze-out (elastic interactions changing only momenta)
    - Kinetic freeze-out of strange particles might happen before the kinetic freeze-out of non-strange particles





Decoupled photons (WMAP)

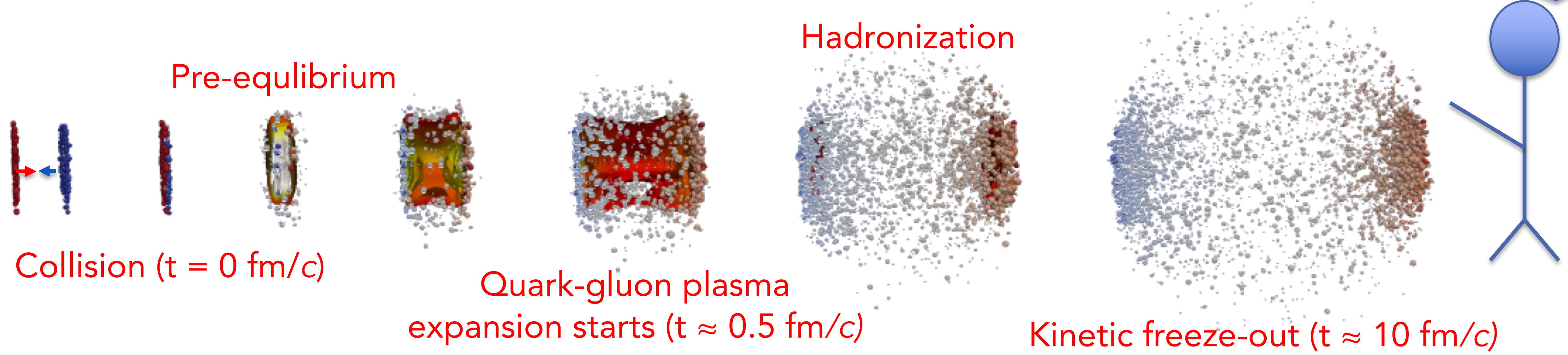
Can we reach such temperatures in the experiment?

→ We would need initial temperatures of more than 200 MeV.

→ Let’s look first at a schematic evolution of a heavy-ion collision:

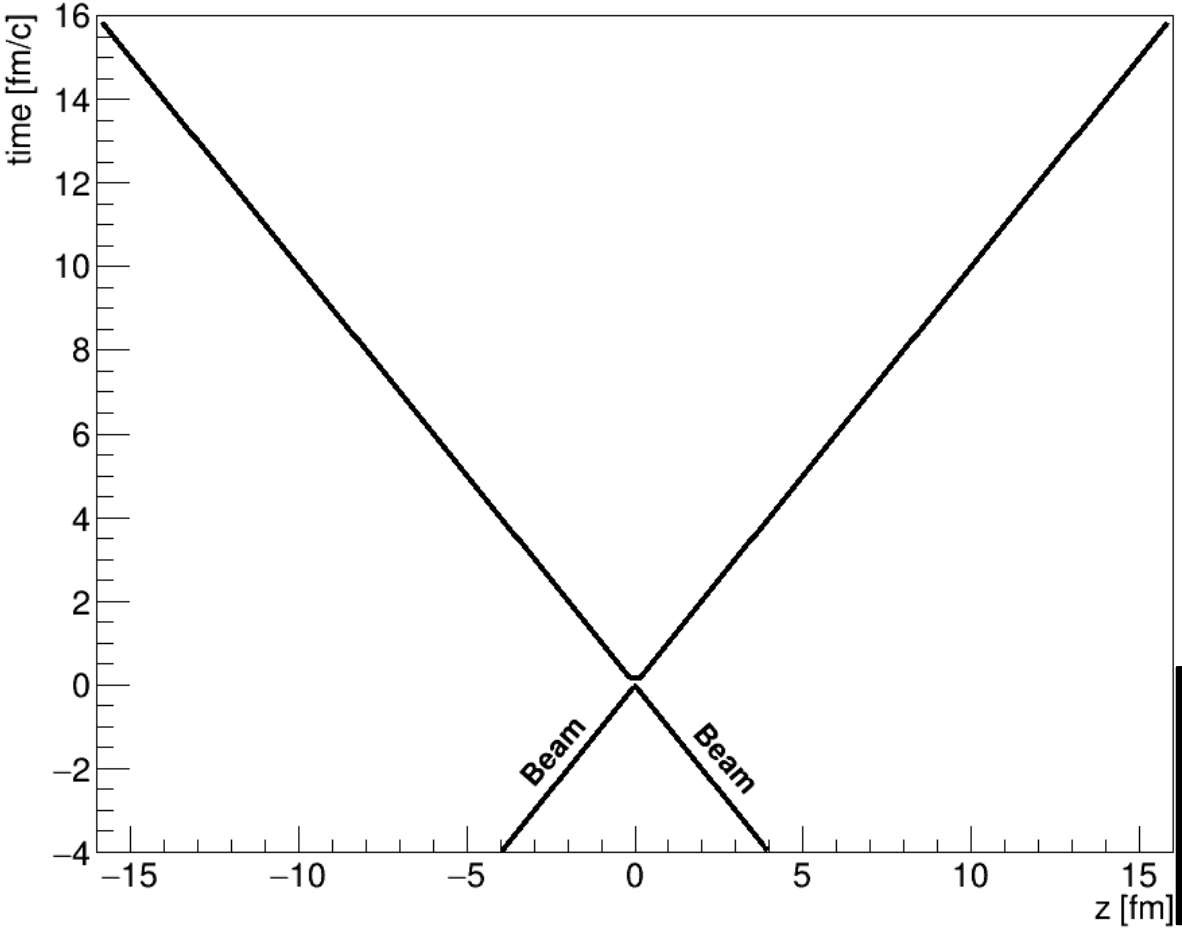
What is the temperature reached in a heavy-ion collision? Let’s measure it..

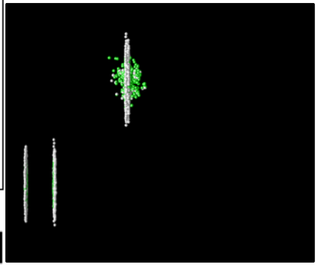
T > 300 MeV — System cools down by (isentropic) expansion — T ~ 90 MeV



Heavy ion collision

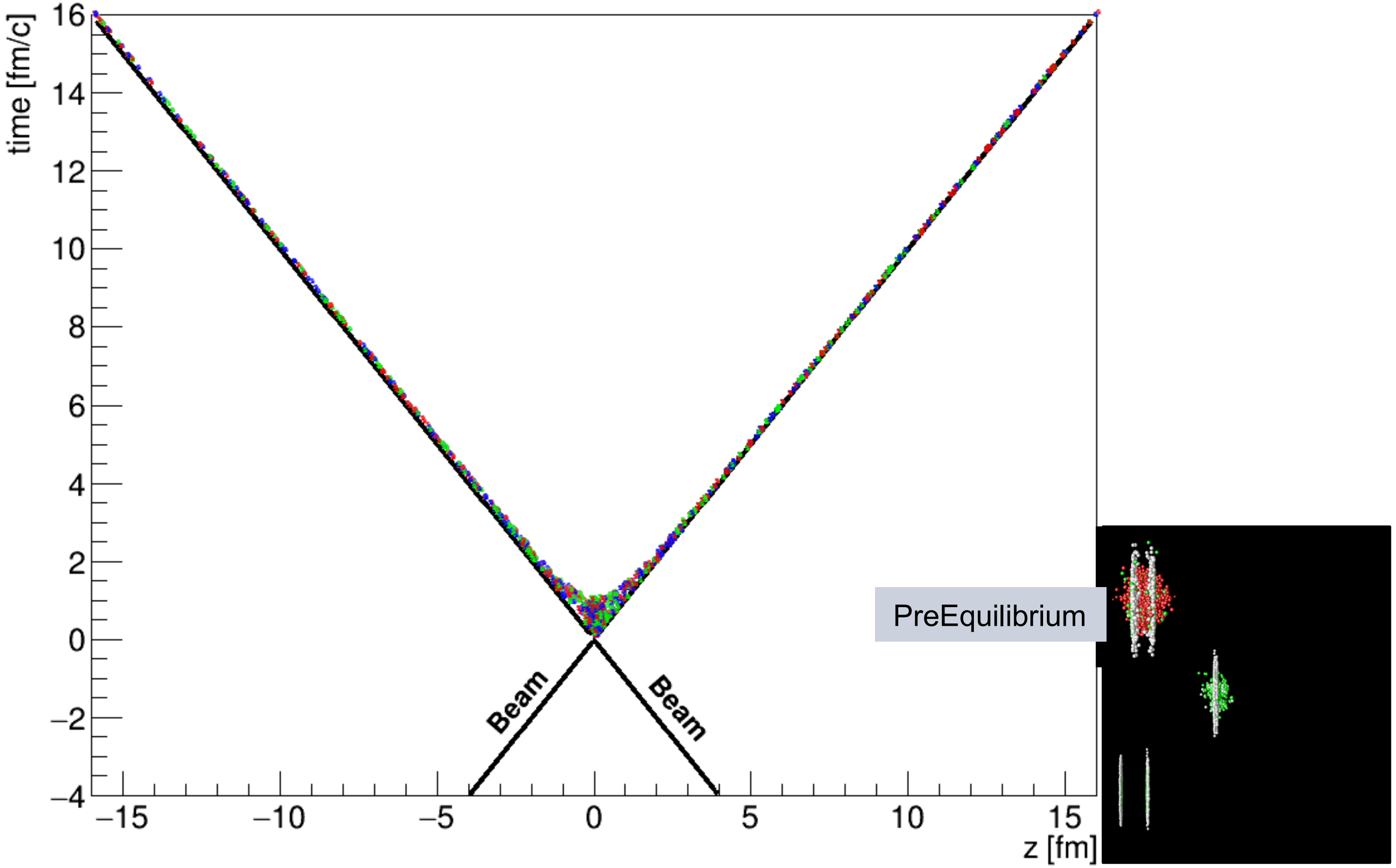
Colliding nuclei





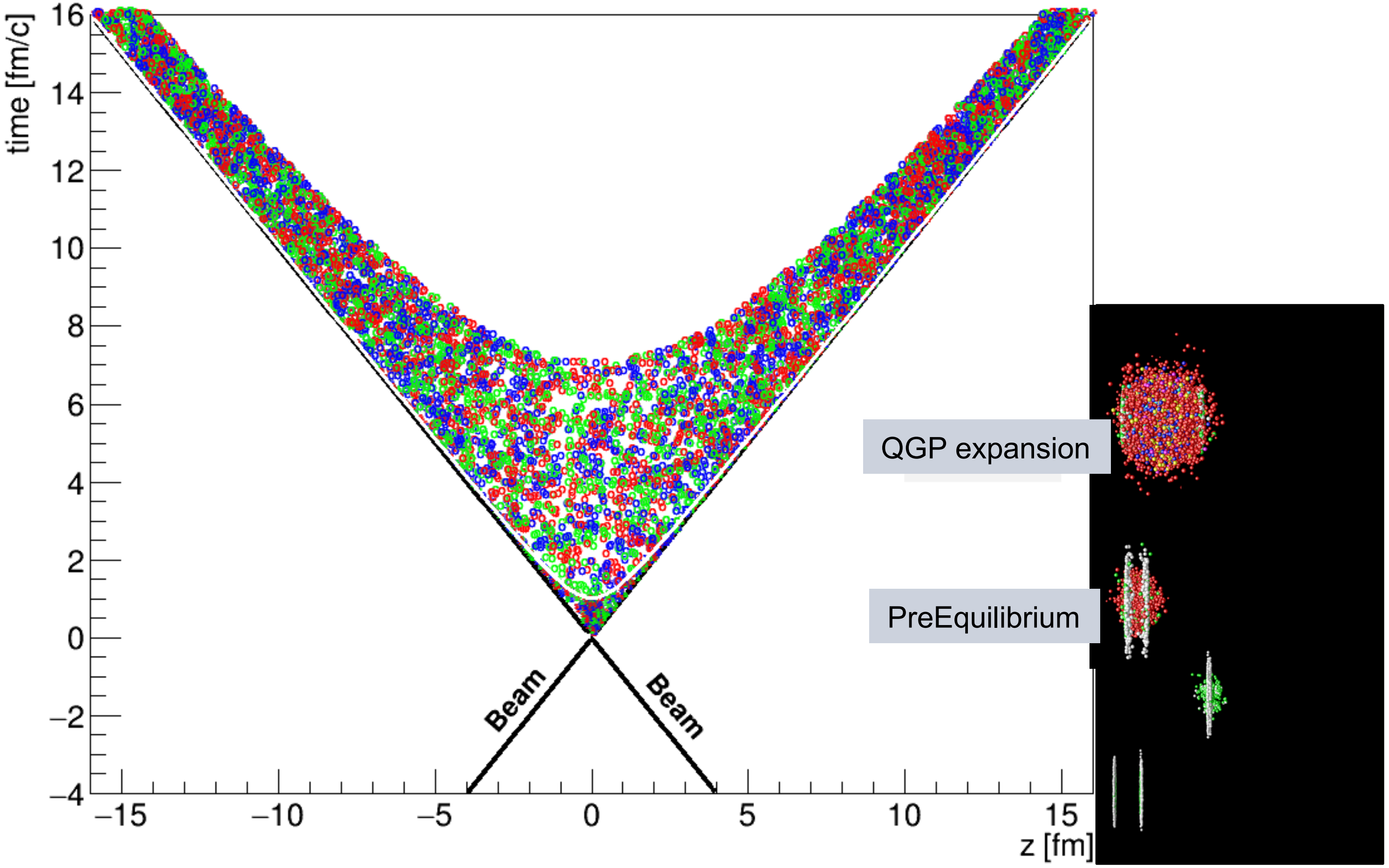
Heavy ion collision

Production of colour medium and equilibration



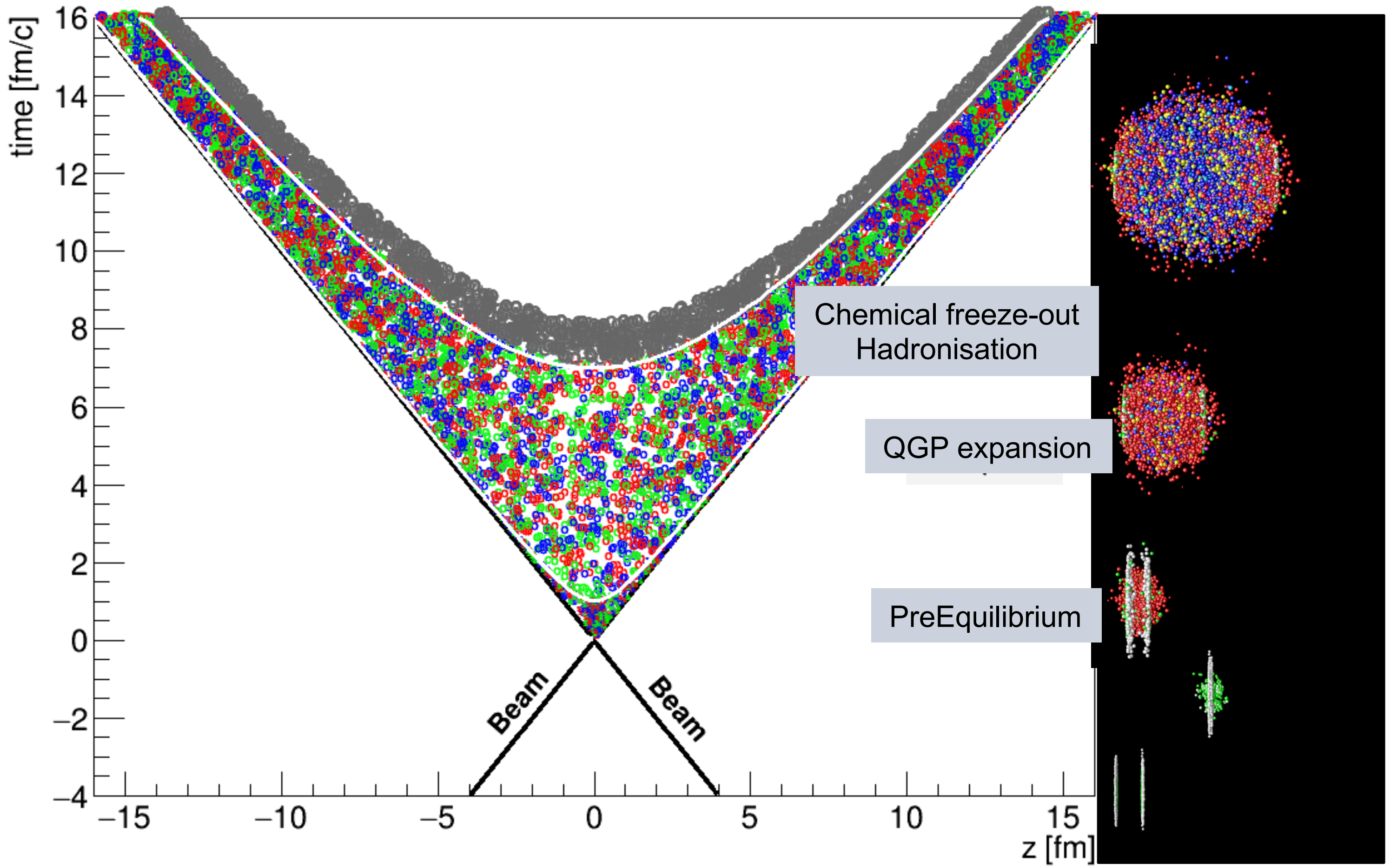
Heavy ion collision

QGP and expansion



Heavy ion collision

Hadronisation and Chemical freeze-out



Heavy ion collision

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

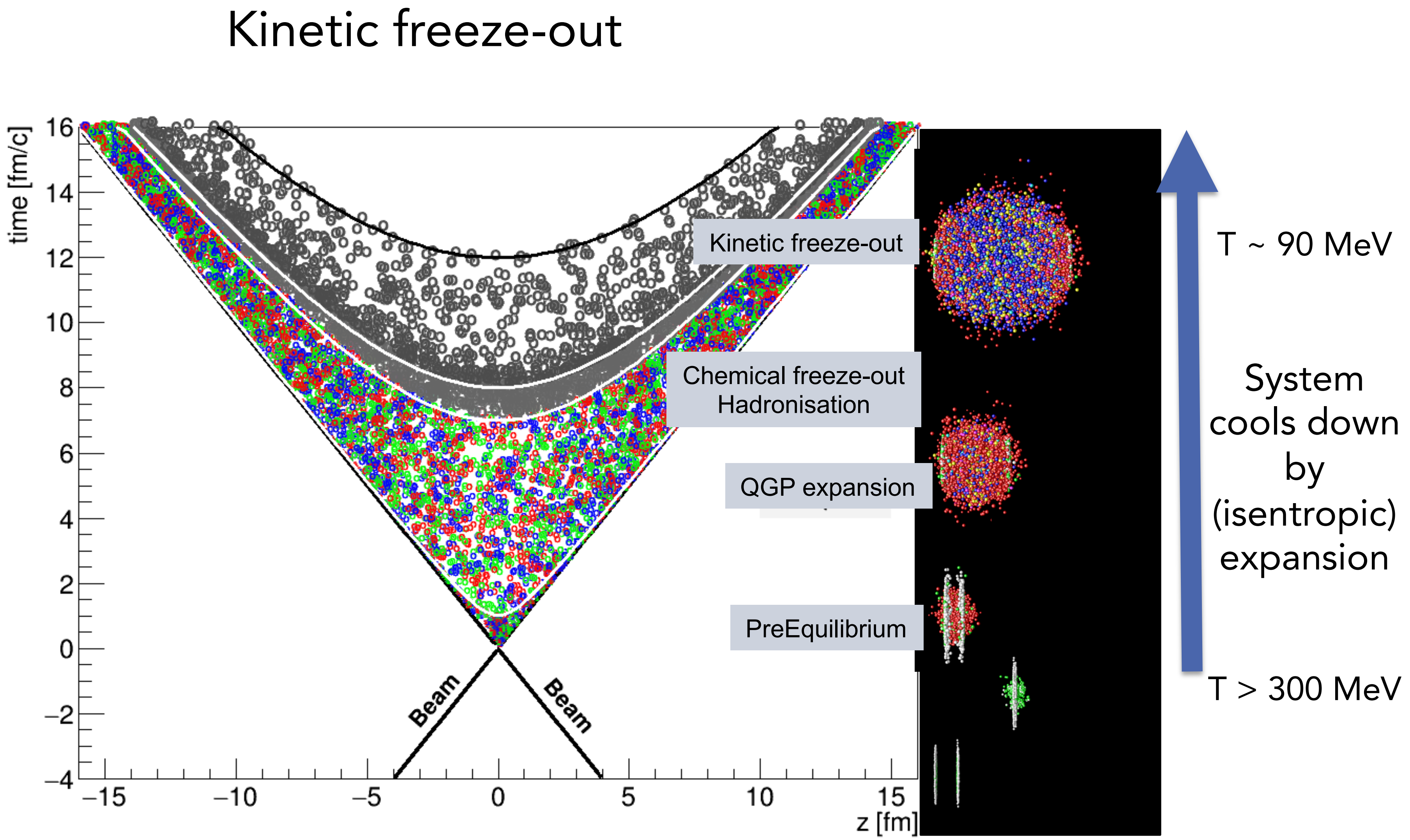
Kinetic freeze-out
(t=10fm/c)

Chemical freeze-out

Hydrodynamic
evolution (t~0.5fm/c)

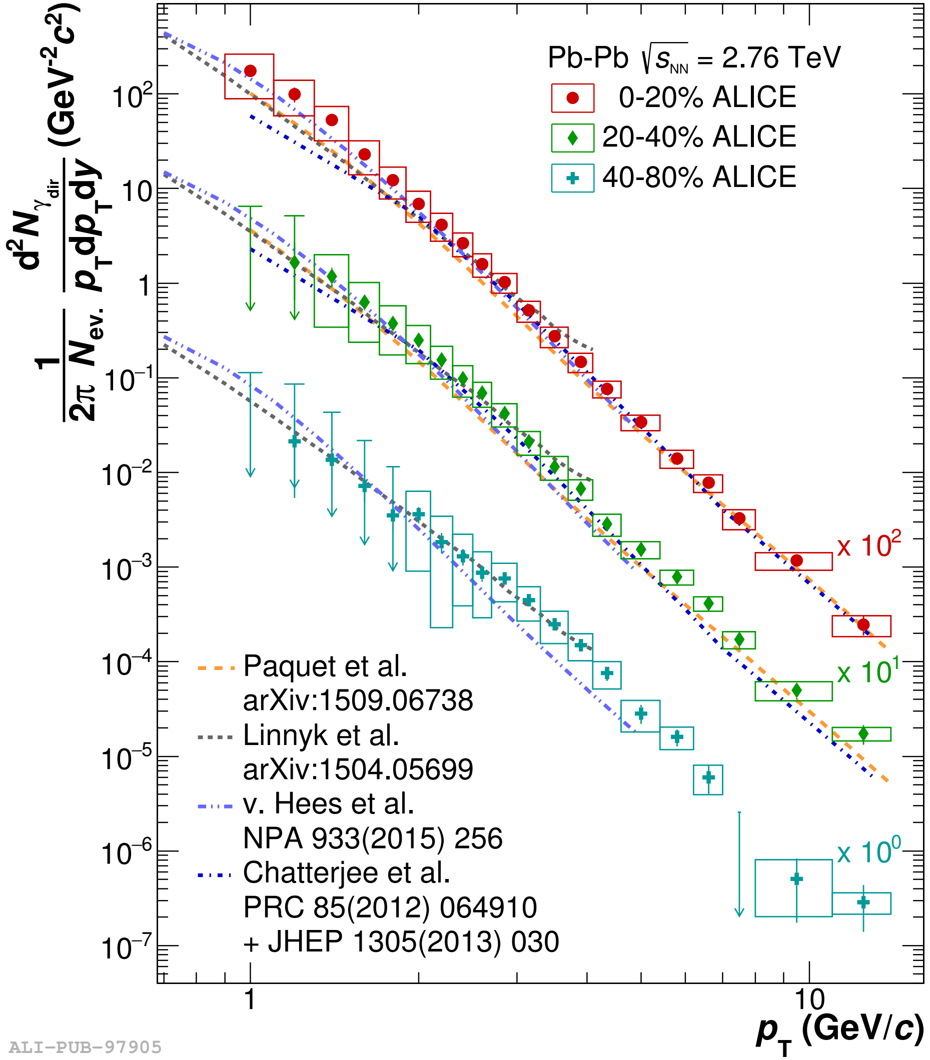
Pre-equilibrium

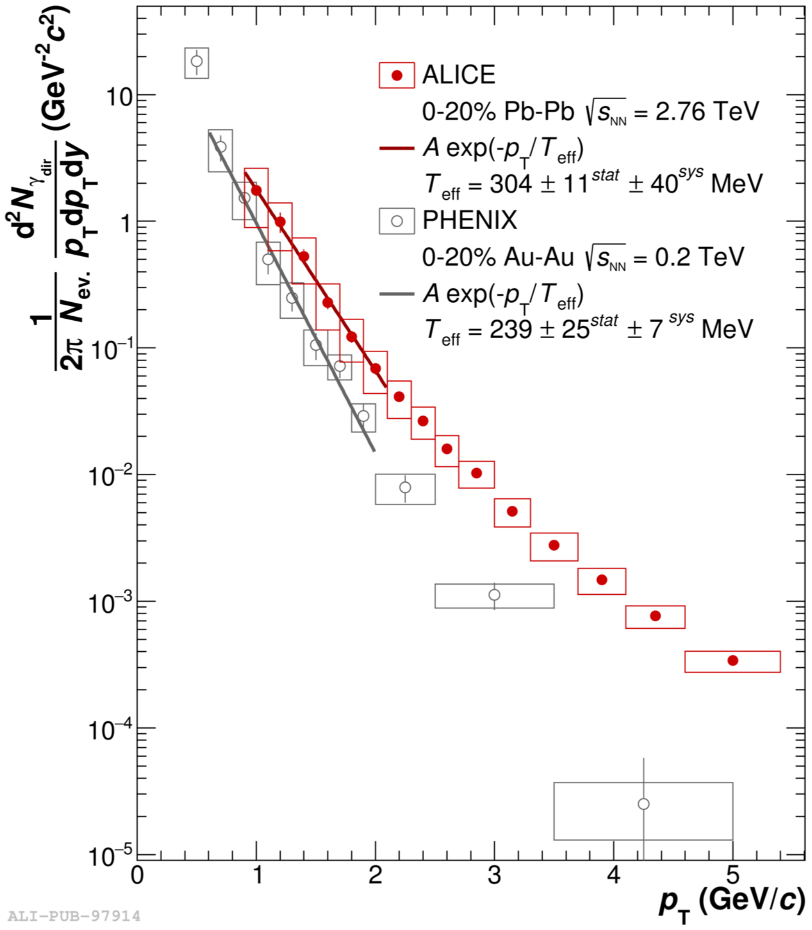
Collision (t=0fm/c)



Direct photons – black body radiation from the QGP

The challenging measurement of direct (subtract decay 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]

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.

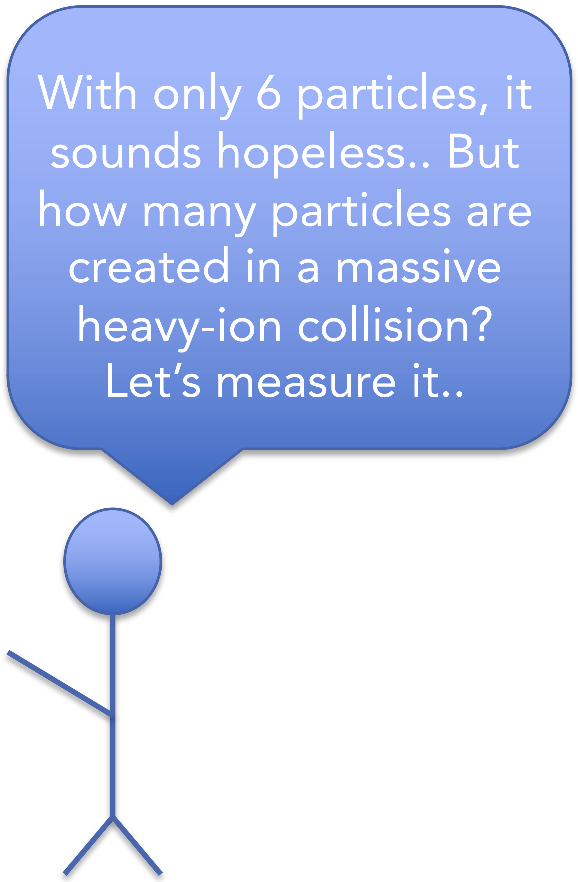
QGP thermodynamics and soft probes

Thermodynamics

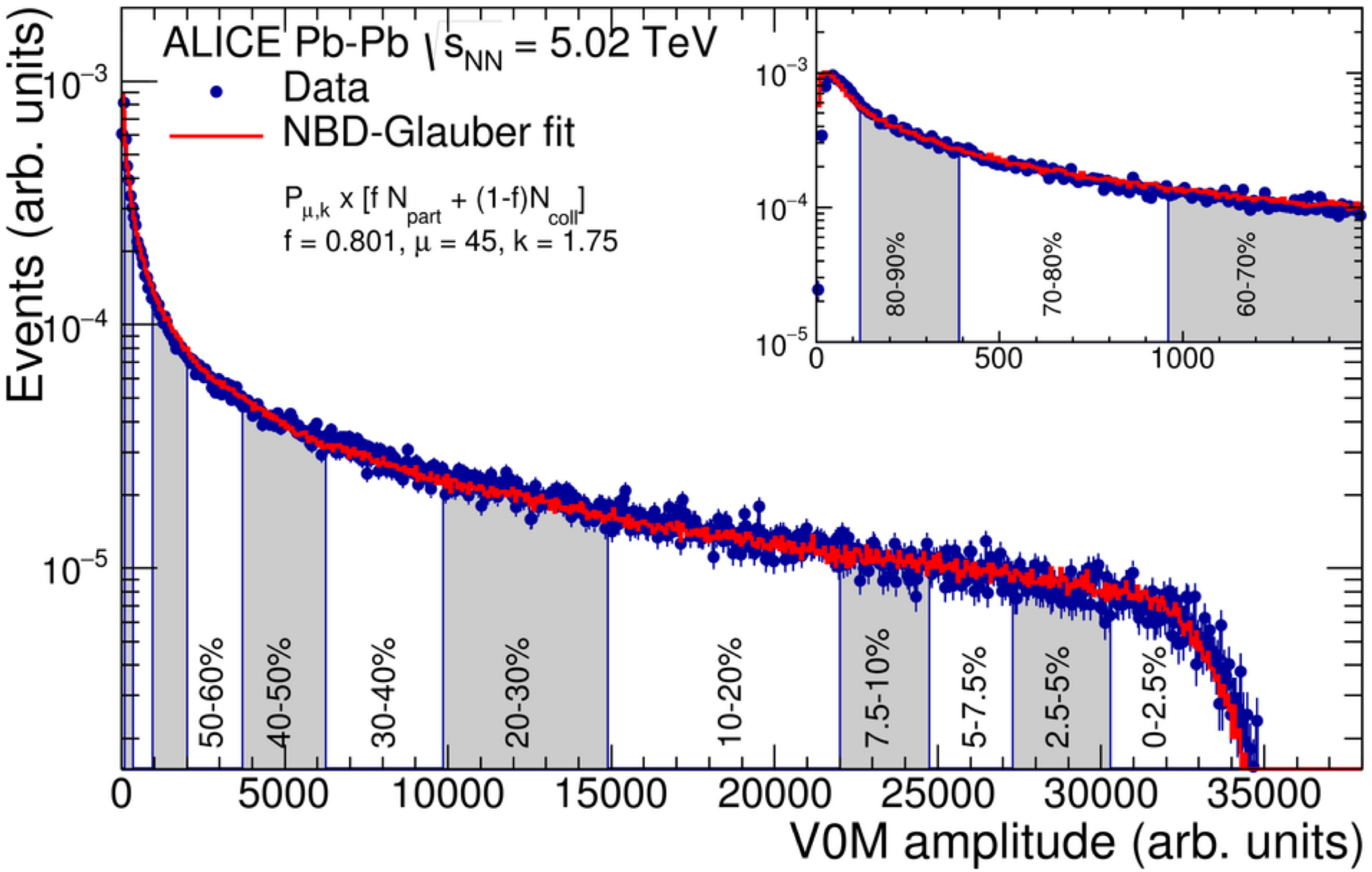
- It is important to distinguish between:
  - a system of *individual particles*
  - a ***medium*** in which individual degrees of freedom do not matter anymore and thermodynamic (hydrodynamic) concepts (many body theories) can be applied.

- Thermodynamic (hydrodynamic) are typically used for systems with 10^5-10^{23} particles in *local thermodynamic equilibrium*.
  - *Average (minimum bias)* pp collision at the LHC: $dN_{ch}/d\eta \approx 6$

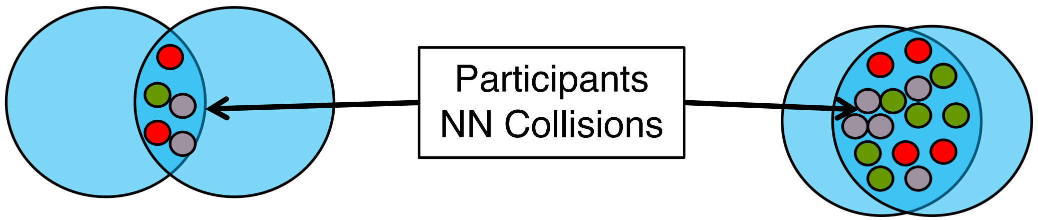
- Lifetime of the system must be long enough so that equilibrium can be established by several (simulations indicate 5-6) interactions between its constituents.



Geometry of heavy ion collisions



~ # charged particles



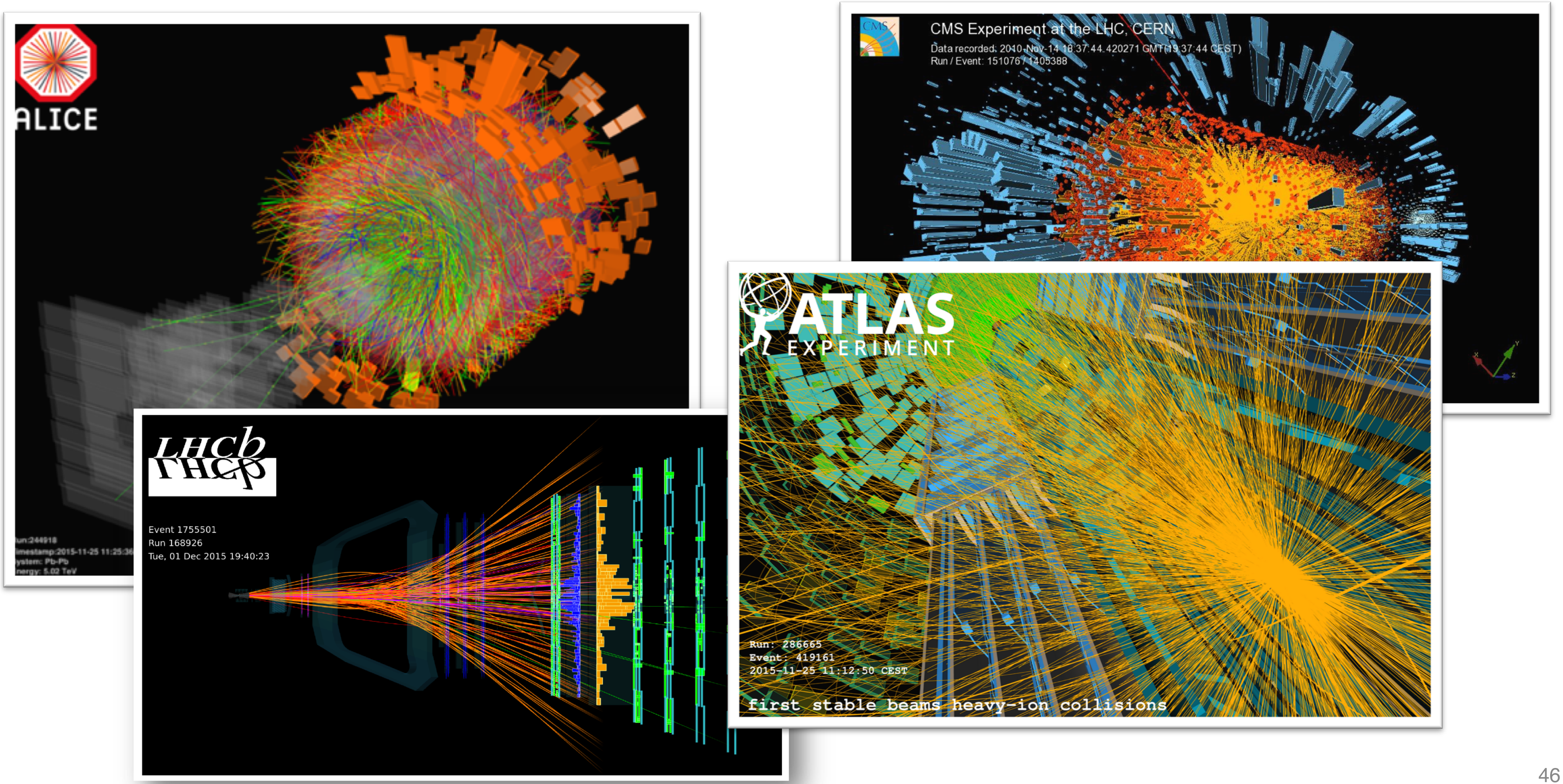
Centrality Variables:

- ***N_{coll}***: Number of nucleon-nucleon collisions
- ***N_{part}***: Number of participating nucleons

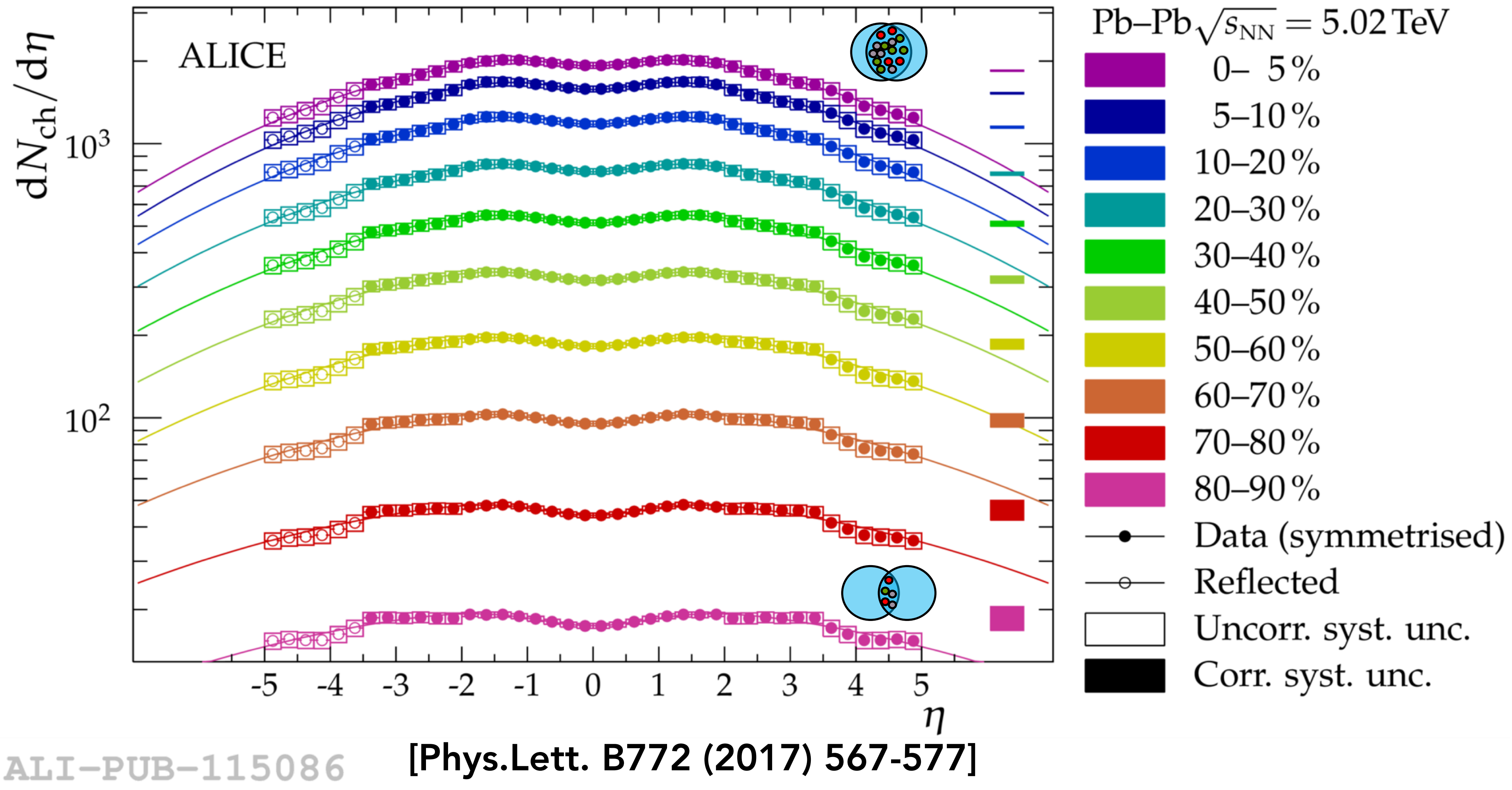
- Percentile of hadronic cross-section:
0-5% => central ("many particles")
80-90% => peripheral ("few particles")

→ We can determine (a posteriori) the geometry of heavy ion collisions based on the ***Glauber model.***

How many particles are created in such a collision?



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



[Phys.Lett. B772 (2017) 567-577]

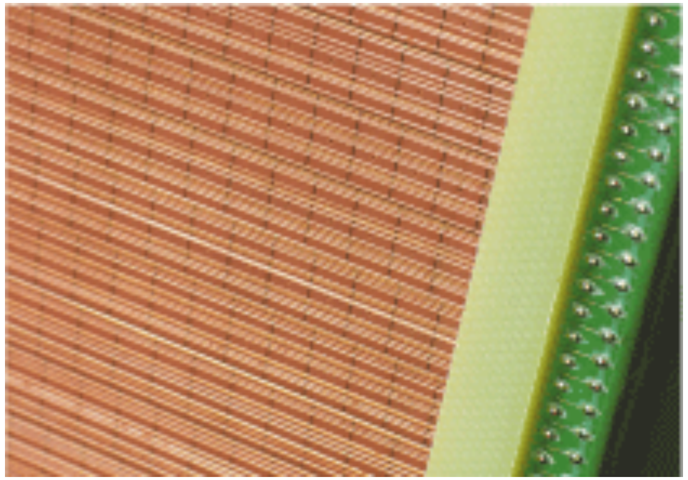
$dN_{ch}/d\eta \approx$ 1943 ± 54 at midrapidity.

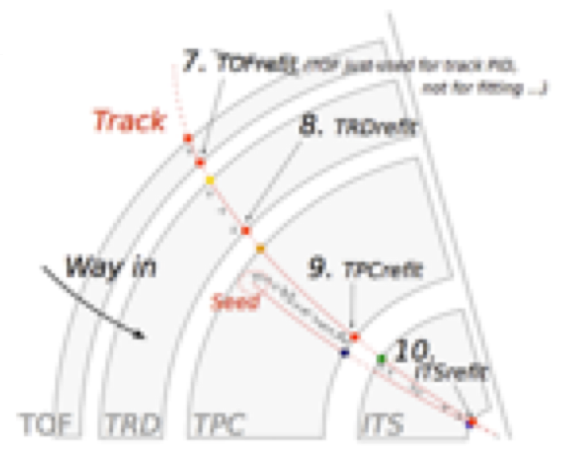
→ Even at LHC energies, 95% of all particles are produced with p_T < 2 GeV/c in pp and Pb-Pb collisions.

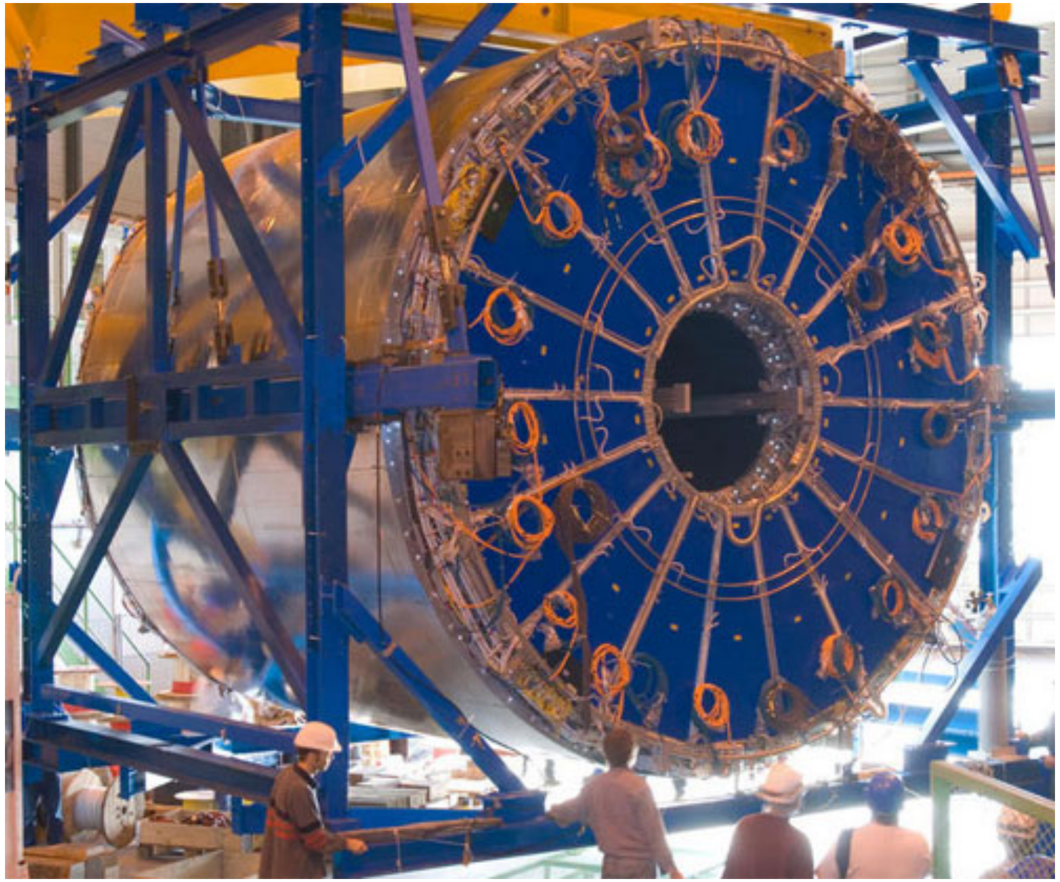
→ Bulk particle production and the study of collective phenomena are associated with ***"soft" physics*** in the non-perturbative regime of QCD.

Instrumentation for heavy-ion experiments: granularity

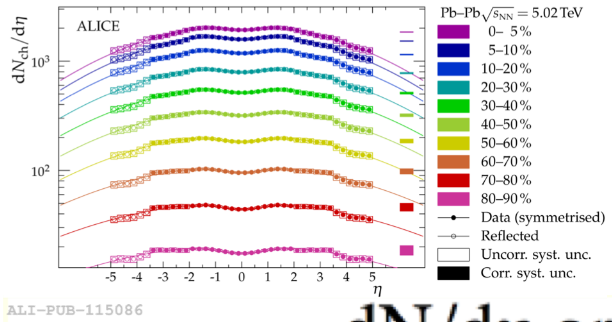
- In order to cope with the high density of particles, heavy-ion detectors have to be very granular (e.g. large TPC with small read-out pads).
- Track seeding typically in outer detectors (where track density is lower) and then Kalman filter propagation to the primary vertex.

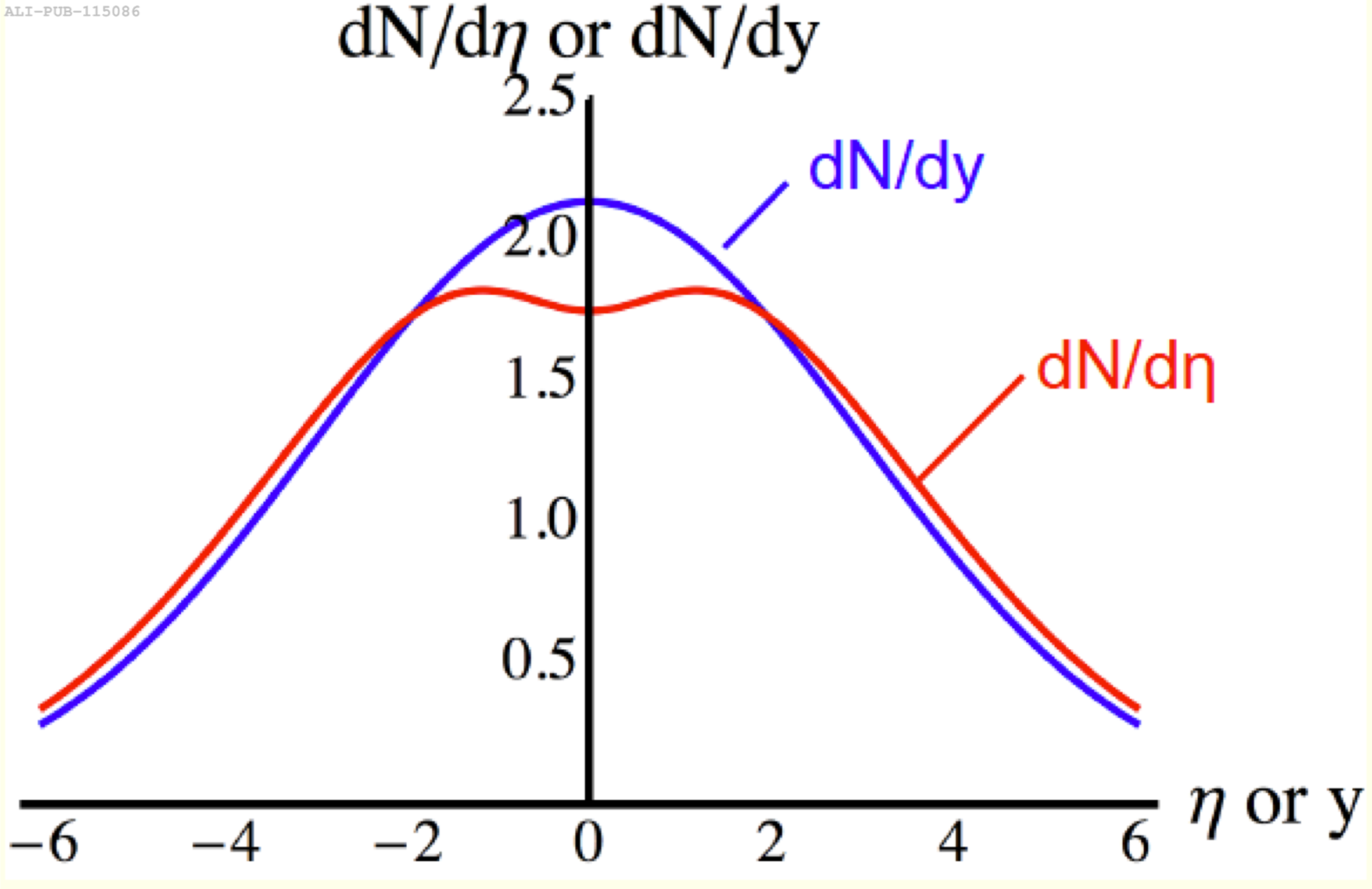






Short reminder: (Pseudo-)rapidity

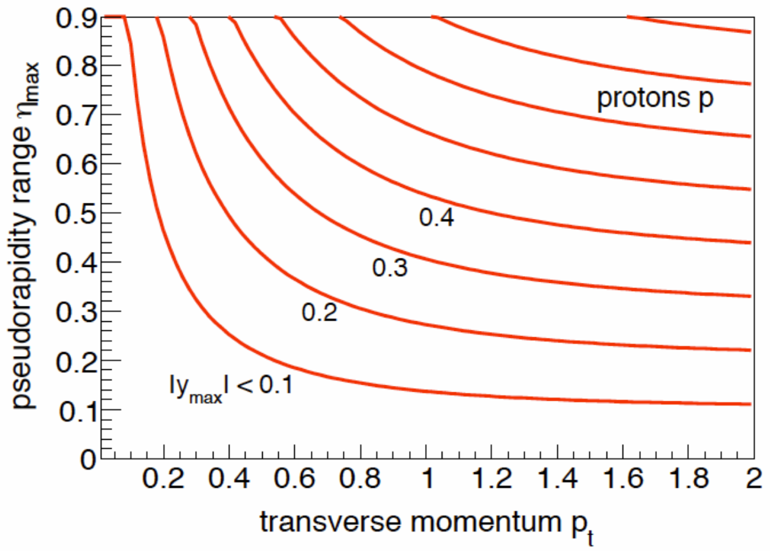




From: K. Reygers

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

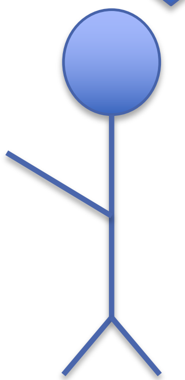
→ Always keep in mind: Rapidity and pseudo-rapidity are not the same, especially at low transverse momenta!

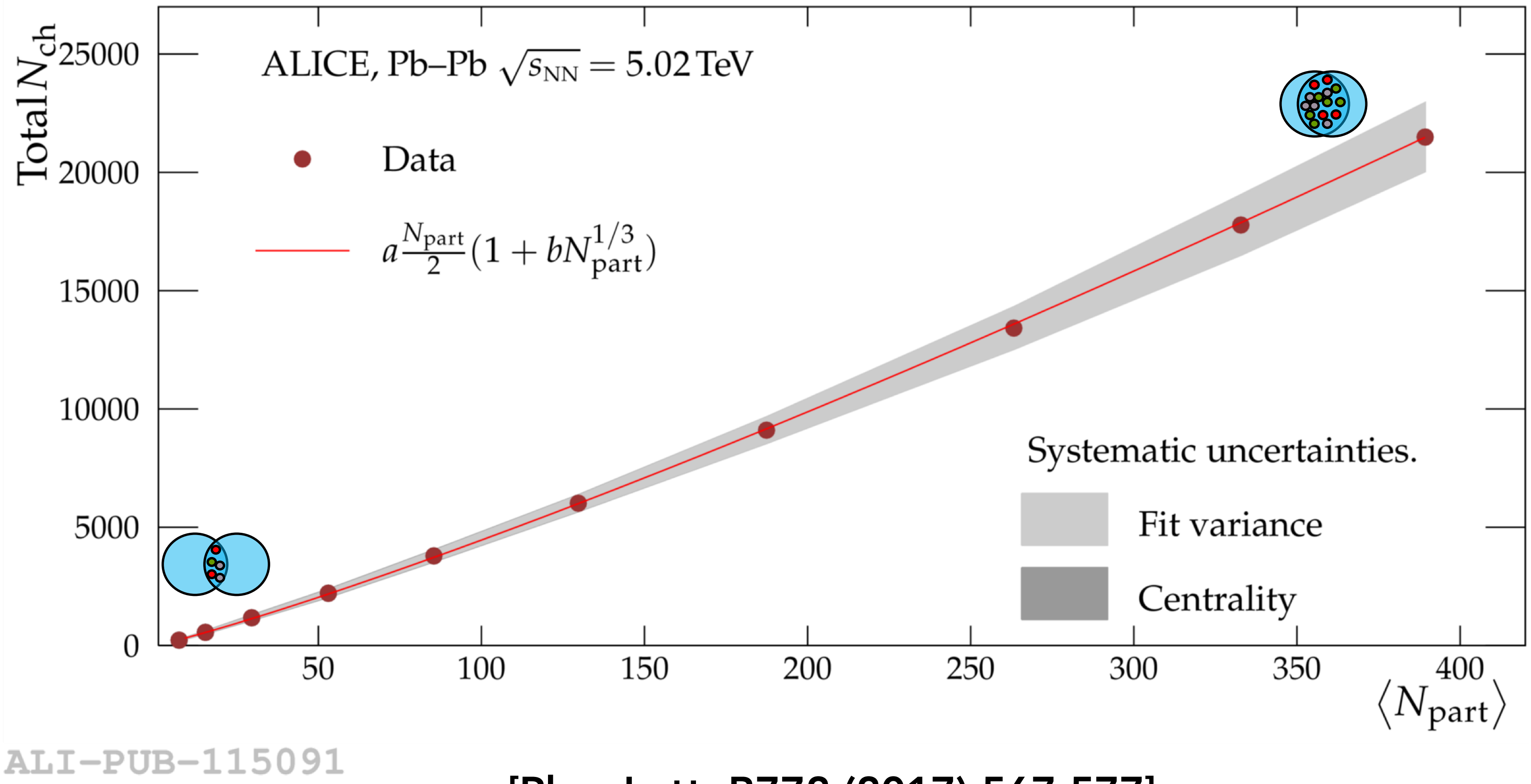


Total number of charged hadrons in Pb-Pb collisions

→ 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.

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





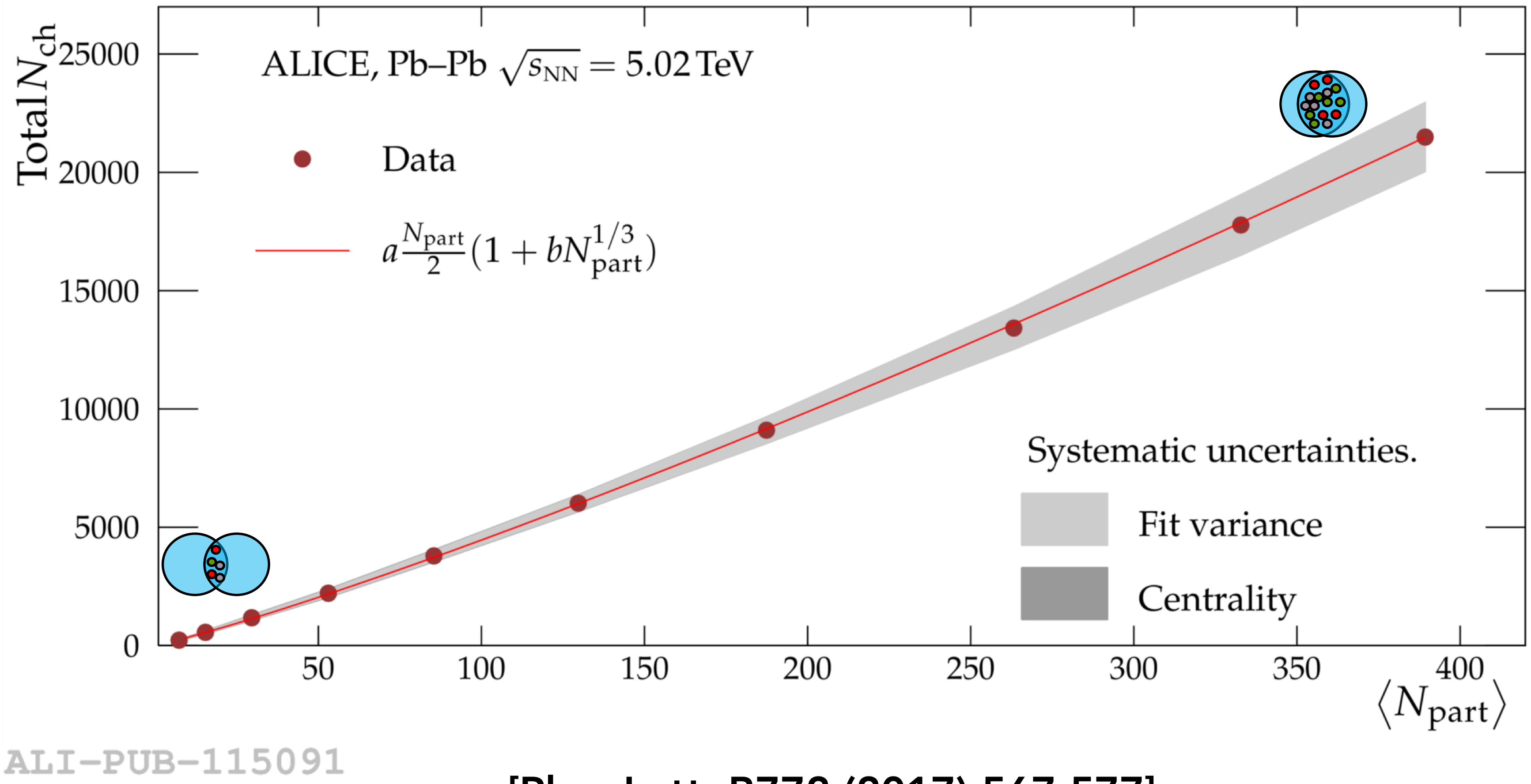
[Phys.Lett. B772 (2017) 567-577]

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.

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*).



[Phys.Lett. B772 (2017) 567-577]

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 (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!):

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

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

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

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

g_i: *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*

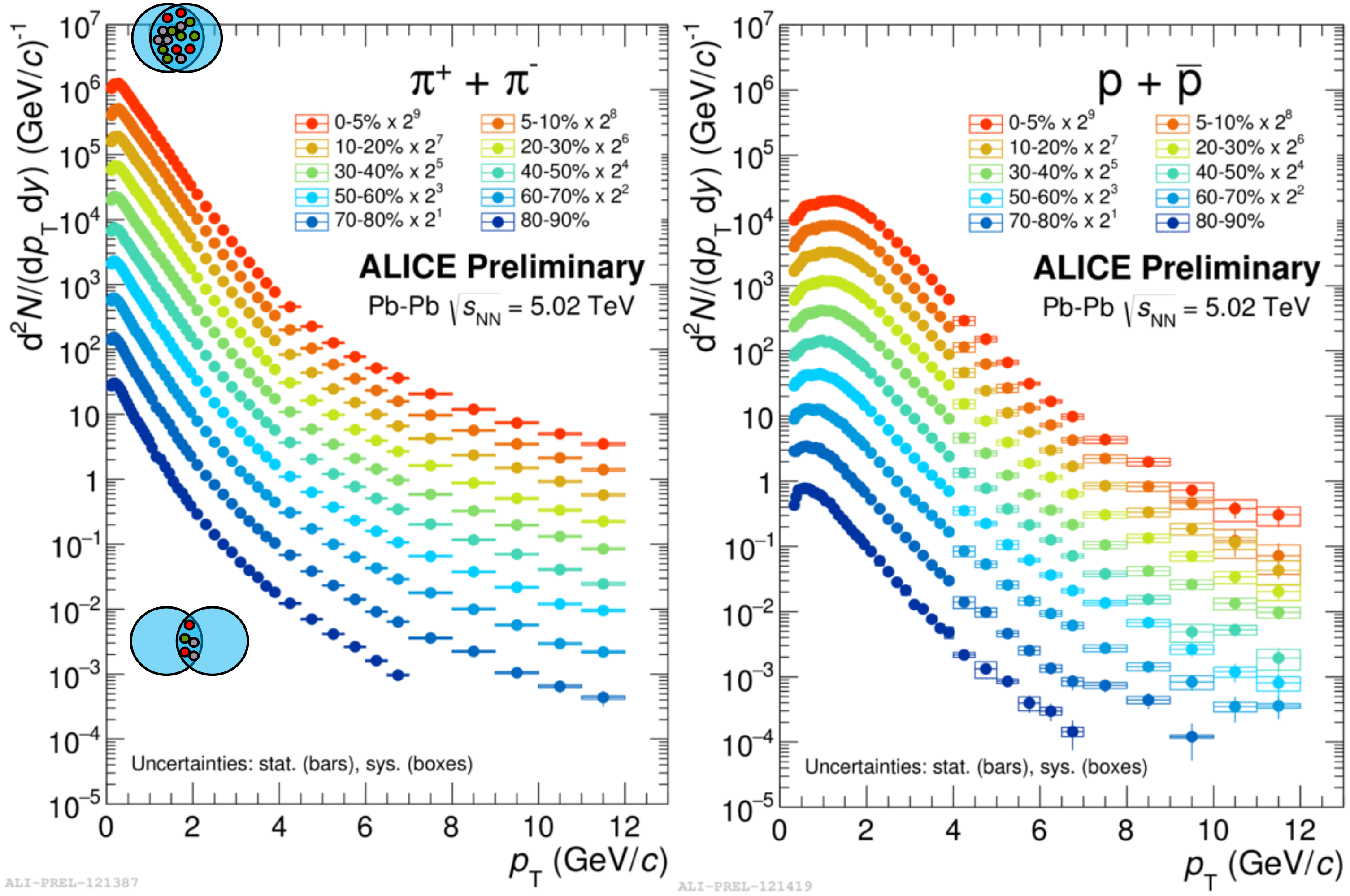
Only two free parameters are needed: **(T,μ_B)**. Volume cancels if particle ratios n_i/n_j are calculated. If yields are fitted, it acts as the third free parameter.

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

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

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.

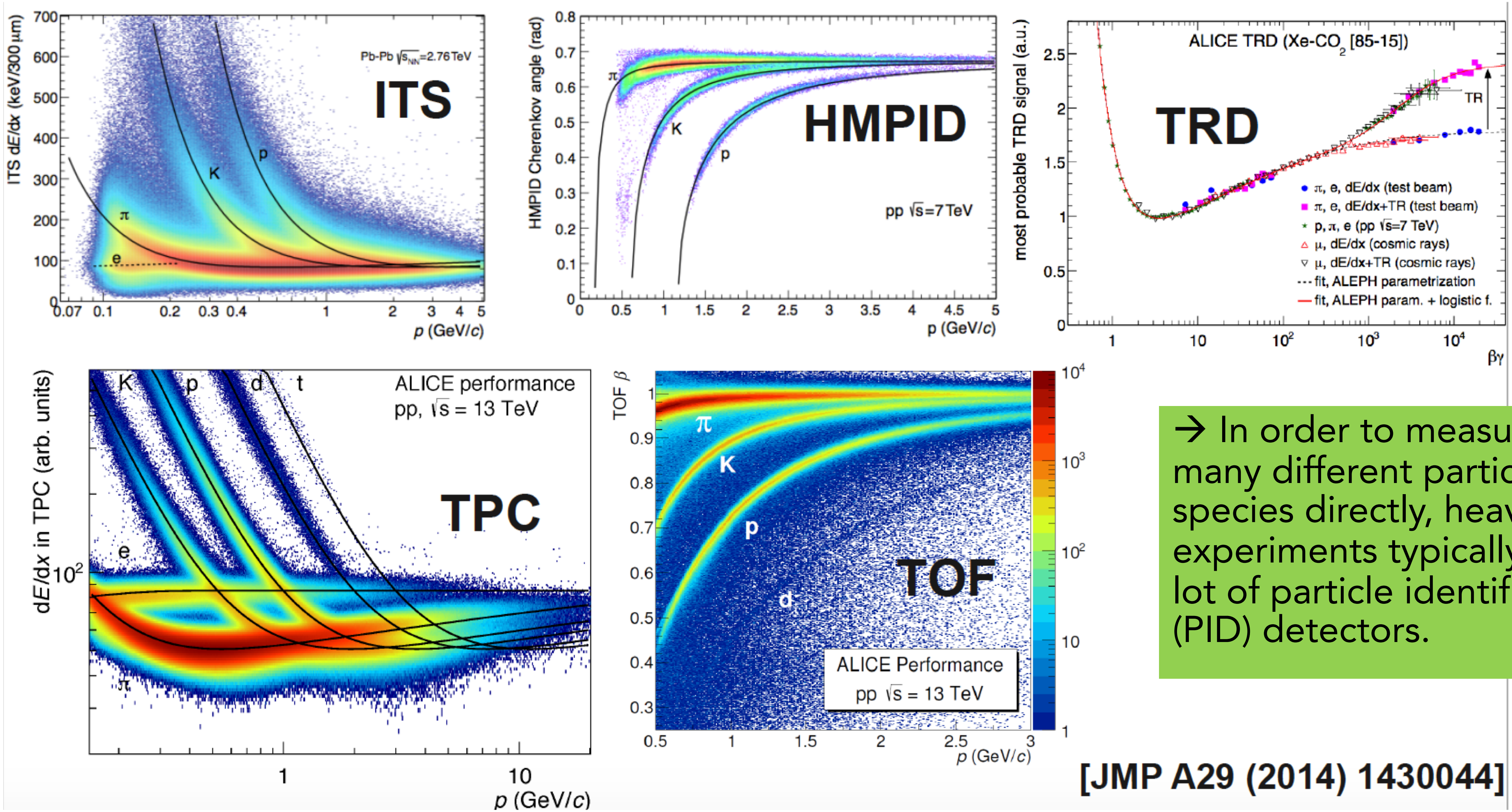
p_T-spectra of identified particles



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]

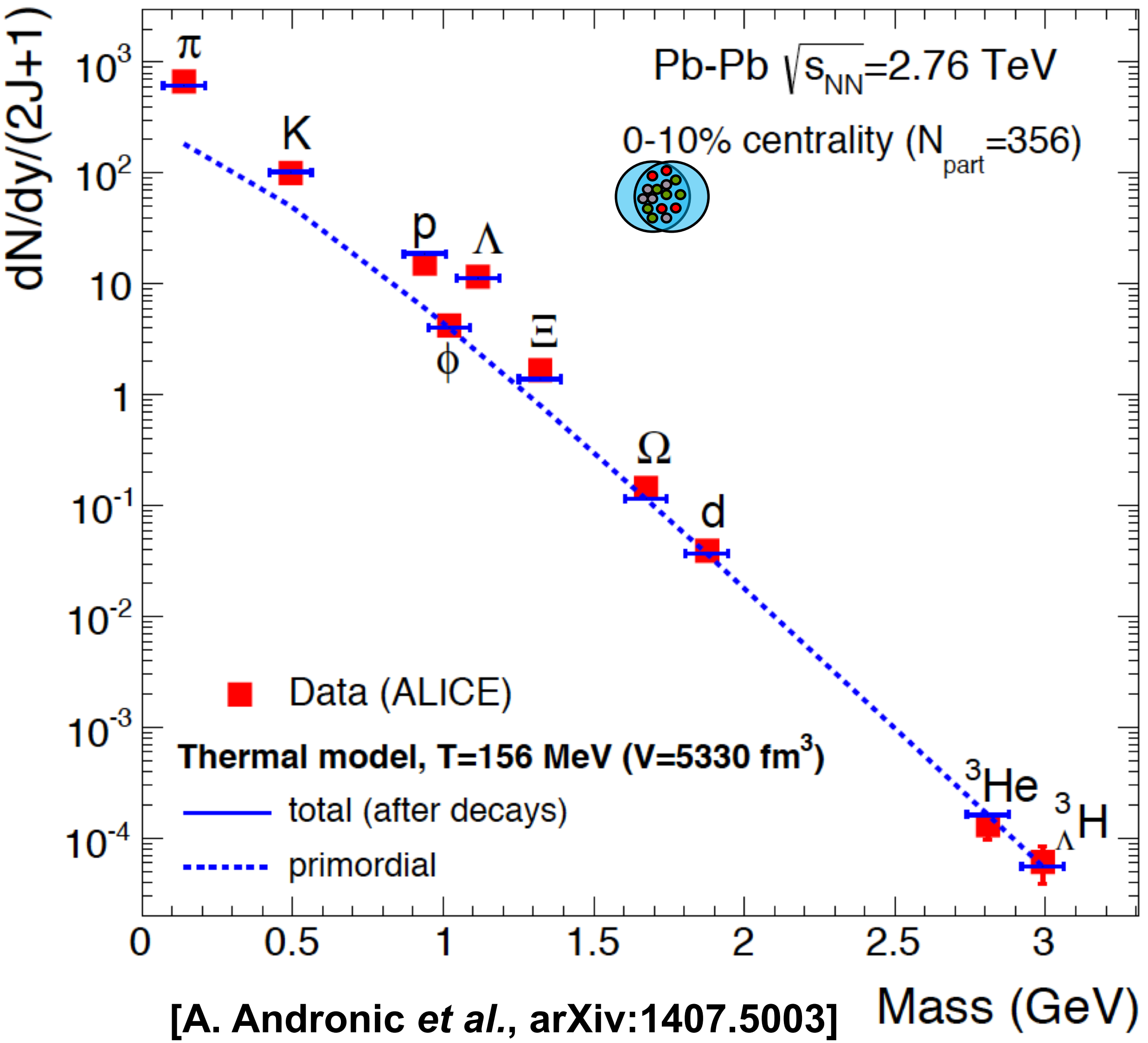
Chemical equilibrium at the LHC (1)

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**.

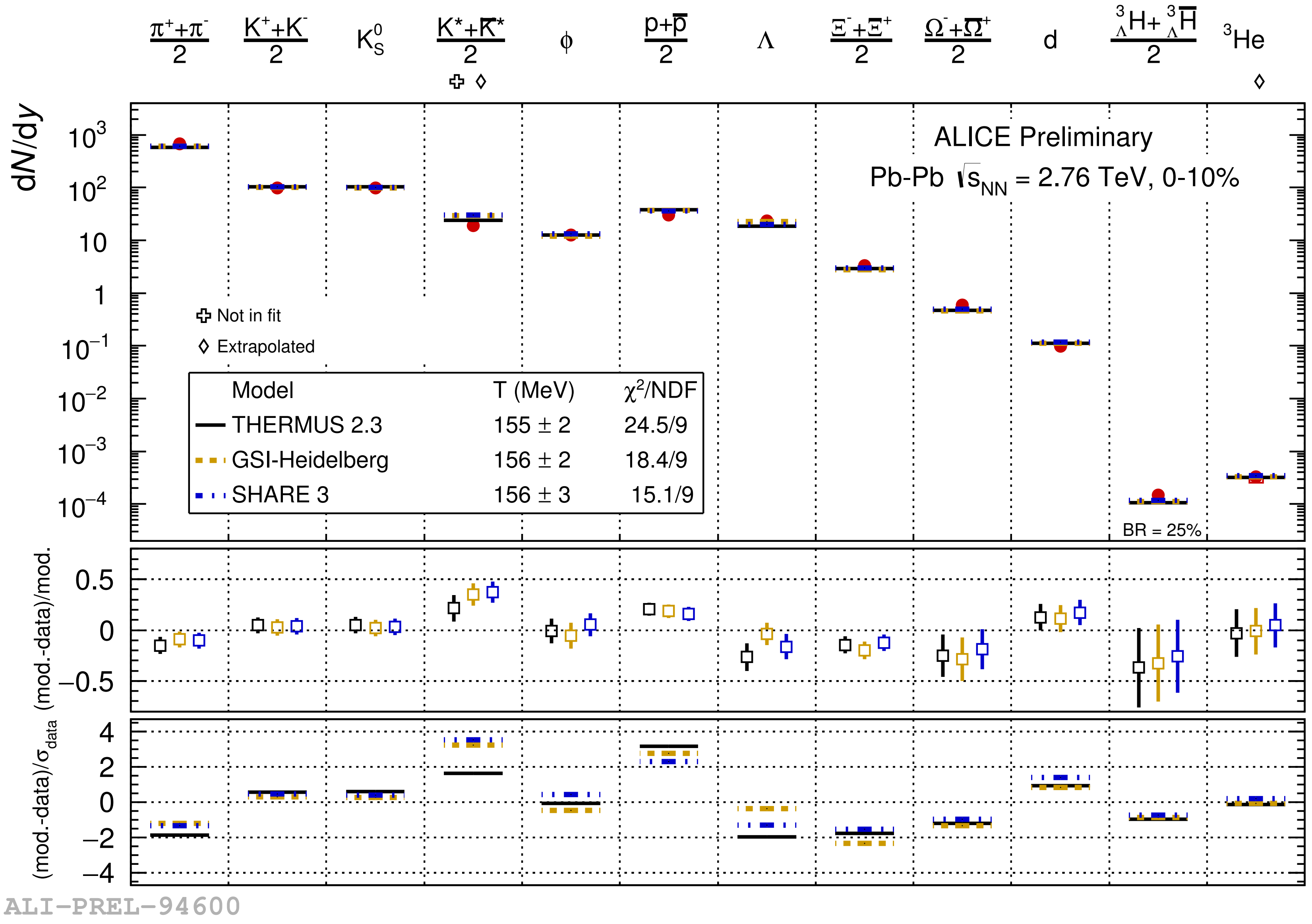
→ This includes **strange hadrons** which are rarer than u,d quarks. Approx. every fourth to fifth quark (every tenth) is a strange quark in Pb-Pb collisions (in pp collisions).

→ 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.

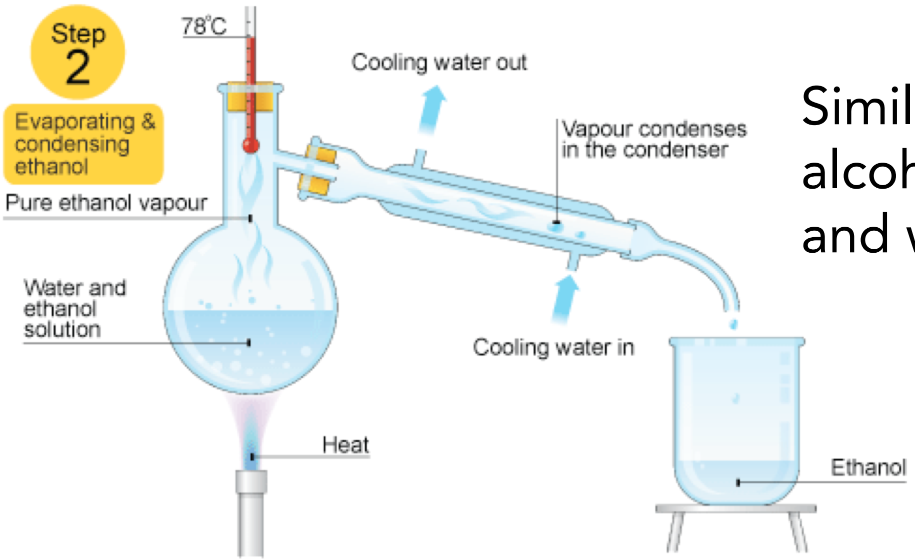
[Wheaton et al, Comput.Phys.Commun, 18084]
[Petran et al, arXiv:1310.5108]
[Andronic et al, PLB 673 142]

Sequential freeze-out?

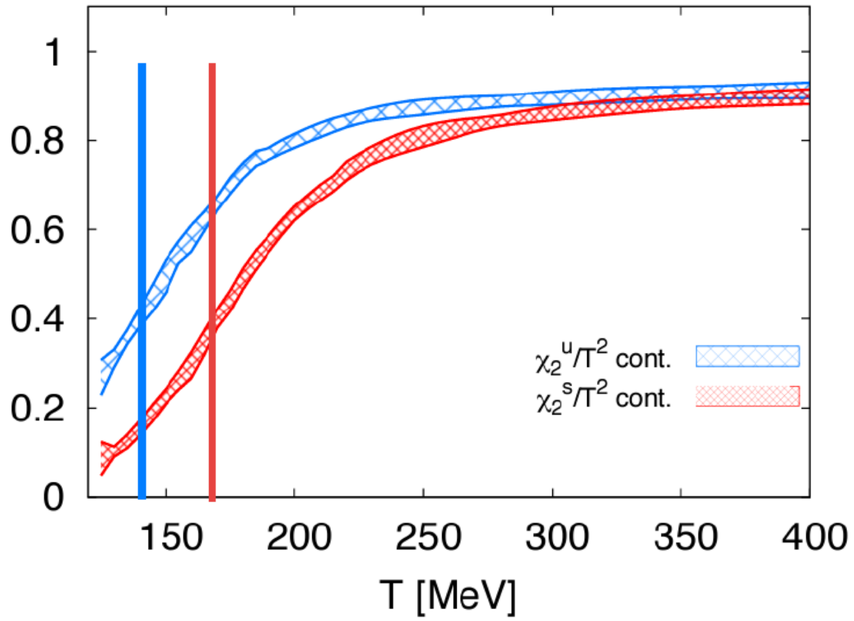
- Are the deviations observed in the thermal model fit for p and Ξ due to physics?

- 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 (1)

[A. Andronic et al **Nature 561 (2018) no.7723, 321-330**]

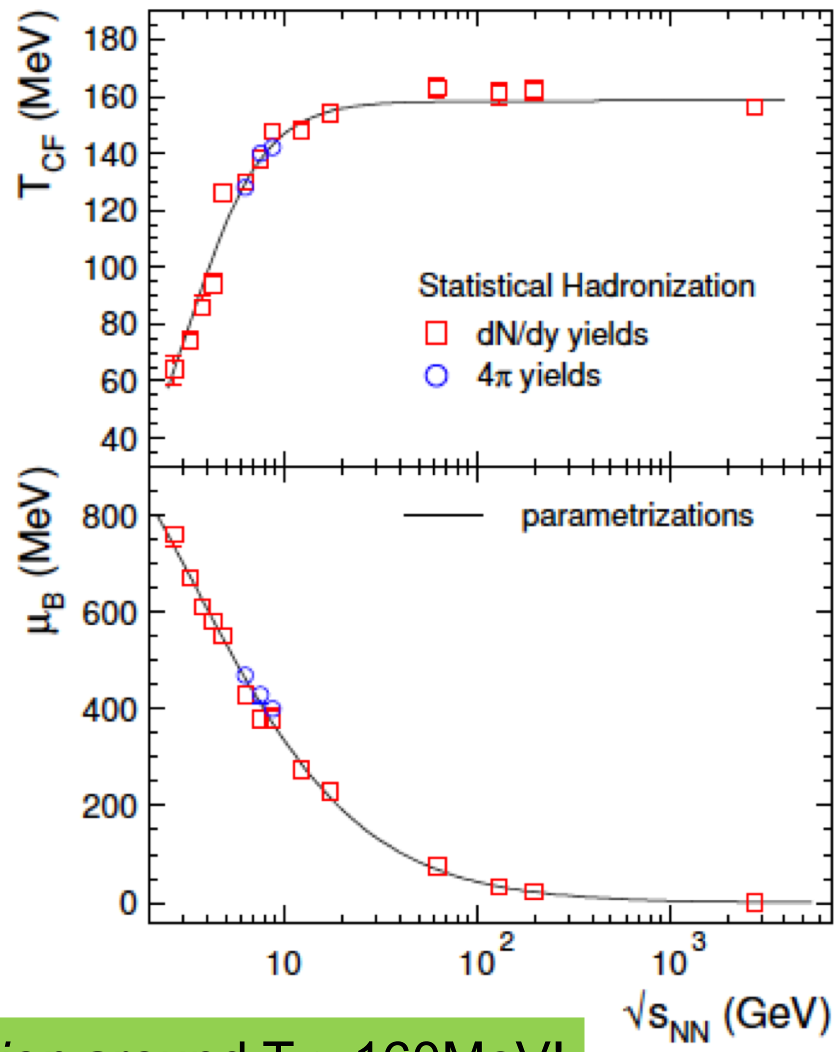
- Hadron yields from SIS up to RHIC and LHC can be described in a hadro-chemical model applying thermal fits.

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

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

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

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



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

Chemical equilibrium vs collision energy (2)

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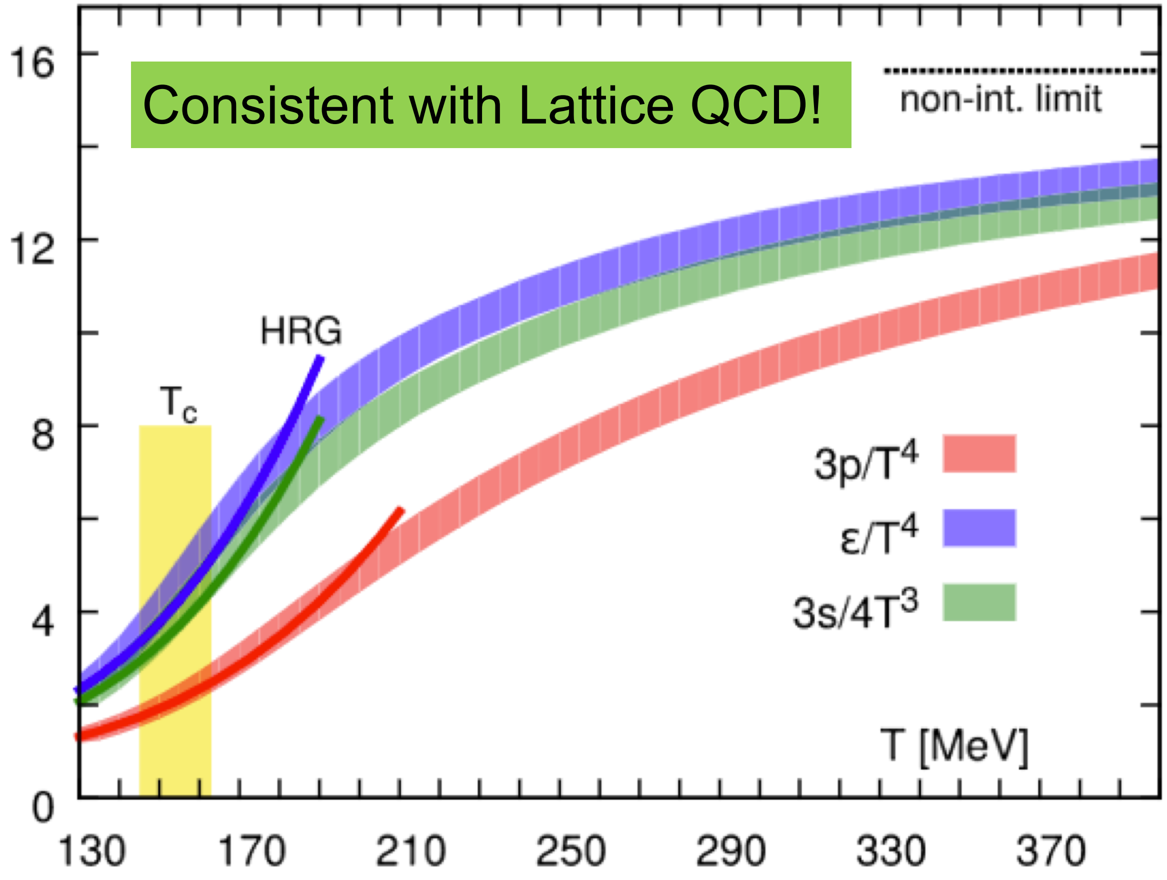
[PRD 90 094503 (2014)]



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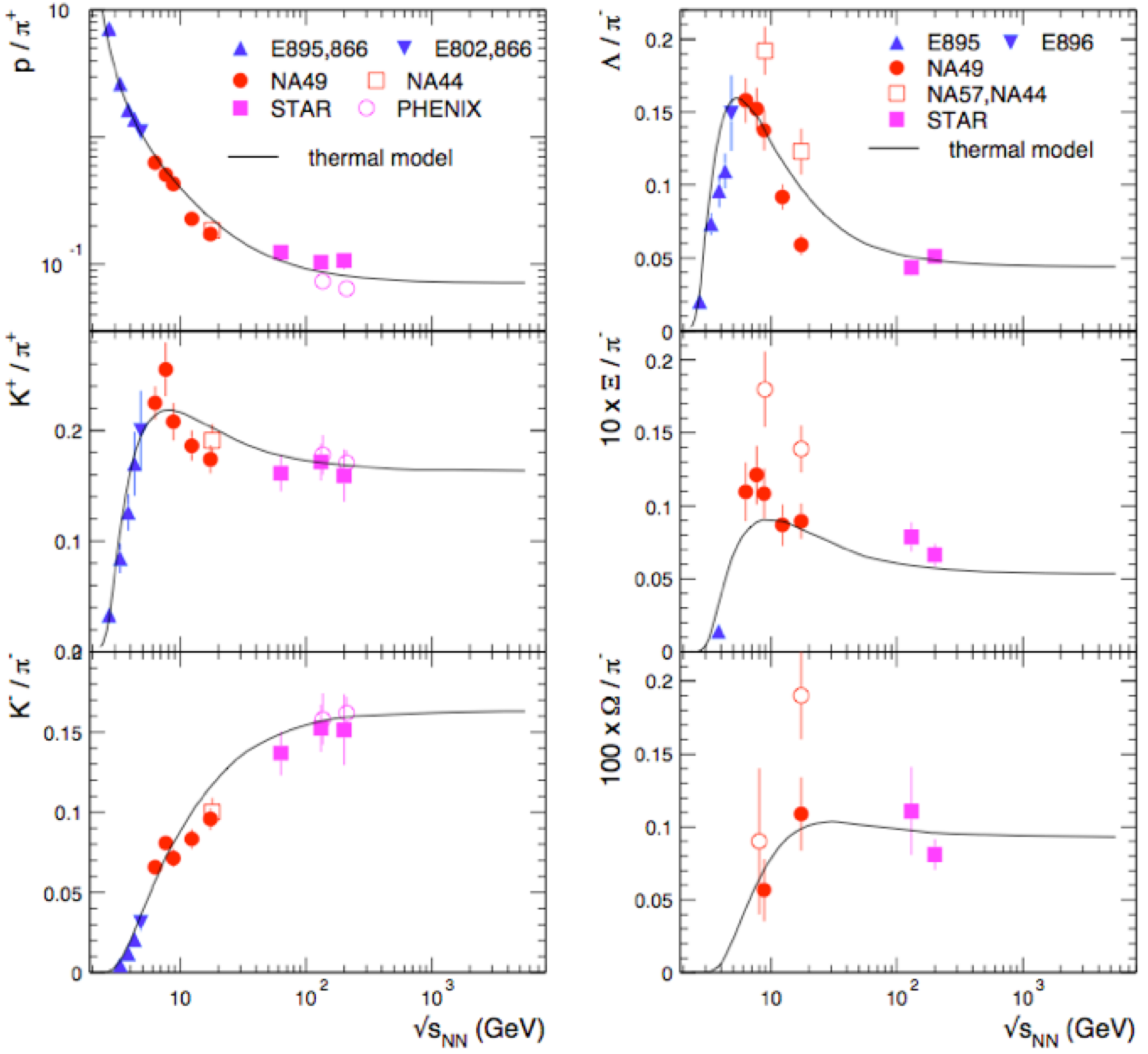
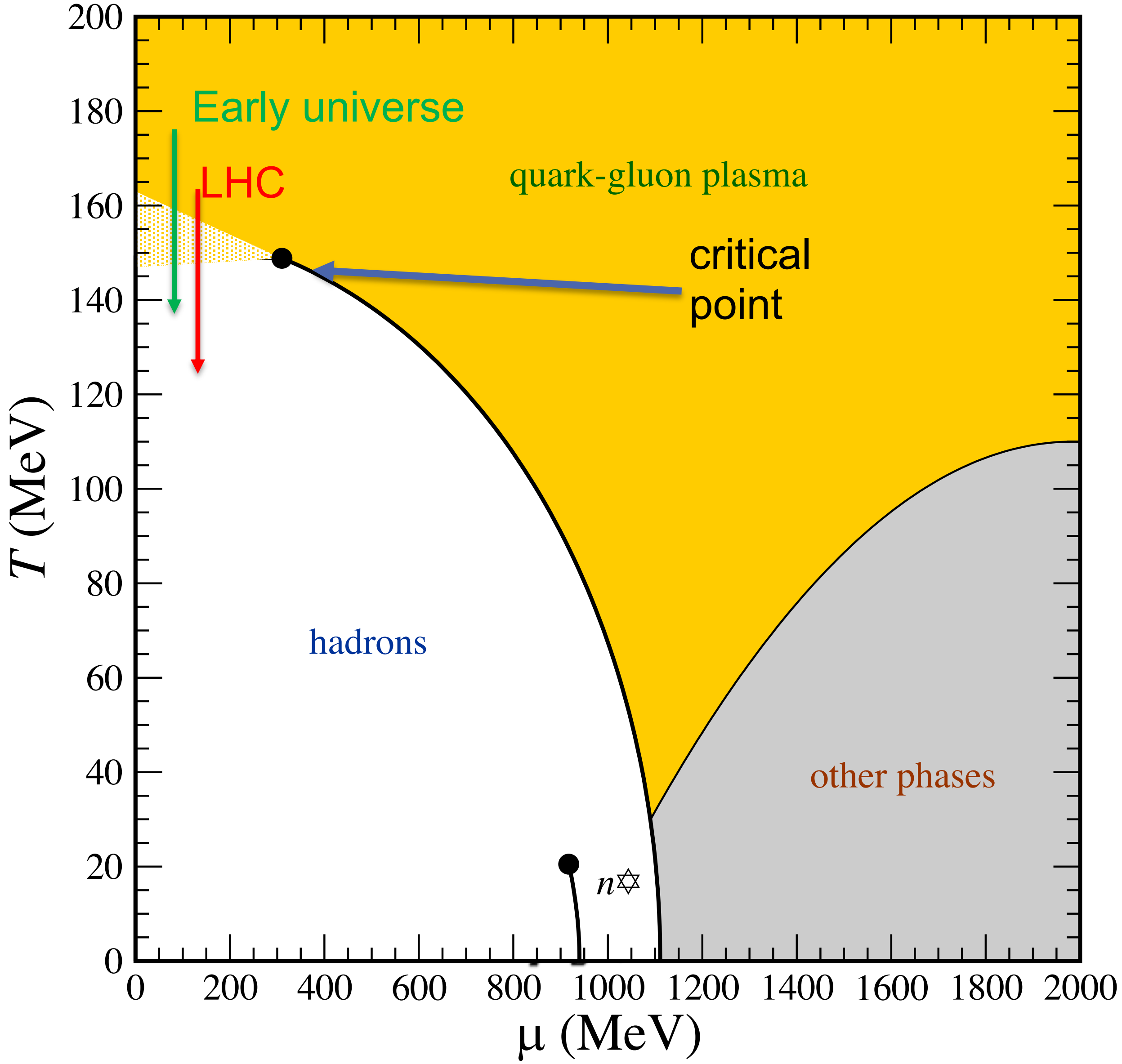


Chemical freeze-out line

- 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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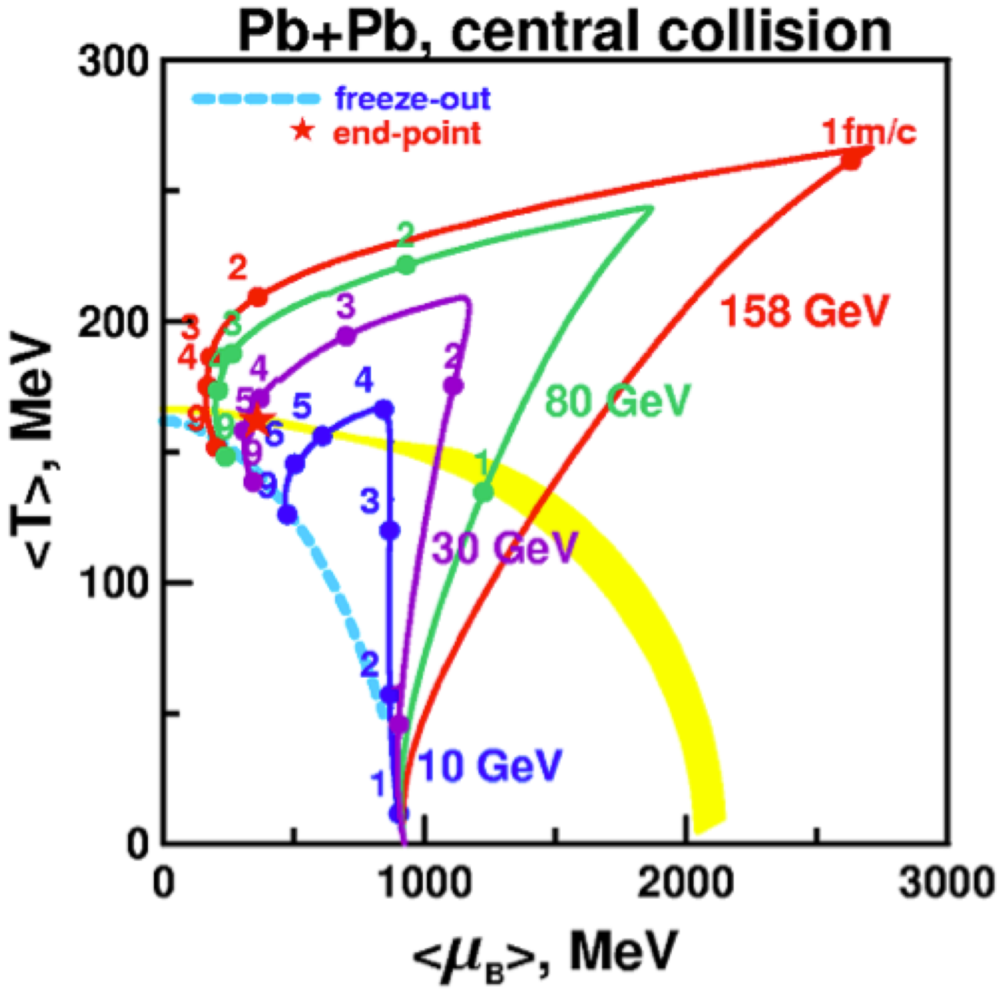

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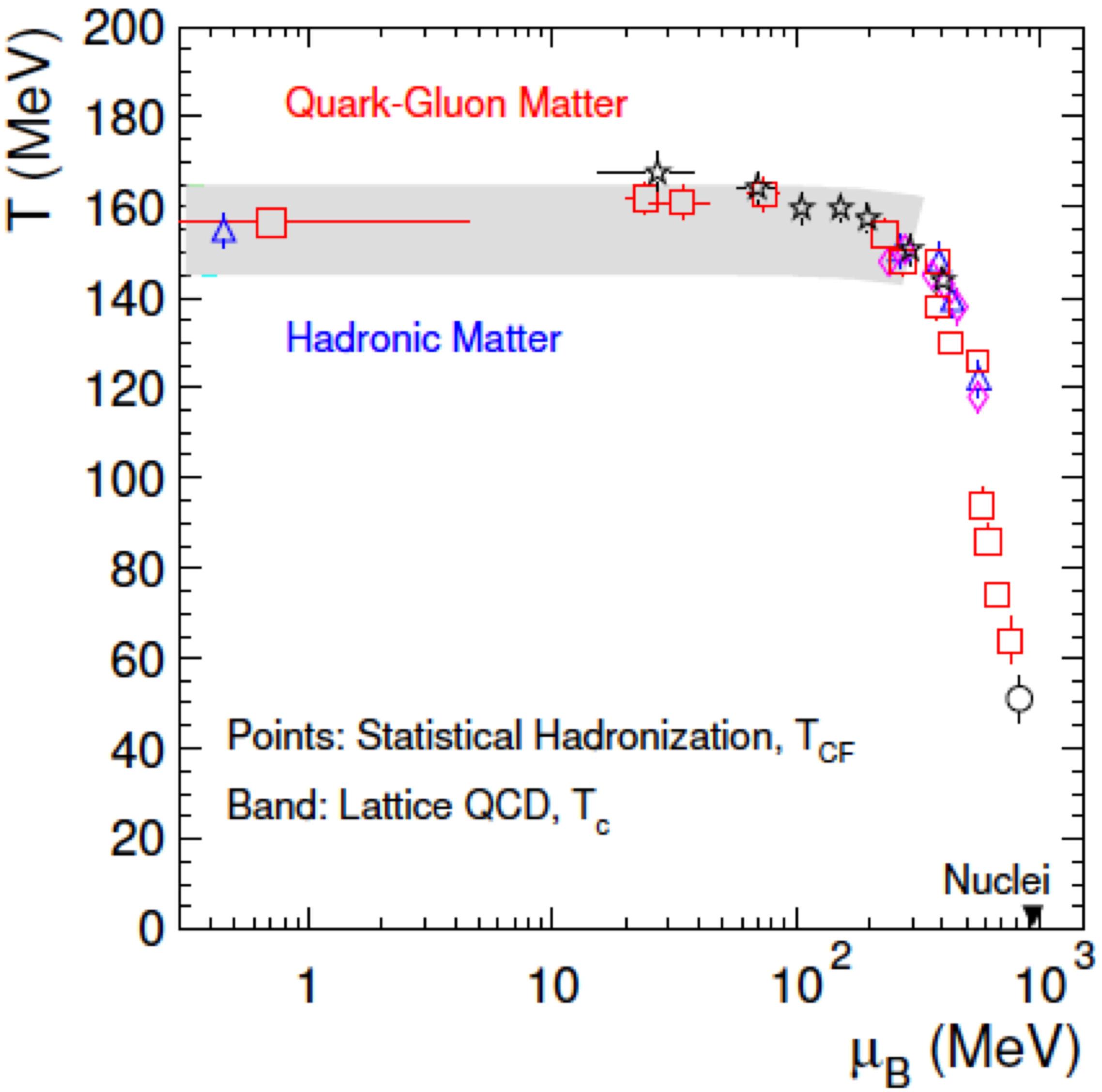
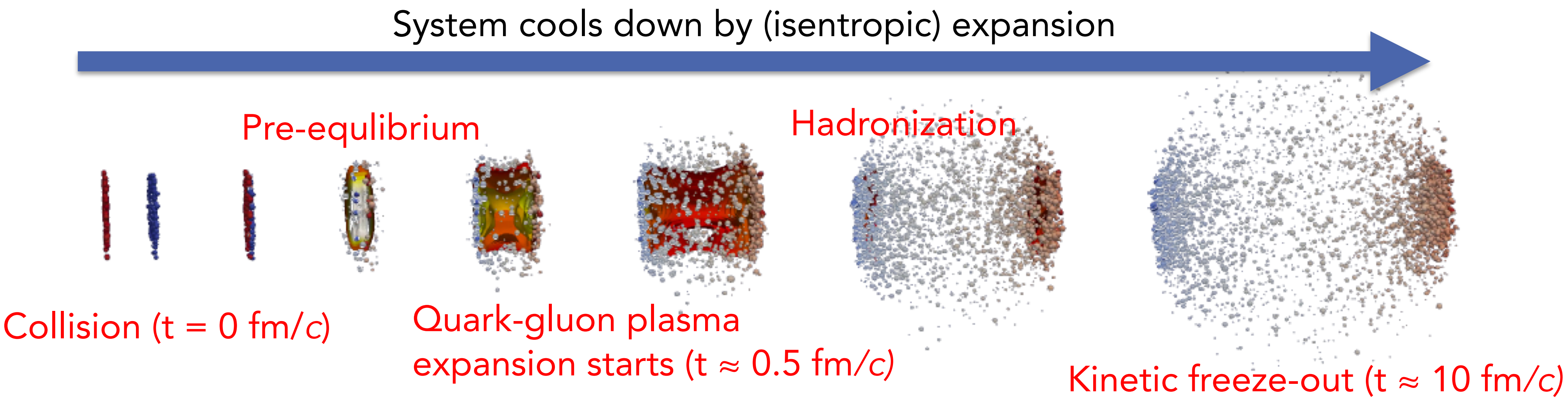
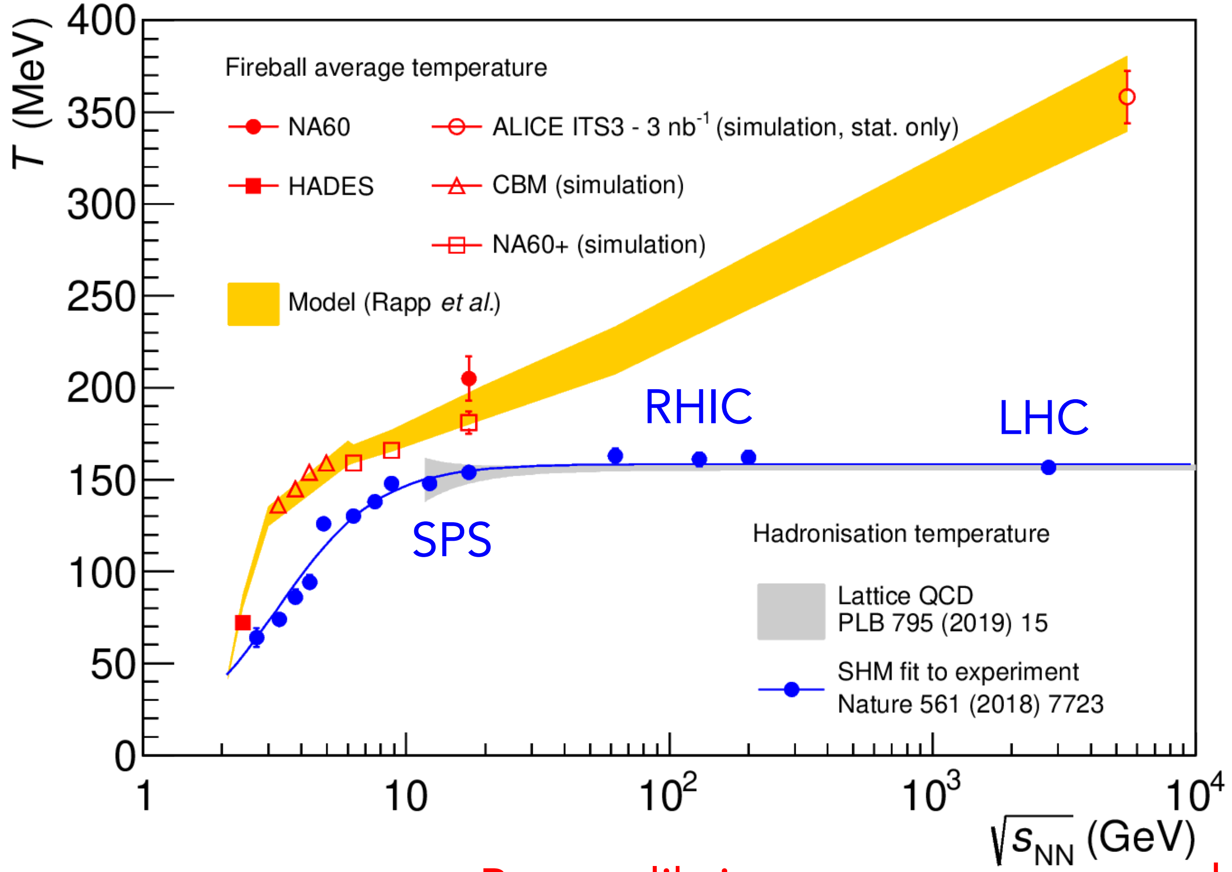


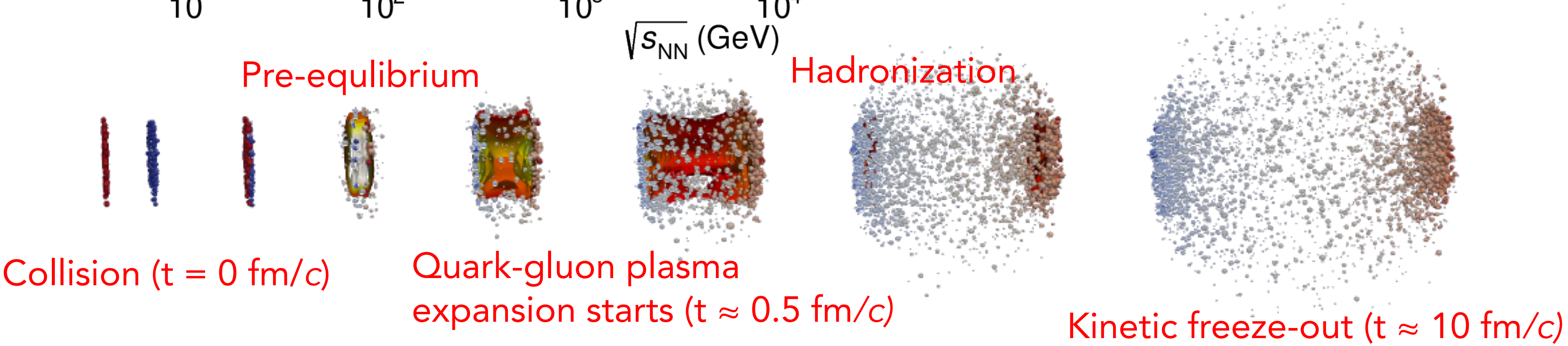
[Nature 561 (2018) no.7723, 321-330]

Recap: temperatures in heavy-ion collisions (1)

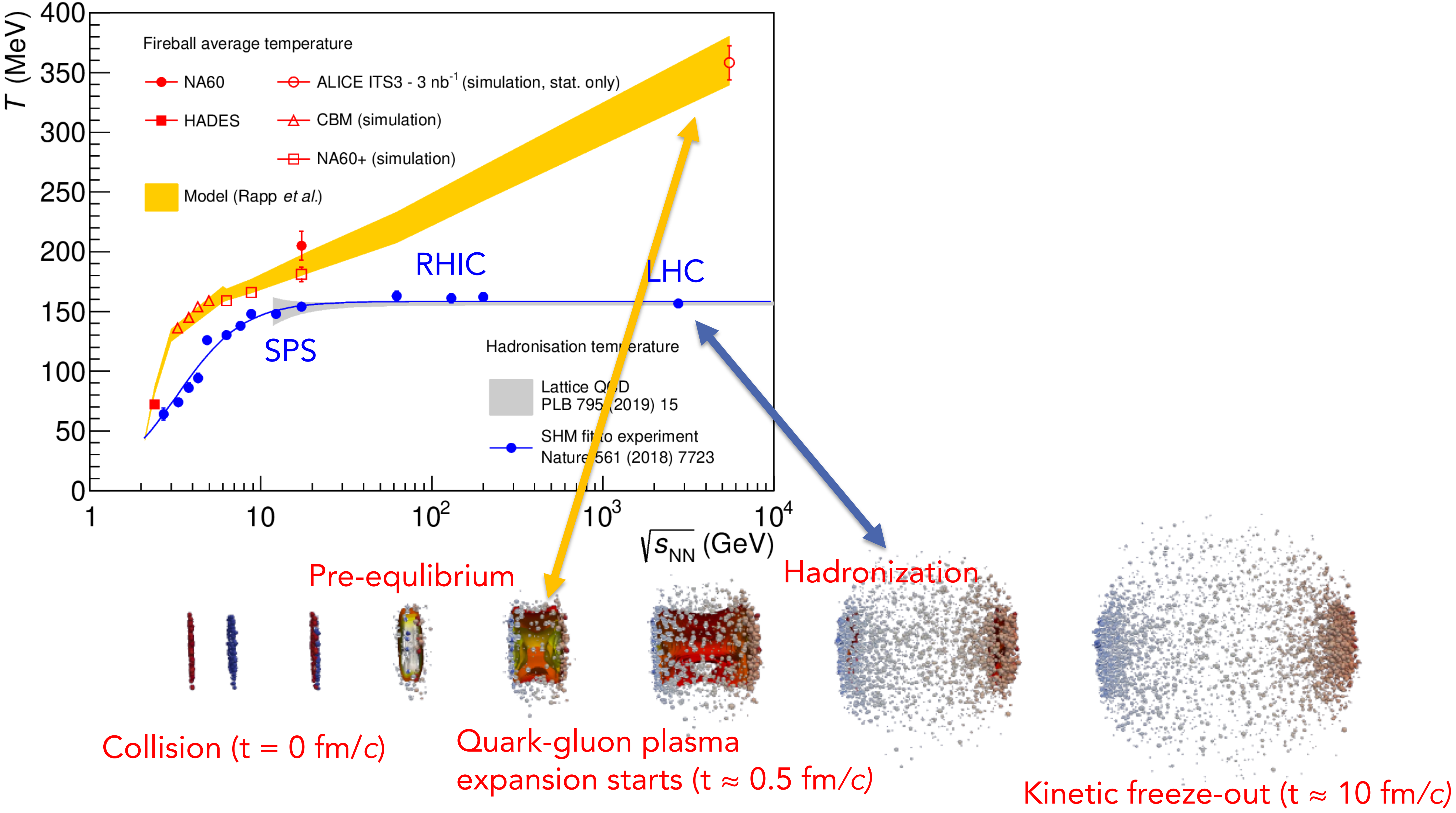


Recap: temperatures in heavy-ion collisions (2)

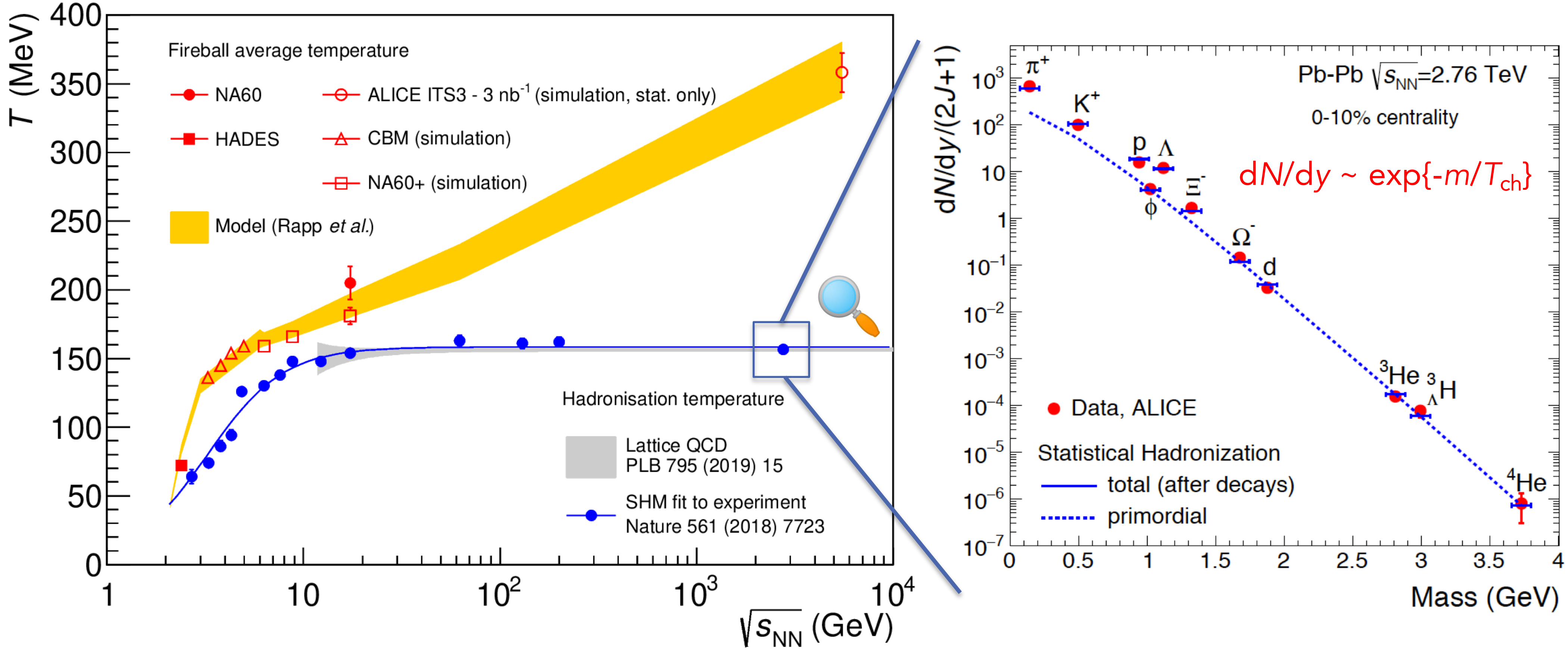




Recap: temperatures in heavy-ion collisions (3)



Recap: temperatures in heavy-ion collisions (4)



→ Systematic measurements of light flavor hadrons demonstrate that chemical freeze-out (hadronization) temperature saturates at:

$T_{ch} \approx 156$ MeV ± 3 MeV (≙ $1.8 \cdot 10^{12}$ K)

→ In agreement with first principle Lattice QCD calculations

[Nature 561 (2018) no.7723, 321-330] [ALICE, Nucl. Phys. A 971 (2018) 1-20]

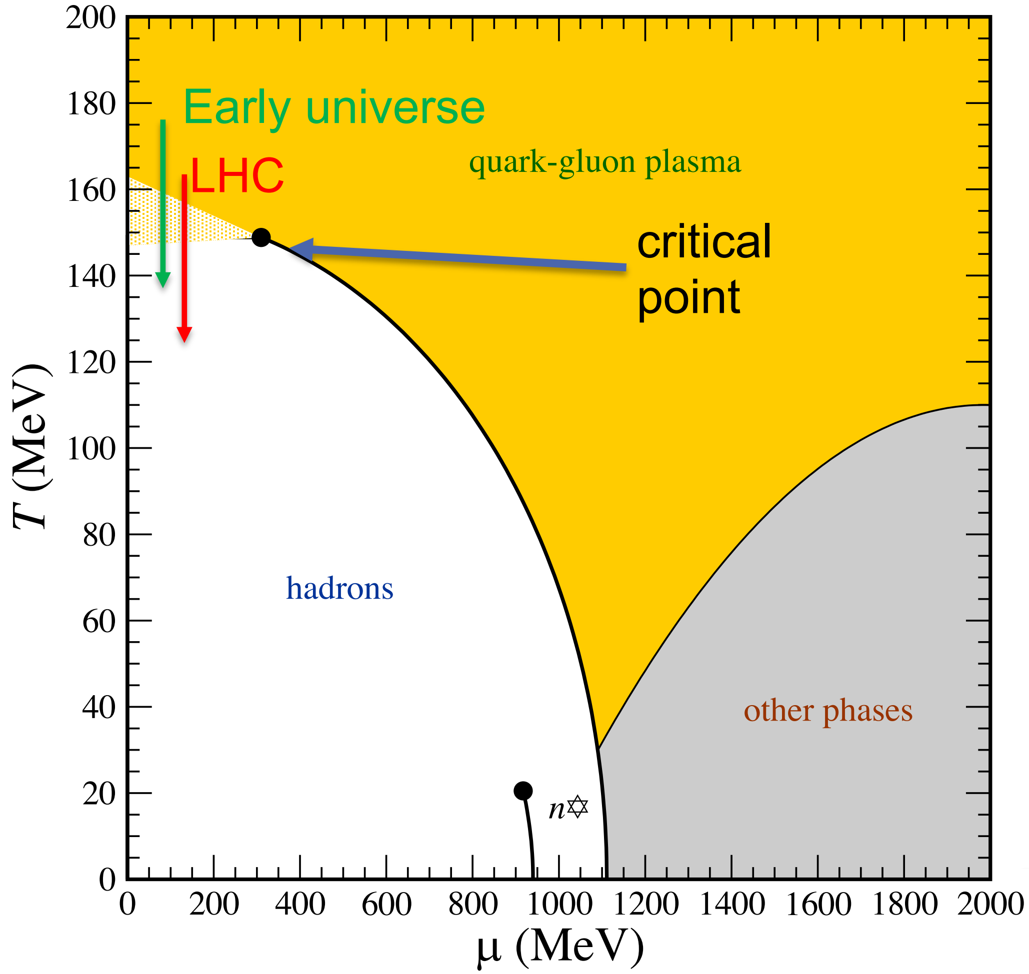
END OF LECTURE 1..

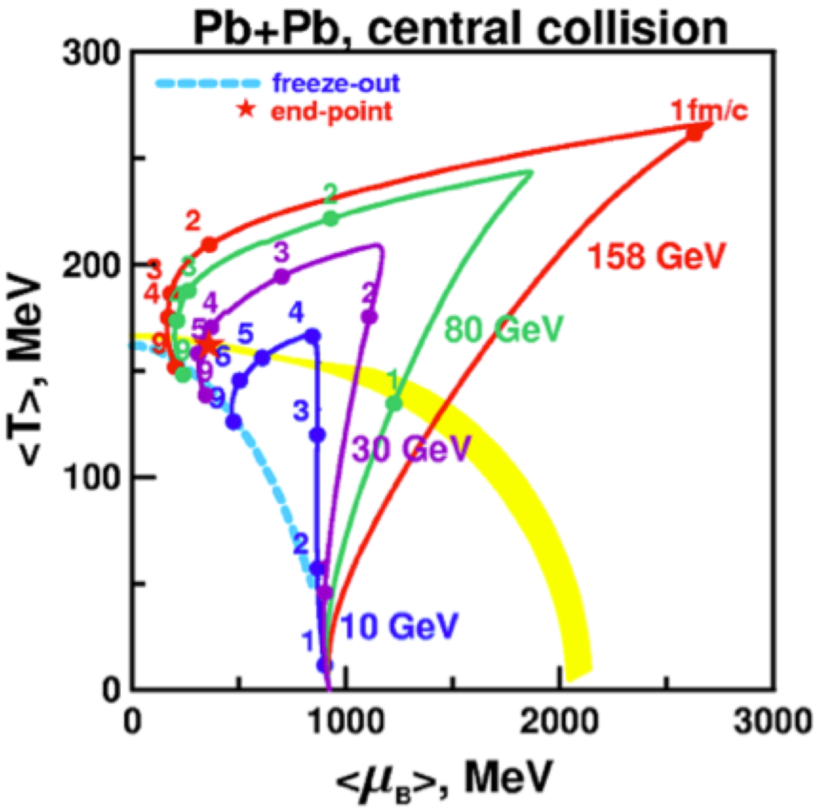
QGP thermodynamics and soft probes

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***.





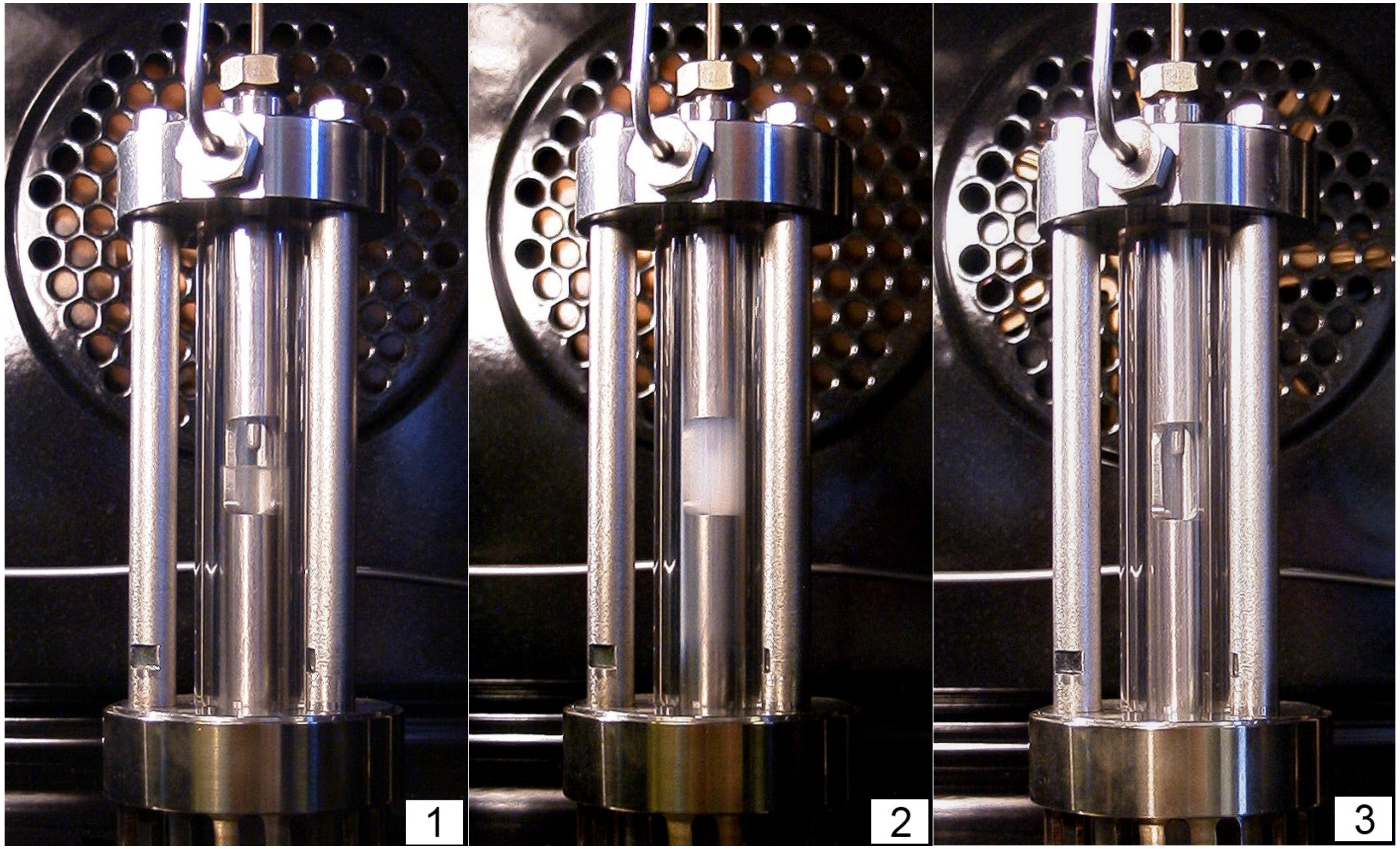
Y.B. Ivanov et al., Phys. Rev. C 73 (2006) 30.

→ 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:

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

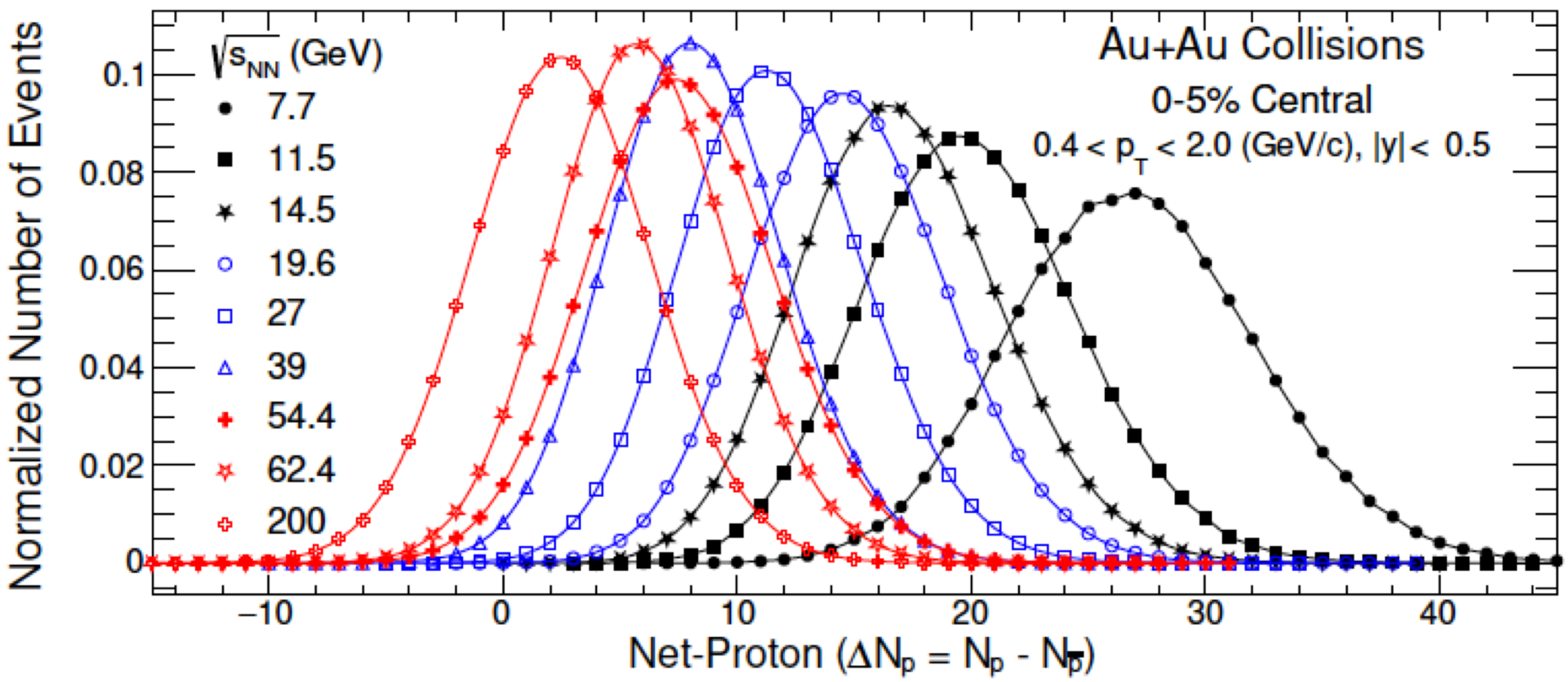
$$\mu_i = \langle (\delta N)^i \rangle$$

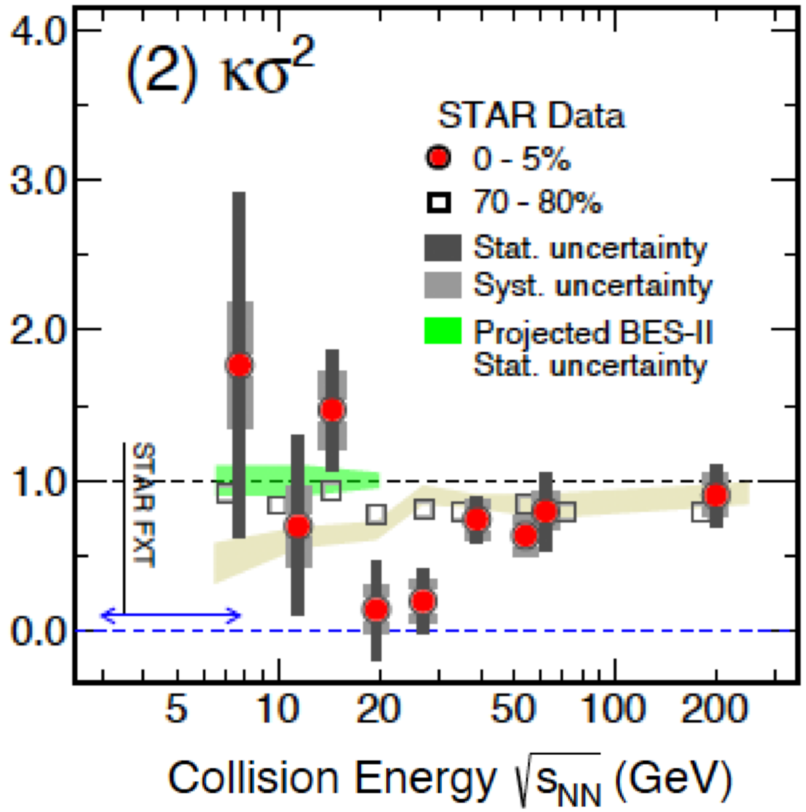
$$\delta N = N - \langle N \rangle$$

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-p}) distribution => fixed at chemical freeze-out

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





[*Phys.Rev.Lett.* 126 (2021) 9, 092301]

QGP thermodynamics and soft probes
Radial and elliptic flow

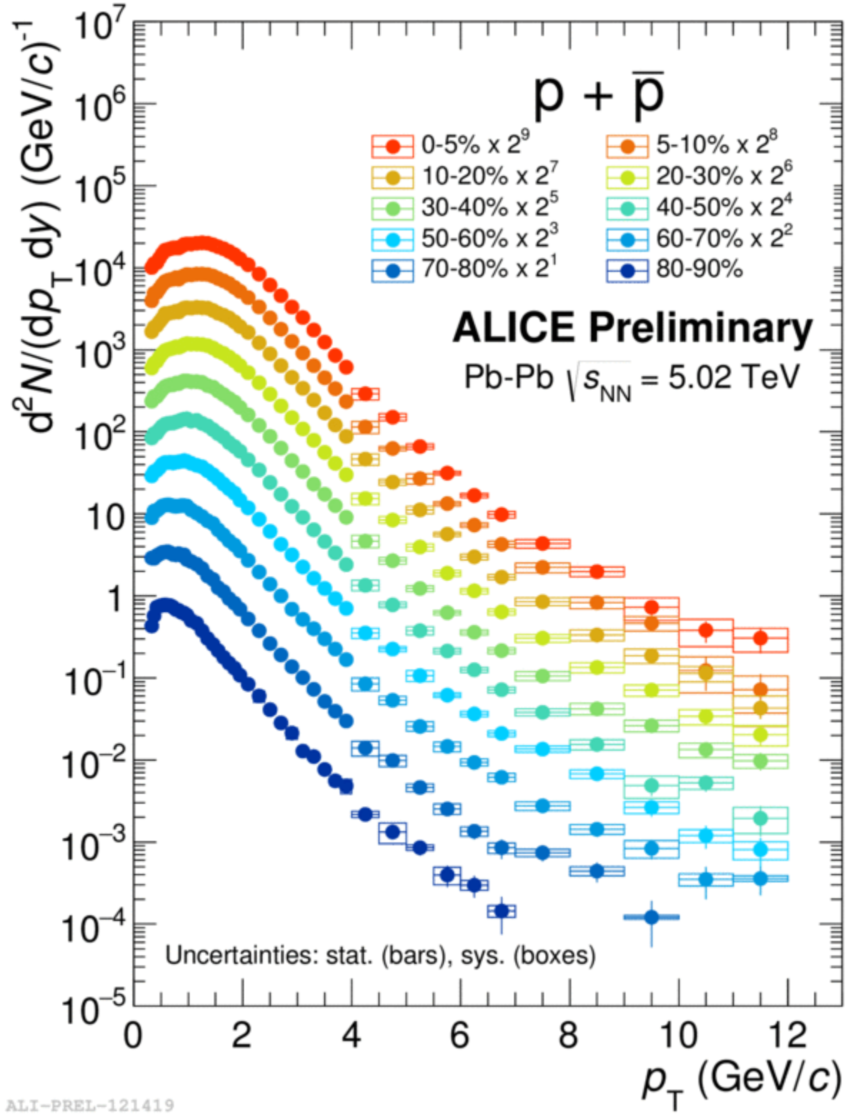
Bulk particle production and collectivity

- Low p_T hadrons composed of (u,d,s) valence quarks define the collective behaviour of the fireball.
- "Baseline model of ultra-relativistic heavy-ion physics"

A fireball in *local thermodynamic equilibrium*:

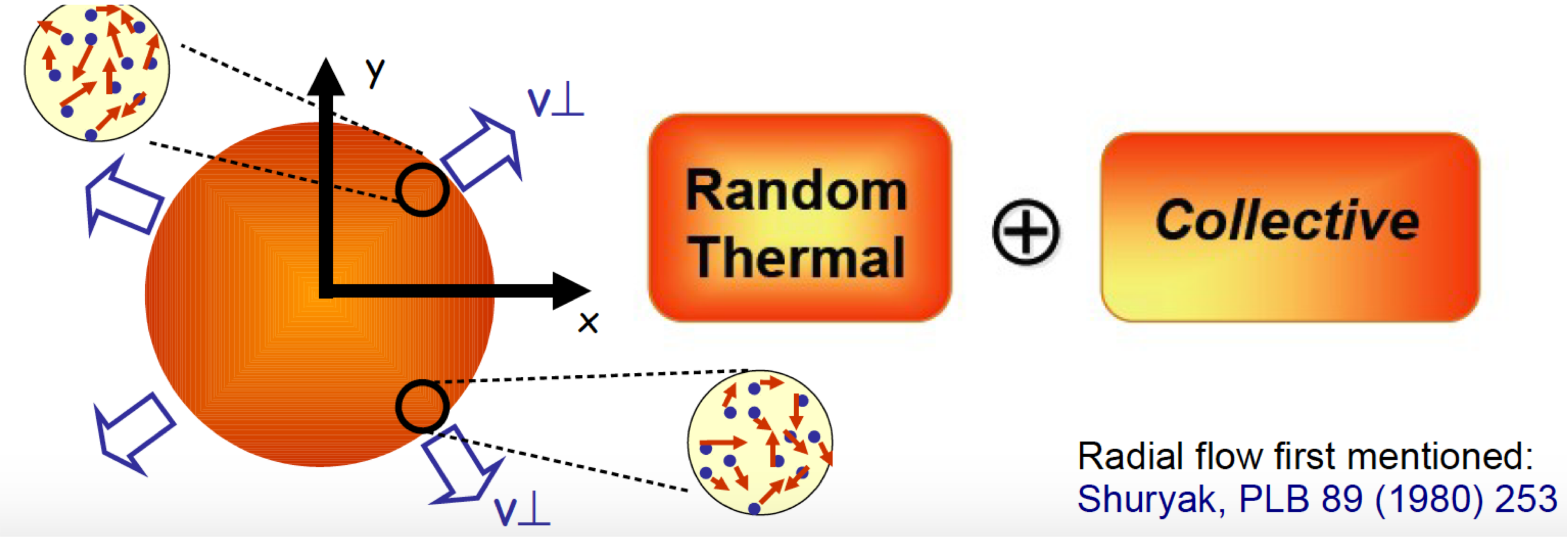
- particle chemistry in agreement with thermal model predictions
- p_T-spectra and v_2 measurements show patterns of radial and elliptic hydrodynamic flow.

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



Flow in AA collisions

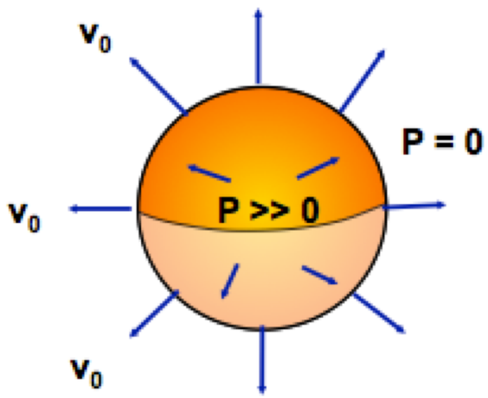
- Flow picture: Collective motion of particles superimposed to the thermal motion.
- Radial flow is a natural consequence of any interacting system expanding into the vacuum.

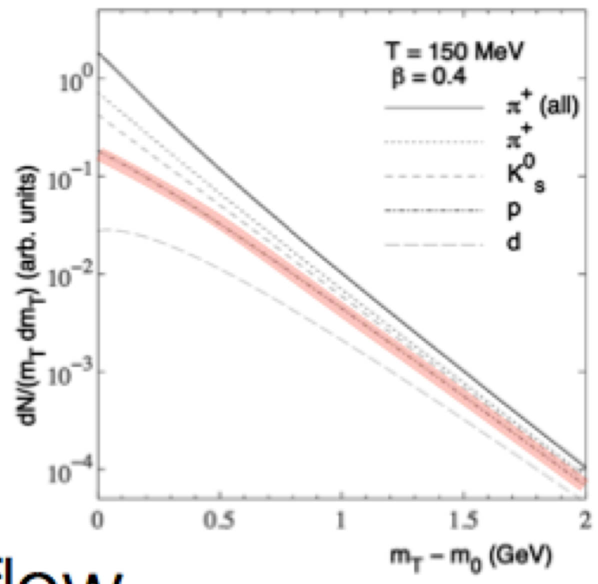


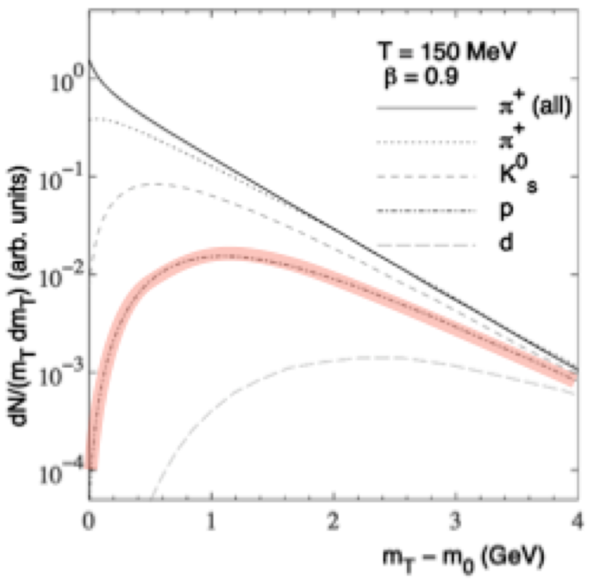
Radial flow first mentioned:
Shuryak, PLB 89 (1980) 253

From: C. Loizides

Isotropic radial flow

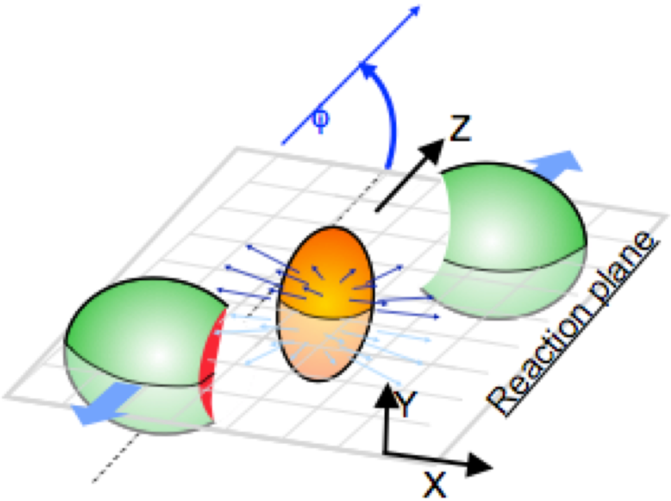




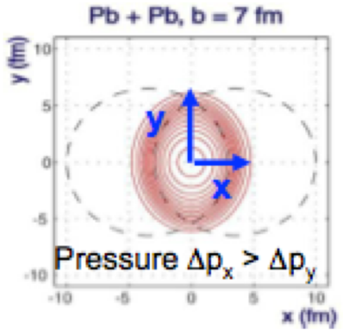


Anisotropic (elliptic) flow

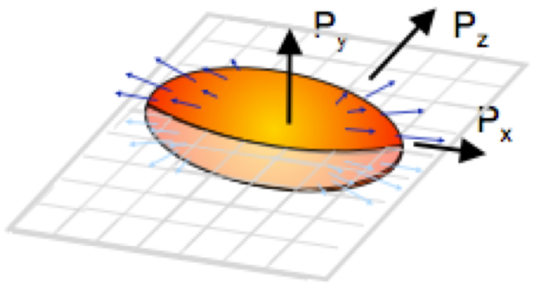
Spatial deformation



Azimuthal (φ) pressure gradients

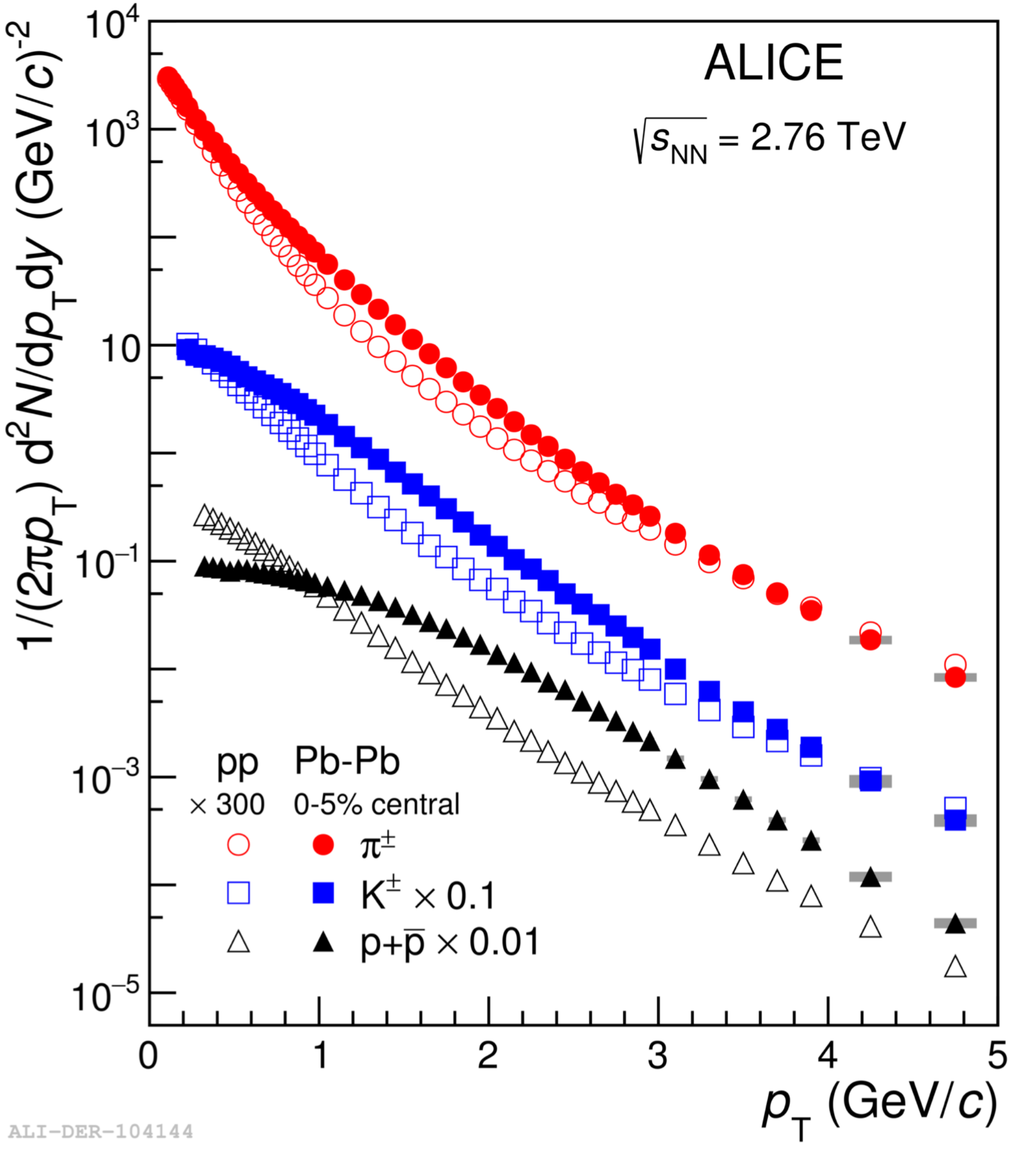


Anisotropic particle density



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

Radial flow



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

→ p_T-spectra harden with centrality.

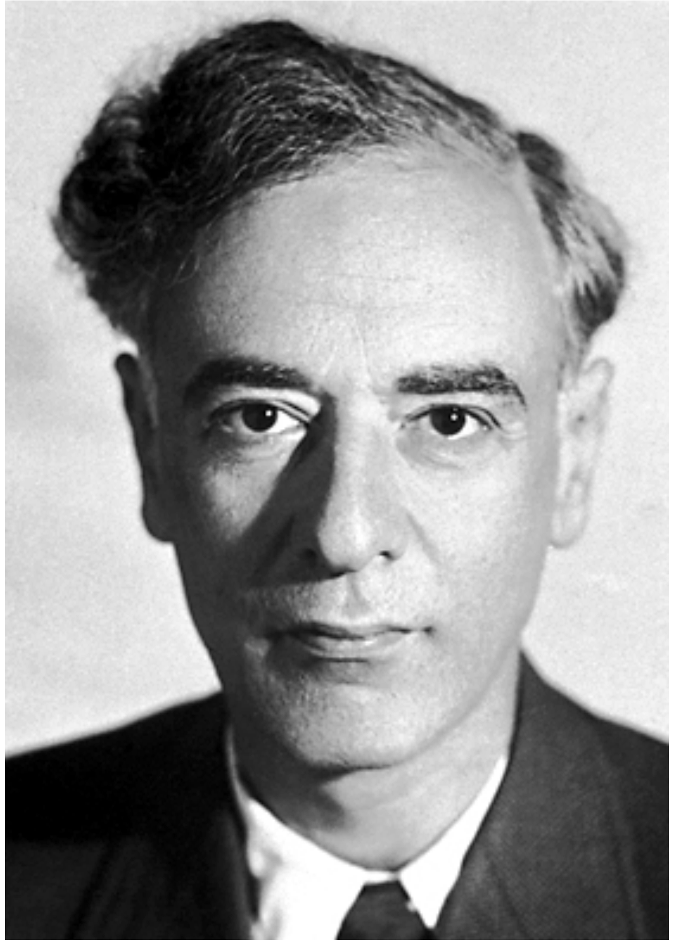
→ More pronounced for heavier particles(e.g.: *p* > *K* > π) as *velocities* become equalized in the flow field (p = **βγ**·m).

→ Hydrodynamic models show a good agreement with the data.

→ Kinetic freeze-out temperature from Blast-Wave model: ~90 MeV

Relativistic Hydrodynamics

- General framework of relativistic hydrodynamics was first developed by Landau and is textbook knowledge since then.
- Only requirement for applicability: *local thermodynamic equilibrium*.
- **Perfect fluid: no dissipation**
  - Conservation of energy and momentum: $\partial_\mu T^{\mu\nu} = 0$
  - Conservation of baryon number current: $\partial_\mu j_B^\mu(x) = 0$
    → gives five independent equations
- Six thermodynamic variables: the energy density $\varepsilon(x)$, the momentum density $P(x)$, the baryon number density $n_B(x)$, and the fluid velocity $v(x)$.
- Equation-of-state: functional relation of ε, P, and n_B (taken from Lattice QCD).
- In reality: dissipative corrections play an important role:
  → **shear viscosity** η and bulk viscosity ζ (so called *transport coefficiencts*)enter in correction terms on the right hand side of the equations above.



Lew Landau (1908-1986)

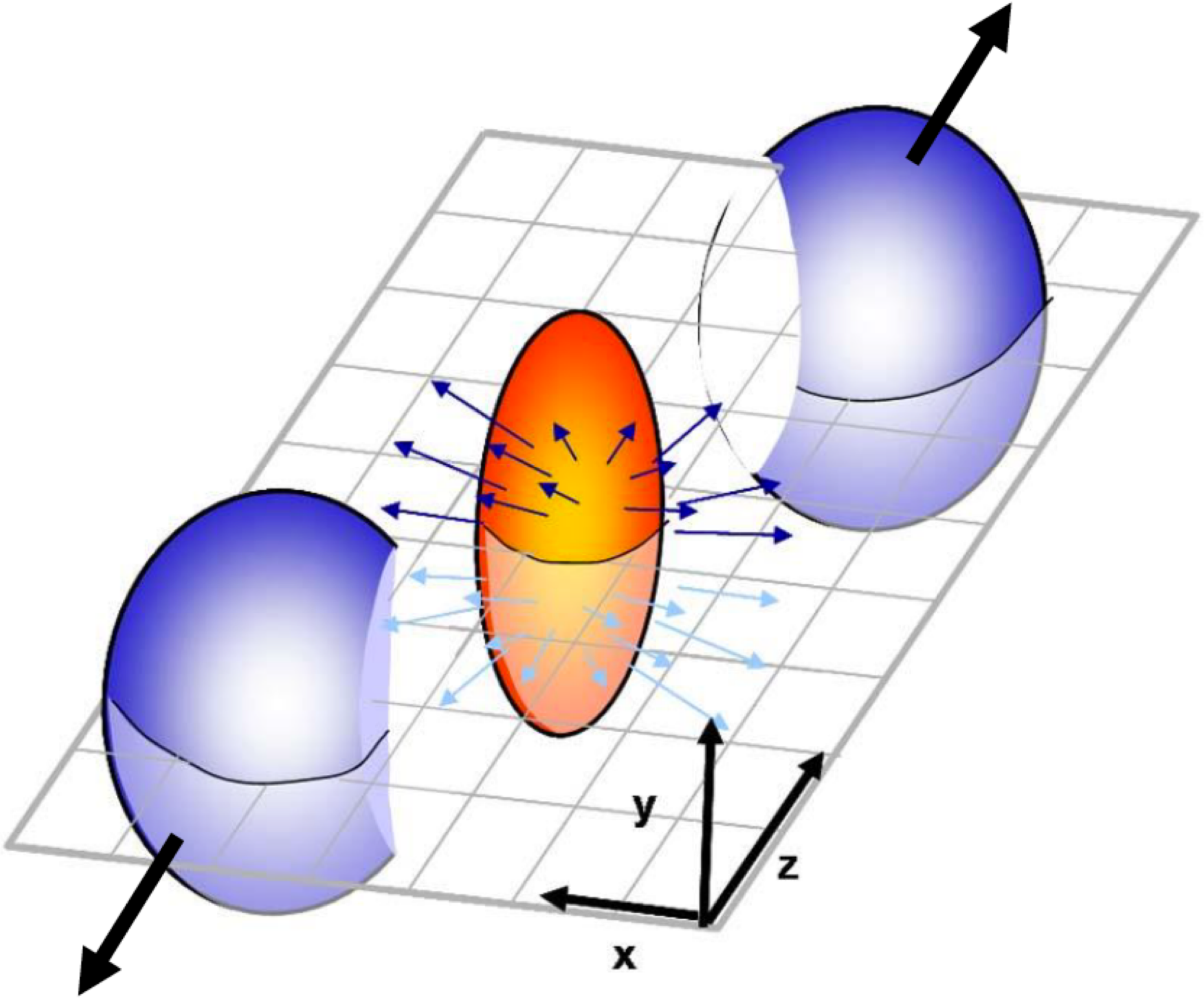
Elliptic flow v_2

- Not only the observed particle spectrum in p_T, but also in φ is the result of the fireball expansion.
- If the system is asymmetric in spatial coordinates, scattering converts it to **anisotropy in momentum space:**

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

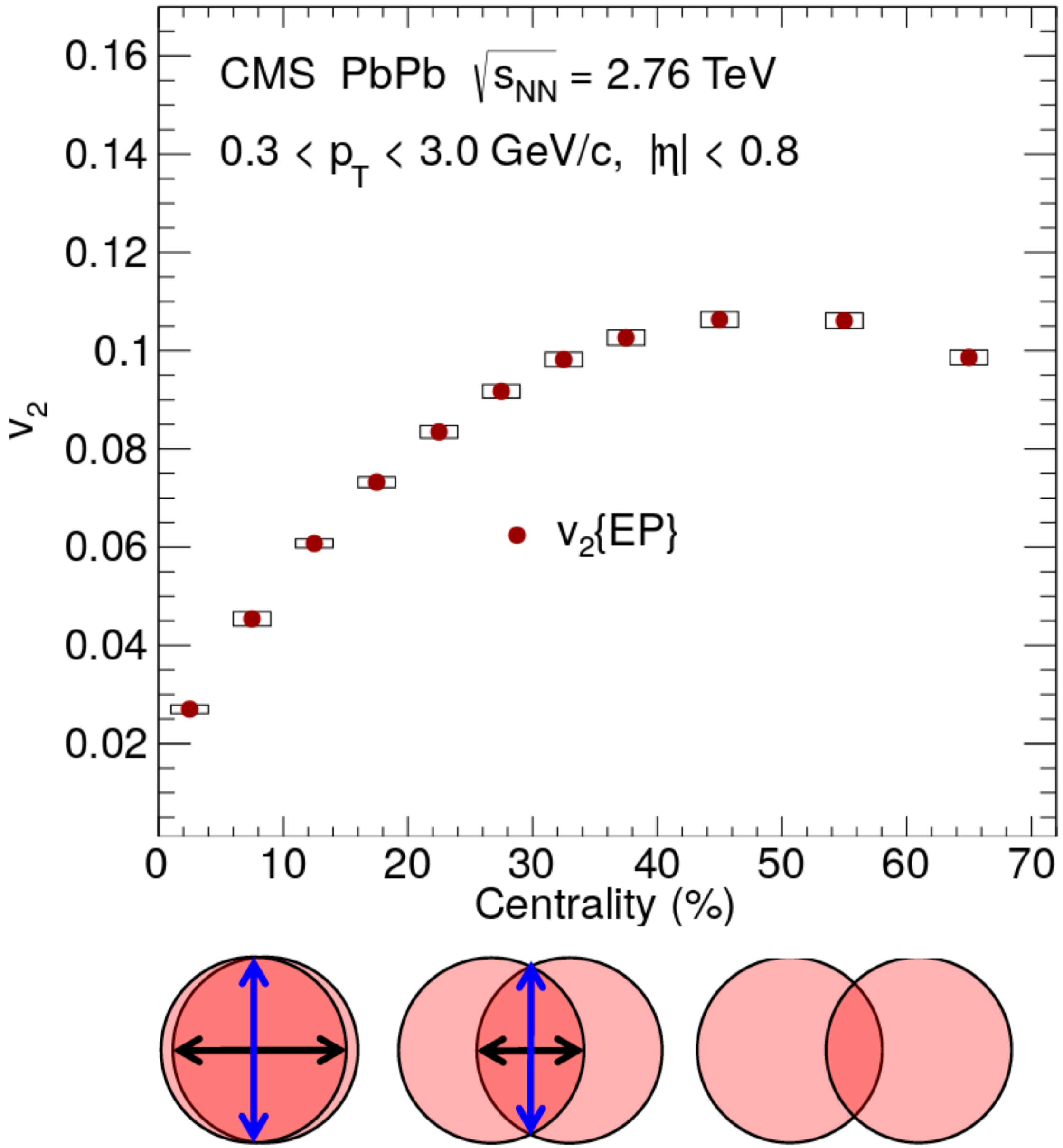
Radial flow v_1 – direct flow, **v_2- elliptic flow**

- If nuclei overlap was a smooth almond shape, odd harmonics (v_3,..) would be zero.



Centrality dependence of v_2

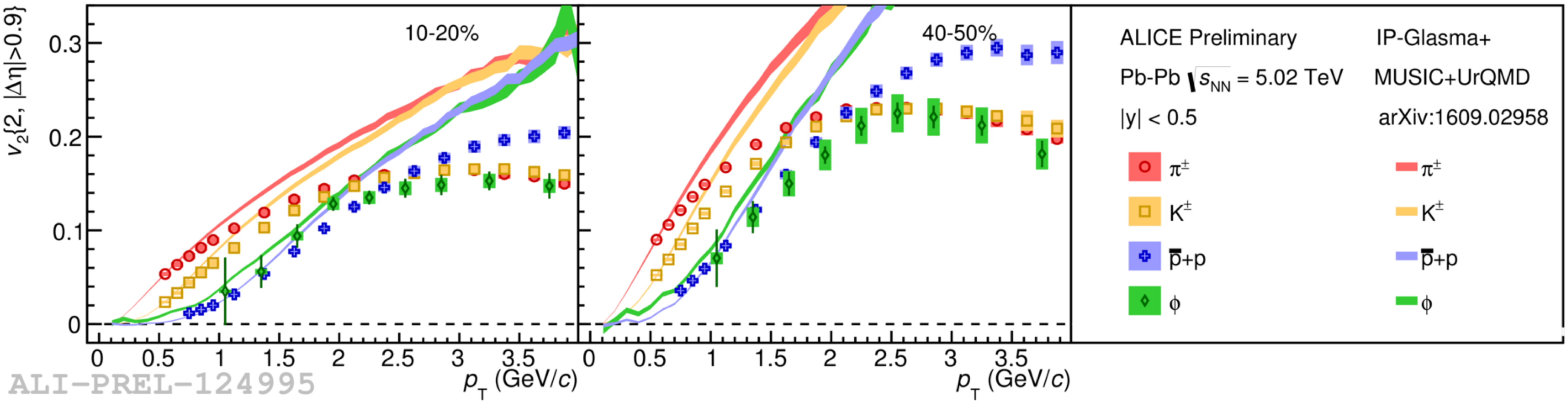
- v_2 exhibits a strong centrality dependence
- v_2 largest for 40-50%
- Spatial anisotropy very small in central collisions
- Largest anisotropy in mid-central collisions
- Small overlap region in peripheral collisions



CMS, PRC 87(2013) 014902

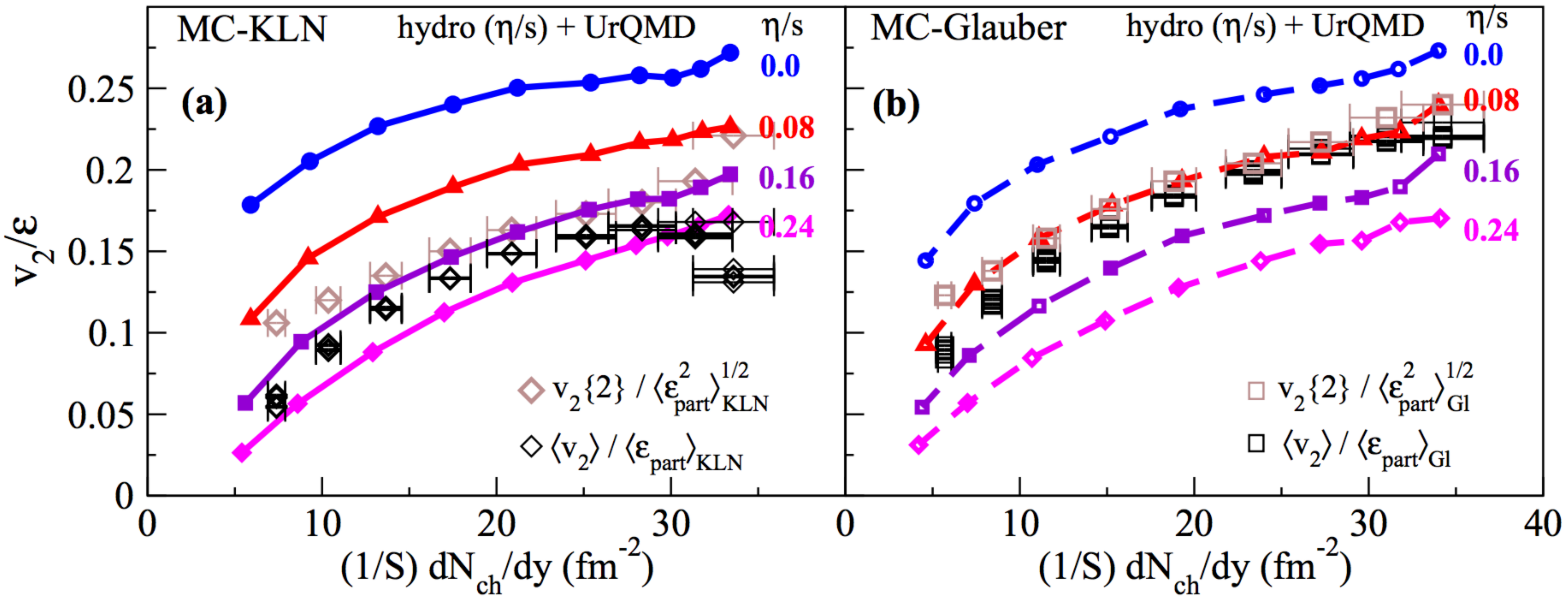
Mass ordering of v_2 vs. transverse momentum

Transverse momentum dependence of elliptic flow shows the same mass ordering ($p = \beta\gamma \cdot m$) as radial flow and as expected from hydrodynamics.
→ interplay of radial and elliptic flow.



Sensitivity of v_2 to shear viscosity

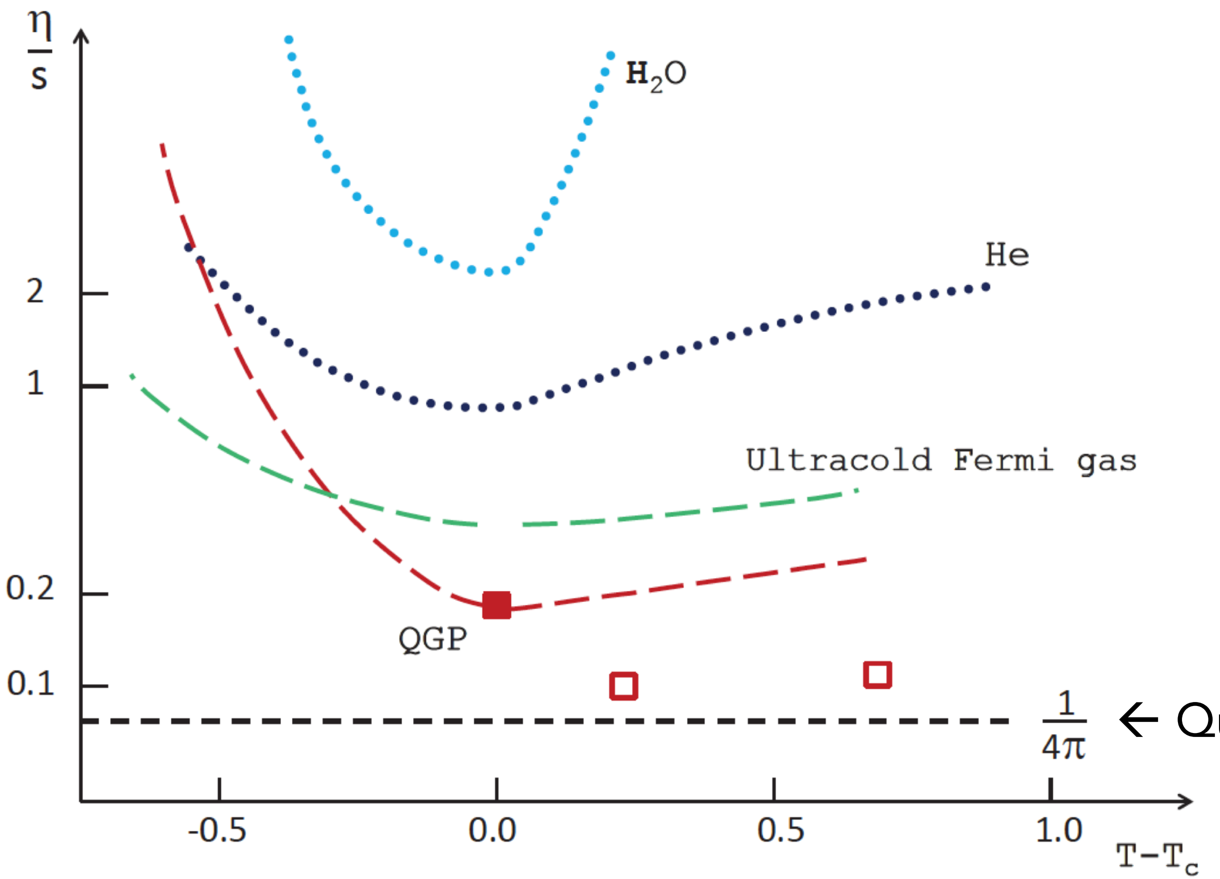
[Phys.Rev.Lett. 106 (2011) 192301]



- The larger the shear viscosity per entropy density ratio *η/s* of the QGP, the more v_2 is reduced.
- Dissipative losses hamper the buildup of flow => measuring the magnitude of v_2 and comparing it to models, we can determine how *ideal* the QGP liquid is.

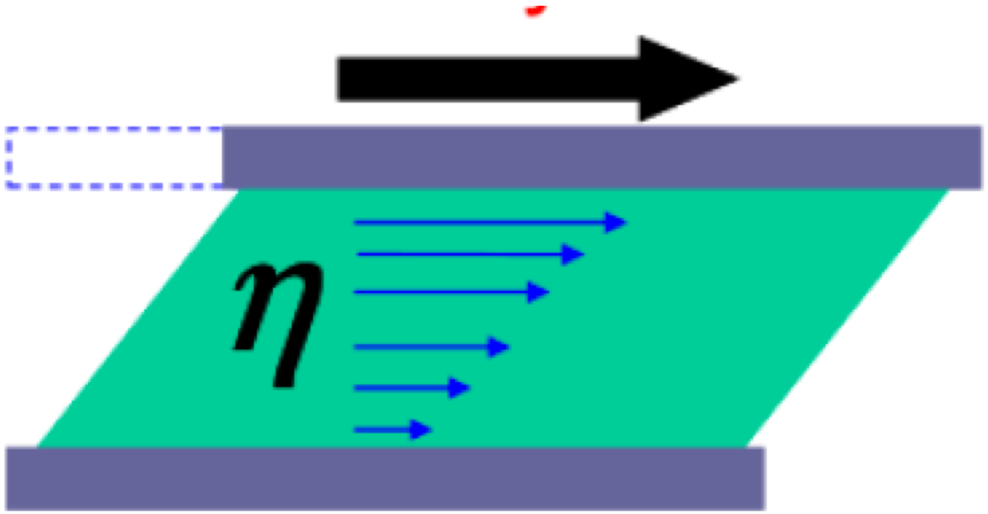
Ideal fluids (1)

→ Why are ideal fluids (η/s very small) fascinating? Look at superfluid Helium as an example: https://www.youtube.com/watch?v=2Z6UJbwxBZI



← Quantum limit derived from string theory via AdS-CFT

[JHEP 1208 (2012) 167]



Ideal fluids (2)

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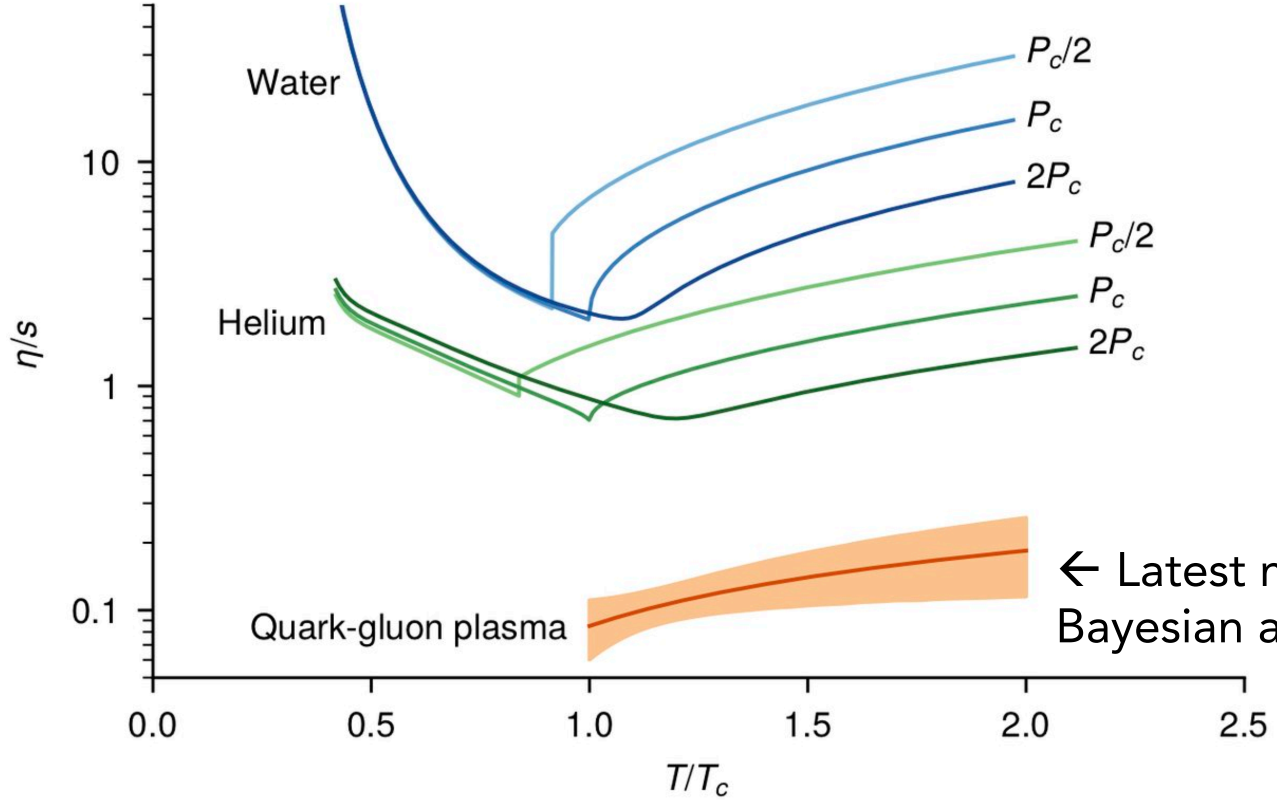
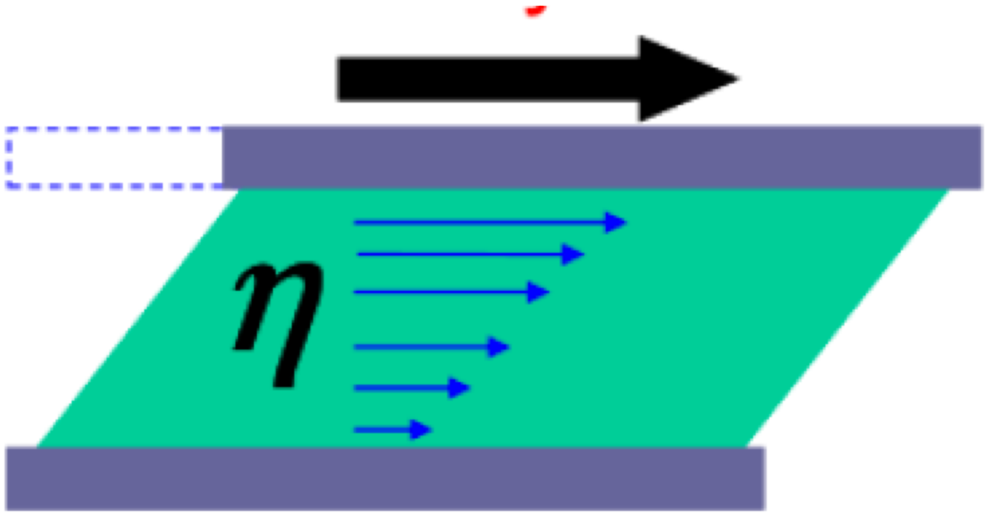


← Latest measurement based on Bayesian analysis of LHC data

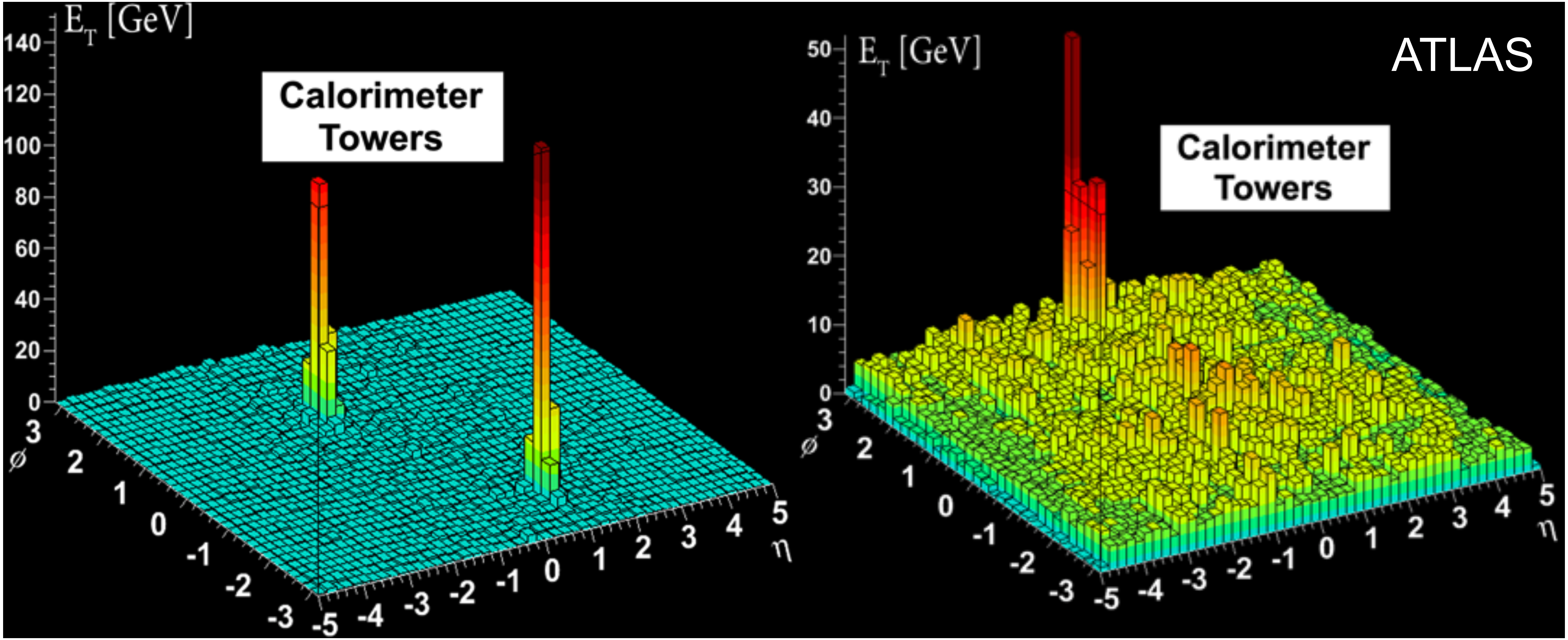


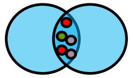
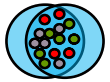
[J. Bernhard et al, *Nature Physics* (2019)]

END OF LECTURE 2..

Hard scatterings and jets

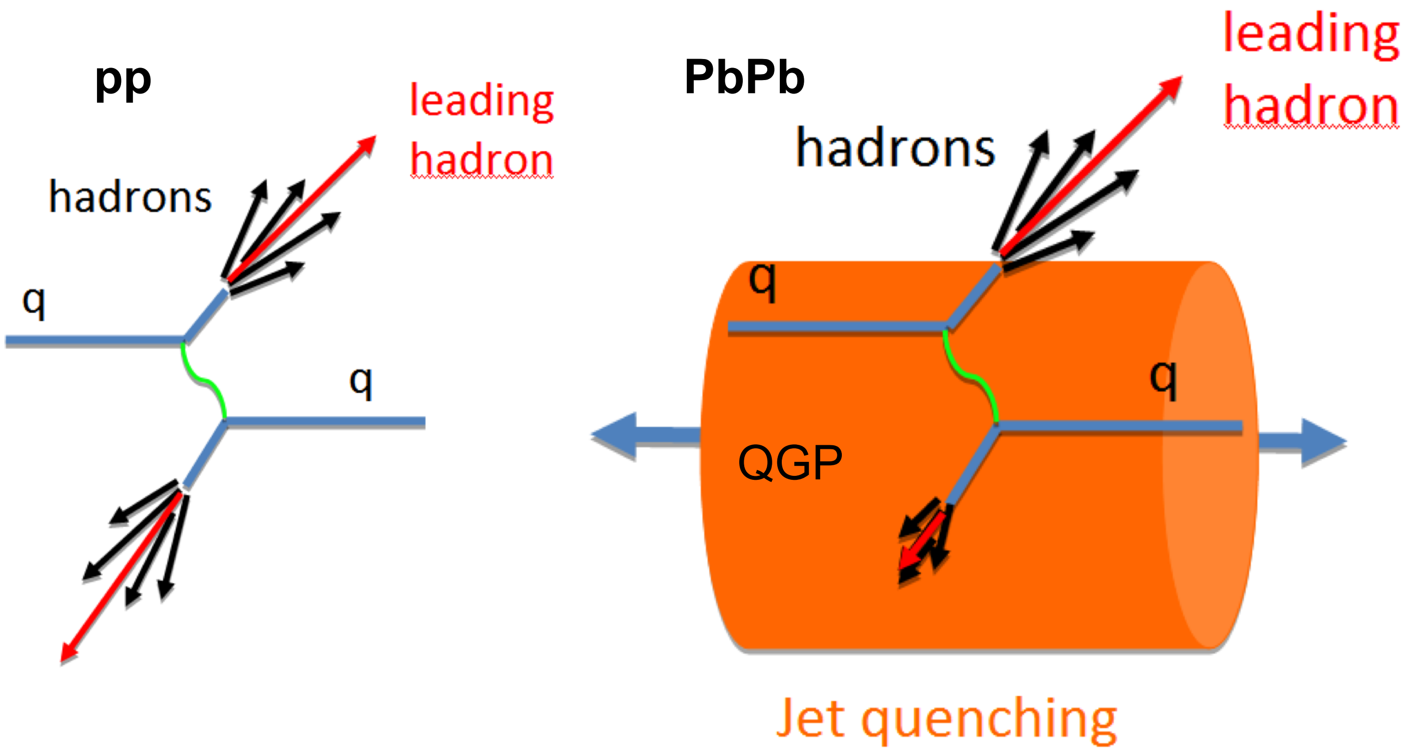
Jet-medium interactions (1)

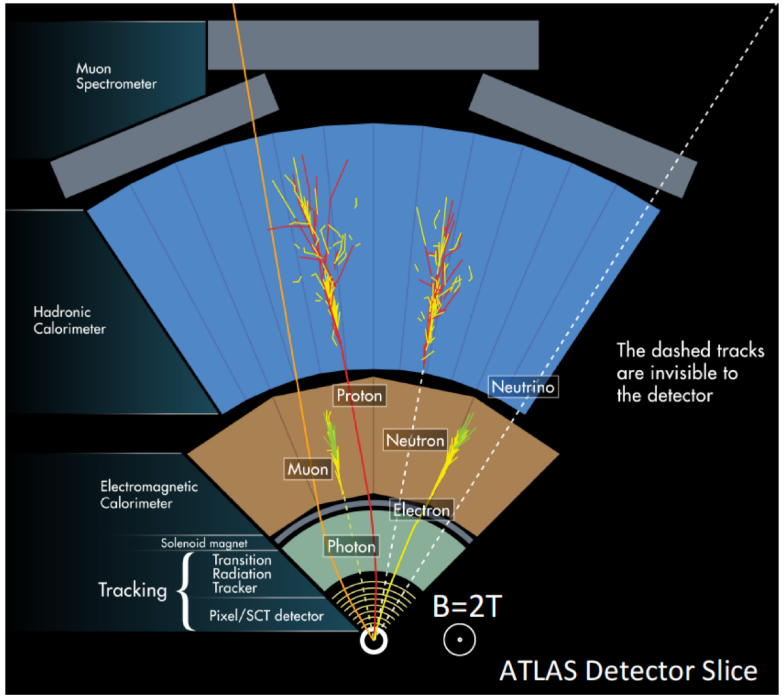


Peripheral Pb-Pb  [PRL105:252303,2010] Central Pb-Pb 

Jet-medium interactions (2)

- One jet disappears (or loses a substantial amount of its energy) in the QGP
  → ”jet quenching”





→ N.B.: To stop a highly energetic jet (e.g. 100 GeV), it needs a 10fm droplet of QGP or ~1.5m of hadronic calorimeter.

Drawing: M. Knichel

Dijet asymmetry

[PRC 84 (2011) 024906]

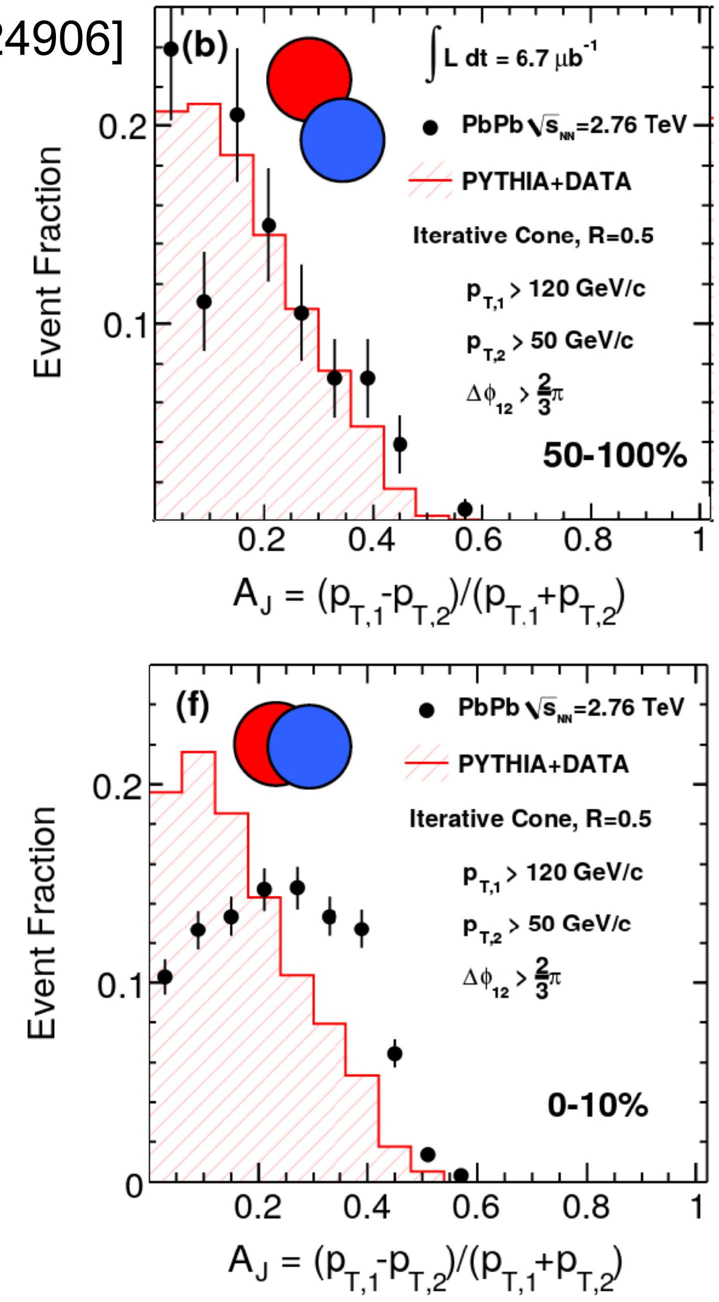
- How often do jets lose a large amount of energy?
  → quantified by the dijet asymmetry
- Two highest energy jets with $\Delta\varphi > 2\pi/3$:

$$A_J = \frac{|p_{T1} - p_{T2}|}{p_{T1} + p_{T2}}$$

$p_{T1} = p_{T2} \rightarrow A_J = 0$

$1/3\ p_{T1} = p_{T2} \rightarrow A_J = 0.5$

- Peripheral collisions: distribution as in Pythia (as in pp)
- Central collisions:
  - Symmetric configuration is significantly depleted
  - Enhancement of asymmetric configurations



Nuclear modification factor R_{AA}

- Hard process occur in *initial* nucleon-nucleon (NN) collisions. The momentum transfers in the later evolution of the system are smaller.

- Heavy-ion collision: many NN collisions

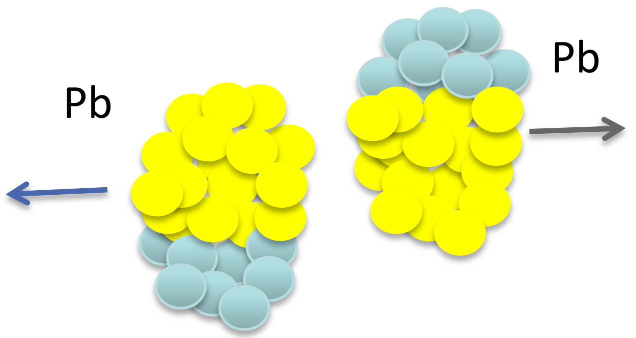
- Without *nuclear effects* (interaction with the QCD medium), a heavy-ion collision would just be a superposition of independent NN collisions with incoherent fragmentation.

- The number of independent NN collisions $\langle N_{coll} \rangle$ can be calculated for a given impact parameter/centrality in the Glauber model.

Spectrum in AA collisions

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

Spectrum in pp collisions

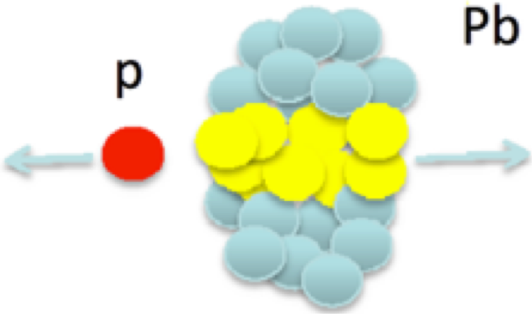


R_{AA} = 1 →no modification
R_{AA} != 1 →medium effects

The most simple example: R_{pA}

[Phys. Rev. Lett. 110 (2013) 082302]

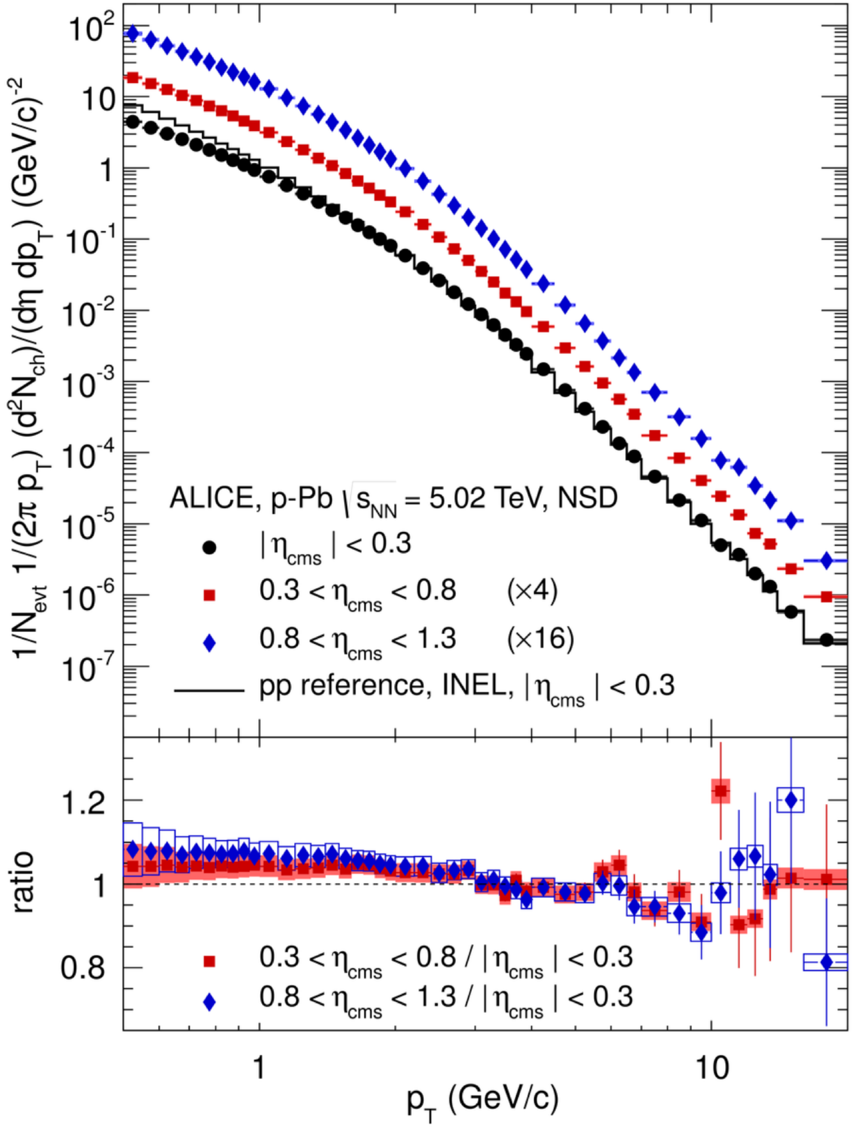
- In a pA collision, the proton hits on average 6.9 nucleons of the Pb nucleus:



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

→ $\langle N_{coll} \rangle = 6.9 \pm 0.6$

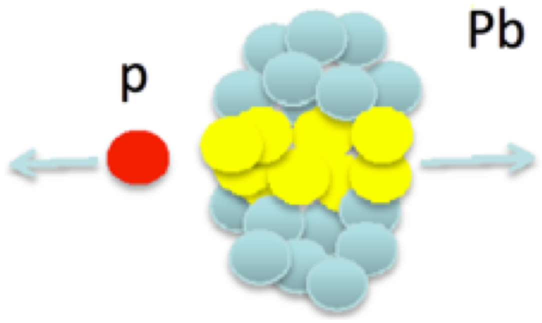
- We distinguish number of collisions N_{coll} and number of participants N_{part}:
  - A nucleon can *collide* several times with nucleons of the target nucleus (Glauber assumes that it stays intact after each collision).
  - Each nucleon with experiences at least one collision, is called a participant (N_{part}).
    => $N_{part} = N_{coll} + 1$ in pPb



The most simple example: R_{pA}

[Phys. Rev. Lett. 110 (2013) 082302]

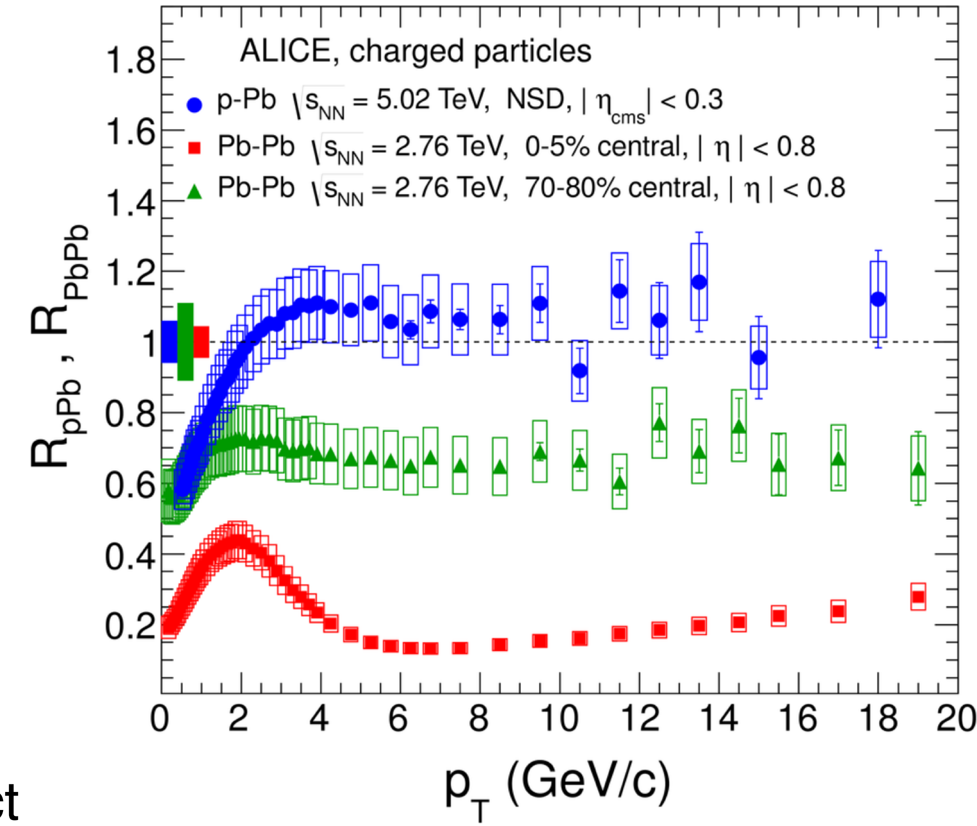
- In a pA collision, the proton hits on average 6.9 nucleons of the Pb nucleus:



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

→ $\langle N_{coll} \rangle = 6.9 \pm 0.6$

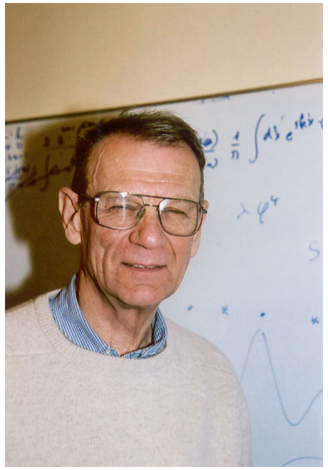
- We distinguish number of collisions N_{coll} and number of participants N_{part}:
  - A nucleon can *collide* several times with nucleons of the target nucleus (Glauber assumes that it stays intact after each collision).
  - Each nucleon with experiences at least one collision, is called a participant (N_{part}).
    => $N_{part} = N_{coll} + 1$ in pPb



How to determine N_{coll} and N_{part}?

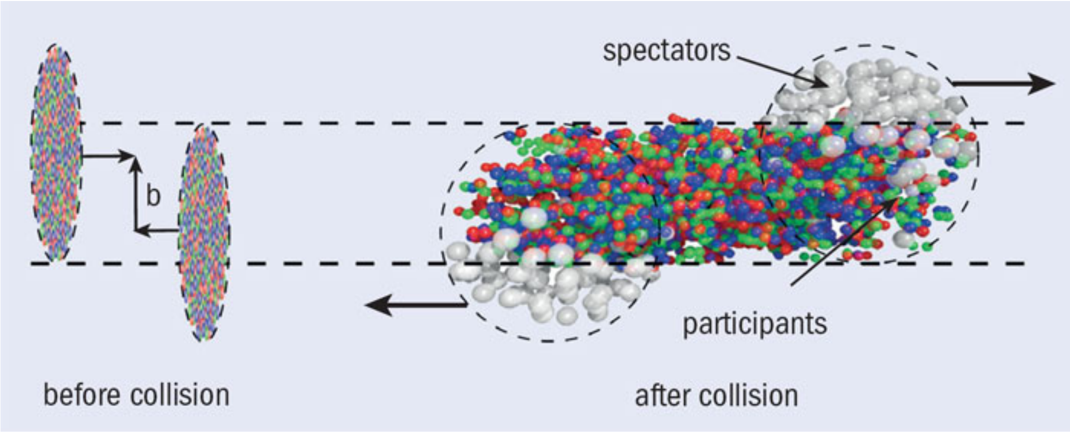
- "Billard ball" Monte-Carlo, named after Roy Glauber, but orginally introduced to heavy-ion physics by Bialas, Blezynski, and Czyz (Nucl. Phys. B111(1976)461).

R. Glauber



A. Bialas

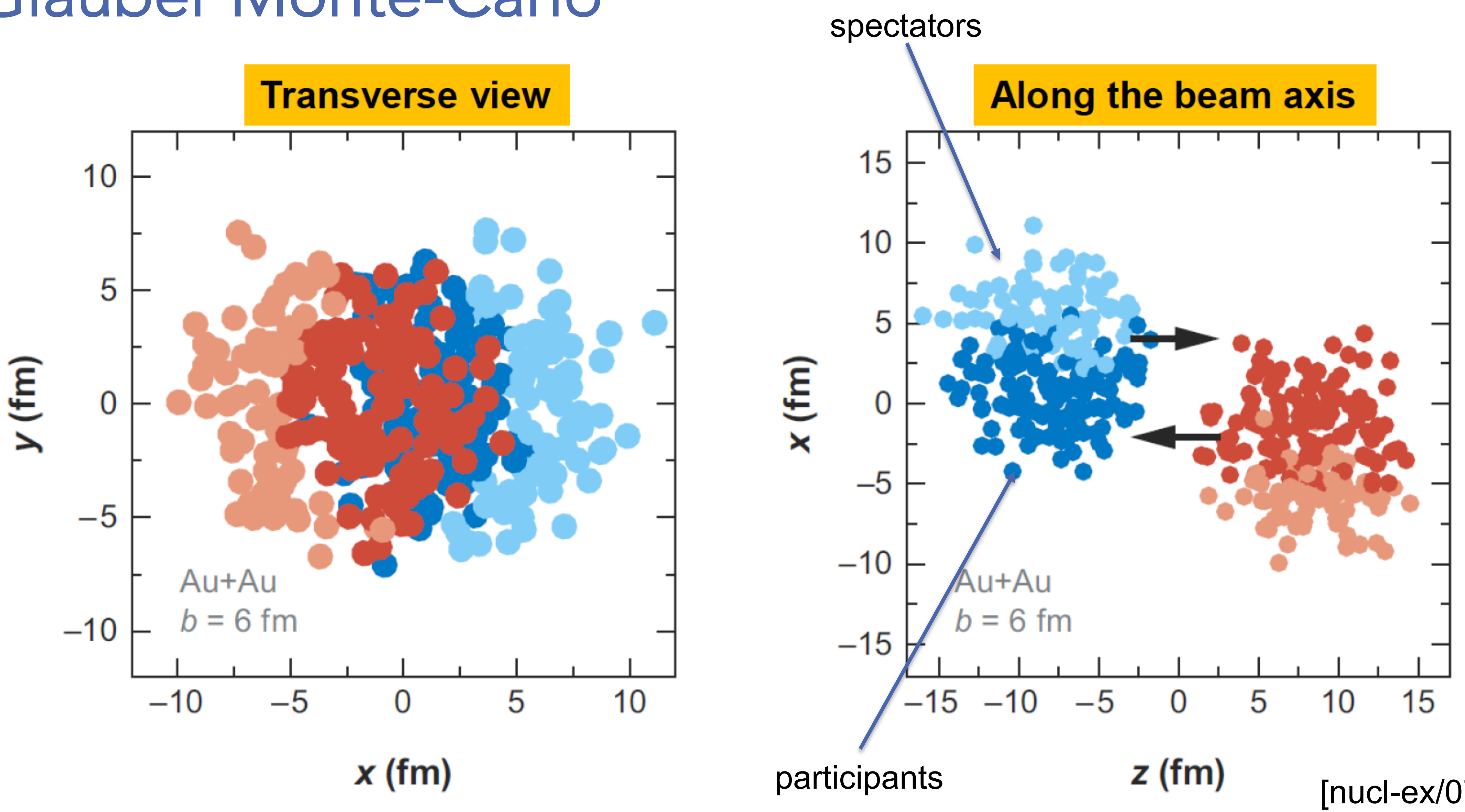
- Assumptions:
  - Nucleons travel on straight lines
  - Collisions do not alter their trajectory (nor anything else, they remain intact) assuming their energy is large enough
  - No quantum-mechanical interference
  - Interaction probability for two nucleons is given by the nucleon-nucleon (pp) cross-section.



http://cerncourier.com/cws/article/cern/53089

- Strong dependence on *impact parameter b*

Glauber Monte-Carlo



[nucl-ex/0701025]

Input to Glauber MC (1)

[nucl-ex/0701025]

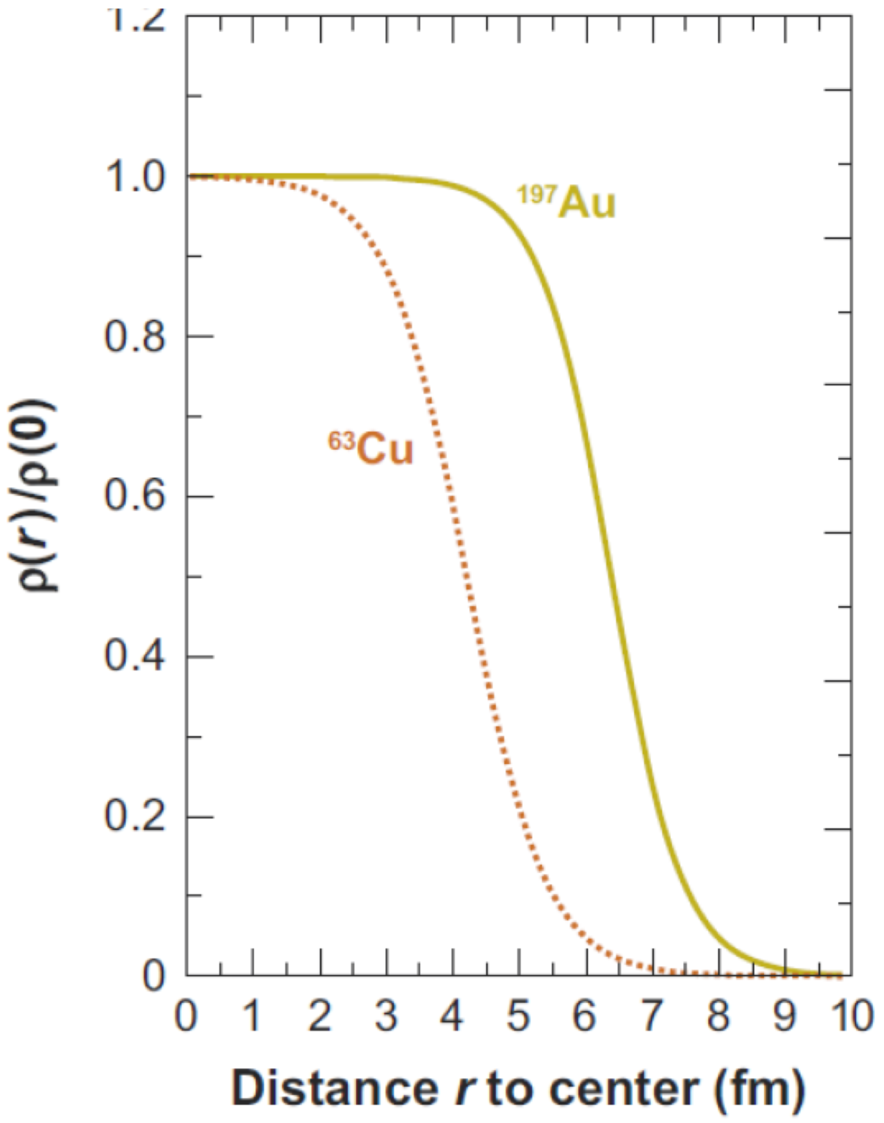
- Distributions of nucleons in nuclei:
  - well measured by electron-ion scattering experiments
  - Paramterised as Woods-Saxon disitrubtion

$$\rho(r) = \rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

Nuclear radius R

Skin depth a

Density in the center



- Nucleon-nucleon cross-section
  - Measured in pp collisions or from extrapolations

Input to Glauber MC (2)

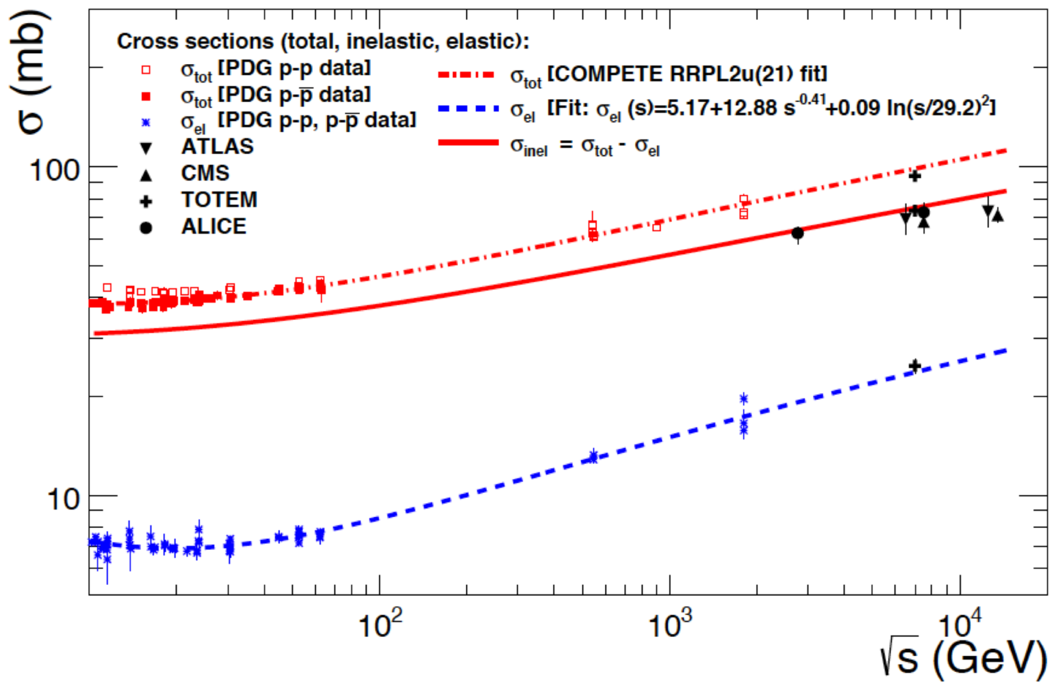
- Distributions of nucleons in nuclei:
  - well measured by electron-ion scattering experiments
  - Paramterised as Woods-Saxon disitrubtion

$$\rho(r) = \rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

Nuclear radius R

Skin depth a

Density in the center



[arXiv:1603.07375v3]

- Nucleon-nucleon cross-section
  - Measured in pp collisions or from extrapolations

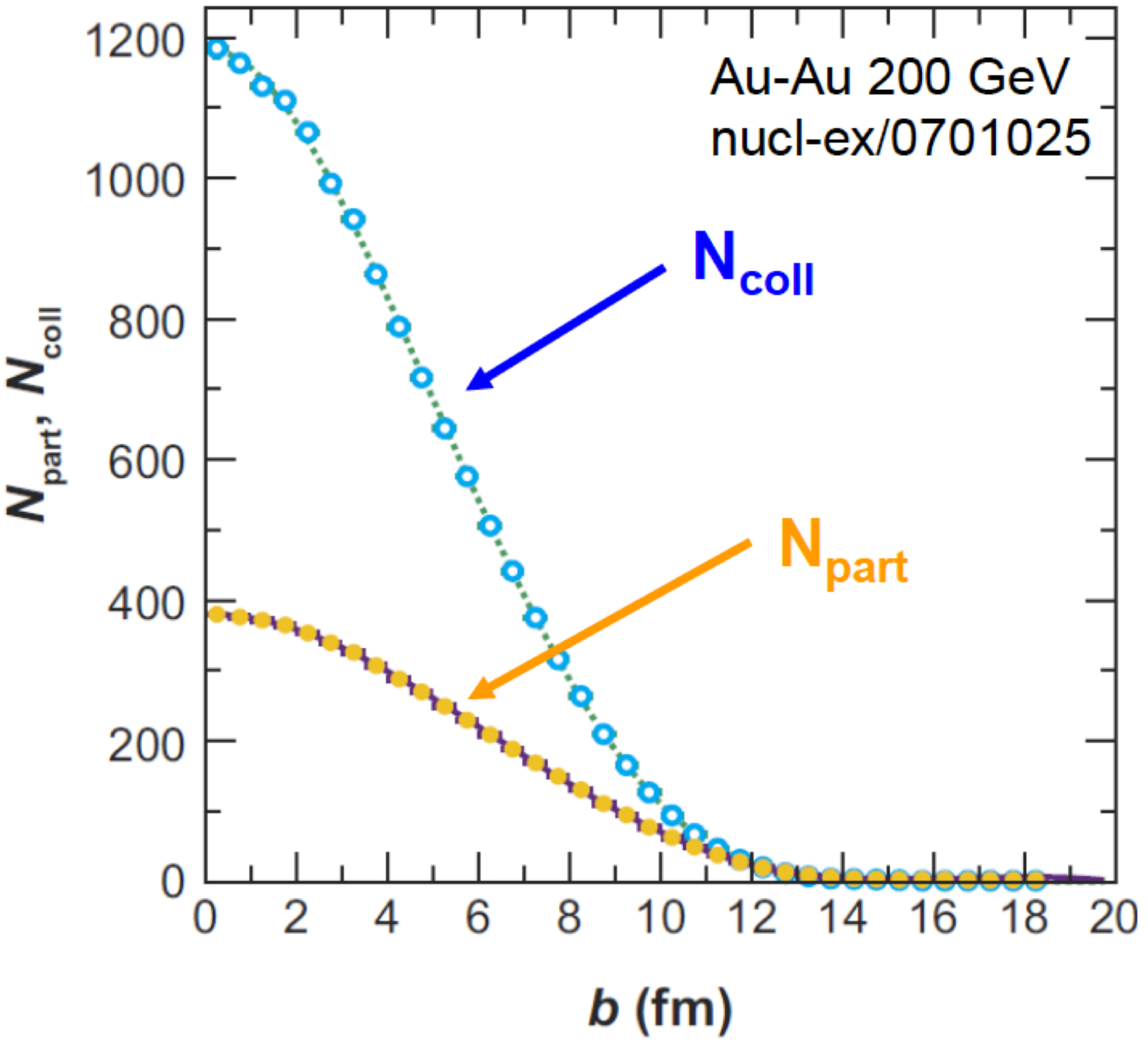
Glauber MC output

Typical values:

- 10% most central collisions at RHIC (Au-Au, 200 GeV)
  - N_{coll} ~1200
  - N_{part} ~380

- 5% most central collisions at LHC (Pb-Pb 2.76 TeV)
  - N_{coll} ~1680
  - N_{part} ~382

- Difference mainly from cross-section increase and slightly larger nucleus

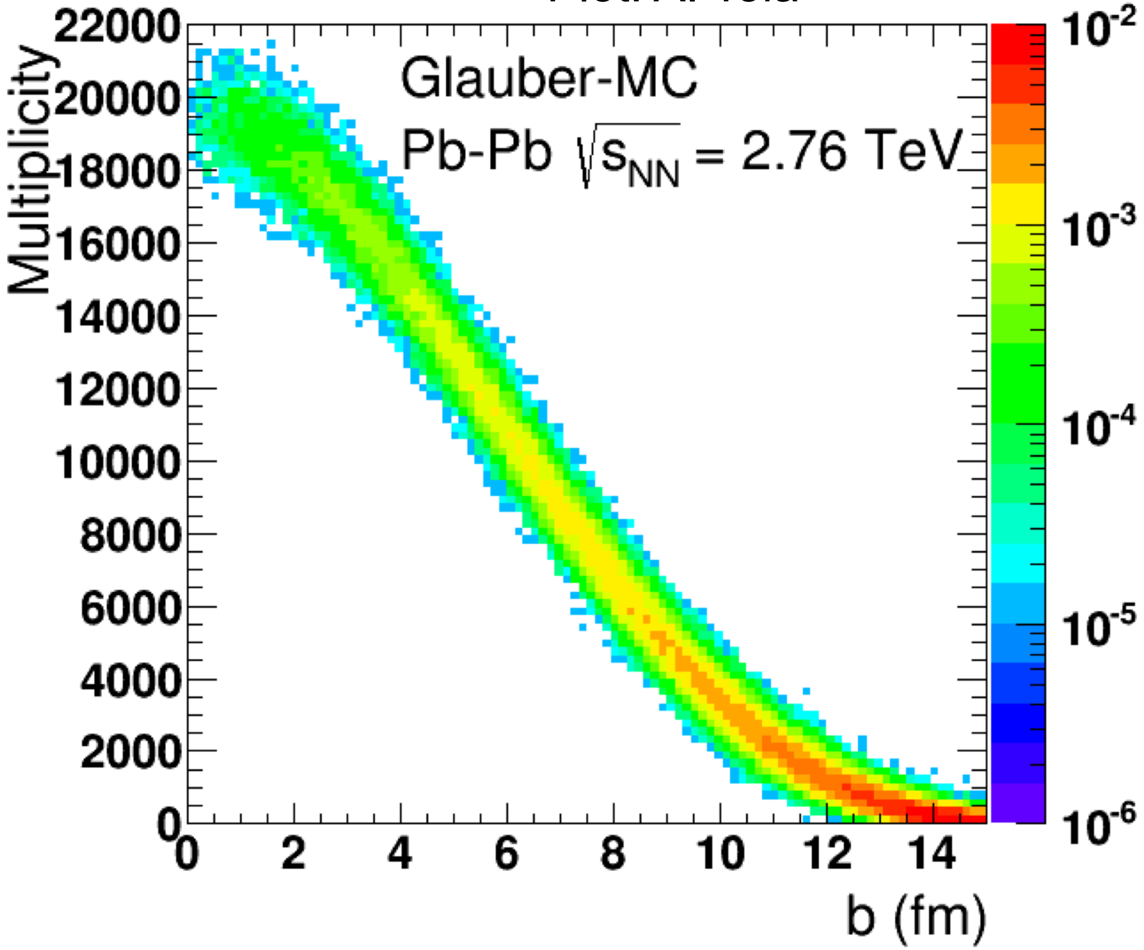


Centrality and Glauber model

- Multiplicity is inversely proportional to the impact parameter
  => Knowing the multiplicity of the event, we roughly know the impact parameter (and thus also N_{coll} and N_{part}). We *fit* the multiplicity distribution with the Glauber model (see next slide).

- Multiplicity is strongly correlated in different phase space regions in heavy-ion collisions (e.g. forward and mid-rapditity).

Plot: A. Toia

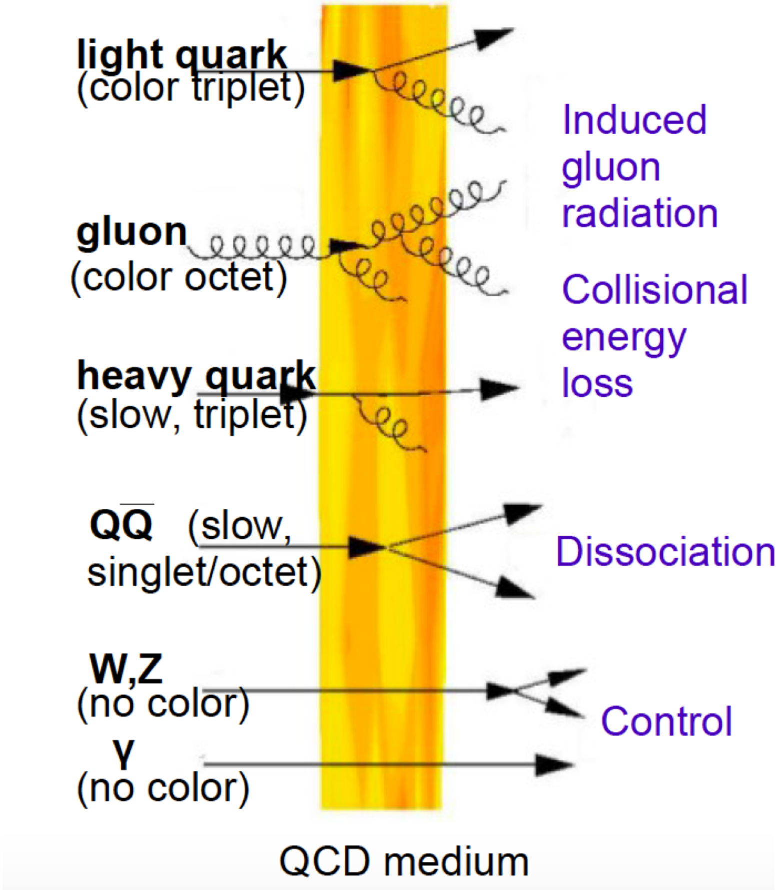


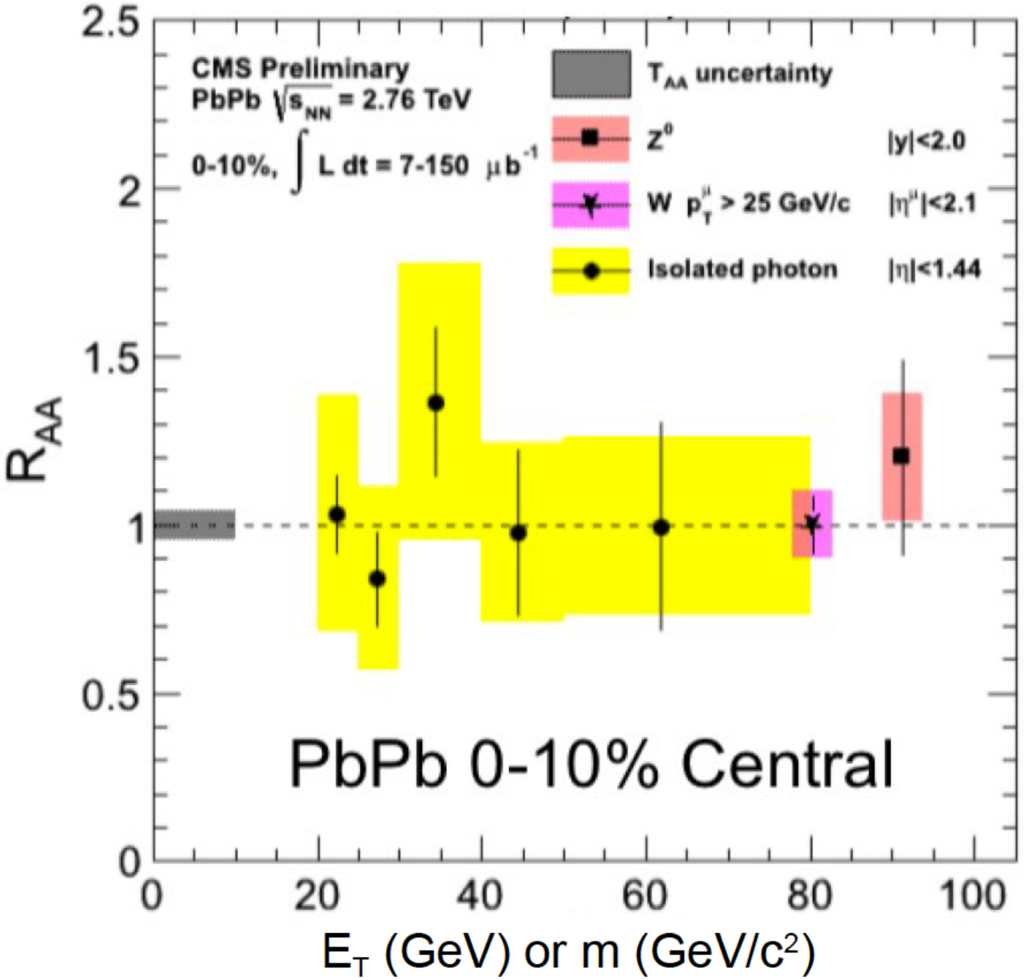
Does the Glauber model work?

→ Yes, we can test it with electroweak control probes.

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

→ No medium modification observed (despite multiplying by N_{coll}~1680!).



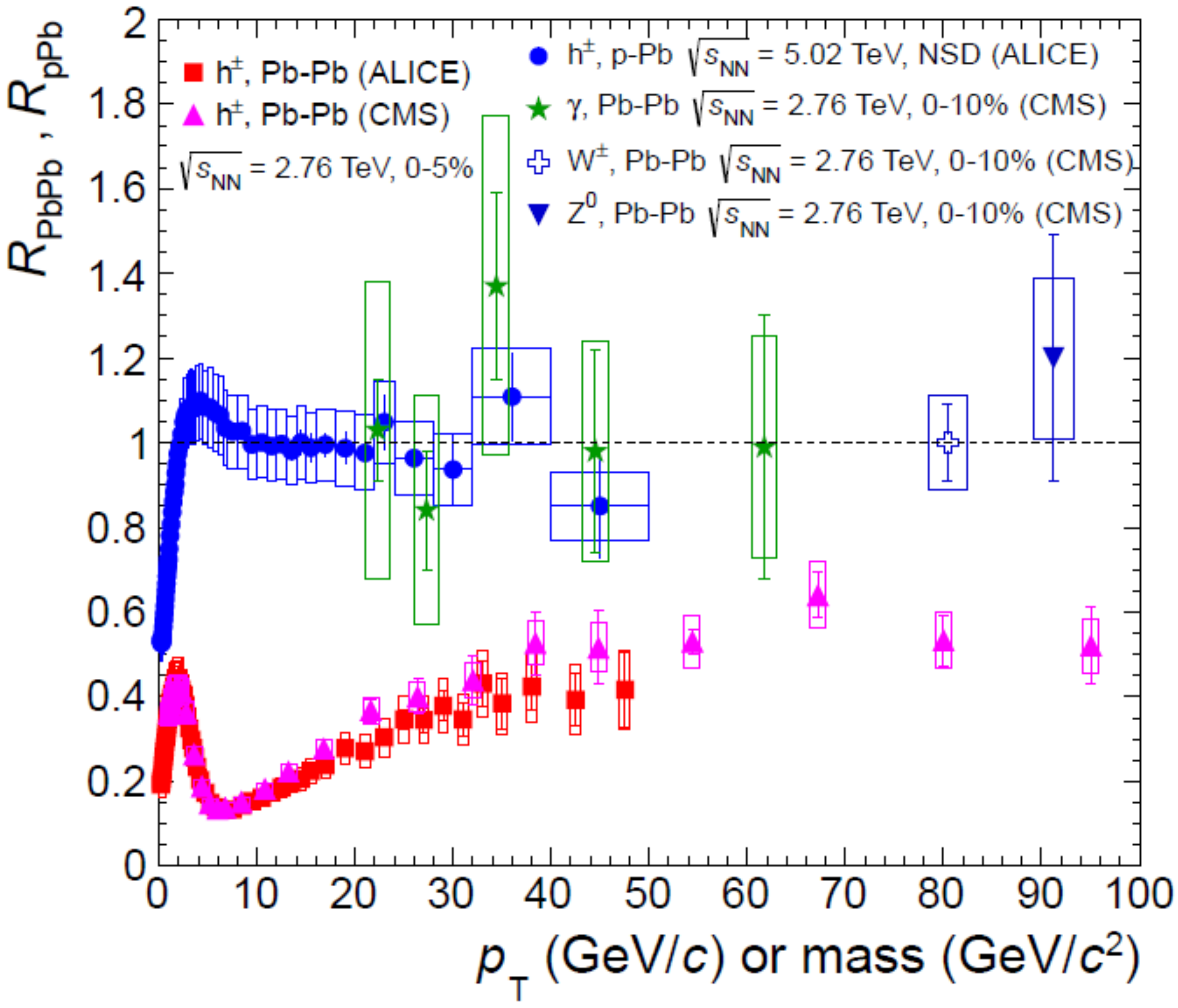


R_{AA} for charged hadrons (1)

- N_{coll} scaling works well above $p_T > 4$ GeV/c for electroweak probes and also in pPb.
  => There are no *cold nuclear matter effects* and N_{coll}-scaling is a reasonable assumption for AA.

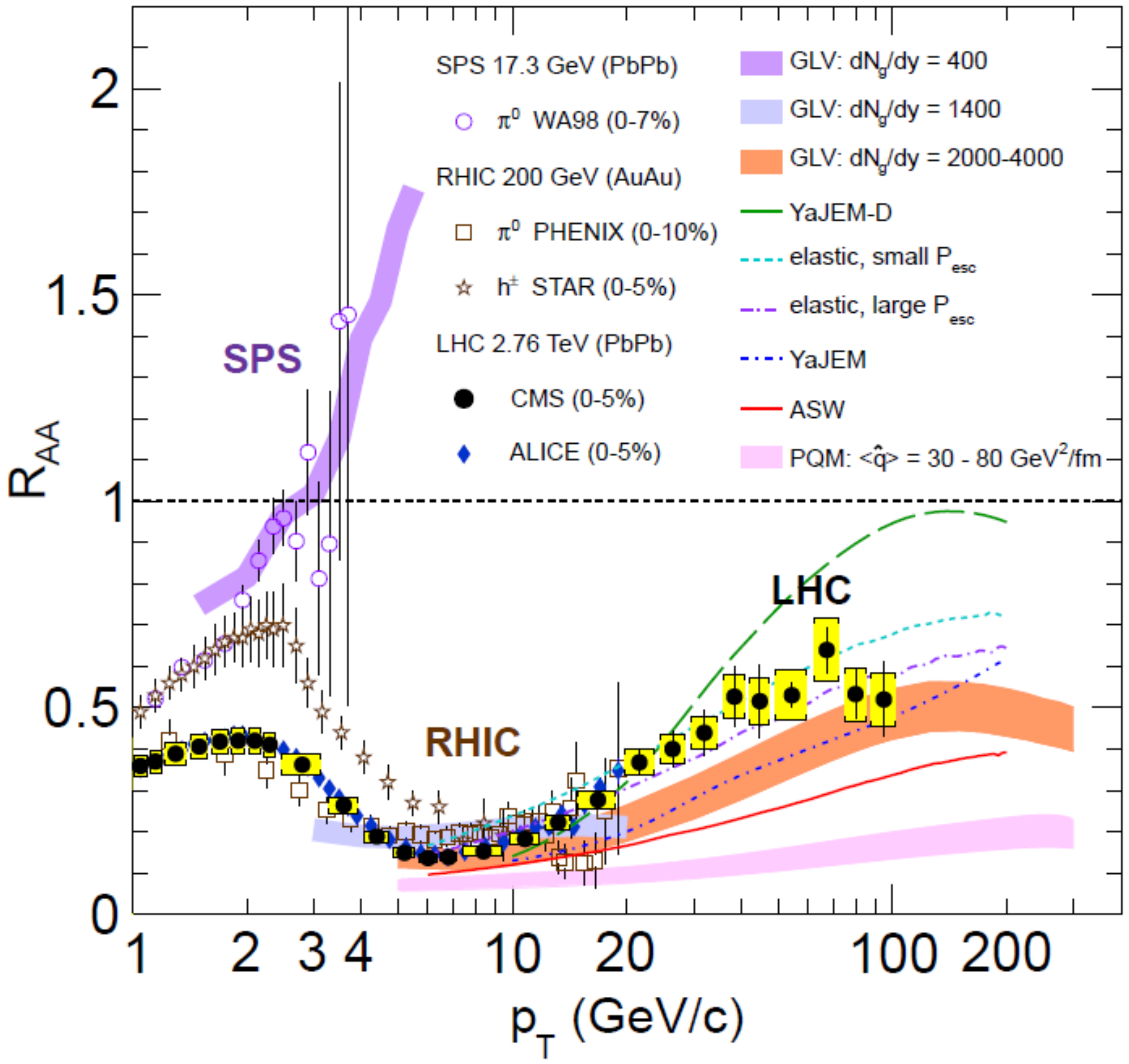
- There is a significant suppression of high p_T-particles observed in AA collisions which is a true medium effect.
  => High p_T particle production in AA collision is not a simple superposition of incoherent nucleon-nucleon collisions.

- How does the medium achieve this suppression?

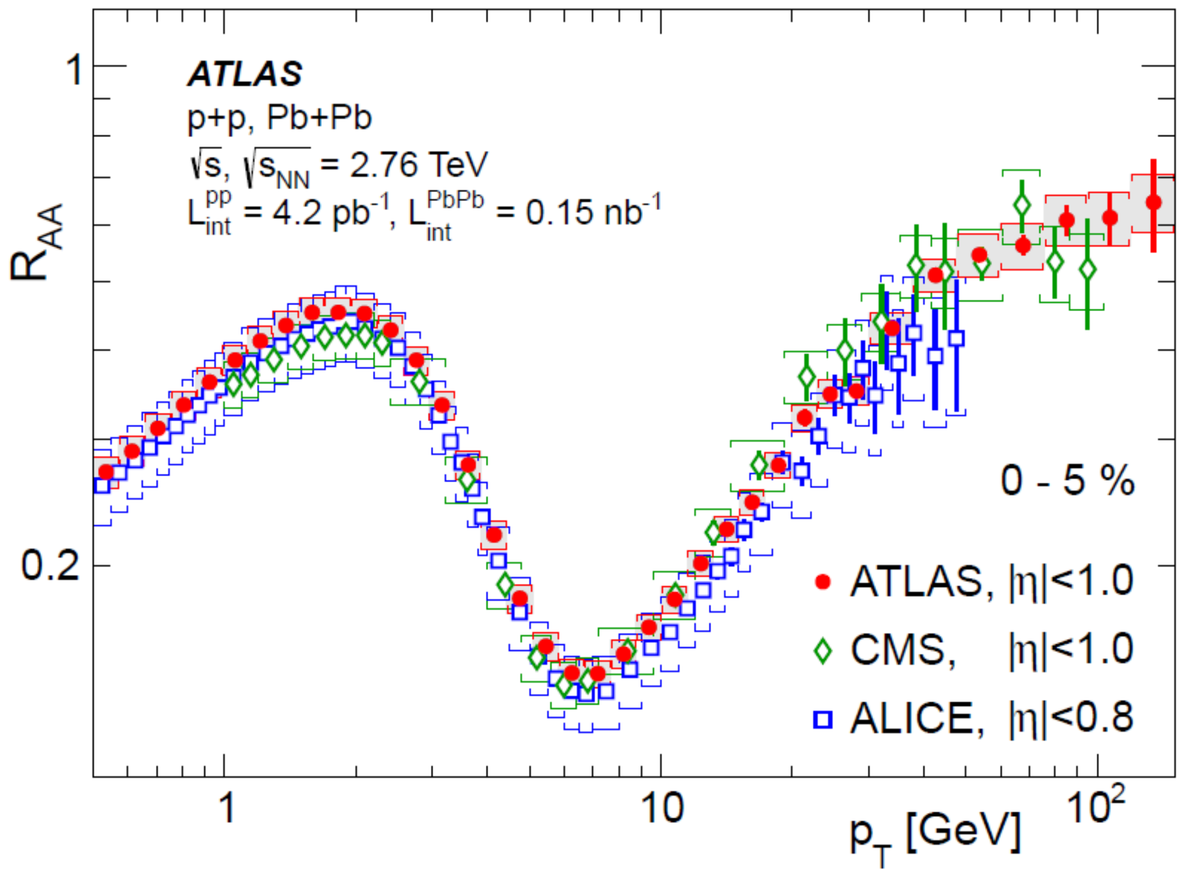


R_{AA} for charged hadrons (2)

CMS Collaboration, Eur. Phys. J. C (2012) 72:1945



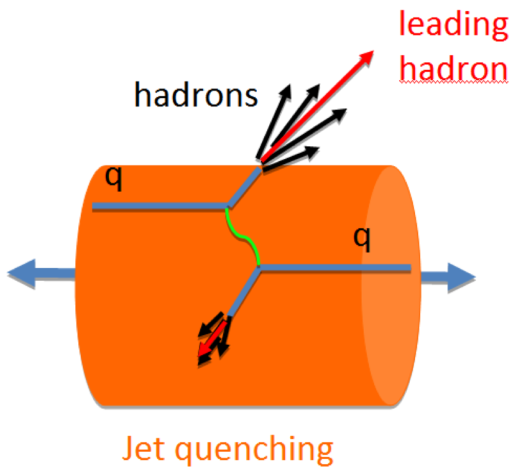
ATLAS Collaboration, JHEP09(2015)050



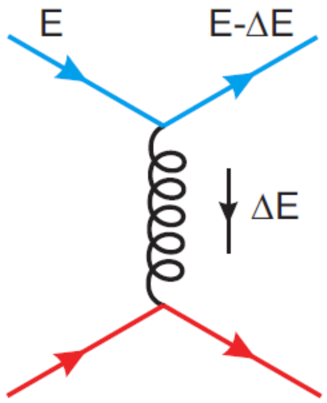
→ No high p_T particle suppression at SPS energies.
→ All LHC experiments in agreement.

Energy loss in the QGP

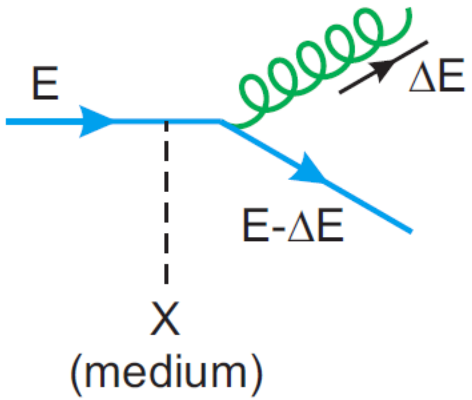
- The QGP is a high density source of color sources (quarks and gluons) which are felt by the traversing quark or gluon.
- It experiences
  - Collisional energy loss: elastic scatterings, dominant at low momentum
  - Radiative energy loss: inelastic scatterings, **gluon bremsstrahlung**, dominates at high momentum
- Total energy loss is a sum of the two processes.



[Lect. Notes Phys. 785,285 (2010)]



(Collisional energy loss)



(radiative energy loss)

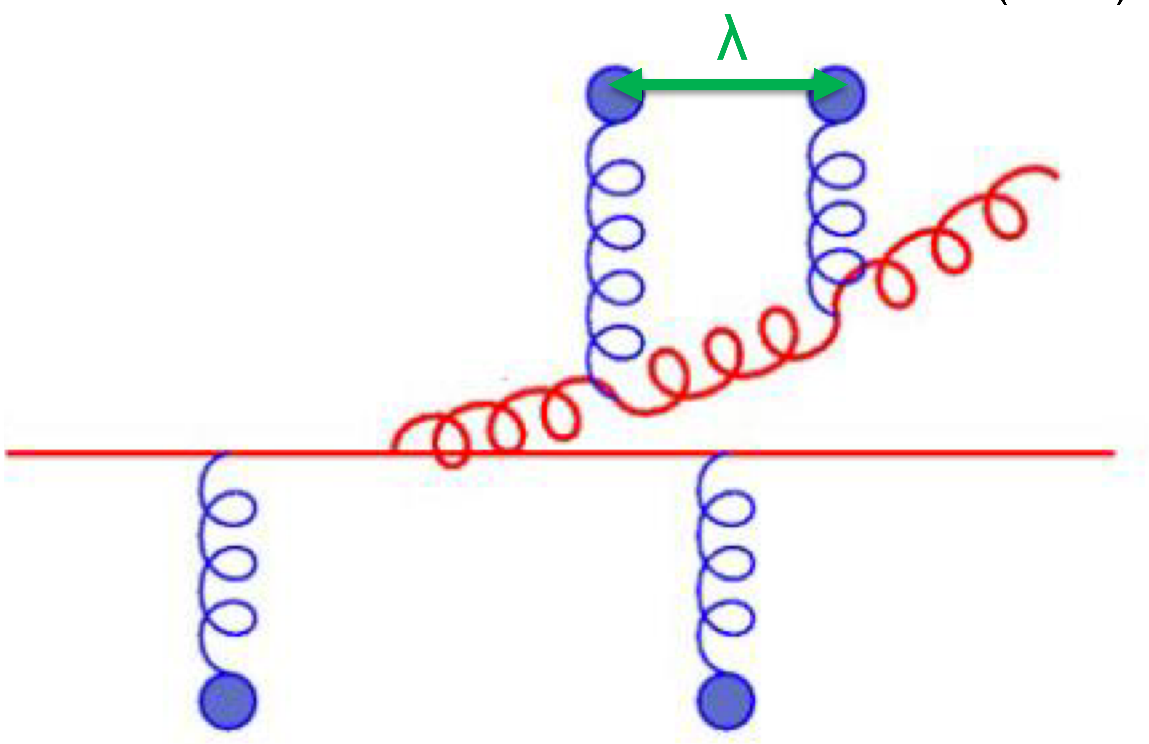
Radiative energy loss

NPB 483 (1997) 291

- BDPMS formalism
  - Baier, Dokshitzer, Mueller, Peigne, Schiff
  - Infinite energy limit
  - Static medium

$$\Delta E \propto \alpha_S \cdot C_R \cdot \hat{q} \cdot L^2$$

- Energy loss proportional to:
  - Path length through medium **squared**
  - Casimir factor
    - CR = 4/3 (quarks)
    - CR = 3 (gluons)
  - Medium properties are encoded in the parameter "q-hat" which corresponds to the average squared transverse momentum transfer per mean free path.



→ For the **characterization of the QGP medium**, q-hat has a similar significance as e.g. the shear viscosity.

$$\hat{q} = \frac{\langle q_T^2 \rangle}{\lambda}$$

$\langle q_T^2 \rangle$ ← average momentum transfer

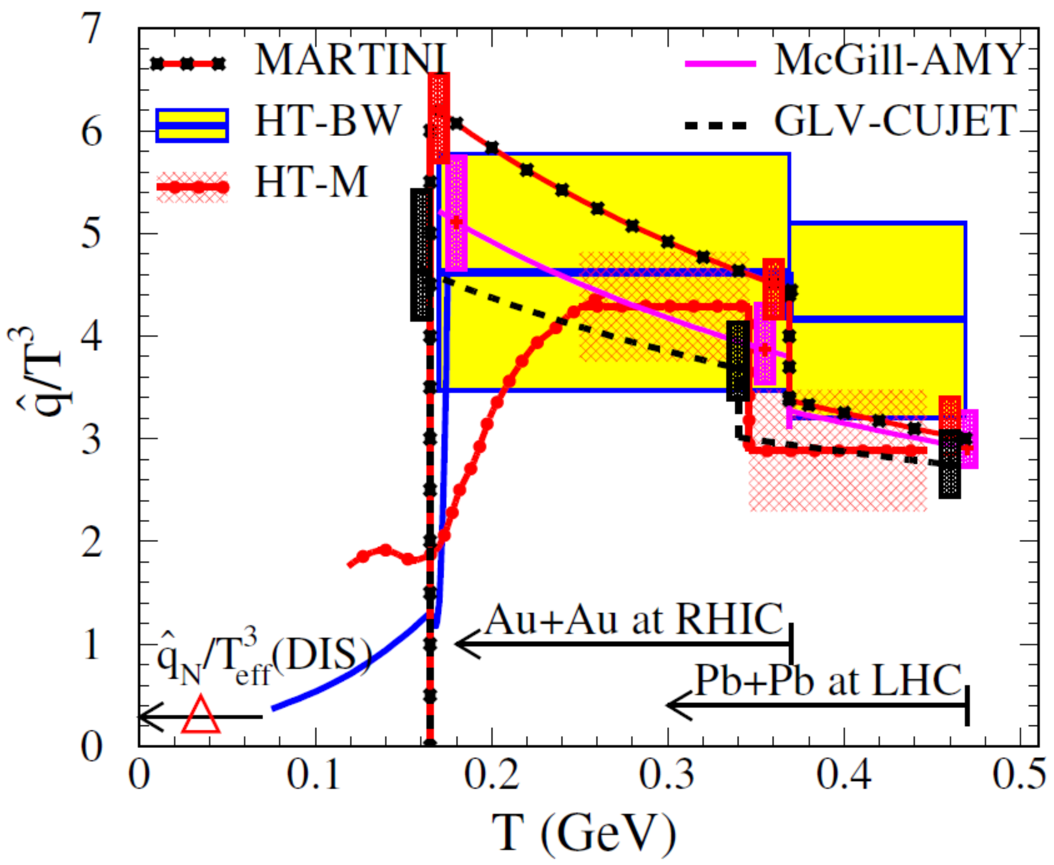
λ ← mean free path

Determination of q-hat

- From the theory side, the JET collaboration extracted q-hat using combined CMS and ALICE LHC R_{AA} data assuming no fluctuations of initial conditions and coupling the same hydro to all energy loss models.

- 5 different models with different approaches:
  - higher twist (HT-BW, HT-M)
  - hard thermal loop (MARTINI, McGill-AMY)
  - opacity expansion (GLV-CUJET)

quark with E = 10 GeV



$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC} \\ 3.7 \pm 1.4 & \text{at LHC.} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \begin{matrix} T{=}370 \text{ MeV} \\ T{=}470 \text{ MeV} \end{matrix}$$

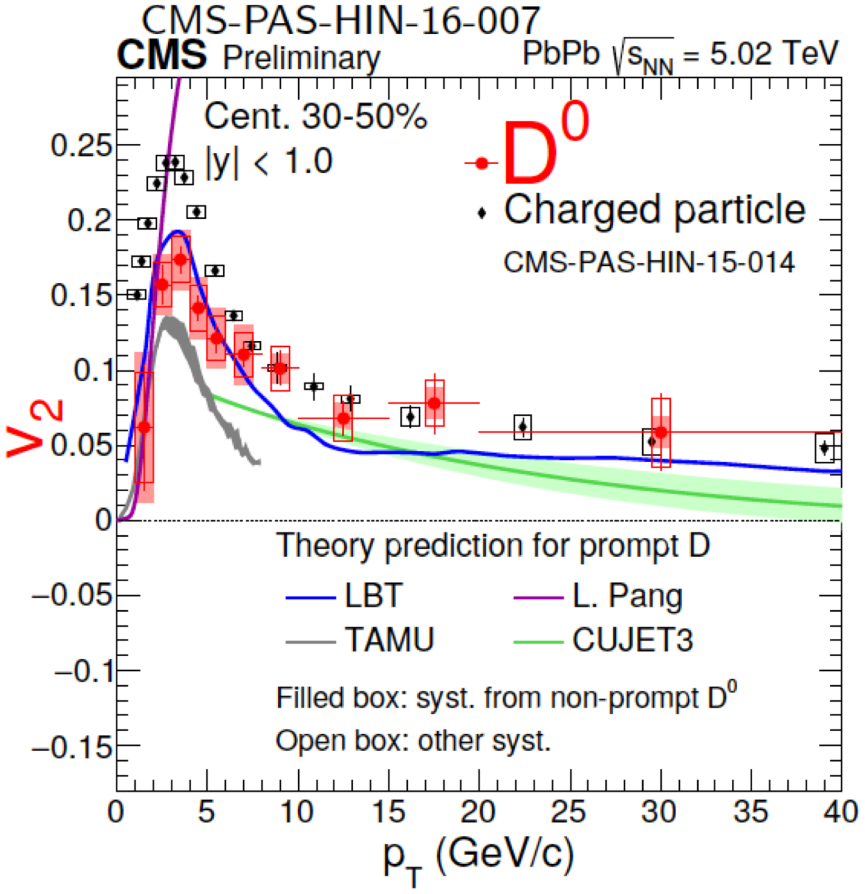
For comparison: in cold nuclear matter q = 0.02 GeV²/fm **(at t_0 = 0.6 fm)**

Quarkonia and heavy flavour

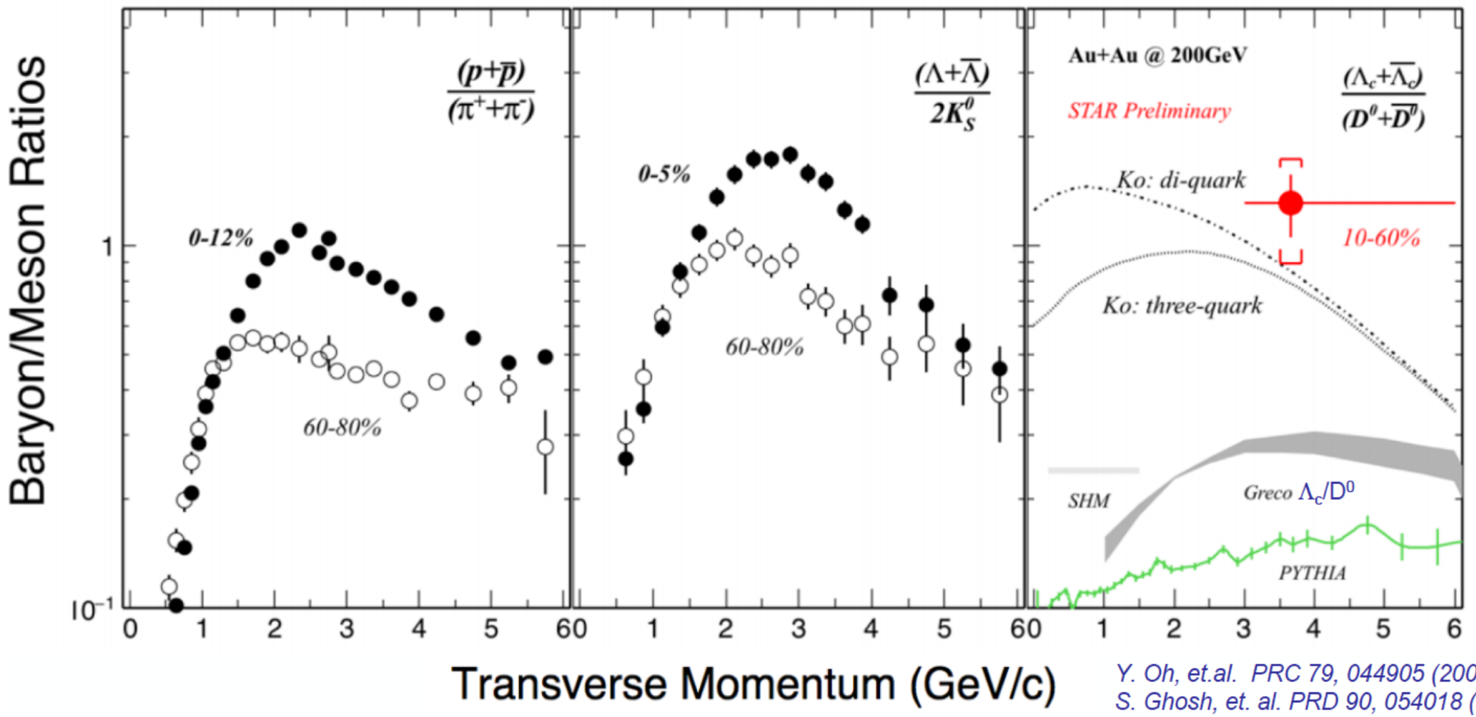
Heavy flavor (1)

- 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:



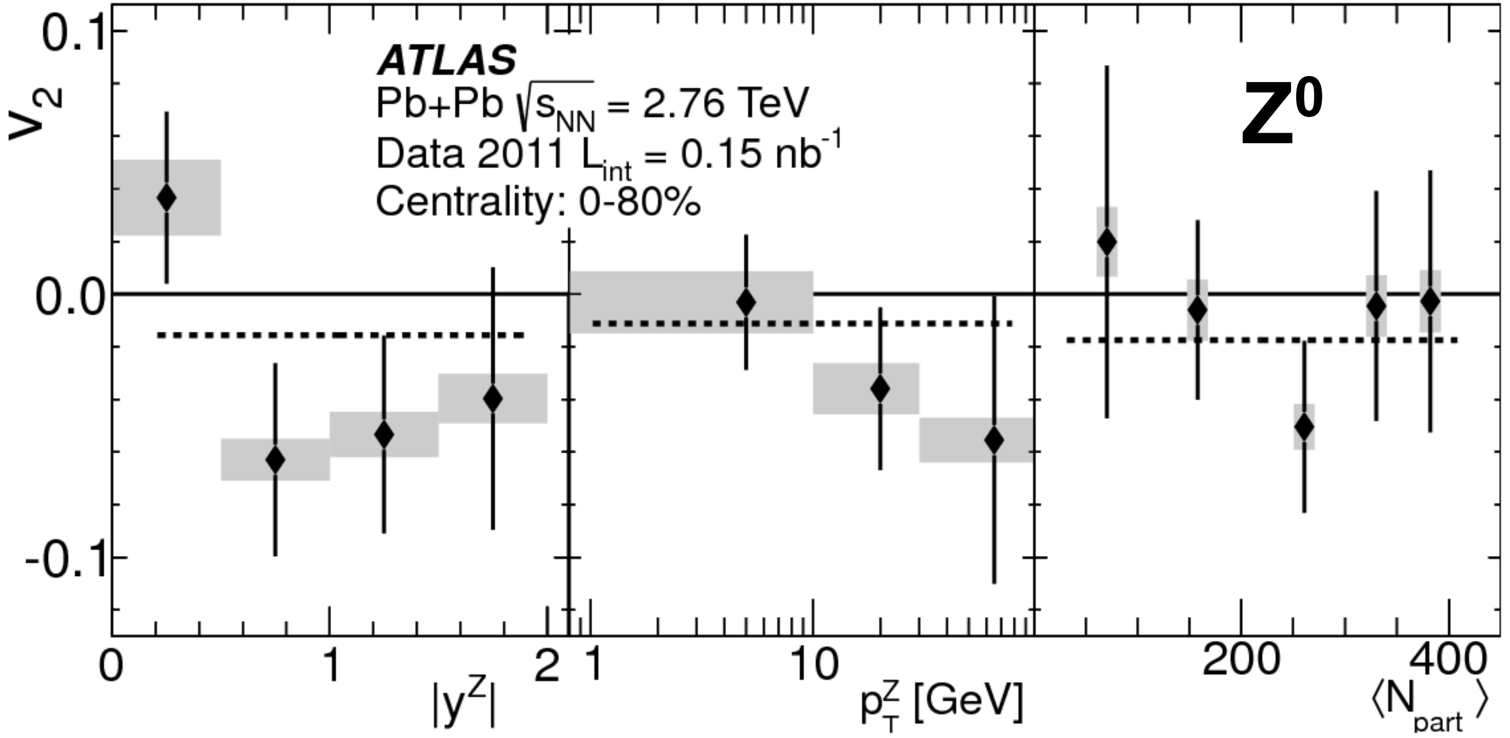
(B.) Baryon-to-meson enhancement seen in Λ_C:



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

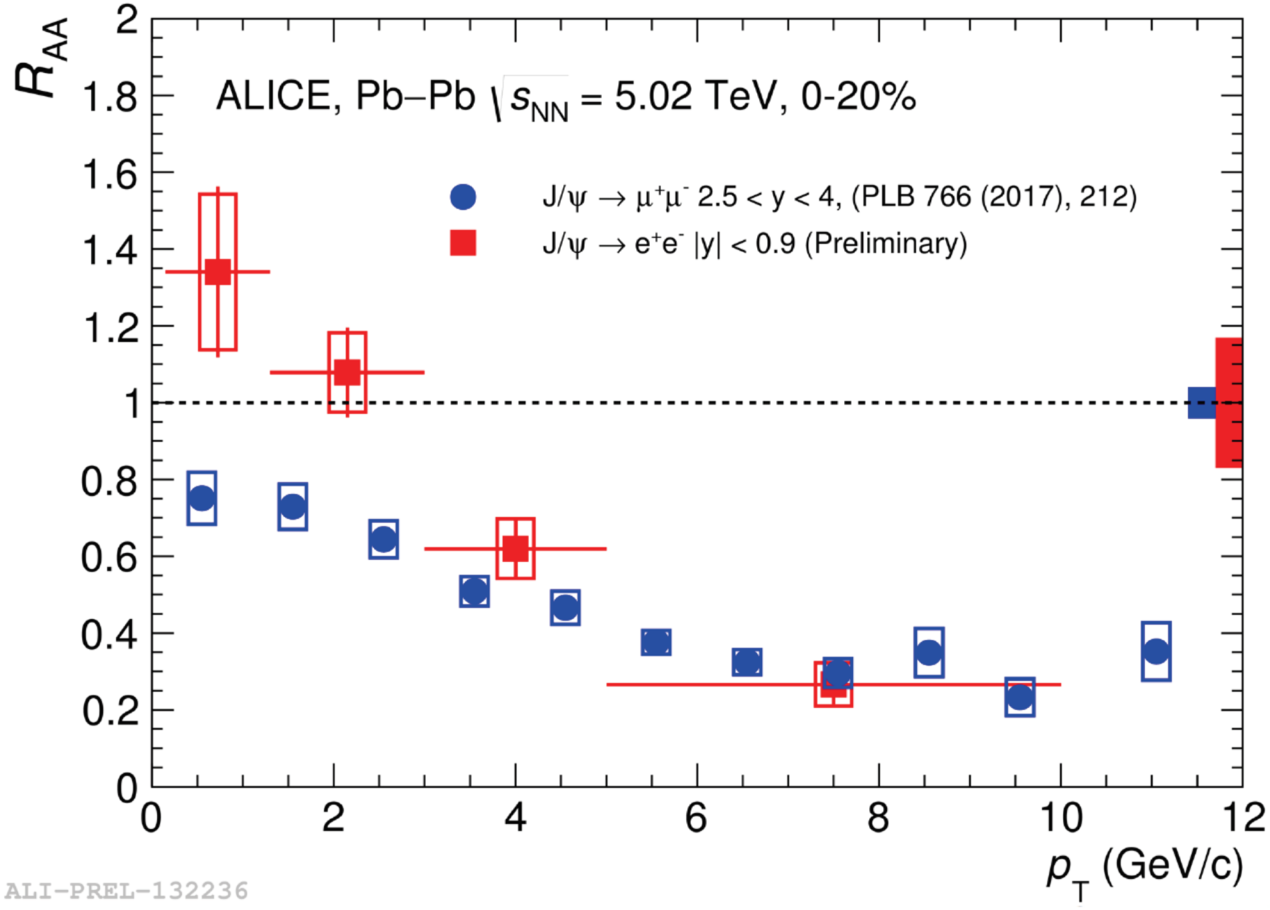
Heavy flavor (2)

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



[PRL 110, 022301 (2013)]

J/ψ recombination



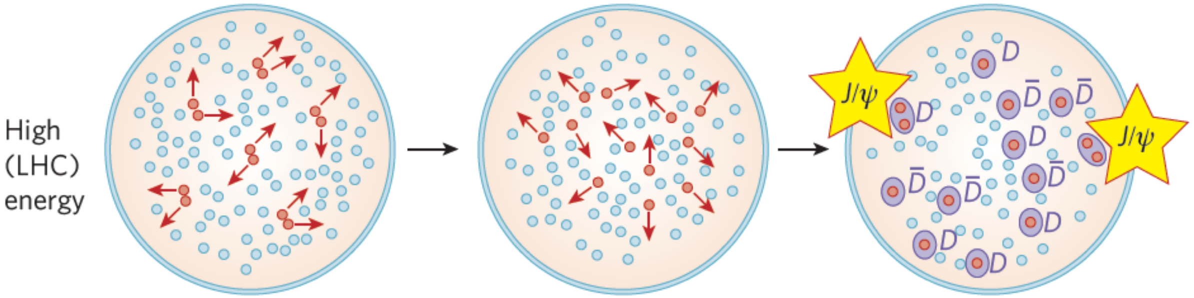
→ As $c\bar{c}$ bound state, the J/ψ is expected not to be bound in the QGP phase (*Matsui/Satz*, 1986), but it can re-generate at the phase boundary.

→ 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.

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

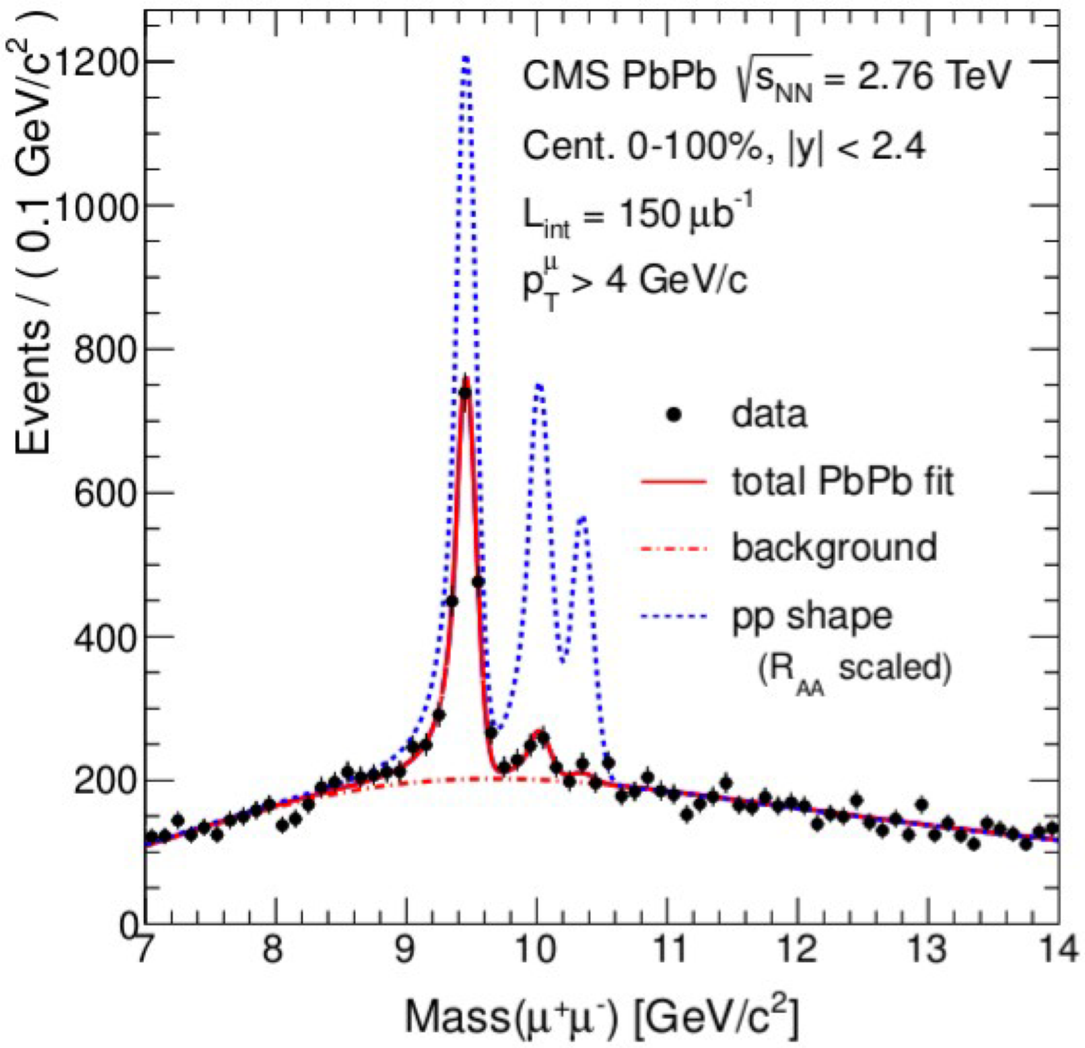


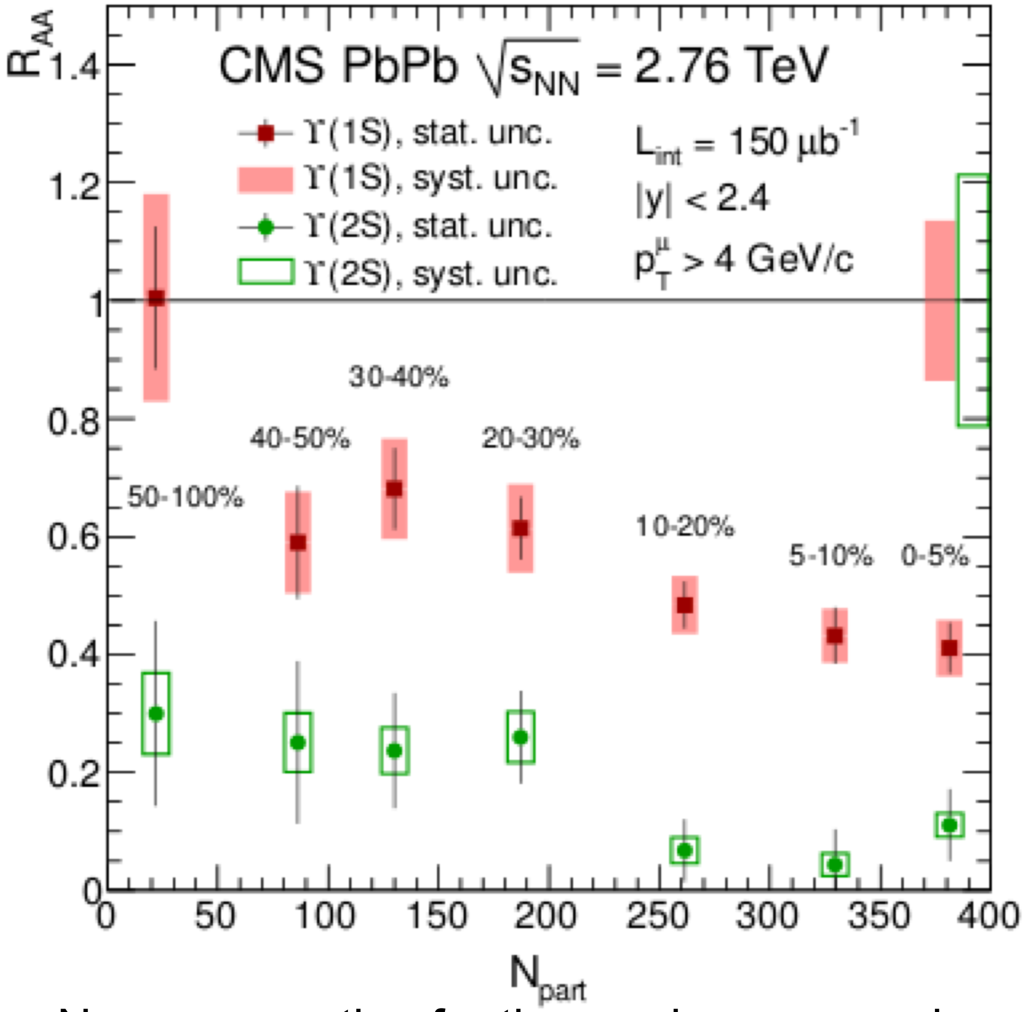
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \cdot dN_{pp}/dp_T}$$

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

Suppression of Upsilon states

[PRL 109 (2012) 222301]

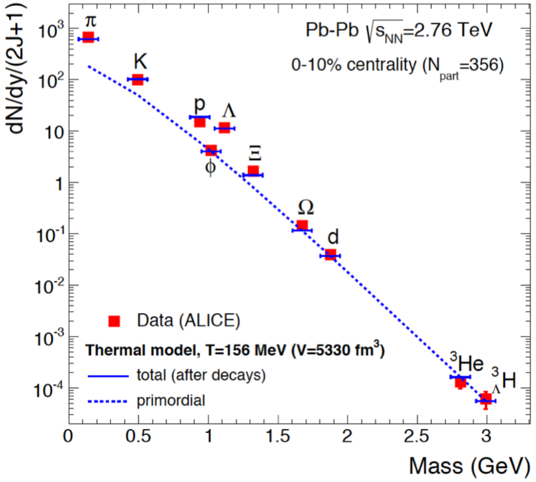


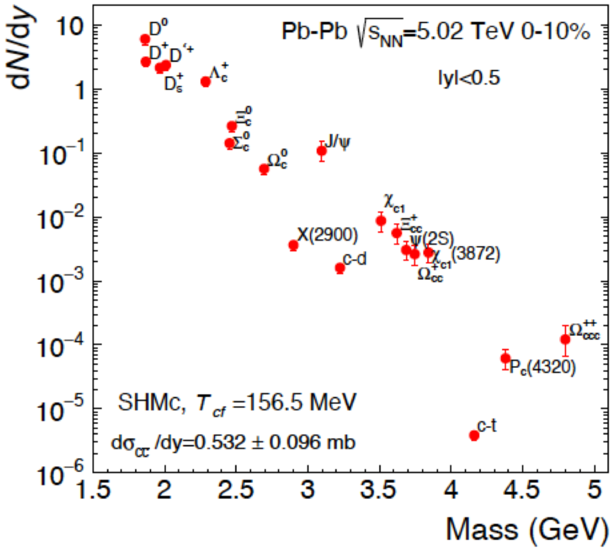


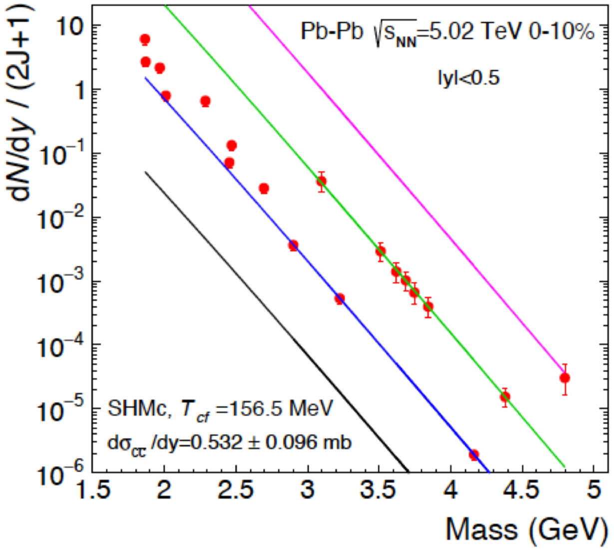
No re-generation for the much more rare b-quarks!

Suppression of Y(1S) ground, and excited Y(2S) and Y(3S) states.
Ordering of R(3S)<R(2S)<R(1S) consistent with sequential melting

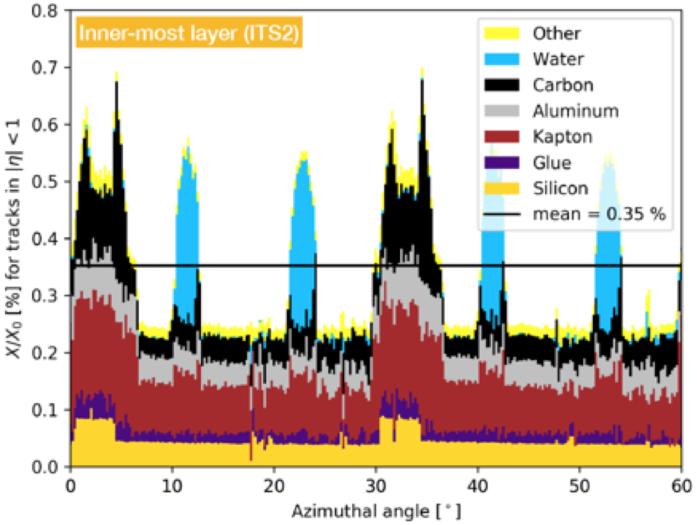
Towards the future: multi-charm and ultra-thin MAPS

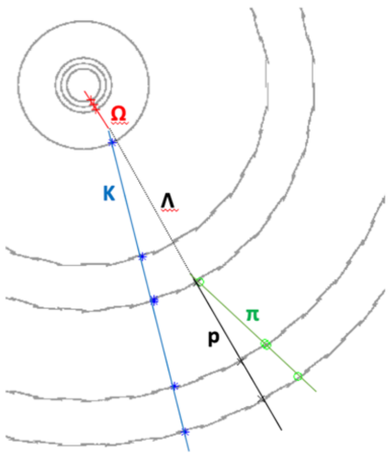


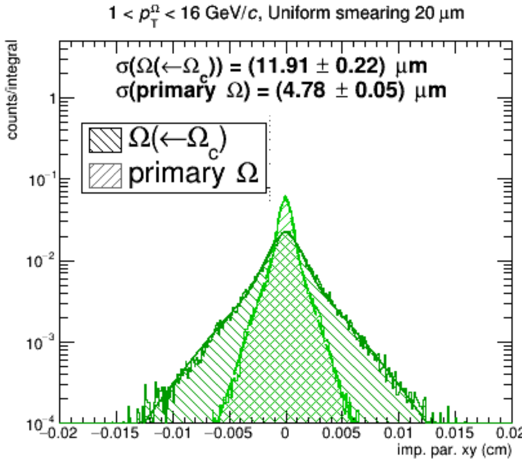




[arXiv:2104.12754v1]

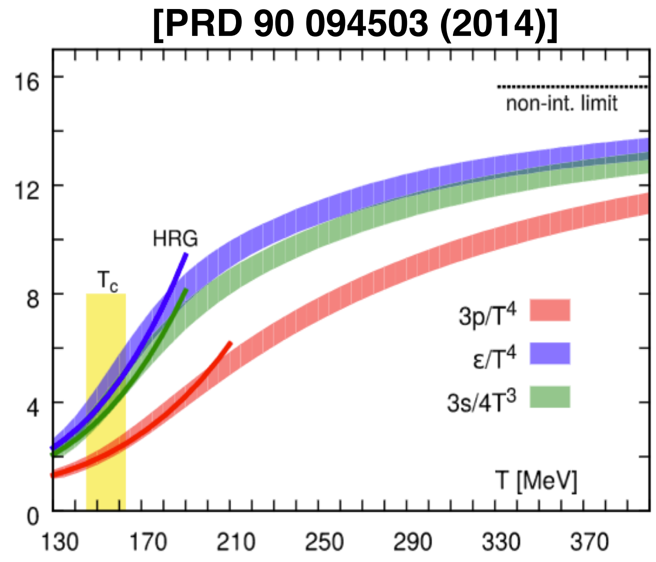


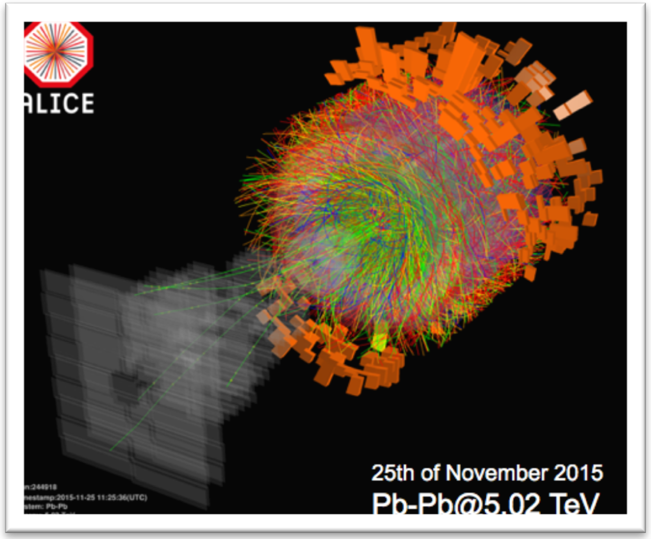


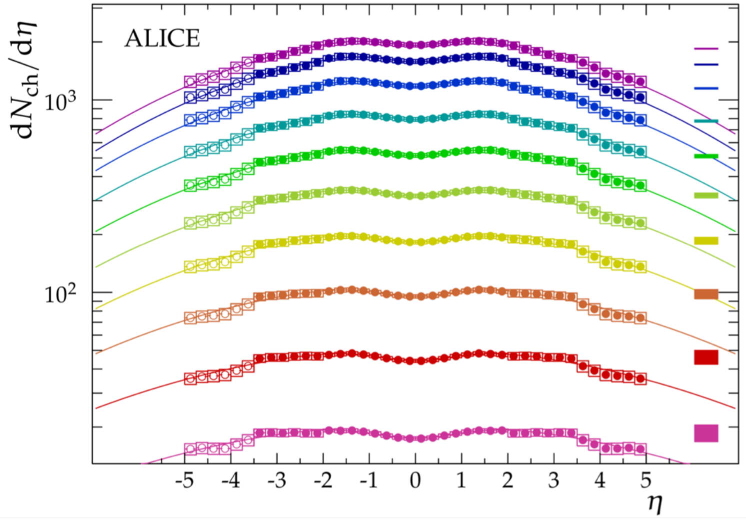


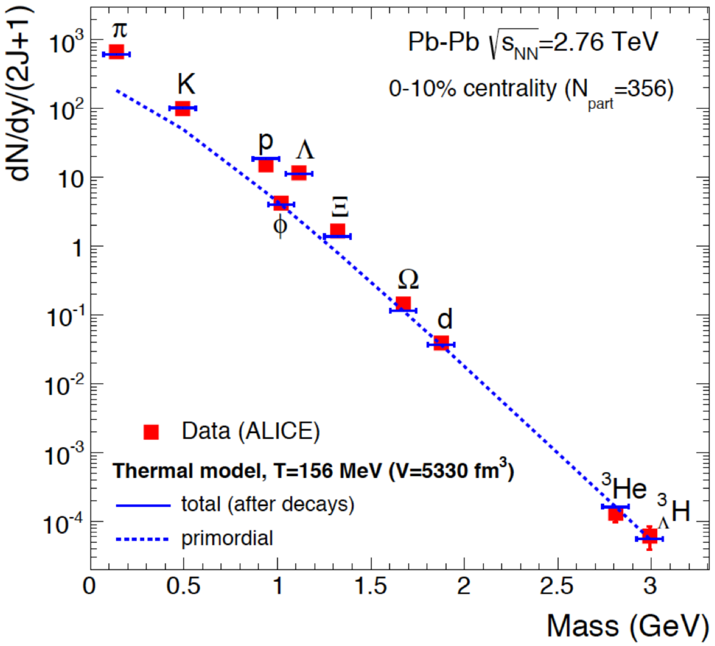
$\Omega_c \rightarrow \Omega + \pi$ ($c\tau \approx 80\mu m$)

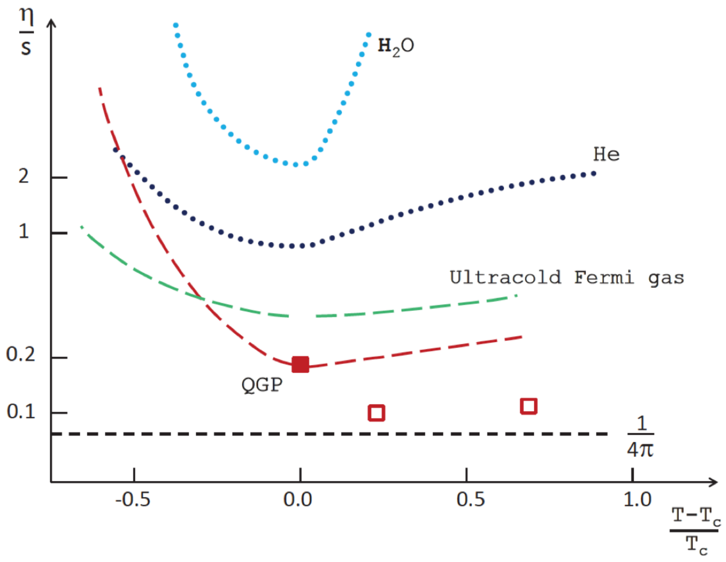
Summary


[PRD 90 094503 (2014)]
non-int. limit
HRG
T_c
$3p/T^4$
ϵ/T^4
$3s/4T^3$
T [MeV]


ALICE
25th of November 2015
Pb-Pb@5.02 TeV


ALICE
$dN_{ch}/d\eta$
η


Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
0-10% centrality (N_{part}=356)
dN/dy/(2J+1)
Data (ALICE)
Thermal model, T=156 MeV (V=5330 fm^3)
total (after decays)
primordial
Mass (GeV)


$\frac{\eta}{s}$
H_2O
He
Ultracold Fermi gas
QGP
$\frac{1}{4\pi}$
$\frac{T-T_c}{T_c}$

Further reading

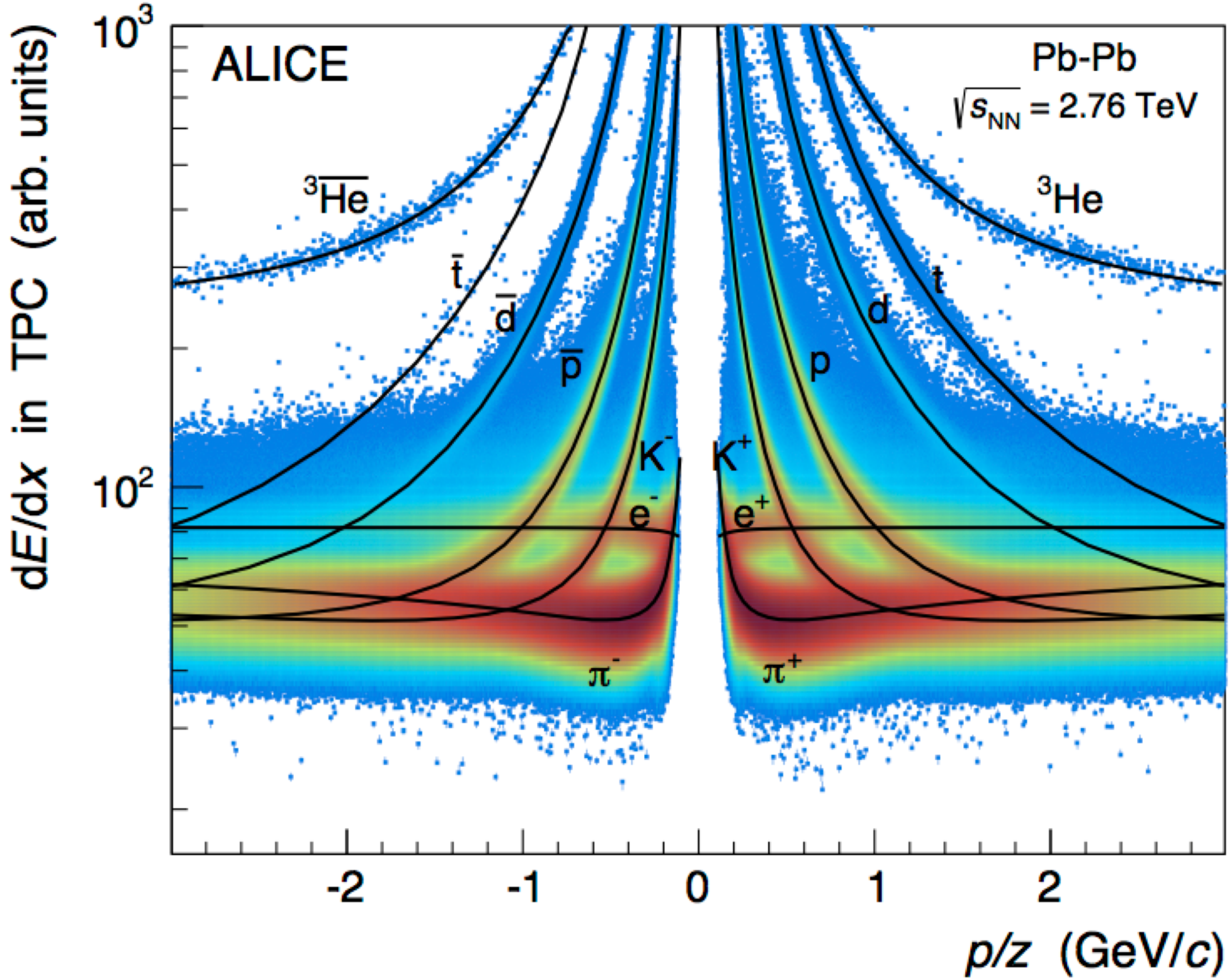
- Lectures
  - J. Stachel, K. Reygers (2011)
    http://www.physi.uni-heidelberg.de/~reygers/lectures/2011/qgp/qgp_lecture_ss2011.html
  - P. Braun-Munzinger, A. Andronic, T. Galatyuk (2012)
    http://web-docs.gsi.de/~andronic/intro_rhic2012/
  - Quark Matter Student Day (2014)
    https://indico.cern.ch/event/219436/timetable/#20140518.detailed
- Books
  - C.Y. Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994
    http://books.google.de/books?id=Fnxvrdj2NOQC&printsec=frontcover
  - L. P. Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994 (**free as pdf**)
    http://www.csernai.no/Csernai-textbook.pdf
  - E. Shuryak, The QCD vacuum, hadrons, and superdensematter, World Scientific, 2004
    http://books.google.de/books?id=rbcQMK6a6ekC&printsec=frontcover
  - Yagi, Hatsuda, Miake, Quark-Gluon Plasma, Cambridge University Press, 2005
    http://books.google.de/books?id=C2bpxwUXJngC&printsec=frontcover
  - R. Vogt, UltrarelativisticHeavy-ion Collisions, Elsevier, 2007
    http://books.google.de/books?id=F1P8WMESgkMC&printsec=frontcover
  - W. Florkowski, Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, World Scientific, 2010
    http://books.google.de/books?id=4gIp05n9lz4C&printsec=frontcover

BONUS SLIDES
(IF TIME ALLOWS…)

QGP thermodynamics and soft probes

(anti-)(hyper-)nuclei

Particle identification via dE/dx



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

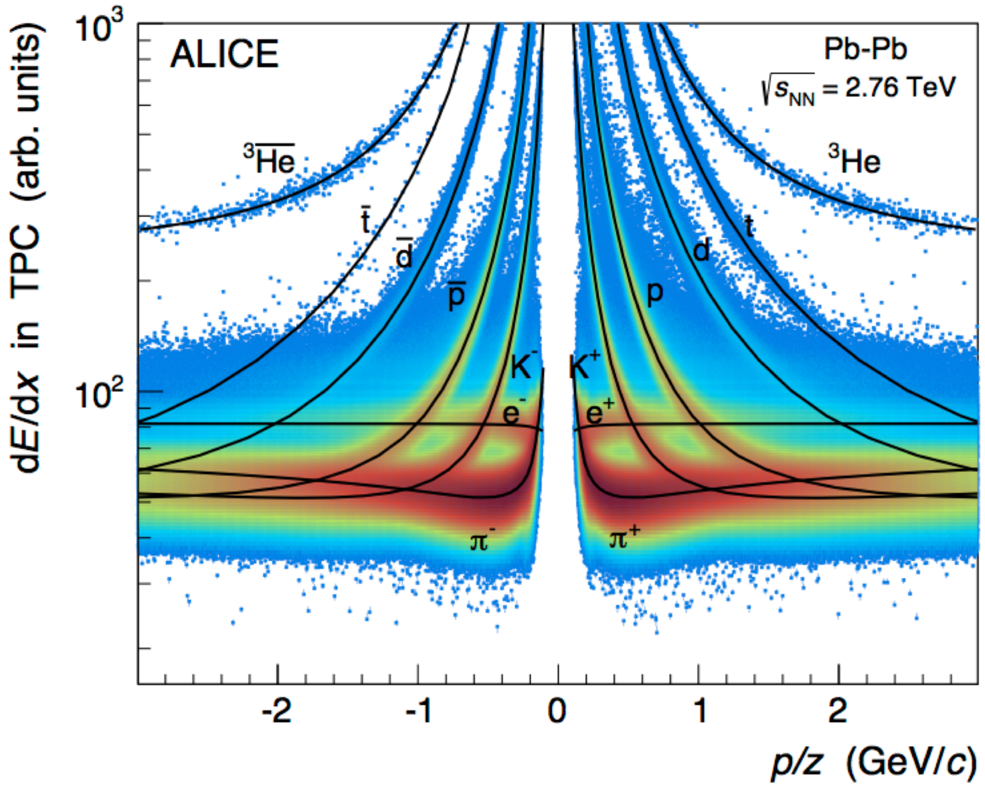
Separation of z = 1 and z = 2 via dE/dx is also very important for the correct determination of the momentum via the track curvature: $p_T \sim 0.3\ B \cdot r \cdot z$

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]

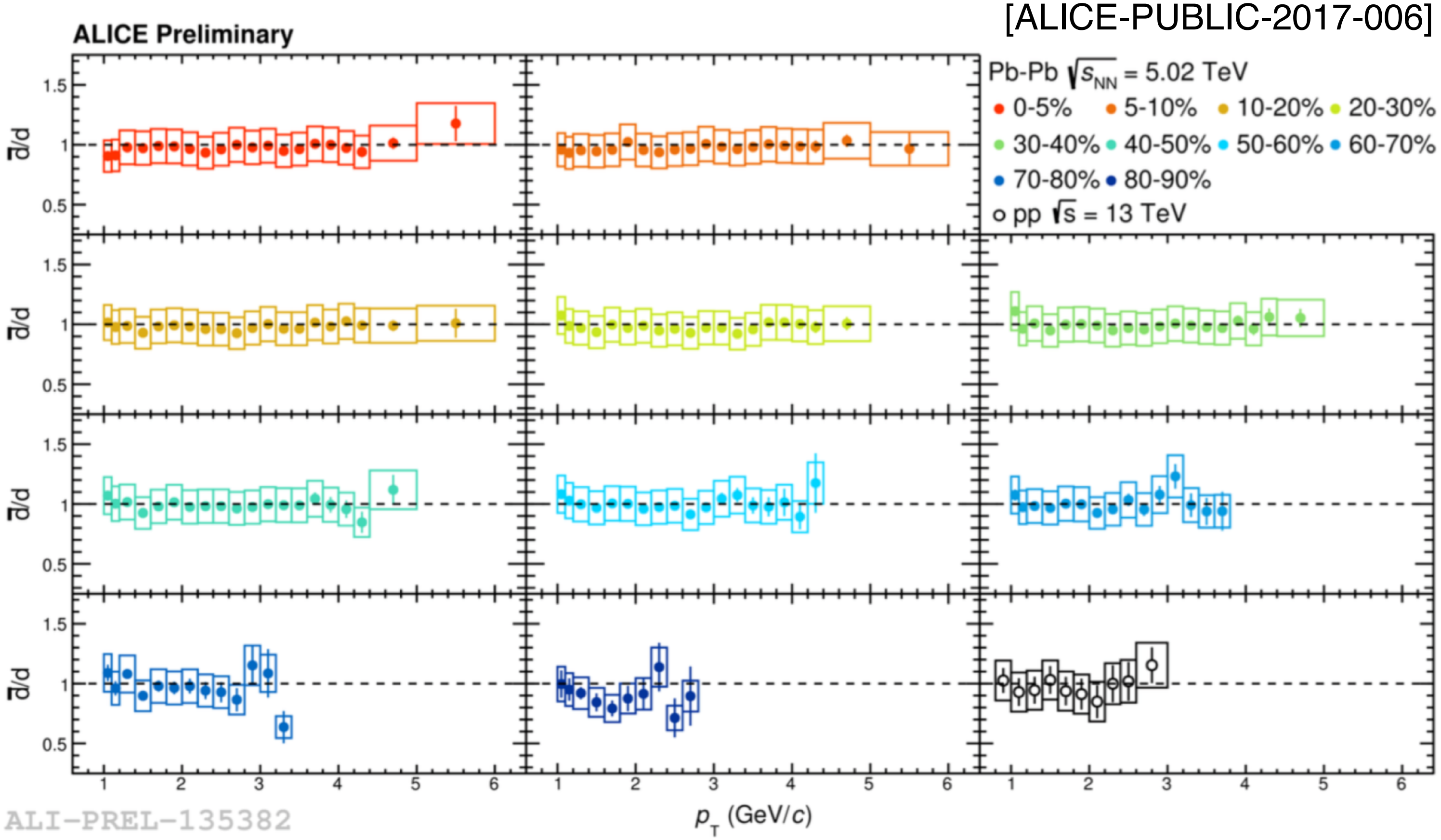
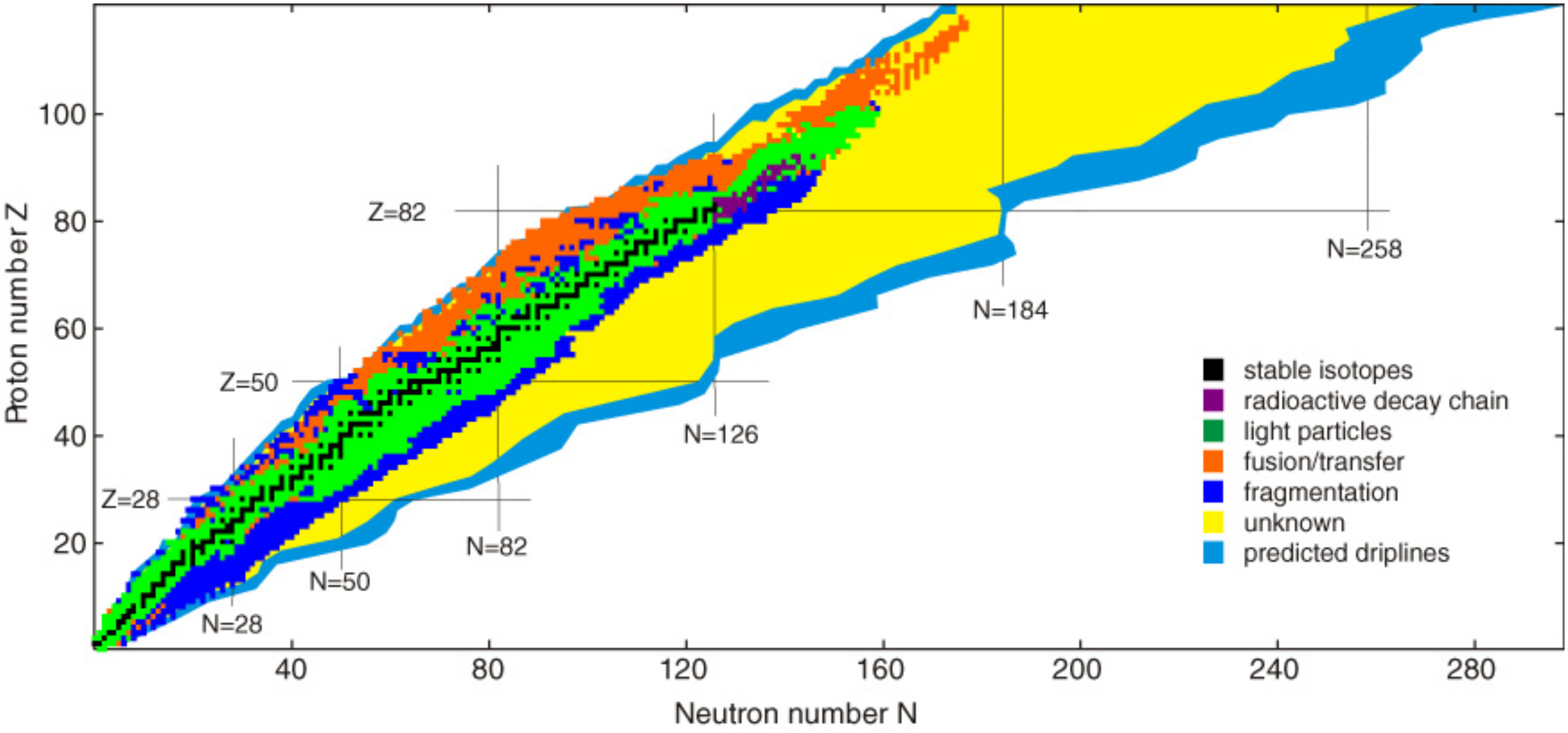


Table of nuclides

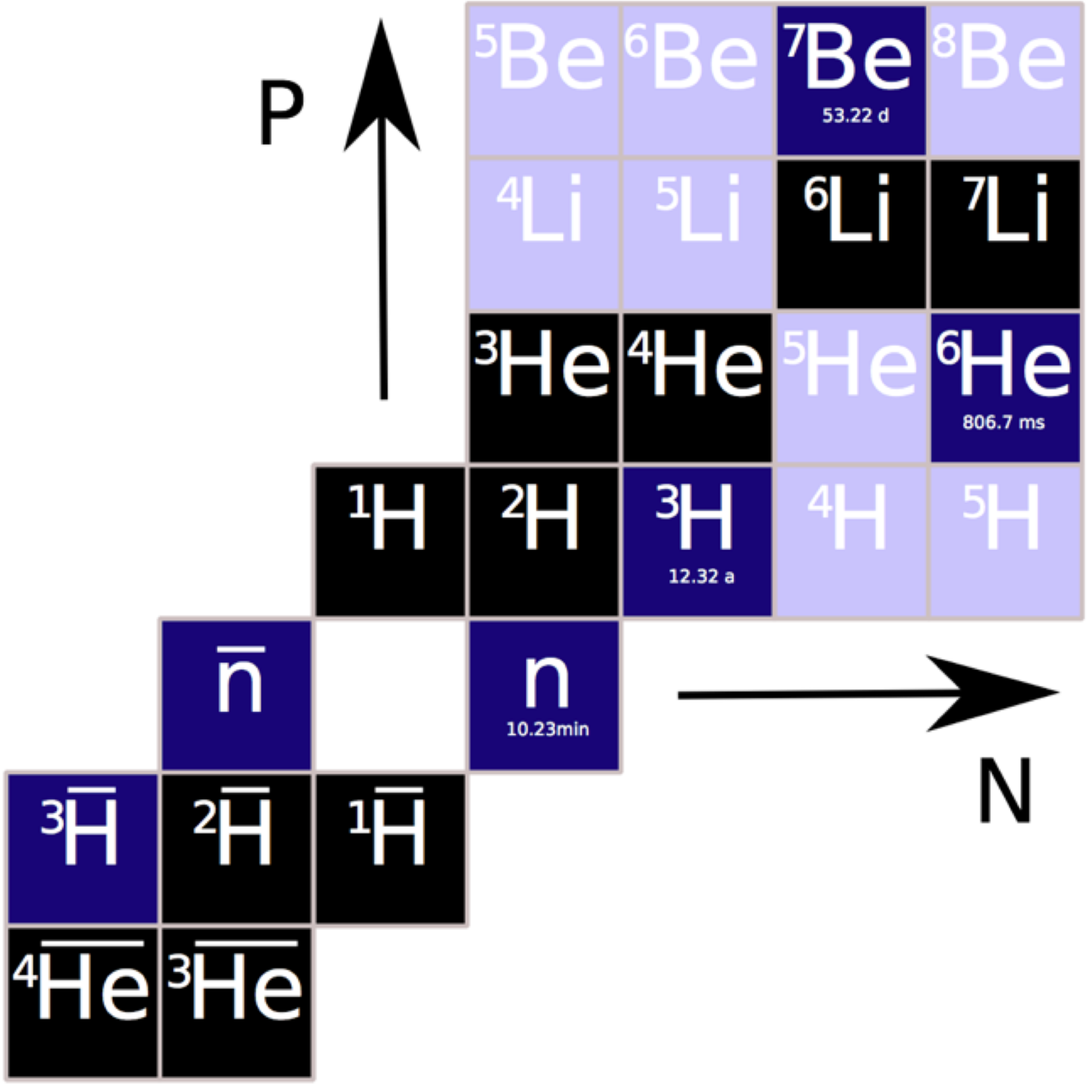


Light (anti-)nuclei

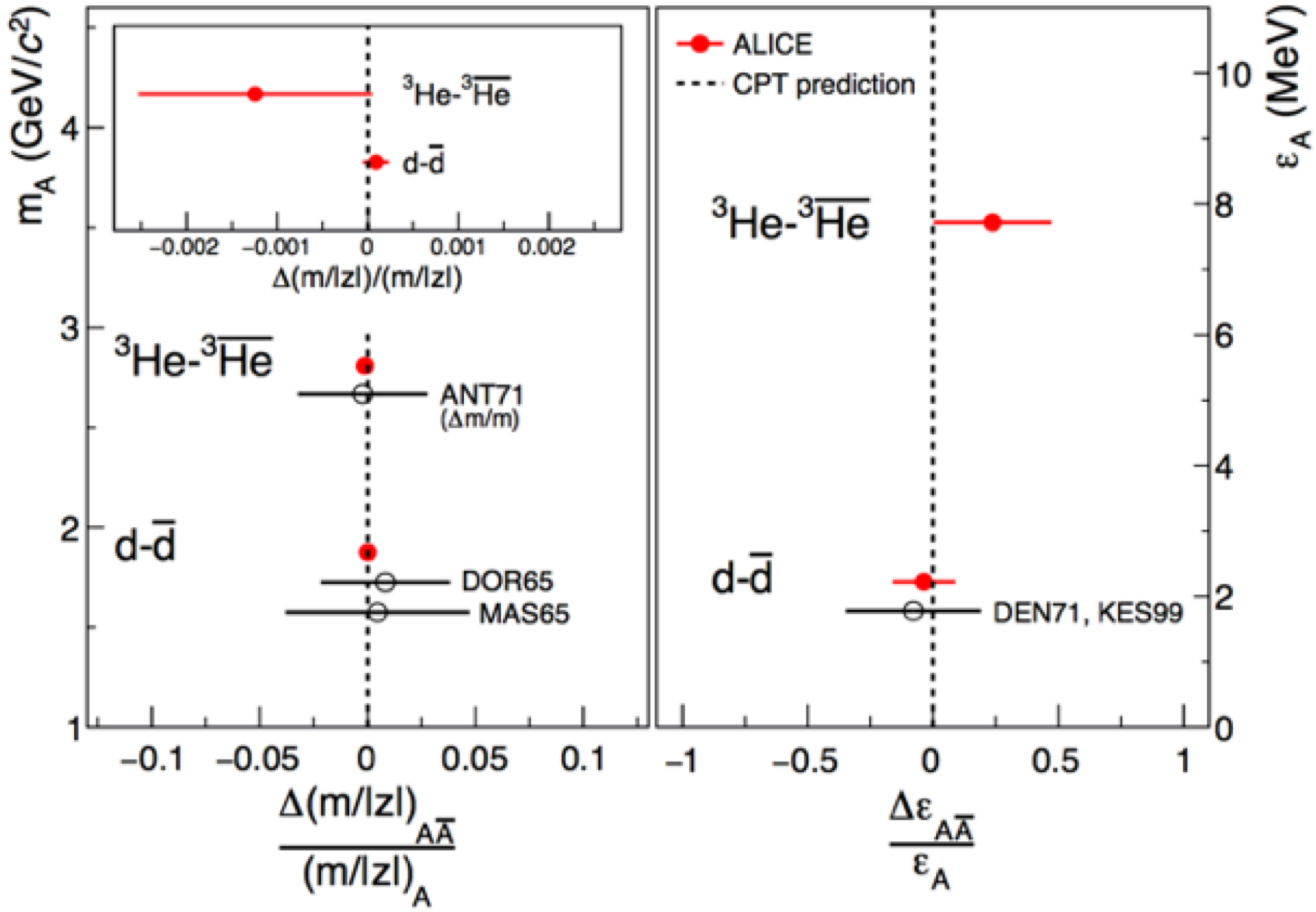
- Even in Pb-Pb collisions at LHC energies, light anti-nuclei are rarely produced.

- (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]

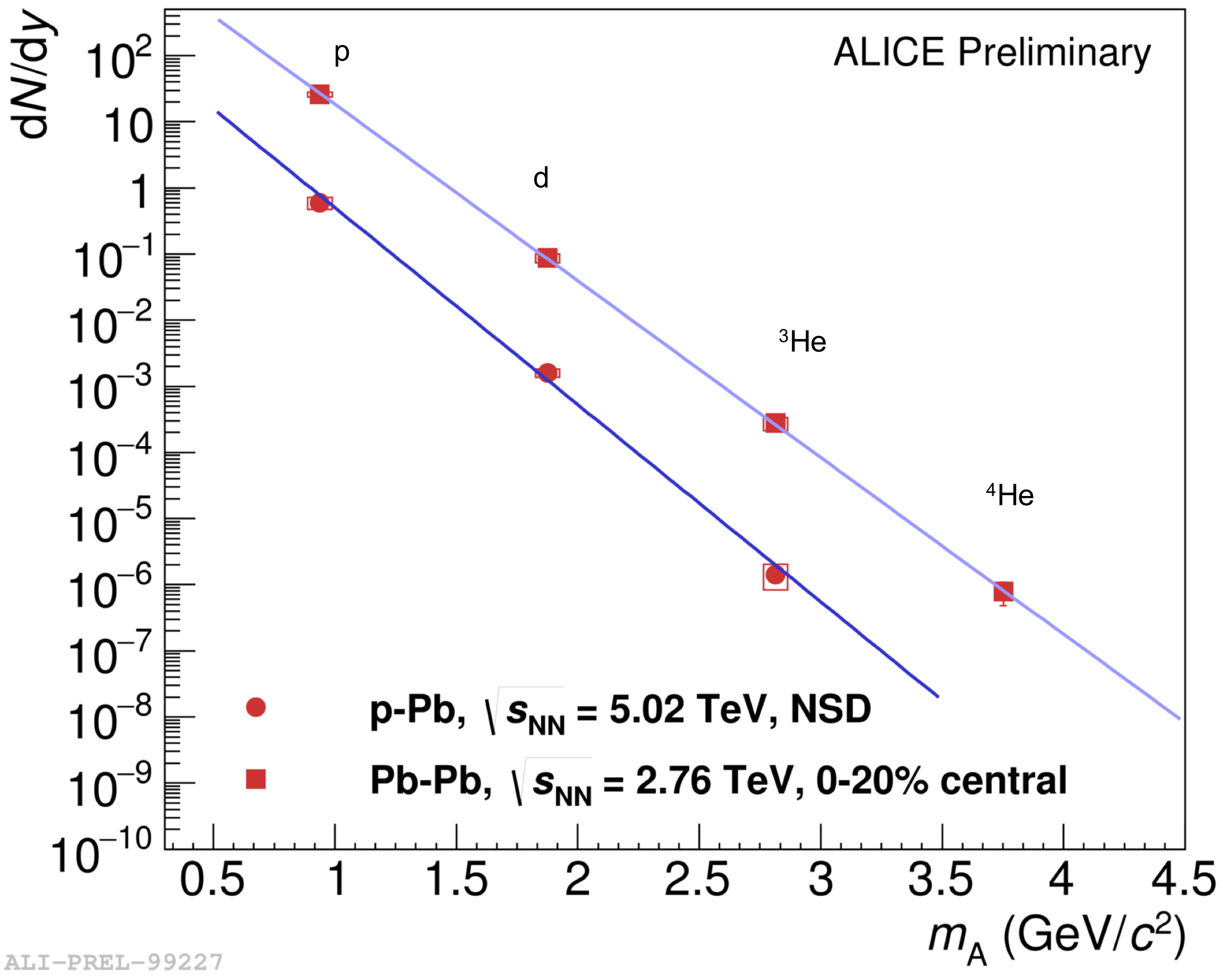
The ALICE collaboration performed a test of the CPT invariance looking at the mass difference between nuclei and anti-nuclei.

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

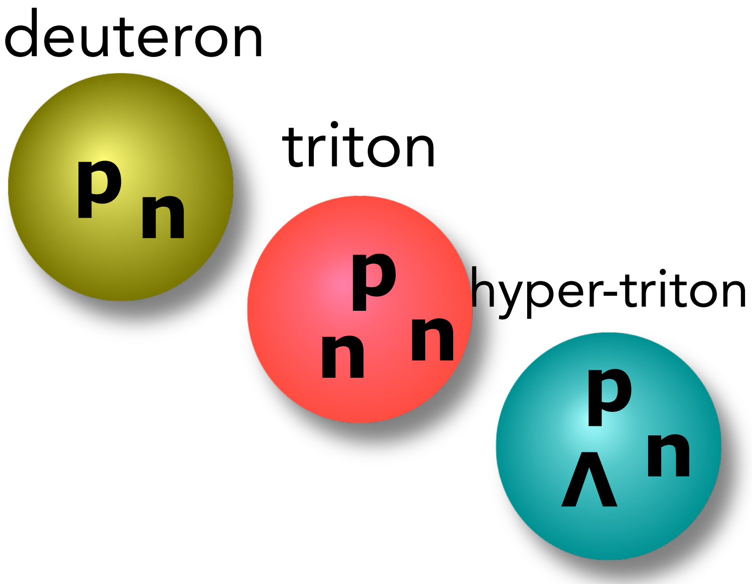
→ For each additional nucleon the production yield decreases by a factor of about 300!

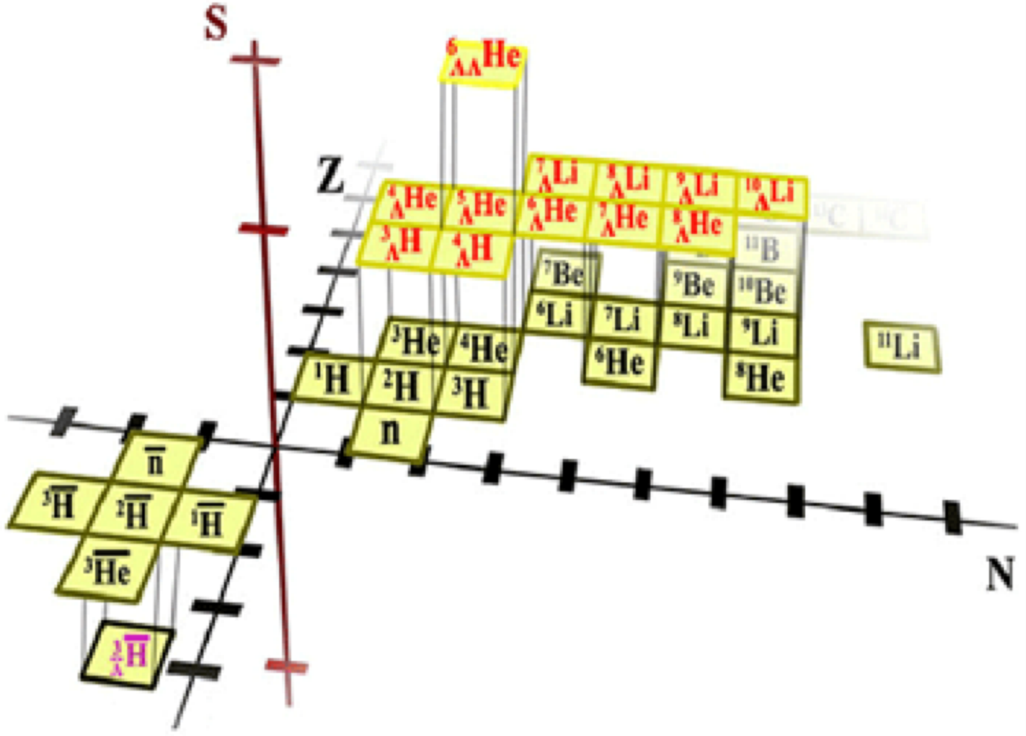
→ Such a behaviour can be directly derived from the thermal model which predicts in first order d*N*/dy ~ exp(-*m*/*T*)



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)

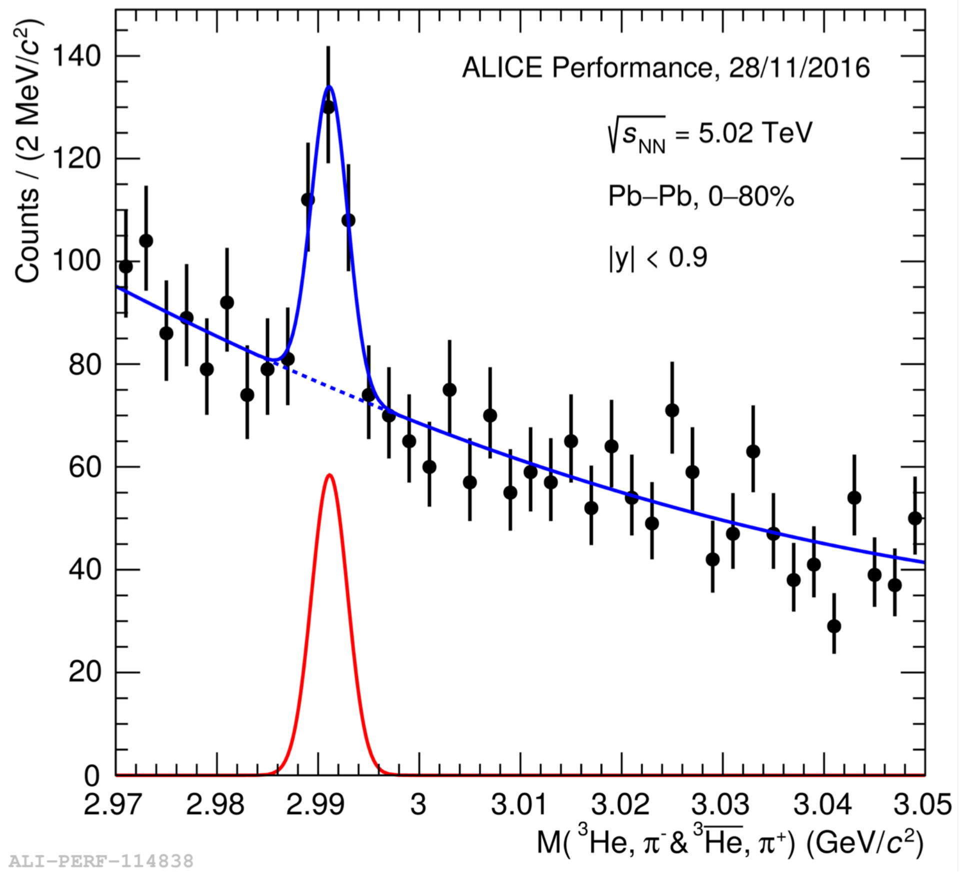
Hyper-nuclei (2)

- 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.

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

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

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

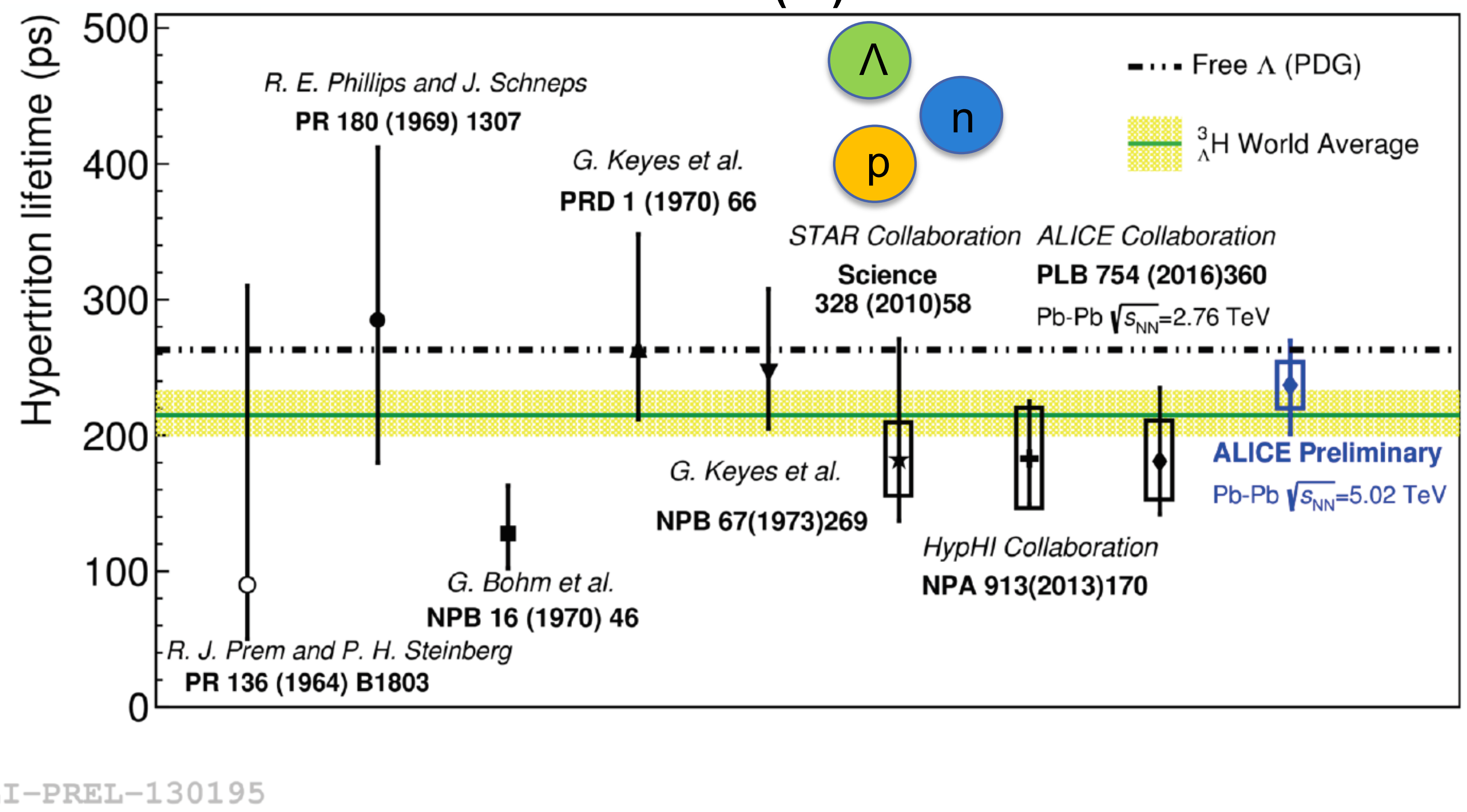


- Branching ratios are only partially constrained by measurements.

(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.)



(B.)

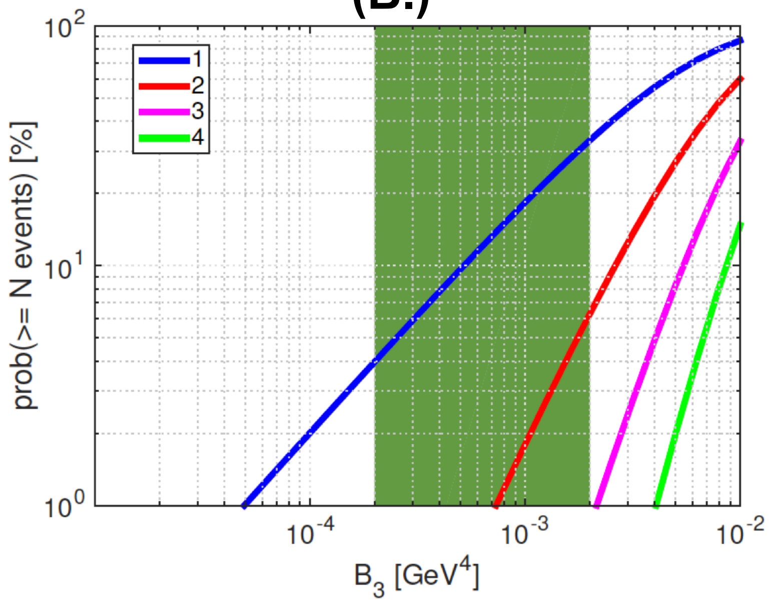
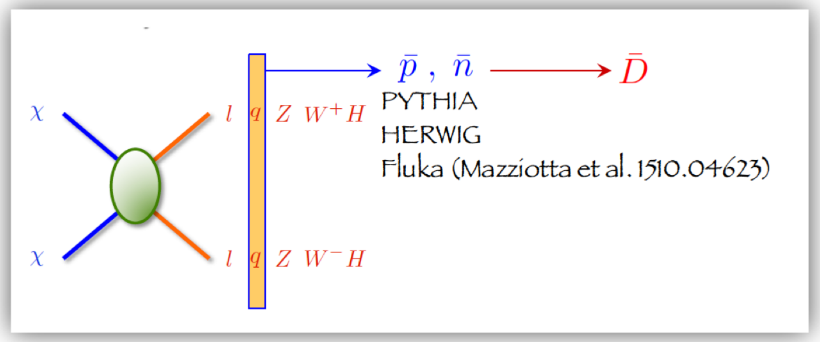


FIG. 5: Poisson probability for detecting $N \geq 1, 2, 3, 4$ $\overline{^3\mathrm{He}}$ events in a 5-yr analysis of AMS02, assuming the same exposure as in the $\bar{p}$ analysis [28]. Eq. (14) shown as green band.

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

Impact on AMS searches

→AMS (and other experiments) search for anti-nuclei in space which are either of primordial origin or from annihilations of dark matter particles.



(see for instance
talk by F. Donato linked here)

(anti-)nuclei measurements in the press

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Fresh antimatter study will help search for dark matter

ANI
29 May 2020

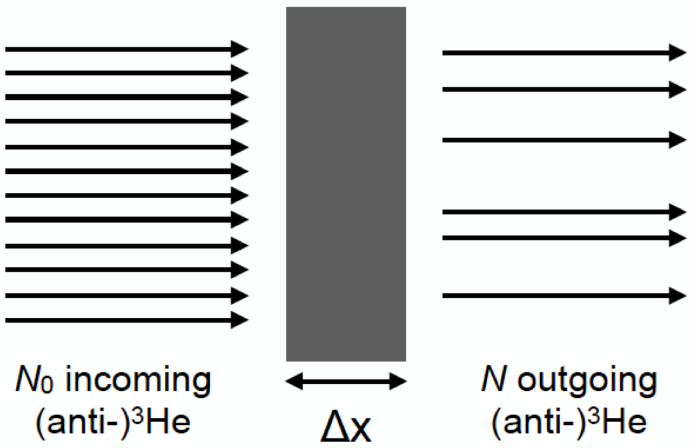
Washington DC [USA], May 29 (ANI): The ALICE collaboration has presented new results on the production rates of antideuterons based on data collected at the highest collision energy delivered so far at the Large Hadron Collider.

The antideuteron is composed of an antiproton and an antineutron. The new measurements are important because the presence of antideuterons in space is a promising indirect signature of dark matter candidates. The results mark a step forward in the search for dark matter.

In the future, these types of studies at ALICE could be extended to heavier antinuclei. "The LHC and the ALICE experiment represent a unique facility to study antimatter nuclei," said ALICE Spokesperson Luciano Musa.

Search for dark matter in space

- Experiments like GAPS and AMS search for anti-nuclei in space as they could be remnants of dark matter annihilation or even primordial remnants.
- But what is the **mean free path of anti-nuclei in the universe**? In other words, how *deep* can these experiments look into the galaxy?
  - We need to know the density of the universe
  - We need to know the composition
  - And we need to know the cross-section (our measurement)



$$N = N_0 \cdot e^{-\Delta x/\lambda_I}$$

$$\lambda_I = \frac{M}{\rho \cdot N_A \cdot \sigma_I}$$

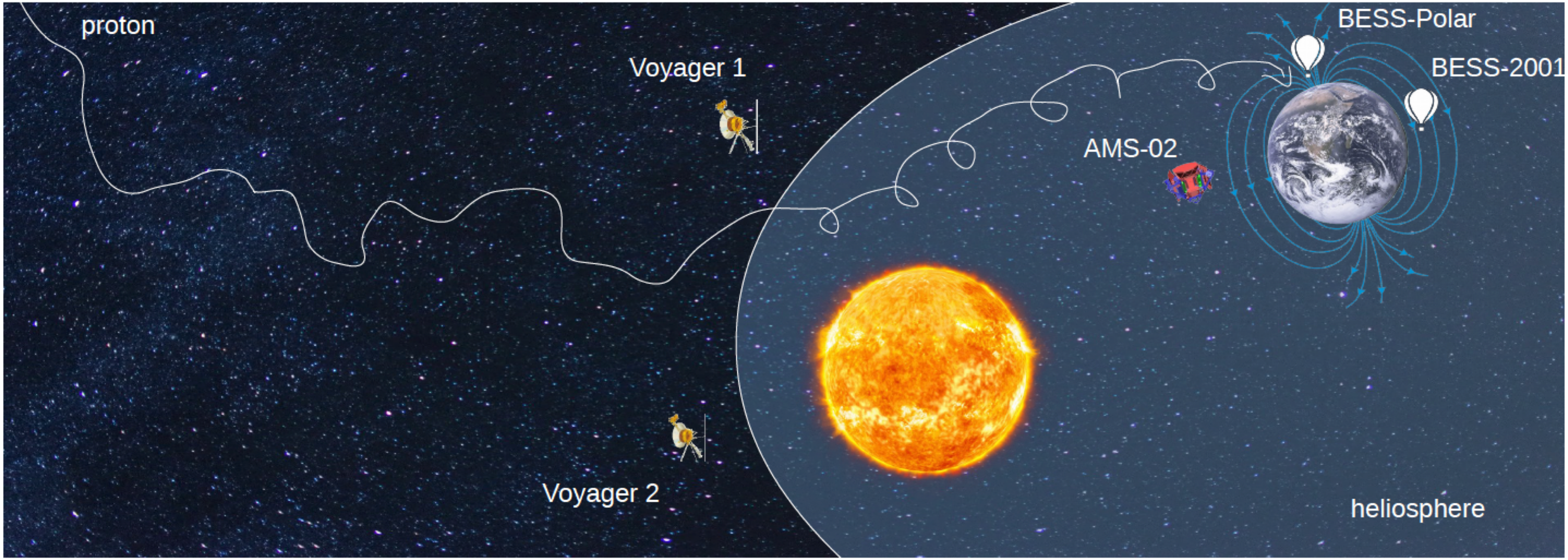
M → Molar mass of the target

ρ → Density

N_A → Avogadro's number

σ_I → Inelastic cross section

[Drawing and formulas taken from A. Caliva]



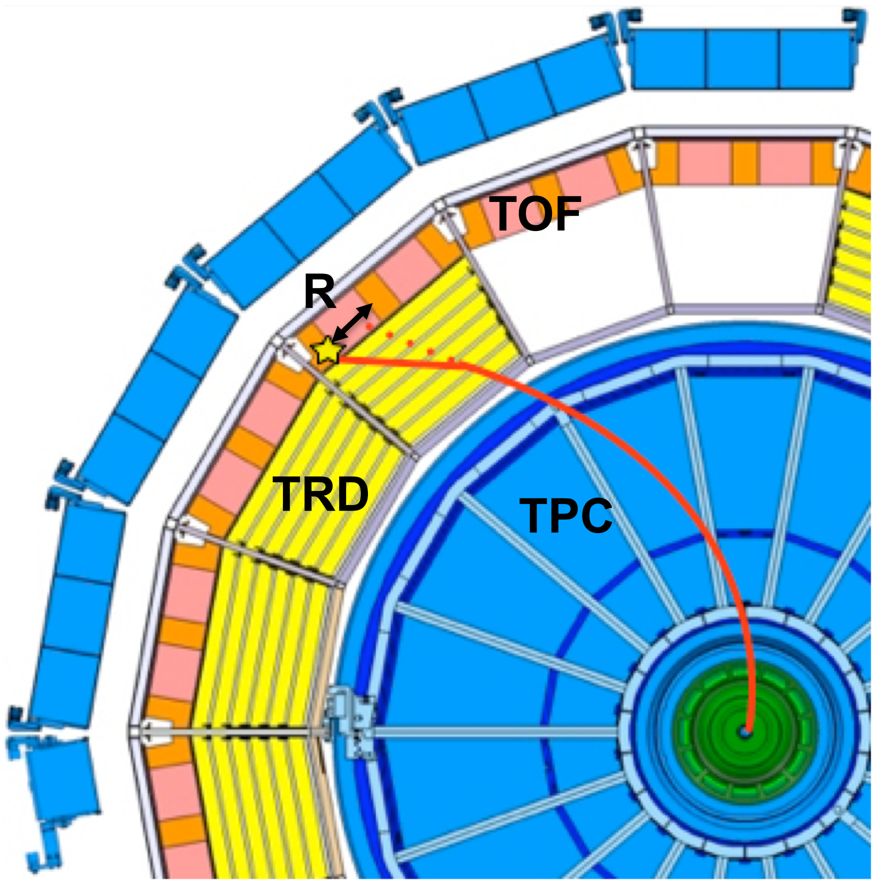
[Taken from Laura Serskynte]

Measuring the unknown hadronic absorption of antinuclei

1. Particle identification for (anti-)^{3}He is essentially perfect (no contamination) for both TPC and TOF.

2. Count number of (anti-)^{3}He particles in the TPC and then count how many arrive in the TOF.

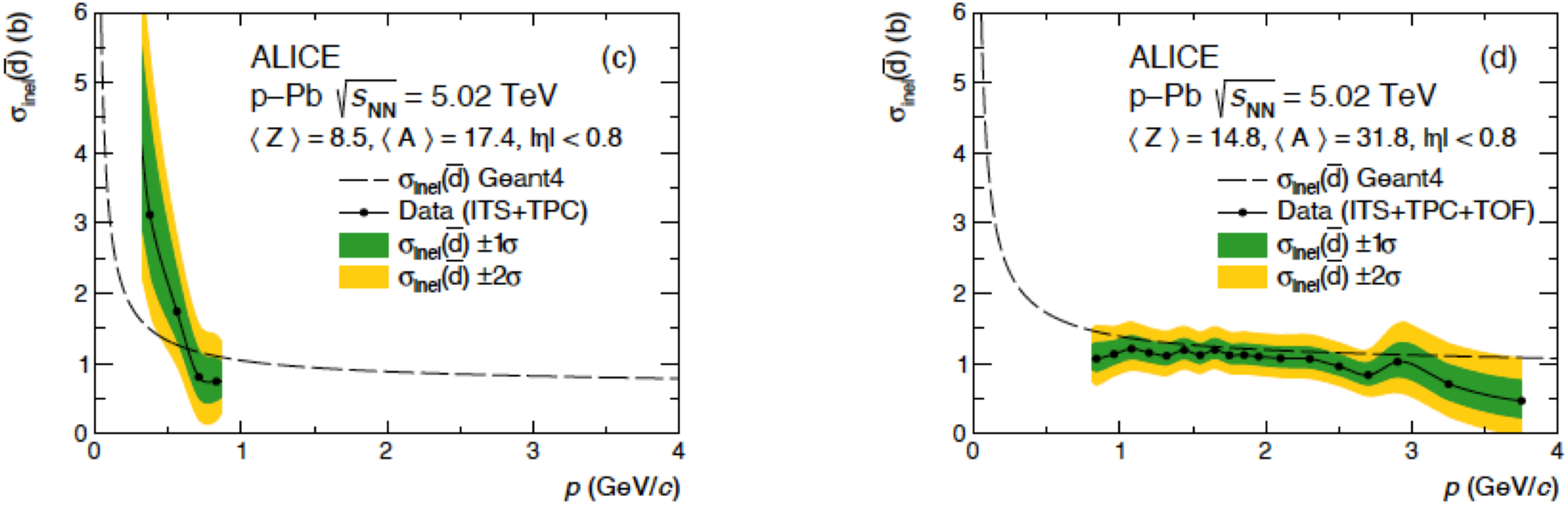
3. Particles are not matched to a TOF track due to either
    1. Dead TOF module
    2. Large-angle elastic electromagnetic scattering
    3. Inelastic hadronic interaction
    4. Large-angle elastic hadronic scattering



PINSTECH collaborators are part of the data analysis team that performs the measurement!

Hadronic cross-section of anti-deuterons (1)

[ALICE, 2005.11122]



→ Very rough estimate of mean free path:

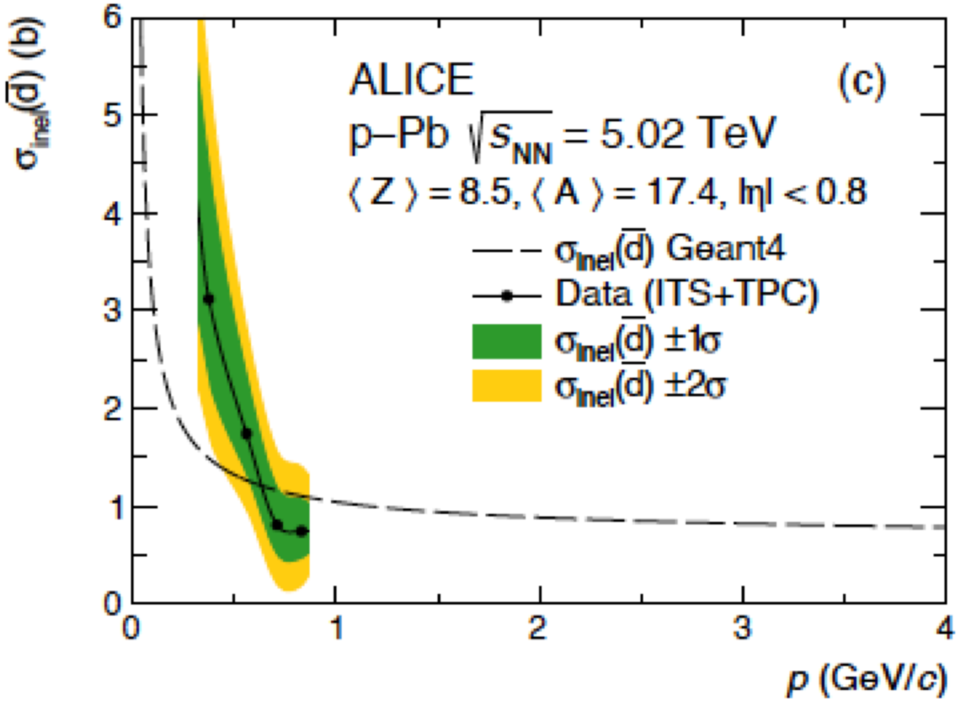
$$\lambda = \frac{1}{n \cdot \sigma} \qquad \lambda \approx \frac{1}{\frac{1}{\mathrm{cm}^{-3}} \cdot 6 \cdot 10^{-24}\,\mathrm{cm}^2} \approx 1.7 \cdot 10^{21}\,\mathrm{m} \approx \underline{180000\,\mathrm{ly}}$$

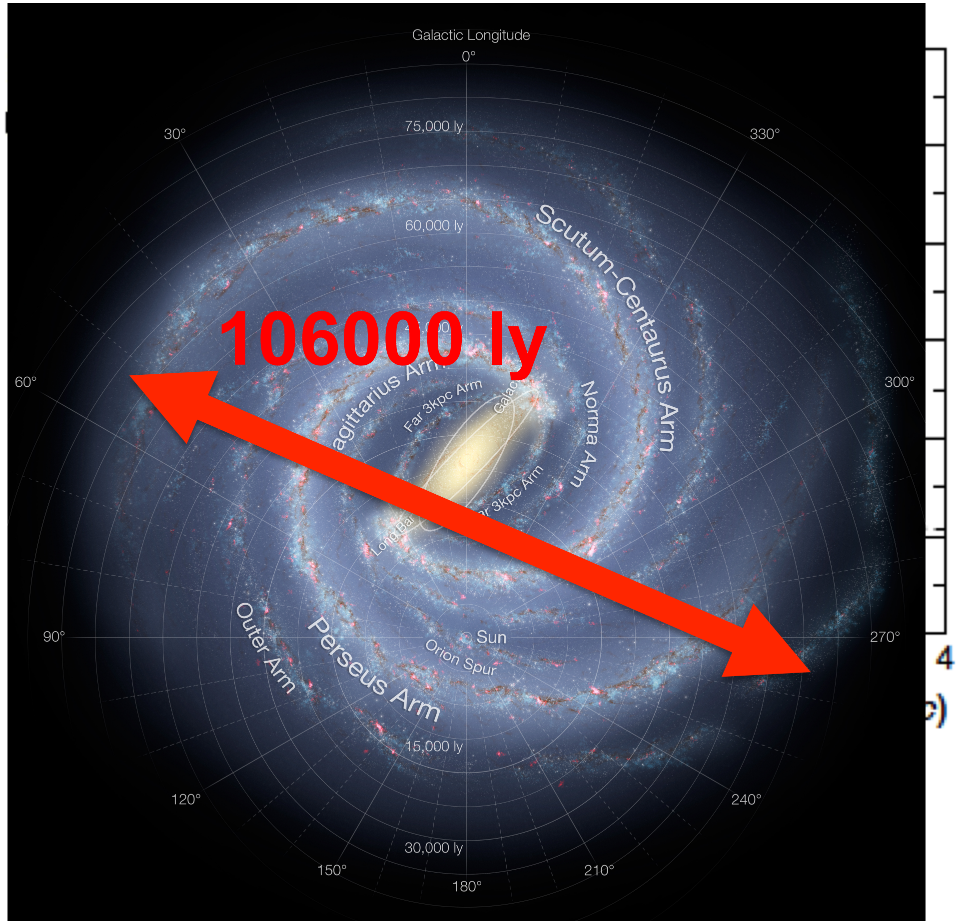
Cross section from ALICE measurement

Number density of hydrogen and He atoms in universe

Hadronic cross-section of anti-deuterons (2)

[ALICE, 2005.11122]





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$$\lambda \approx \frac{1}{\frac{1}{\mathrm{cm}^{-3}} \cdot 6 \cdot 10^{-24}\,\mathrm{cm}^2} \approx 1.7 \cdot 10^{21}\,\mathrm{m} \approx \underline{180000\,\mathrm{ly}}$$

Cross section from ALICE measurement

Number density of hydrogen and He atoms in universe