Overview of recent results from heavy-ion collisions at ultra-relativistic energies

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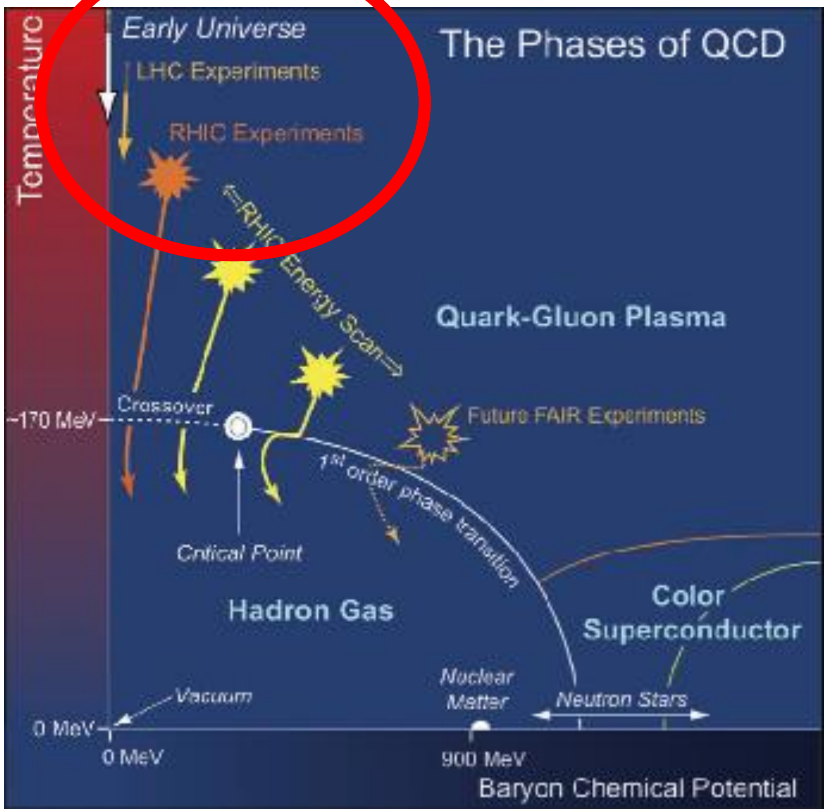
Disclaimer

- Field of ultra-relativistic heavy-ions physics is very rich: 6 large active experiments, with more than 20 years of experimental history, very active and broad theory community
- The presentation will focus on a selection of recent results from an experimental point of view
- The slides were inspired by a few lectures given by various people, and in some by presentations from QM2018. I would like to acknowledge everyone I drew inspiration from

What is the point of ultra-relativistic heavy-ion collisions?

- Study the QCD phase transition from nuclear matter to the **deconfined state of ("free") quarks and gluons** – the **Quark Gluon Plasma (QGP)** → State of strongly interacting matter where quarks and gluons are not confined to hadrons



- Studying Physics of the QGP
  - → role of chiral symmetry in the generation of mass in hadrons → accounts for 99% of mass of nuclear matter
  - → nature of quark confinement

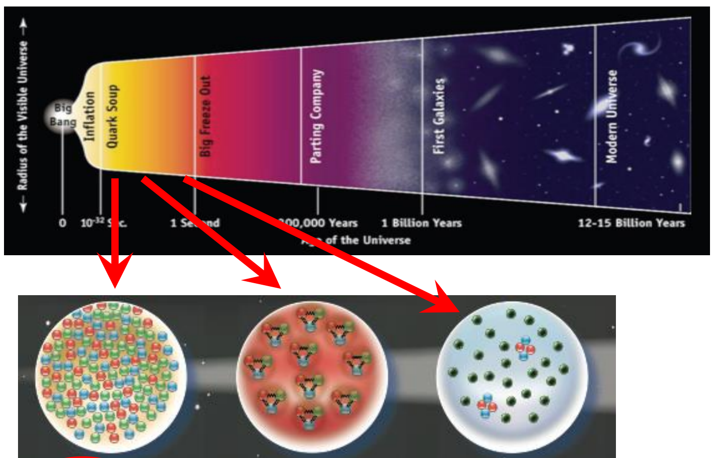
- Phase transitions of hadrons to QGP well established from lattice QCD
  - Temperature, $T \approx 170$ MeV (~ 2.10^{12}K)
  - Energy density $\varepsilon_c \approx 1$ GeV/fm^3

- Ultra-relativistic heavy-ion experiments
  → **ideal environment for QGP factory!!**

PoS CPOD2013 (2013) 001 arXiv:1308.3328

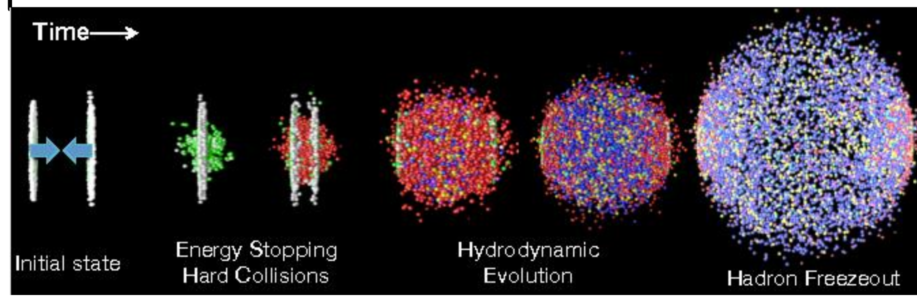
The Quark Gluon Plasma (QGP)

- Key observable to understand the early Universe
- Correspond to the state of the universe ~1 μs after the Big Bang
- QCD phase transition: QGP to normal matter (hadrons) happens at t_{Universe} ~10 μs



Quark Gluon Plasma (QGP) — *formation of nucleons* — *formation of nuclei*

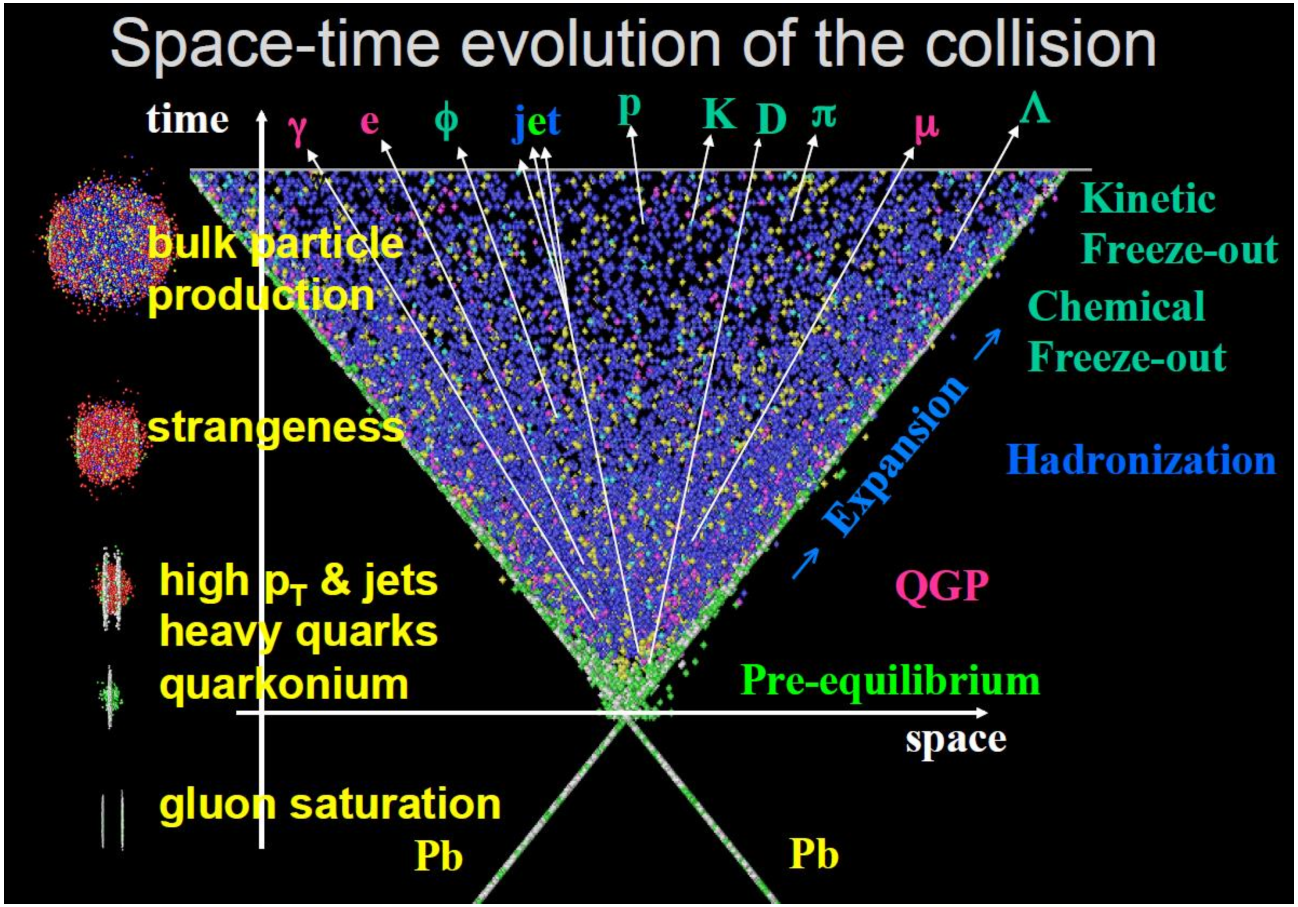
- **Creating the QGP**: "little Big Bang"
- Collide heavy ions at the highest centre-of-mass energy per colliding nucleon, $\sqrt{s_{NN}}$, → **large energy density (> 1 GeV/*fm*³) over large volume (>> 100 *fm*³)**
- For a short time span (about 10^{-23} s, or few fm/c) the conditions for deconfinement are recreated



- The QGP fireball first expands, cools and then freezes out into a collection of final-state hadrons
- Evolution: **Pre-equilibration → QGP → hadronization → freeze out**
- Use particles in the final state to study the evolution of a heavy–ion collision → study the properties of the QGP

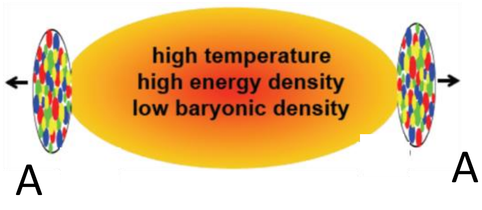
Measuring the QGP in heavy-ion collisions

- Perform various measurements which, when combined, can provide reliable proof of the formation of the QGP → **signatures of the QGP**



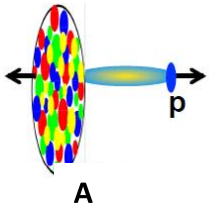
The paradigm

- **CORE business: Heavy-ion collisions → create and characterize the QGP**
  - Global properties ⇔ the QGP fireball
  - Strangeness enhancement ⇔ historic signature of the QGP
  - Anisotropy, correlations ⇔ collective expansion of the QGP
  - Bulk particle production ⇔ hadronisation of the QGP
  - High-p_T and jets ⇔ opacity of the QGP
  - Heavy-flavour production ⇔ transport properties of the QGP
  - Quarkonium production ⇔ de-confinement in the QGP

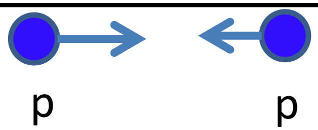


- **Role of the small systems:**

- **Proton-nucleus (p-A) collisions: Control experiment**
  - disentangle initial and final state effects
  - → Investigate cold nuclear effects



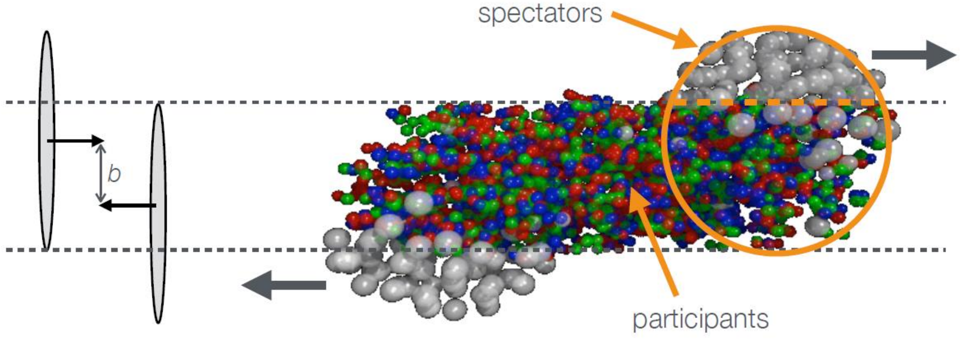
- **Proton-proton (pp) collisions:**
  - Baseline (reference)
  - Test pQCD theories



Definition of concepts

Centrality

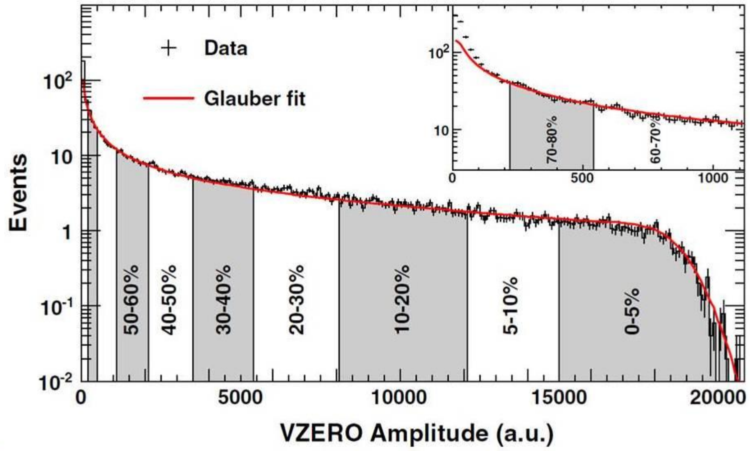
- ❑ Geometry of the heavy-ion collision →system size strongly dependent on collision centrality
- ❑ Given by the impact parameter, *b*



Central collisions: small *b* → large N_{part}
Peripheral collisions: high *b* → small N_{part}

- N_{coll}: number of inelastic nucleon-nucleon collisions
- N_{part}: number of nucleons which underwent at least one inelastic nucleon-nucleon collisions

ALICE PRL 106 (2011), 032301



- ➢ Classify events in "centrality classes"
- ➢ Given as percentiles of total hadronic AA cross section
- ➢ Determine <N_{part}> and <N_{coll}> with a **model of the collision geometry** (**Glauber model**)

Basic Observables

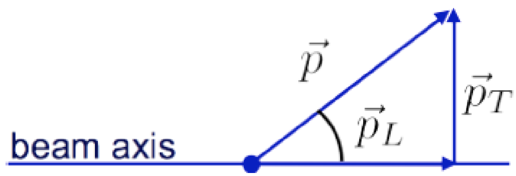
- Transverse momentum

$$p_T = p \sin\theta$$

transverse mass:

$$m_T = \sqrt{p_T^2 + m^2}$$

$$p = \sqrt{p_L^2 + p_T^2}$$



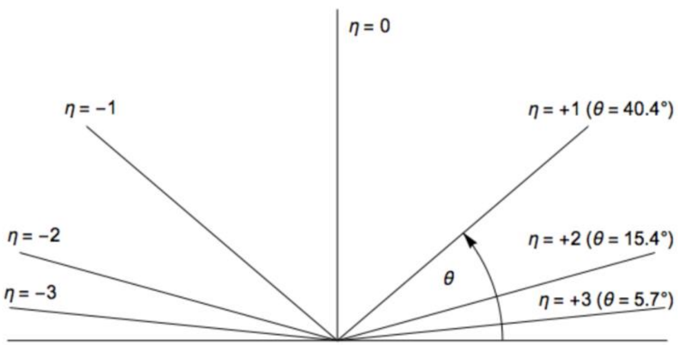
- Rapidity y (additive under Lorentz transformation)

$$y = \operatorname{arctanh} \beta_L = \frac{1}{2} \ln \frac{1+\beta_L}{1-\beta_L} = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$$

- Pseudorapidity η

$$y \overset{p \gg m}{\approx} \frac{1}{2} \ln \frac{1+\cos\vartheta}{1-\cos\vartheta} = -\ln\left[\tan\frac{\vartheta}{2}\right] =: \eta$$

Pseudorapidity



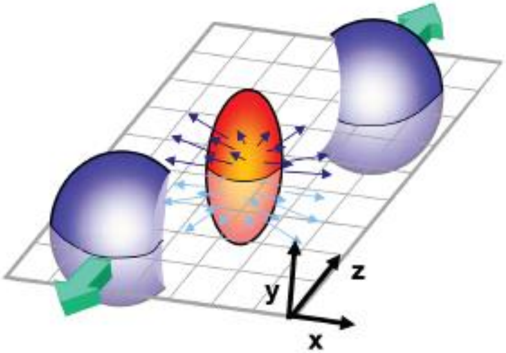
- **In-medium energy loss of particles is quantified by the nuclear modification factor**: comparison of particle yield in A-A collisions to that in binary-scaled pp collisions

$$R_{AA}(p_t,\eta) = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dp_t d\eta}{d^2N_{pp}/dp_t d\eta}$$

= 1 if no medium effects → no modification

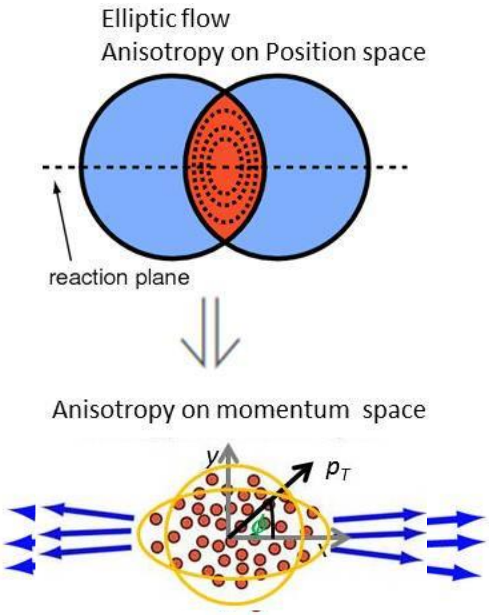
< 1 → it means a **suppression of particle production**

Elliptic flow



- The nature of flow provides information about the transport properties of the medium (QGP)
  - Flow at high p_T → path length dependence of energy loss
  - Flow at low p_T → thermalization / collective motion

- Given by υ_n **coefficients**: **second harmonic coefficient (υ_2)** is generated from the system's approximately almond (elliptic) shape → **elliptic flow**



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t d_y}\left(1+\sum_{n=1}^{\infty} 2\upsilon_n \cos\left[n(\phi-\Psi_R)\right]\right)$$

Fourier coefficient (υ_n)

Reaction plane angle (Ψ_R)

υ_1: Direct flow: $\langle \cos\phi \rangle$ υ_2: **Elliptic flow** = $\langle \cos 2\phi \rangle$

- Elliptic flow, υ_2 is related to the geometry of the overlap zone

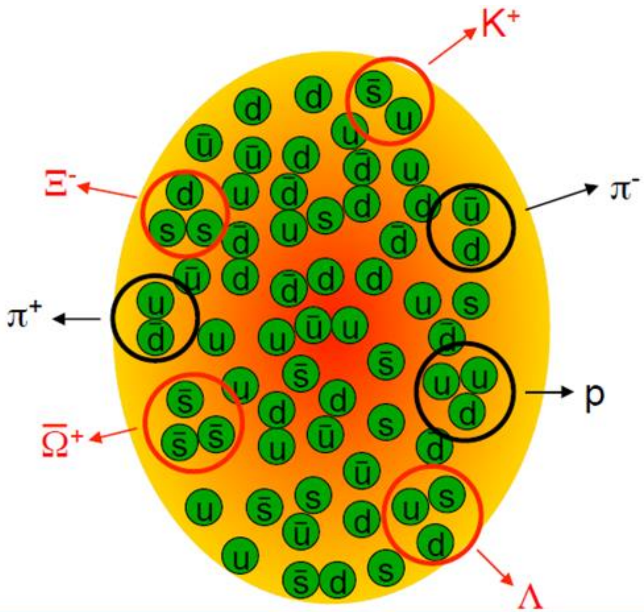
Core business:
high-energy heavy-ion experiments

Heavy-ion experiments

Year	Facility	Particle Beams	Energy, $\sqrt{s_{NN}}$	Findings
1984	Bevalac @ Berkeley	Gold (Au - fixed target	0.2-1 GeV	Collective phenomena: direct (υ_1) and elliptic flow (υ_2)
1992	AGS @ Brookhaven	Au-Au (fixed target)	5 GeV	Below critical energy density, ε_c
1994	SPS @ CERN	Lead (Pb) on Pb (fixed target)	17 GeV	Estimated energy density ~ 1 x critical value, ε_c . First signature of the QGP observed
2000	RHIC @ Brookhaven	Au-Au	8-200 GeV	Discovery of several properties of the QGP
2010-2011	LHC @ CERN	Pb-Pb	2.76 TeV	Qualitative similar results in A-A
2010-2014	RHIC-BES Phase I @ Brookhaven	Au-Au	62, 130 and 200 GeV	Direct flow (υ_1) of charged hadrons similar to hydro-model predictions?
2013	LHC @ CERN	p-Pb	5.02 TeV	Control experiment:– disentangle initial & final state effects
2015 – 2017 2018	LHC RUN 2 @ CERN	Pb-Pb, p-Pb, Xe-Xe Pb-Pb	5.02 TeV	Ongoing… Precise characterization of the QGP, new probes available
From 2017	RHIC-BES Phase II @ Brookhaven	Au-Au (fixed target)		Access ~μ_B from 400 MeV (current) to ~ 800 MeV, (corresponds to $\sqrt{s_{NN}}$~2.5GeV in QCD phase diagram

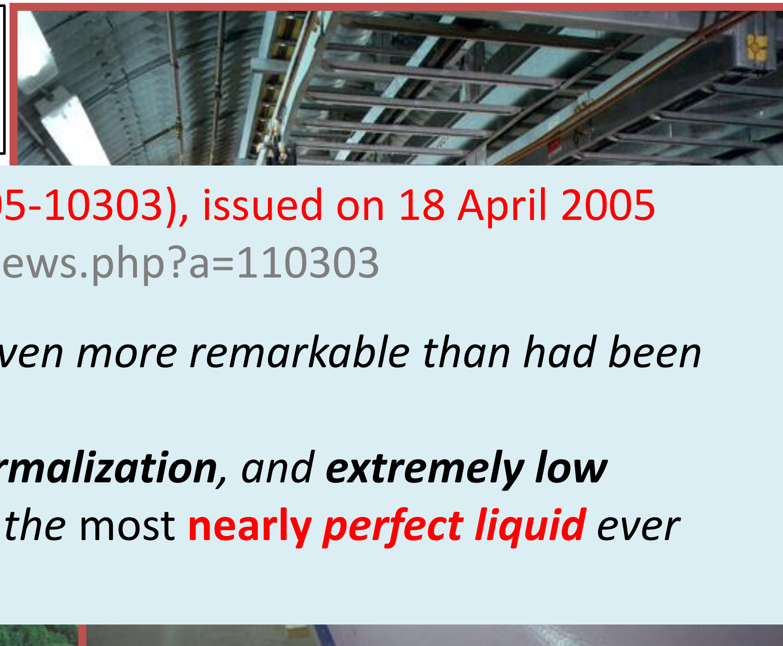
Discovery of strangeness enhancement at the CERN SPS

- **First signature of the QGP - observed in the 1980s at CERN SPS**
- Strange hadrons contain 1 or more strange quark (s). They are heavier than normal matter around
  - Harder to produced → "freshly" made from the kinetic energy of the colliding system
  - Their abundance is sensitive to **conditions**, **structure** and **dynamics of the QGP**
  - → **if number is large, it can be assumed that the QGP has been formed**
- Measurements:
  - Count strange particles produces and calculate the ratio = strange particles/non-strange particles
  - Higher ratio than predicted by theories that do not predict the QGP → enhancement has been observed.



Discovery of several properties of the QGP at Relativistic Heavy Ion Collider (RHIC)

- ❑ 2 independent rings; circumference: 3.8 km
- ❑ **Au-Au, $\sqrt{s_{NN}}$ = 200 GeV**



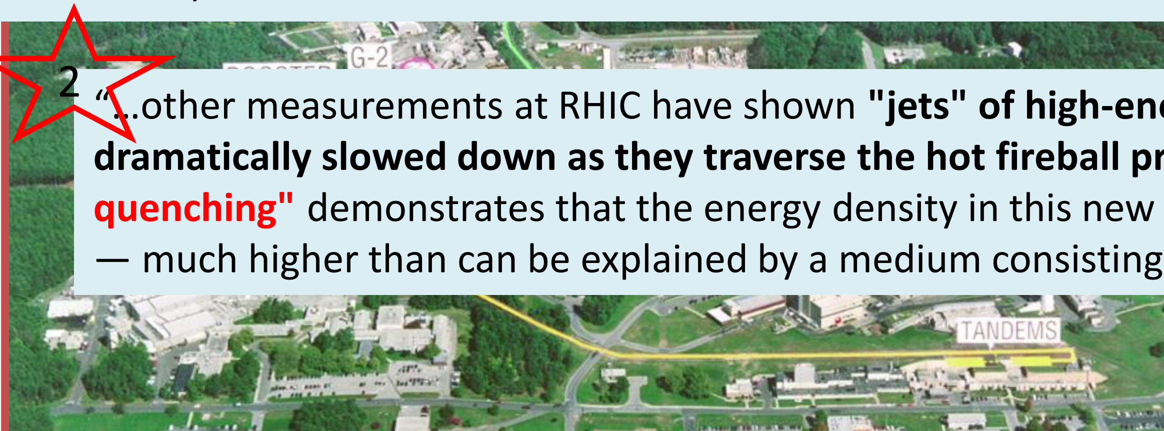
1

RHIC Scientists Serve Up Perfect Liquid (BNL 2005-10303), issued on 18 April 2005

https://www.bnl.gov/newsroom/news.php?a=110303

"New state of hot, dense matter .. quite different and even more remarkable than had been predicted .."

*"In fact, the **degree of collective interaction**, **rapid thermalization**, and **extremely low viscosity** of the matter being formed at RHIC make this the* most ***nearly perfect liquid*** *ever observed,"*



2

"...other measurements at RHIC have shown **"jets" of high-energy quarks and gluons being dramatically slowed down as they traverse the hot fireball produced in the collisions.** This **"jet quenching"** demonstrates that the energy density in this new form of matter is extraordinarily high — much higher than can be explained by a medium consisting of ordinary nuclear matter."

STAR

PHENIX

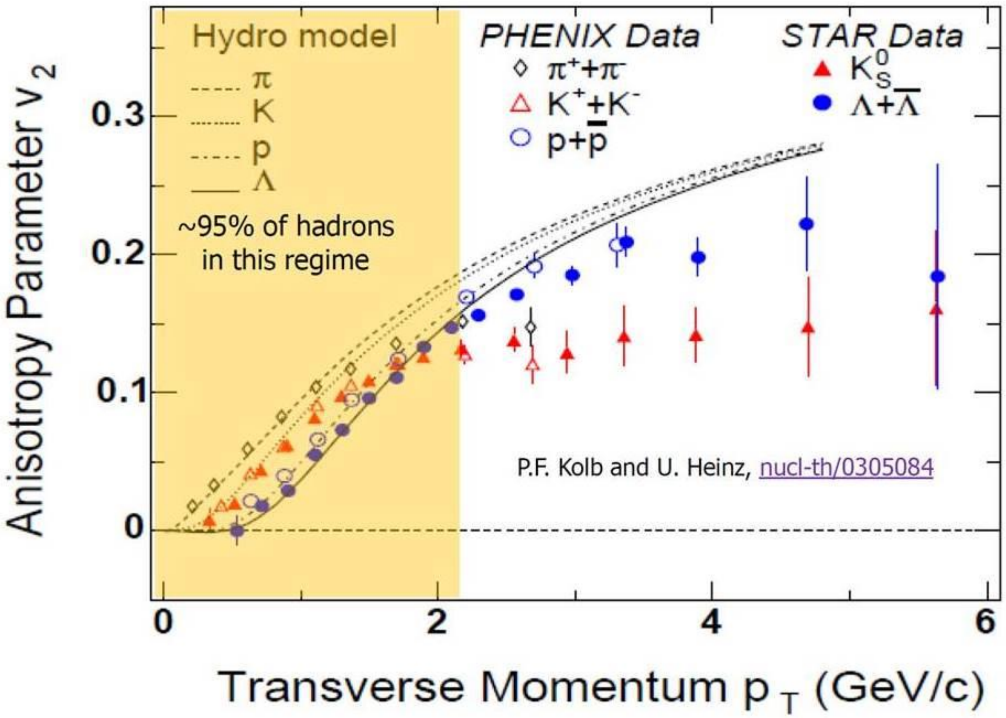
Does the QGP have flow?

1

Measurement of the elliptic flow (υ_2) of identified particles vs p_T showed that as the deconfined matter (QGP) evolves it flows due to pressure gradients

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1 \cos(\varphi - \Psi_1) + 2v_2 \cos[2(\varphi - \Psi_2)] + \ldots\right)$$

υ_1: Direct flow= $\langle cos\phi \rangle$ υ_2: Elliptic flow = $\langle cos2\phi \rangle$

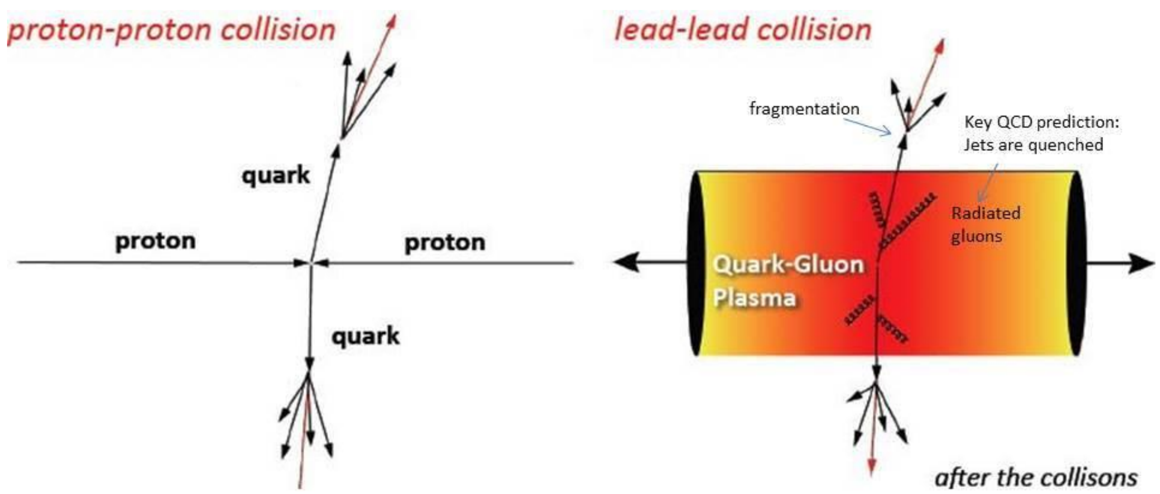


- ❑ Elliptic flow almost as large as expected at hydro limit ➔ Flow patterns consistent with ideal hydrodynamics
- ❑ Looks like a "liquid"
- ➢ Small viscosity over entropy density (η/s)
- ➢ Particles interact frequently
- → strongly coupled QGP is nearly a "perfect liquid"

Jet quenching in heavy-ion collisions

2

- Fast partons produced from HIC propagate through the QGP fireball lose energy via gluon radiation or elastic scattering
- They are **observable as jets of hadrons** when they hadronize and **the energy loss becomes evident** in a phenomenon known as **"jet quenching"** → Instead of two jets going back-to-back (e.g. pp collision) and having similar energies, **a striking imbalance is observed**: one jet being almost absorbed by the medium

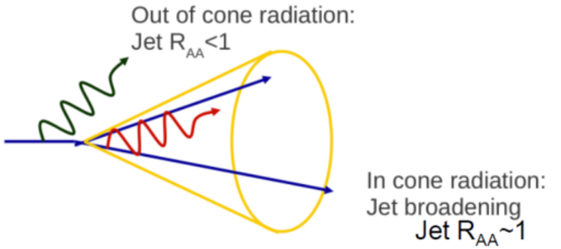


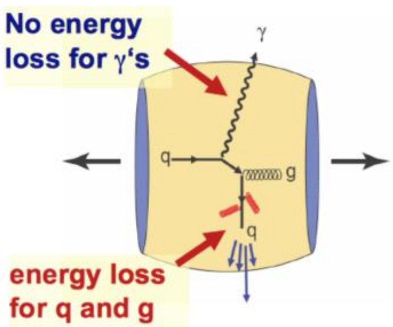
Jet Quenching at RHIC

- ❑ **Where does the radiated energy (gluon) go?**

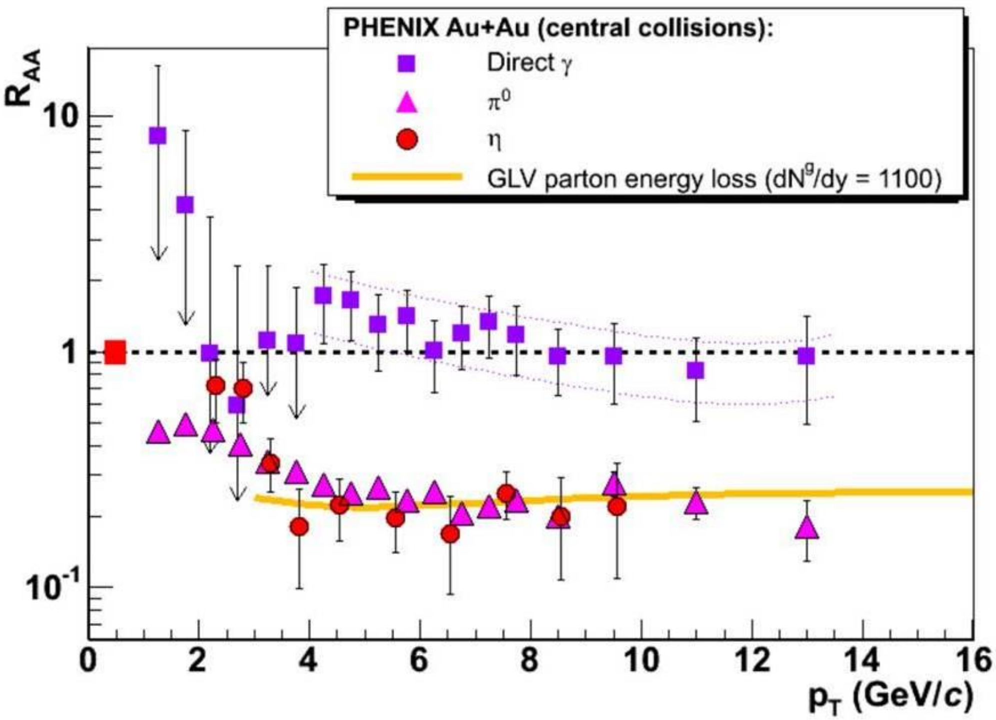
→ **Measure the R_{AA} of jets and direct photons (γ)**

$$R_{AA}(p_t,\eta) = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dp_t d\eta}{d^2N_{pp}/dp_t d\eta}$$

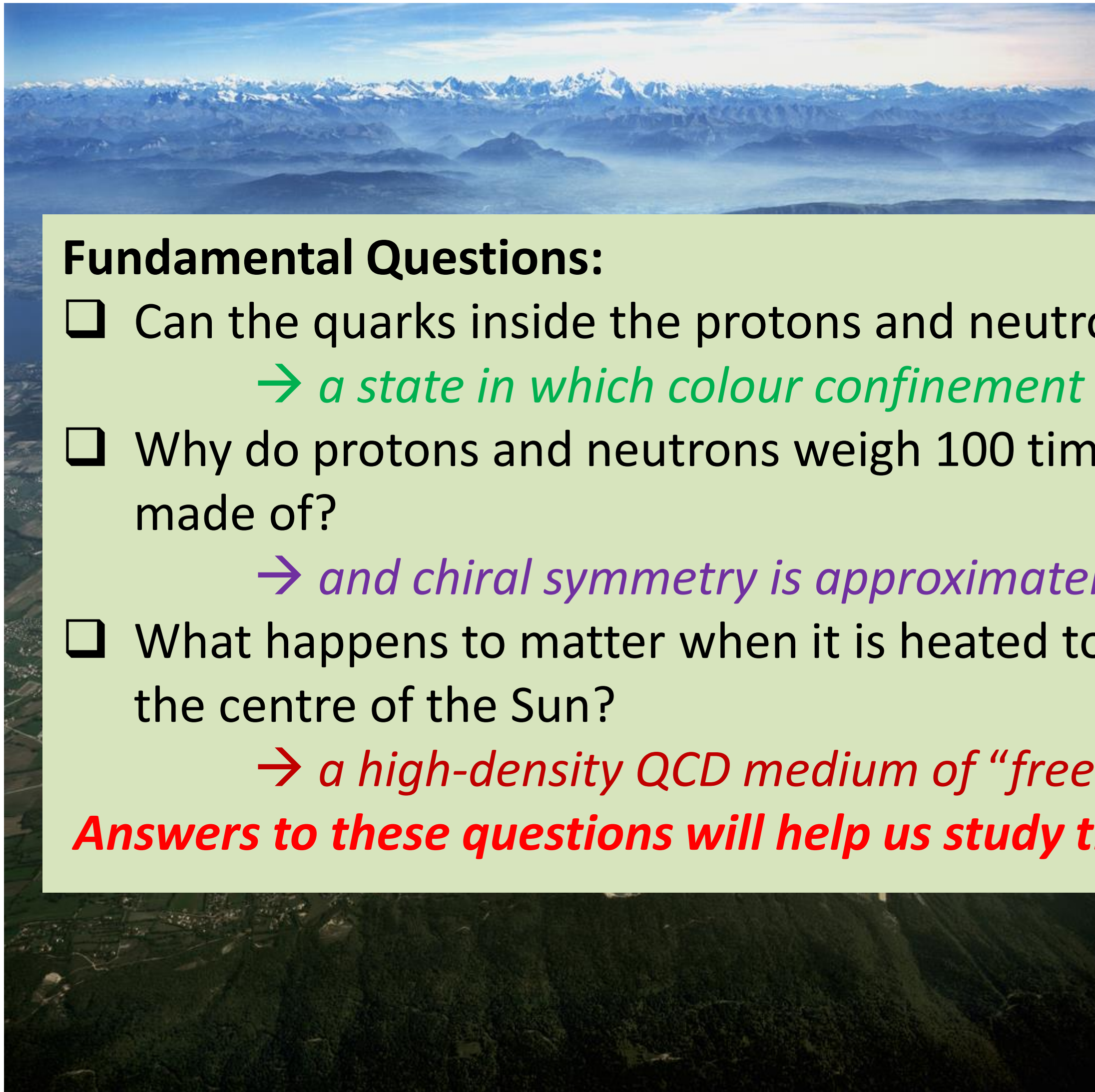




- ❑ Hadron suppression at high p_T, "Jet quenching"
- ❑ Direct photons are not
- ❑ Evidence of parton energy loss (creation of a dense and opaque system)



Heavy Ions at the CERN Large Hadron Collider (LHC)



Fundamental Questions:

- Can the quarks inside the protons and neutrons be freed?
  - → *a state in which colour confinement is removed*
- Why do protons and neutrons weigh 100 times more than the quarks they are made of?
  - → *and chiral symmetry is approximately restored*
- What happens to matter when it is heated to 100,000 times the temperature at the centre of the Sun?
  - → *a high-density QCD medium of "free" quarks and gluons*

Answers to these questions will help us study the properties of the QGP

cooled to 2 Kelvin

- 150 MJ beam energy (kinetic energy of a train)

Heavy-ion collisions at the LHC

❑ LHC RUN 1 (2010-2013)

- ➢ Qualitatively similar results in AA collisions → confirm findings from RHIC
- ➢ A surprise: striking similarities between pp/p-Pb /Pb-Pb

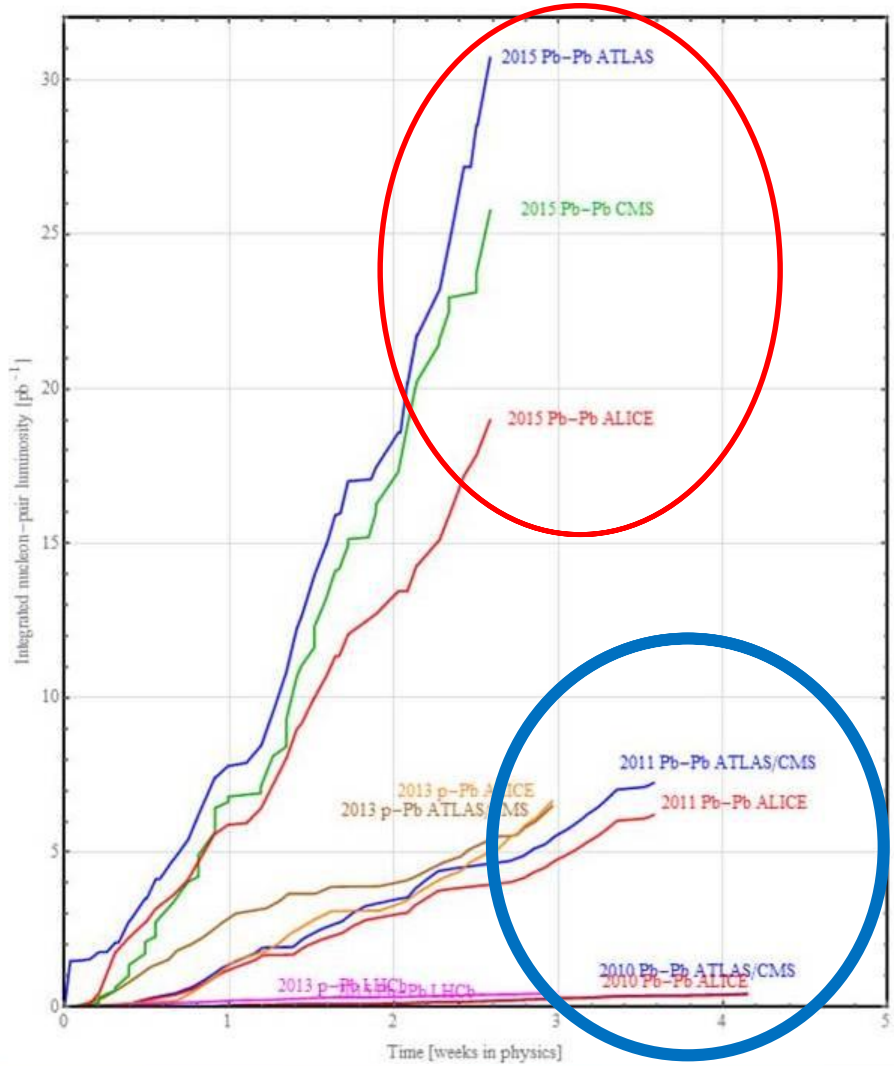
❑ LHC Run 2 (2015 -2018)

➢ equivalent energy runs:

$\sqrt{s_{NN}}$ = 5.02 TeV ($\sqrt{s}$ = 1.045 PeV),

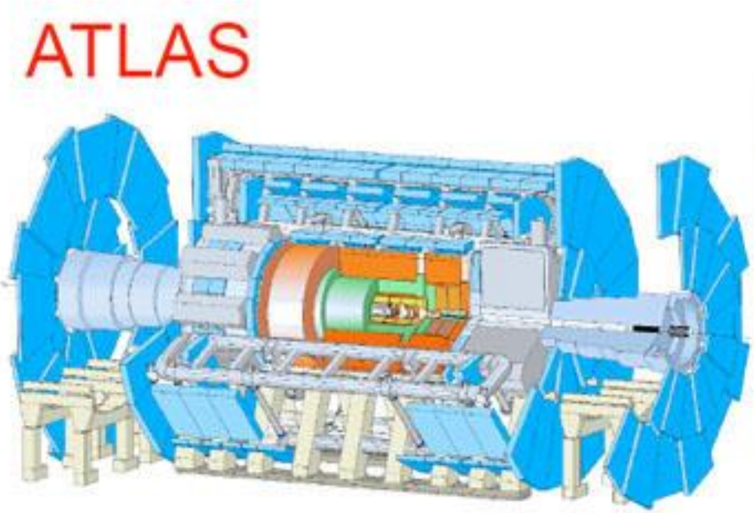
$$E_b = \begin{cases} 6.37\ \mathrm{Z\ TeV} & \mathrm{in\ Pb-Pb} \\ 4\ \mathrm{Z\ TeV} & \mathrm{in\ p-Pb} \\ 2.51\ \mathrm{TeV} & \mathrm{in\ p-p} \end{cases}$$

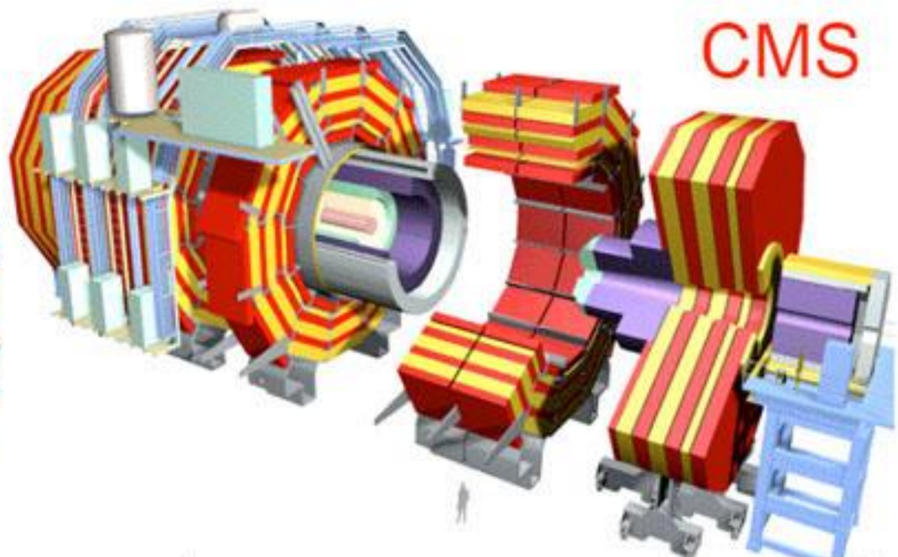
➢Data analysis ongoing → available results

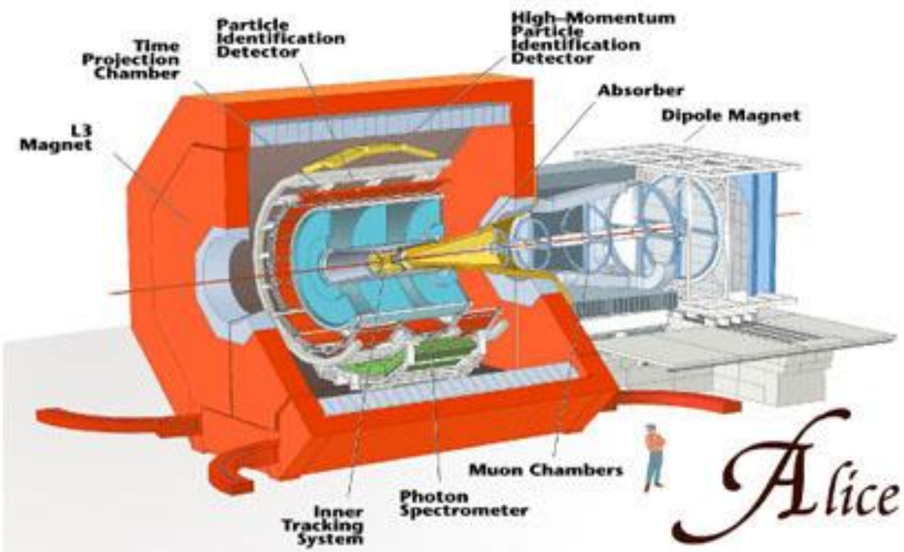


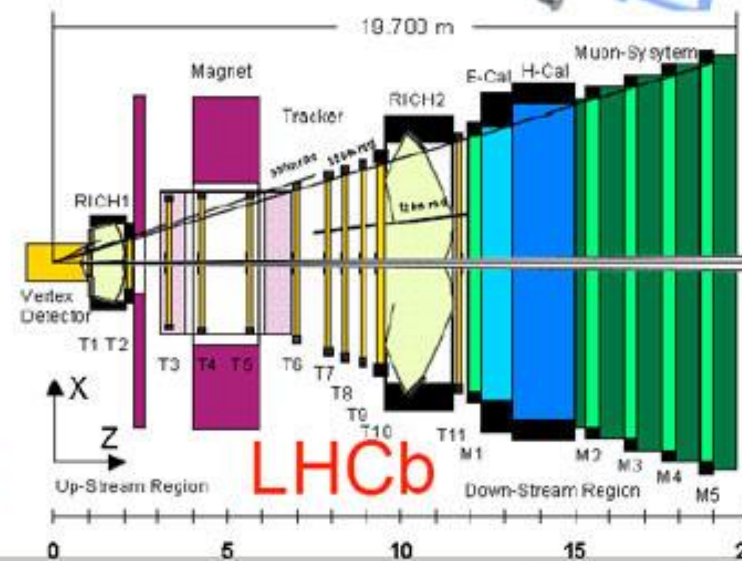
Plot taken from slides of

Heavy-ion experiments at the LHC









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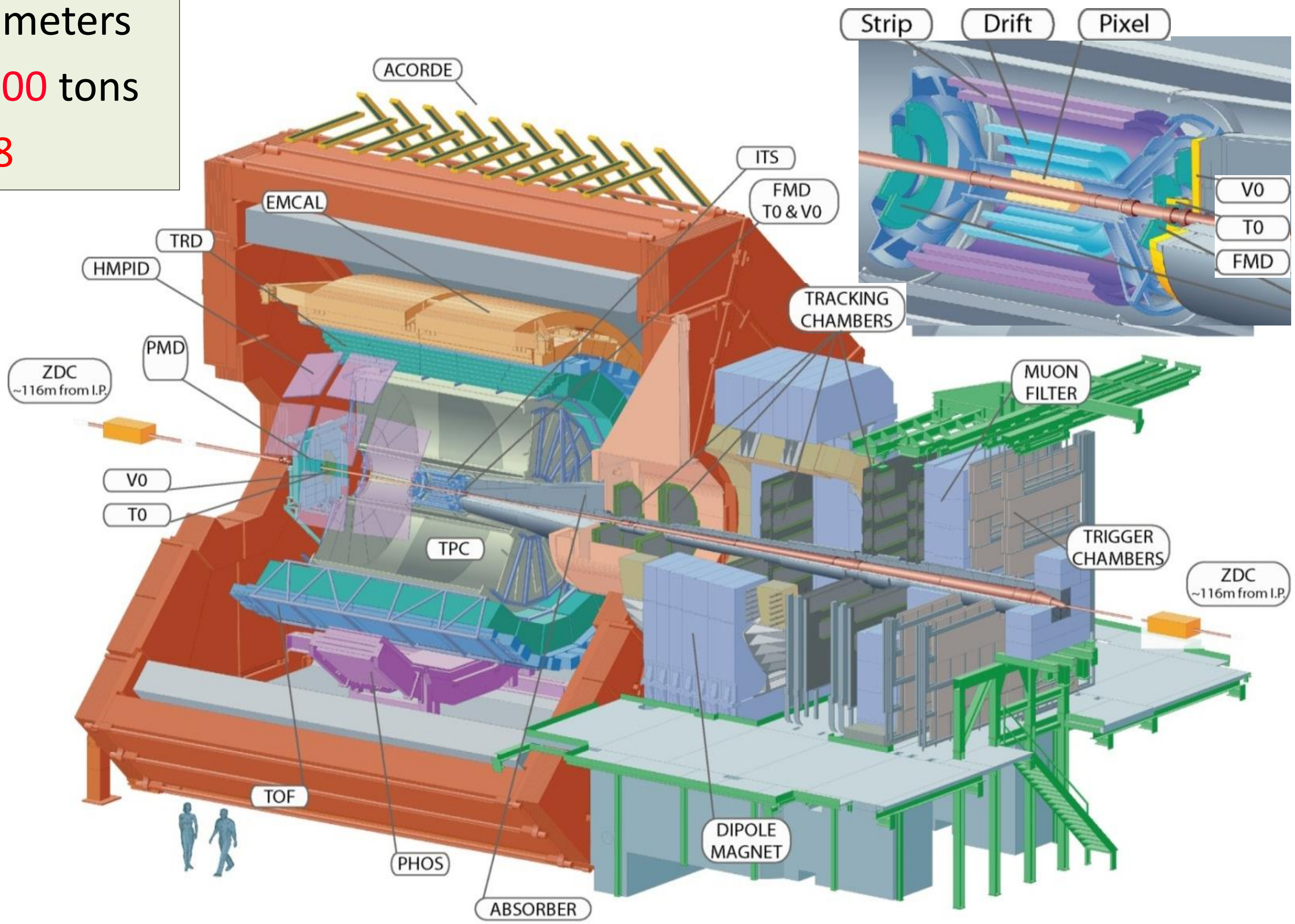
A Large Ion Collider Experiment - ALICE

Size: 16 x 26 meters

Weight: 10,000 tons

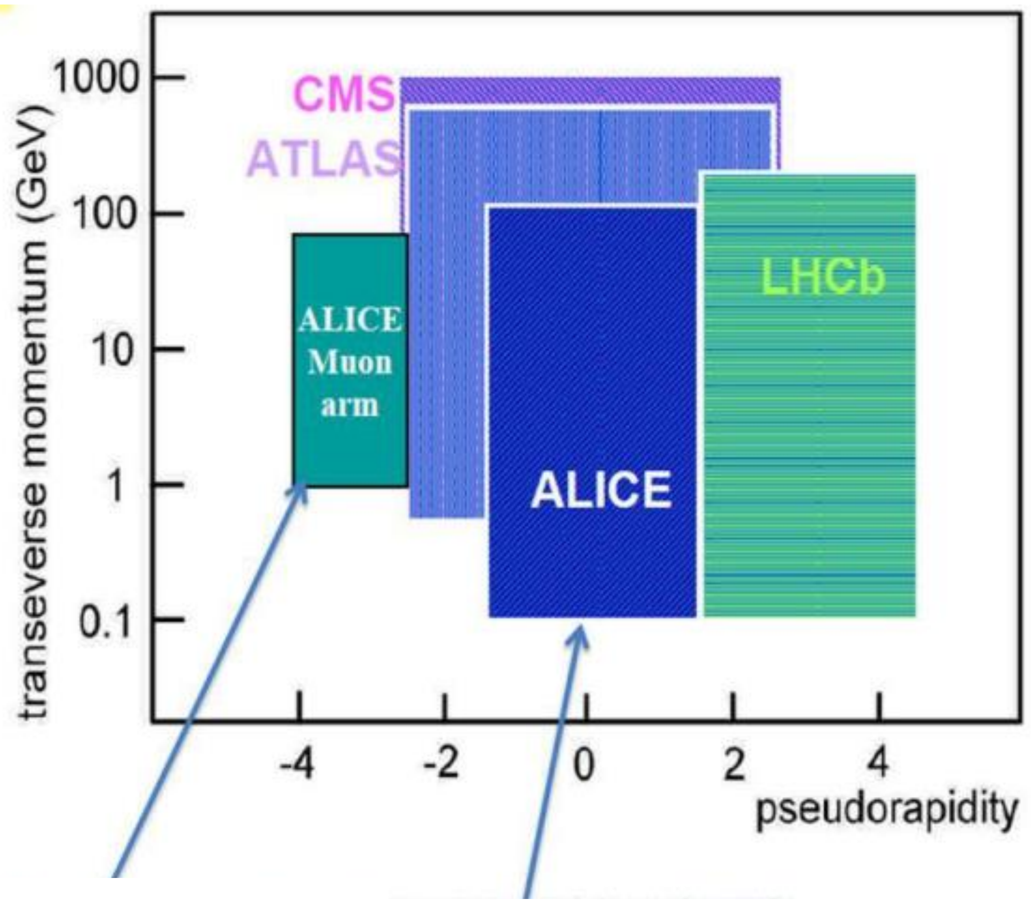
Detectors: 18



HI collisions: measure all known observables to characterise the QGP

pp collisions: baseline for HI and to test pQCD models J. Instrum. 3, S08002 (2008)

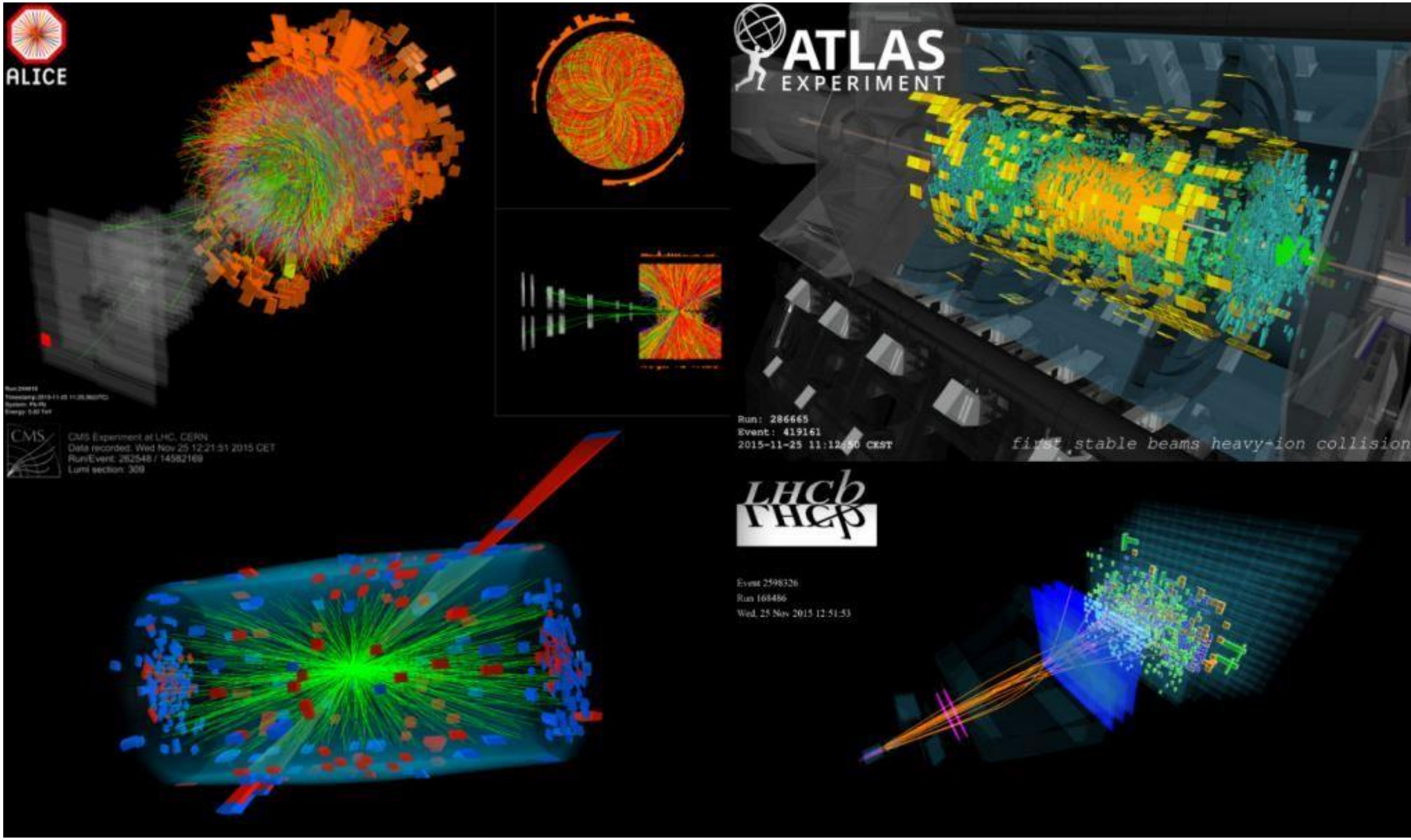
Complementary kinematic coverage at the LHC



ALICE Muon Spectrometer

ALICE Central barrel

Example of an event from a Pb-Pb collision at the LHC



A few results from measurements of global properties

Energy density reached in HI collisions at the LHC

Bjorken's formula

$$\varepsilon = \frac{E}{V} = \frac{1}{S c \tau_0} \frac{dE_T}{dy}\Big|_{y=0}$$

S – transverse dimension of nucleus

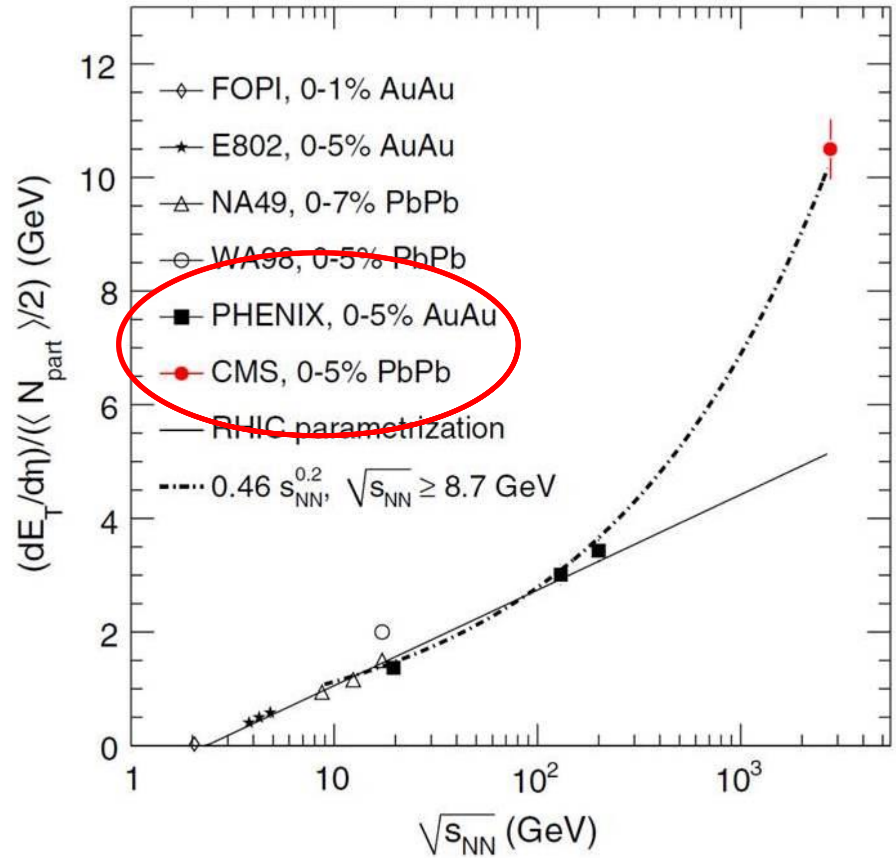
τ_0 *– "formation time" ~1 fm/c*

1 femtometer (*fm*) → 1×10^{-15} meter (m)

- ❑ Transverse dimension:

  $S \approx 160\ fm^2$ ($R_A \approx 1.2\ A^{1/3}\ fm$)

CMS, PRL 109 (2012) 152303



At the ALHC the transverse energy is ~3 x RHIC. Estimated ε >15GeV/fm³

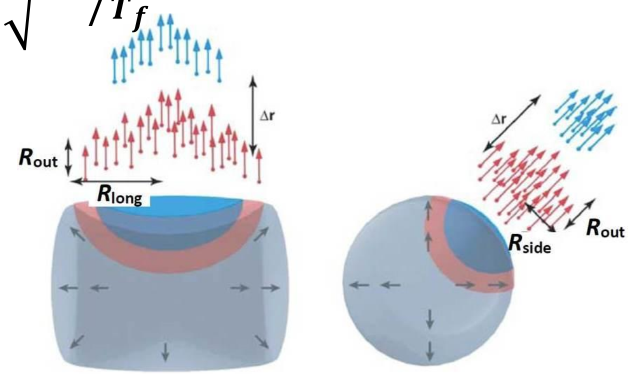
Size of the QGP fireball

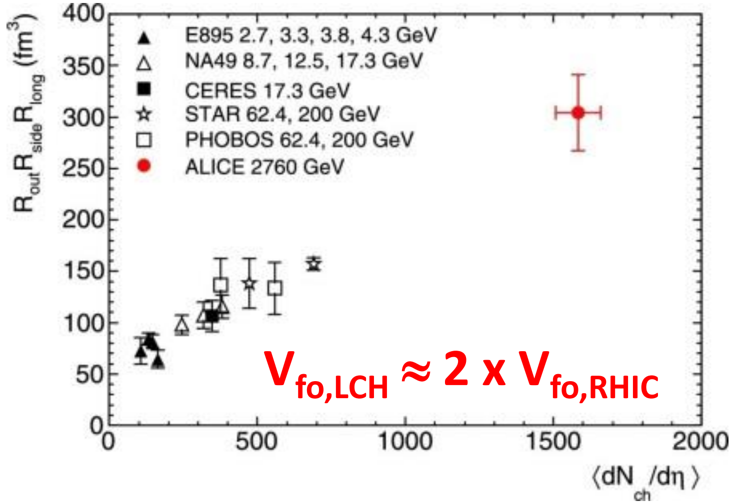
ALICE, PLB 696 (4) 328

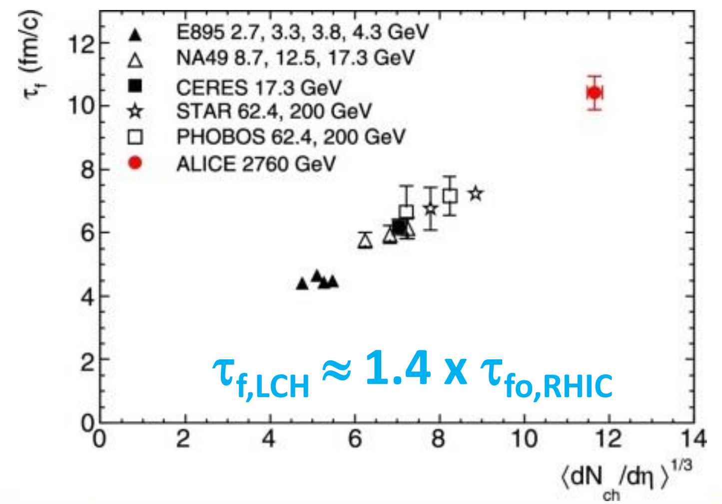
- Determine the freeze-out volume (V_{fo}) and emission time (τ_f)
- Method: Hanbury Brown and Twiss (**HBT**) interferometry radius → two-pion Bose-Einstein correlations

Freeze-out volume: $V_{fo} \sim (2\pi)$

Emission time: $\tau_f R_{long}\sqrt{m_T/T_f}$





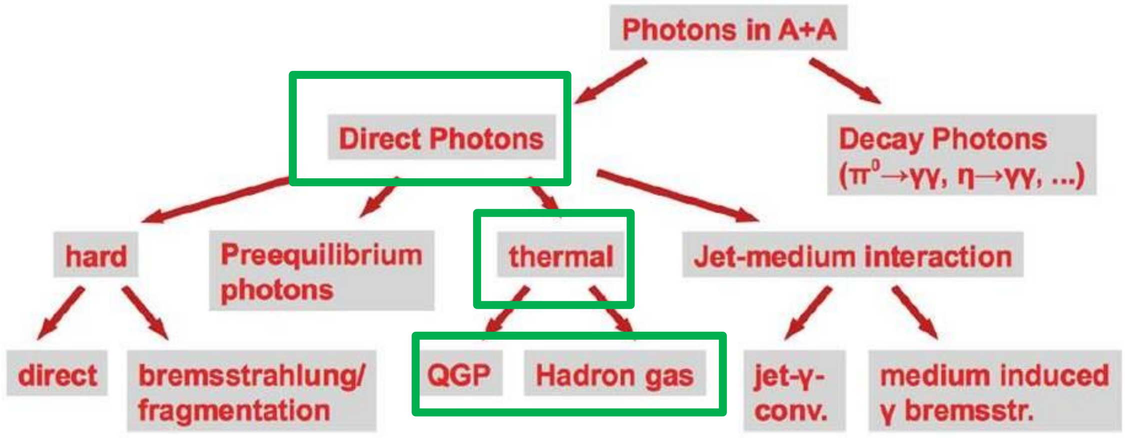


At LHC: $V_{PbPb,central} \approx 5000\ fm^3$, $V_{Pb} \approx 800\ fm^3$

→ $V_{PbPb,central} \approx 6.25 \times V_{Pb}$

What is the QGP temperature?

- Use direct photons (γ). They are produced from initial hard-scattering (prompt γ and fragmentation of jets)
  - Not coming from decays of hadrons
  - They leave the reaction zone unscathed due to larger mean-free path than nuclear scales
  - Provide a direct means to examine the early hot phase of the collision
- Thermal γ are produced throughout the evolution of a HI collision and after the transition of the QGP to a hot gas of hadrons
- **Experimental challenge:** detection from huge background from hadronic decays



QGP temperature from photon spectra

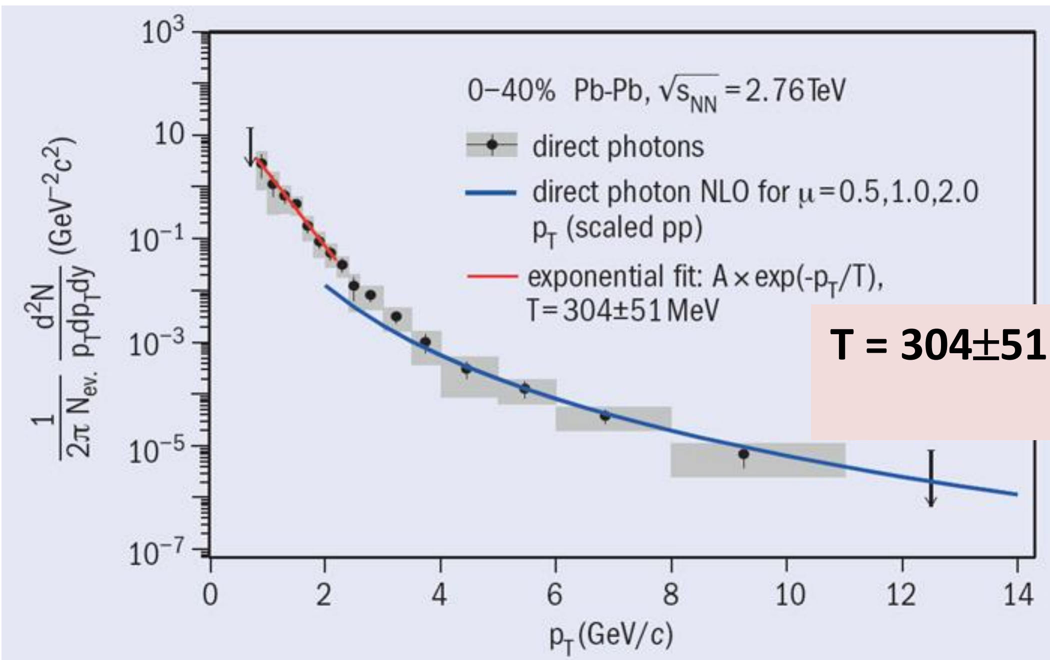
- ❑ Prompt γ = Inclusive γ - γ from π^0 decays
- ➢ **Direct** γ from QCD processes:

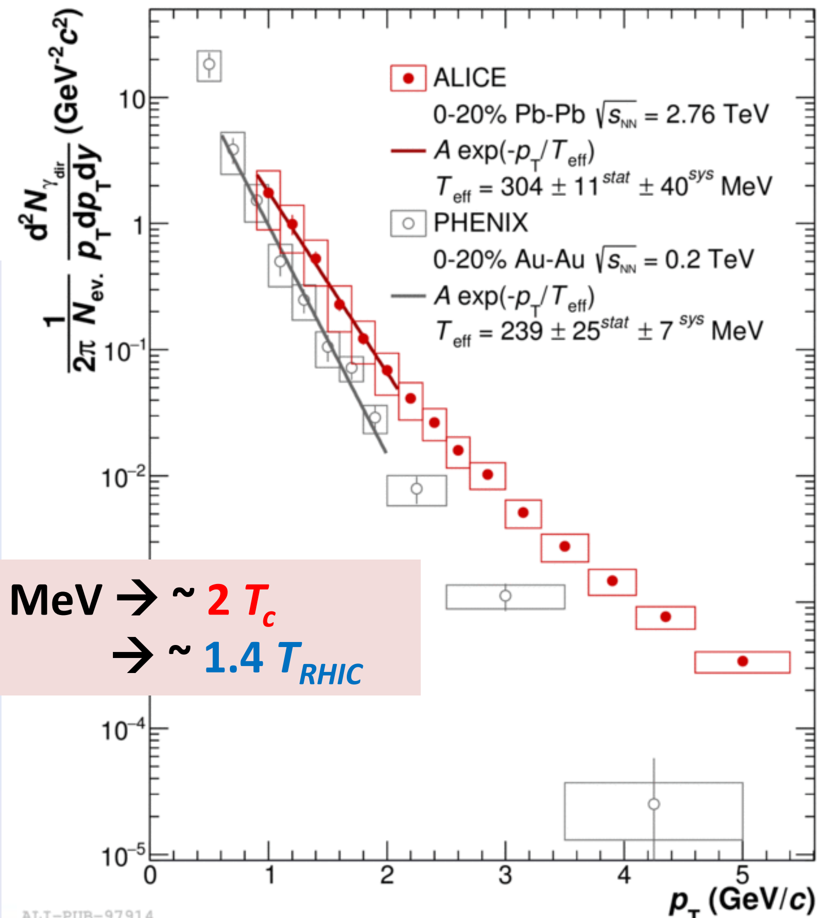
→ **power law spectrum - dominant at high p_T**

- ➢ **Thermal Photons** - emitted by the hot system (analogy with black body radiation):

→ **exponential spectrum - dominant at low p_T**

ALICE PLB 754 (2016) 23-248





T = 304±51 MeV → ~ 2 T_c
→ ~ 1.4 T_{RHIC}

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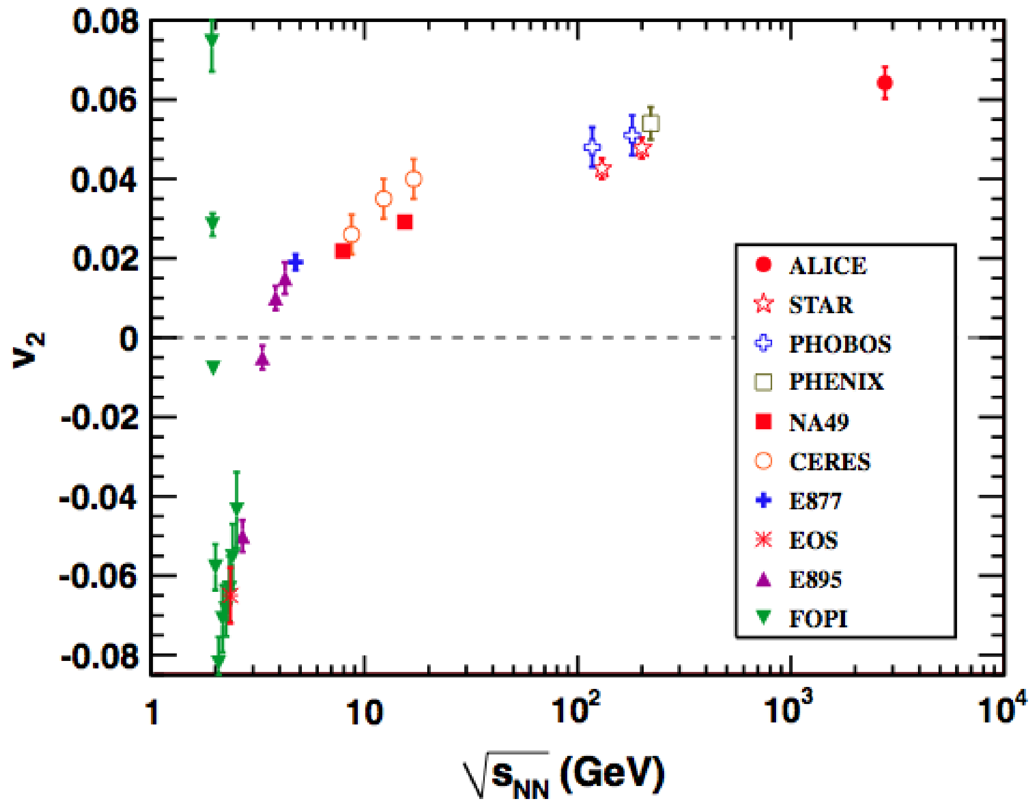
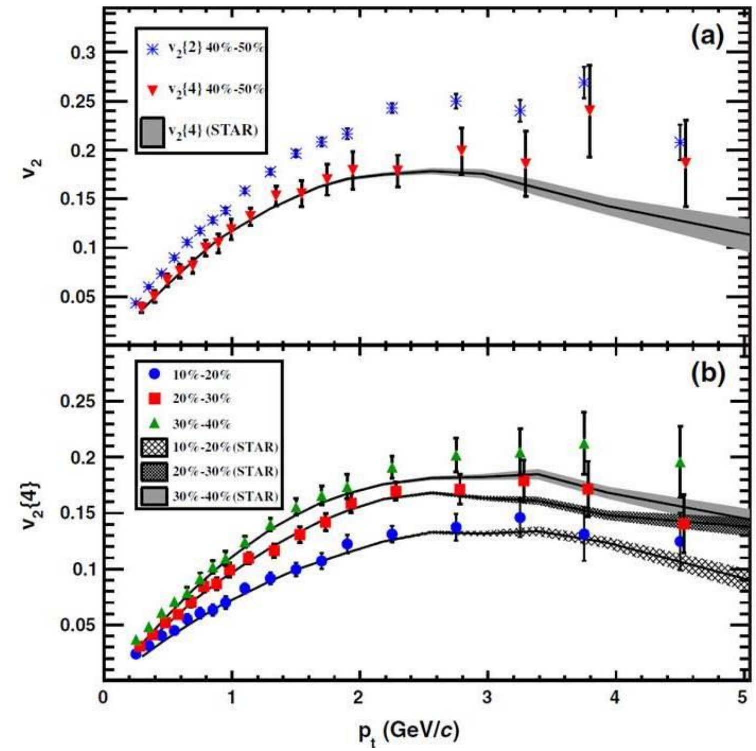
Elliptic Flow of identified particles at the LHC

- ❑ υ_2 large at the LHC

ALICE, PRL 105(2010) 252302

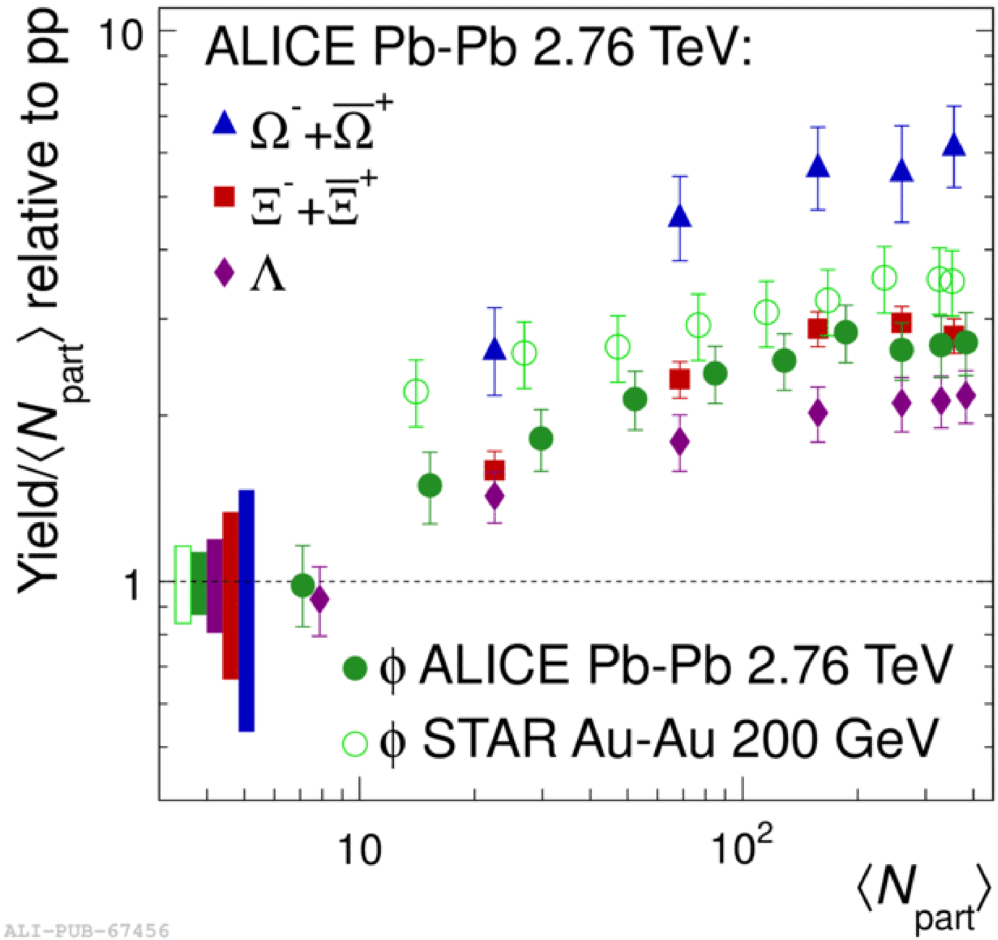




- ❑ **System still behaves very close to ideal liquid**
- ❑ **Similar hydrodynamic behaviour**

Strangeness enhancement at the LHC

ALICE, PR 142 (1986) 167



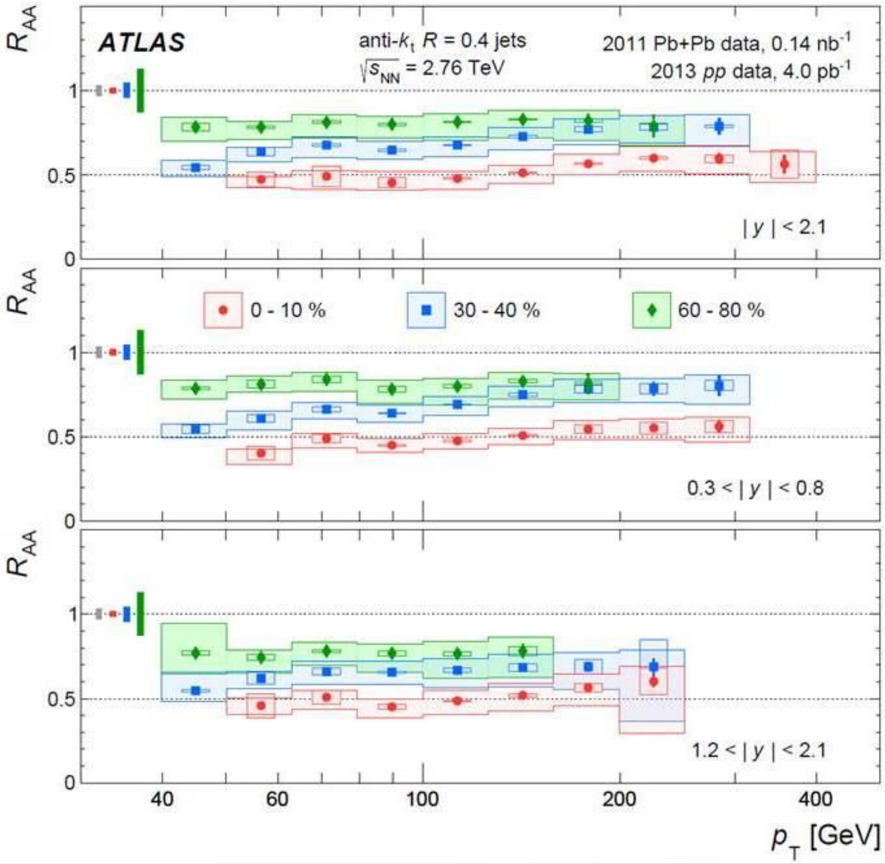
- ❑ Increase production of strange hadrons
- → copious production of $s\bar{s}$ pairs by gg fusion PR 88(1982) 331, PRL 48(1982) 1066
- → Restoration of chiral symmetry

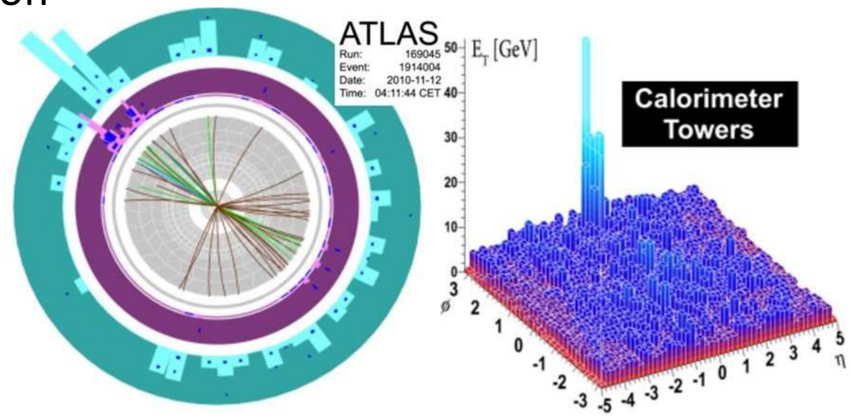
- ❑ Deconfinement: stronger effect for multi-strange baryons

→ **strangeness enhancement increases with strangeness content**

Jet Quenching at the LHC

- Pb-Pb @ 2.76 TeV events with large di-jet imbalance observed
- $R_{AA} \approx 0.5$ in central collisions
- Not much p_T dependence of the jet suppression





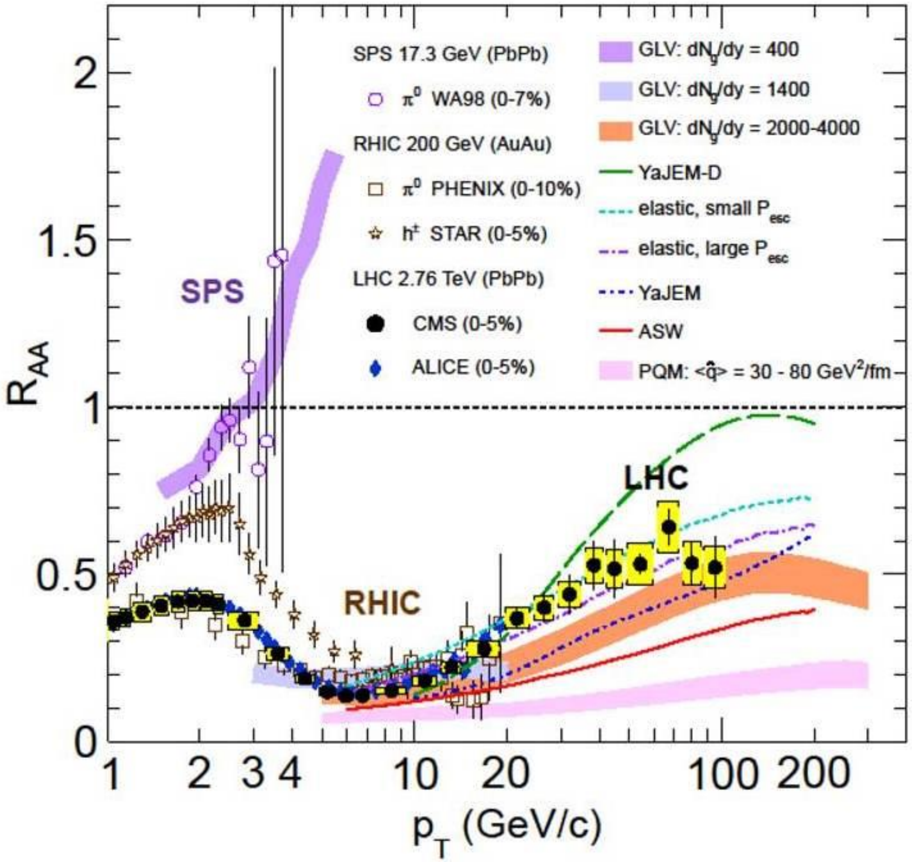
- Production dominated by quark jets which may lose less energy than gluon jets

ATLAS, PRL 105 (2010) 252303
arXiv:1411.2357

High p_T suppression at the LHC

- Parton energy loss by
- → Medium-induced gluon radiation
- → Collisions with medium gluons

CMS, EPJC 72 (2012) 1945



- R_{AA} of charged particles produced in most central collisions at LHC
  - Minimum (~0.14) for pT ~ 6-7 GeV/c
  - Slow increase at high pT
  - Still Significant suppression at pT ~ 100GeV/c
- Essential quantitative constraint for parton energy loss models

A surprises from the recent results

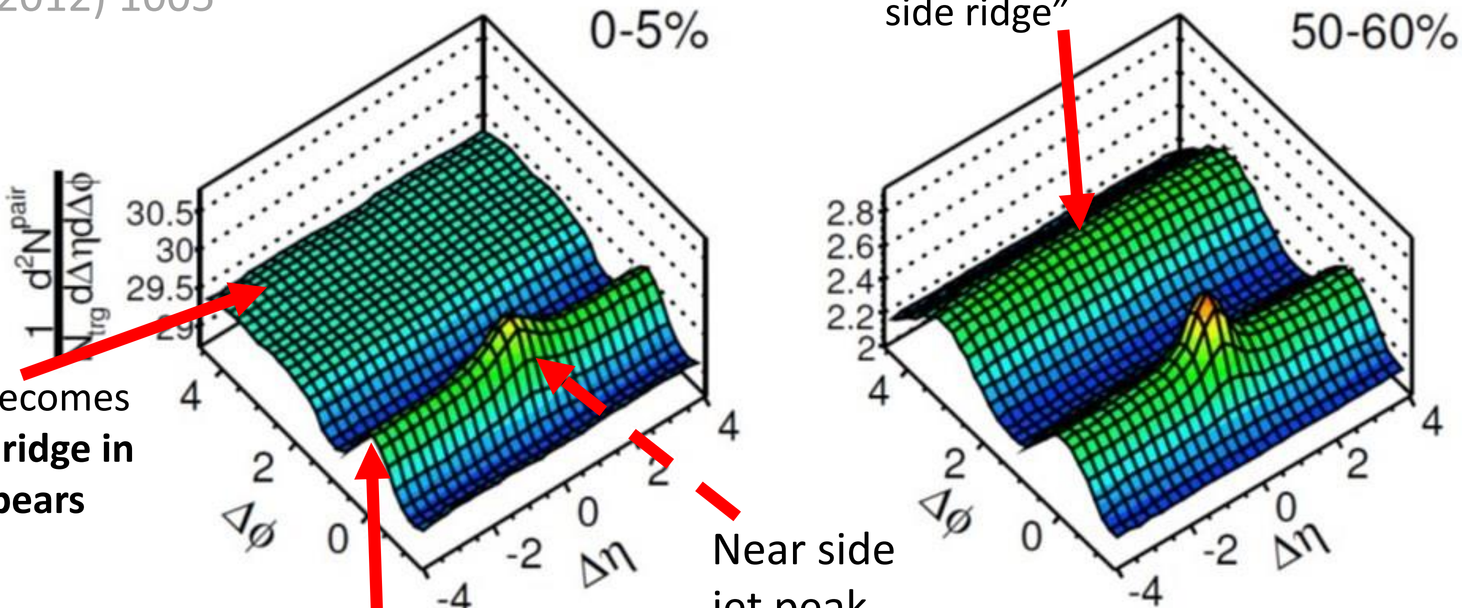
- A surprise from the RUN 1 (2010-2013) results:
  → **collective behaviour, a feature of HI, also in high-multiplicity small systems (pp, p-Pb collisions)?**
- Some results from RUN 2 (2015-2017) data analysis
  → do we see collective behaviour?

Long-range two-particle correlation measurements

- Provide important **insights into the underlying mechanism of particle production** in high-energy HI collisions
- Technique**:** high-p_T particles in the event ("trigger particle"), correlate all other particles ("associated particles") → **$|\Delta\phi|$, $|\Delta\eta|$ correlation distributions**
- <u>Key feature</u>: **pronounced structure on the near side: $|\Delta\phi| \approx 0$**, extending over a large $|\Delta\eta|$ up to 4 units or more: **"ridge"**
- **Correlations are long-range**: saturation of the υ_2 with $|\Delta\eta|$ separation

CMS, EPJC 72 (2012) 1005

Long-range structure in η on "away-side ridge"



"away-side" becomes very broad **– a ridge in the middle appears**

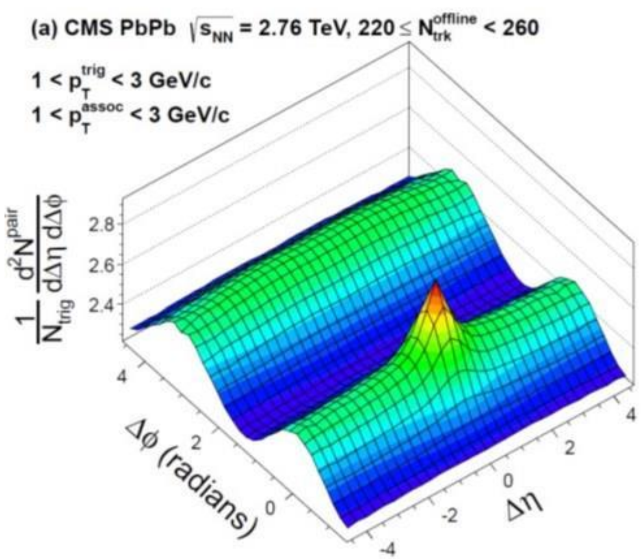
Near side jet peak

"near-side ridge"

Long-range correlation measurement in high-multiplicity pp and p-Pb

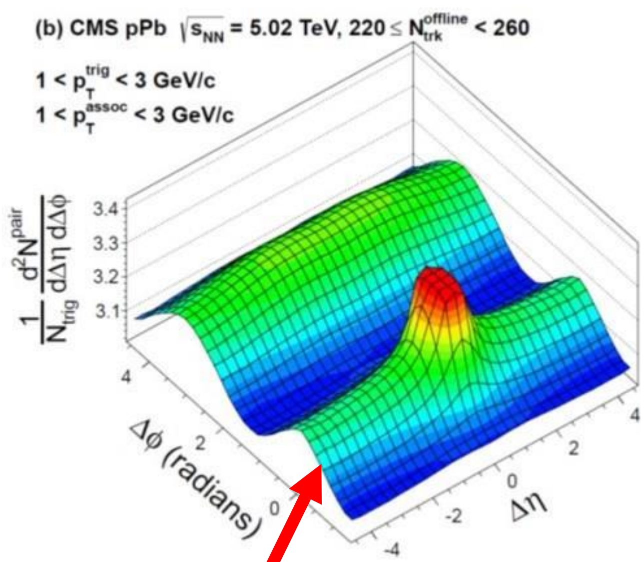
- **Near-side ridge** (long-range correlations in η at Δϕ=0) observed by the CMS experiment in high-multiplicity pp and p-Pb

Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV



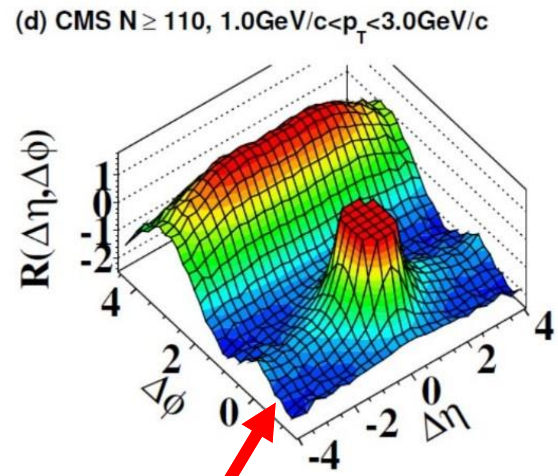
CMS, JHEP 1009 (2010) 091

pPb $\sqrt{s_{NN}}$=5.02 TeV, high multiplicity



Pronounced structure at Δη around Δϕ≈0!

pp at 7 TeV, high multiplicity



Pronounced structure at Δη around Δϕ≈0!

CMS, PLB 724 (2013) 213

Flow-like two-particle correlations become visible in high-multiplicity pp and p-Pb collisions at the LHC

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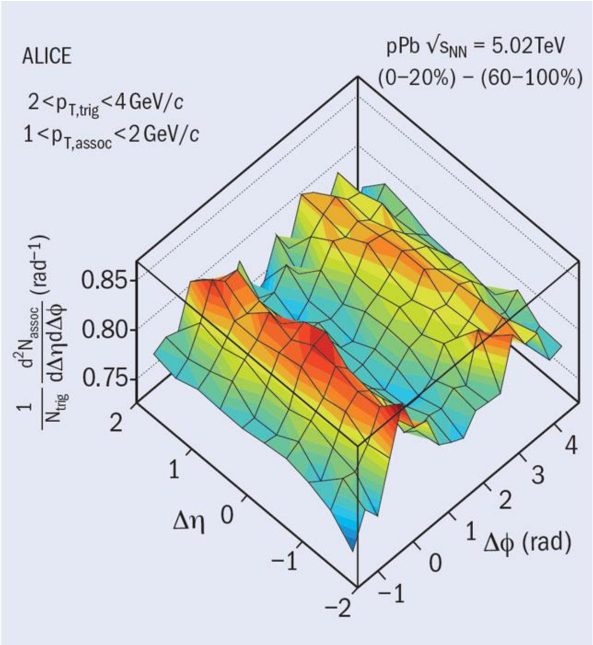
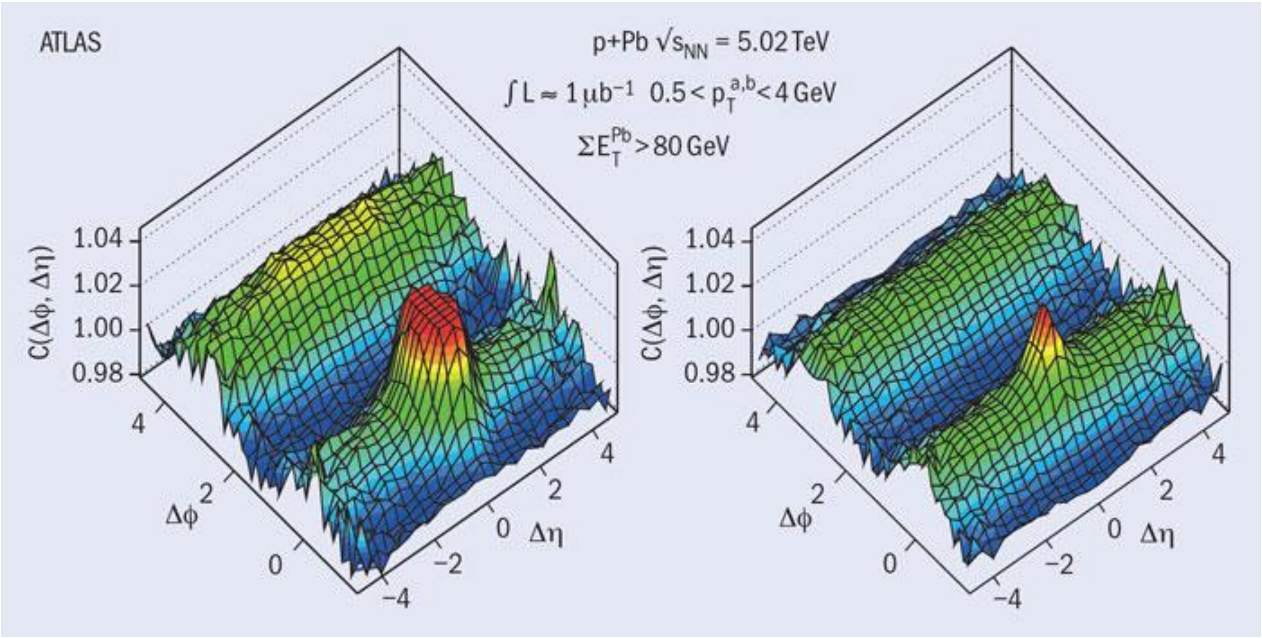
Long-range two-particle correlations measurement in high-multiplicity p-Pb collisions

- **Double ridge** discovered by ALICE and ATLAS experiments → resembles structure attributed **to collective phenomena (flow) occurring in the QGP created in the Pb-Pb collision**



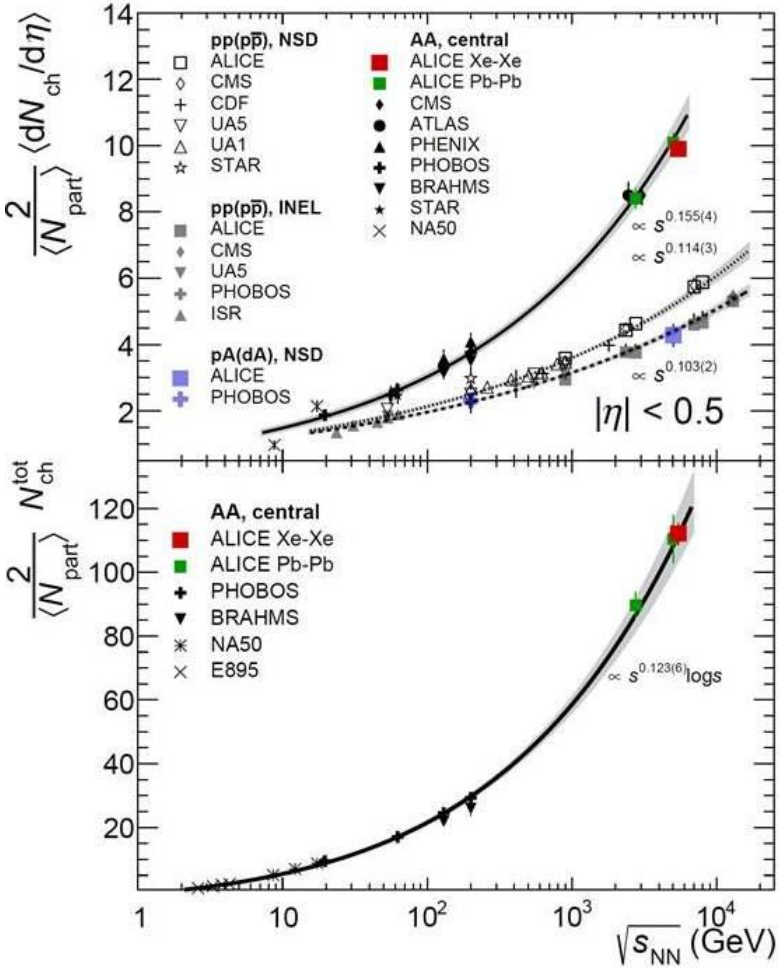
ALICE, Phys. Lett. B 719 29 (2013)



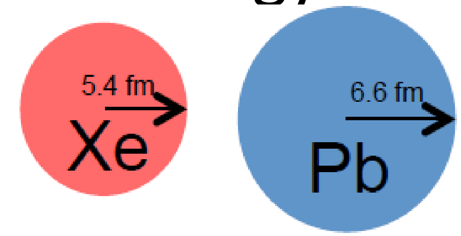
ATLAS, arXiv:1212.5198 [hep-ex]

- Models producing almost identical near- and away-side ridges based on the CGC framework or hydrodynamical calculations that assume collective effects to occur also in p-Pb collisions.

Charged-particle multiplicity vs centre-of-mass-energy



NEW Run 2 data



ALICE, arXiv:1805.04432

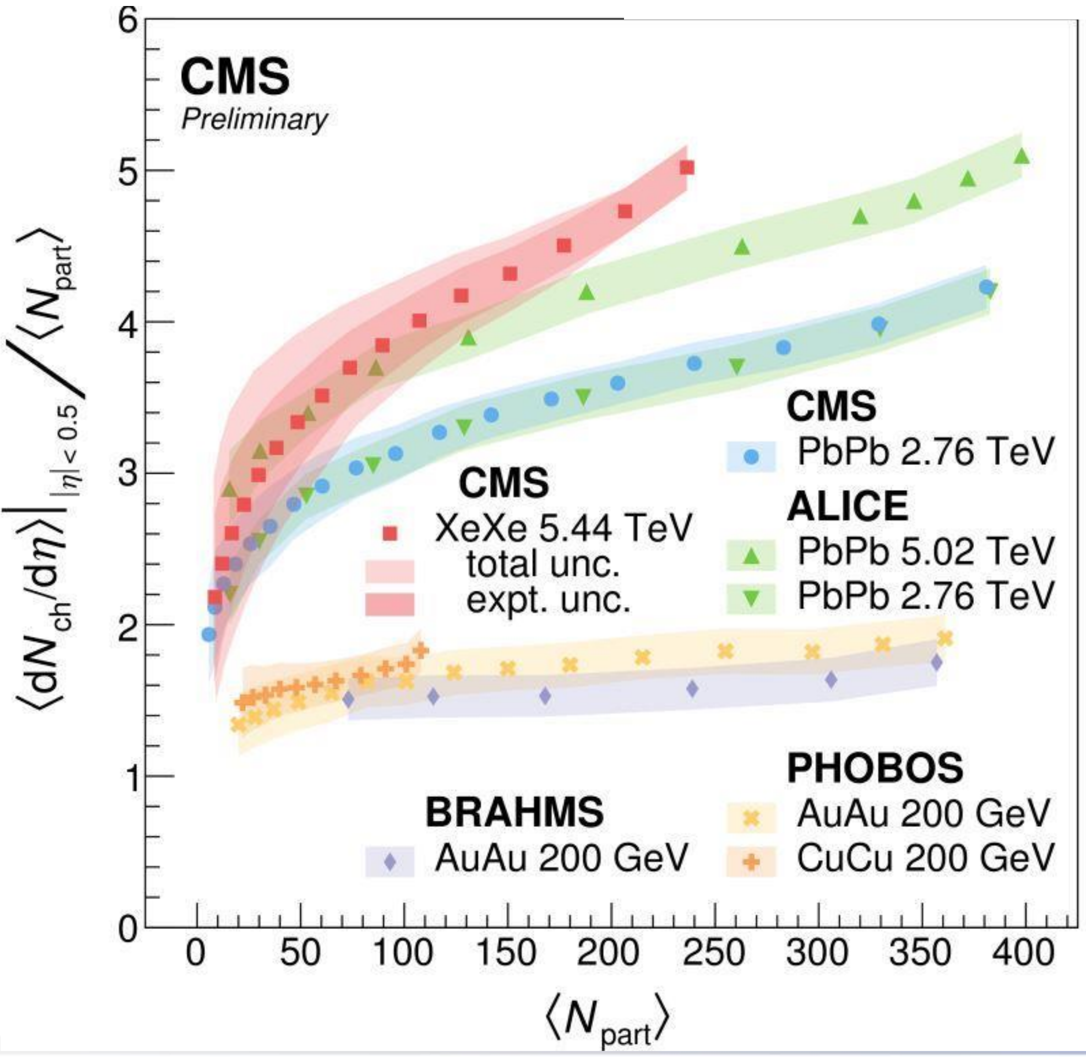
$^{dN_{ch}}/_{d\eta}$: **1167 ± 26 Xe-Xe $\sqrt{s_{NN}}$ = 5.44 TeV**

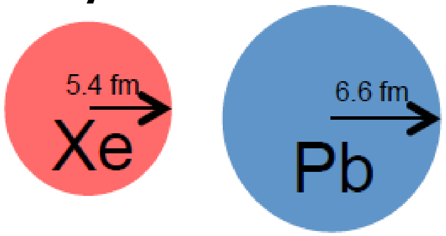
1943 ± 54 Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

- ❑ Same trend established in all heavy-ion measurements
- → **Charged-particle multiplicity rises faster as a function of $\sqrt{s_{NN}}$ than pp and p-A collisions**
- ❑ p-A results from LHC experiments and d-A results from RHIC fall on the curve of pp collisions
- → **Fast rise in AA is not only related to multiple collisions undergone by the participants since the proton in p-A collisions also encounters multiple nucleons**

Charged-particle multiplicity vs centrality

CMS PAS HIN-17-006



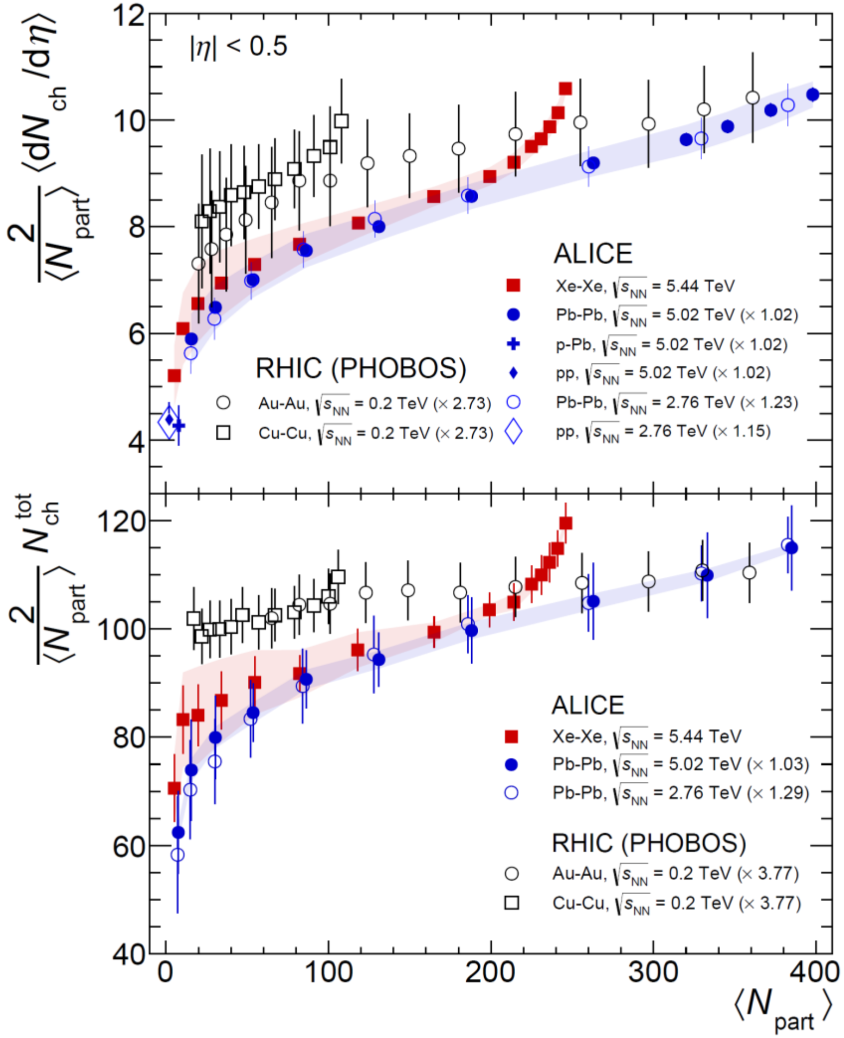


NEW Run 2 data

- For fixed and large number of participant (N_{part}) we observe that Xe-Xe is much larger than Pb-Pb

→ no system size scaling

Multiplicity vs centrality in pp, p-Pb, Xe-Xe and Pb-Pb



ALICE arXiv:1805.04432

NEW Run 2 data

- ❑ Number of particle (N_{part}) scaling violation: → known since a long time, confirmed by new Xe-Xe data

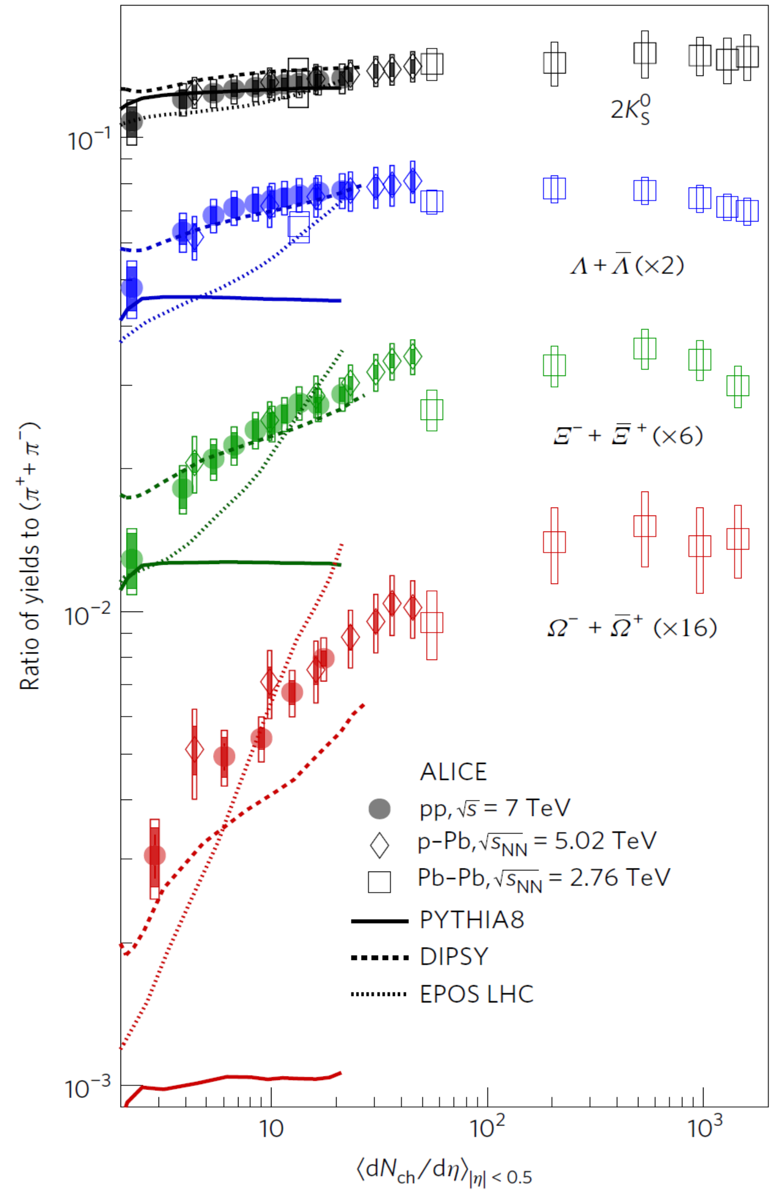
➔ well described by participant quark scaling $N_{q\text{-}part}$ and many theoretical models

- ❑ Central collisions of medium-size nuclei produce more particles per N_{part} than mid-central collisions of large nuclei at the same N_{part} → not explained by participant quark scaling and not fully reproduced by models

Strangeness enhancement: pp, p-Pb Xe-Xe and PbPb

ALICE, Nature Phys. 13 (2017) 535-539

- **p_T-integrated yield ratios to pions vs multiplicity**
  - Smooth evolution of particle ratios with multiplicity
  - **Enhanced production of multi-strange hadrons in high-multiplicity pp collisions**
- **Strangeness enhancement** is considered a **defining feature of HI** → explained as **collective expansion of the system**
- **Now also seen in high-multiplicity pp / p-Pb!**
  - Not produced by traditional soft QCD models, e.g. PYTHIA → challenges universality and factorisation of fragmentations JHEP01 (2017) 140



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Summary

- ❑ Presented selection of HI results from the LHC
- ❑ Measurements in high-multiplicity pp, p-Pb collisions show:
  - ➢ Striking similarities between pp,p-Pb,PbPb
  - ➢ High-multiplicity pp and p-Pb results exhibit collective phenomena
  - → Is a strongly-correlated QGP liquid also formed in small systems (pp and p-Pb collisions)??
  - → Important consequence for the interpretation of all hadronic collisions!
- ❑ Exciting physics ahead
- ➢ RUN 2 data: increased energy and luminosity, to shed light
- ➢ Rich LHC RUN 3 (2020 onwards) upgrade programme to come

THANK YOU

EXTRA slides

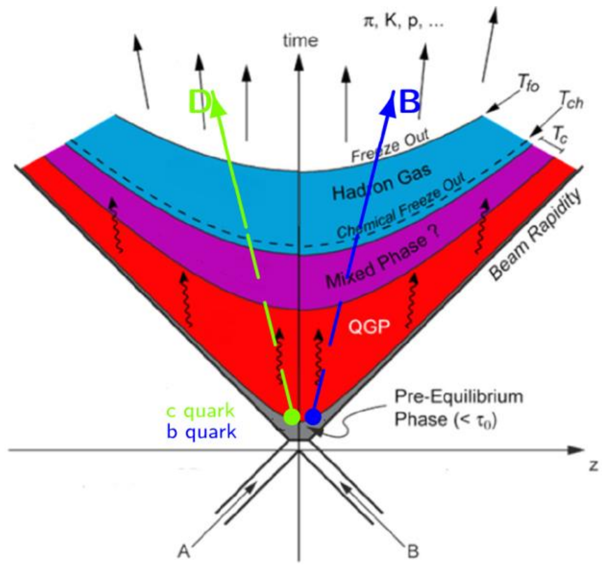
Current questions

- What are the mechanisms for the fast thermalization in HIC?
- What is the physical origin of equilibrium particle yields or how does hadronization work?
- What are the transport properties of the QGP?
  - → Dependence on *T* and μ_B?
- How can one make contact with *ab-initio* QCD predictions?
- Can one experimentally determine the properties of the QCD phase Diagram?
  - → Nature of the transitions at μ_B -= 0 (crossover, 1st order)?
  - → Is there a critical endpoint? If so, where? → Being explored in the RHIC beam energy scans (BES) programme
- Can one identify the onset of de-confinement in HIC at some $\sqrt{s_{NN}}$?
- Is a strongly-correlated QGP liquid also formed in small systems (pp and p-Pb collisions)? What about e+e-…?

Heavy-flavour production

Charm and beauty hadrons: large masses

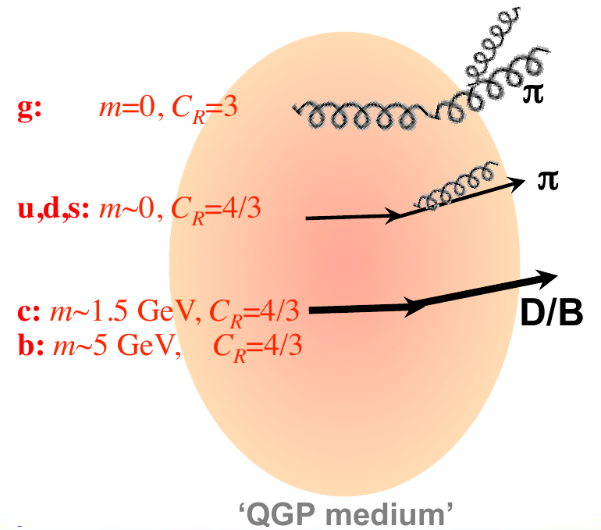
- Tools to characterize the properties of the interaction parton-QGP:
- Produced at the beginning of the collision
- No flavour change during the collision
- No extra production at the hadronization
- Parton Energy Loss by medium-induced gluon radiation and collisions with medium gluons depends on
  - Medium properties (energy density, size)
  - Parton colour charge (Casimir factor)
  - Parton mass



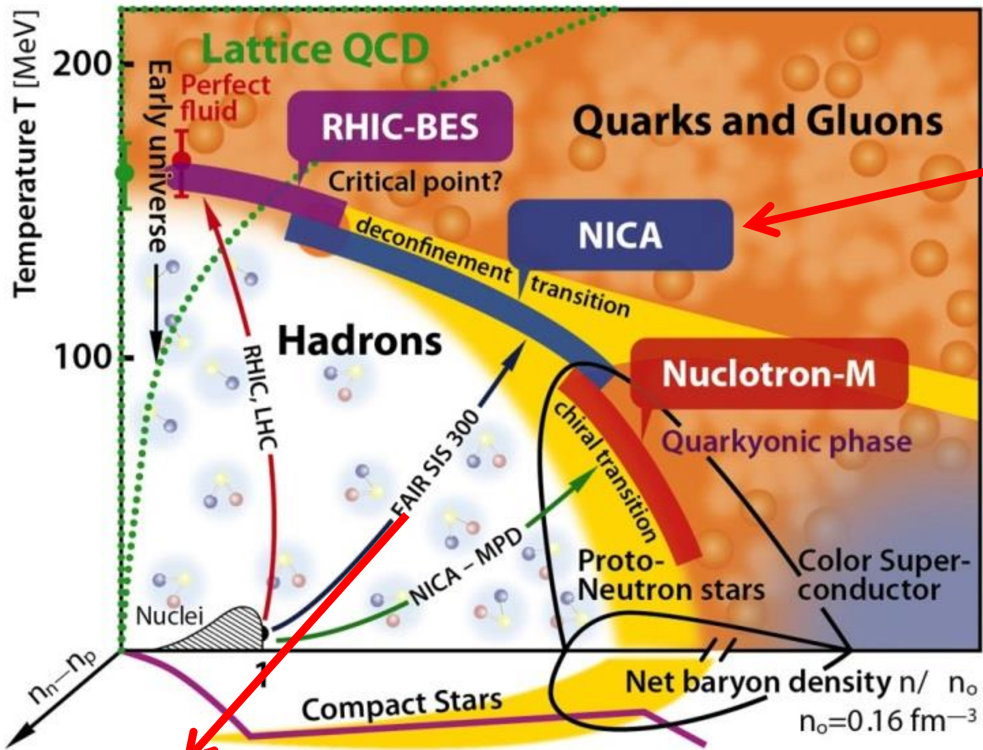
$$\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$$

$$\mathrm{R}_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{Y_{AA}}{Y_{pp}}$$

$$\mathrm{R}_{AA}(B) > \mathrm{R}_{AA}(D) > \mathrm{R}_{AA}(\pi)$$



Future Heavy-Ion Experiments



NICA - Nuclotron-based Ion Collider fAcility @ Dubna in Russia

- ❑ Determining the existence and location of the transition region,
- ❑ Establish the character of the associated phase transformation, namely, whether it remains a smooth cross over, or has become a first-order one, as several models predict.

CBM - Condensed Baryonic Matter experiment @ **FAIR (GSI, Germany)**

- ❑ Study the fundamental aspect of QCD: the equation-of-state of strongly interacting matter at high baryon densities, the restoration of chiral symmetry, the origin of hadron masses, the confinement of quarks in hadrons, the structure of neutron stars, the dynamics of core-collapse supernovae.

History: idea of the quark-gluon plasma (QGP)

- 1973 birth of QCD:
  - All ideas in place. Yang-Mills theory, SU(3) color symmetry, asymptotic freedom; confinement in color-neutral objects
- 1975 – idea of quark deconfiment at high temperatures and/or density:
  - Collins, Perry, PRL 34 (1975) 1353 :

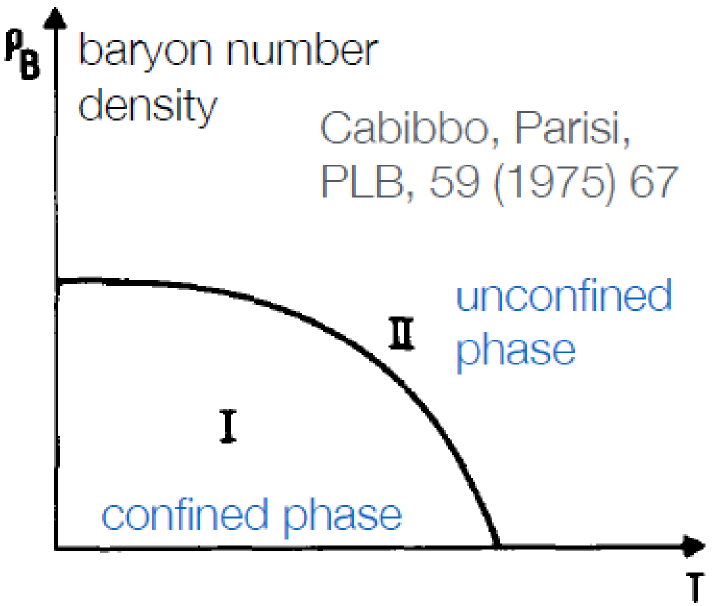
"**Our basic picture then is that matter at densities higher than nuclear matter consist of a quark soap.**"

- Idea based on weak coupling (asymptotic freedom)

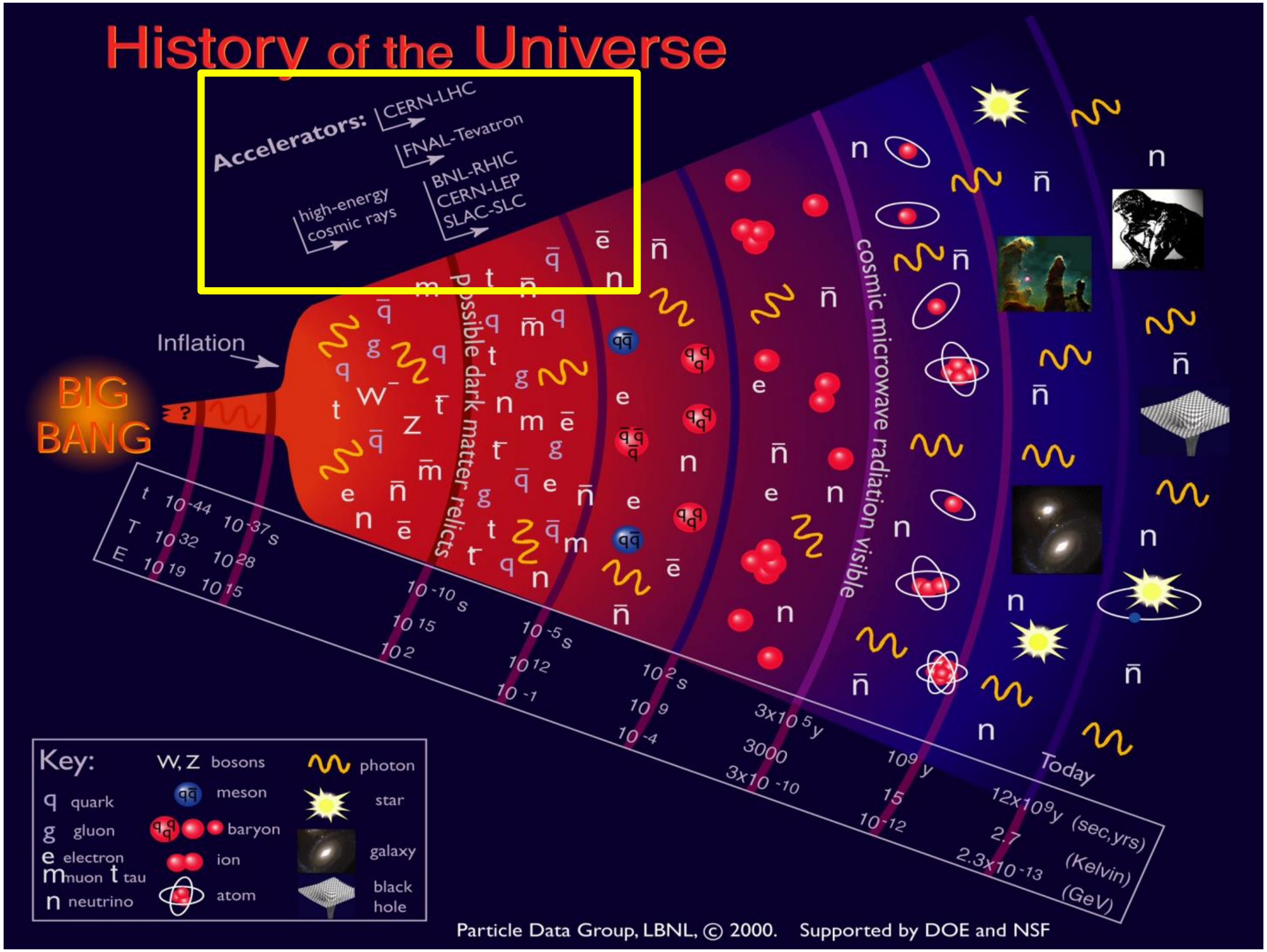
  - Cabbibo, Parisi, PLB, 59 (1975) 67:

- exponential hadron spectrum not necessarily connected with a limiting temperature
- Rather: Different phase in which quarks are confined

- It was soon realised that this new state could be created and studied in heavy-ion collisions



Probing the early UNIVERSE



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