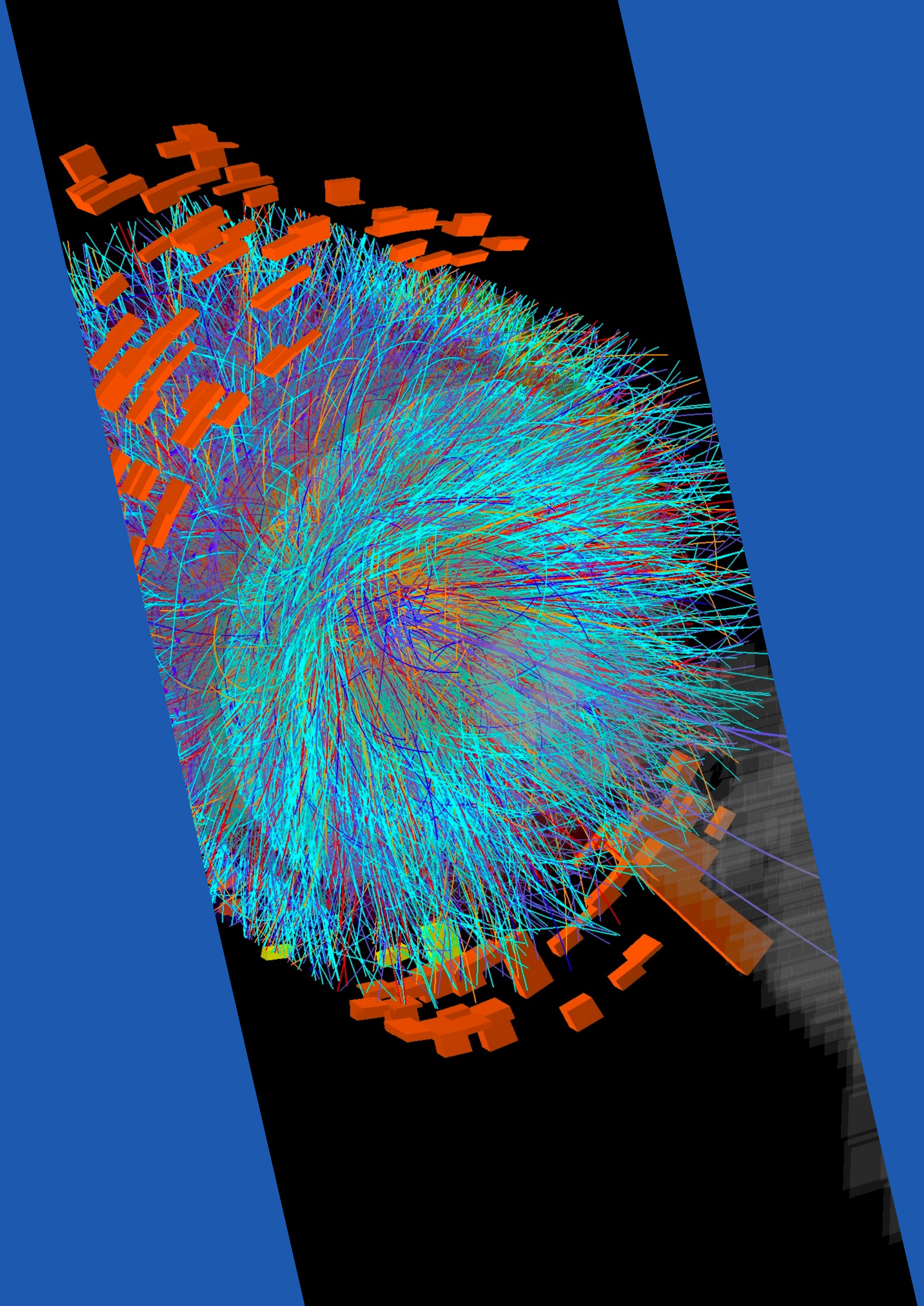
CERN Summer Student Lectures 2024



Heavy Ions 2/3

Francesca Bellini
University and INFN, Bologna, Italy
Contact: francesca.bellini@cern.ch

Experimental principles

QCD in extreme conditions in the laboratory

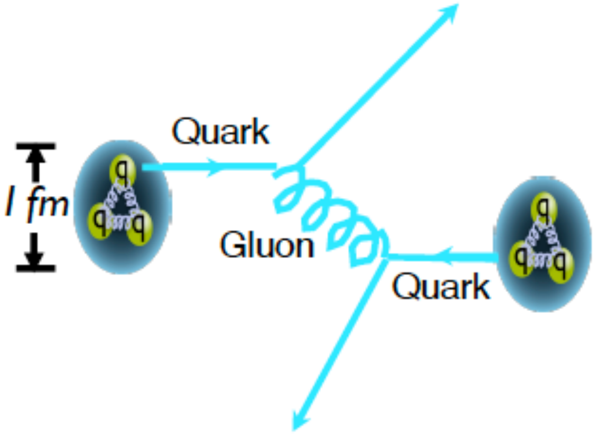
A QGP can be formed by compressing **large amount of energy in a small volume**

→ collide **heavy nuclei** (multiple, ~simultaneous nucleon-nucleon collisions)

→ **control the energy deposited** in the collision region by varying the collision system

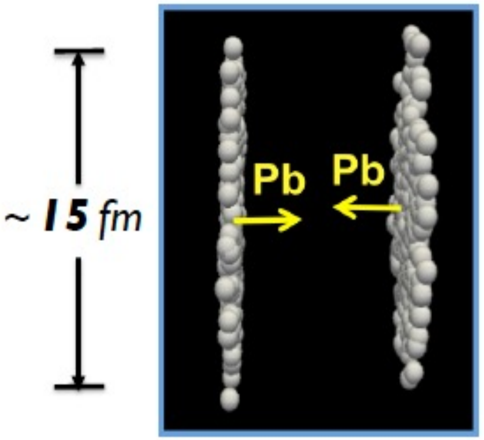
- nuclear species, p-Pb, pp
- vary impact parameter (centrality)

Colliding protons

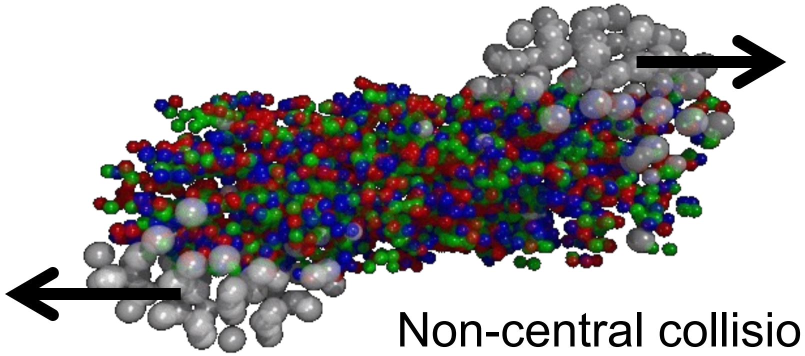


Colliding large nuclei

T.D. Lee, RMP 47, 267(1975)



Head-on collision, b = 0



Non-central collision
b > 0

Hadron and ion colliders

With symmetric proton beams with energy E, the centre-of-mass energy is $\sqrt{s} = 2E$.

With heavy-nuclei, only protons can be accelerated, but neutrons are there too:

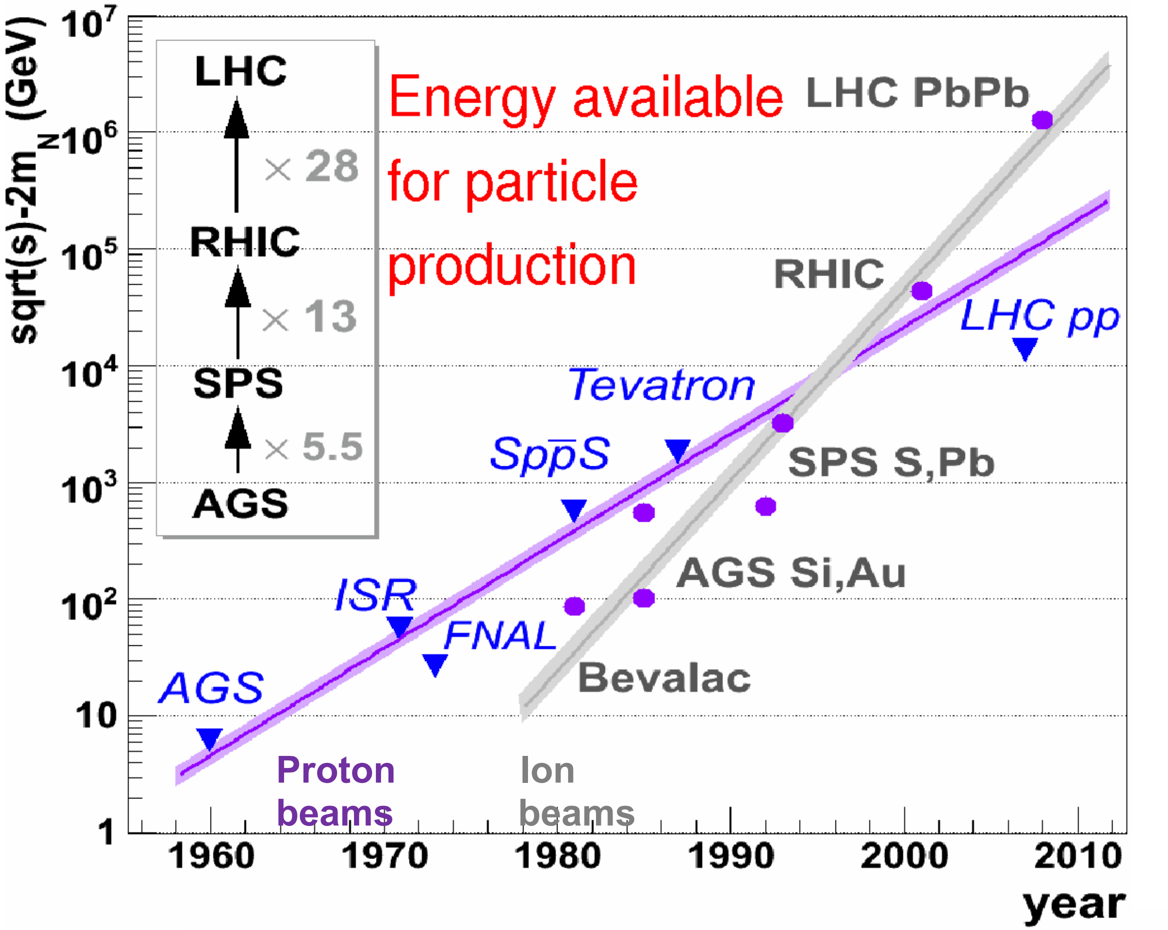
$$p_A = Z/A \, p_{proton}$$

At the LHC, the rigidity of accelerated particles is fixed by the magnet field configuration (B_{max} = 8.3 T).

For the **$^{208}Pb^{82+}$** ions used at the LHC:

$p_{Pb} = 82 / 208 \, p_{proton}$

p_{proton} = 6.5 TeV (Run 2) ⟶ p_{Pb} = 2.56 TeV
⟶ $\sqrt{s_{NN}}$ = 5.02 TeV ⟶ **$\sqrt{s} \sim 1.04$ PeV**



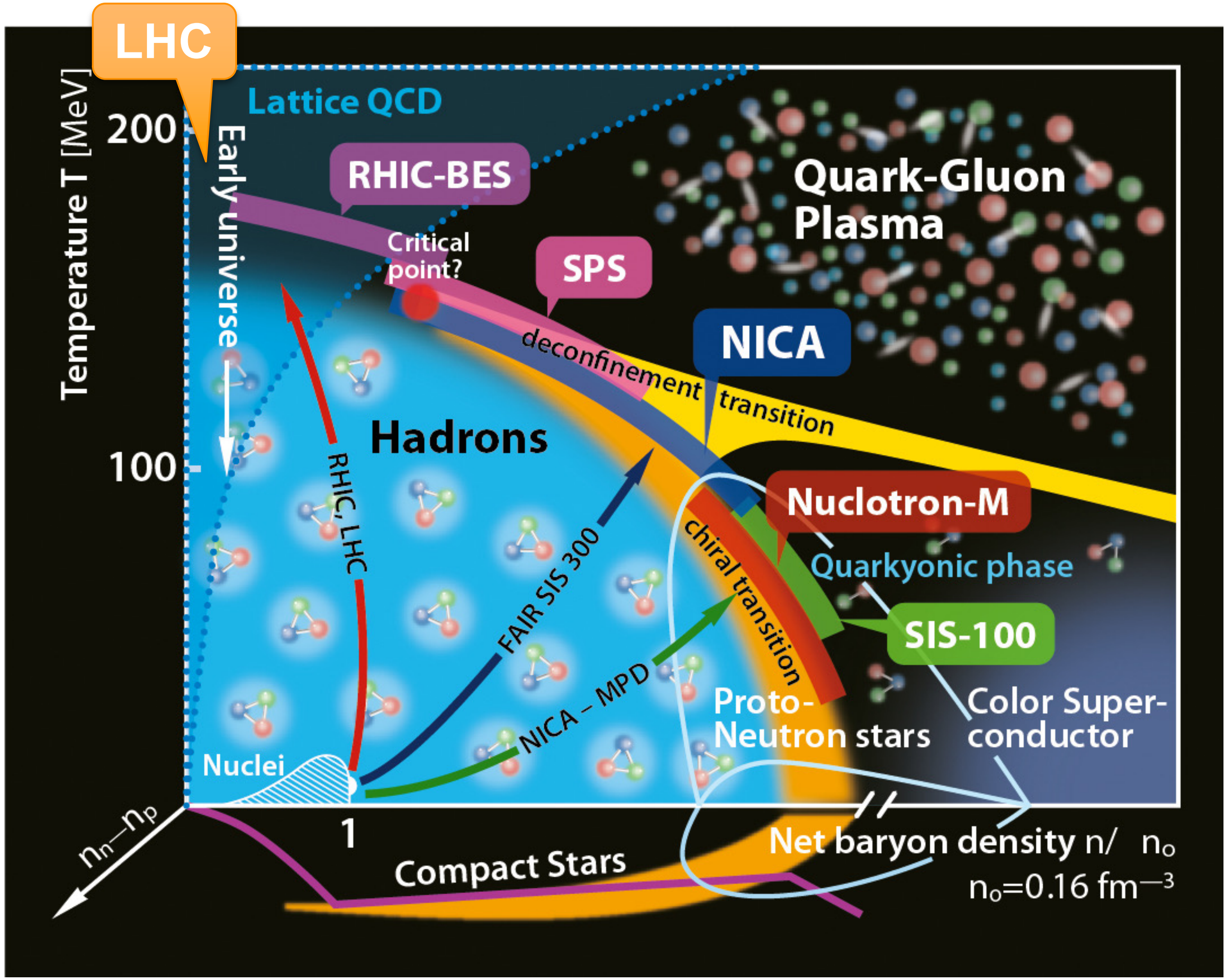
Some numbers (colliders):
RHIC @ BNL (2000-) $\sqrt{s_{NN}}$ <200 GeV
[beam energy scan $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, and 62.4 GeV]
LHC @ CERN (Run I, 2009-2013) $\sqrt{s_{NN}}$ = 2.76 TeV
LHC @ CERN (Run II, 2015-2018) $\sqrt{s_{NN}}$ = 5.02 TeV
HL-LHC @ CERN (Run III+IV, 2022-2030) $\sqrt{s_{NN}}$ = 5.5 TeV
NICA @ JINR (2021) $3 < \sqrt{s_{NN}} < 11$ GeV

Experimental exploration of the QCD phase diagram

RHIC and the LHC explore the region of the phase diagram for $\mu_B \sim 0$.

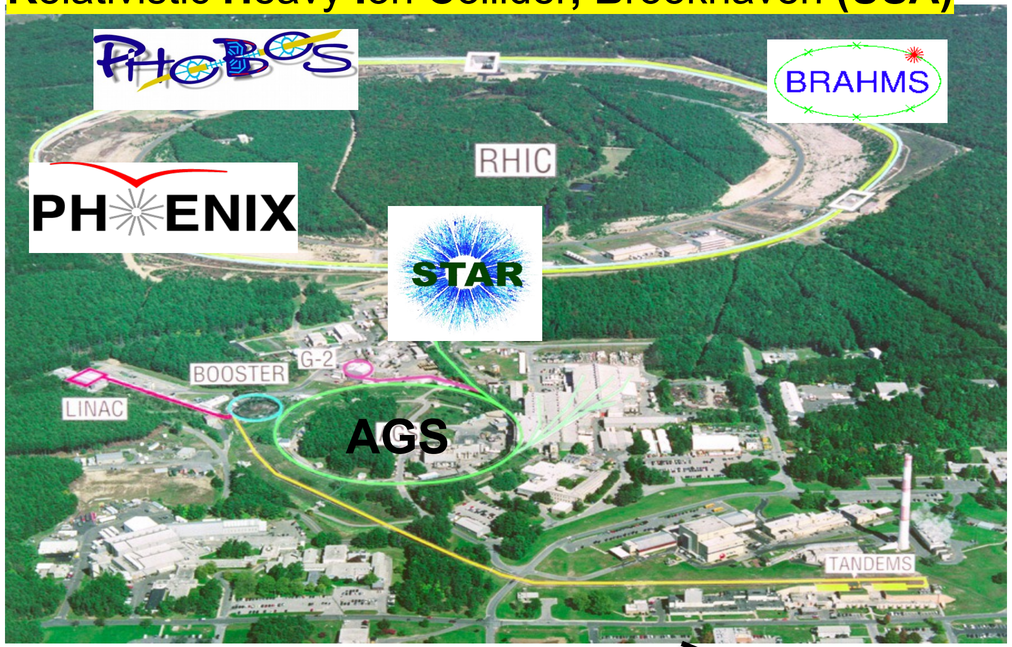
which is also the region of the phase diagram where lattice QCD calculations can be performed.

Low energy (& high μ_B) are the conditions to study the 1st order transition and the search for the critical point, the key regime being $2.5 < \sqrt{s_{NN}} < 8\text{-}10$ GeV



Heavy-ion physics worldwide: high energy

Relativistic Heavy Ion Collider, Brookhaven (USA)



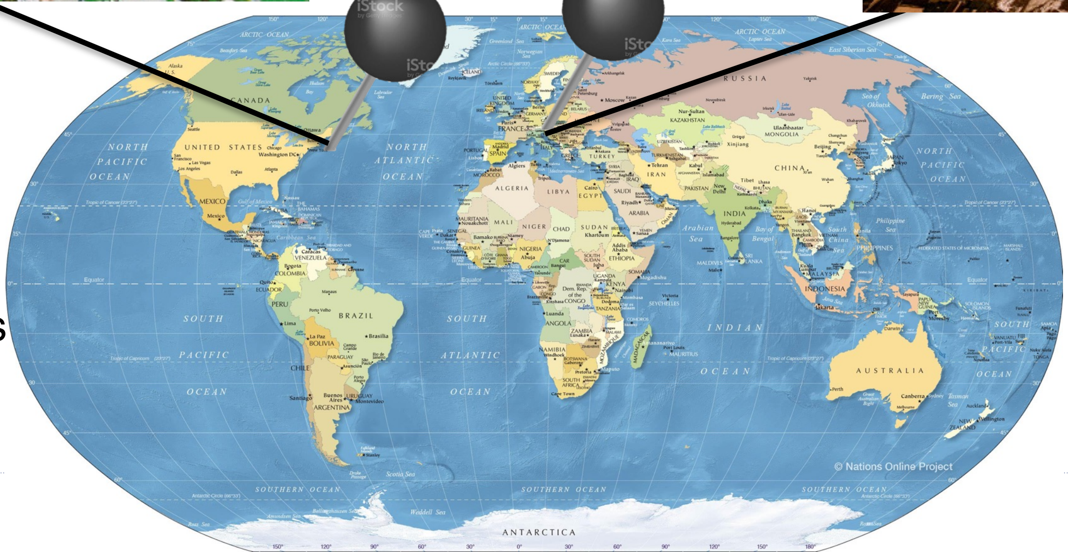
Super Proton Syncrotron and Large Hadron Collider, CERN (Switzerland/France)

CERN SPS

- Operating since 1986
- Circumference 6.9 Km
- max p = 450 A/Z GeV
- $\sqrt{s_{NN}} < 20$ GeV
- Ongoing: NA61/Shine

Brookhaven RHIC

- Operating since 2000
- Circumference 3.83 km, 2 rings
- Superconducting magnets
- $\sqrt{s_{NN}}$ = 3 - 200 GeV in Au-Au
- 3 Beam-energy scans campaigns
- Ongoing exp: STAR

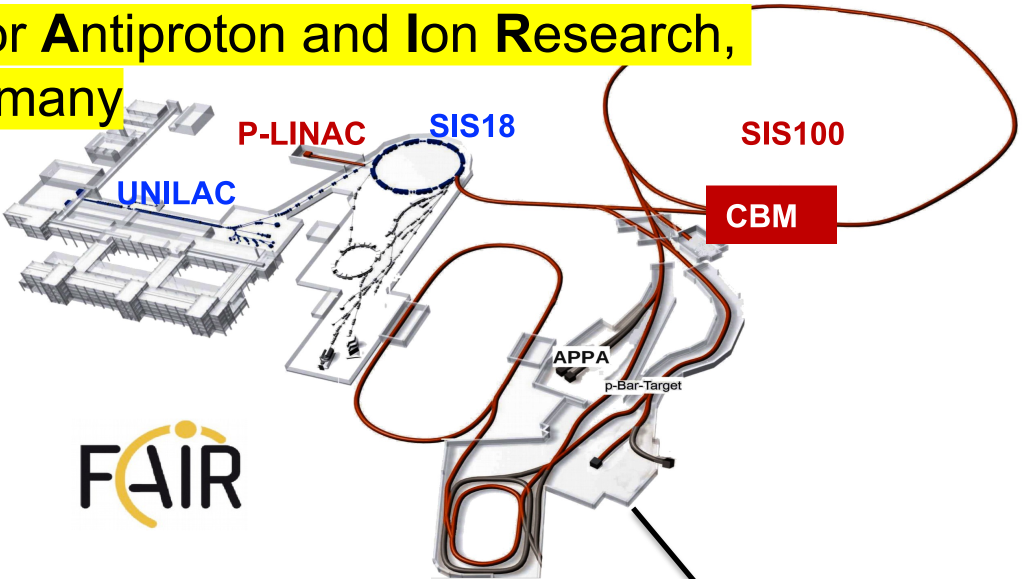


CERN LHC

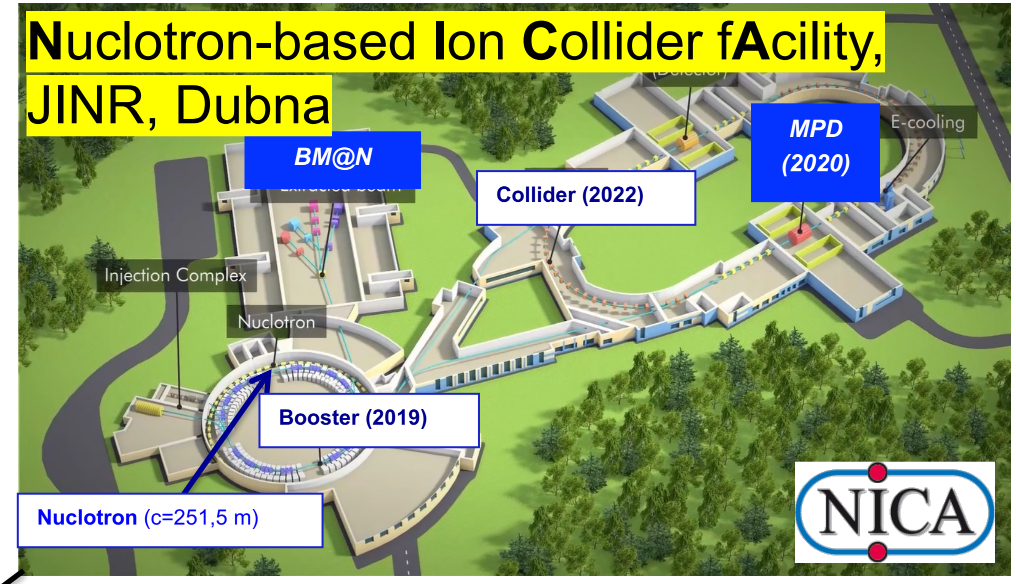
- Operating since 2009
- Run 3 started in 2022
- Circumference: 27 km
- B-field: 8 T, superconducting
- pp $\sqrt{s}$ = 0.9 – 13.6 TeV
- Pb-Pb $\sqrt{s_{NN}}$ = 2.76-5.36 TeV
- Main ongoing exp.:
  ALICE, ATLAS, CMS, LHCb

Heavy-ion physics worldwide: low energy

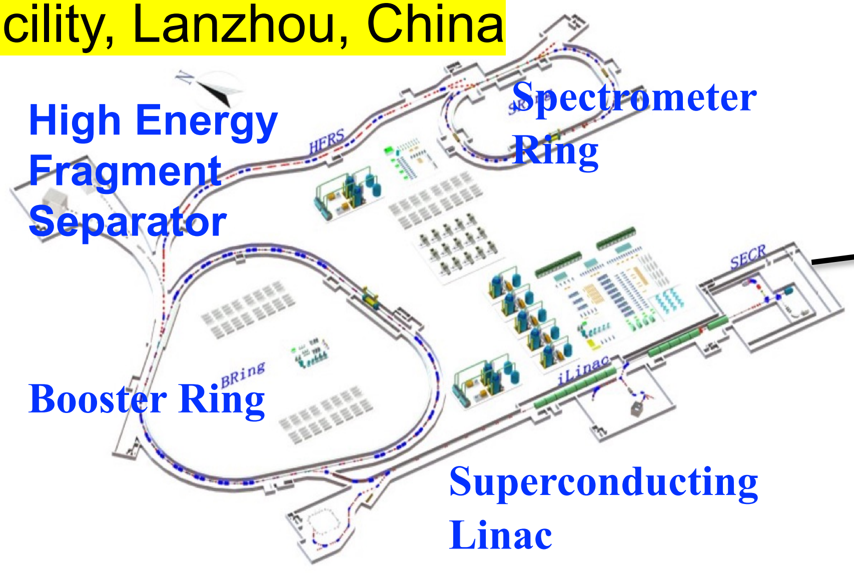
Facility for **A**ntiproton and **I**on **R**esearch, GSI, Germany

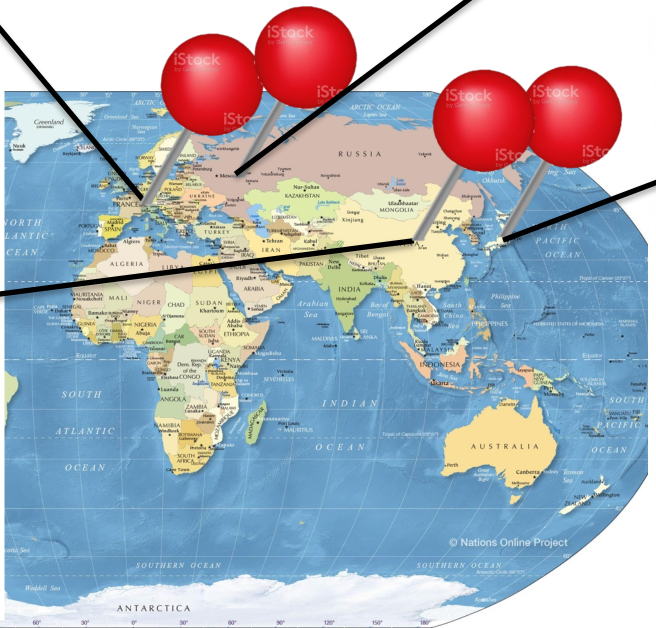


Nuclotron-based **I**on **C**ollider f**A**cility, JINR, Dubna

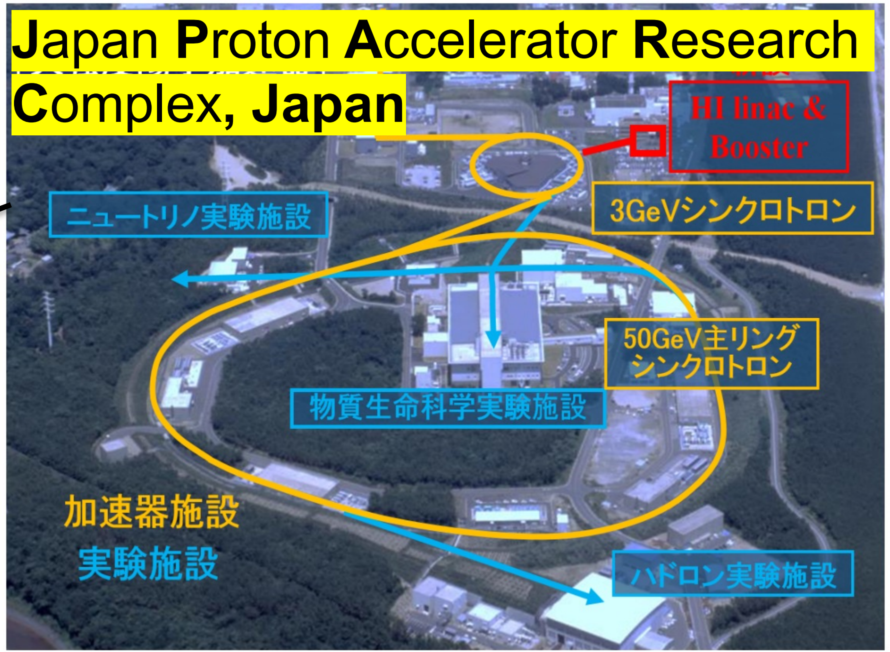


High-**I**ntensity Heavy Ion **A**ccelerator **F**acility, Lanzhou, China





Japan **P**roton **A**ccelerator **R**esearch **C**omplex, **J**apan



Heavy-ion physics at the LHC

2010-2012		2015-2018		2022-2025		2029-2032		2035...		2041...
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

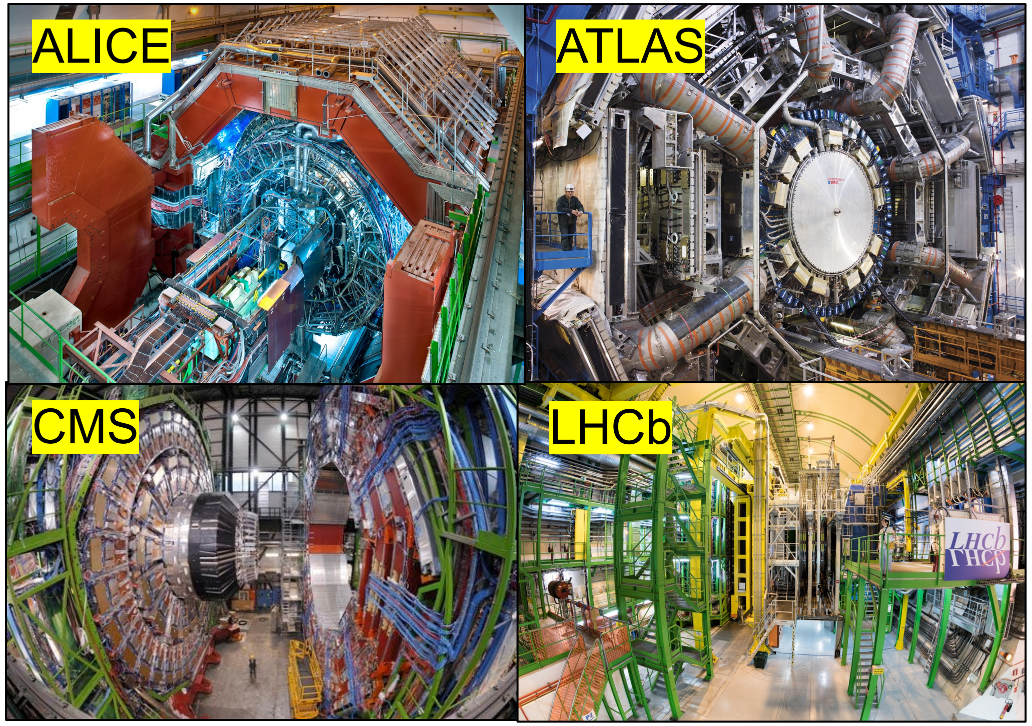
High luminosity LHC

Major upgrades for **ALICE and LHCb**

We are here

ATLAS and CMS phase II
ALICE ITS3 and FoCal

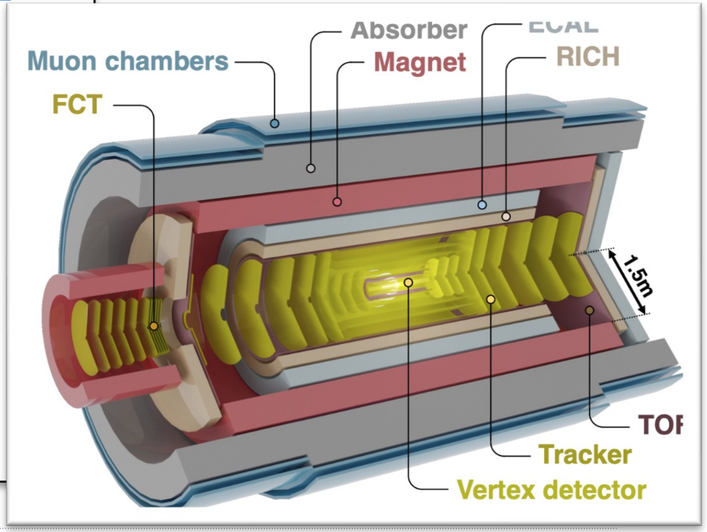
ALICE 3: a whole new dedicated HI detector!
LHCb upgrade II



ALICE 3

- Letter of Intent: CERN-LHCC-2022-009
- next-generation HI experiment
- all-Si MAPS tracker
- ultimate vertex detector
- minimal mass (essentially only sensor)
- 5 mm from beam (LHC aperture)

Physics focus:
- low-p_T heavy-flavour
- electromagnetic radiation from QGP



Guidance for the experimental study of the QGP

How can a QGP, once formed, be detected and investigated?

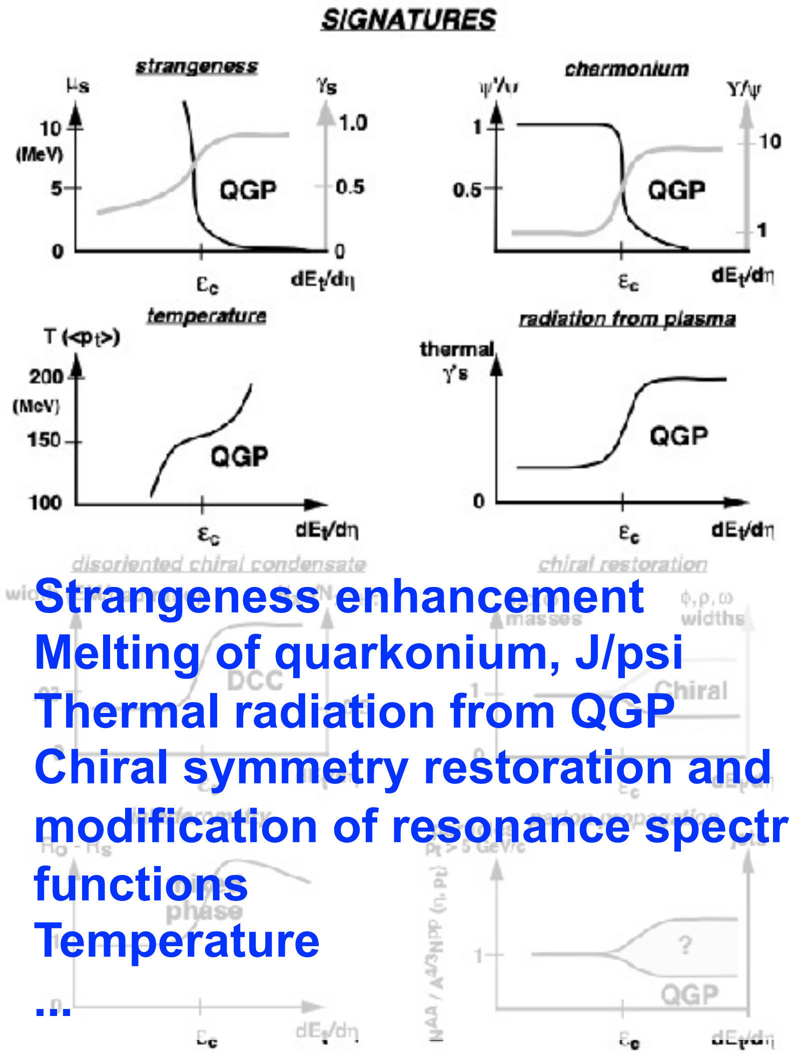
How can the physical properties be determined?

Back in 1990's, some **''smoking gun''** observables were proposed, however these were not based on solid calculations (lQCD was still a ''baby''…)

Today, we have several powerful theoretical tools at disposal:

- Lattice QCD (the only one from first principles)
- Hydrodynamics and standard model of HIC
- Bayesian analysis
- Transport models

Remember: the QGP is not static but an evolving system!

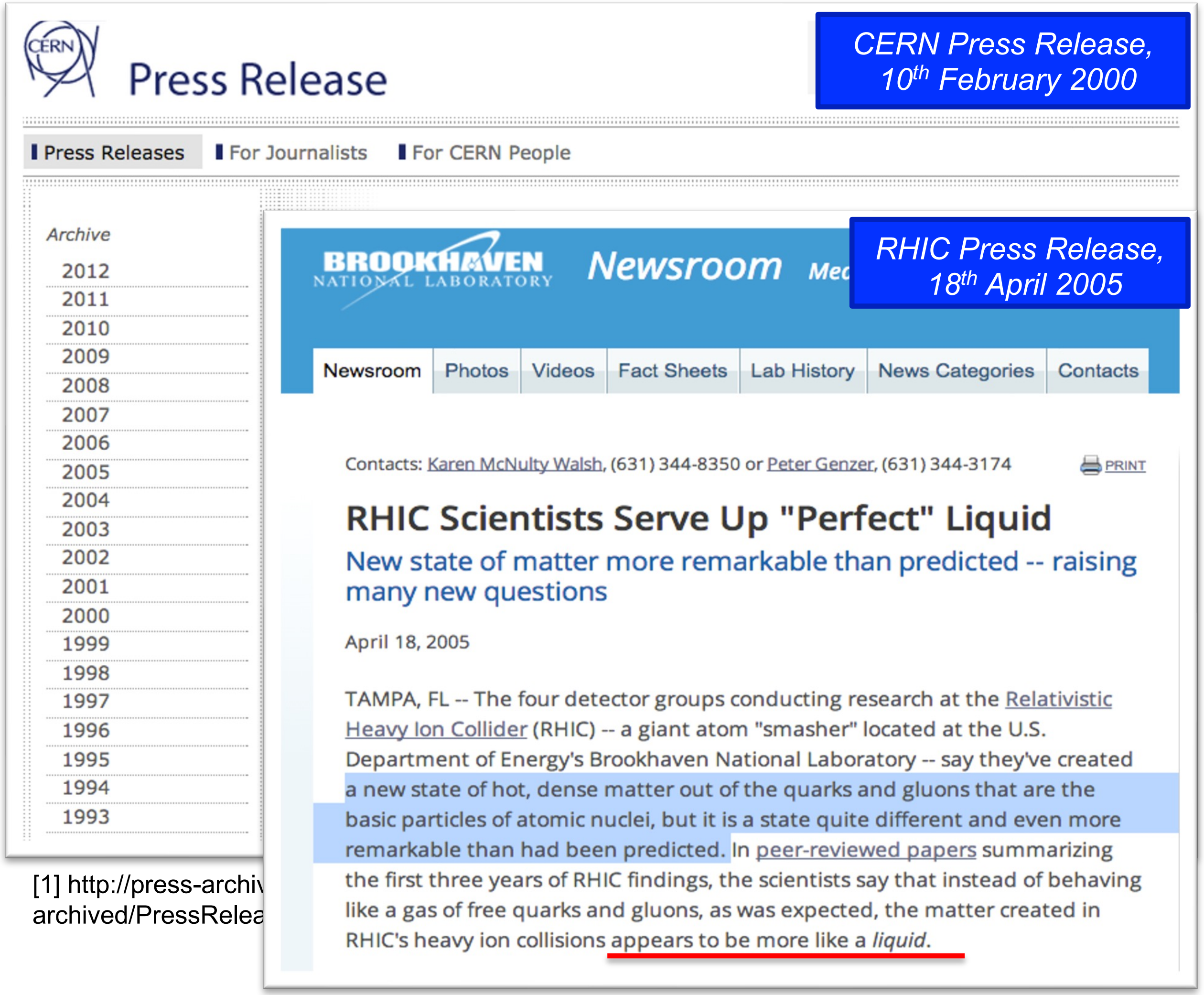


- **Strangeness enhancement**
- **Melting of quarkonium, J/psi**
- **Thermal radiation from QGP**
- **Chiral symmetry restoration and modification of resonance spectral functions**
- **Temperature**
- **…**

Reading suggestion: B. Muller, arXiv:2106.11923

J.Harris, B.Muller, *Annu Rev. Part. Nucl. Physics* 46 (1996) 71

QGP: from “discovery” to “measurement”



CERN Press Release, 10th February 2000

Press Release

Press Releases | For Journalists | For CERN People

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RHIC Press Release, 18th April 2005

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Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174 PRINT

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

[1] http://press-archiv
archived/PressRelea

[2] http://www.bnl.gov/newsroom/news.php?a=1303

First “compelling” evidence of QGP at the CERN SPS.

At BNL RHIC, “remarkable” evidence that the hot matter formed is

- Extremely strongly interacting (sQGP)
- Absorbing energy of traversing partons
  → An almost opaque medium
- Reacting to pressure gradients by flowing with very small shear viscosity
  → An almost perfect liquid

At the LHC, the increased beam energies leads to the production of a hotter, larger and longer-lived QGP

→ Measure QGP probes with increased precision.

The “little bang” in the laboratory

“Little bangs” of heavy nuclei can be studied similarly as the Early Universe

No direct observation of the QGP is possible

→ use particles that decouple from the system at different phases of the evolution as probes

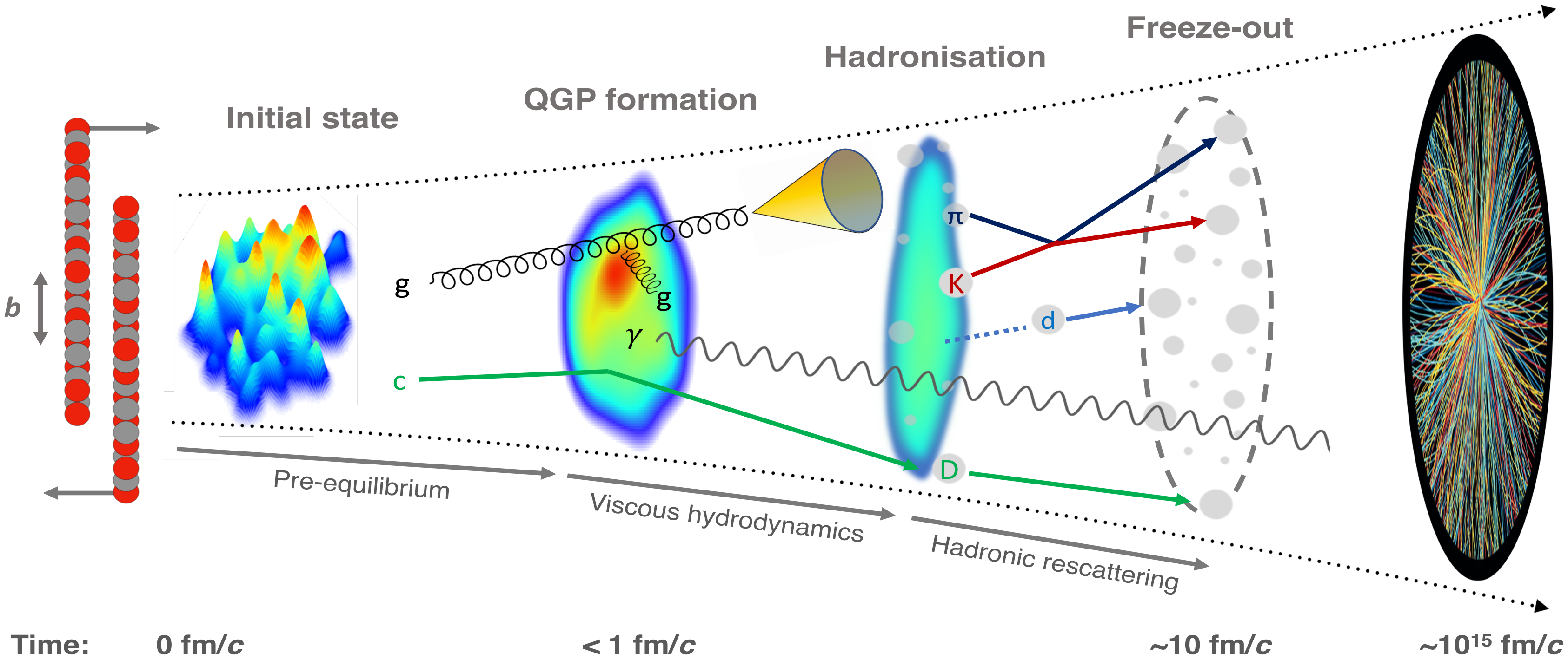


Figure from ALICE Coll., arXiv:2211.04384

The “little bang” in the laboratory

High-p_T partons (→ jets), charm and beauty quarks (→ open HF, quarkonia),
produced in the early stages in hard processes,
traverse the QGP interacting with its constituents
→ rare, calibrated probes, pQCD
→ **interaction (energy loss) and transport properties in QGP**
→ **modification of the strong force in a colored medium**

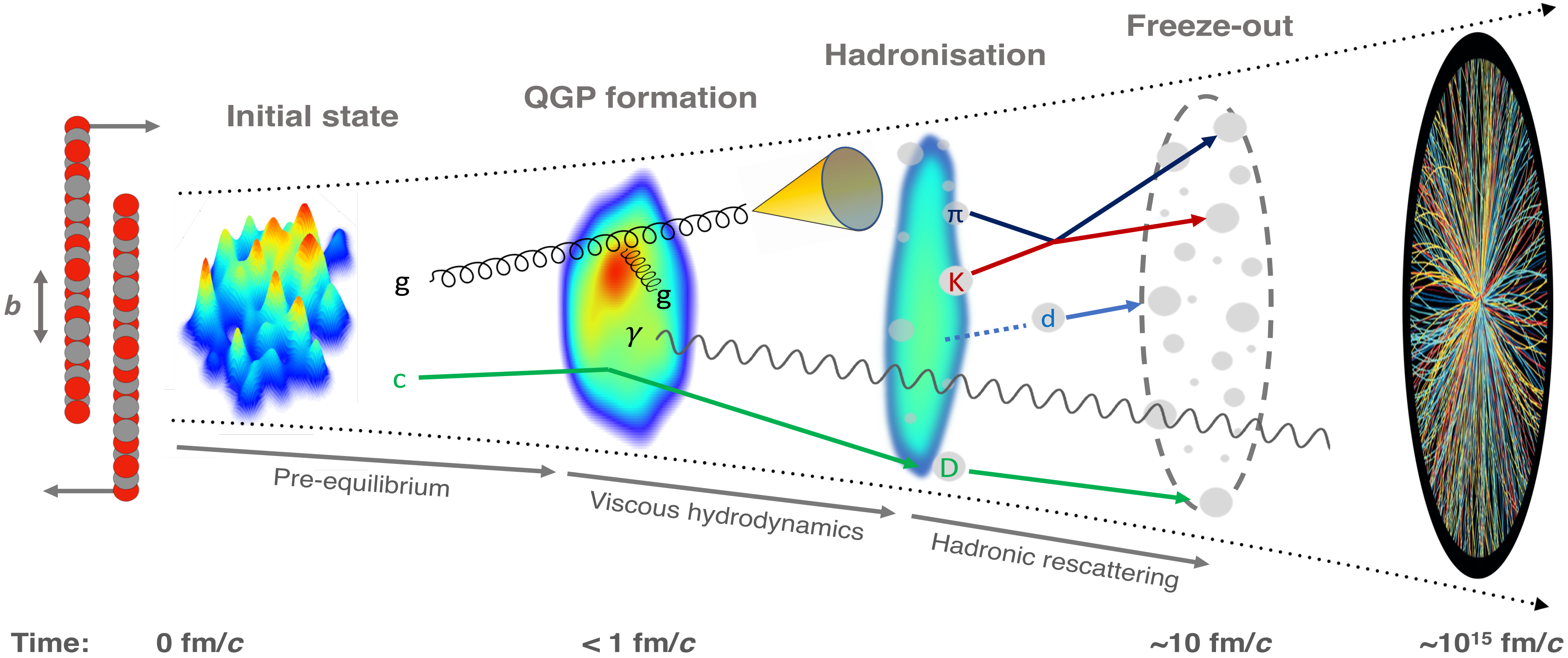
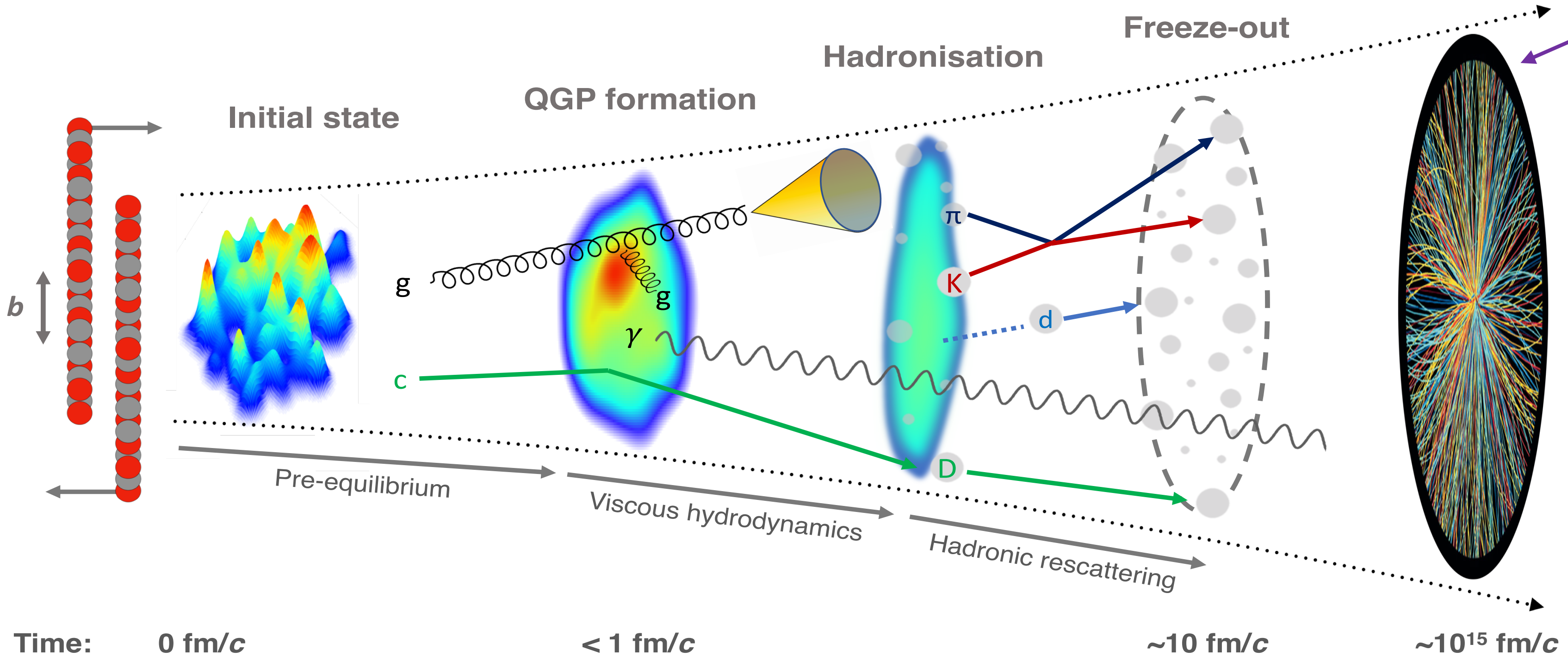


Figure from ALICE Coll., arXiv:2211.04384

The “little bang” in the laboratory

Low-p_T particles, light flavour hadrons (u,d,s, + nuclei)
produced from hadronization of the strongly-interacting, thermalized QGP constitute the bulk of the system and undergo collective expansion
→ non-perturbative regime
→ **thermodynamics, flavour composition and equilibration in QGP**
→ **hydrodynamical and transport properties of the QGP**



>2k charged particles per unit of rapidity in 5% most central Pb-Pb: 98% with p_T < 2 GeV/c, 90% pions

Figure from ALICE Coll., arXiv:2211.04384

Heavy-ion and high-energy physics have different goals and thus different detector requirements.

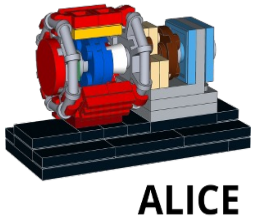
Observables:

- soft (low p_T) and hard (high p_T) probes
- hadron production rates (needs PID)
- collectivity, flow (needs acceptance coverage)
- photon/W/Z (calorimetry)
- jets (coverage, high p_T)

In HI physics special emphasis on:

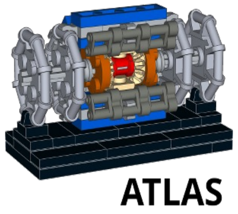
- soft (non-perturbative) regime, i.e. **low p_T**
- **identification** of hadron species
- **minimum bias** events → **centrality** dependence
- **midrapidity** measurements

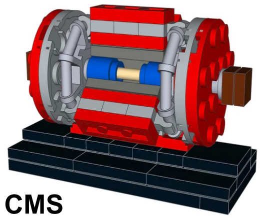
Complementarity of the LHC experiments



ALICE

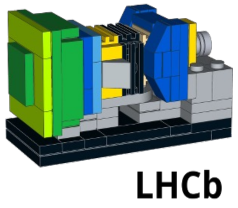
- Low p_T
- PID
- Low material budget next to IP





ATLAS/CMS

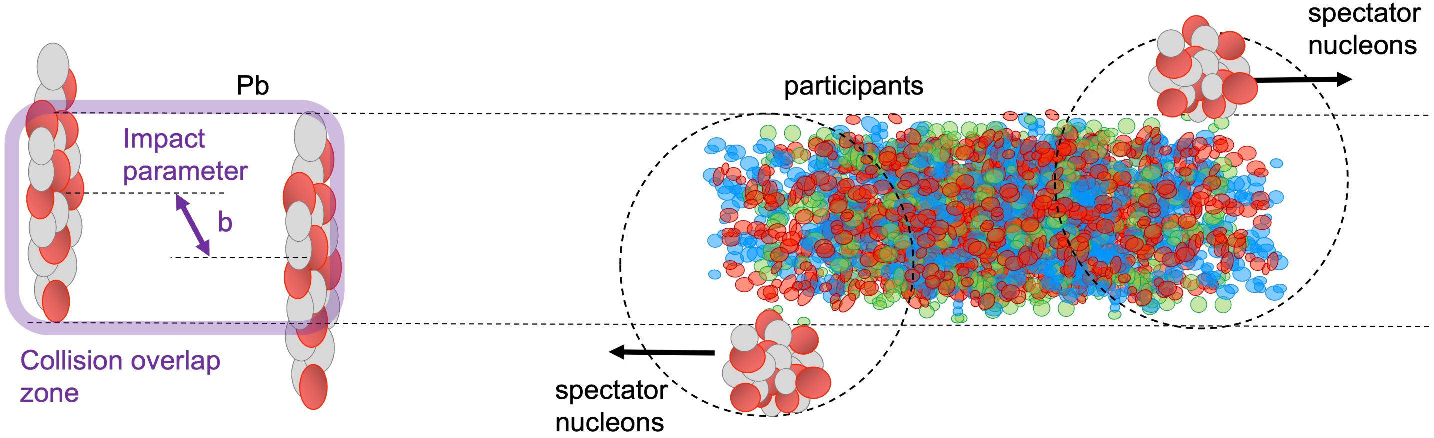
- Wide pseudorapidity coverage
- High $p_{T,}$ jets



LHCb

- Forward pseudorapidity
- PID
- Fixed target

Centrality



Centrality = fraction of the total hadronic cross section of a nucleus-nucleus collision, typically expressed in percentile, and related to the **impact parameter**, **b**, of the collision.

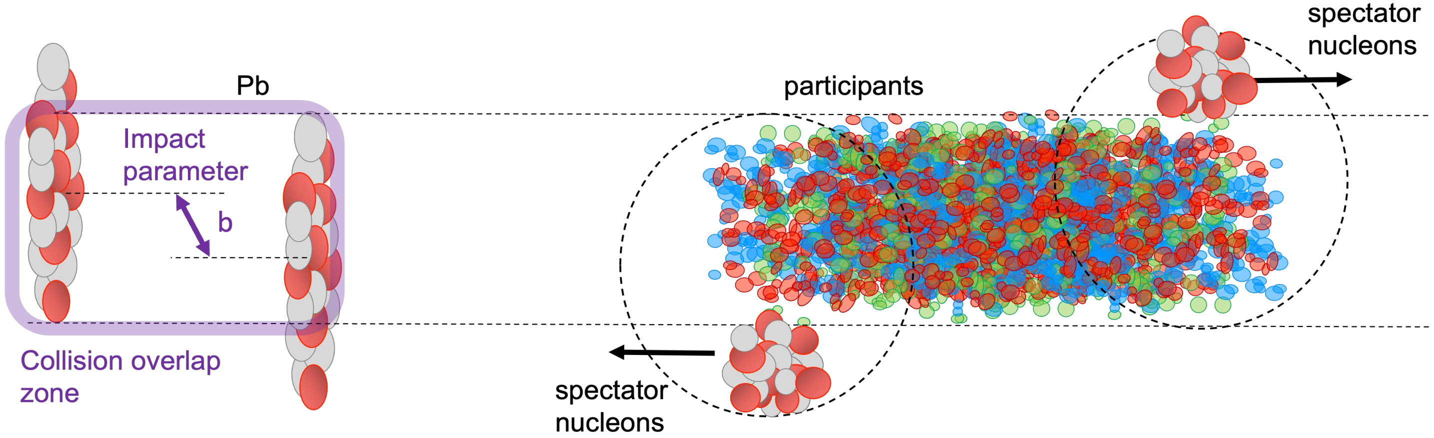
Central collisions (e.g. 0-5%)
→ smaller impact parameter
→ larger overlap region
→ more participants, N_{part}
→ more binary collisions, N_{coll}
→ more particles produced

Peripheral collision (e.g. 80-90%)
→ larger impact parameter
→ smaller overlap region
→ less participants
→ less binary collisions
→ less particles produced

N_{part}, N_{coll}, b determined with a Glauber model fit to the signal amplitudes.

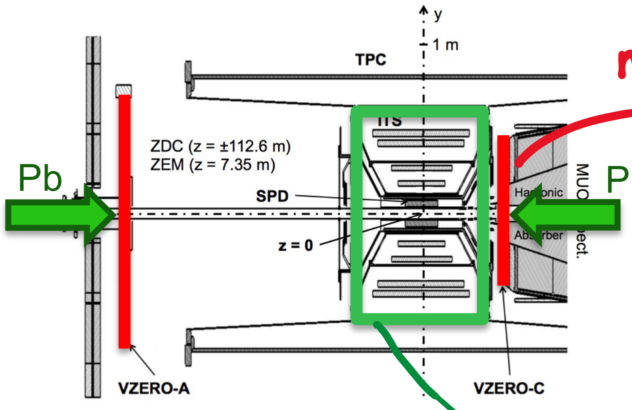
M. L. Miller et al., An.Rev.Nucl.Part.Sci. 57 (2007) 205

Centrality - Experimental determination



Centrality is determined by counting the number of particles (**multiplicity**) or measuring the **energy deposition** in different phase space regions
→ correlation observed!

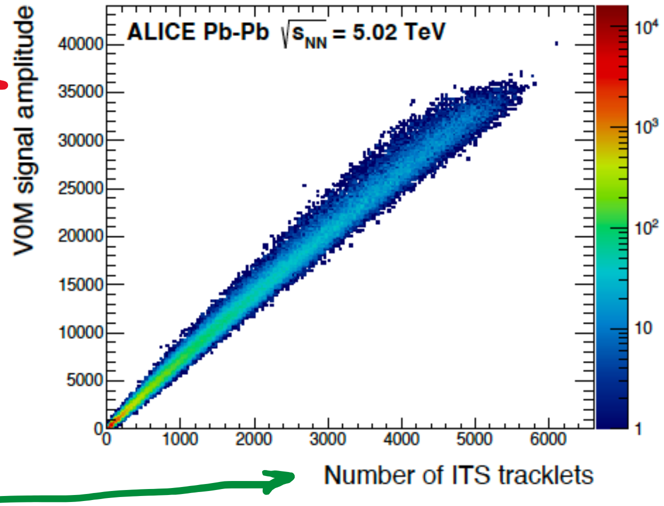
Example: centrality determination in ALICE



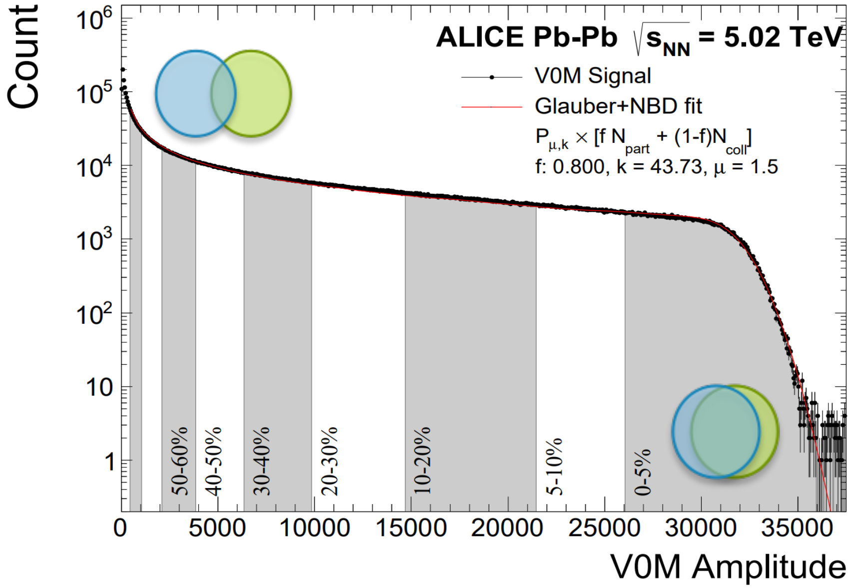
Schematic view of the ALICE subdetectors near the interaction region in Run 1 and 2

multi in V0

multi in ITS



Centrality from V0M multiplicity in ALICE



ALICE, PRL 106 (2011) 032301, PRC 91 (2015) 064905

Rapidity and pseudorapidity

The rapidity can be approximated by **pseudo-rapidity** in the ultra-relativistic limit in which *p>>m:*

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

$$\cos(2\alpha) = 2\cos^2\alpha - 1 = 1 - 2\sin^2\alpha$$

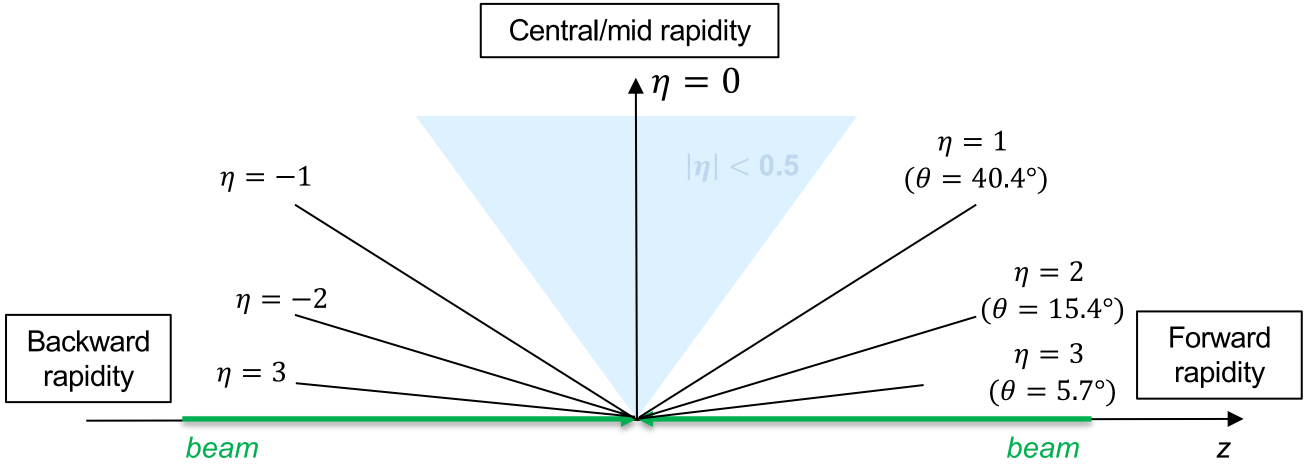
Where ϑ is the angle between the direction of the beam and the particle.

The relation to transverse and longitudinal momenta are

$$p = p_T \cdot \cosh\eta, \qquad p_L = p_T \cdot \sinh\eta$$

For m = 0, *y* = η is a special case

In general y ≠ η, especially at low momenta



High energy HI collisions – the midrapidity region

In **high-energy** collisions (RHIC, LHC), the beams have large rapidity difference before the collision.

After the collision nuclei slow down to lower γ and y, particles are produced with a ‘’plateau’’ in the central rapidity region → **Transparency regime**

The baryon number carried out by the colliding nuclei is outside the centre-of-mass rapidity region, $y_{CM} = 0$.
The **midrapidity region** is the hottest region, where particle production is maximal and the highest temperatures are reached.

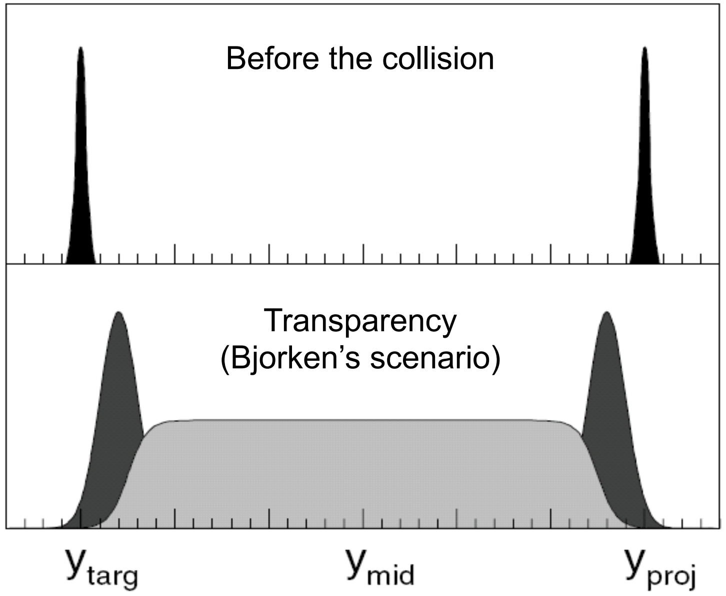
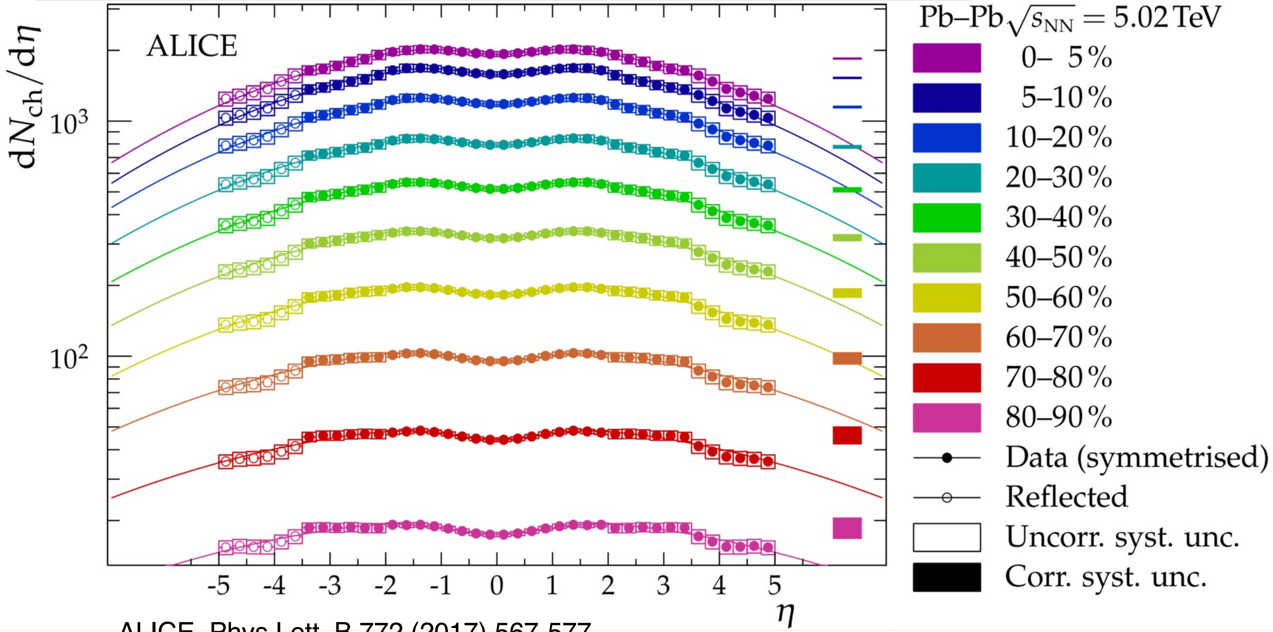


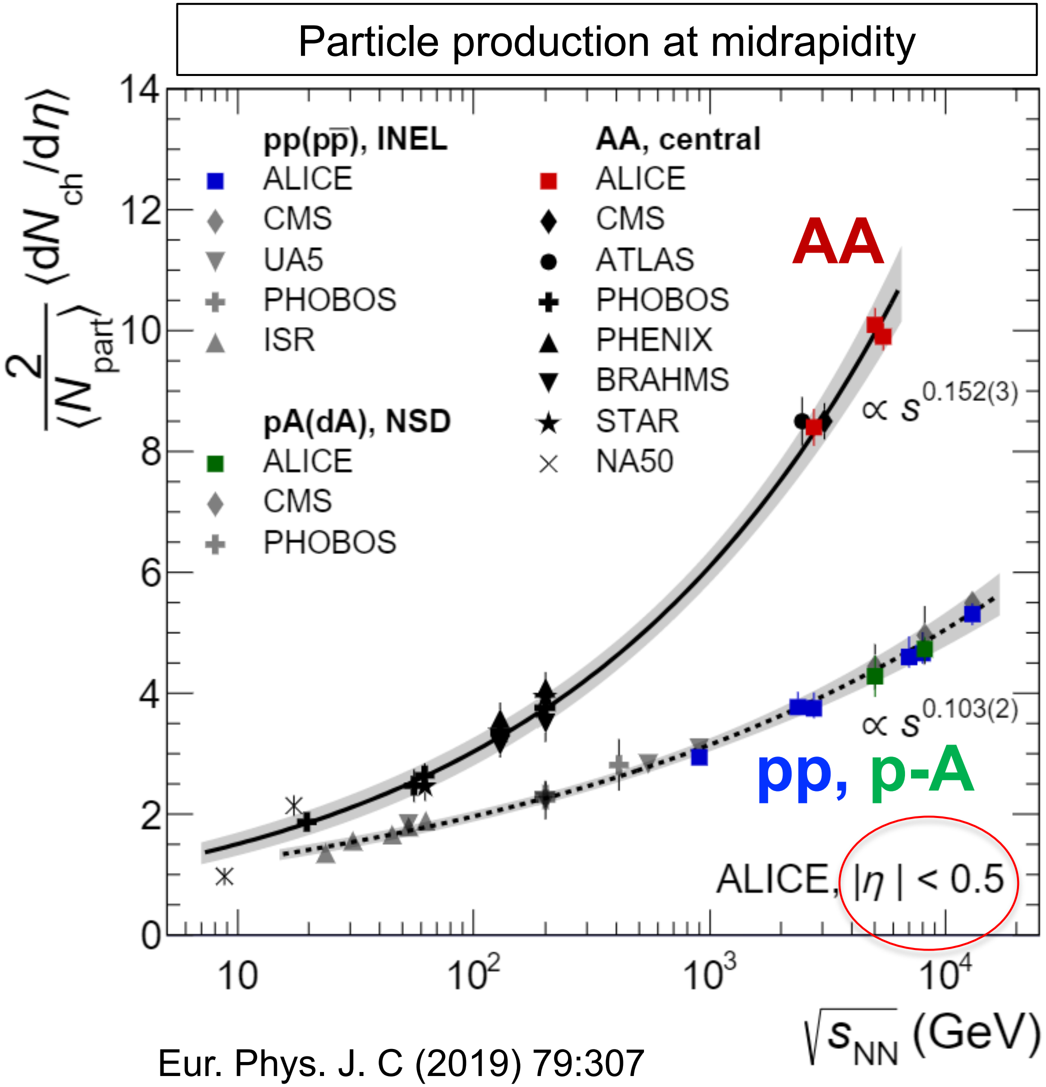
Figure from K. Reygers

Charged particle multiplicity vs pseudo-rapidity



ALICE, Phys.Lett. B 772 (2017) 567-577

Charged particle production in central HI collisions

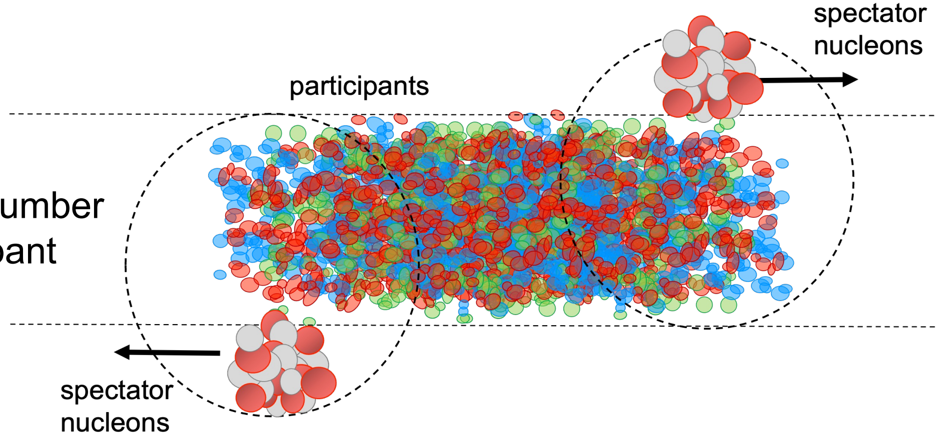


Eur. Phys. J. C (2019) 79:307

Particle production per participant in HI collisions follows a steeper power law than in pp, pA and increases by 2-3x from RHIC to the LHC.

Heavy-ion collisions are more efficient in transferring energy from beam- to mid- rapidity than pp.

$\langle N_{part} \rangle$ = average number of participant nucleons



Determination of the initial energy density

Measurement of the multiplicity dN_{ch}/dy and the $\langle p_T \rangle$, or of the transverse energy, can be used to determine the initial energy density available in the collision.

J. D. Bjorken, Phys. Rev. D 27 (1983) 140–151.

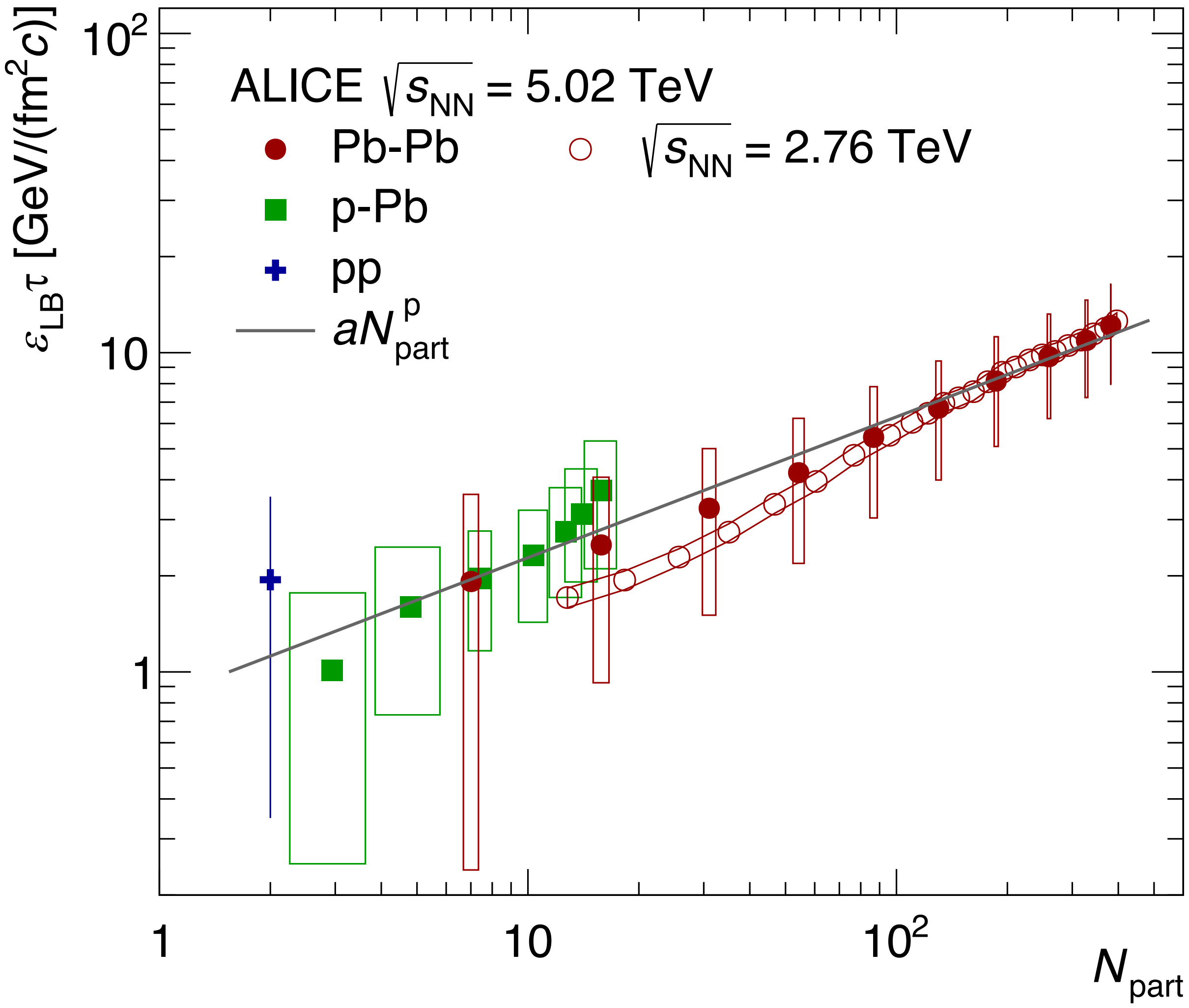
$$\varepsilon_{LB}\tau = \frac{1}{S_T}\frac{1}{f_{total}}\sqrt{1+a^2}\langle m\rangle\frac{dN_{ch}}{dy}$$

S_T = Transverse area from Glauber model
f_{total} = *0.55 ± 0.01* = fraction of charged particles
$\sqrt{(1+a^2)}$ <m> = effective transverse mass

$\varepsilon_{LB}\tau_0$ (0-5%) = (12.5 ± 1.0) GeV/fm²/*c*

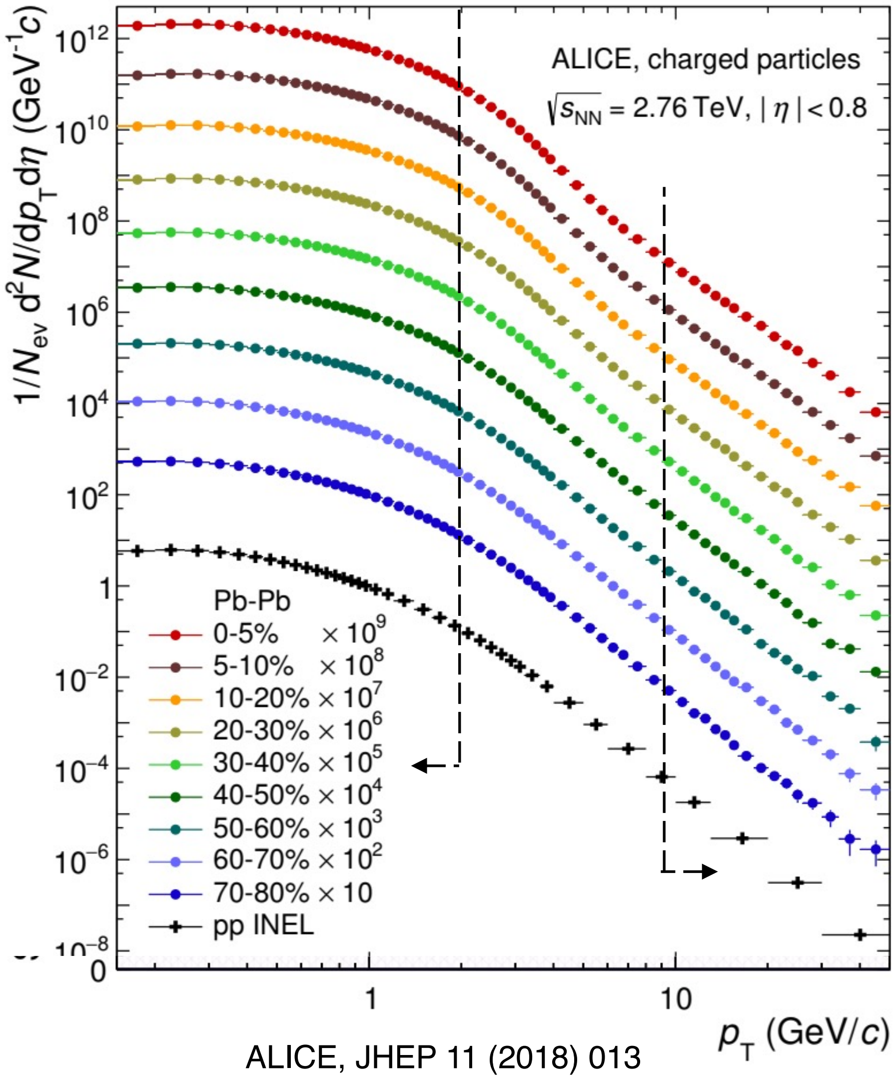
For τ_0~1fm/c, ~20x the energy density of a hadron, ~70x the density of atomic nuclei

Well above the critical energy density for the phase transition to occur!



Key observable: particle “spectrum”

Charged particle transverse momentum distribution



ALICE, JHEP 11 (2018) 013

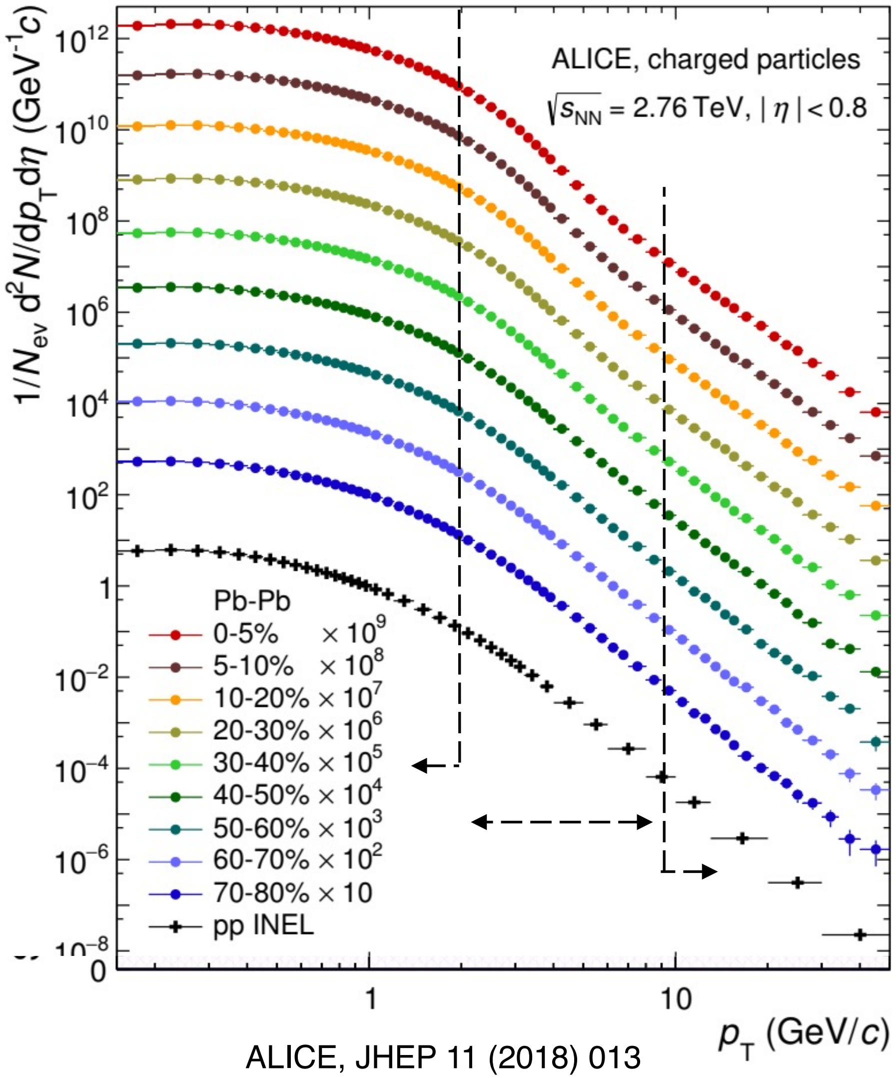
Particle **“spectra”**: $d^2N/(dydp_T)$ = yield per event per (pseudo)rapidity unit per transverse momentum unit

~95% of the produced charged particles are “soft”, i.e. have $p_T < 2$ GeV/c.

Low/high-p_T ends of the spectra are due to different hadron formation mechanisms

Features of particle spectra

Charged particle transverse momentum distribution



ALICE, JHEP 11 (2018) 013

Low p_T *(< 2 GeV/c)*

- Particle spectra are described by a Boltzmann distribution → "**thermal**", ~ exp(-1/k_BT)
- "Bulk" dominated by light flavor particles produced by hadronization of the **QGP**
- Non-perturbative QCD regime

Mid p_T *(2 to 8 GeV/c)*

- **Interplay** of parton fragmentation and recombination of partons from QGP

High p_T *(> 8-10 GeV/c)*

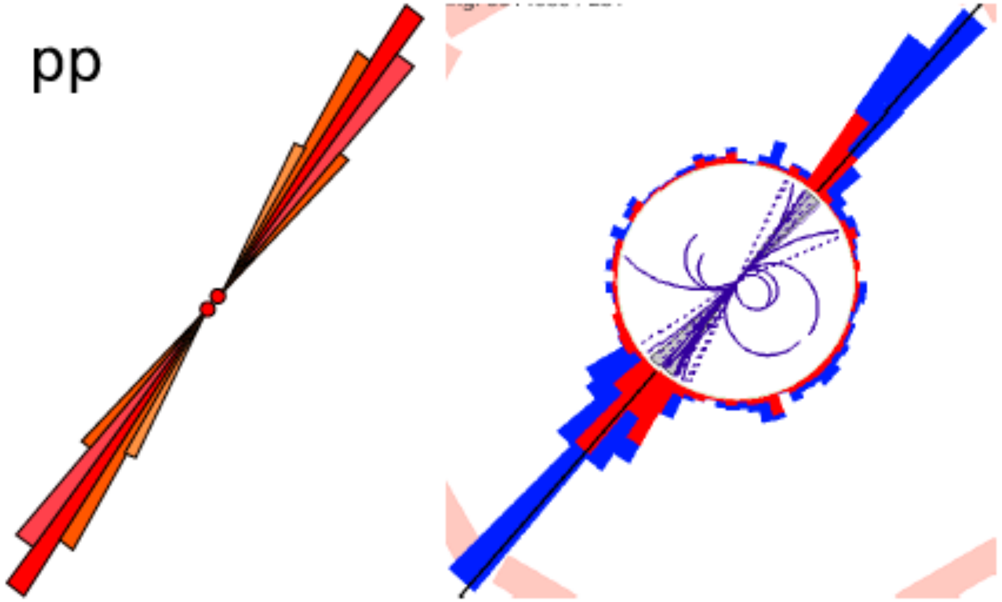
- Particle spectra described by a power law
- Dominated by **parton fragmentation** (jets!)
- Perturbative QCD regime

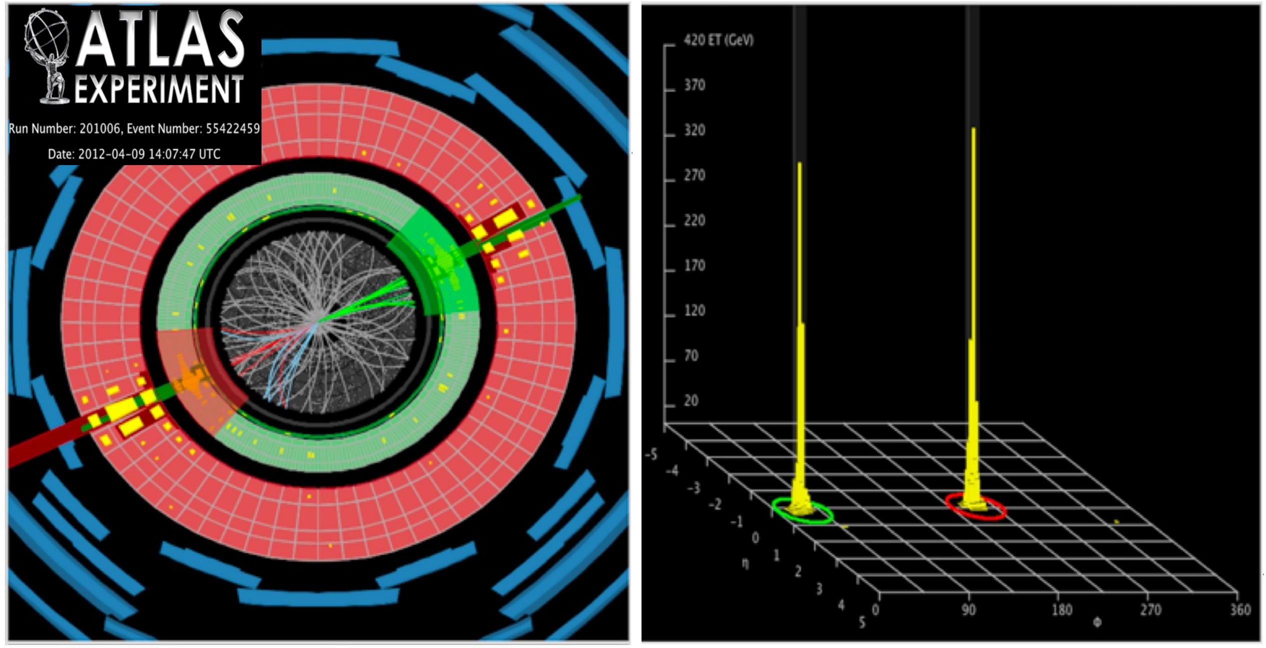
How does the presence of a colored QGP affect particle production?

Jets

In the early stages of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated ‘’sprays’’ of hadrons.

→ **in-vacuum fragmentation**





ATLAS, pp collision event display

Jets through a colored medium

In the early stages of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated ‘’sprays’’ of hadrons.

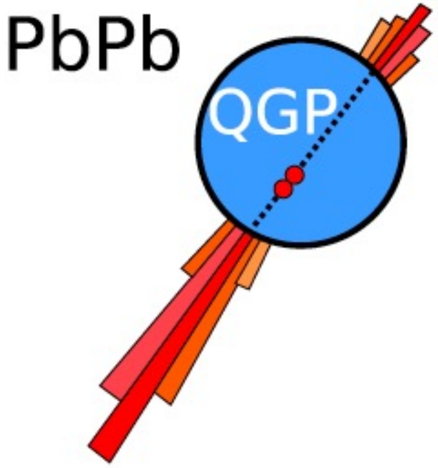
→ **in-vacuum fragmentation**

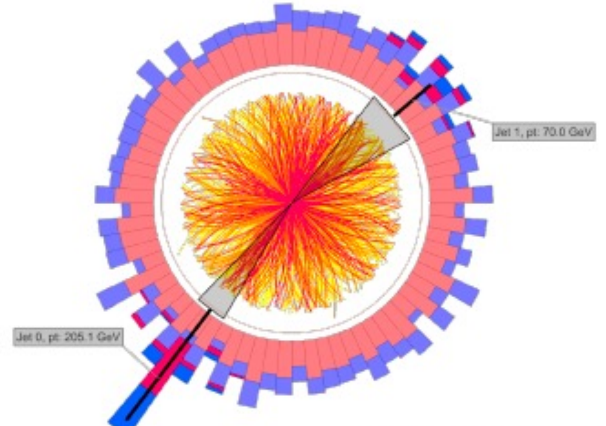
When a QGP is formed, the colored partons traverse and interact with a colored medium.

→ **in-medium fragmentation**

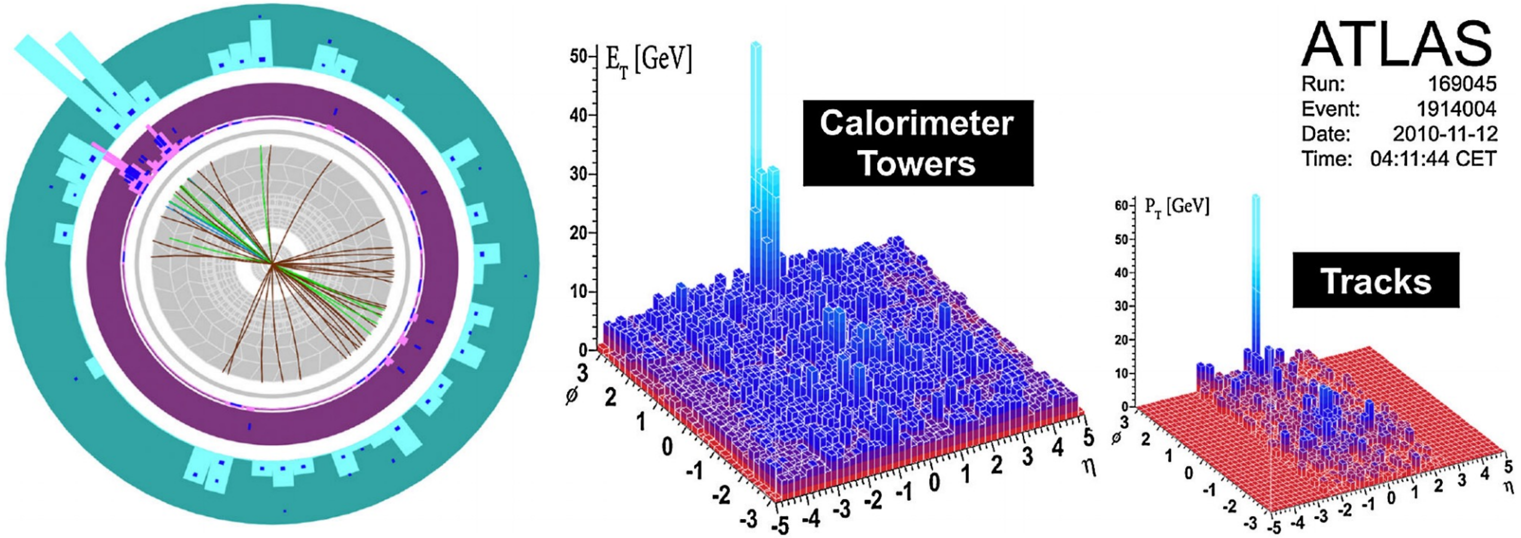
→ **jet ‘’quenching’’ (energy loss)**

Goal: understand the nature of this energy loss to characterize the strongly-interacting QGP



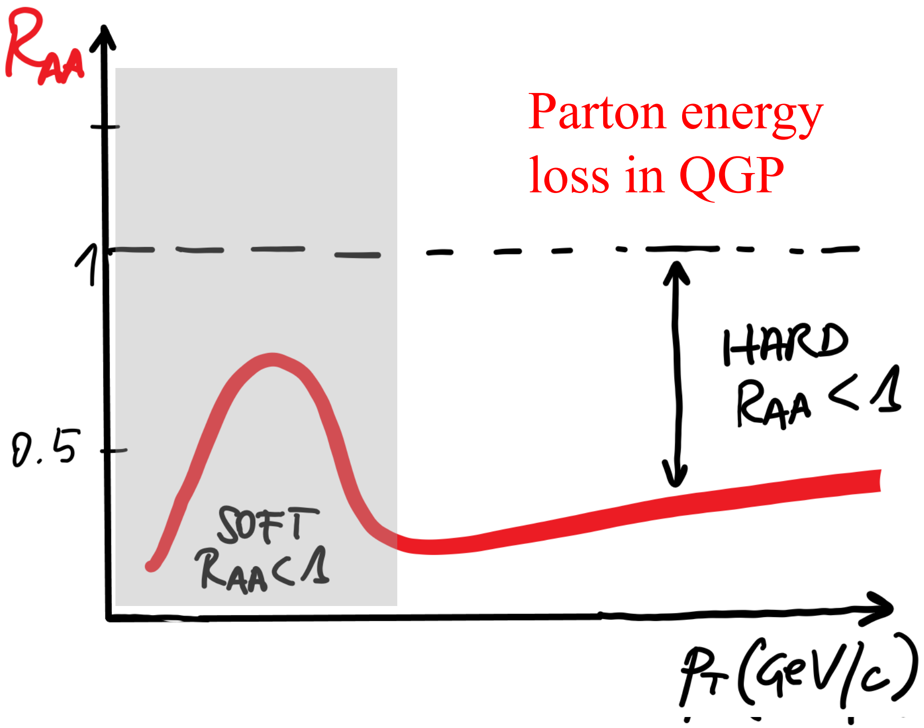


CMS event displays



The nuclear modification factor, R_{AA}

$$\boxed{R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}}$$



Parton energy loss in QGP

If a AA collision is a incoherent superposition of independent pp collisions:

$$\mathrm{d}N_{AA}/\mathrm{d}p_T = N_{coll} \times \mathrm{d}N_{pp}/\mathrm{d}p_T$$

and $R_{AA} = 1$ at high p_T
→ the medium is transparent to the passage of partons

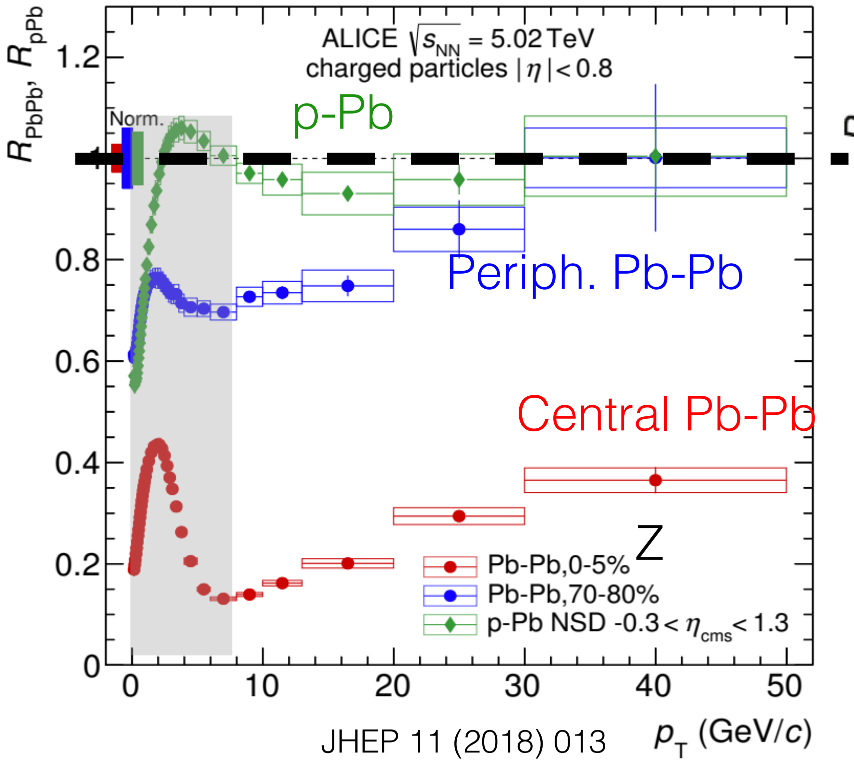
Note: at low p_T, soft, non perturbative regime → R_{AA} not a good observable

If $R_{AA} < 1$ at high p_T
→ the medium is opaque to the passage of partons
→ **parton-medium final state interactions, energy loss, modification of fragmentation in the medium**

Evidence of parton energy loss in QGP

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

Charged particles



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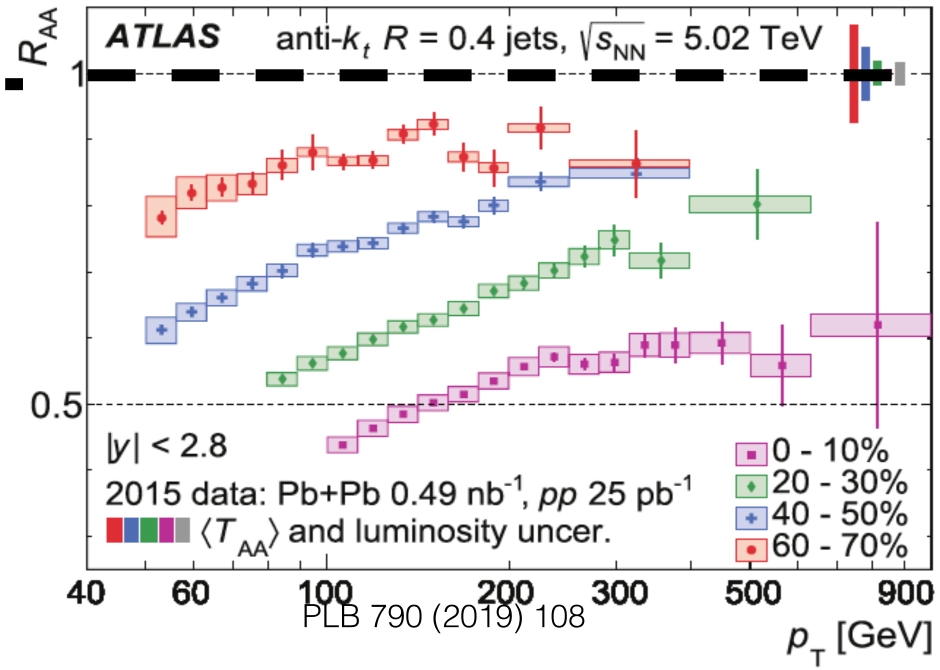
Inclusive jets



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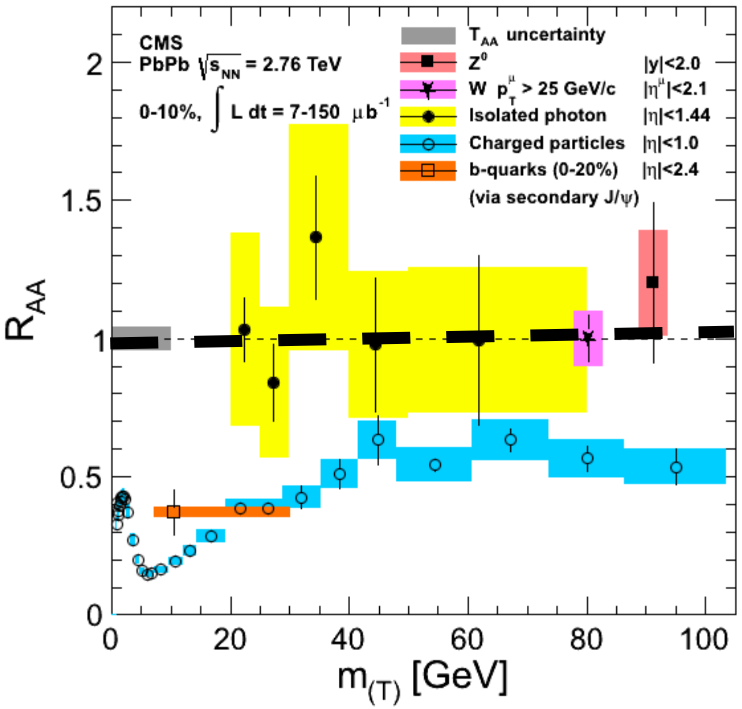
EW bosons



A strong suppression of high-p_T hadrons and jets is observed in central Pb-Pb collisions.

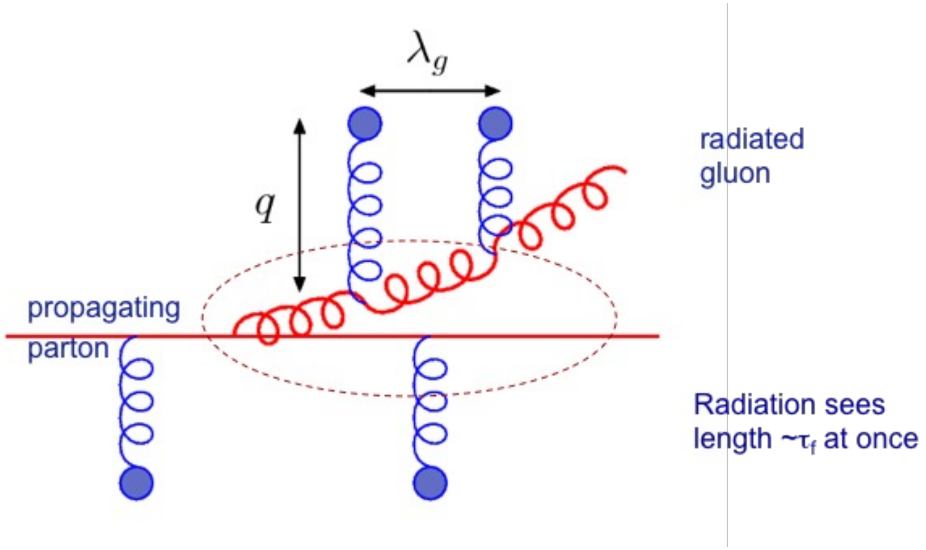
No suppression observed in p-Pb collisions, nor for the color-less Z bosons and photons.

→ Jet quenching is explained as **parton energy loss in a strongly interacting plasma**

Radiative energy loss

In the BDMPS (*Baier-Dokshitzer-Mueller-Peigné-Schiff*) approach, the energy loss depends on

- the **color-charge** via the Casimir factors C_r
  - $C_r = C_A = 3$ for g interactions
  - $C_r = C_F = 4/3$ for q,qbar interactions
- the **strong coupling**
- the **path length** L
- the **transport coefficient** $\hat{q}$ ("q-hat")
  - gives an estimate of the "strength" of the jet quenching
  - is not directly measurable → from data through model(s)



$$\boxed{\frac{dE}{dx} = -C_r \alpha_s \hat{q} L}$$

$$\boxed{\hat{q} = \frac{\mu^2}{\lambda}}$$

Average transverse momentum transfer

Mean free path

$$\boxed{\lambda \propto \frac{1}{\rho}}$$

Density

Baier-Dokshitzer-Mueller-Peigné-Schiff, Nucl. Phys. B. 483 (1997) 291

How much energy is lost?

From the BDMPS formula :

$$\langle \Delta E \rangle = \frac{1}{4} \alpha_s \, C_R \, \hat{q} \, L^2 \xrightarrow{\text{Dimensional analysis}} \langle \Delta E \rangle = \frac{\alpha_s \, C_R \, \hat{q} \, L^2}{4\hbar c}$$

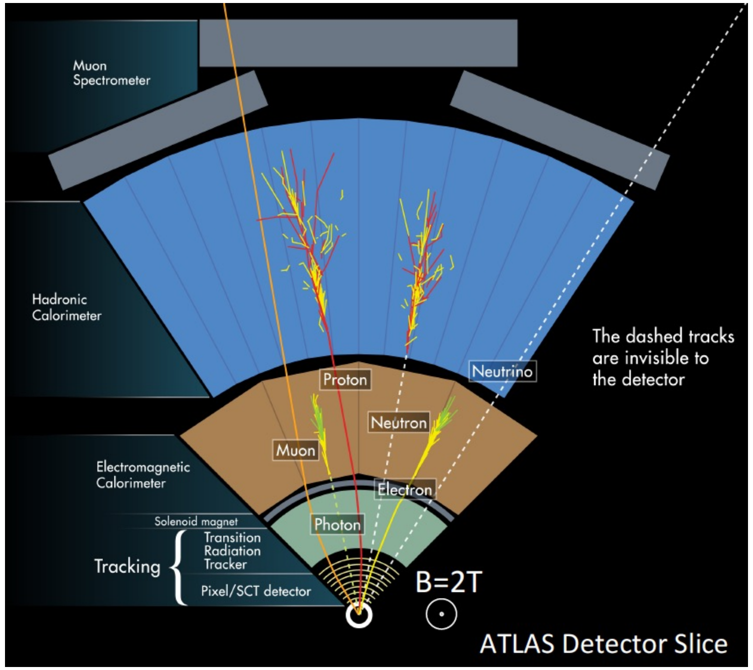
If we take

- $\hat{q}$ ~ 5 $\mathrm{GeV}^2/\mathrm{fm}$
- $\alpha_S = 0.2$, strong coupling for $Q^2 = 10$ GeV
- $C_R = 4/3$
- L = 7.5 fm

we obtain <ΔE> ~ 95 GeV

Only partons with E ≳ 105 GeV can traverse a 7.5 fm radius fireball and exit with $p_T \gtrsim 10$ GeV/c

In other words, it takes a ~7.5 fm radius QGP droplet to stop a jet of ~ 100 GeV (or ~1.5m of hadronic calorimeter!)



Jet transport coefficient $\hat{q}$

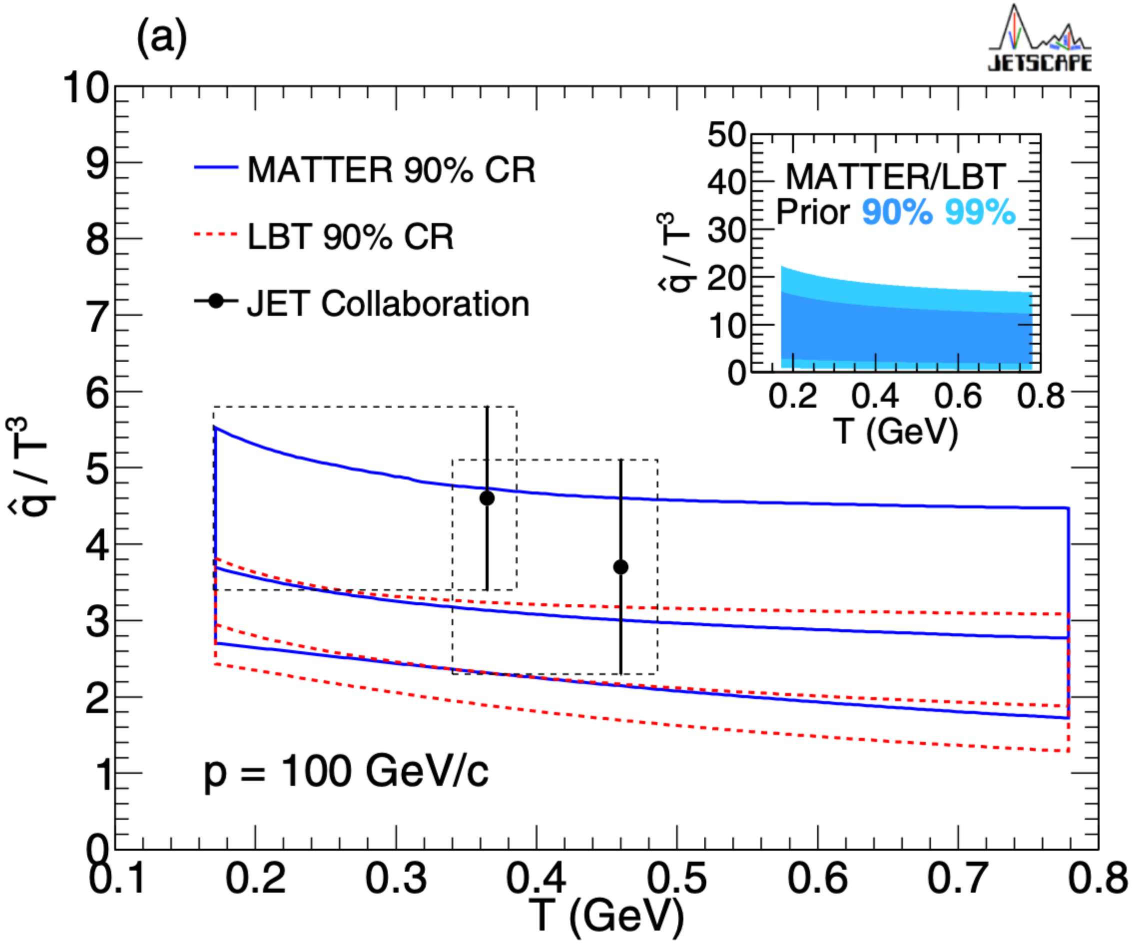
A recent combined analysis of the RHIC and the LHC data on jet quenching (inclusive hadron R_{AA}) allowed to extract a value for the $\hat{q}$ parameter

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

For a quark jet with E = 10 GeV

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

→ Still large uncertainties, but important **step towards a quantitative characterisation** of the QGP.



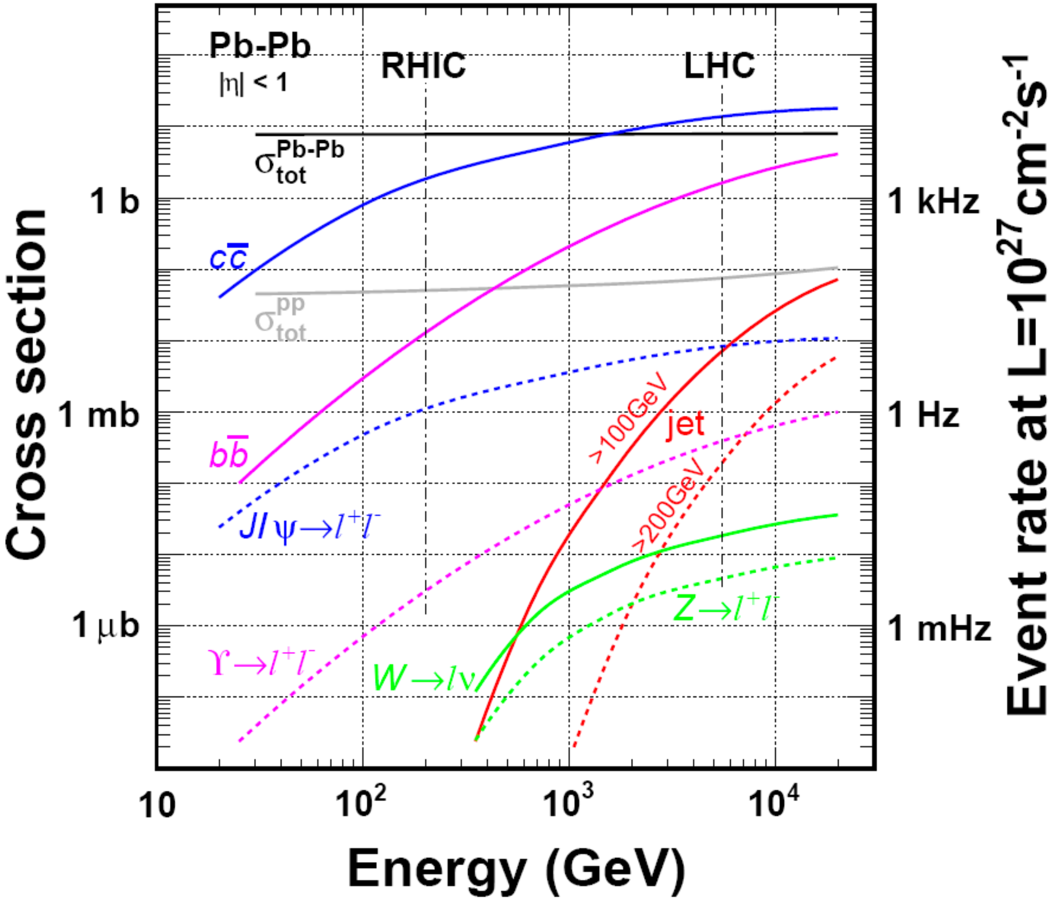
S. Cao et al., PRC 104, 024905 (2021)

Heavy-flavour quarks and hadrons as probes

Ideal probes of the QGP:

- **large production cross sections**
- produced in **initial hard** parton scatterings
- **Caibrated probes** (p-QCD)
- subject to various processes in a QGP

m(charm) ~ 1.3 GeV/c^2
m(beauty) ~ 4.7 GeV/c^2



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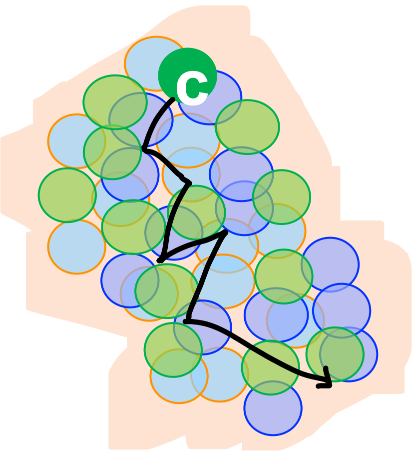
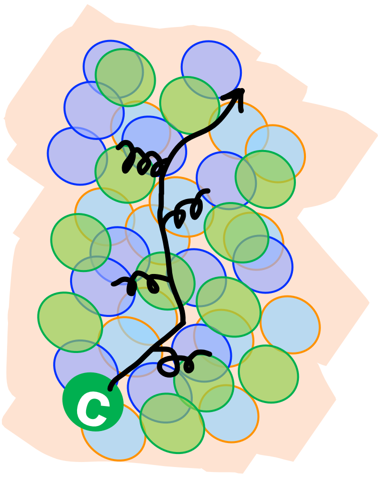
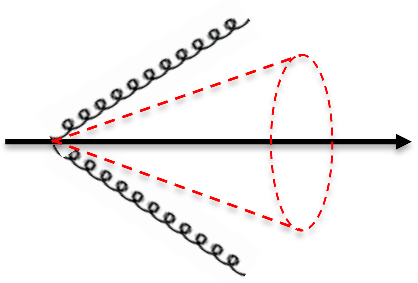
Diffusion: brownian motion at low p_T



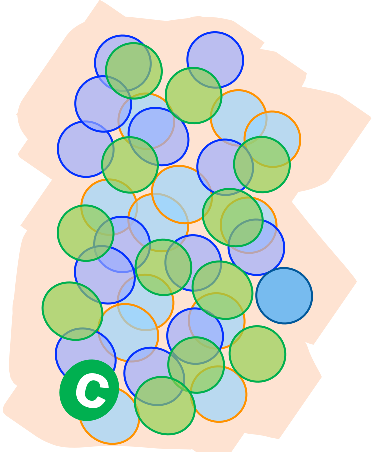
Parton energy loss, radiative + collisional



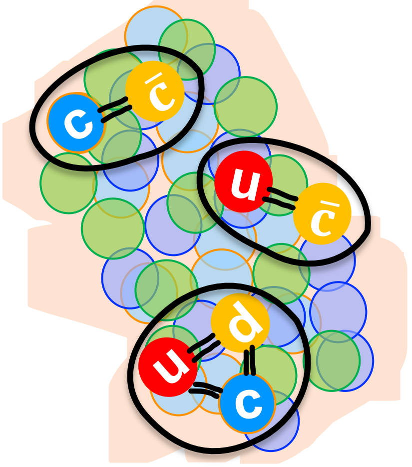
Dead cone effect Suppression of radiative energy loss



q-qbar suppression medium-induced dissociation



Recombination Regeneration or coalescence



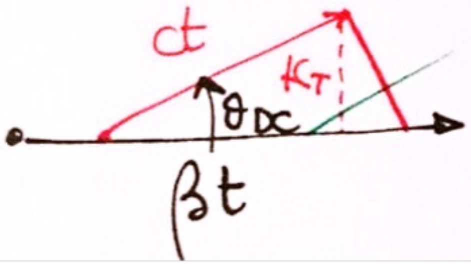
Energy loss of charm and beauty

- by **gluon radiation** (ref. BDMPS formula)
- by **elastic collisions**
- **dead cone effect** = suppression of the gluon radiation emitted by a (slow) heavy quark at small angles, $\vartheta < \vartheta_{DC} \sim m_q/E_q$
  → observed for the first time in pp collisions by ALICE: *Nature 605 (2022) 7910, 440-446*

→ **hierarchy** in energy loss: $\Delta E_g > \Delta E_c > \Delta E_b$

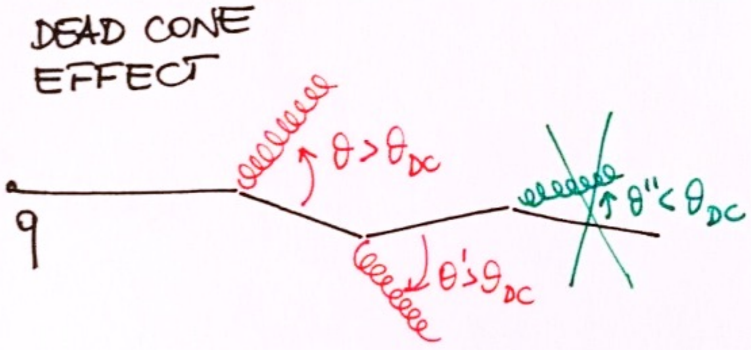
→ radiative energy loss reduced by 25% for charm and 75% for beauty *[for μ = 1 GeV/c^2]*

Dead cone effect



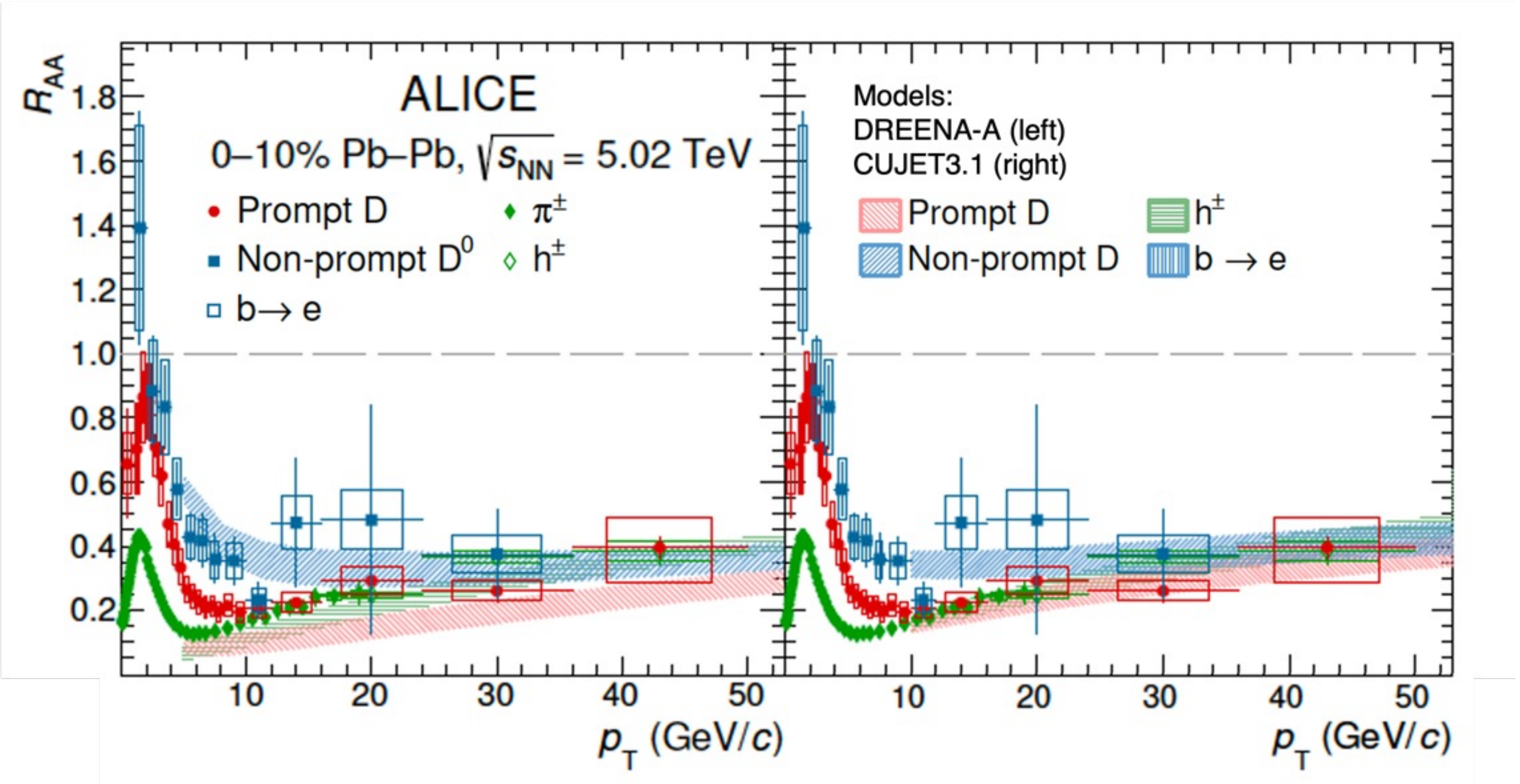
Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602; Dokshitzer and Kharzeev, PLB 519 (2001) 199

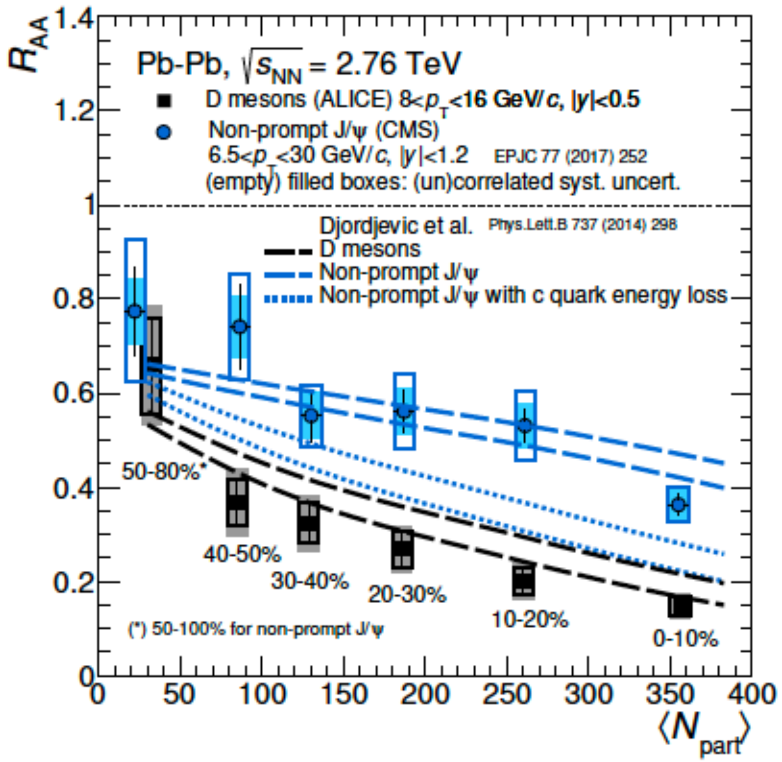
$$\sin\theta_{DC} = 1 - \beta^2 = \left(\frac{M}{E}\right)^2$$



R_{AA} of heavy flavours

- Strong suppression observed for charm and beauty via open charm mesons and leptons from c and b decay.
- Similar suppression for D and pions
- Less suppression for J/ψ from beauty than for D mesons → $\Delta E_c > \Delta E_b$





Prompt: from c quark

Non-prompt: from beauty decay → proxy for b quark

Summary

Evidence of the creation of a strongly-interacting medium in central heavy ion collisions comes from the observed strong suppression of particle production, explained by the energy loss of colored partons in the colored QGP.

- Radiative energy loss dominates at high p_T for light flavours, gluons and charm
- Collisional and radiative energy loss, dead cone effect play a role for beauty

A **quantitative characterization** of the properties of the medium (e.g. transport coefficient, …) requires **models**.