CERN Summer Student Lectures 2024

Heavy Ions 1/3

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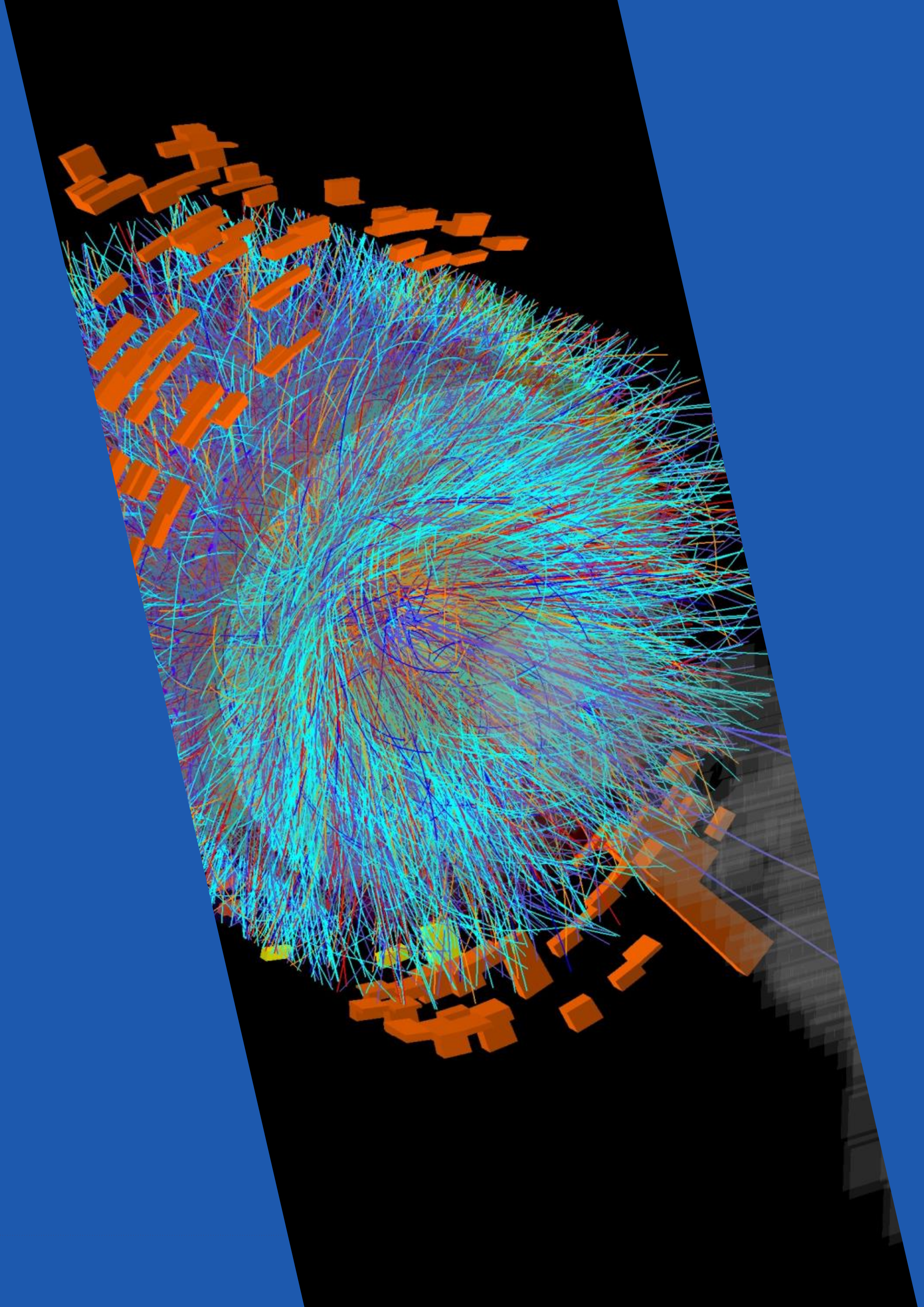


Heavy-ion physics

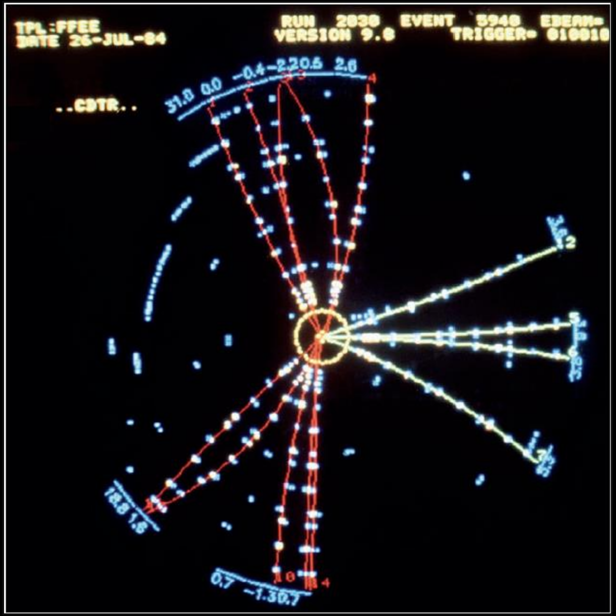
QCD physics

In these lectures:

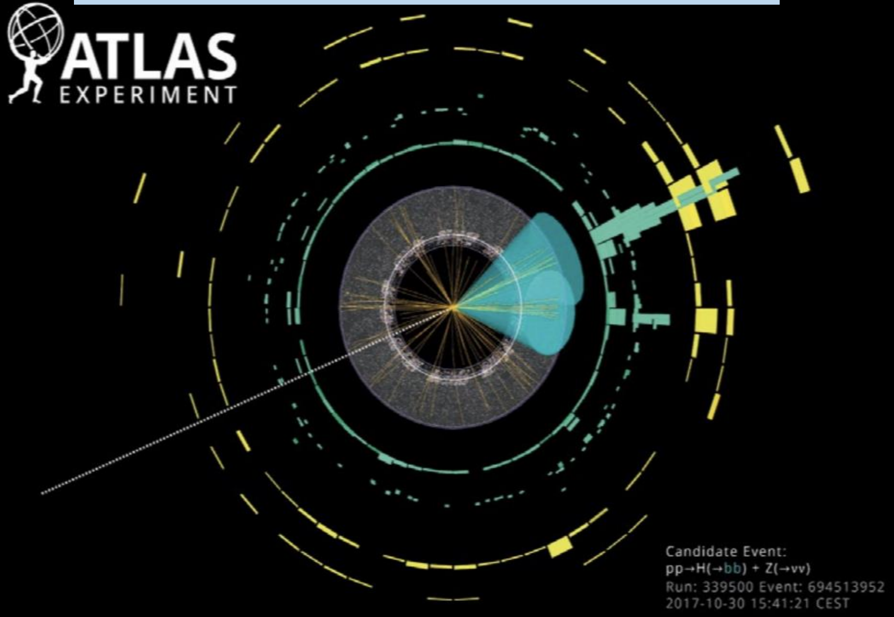
- Basic concepts of QCD and heavy-ion physics
- Experimental principles
- Production and characterization of the QGP at the LHC
- The HIP programme at the LHC: present and future

Take home message in
blue background slides

3 jets at PETRA: $e^+e^- \rightarrow q\bar{q}g$

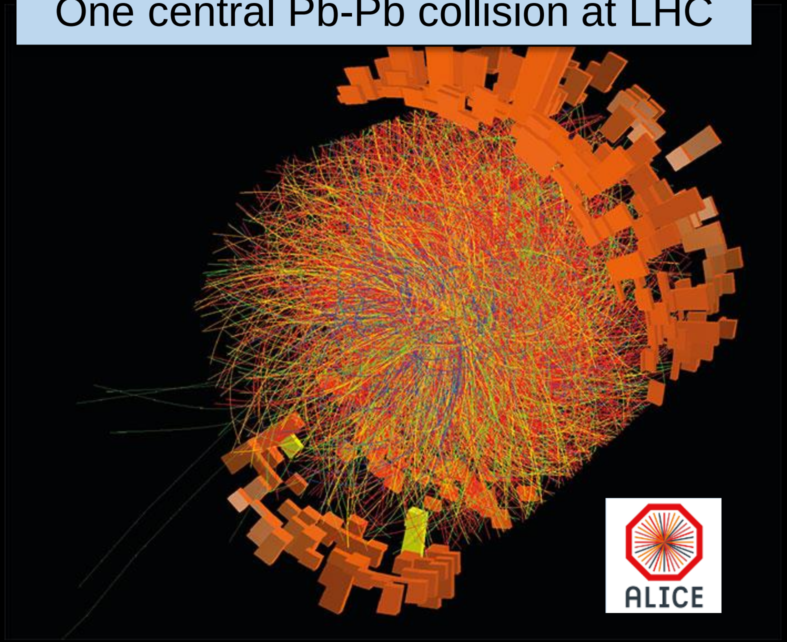


pp → H(→ bbar)+Z event at LHC

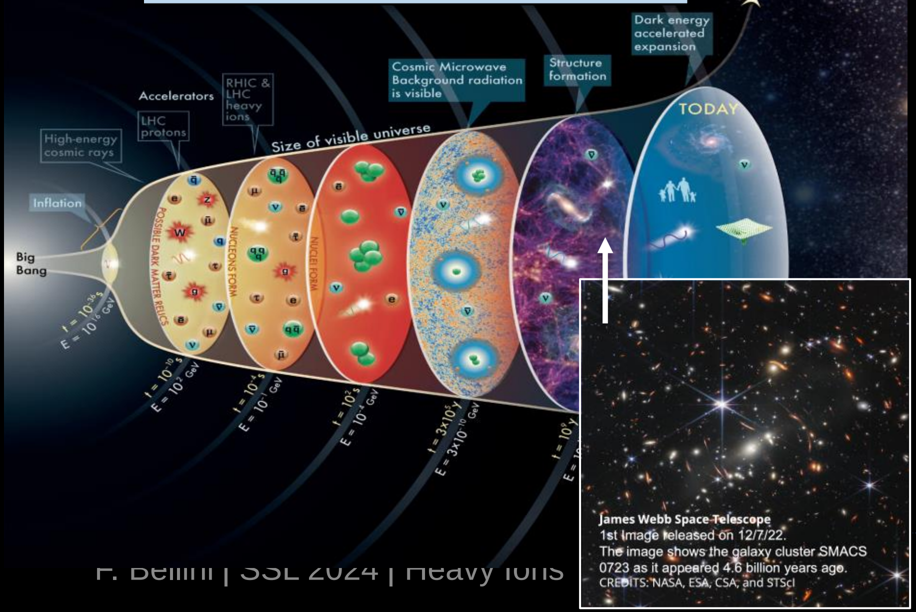


Candidate Event:
pp→H(→bb) + Z(→νν)
Run: 339500 Event: 694513952
2017-10-30 15:41:21 CEST

One central Pb-Pb collision at LHC

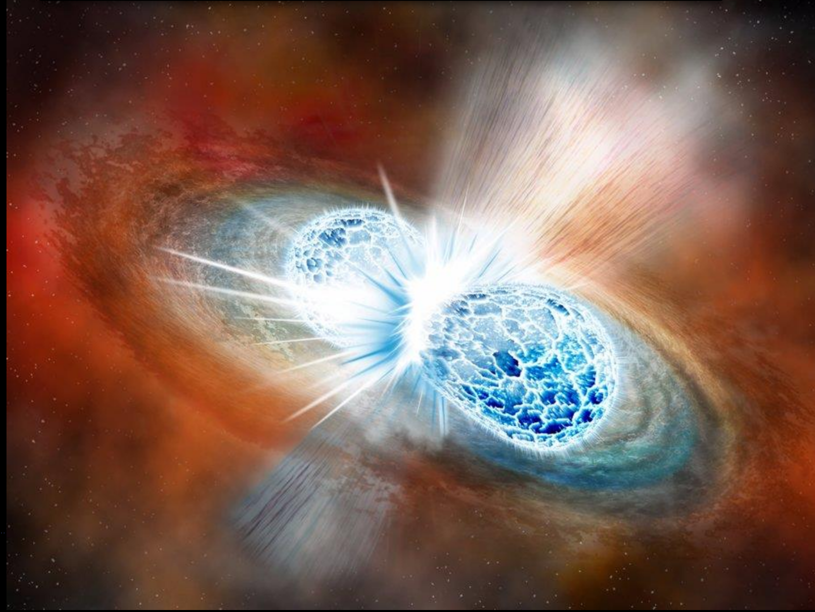


early Universe t ~ 10^{-6} s



James Webb Space Telescope
1st Image released on 12/7/22.
The image shows the galaxy cluster SMACS 0723 as it appeared 4.6 billion years ago.
CREDITS: NASA, ESA, CSA, and STScI

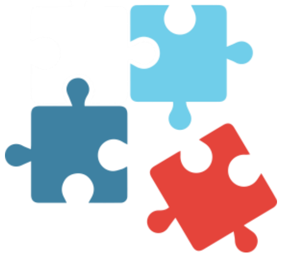
neutron stars and NS mergers



Artist's impression of a neutron-star merger (Image: NASA)

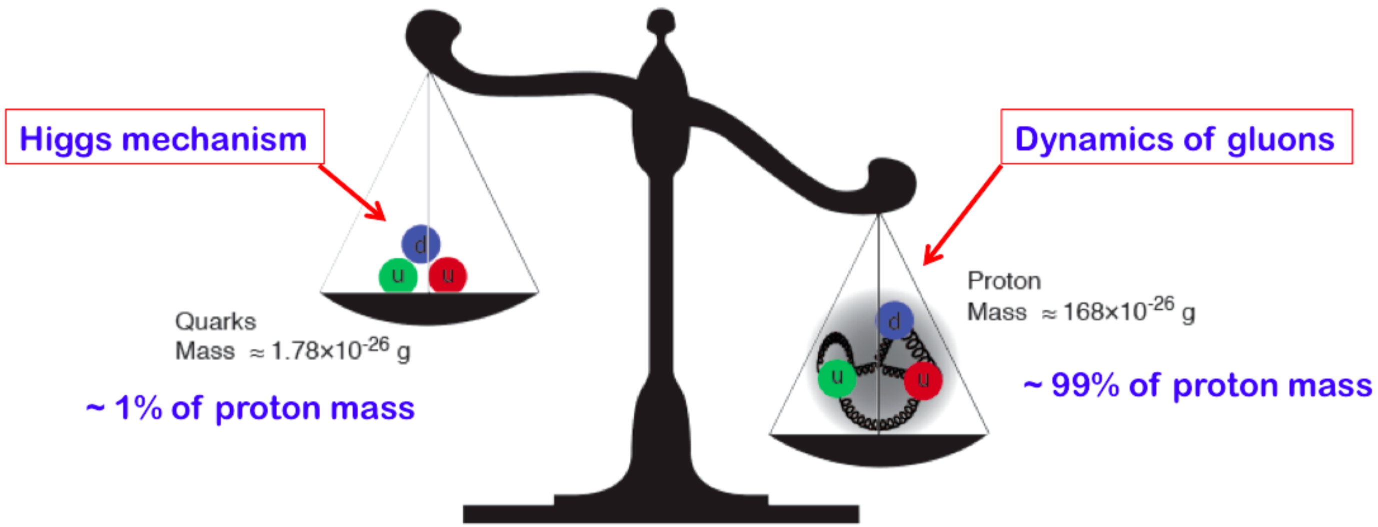
(extra)ordinary matter

Why studying QCD 1/3



Because we have **mass**

- → Mass is concentrated in atomic nuclei, i.e. in protons and neutrons but the mass of protons and neutrons is much larger than the sum of the masses of the valence quarks that come from the Higgs mechanism
- → **Most of the hadron mass comes from the strong interaction among color charges!**

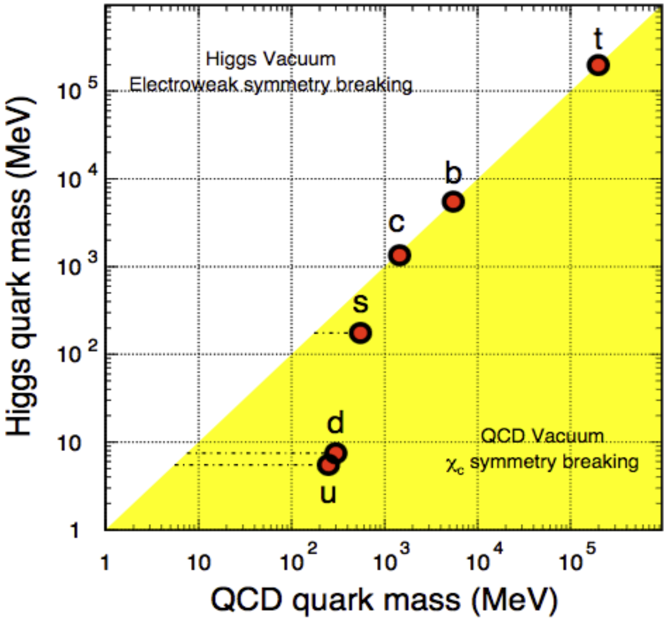


Higgs mechanism

Dynamics of gluons

~ 1% of proton mass

~ 99% of proton mass



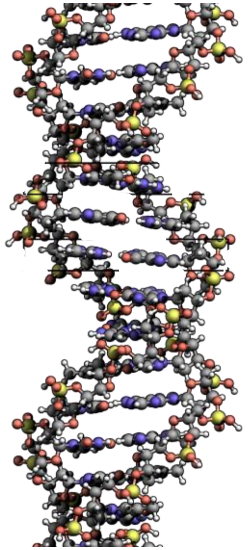
$$\mathcal{L}_{\text{Yukawa}} = -\hat{h}_{d_{ij}}\bar{q}_{L_i}\Phi\, d_{R_j} - \hat{h}_{u_{ij}}\bar{q}_{L_i}\tilde{\Phi}u_{R_j} - \hat{h}_{l_{ij}}\bar{l}_{L_i}\Phi\, e_{R_j} + h.c.$$

Why studying QCD 2/3

Because we are made of **bound (=strongly-interacting!) objects**

→ Nuclear many-body theories attempt to describe how the nuclear structure emerges from the basic properties of the strong interaction… but *«the description of all but the lightest nuclei at the QCD level is inefficient at best, and impossible at worst»* *[H. Hergert (2020), Front. Phys. 8:379]*

→ **We have effective field theories but not yet a complete understanding!**



Carbon-12
98.9%
6 protons
6 neutrons

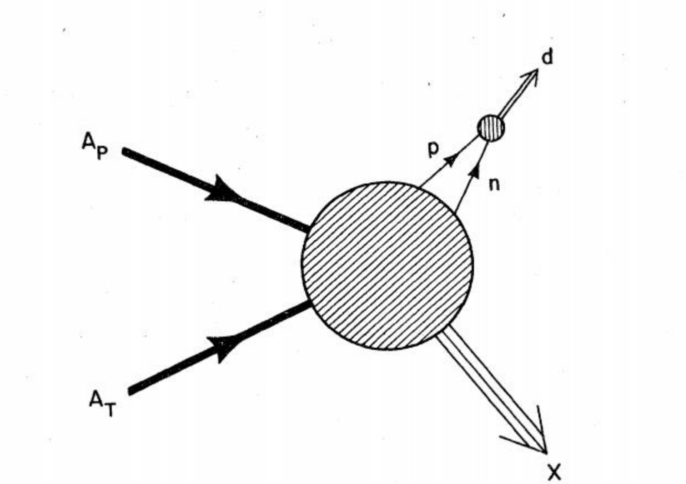
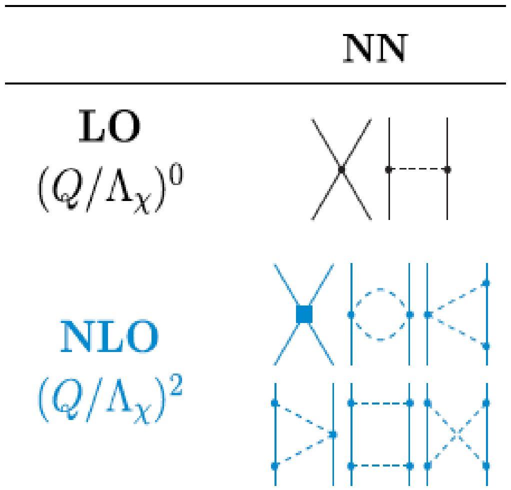


FIG. 1. Schematic for the production of a deuteron in the final state of a relativistic collision between two heavy nuclei.



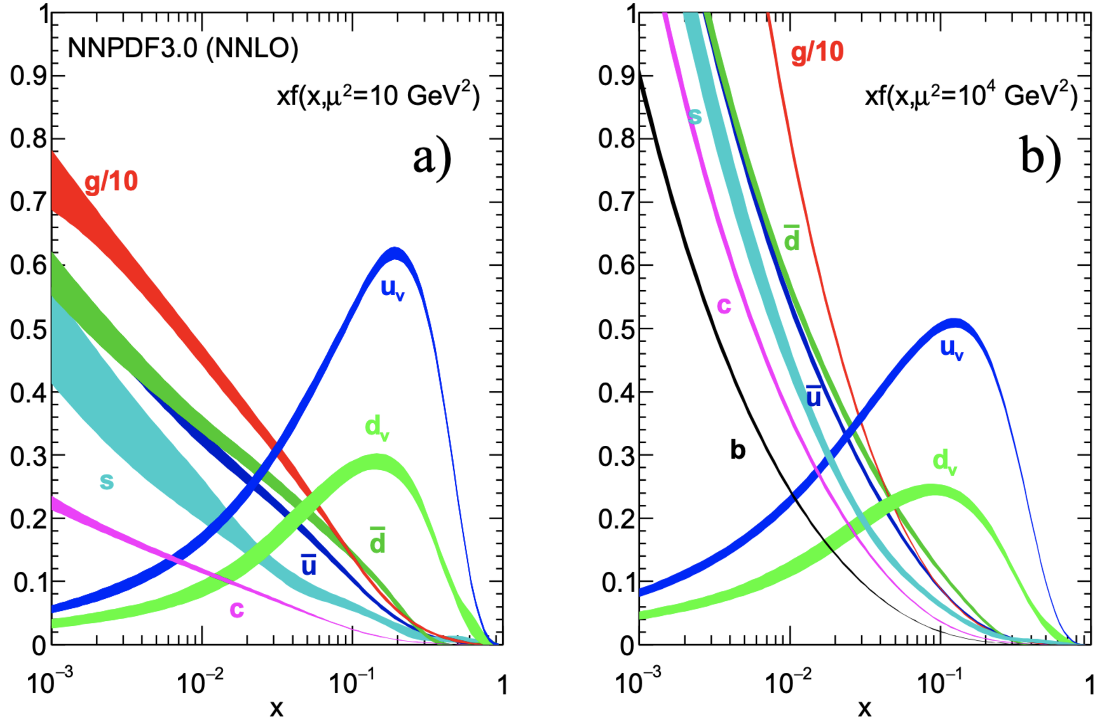
Example of chiral EFT
π-exchange diagrams

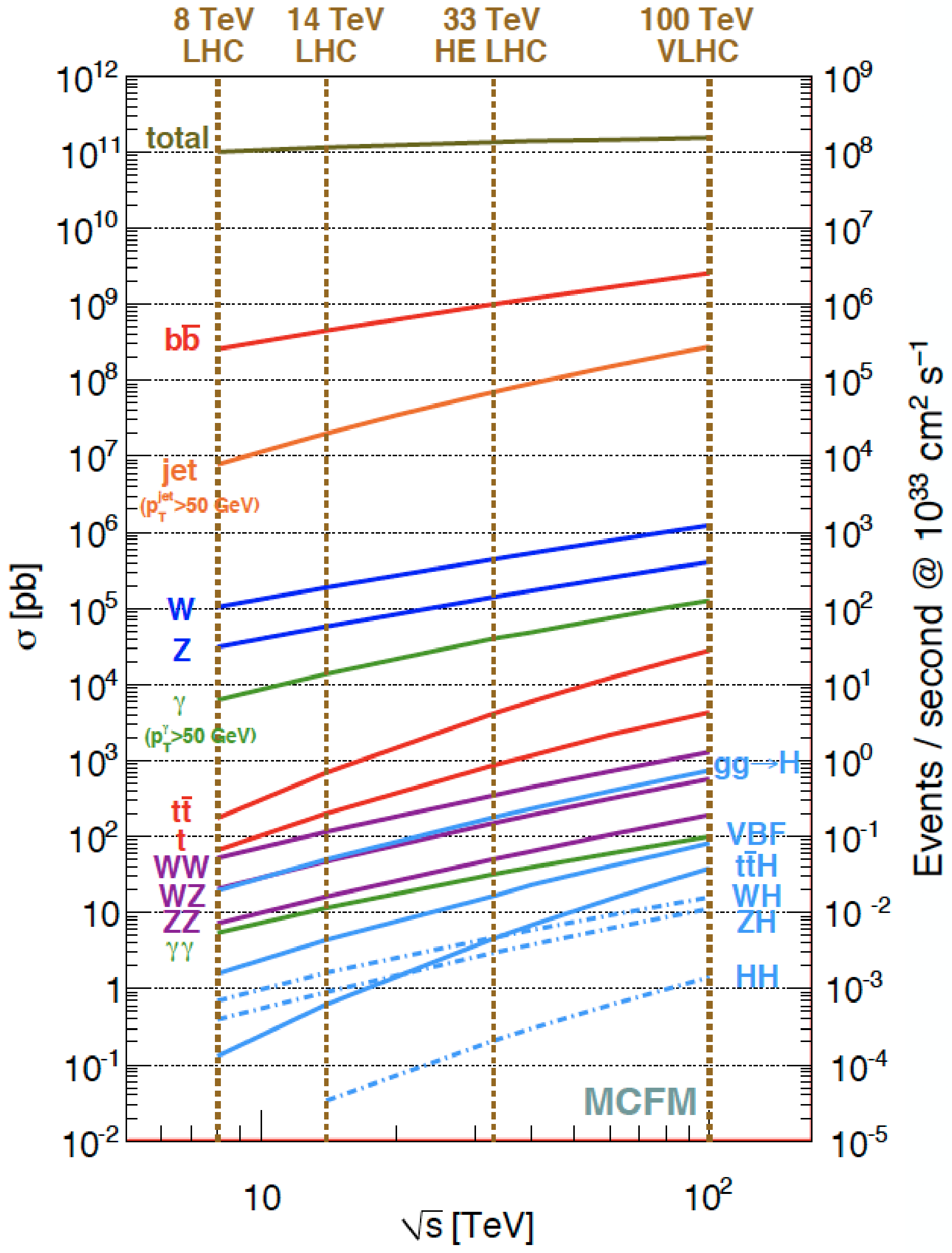
Why studying QCD 3/3

At hadron colliders we **need** knowledge of

- the projectile/target PDFs
- The physical background for Standard Model precision measurements and BSM searches

Proton parton distribution functions (PDFs)





Recall: fundamental properties of QCD

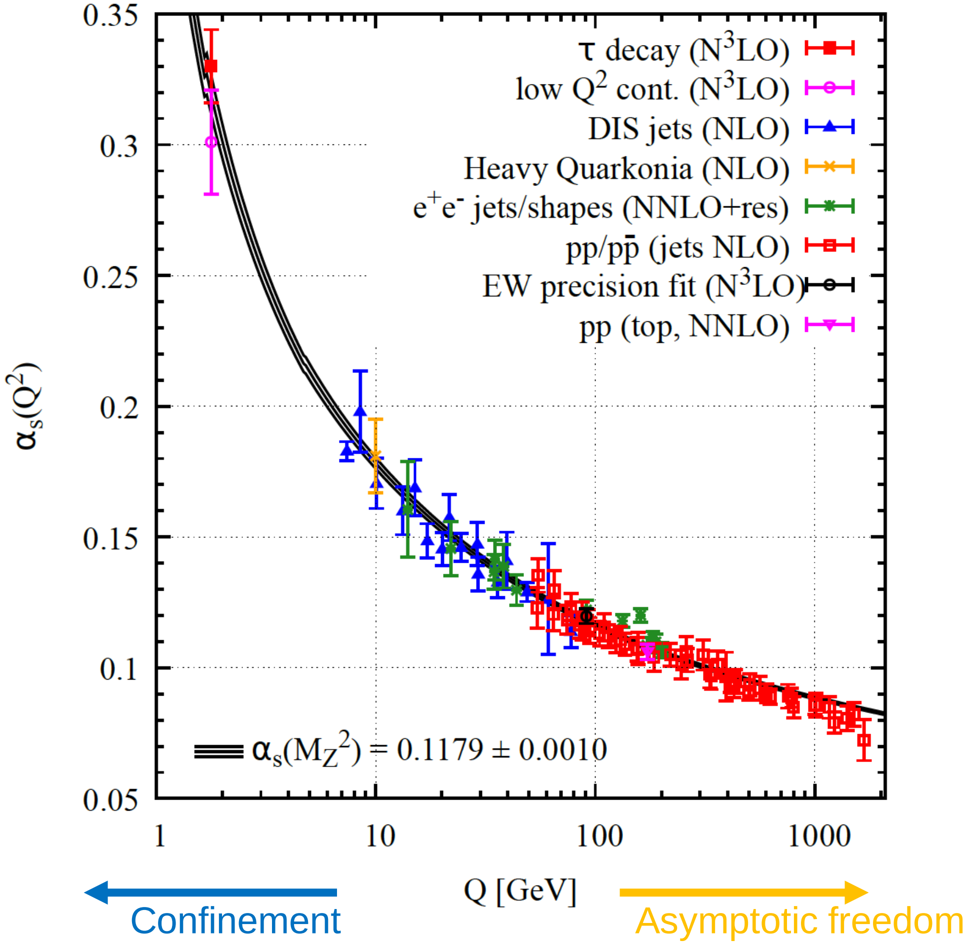
Quarks and gluons exist in nature as confined in colorless hadrons: ordinary matter at room temperature.
→ confining property of QCD

The strong coupling, i.e. the effective strength of the interaction, becomes weaker for processes involving larger quadrimomentum exchange.
→ asymptotic freedom

Chiral symmetry in QCD:

- Spontaneously broken in the chiral limit
- Explicitly broken by non-zero quark masses

→ the **mass** of hadrons is a consequence of the strong interaction acting among their constituents.



The QCD phase transition (a very simplified picture)

At low temperature and “normal” density, i.e. us in this room at T ~ 1/40 eV, colored partons are confined in hadrons with chiral symmetry being broken (giving 99% mass to the proton!)

Idea developed back in the 1970’s:

by **heating** hadronic matter up to high T and **compressing** it at high pressures, we can observe a **phase transition** from **confined** matter to a deconfined state made of colored quarks and gluons

→ *What are the critical conditions at which the QCD phase transition occurs?*

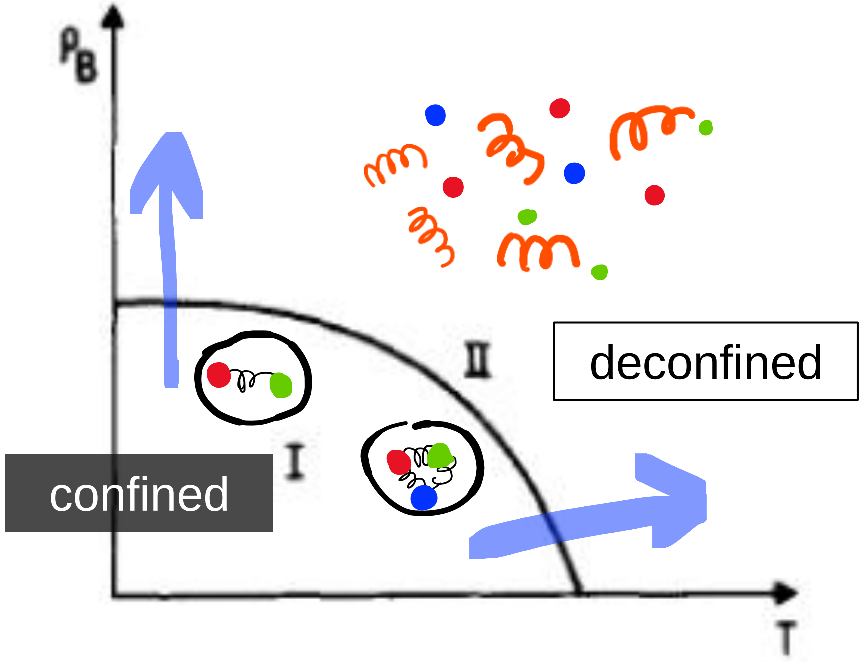


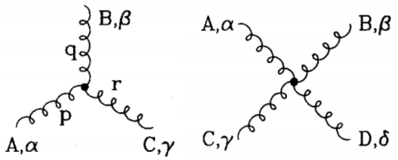
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

N. Cabibbo, G. Parisi, Phys. Lett. B59 (1975) 67
J.C. Collins, M.J. Perry, Phys. Rev. Lett. 34 (1975) 1353

Understanding confinement

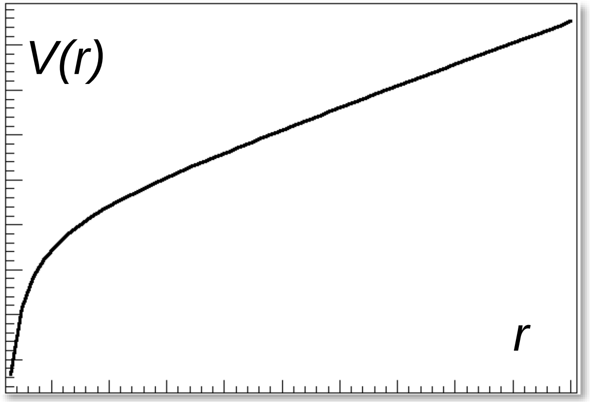
Properties of the QCD vacuum:

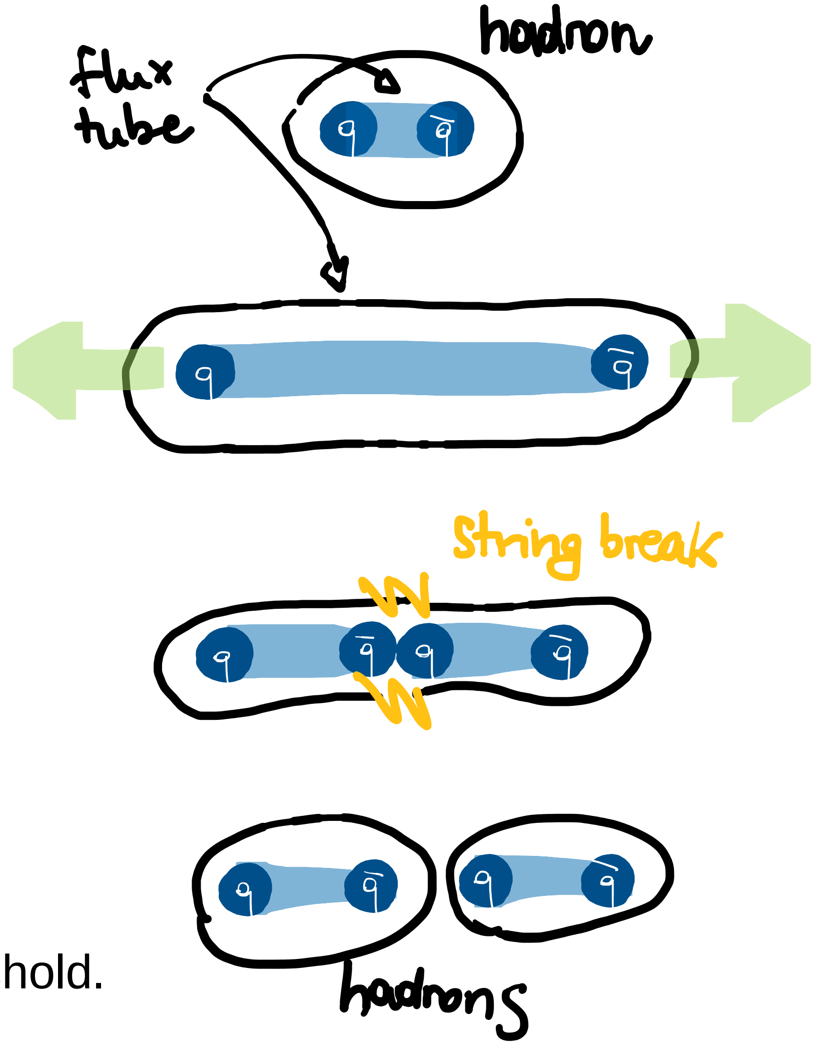
- Gluon-gluon self-interaction (non-abelian)
- QCD field lines compressed in flux tube (or “string”)



The q-qbar potential is of the form (Cornell potential):

$$\boxed{V(r) = -\frac{a}{r} + \sigma r}$$

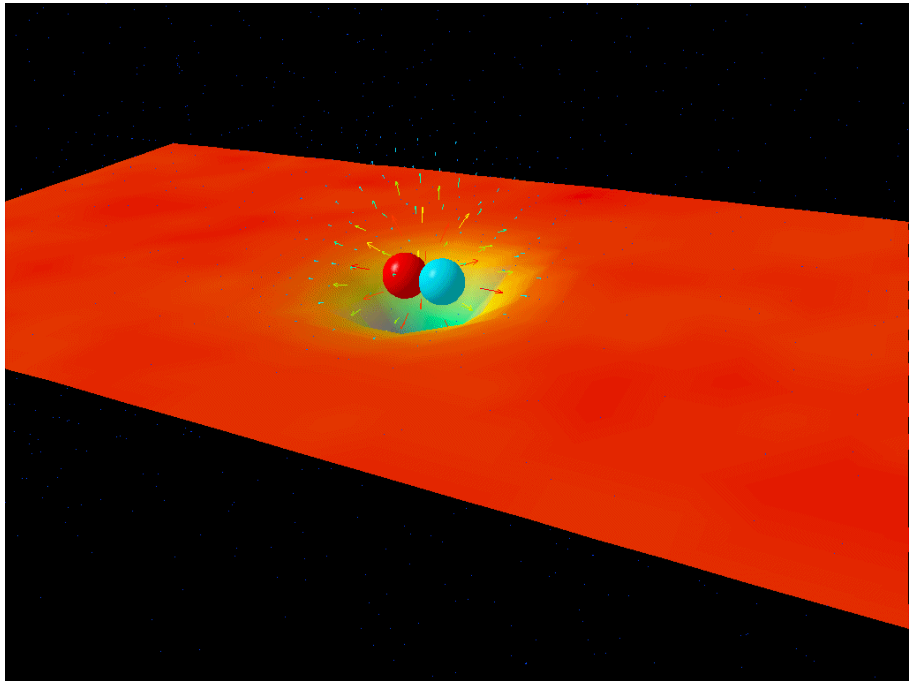


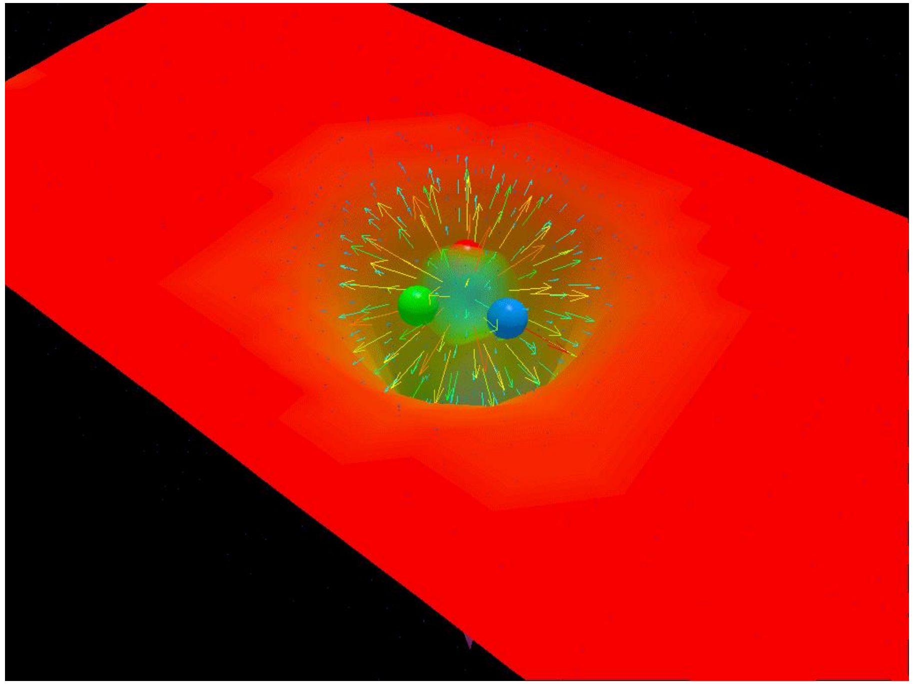


- The potential grows with distance.
- If pulled apart, the energy in the string increases
- A new q-qbar pair is created once the energy is above production threshold.
- No free quark can be obtained by breaking a flux tube → confinement

QCD flux tubes in lattice QCD

The animations represent confinement of quarks in mesons and baryons as due to flux tubes. The color-scaled surface represent the QCD vacuum action density, which gets suppressed in the region among the (two or three) quarks (coloured spheres). A linear confinement potential is felt between quarks in baryons as well as mesons.





Animations from: http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/ImprovedOperators/index.html
F. Bissey, et al, Phys. Rev. D **76**, 114512 (2007) [arXiv:hep-lat/0606016]

The MIT Bag model

A simple phenomenological model, describes confinement by assuming that hadrons are confined in bubbles of perturbative (= empty) vacuum and are surrounded by QCD vacuum (a fluid of gg pairs) exerting pressure.

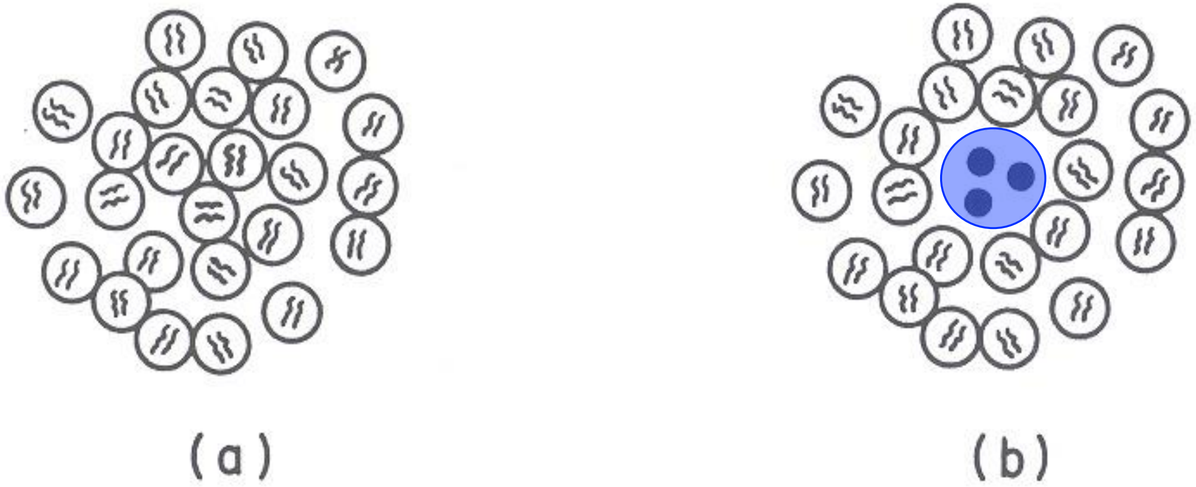


FIG. 9. The QCD vacuum state is depicted in (a). It is a random distribution of cells that contain a gluon pair in a color and spin singlet state. Quarks (in a color singlet configuration) displace these cells, creating a region (or "bag") of "empty" vacuum, as shown in (b).

A. Chodos, R. L. Jaffe, K. Johnson, C. B. Thorn, and V. F. Weisskopf, Phys. Rev. D ***9****, 3471;*
T. DeGrand, R.L. Jaffe, K. Johnson, J. Kiskis, Phys. Rev. D12 (1975) 2060

The MIT Bag model (2)

Inside the bag, quarks have very small masses and the interaction is weak

Outside the bag, quarks are not allowed to propagate, no colored partons, but quark and gluon condensates

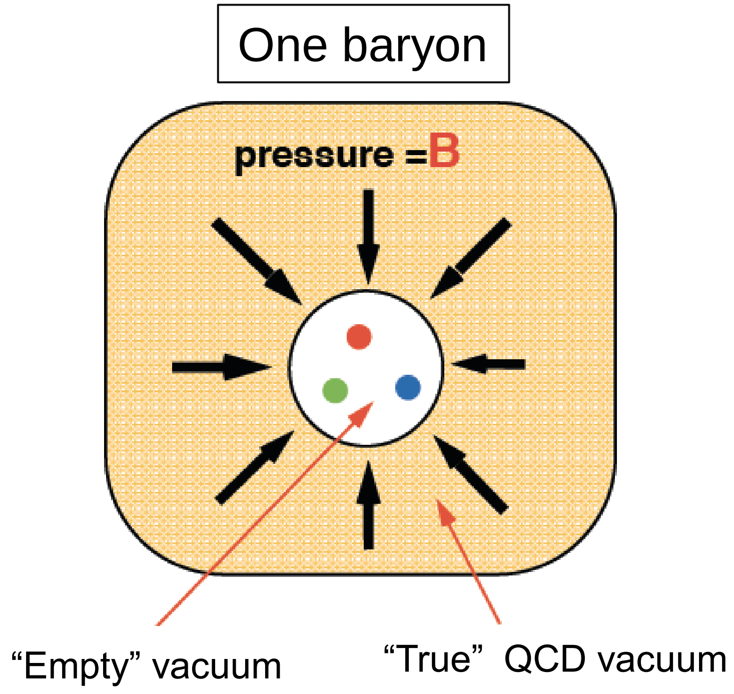
The equilibrium between the kinetic pressure of the quarks inside the hadron vs the pressure of the surrounding QCD vacuum ("bag pressure", *B*) defines the radius *R* of the hadron.

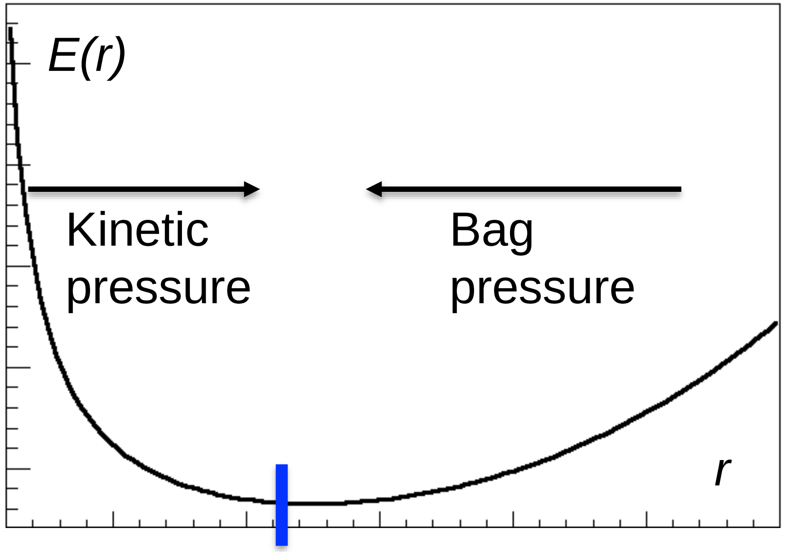
If the hadron can be modeled as *N* massless Dirac fermions in a spherical cavity,

$$E = \frac{2.04N}{R} + \frac{4\pi}{3}R^3B$$

By asking $\partial E/\partial R = 0$ and $R(p) \sim 0.8$ fm

→ $B_{MIT} \sim (200\ \text{MeV})^4$





Deconfinement

For a gas of massless, relativistic partons the pressure can be calculated from the Stefan-Boltzmann law

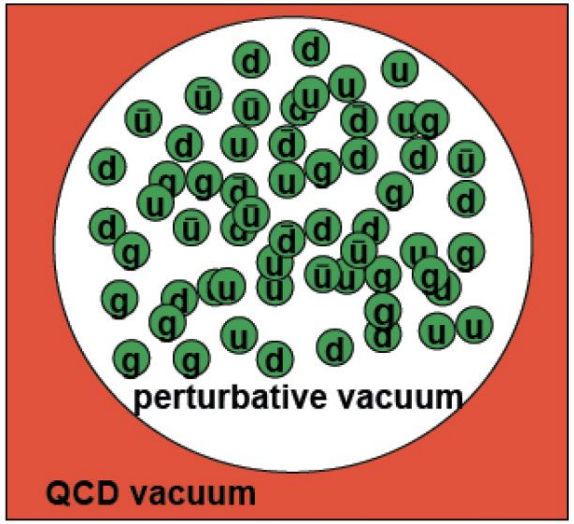
$$P = \left(n_g + \frac{7}{8}n_f\right)\frac{\pi^2 T^4}{90}$$

where the degrees of freedom of the system are

n_g = 8 gluons x 2 spin = 16

n_f = 2 quark flavors x 2 spin x 3 colors + anti-q = 24

A gas of relativistic partons

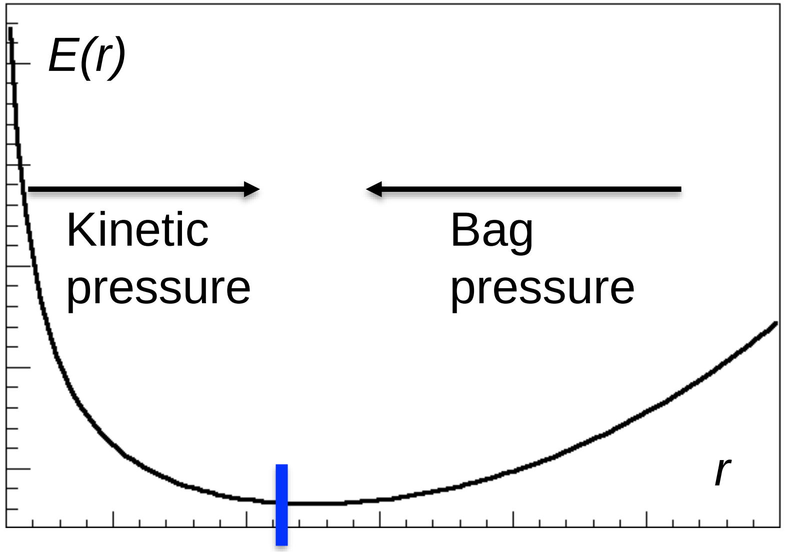


The systems gets **deconfined** if the kinetic pressure exceeds the bag pressure

$P > B \rightarrow T^4 > (200\ \text{MeV})^4 * 90 / (16+7/3) / \pi^2$

$\rightarrow T_c > 141$ MeV (critical temperature)

Above T_c, the system undergoes a phase transition to a state of matter where quark and gluons are (quasi) free, the Quark-Gluon Plasma

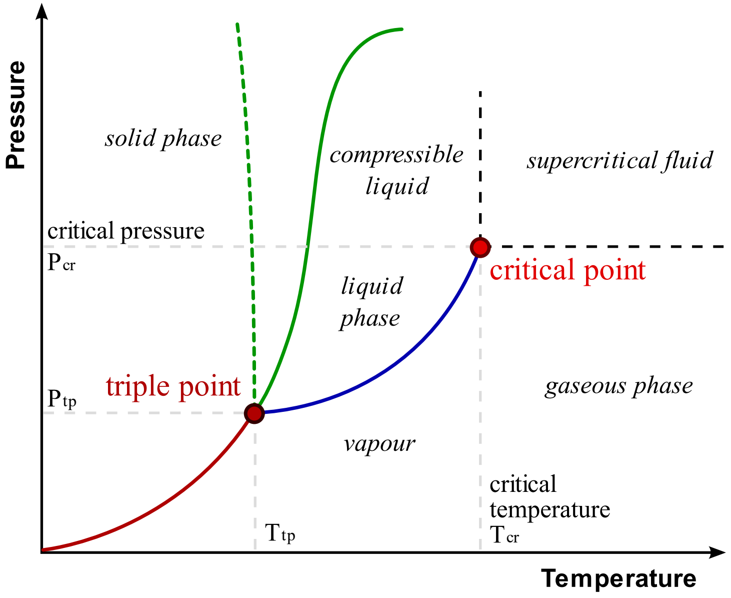


Recall: phase transitions

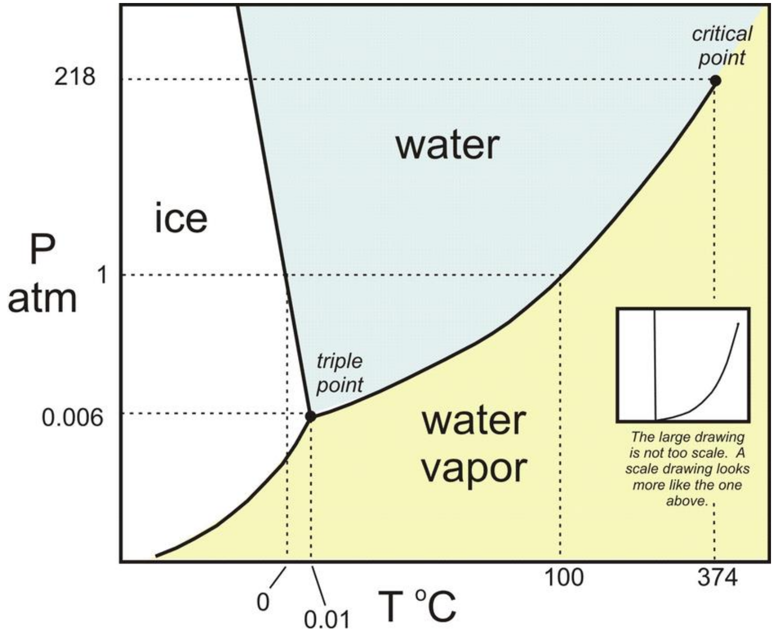
A **phase transition** is the transformation of a thermodynamic system from one phase (or state of matter) to another.
e.g. ice ⇔ water ⇔ vapour
e.g. confinement ⇔ deconfinement in QCD

During a phase transition, certain properties of the medium change, often discontinuously, as a result of external conditions
e.g. pressure, temperature, …

The measurement of these external conditions at which the transformation occurs is called the phase transition point.



Source: wikipedia



Source:http://serc.carleton.edu/research_education/equilibria/phaserule.html%5D

The QCD phase diagram

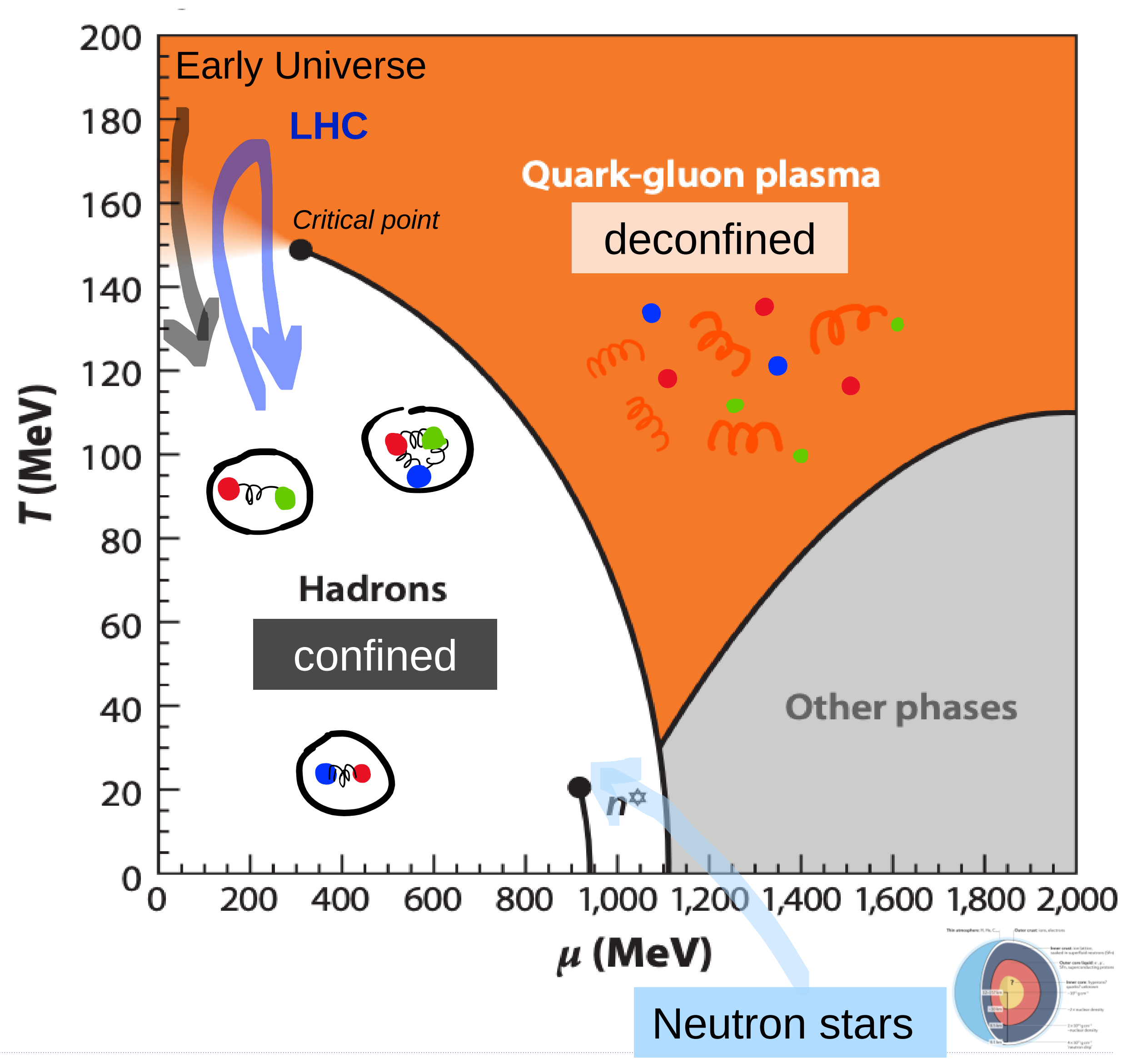
The phases of QCD matter can be summarized in a phase diagram as a function of two parameters:

temperature T and
baryochemical potential μ_B

$$\mu_B = \frac{\partial E}{\partial n_B}\,, \qquad n_B = n(B) - n(\overline{B})$$

$\mu_B = 0$ → antimatter / matter = 1
as at the LHC and in the Early Universe!

The quark-gluon plasma is the deconfined phase of strongly-interacting matter.



Which QCD energy regime are we dealing with?

Having in mind:

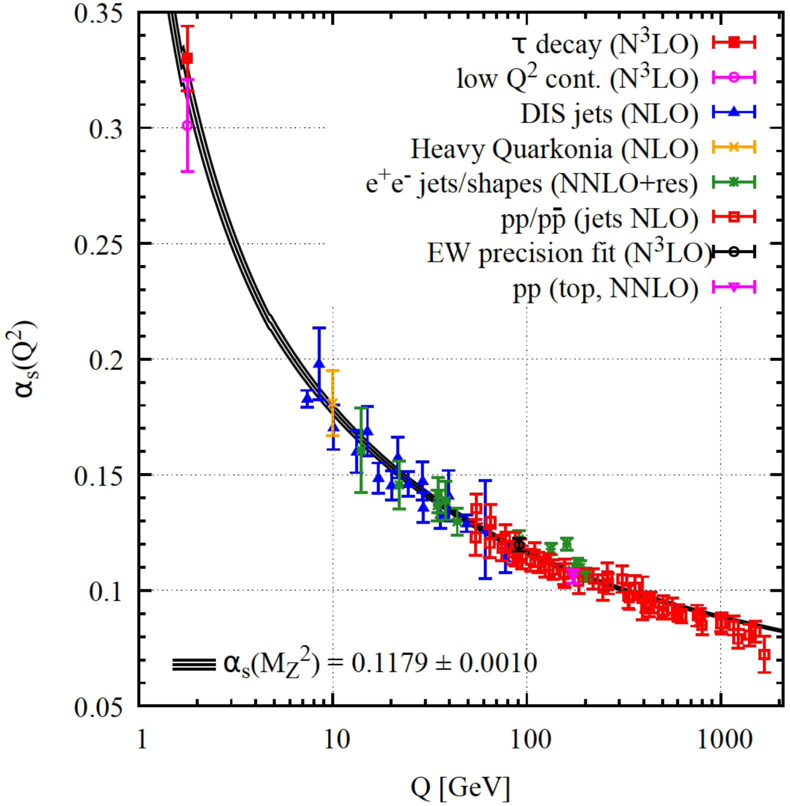
- MIT bag model estimate for the critical temperature: $T_c \sim 140$ MeV
- $\mathbf{\Lambda}_{QCD}(m_{Z,}\, N_f = 3) = 244$ MeV

But also that at $T = 200$ *MeV*, the typical kinetic energy

- for a non-relativistic particle is $E = 3/2\, k_B T = 300$ MeV
- for a relativistic particle is $E = 3k_B T = 600$ MeV

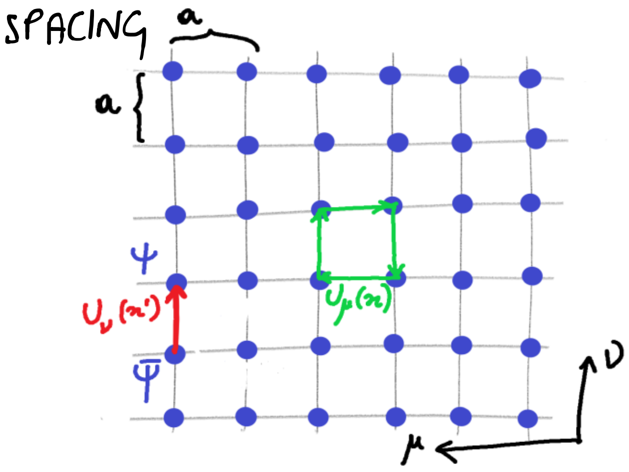
Low Q → α_s is not small!
→ The QCD transition is a non-perturbative QCD problem

- Need models to deal with (phenomenology)
- Use Lattice QCD for calculations from first principles



Lattice QCD basics

Lattice QCD (lQCD) is a well-established non-perturbative method to solve QCD starting from first principles, i.e. the QCD Lagrangian.



The Euclidean space-time is discretized in a 4D-hypercubic lattice with 3 real spatial and 1 imaginary time.

The finite lattice **spacing *a*** acts as an ultraviolet cutoff for the theory.
The quark fields $\psi(x)$ are defined on lattice sites.
The gluon fields $U_\mu(x)$ are defined as links between lattice sites.

The QCD Lagrangian in the Minkowski space is transformed into the action in Euclidean space and then the theory is solved by numerical integration.

IBM BlueGene
Image: Argonne Nat. Lab.

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma_\mu \mathcal{D}^\mu - m)_{ab}\psi_{q,b} - \frac{1}{4}F^A_{\mu\nu}F^{\mu\nu}_A$$

$$i\int d^4x\mathcal{L}(x) \to S_E$$

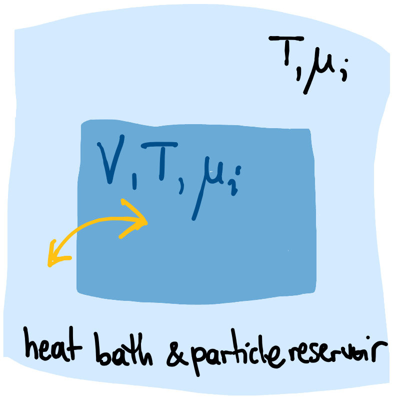
$$S_E = \int d^4x\left[\sum_{\mu,\nu}\underbrace{\frac{1}{2}Tr\{t\cdot F^{\mu\nu}(x)t\cdot F^{\mu\nu}(x)\}}_{\text{Gluon action}} + \underbrace{\bar{\psi}(x)(\sum_\mu \hat{\gamma}^\mu\partial^\mu + m)\psi(x)}_{\text{Fermion action}}\right]$$

Thermodynamics of QCD matter on the lattice

Thermodynamical properties of a quantum system can be calculated according to the principles of statistical mechanics from the **partition function, Z.**

$$\boxed{Z = Tr\left[e^{-\beta(\hat{H}-\mu_i \hat{N}_i)}\right]}$$

$$\begin{aligned} P &= T\frac{\partial \log Z}{\partial V}; \qquad & N_i = T\frac{\partial \log Z}{\partial \mu_i}; \\ S &= \frac{\partial T \log Z}{\partial T} \qquad & E = -PV + TS + \mu_i N_i \end{aligned}$$



A system of **QCD degrees of freedom** can be represented by a **grand canonical** (GC) ensemble, where a given volume element can exchange particles and heat with its surrounding (heat bath and particle reservoir).

$$\mathcal{Z}(T,V,\vec{\mu}) = \int \prod_{\mu} \mathcal{D}A_\mu \prod_{f=u,d,s\ldots} \mathcal{D}\psi_f \mathcal{D}\bar{\psi}_f \; e^{-S_E(T,V,\vec{\mu})}$$

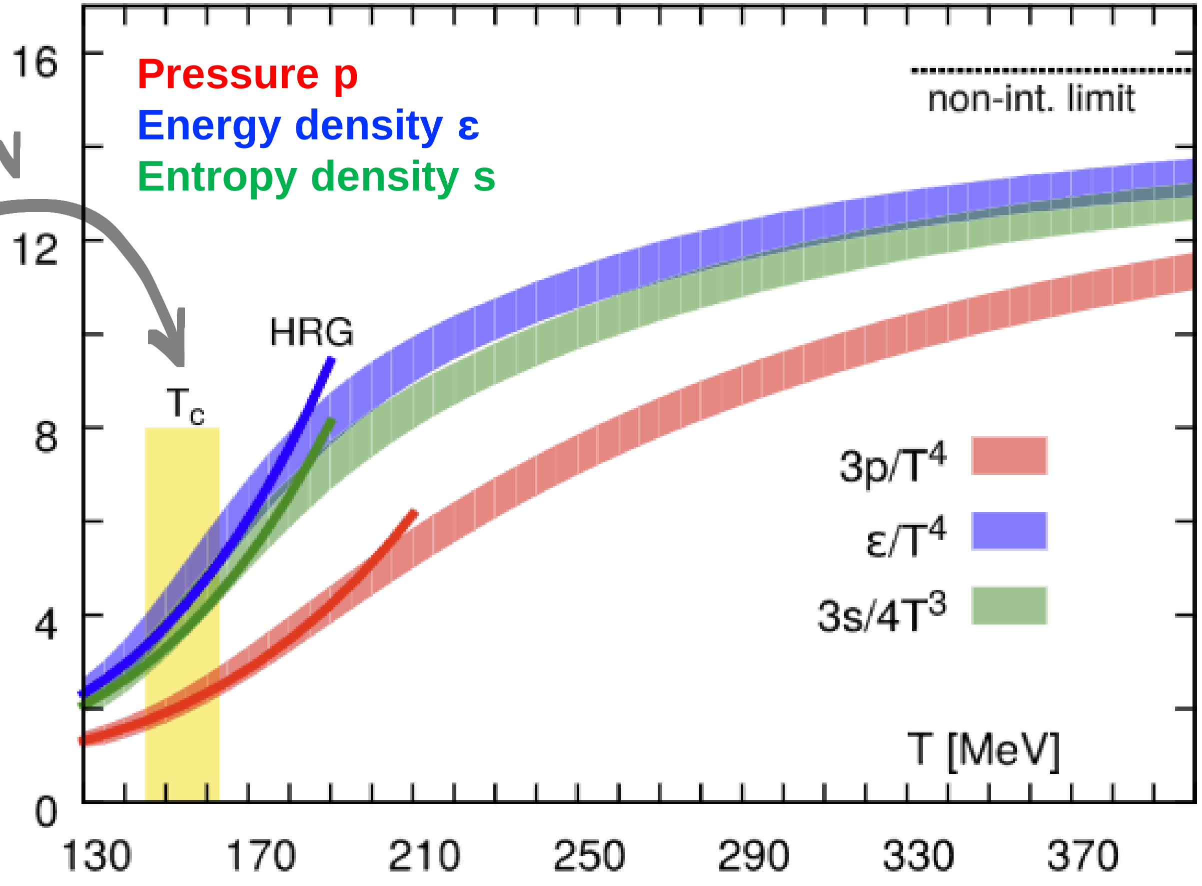
On the lattice, the GC partition function can be used to extract the expectation value of the physical observables.

$$\langle \mathcal{O} \rangle = \frac{1}{Z(T,V,\vec{\mu})} \int \prod_{\mu} \mathcal{D}A_\mu \prod_{f} \mathcal{D}\psi_f \mathcal{D}\bar{\psi}_f \, \mathcal{O} \, e^{-S_E(T,V,\vec{\mu})}$$

Equation of State (EoS) from lattice QCD

HADRONS ← → QUARK–GLUON PLASMA

INFLECTION POINT



A. Bazavov et al., Phys. Rev. D 90 (2014) 094503

↕ STRONGLY INTERACTING!

The steep rise in the thermodynamic quantities is understood as due to a change in the number of degrees of freedom: hadrons ⇔ partons

T_c ~ 155 - 159 MeV

HotQCD Coll. *PLB* 795 (2019) 15-21,
Borsaniy et al. PRL 125 (2020) 5, 052001

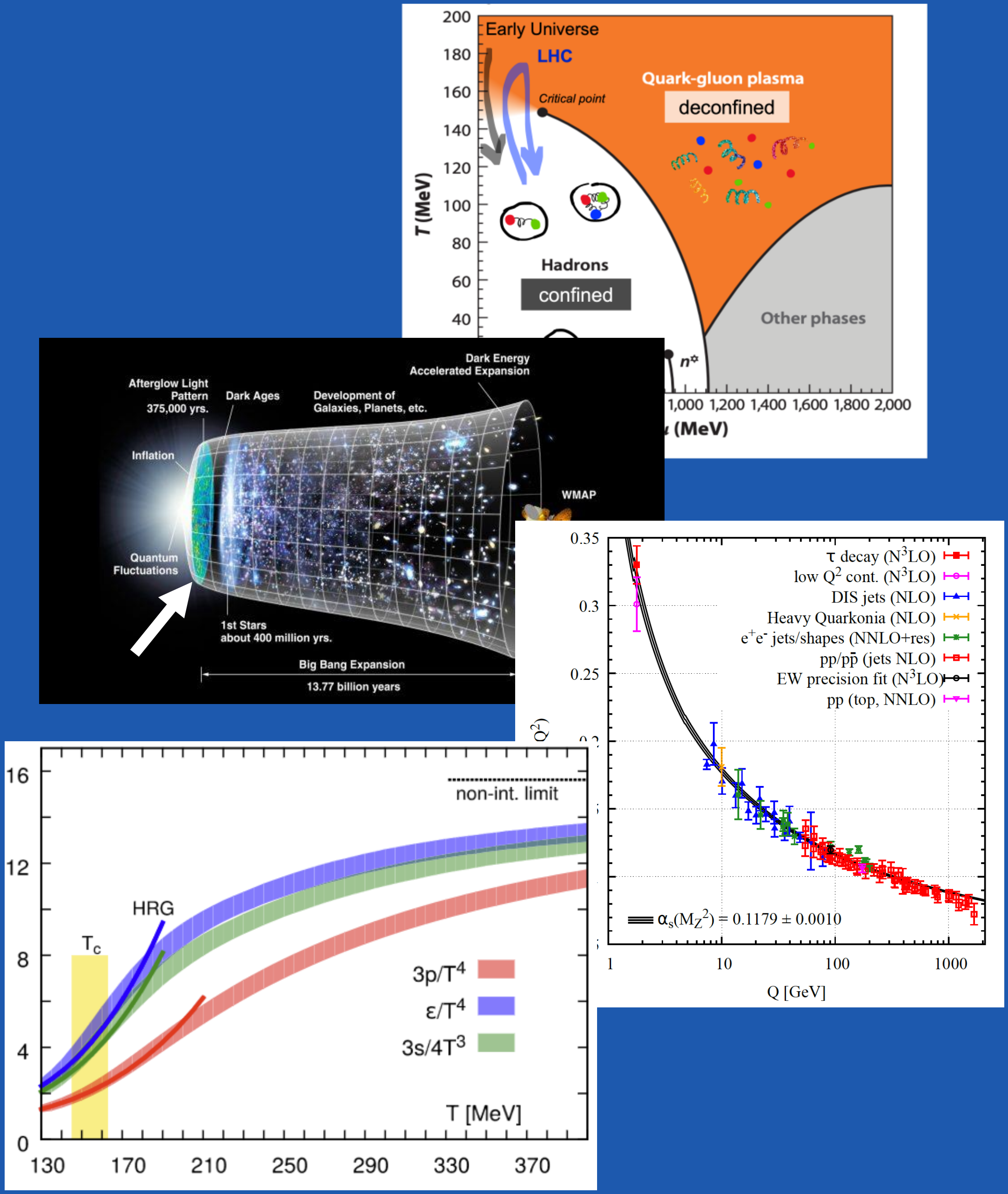
The QGP is a state of strongly-interacting matter resulting from the phase transition of nuclear/hadronic (color-neutral) matter under extreme conditions of pressure or temperature

→ the **Universe** up to O(1-10μs) after the Big Bang

→ the properties of the QGP **emerge** from the fundamental properties of the strong interaction

→ physics of **condensed** QCD matter

Next: the experimental quest towards a **quantitative characterization** of the QGP



Experimental principles

QCD in extreme conditions in the laboratory

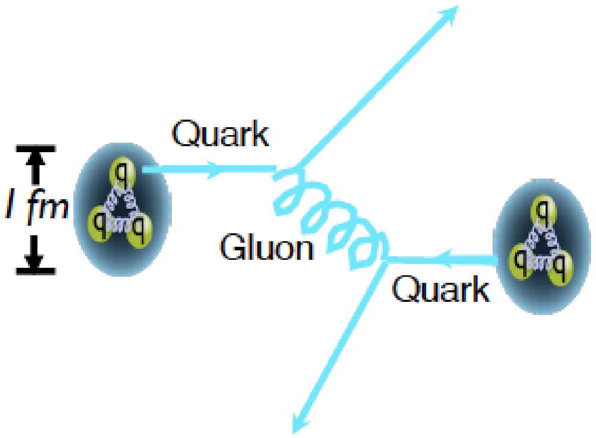
A QGP can be formed by compressing large amount of energy in a small volume

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

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

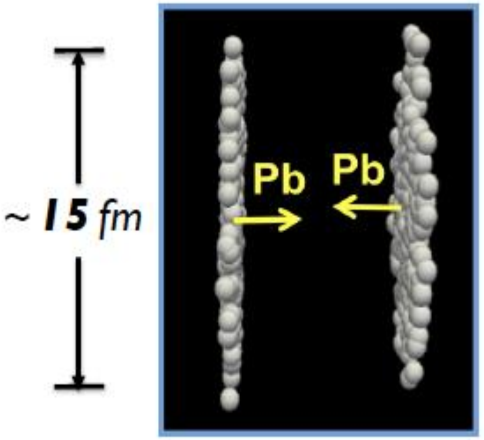
- nuclear species, p-Pb, pp
- vary impact parameter (centrality)

Colliding protons

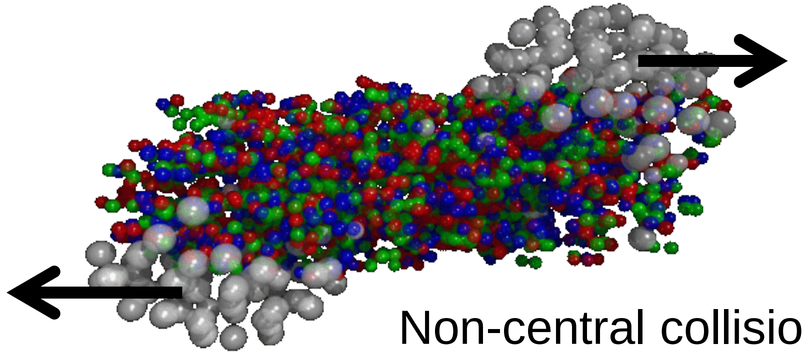


Colliding large nuclei

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:

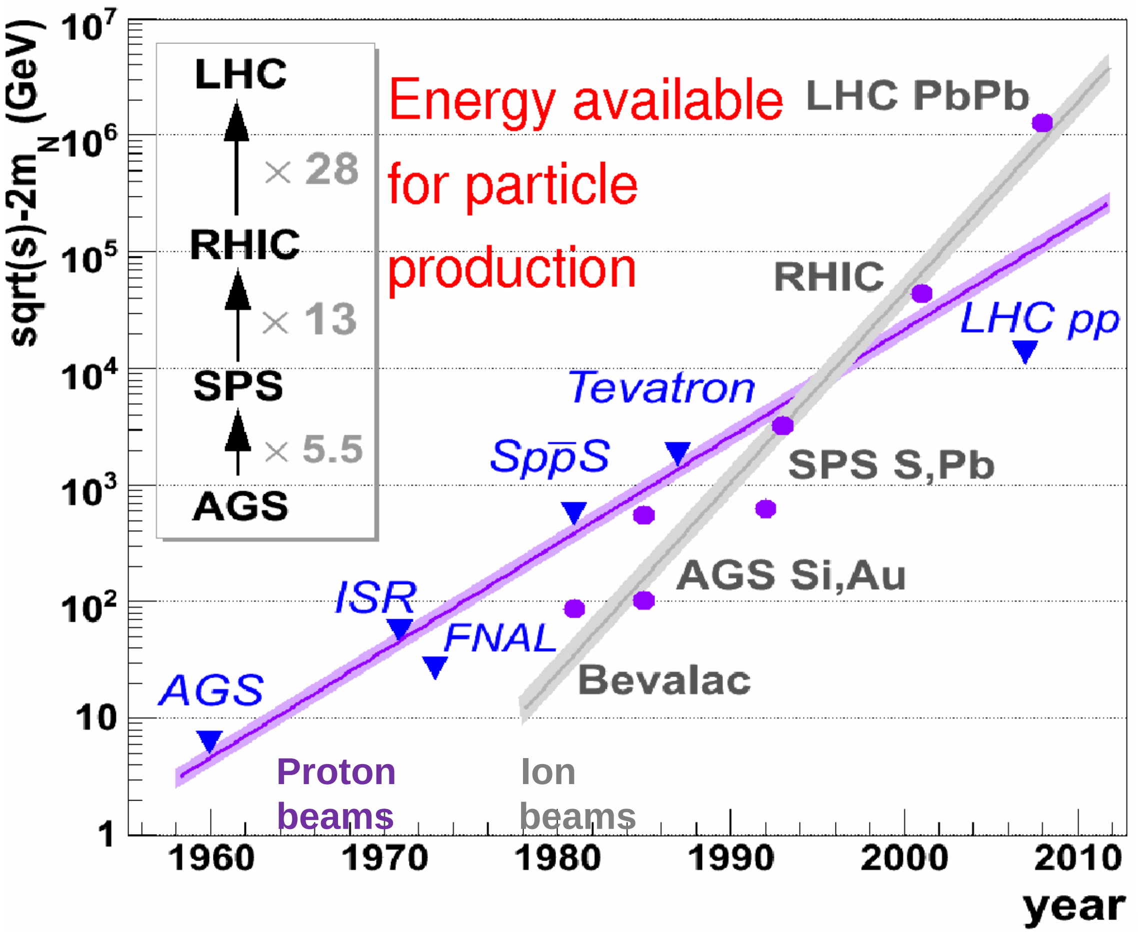
$$p_A = Z/A\ p_{\text{proton}}$$

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:

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

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

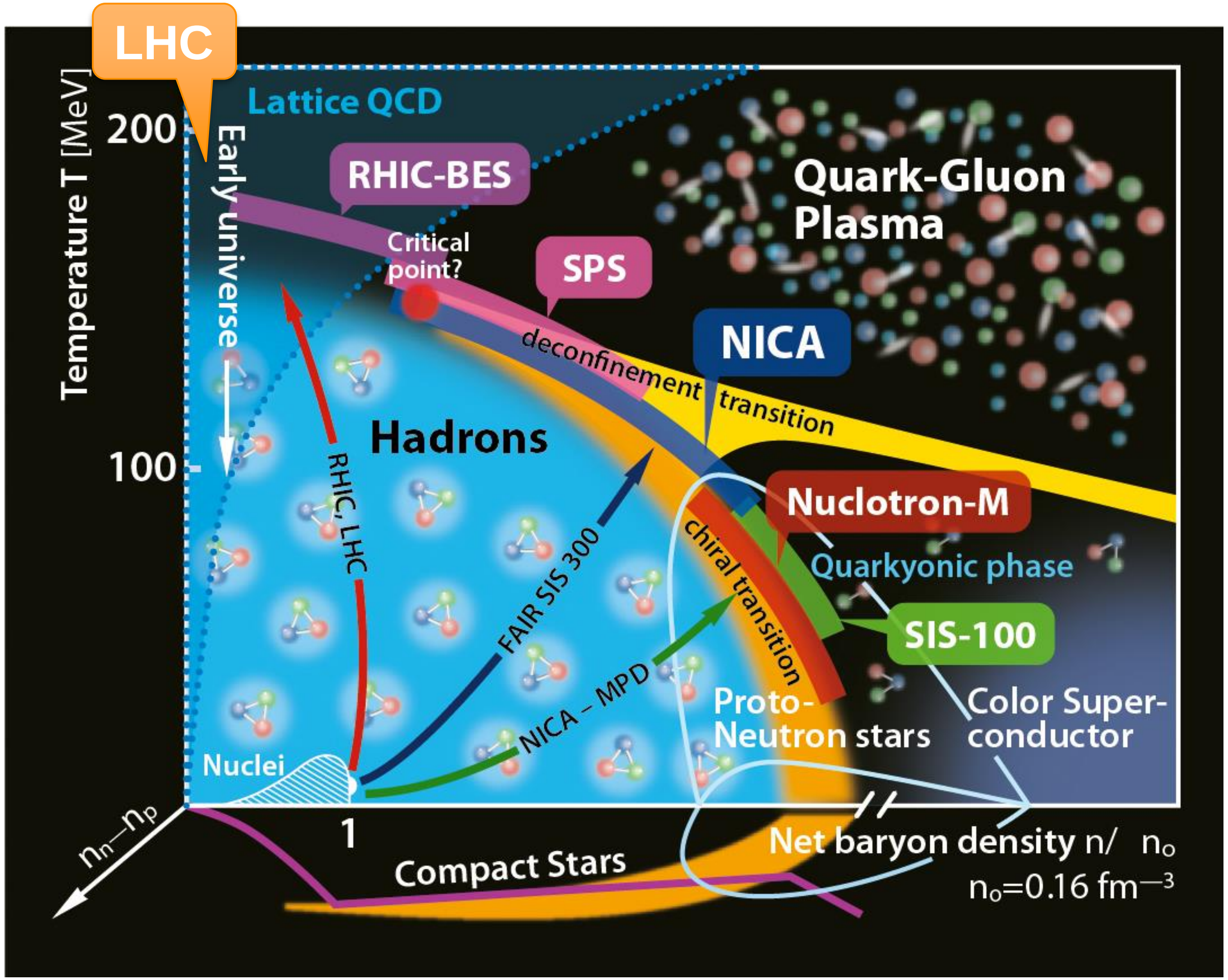
NICA @ JINR (2021) $3 < \sqrt{s_{NN}} < 11$ GeV

Experimental exploration of the QCD phase diagram

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

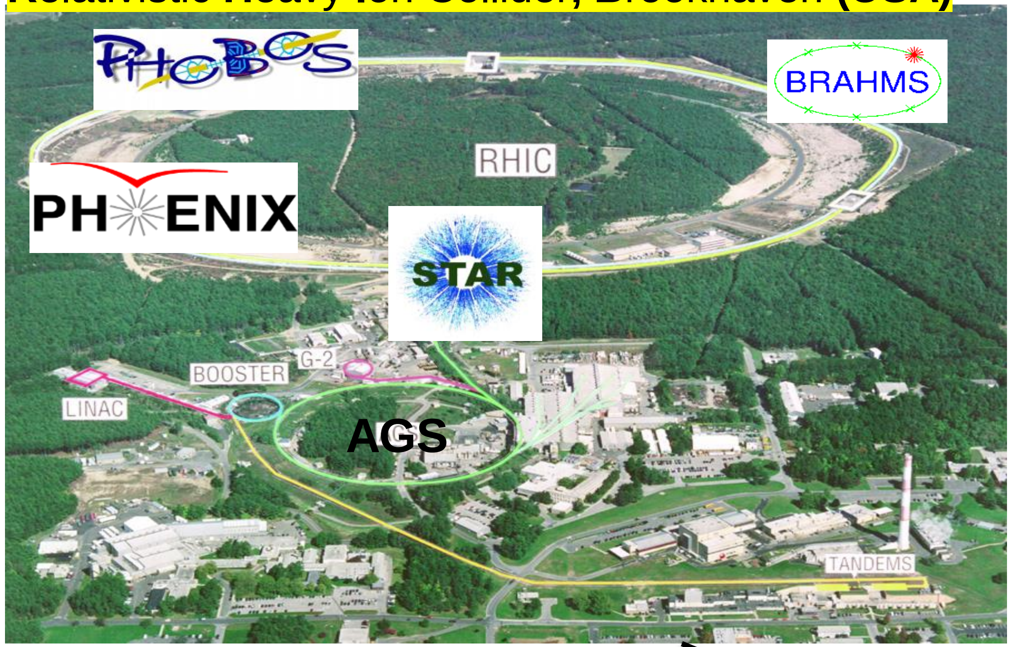
which is also the region of the phase diagram where lattice QCD calculations can be performed

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 $2.5 < \sqrt{s_{NN}} < 8$ GeV

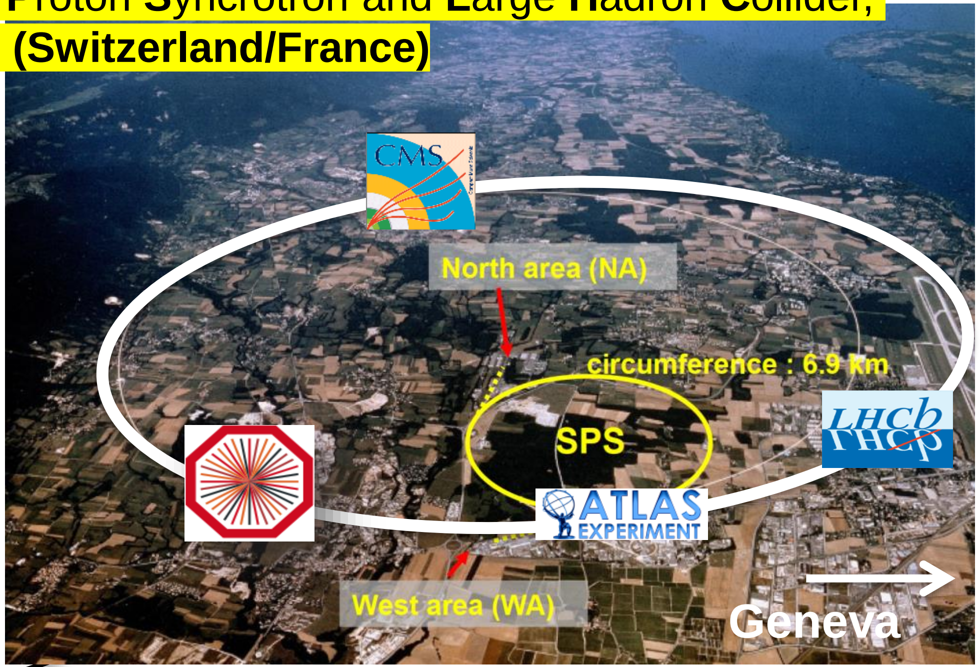


Heavy-ion physics worldwide: present / high energy

Relativistic **H**eavy **I**on **C**ollider**, B**rookhaven **(USA)**

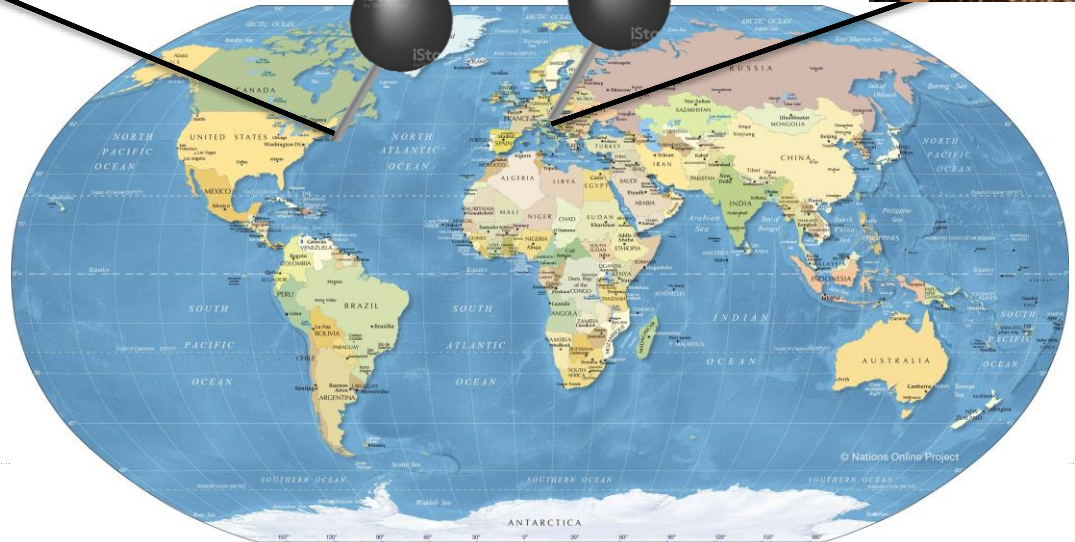


Super **P**roton **S**yncrotron and **L**arge **H**adron **C**ollider,
CERN (Switzerland/France)



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

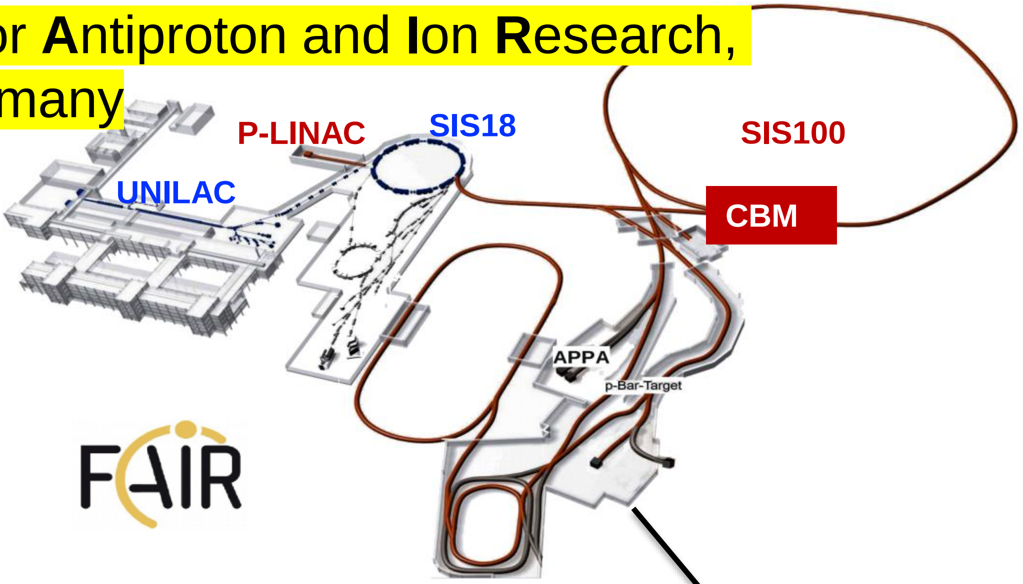
- Operating since 2000
- Circumference 3.83 km, 2 rings
- Superconducting magnets
- $\sqrt{s_{NN}} = 3 - 200$ GeV in Au-Au
- Beam energy scan I: 2010-11
- Beam energy scan II: 2019-22
- Ongoing exp: STAR

CERN LHC

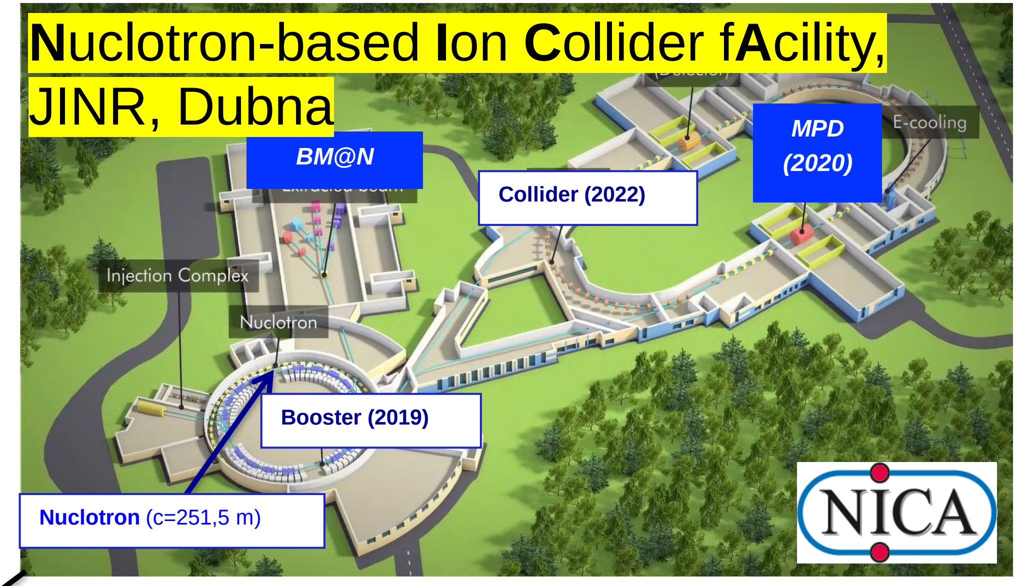
- Operating since 2009
- Run III: started in 2022
- Circumference: 27 km
- B-field: 8 T, superconducting
- pp $\sqrt{s} = 0.9 – 13.6$ TeV
- Pb-Pb $\sqrt{s_{NN}} = 2.76\text{-}5.5$ TeV
- Main ongoing: ALICE, ATLAS, CMS, LHCb

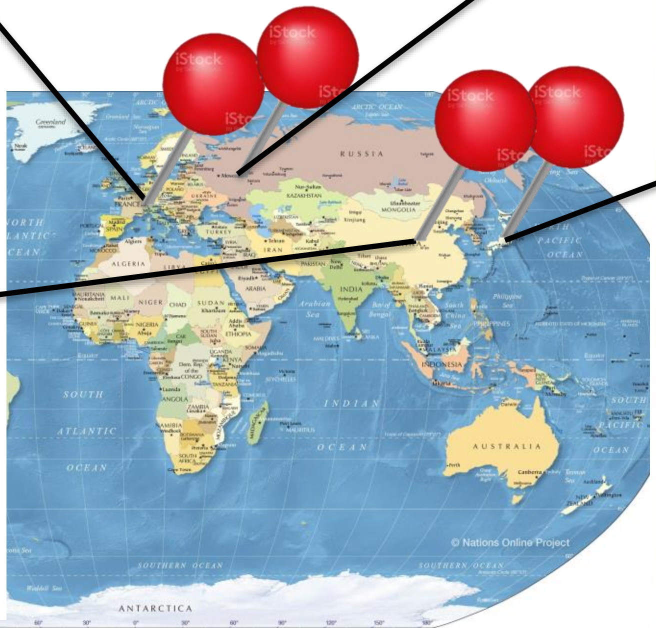
Heavy-ion physics worldwide: future / low energy

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

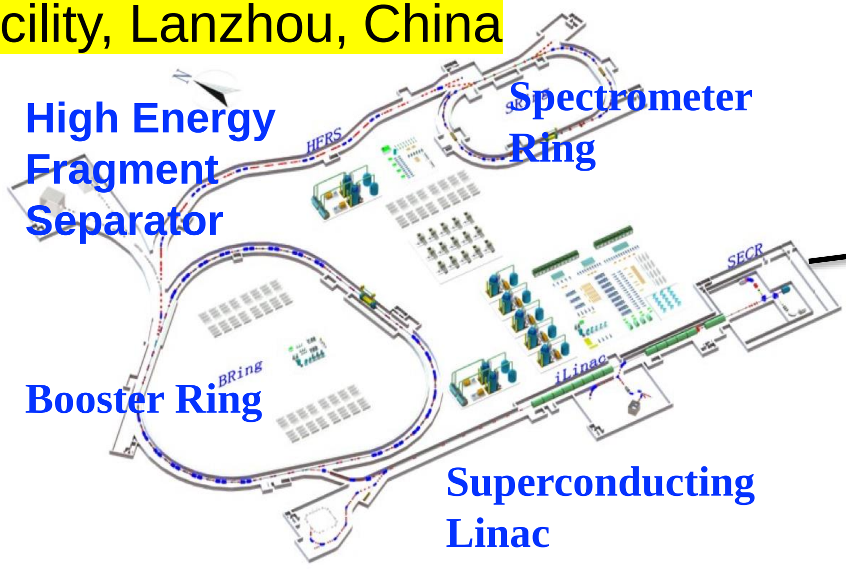


Nuclotron-based **I**on **C**ollider f**A**cility, JINR, Dubna

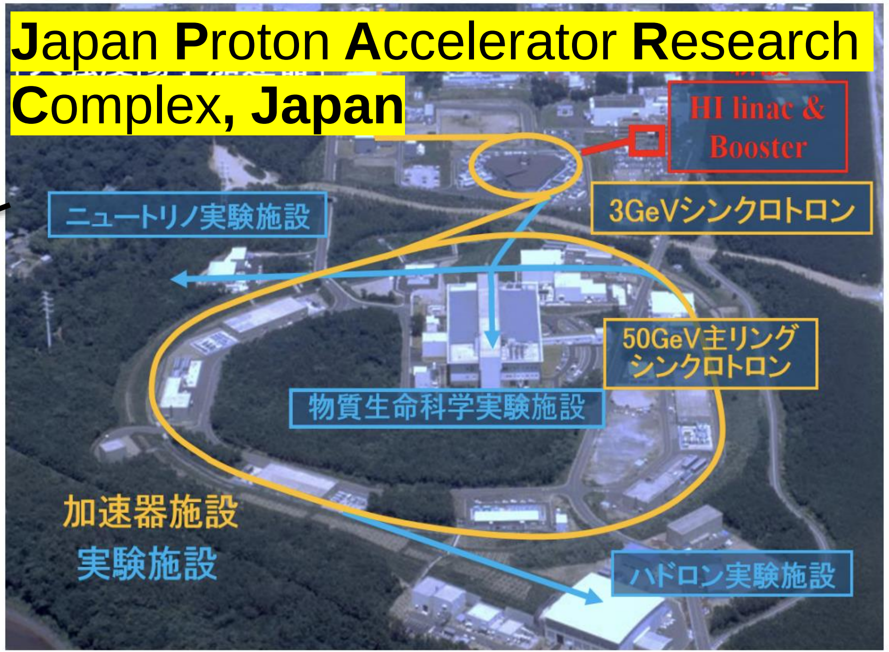




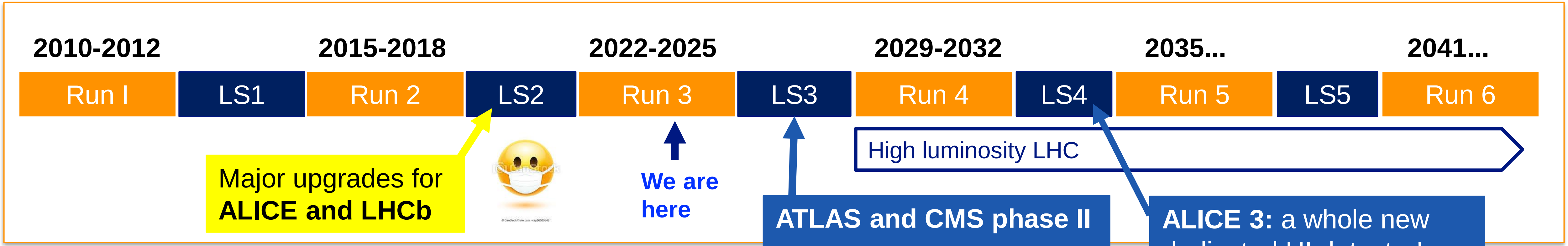
High-**I**ntensity Heavy Ion **A**ccelerator **F**acility, Lanzhou, China



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



Heavy-ion physics at the LHC

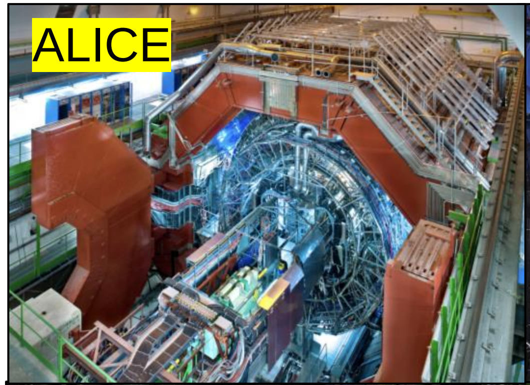


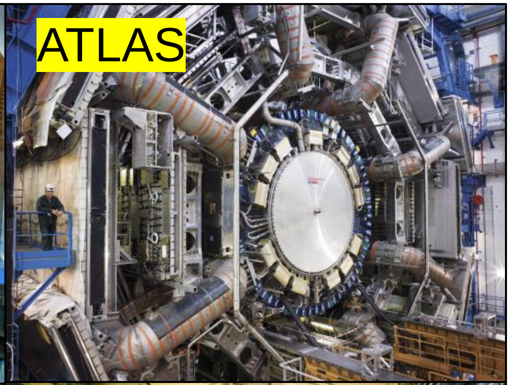
Major upgrades for **ALICE and LHCb**

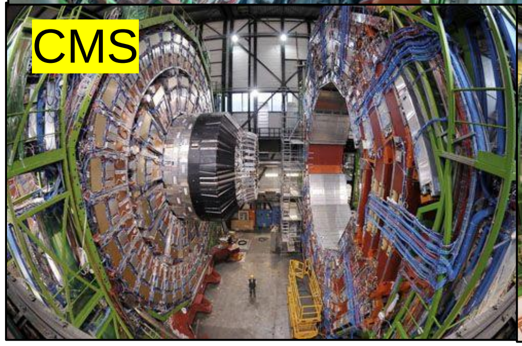
We are here

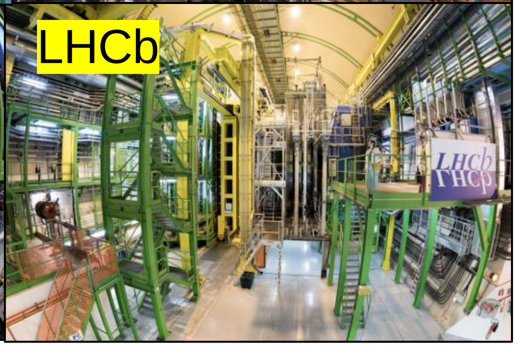
ATLAS and CMS phase II
ALICE ITS3 and FoCal

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


ALICE


ATLAS

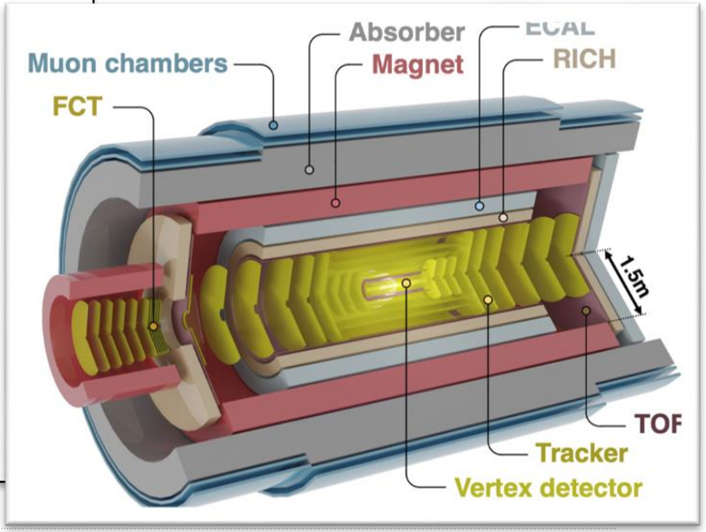

CMS


LHCb

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?

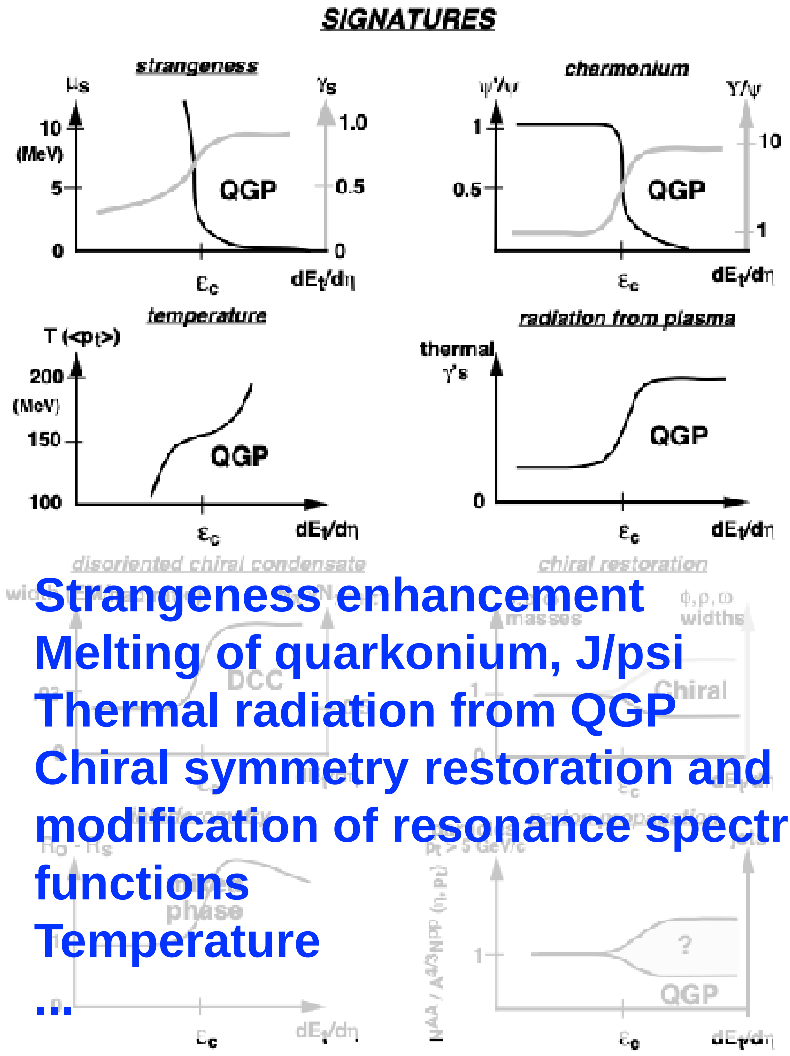
How can the physical properties be determined?

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!

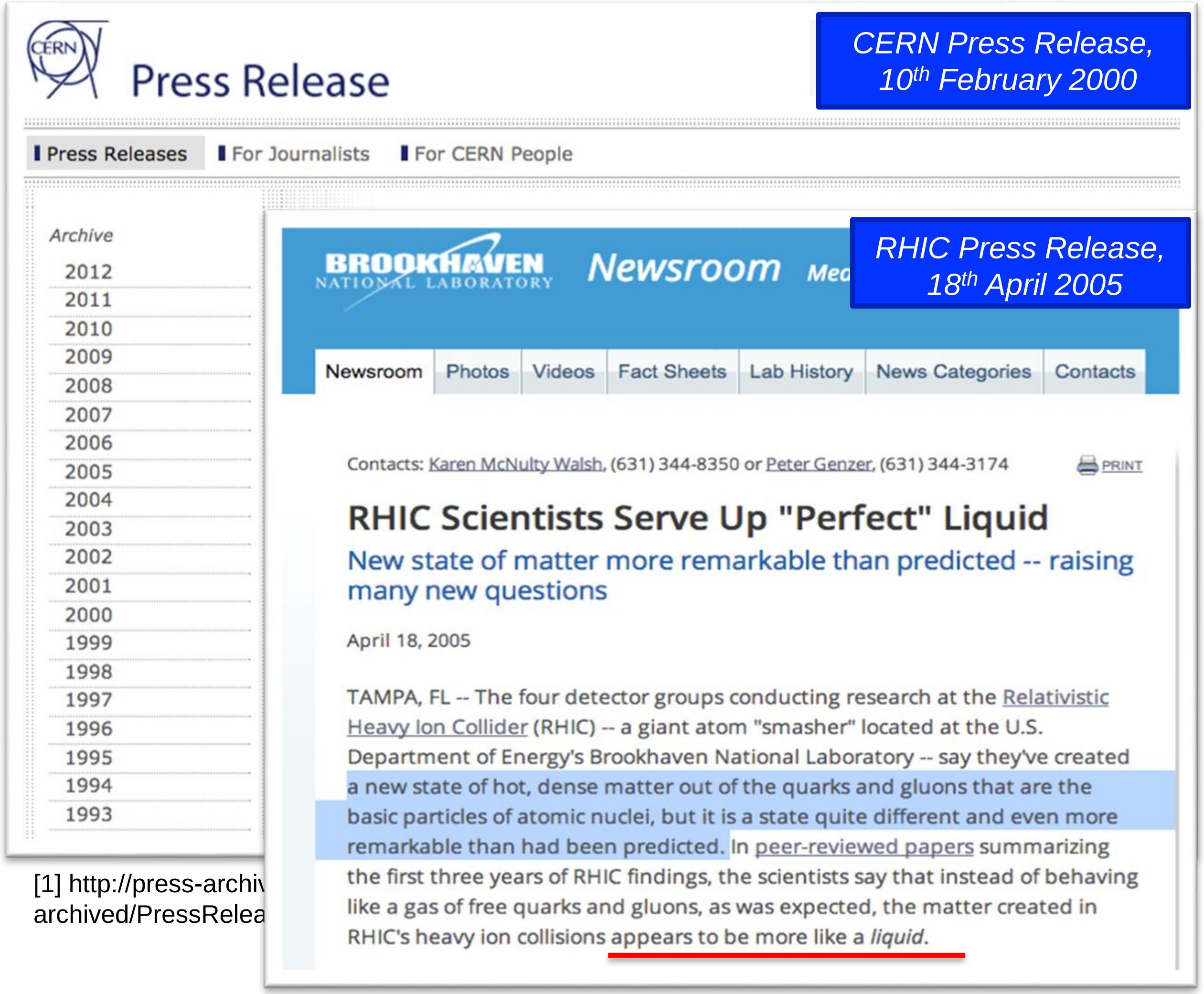


- **Strangeness enhancement**
- **Melting of quarkonium, J/psi**
- **Thermal radiation from QGP**
- **Chiral symmetry restoration and modification of resonance spectral functions**
- **Temperature**
- **…**

Reading suggestion: B. Muller, arXiv:2106.11923

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

QGP: from “discovery” to “measurement”



Press Release

Press Releases | For Journalists | For CERN People

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CERN Press Release, 10th February 2000

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RHIC Press Release, 18th April 2005

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 SPS

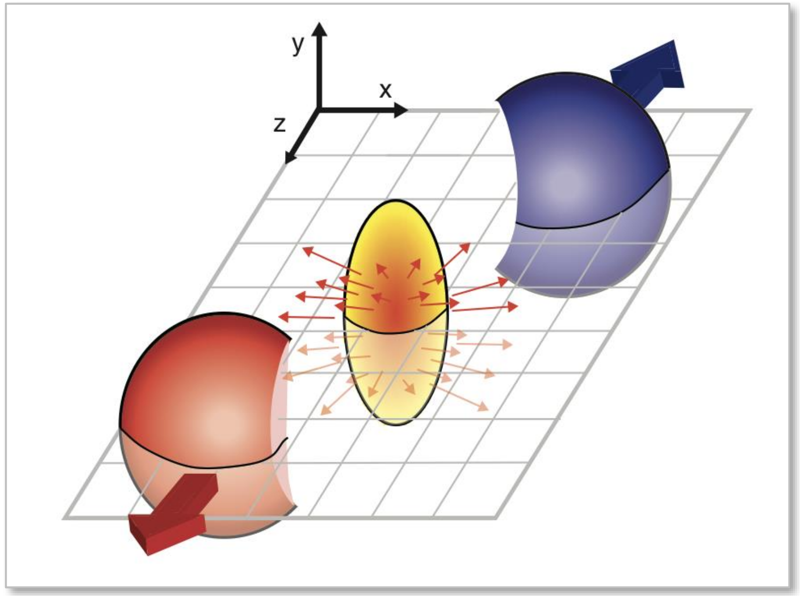
The “remarkable” evidence at RHIC that the hot matter formed is

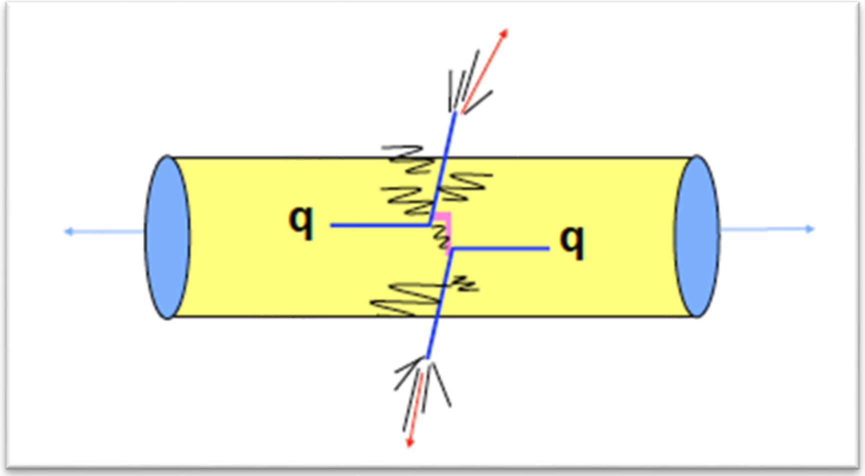
- Extremely strongly interacting (sQGP)
- Absorbing energy of traversing partons
  → Almost opaque medium
- Reacting to pressure gradients by flowing with very small shear viscosity
  → Almost perfect liquid

At the LHC the increased beam energies and the state-of-the-art experiments allow the measurement of a hotter, larger and longer-lived QGP with increased precision

Experimental characterisation of the QGP

1. **Thermodynamics and global properties**
   - Energy density
   - Temperature
   - Lifetime and size
2. **Hydrodynamics and transport properties**
   - Shear viscosity *η/s*
   - Bulk viscosity *ζ/s*
3. **Hadron formation and flavour equilibration**
   - Formation of hadrons and bound states
   - Chemistry / flavour composition and hadron rates
   - Charm equilibration
4. **Interaction of partons in a colored medium**
   - Energy loss of partons / jet quenching
   - Transport coefficients
   - Diffusion
5. **Influence of deconfined medium on the strong force**
   - Color screening





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

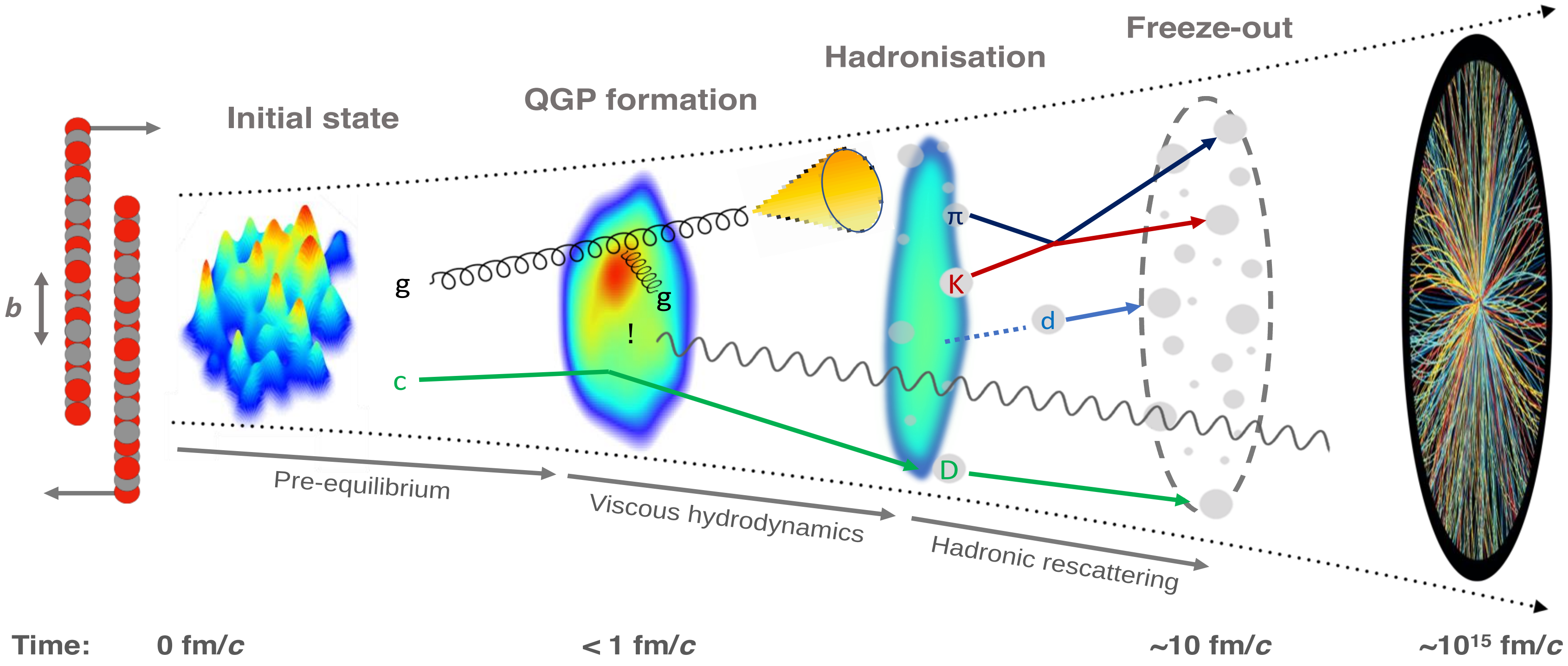


Figure from ALICE Coll., arXiv:2211.04384

The “little bang” in the laboratory

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

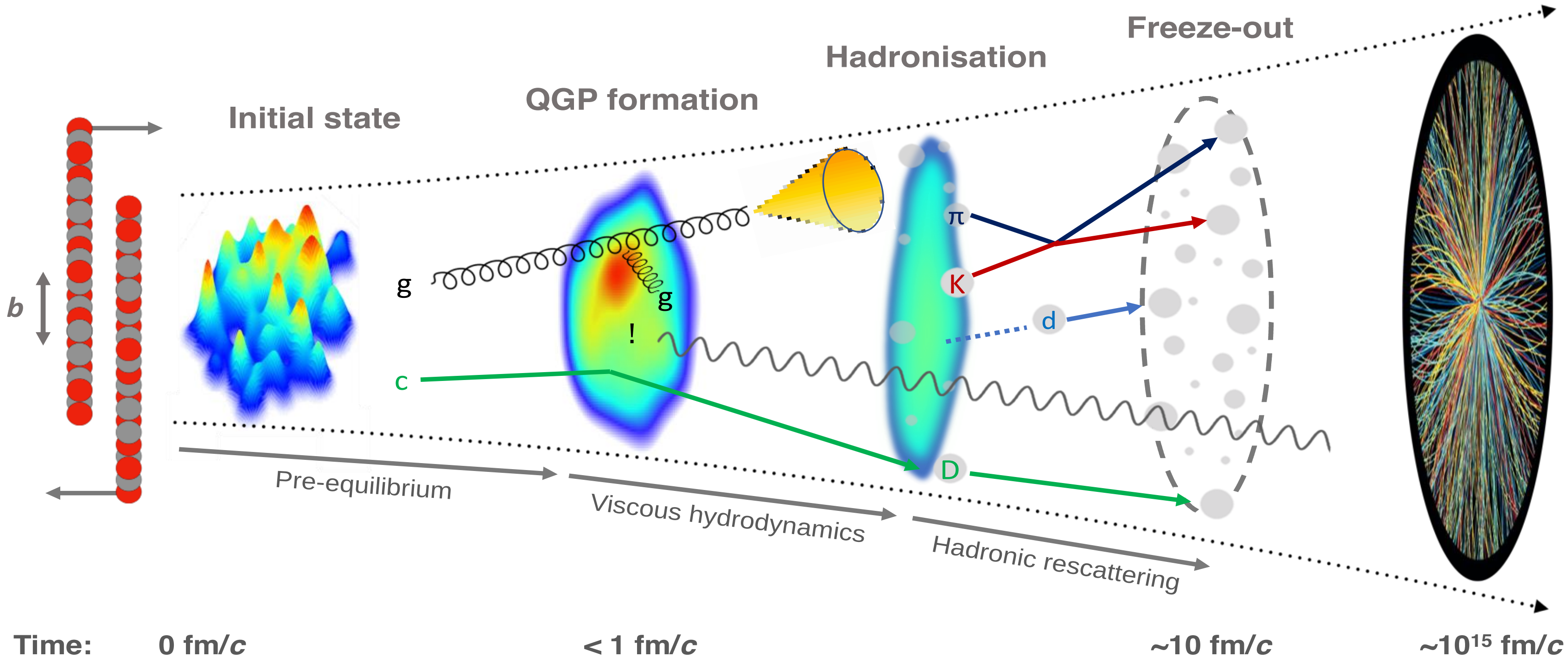


Figure from ALICE Coll., arXiv:2211.04384

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

→ non-perturbative regime

→ **thermodynamical, hydrodynamical and transport properties**

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

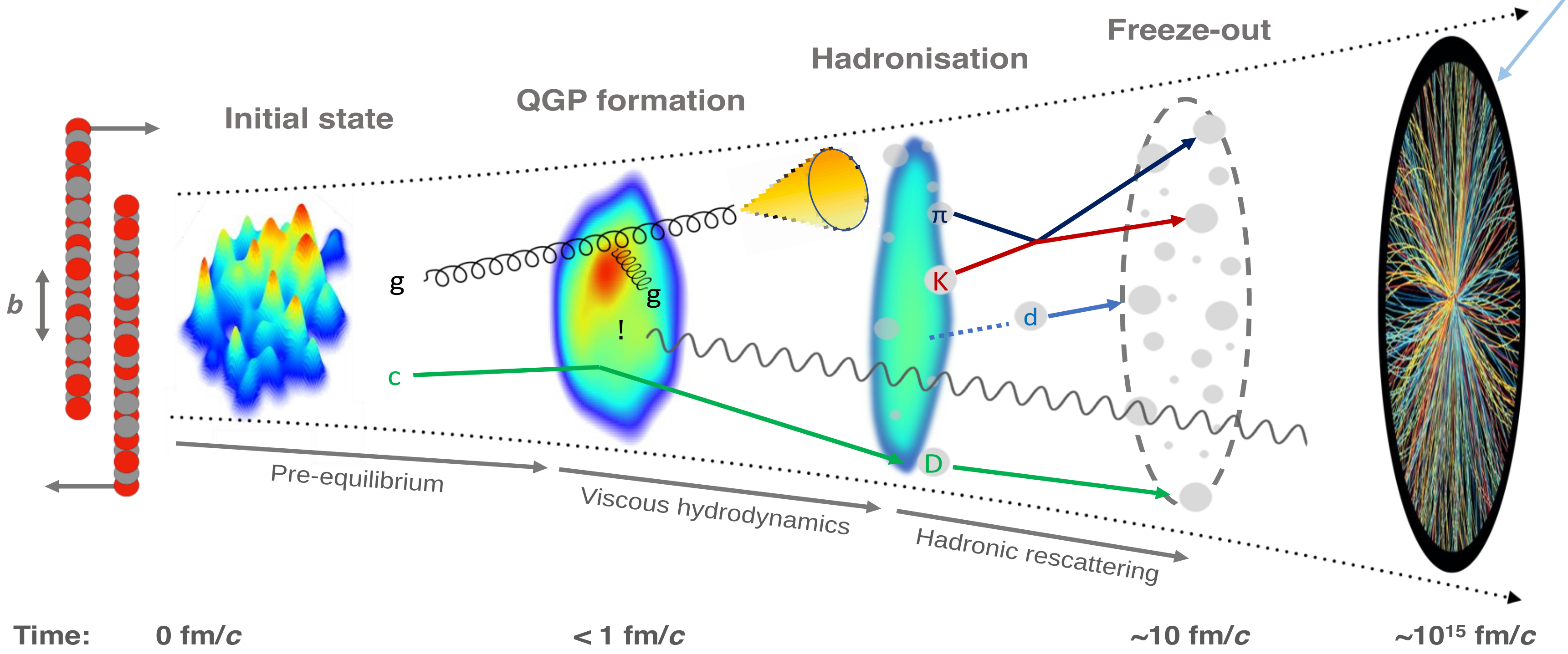
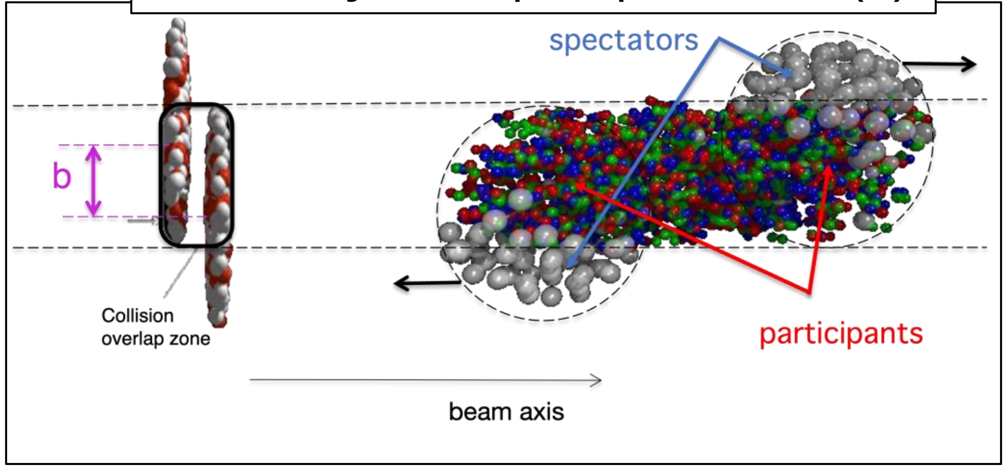


Figure from ALICE Coll., arXiv:2211.04384

Centrality

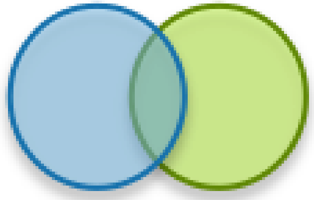
Centrality ⇔ impact parameter (**b**)



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

Correlation observed between number of particles produced at forward and at mid- rapidity → Centrality is determined by counting the number of particles (multiplicity) or measuring the energy deposition in a region of phase space *independent* from the measurement.

Central collisions (e.g. 0-5%)
→ smaller impact parameter
→ larger overlap region
→ more participants
→ more binary collisions
→ more particles produced



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

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.

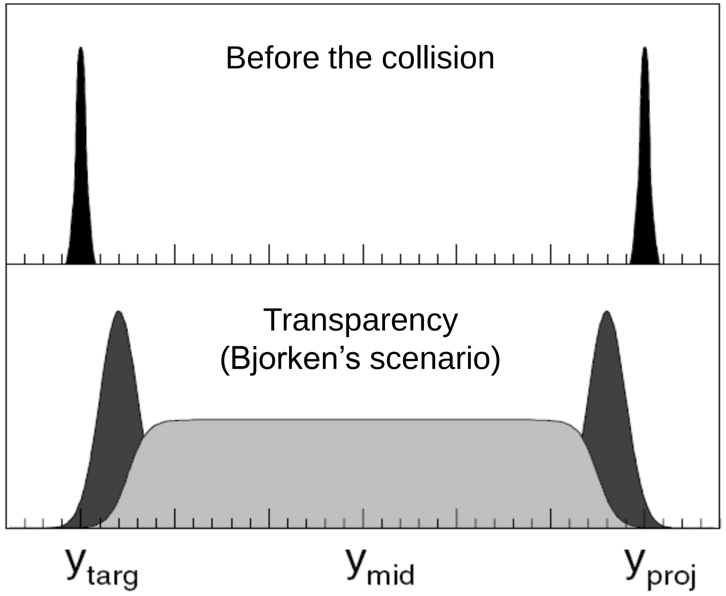
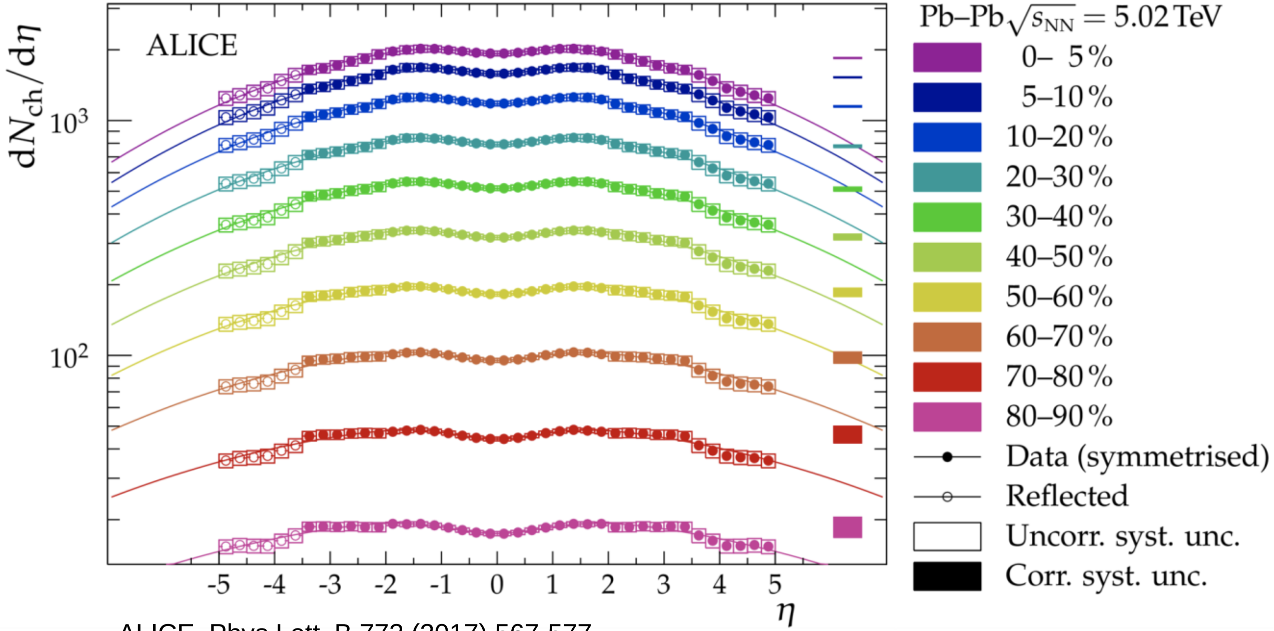


Figure from K. Reygers

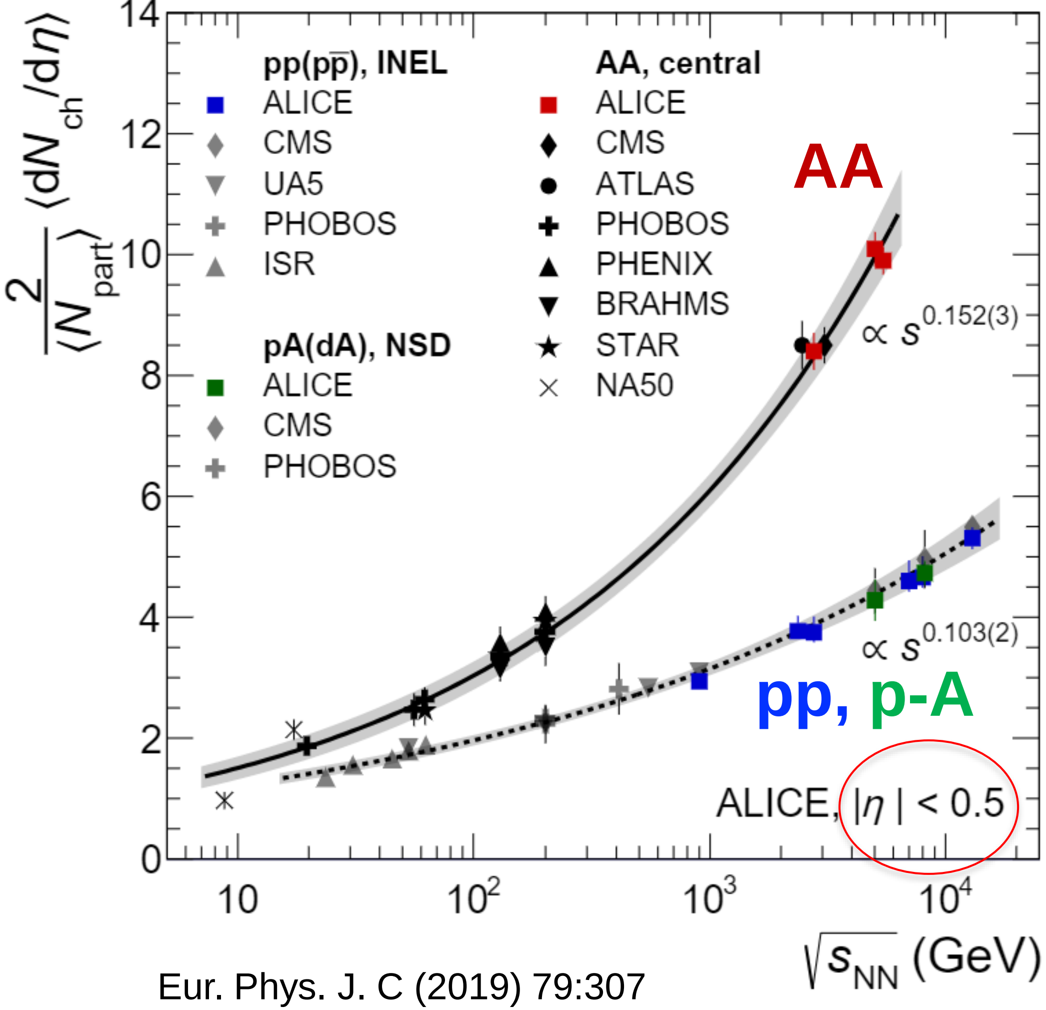
Charged particle production vs pseudo- rapidity



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

Charged particle production in central HI collisions

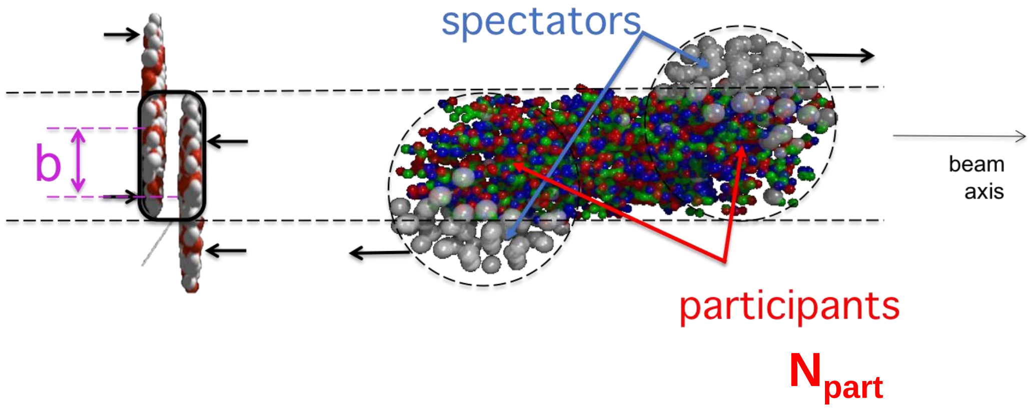
Particle production at midrapidity



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



Pseudorapidity

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

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

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

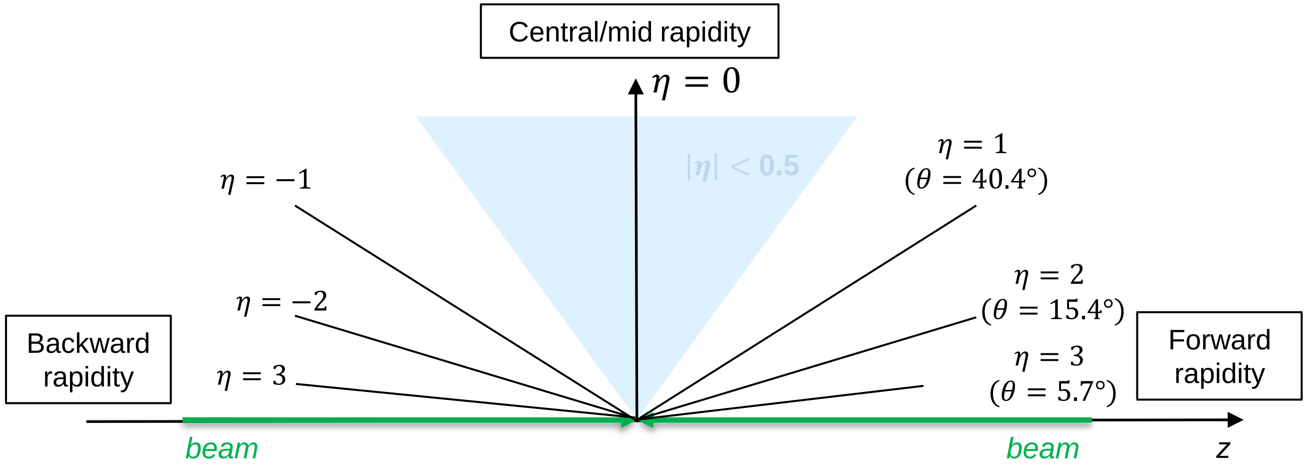
Where ϑ is the angle between the direction of the beam and the particle.

The relation to transverse and longitudinal momenta are

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

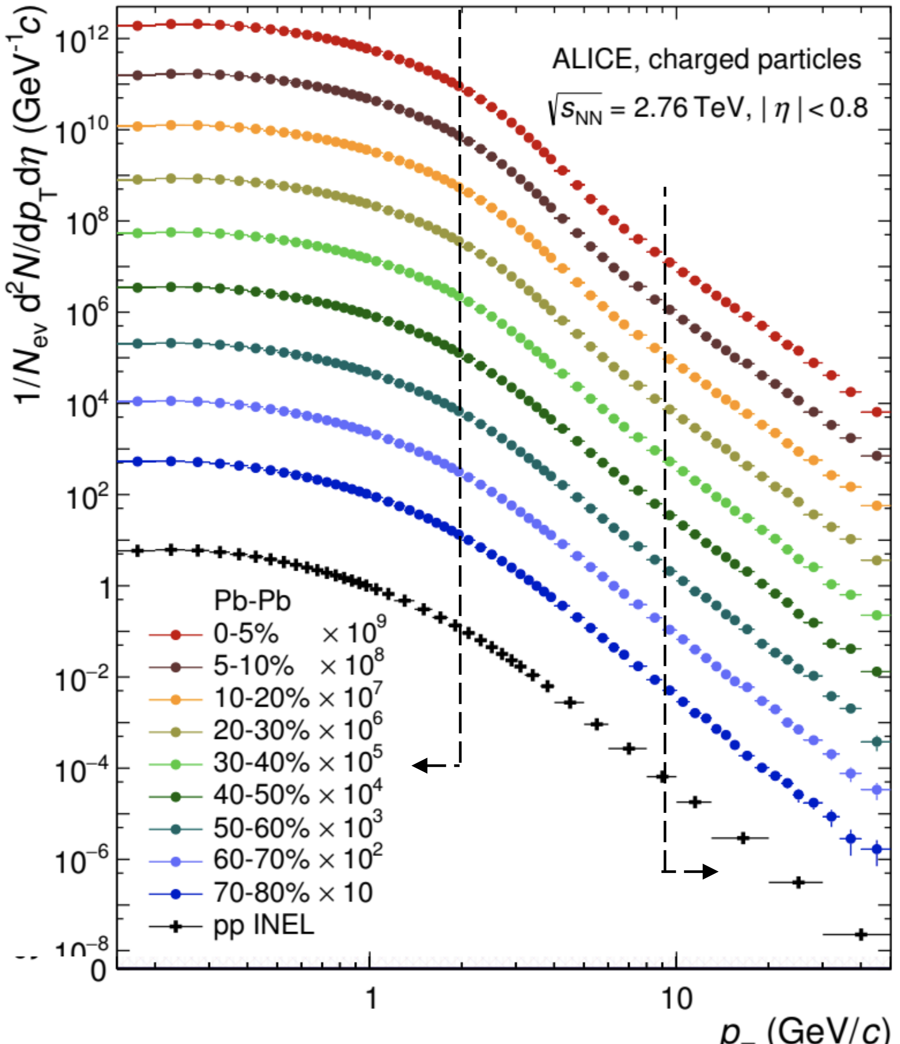
For m = 0, $y = \eta$ is a special case

In general $y \neq \eta$, especially at low momenta



Key observable: particle “spectrum”

Charged particle transverse momentum distribution



ALICE, JHEP 11 (2018) 013

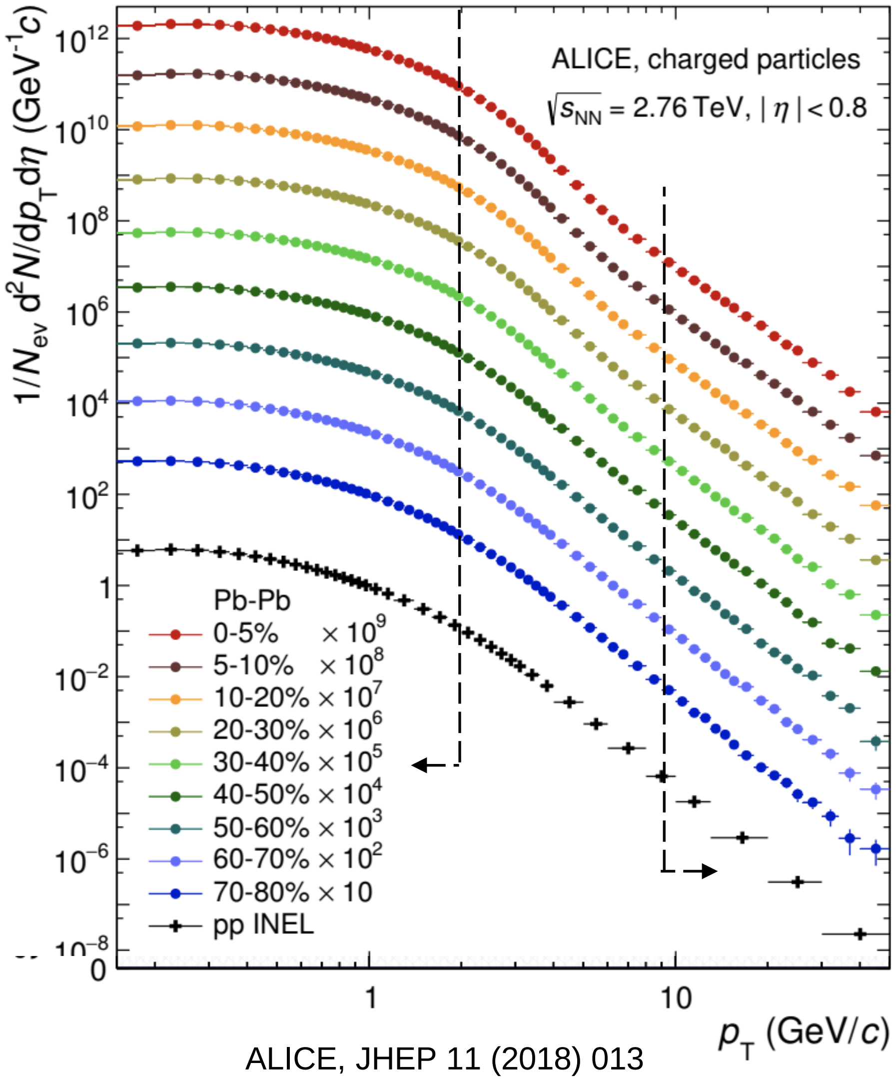
Particle **“spectra”**: $d^2N/(dydp_T)$ = yield per event per (pseudo)rapidity unit per transverse momentum unit

~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**", ~ $\exp(-1/k_B T)$
- "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

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

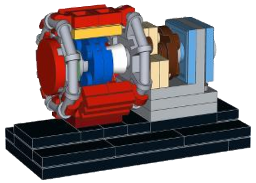
Observables:

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

In HI physics also emphasis on:

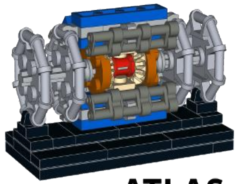
- **midrapidity** measurements
- **identification** of hadron species
- soft (non-perturbative) regime, i.e. **low p_T**
- **minimum bias** events

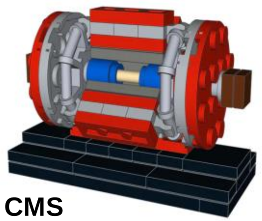
Complementarity of the LHC experiments


ALICE

ALICE

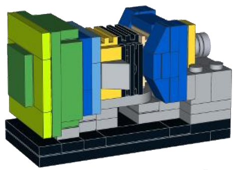
- Low p_T
- PID
- Low material budget next to IP


ATLAS


CMS

ATLAS/CMS

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


LHCb

LHCb

- Forward pseudorapidity
- PID
- Fixed target

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.

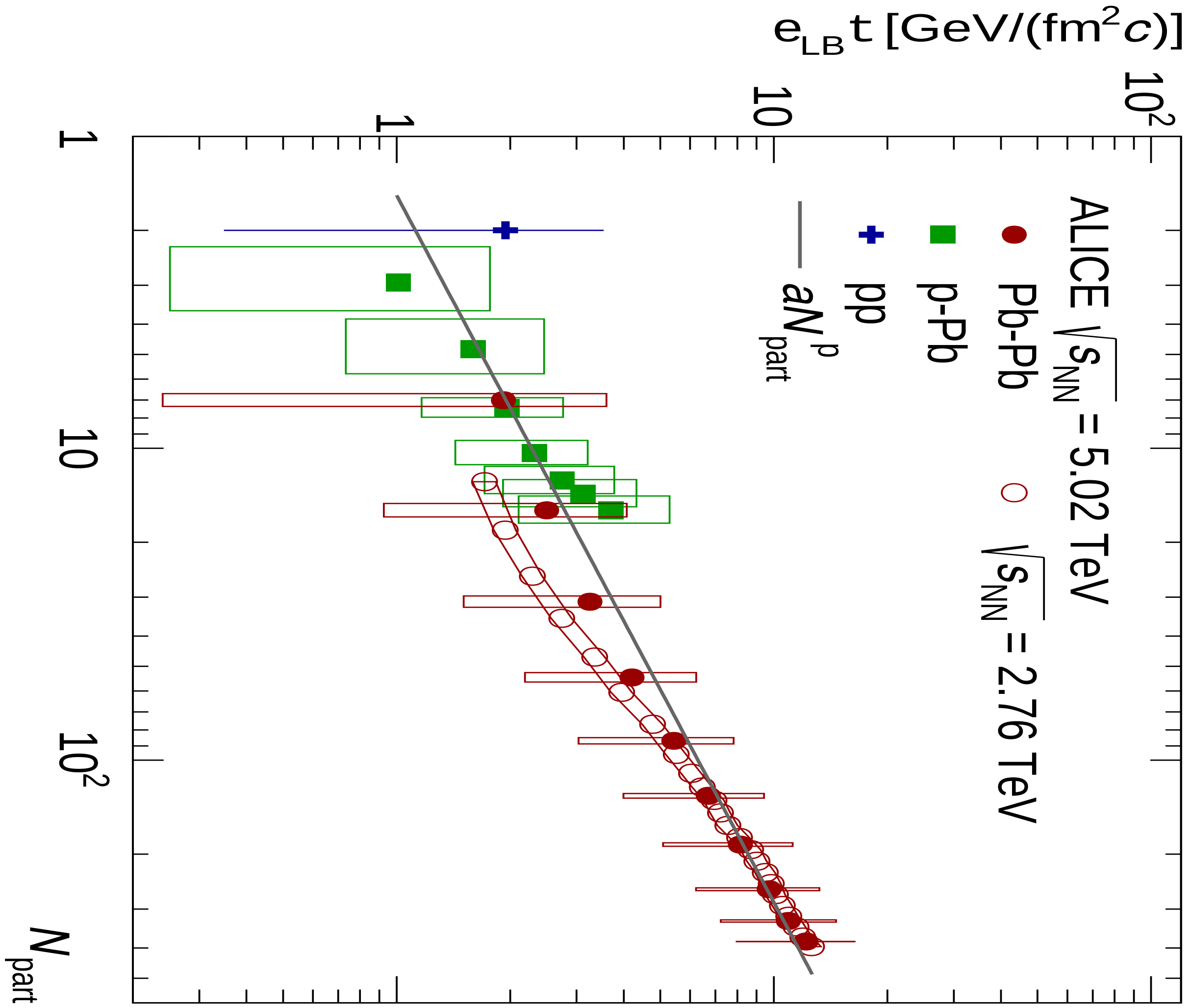
$$\varepsilon_{LB}\tau = \frac{1}{S_T}\frac{1}{f_{total}}\sqrt{1+a^2}\langle m\rangle \frac{dN_{ch}}{dy}$$

S_T = Transverse area from Glauber model
$f_{total} = 0.55 \pm 0.01$ = 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!

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



Formation of quark-gluon plasma at the LHC

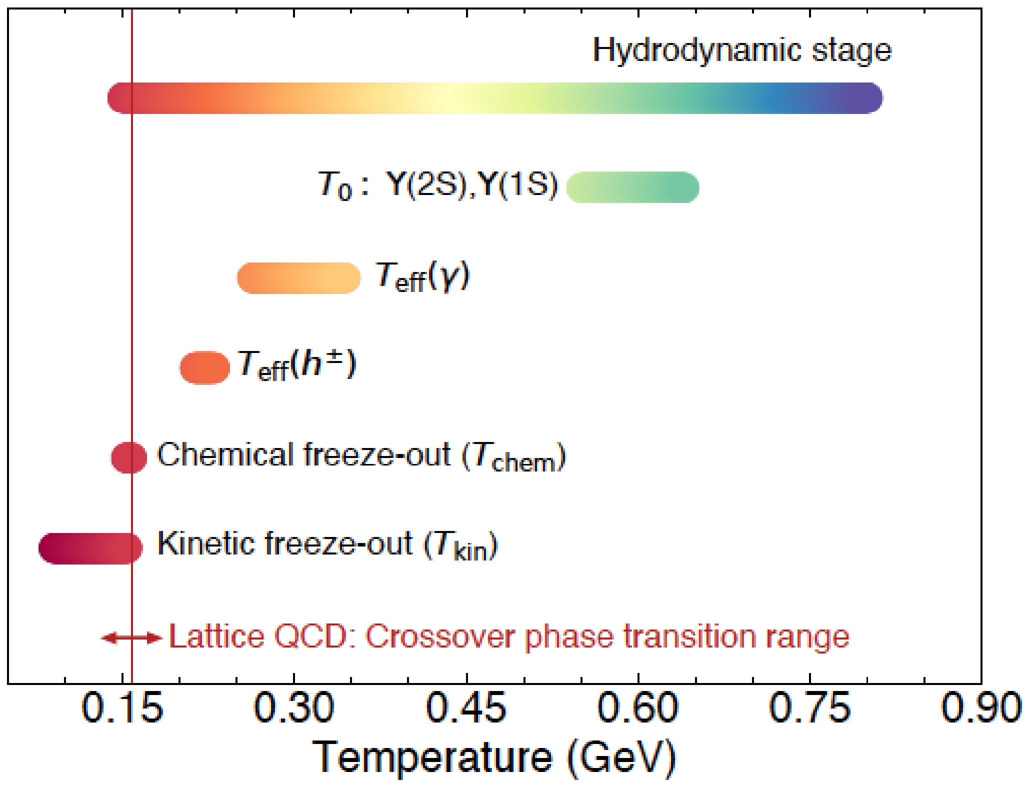
The conditions to form a QGP are met and exceeded in heavy-ion collisions at the LHC.

The **initial energy density** estimated in central collisions is ~12 GeV/fm^3 at the early time of 1 fm/c
→ ~70x the density of atomic nuclei

The **initial QGP temperature** is up to 5 times higher than the QCD decofinement temperature predicted by ab-initio lattice QCD calculations, T_{pc} = 155–159 MeV

The matter created has the largest temperature and energy density ever observed!

ALICE review paper

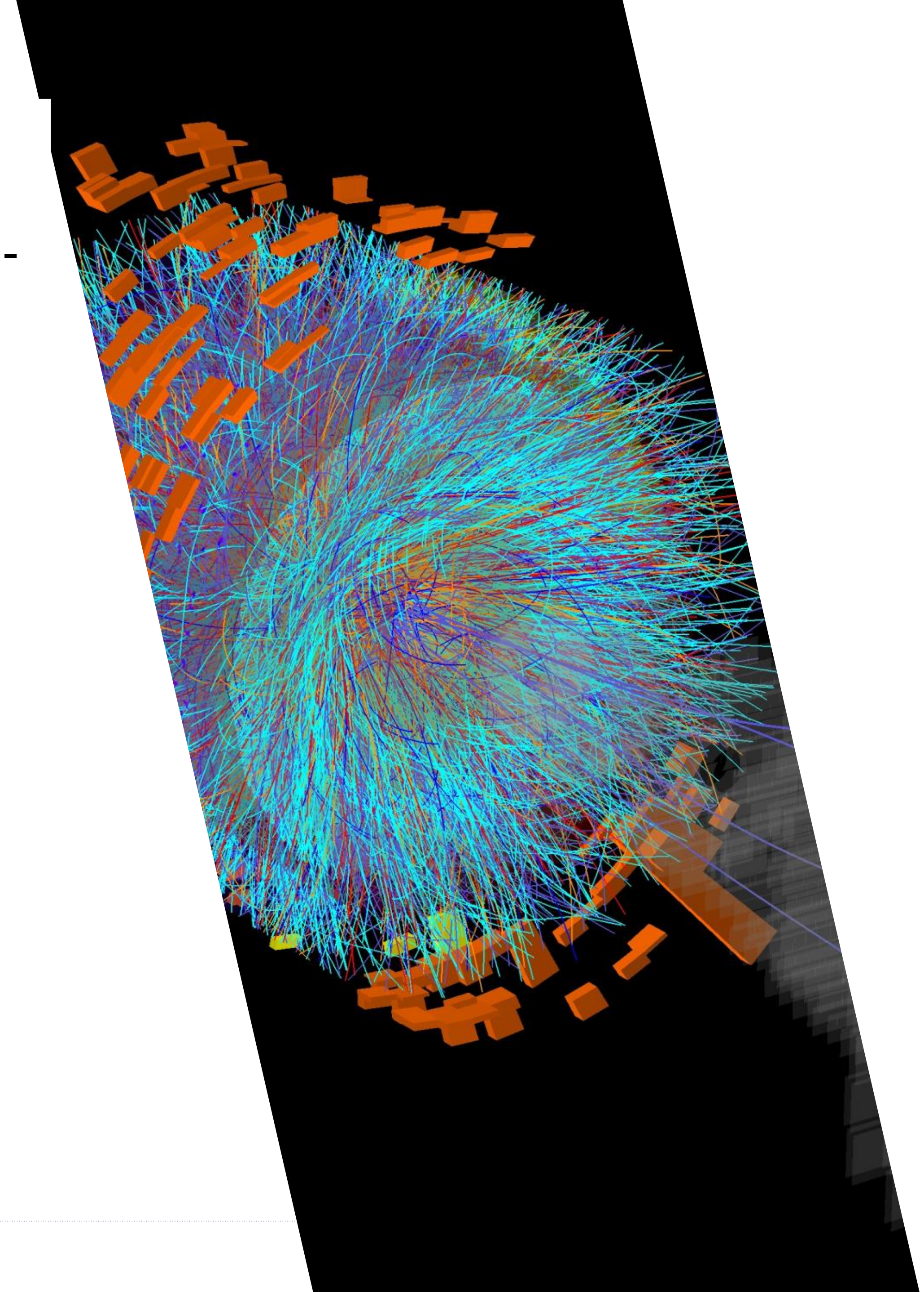


Bonus material

Further readings:

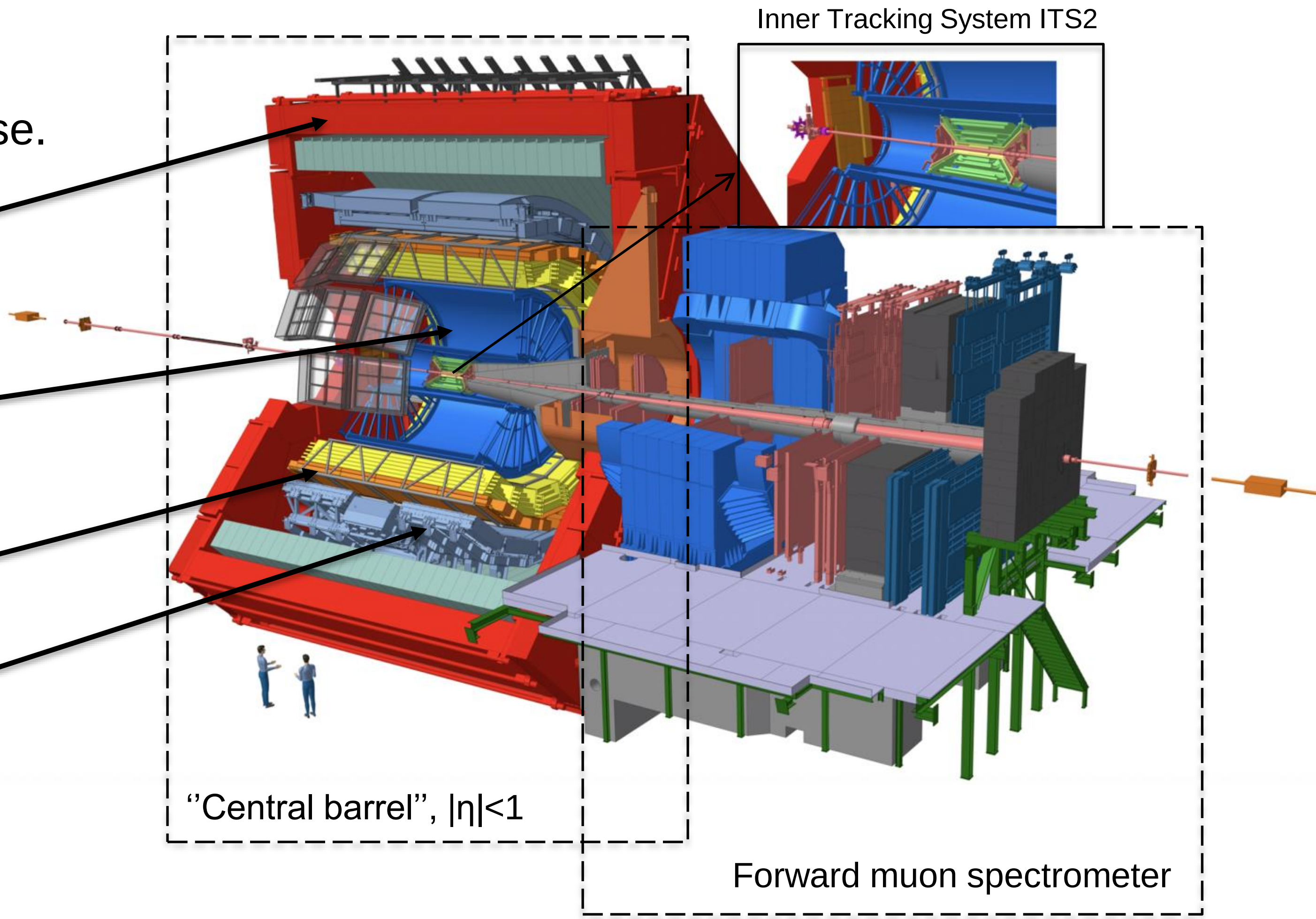
- [review] ALICE Collaboration, The ALICE experiment -- A journey through QCD, arXiv:2211.04384
- [future] CERN Yellow Report on QCD with heavy-ion beams at the HL-LHC, arXiv:1812.06772
- [future] Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC, arXiv:2211.02491

+ many more reviews on specific topics can be found on arXiv



Characteristics of a heavy-ion detector: ALICE

ALICE is the dedicated heavy-ion detector at the LHC, designed and built specifically for this purpose.



Solenoid: magnetic field B = 0.5 T

Inner Tracking System + Time Projection Chamber: vertexing and tracking + identification (TPC) down to very low $p_T \sim 0.1$ GeV/*c*

Time-Of-Flight, TRD, HMPID, etc.: Particle identification detectors

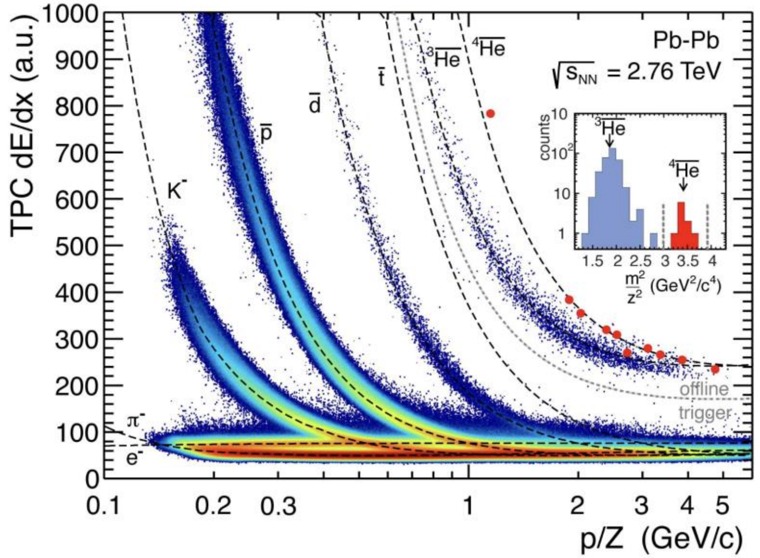
Electromagnetic calorimeters

+ Forward rapidity detectors and ZDC: trigger, centrality, event time determination, …

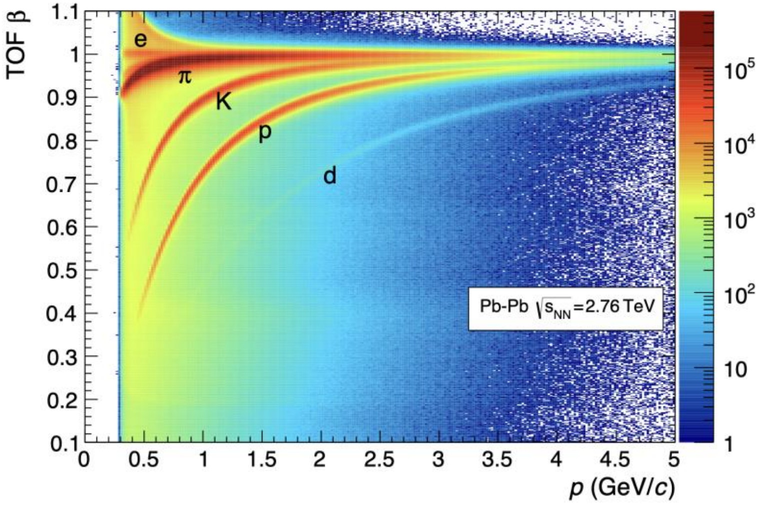
Particle identification

- Direct identification: π, K, p, light (anti)nuclei
- Electron identification using calorimeters and transition radiation detectors
- Strange and heavy-flavour hadrons:
  - reconstruction of secondary vertex and weak decay topology + PID + invariant mass reconstruction
- Photons detected in calorimeters and through pair production
- Quarkonia through leptonic decays

Energy loss of long lived particles in TPC

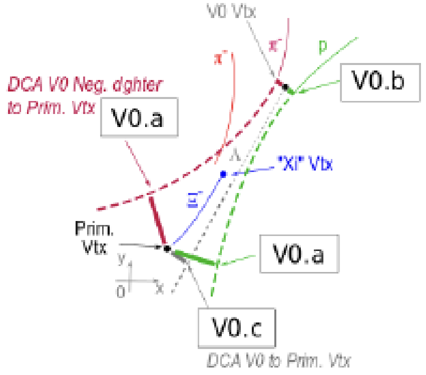


Particle velocity from TOF measurement and momentum



$\Xi \to \Lambda\pi^-$

(similarly for $\Omega \to \Lambda K^-$)



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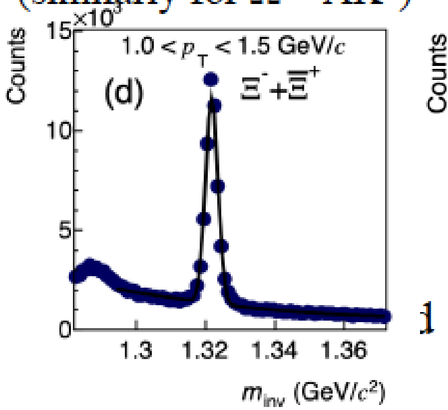
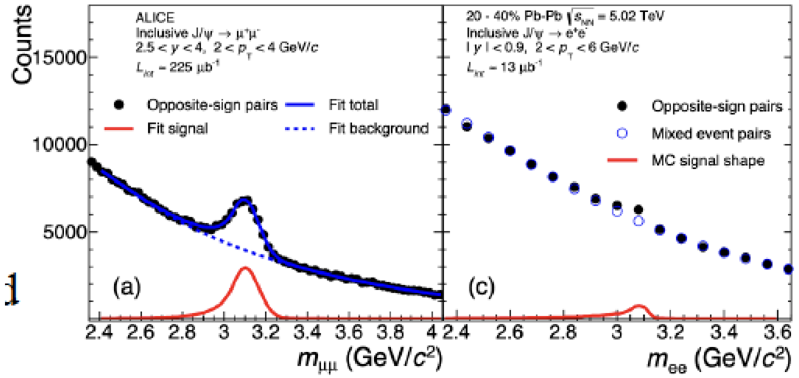
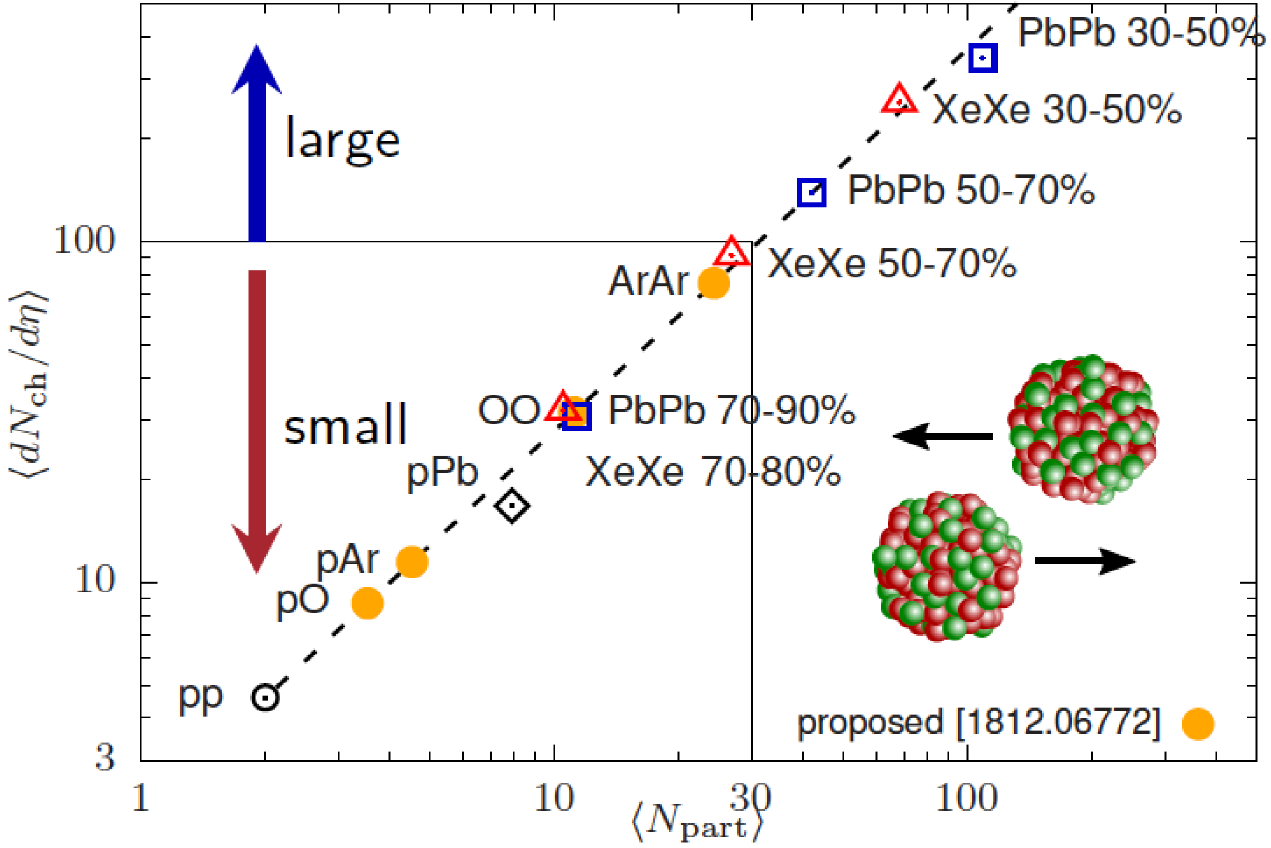


$J/\psi \to \mu^+\mu^-$

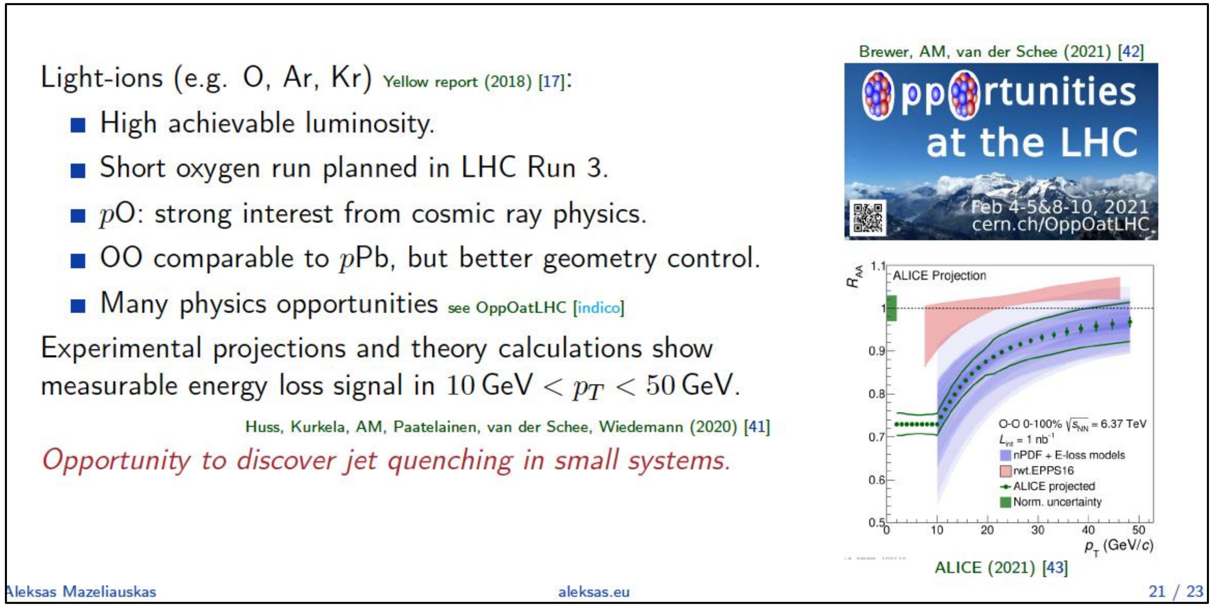
$J/\psi \to e^+e^-$



Light ions at the LHC



From A. Mazeliauskas, EPS-HEP 2021:



Light-ions (e.g. O, Ar, Kr) Yellow report (2018) [17]:

- High achievable luminosity.
- Short oxygen run planned in LHC Run 3.
- pO: strong interest from cosmic ray physics.
- OO comparable to pPb, but better geometry control.
- Many physics opportunities see OppOatLHC [indico]

Experimental projections and theory calculations show measurable energy loss signal in $10\,\mathrm{GeV} < p_T < 50\,\mathrm{GeV}$.

Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann (2020) [41]

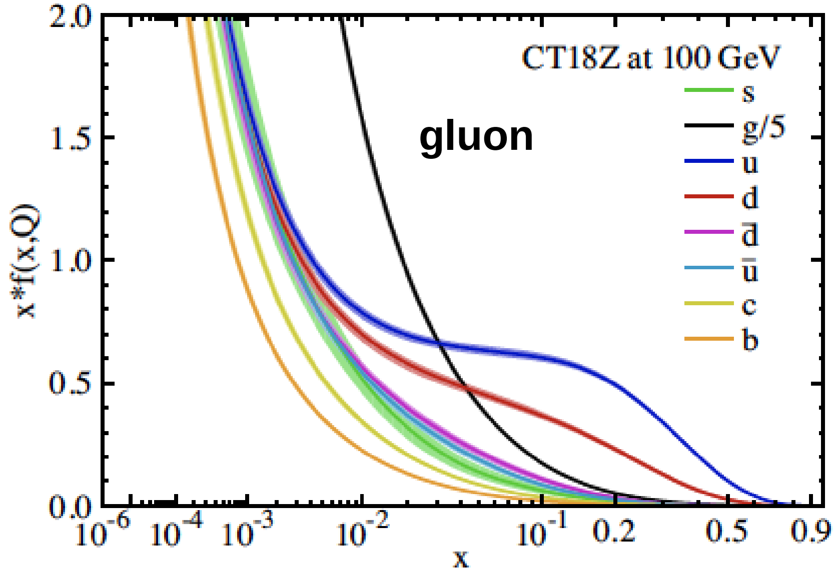
Opportunity to discover jet quenching in small systems.

Brewer, AM, van der Schee (2021) [42]

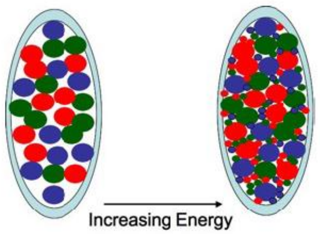
ALICE (2021) [43]

Aleksas Mazeliauskas aleksas.eu 21 / 23

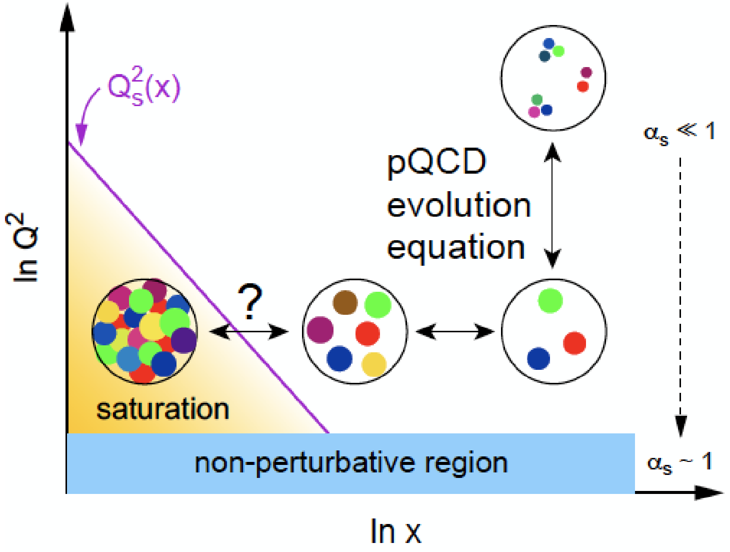
Initial stage of heavy ion collisions

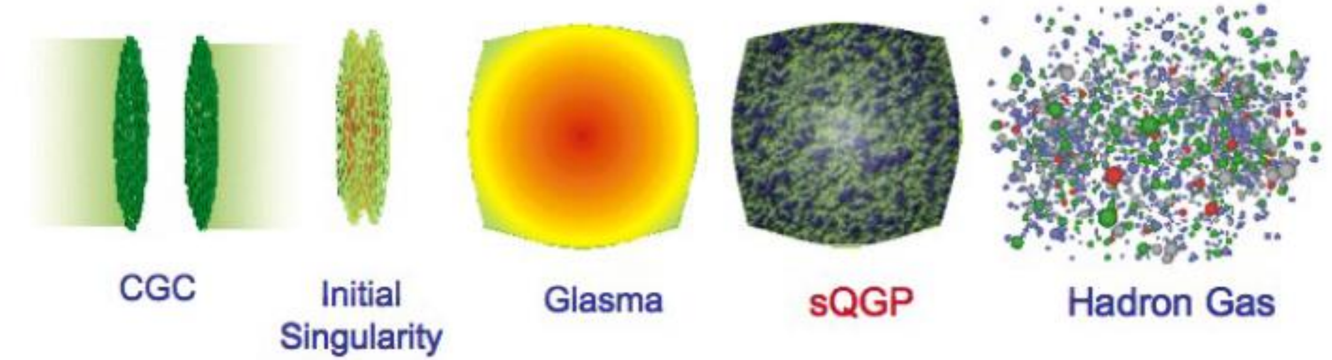


Color Glass Condensate: at high energy and small x, the hadron content is dominated by gluonic matter “packed” into high density



Saturation (momentum) scale Q_{sat} = inverse size scale of smallest gluons which are closely packed
→ gluons of size larger than *$1/Q_{sat}$* no longer fit





L. McLerran, https://bib-pubdb1.desy.de/record/296833/files/ismd08_mcl_intro-corr.pdf
+ more reviews in literature,

Glauber model

Nucleus-nucleus interaction as **incoherent superposition of nucleon-nucleon collisions** calculated in a probabilistic approach

[M. L. Miller et al., An. Rev. Nucl. Part. Sci. 57 (2007) 205-243]

- nucleons in nuclei are considered as point-like and non-interacting
- nuclei (and nucleons) have straight-line trajectories (no deflection)

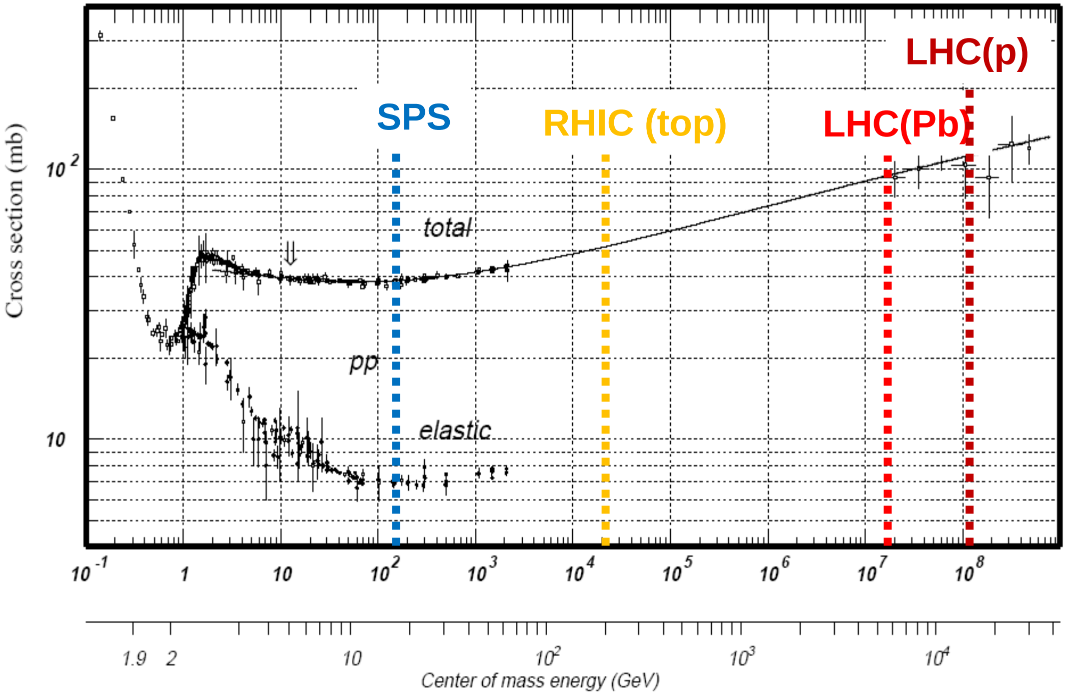
Input:

- Nucleon-nucleon inelastic cross section
- Nuclear density distribution, e.g. Fermi

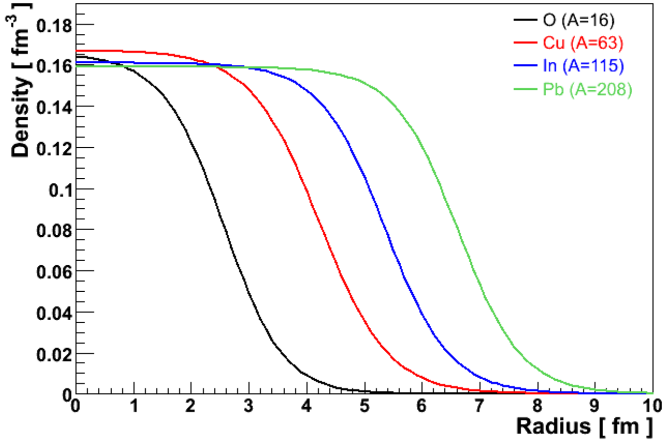
$$\rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}$$

ρ^0 = density in the nucleus center
R = nucleus radius
a = skin depth
w = deviations from spherical shape

Proton-proton cross section (from PDG)



Examples of density distributions of nuclei



Glauber model (2)

Output:

- Interaction probability
- **Number of elementary nucleon-nucleon collisions (N_{coll})**
- **Number of participant nucleons (N_{part})**
- **Number of spectator nucleons**
- Size of the nuclei overlap region

These variables are fundamental to study the scaling properties of observables in HIC – **Rule of thumb**:

- N_{part} scaling of soft particle production
  → bulk of the system
- N_{coll} scaling of high p_T particle production
  → hard partons produced early in the collision