ICPS2017

Big Bang in the lab

Francesco Prino

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

International Conference
OF PHYSICS STUDENTS
AUGUST 7-14TH 2017, TORINO

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Highlights from 30 years of heavy-ion collisions at the accelerators

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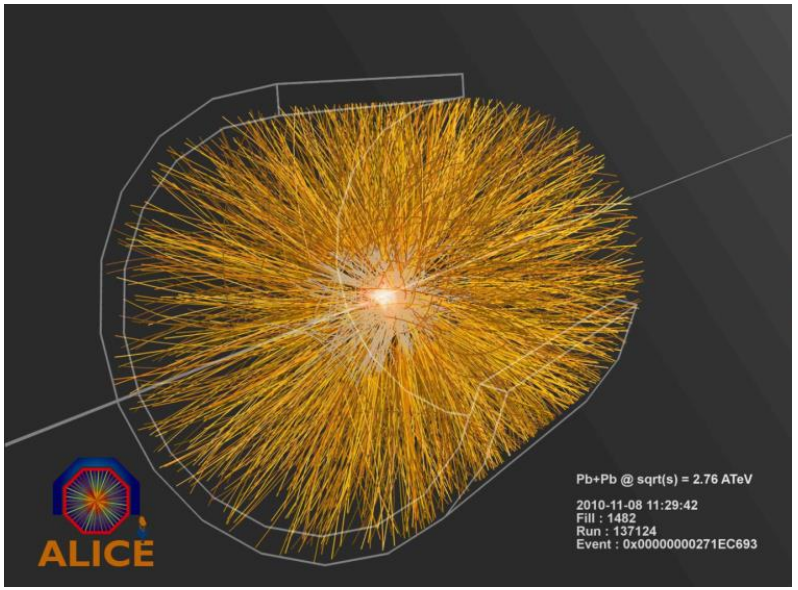
Part 1
Why?

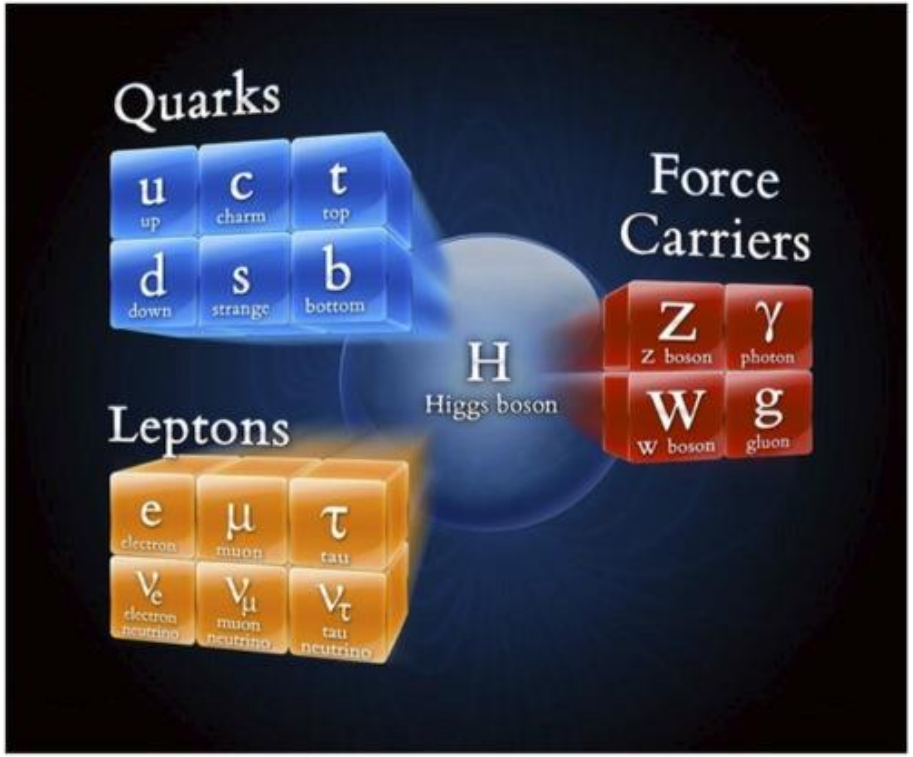
Heavy-ion collisions: why?

- Heavy-ion interactions represent by far the most complex collision system studied in particle physics labs
  - ⇨ Thousands of particles produced in the collision
  - ⇨ Challenge for detectors and tracking
- Why people are attracted to the study of such a complex system ?



- Offer a unique view to study:
  - ⇨ The nature of **confinement** of quarks and gluons into hadrons
  - ⇨ The **origin of the hadron masses**
  - ⇨ The properties of matter at **energy densities** like **10 μs after the Big Bang** and **temperatures** about 10^5 times larger than in the Sun core

Building blocks of matter



- **Hadrons**, and in particular protons and neutrons, which build up nuclei (99.9% of the atom mass) and our world, can be understood as **composite objects**, made of **quarks** and **gluons**
- Bound by the **strong interaction**
  - ⇨ Binds quarks into hadrons
  - ⇨ Binds nucleons into nuclei

Strong interaction

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, …

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS force carriers spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- Strong interaction = interaction by particles carrying **colour charge** (quarks and gluons)
  - ⇨ 3 colour charge states (R,B,G) are postulated in order to explain the composition of **baryons** (3 quarks or antiquarks) and **mesons** (quark-antiquark pairs) as color singlets
  - ⇨ Colour interaction through 8 massless vector bosons -> **gluons** (strong force carriers)
- The theory describing the strong interaction is called **Quantum Chromodynamics** (QCD)
  - ⇨ Very successful theory
  - ⇨ … but with outstanding puzzles

Puzzles in QCD: (i) confinement

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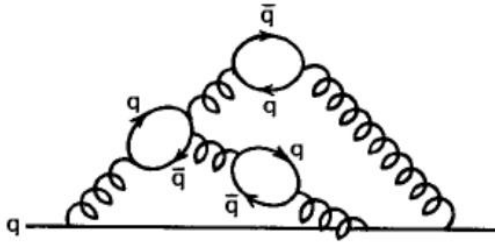
- Nobody ever succeeded in detecting an isolated quark
- Quarks are permanently confined within protons, neutrons, pions and other hadrons.
  - ⇨ It looks like one half of the fundamental fermions are not directly observable…
- Why?

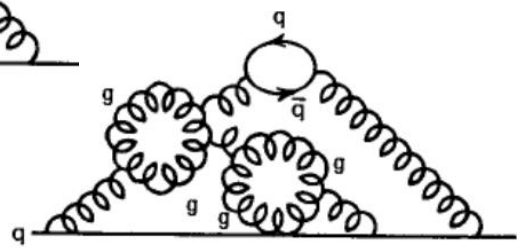
- NOTE:
  - ⇨ At scales of the order of the hadron size (~ 1 fm) the strong coupling constant is large perturbative methods cannot be applied
  - ⇨ Calculations rely on approximate methods (such as lattice numerical calculations or effective theories)

QCD coupling constant

The QCD vacuum consists of:

- Virtual $q\bar{q}$ pairs
  - ⇨ **screening** effect as in QED
- But also virtual gluon pairs
  - ⇨ **anti-screening** (since the gluon cloud carries colour charge)



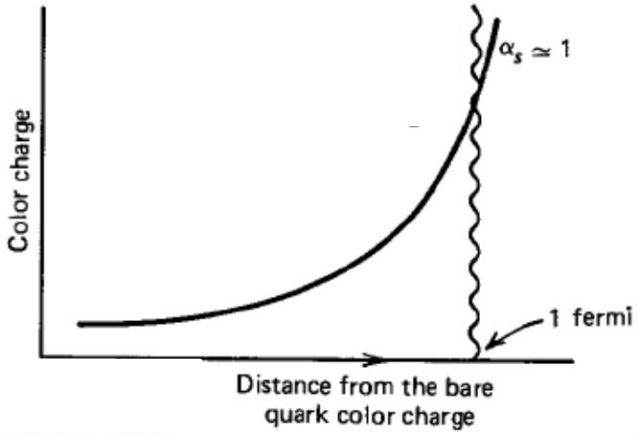


→ Running coupling constant:

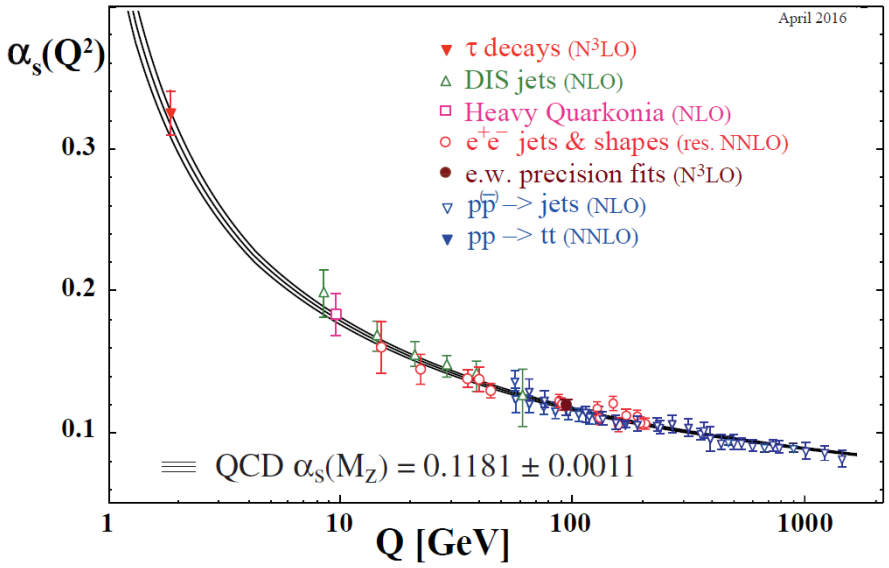
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \beta_0\,\alpha_s(\mu^2)\ln(Q^2/\mu^2)} \quad \text{with} \quad \beta_0 = \frac{11N_c - 2n_f}{12\pi}$$

- ⇨ N_c (number of colours) = 3
- ⇨ n_f (number of quark flavours) = 6

- The virtual gluon contribution dominates and the **effective strong coupling increases with increasing distances**
  - ⇨ Different from QED coupling



Confinement, asymptotic freedom



- Strong coupling at small momentum transfer (large distances)
  - ⇨ Impossible to isolate a quark from a hadron -> **confinement**

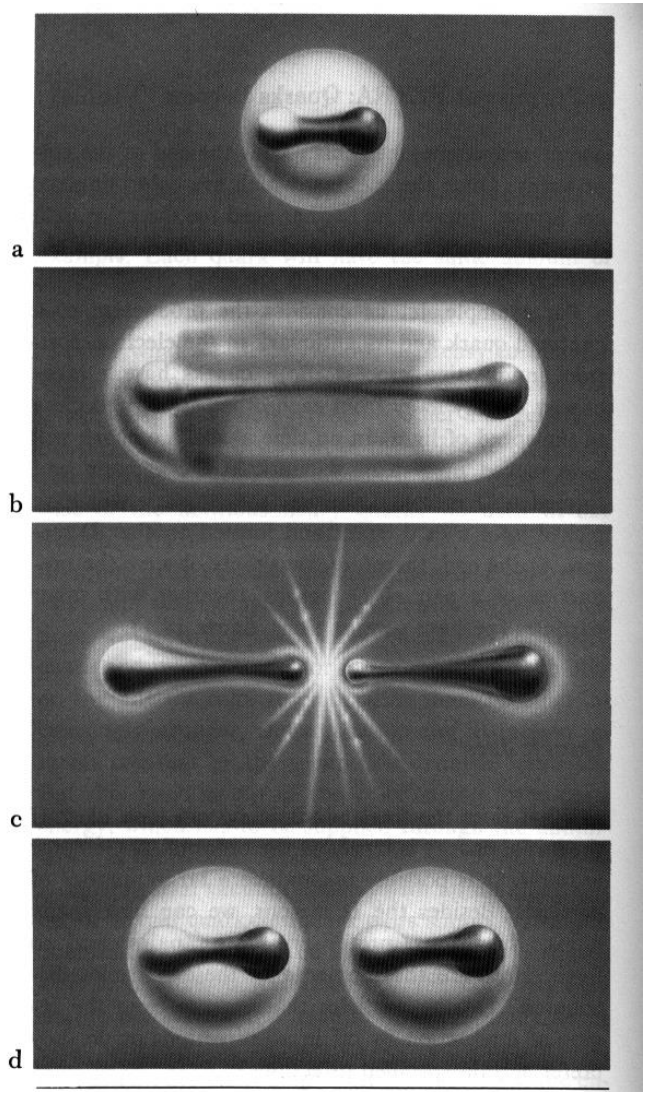
- Small coupling at large momentum transfer (short distances)
  - ⇨ Quarks inside hadrons behave approximately as free particles, when probed at large enough energies -> **asymptotic freedom**

Confinement: "intuitive view"

- Approximate potential for the strong interaction when for example a quark and an antiquark are pulled apart:

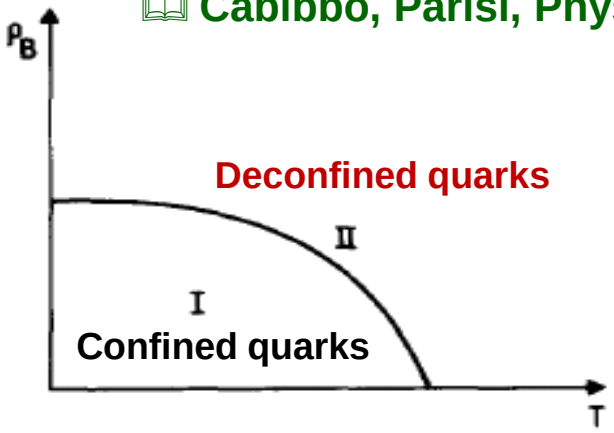
$$V(r) = -\frac{\alpha}{r} + Kr$$

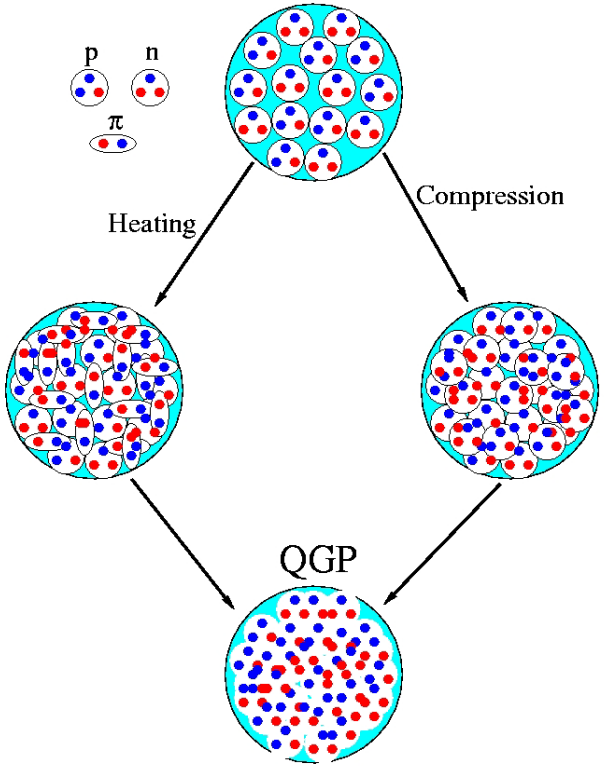
  - ⇨ The term Kr parametrizes the effects of confinement
- When r increases, the colour field can be seen as a "flux tube" (or "string") connecting the quarks
  - ⇨ The interaction strength and the potential increase with increasing distance
- At large r, it becomes energetically favourable to convert the (increasing) energy stored in the colour tube to a new $q\bar{q}$ pair



From a confined world ... … to deconfinement

- What if we compress/heat matter so much that the individual hadrons start to interpenetrate?
  - ⇨ Since the interactions between quarks and gluons become weaker at small distances, it might be possible, by creating a high density/temperature extended system composed by a large number of quarks and gluons, to **create a "deconfined" phase of matter**
  - ⇨ First ideas date back in the '70s
    - 🕮 **Cabibbo, Parisi, Phys.Lett.B, 67 (1975)**

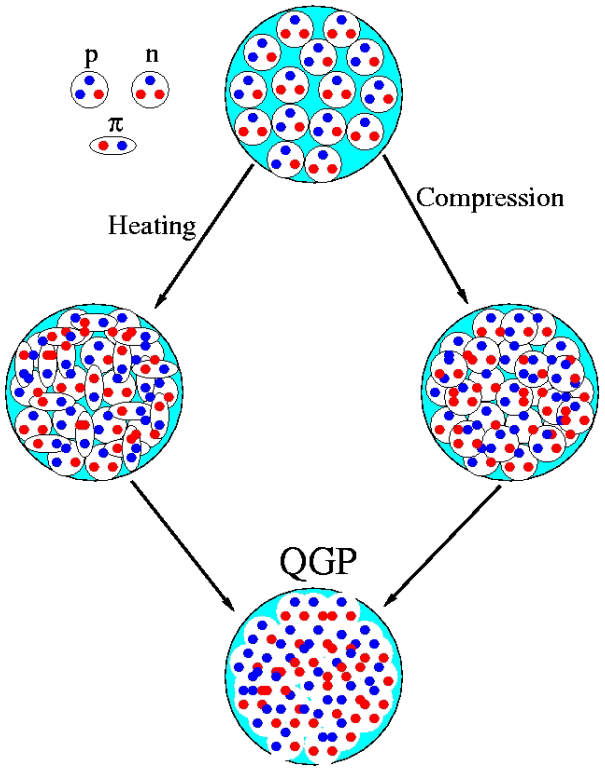




From a confined world ... … to deconfinement

- What if we compress/heat matter so much that the individual hadrons start to interpenetrate?

  - ⇨ If a system of hadrons is brought to sufficiently large density and/or temperature a **deconfinement phase transition** should occur
  - ⇨ In the new phase, called **Quark-Gluon Plasma** (**QGP**), quarks and gluons are no longer confined within individual hadrons, but are free to move around over a larger volume



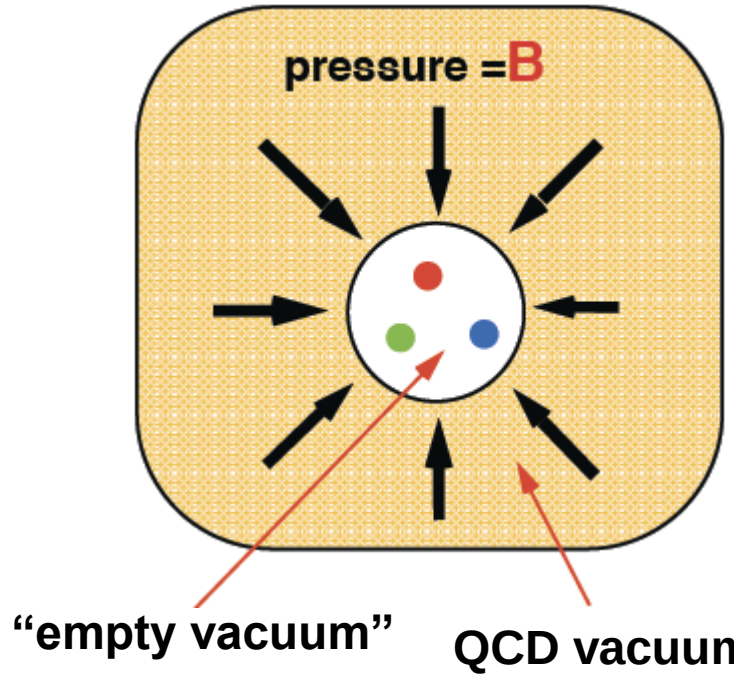
More quantitatively: bag model

- MIT bag model: simple, phenomenological approach
  - ⇨ Quarks considered as massless particles contained in a finite-size bag
  - ⇨ Confinement comes from the balance between the vacuum pressure B and the outward kinetic pressure exerted by the quarks

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

  - ✓ *N = number of quarks, R= bag radius*
- Equilibrium (dE/dR=0) defines bag radius
  - ⇨ From the proton radius:

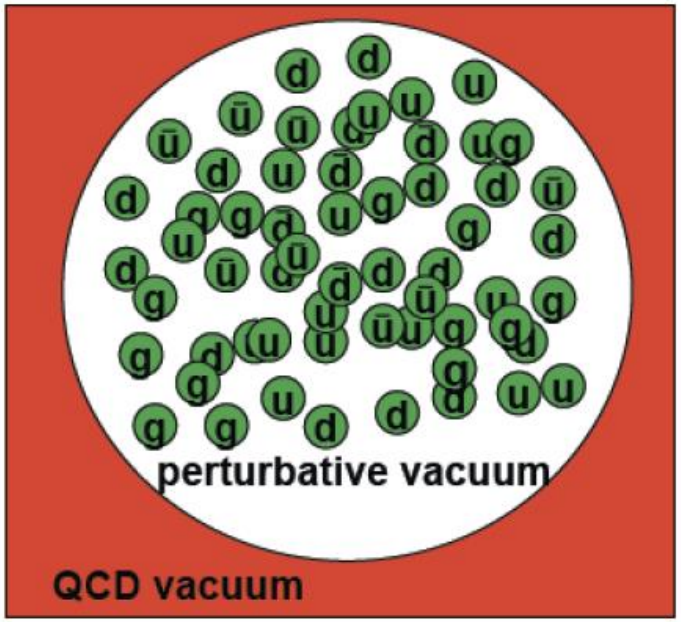
    R~0.8 fm → $B^{1/4}$ ~ 206 MeV



Deconfinement in the bag model

- If the pressure inside the bag increases in such a way that it exceeds the external pressure B → deconfined phase

- How to increase pressure?
  - ⇨ Temperature increase
    - ✓ ***Increases kinetic energy of quarks inside the bag***
  - ⇨ Compression
    - ✓ ***Increases density inside the bag***



- Can estimate with the bag model the critical temperature and density for the phase transition

High temperature QGP

- Pressure for a relativistic massless gas of gluons and light (u,d) quarks:

$$p = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

  - ⇨ g_B = number of degrees of freedom for bosons = 16
    - ✓ *8 colour x 2 spin states for gluons*
  - ⇨ g_F = number of degrees of freedom for fermions = 24
    - ✓ *(3 colours x 2 spin x 2 flavours) + antiquarks*

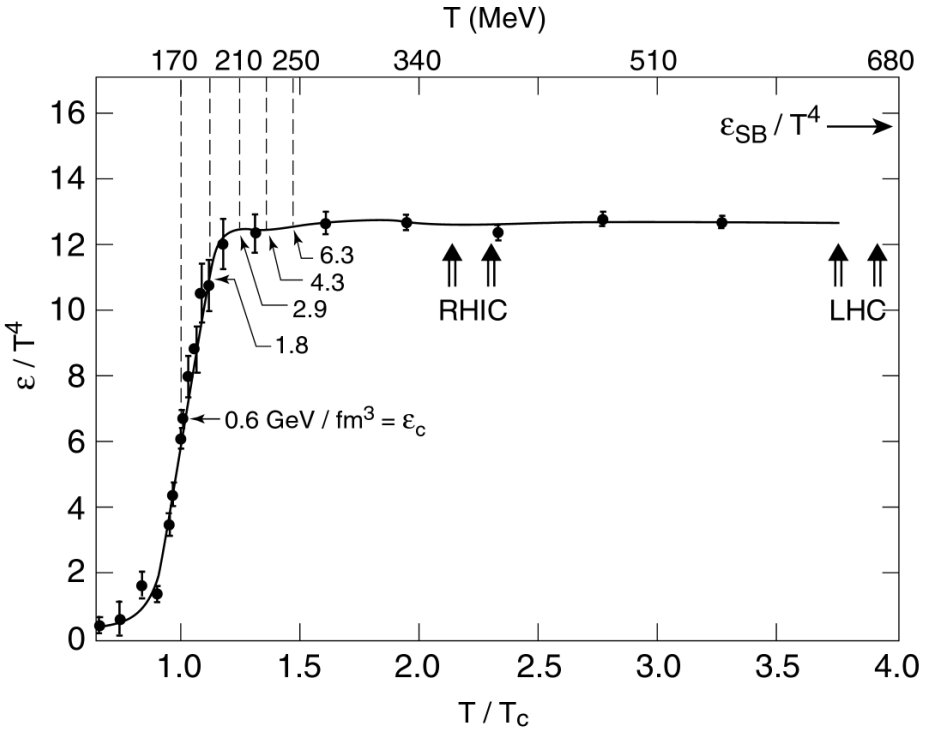
- **Critical temperature**: value of T at which pressure of quarks and gluons equals the bag pressure

$$T_c = \sqrt[4]{\frac{90B}{37\pi^2}} \approx 145\text{MeV}$$

  - ⇨ **Quark-Gluon Plasma for $T>T_c$**

Deconfinement in lattice QCD

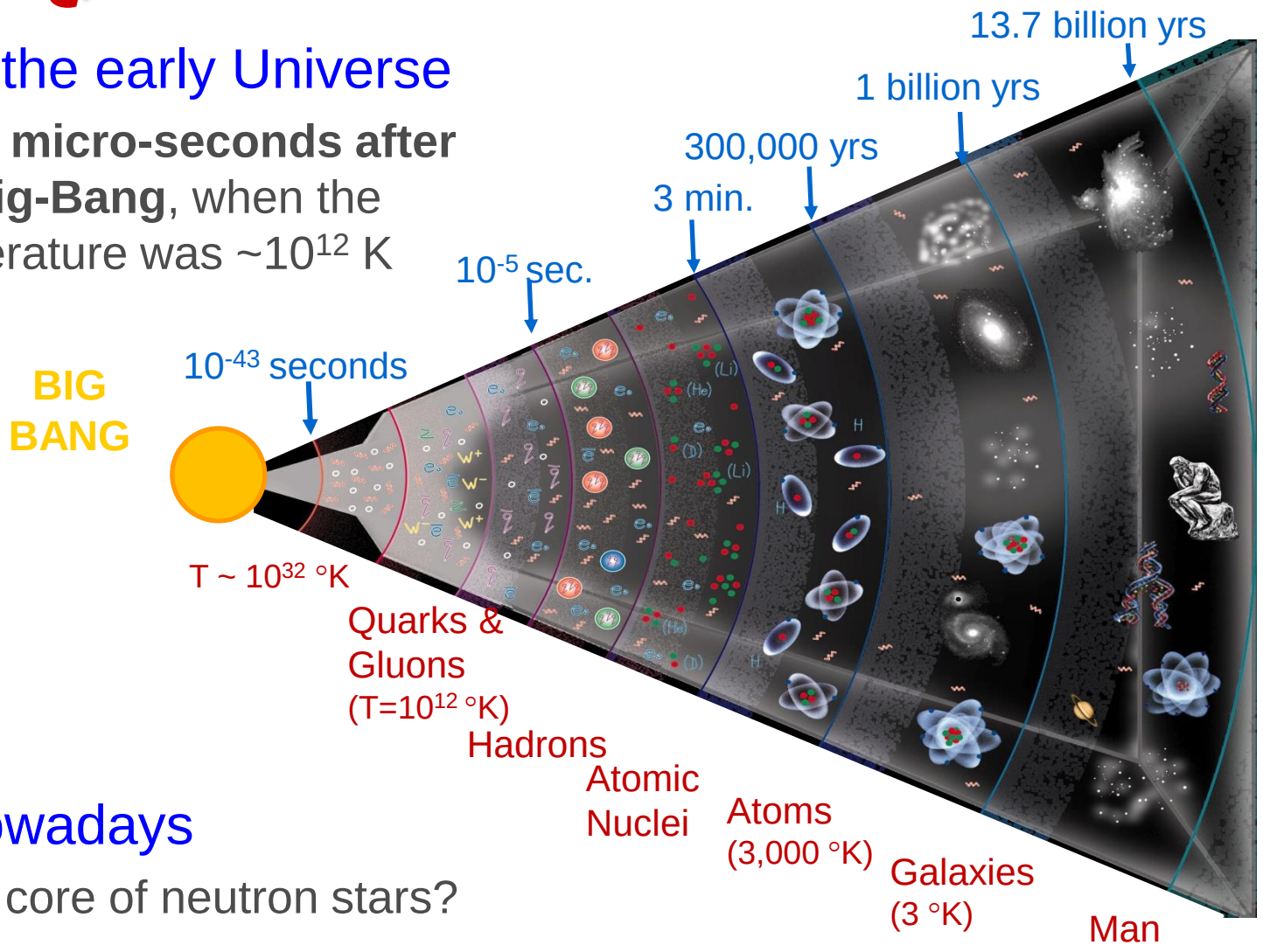
- Lattice QCD = non-perturbative QCD approach based on a discretization of the space-time coordinates (lattice)
  - ⇨ More quantitative results on the occurrence of the phase transition
  - ⇨ Requires intensive use of computing resources



- Energy density increases rapidly at T_c
  - ⇨ Due to the increased number of degrees of freedom: 3 in pion gas (π^+,π^-,π^0) → 37 in QGP
- $T_c \approx 170$ MeV ≈ 2000 billion K
  - ⇨ Recall: $T_{room} \sim 300$ K ~ 25 meV
  - ⇨ Sun core: T ~ 15 million K
- $\varepsilon_c \approx 0.6$ GeV/fm^3
  - ⇨ ≈ 5 times the nucleus density

QGP in the Universe

- QGP in the early Universe
  - ⇨ A **few micro-seconds after the Big-Bang**, when the temperature was ~10^{12} K



- QGP nowadays
  - ⇨ In the core of neutron stars?

Puzzles in QCD: (ii) hadron masses

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Leptons spin = 1/2

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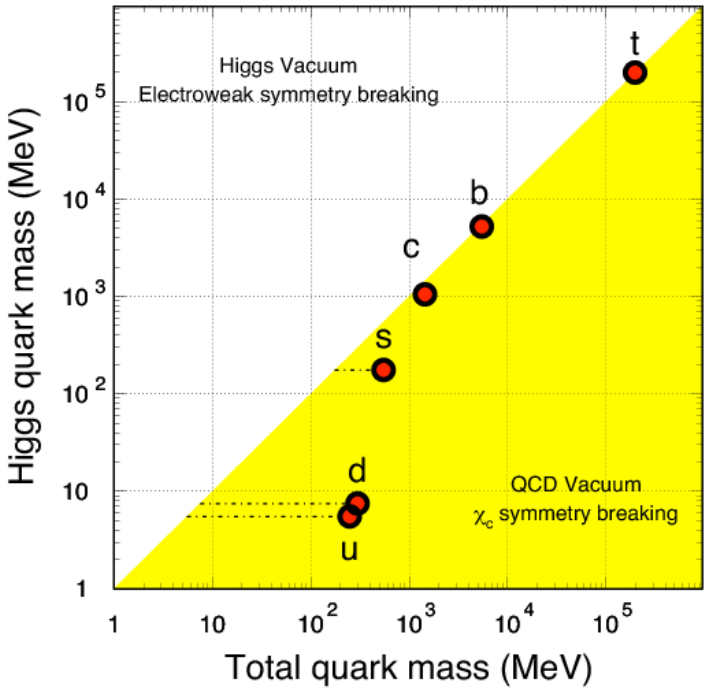
- A proton is made of two u and one d quarks
  - ⇨ The sum of their masses is ≈ 12 MeV
  - ⇨ ... but the proton mass is 938 MeV!
- How is the extra mass generated?

- Note:
  - ⇨ **Bare quark** masses
    - ✓ *Masses entering in the QCD Lagrangian (3, 6, 150 MeV for u,d,s)*
  - ⇨ **Constituent quark** masses
    - ✓ *Effective masses from the quark constituent model*
    - ✓ *Naively $M_{u,d}$ ~ 1/3 of proton mass ~ 300 MeV*

Chiral symmetry and hadron mass

- QCD Lagrangian for massless quarks exhibits **chiral symmetry**
  - ⇨ The Lagrangian is unchanged when rotating the left-handed and the right-handed components of the quark fields independently

- Explicit chiral symmetry breaking
  - ⇨ Due to non-zero quark masses
- Spontaneous breaking of chiral symmetry
  - ⇨ Due to the fact that the ground state (QCD vacuum) does not have the chiral symmetry of the Lagrangian
  - ⇨ Hadrons may be thought of as composed quarks “dressed” by their interactions with the chiral-symmetry-breaking QCD vacuum (**constituent quarks**)



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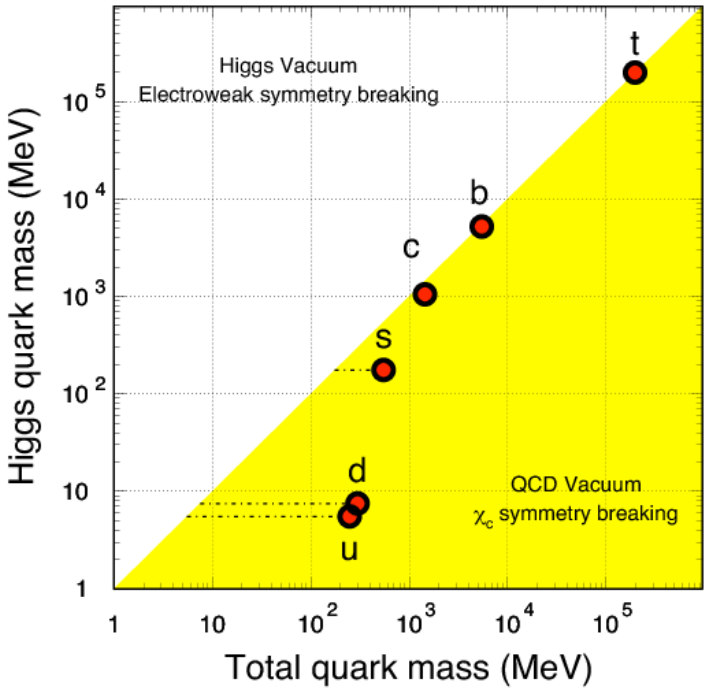
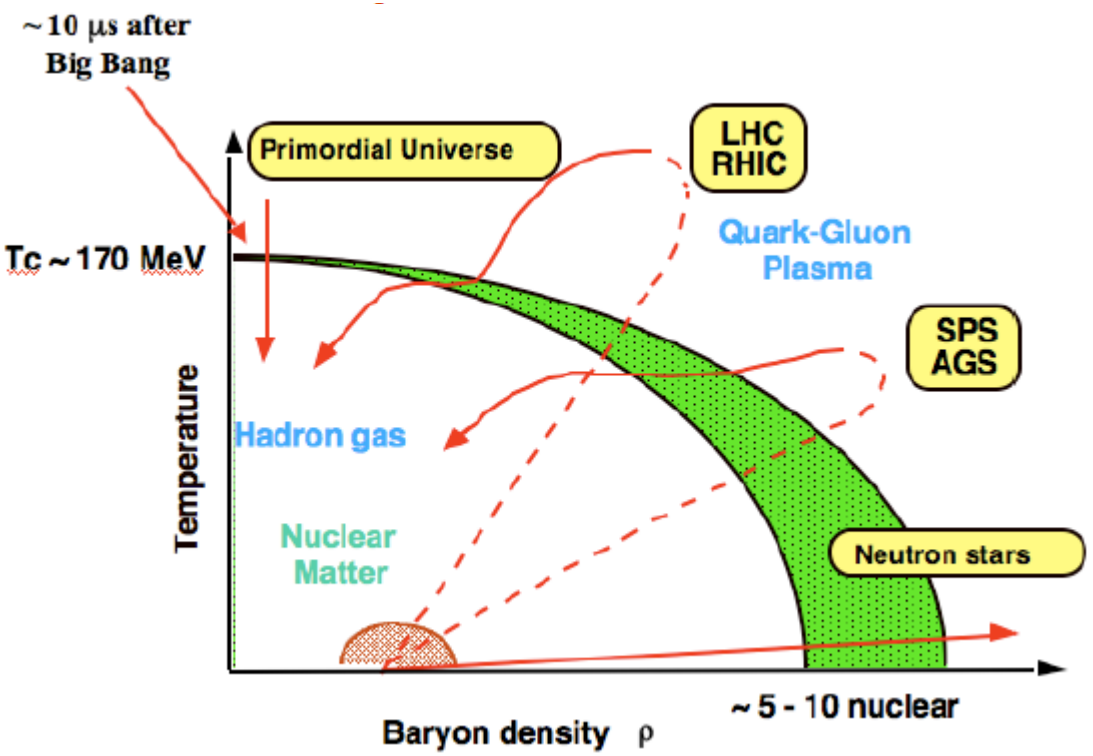
- Explicit chiral symmetry breaking
  - ⇨ Due to non-zero quark masses
- Spontaneous breaking of chiral symmetry
  - ⇨ Constituent quarks acquire an additional mass (~ 300 MeV) dynamically, through the confining effect of strong interactions
    - ✓ ***Relevant only for u, d ,s***
  - ⇨ **99% of the mass of the proton** (and therefore essentially all the mass of ordinary matter in the universe) arises **from chiral symmetry breaking QCD vacuum**



Deconfinement and chiral symmetry restoration

- The transition to a deconfined phase of QCD matter is expected to be accompanied by a restoration of chiral symmetry
  - ⇨ As quarks become deconfined, their masses are expected to go back to the “bare” values they have in the Lagrangian
  - ⇨ This effect is usually referred to as “**Partial Restoration of Chiral Symmetry**”.
    - ✓ ***NOTE:*** *the symmetry is exact only for massless particles, therefore its restoration here is only partial*
- According to Lattice QCD the two phase transitions (deconfinement and chiral symmetry restoration) occur at the same temperature

Phase diagram of QCD matter

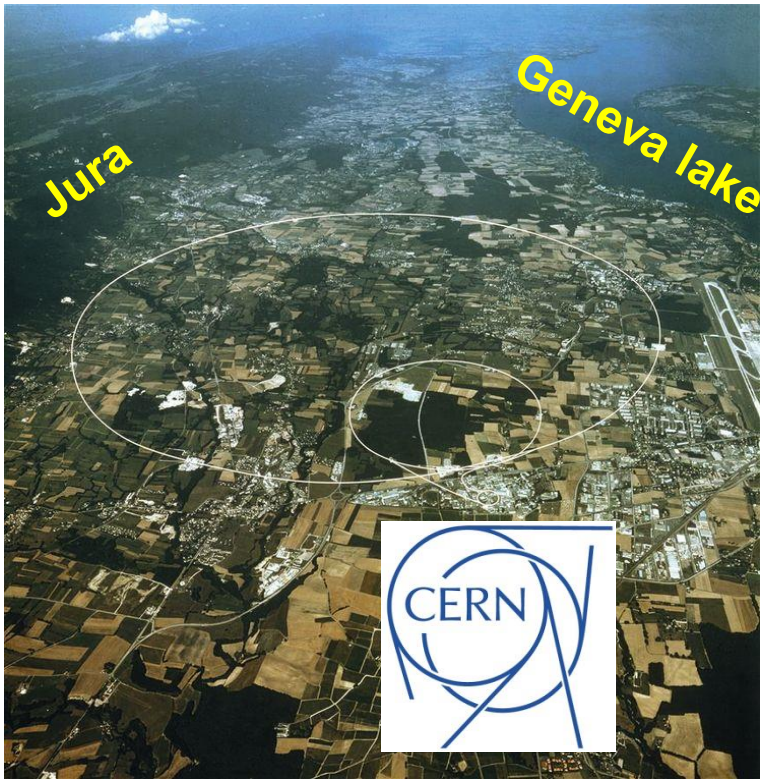


- Goal: explore this phase diagram
- How?
  - ⇨ By creating extended systems of quarks and gluons at high temperature and/or baryon density → heavy-ion collisions

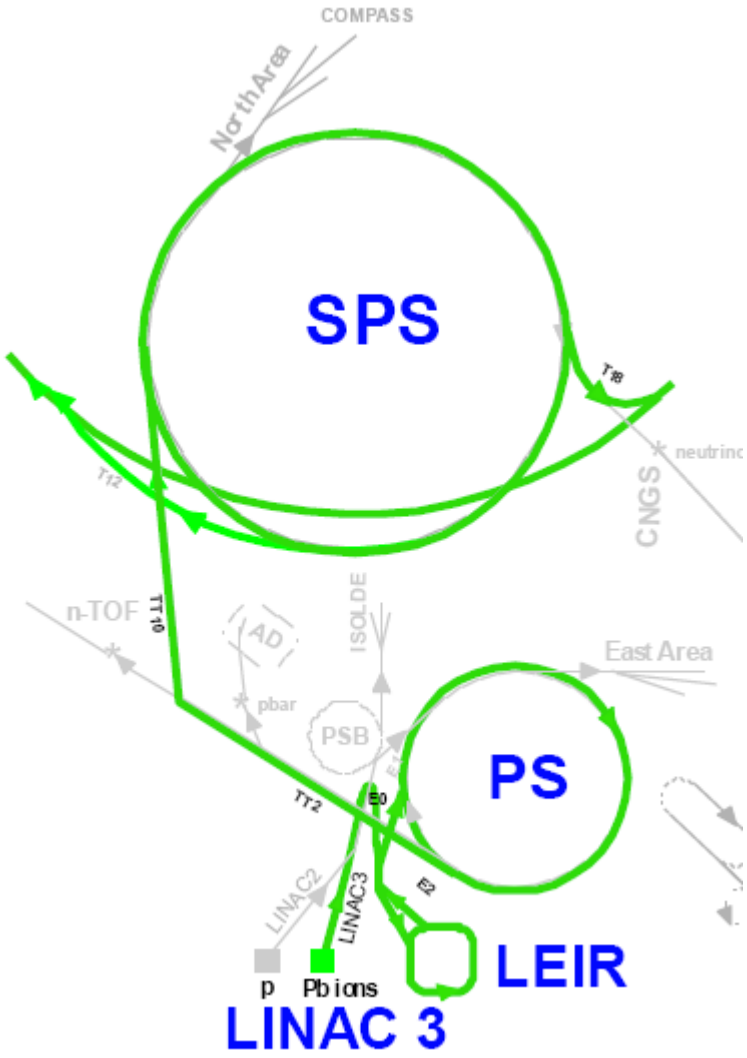
Part 2
How?

Heavy-ions at the accelerators

- **First pioneering studies** with heavy-ion collisions at relativistic energies date back to the **80's** when existing accelerators and experiments at **BNL** and **CERN** were modified to accelerate ion beams and to detect the particles emitted in the collisions



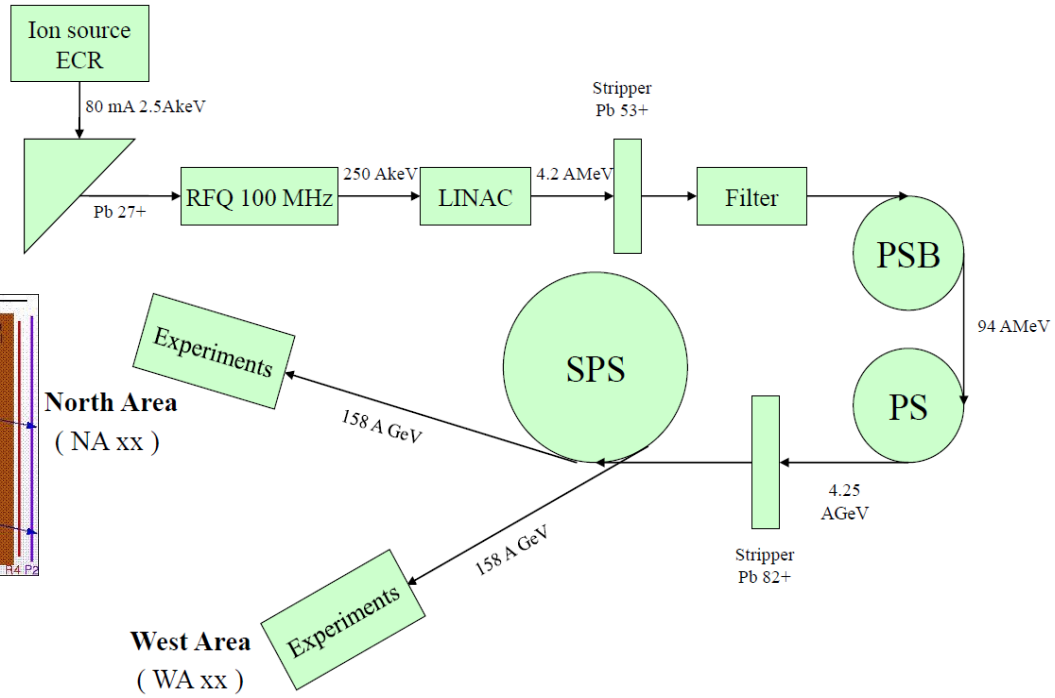
The fixed target era (1986-2000)

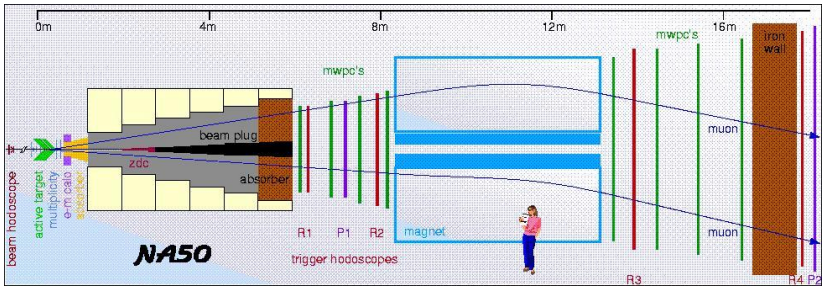


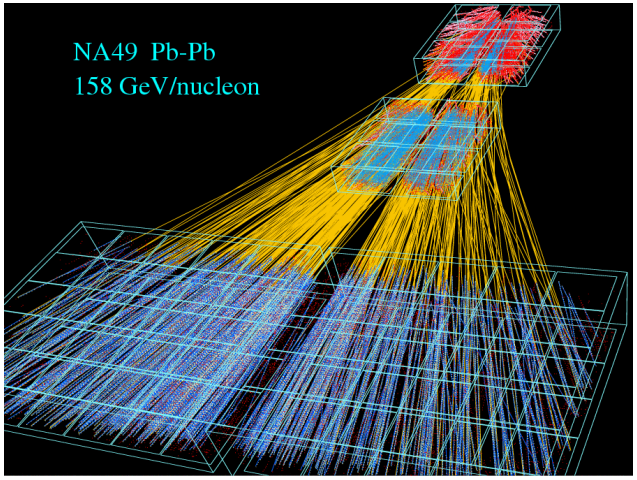
- **AGS at BNL**
  - ⇨ In operation since 1960
  - ⇨ p beams up to 33 GeV
  - ⇨ Si and Au beams up to **14.6 A GeV**
- **SPS at Cern**
  - ⇨ In operation since 1977
  - ⇨ p beams up to 450 GeV
  - ⇨ O, S, In, Pb up to **200 A GeV**
- Recall
  - ⇨ The energy per nucleon of ion beams is always smaller than for proton beams by a factor Z/A

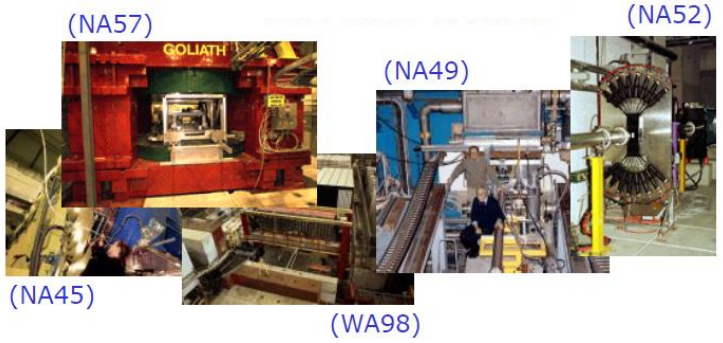
The fixed target era (1986-2000)

- Complex acceleration chain
- “Small and specialized” experiments

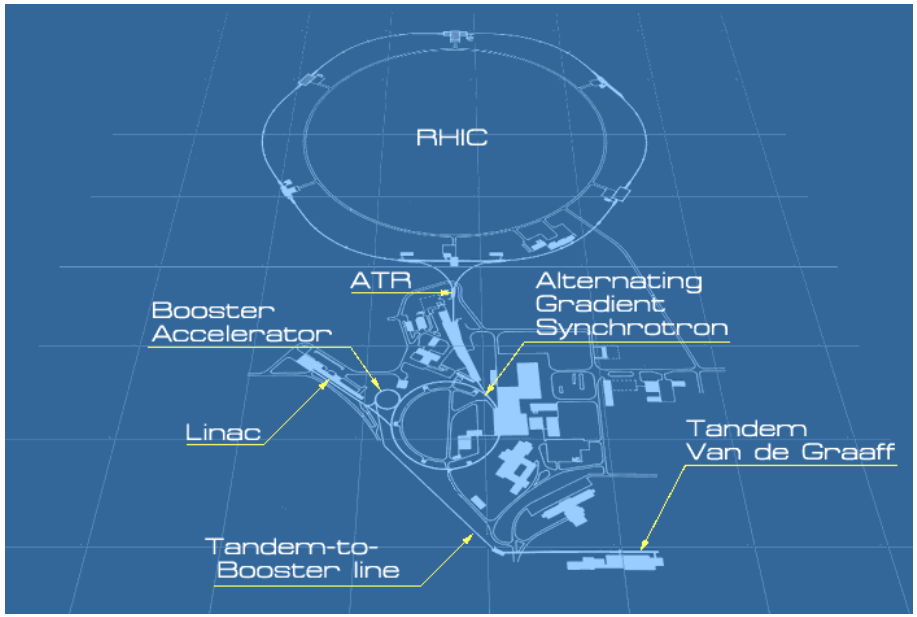








The collider era (2001-today)



- **RHIC at BNL**
  - ⇨ In operation since 2001
  - ⇨ Circumference = 3.8 km
  - ⇨ Au, Cu and U beams up to **100 A GeV**
- **LHC at Cern**
  - ⇨ In operation since 2009
  - ⇨ Circumference = 27 km
  - ⇨ p beams up to 6.5 TeV
  - ⇨ Pb beams up to 2.51 TeV

- Centre-of-mass energy
  - ⇨ Fixed target (nucleon-nucleon collision at SPS):

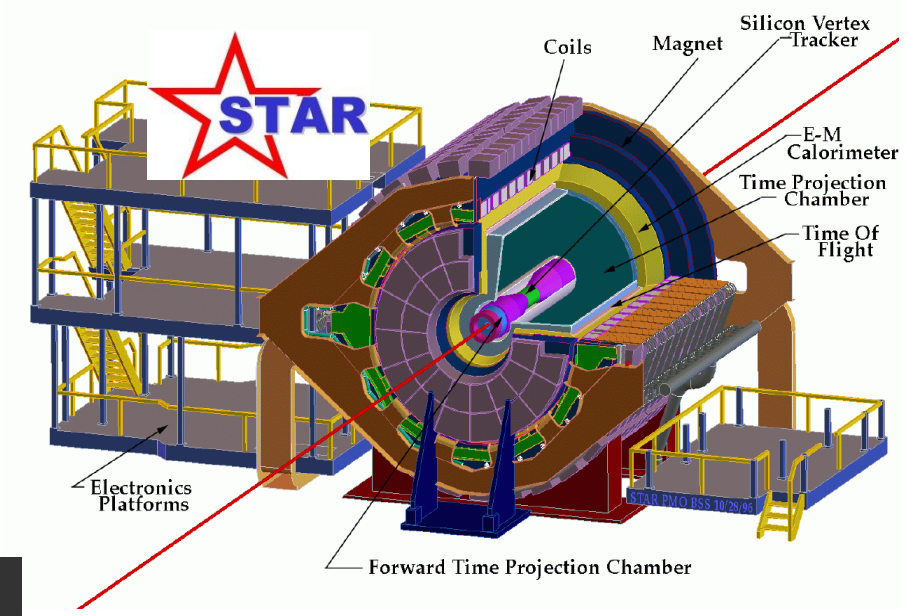
$$E_{\text{beam}} = 158\text{GeV} \rightarrow \sqrt{s} = \sqrt{2m_p^2 + 2E_{\text{beam}}m_p} \approx \sqrt{2E_{\text{beam}}m_p} \approx 17\text{GeV}$$

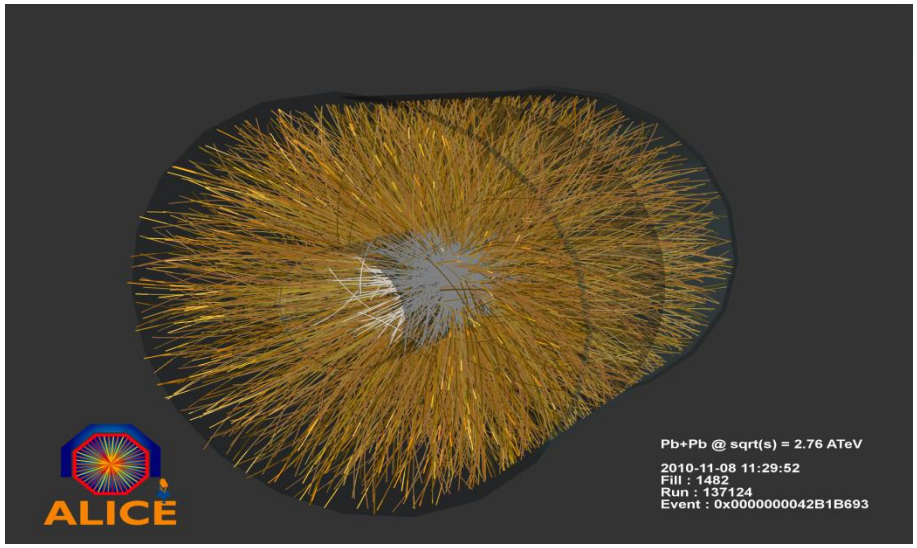
  - ⇨ Collider (nucleon-nucleon collision at RHIC)

$$E_{\text{beam}} = 100\text{GeV} \rightarrow \sqrt{s} = 2E_{\text{beam}} = 200\text{GeV}$$

The collider era (2001-today)

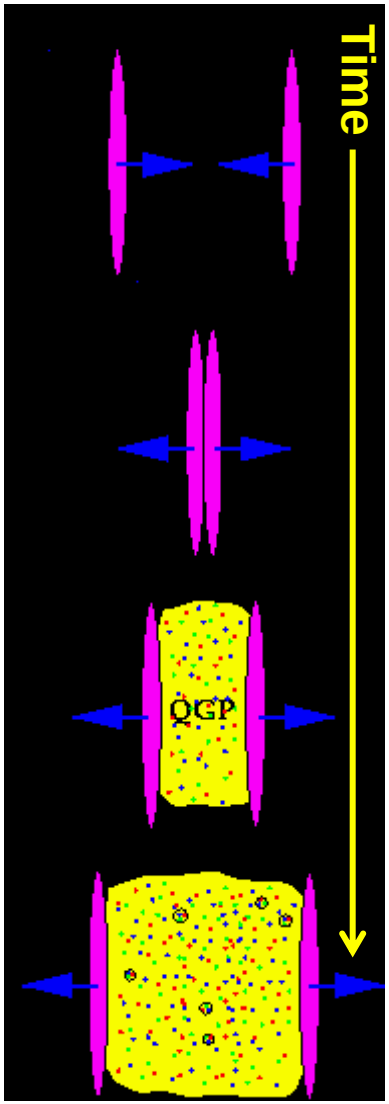
- Big and general purpose experiments composed of many detectors
  - ⇨ 2 main experiments at RHIC
    - ✓ ***STAR and PHENIX***
  - ⇨ 4 experiments at the LHC
    - ✓ ***ALICE (heavy-ion dedicated), ATLAS, CMS, LHCb***





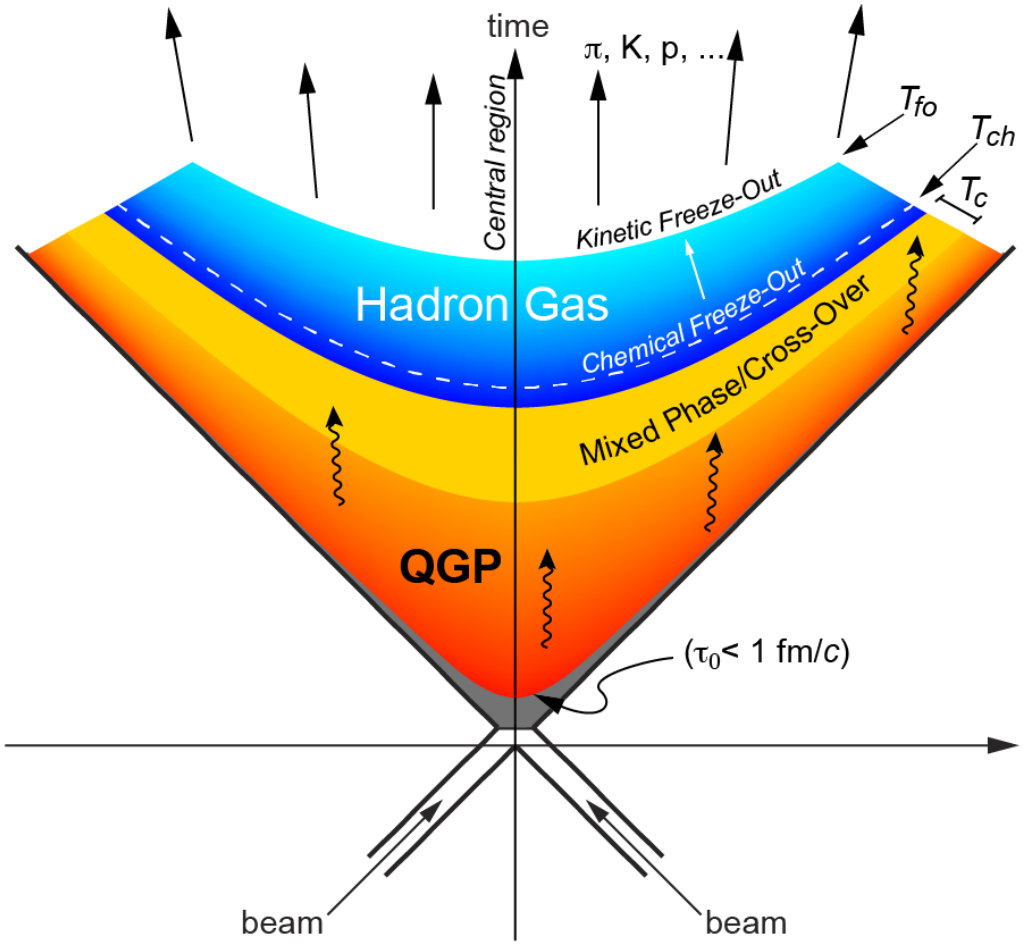
- How big?
  - ⇨ ATLAS: 46m long, 25m in diameter
  - ⇨ CMS weight ≈ 12500 tons
  - ⇨ ALICE Collaboration: 1550 members from 37 countries

Nucleus-nucleus collisions



- By colliding two heavy nuclei at ultrarelativistic energies we recreate, for a short time span the conditions for deconfinement
  - ⇨ Interactions among the medium constituents allow to reach equilibrium → **QGP phase**
- As the system expands and cools down it will reach T_c and undergo a phase transition from QGP to hadrons again
  - ⇨ Like at the beginning of the life of the Universe
- The system continues expanding and becomes more and more dilute
  - ⇨ Interactions among particles cease → **freeze-out**
- Particles (hadrons, leptons) fly towards the detectors

Space-time evolution: more quantitatively

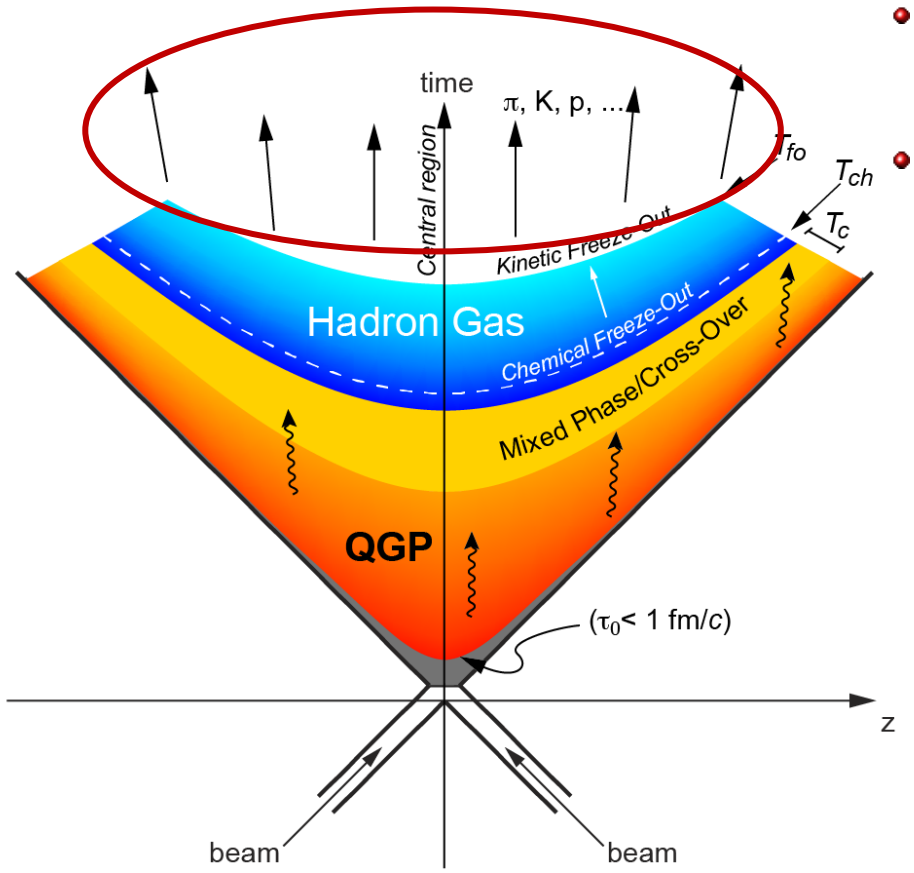


Time

Particle detection	**t~10 cm/c**
Kinetic freeze-out	**t~10 fm/c**
Chemical freeze-out Hadronization	
QGP hydrodynamic evolution	
Pre-equilibrium	**t~1 fm/c**
Collision	**t=0 fm/c**

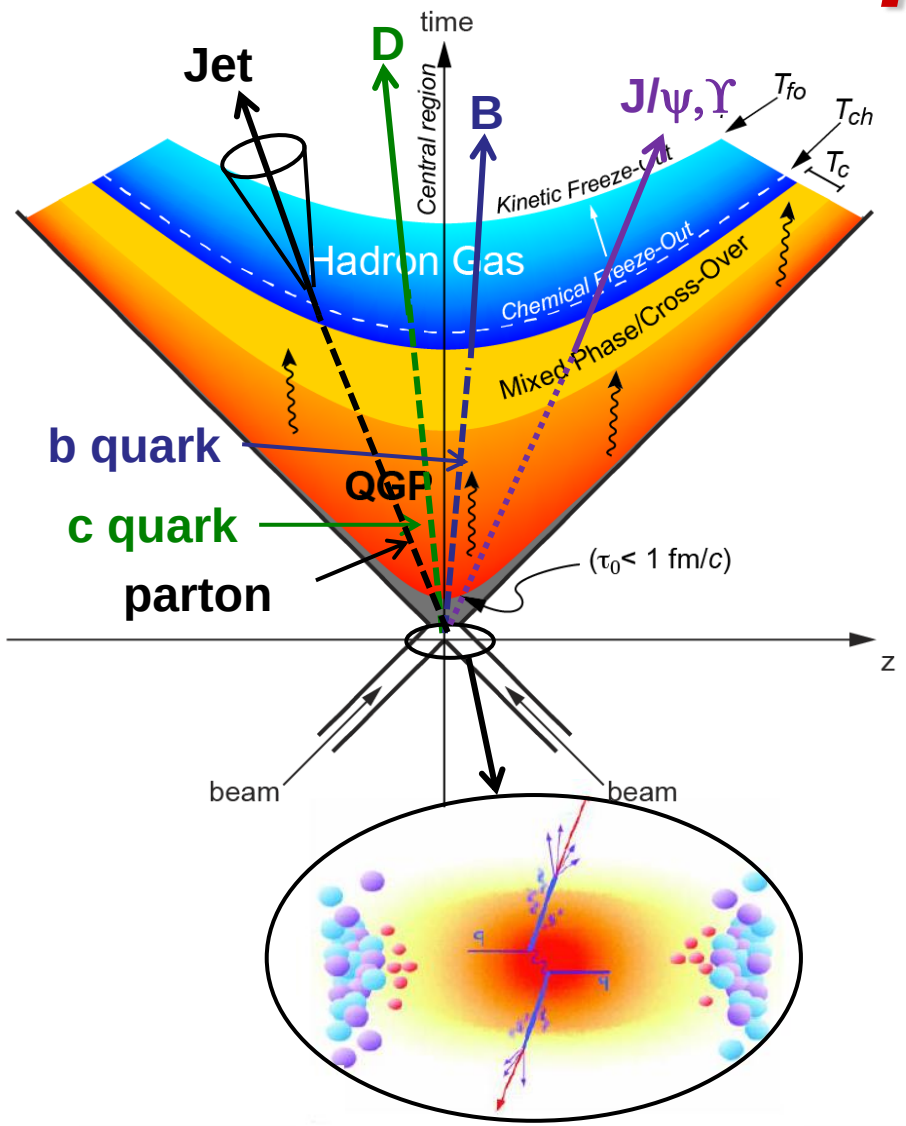
1 fm/c = 3 10^{-24}s

Soft particles



- QGP lifetime ~ a few fm/c
  - ⇨ We cannot access it directly
- The properties of the medium must be inferred from the properties of the hadronic final state
  - ⇨ Large number of particles
    - ✓ *3200 tracks in the ALICE acceptance in Pb-Pb collisions at the LHC*
  - ⇨ Mostly **pions, kaons and protons**
  - ⇨ Predominantly with **low momentum**
    - ✓ *99% of the produced particles have p_T<2 GeV/c*
  - ⇨ In jargon: **soft probes**

Hard probes

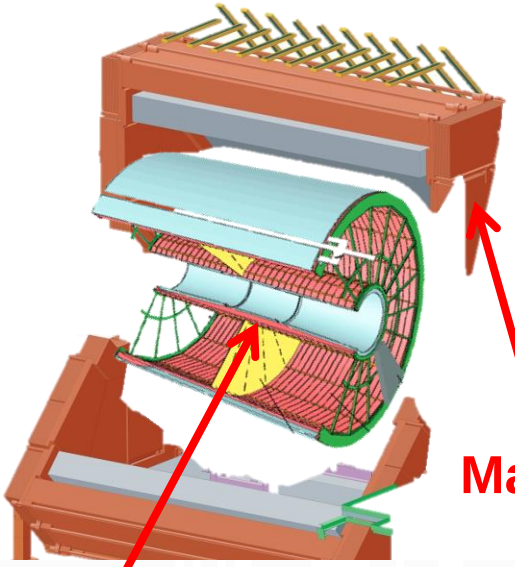


- Hard probes
  - ⇨ Produced at the **very early stage** of the collision in partonic scattering processes with large momentum transfer
  - ⇨ Traverse the hot and dense medium interacting with its constituents
  - ⇨ **Unique probes** of the properties of the QGP medium → **tomography of the medium**
- Observables:
  - ⇨ High-p_T hadrons
  - ⇨ Jets
  - ⇨ Heavy-flavour (charm and beauty)
  - ⇨ Quarkonia

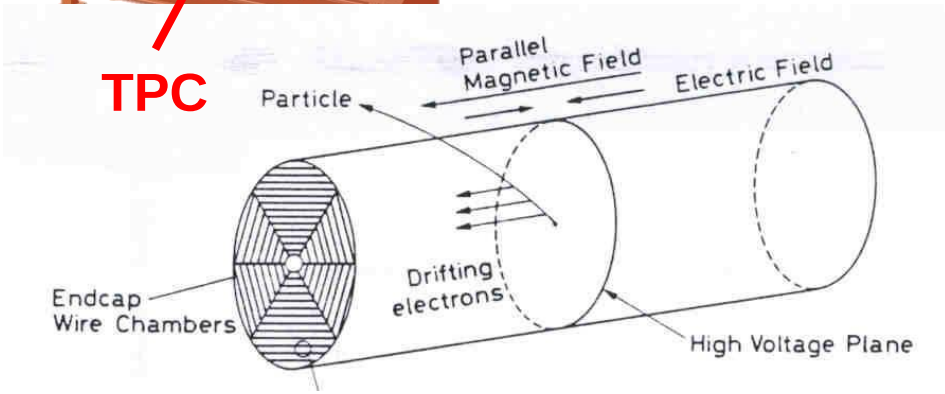
Design the experimental setup: requirements

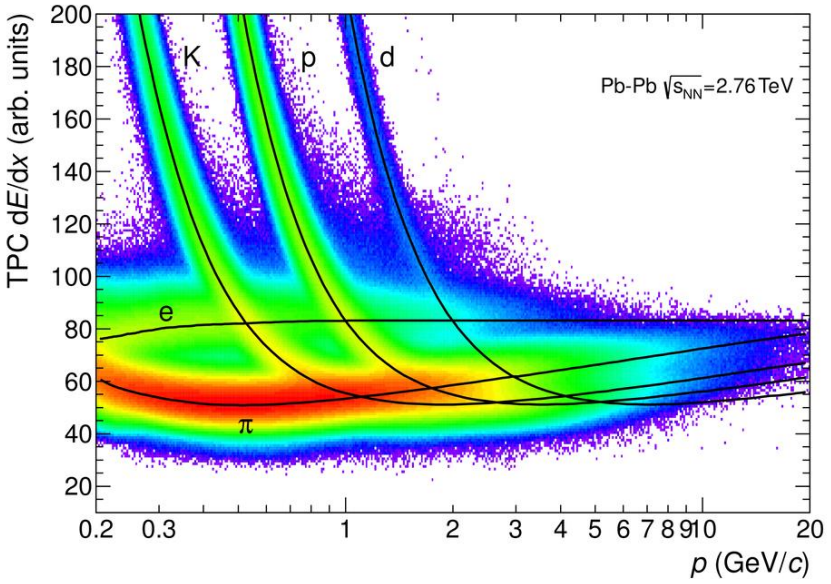
- Reconstruct the trajectories of charged particles (**tracking**)
  - ⇨ Work in high-track density environment
    - ✓ *Need many points (samplings) per track*
  - ⇨ Track particles down to low p_T
    - ✓ *Moderate B field: 0.5T in ALICE (for comparison CMS has B=4T)*
    - ✓ *Low material budget (to limit multiple scattering)*
  - ⇨ Good momentum resolution
    - ✓ *Large dimensions (lever of arm)*
- Identify particle species (**PID**)
  - ⇨ Separate π, K and p tracks … and also deuterons, tritons, ^{3}He…
- Reconstruct strange (e.g. K^0_S, Λ), charm (D's) and beauty hadrons from **hadronic decays**
- Reconstruct quarkonia (J/ψ, ψ', Υ) -> from **dileptonic decays**
- … and also photons, electrons, jets… -> **calorimeters**

Design the experimental setup: i) tracking, PID

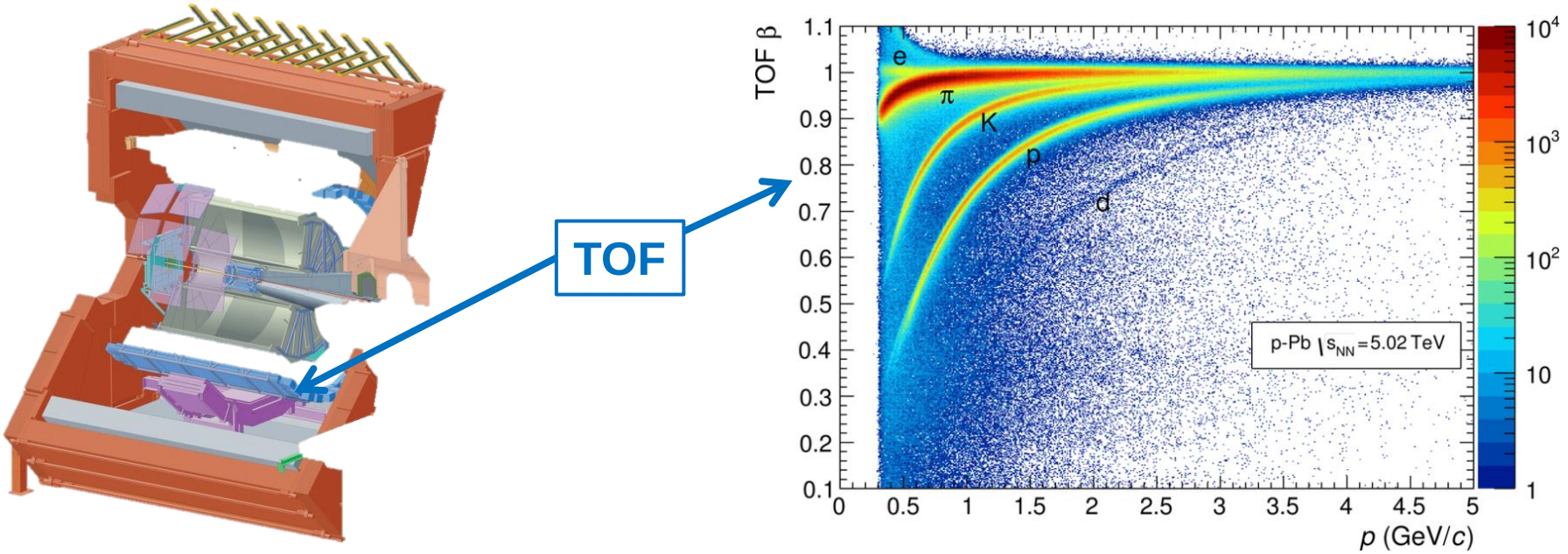


- Magnet + Time-Projection Chamber
  - ⇨ ALICE TPC: 90 m^3 volume
    - ✓ *Largest ever gaseous detector*
    - ✓ *Up to 160 3D points per track*
    - ✓ *2 coordinates from endcap MWPCs, 1 from drift time*
  - ⇨ PID via dE/dx vs. momentum



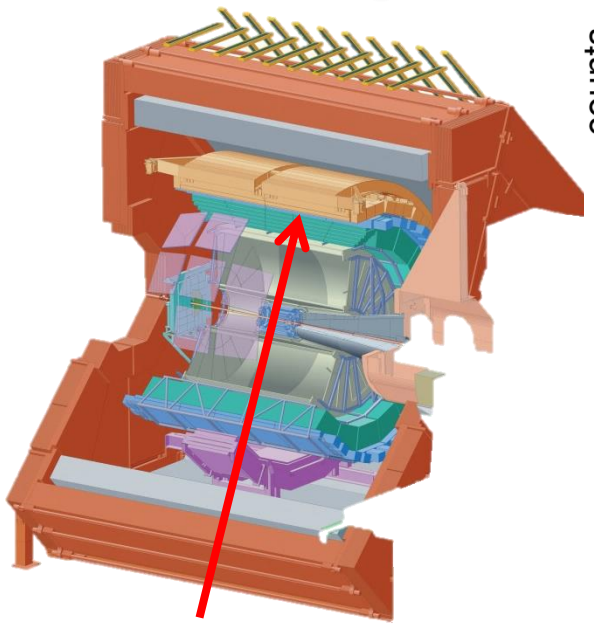


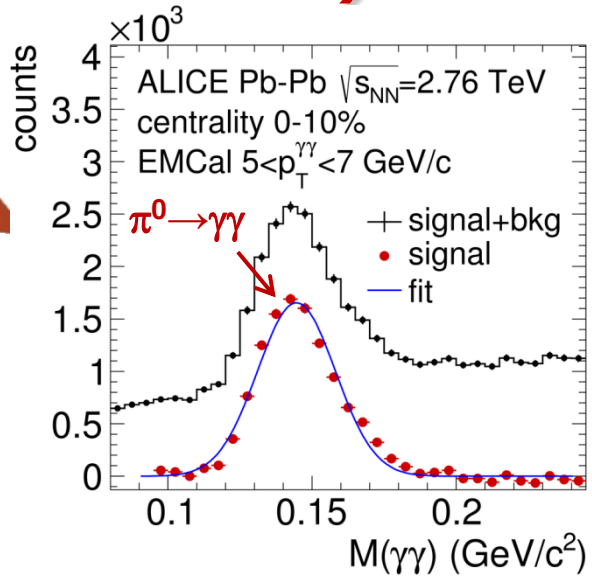
Design the experimental setup: ii) more PID

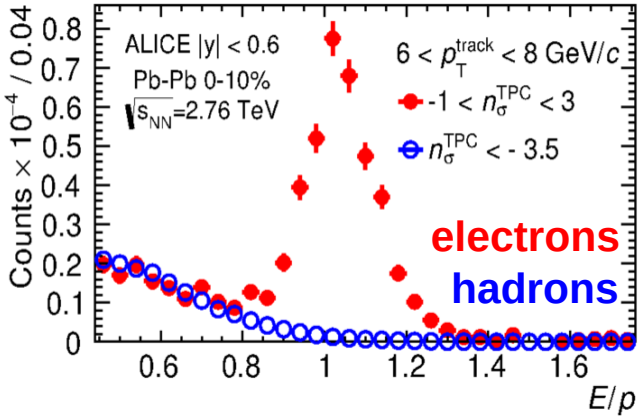


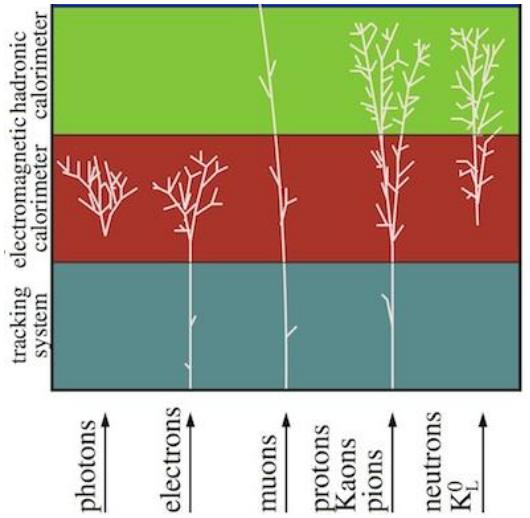
- PID with dE/dx only at low p ($1/\beta^2$ region)
- Extend PID capabilities to higher momentum with TOF
  - ⇨ Multi-Gap Resistive Plate Chamber technology
  - ⇨ ALICE TOF: measures the time of flight of particles from interaction point to TOF with ~ 56 ps resolution

Design the experimental setup: iii) photons, electrons



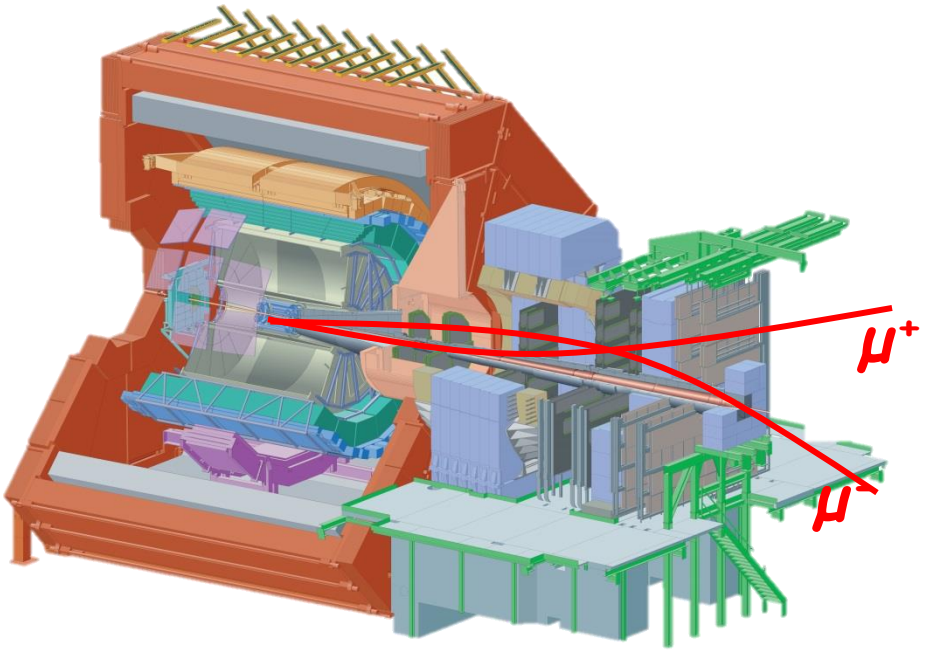


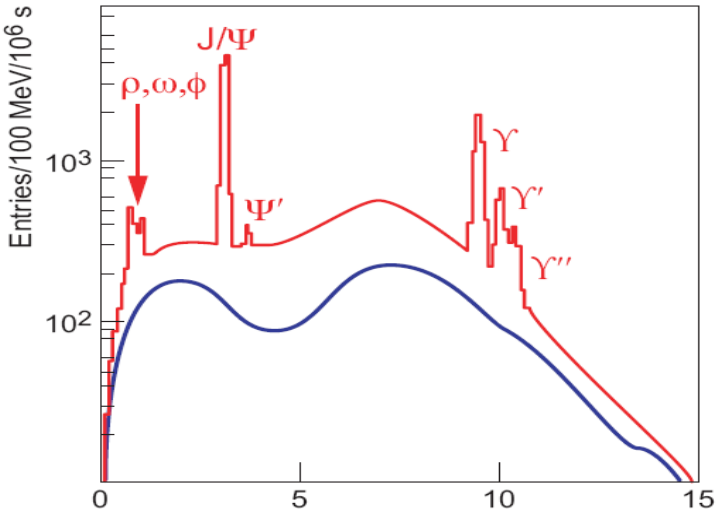




- Electromagnetic calorimeter
  - ⇨ Outside the tracking detectors
  - ⇨ Measure energy of photons and electrons via electromagnetic shower
  - ⇨ Used for $\pi^0 \rightarrow \gamma\gamma$ reconstruction, electron ID via E/p …

Design the experimental setup: iv) hard probes: quarkonia

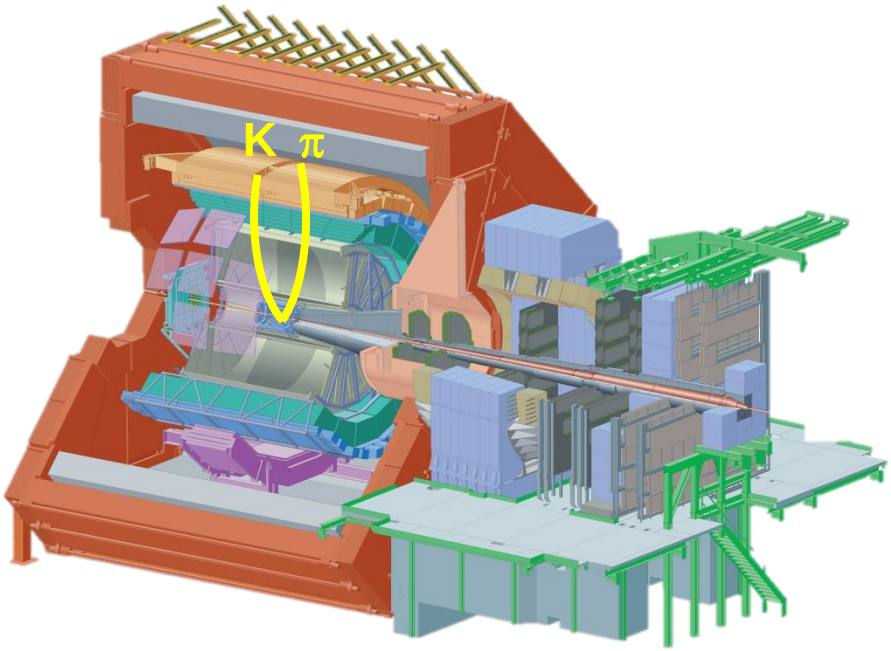




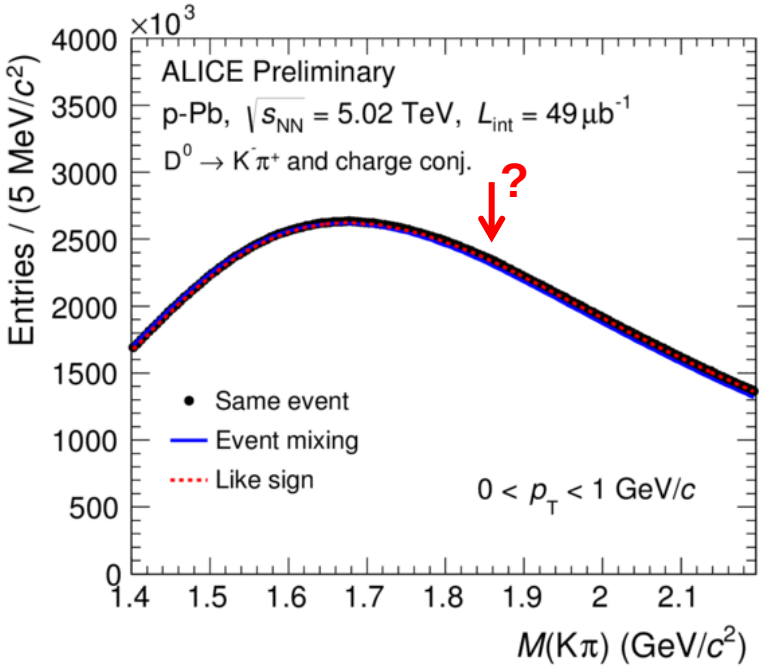
$$m_{\mu^+\mu^-} = \sqrt{(E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2}$$

- **Charmonia** ($c\bar{c}$ bound states, e.g. J/ ψ) and **bottomonia** ($b\bar{b}$ bound states, e.g. Υ) can be reconstructed from their **decays in two muons**
- Absorber (to "kill" hadrons) + muon spectrometer
- Invariant mass distribution of $\mu^+\mu^-$ pairs

Design the experimental setup: v) hard probes: D mesons



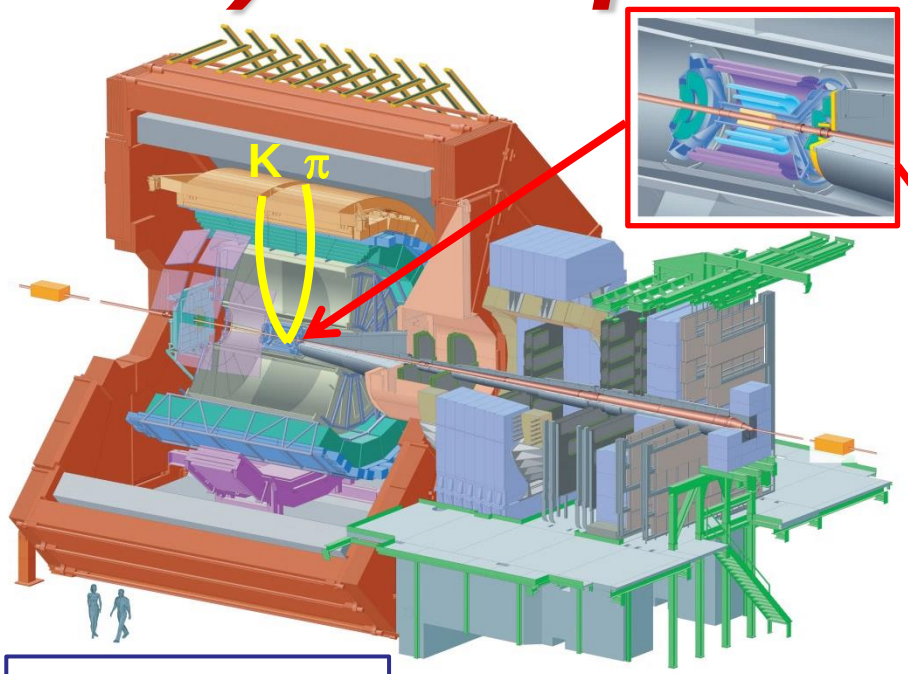
$$m_{K\pi} = \sqrt{(E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2}$$



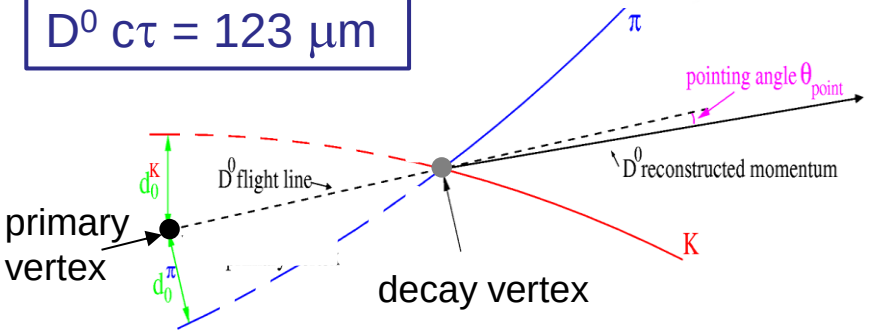
- D^0 mesons decay into $K^-\pi^+$
  - ⇨ Naïve idea: build Kπ pairs; compute invariant mass; search for a peak at the D^0 mass (1.865 GeV/c^2)

DOES NOT WORK!

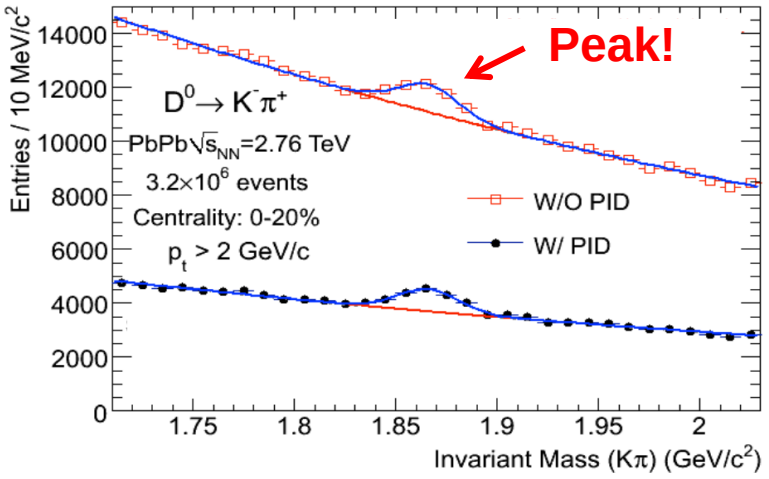
Design the experimental setup: v) hard probes: D mesons



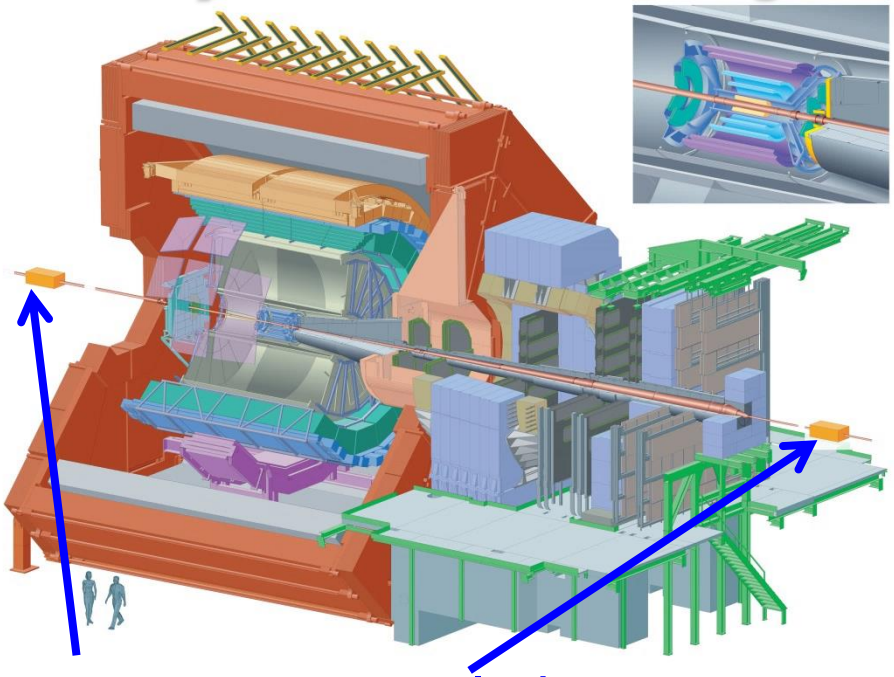
D^0 cτ = 123 μm



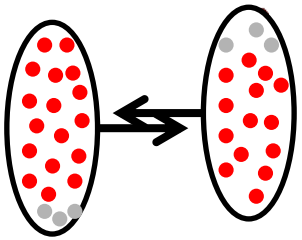
- Solution: exploit **displaced decay topology**
  - ⇨ Need high resolution (≈100 μm) on track position
- Inner tracker made of layers of silicon detectors
  - ⇨ High precision points
  - ⇨ Close to the beam axis
  - ⇨ + minimize material budget



Design the experimental setup: vi) Centrality of the collision

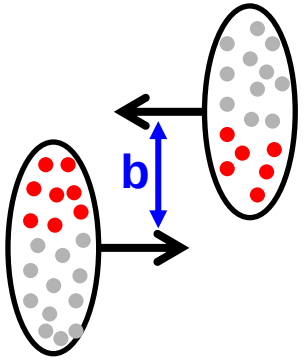


- Zero Degree calorimeters
  - ⇨ Measure energy of spectator nucleons
- Glauber geometrical model
  - ⇨ Estimate impact parameter, number of elementary nucleon-nucleon collisions …



Central collisions

- ⇨ **Small** impact parameter **b**
- ⇨ Many **participant nucleons**
- ⇨ Few **spectator nucleons**

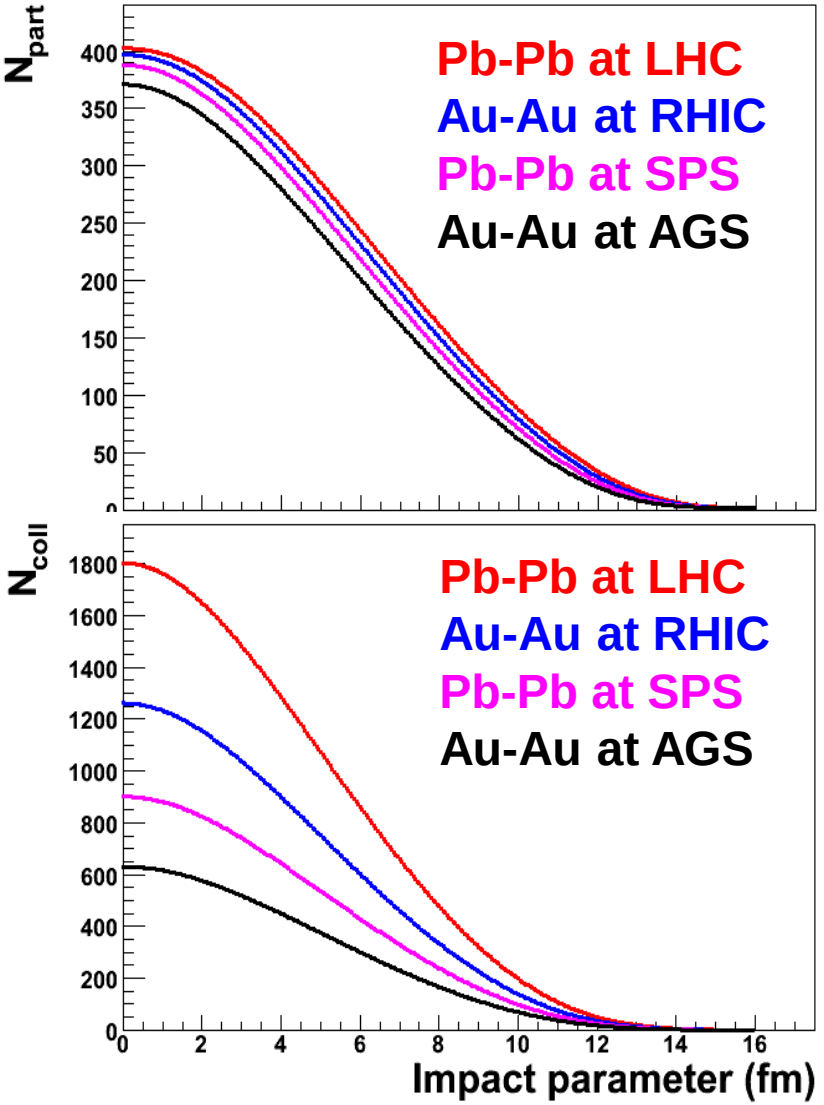


Peripheral collisions

- ⇨ **Large b**
- ⇨ Few **participants nucleons**
- ⇨ Many **spectator nucleons**

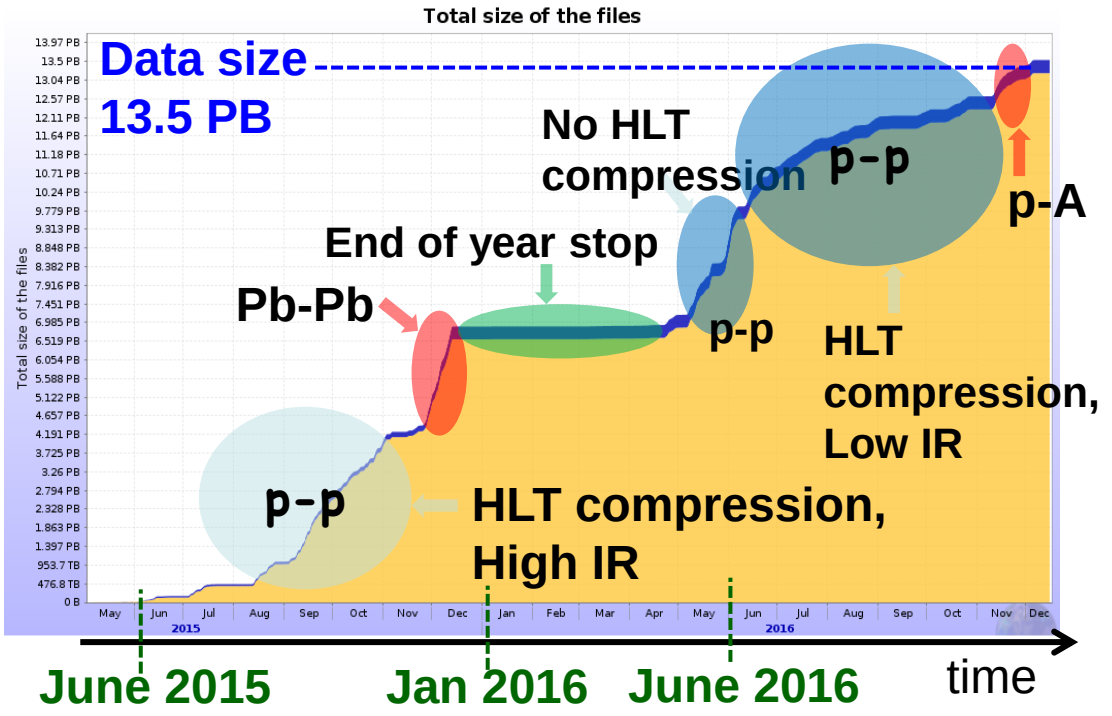
Centrality and the Glauber model

- Glauber model
  - ⇨ Semi-classical approach to nucleus-nucleus collision geometry
- ***Nucleus-nucleus interaction*** treated as ***incoherent superposition of nucleon-nucleon collisions***
  - ⇨ Assumptions:
    - ✓ *Nucleons are **point-like** and distributed in the nucleus according to a **Woods-Saxon***
    - ✓ *Nucleons travel along **straight-line** trajectories (=**not deflected** by interactions)*
  - ⇨ Calculate with a probabilistic approach:
    - ✓ ***Number of participant nucleons, number of nucleon-nucleon collisions as a function of impact parameter***



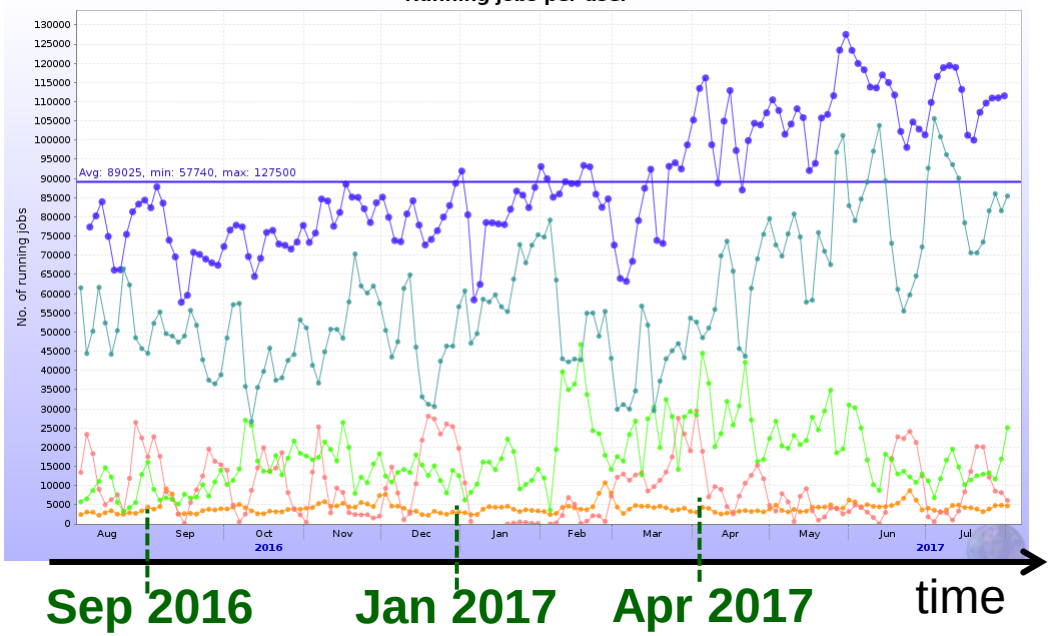
The computing challenge (1)

- Big data!
  - ⇨ Event size
    - ✓ ***Central Pb-Pb > 40 MB***
    - ✓ ***Average Pb-Pb = 12 MB***
    - ✓ ***For comparison: full text of the bible = 5 MB***
  - ⇨ With 500 Hz trigger rate
    - ✓ ***Data flow = 6 GB /s***
    - ✓ ***Corresponds to 1 DVD every second***
  - ⇨ Data volume = 6.5 PB per year
    - ✓ ***About 12M DVD per year***
    - ✓ ***If we would build a stack of this DVDs …. the height would be 12 km***

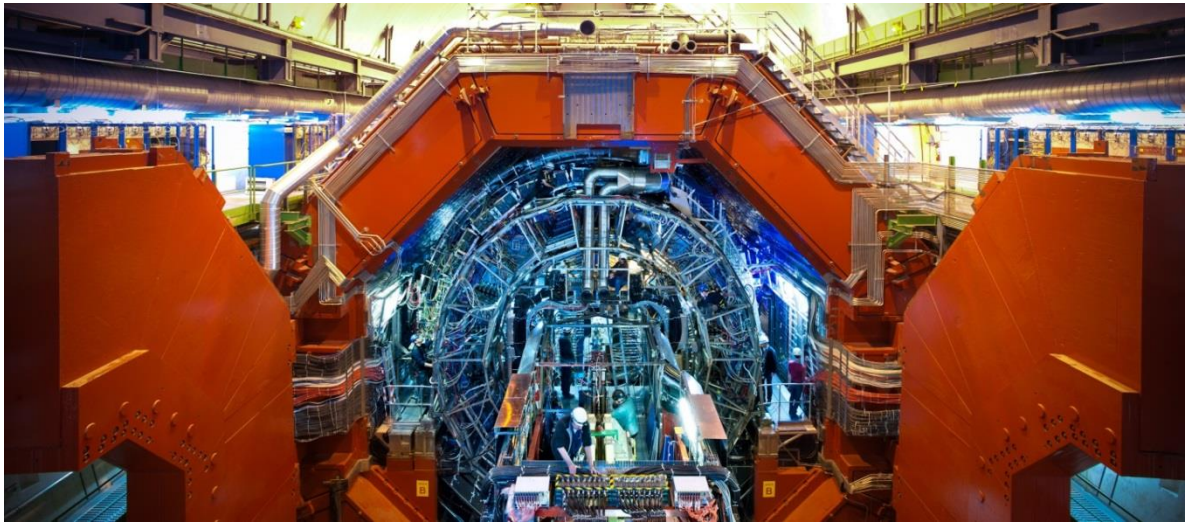


The computing challenge (2)

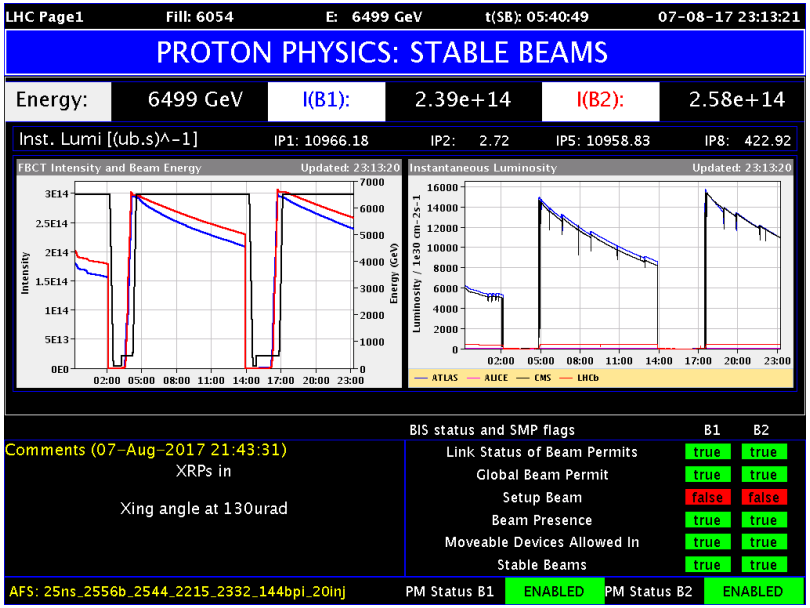
- Distributed computing
  - ⇨ LHC computing **grid** is the world's largest distributed computing grid
  - ⇨ ALICE: over 100 computing sites all over the world
  - ⇨ >60k concurrent jobs at any time
    - ✓ ***Data reconstruction***
    - ✓ ***Monte Carlo simulation***
    - ✓ ***User analysis***



Images from the construction



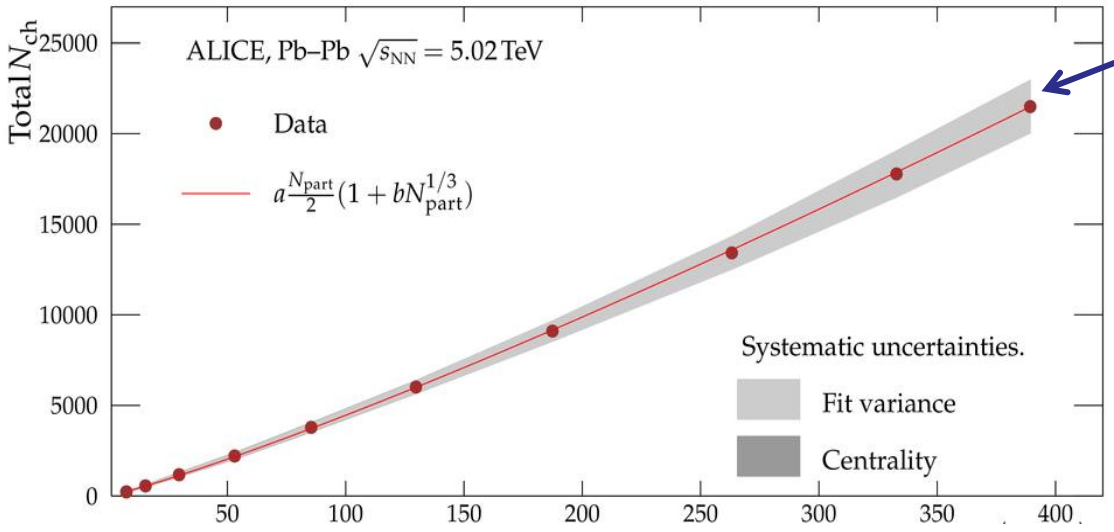
…and from day-by-day operation



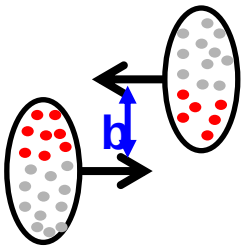
Part 3
What have we learned so far?

How many particles are produced?

- Depends on the centrality of the collision…

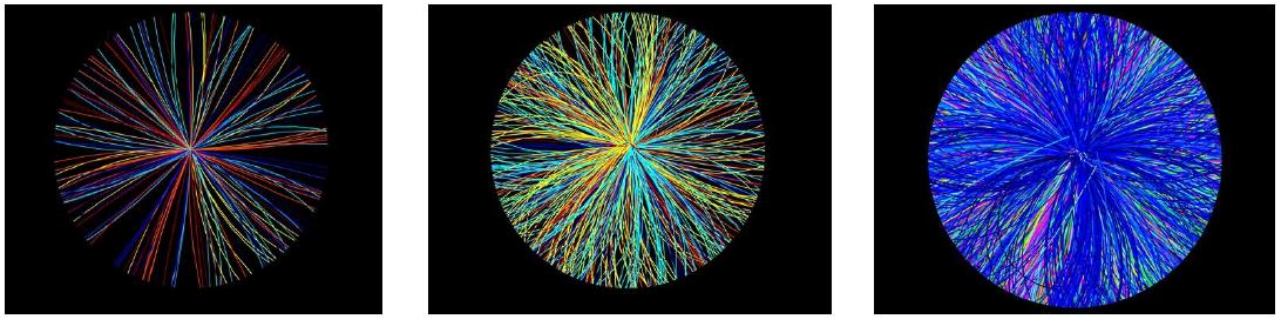


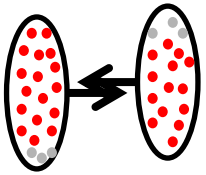
≈ 22000 charged particles in central Pb-Pb collisions at √s= 5 TeV



Peripheral
b > 0

Central
b = 0



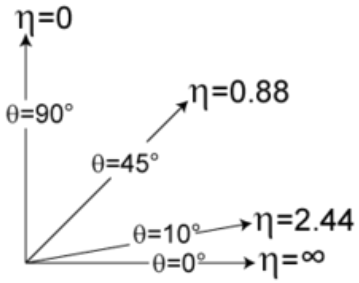


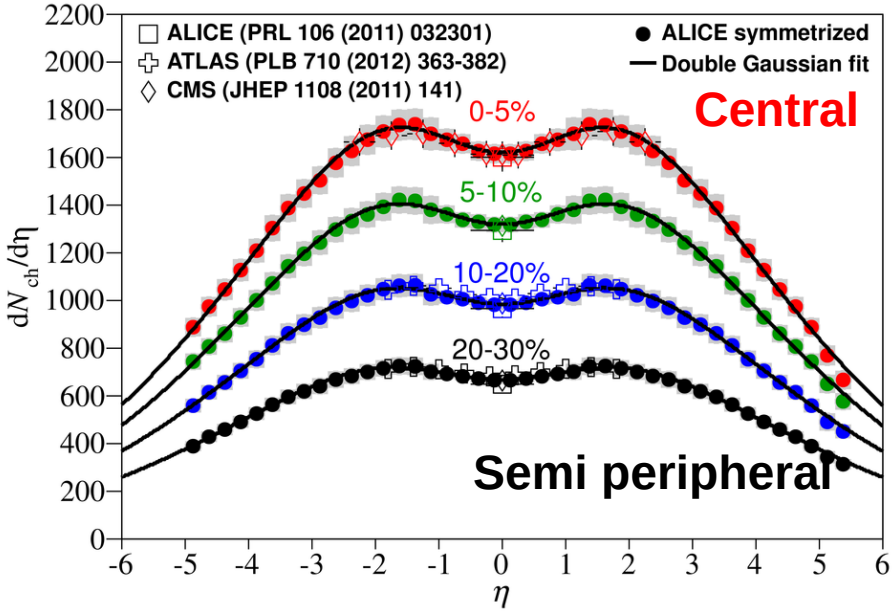
Low multiplicity → High multiplicity

What is the energy density?

- Can be estimated from angular distribution of produced particles
  - ⇨ **Pseudorapidity** is used for the polar angle:

$$\eta = -\ln\left[\tan\frac{\vartheta}{2}\right]$$





- **Bjorken formula** for energy density:

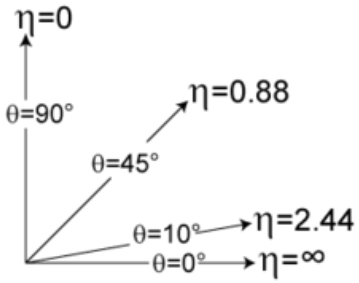
$$\varepsilon_{BJ} = \frac{\langle E_T \rangle}{Ac\tau_f}\left(\frac{dN}{d\eta}\right)_{\eta=0}$$

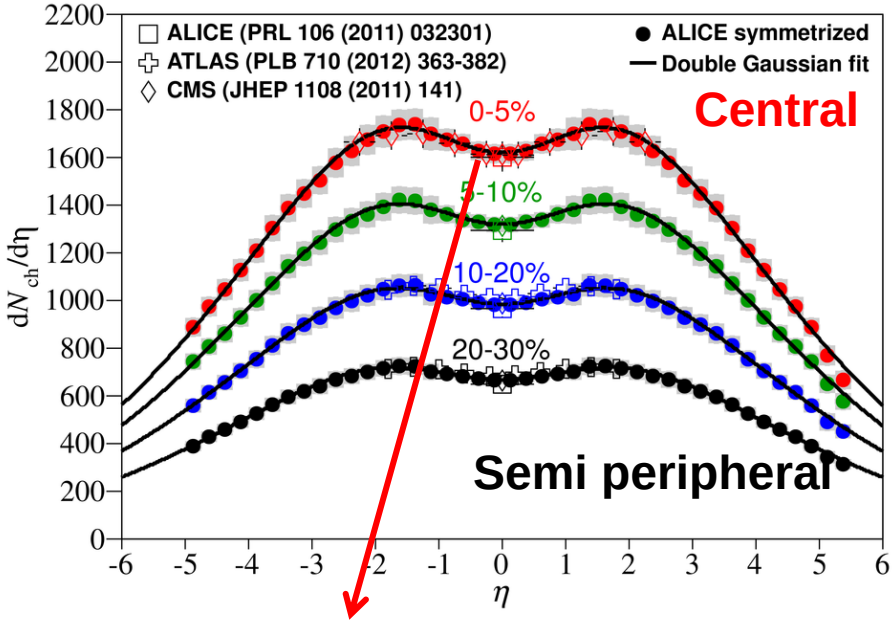
  - ⇨ dN/dη = particle density at 90°
  - ⇨ $\langle E_T \rangle$ = mean particle transverse energy
  - ⇨ A = transverse size of the system
  - ⇨ τ_f = medium formation (equilibration) time

What is the energy density?

- Can be estimated from angular distribution of produced particles
  - ⇨ **Pseudorapidity** is used for the polar angle:

$$\eta = -\ln\left[\tan\frac{\vartheta}{2}\right]$$





- **Bjorken formula** for energy density:

$$\varepsilon_{BJ} = \frac{\langle E_T \rangle}{A c \tau_f}\left(\frac{dN}{d\eta}\right)_{\eta=0}$$

Central Pb-Pb at √s= 2.76 TeV

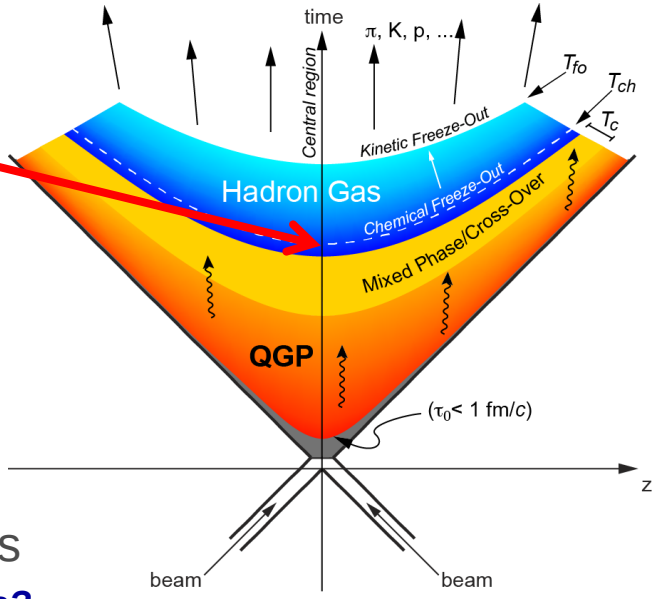
- ⇨ dN/dη = particle density at 90° **= 1600*3/2 = 2400**
- ⇨ $\langle E_T \rangle$ = mean particle transverse energy **≈ 0.75 GeV**
- ⇨ A = transverse size of the system **≈ πR_{Pb}^2 ≈ 150 fm²**
- ⇨ τ_f = medium formation (equilibration) time **≈ 1 fm/c**

$$\varepsilon_{BJ} \approx 12\,\mathrm{GeV/fm^3}$$

Above the critical value for QGP

“Chemical” composition

- At the **chemical freeze-out**
  - ⇨ Hadronization has occurred
  - ⇨ Inelastic collisions cease
  - ⇨ **Abundances of hadron species fixed**
- Assume system in chemical **equilibrium**
  - ⇨ Particle yields can be calculated with **statistical thermodynamics**
  - ⇨ **Partition function** for a quantum gas of hadrons
    - ✓ ***How is probability distributed among hadronic states?***



$$\ln Z_i(T,V,\mu) = \pm g_i V \int \frac{d^3p}{(2\pi\hbar)^3} \ln\left(1 \pm \exp\left(-(E_i(p) - \mu_i)/T\right)\right)$$

$$E_i = \sqrt{p^2 + m_i^2}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i$$

Index *i* = π, K , p …

volume

spin degeneracy

Temperature

chemical potential (conserved quantities)

baryon number

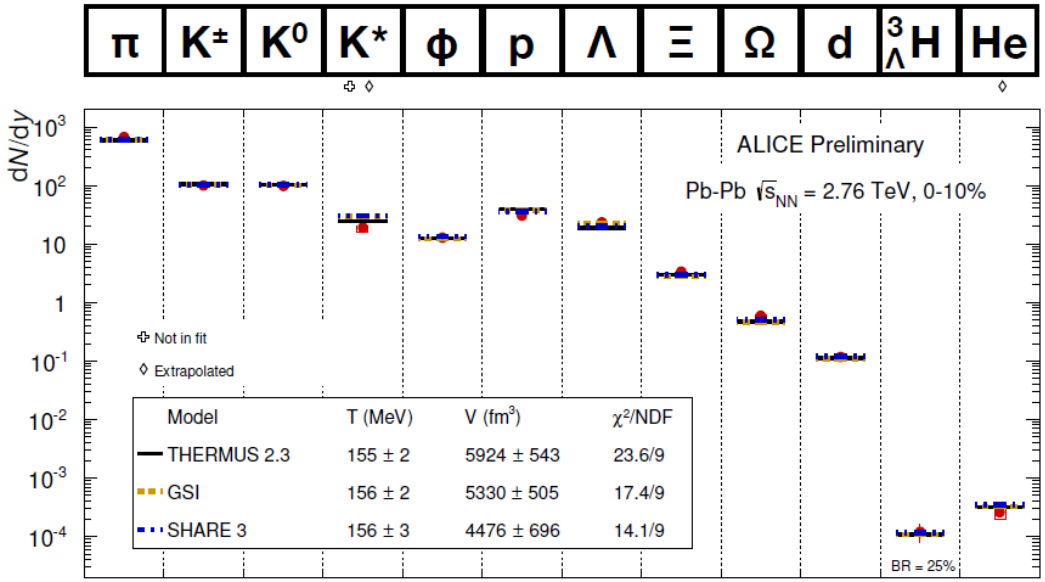
strangeness

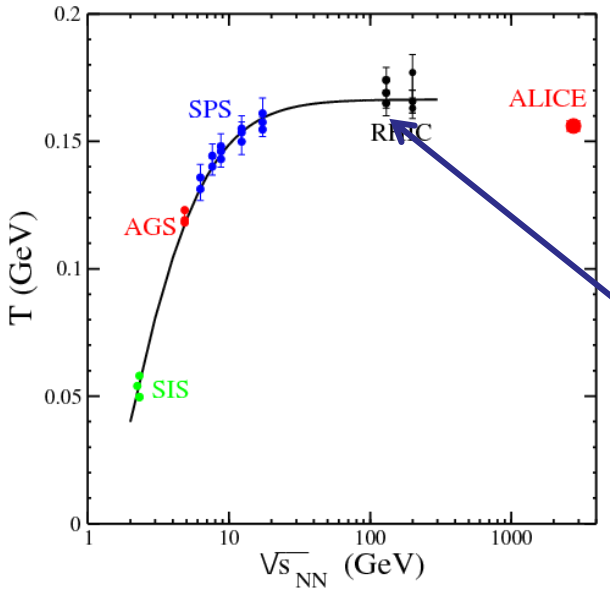
isospin

charm

Chemical freeze out

- Measured multiplicities of different hadron species
  - ⇨ Well describes by statistical thermodynamic calculations
  - ⇨ Estimate **temperature**, baryochemical potential, volume of the system at the **chemical freeze-out**





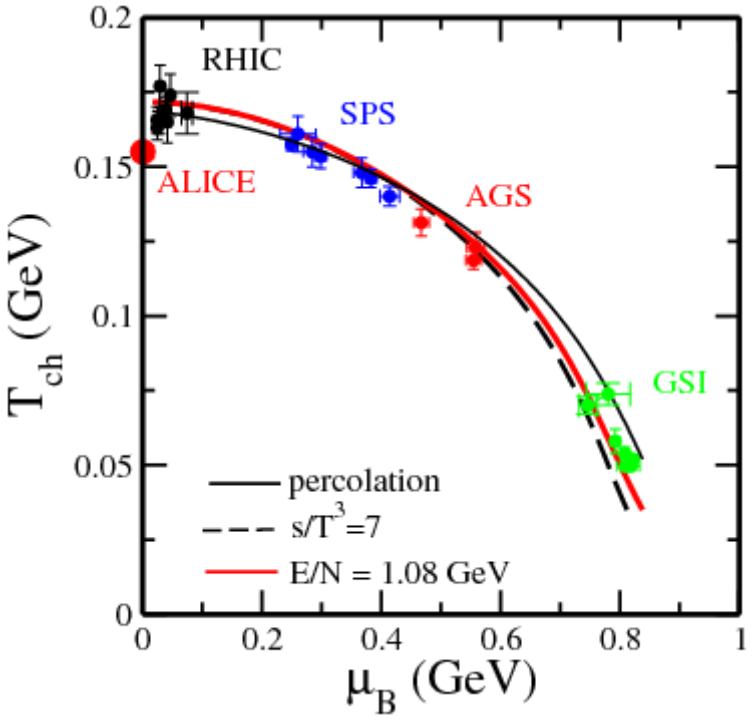
T increases with collision energy at low √s

Plateau at **T~160 MeV** for √s>20 GeV

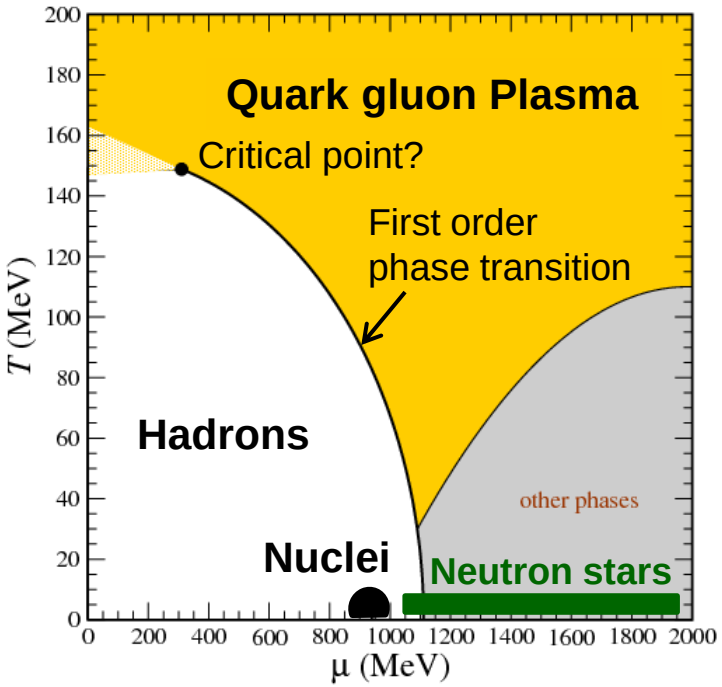
Temperature of the medium at the chemical freeze-out very close to the critical temperature for QGP transition

Exploring the phase diagram

- Chemical freeze-out line
  - ⇨ From measured **hadron abundances** + **statistical thermodynamic** calculations

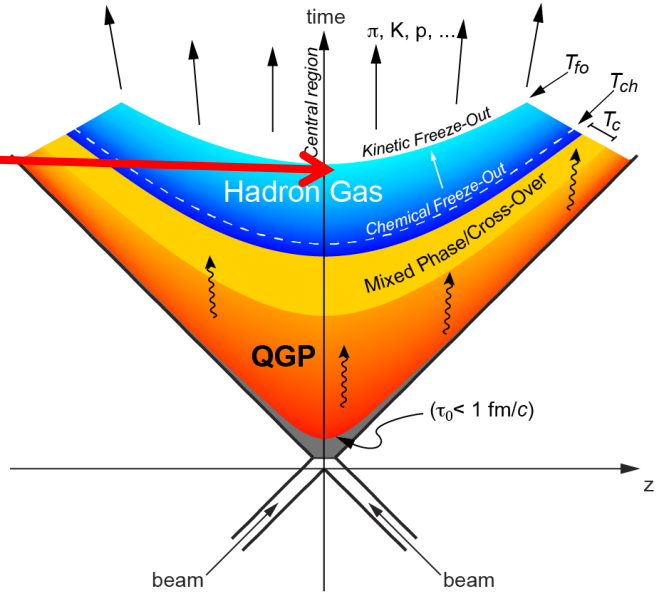


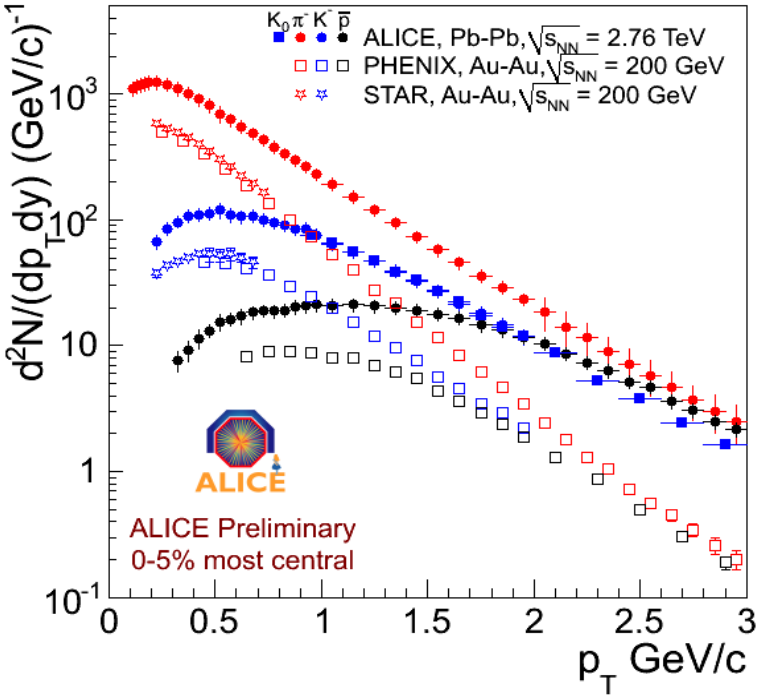
- Phase diagram of QCD matter
  - ⇨ From **lattice QCD** calculations, bag models …



Thermal freeze-out

- Particle momenta frozen at the **thermal freeze-out**
  - ⇨ Elastic collisions among particles cease
- What can we learn from the p_T distributions of identified hadrons?

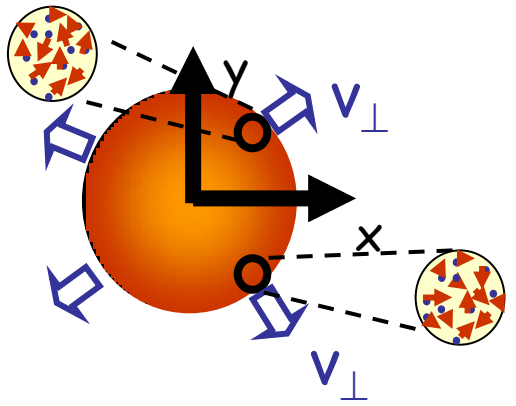


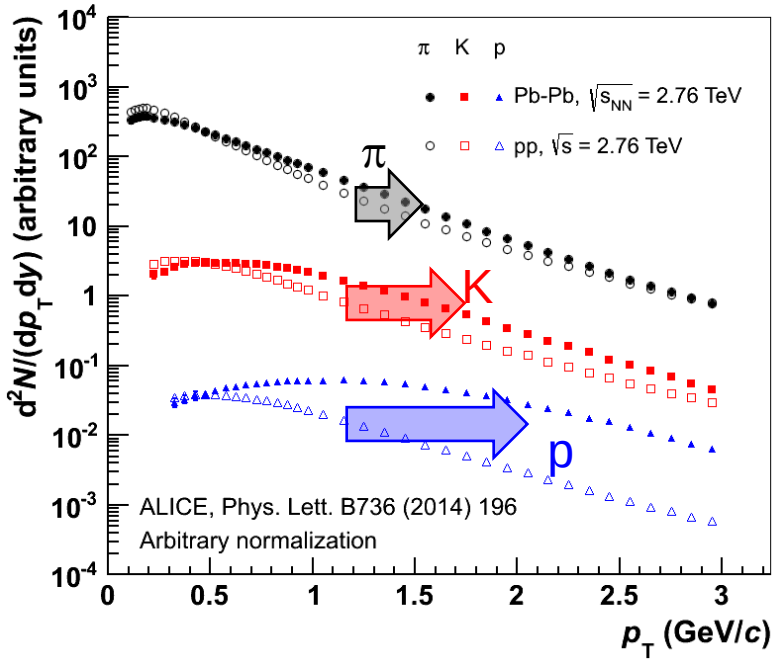


- Momentum spectra of π, K, p have ≈ exponential shape at low p_T
  - ⇨ Recall: **Maxwell-Boltzmann** distribution for emission from a thermal source
- Note on the slopes:
  - ⇨ Different for π, K, p (**mass dependence**)
  - ⇨ Become "less steep" with increasing √s

Collective expansion

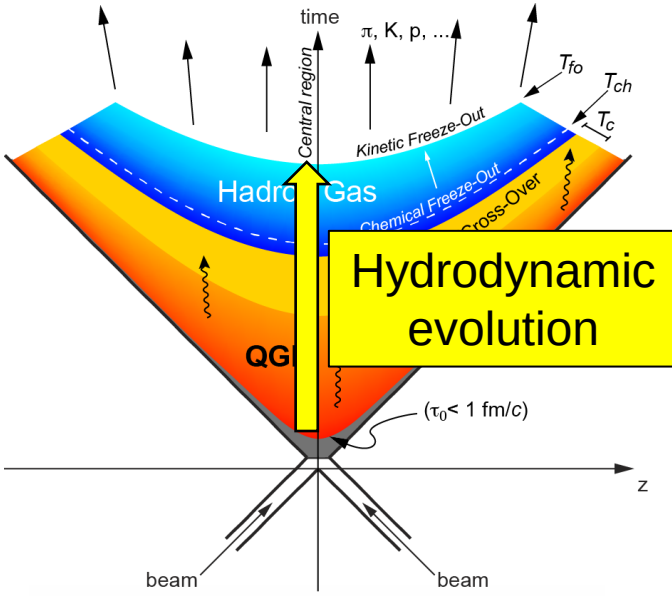
- System undergoes a **rapid expansion**
  - ⇨ After collision: high-density QGP droplet in vacuum
  - ⇨ Strong **pressure gradient** from center to boundary
- Particles (quarks and gluons in the QGP phase and hadrons in the hadronic phase) get pushed by this pressure gradient
  - ⇨ ***FLOW = Collective motion*** superimposed **on top of the *thermal* motion**
  - ⇨ Particle p_T increases -> spectra "pushed" to higher p_T by the *common velocity field* $v_\perp$ **(radial flow)**
  - ⇨ Recall: p = mv -> **mass dependence**

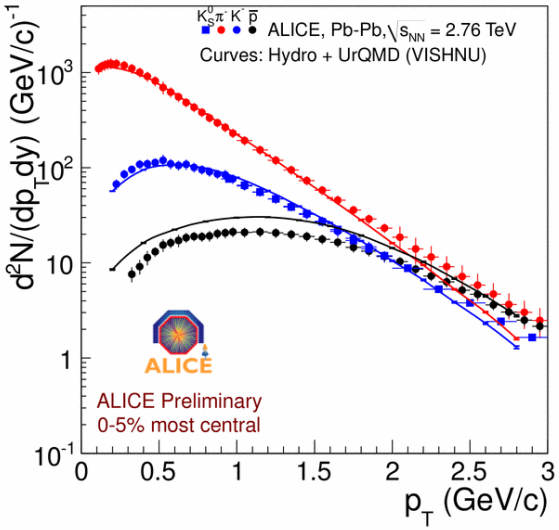




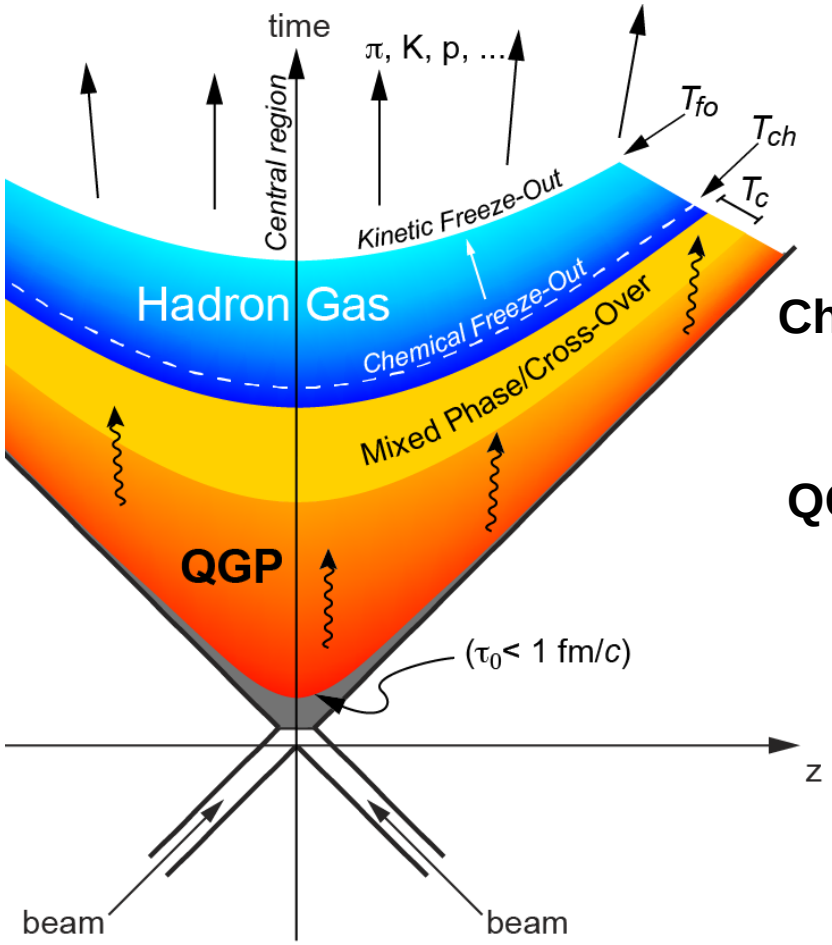
Hydrodynamics

- Expanding medium can be described macroscopically with **hydrodynamical** models
  - ⇨ Valid from the equilibration time (~1 fm/c) to the thermal-freeze out
    - ✓ *Need model for initial state and freeze-out*
  - ⇨ Equations for relativistic fluid dynamics:
    - ✓ *Conservation of energy-momentum*
    - ✓ *Conservation of charges, mainly baryon number*
    - ✓ *Equation of State (EoS), from lattice QCD*
  - ⇨ Deduce conclusions on initial conditions, EoS… by data comparison
- Examples for central Pb-Pb collisions at the LHC:
  - ⇨ **Thermal freeze-out** temperature = **100 MeV**
  - ⇨ **Radial flow** velocity = **0.65c**





Space-time evolution: more quantitatively



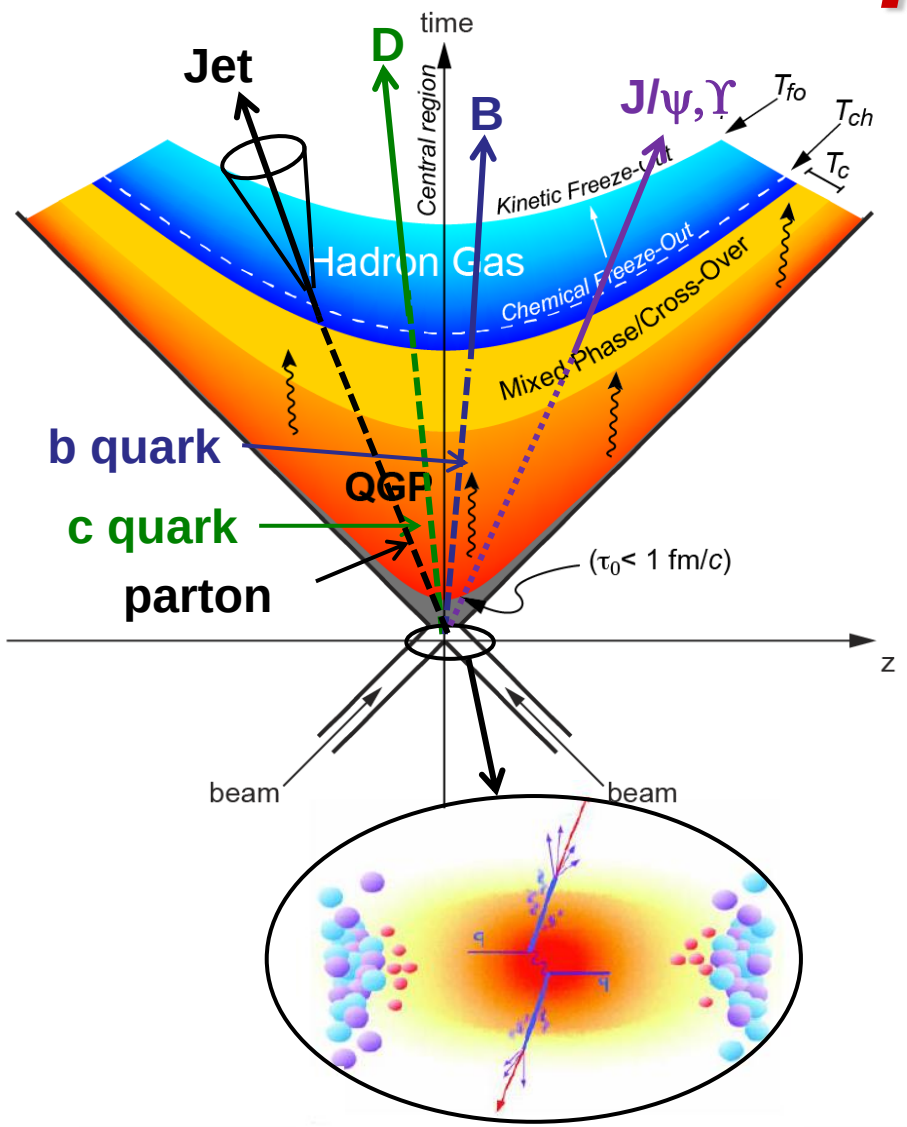
	Time	Temperature
Particle detection	t~10 cm/c	
Kinetic freeze-out	t~10 fm/c	T~100 MeV
Chemical freeze-out Hadronization		T~170 MeV
QGP hydrodynamic evolution		
Pre-equilibrium	t~1 fm/c	T~400 MeV
Collision	t=0 fm/c	

Large pressure -> collective flow

1 fm/c = 3 10^{-24}s

1 MeV = 1.16 10^{10}K

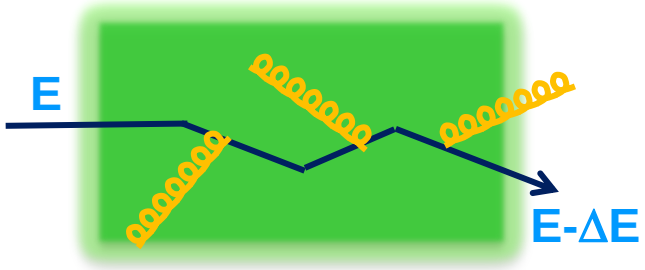
Hard probes

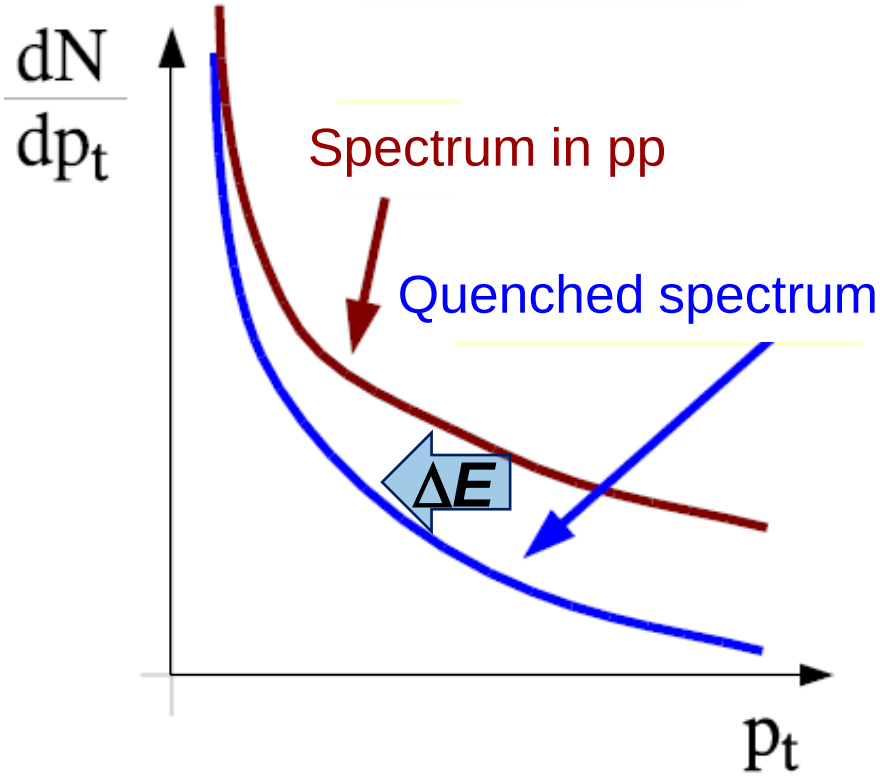


- Hard probes
  - ⇨ Produced at the **very early stage** of the collision in partonic scattering processes with large momentum transfer
  - ⇨ Traverse the hot and dense medium interacting with its constituents
- **Unique probes** of the properties of the QGP medium
  - ⇨ Produced out-of-equilibrium
  - ⇨ Expected to conserve memory of the history of the medium evolution
  - ⇨ **Tomography of the medium**

Hard partons traversing the QGP

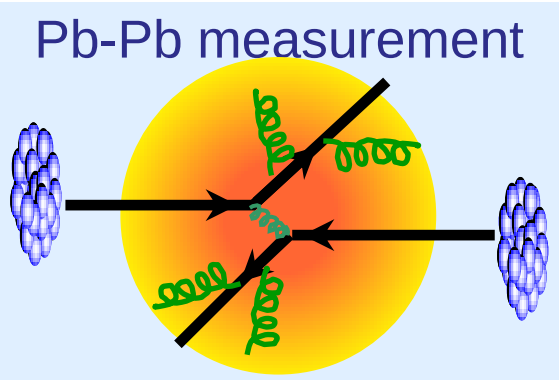
- The hard parton interacts with the medium constituents -> **energy loss**
  - ⇨ Elastic collisions (-> collisional energy loss)
  - ⇨ Gluon radiation
    - ✓ *Dominant mechanism for high p_T partons*
- Energy loss depends on:
  - ⇨ Medium density, path-length in the medium, parton species and mass
- Modification of the particle momentum distributions
  - ⇨ Suppression of hadron yield at high p_T (**jet quenching**) relative to pp collisions where no medium is present





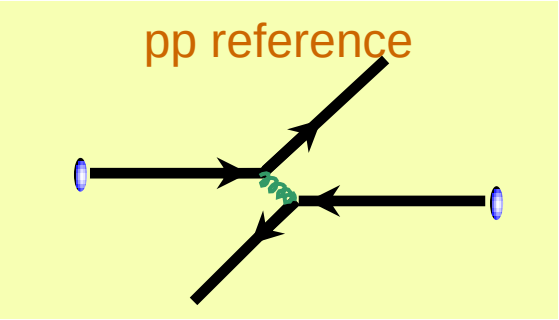
Nuclear modification factor

- Hard processes in nuclear collisions
  - ⇨ Expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)



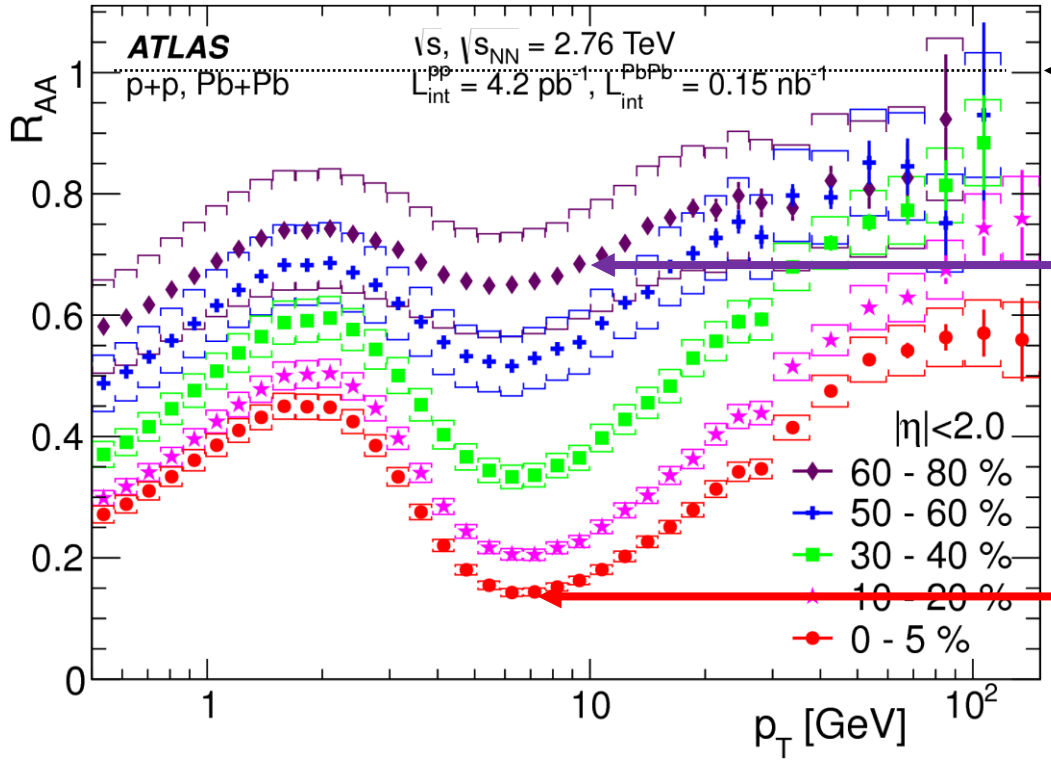
- Observable: **nuclear modification factor**

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



- If no nuclear effects are present
  → $R_{AA}=1$
- **QGP** created in the collision can modify the energy distributions of the final state hadrons
  → $R_{AA}\neq 1$

Charged-particle R_{AA}



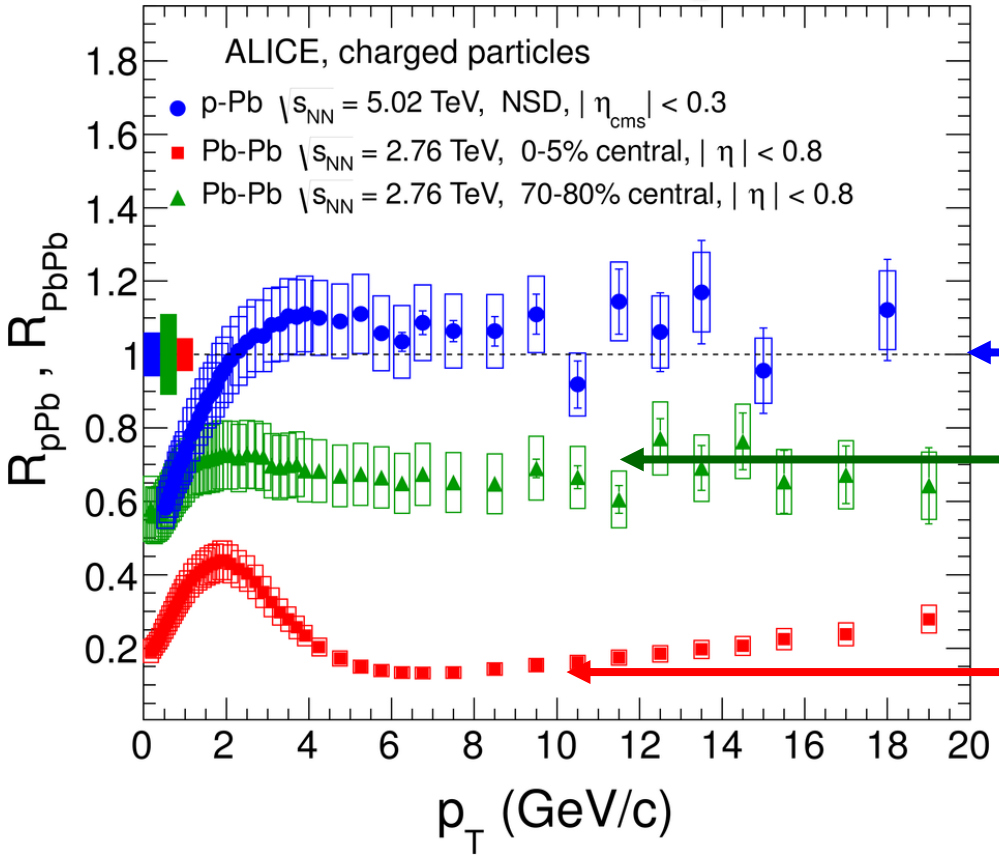
R_{AA} = 1
→ no modification

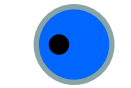
Peripheral collisions
→ **R_{AA} ~ 0.7**

Central collisions
→ **R_{AA} ~ 0.14**

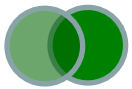
- **Strong modification** of the p_T-spectrum of charged hadrons
  - ⇨ **Suppression** (R_{AA}<1) of yield of **high-p_T** particles
    - ✓ *Minimum R_{AA} at p_T ≈ 6-7 GeV/c, followed by rise in 6<p_T<50 GeV/c*
  - ⇨ Suppression **increases with increasing centrality**
    - ✓ *Larger medium size and density*

Control experiment (i): p-Pb





p-Pb collisions
→ R_{AA} ~ 1

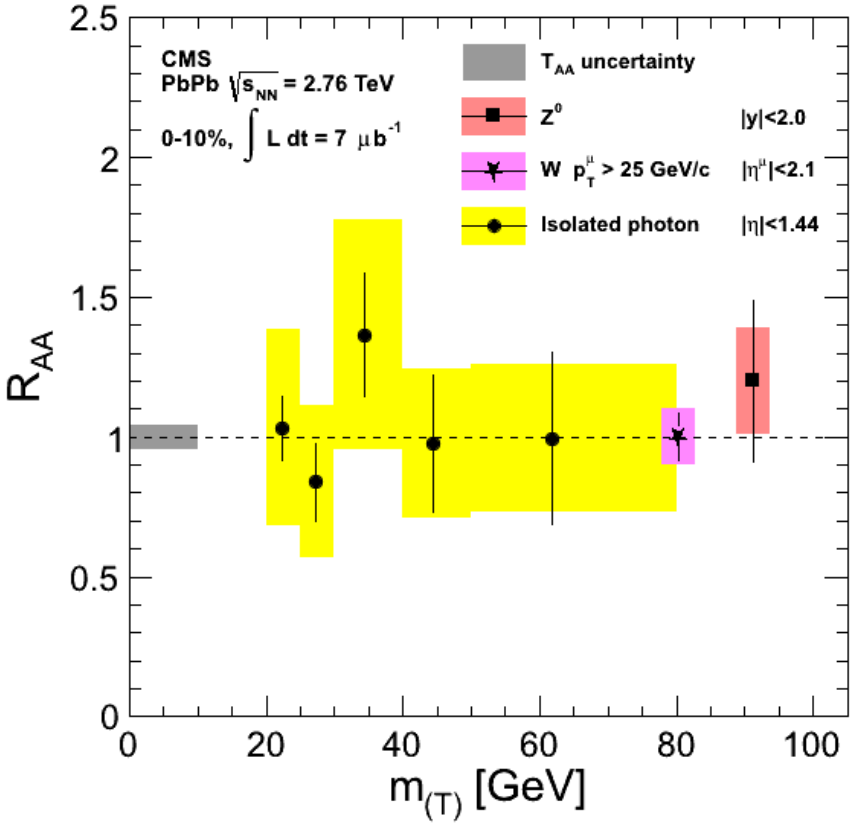


Pb-Pb peripheral
→ R_{AA} ~ 0.7

Pb-Pb central
→ R_{AA} ~ 0.14

- **No modification** of yield at high p_T in **p-Pb collisions**
  - ⇨ Modification observed in Pb-Pb collisions is a **final-state effect** due to interactions with the medium created in the collision

Control experiment (ii): γ, Z, W



- R_{AA}=1 for **colorless objects** (γ, W, Z^0)
  - ⇨ Colour neutral particles have no interaction with QGP (**medium-blind probes**)
    - ✓ ***No energy loss expected***
  - ⇨ Experimental check on N_{coll} calculation

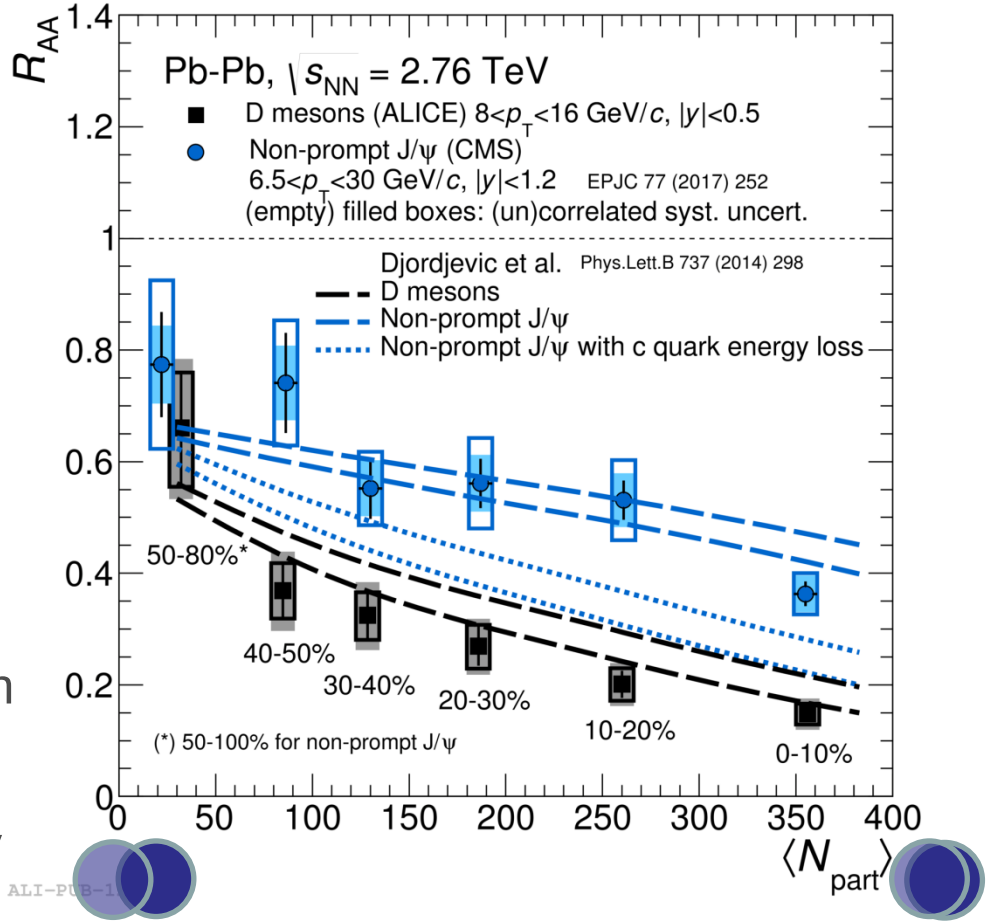
The **suppression of hadron yield at high p_T** is a **final-state effect** due to the strong interaction of hard-scattered partons with the **hot and dense partonic medium**

Heavy flavour R_{AA}

- In-medium energy loss expected to depend on species and mass of the parton traversing the QGP:

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

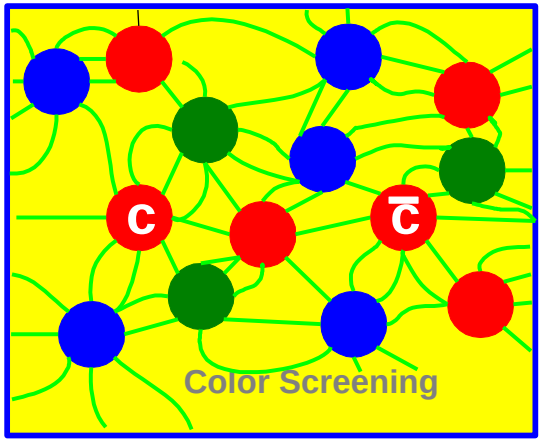
- Tested experimentally by comparing R_{AA} of D mesons and J/ψ from B decays
- Clear indication for $R_{AA}(B) > R_{AA}(D)$
  - ⇨ Consistent with the expectation $\Delta E_c > \Delta E_b$
  - ⇨ Described by models including quark-mass dependent energy loss



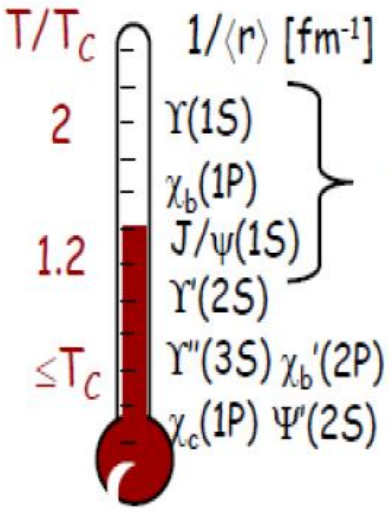
Observed R_{AA} hierarchy consistent with prediction of **quark-mass dependent in-medium energy loss**

Quarkonium: in-medium dissociation

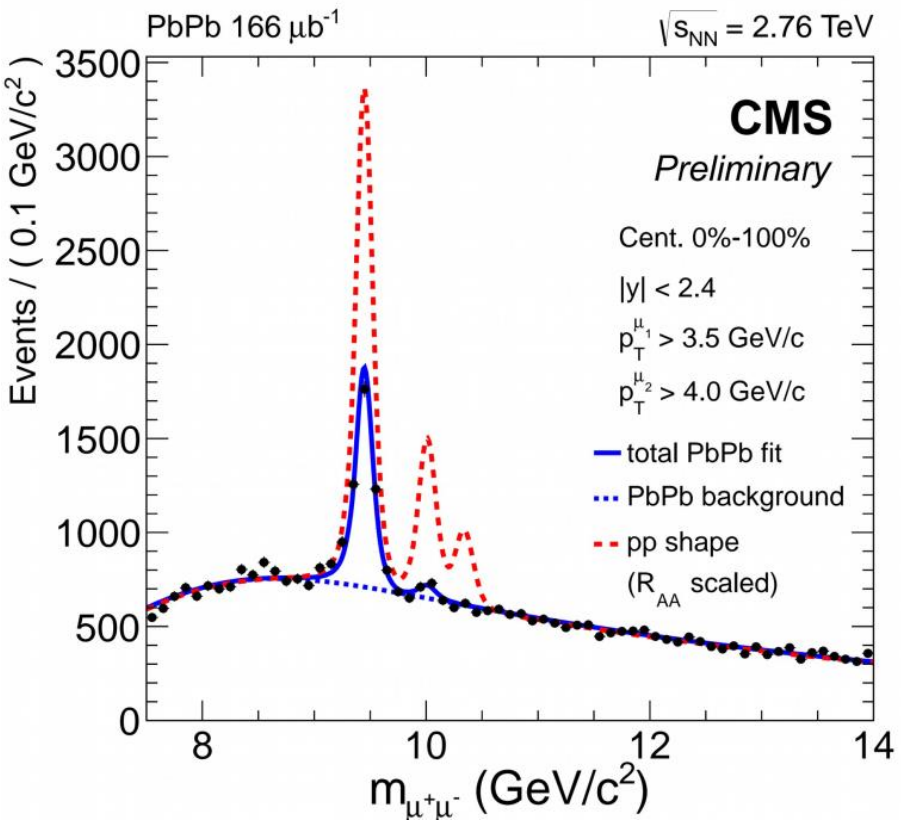
- In the QGP, quarkonium states with radius larger than Debye screening length are expected to **melt** due to colour screening of the qq̄ potential.
  - ⇨ Quarkonium production **suppressed** in A-A collisions due to colour screening in the QGP
    - 🕮 **Matsui, Satz, PLB178 (1986) 416**

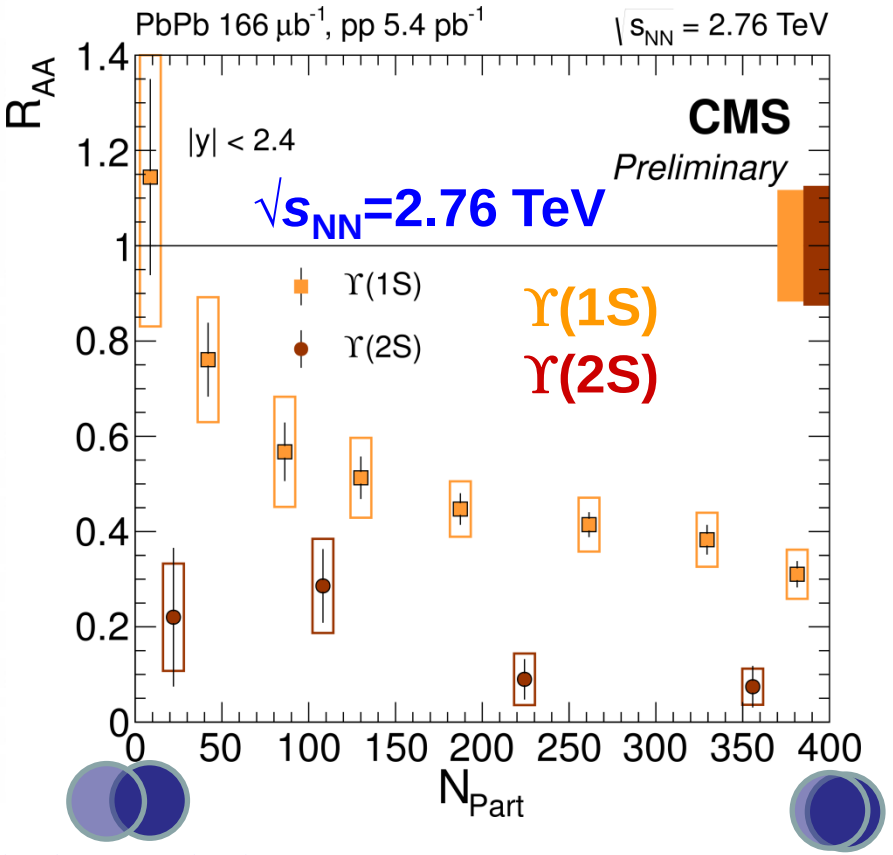


- Different quarkonium states melt at different temperatures, depending on their binding energy
  - ⇨ **Sequential suppression pattern**
- Melting sequence of quarkonia as a **QGP thermometer**
  - ⇨ Relevant for the interpretation of experimental results: **feed-down** from higher quarkonium states
    - 🕮 **Digal et al., PRD64 (2001) 094015**



Bottomonium thermometer



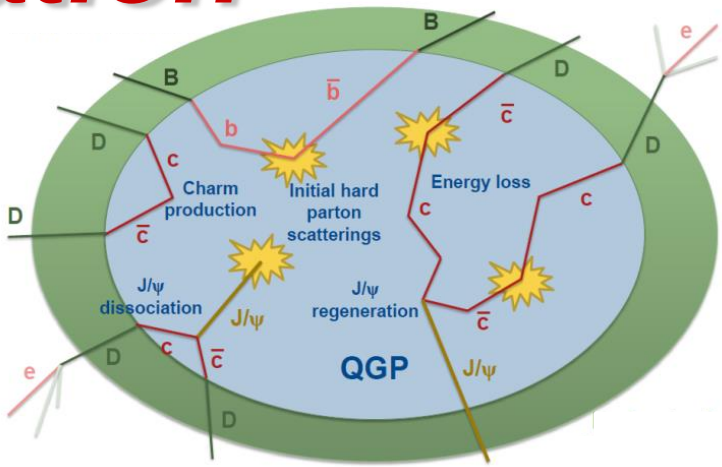


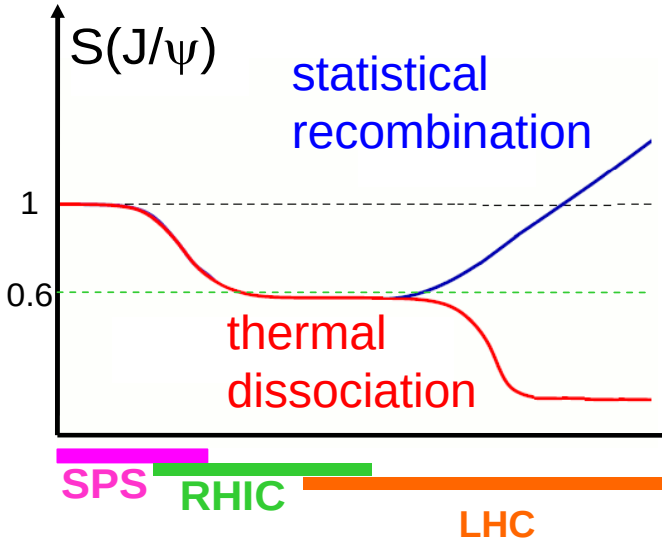
- Hierarchy observed: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
- Suppression of ϒ(1S) and ϒ(2S) increases with centrality

Sequential suppression as expected from melting in QGP

Charmonium production via (re)combination

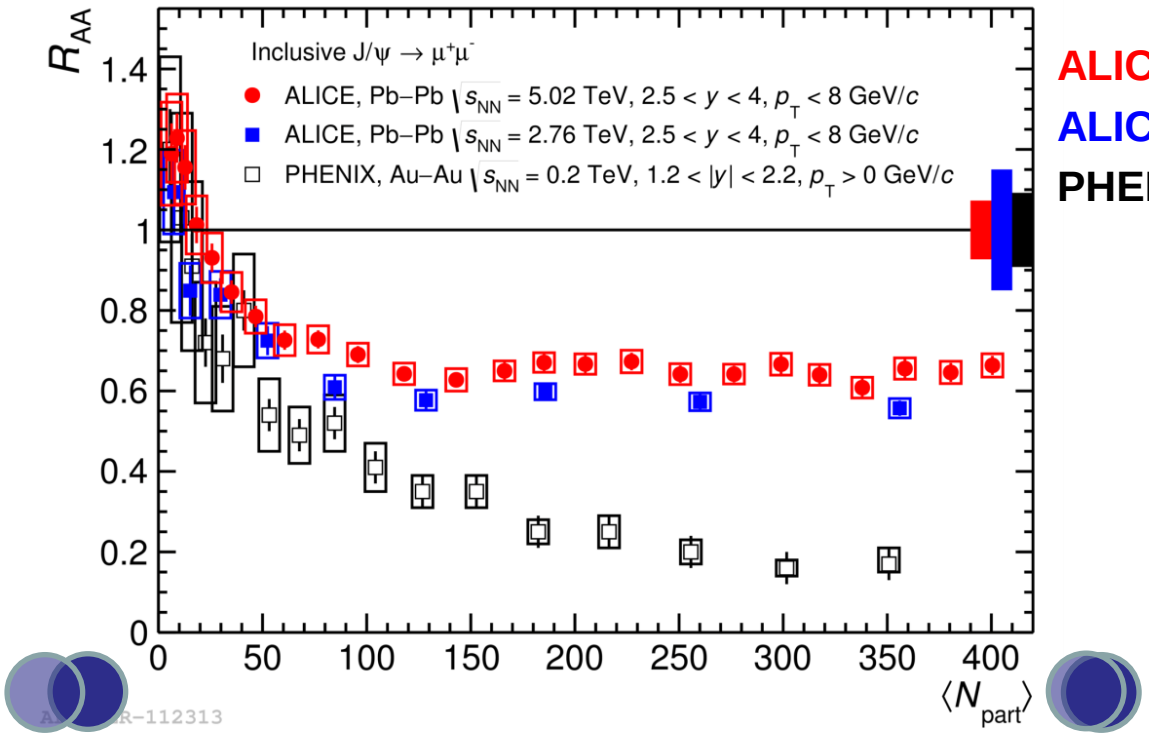
- Charmonium production in A-A collisions expected to occur also via **$c\bar{c}$ (re)combination** in the QGP or at the phase boundary
  - ⇨ J/ψ from (re)combination mainly produced with **low momentum**
  - ⇨ (Re)combination expected to be less relevant for bottomonium
- Charm production cross section increases with increasing $\sqrt{s}$
  - ⇨ (Re)combination increases with $\sqrt{s}$
  - ⇨ Quarkonium production **enhanced** in A-A collisions at higher $\sqrt{s}$





J/ψ R_{AA} at different $\sqrt{s_{NN}}$

- J/ψ R_{AA} as a function of centrality
  - ⇨ **Less suppression at LHC** ($\sqrt{s}$=2.76, 5.02 TeV) **than at RHIC** ($\sqrt{s}$=200 GeV)



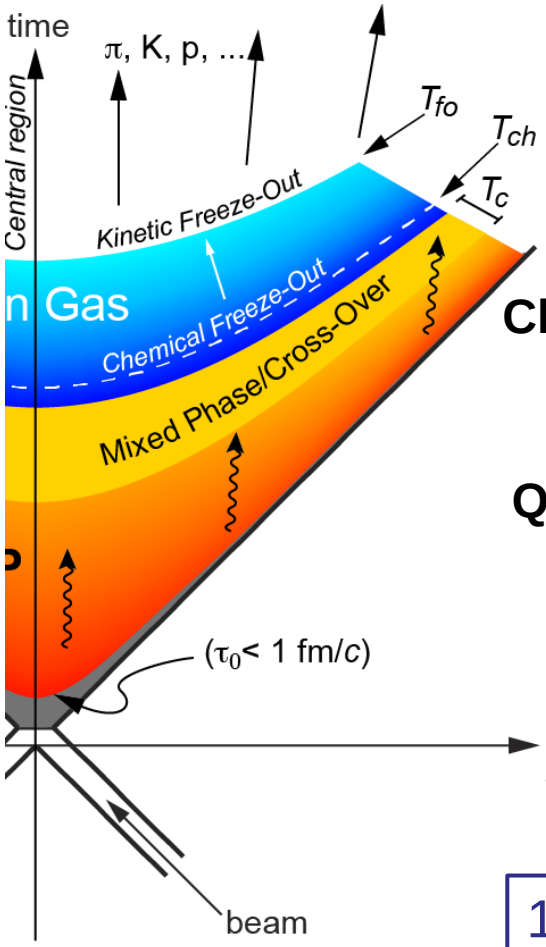
ALICE $\sqrt{s_{NN}}$=5.02 TeV

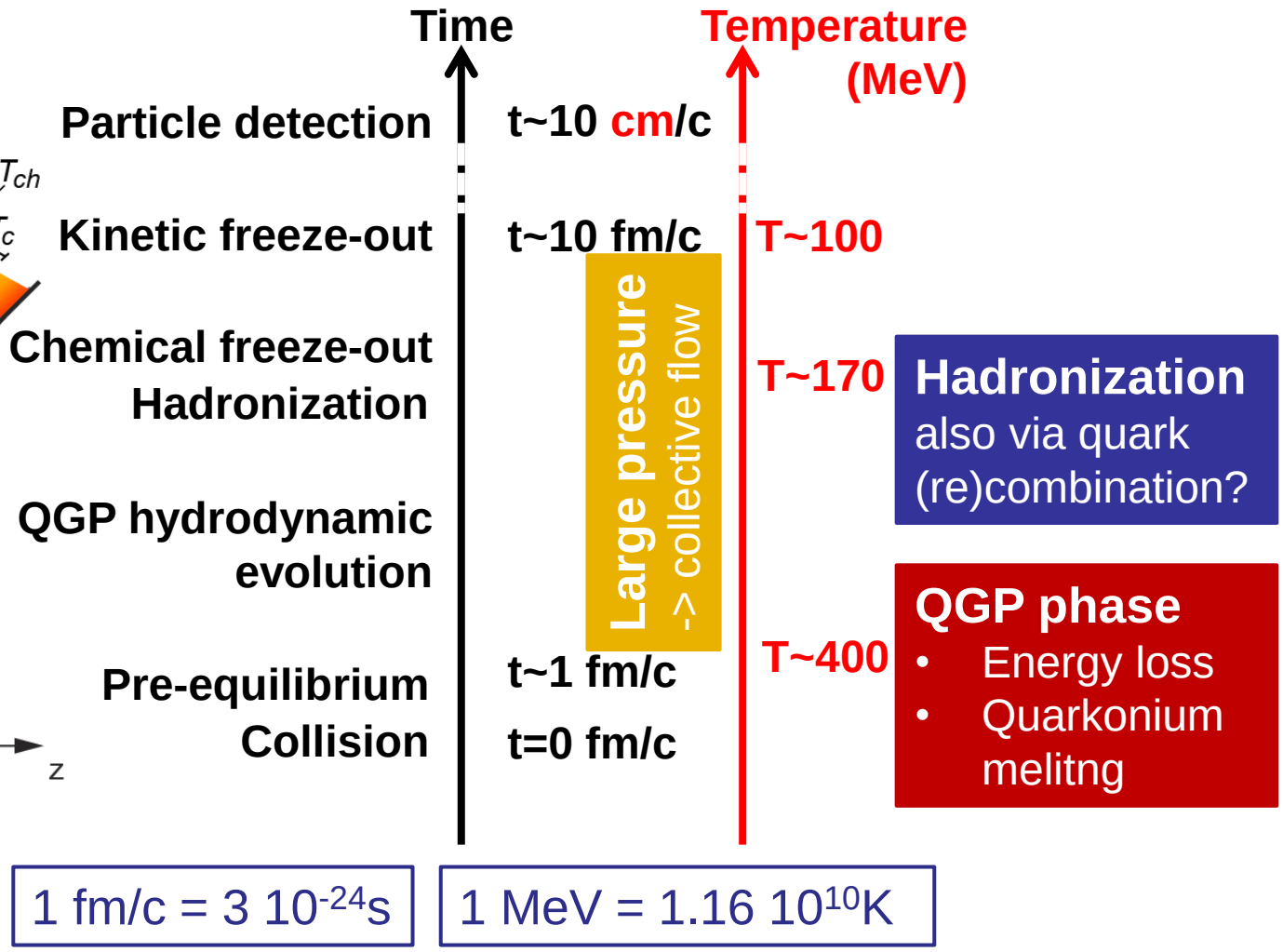
ALICE $\sqrt{s_{NN}}$=2.76 TeV

PHENIX $\sqrt{s_{NN}}$=200 GeV

As expected in a scenario with melting in QGP followed by J/ψ formation via (re)combination

What have we learned?





Part 4
What next?

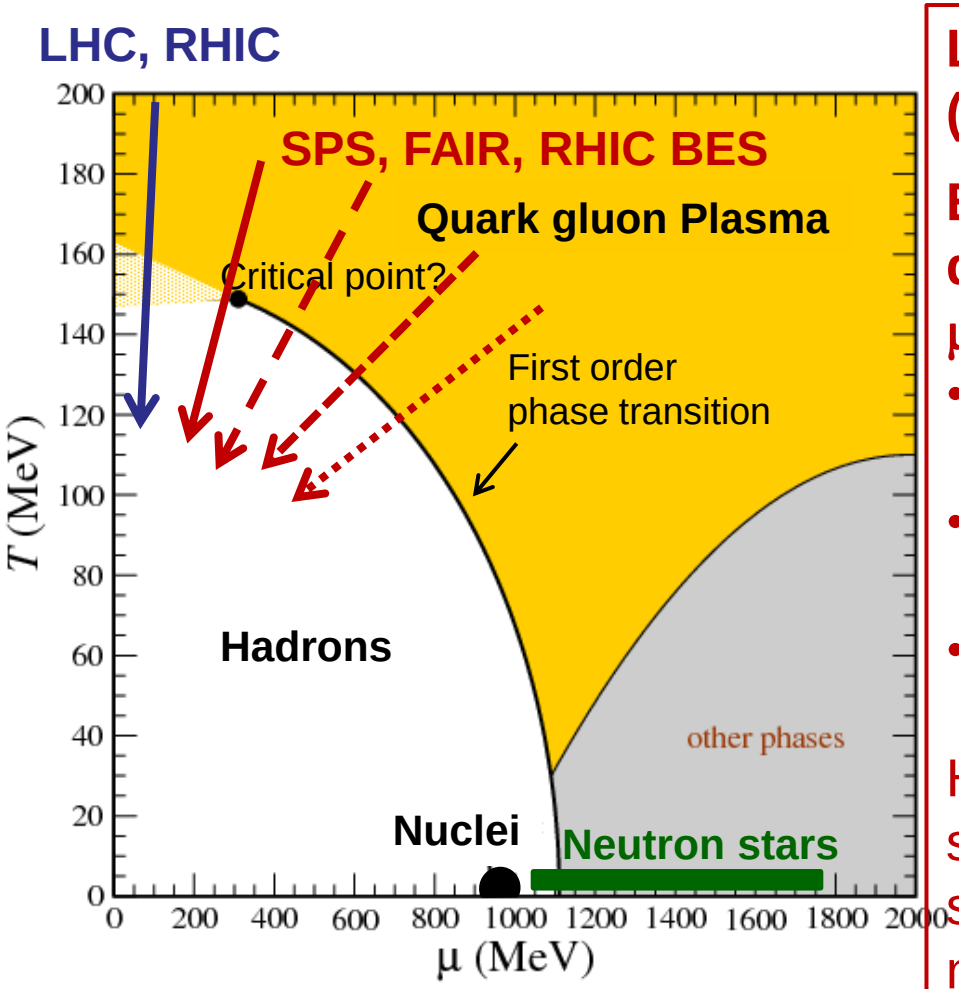
Exploring the phase diagram

HIGH ENERGY (RHIC, LHC)

Precision measurements of the QGP properties

- Transport coefficients
- Viscosity
- …

How: higher **luminosity** + **upgraded** detectors



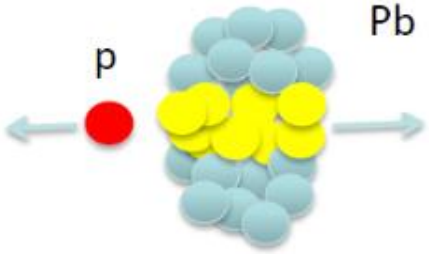
LOW ENERGY (RHIC, SPS, FAIR)

Explore the phase diagram at higher μ_B:

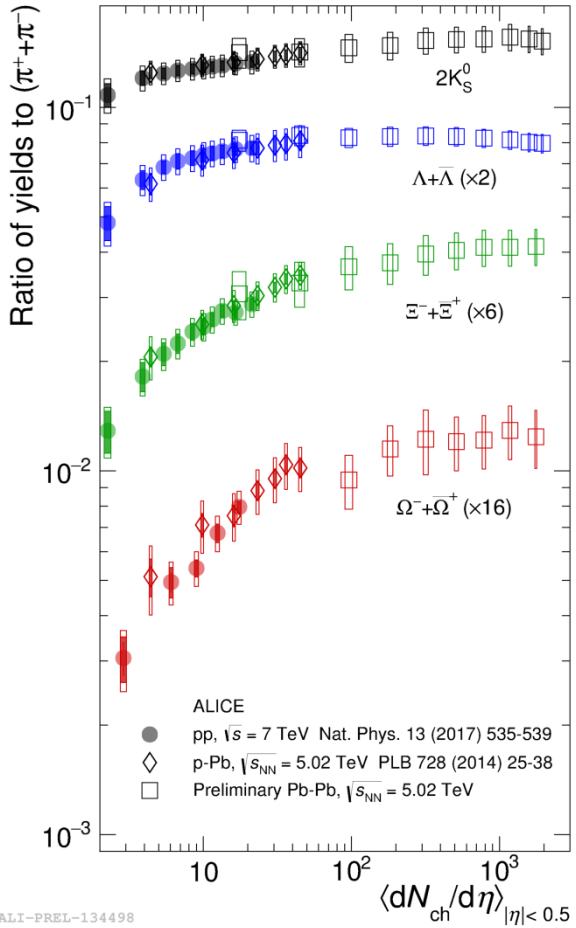
- Onset of deconfinement
- Chiral symmetry restoration
- Critical point?

How: beam energy scans at lower $\sqrt{s}$, smaller colliding nuclei

Small systems



- **Surprising observations** in high-multiplicity p-Pb (and pp) collisions at the LHC
  - ⇨ Unexpected results **qualitatively resembling the collective behaviour** observed in Pb-Pb and Au-Au collisions
- Investigate other observables which are typically associated with hot and dense medium formation in nuclear collisions:
  - ⇨ **Strangeness production evolves smoothly with multiplicity** from pp to Pb-Pb
  - ⇨ No suppression observed for high-p_T hadrons
- Open questions
  - ⇨ What is the origin of QGP-like effects in p-Pb?
    - ✓ *Small droplets of QGP created in p-Pb collisions?*
  - ⇨ Is the physics underlying soft "collective" signals the same in all high energy reactions (from e^+e^- to central Pb-Pb)?
    - ✓ *Common property of all strongly-interacting many-body systems?*



Conclusion

- The study of properties of matter at extreme conditions of temperatures and energy density is a rich and successful field of research
  - ⇨ Could answer to **fundamental questions of QCD**
- **Evidence for QGP** (deconfined state of quarks and gluons) formation in heavy-ion collisions
  - ⇨ Also of **astrophysical interest**: state of the universe 10 μs after the Big Bang, core of neutron stars
- Theoretical and experimental investigation has provider deeper and deeper insight since 30 years
  - ⇨ But also triggered new questions
- A **stimulating future** ahead!
  - ⇨ More and more precise measurements to constrain theory
  - ⇨ Large part of the phase diagram of QCD matter (large baryonic density) still to be explored in detail

Backup

LHC some numbers

- Number of magnets ~ 9500
- Dipole magnet operating temperature = 1.9K
  - ⇨ Reached by pumping superfluid Helium
- Dipole magnetic field (peak) = 7.74 T

- Number of bunches per proton beam = 2808
- Number of protons per bunch = 1.2 1011
- Number of turns per second = 11245
- Number of pp collisions per second = 1 billion

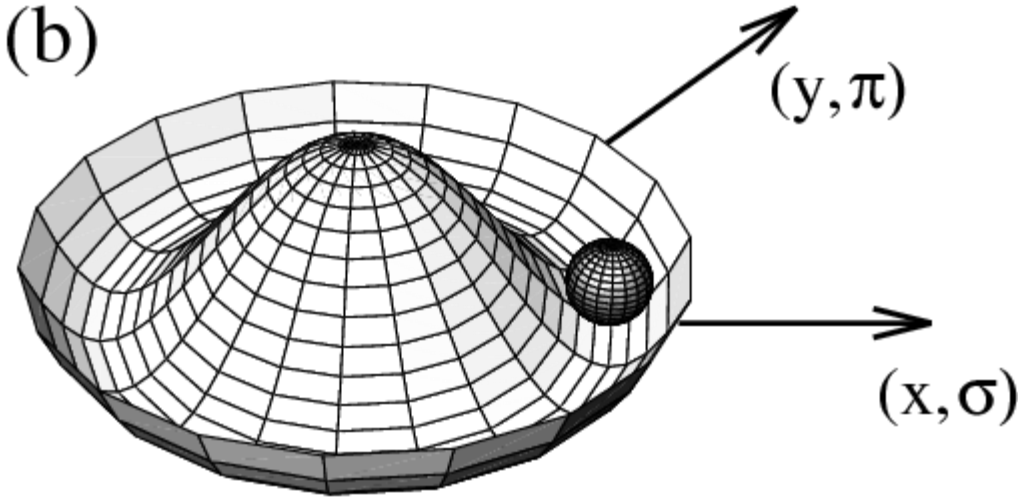
- Power consumption = 120 MW
  - ⇨ About 1/3 of power consumption of households in Geneva Canton
  - ⇨ Power consumption per year = 1.3 TWh

How much does it cost?

- LHC accelerator construction
  - ⇨Material costs of about 4,6 billion euros
- LHC experiments
  - ⇨Material costs of about 1,3 billion euros
- Costs for running the LHC
  - ⇨Electricity costs ~ 19 million euros per year

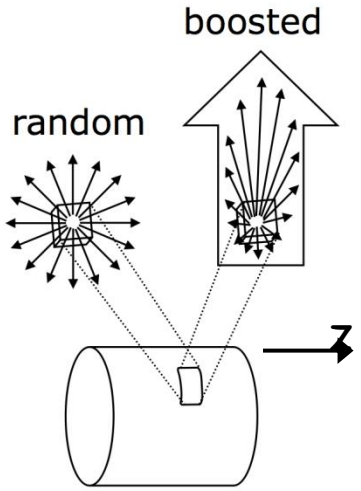
Spontaneous symmetry breaking

- Symmetry present in the Lagrangian
- Ground state does not exhibit the symmetry
  - ⇨ Example: the “Mexican hat” potential: rotational symmetry is broken when the ball reaches a rest position in the “valley”
- Examples:
  - ⇨ Magnetization of ferromagnetic material below Curie temperature



Blast-wave fits

- Simplified model that reproduce basic features of hydro-dynamical calculations
  - ⇨ Allow quantification of radial flow
  - ⇨ Via fits to p_T distributions of identified hadrons
- Assumptions
  - ⇨ Locally thermalized medium
  - ⇨ Common velocity field
  - ⇨ Instantaneous freeze-out



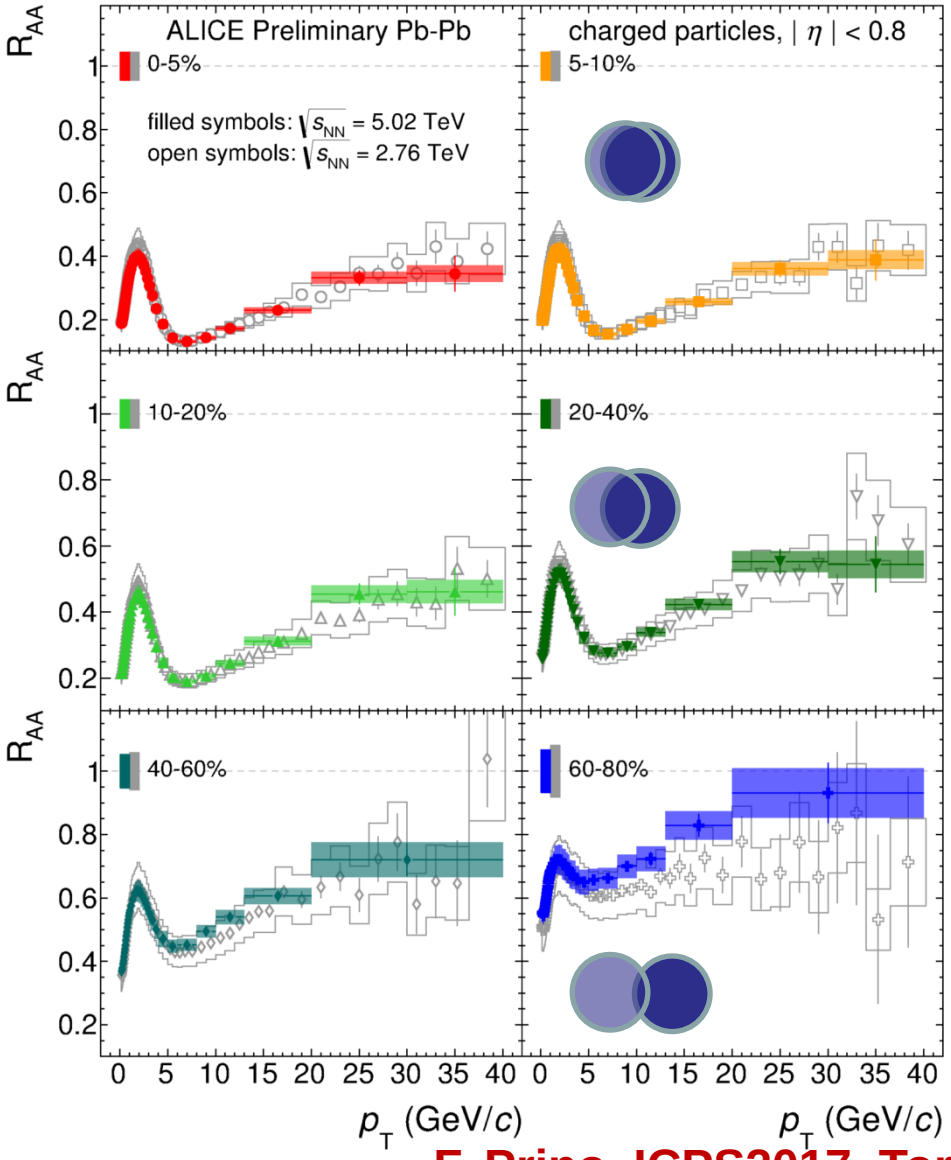
$$\frac{dN}{p_T dp_T d\varphi dy} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho(r)}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho(r)}{T_{fo}}\right)$$

$$\rho(r) = \tanh^{-1}\beta_\perp\left(\frac{r}{R}\right)^k$$

Kinetic freeze-out temperature

Radial flow velocity

Charged-particle R_{AA} vs $\sqrt{s}$

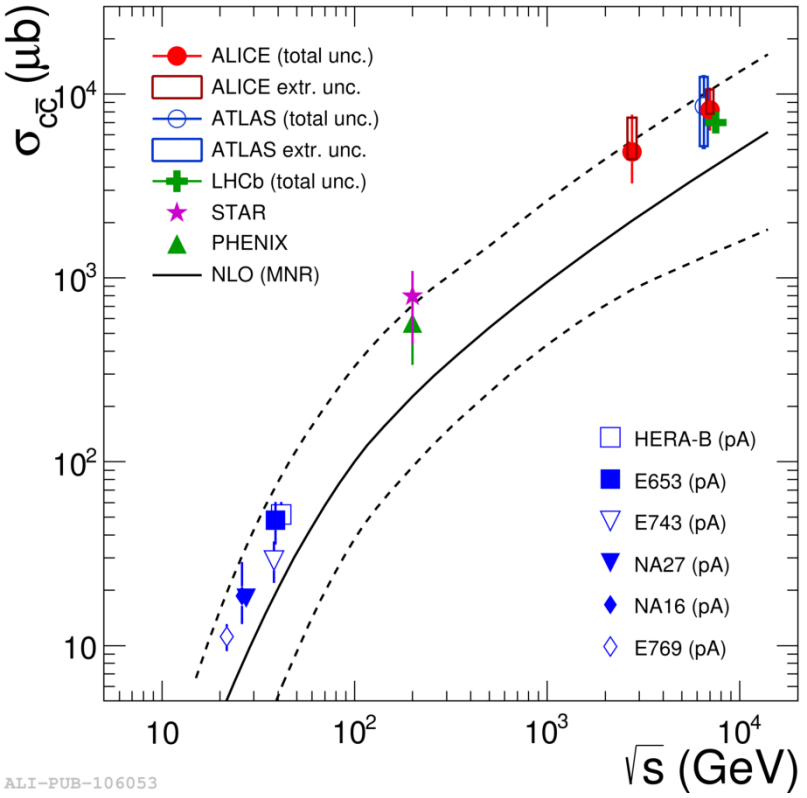


- Strong modification of the p_T-spectrum shape of charged hadrons in most central Pb-Pb collisions
  - ⇨ Minimum at $p_T \approx$ 6-7 GeV/c
  - ⇨ Strong rise in 6<p_T<50 GeV/c
  - ⇨ Strong centrality dependence
- R_{AA} at $\sqrt{s_{NN}}$=5.02 TeV similar to 2.76 TeV
- But spectra are harder at $\sqrt{s_{NN}}$=5.02 TeV
  - ⇨ Suggests larger energy loss due to larger, hotter and denser medium

ALI-PREL-107300

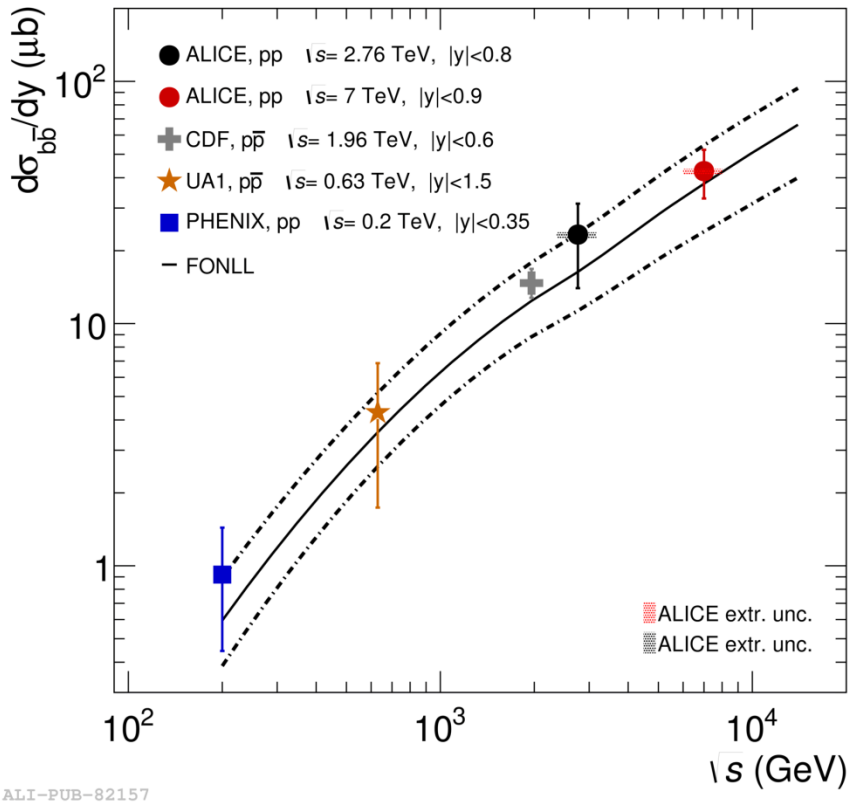
HF production cross section

Charm



📖 **ALICE, arXiv:1605.07569**

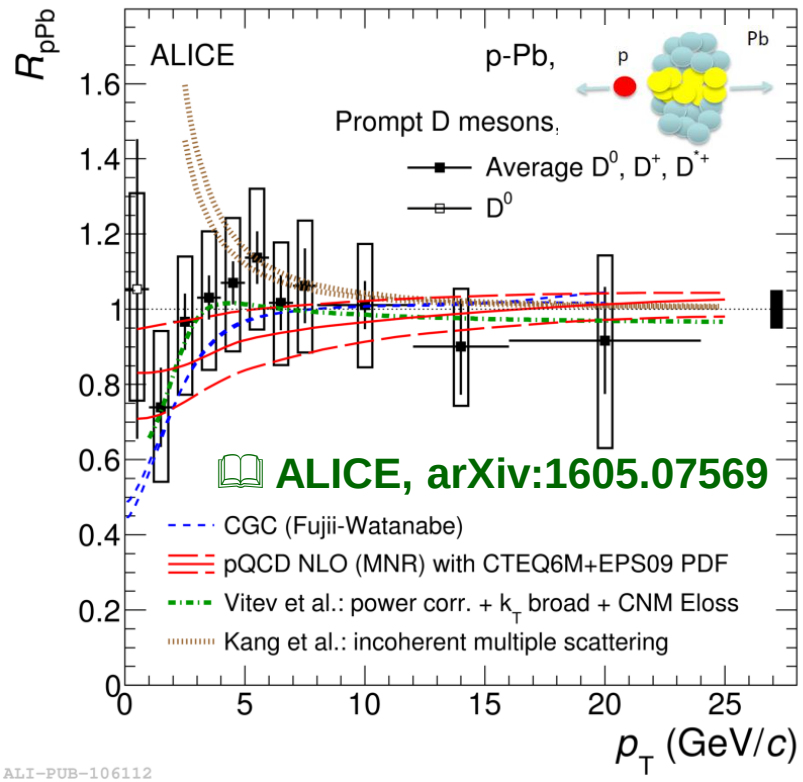
Beauty

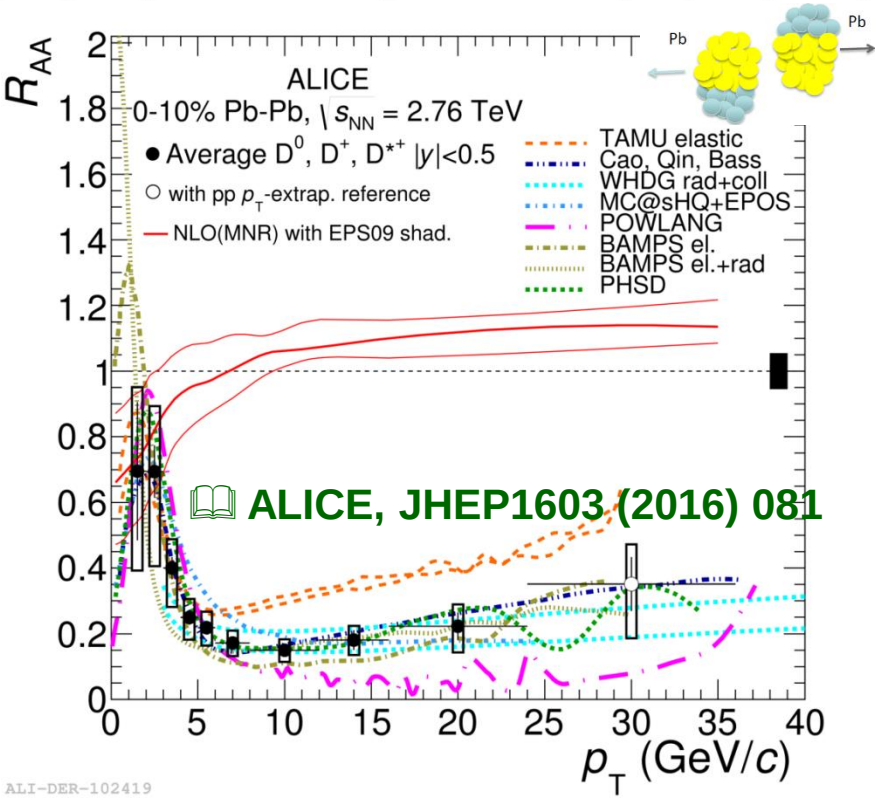


📖 **ALICE, PLB 738 (2014) 97**

- Total charm and beauty production cross sections described by NLO pQCD calculations within uncertainties
  - ⇨ Charm on the upper edge of the theoretical uncertainty band at all collision energies

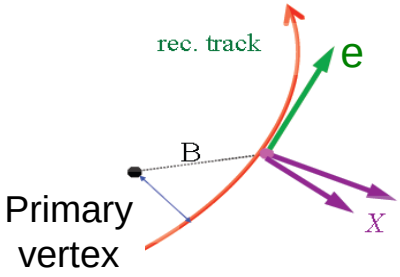
D-meson modification vs. models





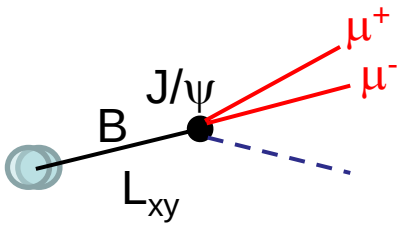
- Calculations based on pQCD+nuclear PDFs (no QGP)
  - ⇨ Describe p-Pb results, but fail in describing the Pb-Pb data
- Models including interactions of charm quarks with QGP
  - ⇨ describe qualitatively (and in some cases quantitatively) the data

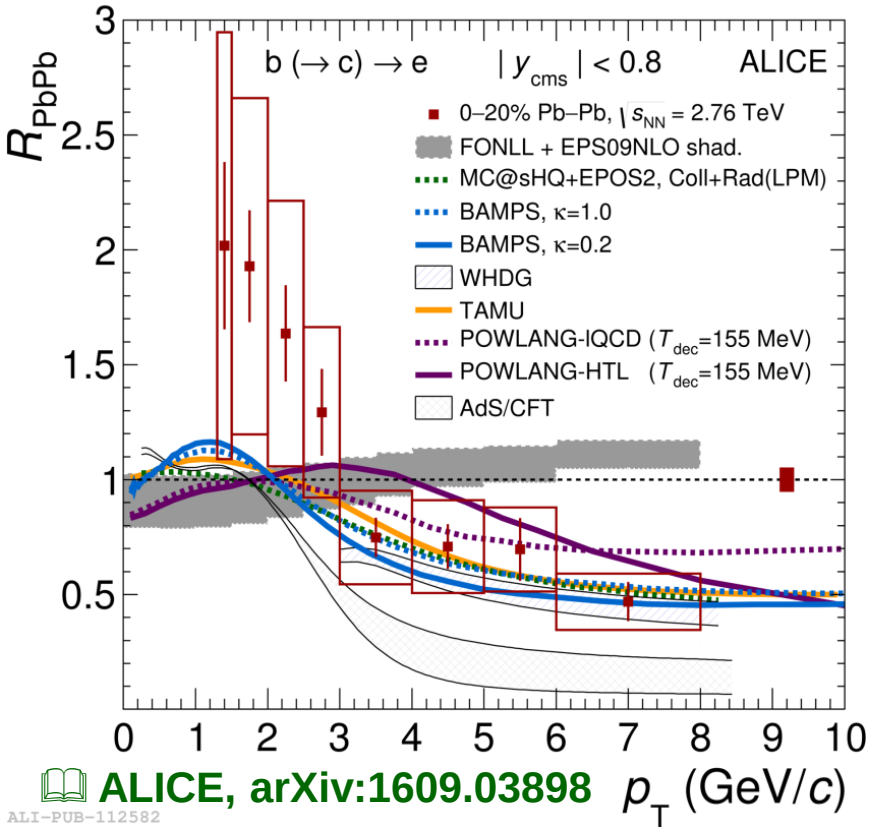
Beauty in Pb-Pb collisions

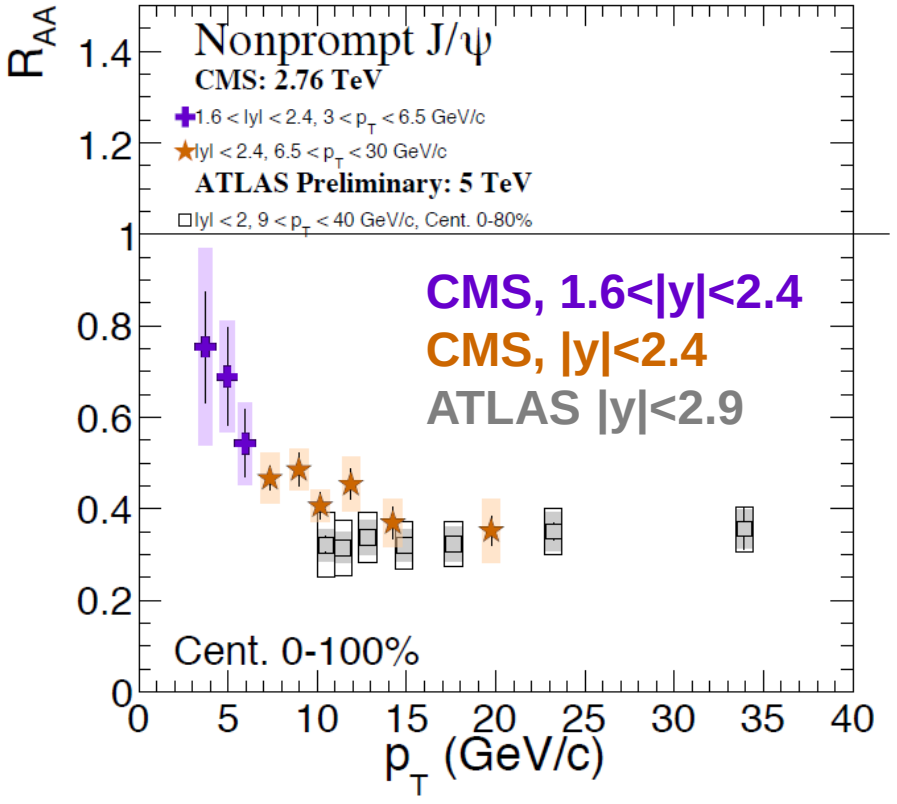


Beauty-decay electrons

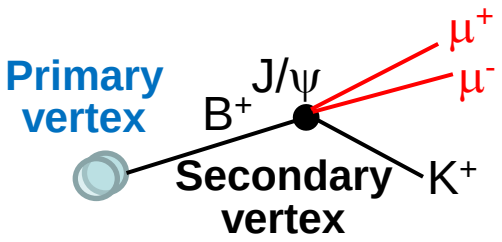
Non-prompt J/ψ





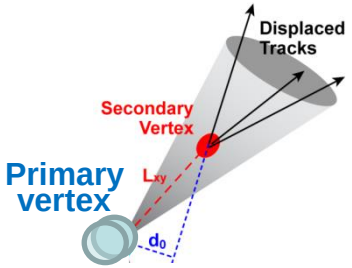


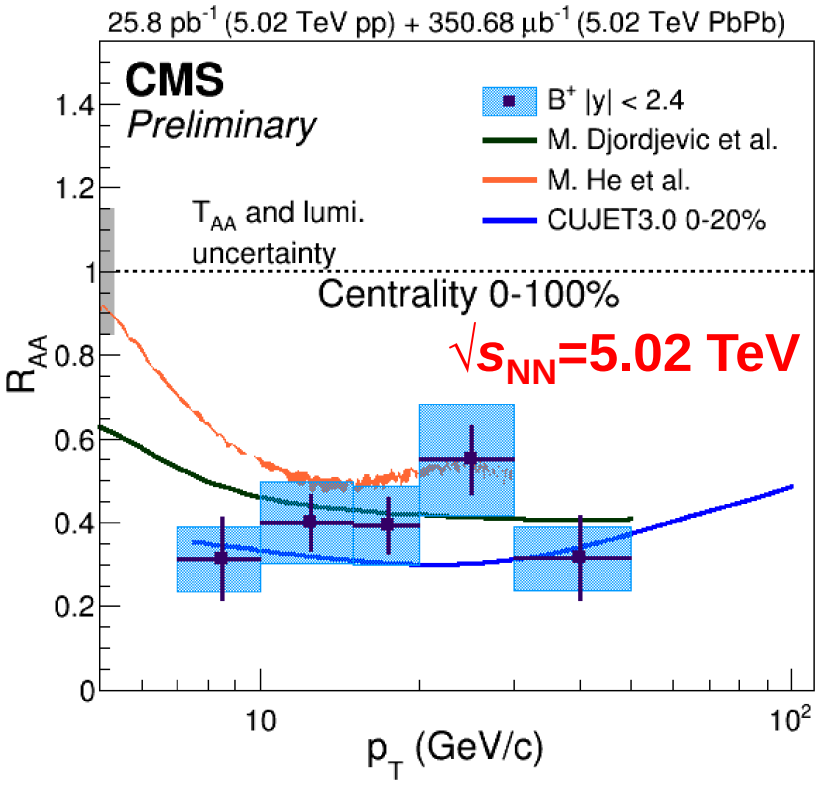
More beauty in Pb-Pb collisions

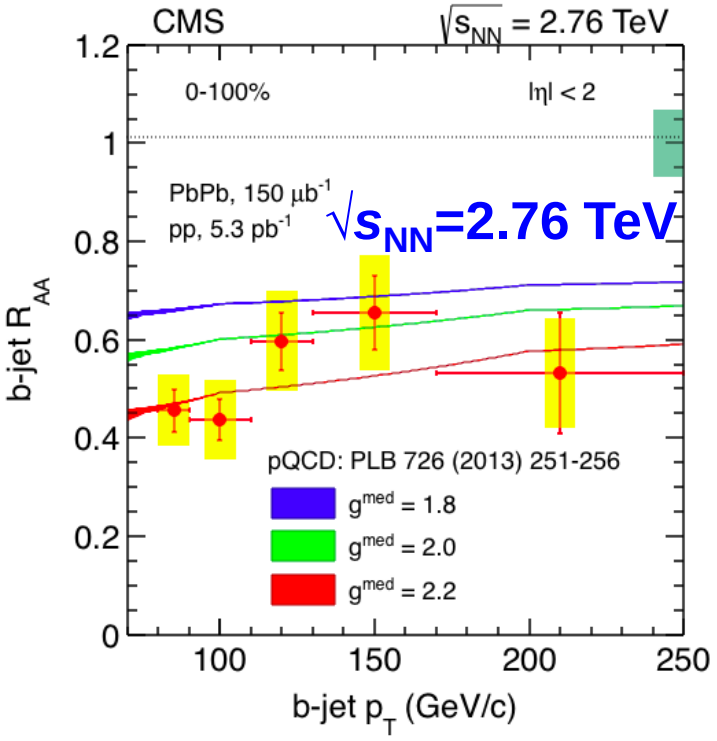


B⁺ mesons

b-jets



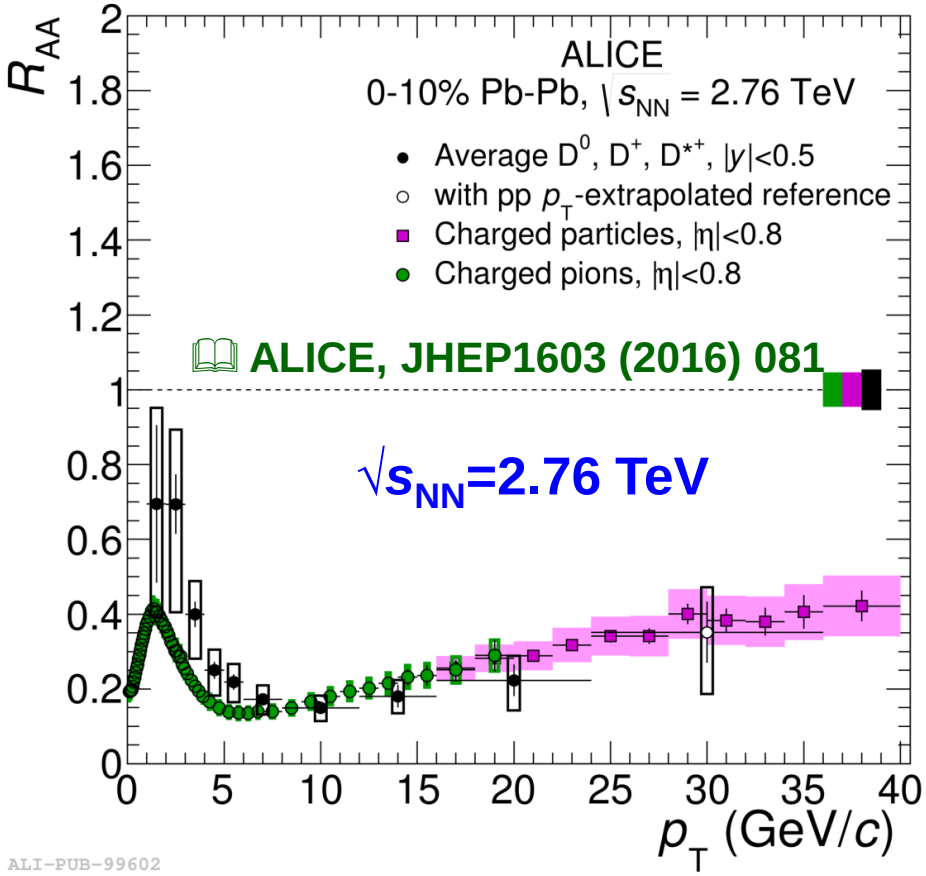




📖 CMS, PRL 113 (2014) 132301

R_{AA}: D mesons vs. pions

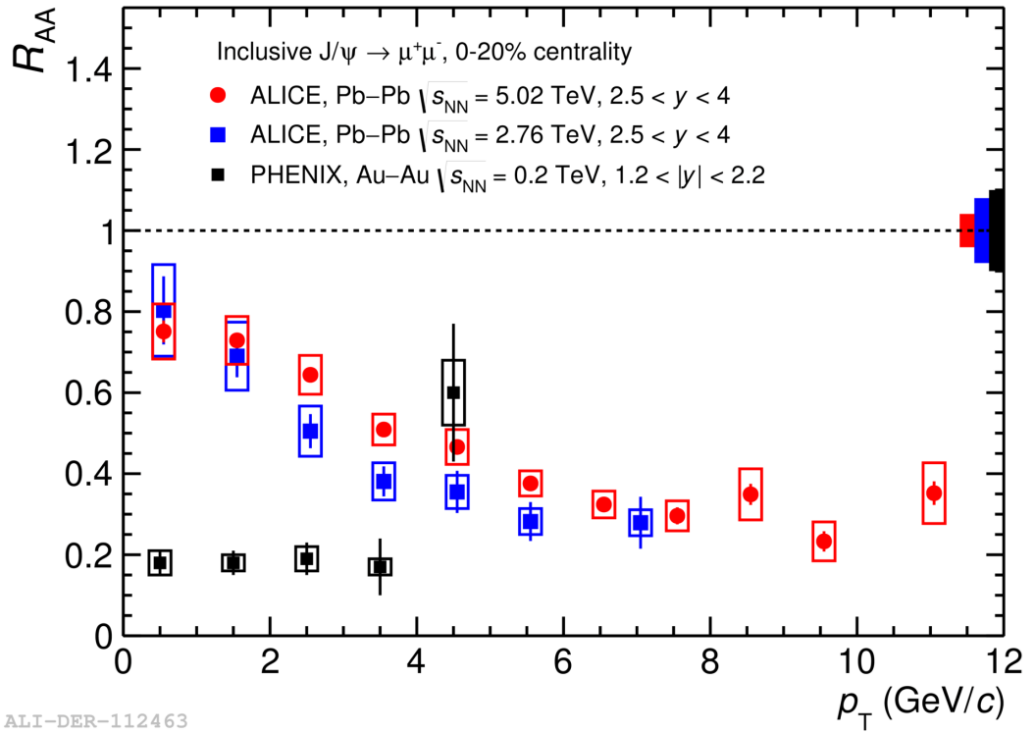
- Expectation: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Is this reflected in a R_{AA} hierarchy: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?



- D-meson and pion R_{AA} compatible within uncertainties
- Described by models including
  - ⇨ energy loss hierarchy ($\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$)
  - ⇨ different p_T shapes of produced partons
  - ⇨ different fragmentation functions of gluons, light and charm quarks

J/ψ R_{AA} at different $\sqrt{s_{NN}}$

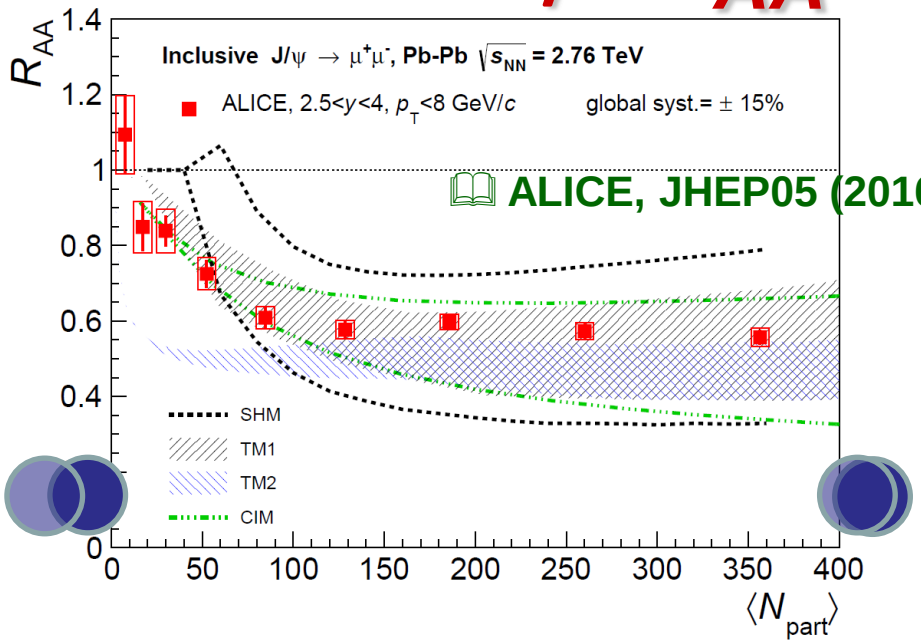
- J/ψ R_{AA} as a function of p_T for central collisions
  - ⇨ **Less suppression at low p_T** than at high p_T



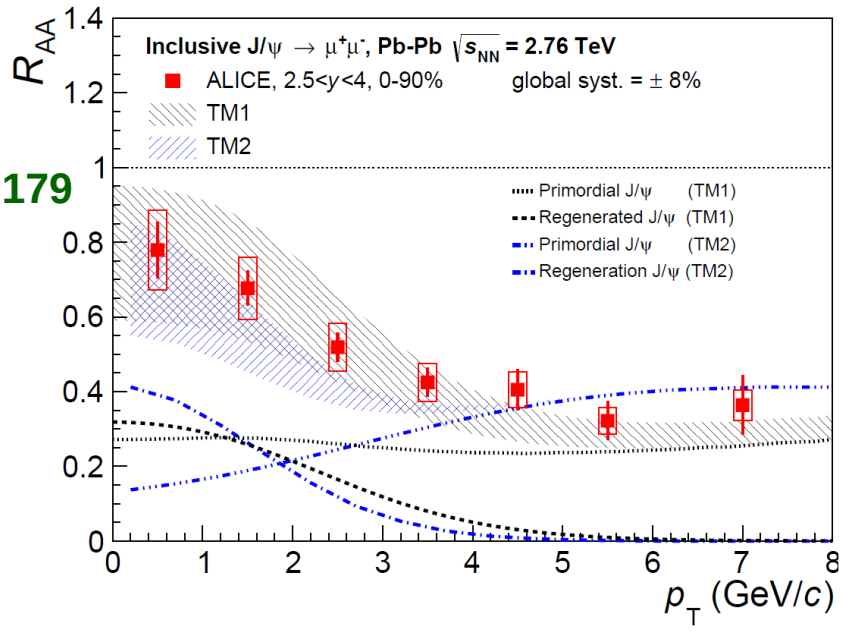
ALICE $\sqrt{s_{NN}}$=5.02 TeV
ALICE $\sqrt{s_{NN}}$=2.76 TeV
PHENIX $\sqrt{s_{NN}}$=200 GeV

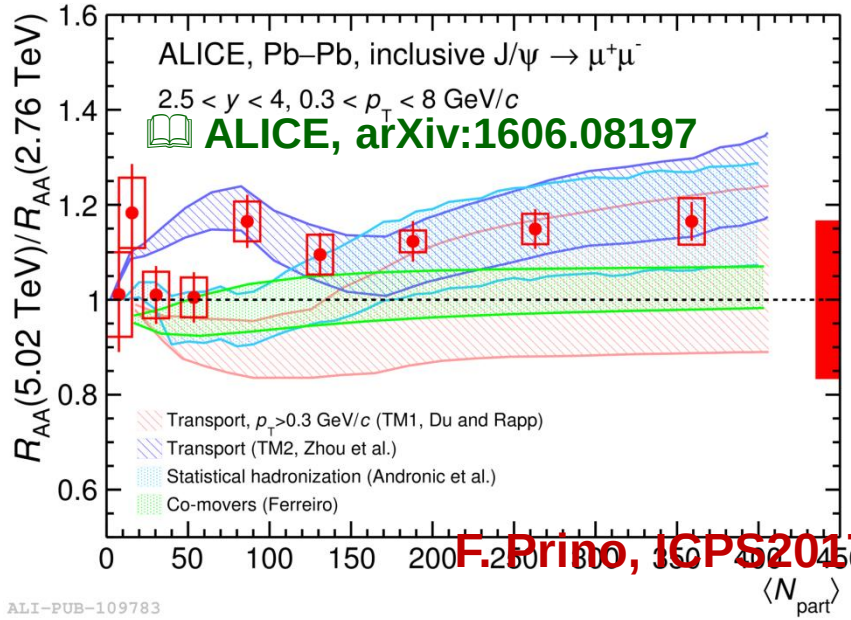
Qualitatively as expected in a scenario with melting in QGP followed by J/ψ formation via (re)combination

J/ψ R_{AA} vs. models



ALICE, JHEP05 (2016) 179





ALICE, arXiv:1606.08197

- Models including (re)combination can describe the data
  - ⇨ In Statistical Hadronization Model all J/ψ produced at hadronization
  - ⇨ In Transport Models (TM)
    - ✓ ***~50% of low-p_T J/ψ from recombination***
    - ✓ ***Recombination negligible at high p_T***

SHM: Andronic et al., JPG38 (2011) 124081
CIM: Ferreiro, PLB731 (2014) 57
TM1: Zhao, Rapp, NPA859 (2011) 114
TM2: Zhou et al., PRC89 (2014) 054911

ALI-PUB-109783