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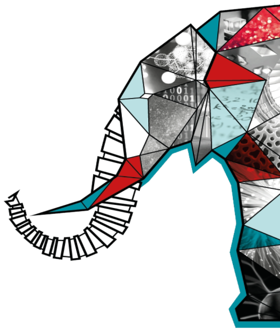
Is a quark-gluon plasma produced in proton-proton collisions at the LHC?

SARAH PORTEBOEUF-HOUSSAIS

25e Congrès Général
de la Société Française
de Physique



Quark-gluon plasma ?

LHC ?

Is a quark-gluon plasma produced in proton-proton collisions at the LHC ?

Where should it be usually produced and studied ?

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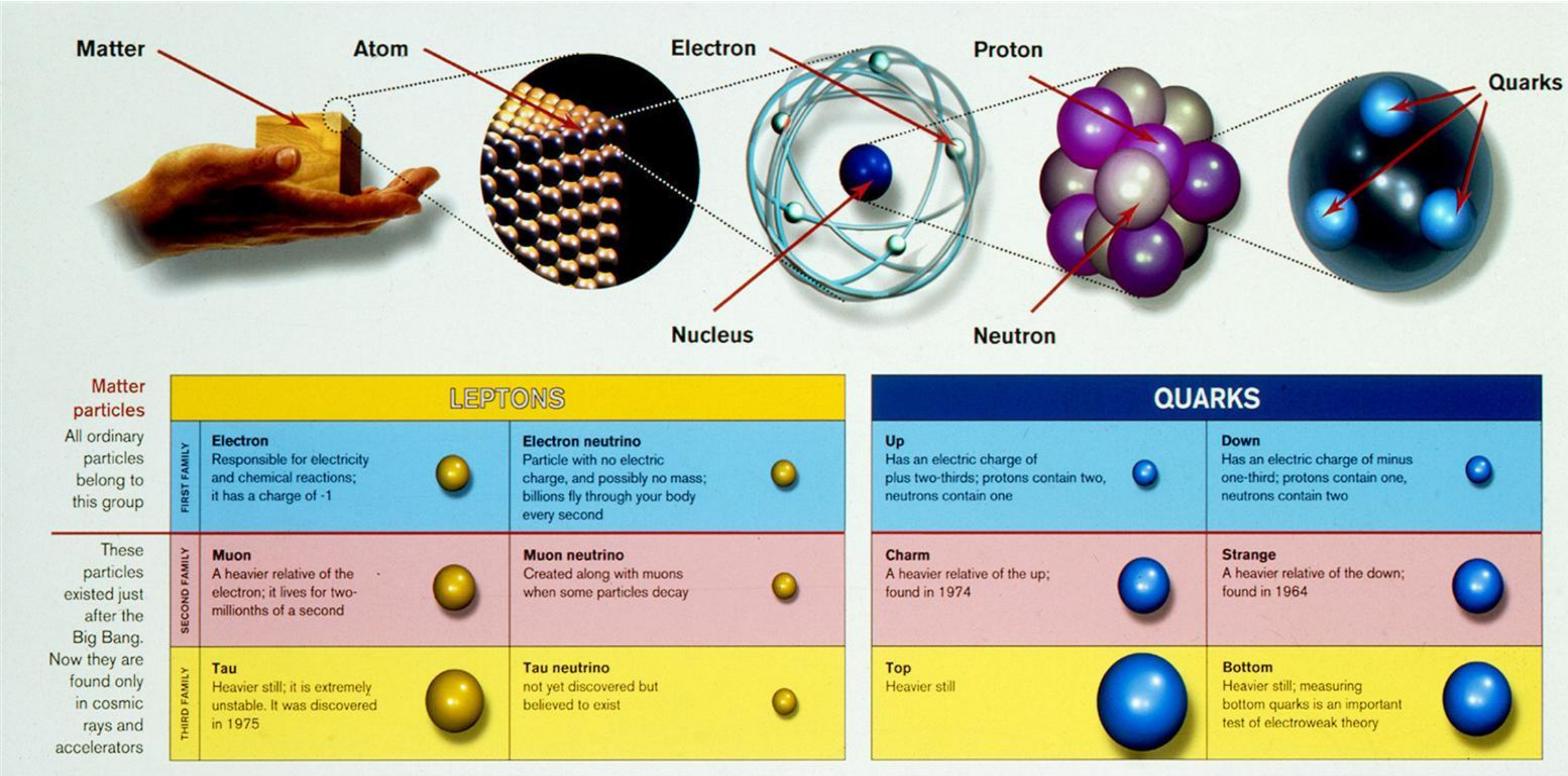
Matter at the QCD scale



Matter particles		LEPTONS		QUARKS	
All ordinary particles belong to this group	FIRST FAMILY	**Electron** Responsible for electricity and chemical reactions; it has a charge of -1	**Electron neutrino** Particle with no electric charge, and possibly no mass; billions fly through your body every second	**Up** Has an electric charge of plus two-thirds; protons contain two, neutrons contain one	**Down** Has an electric charge of minus one-third; protons contain one, neutrons contain two
These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators	SECOND FAMILY	**Muon** A heavier relative of the electron; it lives for two-millionths of a second	**Muon neutrino** Created along with muons when some particles decay	**Charm** A heavier relative of the up; found in 1974	**Strange** A heavier relative of the down; found in 1964
	THIRD FAMILY	**Tau** Heavier still; it is extremely unstable. It was discovered in 1975	**Tau neutrino** not yet discovered but believed to exist	**Top** Heavier still	**Bottom** Heavier still; measuring bottom quarks is an important test of electroweak theory

Quantum ChromoDynamics (QCD) is the theory of strong interaction

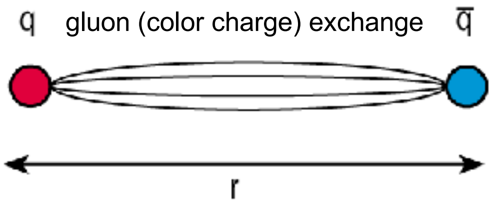
Matter at the QCD scale

- **Quantum ChromoDynamics** (**QCD**) is the theory of strong interaction, it describes quark interaction by gluon exchange, gluons carrying color charge (standard model)

  Quarks are colored (**R**,**G**,**B**)

  Quarks interact via gluon exchange

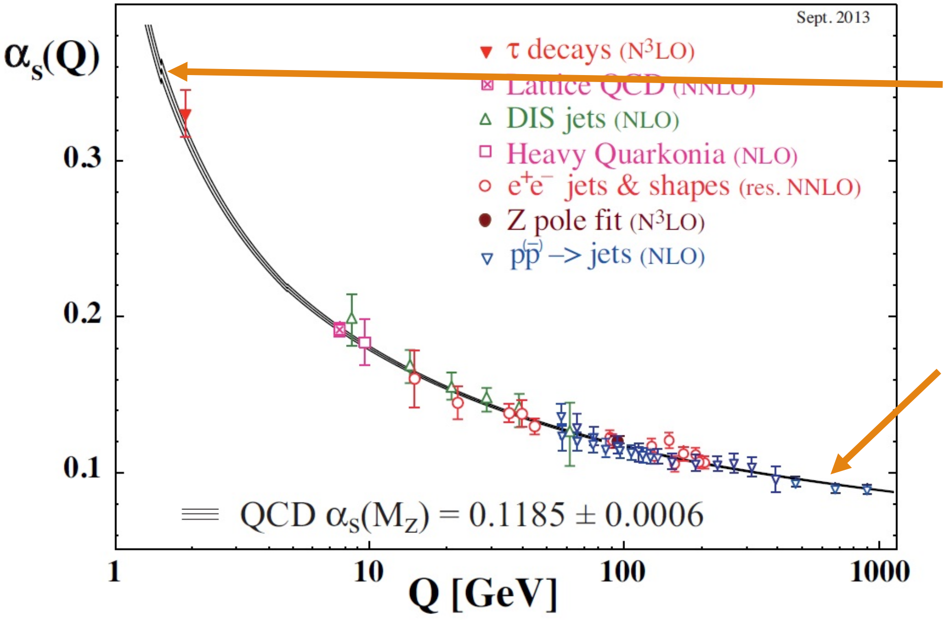
- **Big difference with QED:** gluon self-interaction



$$V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + k\,r$$

QCD potential between 2 quarks, 4/3 colour factor

Gluons attract each other: string with tension k



Confinement :

At long distance, low energy, the attractive force between quarks increases

Quarks are confined into hadrons

Asymptotic freedom:

At short distance, interaction becomes weak

Quarks can be considered as free in hadrons

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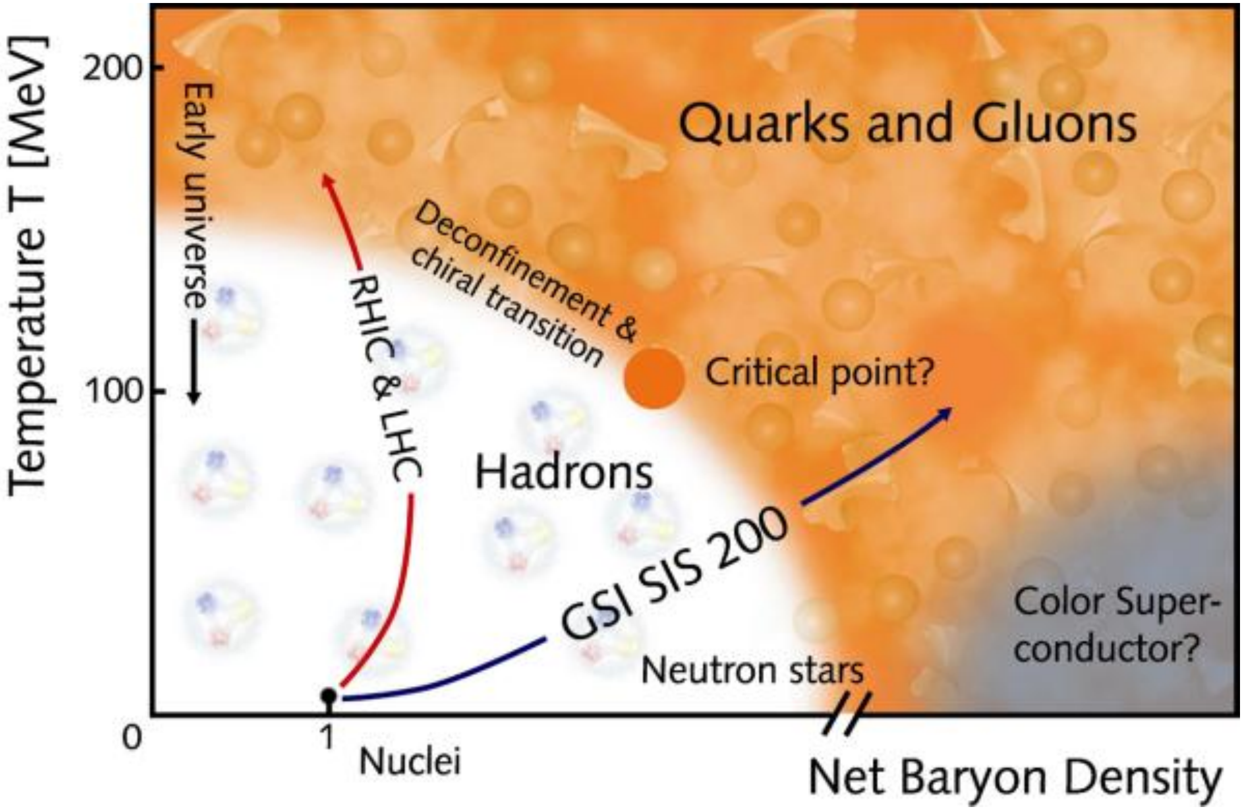
Quark-Gluon Plasma

Quark-Gluon Plasma (QGP) is a deconfined state of quarks and gluons (asymptotic freedom regime) predicted by QCD and studied in high-energy heavy-ion collisions

Credit: GSI



Why to call this deconfined state of QCD matter a plasma ?

- A “standard” plasma is a state of matter which contains ionized atoms: positive ions and negative electrons.

  At high temperature, ions are ionized and the gas makes a transition into a plasma phase (electron and ion soup). In this plasma, electric charges are screened due to the presence of other mobile charges. Globally the plasma is electrically neutral.

- In our case: at high temperature (and/or pressure) QCD matter undergoes a transition into a phase where quarks and gluons are deconfined. They move freely (asymptotic freedom): quark and gluon soup. Color charges are screened. Globally the state is color neutral .

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This deconfined state of QCD matter looks like a
color analogue of the electric plasma

The Quark-Gluon Plasma

! Historical analogy, the QGP looks like a perfect fluid more than a plasma …
!Also QGP at low temperature and high baryonic density

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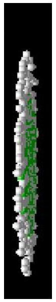
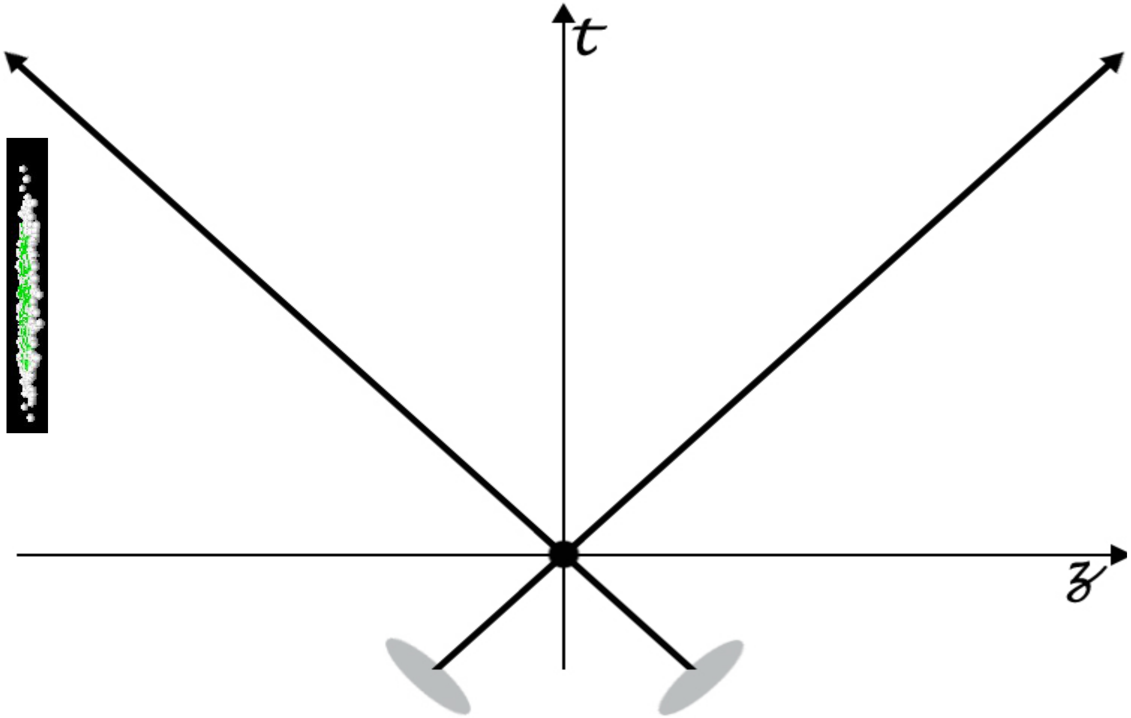
QGP with heavy-ion collisions

Quark-Gluon Plasma (QGP) is a deconfined state of quarks and gluons predicted by QCD and studied in high-energy heavy-ion collisions





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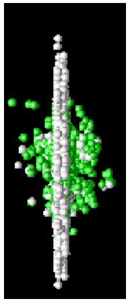

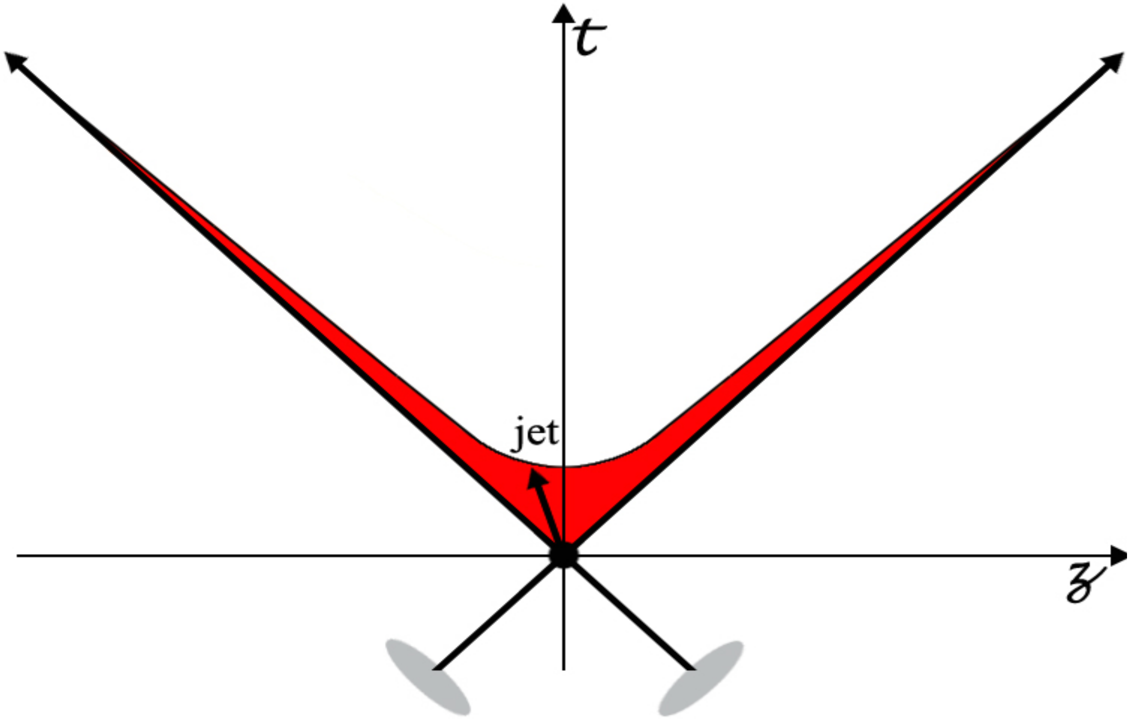

Initial-state interactions

Hard scattering: production of high-momentum particles e.g: heavy quarks, quarkonia, jets, direct photons, vector bosons

QGP with heavy-ion collisions

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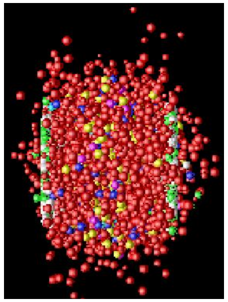

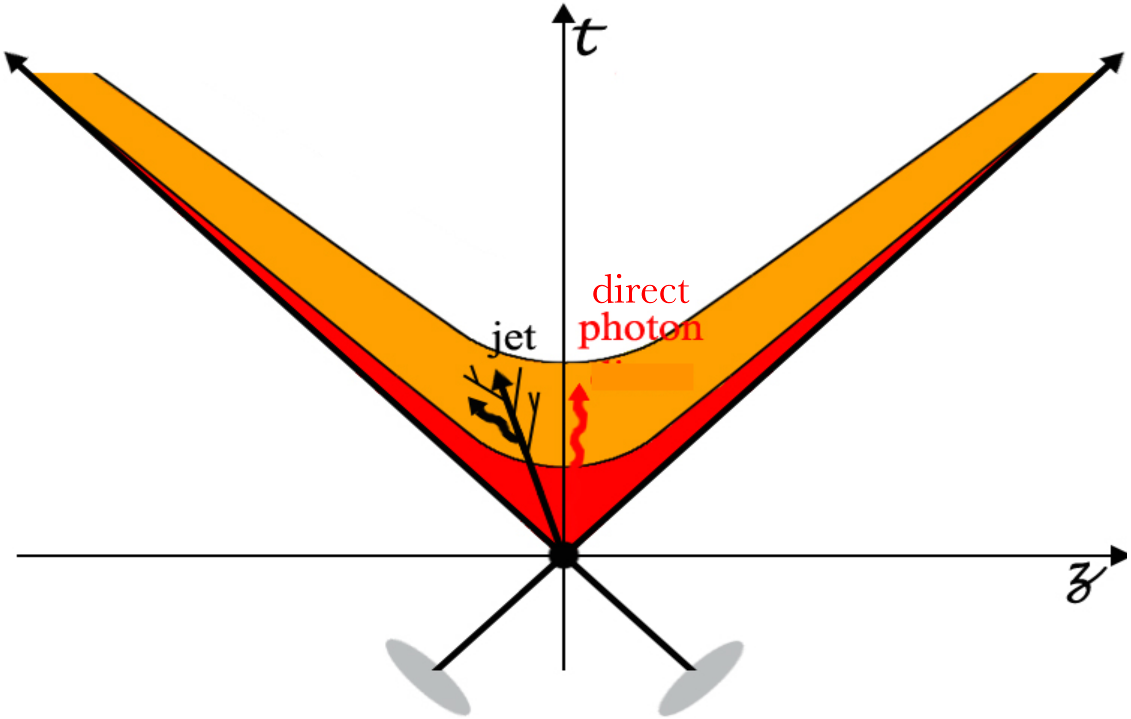

QGP ?

QGP with heavy-ion collisions

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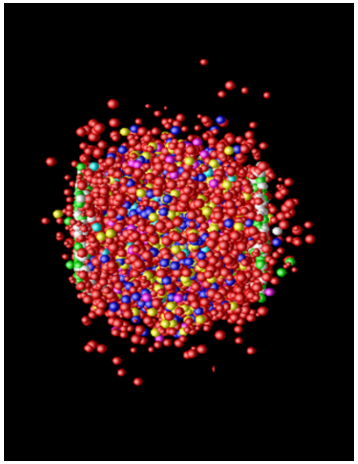

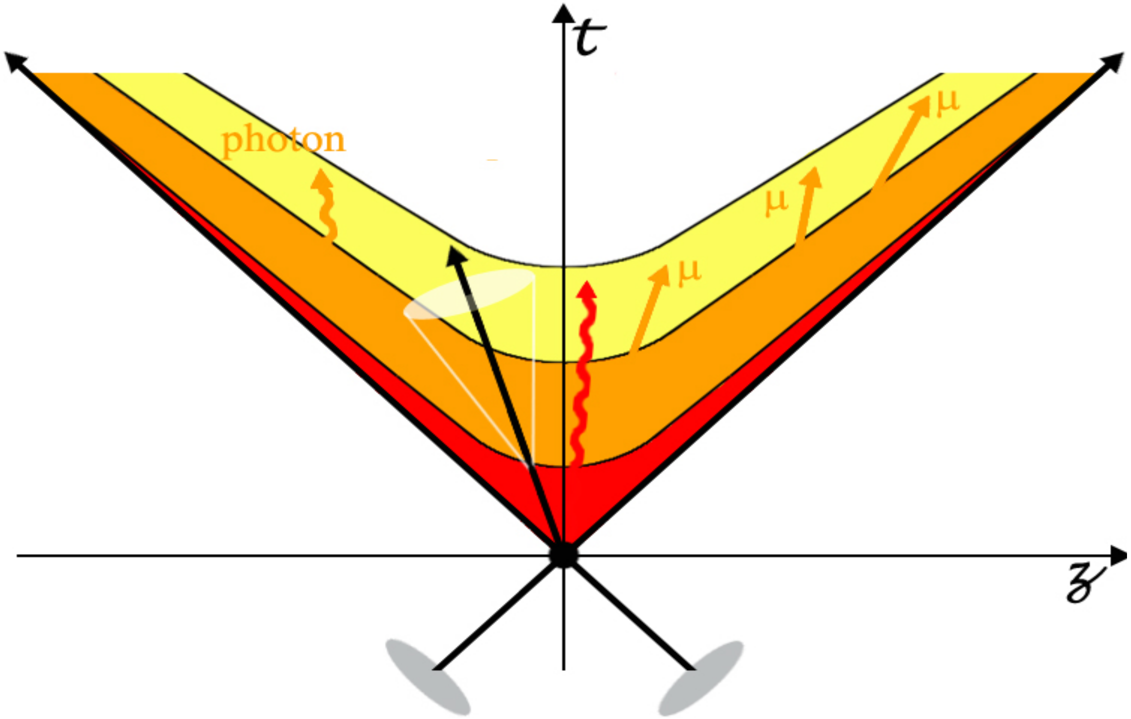

Plasma hadronization

Hadron gas

QGP with heavy-ion collisions

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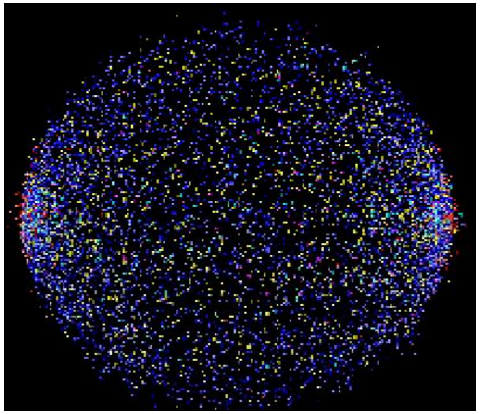

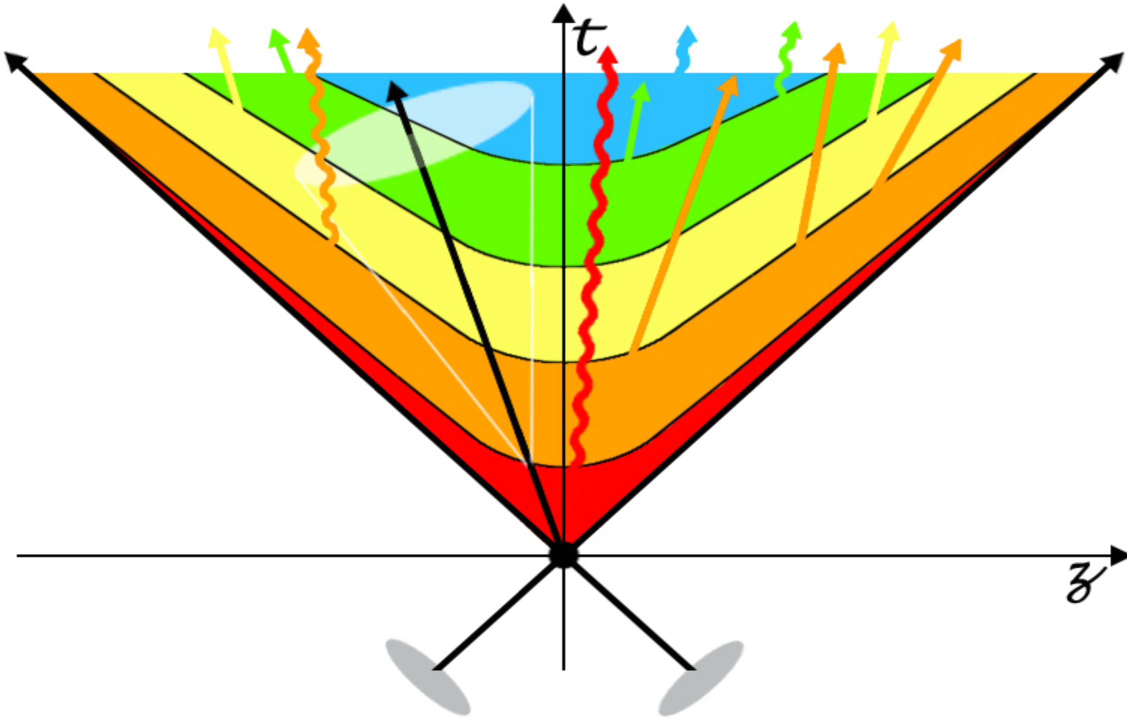

Chemical freeze-out
(no more inelastic collisions)

Thermal freeze-out
(no more elastic collisions)

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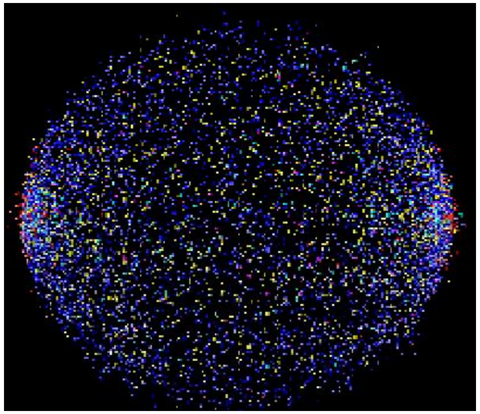
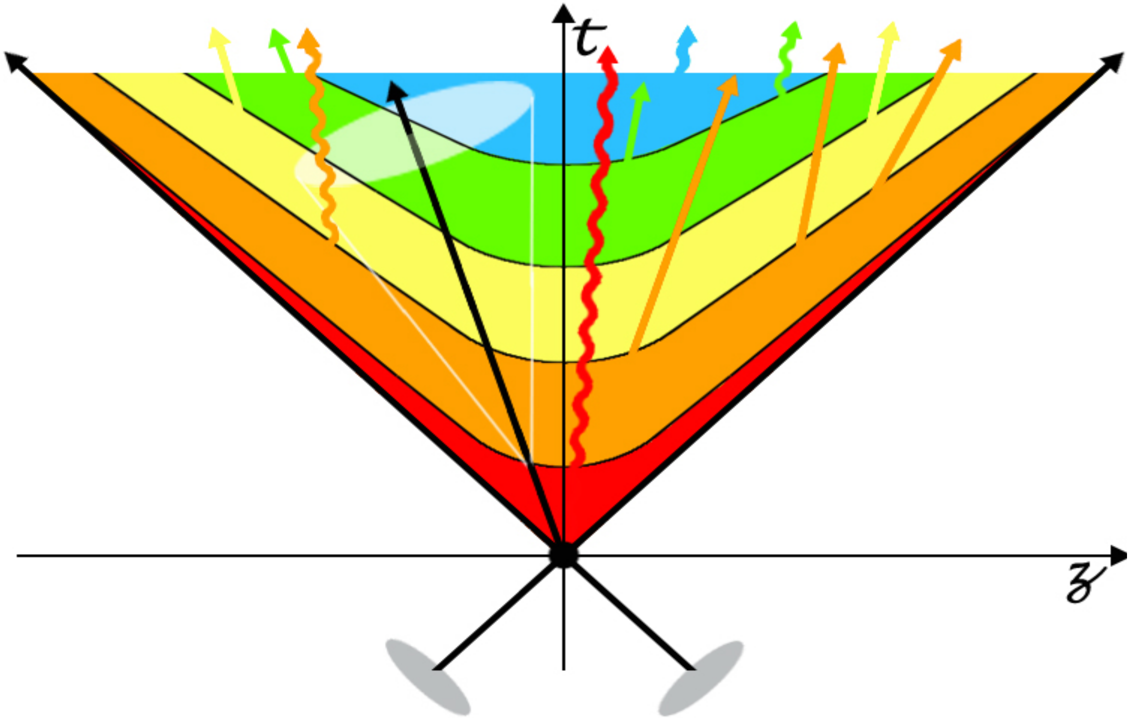
QGP with heavy-ion collisions

Various measurements, referring to various stages of the collision





- ✓ Soft probes are produced at the QGP hadronization stage
- ✓ Hard probes are produced at the initial stage of the collision and can interact with the QGP

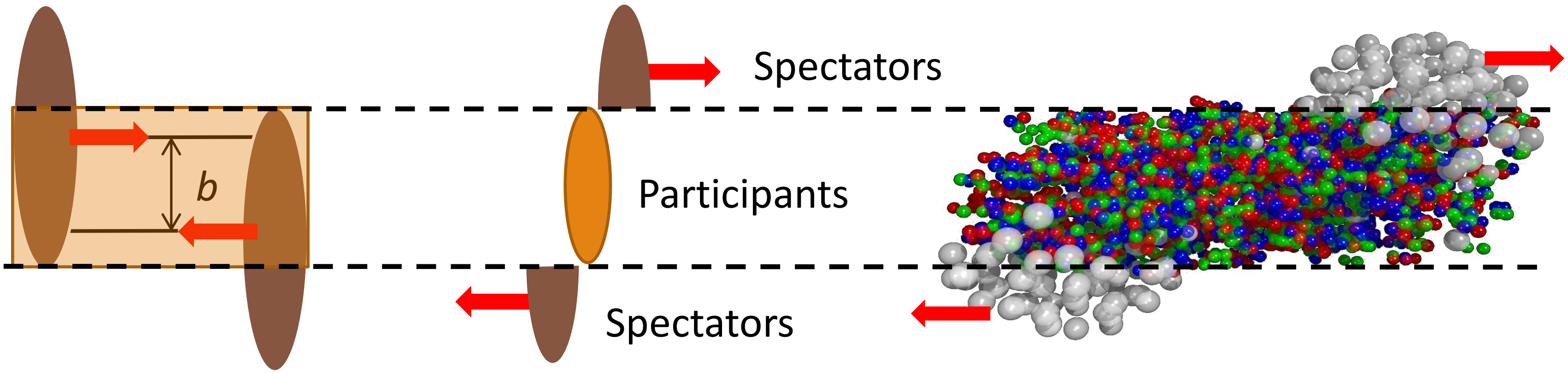
See review from Zaida Conesa Del Valle and focus on direct photon from Erwann Masson , Parallel C 1.3

QGP with heavy-ion collisions

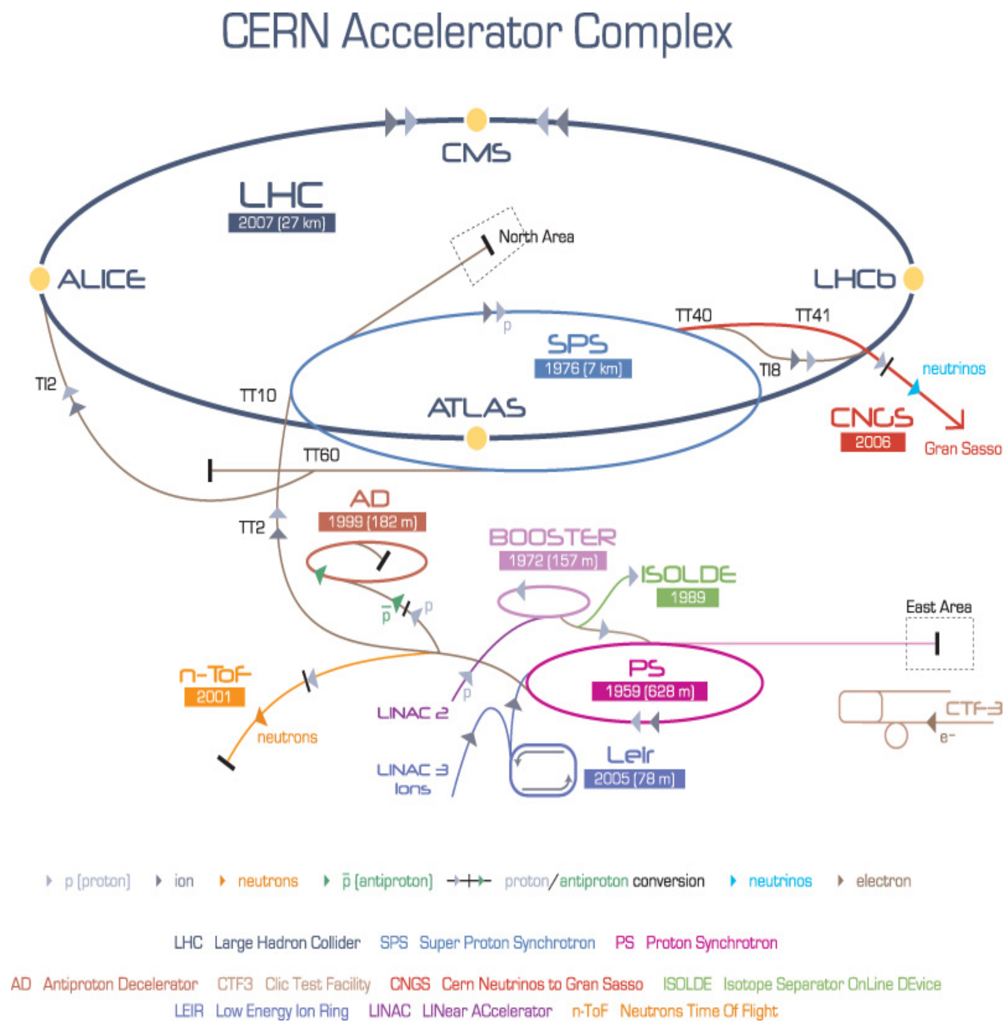
- **pp** collisions are considered as the vacuum **reference**

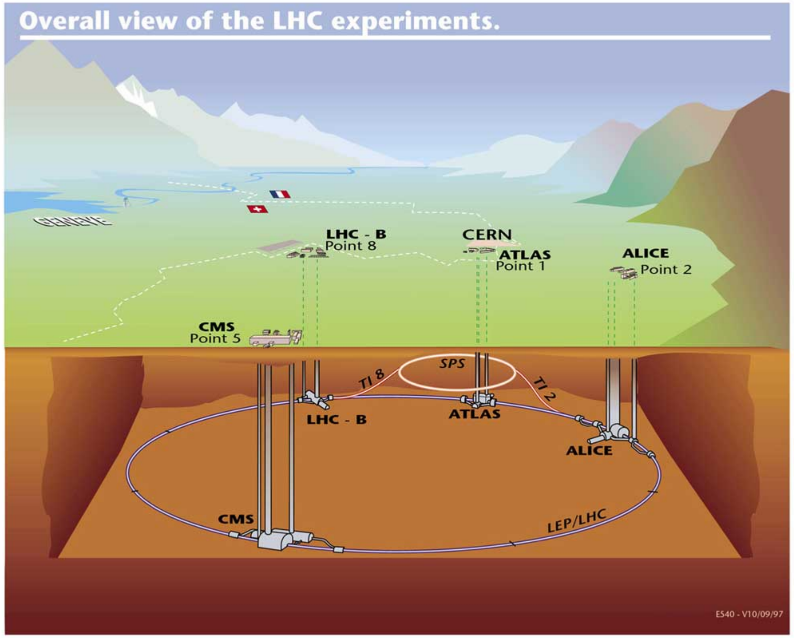
- **pA** collisions are a **control experiment** to estimate cold matter effects

- **AA** collisions are described by a (geometrical) **Glauber model** defining the number of participants and the number of binary collisions (N_{coll}) for a given impact parameter b



The Large Hadron Collider (LHC)





LHC 27 km circumference
50 to 175 m underground
At the French-Swiss border (Geneva area)

Collision systems and energies

- pp $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8, 13 TeV
- p-Pb $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV
- Pb-Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
- Xe-Xe $\sqrt{s_{NN}}$ = 5.44 TeV

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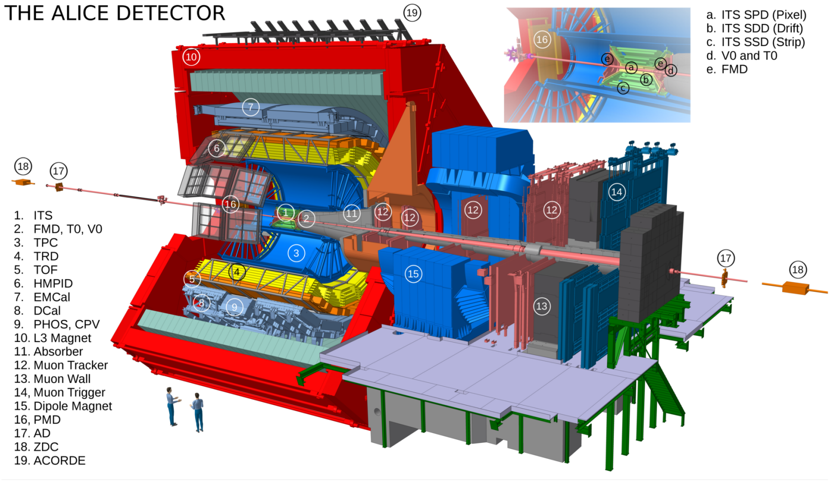
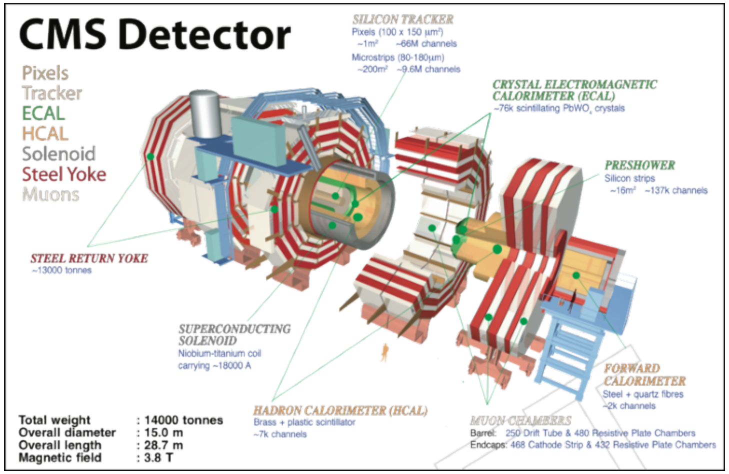
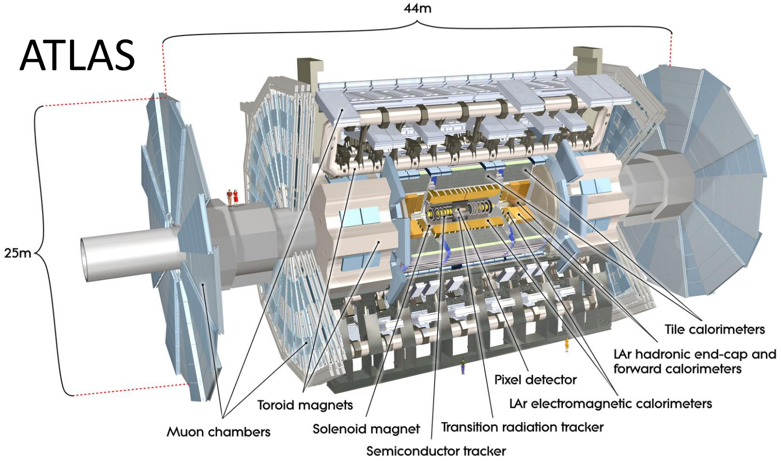
QGP experiments at LHC

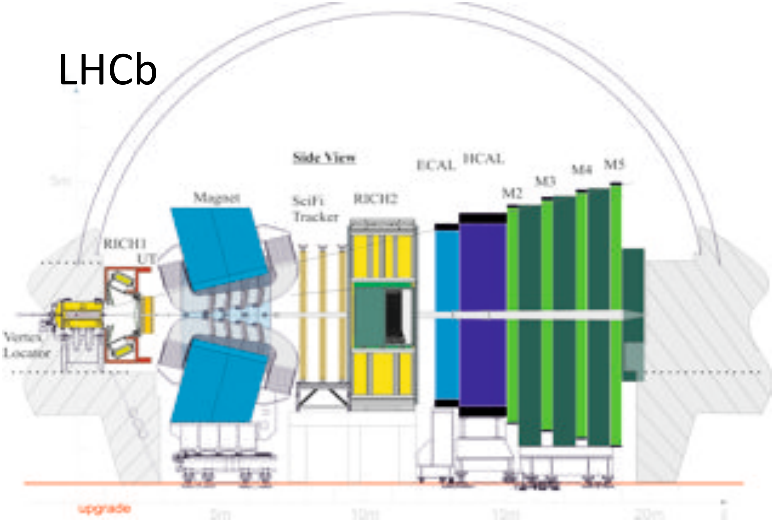




ATLAS

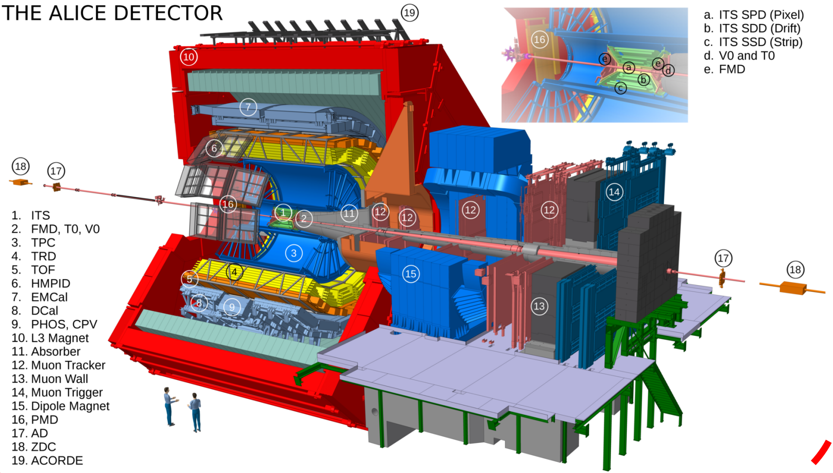


LHCb

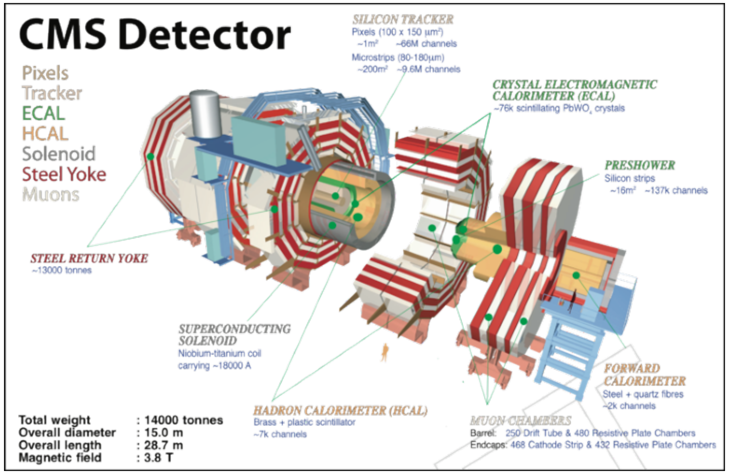


QGP experiments at LHC

Dedicated to heavy-ion physics



Developed an heavy-ion program



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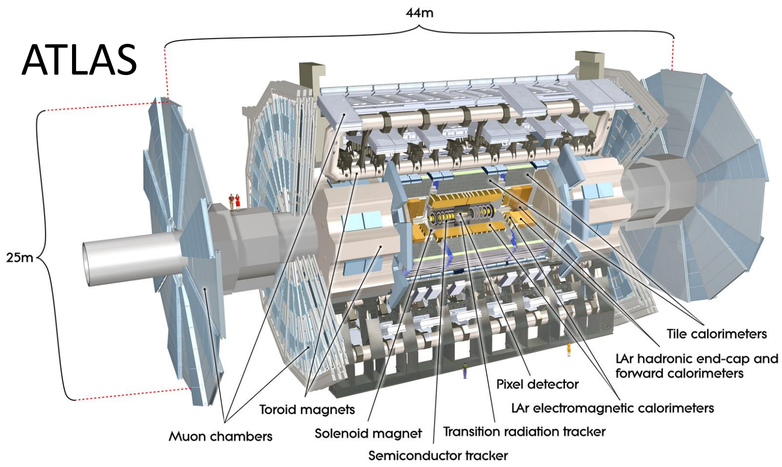
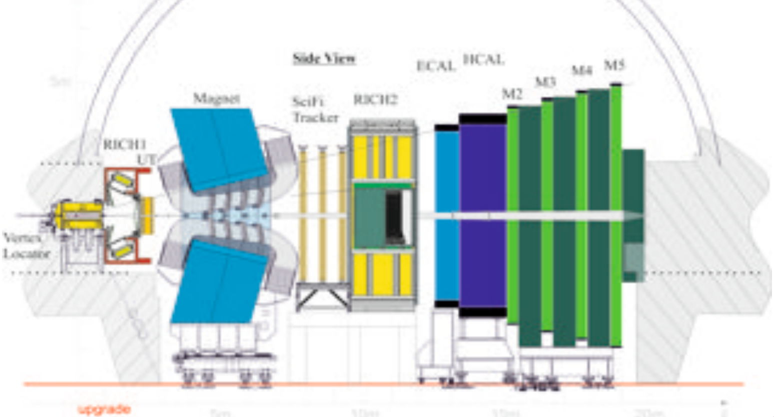
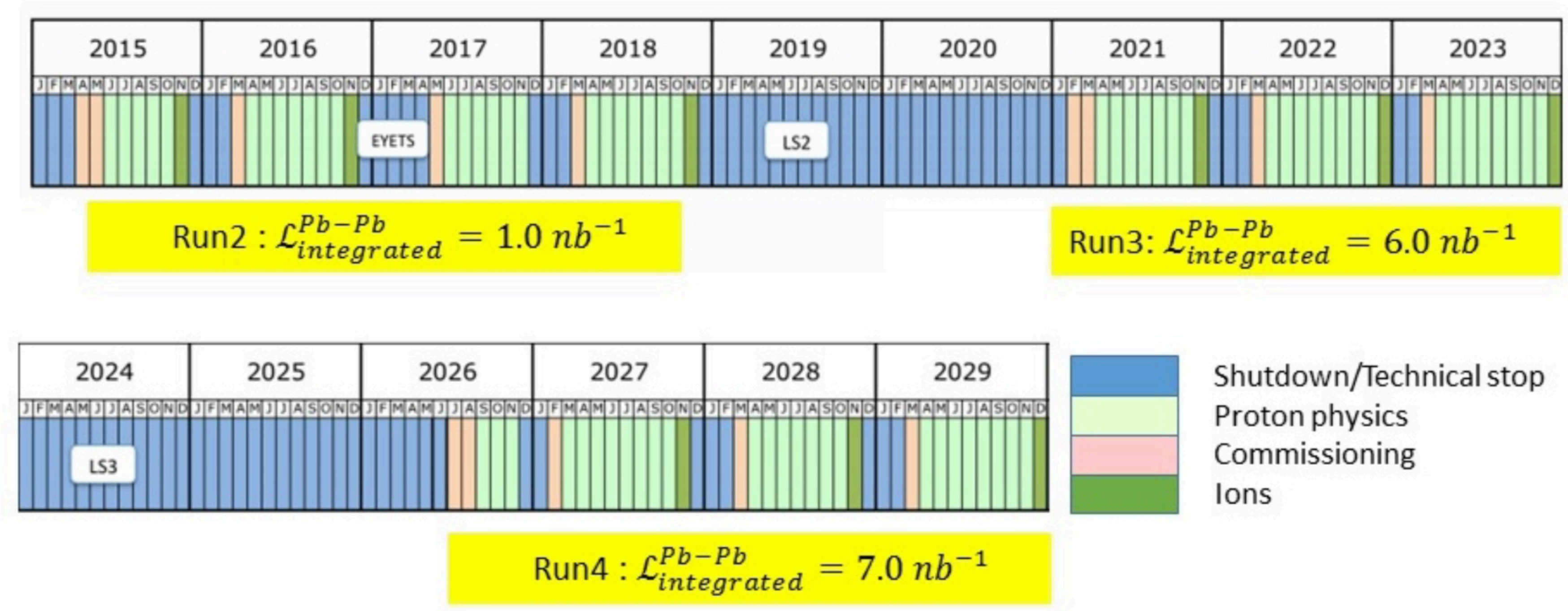


LHCb



LHC Schedule

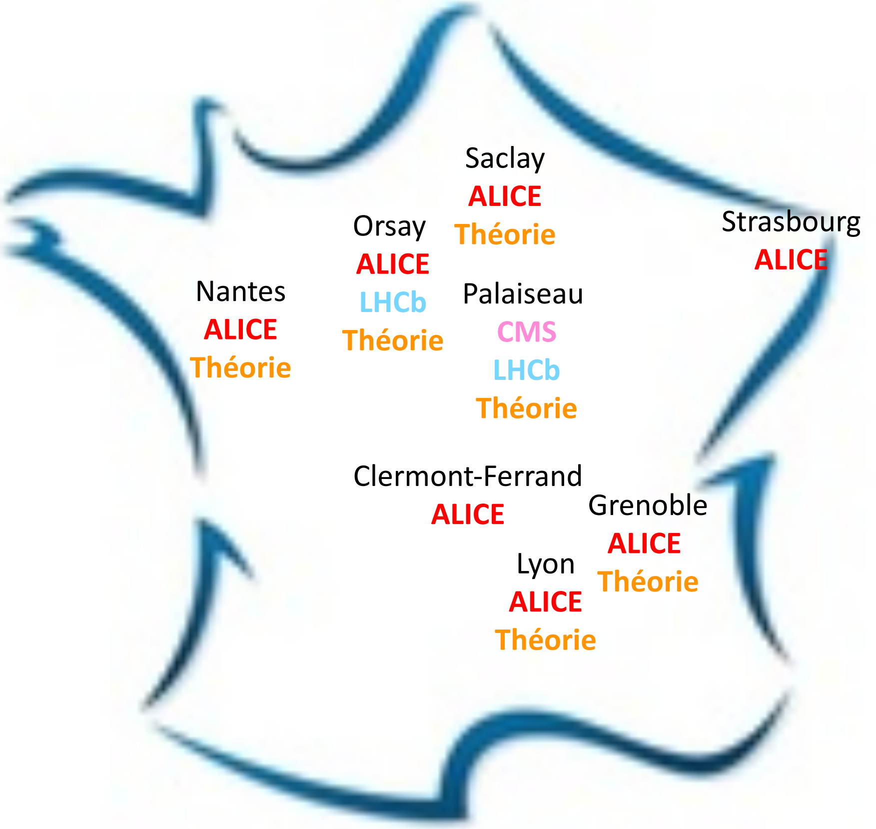


- A LHC Run: period of 3 to 4 years of data taking, improvement of machine conditions (energy, luminosity) every run
- A year of data taking starts around April (technical operations in Jan.-Mar) with pp collisions, heavy-ion physics in Nov-Dec
- Long Shutdown (LS) in between runs: 2 to 3 years of detector upgrades and maintenance

Now in LS2, in preparation for Run 3

The French QGP community

- ➢ O(100) physicists
- ➢ + Ingeniors and technicians
- ➢ QGP-France annual meeting



+ Linked to the GDR QCD
+ Linked to the SFP Division Nucléaire and Division Champs et particules

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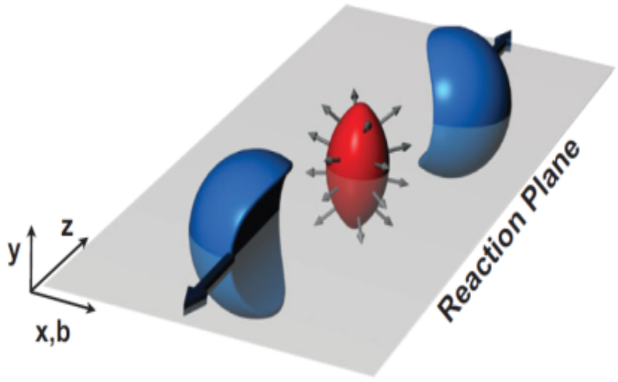
LHC: QGP studies in heavy-ion collisions

Disclaimer: **A large variety of measurements**
referring to various stages of the collisions from different probes,
implying different mechanisms

It is not possible to present one single measurement as THE QGP signature.
A convergent beam of signatures is needed as evidence for QGP

Highlights on Flow and Quarkonia

Elliptic flow of charged particles



Initial spatial anisotropy

➡ momentum anisotropy of particles

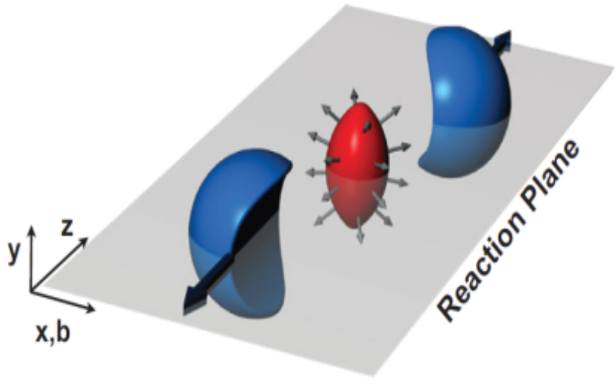
The anisotropy is quantified via a Fourier expansion in azimuthal angle ϕ with respect to the reaction plane Ψ_{RP}

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi n))$$

The second coefficient is v_2 (elliptic flow)

$v_2 > 0$, interpreted as collective expansion of the medium

Elliptic flow of charged particles



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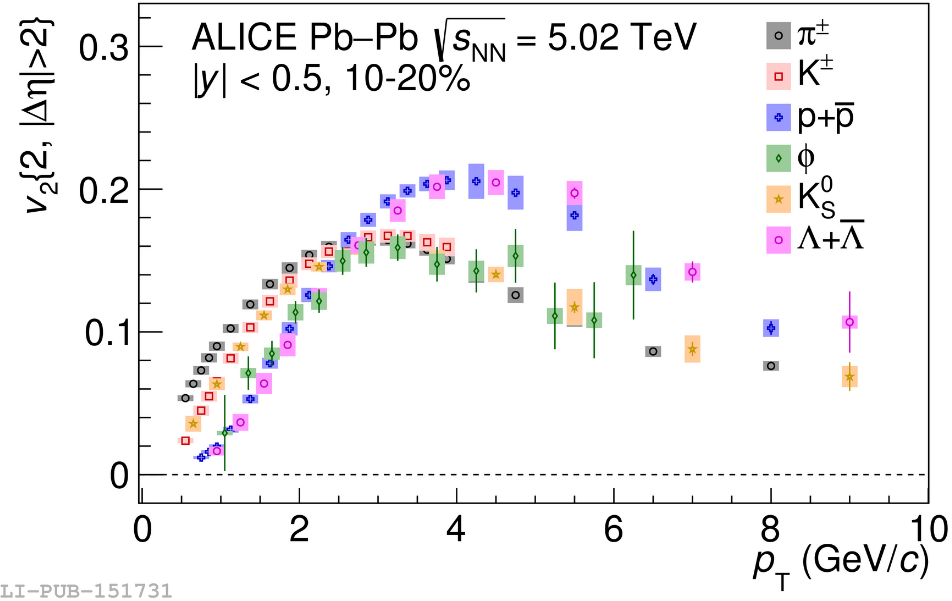
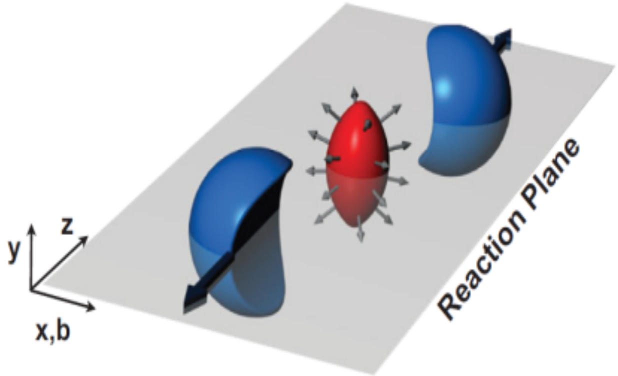


ALI-PUB-151731

Charged particles flow
in Pb-Pb collisions
with expected characteristics of
mass ordering.
Confirmed by advanced analysis
subtracting non flow component.

Elliptic flow of charged particles



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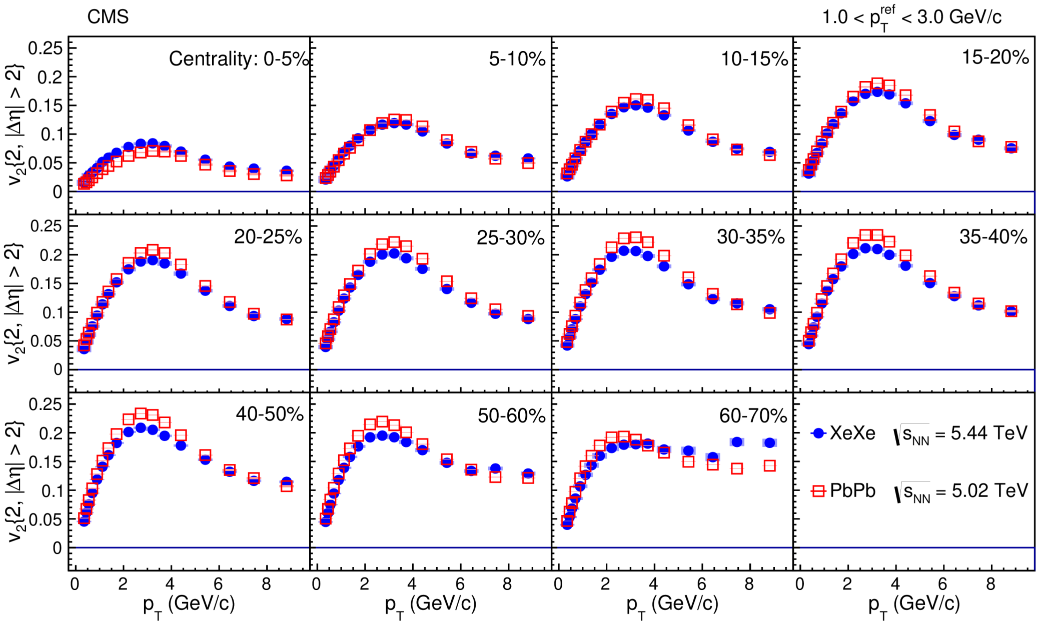

Charged particles flow

in Pb-Pb and Xe-Xe collisions

With v_2 amplitude depending of centrality of the collision.

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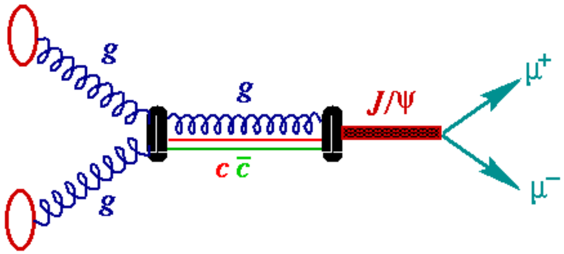
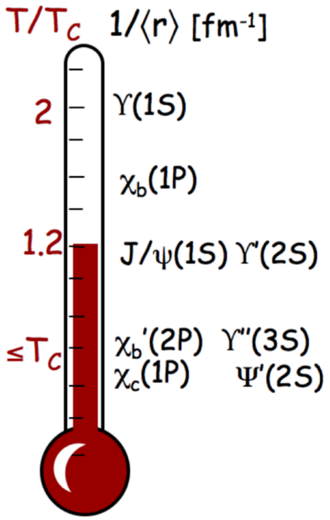
Quarkonia

See contribution from
Roland Katz C1.3

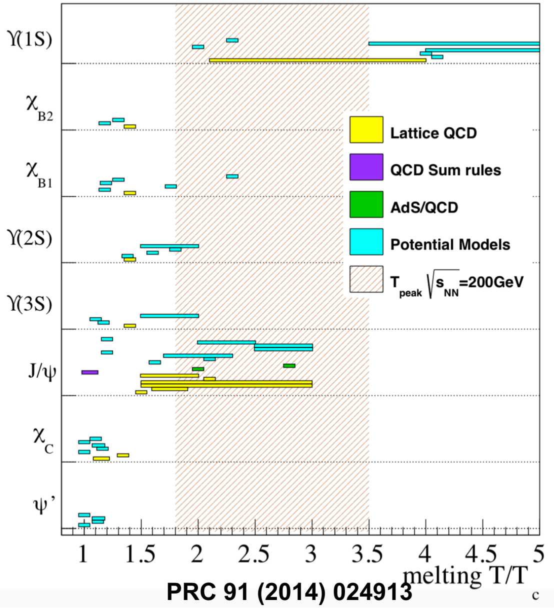


- **Quarkonia**, bound states of charm and beauty quarks,
  - Charmonia ($c\bar{c}$): e.g. J/ψ and Ψ(2S)
  - Bottomonia ($b\bar{b}$): e.g. ϒ(1S), ϒ(2S) and ϒ(3S)

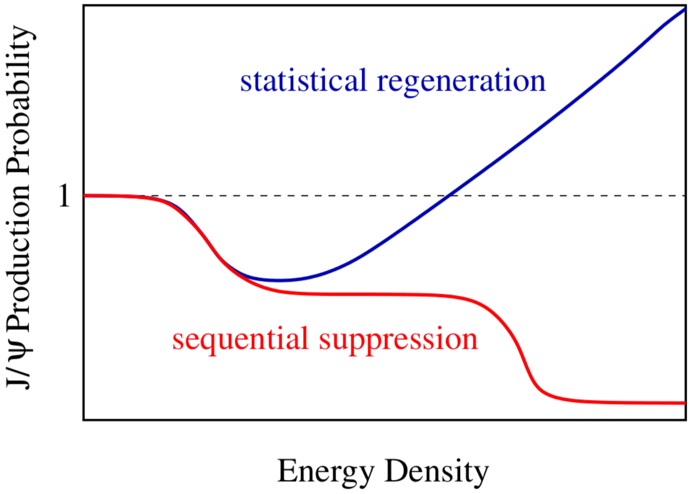
- Quarkonia, produced in first stage of AA collisions, experience the full QGP evolution:
  - **Quarkonium sequential suppression** via color screening **[Matsui and Satz, PLB178 (1986) 416]**
  - **Quarkonium regeneration**
    [Braun-Munzinger & Stachel, PLB 490 (2000) 196 ; Thews, Schroedter & Rafelski, PRC 65 (2001) 054905]



Eur Phys J C61 (2009) 705



PRC 91 (2014) 024913



NPB 214 (2011) 3

Quarkonia at Runs 1+2

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< N_{\mathrm{coll}} > \times \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

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Quarkonia at Runs 1+2

Nuclear modification factor

Measurement in AA

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Normalization by the number of collision (N_{coll})

Same measurement in pp

Quarkonia at Runs 1+2

Nuclear modification factor

Measurement in AA

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Normalization by the number of collision (N_{coll})

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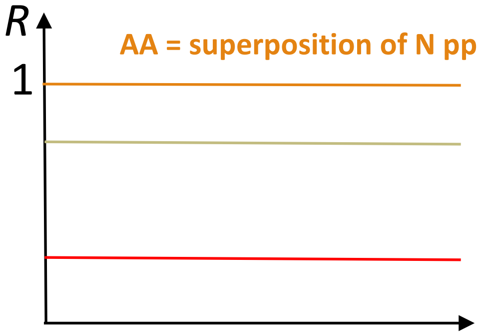


AA = superposition of N pp

Some probe sensitive to the nuclear environment: cold matter effect (pA)

Suppression

Quarkonia at Runs 1+2

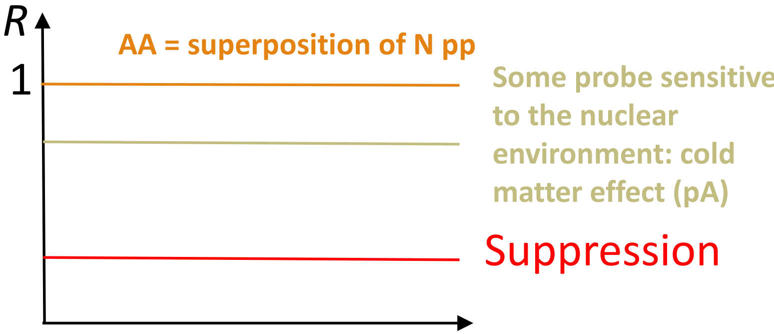
Nuclear modification factor

Measurement in AA

$$R_{AA} = \frac{dN_{AA}/dp_T}{< N_{coll} > \times dN_{pp}/dp_T}$$

Normalization by the number of collision (N_{coll})

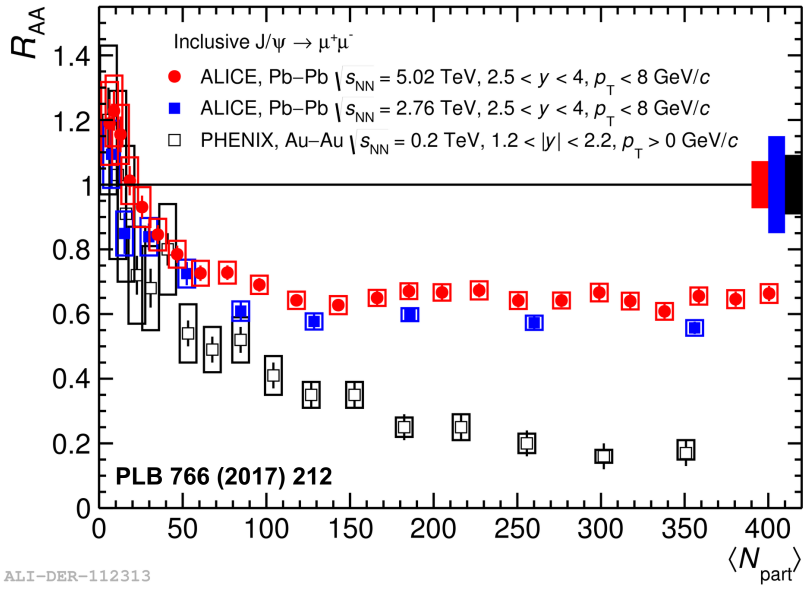
Same measurement in pp

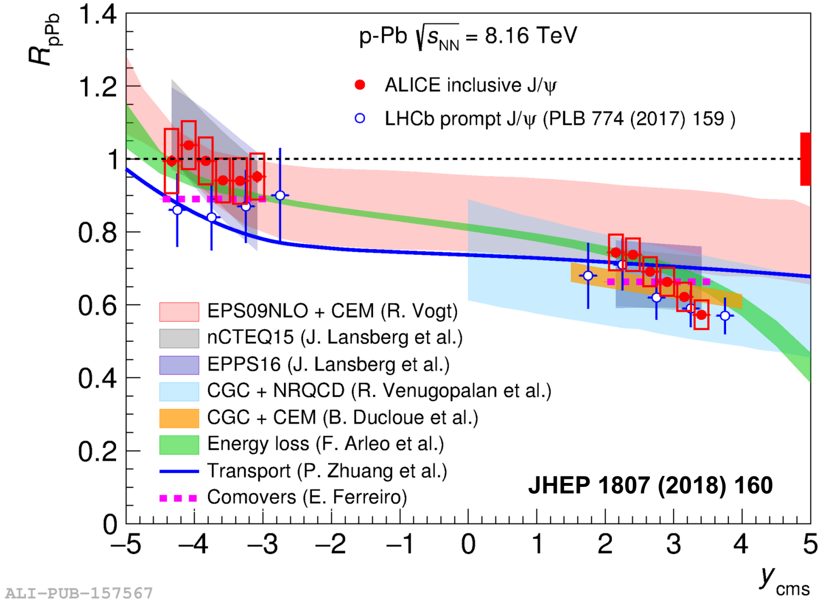


AA = superposition of N pp

Some probe sensitive to the nuclear environment: cold matter effect (pA)

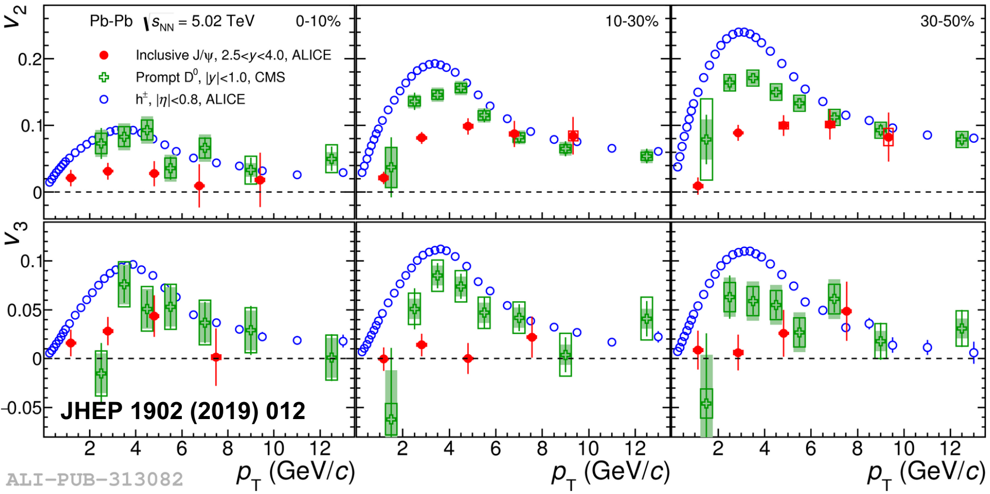
Suppression





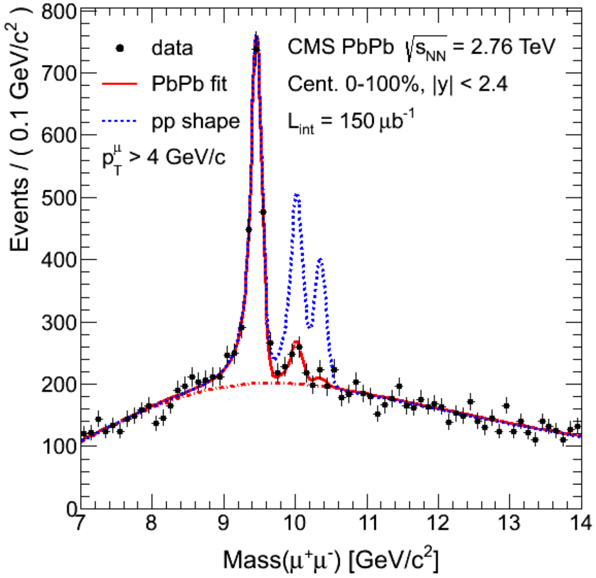
- J/ψ less suppressed at the LHC than at RHIC when varying the centrality of the collision
- Cold matter effects studied with p-Pb reference measurements
- Contribution from **regeneration** at low p_T

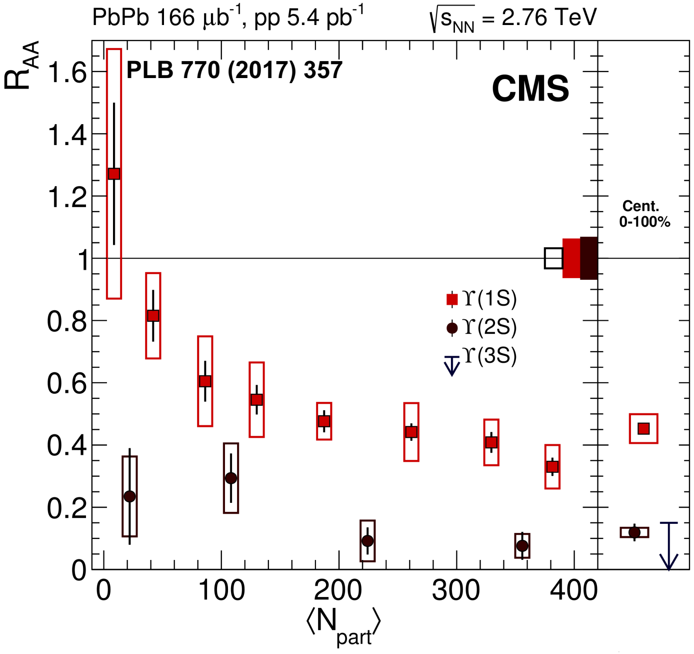
Quarkonia at Runs 1+2



- **Unambiguous observation of non-zero J/ψ v_2**
- At high p_T, stronger effect than expected: possible path-length dependence effect
- At low and intermediate p_T: $v_n(J/\psi) < v_n(D) < v_n(h)$

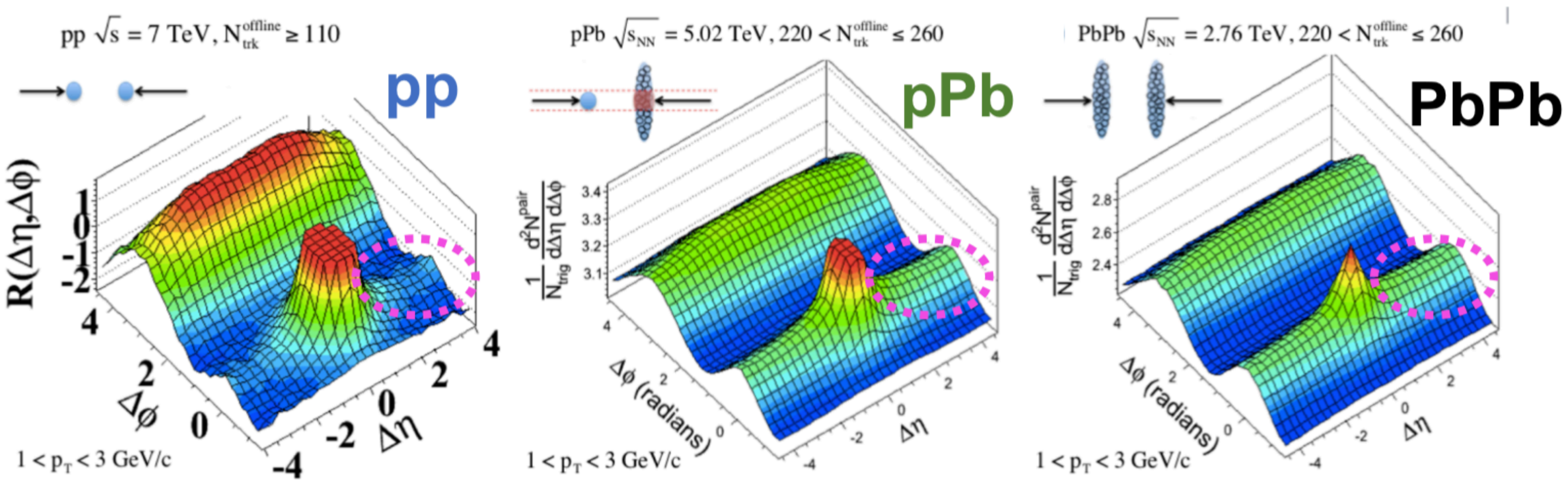
- **Strong Υ suppression at the LHC**
- Exited states melting
- $R_{AA}(Y(1S)) > R_{AA}(Y(2S))$





A Heavy-Ion LHC discovery
Small System Physics

Double ridge structure



CMS, JHEP09 (2010) 091

CMS, PLB 724 (2013) 213

A **long-range angular correlation** (elliptic flow) is observed for **all systems** (pp, p-A and A-A) in the **high multiplicity** regime.

Confirmed by the 4 experiments

ALICE PLB 719 (2013) 29 | ATLAS PRL 110 (2013) 182302 | LHCb PLB 762 (2016) 473

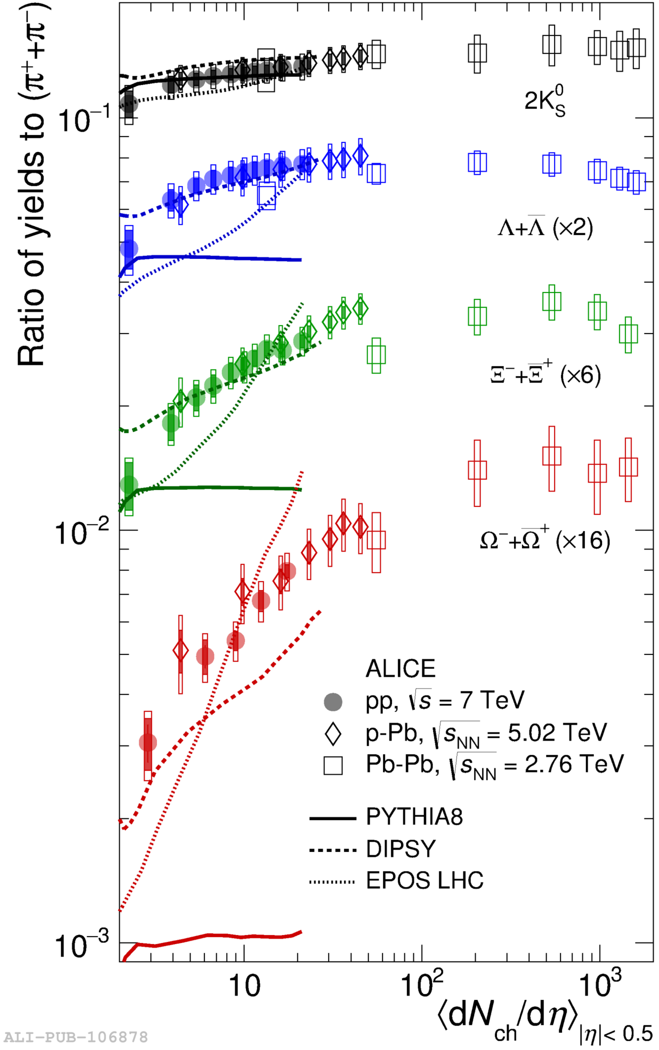
In Pb-Pb collisions it is interpreted as a signature of the collective expansion of the system

Figure credit Yen-Jie Lee (MIT)

« small system» physics at the LHC

- ”small” refers to system size: protons at the initial stage
- But with sometimes a final state looking like a large system (charged-particle multiplicity)
- At the LHC, minimum bias pp collisions can be used as reference
- High-multiplicity events represent a small contribution to the total cross section O(10^{-4}) in statistics
- Role of system size in question
  - pp is smaller than p-Pb
  - nuclear environment includes cold matter effects

Nature Physics 13 (2017) 535-539



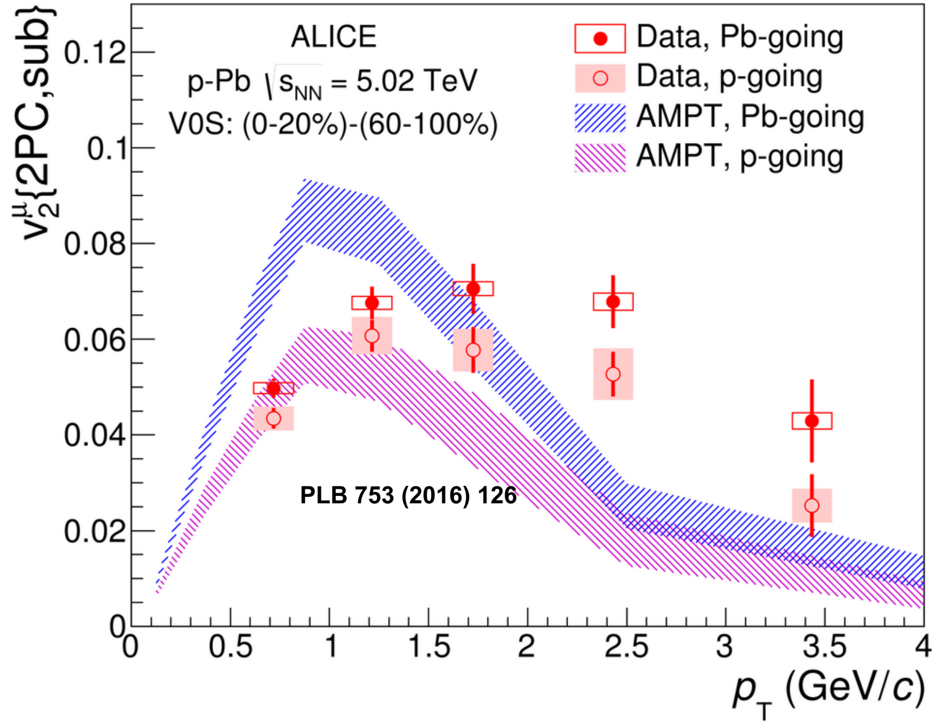
« small system» physics at the LHC

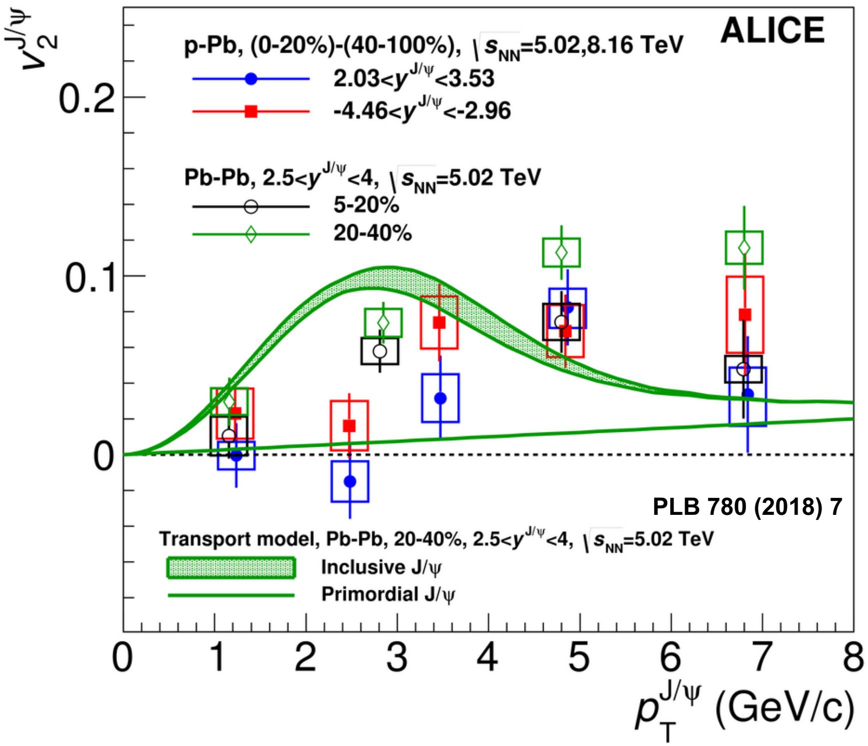
Table prepared by the WG small systems from the HL/E-LHC working group (~140 refs)

arXiv:1812.06772 arXiv:1602.09138

Observable of effect	Pb-Pb	pPb (high mult)	pp (high mult)
SOFT Probes			
low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
HBT radii	R_{out}/R_{side}~1	$R_{out}/R_{side} \leq 1$	$R_{out}/R_{side} \leq 1$
Azimuthal anisotropy (v_n) (2 prt. correlations)	v_1-v_7	v_1-v_5	v_2-v_4
Characteristic mass dependence	v_2-v_5	v_2-v_3	v_2
Higher order cumulants	"4~6~8 " + higher harmonics	"4~6~8 " + higher harmonics	"4~6 "+ higher harmonics
Event by event v_n distributions	n=2-4	Not measured	Not measured
Event plane and v_n correlations	yes	yes	yes
HARD Probes			
Direct photons at low p_T	yes	Not measured	Not measured
Jet Quenching	yes	Not observed	Not measured
Quarkonia Nuclear Modification Factor	J/ψ regeneration / Υ suppression	suppressed	Not measured
Heavy-flavor anisotropy	yes	yes	Not measured

Collective behavior of heavy quarks in p-Pb collisions ?





- Measurement of single-muon elliptic flow in p-Pb collisions in two rapidity regions
- Unambiguous observation of non-zero v_2 in the p_T range 0-4 GeV/c

- Measurement of J/ψ elliptic flow in p-Pb collisions in two rapidity regions
- Low p_T: v_2 compatible with zero
  High p_T: positive v_2

Not yet understood

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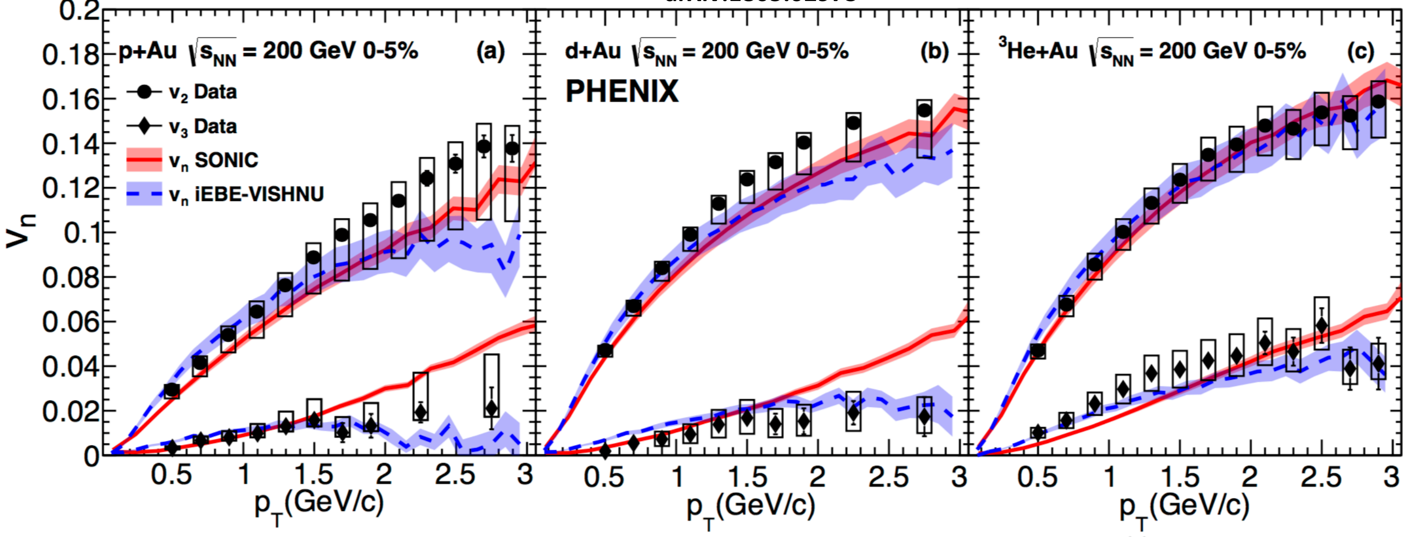
Turning off Collectivity: RHIC ?

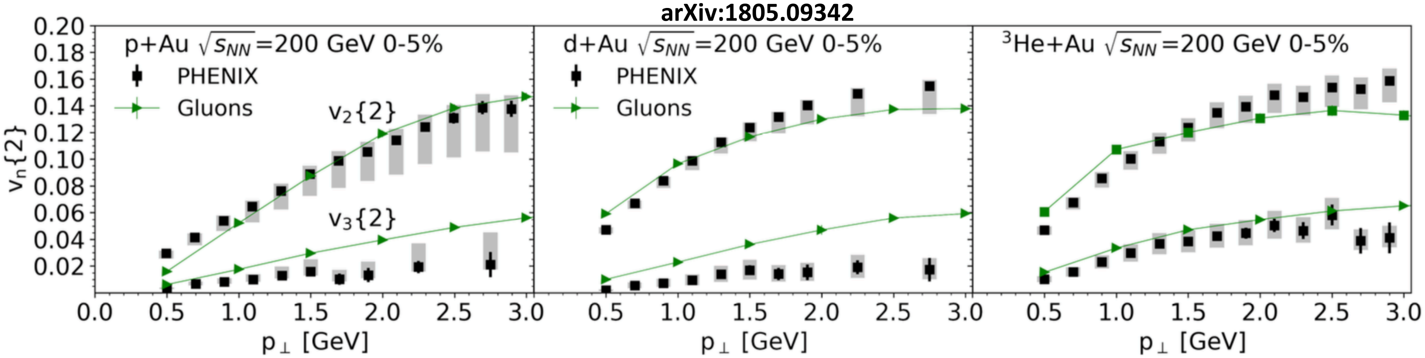
Relativistic Heavy Ion Collider, Brookhaven National Laboratory, New-York, USA
The QGP facility before LHC

arXiv:1805.02973



- PHENIX claim for QGP in small systems …

arXiv:1805.09342



- … also explained by Color Glass Condensate (initial state effects).

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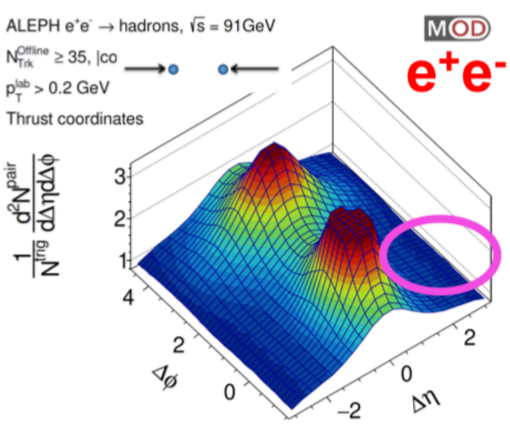
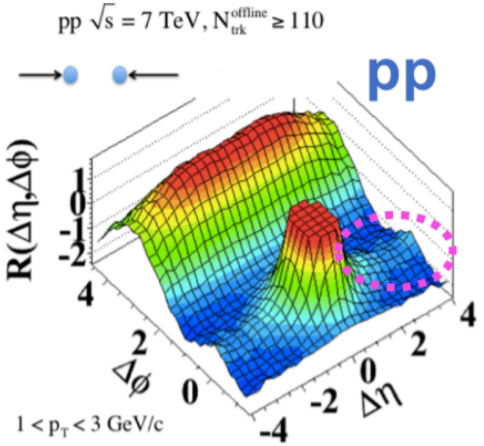
Turning off Collectivity: e^+e^- ?



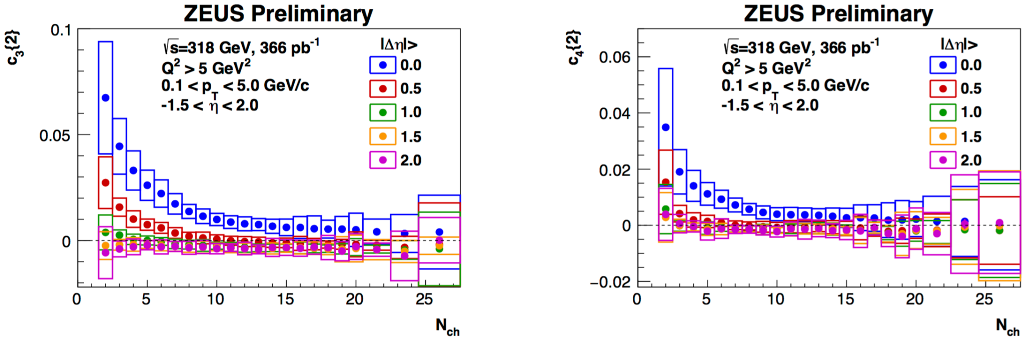
Badea et al., arXiv:1906.00489



CMS, JHEP09 (2010) 091

QM2018, Yen-Jie Lee

- LEP e^+e^- $\sqrt{s}$=91 GeV
- High mult = 55 particles in $|\eta|$<5
- No ridge observed, compatible with PYTHIA



$|\Delta\eta| > 2.0$: $c_3\{2\}$ and $c_4\{2\}$ are consistent with zero.

QM2018, Jacobus Onderwaater

- HERA ep $\sqrt{s}$=318 GeV
- High mult = 35 particles in -1.5<η<2
- No observation of 2-particle correlations, compatible with Ariadne (dipole cascade model) and Lepto (Lund string)

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Beyond the « standard model » of QGP

- Do we observe QGP droplets in small systems (Collectivity ≠ QGP) ?

Hydro requires the Reynolds number R_e >> 1 => small $\frac{\eta}{s}$

- What about hard probes interaction with QGP droplets ?

Energy loss $\propto$ system size => small system = small effect

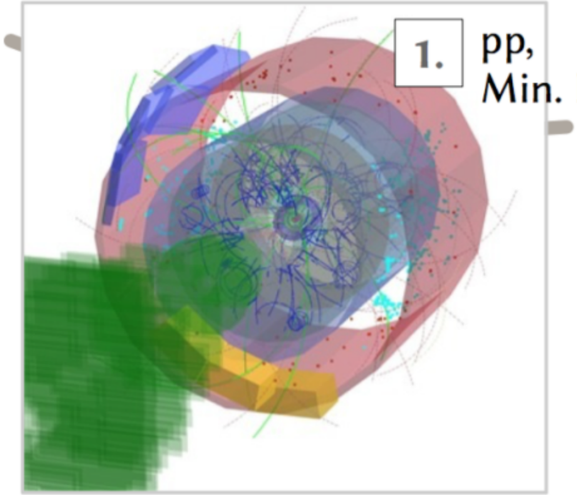
- For small systems, which mechanism in the initial state can allow to reach the energy density needed for a phase transition ?

- Is it the same mechanism for all systems ?

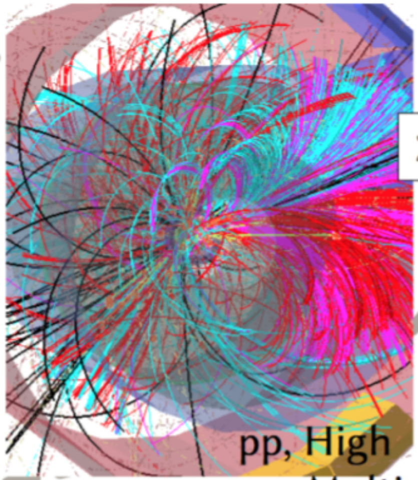
- Can high energy hadronic collisions be described in one single formalism ?
  Nucleon-nucleon vs. parton-parton interactions

Small systems: not a nth QGP probe
But a change of paradigm

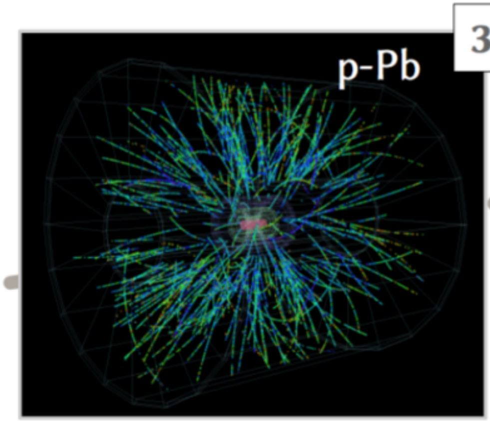
How does collectivity emerge in hadronic collisions ?



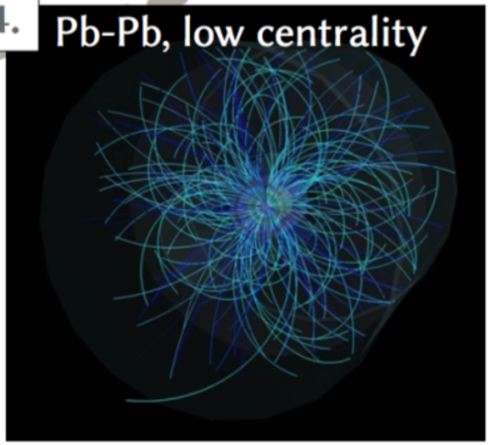
1. pp, Min. Bias



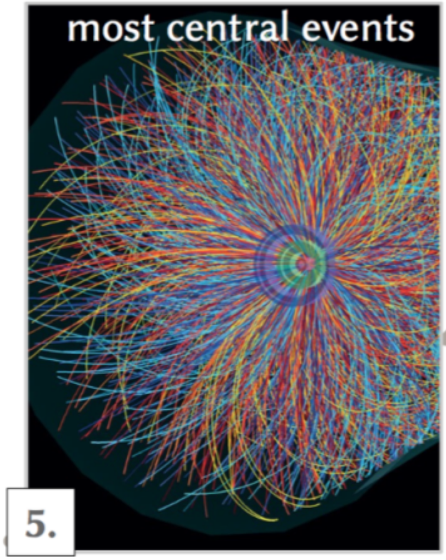
2. pp, High Multiplicity



3. p-Pb



4. Pb-Pb, low centrality



5. Pb-Pb, most central events

CDS/record-1305398

Courtesy of Antonin Maire

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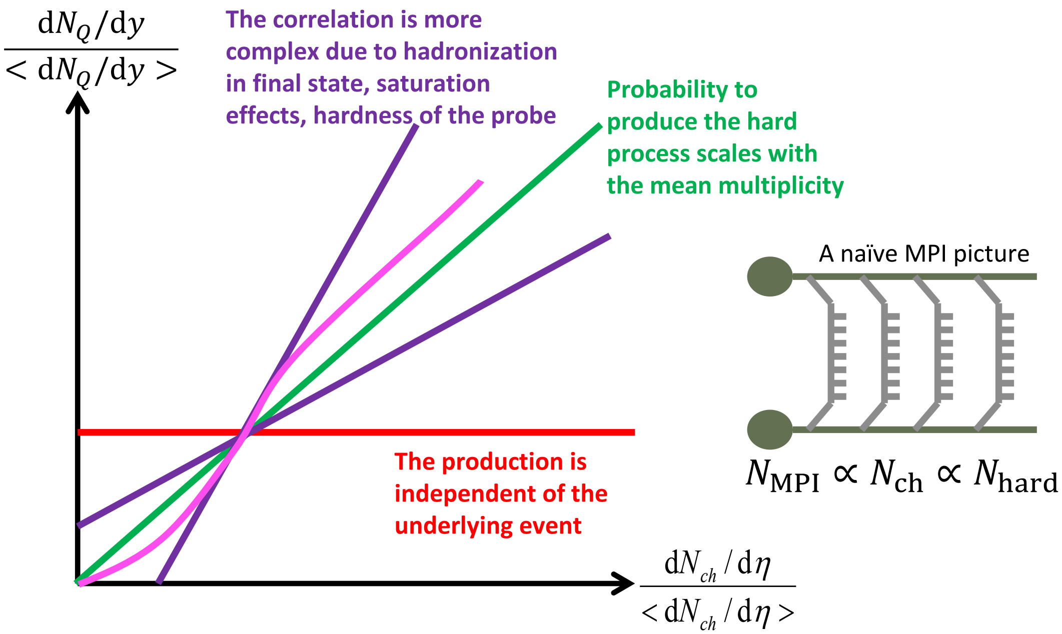
Need new observables !
(a biased selection)

Charm/beauty vs. multiplicty

- **Soft-hard correlations**: measurement of quarkonium and single muon production as a function of the charged-particle multiplicity for various systems and energies (first proposed Nucl.Phys.Proc.Suppl. 214 (2011) 181-184)

- Goal to understand the **initial state** of hadronic collisions, potentially in terms of Multi-Parton Interactions (MPI) and to study the specific regime of **high multiplicity**



The correlation is more complex due to hadronization in final state, saturation effects, hardness of the probe

Probability to produce the hard process scales with the mean multiplicity

The production is independent of the underlying event

A naïve MPI picture

$N_{\mathrm{MPI}} \propto N_{\mathrm{ch}} \propto N_{\mathrm{hard}}$

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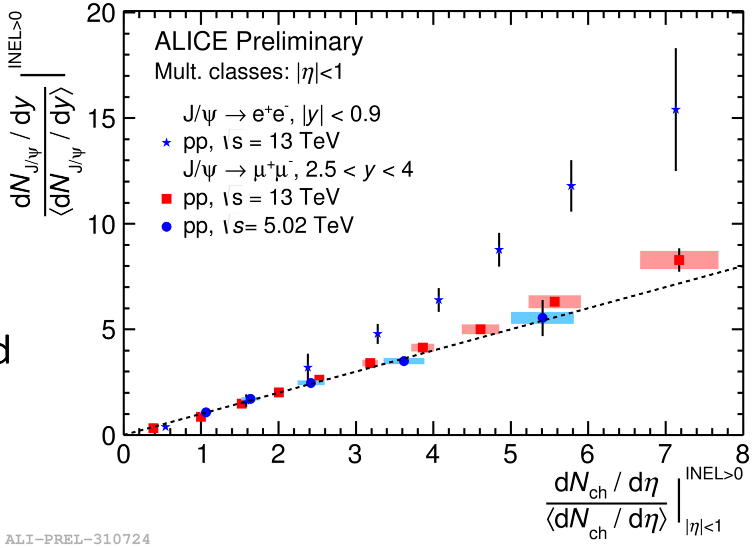

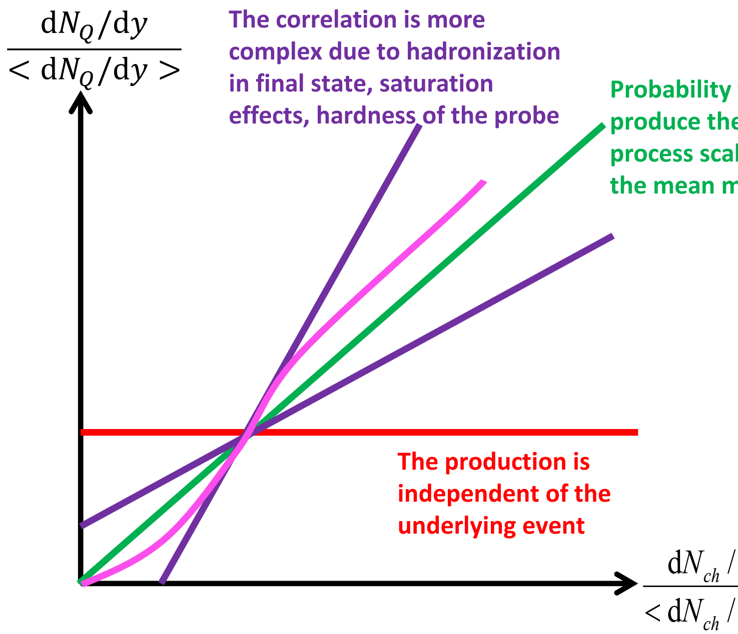

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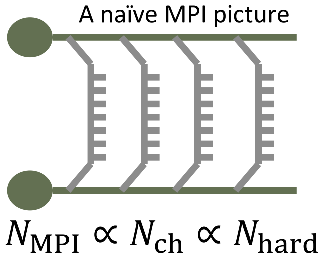

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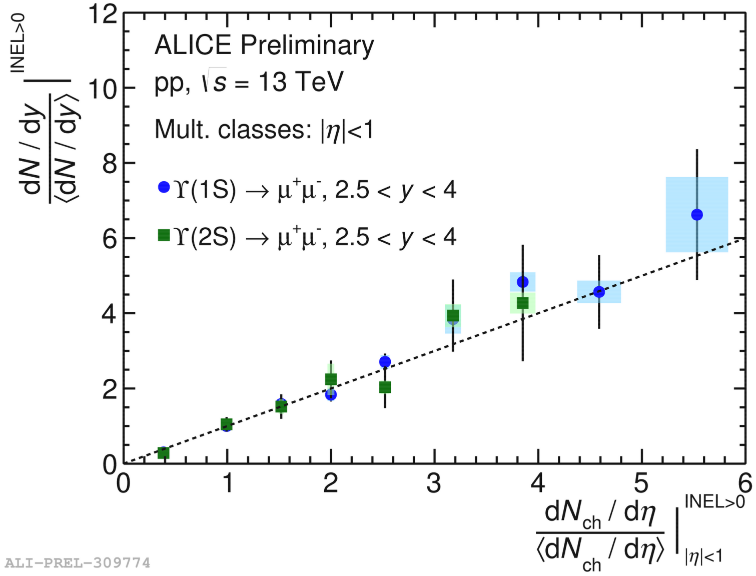
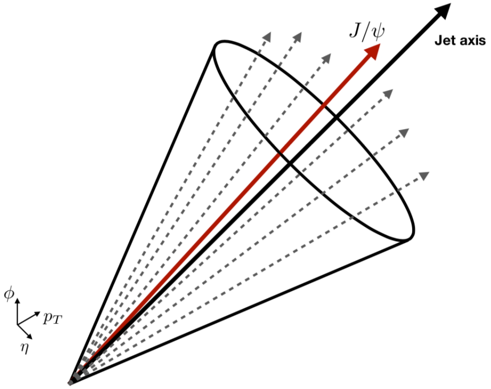
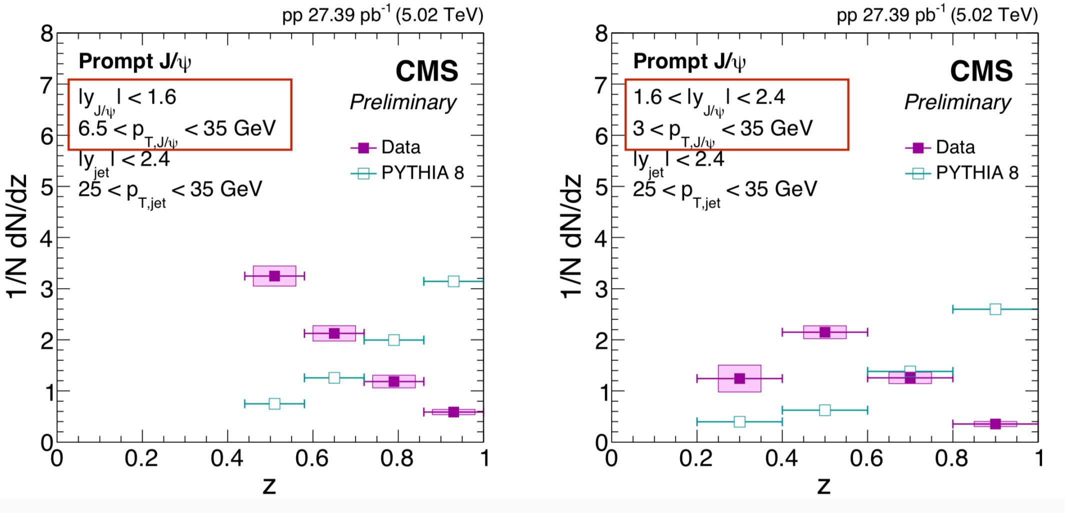


Understanding quarkonium production in dense hadronic environment

- In the quarkonium sector a large fraction of LHC Runs 1+2 results are linked with the associated event activity
- But, quarkonium production are not yet understood and no theoretical knowledge about quarkonium fragmentation function, poor implementation in MC event generators
- **A key measurement is quarkonia in jet**, see workshop *Quarkonia as Tools**
- First measurements from CMS: J/ψ less isolated in data than in PYTHIA 8





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*https://indico.cern.ch/event/745939/

Looking for the proper scaling quantity

- To go **beyond the Glauber model** for heavy-ion and avoiding normalizing by N_{coll}

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Looking for the proper scaling quantity

- To go **beyond the Glauber model** for heavy-ion and avoiding normalizing by N_{coll}
- To have a quantity **system and energy independent**

Looking for the proper scaling quantity

- To go **beyond the Glauber model** for heavy-ion and avoiding normalizing by N_{coll}
- To have a quantity **system and energy independent**
- **What is the best system size estimator?**
  - Multiplicity is the measured quantity (caveats: experimental estimator has to be well defined)
  - Multiplicity is protected from theoretical biases (N_{part}, N_{coll} from Glauber models ...)
  - But hard to compare to formal calculation and first principle

Bjorken estimates

$$\varepsilon \sim \frac{n\pi}{\tau_0 A}\frac{3}{2}\frac{dN_{\mathrm{ch}}}{d\eta}\bigg|_{\eta=0}$$

Multiplicity per volume unit

$$\frac{N_{\mathrm{ch}}}{\pi R^3}$$

Problem of the definition of the normalization size in pp and p-Pb (*A* or *R* or ?)

Conclusions

- The **Quark-Gluon Plasma** is a deconfined state of matter studied in high energy heavy ion collisions

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Conclusions

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- The **LHC** is the most powerful particle accelerator colliding pp at 14 TeV and Pb-Pb at 5.02 TeV. 4 main experiments (ALICE, ATLAS, CMS and LHCb) collecting and analyzing data.

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- **A heavy-ion LHC discovery: small system physics**
  - QGP signatures are observed for soft probes in high multiplicity sector of reference systems pp and p-A => unexpected!
  - Is a quark-gluon plasma produced in proton-proton collisions at the LHC?
    Not yet possible to answer to the (provocative) question
    A better formulation: **How does collectivity emerge in hadronic collision ?**
  - Need already to understand the initial state of hadronic collisions and how the multiplicity is built up to the very high multiplicity sector (pp vs. p-A vs. A-A)
  - New observables: examples of soft-hard correlations and hadronic activity

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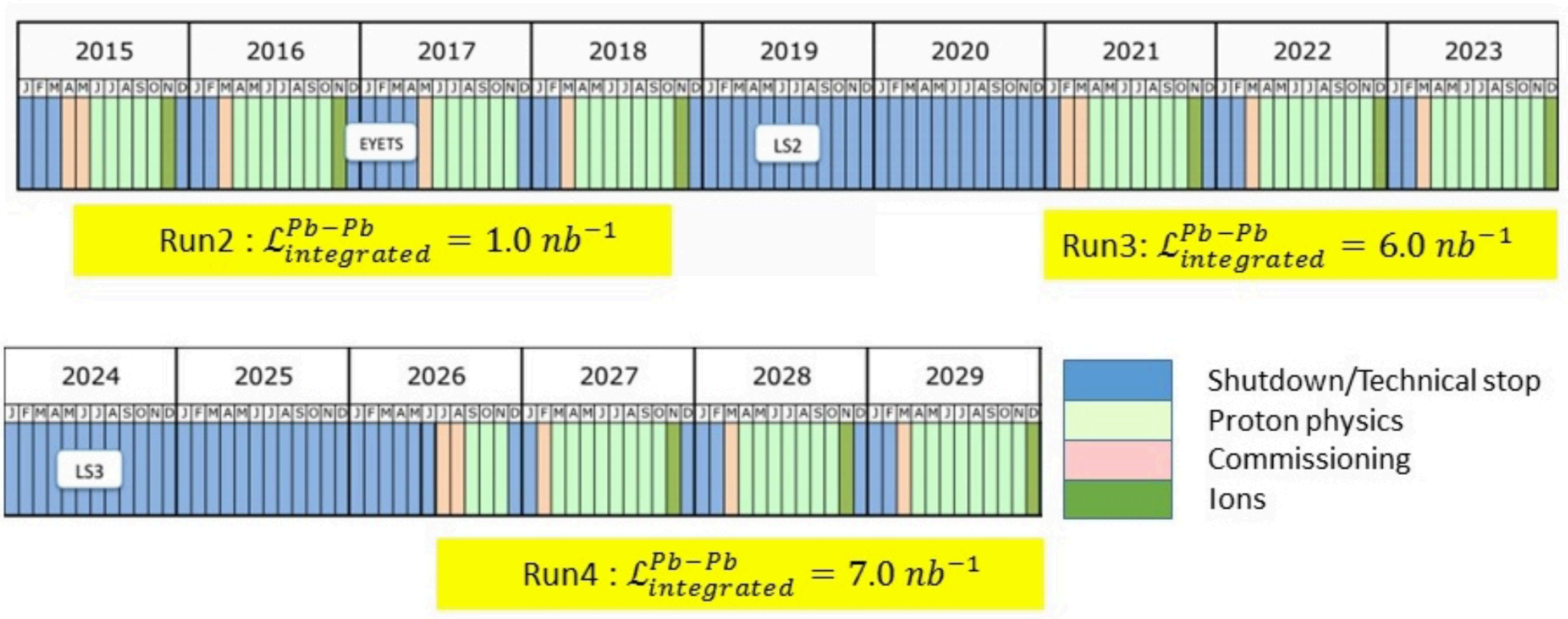
What's next ?

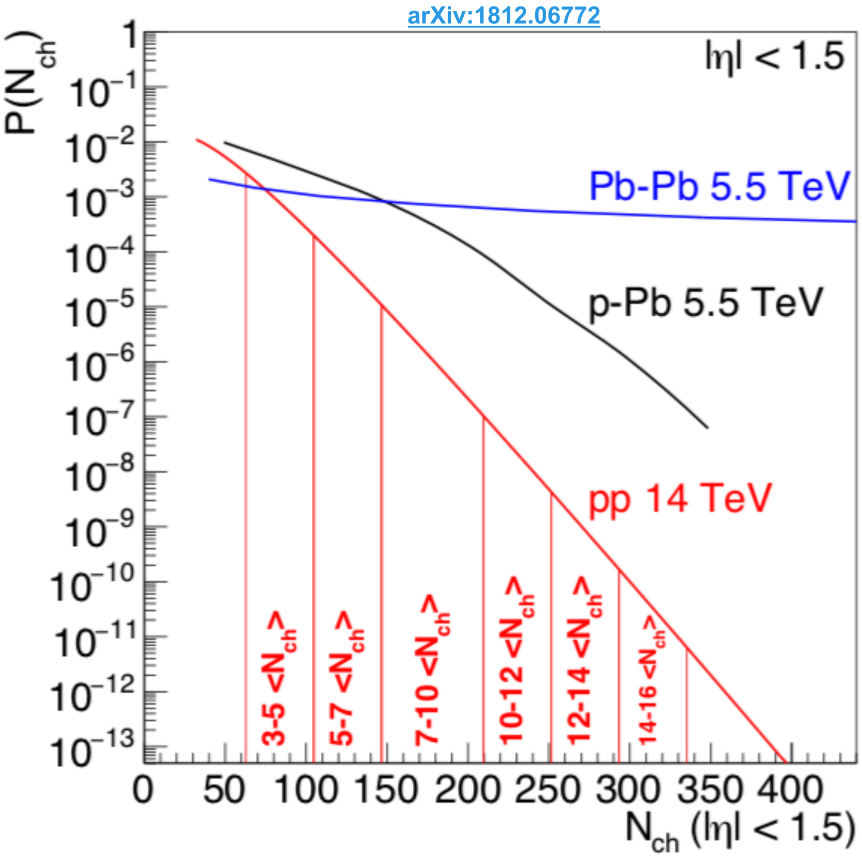
LHC at Runs 3+4



- **LHC luminosity increase**
- **ALICE will run at 50 kHz in Pb-Pb** (i.e. $\mathcal{L} = 6\times10^{27}$ cm^{-1} s^{-1}) with minimum bias (pipeline) readout (maximum readout with present ALICE set-up: ≈ 0.5 kHz)
- **Expected for Pb-Pb:** $\mathcal{L}_{\text{int}} > 10$ nb^{-1}
  (ALICE LoI: 10 nb^{-1} with nominal solenoidal field + 3 nb^{-1} with reduced solenoidal field)
  - ×100 larger min. bias sample for ALICE w.r.t. Run 2 (x10 from integrated luminosity and x10 from readout)
  - ×10 larger rare trigger sample w.r.t. Run 2
- **pp reference, p-A.**

LHC at Runs 3+4

- Increase in energy, pp to 14 TeV, important for high multiplicity in small systems
- Increase in luminosity, also important for high multiplicity in small systems
- Detector upgrades
- Run 3+4 running conditions are favorable for small systems studies in high multiplicity environment (statistics hungry)
- Many new measurements will become accessible



Many new ideas popping up!

Thanks!

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Usual units & constants in subatomic physics

Angström	$1Å = 10^{-10}$ m	(typical size of an atom)
Fermi	$1F = 10^{-15}$ m	(typical size of the proton)
Barn	$1b = 10^{-28}$ m2 = $(10^{-4}\ Å)^2 = (10F)^2$	(cross section often expressed in mb)
Electron-Volt	1 eV=$1{,}602.10^{-19}$ J	(energy expressed in eV)

Planck constant $h = 6{,}626.10^{-34}$ Js

$\hbar = h/2\pi = 1{,}054.10^{-34}$ Js

Speed of light (in vacuum) $c = 2{,}997.10^{8}$ m/s

Electron charge $q = -1{,}6.10^{-19}$ C

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Natural Units

ħ and c appear in many formulas
It is convenient to define the "natural units" where $\hbar = c = 1$

Thus mass (m), momentum (mc) and energy (mc^2) can all be expressed in term of GeV
Length ($\hbar$/mc) and time ($\hbar/mc^2$) in term of GeV^{-1}

Conversion factor	**Natural units ($\hbar=c=1$)**	**Actual dimension**
1 kg = $5{,}61.10^{26}$ GeV	GeV	GeV/c^2
1 m = $5{,}07.10^{15}$ GeV^{-1}	GeV^{-1}	ħc/GeV
1 s = $1{,}52.10^{24}$ GeV^{-1}	GeV^{-1}	ħ/GeV

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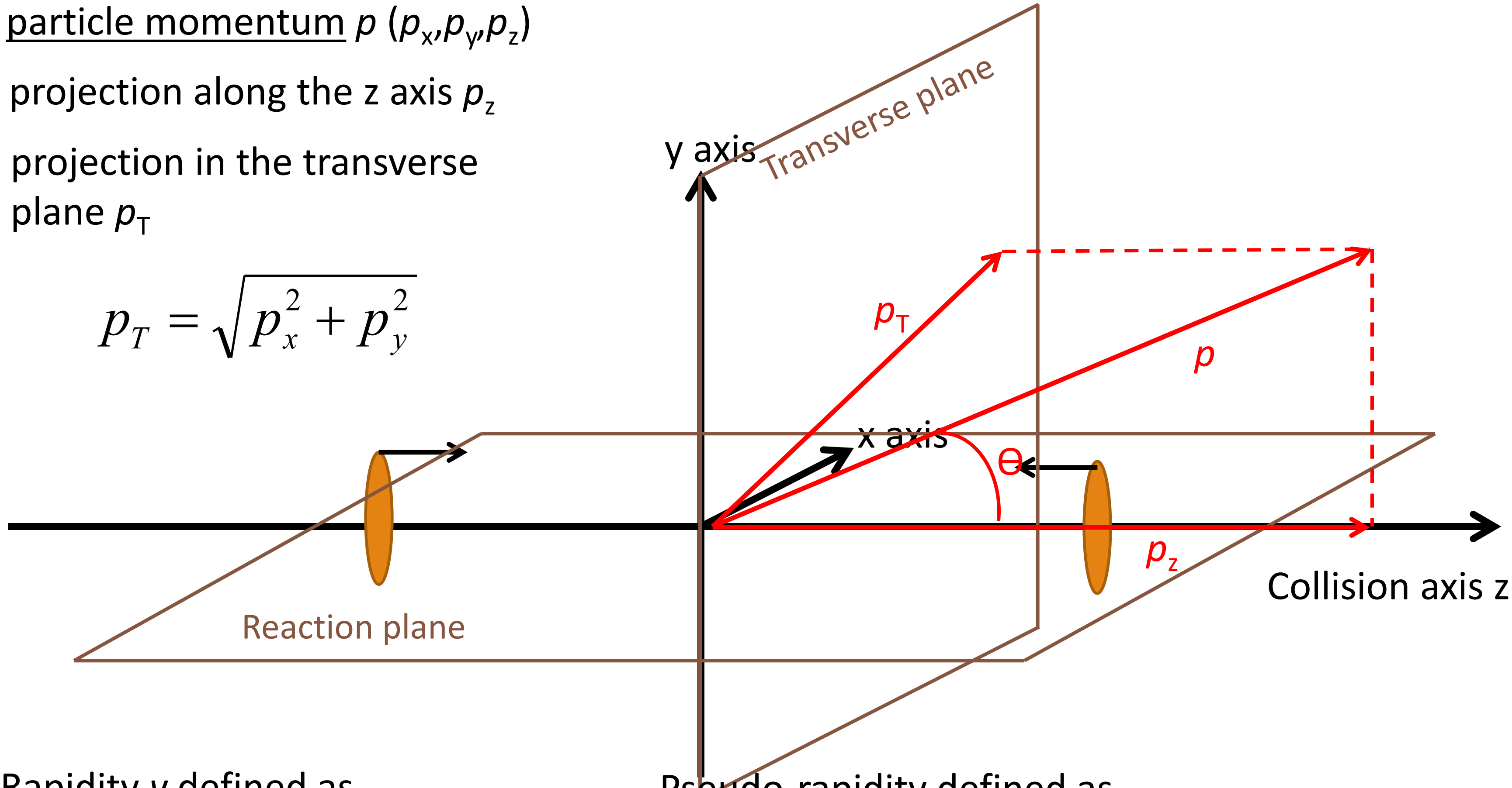
Kinematic variables

particle momentum p (p_x, p_y, p_z)

projection along the z axis p_z

projection in the transverse plane p_T

$$p_T = \sqrt{p_x^2 + p_y^2}$$



Rapidity y defined as

$$y = \frac{1}{2}\ln\left[\frac{E+p_z}{E-p_z}\right] = \frac{1}{2}\ln\left[\frac{1+v}{1-v}\right]$$

Pseudo-rapidity defined as

$$\eta = \frac{1}{2}\ln\left[\frac{|p|+p_z}{|p|-p_z}\right] = -\ln(\tan(\frac{\vartheta}{2}))$$

$\eta \sim y$ pour $p >> m$

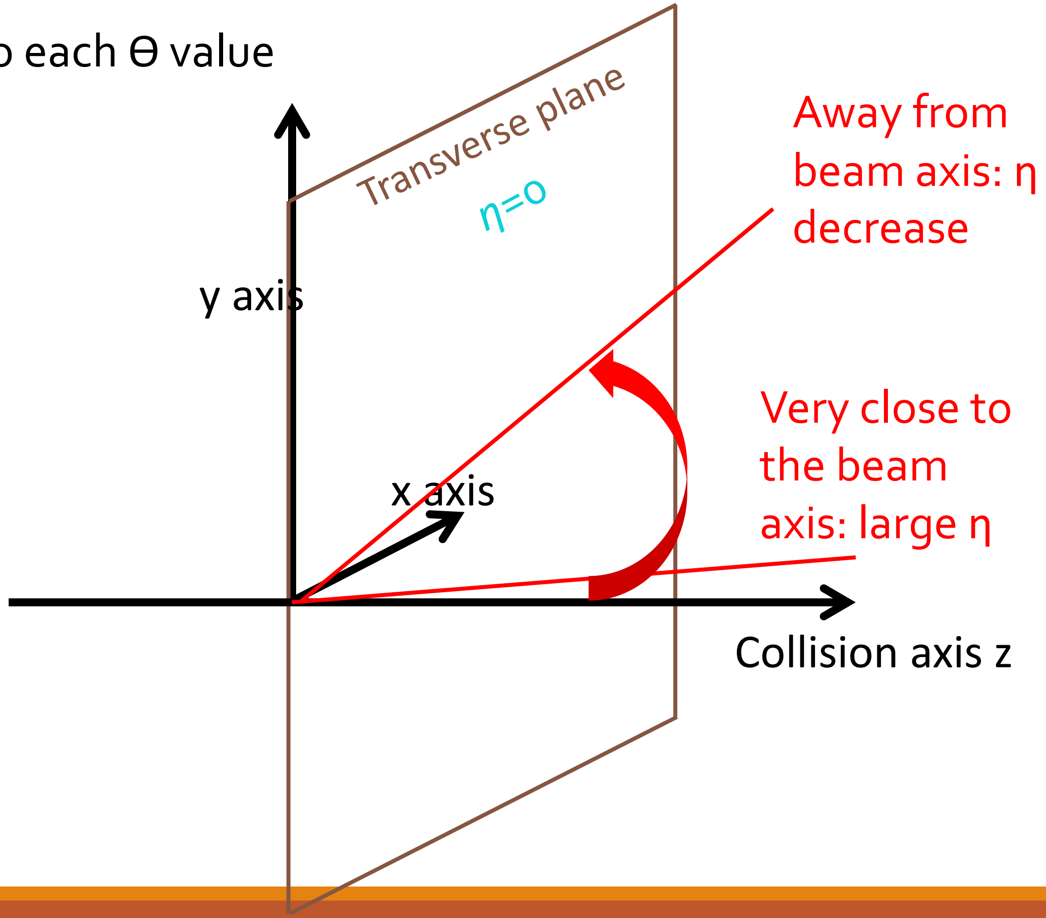
Kinematic variables

In experiment the measured quantity is commonly Ө which gives access to η

$$\eta = -\ln(\tan(\frac{\vartheta}{2}))$$

Compute η value corresponding to each Ө value

θ	η~y
2°	4
5°	3,13
10°	2,4
25°	1,5
45°	0,88
60°	0,55
90°	0



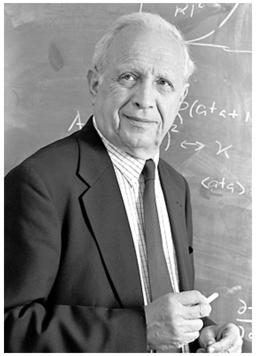
Away from beam axis: η decrease

Very close to the beam axis: large η

Glauber Model

Describe multiple nucleons scatterings based on a geometrical picture

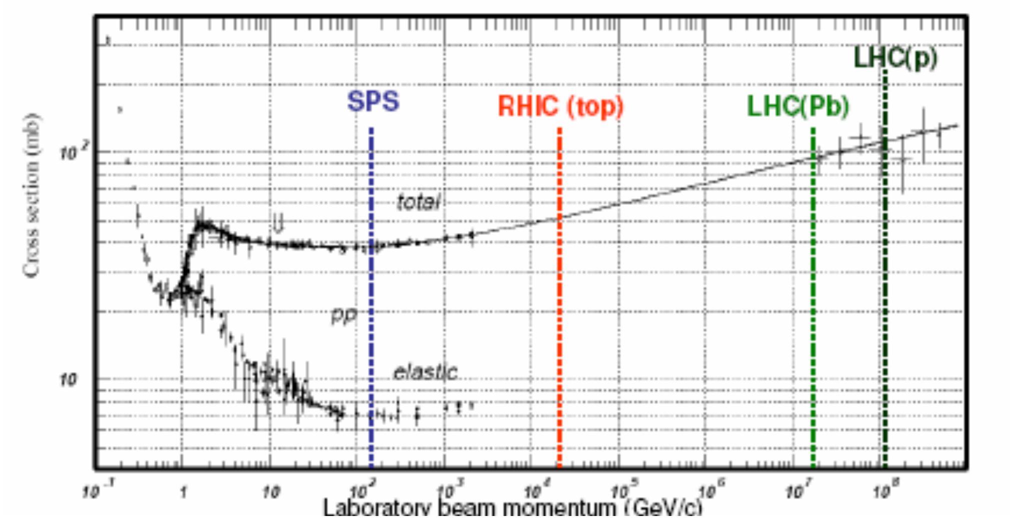
Evaluate N_{part}, N_{coll} and N_{spec} and connect it to b and the multiplicity



Nobel prize 2005

Main assumptions and inputs:

- ✓ Nucleons travel on straight lines, no deflection after NN collisions
- ✓ NN cross section remains constant independent of the number of collisions a nucleon suffered
- ✓ NN cross section from measured inelastic cross section in pp (experimental data input)



√s (GeV)	σ_{in}^{pp} (mb)
20	32
200	42
2700	~64

Particle Data Book: W.-M. Yao et al., J. Phys. G 33,1 (2006) Fig 40.11

Glauber Model

Main assumptions and inputs:

✓ Nucleon density parameterized by a Fermi distribution

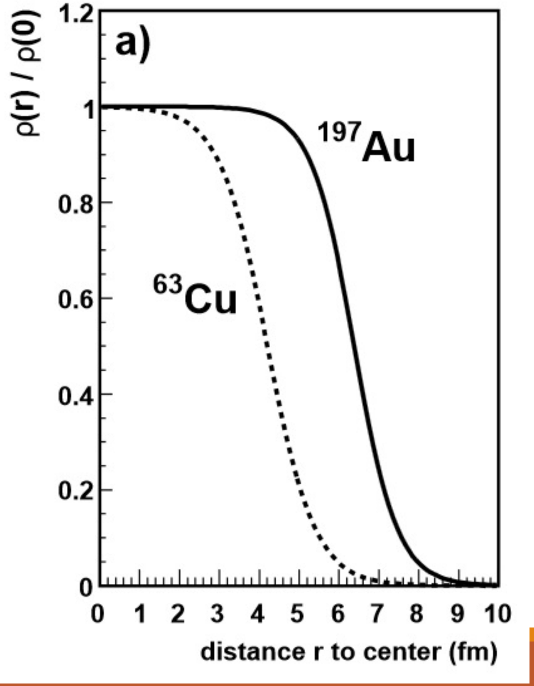
$$\rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp(\frac{r-R}{a})}$$

ρ_0: nucleon density in the center of the nucleus

R: nuclear radius (R~1,3$A^{1/3}$(fm))

a: “skin depth”

w: deviation from spherical shape



arXiv:nucl-ex/0701025v1

Nucleus	A	R (fm)	a (fm)	w
Cu	63	4,20641	0,5977	0
Au	197	6,38	0,535	0
Pb	208	6,68	0,546	

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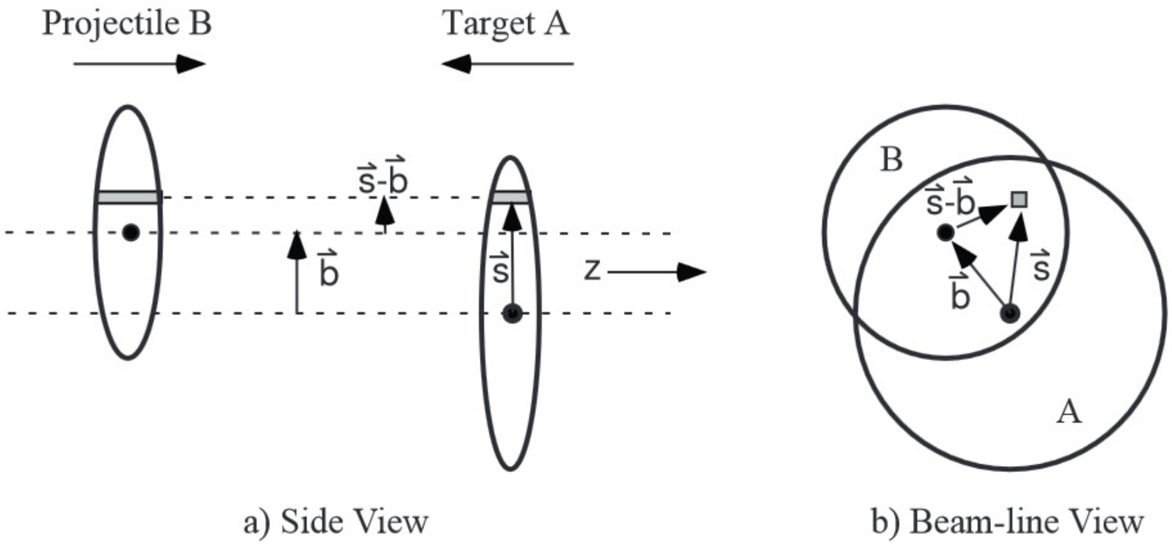
Glauber Model



arXiv:nucl-ex/0701025v1

- The probability per unit transverse area of a given nucleon being located in the target flux tube:

$$T_A(\vec{s}) = \int \rho_A(\vec{s}, z_A) dz_A$$

$\rho_{A:}$ proba per unit volume, normalized to 1, for finding nucleons at location (s,z_a)

- Nuclear overlap function (or thickness function)

$$T_{AB}(\vec{b}) = \int T_A(\vec{s}).T_B(\vec{s} - \vec{b}) d^2 s$$

Integrand: joint proba per unit area of nucleons being located in the respective overlapping target and projectile flux tube of differential area d^2s

Glauber Model

Based on probability considerations, one can derive

- ✓ The total number of nucleon-nucleon collisions (N_{coll})

$$N_{coll}(b) = \sum_{n=1}^{A.B} nP(n,b) = A.B.T_{AB}(b)\sigma_{inel}^{NN}$$

- ✓ The number of participants N_{part}:

$$N_{part}(\vec{b}) = A\int T_A(\vec{s})\left[1-\left(1-\sigma_{inel}^{NN}T_B(\vec{s}-\vec{b})\right)^B\right]d^2s$$
$$+B\int T_B(\vec{s}-\vec{b})\left[1-\left(1-\sigma_{inel}^{NN}T_A(\vec{s})\right)^A\right]d^2s$$

- ✓ The number of spectators N_{spec}

$$N_{spec}(\vec{b}) = 2A - N_{part}(\vec{b})$$

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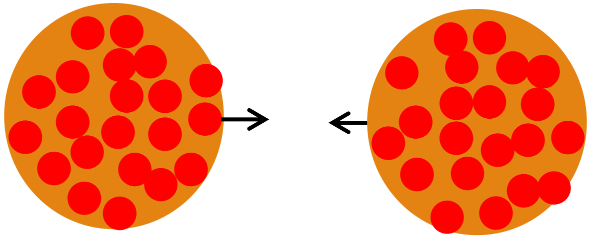
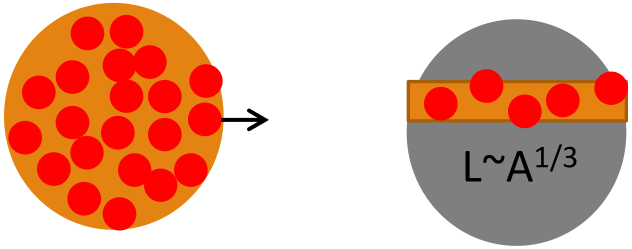
Glauber Model

- Participant nucleon scaling

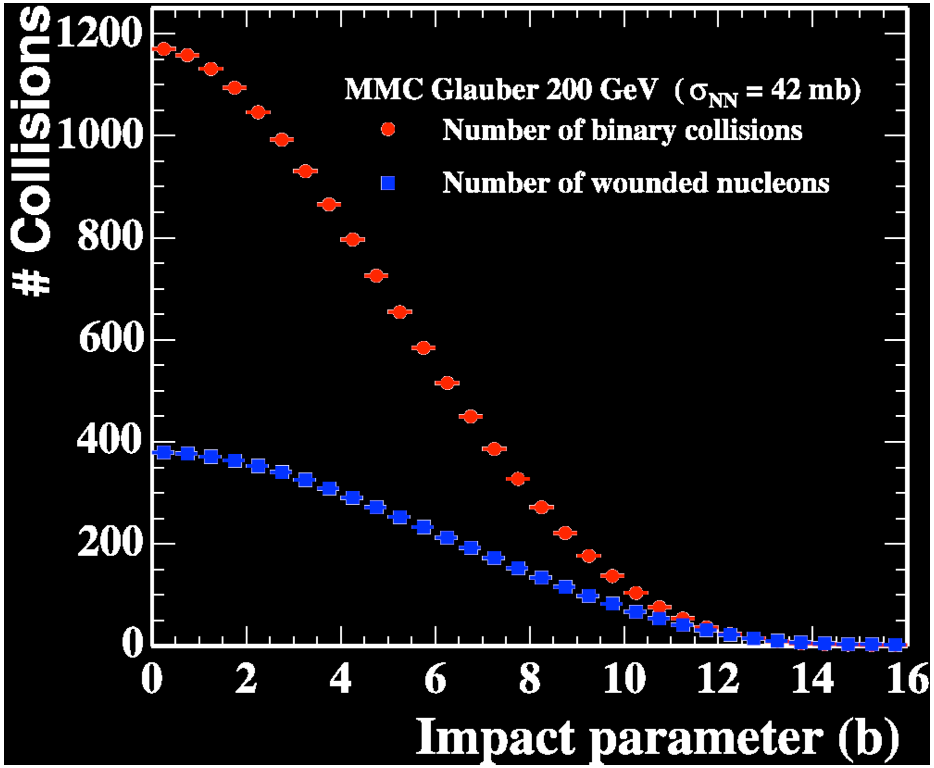


number of participating nucleons scales with volume ~2A

- Binary scaling



number of NN collisions, point like, scales with ~$A^{4/3}$



Courtesy of Raimond Snellings

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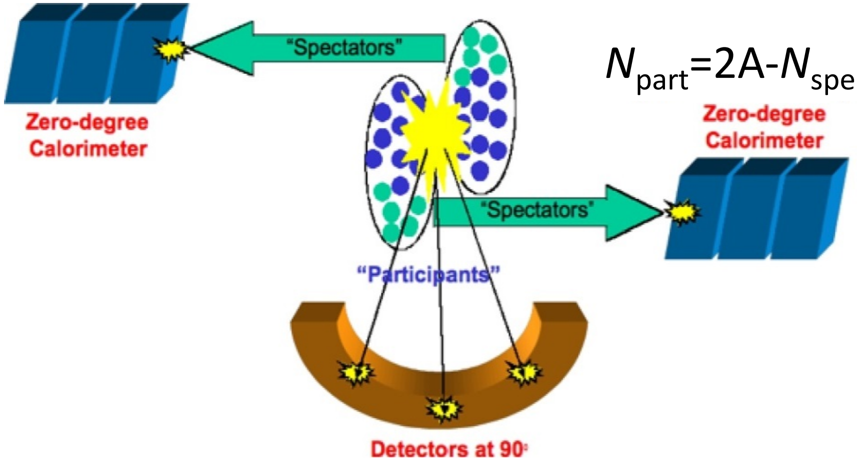
Centrality Determination

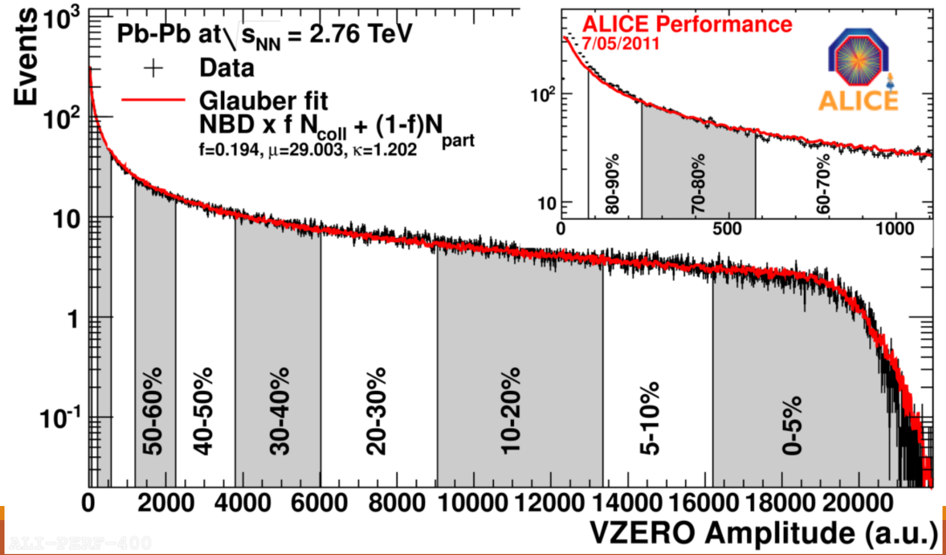


N_{part}=2A-N_{spec}

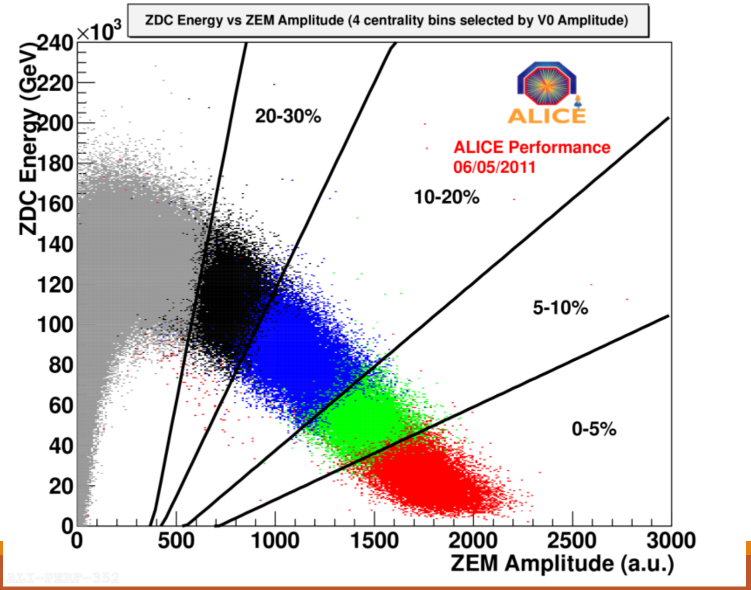
Collision centrality determine the number of participating nucleons and the remaining spectators.

- ZDCs (~116m from IP) measure spectator nucleons
- V0, SPD, TPC are sensitive to participating nucleon

"Fit" multiplicity distributions with a Glauber MC
(V0 amplitude, SPD clusters, TPC tracks)



Energy deposit on the ZDCs and ZEMs



Bjorken Estimate of the initial energy density ε

The formation (or not) of a Quark-Gluon Plasma phase depends on the initial energy density *ε*

In 1983, Bjorken propose an estimate based on measured charged particles

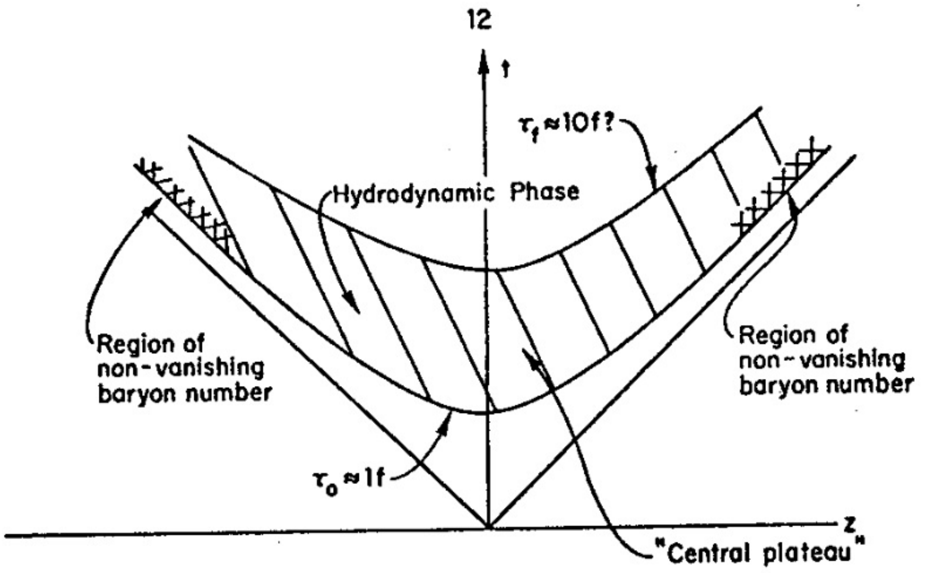
➢ The space-time picture of nucleus-nucleus collisions

1) Soon after the collision of the 2 nuclei, the energy density in the central rapidity region may be high enough to produce a QGP

2) The plasma initially may not be in thermal equilibrium, but subsequent equilibration bring it to local equilibrium at proper time τ_0

3) The plasma evolves then accordingly to hydrodynamics

Phys.Rev. D27 (1983) 140-151



Bjorken Estimate of the initial energy density ε

- Estimation of the initial energy density, before hydro evolution
  via energy deposit in the collision region and the relevant volume

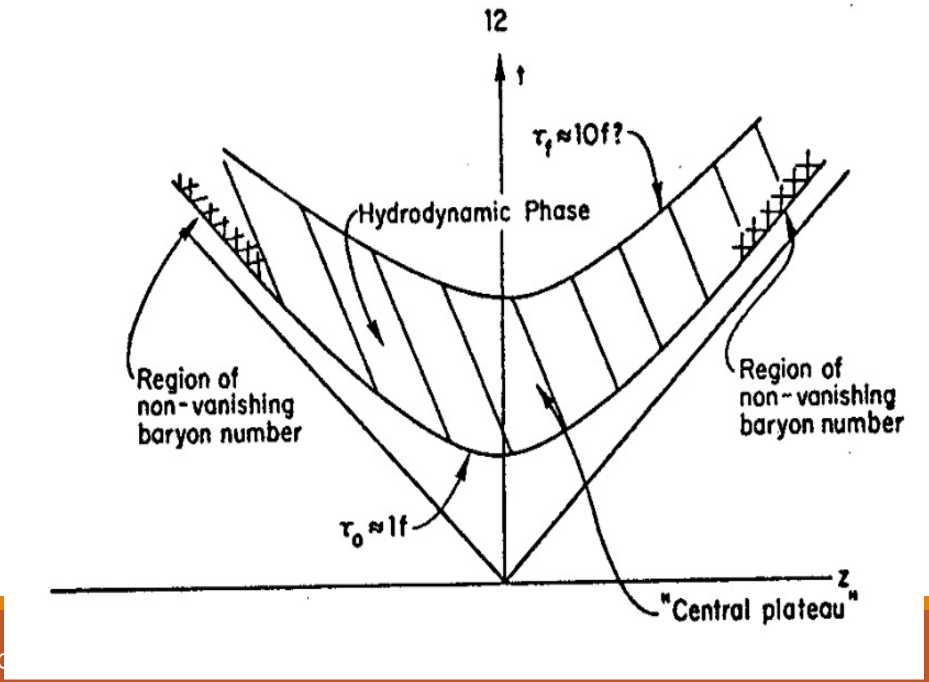
- Energy deposit in the collision region (z=o, $\tau=\tau_o$) linked to produced hadrons from this region

Phys.Rev. D27 (1983) 140-151

- Central rapidity region (y=0, “central plateau”) associated with the central spatial region (z=0)

→

Particles produced around y=o can be directly linked to ε



Bjorken Estimate of the initial energy density ε

$$\varepsilon = \frac{m_T}{\tau_0 A}\frac{dN}{dy}\bigg|_{y=0} \approx \frac{m_T}{\tau_0 A}\frac{3}{2}\frac{dN_{ch}}{d\eta}\bigg|_{\eta=0}$$

m_T: transverse mass of produced particles

$$m_T = (m^2 + p_T^2)^{1/2}$$

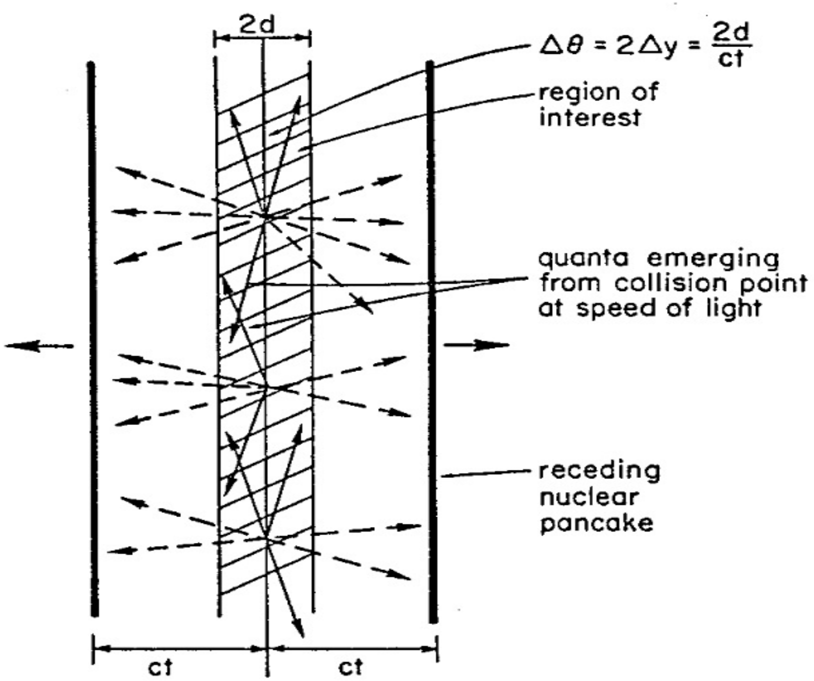
A: transverse overlapping area of the 2 nuclei

$$A = \pi R^2 \qquad A = \pi(1.2)^2 \mathrm{A}^{2/3}$$

With *R* from HBT measurement

τ_0: local equilibrium proper time, estimated to be ~1fm/*c* by Bjorken, still debated

N_{ch} : number of charged particles

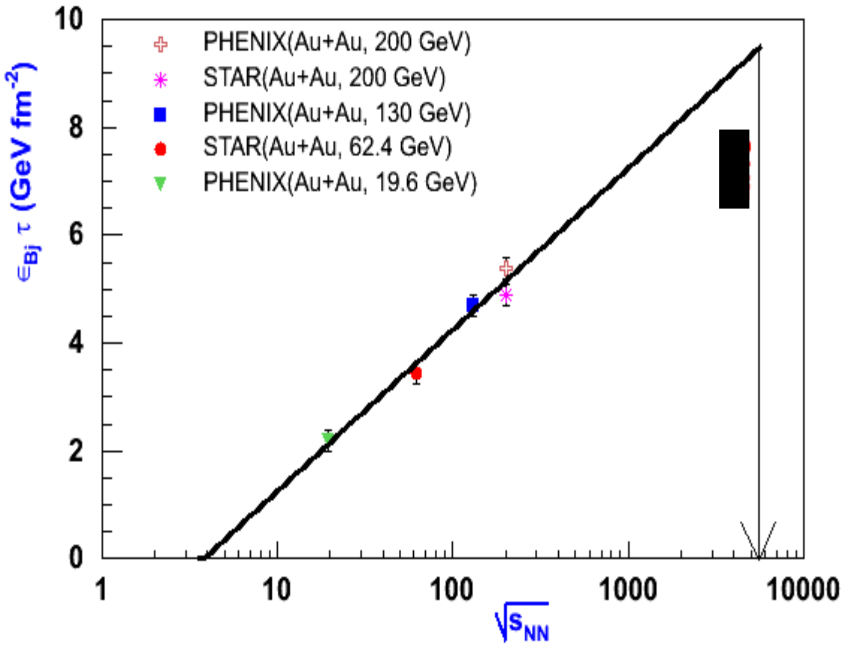


Phys.Rev. D27 (1983) 140-151

Bjorken Estimate of the initial energy density ε @ RHIC

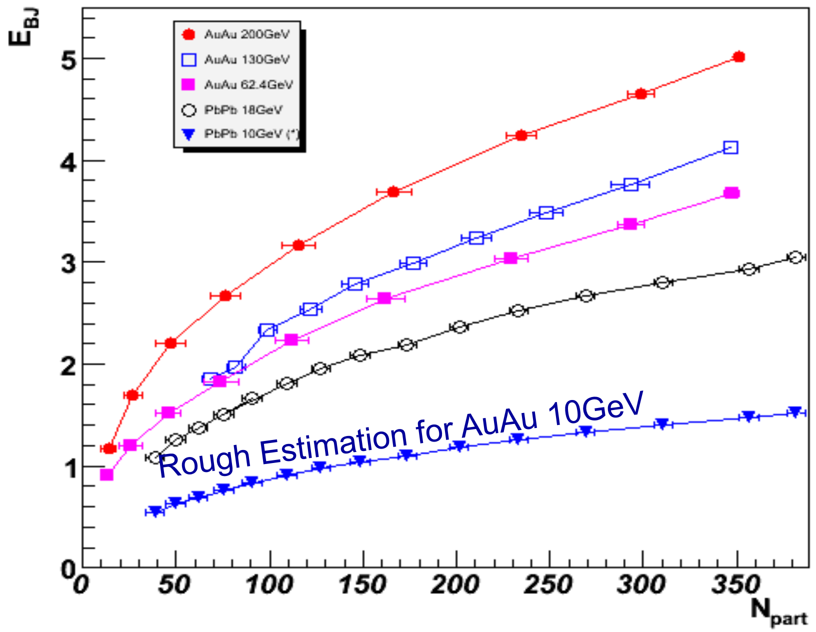
Plots from Tapan Nayak – ICHIC-Goa School

Bjorken energy density vs. collision energy



[redacted]

Bjorken energy density vs. centralities



From LQCD transition to a QGP occurs at a few GeV/fm^3

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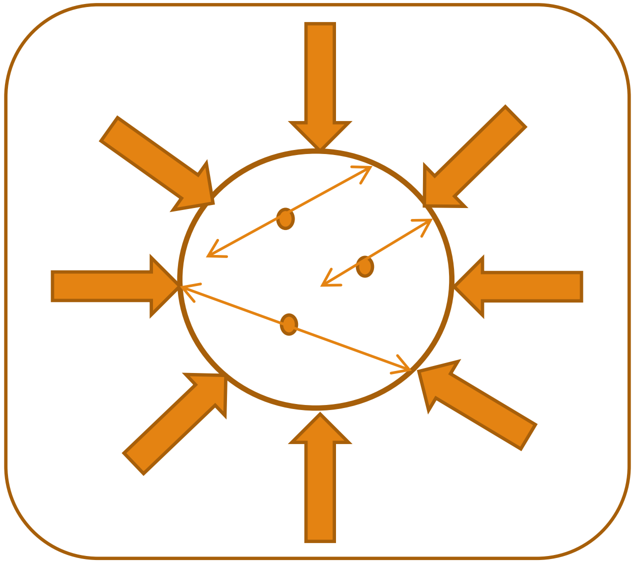
Description of quarks in hadrons: the (MIT) bag model

Quarks = massless particles inside a bag of finite dimension and infinitely massive outside the bag

Confinement is the result of the balance between:

- The bag pressure *B* (inward)
- Stress arising from kinetic energy of the quarks *P*



P<*B*: confinement (hadrons)

P>*B*: deconfinement, the bag cannot holds quarks anymore

P=*B*: Phase transition

P can increase if we heat matter or compress it

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Ideal Gas equation of state

(to describe quarks inside the bag)

pressure

$$P = \frac{1}{3}\varepsilon = g\frac{\pi^2}{90}T^4$$

temperature

energy density

g massless degree of freedom

- ➢ Hadronic matter is dominated by lightest mesons (π^+, π^-, π^o) g= 3
- ➢ In deconfined matter, degrees of freedom are quarks and gluons g= 37

$$g = 2_{\text{spin}} \text{ x } 8_{\text{gluons}} + 7/8 \text{ x } 2_{\text{flavors}} \text{ x } 2_{\text{quark/antiquark}} \text{ x } 2_{\text{spin}} \text{ x } 3_{\text{color}}$$

During phase transition large increase in degrees of freedom!

Rough estimate of QCD phase transition temperature

From ideal gaz EOS $$T = (\frac{90P}{g\pi^2})^{1/4}$$

At the transition T=T_c and P=B $$T_c = (\frac{90B}{g\pi^2})^{1/4}$$

The computation of Dirac equation for massless fermions in a spherical cavity of Radius R=0,8fm gives $B^{1/4}$~200 MeV (in literature 145 MeV < $B^{1/4}$ < 235 MeV)

T_c~ 140 MeV ! Very crude estimate

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Nuclear matter phase diagram 1975

N. Cabibbo and G. Parisi: Phys. Lett. 59B (1975)

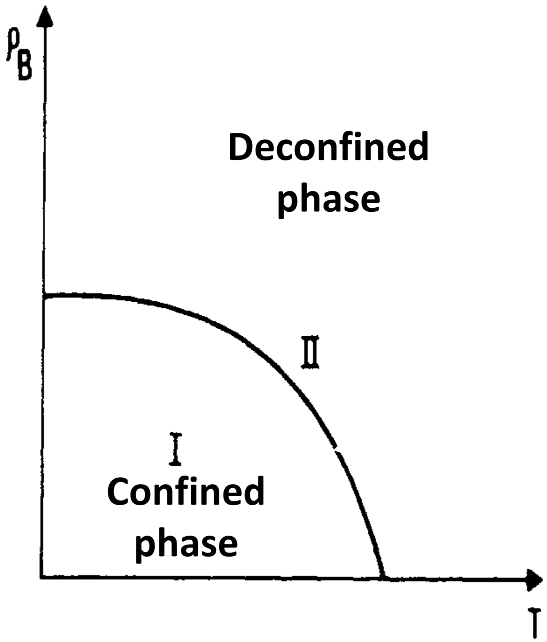

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Phase transition

Quark-Gluon Plasma

- Is the measurement the consequence of the evolution of a hydrodynamic fluid?
- Warning: hydro application do not necessarily imply QGP
- Hydro requires $R_e >> 1$ => small $\frac{\eta}{s}$, with R_e the Reynolds number:

$$R_e = \frac{\mathrm{R}v}{\nu} = \frac{\mathrm{R}v}{\eta/\rho} = \frac{\mathrm{R}vT}{\eta/s}$$

R: characteristic spatial dimension
v: characteristic velocity
$\nu = \frac{\eta}{\rho}$: kinematic velocity
η: shear viscosity
s: entropy density

- Small η/s (<0.2) is a feature of observed QGP