Relativistic Heavy-Ion Collisions: Experimental Overview:I

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Plan of the lectures

Lecture-1 & 2
Introduction to the basic terminologies and ideas in HIC with a brief discussion on kinematics

Lecture- 3 &4
Some selected probes of QGP (transverse spectra, flow,em probes, heavy-flavor & quarkonia)

Introduction

Our aim:

To study physics of ultra-relativistic heavy-ion collisions (URHIC)

Interdisciplinary field:

High energy physics of elementary particles + nuclear physics

Heavy-Ion:

Heavy atomic nuclei (eg: Pb/Au)
In LNP, heavy indicates $Z > 2$ (α-particle)

Ultra-relativistic:

K.E (T) >> rest mass energy (mc^2)

High energy particle physics deals with single particles (eg: leptons, quarks, hadrons)

Derive the underlying interaction, spectroscopy

Nuclear Physics deals with extended complicated objects (nuclei)

Interaction described by effective models

In URHIC one tries to
analyse the properties of the hot and dense produced matter in terms of elementary interactions
search (experimentally) theoretically predicted new phases of nuclear matter
identification of phase transitions between the phases and a possible reconstruction of the QCD phase in terms of thermodynamic parameters temperature and baryon chemical potential

The Big Idea

Quantum Chromodynamics (QCD): theory of strong interaction

QCD exhibits a rich phase structure (non-perturbative)

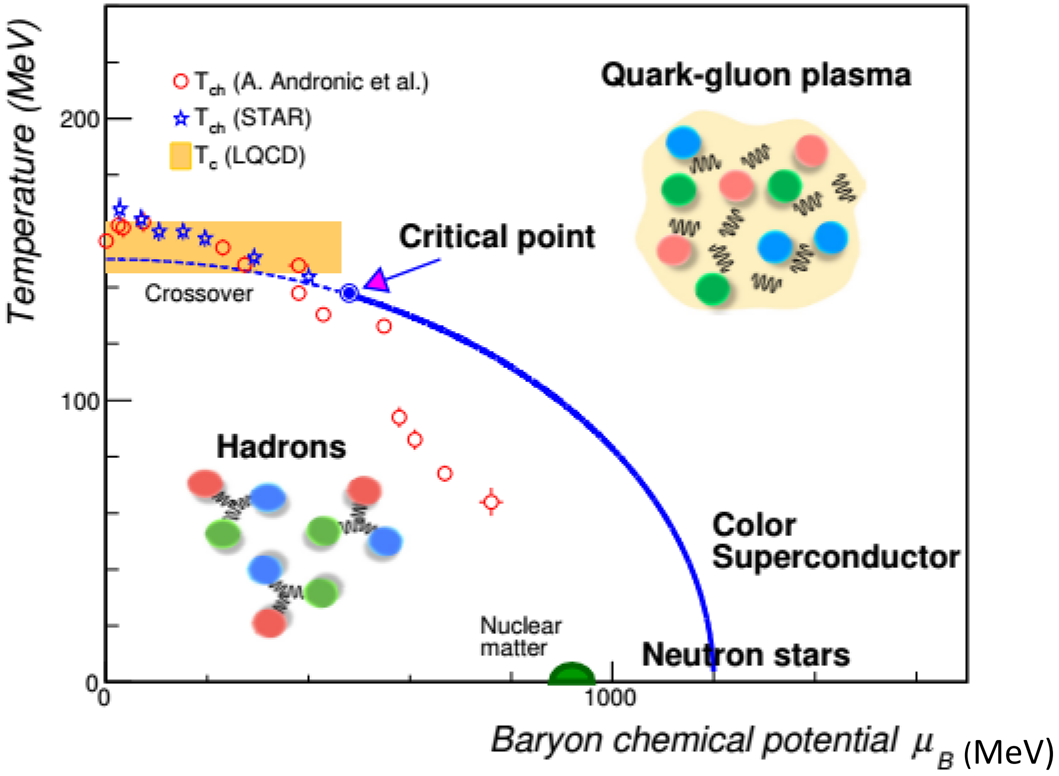
(Ultra)-relativistic heavy-ion collisions: creates QCD matter at extreme temperature and densities in the laboratory

Vary collision energy/colliding species: create hot and dense nuclear matter over wide range of temperature and densities: access different phases of nuclear matter

The experimental tool to map out the QCD phase diagram in the laboratory

QCD phase diagram

arXiv:2104.11406



Question(s):

Why is QCD phase diagram often plotted in terms of (T,μ_B) ?

Why normal nuclear matter has μ_B ~ 1 GeV?

Count the dof of a pion gas and a 2 flavor (u,d) quark-gluon gas

Thermodynamic properties of macroscopic matter most readily expressed via phase diagram

Graphical representation of different phases occupying different regions of a plot whose axes calibrated in terms of external/control parameters

Each point in the diagram corresponds to stable thermodynamic phase

Nuclear matter governed by strong interaction: believed to have a rich phase structure, often expressed in terms of (T,μ_B)

Low (T,μ_B): confined phase: hadronic dof (small)
High (T,μ_B): de-confined phase: quark & gluon dof (large)

Two underlying transition:
Deconfinemmet transition (Centre symmetry)
Chiral transition (Chiral symmetry)

QCD phase diagram: present understanding

Deconfinement transition

DOF changes from color neutral hadrons to colored partons (quarks & gluons)
Equivalent to insulator-conductor transition in QED
Order parameter: Expectation value Polyakov Loop <L> ~ $e^{-F/T}$
Confined phase: Large F => <L> ~ 0 :: Deconfined phase: small F => <L> ≠ 0
Centre symmetry broken: disorder to order transition

Chiral transition

Spontaneously broken chiral symmetry restored
Order parameter: chiral condensate
Hadronic phase: non-zero chiral condensate :: QGP phase: zero chiral condensate
Chiral symmetry restored: order to disorder transition

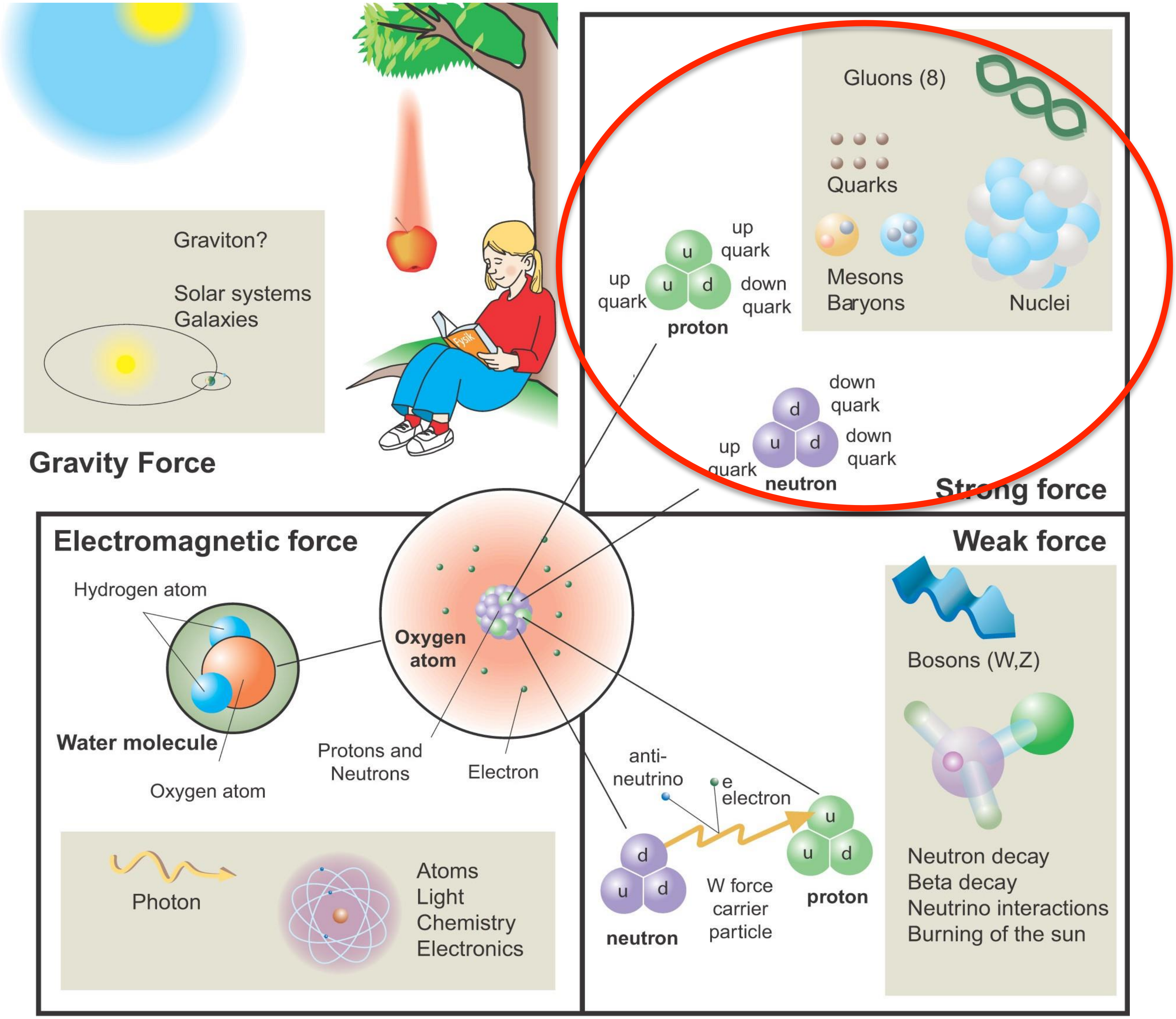
At small μ_B

Lattice QCD predicts smooth but rapid cross over between hadronic phase and QGP phase
Chiral susceptibility shows a pronounced peak as a function of temperature
Peak and width are independent of the volume : analytic cross over transition
Transition temperature T_c ~ 155 MeV
Chiral and deconfinement occurring at nearly same T

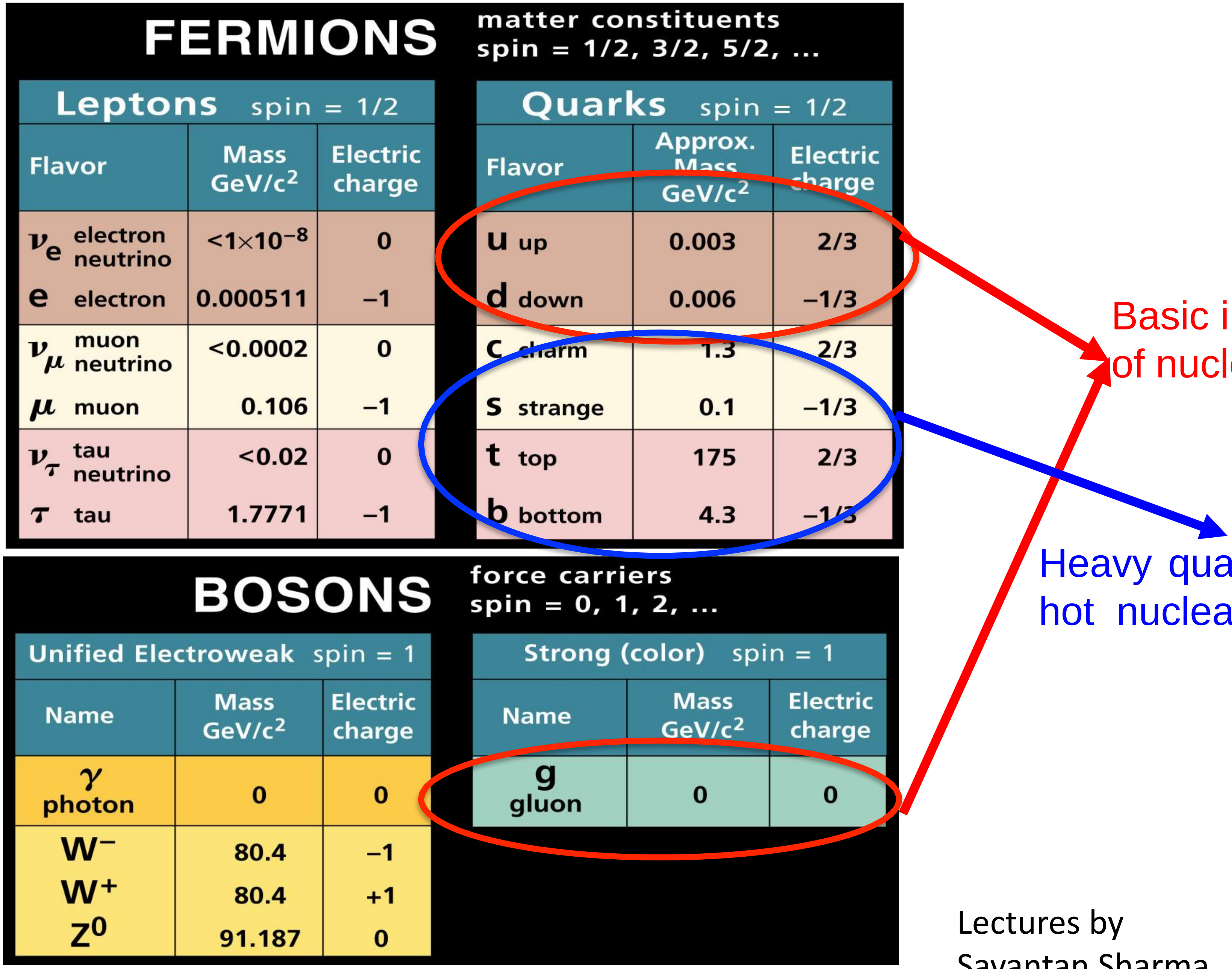
At large μ_B

Theoretical model suggests a 1st order transition between hadronic and partonic phase
1st order line ends at a critical end point (CEP) where transition is 2nd order
CEP unfavored when $\mu_B/T < 2.5$: cross over line

Fundamental Interactions in Nature



Fundamental constituents of matter



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	<1×10^{-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

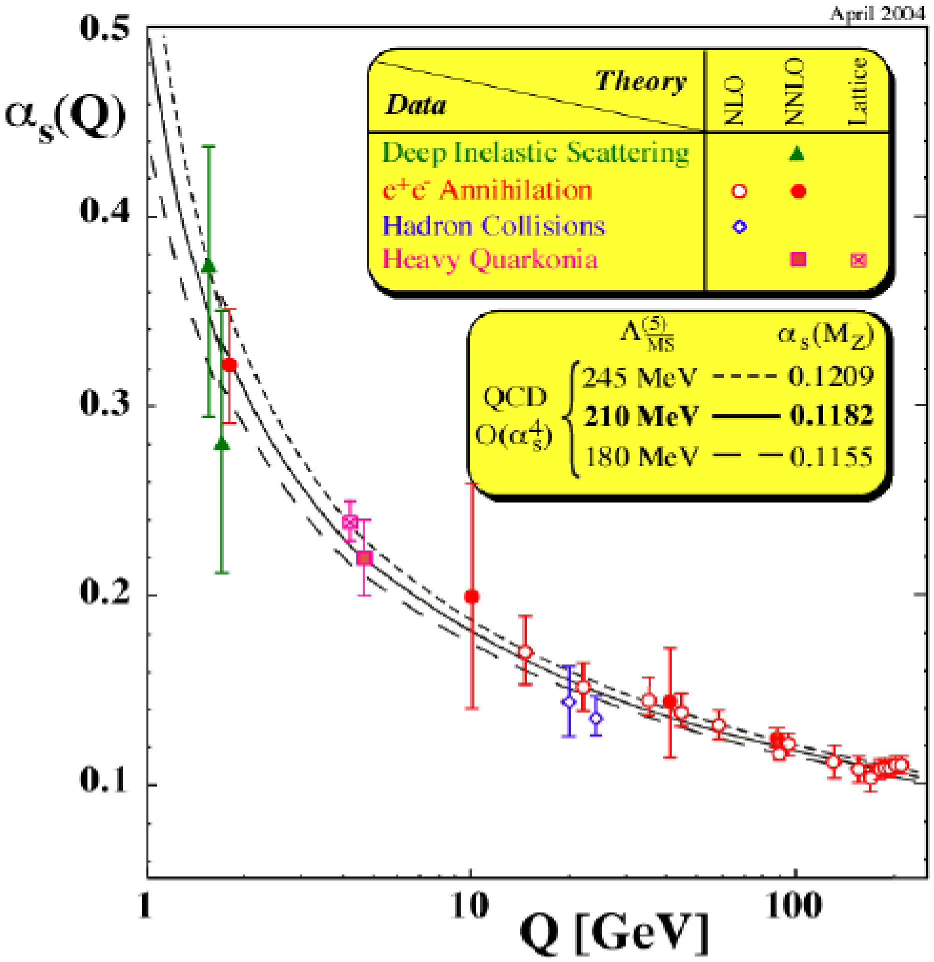
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Basic ingredients of nuclear matter

Heavy quarks appear in hot nuclear matter

Lectures by
Sayantan Sharma
Sandeep Chatterjee

QCD Running Coupling



Lectures by
Kirtiman Ghosh
Sandeep Chatterjee

Coupling constant: measures strength of interaction

$\alpha_s(Q^2)$ decreases logarithmically as Q^2 increases (or *r* decreases)   running coupling

High Q^2 → small α_s → ***asymptotic freedom***

Successful application of pQCD for describing high energy physics processes

At large distance (small *Q*), comparable to the size of a nucleon, interaction between two quarks is strong

Amplification of strong force with decreasing *Q* or increasing *r* → ***infrared slavery***

QCD vacuum is an ***anti-screening*** medium

Confinement of quarks inside the hadrons

Small *Q*, pQCD inapplicable → non-perturbative domain
→ no first principle analytical calculation till date

Phase transitions in strongly interacting matter occur in non-perturbative domain of QCD

Theory: Model calculations/numerical techniques
Experiment: Relativistic Heavy-Ion Collisions

A little bit of history: how did it start?

Pomeranchuk (1951):

Hadrons have an intrinsic size, $r_h \sim 1$ fm
Occupy a finite volume in space, $V_h \sim 4/3\pi r_h^3$
Limiting density $n_c = (V_h)^{-1} \sim 0.24$ fm^{-3} of hadronic matter
Beyond n_C, hadrons overlap more & more eventually loose their identity

Hagedron (1965):

First addressed the question of the fate of strongly interacting matter at very high temperature
Pre-QCD “statistical bootstrap” model
Mass spectrum of hadrons $\rho(M_h) \sim M_h^{-5/2} e M_h/T_H$
Hagedron limiting temperature: $T_H \sim 160 – 180$ MeV
All thermodynamic quantities diverge for $T > T_H$
All energy supplied to a system beyond Th is used for particle production

Early and middle of 1970’s:

Hadrons are not elementary objects
Hadrons have a sub-structure, made of fundamental quarks and gluons
Free quarks (and gluons) carry color, cannot be directly observed in laboratory experiments

Cabibbo and Parisi (1975):

Quark-gluon substructure of hadrons opened up the possibility for a phase transition to a new state of deconfined quarks and gluons

$T_H \longrightarrow T_c$ for the phase transition between colorless finite size hadrons to colorful point like quarks and gluons

First sketch of QCD phase diagram of nuclear matter

Collins and Perry (1975):

Asymptotically free QCD also realized for large densities → superdense nuclear matter

Question: How to produce such exotic states of strongly interacting matter in the laboratory?

T.D. Lee and G.C Wick (1974):

In high energy heavy-ion collisions one may possibly create the novel abnormal states of dense nuclear matter by distributing high energy or high nucleonic density over a large volume that could restore the broken symmetries of physical vacuum temporarily.

Edward Shuryak (1978):

First used the tem quark-gluon plasma (QGP) along with the initial ideas of space-time picture of hadronic collisions

Name give due to analogy with similar phenomena in atomic physics

Definition of QGP:

A *locally thermally* equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that the color degrees of freedom become manifest over nuclear rather than merely nucleonic volume

→

quarks and gluons are no longer confined inside hadrons and are relatively free to propagate over a nuclear (rather than hadronic) volume scale.

Essential features of QGP:

Degrees of freedom should be quarks and gluons (parton)

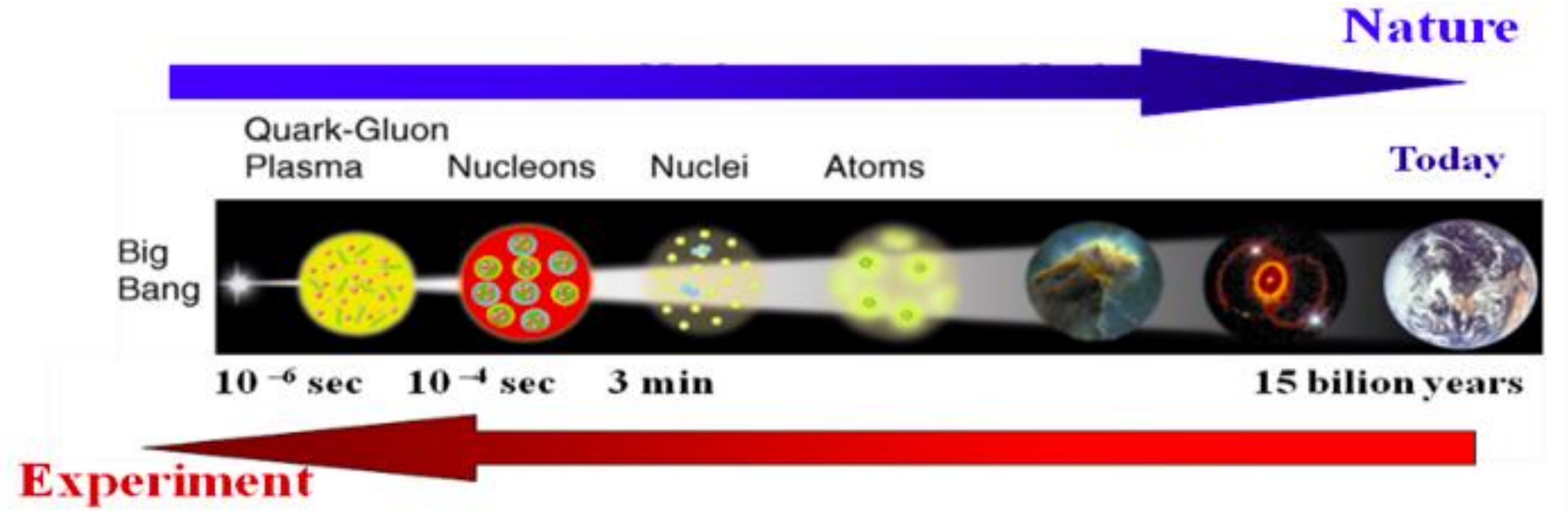
Matter should attend local thermal equilibrium → collective properties of the dense medium

Corresponding experimental signatures:
(i) A “large” collective flow seen in Au-Au (Pb-Pb) collisions at RHIC (LHC) : thermal equlibrium

(ii) Quarkonia suppression (enhancement), Jet Quenching seen at RHIC/LHC: dense matter produced in early times is partonic in nature

Dedicated lectures on Jet Quenching by Nihar Ranjan Sahoo

How to study QGP ?



Nature:

Micro second old baby universe (baryon free hot QGP)
Core of neutron stars (baryon rich cold QGP)

Recreate QGP in the laboratory (mini-bang):

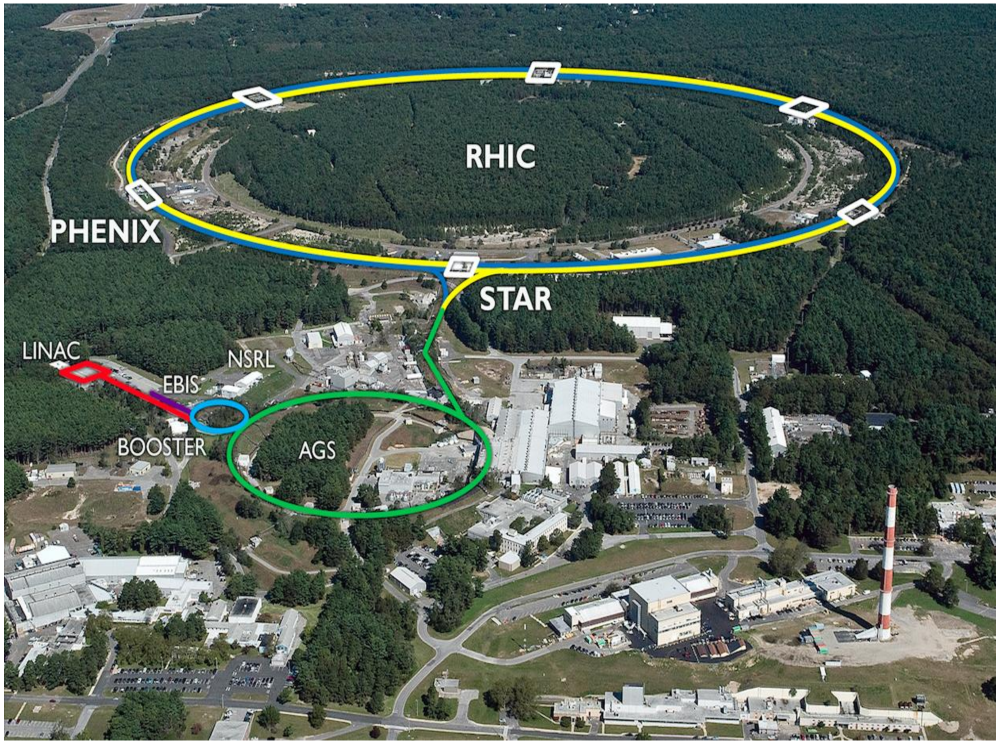
Relativistic heavy-ion collisions are the tool

- System formed expands instantaneously and remains far from turning to be homogeneous
- Global equilibrium cannot be achieved
- λ (mfp) << R (system size) ⟶ Establishment of LTE

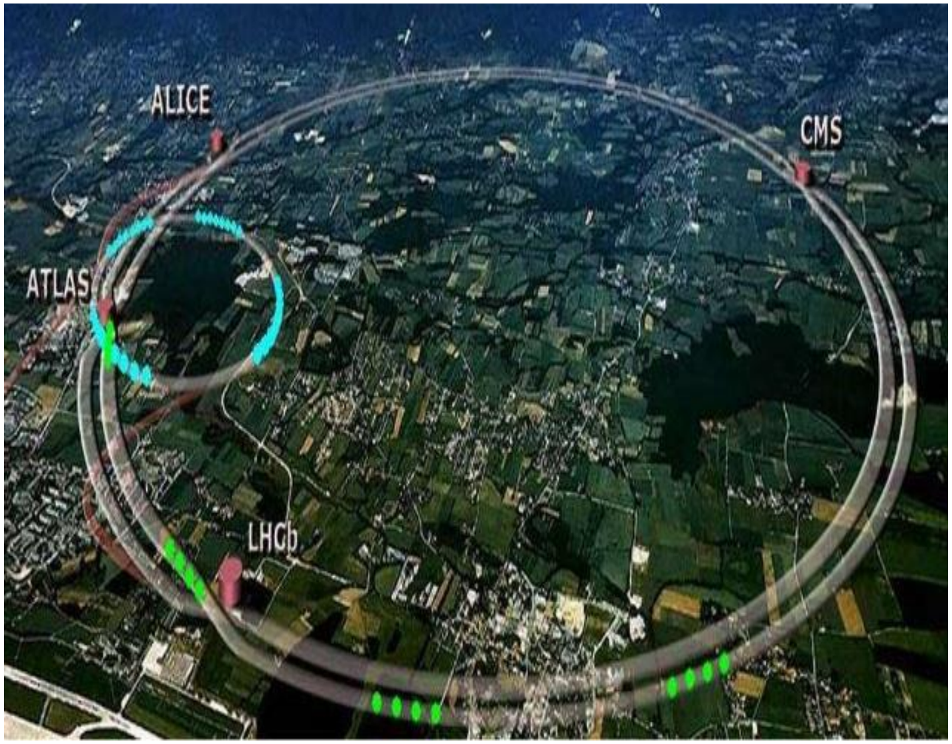
Run the evolution film backward

Creating QGP in the laboratory

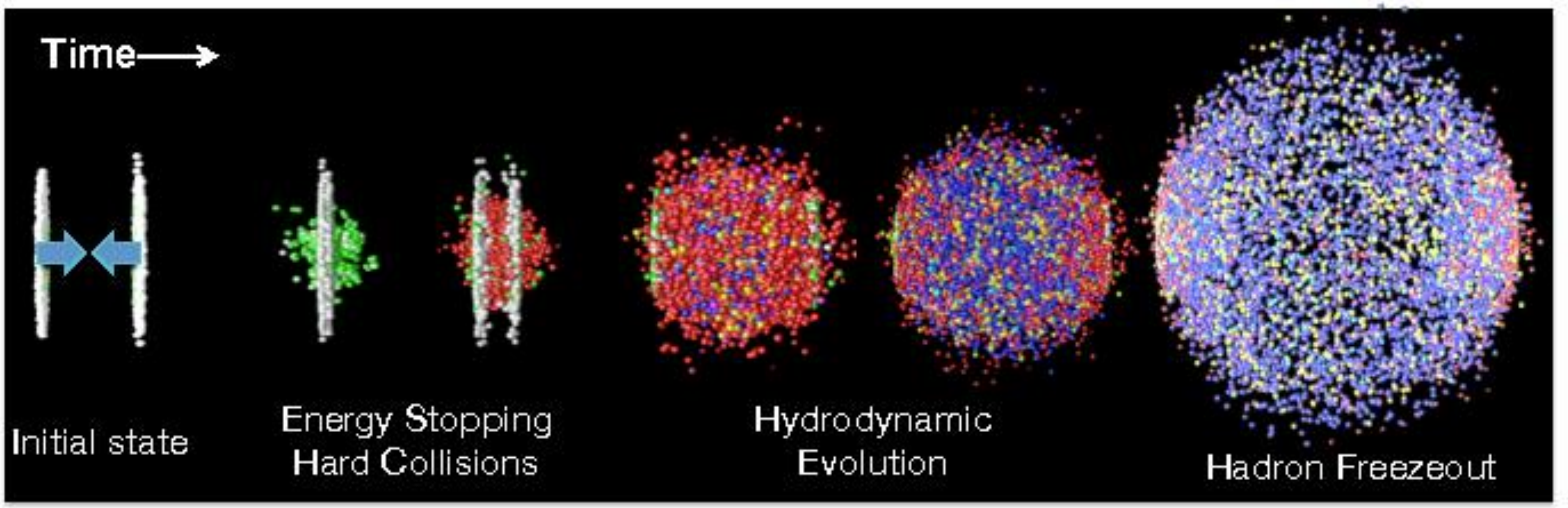
RHIC: Au+Au



LHC: Pb+Pb



How to study QGP in laboratory?



- Extremely small lifetime of QGP produced in relativistic heavy-ion collisions
- No direct detection possible of the transient system
- Indirect probes: final state particles coming out from the collision zone
- Need detectors
- Different types of particles: different detection techniques
- Multi-purpose detector system

General requirements of a detector

Large geometrical acceptance

Maximum coverage for the produced particles (4pi)

Requires Monte-Carlo simulation for evaluation

High Efficiency & good S/N ratio

Detect as many particles as possible within acceptance

Noise/background suppression

High Resolution

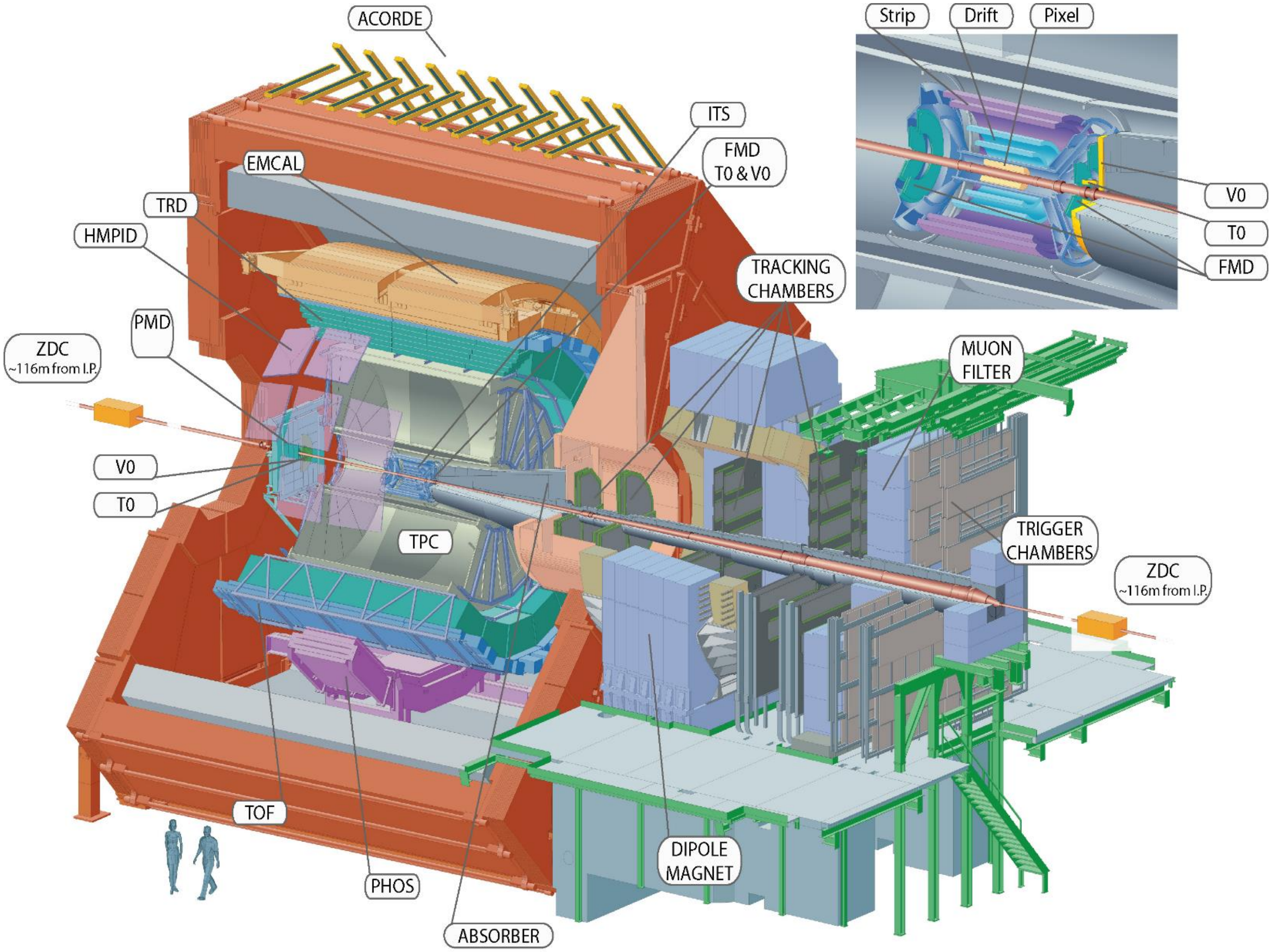
Precise determination of particle properties (eg:position, momentum, time etc.)

Particle identification:

Dedicated techniques for identification of

hadrons, electrons, photons, muons

ALICE detector setup @ LHC



Caveat: old picture

Details on lectures by B. K. Nandi, R. Singh

Raw data to physics

Data taking

Record electronic signals

Different detectors operate at different rate

Calibration

Data production

Analysis:

How to create QGP in laboratory?
Order of magnitude calculations:

Critical temperature at vanishing net baryon number

Consider an ideal gas made of u,d quarks, anti-quarks and gluons

Calculate the temperature at which the energy density equals to that within a prorton

Energy density within a proton:

$$\in_{proton} = \frac{m_N}{V} = 0.94\ GeV/\left(\frac{4}{3}\right)\pi(0.8fm)^3 \sim 0.44\ \text{GeV/fm}^3$$

Energy density of an ideal (quark gluon gas):

$$\Rightarrow \qquad \epsilon_{qgp} = 37(\pi^2/30)T^4 = 0.44\ \text{GeV/fm}^3$$

$$T \sim 130\ \text{MeV}\ (k_B = 1) = 1.5 \times 10^{12}\ \text{K}$$

Critical temperature similar to pion rest mass

Order of magnitude calculations

Critical net-baryon density at vanishing temperature

Normal nuclear matter:

$\rho_0 = A/(4/3\pi R_A^3) = 1/(4/3\pi r_0^3) \sim 0.16\ \mathrm{fm}^{-3}$

Inter-nucleon separation: $(1/\rho_0)^{1/3} \sim 2$ fm

If nuclear matter is compressed inter-nucleon separation starts decreasing density increases

Critical condition: nucelons touching each other

inter nucleon separation = nucleon radius

$$\Rightarrow \quad \boldsymbol{\rho_C = 3\rho_0}$$

Relativistic Heavy-Ion Collisions: Evolution of experiments

Figures of merit:

- CM energy of the colliding nucleon pair
- Atomic number of the colliding nuclei

Physics driven by continuous improvements of both accelerator and detector technology

- ■ 1984:
  - 1-2 GeV/*c* per nucleon beam from SuperHILAC into Bevalac at Berkeley
- ■ 1986
  - beams of silicon at Brookhaven AGS ($\sqrt{s_{NN}} \approx 5$ GeV)
  - beams of oxygen/sulfur at CERN SPS ($\sqrt{s_{NN}} \approx 20$ GeV)
- ■ 1992/1994
  - beams of gold at Brookhaven AGS ($\sqrt{s_{NN}} \approx 5$ GeV)
  - beams of lead at CERN SPS ($\sqrt{s_{NN}} \approx 17$ GeV)
- ■ 2000: gold-gold collisions at RHIC ($\sqrt{s_{NN}} \approx 200$ GeV)
- ■ 2010: lead-lead collisions at the LHC ($\sqrt{s_{NN}} \approx 2760$ GeV)
- ■ 2015: lead-lead collisions at the LHC ($\sqrt{s_{NN}} \approx 5020$ GeV)

Slide from B. Mohanty

Fixed target vs. Colliding beams

Fixed target:

- CM energy limited by E_{CM}=Sqrt(2*m_N*E_{beam}) (Q. Prove it)
- Highest ever achieved at CERN SPS with Ebeam of ~ 160 GeV/n corresponding to E_{CM} ~ 20 GeV per NN pair
- Very high beam intensity/luminosity leads to high reaction rate (Q. Why?)

Collider:

- Much higher CM energy E_{CM} ~ 2*E_{beam} (Q. Show this)
- Highest achieved 5500 GeV per NN pair at LHC
- Lower luminosity leads to low reaction rate

Heavy Ion Colliders at operation:

- RHIC at BNL since 2000
- LHC at CERN since 2010

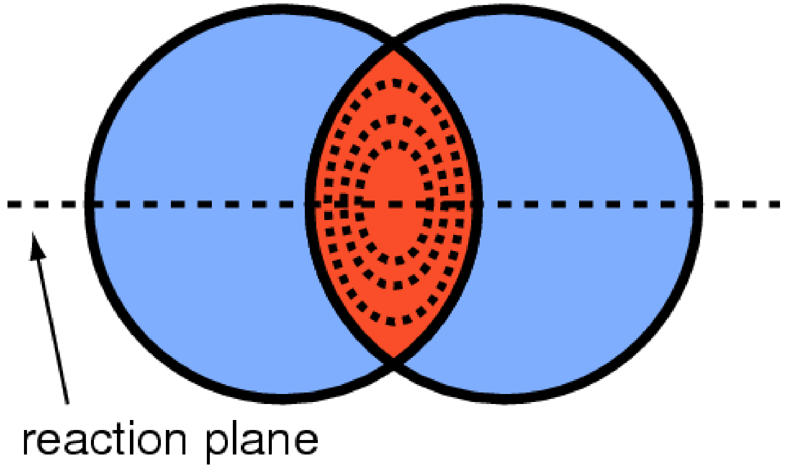
In a particle accelerator:

Maximum energy of a proton beam E_p
Maximum energy of a heavy-ion beam (Z/A)*E_p

Highlights from the RHIC heavy-ion programme

- Azimuthal anisotropy of particle production at low p_T (< 2 GeV/c)
  - Interpreted as a result of the collective expansion of the QGP
  - Ideal hydrodynamics close to data
  - Small viscosity over entropy density: strongly coupled QGP, ”perfect liquid“
  - Evidence for early QGP thermalization ($\tau \lesssim$ 1-2 fm/c)
- Hadron suppression at high p_T
  - Medium is to large extent opaque for jets (”jet quenching“)
- Yields of hadron species in chemical equilibrium with freeze-out temperature T_{ch} close to T_c
  - $T_{ch} \approx$ 160 MeV, $\mu_B \approx$ 20 MeV

Elliptic Flow:
Anisotropy in position space



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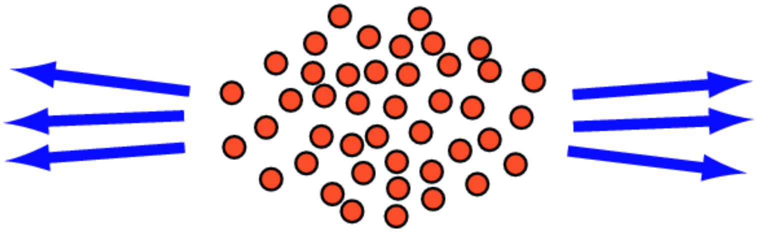
Anisotropy in momentum space



Heavy-ions at the LHC

- Qualitatively similar results in A-A collisions
  - Jet quenching
  - Elliptic flow
  - Particle yields in or close to chemical equilibrium values
  - Hints of Jpsi regeneration, upsilon suppression
- A surprise:
Observation of elliptic flow and other effects first seen in heavy-ion collisions also in pp and p-Pb collisions
  - QGP in small systems?
  - But no jet quenching seen in small systems
  - Ongoing discussion

Natural Units

- Most constants in formulae are there due to the arbitrary system of units used.
- Hence we find the constants c, h, k_B all over the place just because of the system of units we are using.
- It is possible to setup a self-consistent system of units
- where $\boldsymbol{c = h = k_B = 1}$
- All speeds are just measured as a fraction of the speed of light and have no units i.e. $\beta = v/c$
- Einstein's equations simplify to $E = \gamma m$ and $E^2 = p^2 + m^2$

  - De Broglie's equation $p = h/\lambda$ → $p = 1/\lambda$
  - K.E. of particle with temperature $E \approx k_B T$ → $E \approx T$

Natural Units

Hence

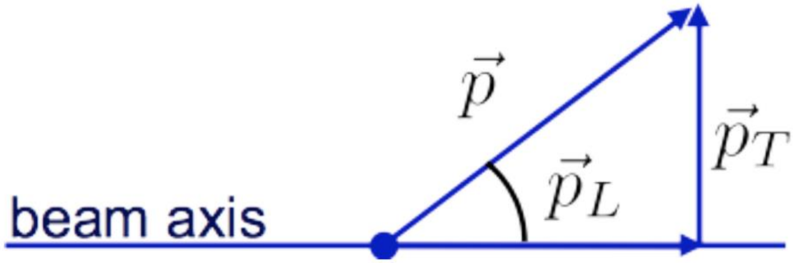
- Energy has units of GeV
- Mass has units of GeV/c^2
- Momentum has units of GeV/c
- Temperature has units of GeV
- Distance has units of GeV^{-1} (as $p = 1/\lambda$)
- Time has units of GeV^{-1} (as distance = speed x time)

Experimentalists will often only have c and $k_B = 1$ but measure distance in terms of Fermi's: (1 fm = 10^{-15} metres) Hence we also measure time in fm (note 1 fm is the time taken for light to travel 10^{-15} m i.e. traverse a proton)

Basic Kinematics

Transverse momentum: $p_T = p \sin\theta$

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



Rapidity *y* (additive under Lorentz Transformation):

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

E = $m_T\cosh y$; pz=$m_T\sinh y$ (Pl. prove this)

dN/dy is frame invariant (Pl. prove this)

Pseudo-rapidity (η):

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

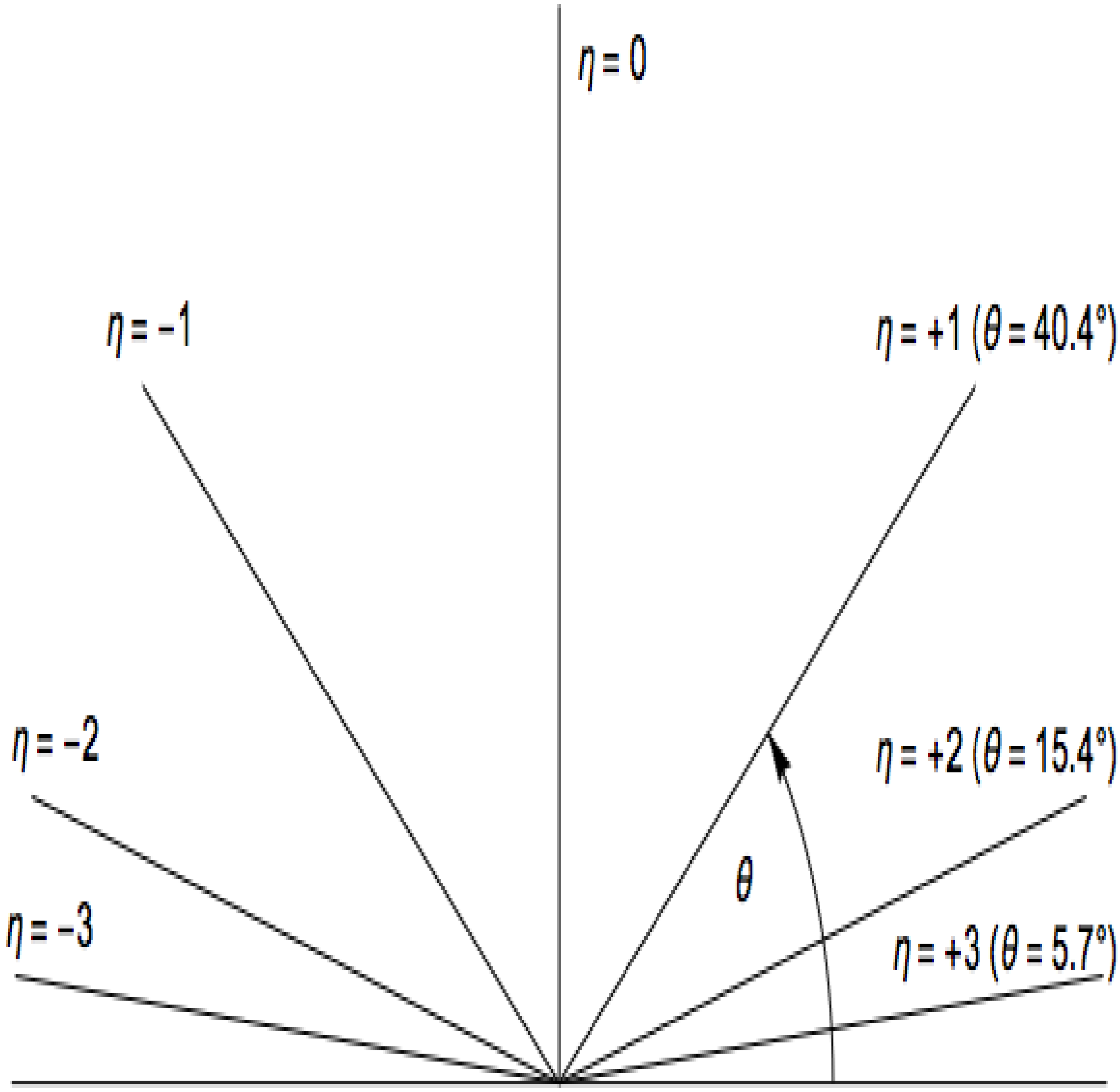
p=$p_T\cosh y$; $p_z=p_T\sinh y$

dN/dη is frame dependent (Q. How dN/dy and dN/dη are connected?)

Q. What is the advantage of η over y?

Q. Show that Ed^3N/d^3p is a Lorentz invariant quantity

Pseudo-rapidity



Can be measured knowing angle of emission

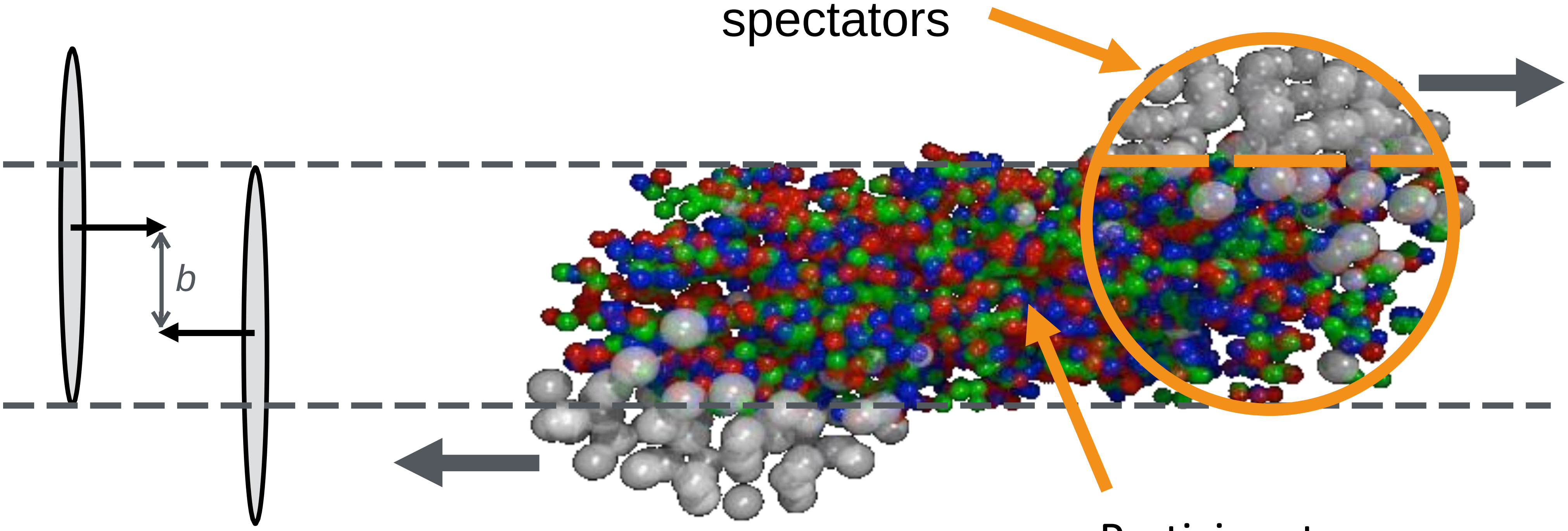
Does not need particle identification

Distribution not invariant under L.T

For massless particles $y = \eta$

Centrality of a collision
Participants and spectators

Lorentz contracted nuclei (R_A/γ)



spectators

Participants

b: impact parameter of the collision

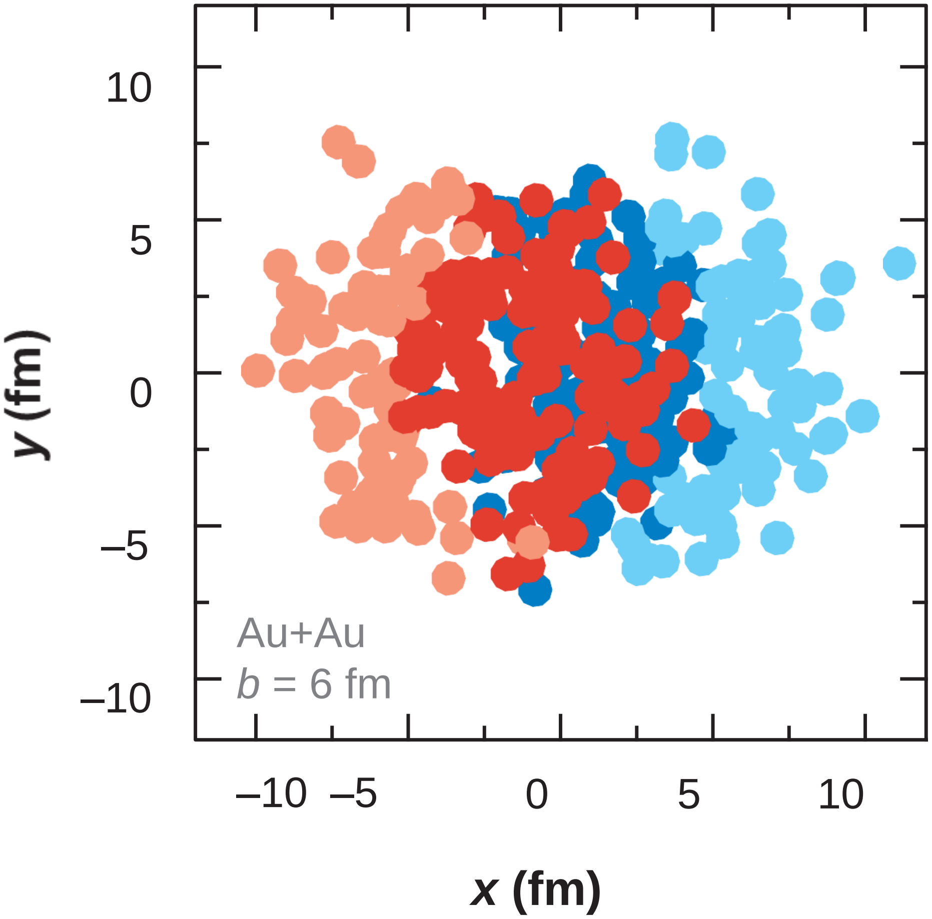
N_{coll}: number of inelastic nucleon-nucleon collisions

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

Q: What is amount of Lorentz contraction at top RHIC energy?

Glauber Monte Carlo calculations

Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243



■ In heavy-ion physics

- Pure geometry, no quantum effects

■ Procedure:

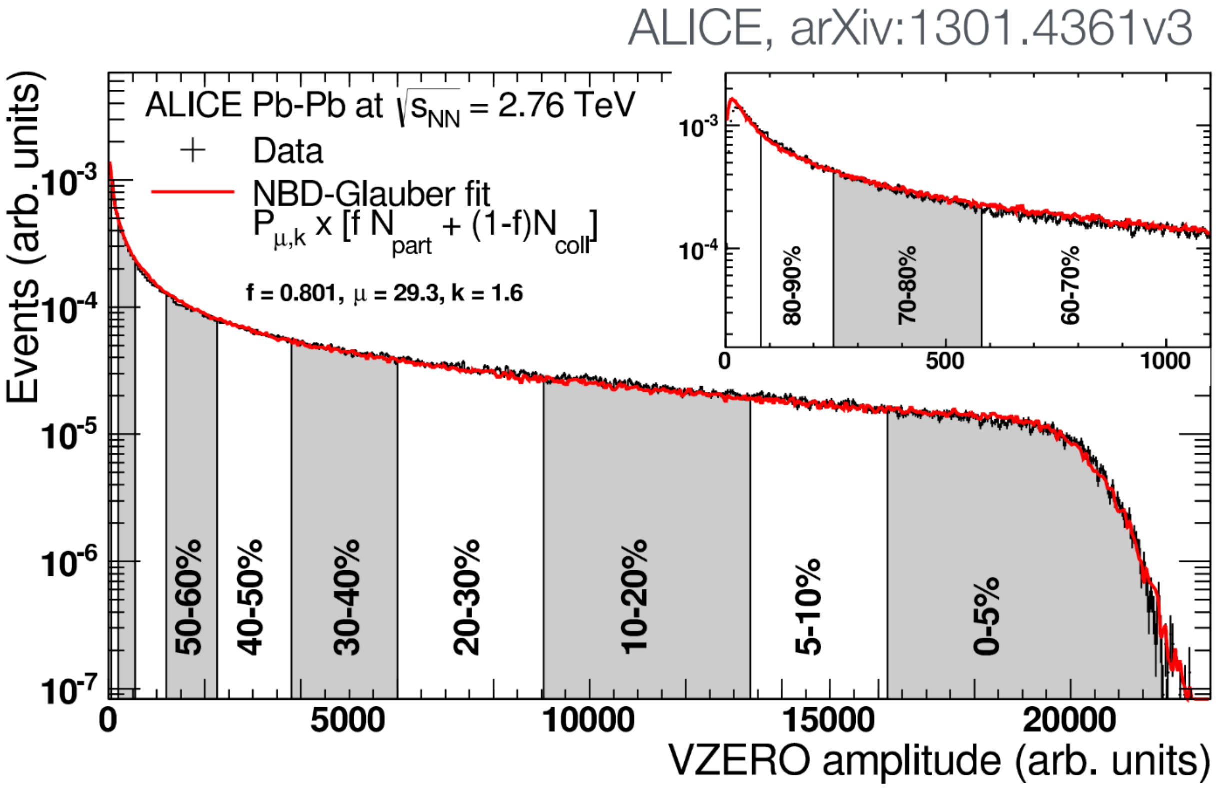
- Randomly select impact parameter *b*
- Distribute nucleons of two nuclei according to nuclear density distribution
- Consider all pairs with one nucleon from nucleus A and the other from B
- Count pair as inel. n-n collision if distance *d* in *x*-*y* plane satisfies:

$$d < \sqrt{\sigma_{NN}/\pi}$$

- Dynamics only through inelastic NN x-section σ_{NN}

■ Repeat many times: $\langle N_{part}\rangle(b)$ $\langle N_{coll}\rangle(b)$

Connection to experimental centrality classes

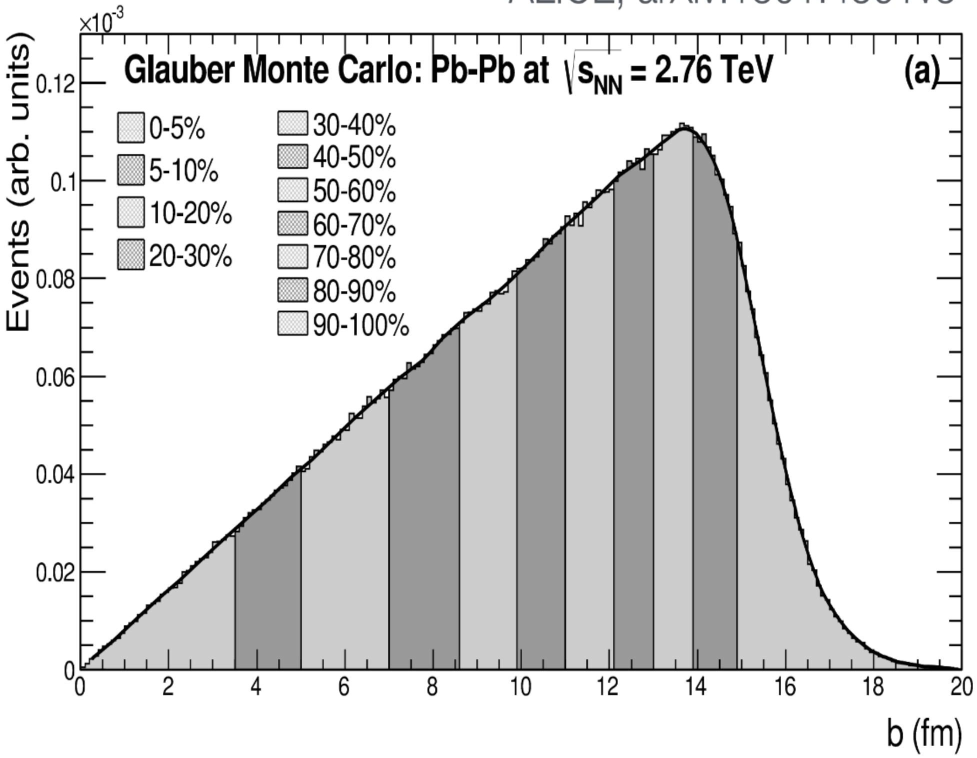


Measure charged particle multiplicity (VZERO detectors in ALICE)

Assume $N_{ch}(b)$ increases monotonically with decreasing b

Define centrality class by selecting a percentile of measured multiplicity distribution (eg: 0 – 5 %)

Connection to experimental centrality classes



ALICE, arXiv:1301.4361v3

Use Glauber MC to find:

Impact parameter interval [bmin, bmax] corresponding to same percentile

Average N_{part} N_{coll} in the interval

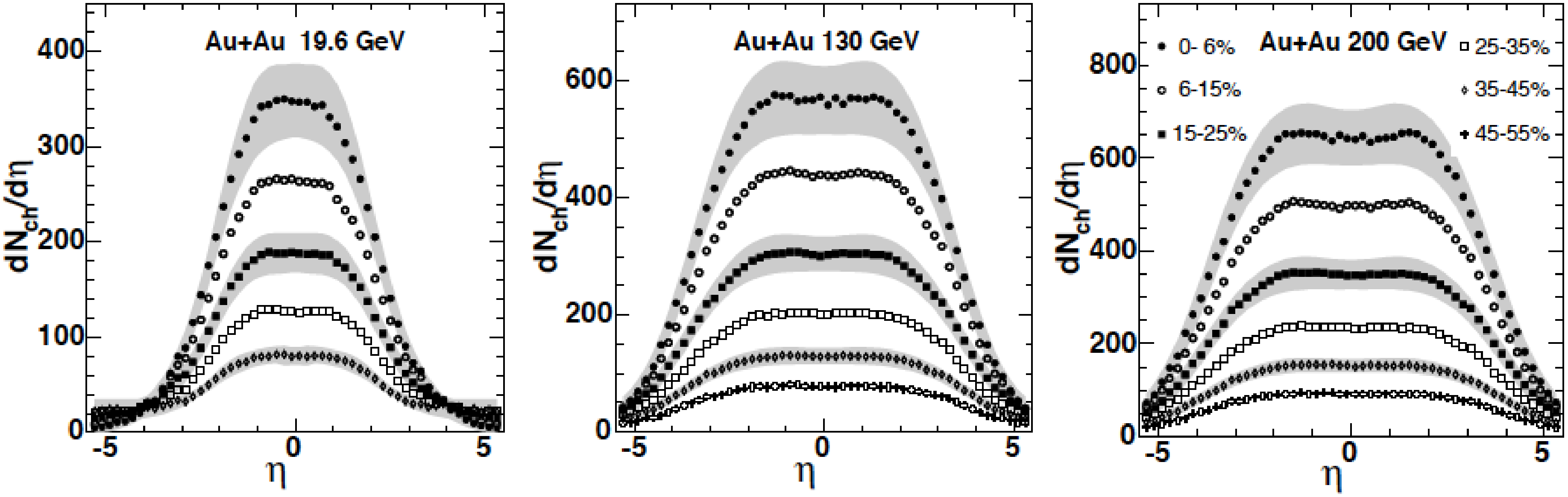
2.76 TeV Pb+Pb collisions

σ_{NN} = 64 ± 5 mb

Centrality	b_{min} (fm)	b_{max} (fm)	$\langle N_{part} \rangle$	RMS	(*sys.*)	$\langle N_{coll} \rangle$	RMS	(*sys.*)	$\langle T_{AA} \rangle$ 1/mbarn	RMS 1/mbarn	(*sys.*) 1/mbarn
0–5%	0.00	3.50	382.7	17	3.0	1685	140	190	26.32	2.2	0.85
5–10%	3.50	4.94	329.4	18	4.3	1316	110	140	20.56	1.7	0.67
10–20%	4.94	6.98	260.1	27	3.8	921.2	140	96	14.39	2.2	0.45
20–40%	6.98	9.88	157.2	35	3.1	438.4	150	42	6.850	2.3	0.23
40–60%	9.88	12.09	68.56	22	2.0	127.7	59	11	1.996	0.92	0.097
60–80%	12.09	13.97	22.52	12	0.77	26.71	18	2.0	0.4174	0.29	0.026
80–100%	13.97	20.00	5.604	4.2	0.14	4.441	4.4	0.21	0.06939	0.068	0.0055

Charged Multiplicity

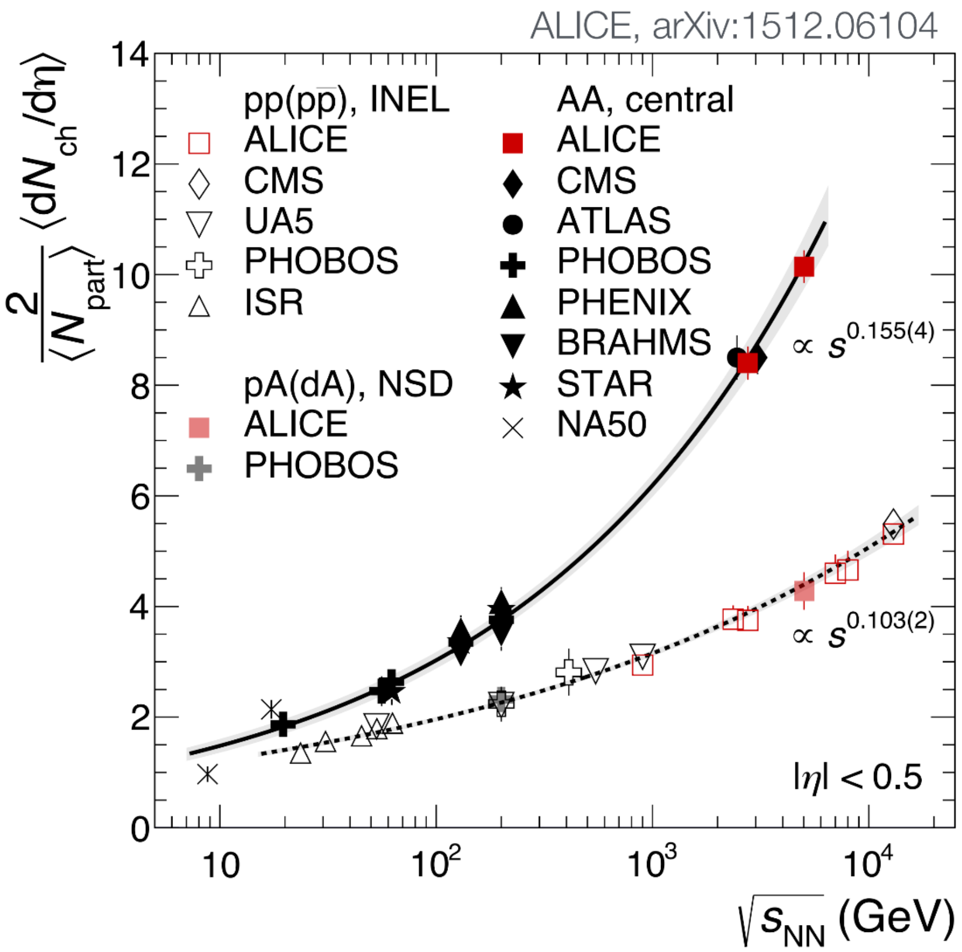
PHOBOS experiment at RHIC accelerator



- Charged particle multiplicity as a function of pseudorapidity
- Increasing collision energy: 19, 130, 200 GeV/A
- Different centrality: peripheral to central

- Very clear increase in multiplicity with energy and centrality

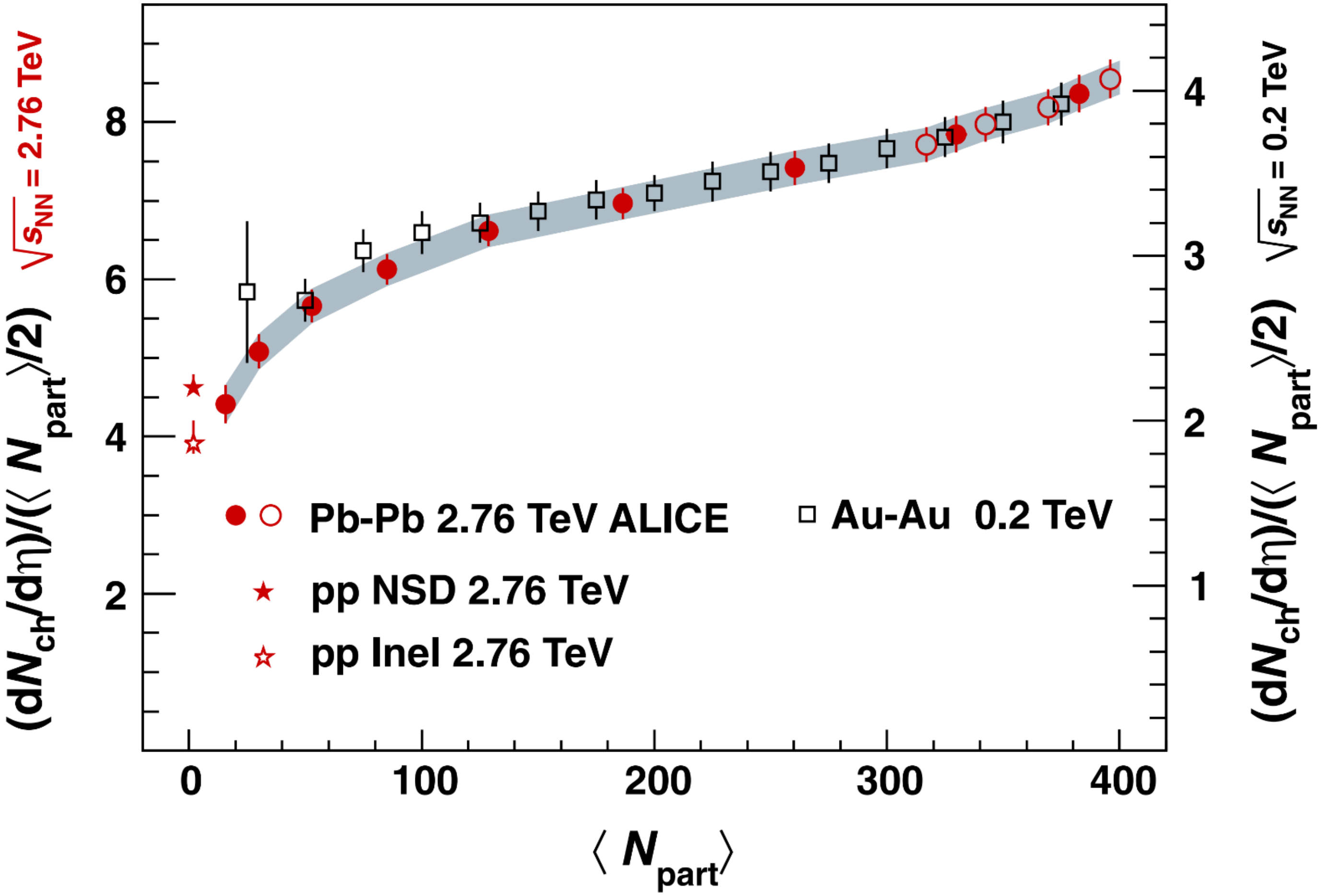
Charged multiplicity η=0 vs √s



$dN_{ch}/d\eta$ show a power law scaling

Increase in central A+A collisions stronger than in p+p

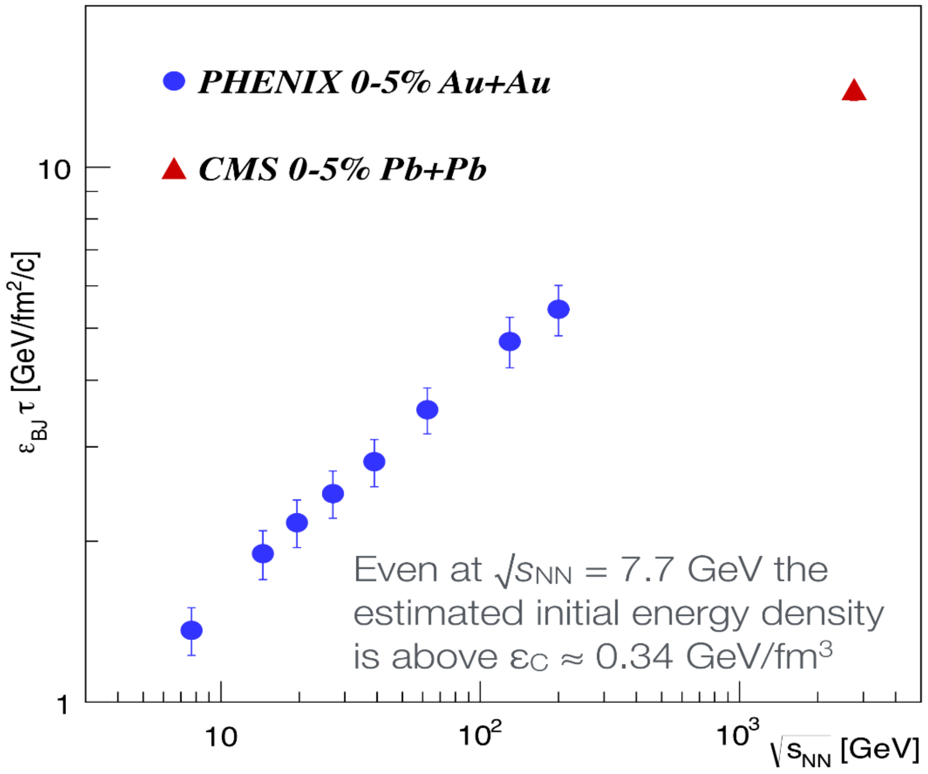
Centrality dependence of $dN_{ch}/d\eta$



- $(dN_{ch}/d\eta)/N_{part}$ increases with centrality
- Relative increase similar at RHIC and LHC: geometrical effect

Estimation of initial energy density

PHENIX, arXiv:1509.06727



Even at $\sqrt{s_{NN}} = 7.7$ GeV the estimated initial energy density is above $\varepsilon_C \approx 0.34$ GeV/fm^3

Bjorken's formula:

$$\varepsilon = \frac{1}{A \cdot \tau_0} \left. \frac{\mathrm{d}E_T}{\mathrm{d}y} \right|_{y=0}, \quad \tau_0 \approx 1\,\mathrm{fm}/c$$

Can be estimated from $dN_{ch}/d\eta$

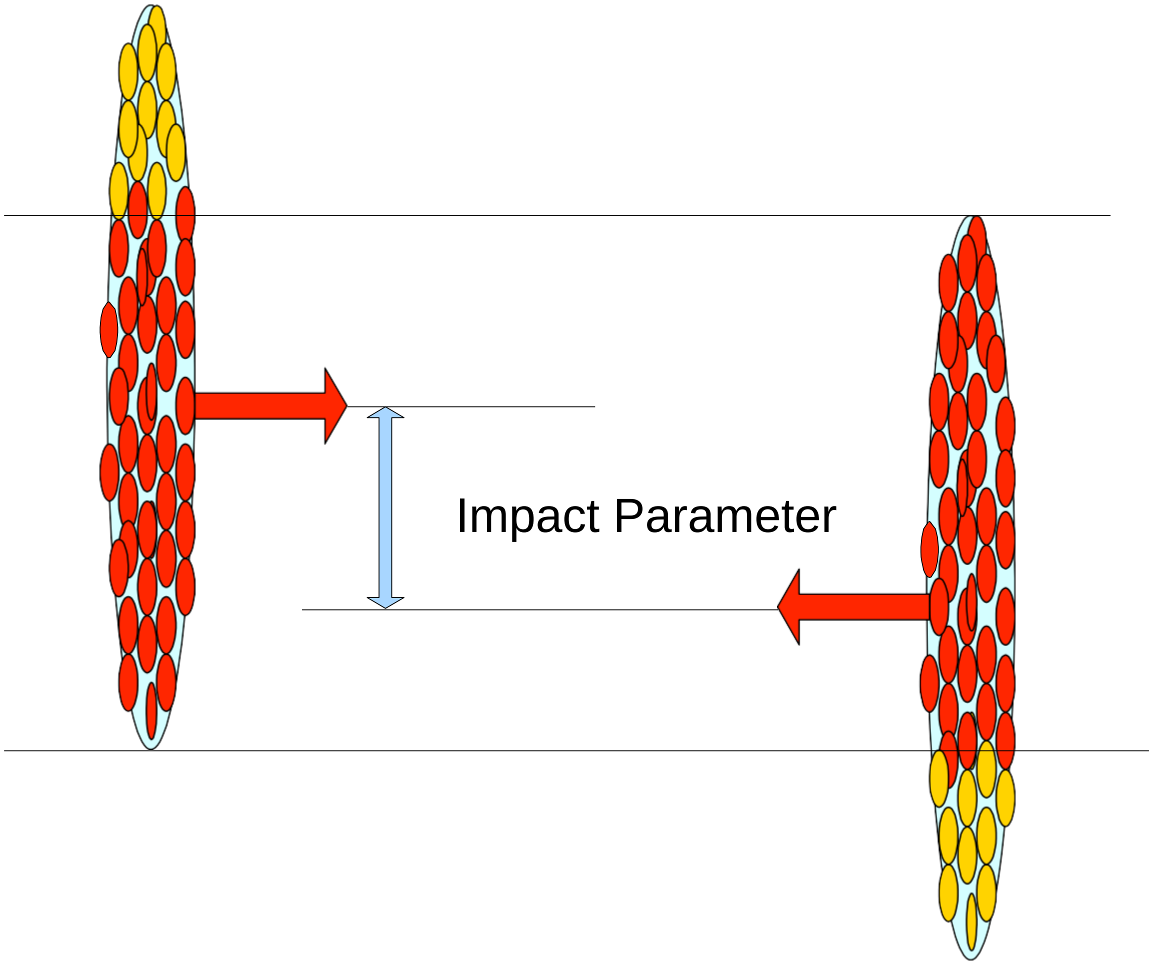
In central collisions initial energy densities much higher than critical value for QGP production

Summary so far

- Heavy ion collisions clearly produce hot region of space with energy densities sufficiently high to enter the quark-gluon plasma phase
- The mean free path for the ingredients seems to be much smaller than the size of the hot region, implying thermalization
- The hot matter expands and cools very fast, the measurements have to be done very quickly

Collision Geometry

Number of produced particles ~ max. energy density ~ number of participating nucleons



Spectators

Participants

Participants

Spectators

Most central collisions: impact parameter (b) ~ 0 fm

Aim of relativistic heavy-ion collisions

- **Study strongly interacting matter at extreme energy densities over large volumes and long time-scales.**
- **Study the role of chiral symmetry in the generation of mass in hadrons (accounts for over 98% of mass of nuclear matter).**
- **Study the nature of quark confinement.**
- **Study the QCD phase transition from hadronic matter to a deconfined state of quarks and gluons - The Quark-Gluon Plasma.**
- **Study the physics of the Quark-Gluon Plasma**
- **(QCD under extreme conditions).**