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Heavy-ion physics, lecture 1

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Today

Introduction to heavy-ion collisions (HIC)
& the quark-gluon plasma (QGP)

- Some brief QCD reminders
- Thermodynamics of the QCD phase transition
- Space-time evolution of heavy-ion collisions
 - Concept of collision centrality
 - Produced energy density in the Bjorken picture
- Particle production from the QGP
 - Statistical hadro-production
 - Strangeness enhancement

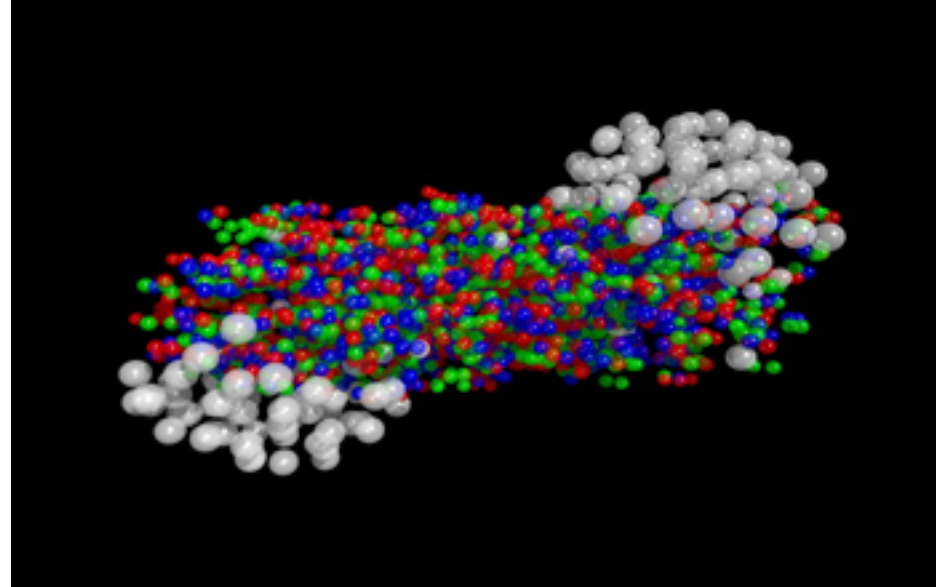
Tomorrow focus on a few types of measurements
that probe properties of the quark gluon plasma

HIC: definition

Au: 79 protons & 100 neutrons

Pb: 82 protons & 126 neutrons

Note: Nuclear size of order 10 fm



↑
Heavy

↓
Ion

Collisions

Interested in colliding nuclei, we strip off the e's to accelerate them
The proton is also an ion (of hydrogen). proton-ion collisions are also of interest

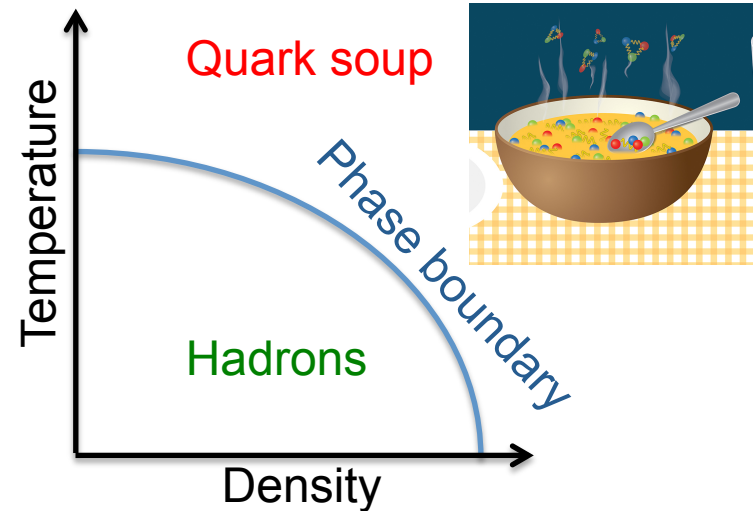
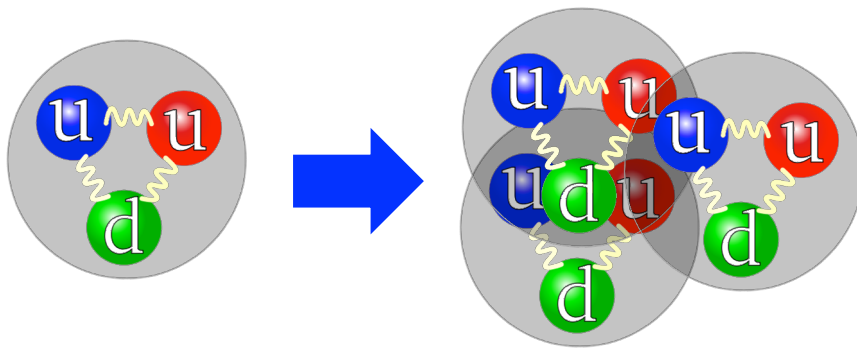
Currently performed at RHIC and the LHC

Max energy per nucleon pair ($\sqrt{s_{NN}}$) of 5 TeV \rightarrow 1PeV (\sqrt{s}) total energy !

So one should expect large energy density from HIC's (we'll estimate it later)
What happens to matter in these conditions?

Why collide heavy ions?

In normal matter, parton degrees of freedom confined to hadrons
Does this change at high temperature and/or large density?

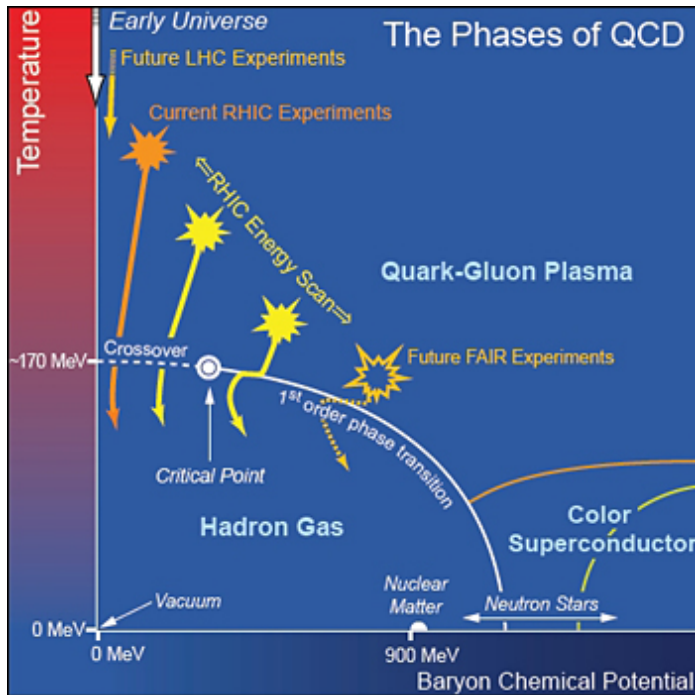


Based on the recent discovery of asymptotic freedom (1973), Collins & Perry hypothesized that it would in 1975:

“A neutron has radius of about 0.5 – 1 fm and so has a density of about 8×10^{14} gm/cm³, whereas the central density of a neutron star, can be as much as 10^{16} – 10^{17} gm / cm³. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore we suggest that there is a phase change, and that the nuclear matter at such high densities is a quark soup”

The quark-gluon plasma

10^5 x hotter than core of the sun!



- Critical temperature ($T_c \approx 150 \text{ MeV}$) estimated pre-QCD by Hagedorn based on # of hadrons vs. energy
- Later confirmed with lattice QCD
- Heavy-ion collisions create high temperature, but low density \rightarrow smooth crossover in this region
- Also phase transition at high density, but lattice calculations difficult there due to “sign problem”

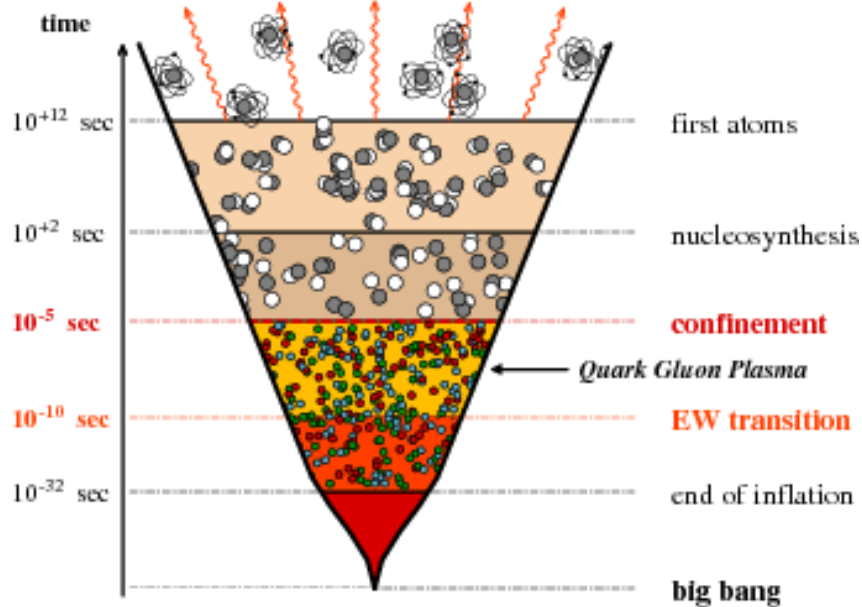
Heavy-ion collisions allow us to probe QCD at high temperature

\rightarrow Requires different theoretical tools, e.g., high temperature QFT, thermodynamics, ...

\rightarrow QCD matter exhibits novel features in these conditions

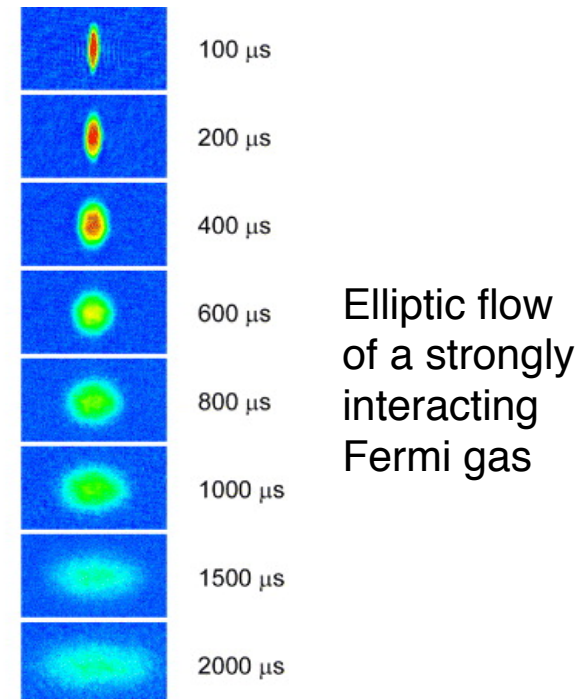
Far-reaching connections

Cosmology



The universe was composed of QGP from 10^{-10} to 10^{-5} sec after the Big Bang

Cold quantum gasses



Ideal fluid behavior observed in QGP & other strongly coupled systems

QCD reminder

Structure of QCD driven by SU(3) color gauge symmetry

In principle, all is calculable from the QCD Lagrangian:

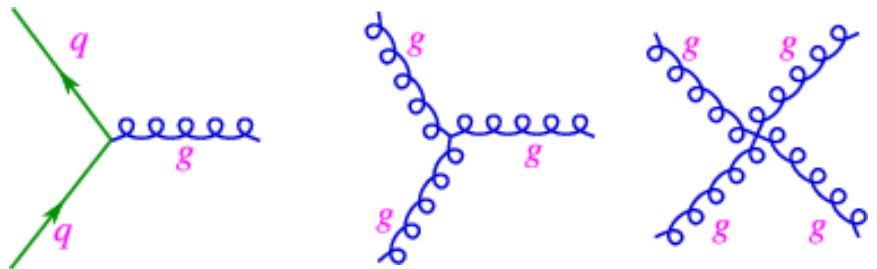
$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \bar{\psi}_a \left((i\gamma^\mu \partial_\mu - m) \delta_{ab} - g_s \gamma^\mu t_{ab}^C A_\mu^C \right) \psi_b - \frac{1}{4} F_{\mu\nu}^A F^{\mu\nu, A} \quad F_{\mu\nu}^A = \partial_\mu \mathcal{A}_\nu^A - \partial_\nu \mathcal{A}_\mu^A - g_s f_{ABC} \mathcal{A}_\mu^B \mathcal{A}_\nu^C$$

$$[t^A, t^B] = i f_{ABC} t^C$$

Quark propagator

Quark-gluon vertex

Field strength tensor



$$N_c^2 - 1 = 8 \text{ gluons}$$

$$N_c * N_f \text{ quarks}$$

Quark masses

charge=+2/3	u (~5 MeV)	c (~1.5 GeV)	t (~175 GeV)
charge=-1/3	d (~10 MeV)	s (~100 MeV)	b (~5 GeV)

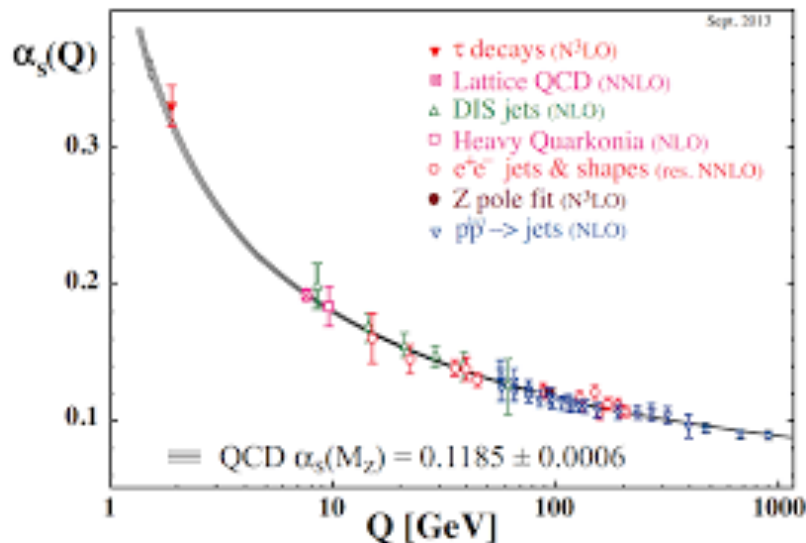
Compare to $T_c \sim 150 \text{ MeV}$

Gluon self-interaction



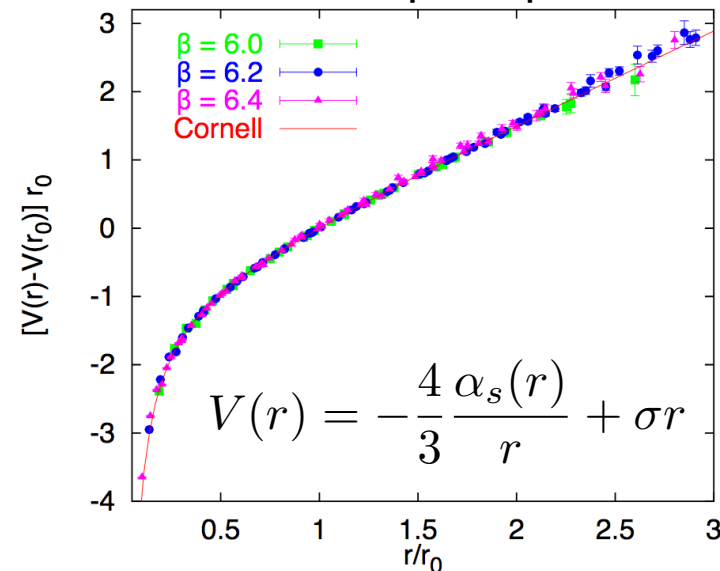
Asymptotic freedom & confinement

Whereas in QED vacuum fluctuation screen charge,
in QCD they “anti-screen”



- At short distance coupling is small
- Quarks can be probed inside the nucleon with high energy leptons (DIS)
- pQCD works well in this regime

Quark-antiquark potential



- At “large” distance (1 fm), potential is linear
- Quarks confined inside hadrons
- Perturbation theory breaks at large coupling

QCD thermodynamics

In high T limit \rightarrow QGP an ideal gas of weakly interacting quarks and gluons

Equation of state is given by pressure vs. temperature
or equivalently energy density vs. temperature

Can be calculated from the partition function

$$\epsilon = \int \frac{d^3p}{(2\pi)^3} \sum_i \frac{E_i}{e^{\frac{E_i}{k_B T}} \pm 1}$$

+1, 0, 1 for fermions, classical or bosons

$$\Rightarrow \epsilon(T) \approx \frac{\pi^2}{30} N T^4 \quad N=3$$

Hadron phase can be approximated as a gas of pions, i.e., 3 states: π^+, π^0, π^-

For a QGP on the other hand, we expect

$$\epsilon(T) = \frac{\pi^2}{30} \left(N_B + \frac{7}{8} N_F \right) T^4$$

$$= \frac{\pi^2}{30} (47.5) T^4$$

$N_B = 2 \times 8$, $N_F = 2 \times 2 \times 3 \times 3$
 spin color spin color flavor: u/d/s
 particle/antiparticle

→ 15x jump in the energy density at T_c

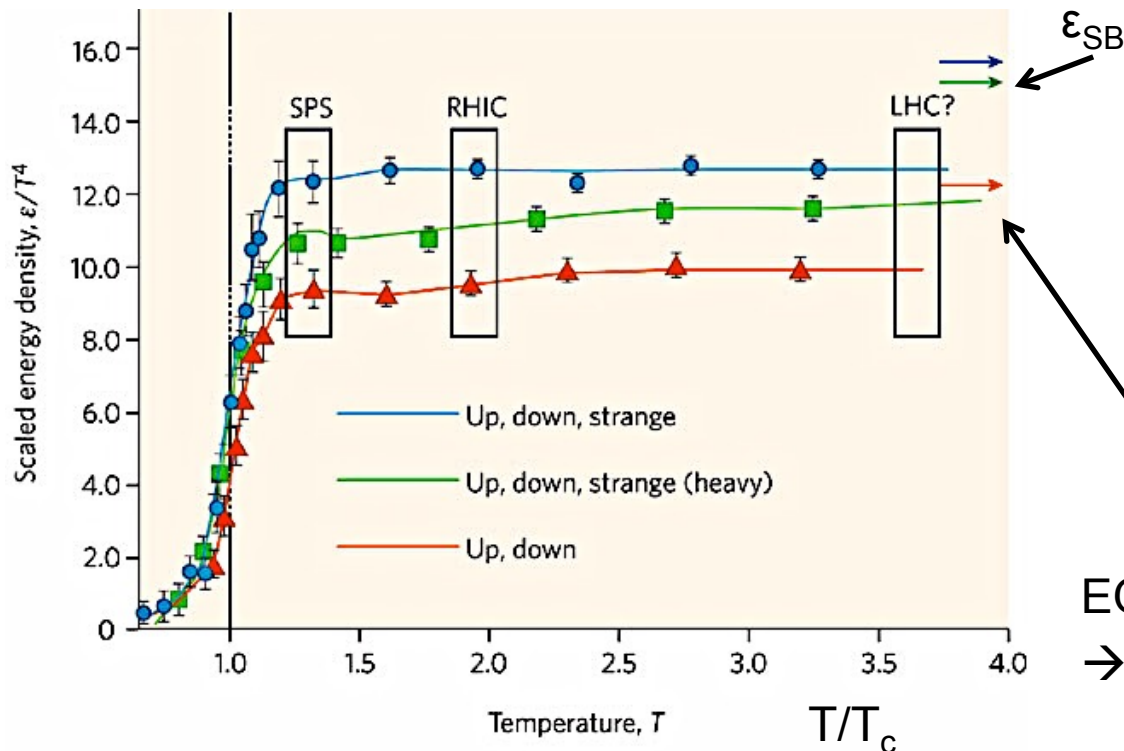
→ 15x jump in the energy density at T_c

E.O.S. from the lattice

Lattice calculations are reliable for zero net baryon density, which is a reasonable approximation for high energy HICs

They indeed show a spike in ratio of ϵ / T^4 ,
Indicating a jump in the degrees of freedom

$$T_c \approx 150 \text{ MeV} \\ \rightarrow \epsilon_{SB} \approx 1.0 \text{ GeV/fm}^3$$

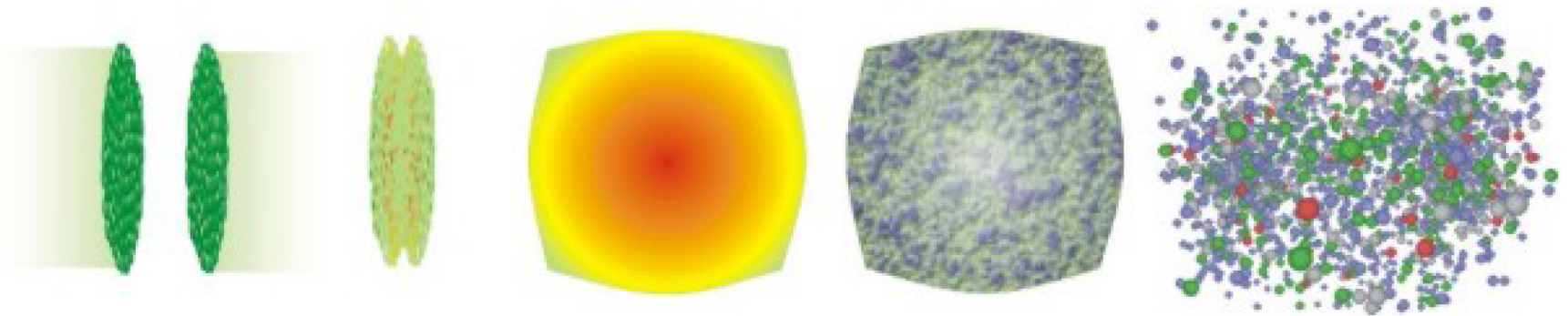


Does that mean the QGP behaves like an ideal gas of quarks and gluons?

Don't reach the SB limit

EOS of N=4 Super Yang-Mills
 \rightarrow may be strongly coupled

Time evolution of a HIC

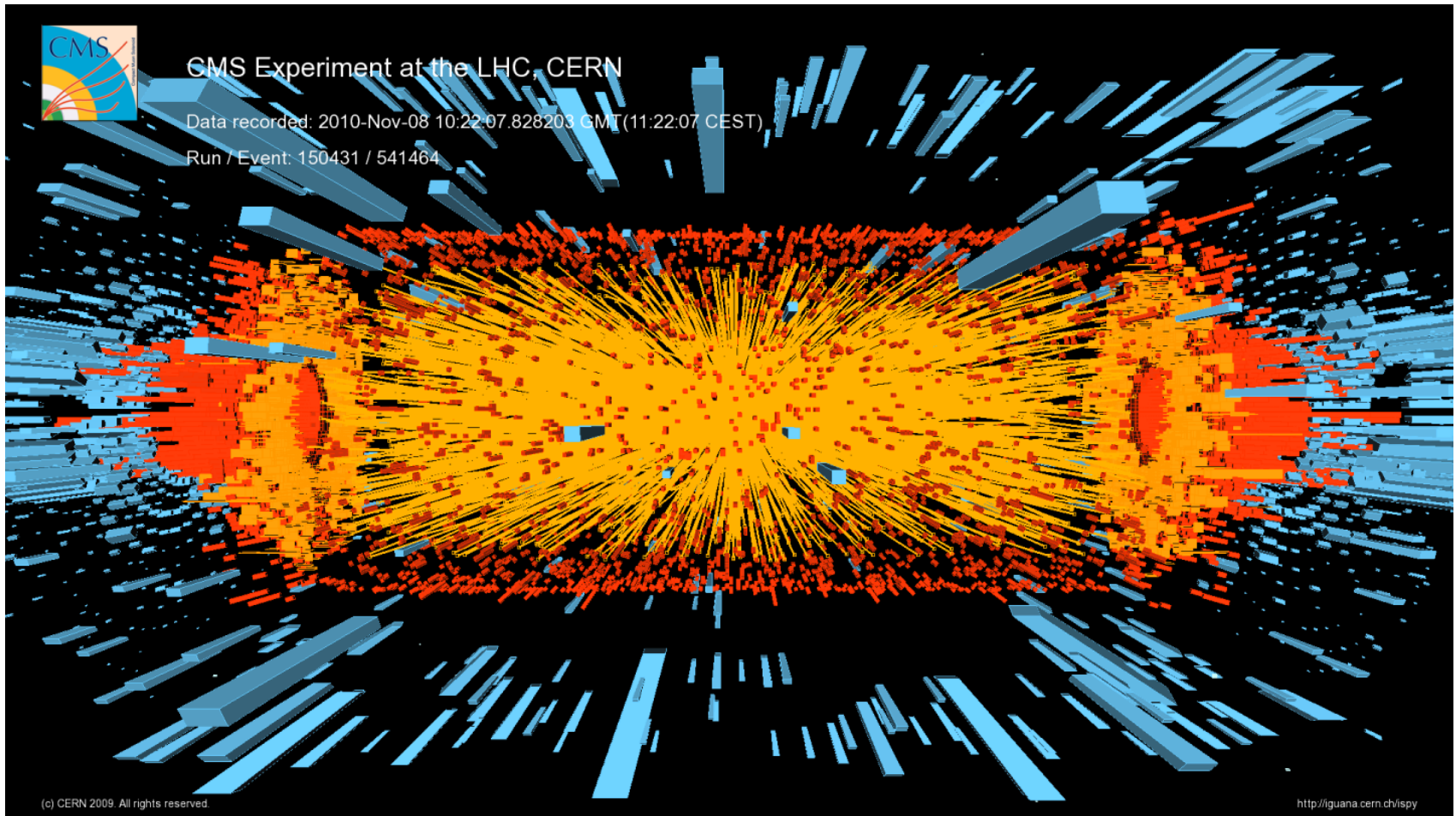


- 1) Prior to collision relativistic nuclei are Lorentz contracted
- 2) After crossing, particles start to scatter ($\tau \sim 1/p$)
- 3) After $t \sim 1$ fm, equilibrium is established, giving a thermalized QGP
- 4) QGP expands and cools until about 10 fm (3×10^{-23} sec !)
- 5) Hadronization occurs (chemical freeze-out), and shortly after particles stop interacting and free stream towards detectors (kinetic freeze-out)

How does one learn about the fleeting QGP from the mess of final state particles we detect?

Important to understand the *initial state*, as well as how to draw conclusions from the *final state* hadrons

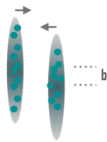
A real heavy-ion collision



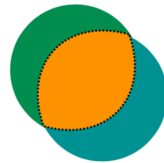
The role of geometry

Not all heavy-ion collisions are created equal, but rather vary in *centrality*

Some are head-on or “central”

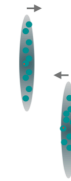


Longitudinal view

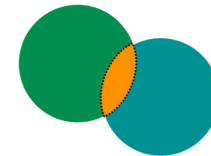


Transverse view

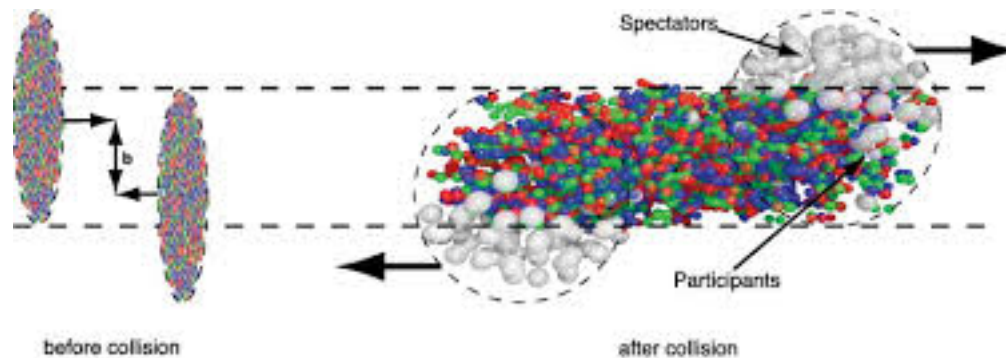
Some are glancing or “peripheral”



Longitudinal view



Transverse view



Struck nuclei are *participants*, others are *spectators*

Energy density achieved depends on # of participants

Not observable → how can we determine it a posteriori ?

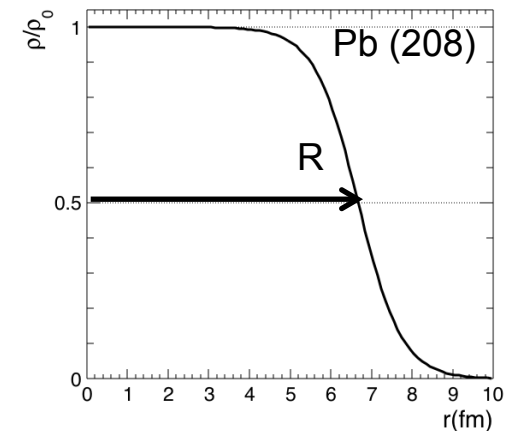
The Glauber model

- Attributed to Roy Glauber (2005 Nobel for quantum optics)
- Main assumptions:
 - Probability of nucleon-nucleon scattering independent of previous scatterings
 - Nucleons move in straight-line trajectories undeflected
- Woods-Saxon distribution of nuclear charge density

e.g., for Pb(208)
 $R = 6.68 \text{ fm}$
 $a = 0.55 \text{ fm}$

$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]} \quad (\text{spherical case})$$

nuclear size
surface thickness

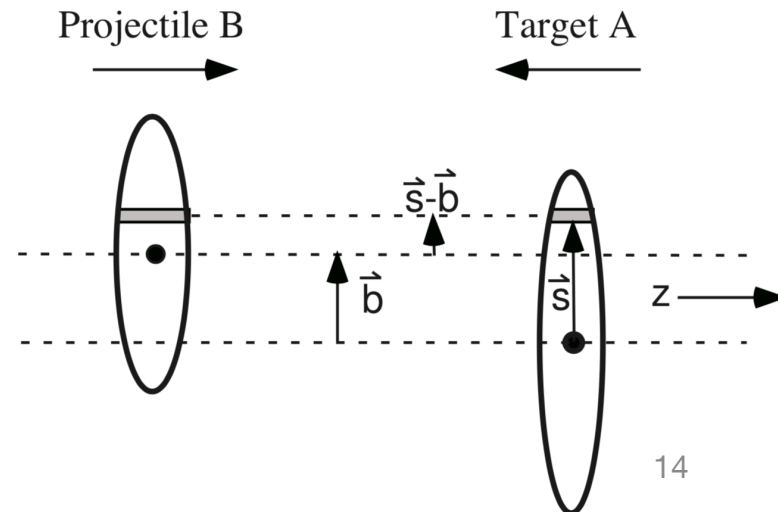


- Nuclear thickness function in the optical limit

Define nuclear thickness $T_A(\vec{s}) = \int \rho_A(\vec{s}, z) dz$ where $\int T_A(\vec{s}) d^2s = A$

Take the product of nucleus A & B, and integrate over s :

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



Two key numbers: N_{coll} & N_{part}

- The total number of inelastic nucleon-nucleon collisions

$$N_{\text{coll}}(b) = T_{\text{AB}}(b) \cdot \sigma_{\text{inel}}^{\text{nn}}$$

- The total number of participants or “wounded nuclei”, derivation:

Prob. for a nucleon in nucleus A to scatter with one from nucleus B:

$$p_{\text{int}} = T_B(\vec{s} - \vec{b}) \cdot \sigma_{\text{inel}}^{\text{nn}} / B$$

Prob. for a nucleon in A not to interact: $(1 - p_{\text{int}})^B$

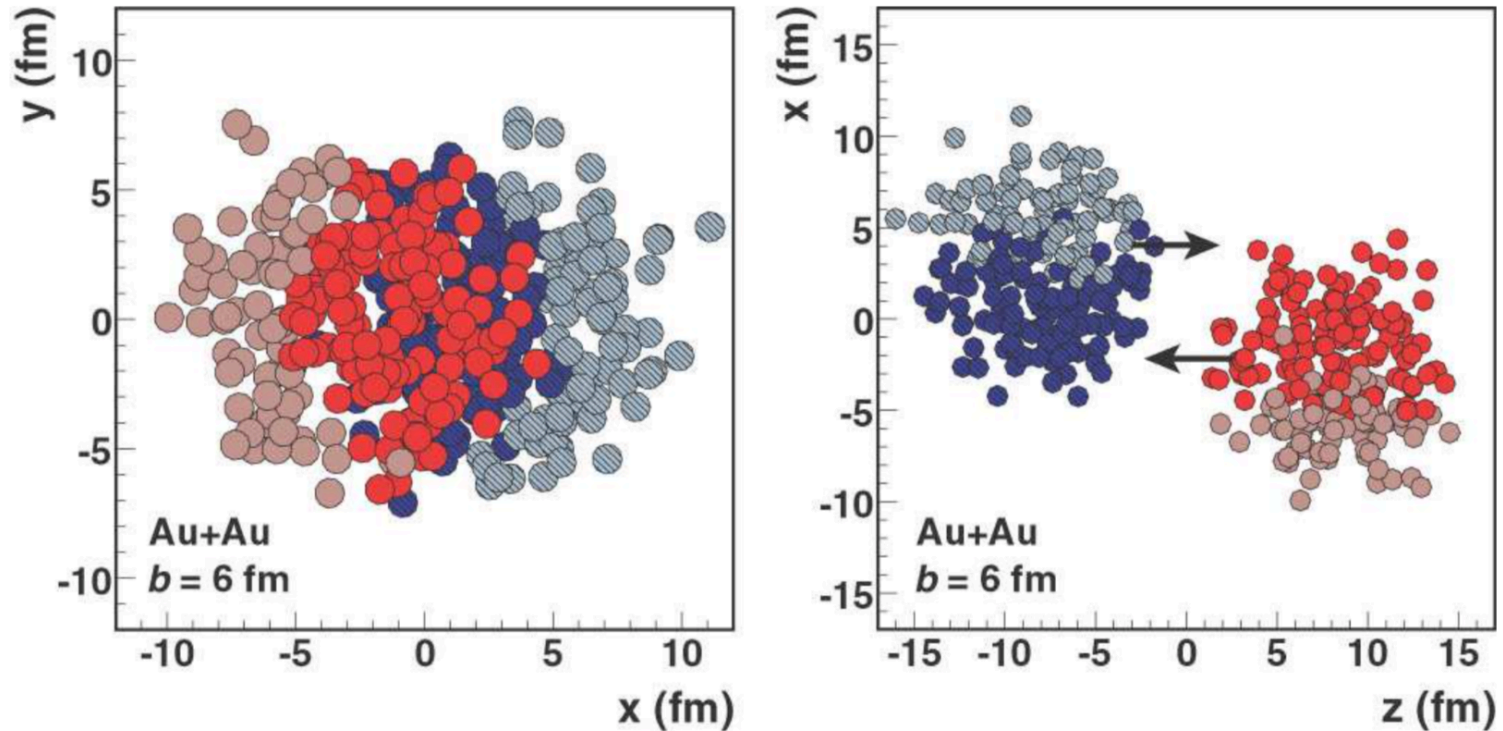
Prob. for a nucleon in A to interact at least once: $1 - (1 - p_{\text{int}})^B$

Number of participants from A:

$$N_{\text{part}}^{\text{A}} = \int T_{\text{A}}(\vec{s}) \cdot \left(1 - \left[1 - T_B(\vec{s} - \vec{b}) \cdot \sigma_{\text{inel}}^{\text{nn}} / B \right]^B \right) d^2s$$

Number of total participants: $N_{\text{part}}(b) = N_{\text{part}}^{\text{A}}(b) + N_{\text{part}}^{\text{B}}(b)$

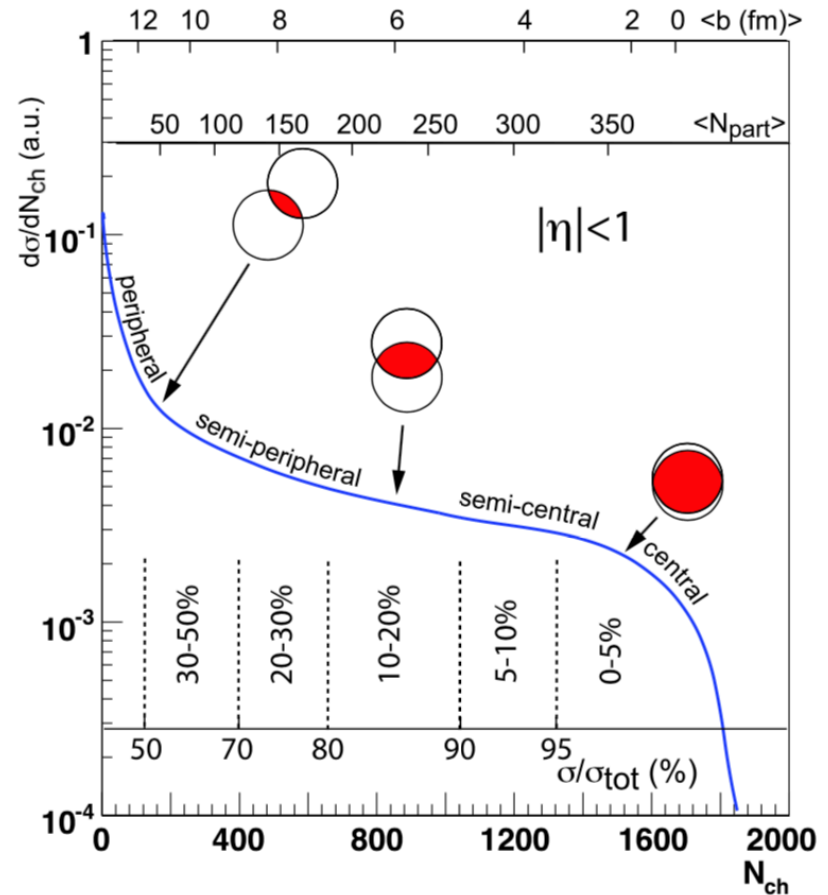
Glauber Monte Carlo



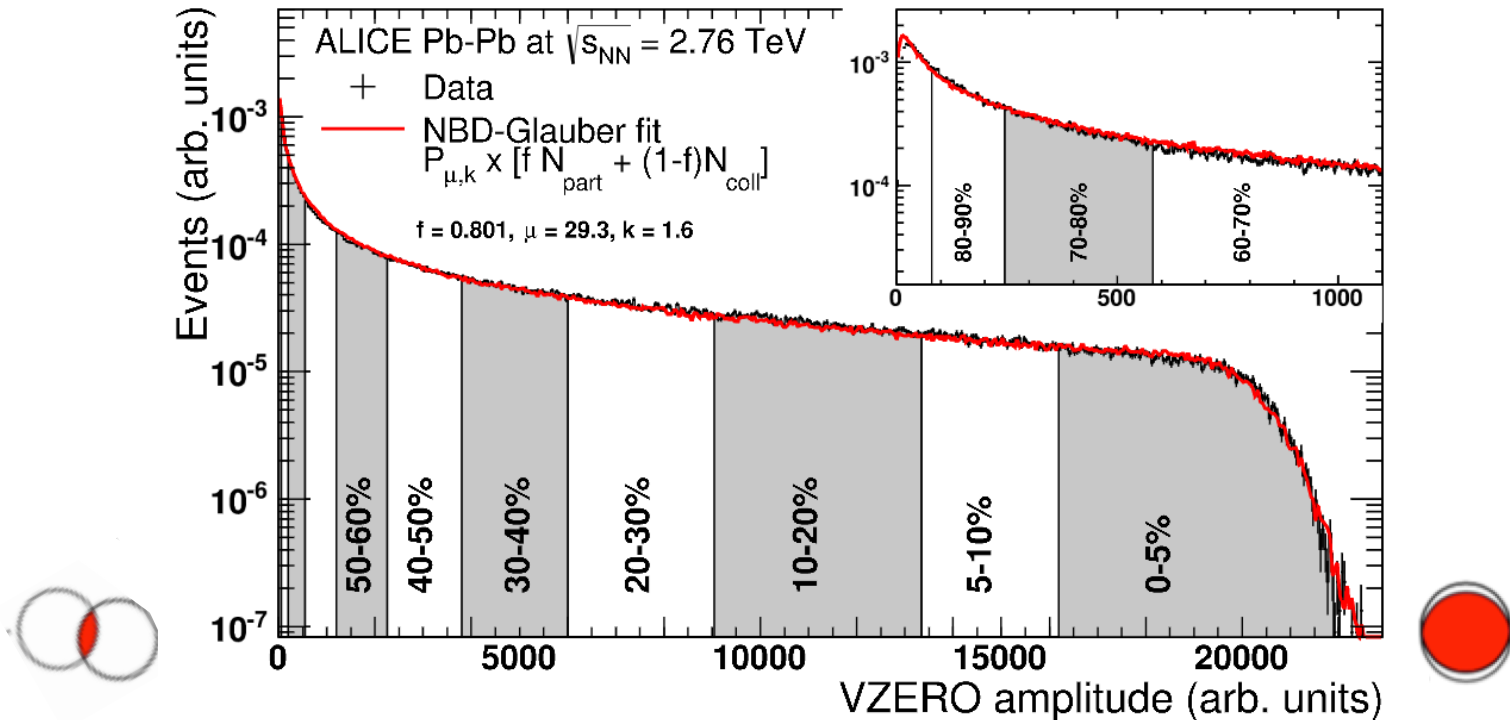
- In MC approach nucleon density discrete rather than continuous
- Sample nucleon positions according to nuclear density distribution
- Nucleons interact if their distance $d < \sqrt{(\sigma^{nn}/\pi)}$
- Fluctuations in overlap geometry will turn out to be important

Centrality

- Centrality is based on an observable, typically event multiplicity, with a monotonic dependence on Glauber quantities, e.g., N_{part}
- Multiplicity then calculated from Glauber
 - Nucleon-nucleon multiplicity parameterized by a negative binomial distribution, verified in pp
 - Total AA multiplicity assumed to scale w/ N_{part}
 \rightarrow randomly sample the n.b.d. N_{part} times
- The multiplicity distributions in data and Glauber then divided into centrality classes, i.e., percentiles of the total cross section
- While centrality is detector dependent, corresponding Glauber values, e.g., $\langle N_{\text{part}} \rangle$, are approximately experiment independent



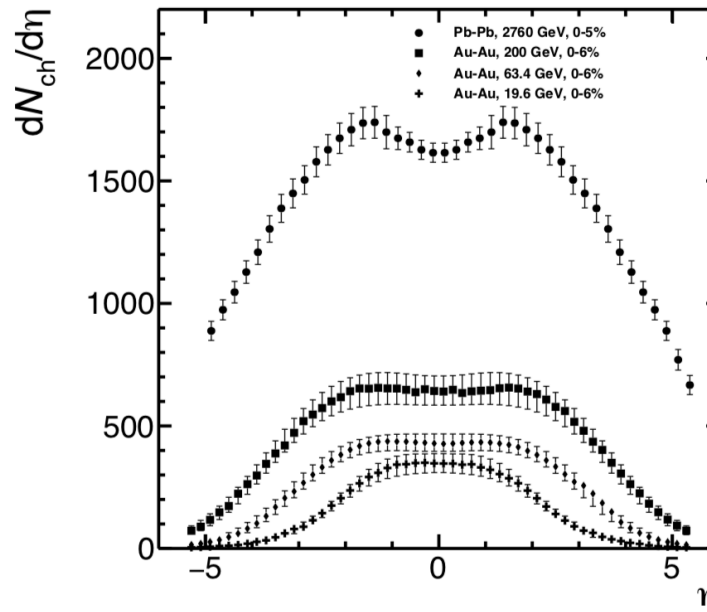
Centrality example: ALICE



- VZERO are scintillators at forward η , collected charged proportional to multiplicity
- Centrality typically measured at forward η to be independent from mid-rapidity measurements
- Glauber-based fit provides an excellent description of the VZERO charge distribution

Multiplicity

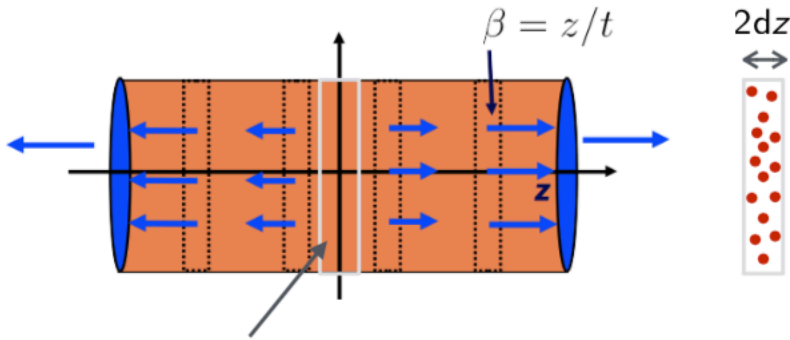
Multiplicity can also be used to constrain the energy density created in HICs



1.7k charged particles
per unit η at mid-rapidity

Notice the flat (pseudo)rapidity dependence near mid-rapidity
This *longitudinal boost invariance* emerges naturally in a
commonly used space-time picture of heavy-ion collisions

The Bjorken picture



Consider total energy in slice at $z = 0$ at time τ_0

Consider nuclei as relativistic pancakes, which cross at the speed of light

- Beam remnants continue at forward y
- Mid- y dominated by produced particles

Radius given by nuclear size

Main assumptions of the model:

- Homogenous expansion of cylinder in z direction, i.e., 1D ideal hydrodynamics
- Particles materialize at formation time τ_0 in their rest frame

Velocity in this system: $\beta = z/t$ $\tau = t/\gamma$

$$\epsilon = \frac{E}{V} = \frac{1}{A} \frac{dE}{dz} \bigg|_{z=0} = \frac{1}{A} \frac{dy}{dz} \bigg|_{z=0} \frac{dE}{dy} \bigg|_{y=0} \uparrow = \frac{1}{A \cdot \tau_0} \frac{dE}{dy} \bigg|_{y=0}$$

Standard relation for rapidity

$$\sinh y = \beta\gamma = z/\tau$$

From multiplicity to E_T

Although E_T is measurable with calorimeters, heavy-ion experiments typically measure charged particle multiplicity

$$\frac{dE_T}{d\eta} \approx \langle m_T \rangle \frac{3}{2} \frac{dN_{ch}}{d\eta}$$

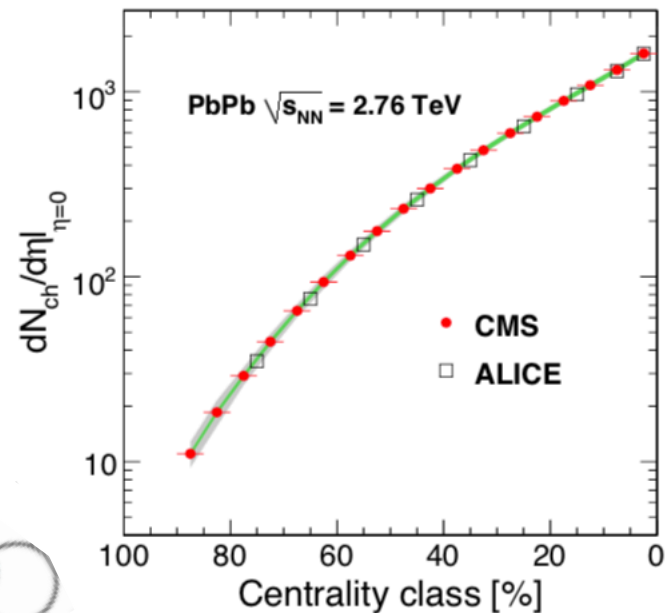
$$m_T^2 = m^2 + p_T^2$$

About 0.65 GeV for pions at the LHC

Mass isn't known unless particles are identified \rightarrow need a correction

$$\frac{dE_T}{dy} = J(y, \eta) \frac{dE_T}{d\eta}$$

\swarrow
 $J(y, \eta) \approx 10\%$



Estimating energy density

$$\epsilon = \frac{1}{A \cdot \tau_0} \left. \frac{dE_T}{dy} \right|_{y=0}$$

$$A = \pi R^2 = \pi (7 \text{ fm})^2 \text{ for lead}$$

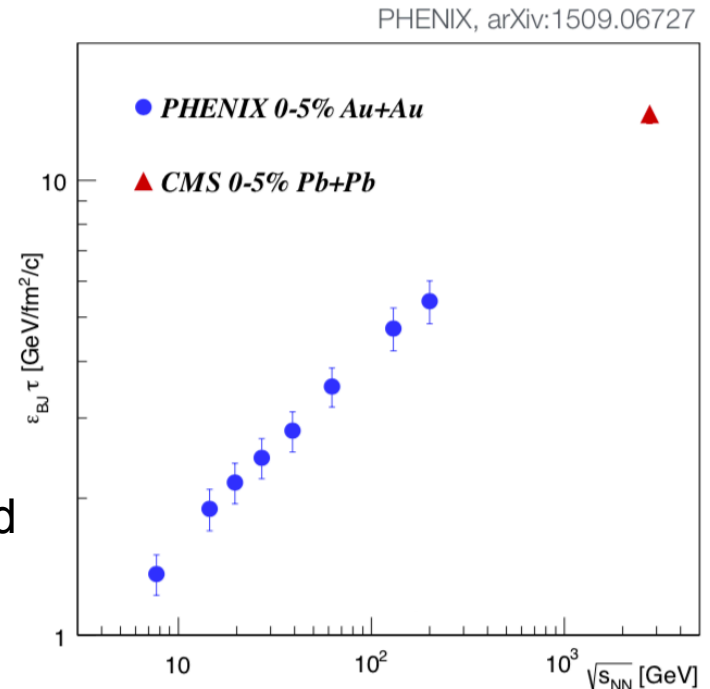
Traditionally assumed that $\tau_0 \sim 1 \text{ fm}$

We'll see later that short formation time is justified

$dE_T / dy|_{y=0} \sim 2 \text{ TeV}$ in central collisions at the LHC

$$\rightarrow \epsilon = 13 \text{ GeV/fm}^3$$

Well in excess of $\epsilon = O(1) \text{ GeV/fm}^3$
for phase transition from lattice QCD



Statistical hadroproduction

What determines the abundance of different hadron species?

- Hadronization is non-perturbative
- Various pheno. models for elementary collisions (cluster, string, etc.)
- For heavy ions instead appeal to thermodynamics
- Postulate that QGP cools into an equilibrated gas of hadrons;
Particle number conserved only over entire volume, not locally
→ grand canonical ensemble
- Particle density given by derivative of the partition function

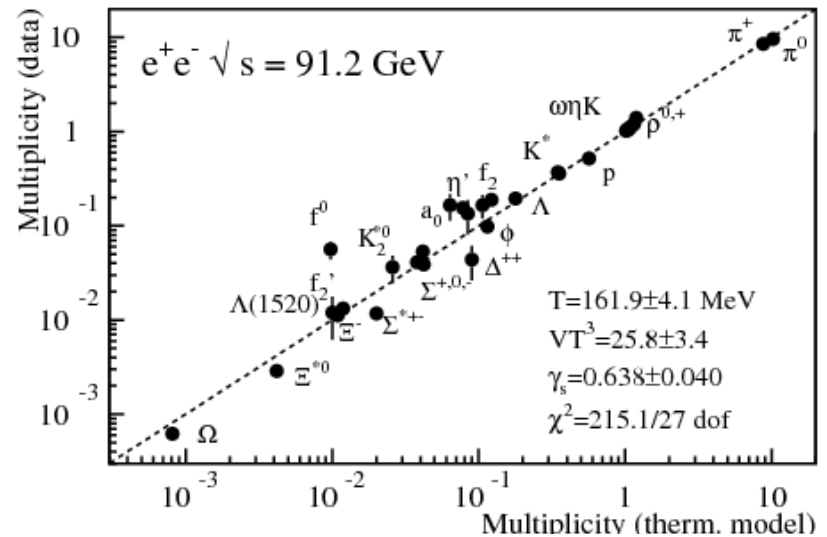
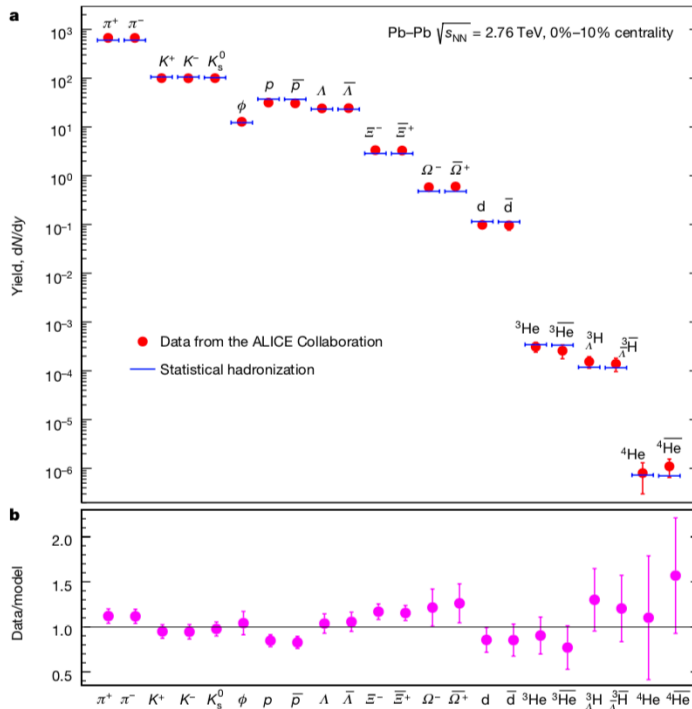
$$n_i = N/V = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp((E_i - \mu_i)/T) \pm 1}$$

- Each conserved quantum number gives a chemical potential μ_i , e.g., charge, baryon number, etc.
- Temperature can be obtained by a fit to the abundance of states

Statistical description of data

$T_{cf} = 156.5 \pm 1.5$ MeV, $\mu_b = 0.7 \pm 3.8$ MeV and $V = 5,280 \pm 410$ fm³.

← Fit result



Fit to the heavy-ion data gives a T of 156 MeV close to the predicted critical temp.

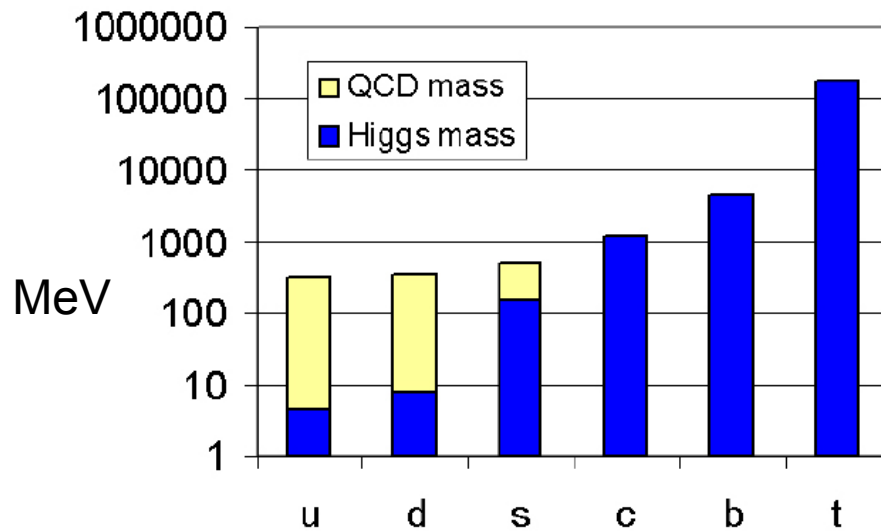
Also work for e^+e^- , but with canonical ensemble (local, not global equilibrium)

→ Statistical production appears to be a generic feature of hadronization

However, an extra chemical potential γ_s is needed in e^+e^- for strange particles

For more details on statistical hadronization see the Nature article handout

The strange quark



Light quark (“dressed”) mass
dynamically generated by QCD

Heavy quark mass directly from
the Higgs mechanism

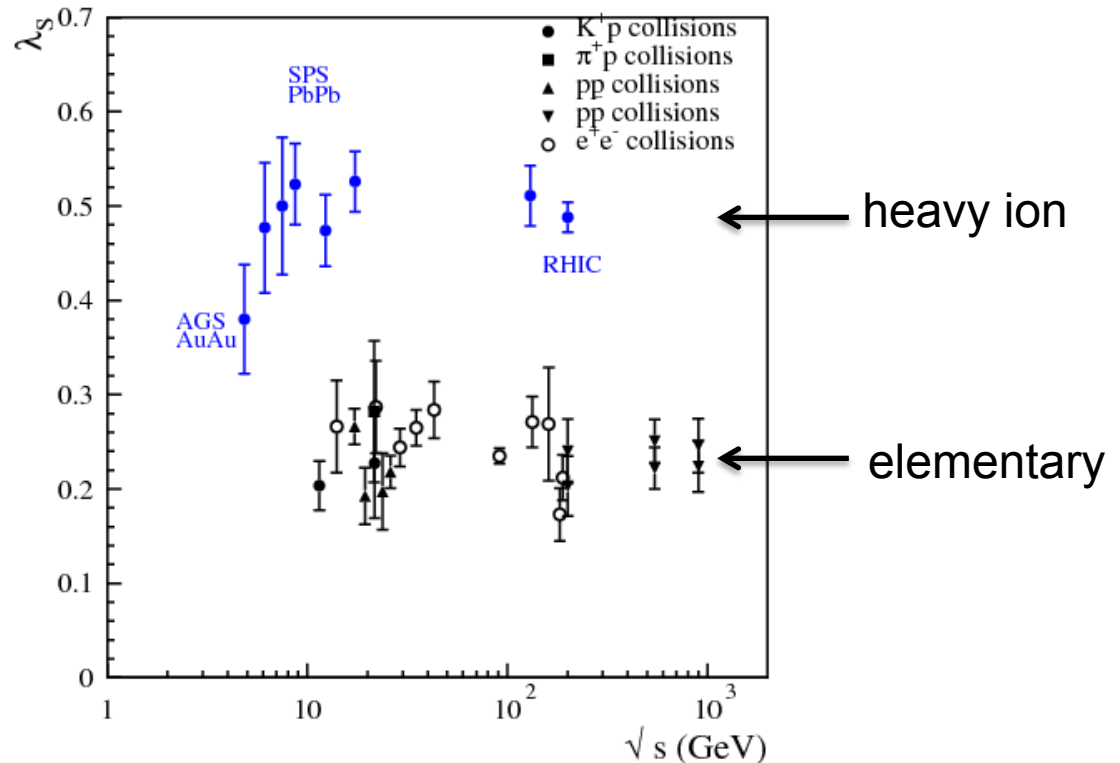
Strange quark is special: both
mechanisms contribute

- Bare mass ~ 100 MeV
- Kaon mass ~ 500 MeV

- Because T_c in excess of the strange quark mass, expect thermal production
- In elementary collisions strangeness is locally conserved
→ γ_s reflects this “canonical suppression”
- In an equilibrated QGP, expect conservation only over global volume ($\gamma_s = 1$)

Strangeness enhancement

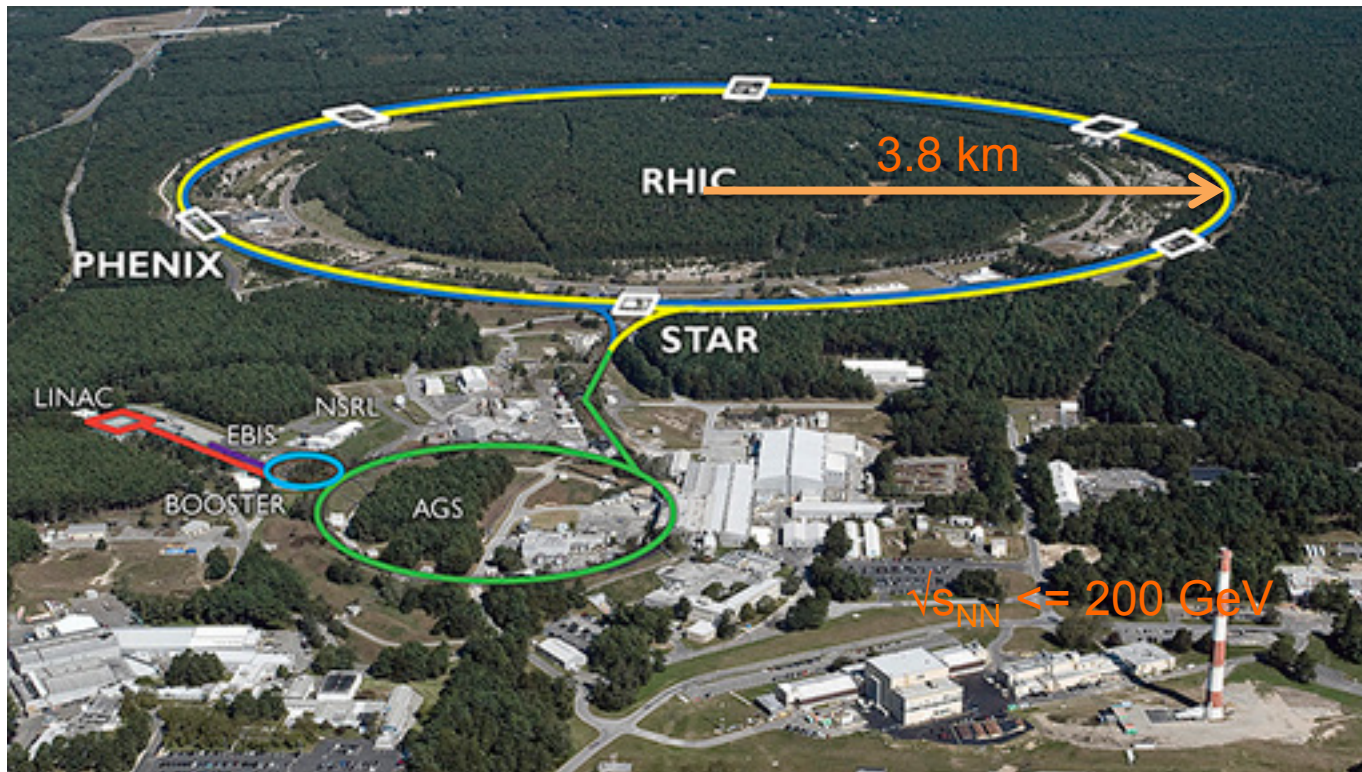
$$\lambda_s = \frac{2\langle s\bar{s} \rangle}{\langle u\bar{u} \rangle + \langle d\bar{d} \rangle}$$



Strangeness indeed enhanced by 2x in AA, compared to elementary collisions
 Larger enhancement factor for multi-strange hadrons (~7x for Ξ , ~15x for Ω)
 Supports picture of QGP as an equilibrated state over a large volume

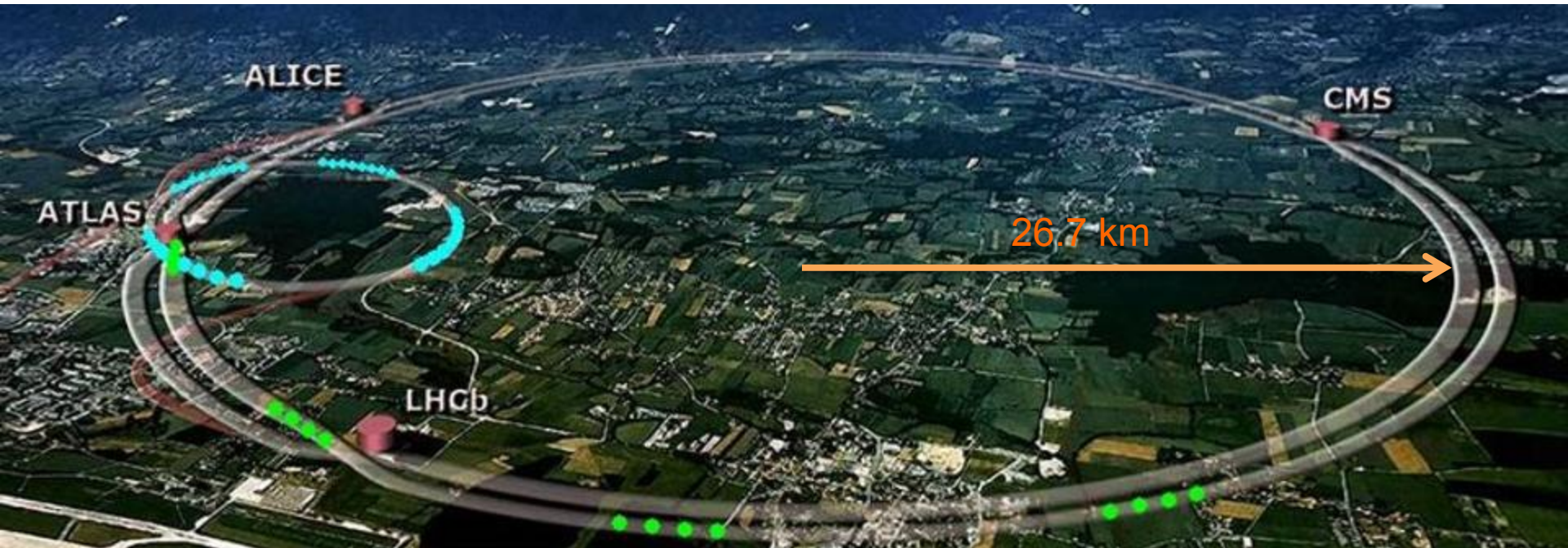
Heavy-ion experiments

RHIC @ Brookhaven



- The first HI collider, after many years of fixed target expt's
- First collisions in 2000, continues to operate today
- STAR searching for the critical point with a beam energy scan
- PHENIX currently being upgraded to sPHENIX for ~ 2023

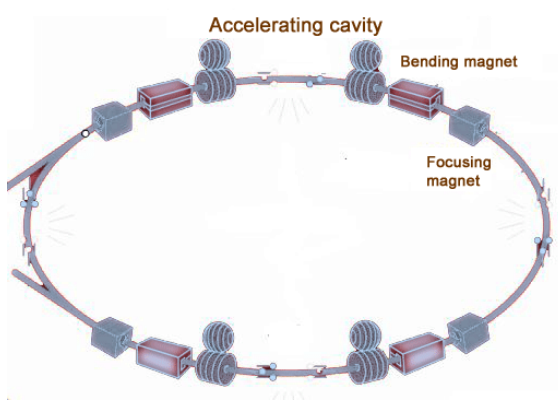
The LHC @ CERN



Collides heavy ions for ~ 1 month per year (PbPb, pPb, ArAr so far)

In operation, since 2010

ALICE dedicated to HI program, but interesting things can also be done with HEP detectors (ATLAS, CMS, and recently LHCb)



Ion beams

Max energy determined by bending power of magnets

$$E \propto \frac{Z}{A}$$

← charge
← mass

Using the Mandelstam variable $s = (p_1 + p_2)^2$, 4-vectors
↙
can derive the equivalent COM beam energy for heavy-ion beams

LHC

Early Run 1, max pp $\sqrt{s} = 7 \text{ TeV} \rightarrow \text{PbPb } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV } (7 \cdot Z/A)$

Later Run 1, max pp $\sqrt{s} = 8 \text{ TeV} \rightarrow \text{pPb } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV } (8 \cdot \sqrt{Z/A})$

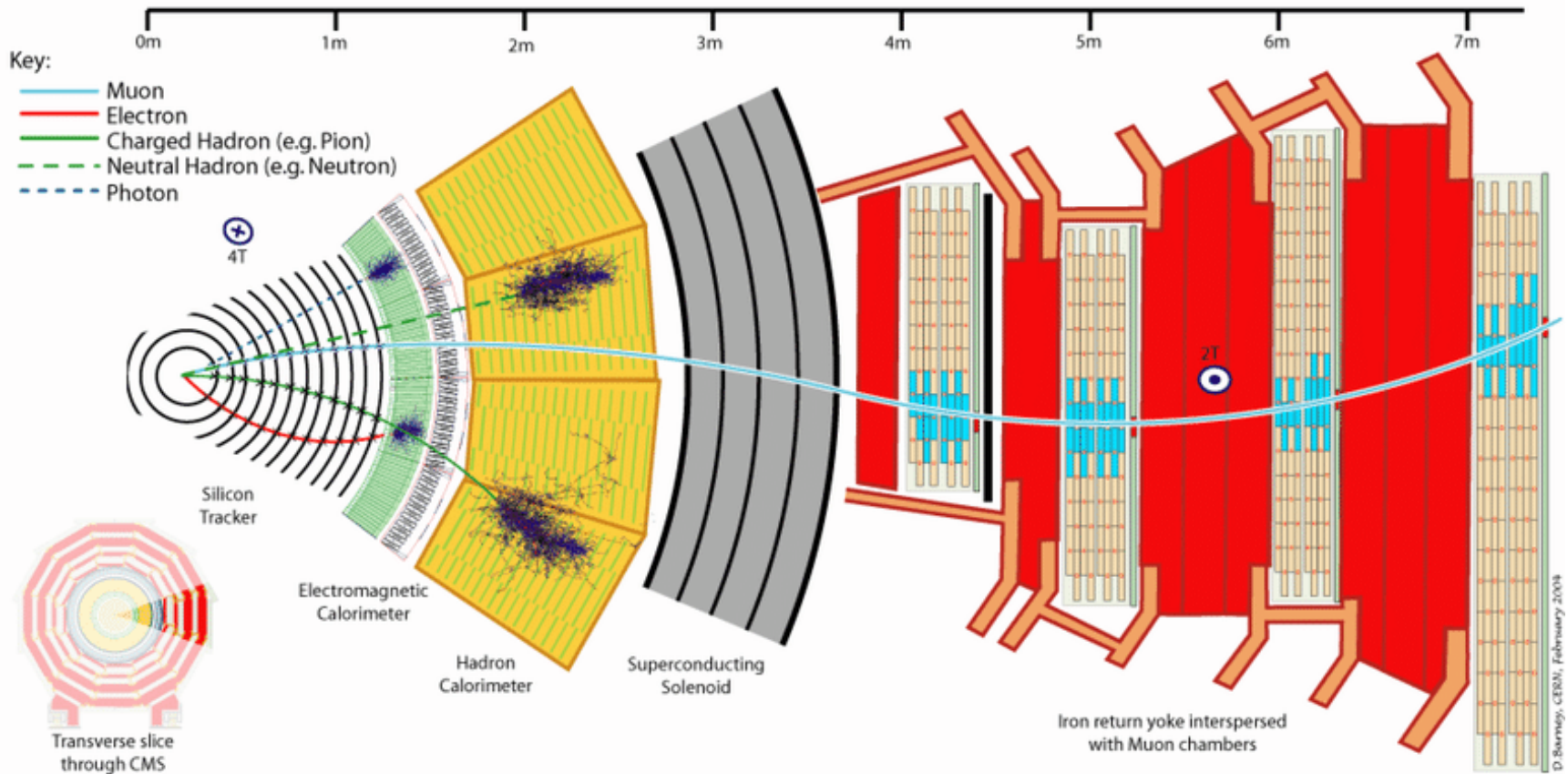
Run 2, max pp $\sqrt{s} = 13 \text{ TeV} \rightarrow \text{PbPb } \sqrt{s_{\text{NN}}} = 5.12 \text{ TeV } (13 \cdot Z/A)$

$\rightarrow \text{pPb } \sqrt{s_{\text{NN}}} = 8.16 \text{ TeV } (13 \cdot \sqrt{Z/A})$

$Z = 82$
 $A = 208$

At RHIC, AuAu $\sqrt{s_{\text{NN}}} = 200 \text{ GeV} \rightarrow \text{pp } \sqrt{s} = 500 \text{ GeV}$ (polarized!)

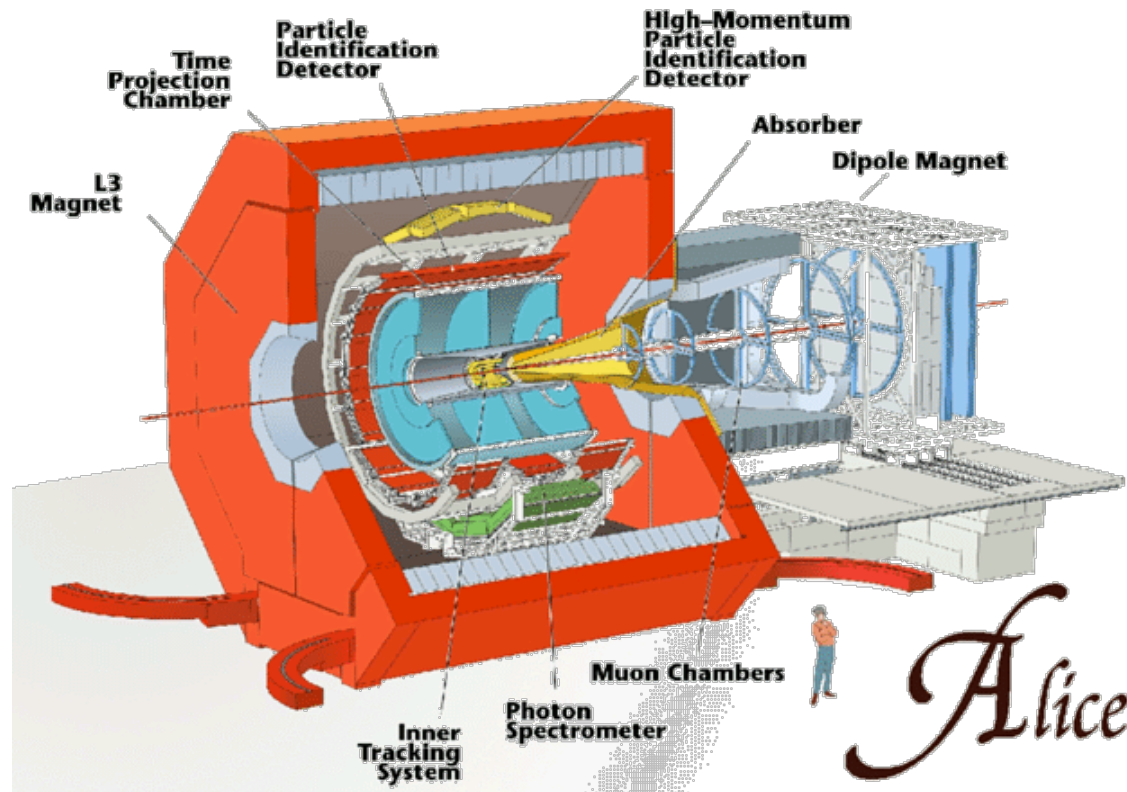
HEP detectors



- Fast & triggerable for huge luminosity
- Precision silicon tracking + high B field, e.g, for b-tagging
- Hermetic calorimeters for jets and missing E_T
- Isolated photons and leptons for EW bosons, Higgs, top

Ex: ATLAS, CMS
Also sPHENIX
follows HEP model

Heavy-ion detectors



- Tracking w/ gaseous detectors for high occupancy, e.g., TPCs (STAR, ALICE)
- Low p_T reach is essential for “bulk” observables
- Emphasis on particle ID, e.g., TOF, dE/dx , RICH
- Low p_T photons and leptons important, often forward η muon detectors independent from barrel system (ALICE, PHENIX)

Probes of the QGP

Observable	Property of the QGP
Strangeness enhancement	Chemical equilibrium
Jet quenching	Density
Quarkonia melting	Temperature
Particle correlations	Collectivity, Viscosity
Thermal photons	Temperature
Hanbury Brown Twiss correlations	Size

And many more...

Summary of today's lecture

- Heavy-ion collisions used to explore QCD at high energy density
- Matter crosses over to a deconfined state, the quark-gluon plasma
- Collision centrality related to observables via a Glauber model
- Energy density estimated from mid-rapidity multiplicity in Bjorken's picture
- Extended QGP alters chemical composition of produced matter, increasing strangeness
- Currently colliding heavy ions at RHIC & LHC w/ various detectors

Tomorrow

Select phenomena / observables for heavy ions:
collective flow, jet quenching and quarkonia melting