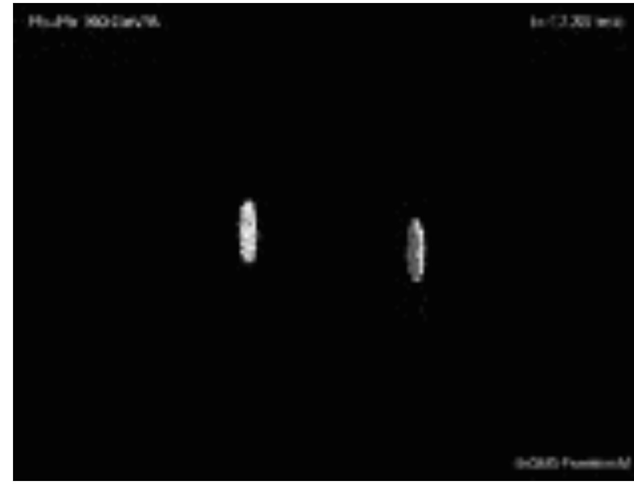
Heavy Ion Collision Physics

Adam Trzupek
adam.trzupek@ifj.edu.pl
Institute of Nuclear Physics PAS
28th January 2021

KISD, Lecture: Particle physics for specialists



- The main goal is to understand the dynamics of dense and hot medium created in heavy-ion collisions
- Quantum Chromo-dynamics (QCD), a non-abelian SU(3)$_{color}$ gage theory describing strong interactions between quarks and gluons

Quantum Chromo-Dynamics (QCD)

Theory describing strong interactions between quarks and gluons

- Quarks: $\psi_i^f(x)$ spin-1/2, Dirac fermions

  color triplet: *i* = 1, 2, 3 (green, red, blue)

  flavour: *f = u, d, s, c, b, t (fractional electric charge)*

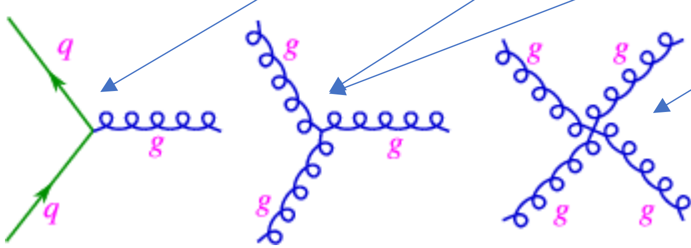
- Gluons: $A_{\mu,a}(x)$ spin-1

  color octet: *a*= 1,…,8

- QCD Lagrangian:

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - g A_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij} \right] \psi_j^f$$
$$- \frac{1}{4} \left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - g C_{abc} A_{\mu,b} A_{\nu,c} \right]^2$$

- Interactions:



"running" coupling constant

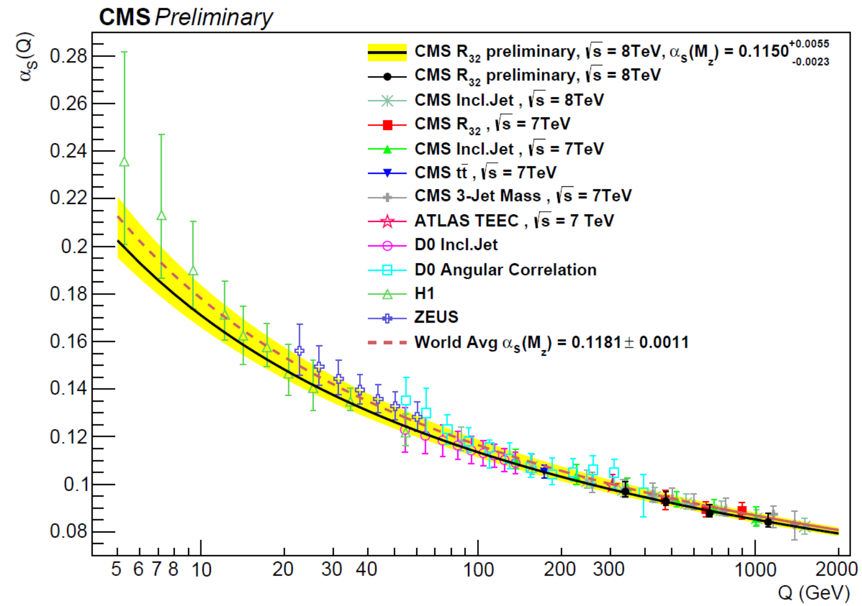
$\alpha_s = \frac{g^2}{4\pi}$

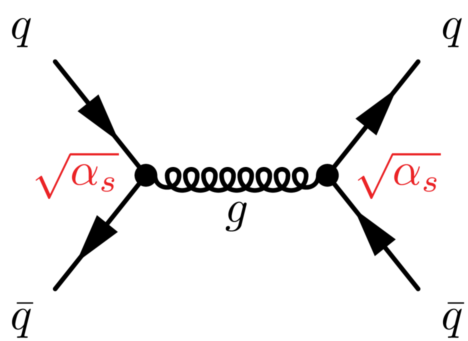
Asymptotic Freedom and Confinement

- High Q : Asymptotic Freedom

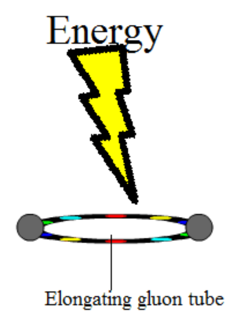
  1973 – D. Gross, F. Wilczek, D. Politzer

  - α_s decreases for r↘0 (anti-screening)
  - Perturbative expansion works α_s <<1





- Low Q: Confinement
  - α_s increases for r ↗ inf
  - Importance of non-perturbative QCD effects
    - Breakdown of perturbative calculations
  - String of gluons between quarks



wikipedia

$$V(r) \sim -\alpha/r + \sigma r$$

A Historical Remark

- 1973: The beginning of QCD as a theory of strong interactions

  D. Gross, F. Wilczek, D. Politzer

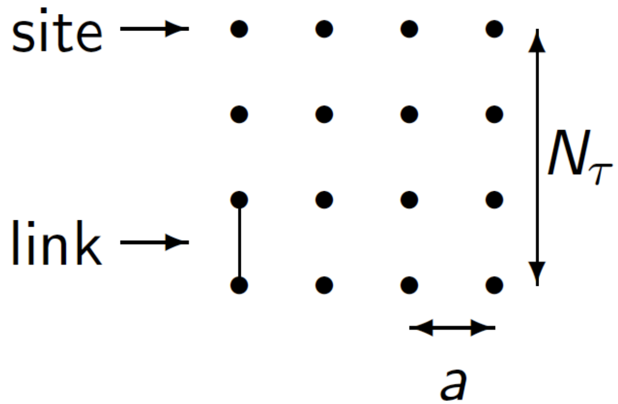
  - Quark Model + Yang-Mills gauge theory

- 1975: Prediction of a deconfined phase
  - J.C. Collins and M.J. Perry, *Superdense Matter or Asymptotically Free Quarks?,* PRL **34**, 1353

The deconfined phase of quark and gluons, called "quark soup", was later called "quark-gluon plasma (QGP)" due to analogies to similar phenomena in other physics branches

QCD Lattice - Ab-initio calculations

- In QCD, the coupling constant is large at the low energy scales, hence non-perturbative approach is used
- QCD is formulated at a discrete space-time grid $N^3_s \, x N_\tau$

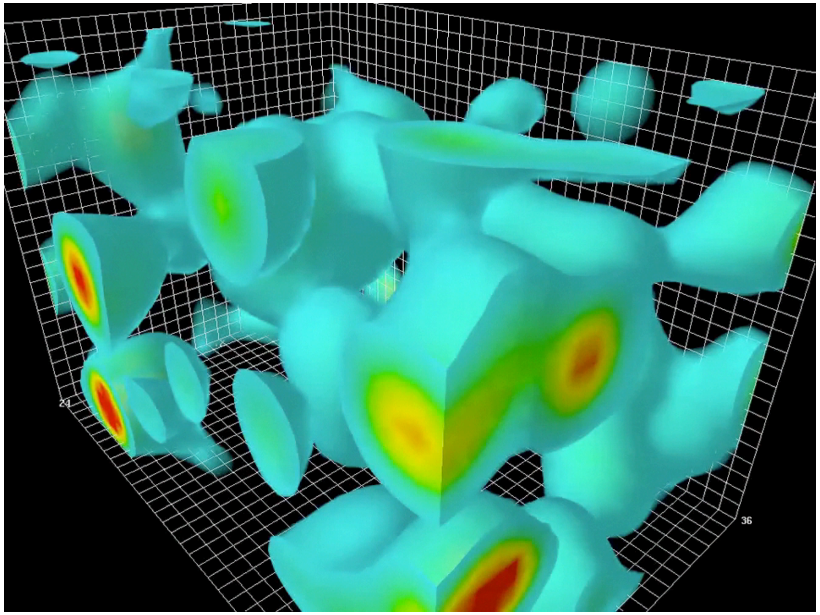


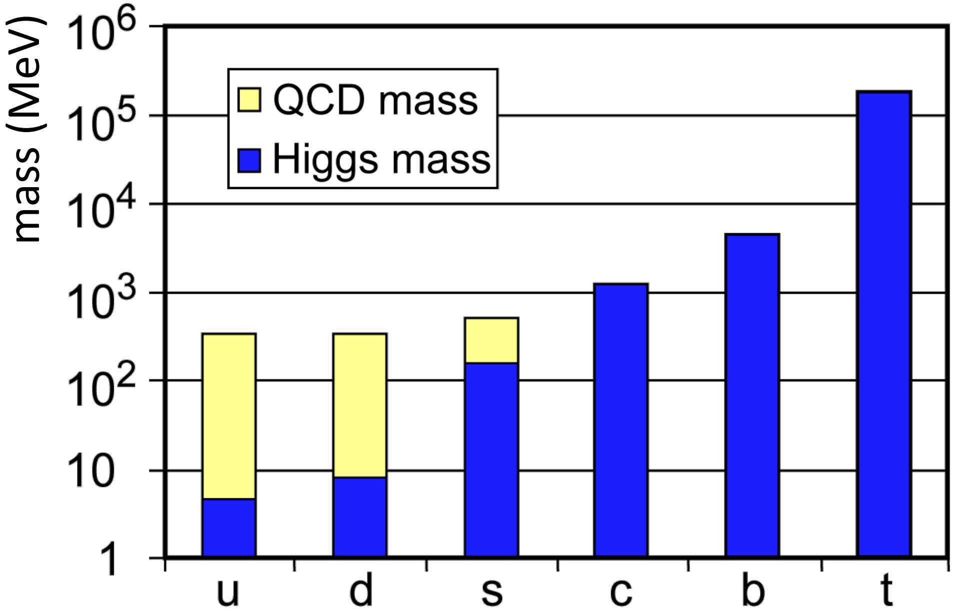
- Fermionic degrees of freedom are on the sites while links represent gauge degrees of freedom
  - Example: on lattice 32^3 x 8 there is 32^3 x 8 x 4 x 18 ≈ $2x10^7$ gauge field DoF which needs to be integrated
- Physical observables are obtained via performing path integrations of partition function with a QCD action $e^{-S_{QCD}}$ as a weight, using modern MC simulation on supercomputers

QCD Vacuum

- The vacuum of QCD is composed a condensate of gluons and quarks – "empty system" unstable

Derek Leinweber physics.adelaide.edu.au

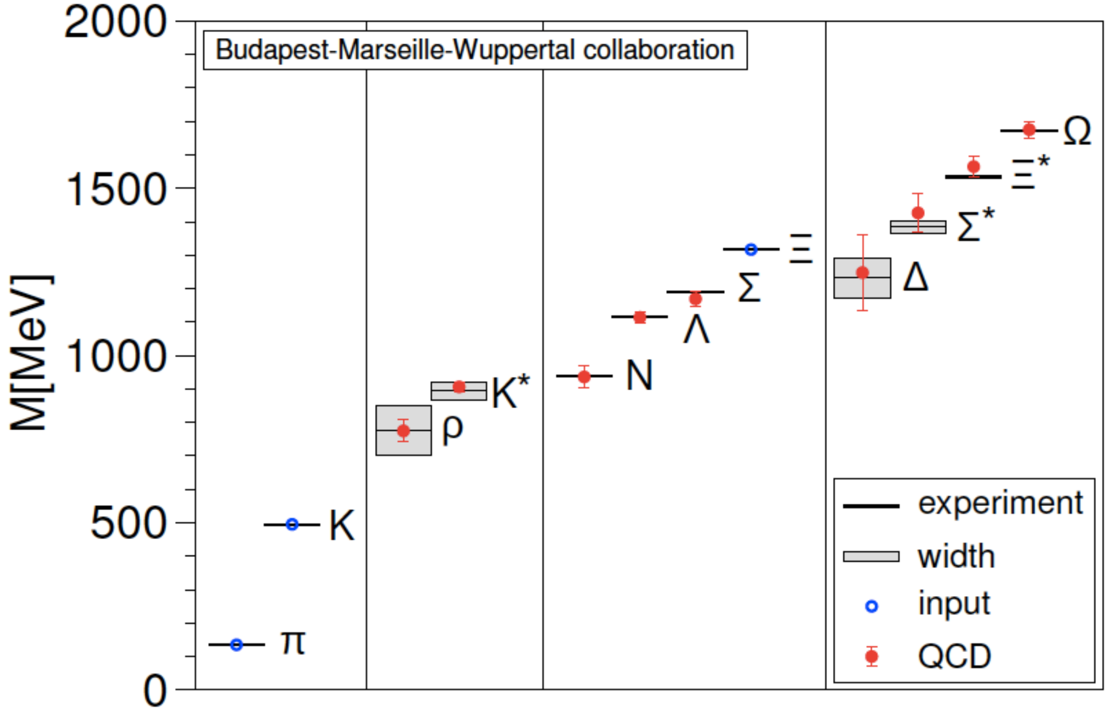




- In the limit $m \approx 0$ $\mathcal{L}_{QCD}$ is invariant with wrt $\psi_R \leftrightarrow \psi_L$ (chiral symmetry, $\psi_{L/R} = 1/2\,(1 -/+ \gamma 5)\,\psi$)
- Chiral symmetry not preserved at particle level, quark bound states, e.g. $m_p \approx 938$ MeV (natural units, $c=\hbar=1$)

Exploring Non-Perturbative Regions of QCD

Using the lattice leads to predictions for the spectrum of hadrons



arxiv 1401.6075

- Predictions from lattice-QCD agree with experimental measurements for wide variety of hadrons including light- and heavy-hadrons and proton-neutron mass difference (-1.7 MeV)

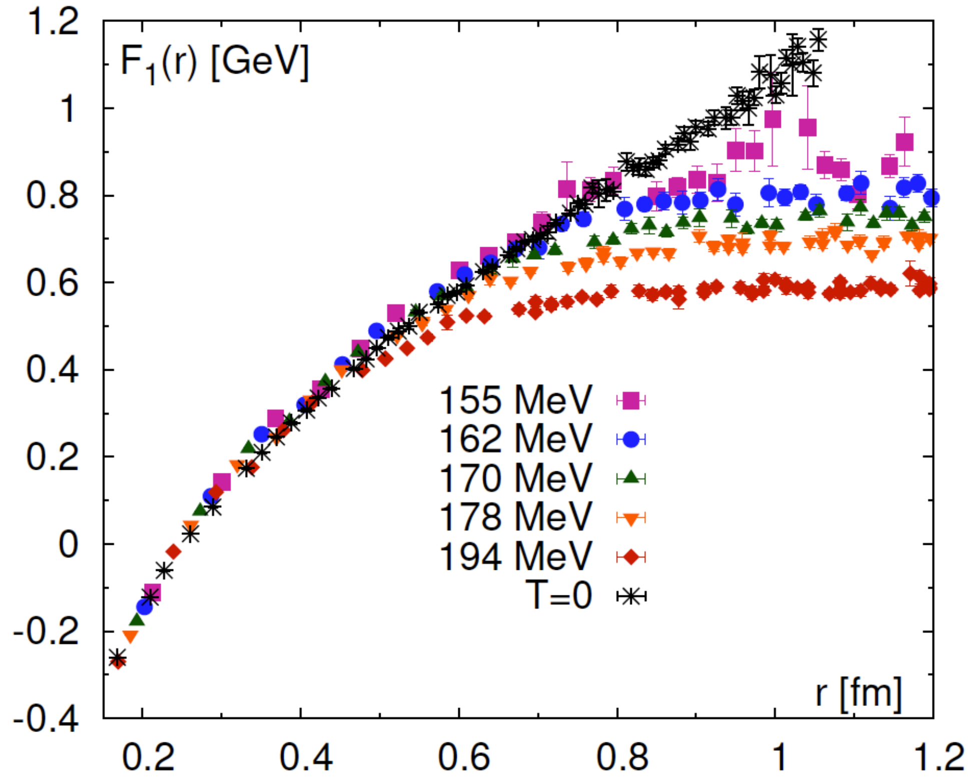
Quark Anti-quark Potential vs T - Lattice Results

- The free energy of quark anti-quark pair as function of separation r

$$V(r) \sim -\alpha/r + \sigma r$$

T=155 MeV ~ 10^{12} K

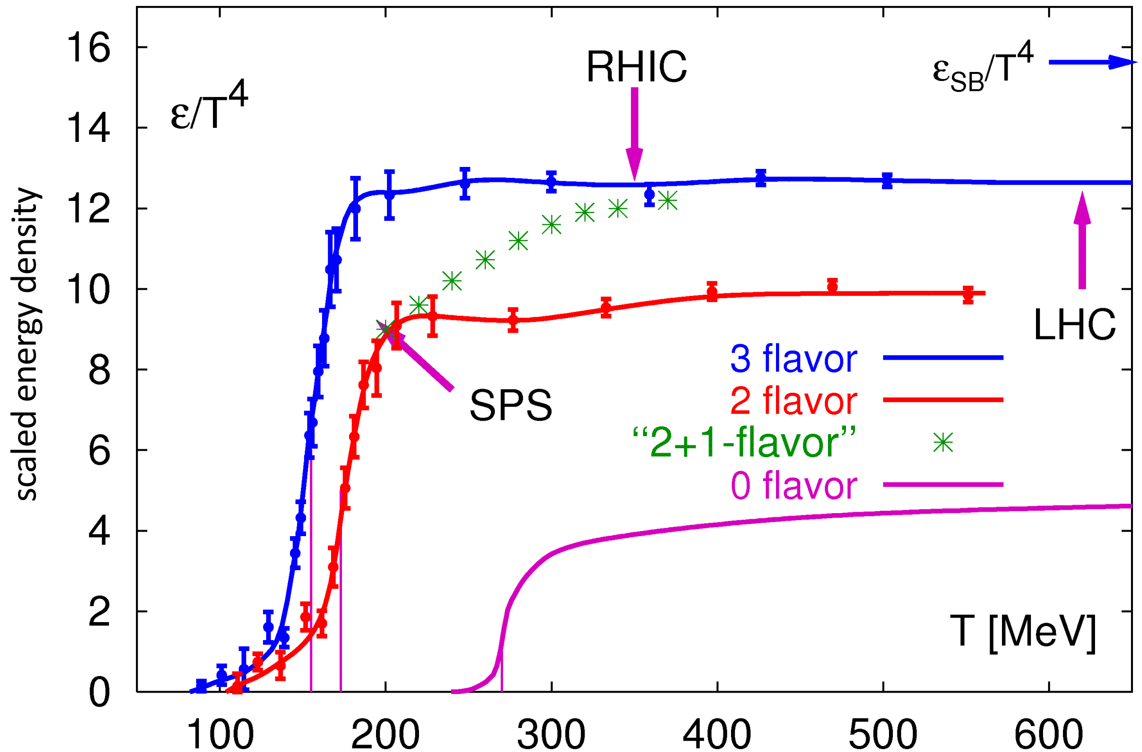
Sun core: ~ 10^{7} K



- Decrease of F_1 with increasing temperature at fixed r is related to the Debye screening effect in QGP

Thermal Behavior of QCD - Lattice Results

- Rapid rise in the number of degrees of freedom at T ~ 150 MeV
- ε below Stefan-Boltzmann limit for free quarks and gluons



[Karsch et al. (2009)]

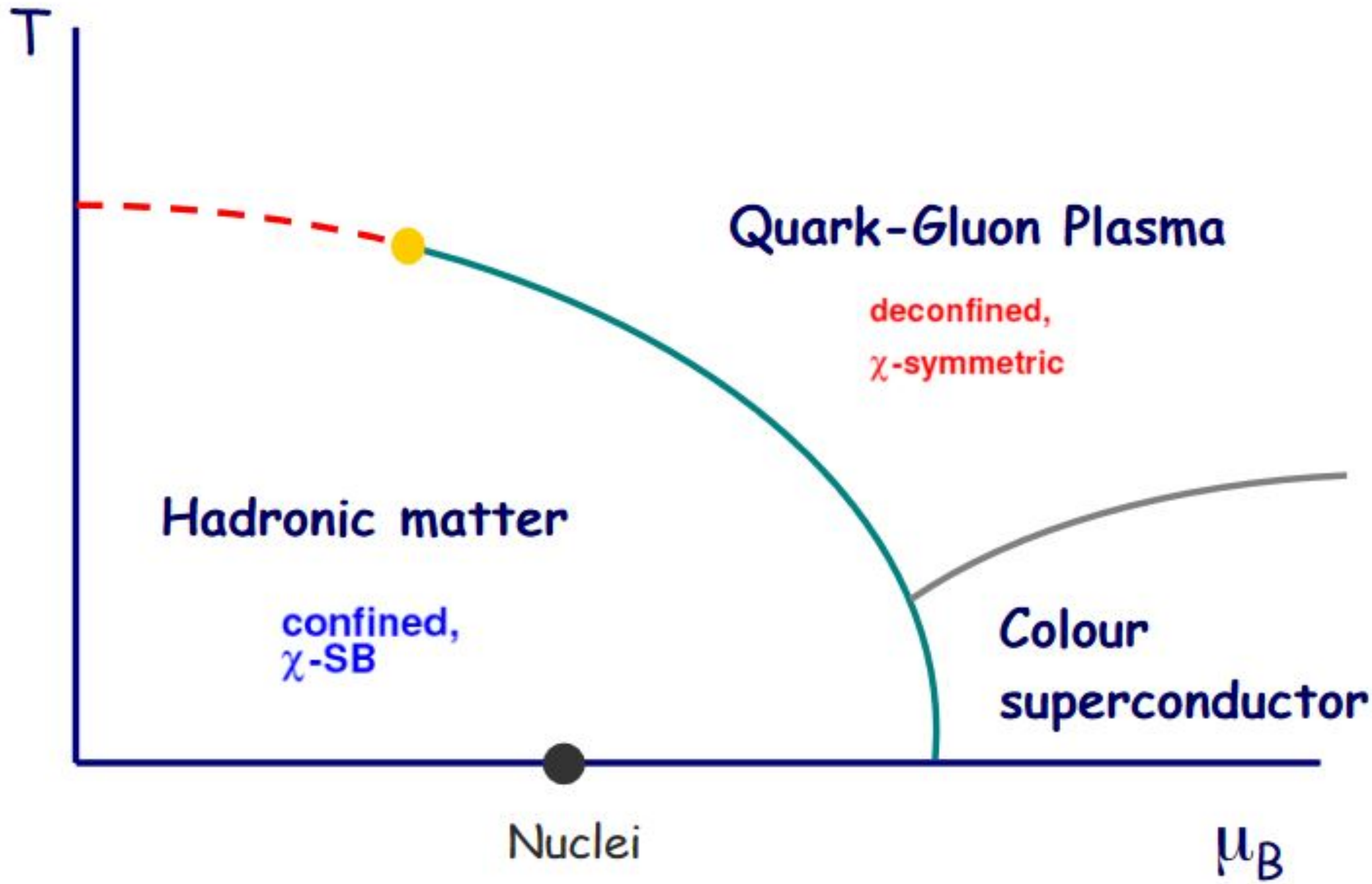
$$\varepsilon_{SB}^{g} = $$
$$= 16 \times 4\pi \int_0^\infty \frac{p^2 dp}{(2\pi)^3} \frac{p}{e^{p/T} - 1}$$
$$= 16 \times \frac{\pi^2}{30} T^4$$

$$\varepsilon_{SB}^{q} + \varepsilon_{SB}^{anti-q} = $$
$$= 36 \times 4\pi \int_0^\infty \frac{p^2 dp}{(2\pi)^3} \frac{p}{e^{p/T}+1}$$
$$= 36 \times \frac{7}{8} \frac{\pi^2}{30} T^4$$

$$\varepsilon_{SB} = \varepsilon_{SB}^{g} + \varepsilon_{SB}^{q} + \varepsilon_{SB}^{anti-q} = 15.6 \times T^4$$

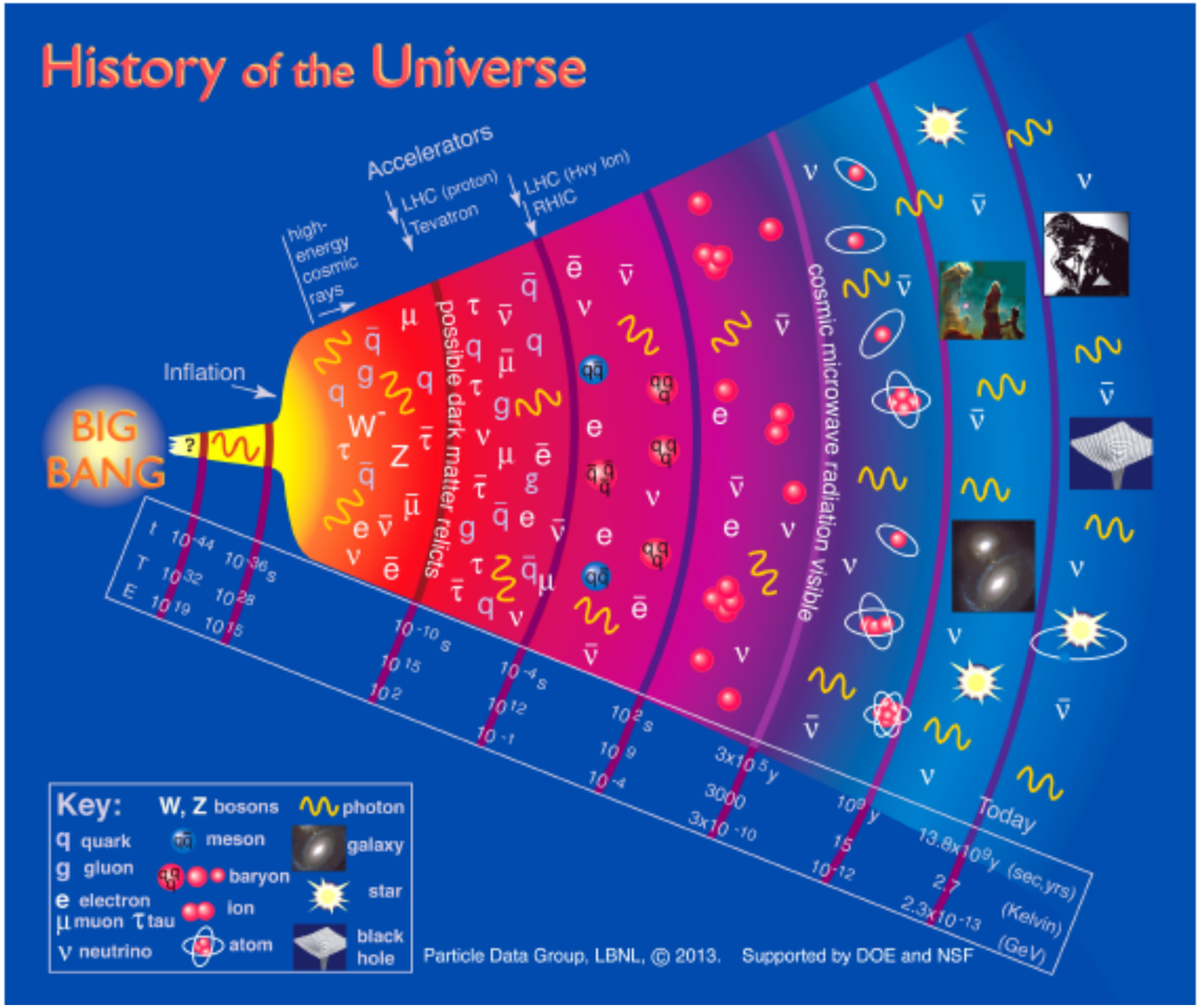
- Quantum Chromodynamics shows a rapid crossover (a smooth transition) from hadronic gas to QGP (μ_B=0)
  - T_c of 150–200 MeV, ε = 1-3 GeV/fm^3

Finite baryon density QCD matter



- Baryon chemical potential measures the imbalance between matter and antimatter

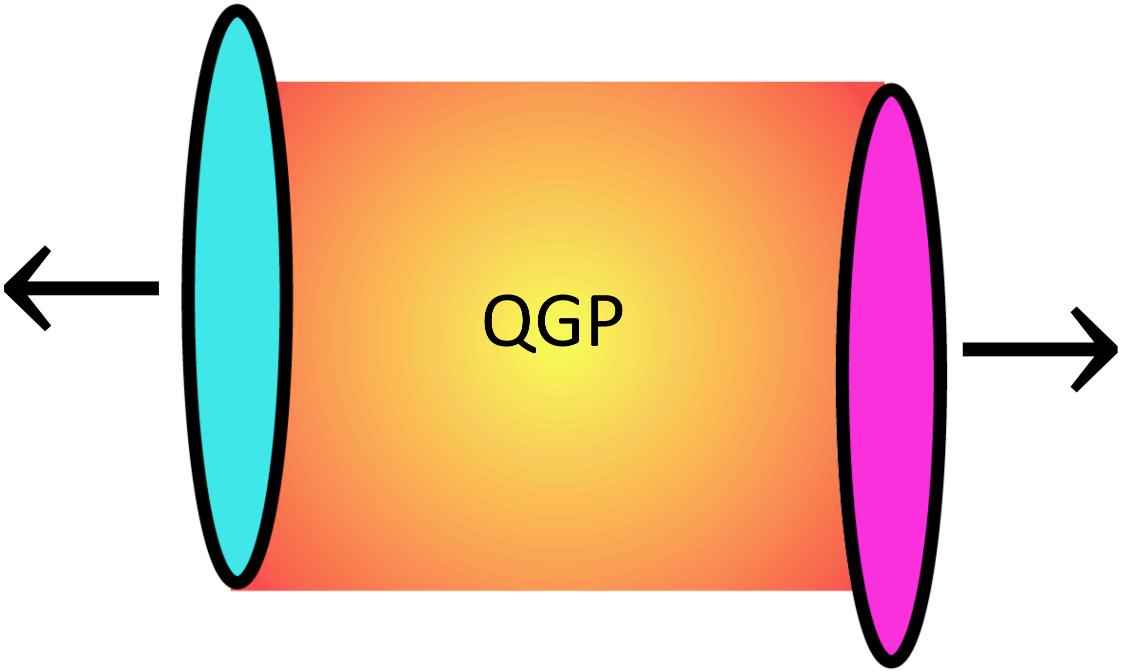
QGP in Cosmology



- QGP existed about ~10 μsec after the big bang
    - Then the temperature of the universe was about 100 000 times larger than the temperatures at the center of the sun

Schematic View of a Heavy-ion Collision

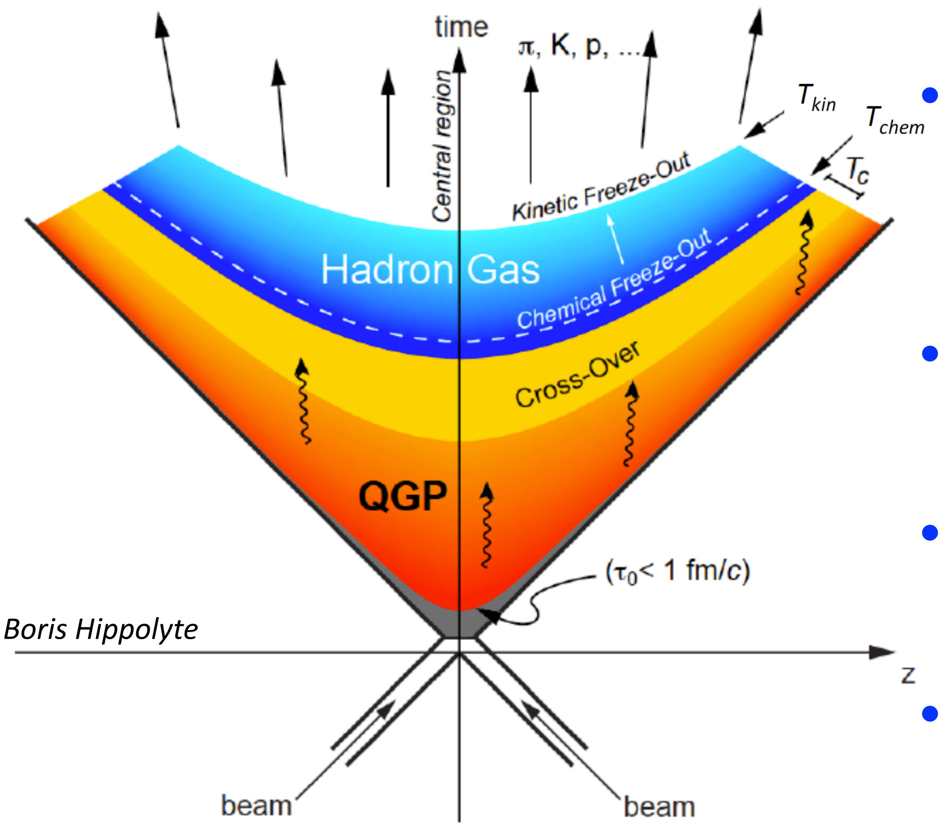
It is expected that in heavy ion collisions there are sufficient conditions to generate a “droplet” of QGP



- The life time of OGP is a few fm/c, i.e. $\sim 10^{-23}$ s

1 fm = 1 fermi = 10^{-15}m

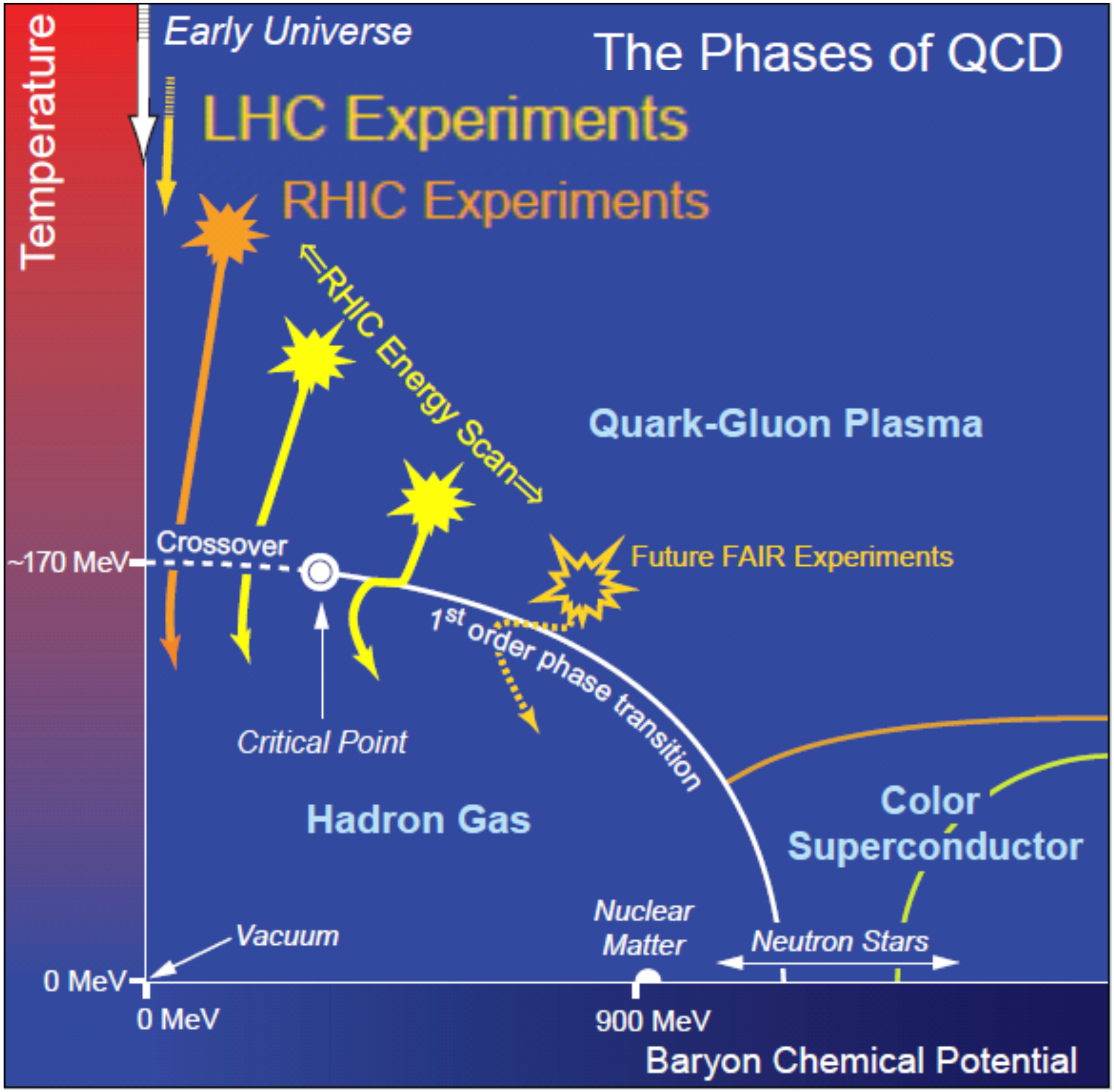
Stages of a Heavy-ion Collision



Boris Hippolyte

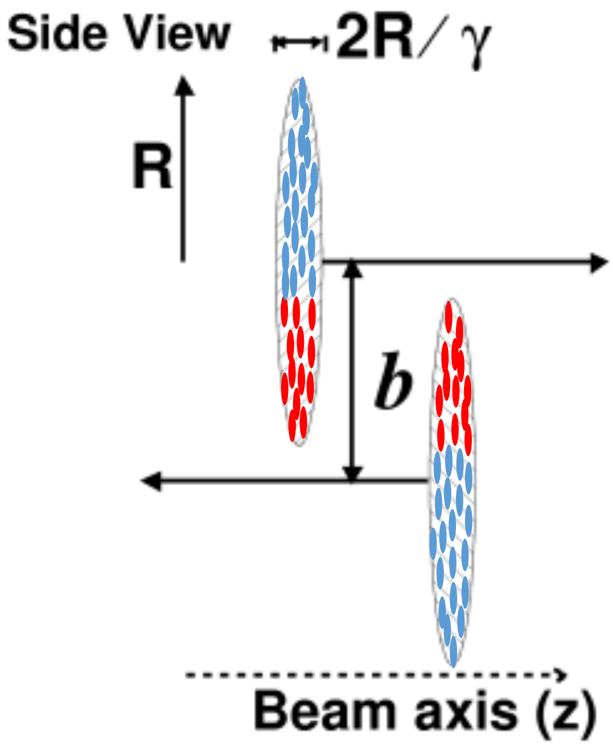
- The space time evolution starts from a hot-fireball in a pre-equilibrium phase (τ_0<1 fm)
- Equilibrate state, thermalization, QGP
- Cross-over phase transition to a hadron gas (T_C).
- Emiting of different kinds of particles (T_{chem}, T_{kin})

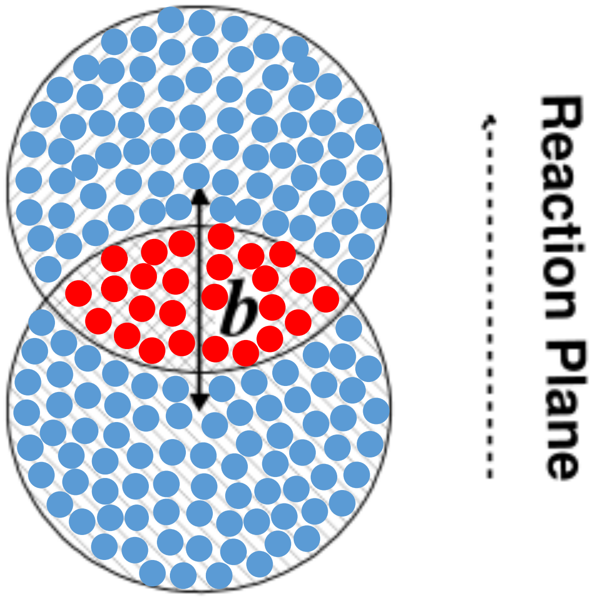
Study of the QCD Phase Diagram



- Changing beam energy leads to changes in the temperature and μ_B of the system

Layout of a Heavy-ion Collision

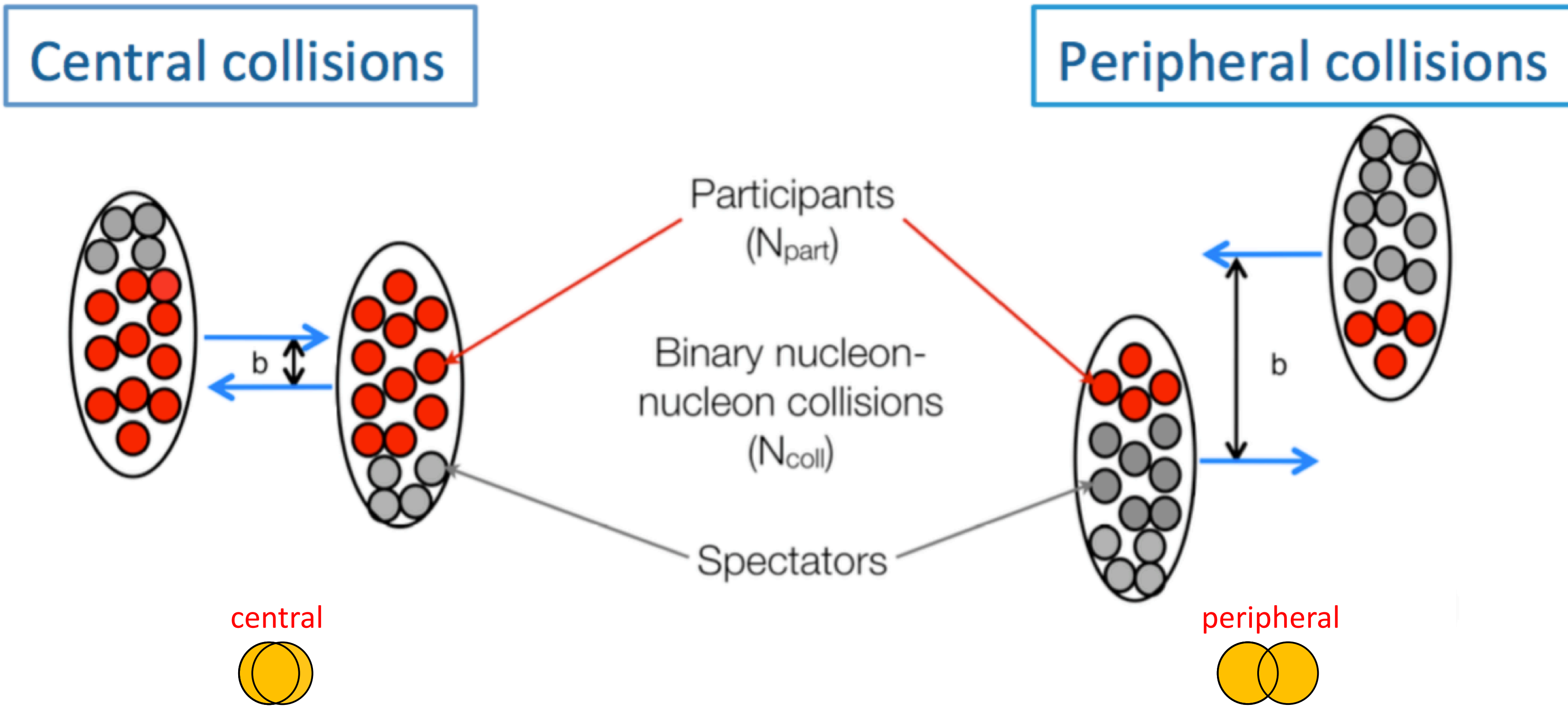




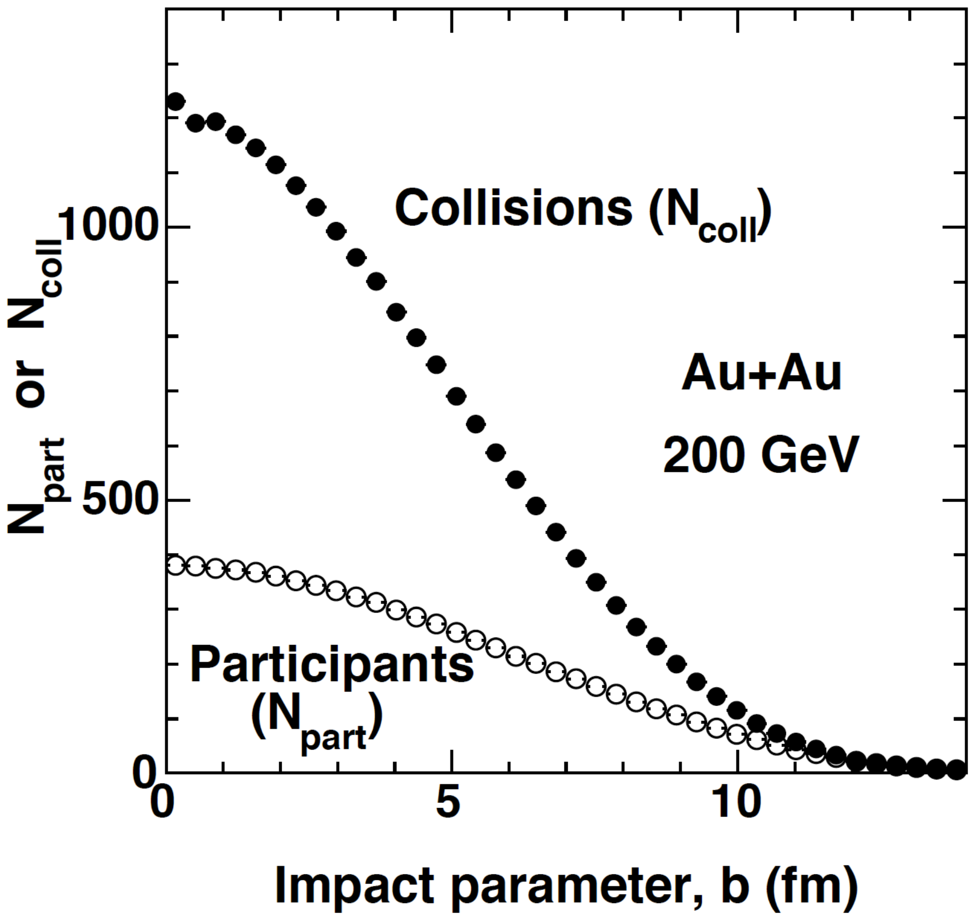
- ● nucleon participating in at least 1 inelastic collision, N_{part}
- ● spectator nucleon

N_{coll} the number of binary nucleon-nucleon collisions in a heavy ion reaction

Heavy-ion Collisions of Different Centrality



N_{coll} and N_{part} versus impact parameter



PHOBOS,
Nucl.Phys.A 757 (2005) 28-101

Woods-Saxon function

$$P(R) = R^2 \left(1 + e^{\frac{(R - r_0)}{a}}\right)^{-1}$$

r_0=6.38 fm, a=0.535 fm

In nucleus (A)-nucleus (B) reaction

$$T_{AB}(\mathbf{b}) = \frac{N_{coll}}{AB\sigma_{in}}$$

$T_{AB}(\mathbf{b})$ - nucleus-nucleus thickness function

σ_{in} - NN inelastic cross section,

$\approx 42\ mb$ RHIC

$\approx 78\ mb$ LHC

arxiv1710.07098

1 b = 100 fm^2 = 10^{-28} m^2