Heavy Ion Collision Physics

Part 1

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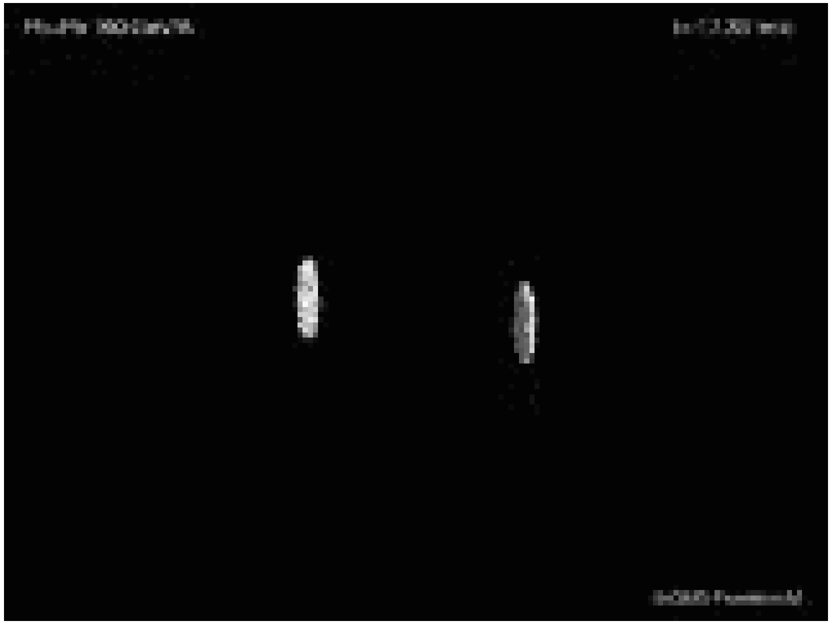
30 January 2025



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), theory describing strong interactions between quarks and gluons

Quantum Chromo-Dynamics (QCD)

(layman's view)

Theory describing strong interactions between quarks and gluons which make up hadrons, like proton or neutron

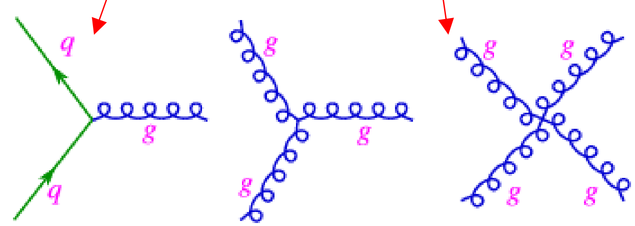
- Quark fields: ψ_i^f fermion particles and anti-particles of spin 1/2
  flavor: $f = d, u, s, c, b, t$ (mass m_f and fractional electric charge)
  color triplet charge: $i = 1, 2, 3$ *(named: green, red, blue)*
- Gluon fields: $A_{\mu,a}$ force mediators of spin-1, m_g=0,
  color octet charge: a= 1,…,8 (e.g. $g\bar{b}$, …)
- QCD Lagrangian:

Kinetic terms

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

g - coupling strength
γ^μ - Dirac matrices
$t_a = \frac{\lambda_a}{2}$, where λ_a are Gell-Mann martrices

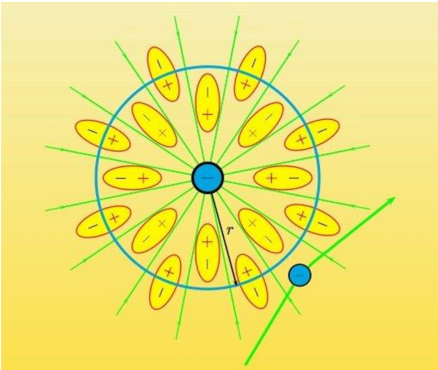
Interaction terms

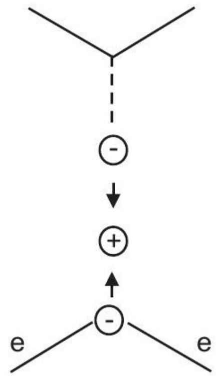


Asymptotic Freedom (short distance or high Q)

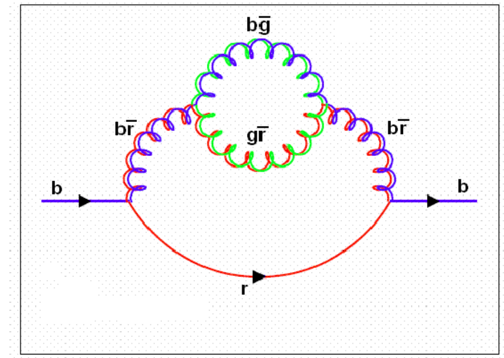
QED screening

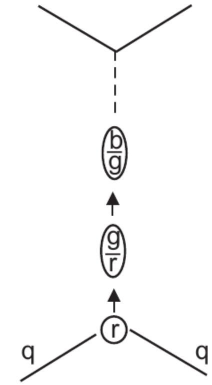
R. Soldati





QCD anti-screening

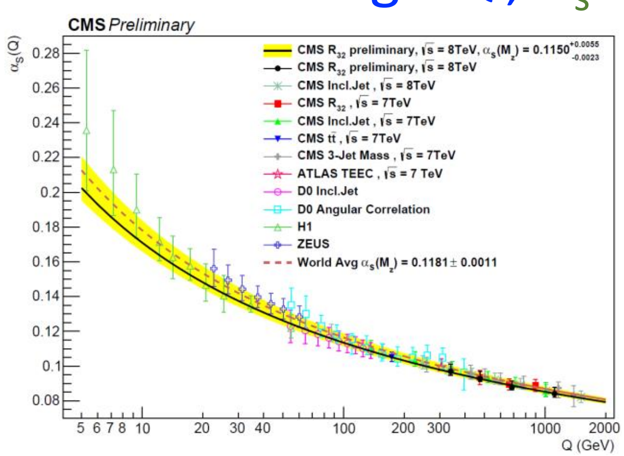


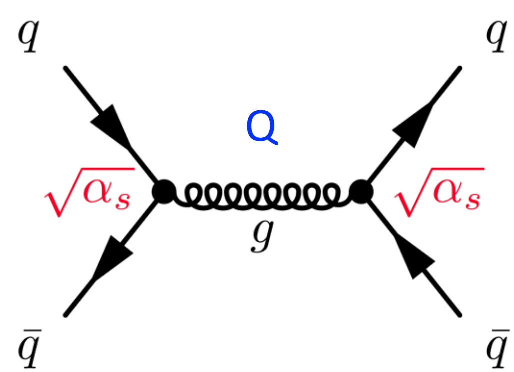


Christiansen

- QED screening weakens *ee* interactions at larger distances or small Q
- QCD anti-screening weakens quark-quark strong interactions at shorter distances or high Q , $\alpha_s = {g^2}/{4\pi}$ decreases with increasing Q

α_s (Q)





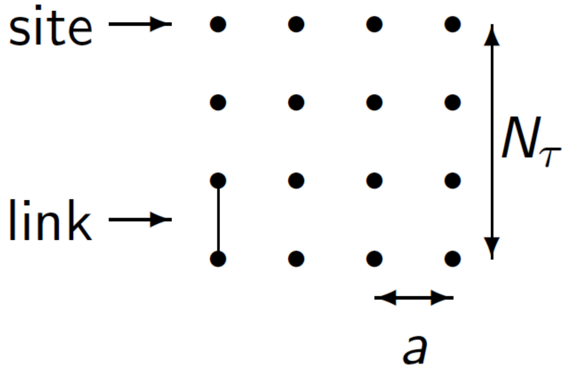
- In the weak coupling limit (α_s <<1) perturbative expansion works

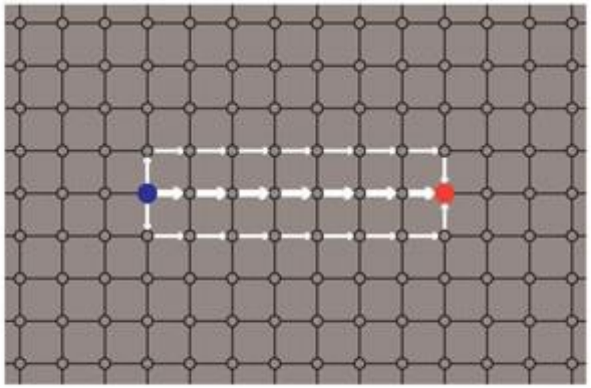
⇒precise results

Color Confinement (long distance or Low Q)

- Color charged quarks and gluons cannot be isolated
- Lattice QCD model was developed to solve non-perturbative problems
  - Perturbative QCD breaks down in the strong coupling limit ($\alpha_s \sim 1$)
- QCD is formulated at a discrete space-time grid $N_s^3 \times N_\tau$

American Scientist





Fermionic degrees of freedom are on the sites while links represent gauge degrees of freedom

Physical observables are obtained via performing path integrations with the QCD Lagrangian $e^{-\int L_{QCD}}$ as a weight

- QCD lattice using modern MC simulation require extensive calculations on large supercomputers

QCD lattice: Cornell Potential

- Direct theoretical evidence that quarks are confined

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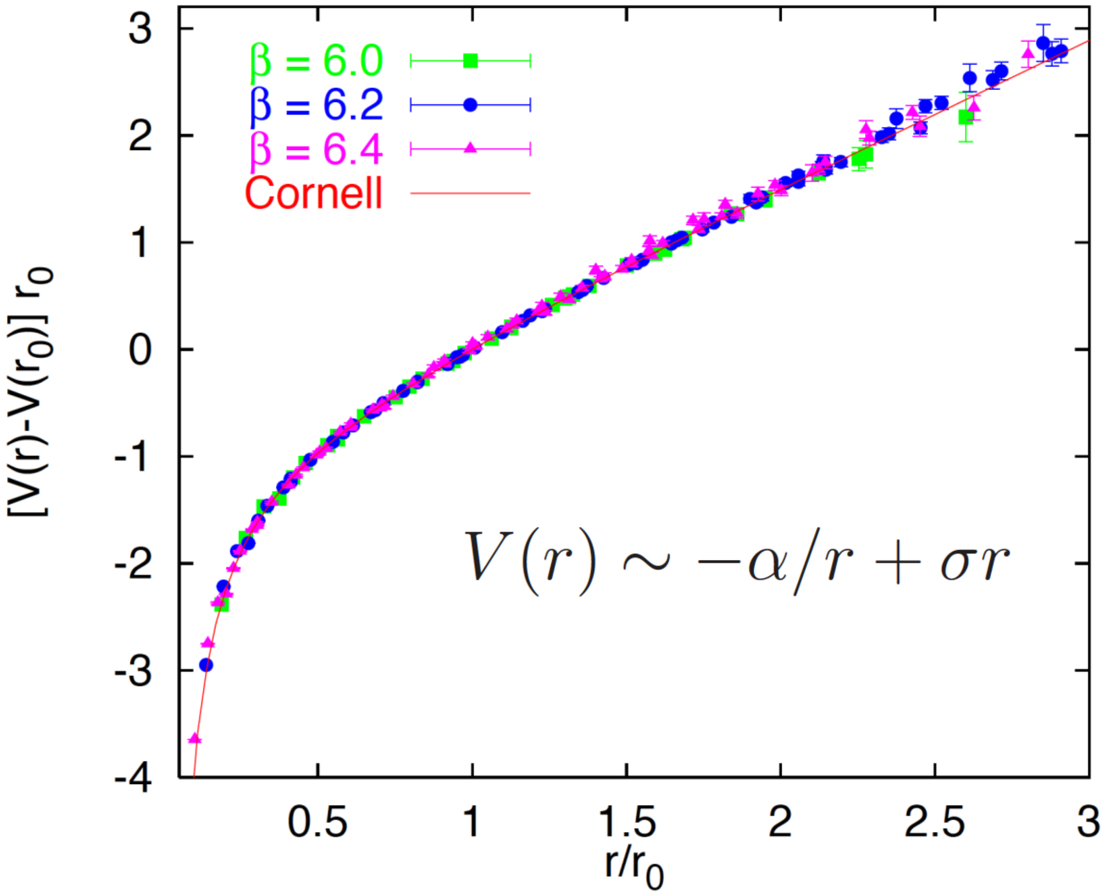

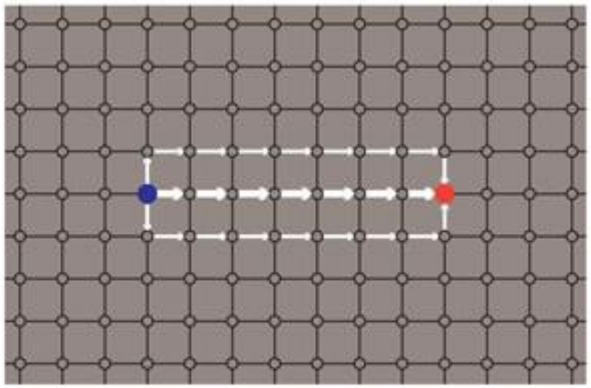

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Force between quarks:
$F = \sigma \approx 1 GeV/fm \approx$ 16 T

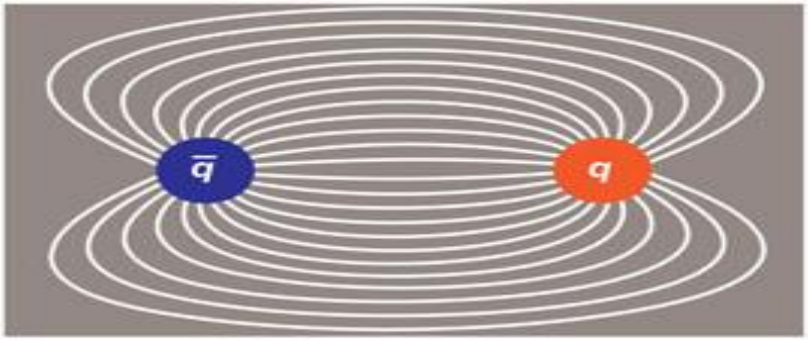
1 fm = 1 fermi = 10^{-15}m

Static quark potential in SU(3) gauge theory

Color Confinement

- In QCD gluons fields between quarks are squeezed to a string/flux tube due to gluon self-interactions

QCD fields



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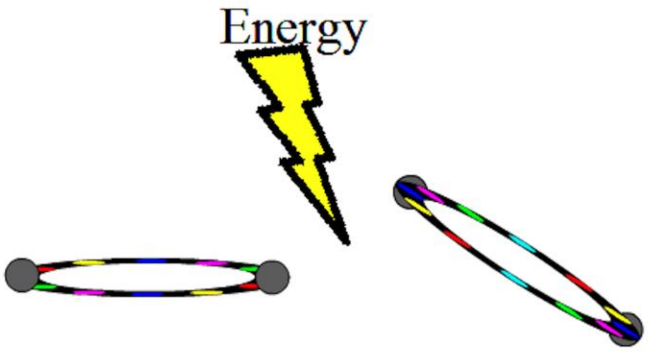


- If large amount of energy is supplied to one quark, the string, ”breaks" and forms a new colourless quark–antiquark pair
  - Therefore, color charged quarks and gluons cannot be isolated

A Historical Remark

- 1964: Quark Model discovery

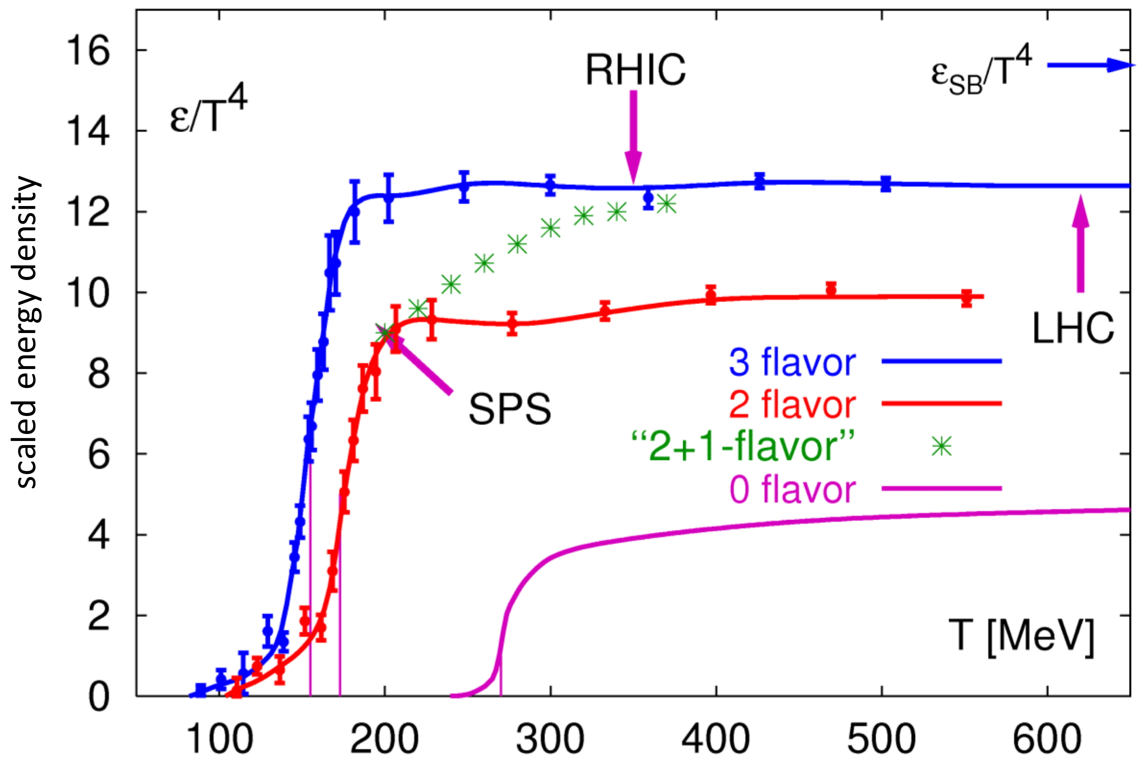
  M. Gell-Man, G. Zweig
- 1973: Discovery of asymptotic freedom in QCD marks the beginning of QCD as the theory of strong interactions

  D. Gross, F. Wilczek, D. Politzer (2004 Nobel Prize)
  - 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
    - Deconfined phase in neutron stars

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

Thermal Behavior of QCD

- Direct theoretical evidence of a phase transition in QGP in hot and dense medium (Lattice QCD)
- Calculations show a rapid but a smooth transition (crossover)



[Karsch et al. (2004)]

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

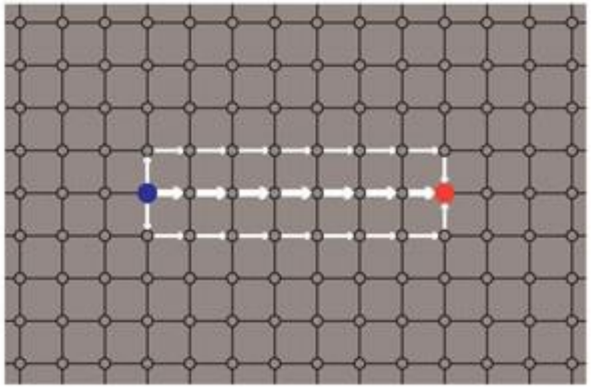
$$\varepsilon_{SB}^{q} + \varepsilon_{SB}^{anti-q} = = 36 \times 4\pi \int_0^\infty \frac{p^2 dp}{(2\pi)^3} \frac{p}{e^{p/T} + 1} = 36 \times \frac{7}{8} \frac{\pi^2}{30} T^4$$

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

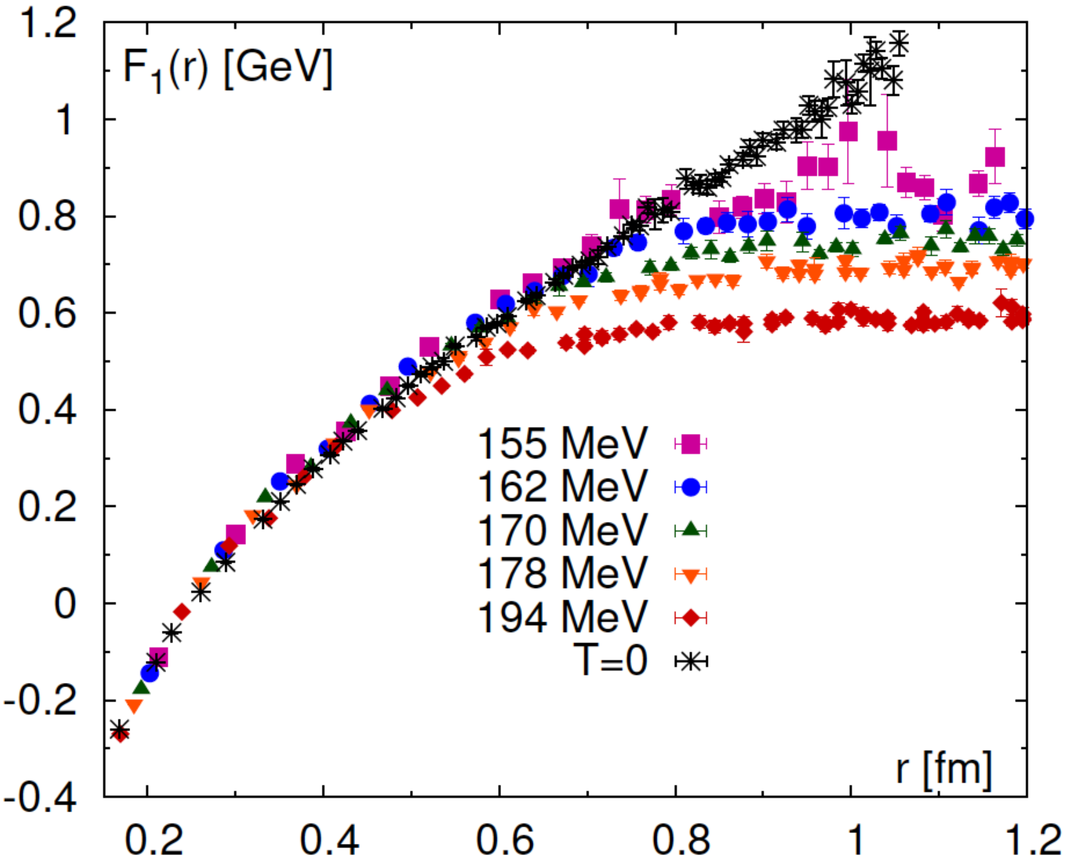
- Rapid rise in the energy density at T_c -> rise in # degrees of freedom
  - T_c of 150–200 MeV, ε_c = 1-3 GeV/fm^3 ~(6∓2)T_c^4
  - T=155 MeV ~ 10^{12} K , Sun core: T_{Sun}~ 10^7 K

Quark Anti-quark Potential vs T

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

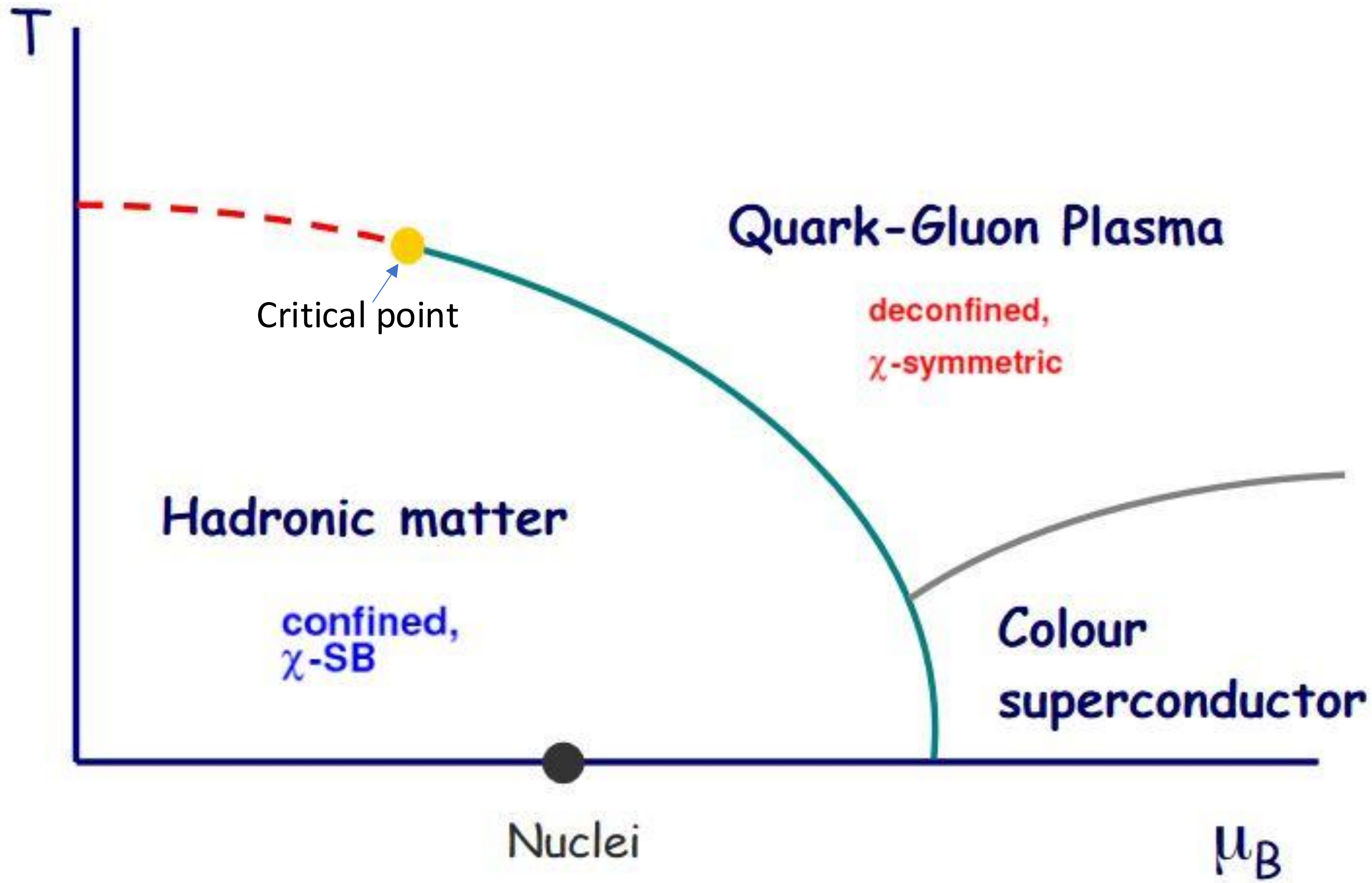


$$V(r) \sim -\alpha/r + \sigma r$$



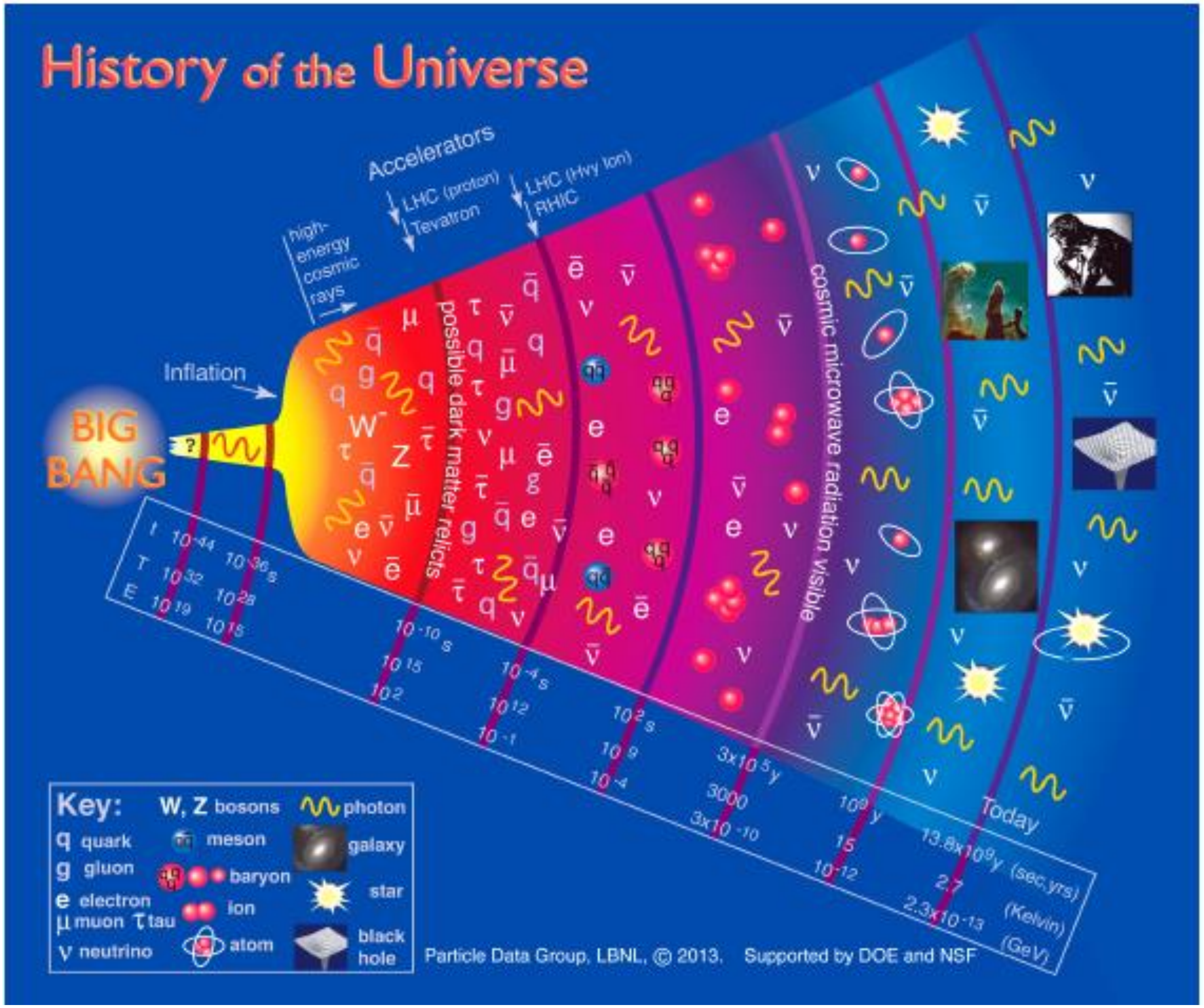
- The long-range force between quarks at high T (≳ 155 MeV) vanishes ($\sigma \searrow 0$ for large r)
  - deconfined phase

QCD Phase Diagram



- Baryon chemical potential measures the imbalance between matter and antimatter

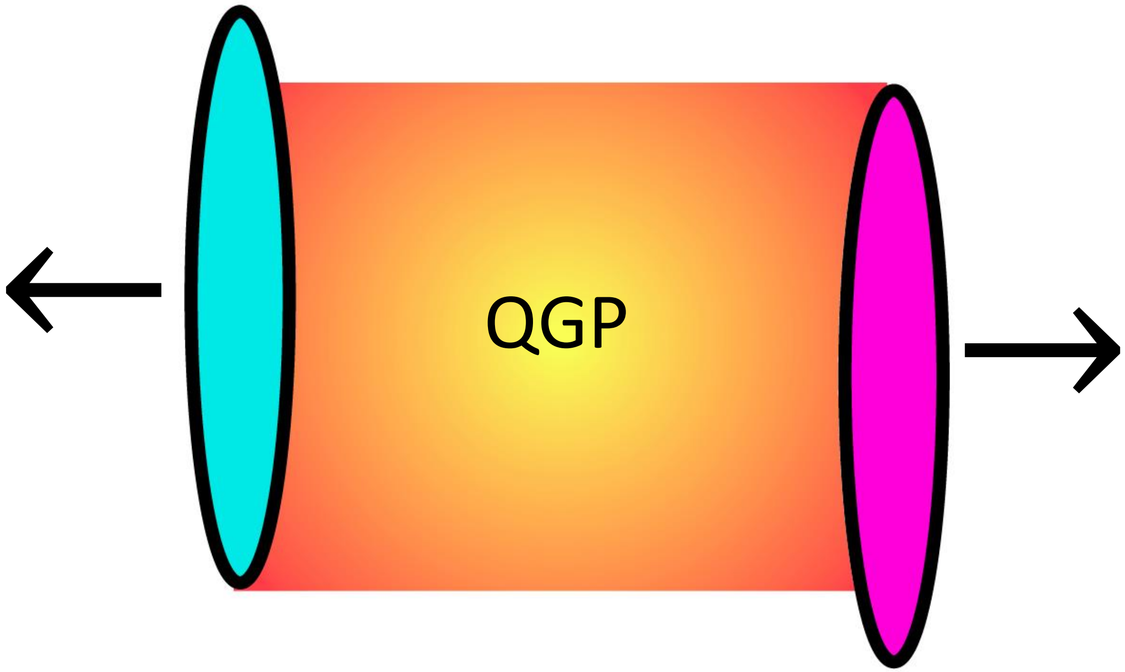
QGP in Cosmology



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

Schematic View of Ultra-relativistic Heavy-ion Collision

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



- The life time of QGP is a few fm/c, i.e. ~ 10^{-23} s

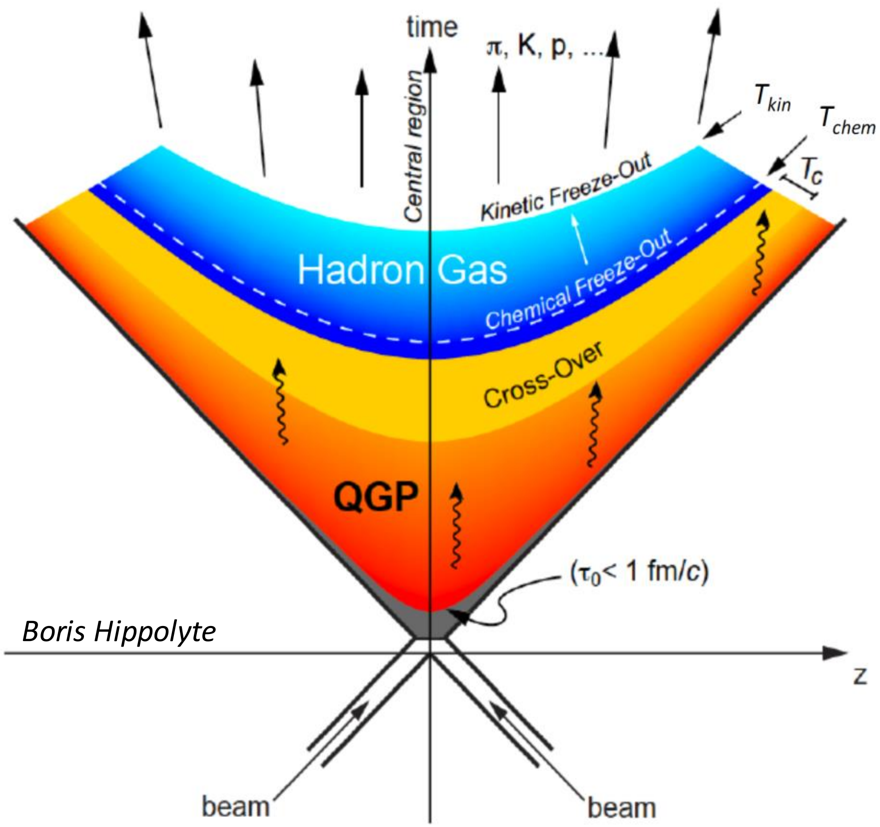
1 fm = 1 fermi = 10^{-15}m

- Collision energy available for QGP production (pre nucleon pair)

$$\sqrt{s_{NN}} = 2\frac{E_A}{A}$$

E_A - beam ion energy
A - atomic mass number

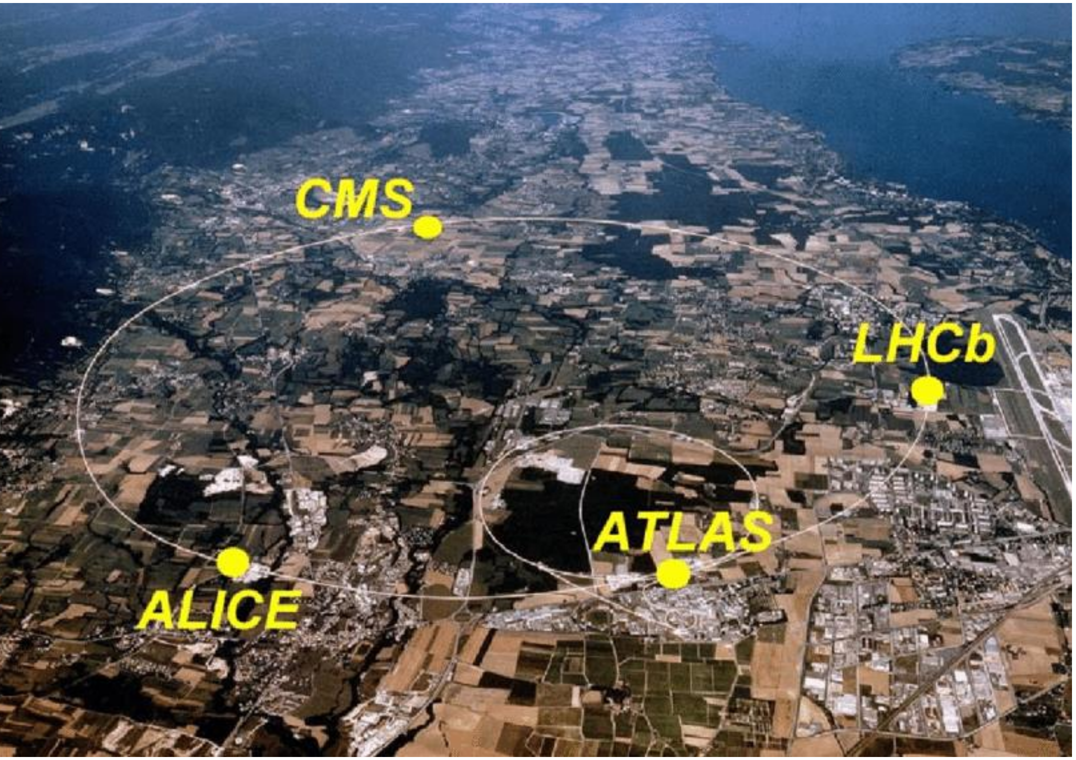
Stages of Ultra-relativistic Heavy-ion Collisions
(scenario with QGP)

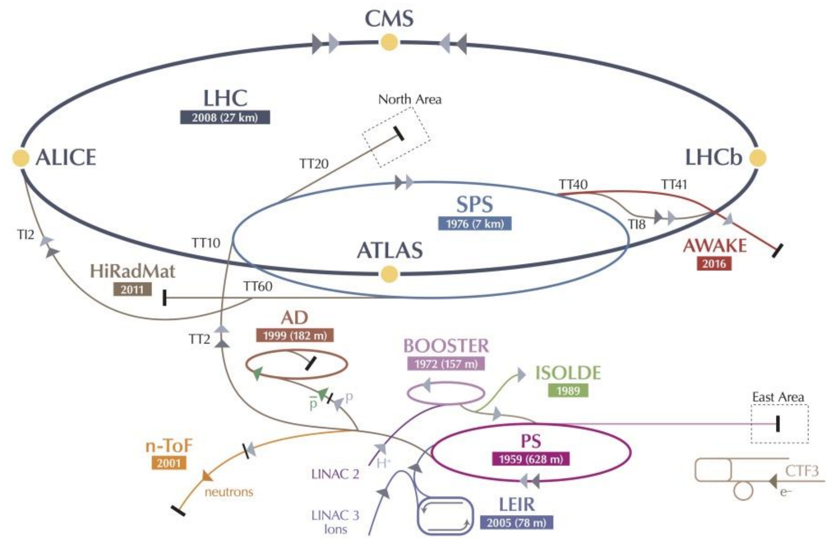


Boris Hippolyte

- The space time evolution starts from a hot-fireball in a pre-equilibrium phase (τ_0<1 fm/c)
  - Color Glass Condensate -> Glasma ?
- Equilibrate state, thermalization, QGP
  - Deconfined state
  - Nearly perfect fluid – hydrodynamical expansion
- Cross-over phase transition from QGP to a hadron gas (T_C).
- Emitting of different kinds of particles measured in the detector (T_{chem}, T_{kin})

Most Powerful Heavy Ion Collider (LHC)

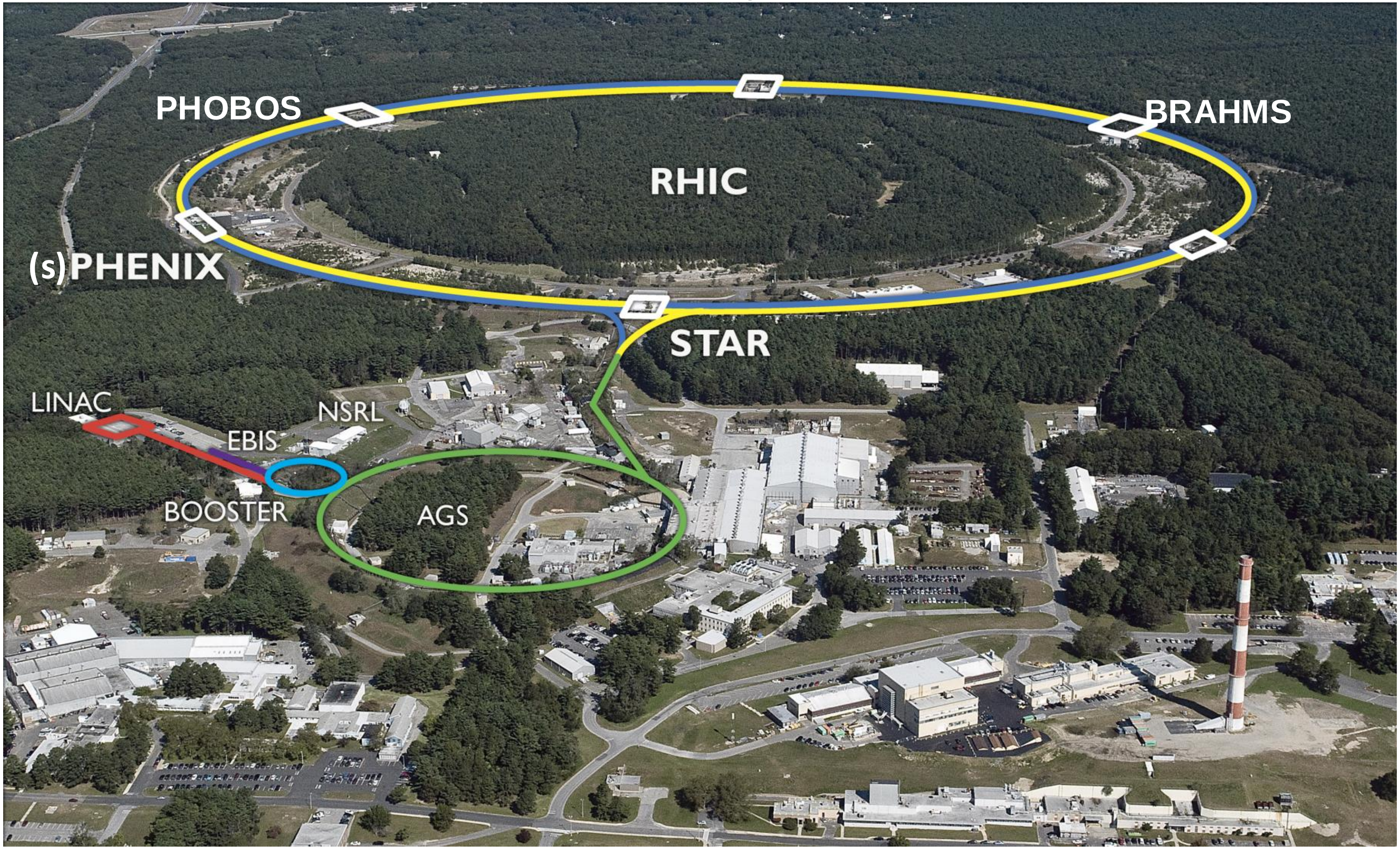




${}^{208}_{82}Pb$: 4.5 →72 MeV (LIER) → 5.9 GeV (PS) → 177 GeV (SPS)→ 2.68 TeV (LHC)

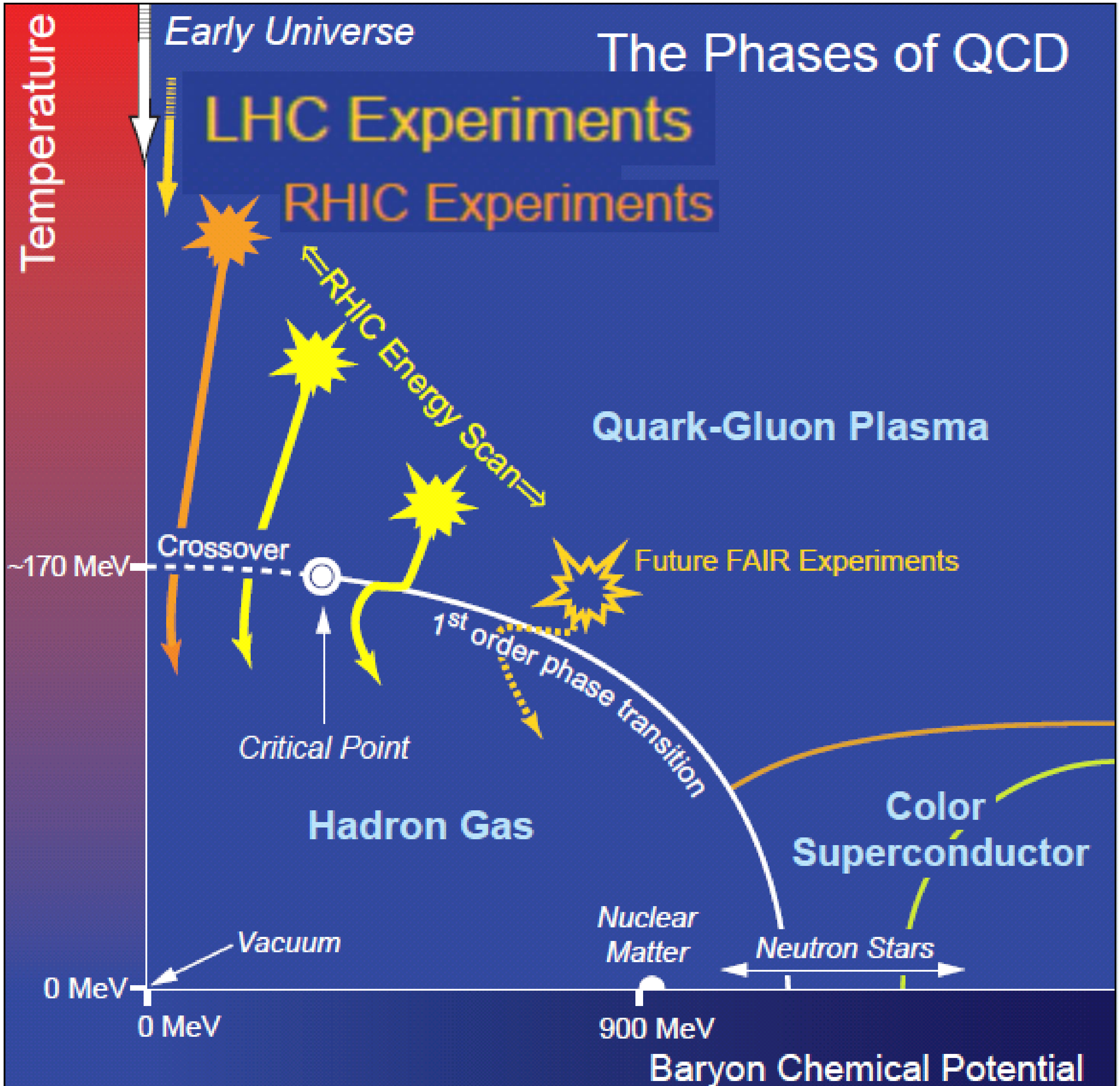
- The LHC consists of a 27-km ring of superconducting magnets located approximately 100 m below the surface
- Record collision energy, for Pb ions $\sqrt{s_{NN}}$ = 5.4 TeV
- First lead ion collisions in the year 2010

Relativistic Heavy Ion Collider



- RHIC circumference is 3.8 km
- Maximal collision energy for gold ions $\sqrt{s_{NN}}$ = 200 GeV
- First gold ion collisions in the year 2000

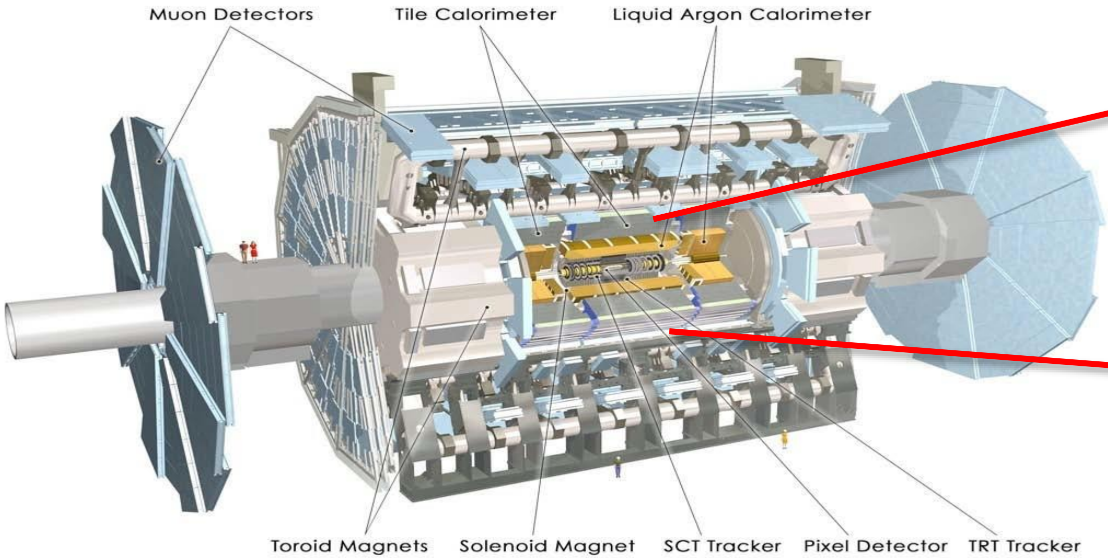
Probing QCD Phase Diagram with HI Collisions

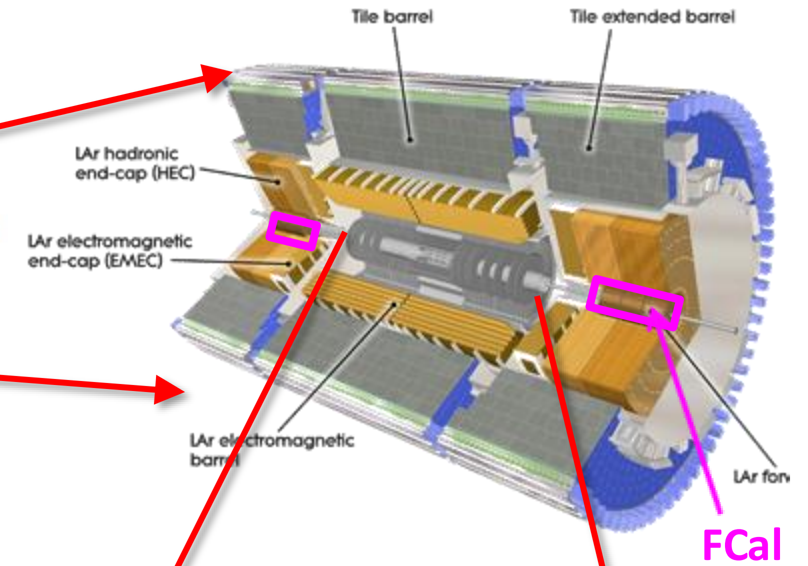


- Changing beam energy leads to changes in the temperature and μ_B of the system
  - $E_{beam} \nearrow$ $\mu_B \searrow 0$, $T \nearrow$
  - Probing location of Critical Point
- LHC
  - Energy nucleon pair: $\sqrt{s_{NN}}$ = 5020 GeV

    $2\frac{E_A}{A}$ -nucleon pair CMS energy
- RHIC
  - $\sqrt{s_{NN}}$ = 8 - 200 GeV
- FAIR
  - $\sqrt{s_{NN}}$ = 2.7 – 5.4 TeV

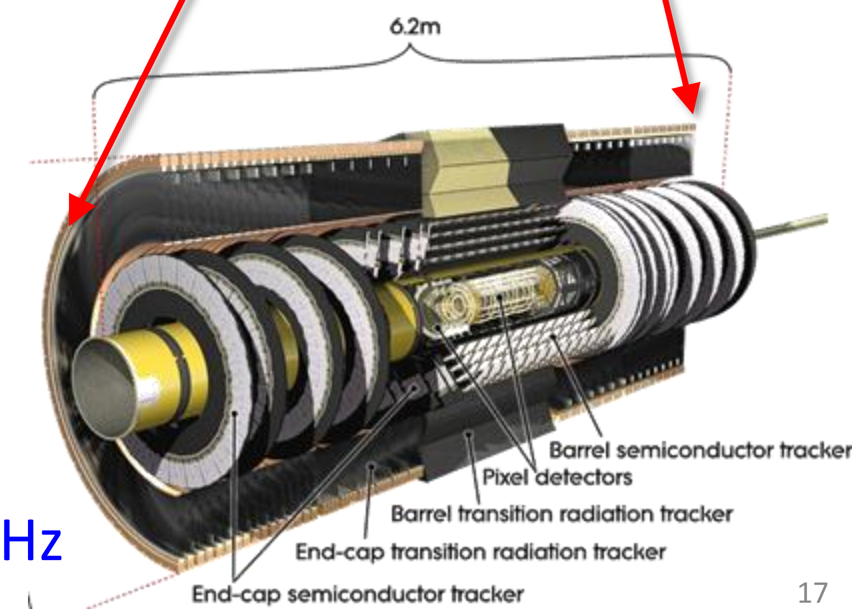
ATLAS at LHC as a Heavy Ion Detector





Three main subsystems:

- Inner Detector – tracking
  - |η|<2.5 , $\eta \equiv -\ln\tan(\frac{\theta}{2})$
  - p_T>0.4 GeV
- Calorimetry – |η|<4.9
- Muon Spectrometer - |η|<2.7



Fast trigger systems:

- Level 1 (L1,hardware), 40 M to 100 kHz
- HLT (software), 100kHz to ~1000Hz

LHC Data Sets

Datasets collected during:

- Run 1 (2010-2012)
- Run 2 (2015-2018)
- Run 3 (2022->2026)

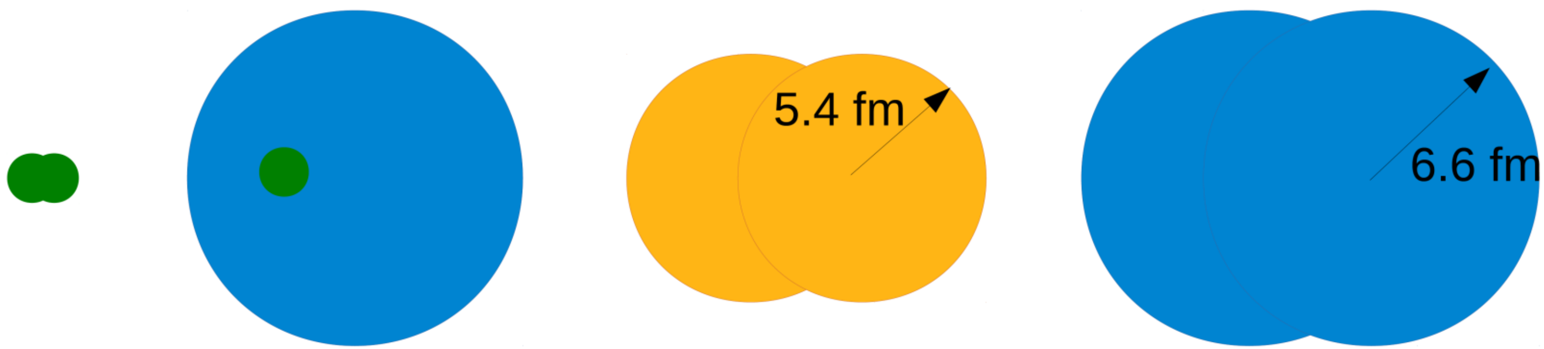
Species	$\sqrt{s_{NN}}$ (TeV)
Pb+Pb	**2.76, 5.02, 5.36**
Xe+Xe	**5.44**
p+Pb	**5.02, 8.16**
p+p	**2.76, 5.02, 5.36, 8**

Reference data (p+Pb, p+p)

In Run 2, 10 times more Pb+Pb collisions than in Run 1

In Run 3 there will be ~3 times more Pb+Pb collisions than in Run 2

Run 4 will start in 2030 after major LHC and ATLAS upgrades (HL-LHC)



pp — up to a few 100 particles

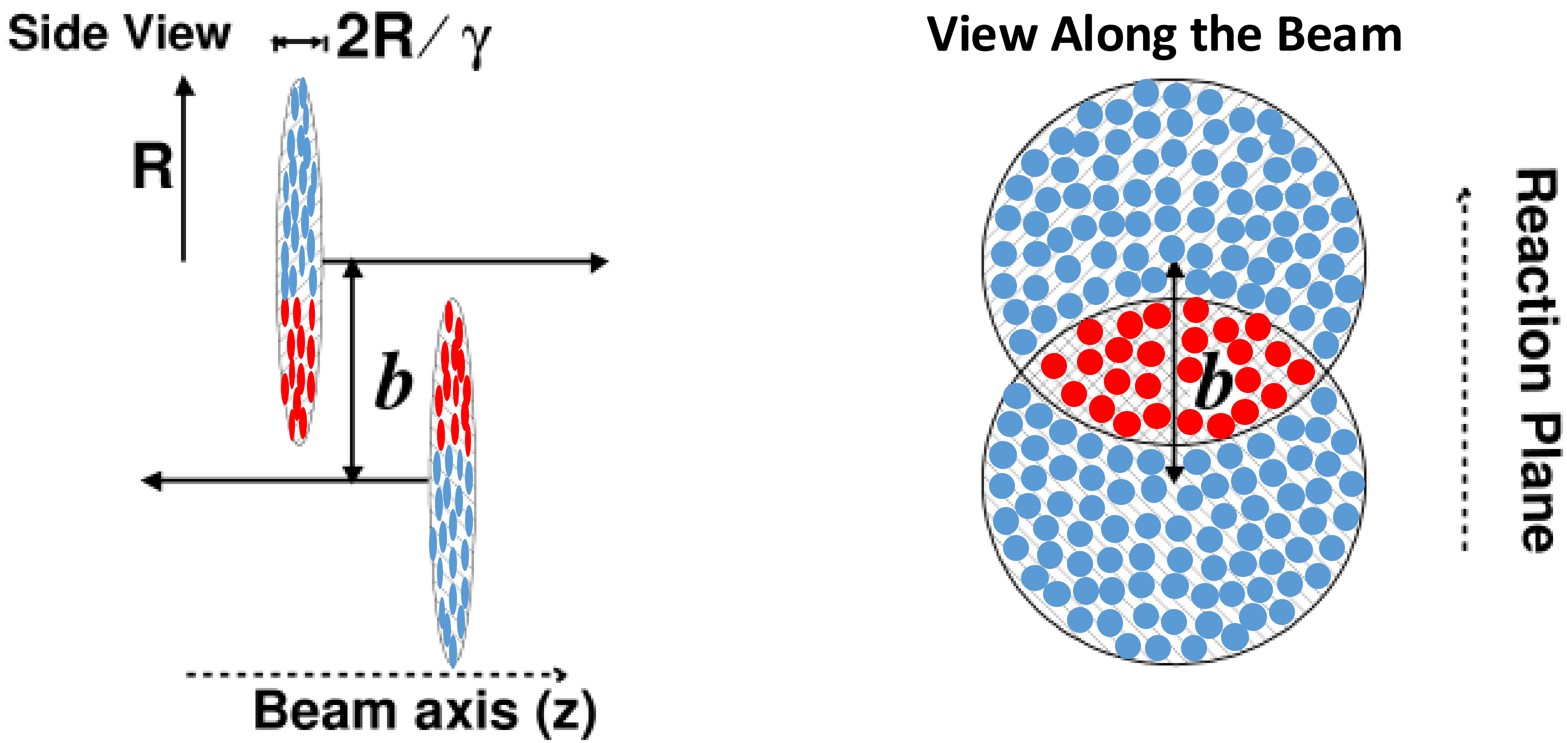
p+Pb — up to a few 100 particles

Xe+Xe — a few 1000 particles

Pb+Pb — up to ~30000 particles

In small systems QGP effects are switched off → calibrate initial conditions in heavy ions

Layout of a Heavy-ion Collision

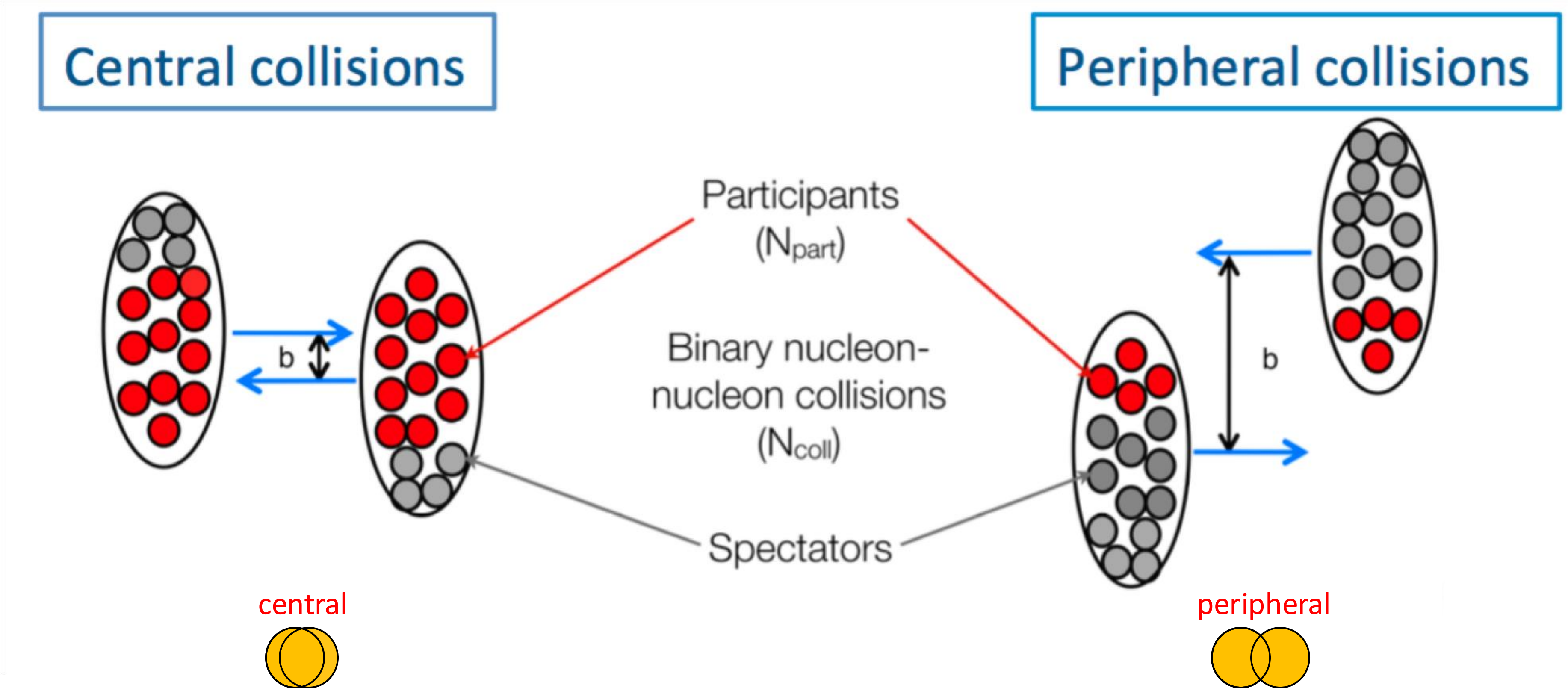


- nucleons participating in at least 1 inelastic collision, N_{part}
- spectator nucleons

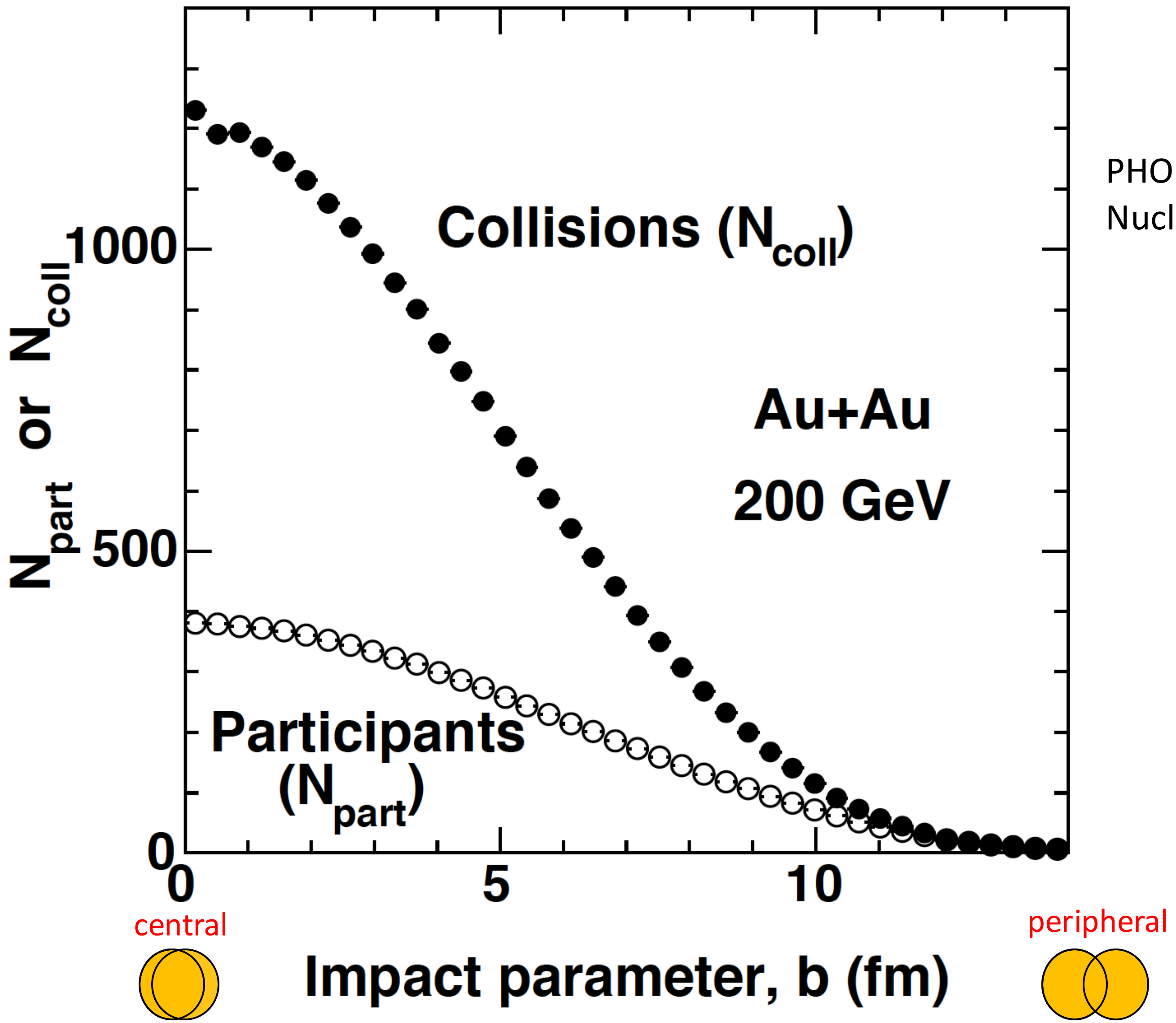
N_{coll} the number of binary nucleon-nucleon collisions in a heavy ion reaction

Lorentz factor: $\gamma = \frac{\sqrt{s_{NN}}}{2m_p c^2}$ = 2676 for Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Heavy-ion Collisions of Different Centrality



N_{coll} and N_{part} vs Impact Parameter



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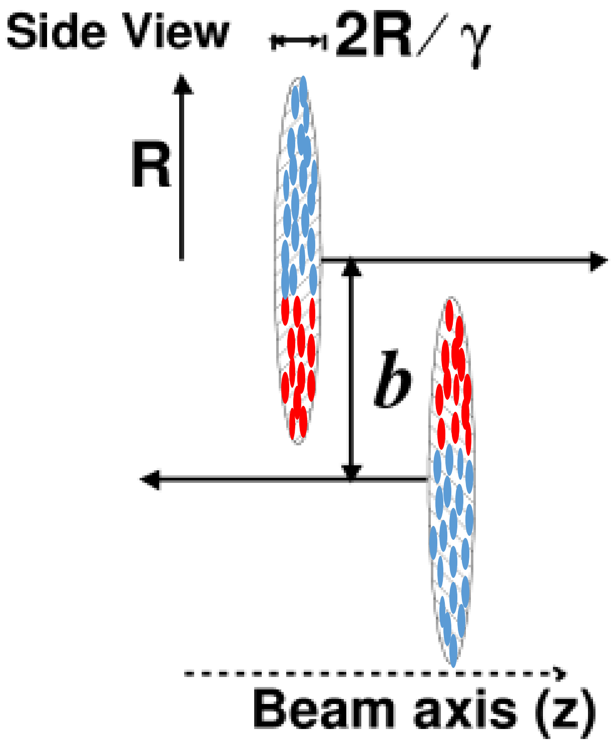
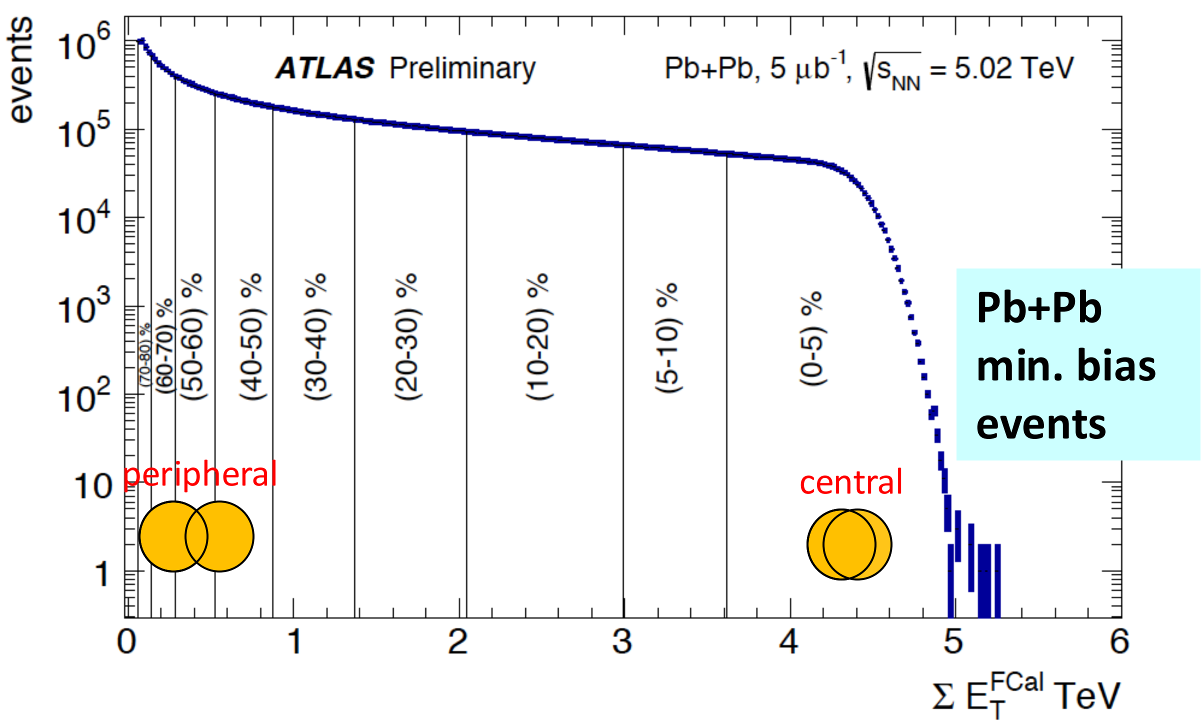
Centrality Determination in Pb+Pb Collisions

- Pb+Pb events are divided into centrality bins according to measured total transverse energy in forward calorimeter (FCal, 3.1<|η|<4.9)



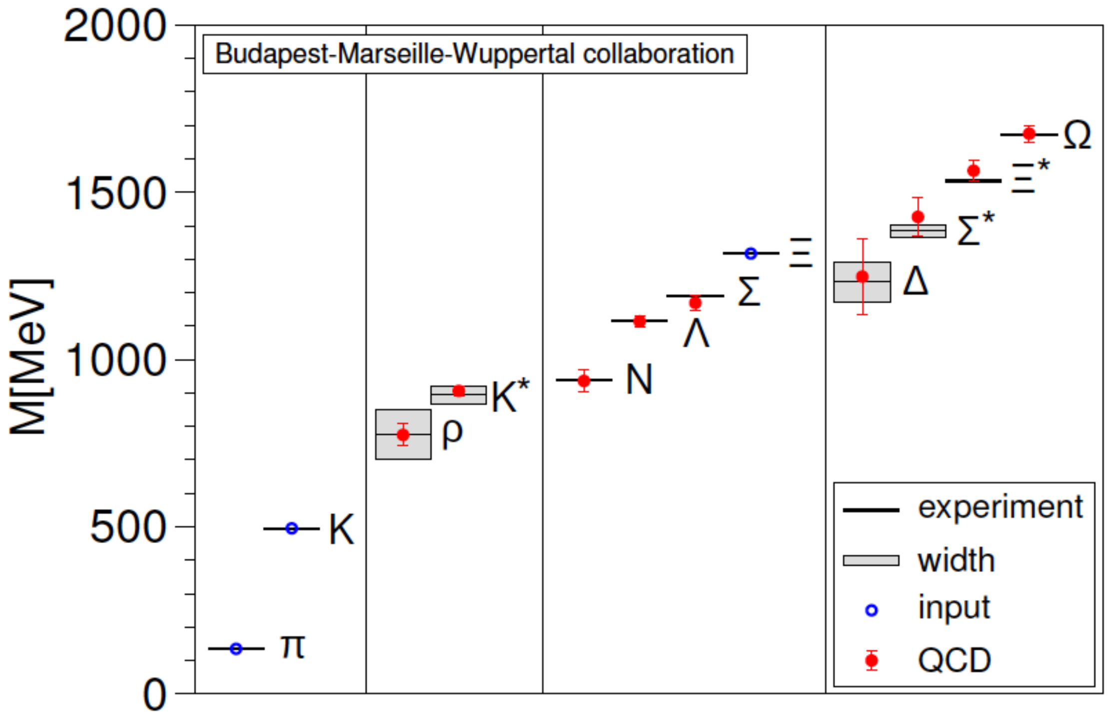


- MC simulations with Glauber model used for determination:
  - N_{coll} - number of binary NN interactions
  - N_{part} - number of participating (wounded) nucleons
  - T_{AA} - nuclear thickness function ~ N_{coll}

backups

QCD predictions for the spectrum of hadrons

Using the lattice leads to predictions for the spectrum of hadrons



arXiv:0906.3599

- 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)

QCD Vacuum

- Quark bound states (hadrons) have large mass wrt small quark masses
  - e.g. $m(\mathrm{uud}) \sim 1\% \, m_{\mathrm{p}}$
- Lattice QCD provides evidence that ground state is a quark-gluon condensate which interactions with quarks contribute to their masses

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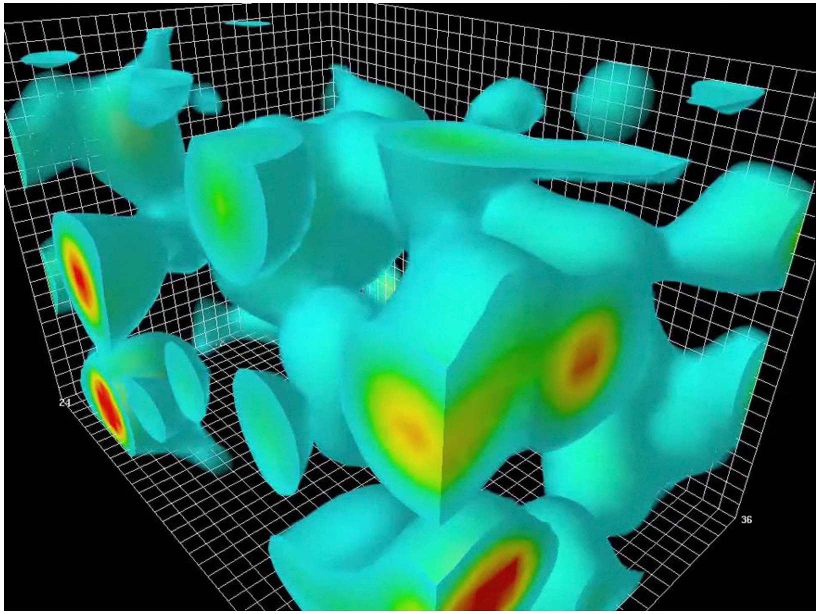

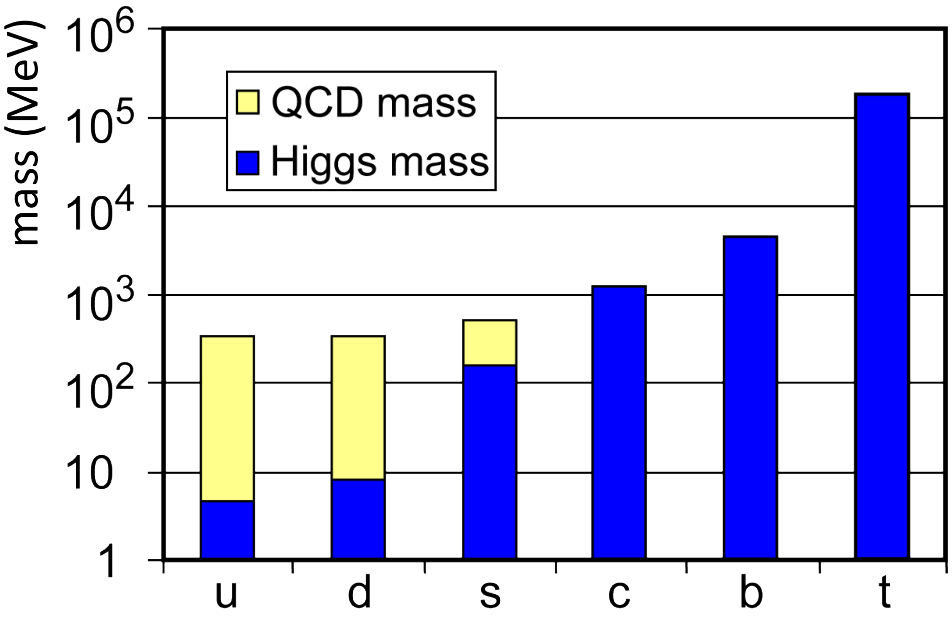

- Spontaneous breaking of chiral symmetry by the formation of quark-gluon condensate
  - Chiral symmetry: L_{QCD} invariance wrt independent rotation of ψ_R , ψ_L