Heavy Ion Collision Physics

Part 1

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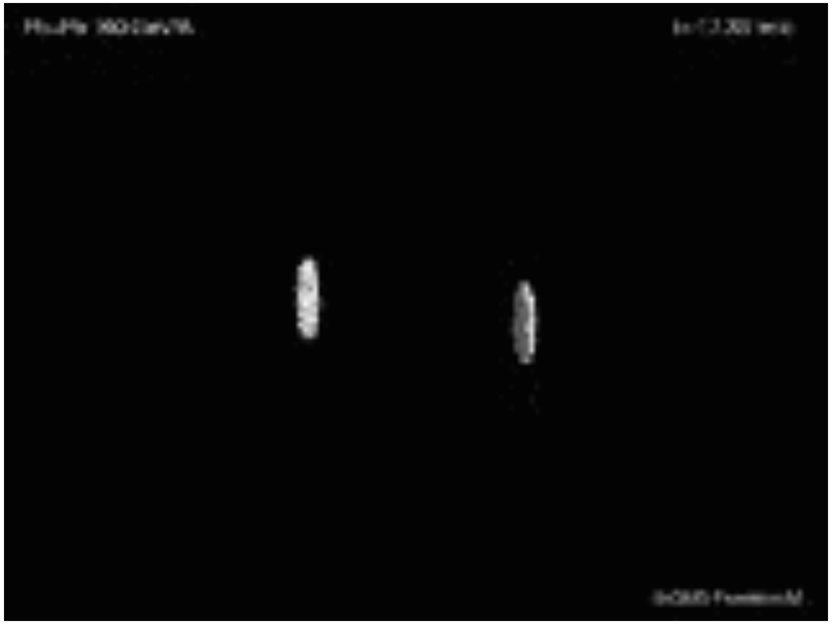


KISD, Lecture: Particle physics
for specialists

- The main goal is to understand the dynamics of dense and hot medium created in heavy-ion collisions
- Quantum Chromo-dynamics (QCD), gage theory describing strong interactions between quarks and gluons

Quantum Chromo-Dynamics (QCD)

(layman's view)

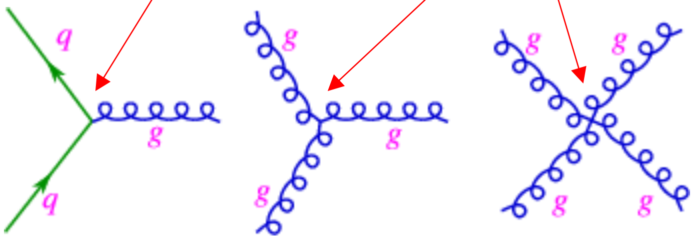
Theory describing strong interactions between quarks and gluons

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

kinetic terms

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

interaction terms:



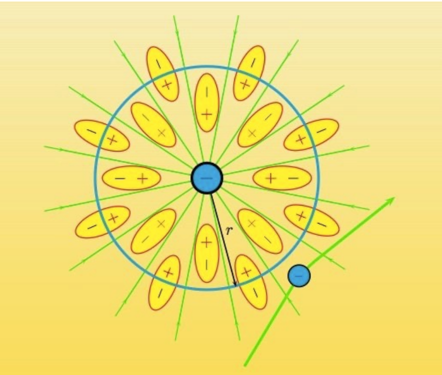
g - coupling strength
γ^μ - Dirac matrices
$t_a=\frac{\lambda_a}{2}$, where λ_a are Gell-Mann martrixes

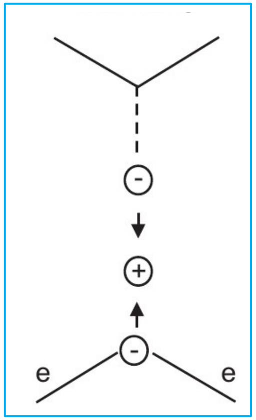
Asymptotic Freedom (High Q or short dsistance)

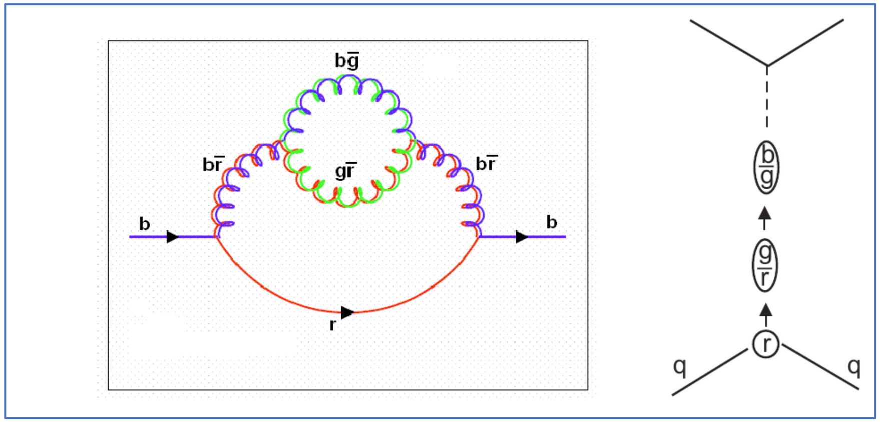
QED screening

QCD anti-screening

R. Soldati

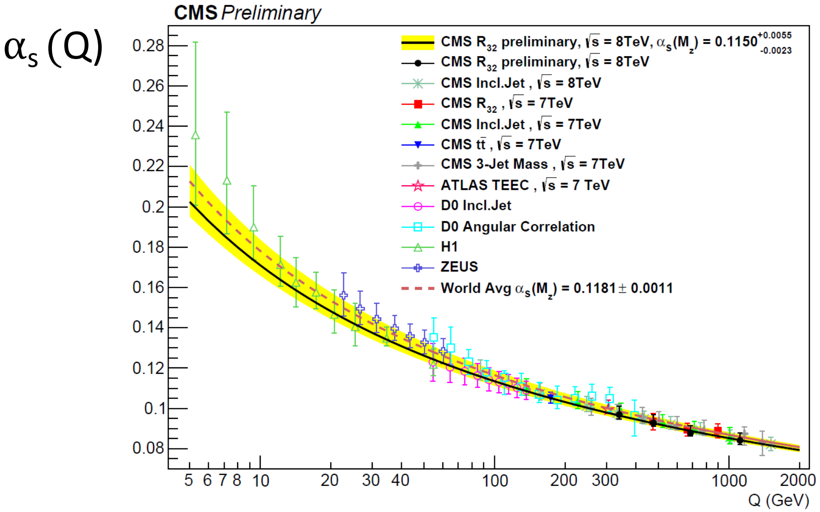


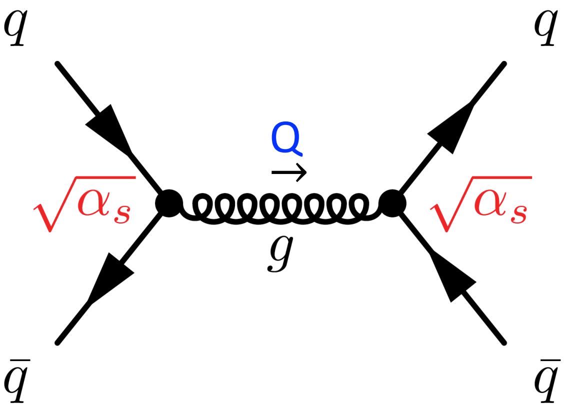




Christiansen

- Anti-screening weakens quark-quark strong interactions at shorter distances or high Q , $\alpha_s = {}^{g^2}/_{4\pi}$ decreases with increasing Q
- In the weak coupling limit (α_s <<1) perturbative expansion works

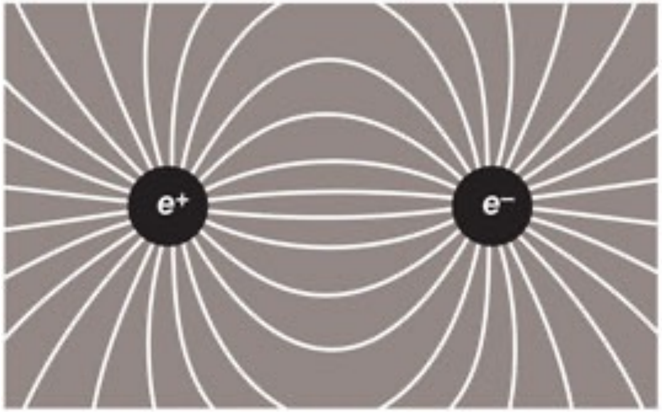




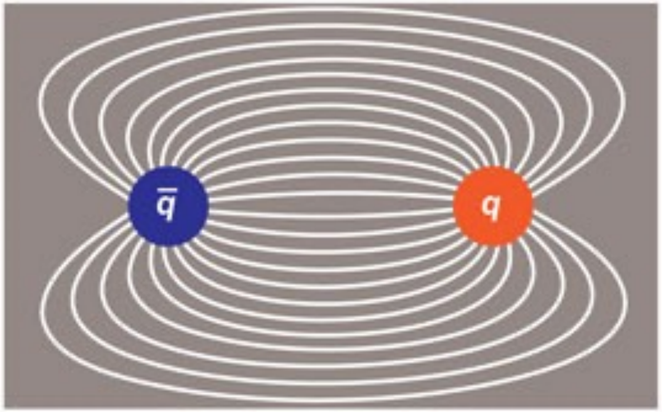
Color Confinement (Low Q or long distance)

- In the strong coupling limit ($\alpha_s \sim 1$), gluons fields between quarks are squeezed to a string/flux tube due to gluon self-interactions

QED fields



QCD fields



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

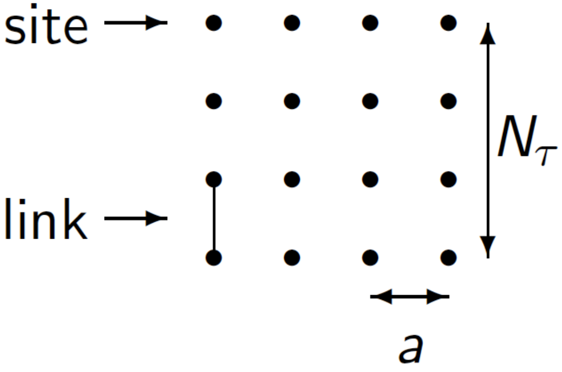
- At large distances the QCD potential gets linear term
  - Force between quarks: $F = \sigma \approx 1GeV/fm \approx$ 16 T

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

- If large amount of energy is supplied to a quark, the string, ”breaks" and forms a new colourless quark–antiquark pair
- In QCD color charged quarks cannot be isolated
  - Quarks are confined in a form of bound states

QCD Lattice - Ab-initio calculations

- In QCD, in the strong coupling limit ($\alpha_s \sim 1$) the perturbative expansions in α_s of QCD breaks down
- The lattice QCD model was developed to solve non-perturbative problems
- QCD is formulated at a discrete space-time grid N_s^3 x N_τ

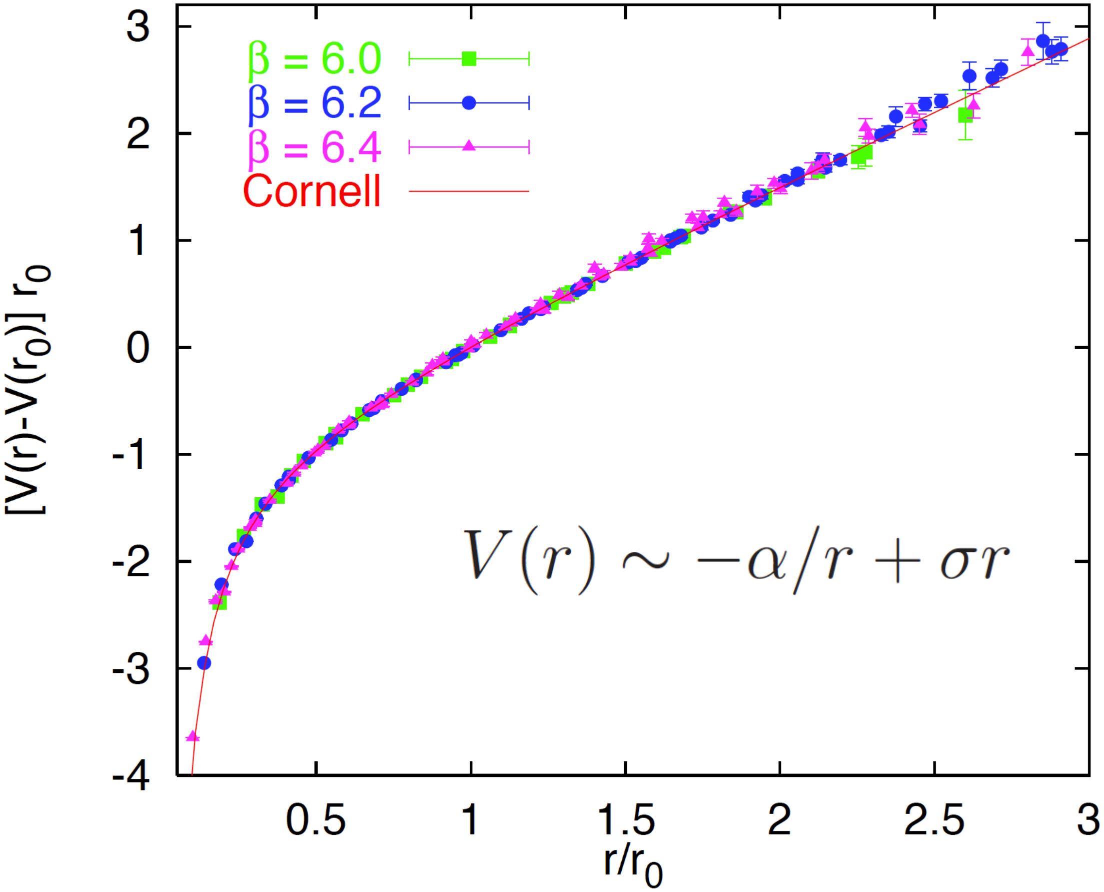


Fermionic degrees of freedom are on the sites while links represent gauge degrees of freedom

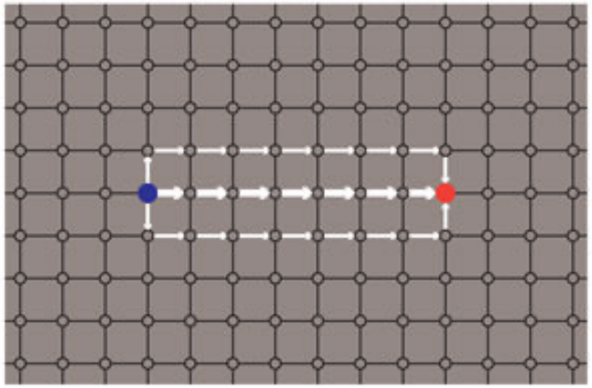
- Physical observables are obtained via performing path integrations with the QCD Lagrangian $e^{-\int L_{QCD}}$ as a weight
  - QCD lattice using modern MC simulation require extensive calculations on large supercomputers
  - Example for pure gauge field lattice of 32^3 x 8 there is 32^3 x 8 x 4 x 18 $\approx$ $2\text{x}10^7$DoF which needs to be integrated

QCD lattice: quark confinement

- Direct theoretical evidence that quarks are confined



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



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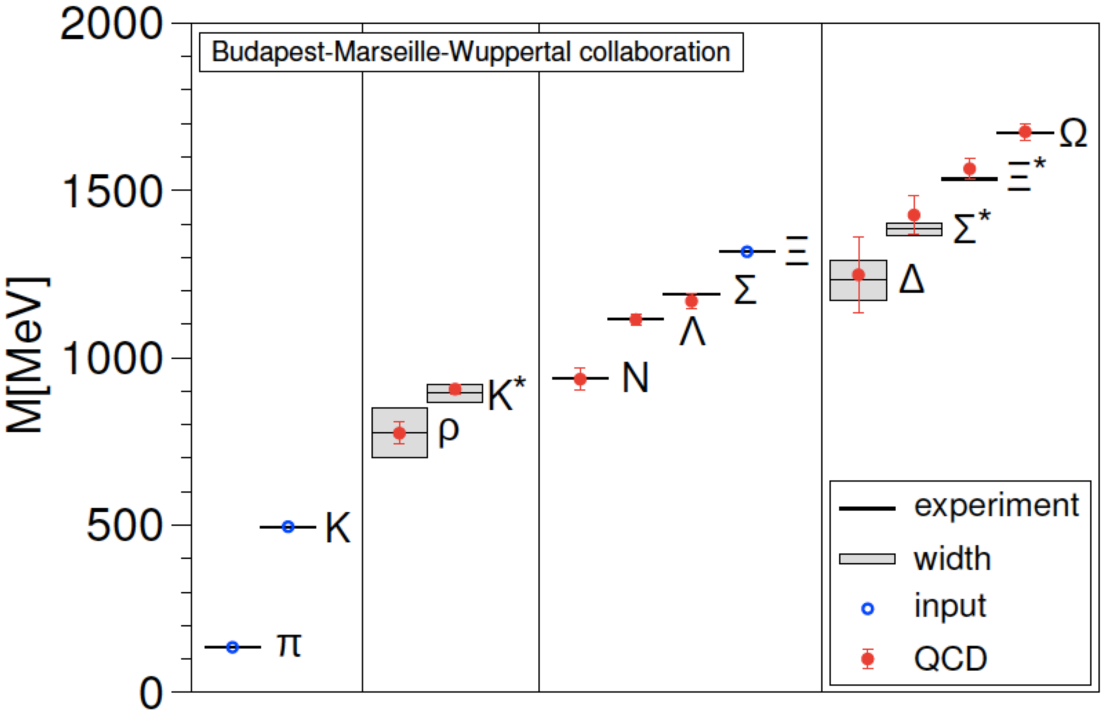
Phys.Rept.343:1

Static quark potential in SU(3) gauge theory

QCD predictions for the spectrum of hadrons

Using the lattice leads to predictions for the spectrum of hadrons



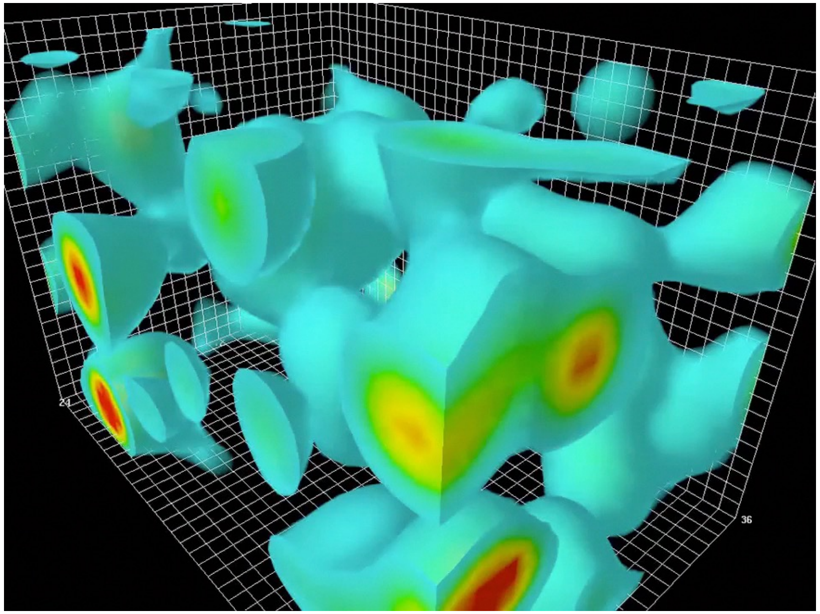
arxiv 1401.6075

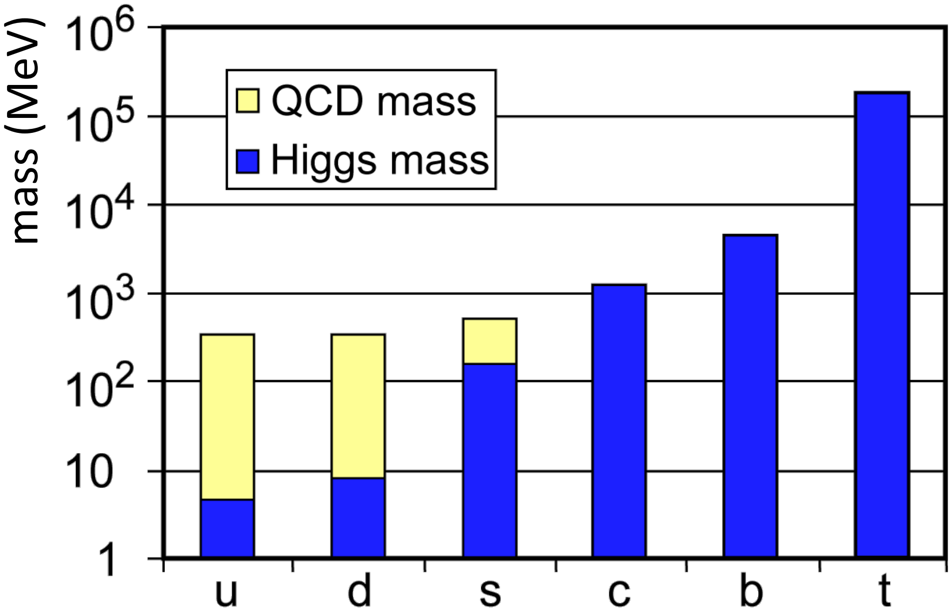
- Predictions from lattice-QCD agree with experimental measurements for wide variety of hadrons including light- and heavy-hadrons and proton-neutron mass difference (-1.7 MeV)

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

Derek Leinweber physics.adelaide.edu.au





- 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

A Historical Remark

- 1964: Quark Model discovery

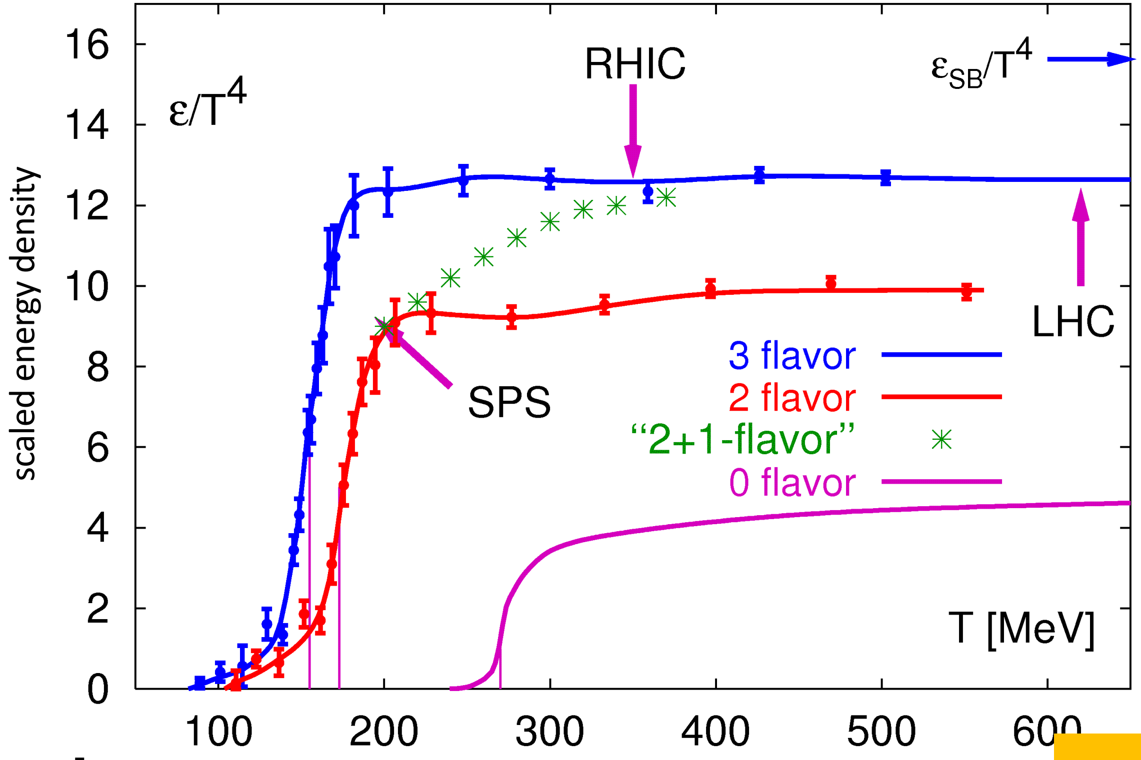
  M. Gell-Man, G. Zweig
- 1973: The beginning of QCD as a theory of strong interactions

  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 deconfined phase from Lattice QCD
- Calculations show a rapid but a smooth transition (crossover) from hadronic gas to QGP (μ_B=0)



[Karsch et al. (2009)]

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

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

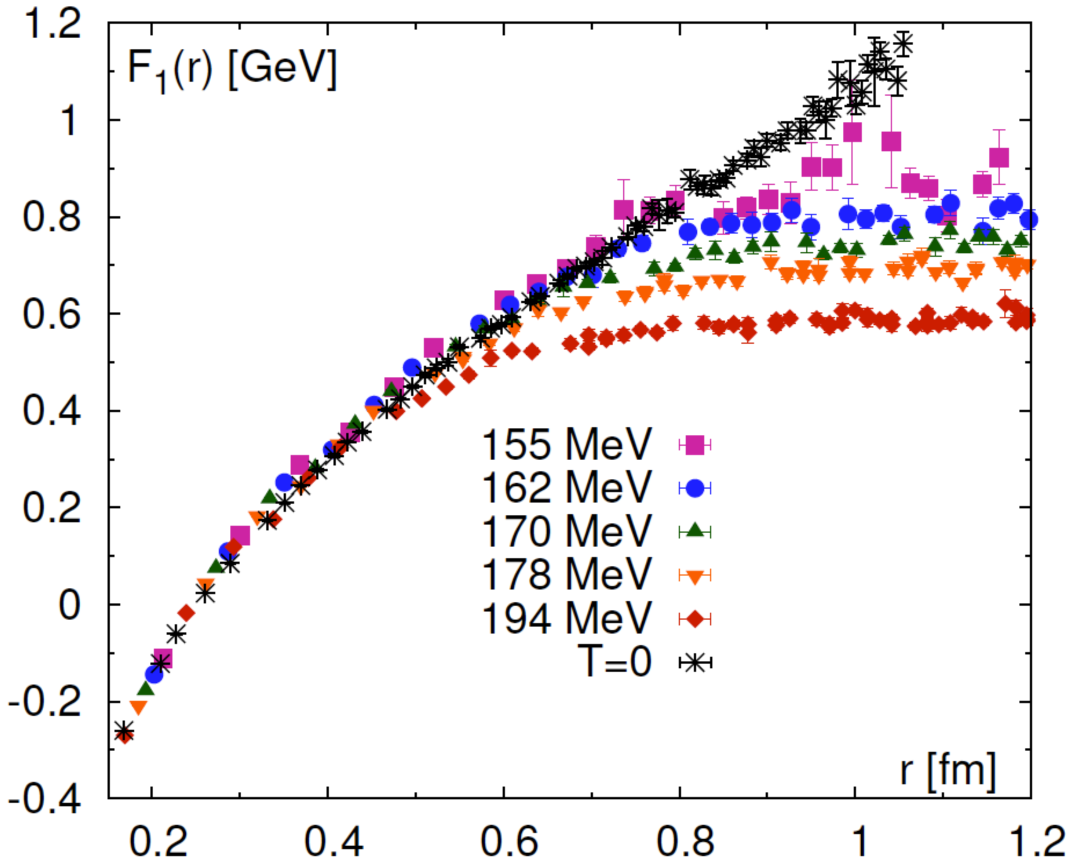
$\varepsilon_{SB} = \varepsilon_{SB}^{g} + \varepsilon_{SB}^{q} + \varepsilon_{SB}^{anti-q}$ = 15.6 $\times T^4$

- Rapid rise in the number of 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

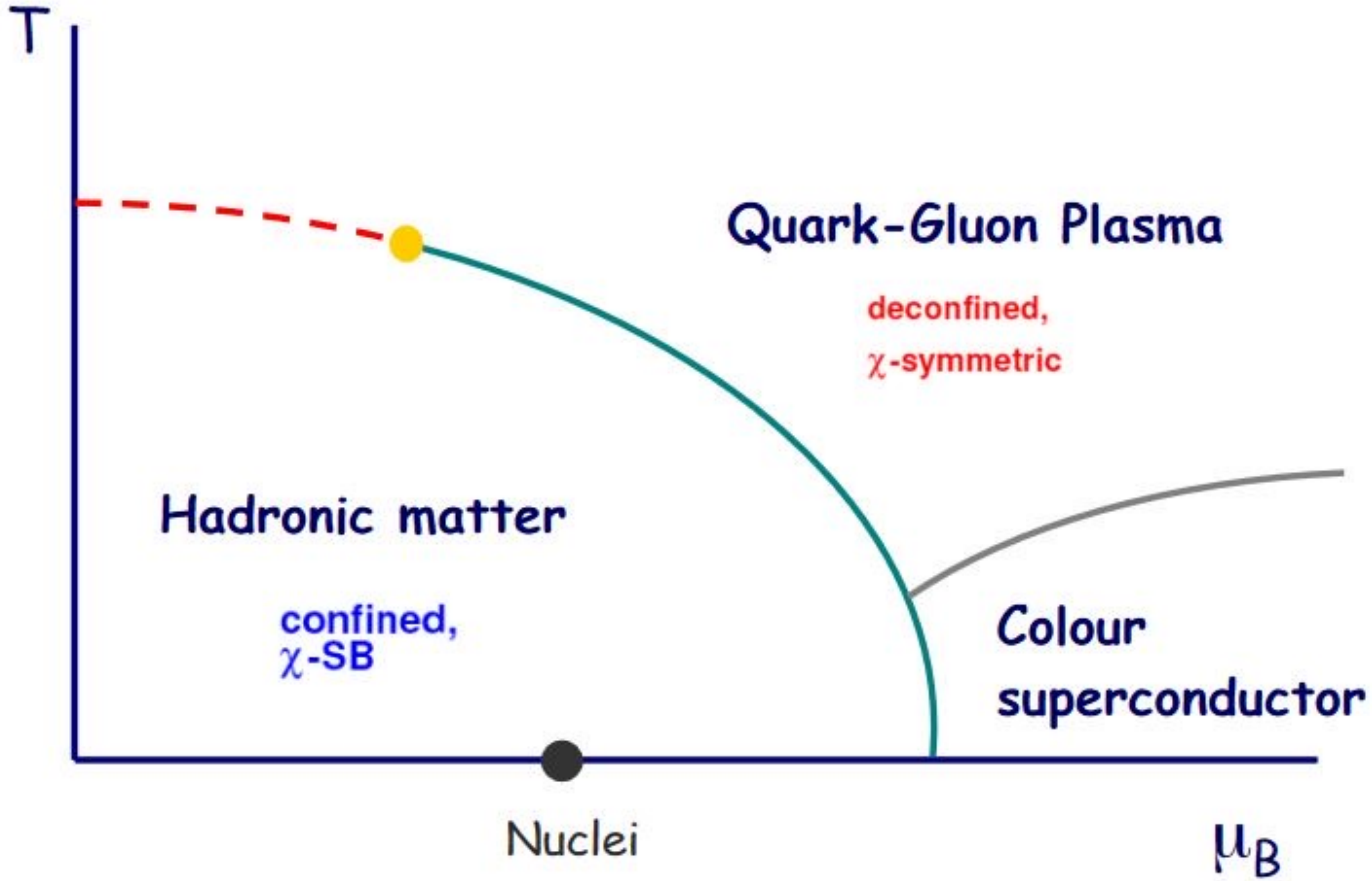
- The free energy of quark anti-quark pair as function of separation r

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



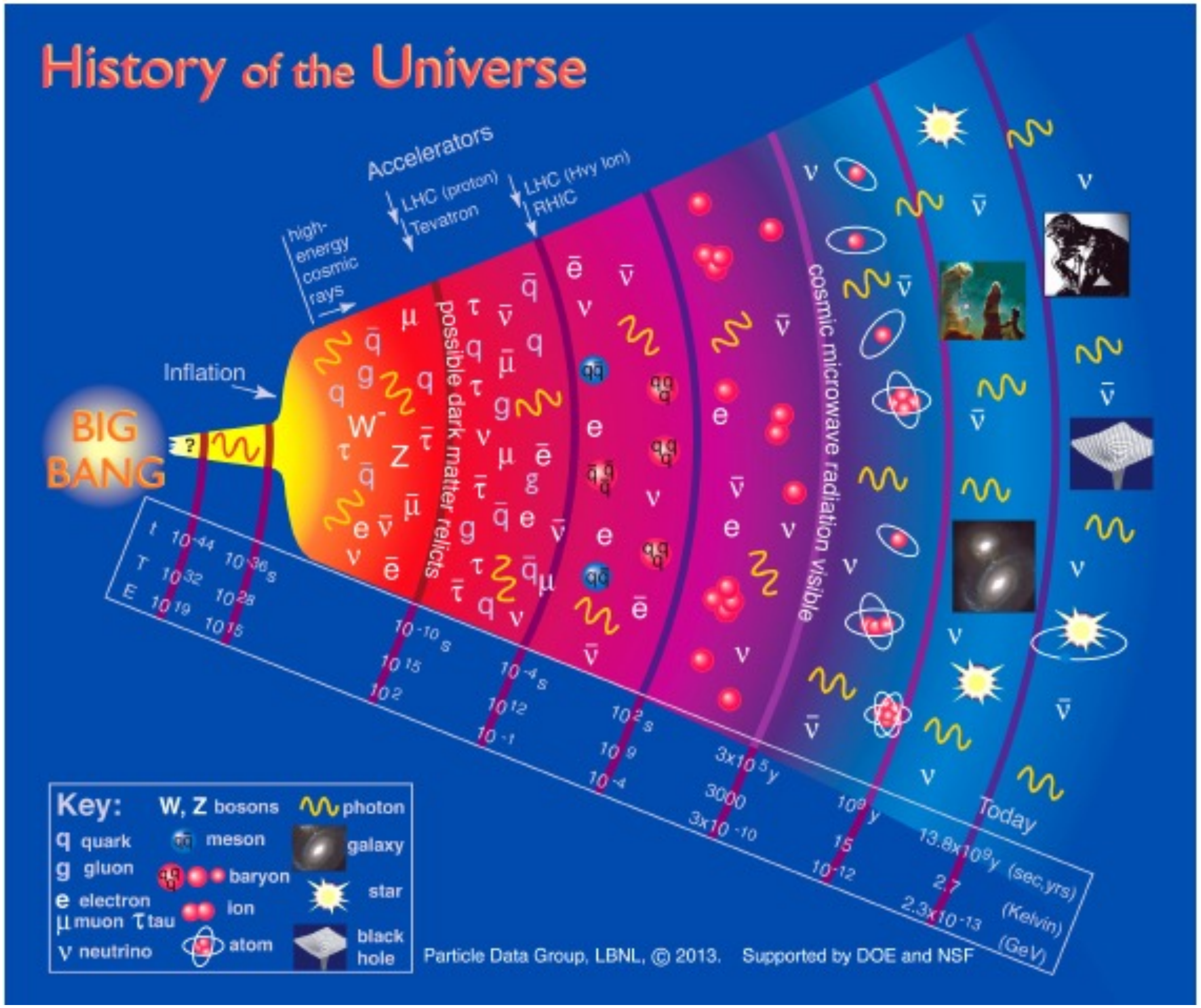
- At fixed r, F_1 decreases with increasing temperature
  - string tension $\sigma \searrow 0$ for T $\nearrow$
  - $\sigma = 0$ – lack of confinement

QCD Phase Diagram



- Baryon chemical potential measures the imbalance between matter and antimatter

QGP in Cosmology

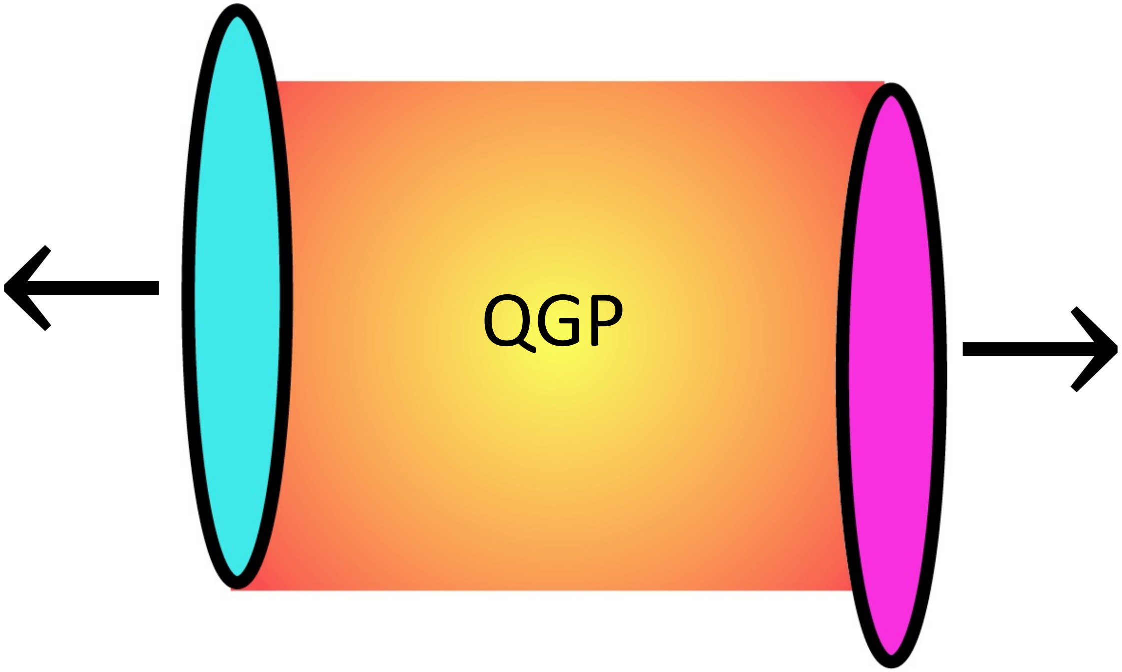


Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

- 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 Sun

Schematic View of Ultrarelativistic Heavy-ion Collision

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



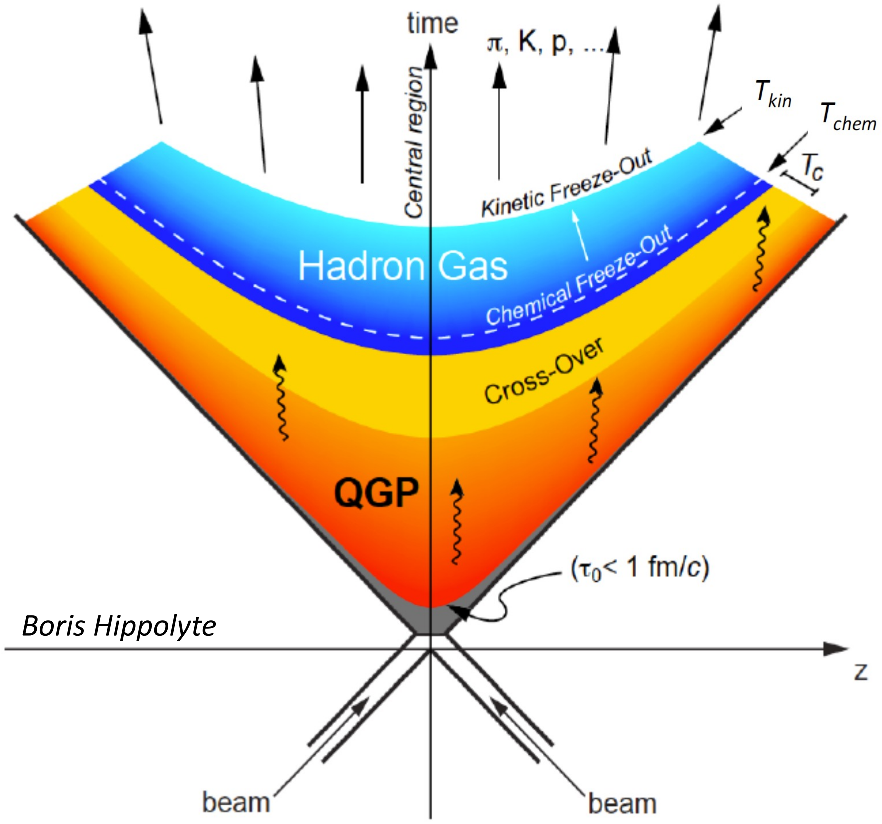
- The life time of QGP is a few fm/c, i.e. ~ 10^{-23}
- Collision energy available for QGP production (pre nucleon pair)

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

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

E_A - beam ion energy
A - atomic mass number

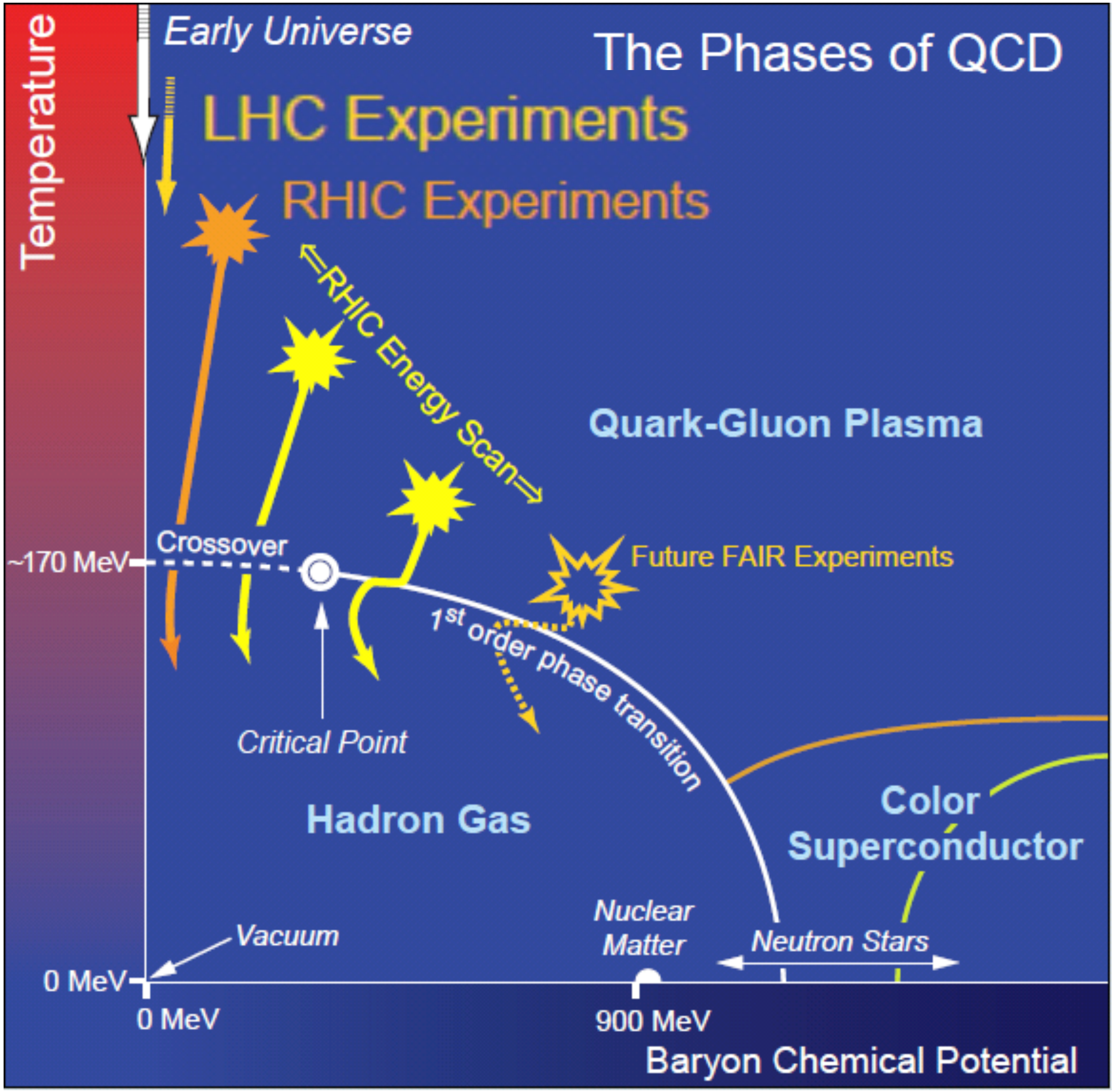
Stages of a Heavy-ion Collision



Boris Hippolyte

- The space time evolution starts from a hot-fireball in a pre-equilibrium phase (τ_0<1 fm/c)
  - Colour 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})

Study of QCD Phase Diagram

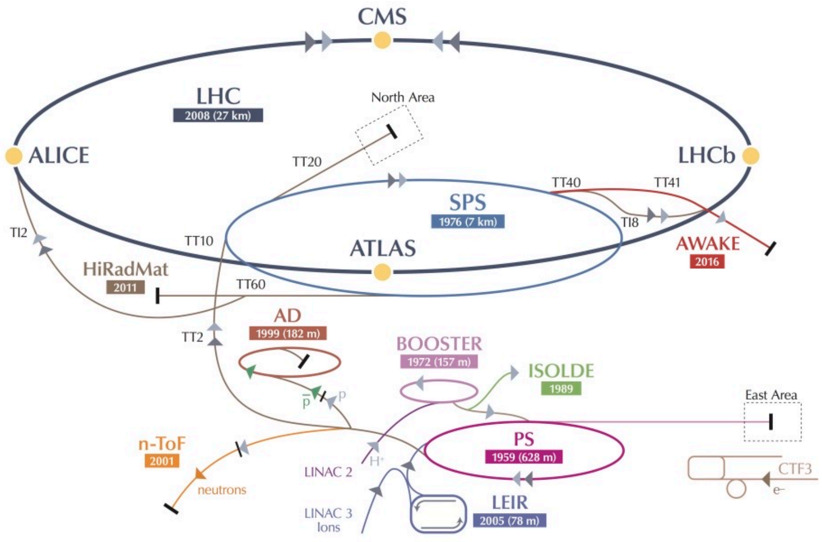


- Changing beam energy leads to changes in the temperature and μ_B of the system
  - $E_{beam} \nearrow$ $\mu_B \searrow 0$, $T \nearrow$
  - Probing location of Critical Point
- LHC
  - Energy nucleon pair: $\sqrt{s_{NN}}$ = 5020 GeV

$2\frac{E_A}{A}$ -nucleon pair CMS energy

- RHIC
  - $\sqrt{s_{NN}}$ = 8 - 200 GeV
- FAIR
  - $\sqrt{s_{NN}}$ = 2.7-5 GeV

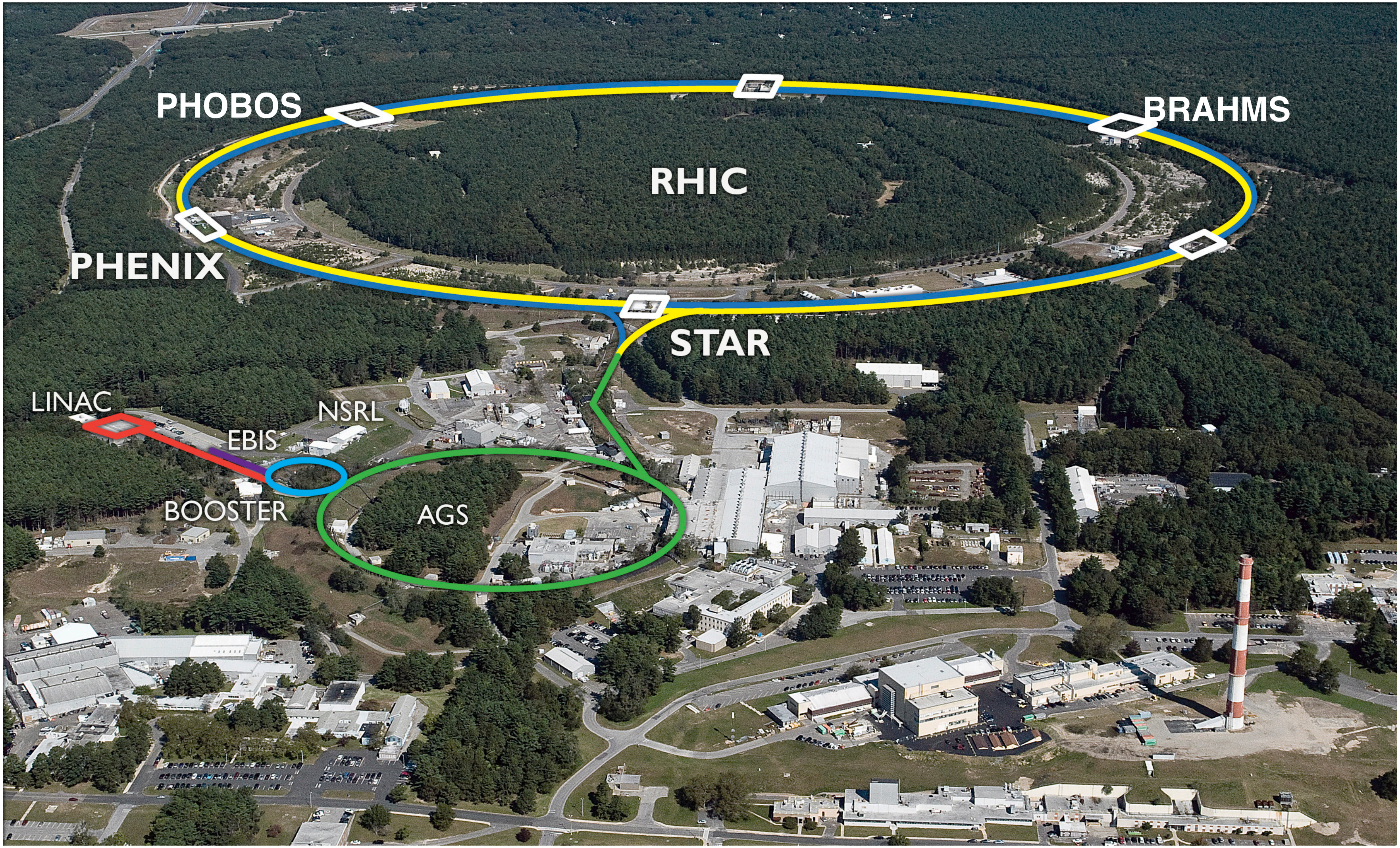
Most Powerful Heavy Ion Collider (LHC)



$^{208}_{82}Pb$: 4.5 →72 MeV (LIER) → 5.9 GeV (PS)
→ 177 GeV (SPS)→ 2.52 TeV (LHC)

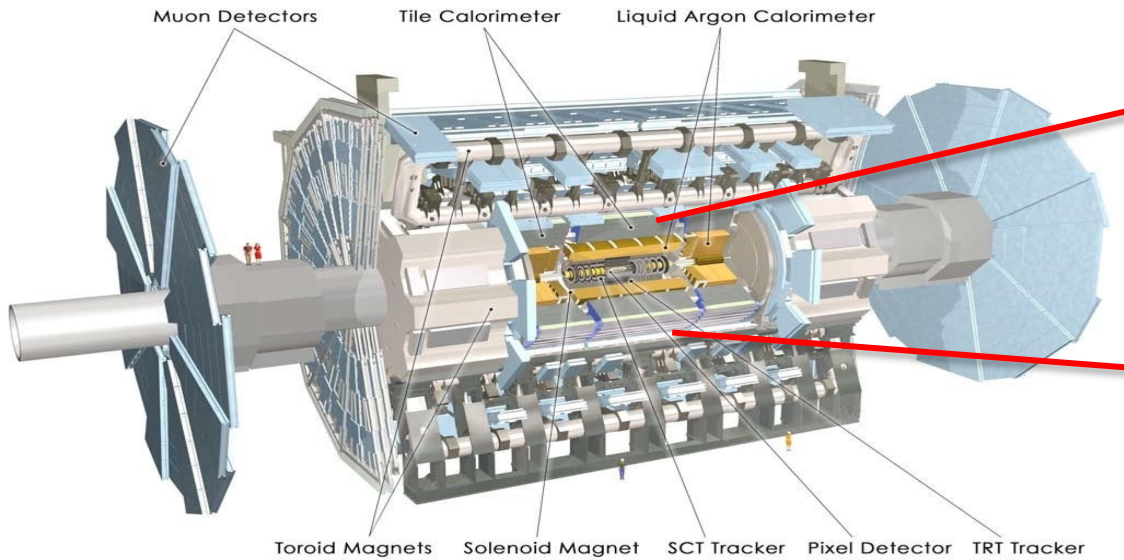
- The LHC consists of a 27-km ring of superconducting magnets located approximately 100 m below the surface
- Record collision energy, for Pb ions $\sqrt{s_{NN}}$ = 5036 GeV
- First lead ion collisions in the year 2010

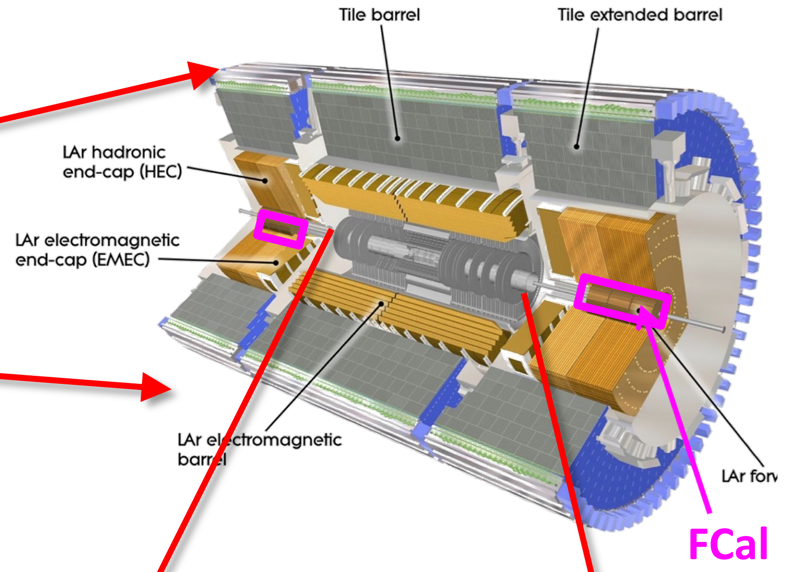
Relativistic Heavy Ion Collider



- 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

ATLAS as a Heavy Ion Detector



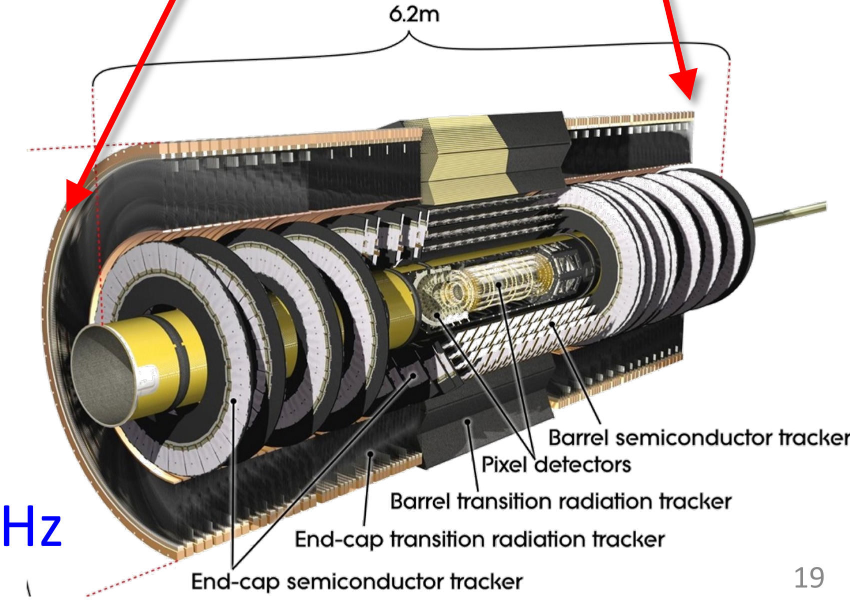


Three main subsystems:

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

Fast trigger systems:

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



LHC data sets

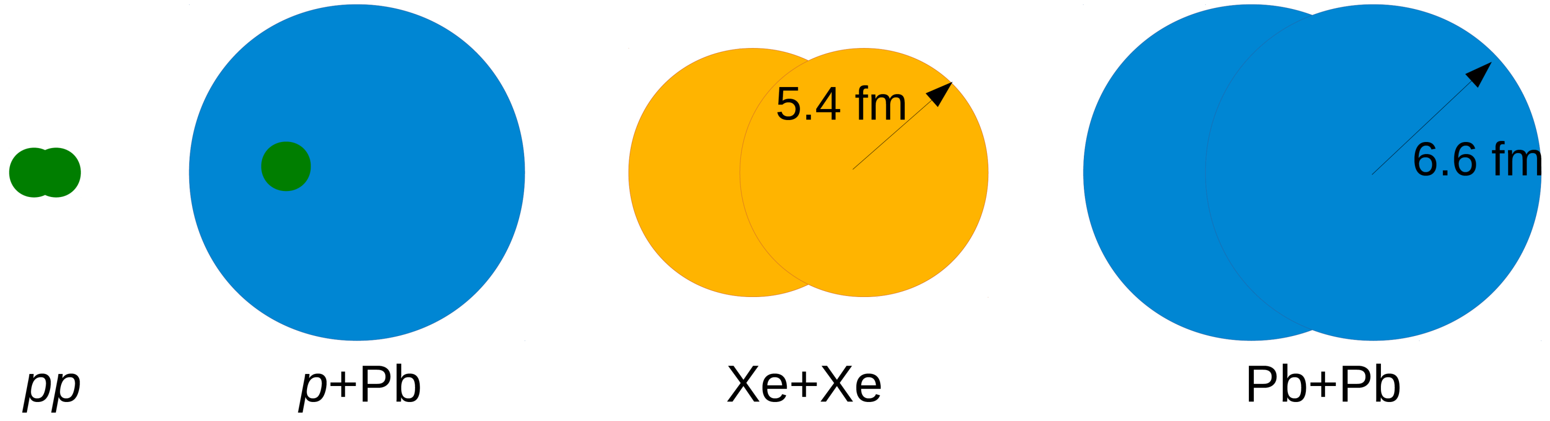
Datasets collected during:

- Run 1 (2010-2013)
- Run 2 (2015-2018)
- Run 3 (2022->2025)

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, 8, 13**

Reference data {

In Run II, 10 times more integrated luminosity of Pb+Pb than in Run 1



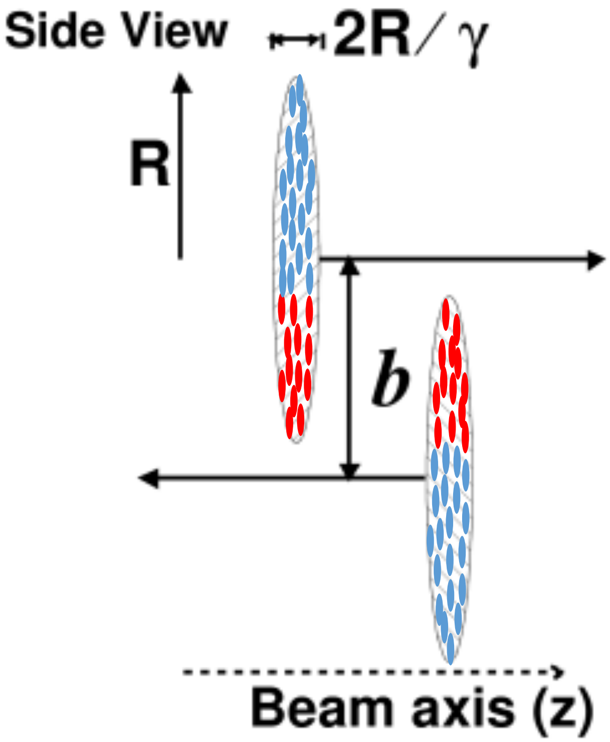
up to a few 100 particles

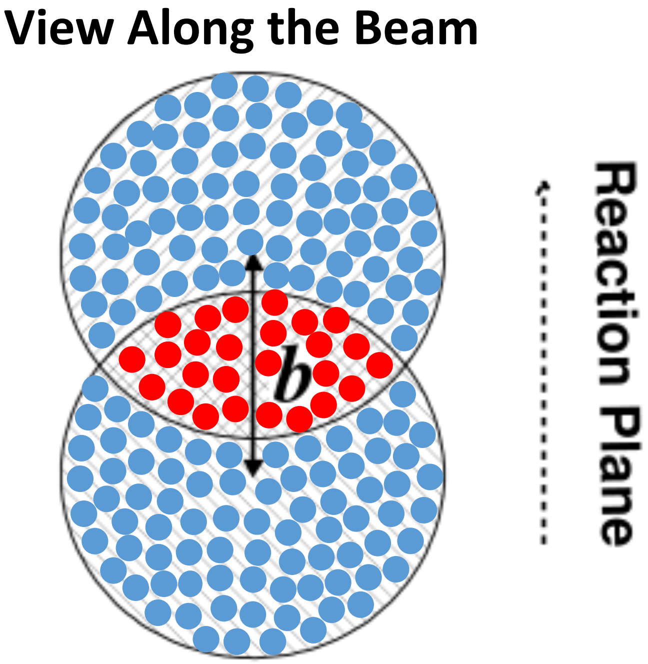
a few 1000 particles

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

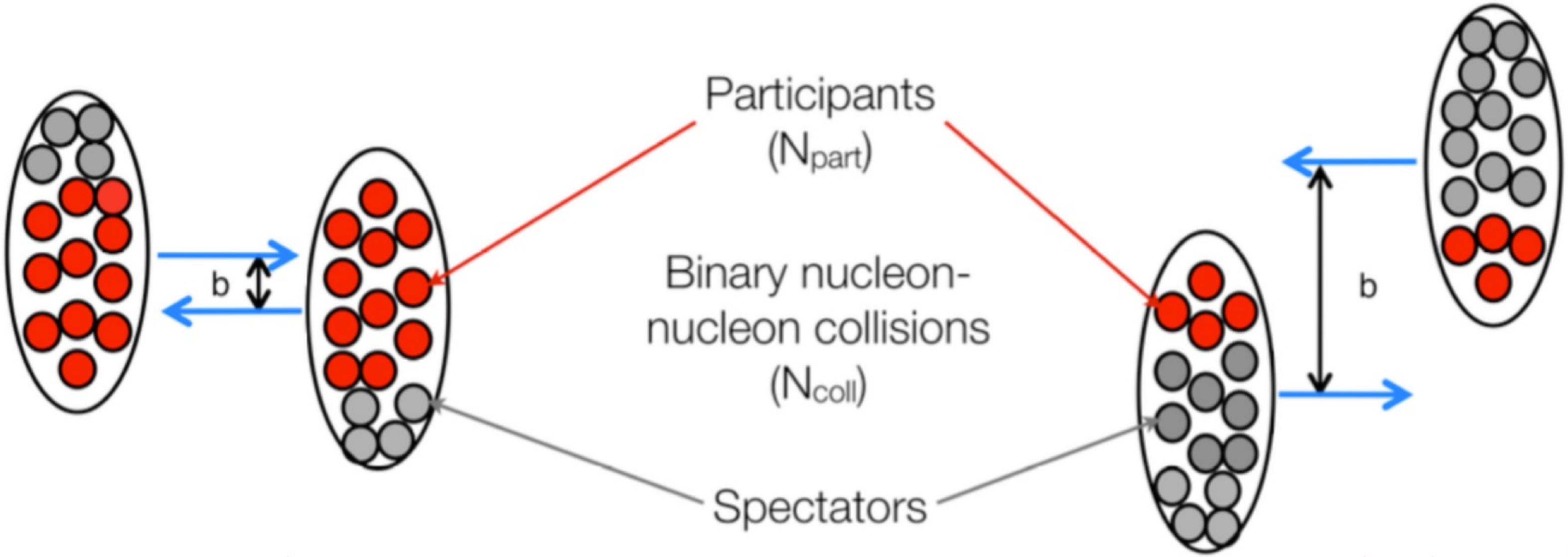
N_{coll} the number of binary nucleon-nucleon collisions in a heavy ion reaction

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

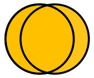
Heavy-ion Collisions of Different Centrality

Central collisions

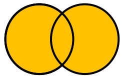
Peripheral collisions



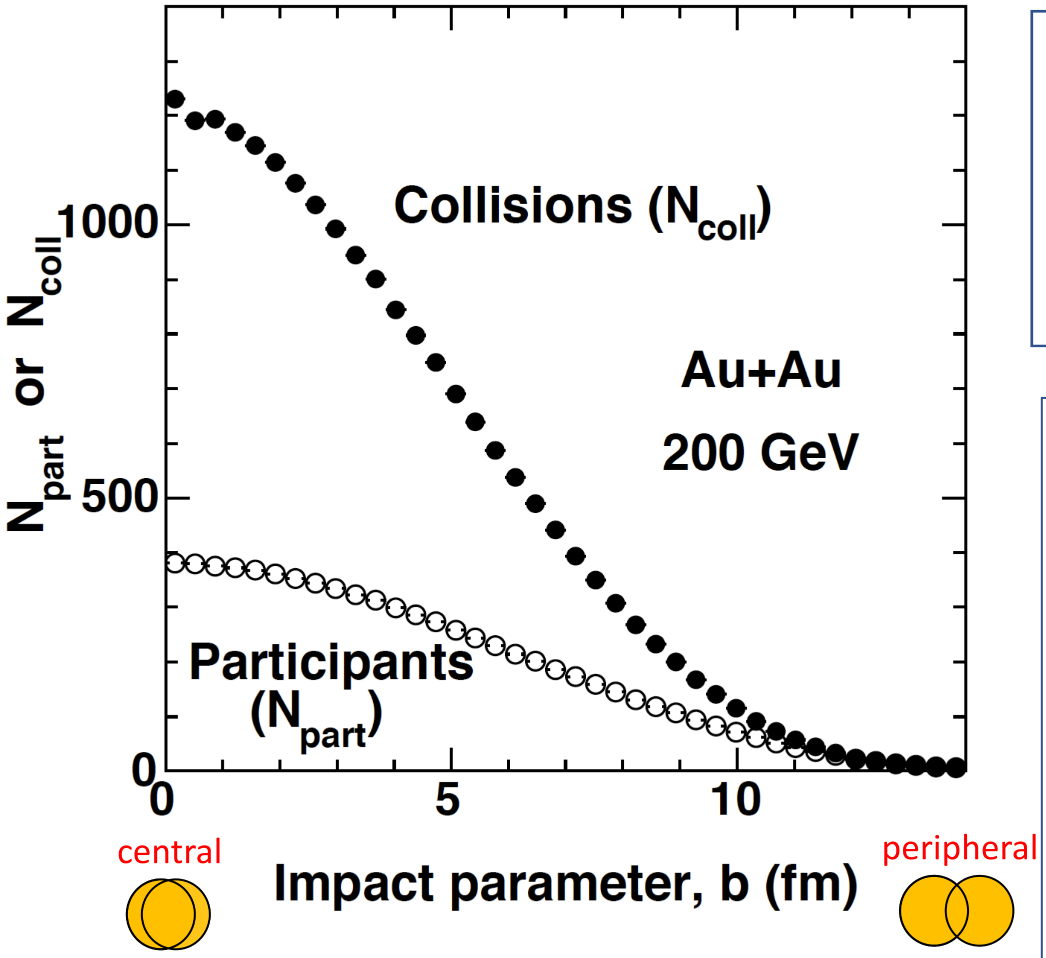
central



peripheral



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

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

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

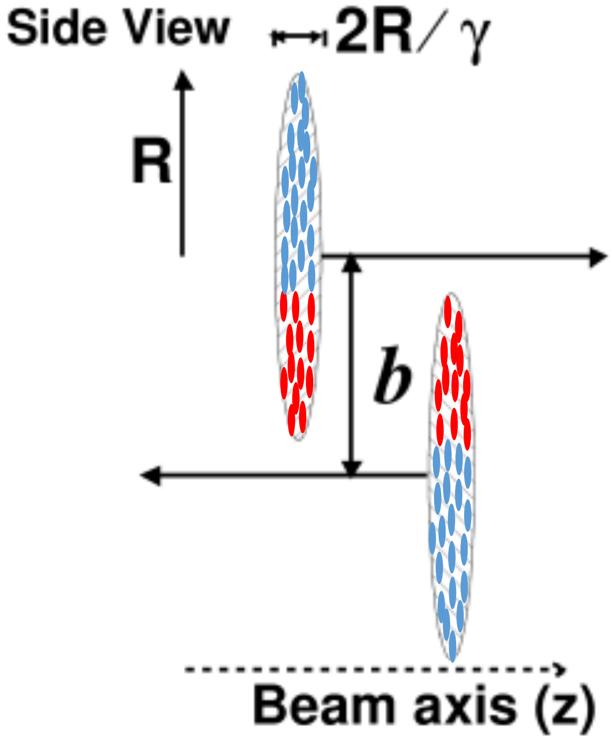
σ_{in} - NN inelastic cross section,
$\approx 42\ mb$ RHIC
$\approx 78\ mb$ LHC

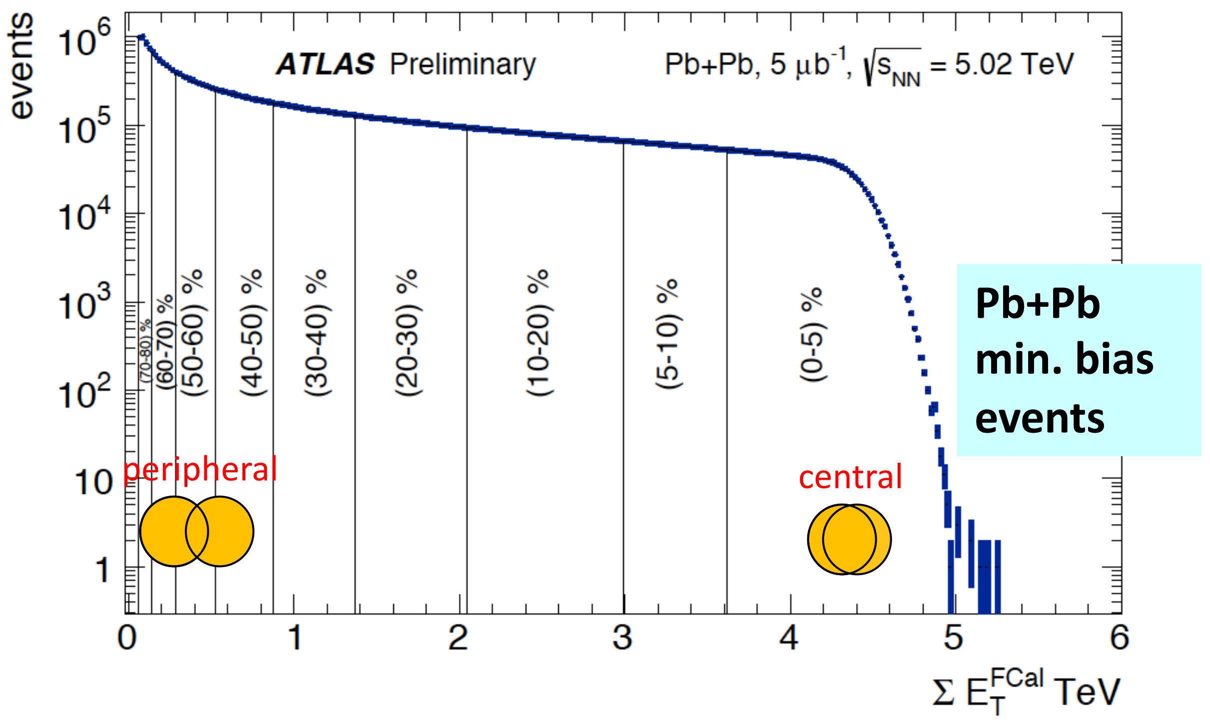
arxiv1710.07098

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

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)





Pb+Pb min. bias events

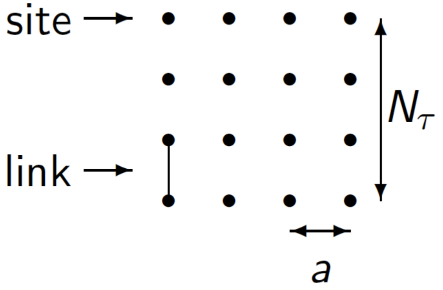
- MC simulations with Glauber model used for determination:

  N_{coll} - number of binary NN interactions
  N_{part} - number of participating (wounded) nucleons
  T_{AA} - nuclear thickness function ~ N_{coll}

backups

QCD Lattice - Ab-initio calculations

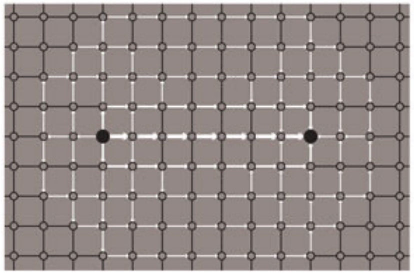
- In QCD, in the strong coupling limit ($\alpha_s \sim 1$) a non-perturbative lattice QCD model is used
- QCD is formulated at a discrete space-time grid N_s^3 x N_τ



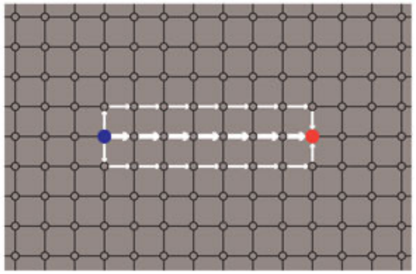
Fermionic degrees of freedom are on the sites while links represent gauge degrees of freedom

- Using extensive modern MC simulation on large supercomputers
  - Example for pure gauge field lattice of 32^3 x 8 there is 32^3 x 8 x 4 x 18 ≈ 2×10^7 gauge field DoF which needs to be integrated
- Physical observables are obtained via performing path integrations of partition function with a QCD Lagrangian $e^{-\int L_{QCD}}$ as a weight,

QED



QCD



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QCD lattice provided first theoretical evidence that quarks are confined

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