Introduction to Ultrarelativistic Nucleus-Nucleus Collisions

Lecture 1

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Warning…

An experimentalist's

(somewhat "hand-waving")

partial

(serious time limitation)

personal

(overview based on personal choice of subjects)

view

Contents

Today

Part 1: The QGP and A-A collisions

- Two puzzles in QCD
- Confinement and deconfinement
  (an "intuitive" view)
- Nucleus-Nucleus collisions

Part 2: SPS and RHIC results

- Bulk particle production
- Strangeness enhancement
- High p_T suppression

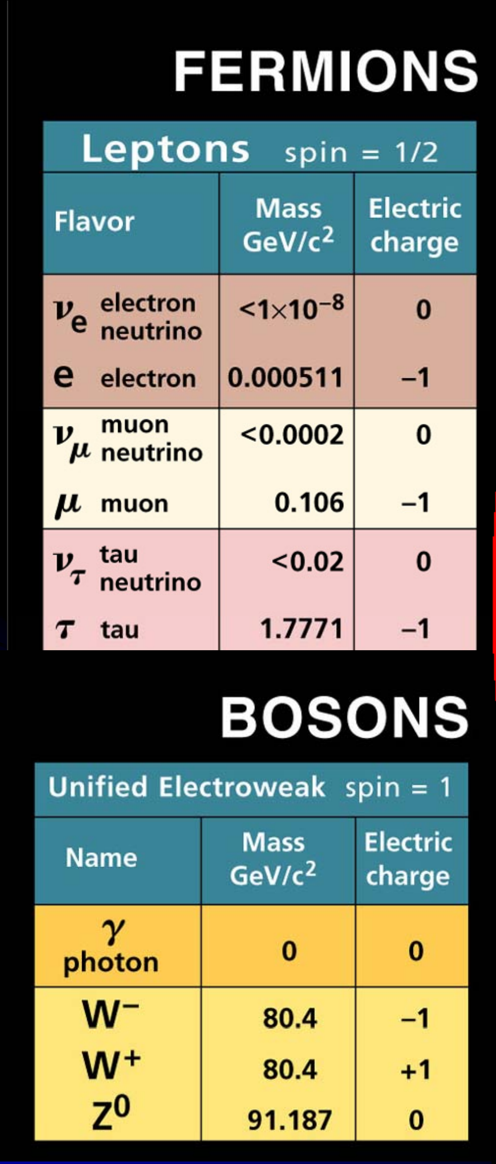
Tomorrow

- Part 2 cont'd: SPS and RHIC results
  - Recombination
  - Elliptic flow
  - Quarkonium suppression
- Part 3: Hard Probes and the LHC
  - Heavy Ions in the LHC
  - LHC physics, with two examples
    - Quarkonia
    - Heavy Flavours

Part 1: The QGP and A-A collisions

Two puzzles in QCD

The Standard Model and QCD



FERMIONS

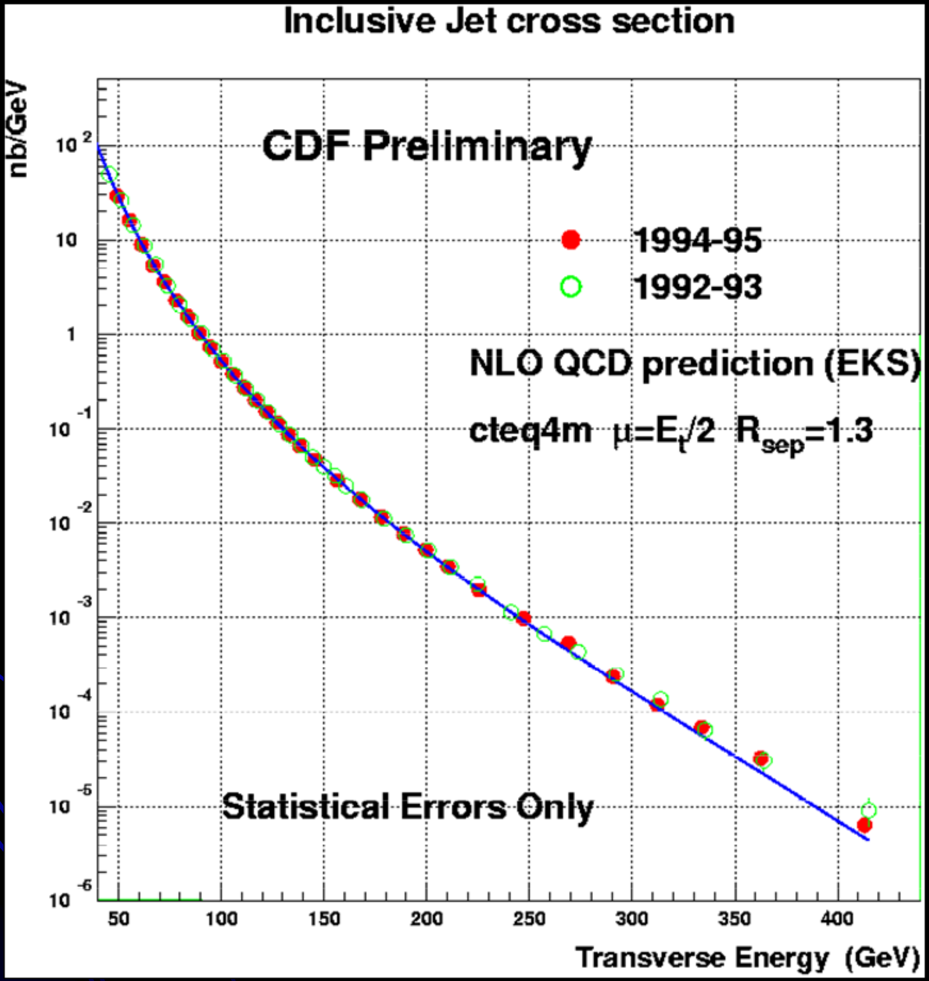
Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

BOSONS

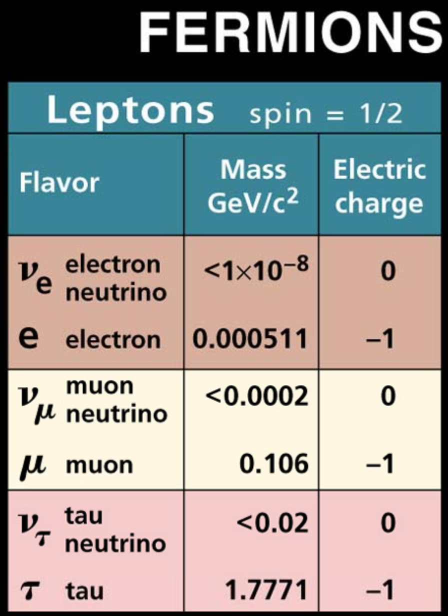
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.4	–1
W$^+$	80.4	+1
Z^0	91.187	0

- strong interaction:
  - binds quarks into hadrons
  - binds nucleons into nuclei
- described by QCD:
  - interaction between particles carrying colour charge (quarks, gluons)
  - mediated by strong force carriers (gluons)
- very successful theory

- e.g.: pQCD vs production of high energy jets



The Standard Model and QCD



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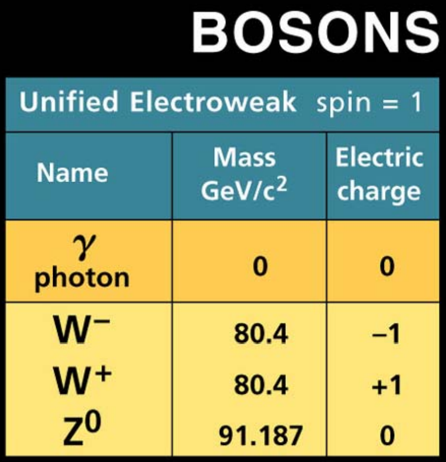

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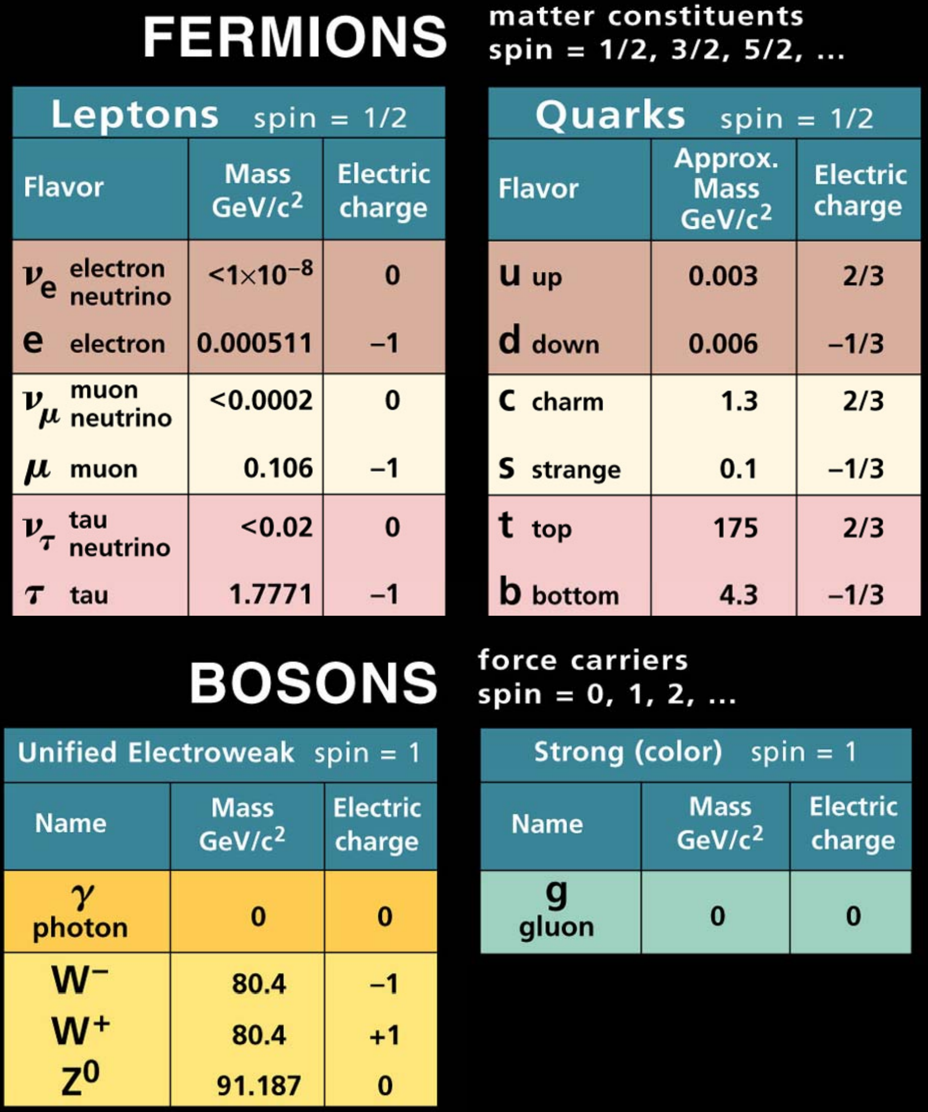
- very successful theory
  - jet production
  - particle production at high p_T
  - heavy flavour production
  - …
- … but with outstanding puzzles

Two puzzles in QCD: i) hadron masses



FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

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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

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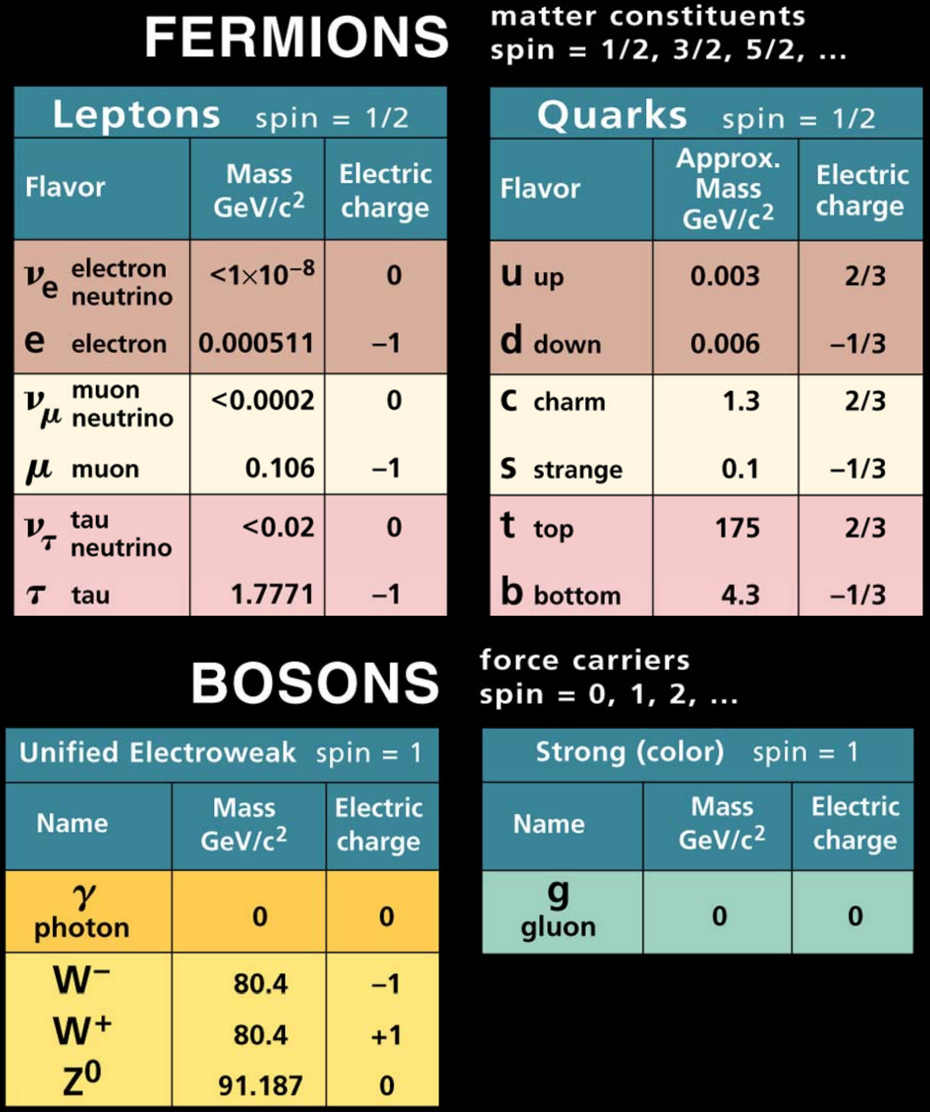
Strong (color) spin = 1

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

- A proton is thought to be made of two u and one d quarks
- The sum of their masses should be around 12 MeV
- ... but the proton mass is 938 MeV!
- how is the extra mass generated?

Two puzzles in QCD: ii) confinement



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Strong (color) spin = 1

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g gluon	0	0

- Nobody ever succeeded in detecting an isolated quark
- Quarks seem to be permanently confined within protons, neutrons, pions and other hadrons.
- It looks like one half of the fundamental fermions are not directly observable…

  how come?

Confinement and deconfinement

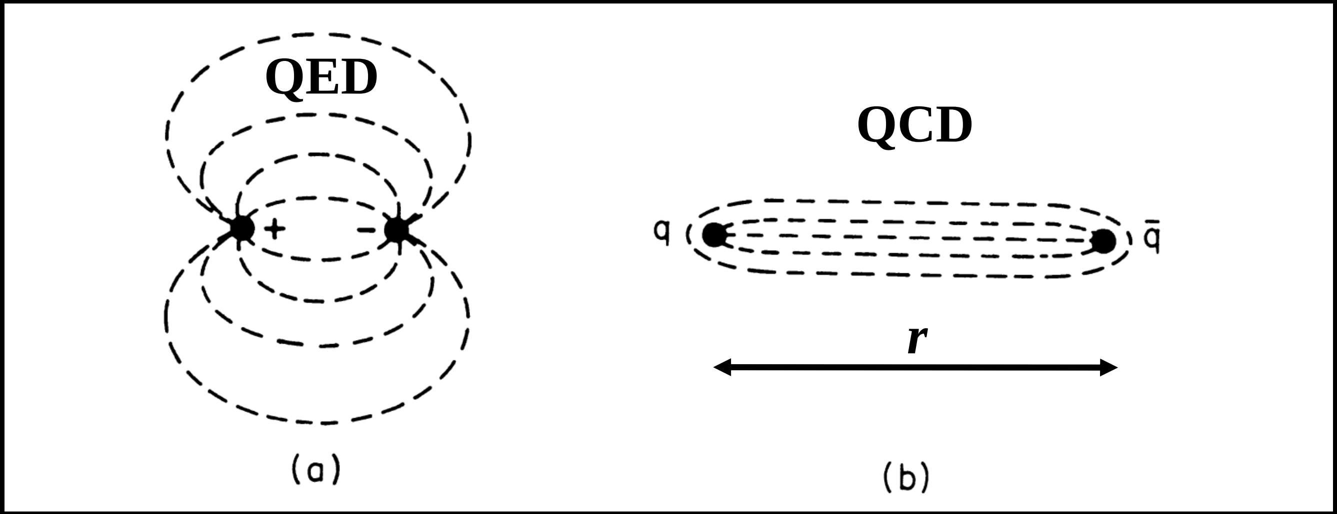
(an “intuitive” view)

Confinement

- At scales of the order of the hadron size (~ 1 fm) perturbative methods lose validity
- Calculations rely on approximate methods (such as lattice theory or effective theories)
- There are compelling arguments (but no rigorous proof) that the non-abelian nature of QCD is responsible for the confinement of colour

[see e.g. Gottfried-Weisskopf, p. 99]

Confining potential in QCD



- In QCD, the field lines are compressed into a “flux tube” (or “string”) of constant cross-section (~fm^2), leading to a long-distance potential which grows linearly with *r*:

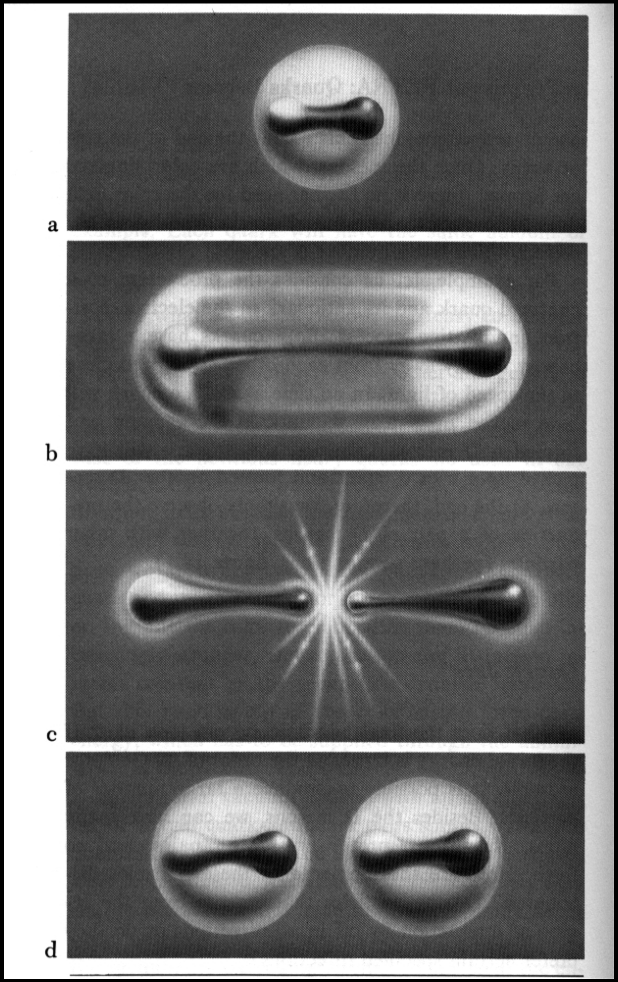
$$\boxed{V_{long} = kr}$$

with k ~ 1 GeV/fm

String breaking

- If one tries to pull the string apart, when the energy stored in the string ($k\,r$) reaches the point where it is energetically favourable to create a $q\bar{q}$ pair, the string breaks…

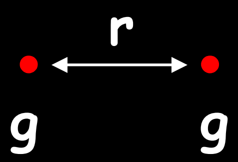
- …and one ends up with two colour-neutral strings (and eventually hadrons)



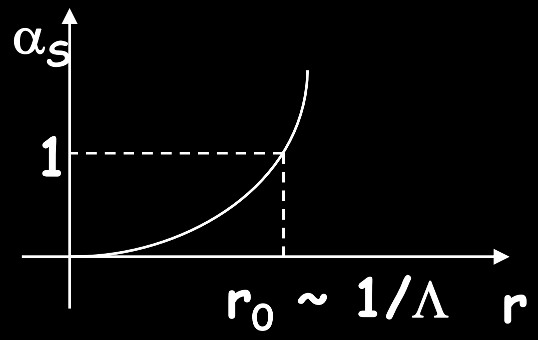
[illustration from Fritzsch]

QCD vacuum

- e.g.: 2 gluons in singlet state at a distance r

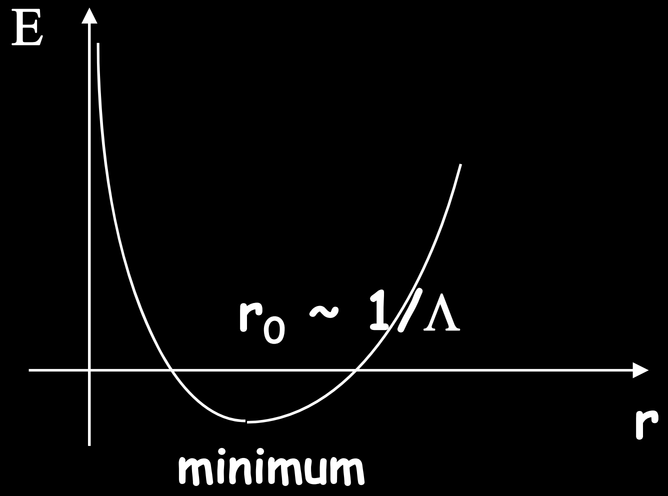


$$\Delta p \Delta r \sim \hbar = 1$$



$$r \sim \frac{1}{p} \sim \frac{1}{E_{KIN}} \quad \rightarrow \quad E_{KIN} \sim \frac{1}{r} \qquad \longrightarrow \qquad E = \frac{1}{r} - C\frac{\alpha_S}{r} = \frac{1 - C\alpha_S}{r}$$

$$\begin{array}{ll} r \rightarrow 0 & E \sim \dfrac{1}{r} \\ r \sim r_0 & E <\sim 0 \\ r \rightarrow \infty & E \sim kr \end{array}$$



QCD vacuum

- The “empty” vacuum is unstable. There is a state of lower energy that consists of cells, each containing a gluon pair in colour- and spin- singlet state. The size of these cells is of order r_0. We may speak of a “liquid” vacuum.

Gottfried-Weisskopf, IV C

Bag Model

- Due to the non-abelian nature of QCD and to the large value of the QCD coupling, the QCD vacuum is a rather complex object, behaving practically as a liquid

- The MIT bag model describes the essential phenomenology of confinement by assuming that quarks are confined within bubbles (bags) of perturbative (= empty) vacuum of radius *R* upon which the QCD vacuum exerts a confining pressure *B*

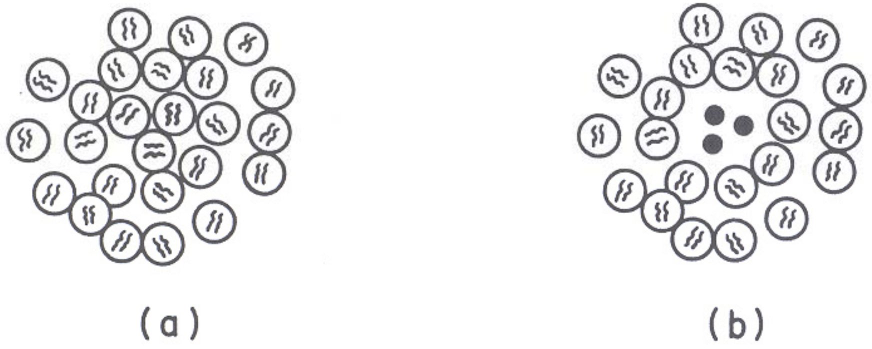

(a) (b)

FIG. 9. The QCD vacuum state is depicted in (a). It is a random distribution of cells that contain a gluon pair in a color and spin singlet state. Quarks (in a color singlet configuration) displace these cells, creating a region (or "bag") of "empty" vacuum, as shown in (b).

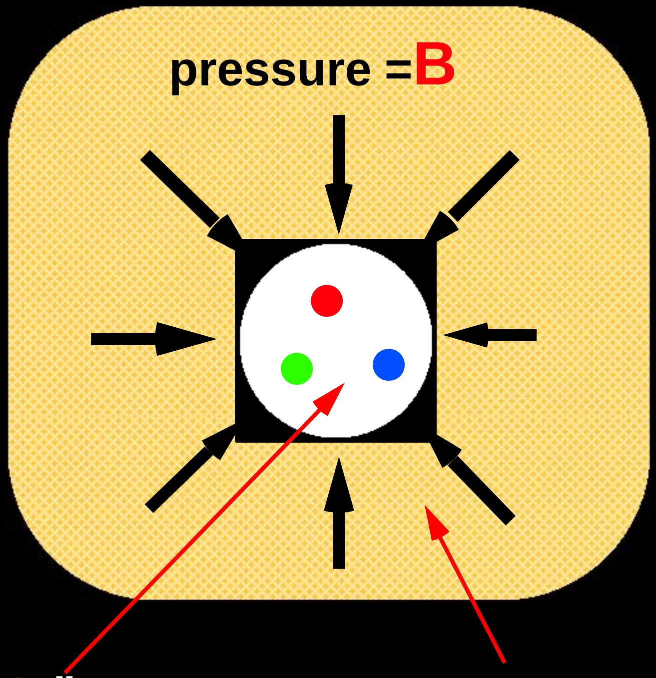
[see e.g. Gottfried-Weisskopf, p. 399]

- The bubble radius *R* is determined by the balance between the vacuum pressure *B* and the outward kinetic pressure exerted by the quarks

- From hadron spectra:

  $B \sim (200\ \text{MeV})^4$

Bag model of a hadron



pressure = **B**

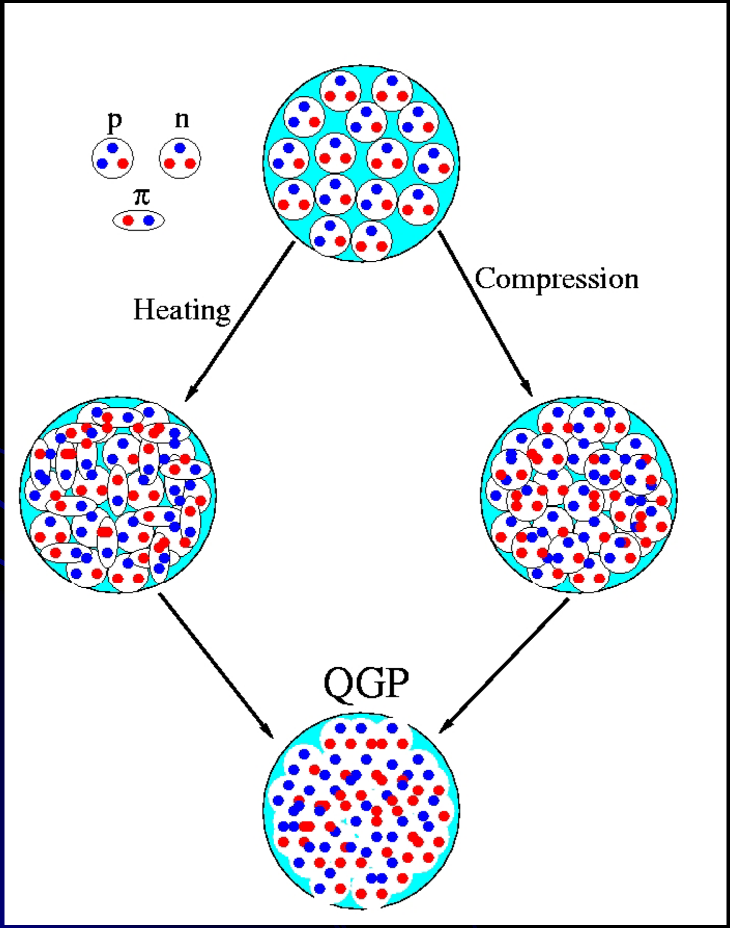
"empty" vacuum

"true" (QCD) vacuum

B = "bag constant" $B^{1/4} \sim 200\ \text{MeV}$

Deconfinement

- What if we compress/heat matter so much that the individual hadrons start to interpenetrate?

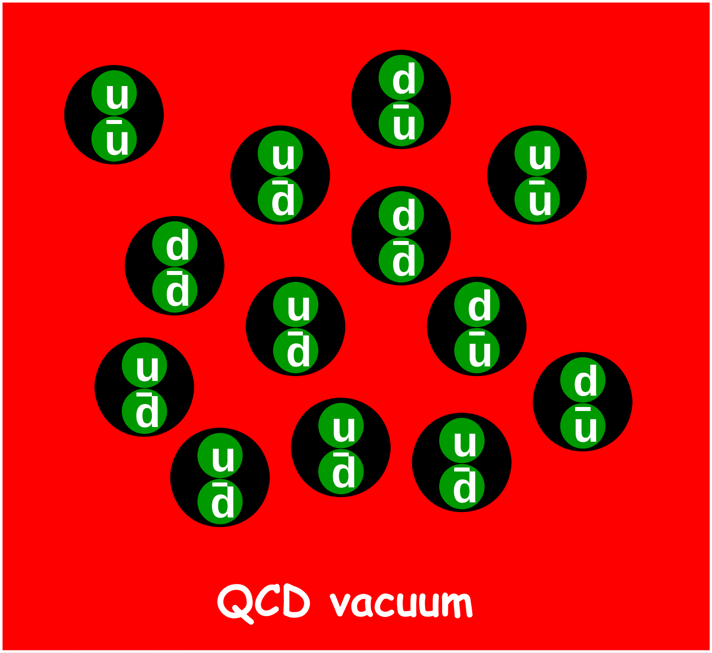


Lattice QCD predicts that if a system of hadrons is brought to sufficiently large density and/or temperature a deconfinement phase transition should occur

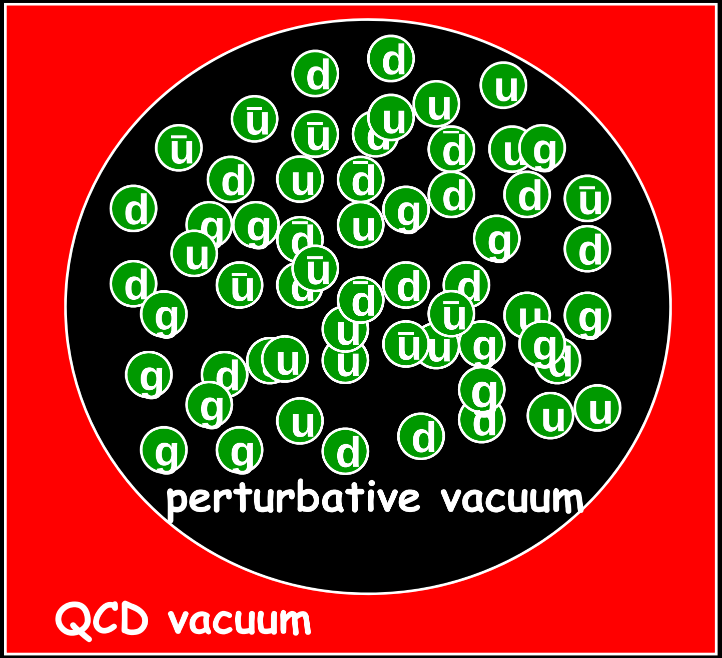
In the new phase, called Quark-Gluon Plasma (QGP), quarks and gluons are no longer confined within individual hadrons, but are free to move around over a larger volume

Deconfinement: a toy model

Hadron (pion) Gas



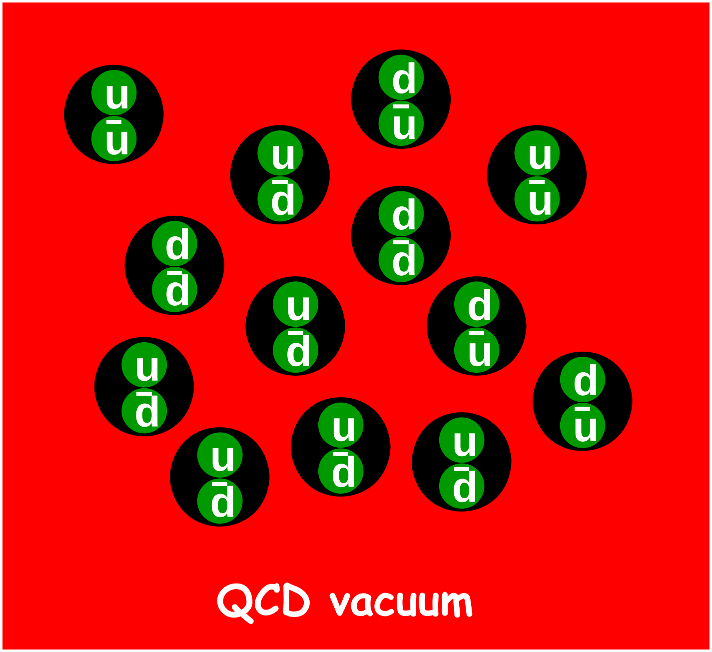
Quark-Gluon Plasma



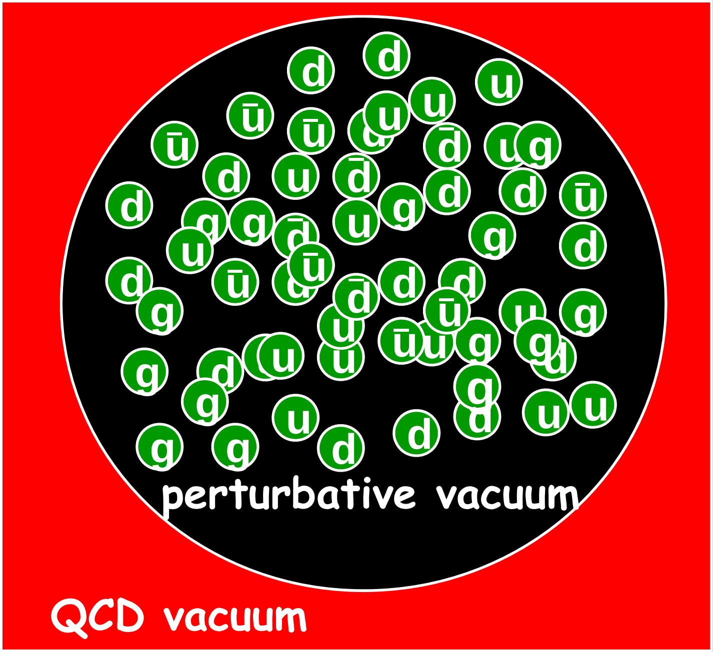
- Gibbs' criterion:the stable phase is the one with the largest pressure
- From statistical mechanics:
  (for an ideal gas)

$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

Hadron (pion) Gas



Quark-Gluon Plasma



$g_B = 3 \quad g_F = 0$

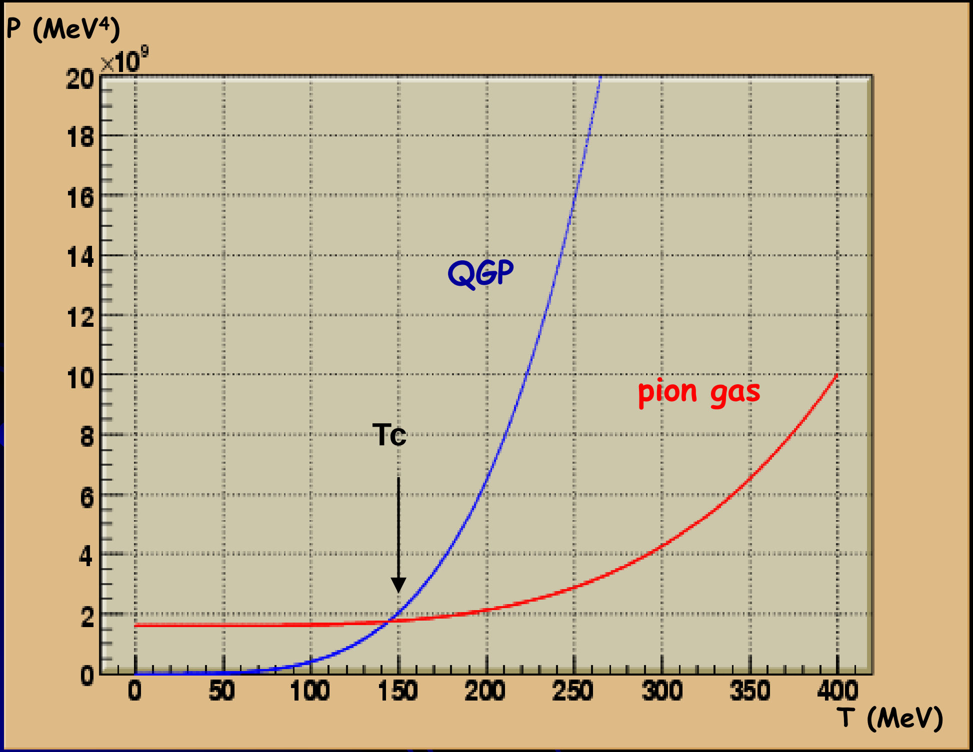
$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

$g_B = 16 \quad g_F = 24$

$$p = \frac{3}{90} \pi^2 T^4 + \boxed{B}$$

$$p = \frac{37}{90} \pi^2 T^4$$

- At low temperature the hadron gas is the stable phase
- There is a temperature T_C above which the QGP "wins", thanks to the larger number of degrees of freedom



$$T_C = \left(\frac{90}{34\,\pi^2} \right)^{1/4} B^{1/4}$$
$$\approx \ 150 \text{ MeV}$$

- very simplified calculation…
  - more refined estimates:

→ Tc ≈ 170 MeV

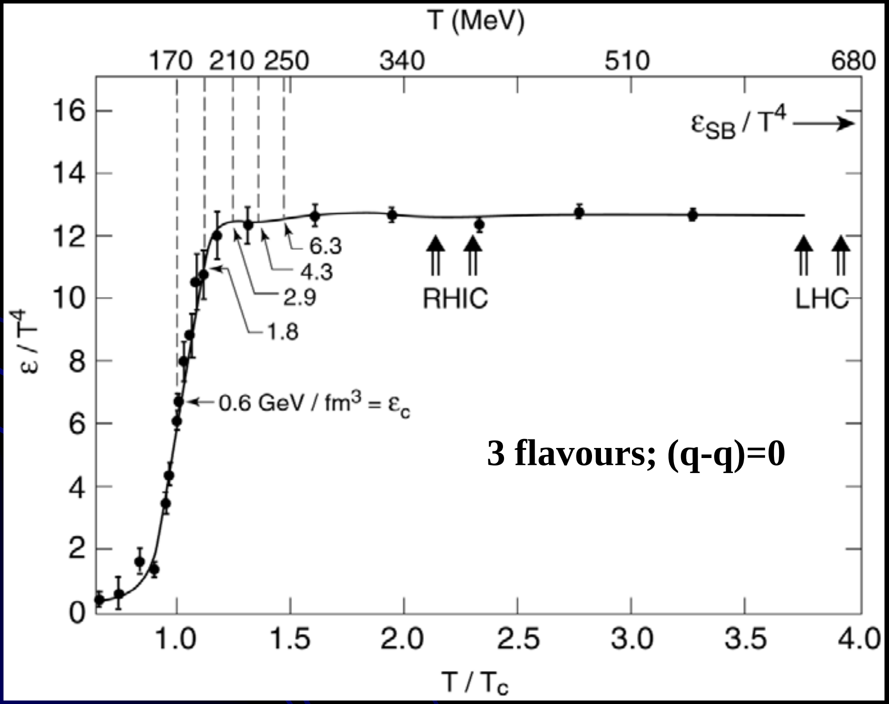
- 170 MeV?

recall: T_{room} (300 K) ~ 25 meV
(of course, lowecase m)

→ Tc ≈ 170 MeV ≈ 2000 billion K
(compare Sun core: 15 million K)

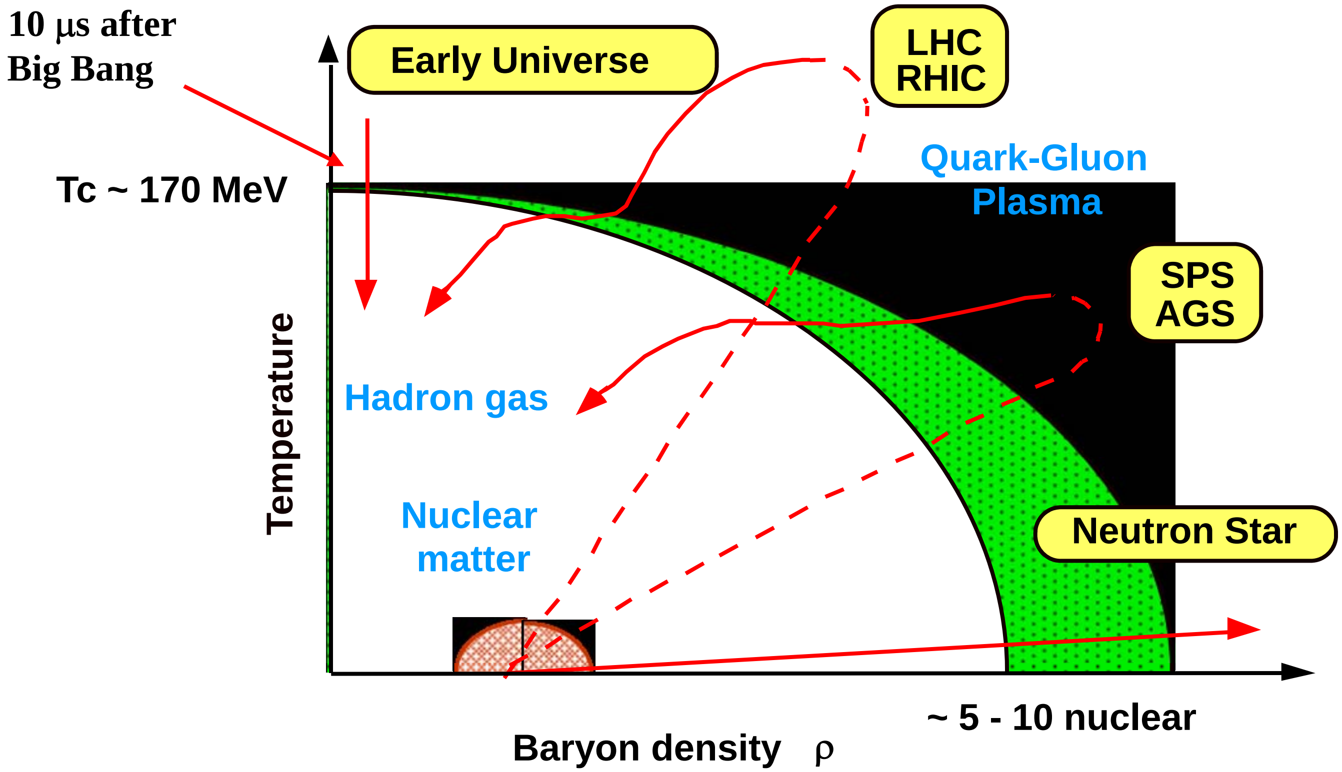
Lattice QCD

- **In lattice QCD, non-perturbative problems are treated by discretization on a space-time lattice. As a result, ultraviolet (large momentum scale) divergencies can be avoided**



- zero baryon density, 3 flavours
- ε changes rapidly around T_c
- T_c = 170 MeV:
  $\rightarrow \varepsilon_c$ = 0.6 GeV/fm^3
- at T~1.2 T_c ε settles at about 80% of the Stefan-Boltzmann value for an ideal gas of q,$\bar{q}$ g (ε_{SB})

QCD phase diagram



10 μs after
Big Bang

Early Universe

LHC
RHIC

Tc ~ 170 MeV

Quark-Gluon
Plasma

SPS
AGS

Temperature

Hadron gas

Nuclear
matter

Neutron Star

~ 5 - 10 nuclear

Baryon density ρ

$$\varepsilon_c \sim 1\ \mathrm{GeV/fm^3}$$

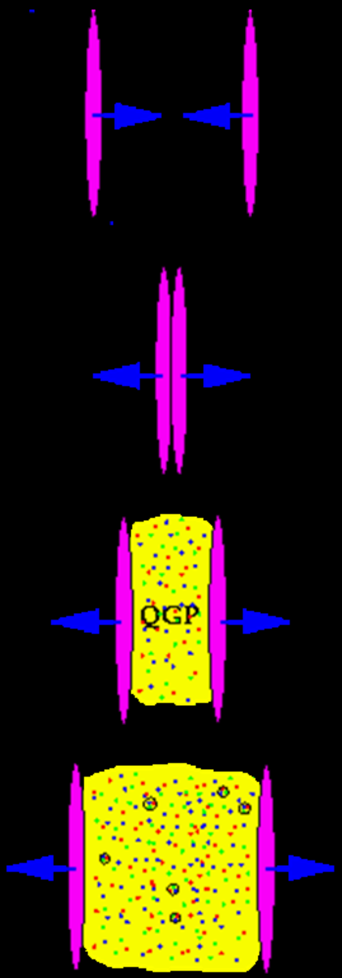
Restoration of bare masses

- Confined quarks acquire an additional mass (~ 350 MeV) dynamically, through the confining effect of strong interactions
  - M(proton) ≈ 938 MeV; m(u)+m(u)+m(d) = 10÷15 MeV
- Deconfinement is expected to be accompanied by a restoration of the masses to the "bare" values they have in the Lagrangian
- As quarks become deconfined, the masses go back to the bare values; e.g.:
  - m(u,d): ~ 350 MeV → a few MeV
  - m(s): ~ 500 MeV → ~ 150 MeV
- (This effect is usually referred to as "Partial Restoration of Chiral Symmetry". Chiral Symmetry: fermions and antifermions have opposite helicity. The symmetry is exact only for massless particles, therefore its restoration here is only partial)

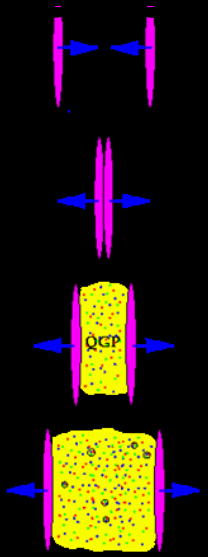
Nucleus - Nucleus collisions

Nucleus-nucleus collisions

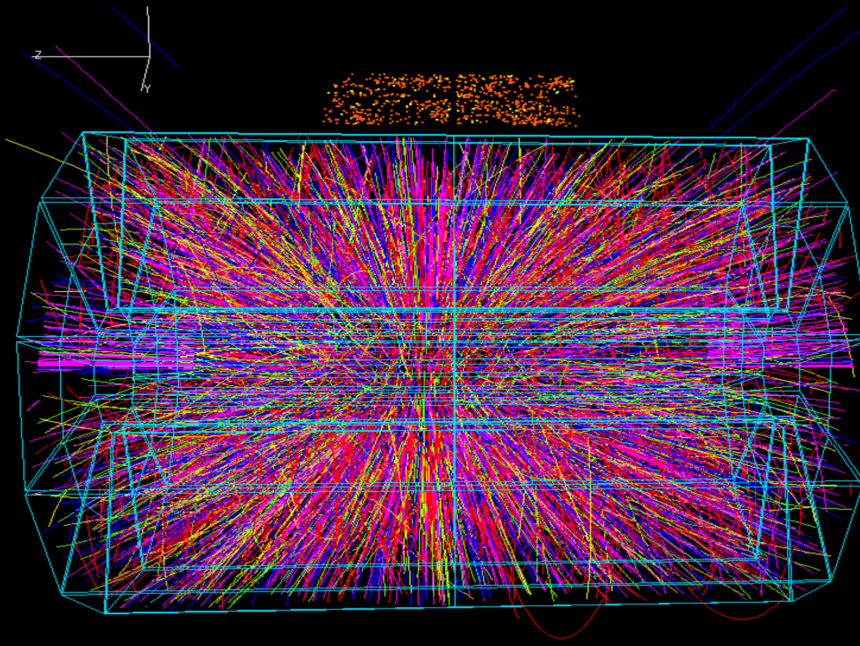
- How do we test this theory in the lab?
- How can we compress/heat matter to such cosmic energy densities?
- By colliding two heavy nuclei at ultrarelativistic energies we hope to be able to recreate, for a short time span (about 10^{-23}s, or a few fm/c) the appropriate conditions for deconfinement



- Even if a QGP is formed, as the system expands and cools down it will hadronize again, as it did at the beginning of the life of the Universe: we end up with confined matter again
  - QGP lifetime ~ a few fm/c



- The properties of the medium must be inferred from the properties of the hadronic final state

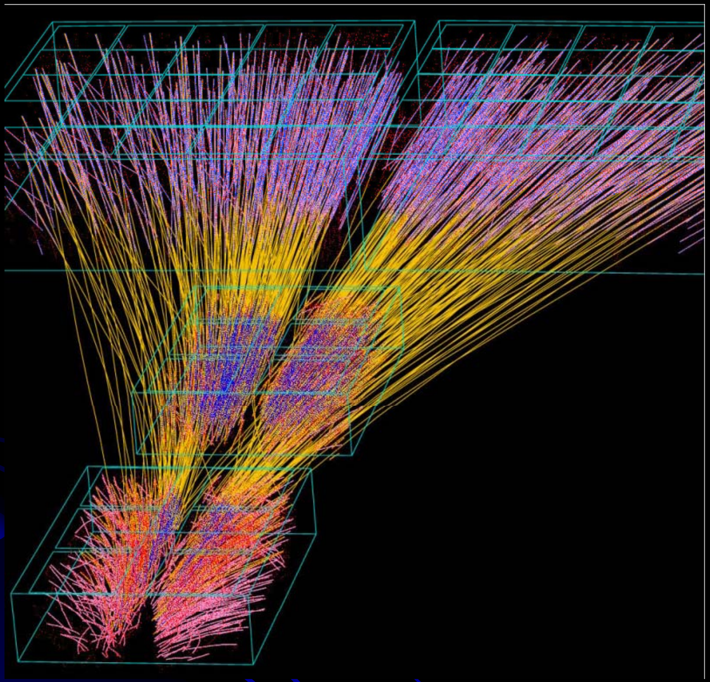


Collisions of Heavy Nuclei at SPS and RHIC

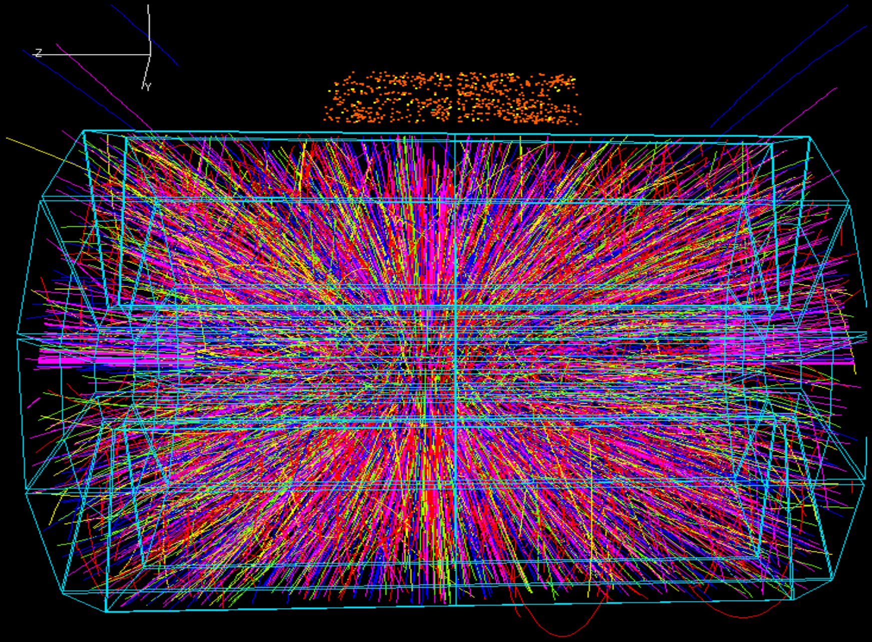
- Super Proton Synchrotron (SPS) at CERN (Geneva):
  - Pb-Pb fixed target, p = 158 A GeV → $\sqrt{s_{NN}} = 17.3$ GeV
  - 1994 - 2003
  - 9 experiments:
    - WA97 (silicon pixel telescope spectrometer: production of strange and multiply strange particles)
    - WA98 (photon and hadron spectrometer: photon and hadronn production)
    - NA44 (single arm spectrometer: particle spectra, interferometry, particle correlations)
    - NA45 (e^+e^- spectrometer: low mass lepton pairs)
    - NA49 (large acceptance TPC: particle spectra, strangeness production, interferometry, event-by-event , …)
    - NA50 (dimuon spectrometer: high mass lepton pairs, J/ψ production)
    - NA52 (focussing spectrometer: strangelet search, particle production)
    - NA57 (silicon pixel telescope spectrometer: production of strange and multiply strange particles)
    - NA60 (dimuon spectrometer + pixels: dileptons and charm)
- Relativistic Heavy Ion Collider (RHIC) at BNL (Long Island)
  - Au-Au collider, $\sqrt{s_{NN}} = 200$ GeV
  - 2000 - …
  - 4 experiments:
    - STAR (multi-purpose experiment: focus on hadrons)
    - PHENIX (multi-purpose experiment: focus on leptons, photons)
    - BRAHMS (two-arm spectrometer: particle spectra, forward rapidity)
    - PHOBOS (silicon array: particle spectra)

A-A collisions

- a Pb-Pb event at the SPS



- a Au-Au event at RHIC



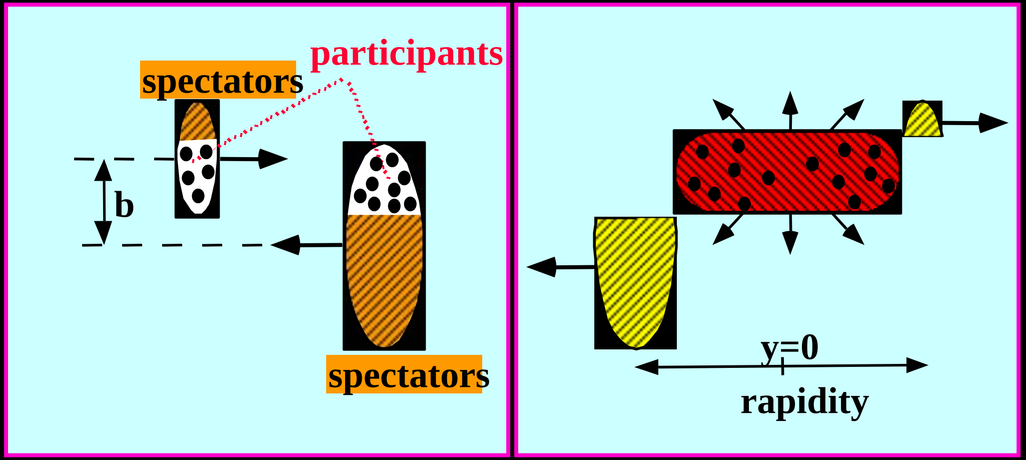
- hundreds of particles per unit rapidity per event !

→ high granularity detectors !

(Time-Projection Chambers, Silicon Pixel Detectors, …)

Collision centrality

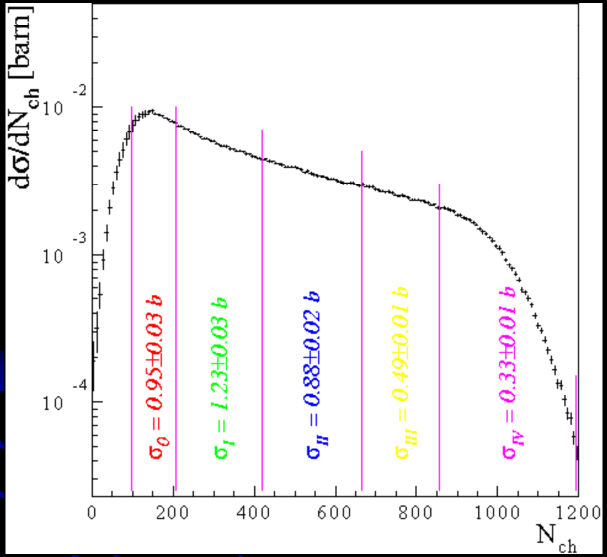
- How far do the centers of the two colliding nuclei pass one another?



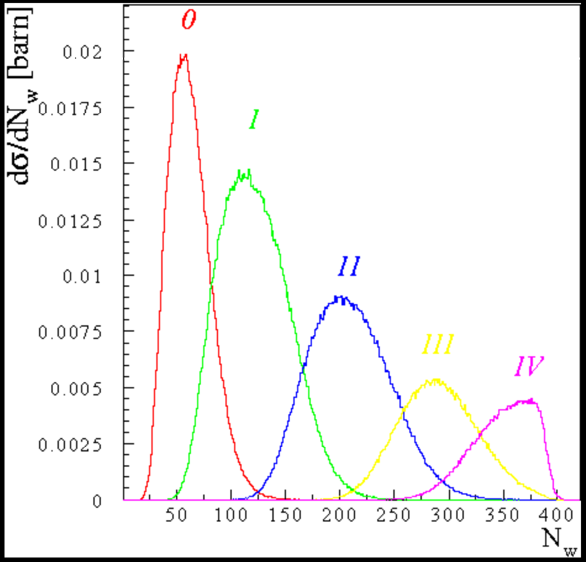
- Usually expressed in terms of:
  - *b* (impact parameter)
  - number of participants $N_{part}(b)$
    - [sometimes one speaks of "number of wounded nucleons": $N_W(b)$]
  - cross section $\sigma(b)$

- Experimentally, the centrality is evaluated by measuring one or more of these variables:
  - N_{ch}: number of charged particles produced in a given rapidity interval (near mid-rapidity)
    - increases (~ linearly) with N_{part}
  - E_T: transverse energy = $\Sigma E_i \sin \theta_i$
    - increases (~ linearly) with N_{part}
  - E_{ZDC}: energy collected in a "zero degree" calorimeter
    - increases (~ linearly) with $N_{spectators}$

- e.g.: NA57 experiment: the centrality is evaluated from the charged particle multiplicity in the pseudorapidity range $2 < \eta < 4$



Pb-Pb events are divided into multiplicity classes

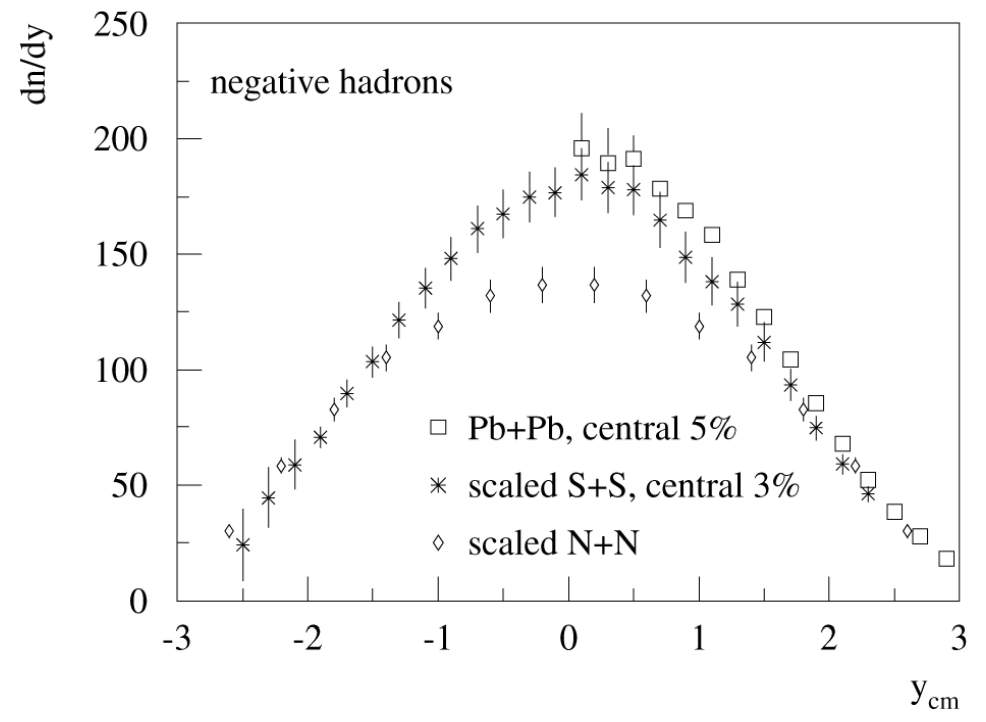


The distribution of the number of participants for the events in each class is evaluated

Part 2: SPS and RHIC Results

Bulk particle production

Particle production



- Rapidity distribution for negative hadrons (mostly pions) for central Pb-Pb collisions at SPS (from NA49)
- ~ 2500 hadrons per collision

Bjorken's formula

- To evaluate the energy density reached in the collision:

$$\varepsilon = \frac{1}{S c \tau_0} \left.\frac{dE}{dy}\right|_{y=0}$$

$S =$ transverse dimension of nucleus

$\tau_0 =$ "formation time" $\sim 1\,\mathrm{fm}/c$

- **Experimentally for central collisions at SPS:** $\left.\frac{dE}{dy}\right|_{y=o} \approx 400\ \mathrm{GeV}$

- **Initial time τ_0 normally taken to be ~ 1 fm/c**
  - **i.e. equal to the "formation time": the time it takes for the energy initially stored in the field to materialize into particles**

- **Transverse dimension:** $S \approx 160\ \mathrm{fm}^2 \qquad (R_A \approx 1.2 A^{1/3}\ \mathrm{fm})$

→ $\varepsilon \sim (400/160)\ \mathrm{GeV/fm}^3 = 2.5\ \mathrm{GeV/fm}^3$

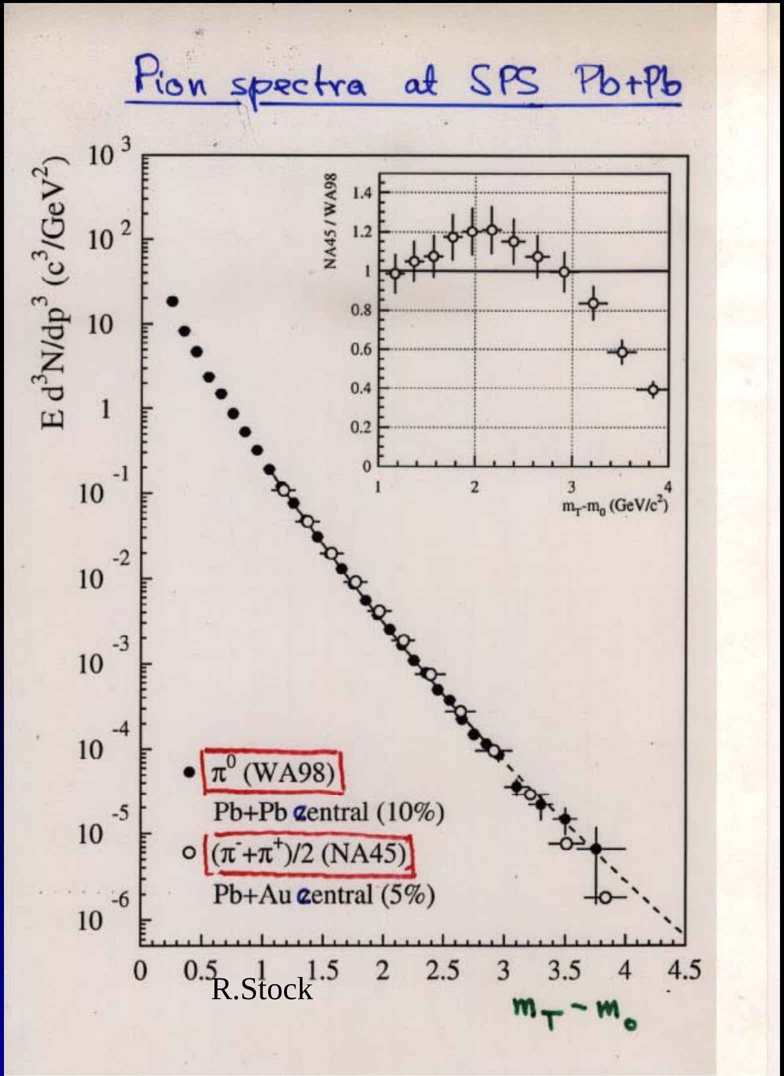
Published estimate from NA49:

$\boldsymbol{\varepsilon = 3.2 \pm 0.3\ \mathrm{GeV/fm}^3}$

[Phys. Rev. Lett. 75 (1995), 3814]

Should be enough for deconfinement!

Transverse mass distributions



R.Stock

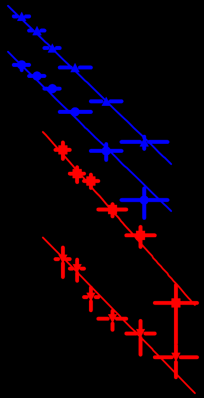
Usually fitted to thermal distributions:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \exp(-\frac{m_T}{T})$$

$$(m_T = \sqrt{p_T{}^2 + m^2})$$

"transverse mass"

T = "inverse slope" or "apparent temperature" or "m_T slope"



What does T mean?

Thermal freeze-out

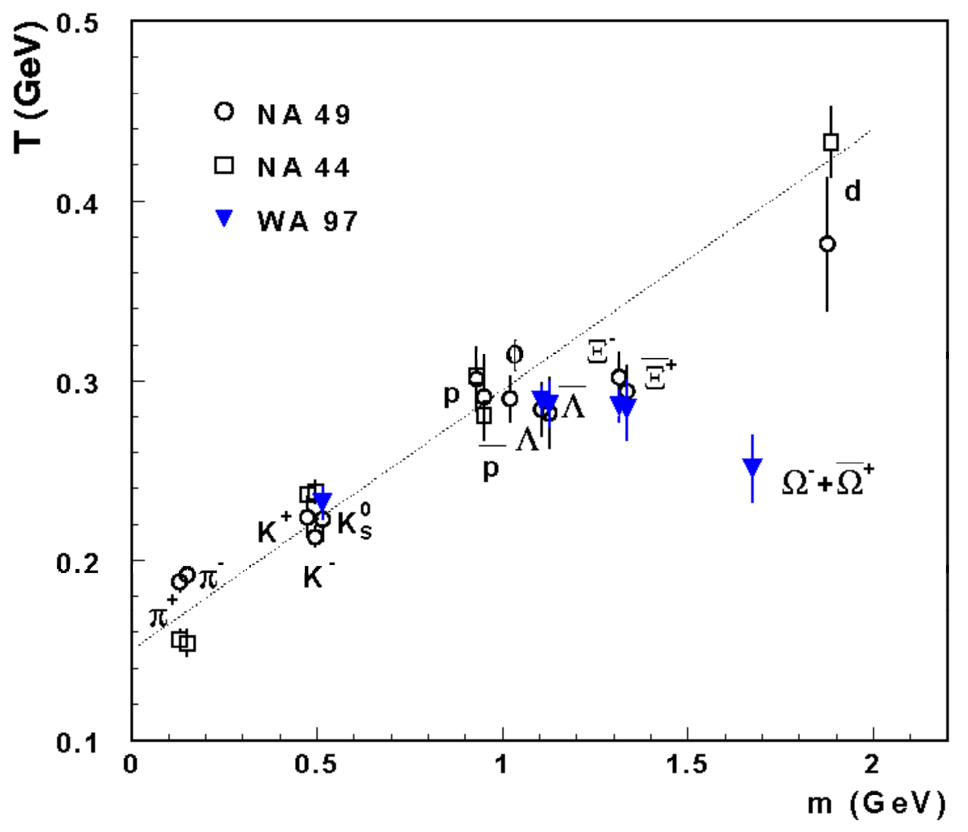
- In nucleus-nucleus collision we form a strongly interacting "fireball" which expands and cools down

- When finally the system is so dilute (i.e. the mean free path is so large) that interactions among the collision products cease, we have "thermal freeze out"

- From then on the collision products just stream out towards the detector

Transverse flow

- The temperature of the m_T spectra is modified by the presence of a collective transverse flow



For $m_T < 2m$:

$$T \cong T_F + \tfrac{1}{2} m < v_T >^2$$

apparent temperature

freeze-out temperature

transv. flow velocity

In practice, it is a complicated business to disentangle the thermal and flow contributions. But additional information (e.g. from HBT interferometry) can be used

Strangeness Enhancement

Historic QGP predictions

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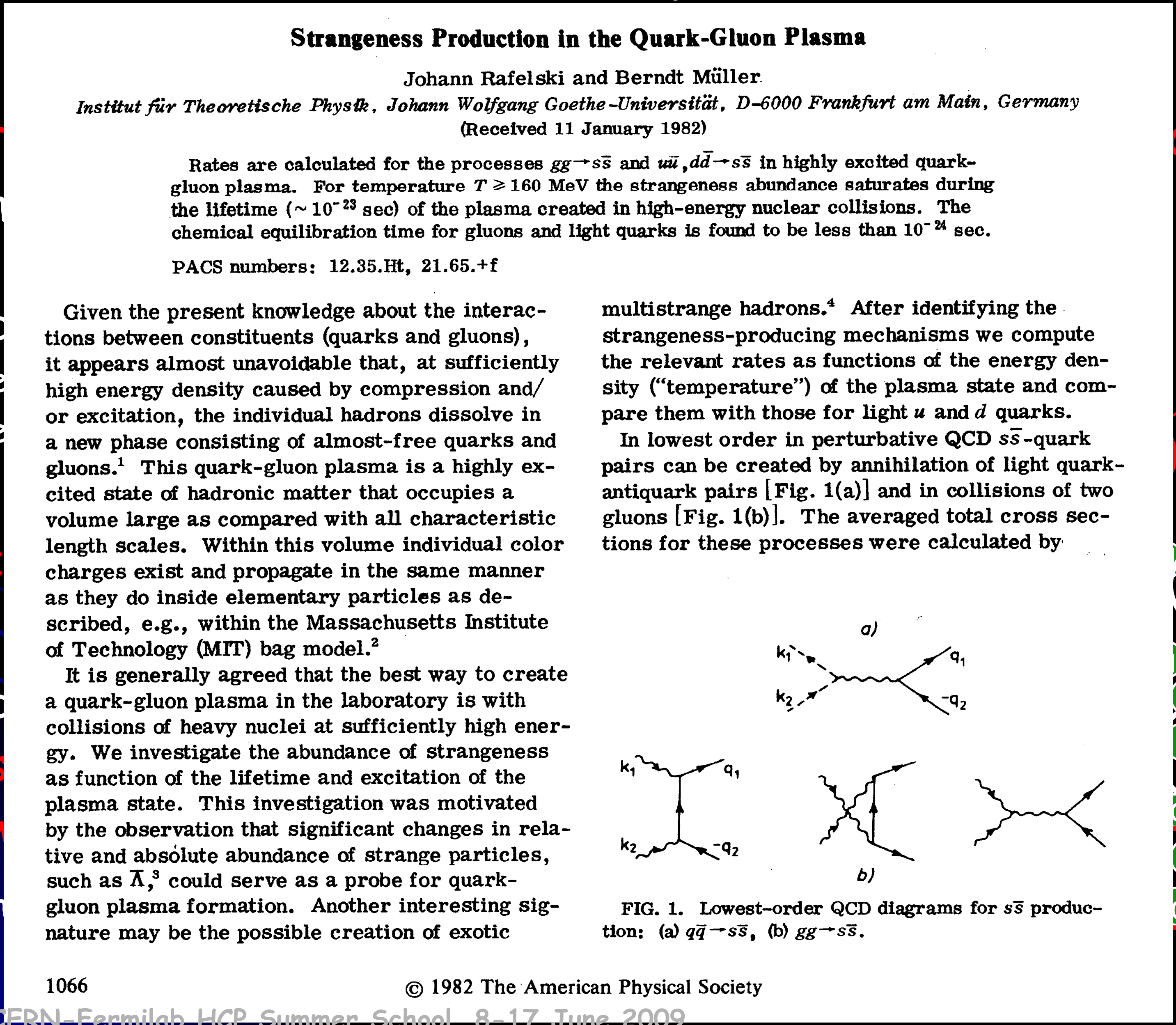

Strangeness Production in the Quark-Gluon Plasma

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(Received 11 January 1982)

Rates are calculated for the processes $gg\to s\bar{s}$ and $u\bar{u}, d\bar{d}\to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \gtrsim 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec.

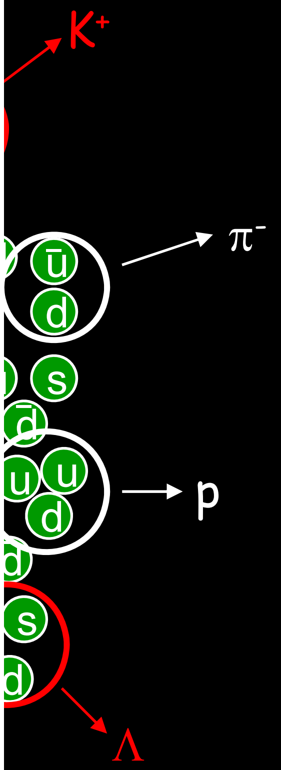
PACS numbers: 12.35.Ht, 21.65.+f

Given the present knowledge about the interactions between constituents (quarks and gluons), it appears almost unavoidable that, at sufficiently high energy density caused by compression and/or excitation, the individual hadrons dissolve in a new phase consisting of almost-free quarks and gluons.[1] This quark-gluon plasma is a highly excited state of hadronic matter that occupies a volume large as compared with all characteristic length scales. Within this volume individual color charges exist and propagate in the same manner as they do inside elementary particles as described, e.g., within the Massachusetts Institute of Technology (MIT) bag model.[2]

It is generally agreed that the best way to create a quark-gluon plasma in the laboratory is with collisions of heavy nuclei at sufficiently high energy. We investigate the abundance of strangeness as function of the lifetime and excitation of the plasma state. This investigation was motivated by the observation that significant changes in relative and absolute abundance of strange particles, such as $\bar{\Lambda}$,[3] could serve as a probe for quark-gluon plasma formation. Another interesting signature may be the possible creation of exotic multistrange hadrons.[4] After identifying the strangeness-producing mechanisms we compute the relevant rates as functions of the energy density ("temperature") of the plasma state and compare them with those for light u and d quarks.

In lowest order in perturbative QCD $s\bar{s}$-quark pairs can be created by annihilation of light quark-antiquark pairs [Fig. 1(a)] and in collisions of two gluons [Fig. 1(b)]. The averaged total cross sections for these processes were calculated by

FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q}\to s\bar{s}$, (b) $gg\to s\bar{s}$.



- The QGP strangeness abundance is enhanced
- As the QGP cools down, eventually the quarks recombine into hadrons ("hadronization")
- The abundance of strange hadrons should also be enhanced
- The enhancement should be larger for particles of higher strangeness content, e.g.:

$$E(\Omega^-) > E(\Xi^-) > E(\Lambda)$$

(sss)	(ssd)	(sud)
$\lvert s\rvert = 3$	$\lvert s\rvert = 2$	$\lvert s\rvert = 1$

Yield, Enhancement

- Yield: multiplicity per event
  e.g.: # of Ω^- / event in $y_1 < y < y_2$:

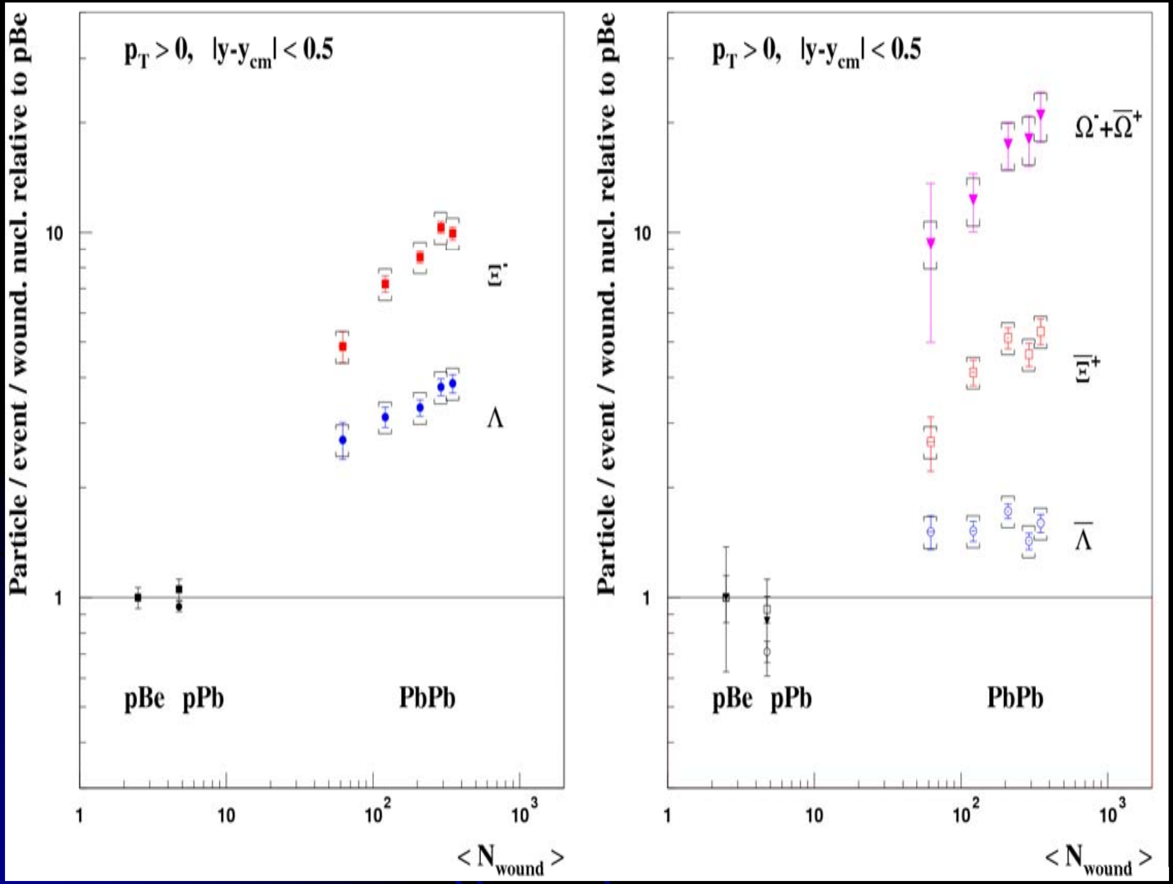
$$N_{\Omega^-} = \frac{1}{\sigma_{TOT}} \int_{y_1}^{y_2} dy \int_0^{\infty} dp_T^2 \, \frac{d^3\sigma_{\Omega^-}}{E dp^3}$$

- Enhancement: yield per participant (i.e. wounded) nucleon relative to yield per participant nucleon in p-Be
  e.g.: Ω^- enhancement:

$$E_{\Omega^-} = \frac{\left(N_{\Omega^-} / \langle N_{wound} \rangle\right)_{Pb-Pb}}{\left(N_{\Omega^-} / \langle N_{wound} \rangle\right)_{p-Be}}$$

Strangeness enhancement pattern

- Enhancement relative to p-Be (WA97/NA57)



Enhancement is larger for particles of higher strangeness content (QGP prediction!)

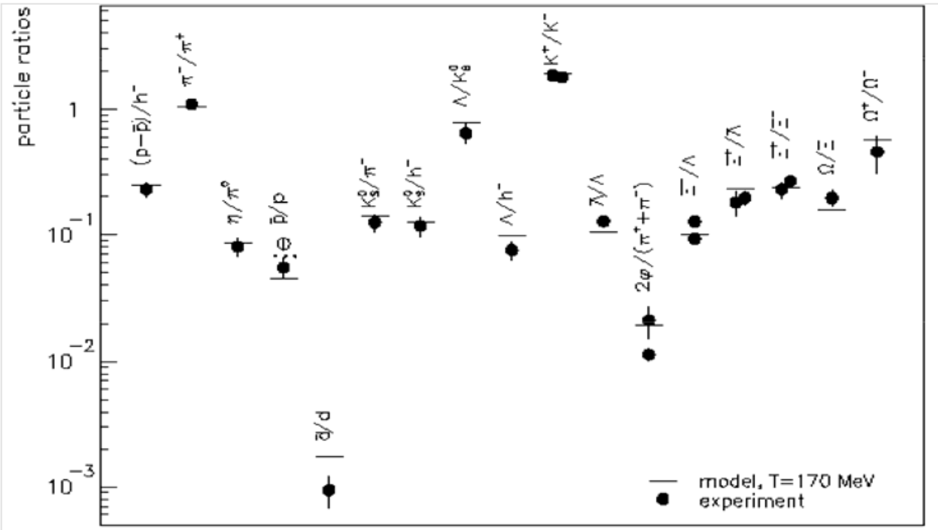
<u>up to a factor ~ 20 for Ω</u>

So far, no hadronic model has reproduced these observations (try harder!)

Actually, the most reliable hadronic models predicted an opposite behaviour of enhancement vs strangeness

Chemical equilibrium

- The relative particle abundances measured in Pb-Pb collisions are close to the thermodynamical (chemical) equilibrium values (maximum entropy) corresponding to a temperature of ~ 170 MeV ("chemical freeze-out temperature")



[P.Braun-Munzinger, I.Heppe, J.Stachel, Phys. Lett. B465 (1999), 15]

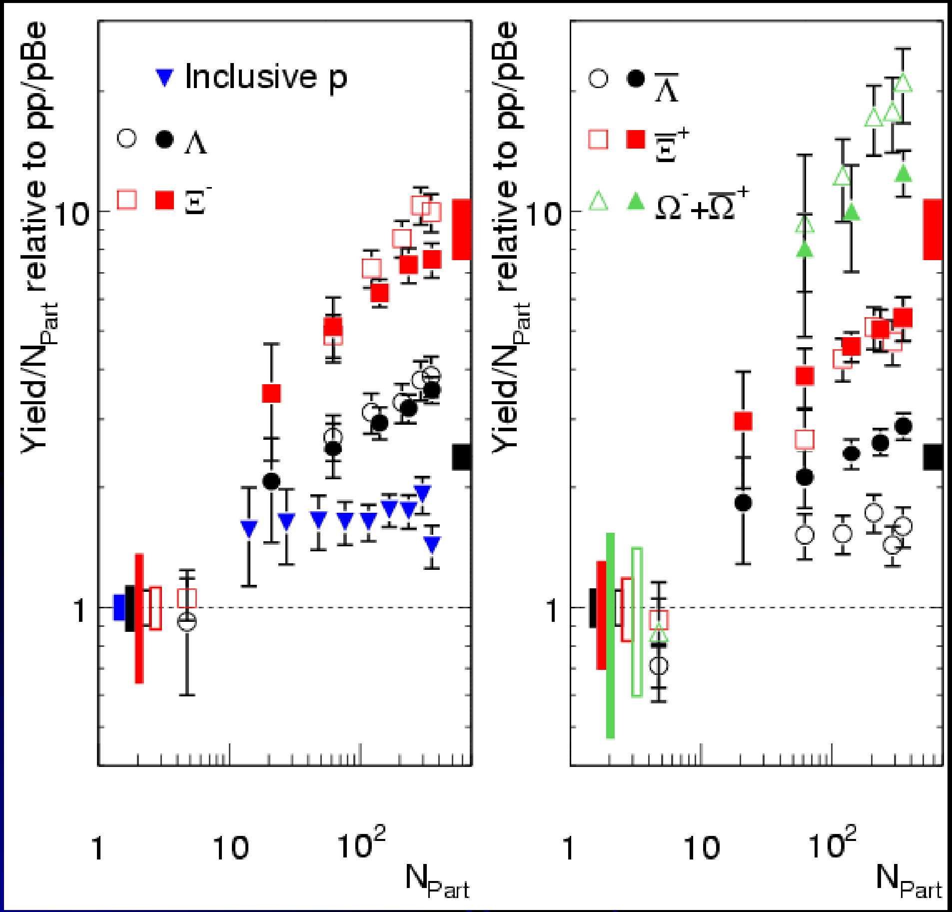
FIG. 3. Comparison between model and experimental particle ratios. Errors are statistical.

this would be a natural outcome of statistical hadronization of uncorrelated quarks

"chemical freeze out": the moment when elastic interactions cease

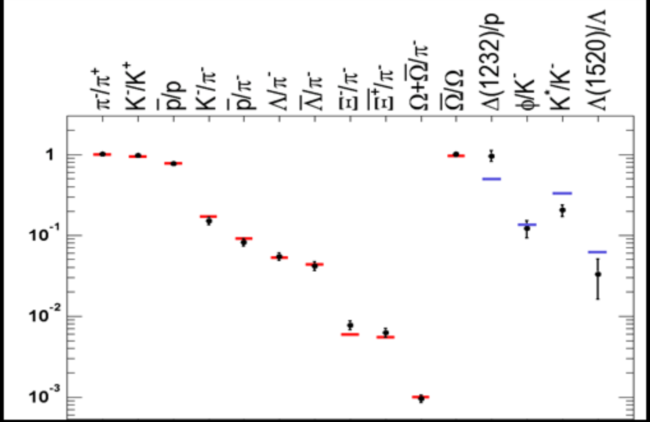
Hyperon enhancements @ RHIC

- similar picture



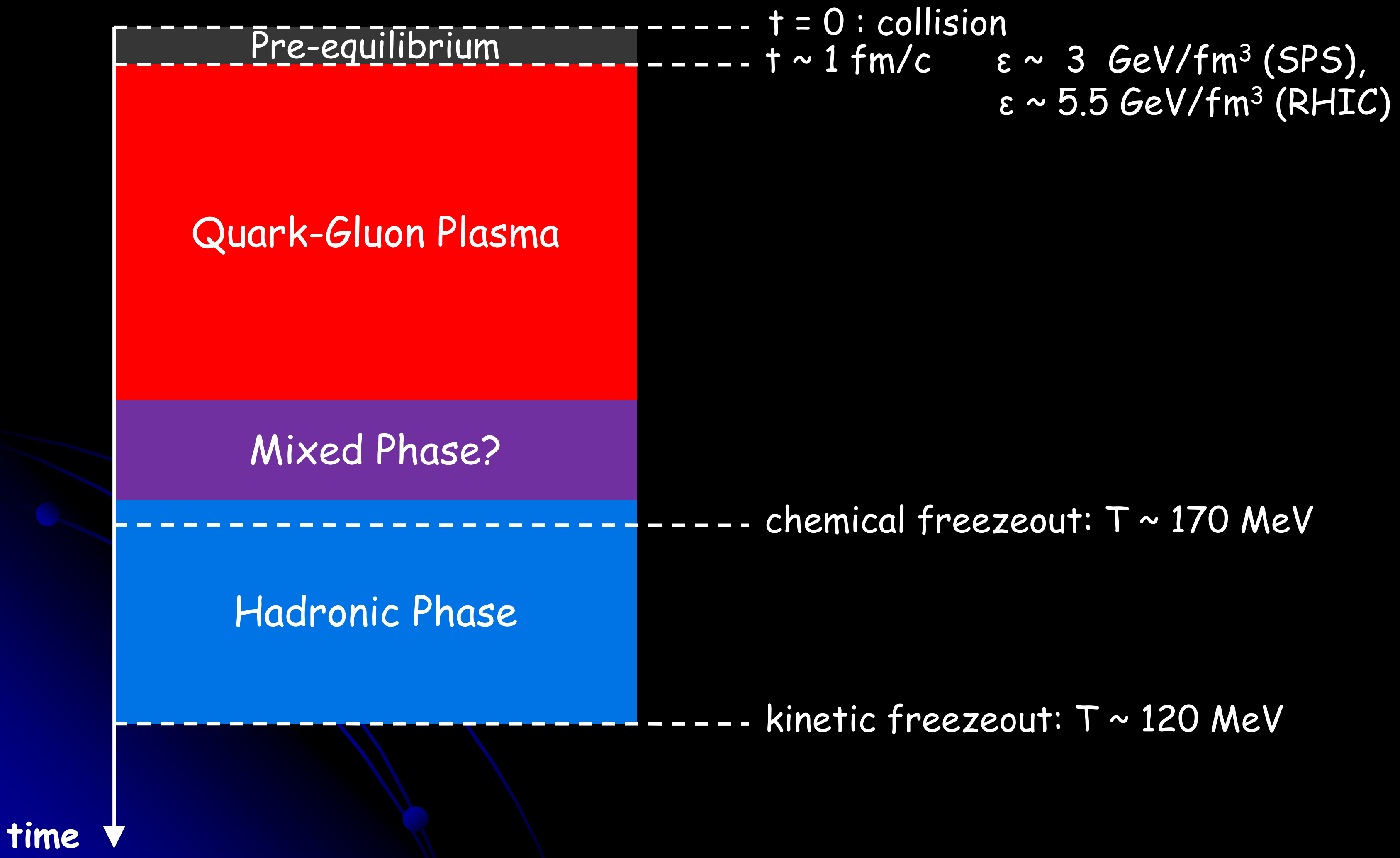
- open: NA57 @ SPS
- closed: STAR @ RHIC

- again, good thermodynamic equilibrium fit



→ T ~ 170 MeV (like SPS)

History of a A-A collision event



t = 0 : collision

Pre-equilibrium

t ~ 1 fm/c $\varepsilon \sim 3$ GeV/fm^3 (SPS), $\varepsilon \sim 5.5$ GeV/fm^3 (RHIC)

Quark-Gluon Plasma

Mixed Phase?

chemical freezeout: T ~ 170 MeV

Hadronic Phase

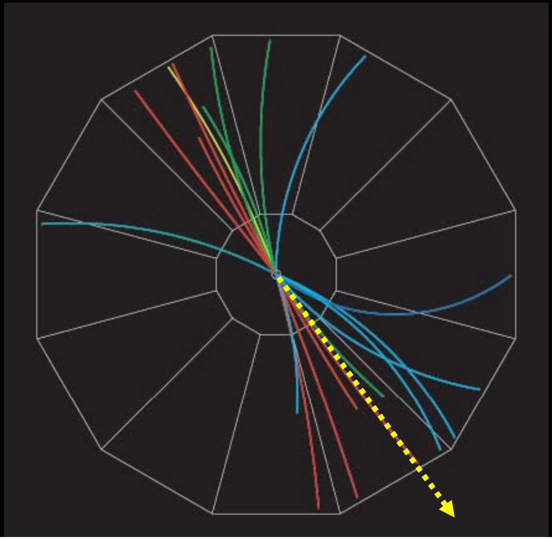
kinetic freezeout: T ~ 120 MeV

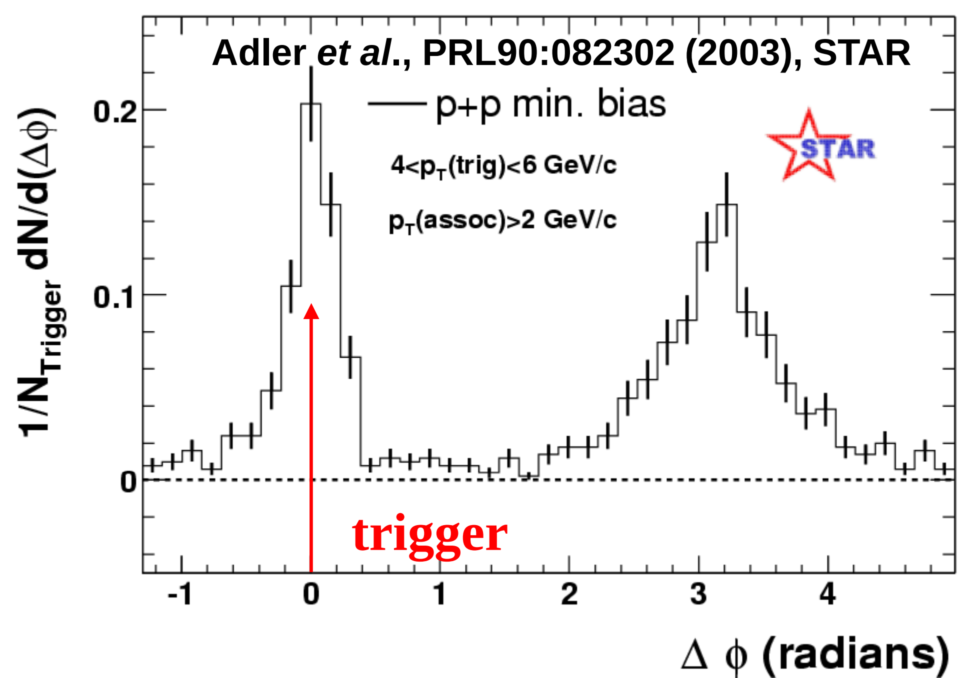
time

High p_T suppression

Azimuthal Correlations (pp)

- In high energy collisions particles are correlated in azimuth due to jets
- e.g.: at RHIC in proton-proton collisions from STAR
  - "trigger" particle: 4 < p_T< 6 GeV/c
  - associated particles: p_T > 2 GeV/c



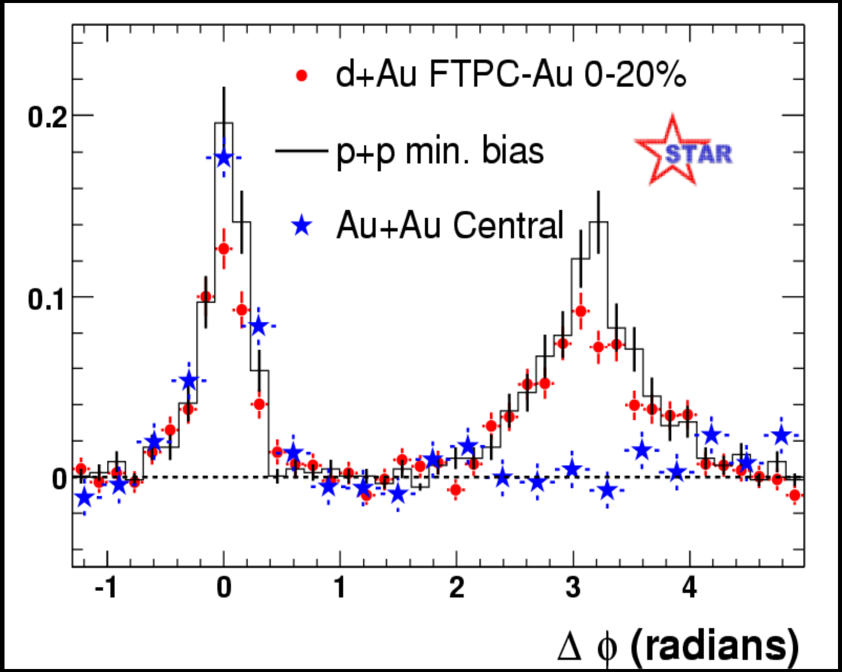


Adler *et al.*, PRL90:082302 (2003), STAR

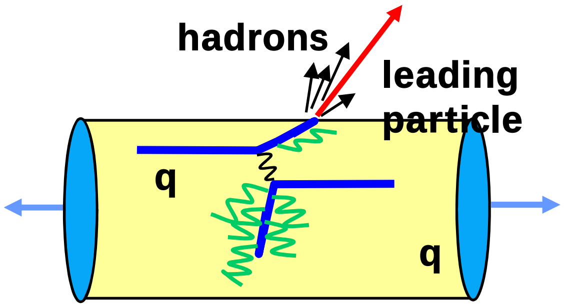
Azimuthal Correlations

- away-side jet still present in dAu
- but disappears in central AuAu
- away-side jet "quenched"?

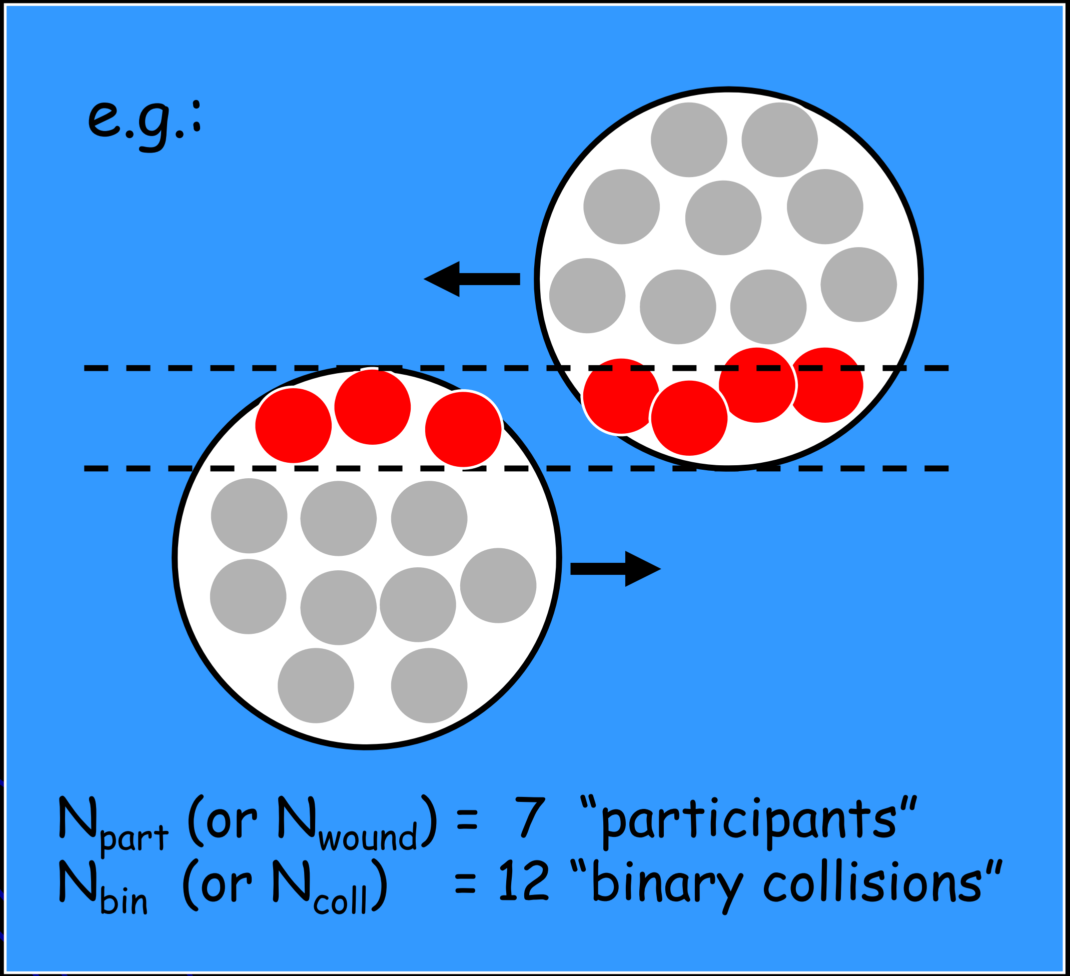
Adams *et al.*, Phys. Rev. Let. 91 (2003)



is this what happens?



Participants Scaling vs Binary Scaling



e.g.:

N_{part} (or N_{wound}) = 7 "participants"
N_{bin} (or N_{coll}) = 12 "binary collisions"

- "Soft", large cross-section processes expected to scale like N_{part}
- "Hard", low cross-section processes expected to scale like N_{bin}

R_{cp}, R_{AA}, R_{dAu}

$$R_{\mathrm{cp}} = \frac{\mathrm{Yield}_{\mathrm{AA,\,central}}}{\mathrm{Yield}_{\mathrm{AA,\,periph}}} \cdot \frac{\langle Nbin \rangle_{\mathrm{AA,periph}}}{\langle Nbin \rangle_{\mathrm{AA,\,central}}}$$

$$\frac{\text{Yield/collision in central collisions}}{\text{Yield/collision in peripheral collisions}}$$

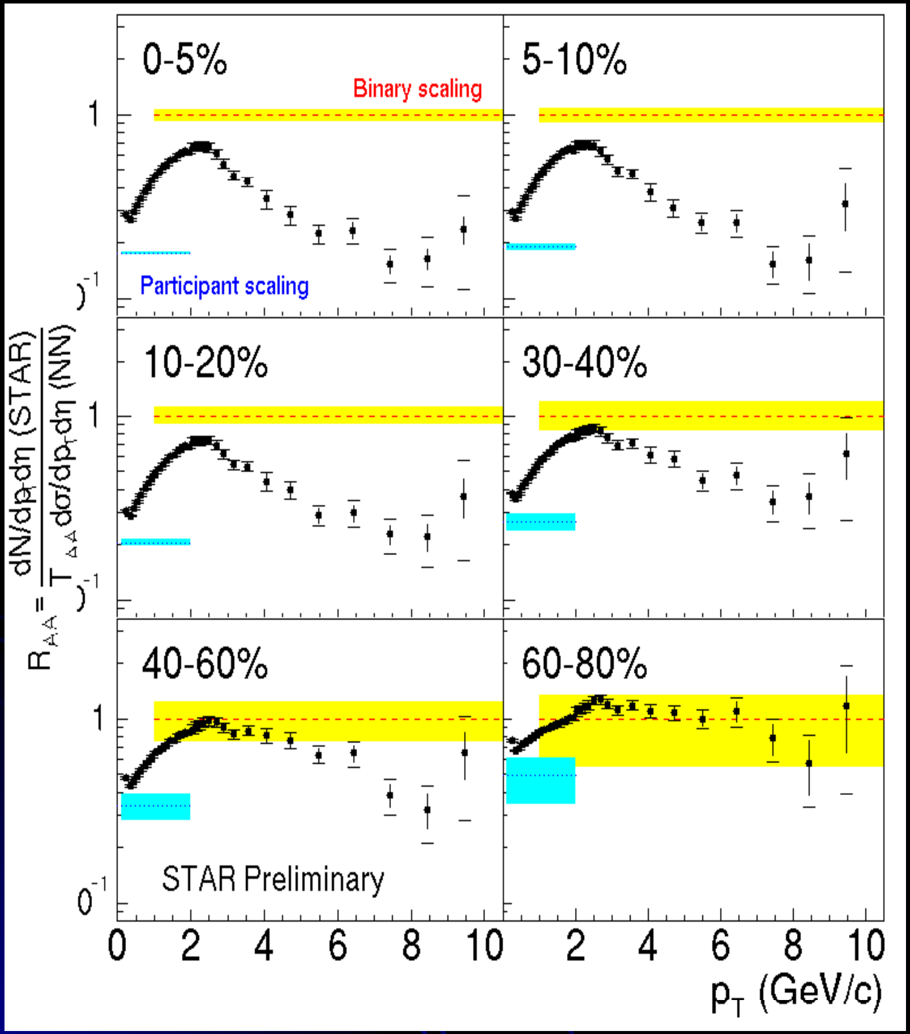
$$R_{\mathrm{AA}} = \frac{\mathrm{Yield}_{\mathrm{AA}}}{\mathrm{Yield}_{\mathrm{pp}}} \cdot \frac{1}{\langle Nbin \rangle_{\mathrm{AA}}}$$

$$\frac{\text{Yield/collision in nucleus-nucleus}}{\text{Yield/collision in proton-proton}}$$

$$R_{\mathrm{dAu}} = \frac{\mathrm{Yield}_{\mathrm{dAu}}}{\mathrm{Yield}_{\mathrm{pp}}} \cdot \frac{1}{\langle Nbin \rangle_{\mathrm{dAu}}}$$

$$\frac{\text{Yield/collision in deuteron-nucleus}}{\text{Yield/collision in proton-proton}}$$

High p_T suppression



- High p_T particle production expected to scale with number of binary NN collisions if no medium effects
- Clearly does not work for more central collisions
- Interpreted as due to parton energy loss