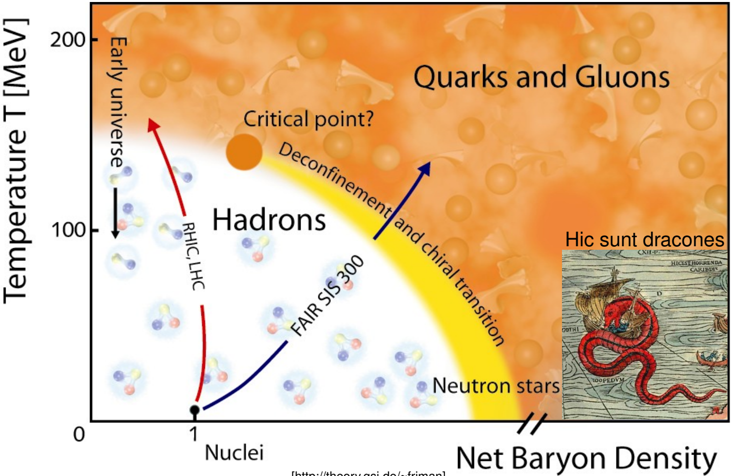
Quark Gluon Plasma
Current Status



[http://theory.gsi.de/~friman]

QGP in the Early Universe

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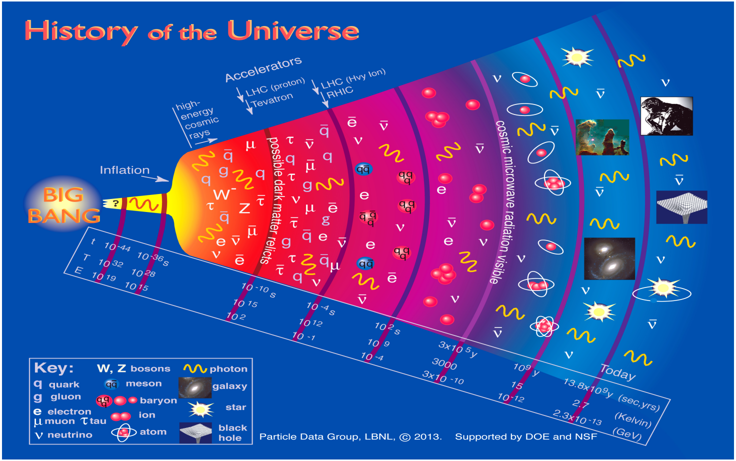

QGP in Heavy Ion Collisions

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Outline

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I) Historical Remarks

- Hagedorn temperature, statistical bootstrap model, MIT bag model

II) Quantum Chromodynamics

- Confinement, asymptotic freedom, chiral symmetry

III) Quark-Gluon Plasma

- Theory: definition, possible probes (thermal radiation, quarkonia, jets)
- Experiment: basics of heavy ion collisions, data from RHIC and LHC

I) Historical Remarks

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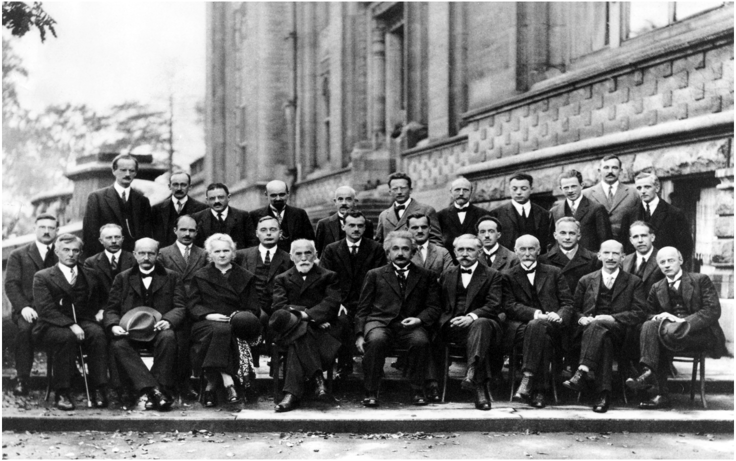


[http://en.wikipedia.org/wiki/Solvay_Conference, 1927 Solvay Conference on Quantum Mechanics]

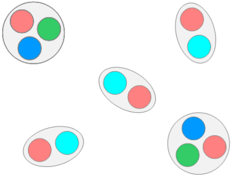
Limiting Density of Hadronic Matter

[I. Ya. Pomeranchuk, Doklady Akad. Nauk. SSSR 78 (1951) 2]
[I. Ya. Pomeranchuk, Doklady Akad. Nauk. SSSR 78 (1951) 889]

Hadrons have finite size:

- proton charge-radius: 0.877 fm
- pion charge-radius: 0.672 fm

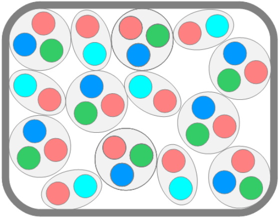
[J. Beringer et al. (Particle Data Group), Phys. Rev. D 86 (2012) 010001]



Limiting density of hadronic matter:

- radius $r_h \approx 1$ fm
- volume $V_h \approx 4\pi r_h^3/3$
- density $n_c \approx 1/V_h \approx 1.5\, n_0$,
  with nuclear density $n_0 \approx 0.17 fm^{-3}$

[H. Satz, Lect. Notes Phys. 785 (2010) 1]



Hagedorn Temperature

[R. Hagedorn, Nuovo Cim. Suppl. 3 (1965) 147]

Consider $N = \sum n_i$ massless particles in a volume V with n_i particles at energy ε_i, i.e. with $\frac{N!}{n_1!n_2!\ldots}$ states of total energy $E = \sum n_i \varepsilon_i$:

$$Z = \sum_{N=0}^{\infty} \sum_{\{n_i\}} \frac{N!}{\prod_i n_i!} e^{-\frac{1}{T}\sum n_i \varepsilon_i} = \sum_{N=0}^{\infty} \left(\sum_i e^{-\varepsilon_i/T} \right)^N$$

$$= \sum_{N=0}^{\infty} \left(\frac{V}{2\pi^2} \int p^2 e^{-p/T} dp \right)^N = \sum_{N=0}^{\infty} \left(\frac{VT^3}{\pi^2} \right)^N$$

$$= \frac{1}{1 - VT^3/\pi^2}$$

The partition function has a pole at temperature $T_c = (\pi^2/V)^{1/3} \approx 185$ MeV for $V = 4\pi/(3m_\pi^3)$

[R. Hagedorn, Quark Matter '84, LNP 221 (1985) 53-76]

Nucleons			Δ particles			Λ particles			Σ particles		
p	$1/2^+$	****	Δ(1232)	$3/2^+$	****	Λ	$1/2^+$	****	Σ^+	$1/2^+$	****
n	$1/2^+$	****	Δ(1600)	$3/2^+$	***	Λ(1405)	$1/2^-$	****	Σ^0	$1/2^+$	****
N(1440)	$1/2^+$	****	Δ(1620)	$1/2^-$	****	Λ(1520)	$3/2^-$	****	Σ^-	$1/2^+$	****
N(1520)	$3/2^-$	****	Δ(1700)	$3/2^-$	****	Λ(1600)	$1/2^+$	***	Σ(1385)	$3/2^+$	****
N(1535)	$1/2^-$	****	Δ(1750)	$1/2^+$	*	Λ(1670)	$1/2^-$	****	Σ(1480)		*
N(1650)	$1/2^-$	****	Δ(1900)	$1/2^-$	**	Λ(1690)	$3/2^-$	****	Σ(1560)		**
N(1675)	$5/2^-$	****	Δ(1905)	$5/2^+$	****	Λ(1800)	$1/2^-$	***	Σ(1580)	$3/2^-$	*
N(1680)	$5/2^+$	****	Δ(1910)	$1/2^+$	****	Λ(1810)	$1/2^+$	***	Σ(1620)	$1/2^-$	*
N(1685)		*	Δ(1920)	$3/2^+$	***	Λ(1820)	$5/2^+$	****	Σ(1660)	$1/2^+$	***
N(1700)	$3/2^-$	***	Δ(1930)	$5/2^-$	***	Λ(1830)	$5/2^-$	****	Σ(1670)	$3/2^-$	****
N(1710)	$1/2^+$	***	Δ(1940)	$3/2^-$	**	Λ(1890)	$3/2^+$	****	Σ(1690)		**
N(1720)	$3/2^+$	****	Δ(1950)	$7/2^+$	****	Λ(2000)		*	Σ(1750)	$1/2^-$	***
N(1860)	$5/2^+$	**	Δ(2000)	$5/2^+$	**	Λ(2020)	$7/2^+$	*	Σ(1770)	$1/2^+$	*
N(1875)	$3/2^-$	***	Δ(2150)	$1/2^-$	*	Λ(2100)	$7/2^-$	****	Σ(1775)	$5/2^-$	****
N(1880)	$1/2^+$	**	Δ(2200)	$7/2^-$	*	Λ(2110)	$5/2^+$	***	Σ(1840)	$3/2^+$	*
N(1895)	$1/2^-$	**	Δ(2300)	$9/2^+$	**	Λ(2325)	$3/2^-$	*	Σ(1880)	$1/2^+$	**
N(1900)	$3/2^+$	***	Δ(2350)	$5/2^-$	*	Λ(2350)	$9/2^+$	***	Σ(1915)	$5/2^+$	****
N(1990)	$7/2^+$	**	Δ(2390)	$7/2^+$	*	Λ(2585)		**	Σ(1940)	$3/2^-$	***
N(2000)	$5/2^+$	**	Δ(2400)	$9/2^-$	**				Σ(2000)	$1/2^-$	*

[http://en.wikipedia.org/wiki/List_of_baryons]

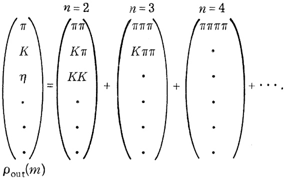
Statistical Bootstrap Model

[R. Hagedorn, Nuovo Cim. Suppl. 3 (1965) 147]
[S. Frautschi, Phys. Rev. D 3 (1971) 2821]

Hadrons are assumed to be compounds of hadrons:

$$\rho_{out}(m) \propto \sum_{n=2}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int dm_i \, \rho_{in}(m_i)$$

$$\int d^3p_i \, \delta\left(\sum_{i=1}^{n} E_i - m\right) \delta^3\left(\sum_{i=1}^{n} \vec{p}_i\right)$$

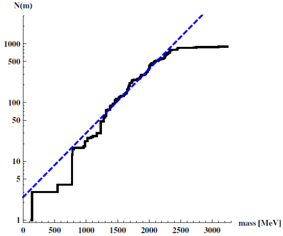


with the bootstrap condition for the density of states:

$$\lim_{m\to\infty} \rho_{out}(m) = \rho_{in}(m)$$

It follows that the density of states grows exponentially:

$$\rho_{in}(m) = c\, m^a e^{bm}$$



[T. D. Cohen and V. Krejcirik, J. Phys. G: Nucl. Part. Phys. 39 (2012) 055001]

Statistical Bootstrap Model

[R. Hagedorn, Nuovo Cim. Suppl. 3 (1965) 147]
[S. Frautschi, Phys. Rev. D 3 (1971) 2821]

Using $\rho(m) = c\, m^a e^{bm}$, the average energy is:

$$\overline{E} = \int_0^\infty dE\, E\, \rho(E) e^{-E/T} \Big/ \int_0^\infty dE\, \rho(E) e^{-E/T}$$

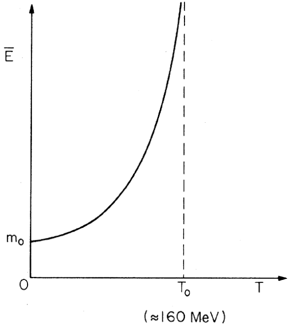
With the center of mass at rest, $E = m$, and the ground-state m_0 this gives integrals of the form

$$\int_{m_0}^\infty dm\, c\, m^{a+1} e^{m(b-1/T)}$$

which are only defined for $T < b^{-1} \equiv T_0$. For $a = 0$:

$$\overline{E} = m_0 + T_0 T/(T_0 - T)$$

Limiting temperature T_0 cannot be reached at finite energy density!



[S. Frautschi, Phys. Rev. D 3 (1971) 2821]

MIT Bag Model

[A. Chodos et al., Phys. Rev. D 9 (1974) 3471]

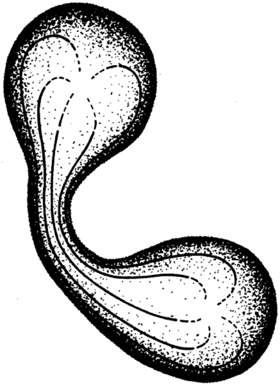
- Hadrons consist of free, or weakly interacting, quarks which are confined to a finite region of space, the bag

- Confinement is accomplished by assuming a constant energy density B inside the bag, corresponding to a negative pressure inside:

$$E_H = \frac{4\pi R^3}{3} B + \frac{C}{R}$$

$$P = -\frac{\partial E_H}{\partial V} = -B + \frac{C}{4\pi R^4}$$

[M. Le Bellac, Thermal Field Theory, Cambridge University Press (1996)]



[A. Chodos et al., Phys. Rev. D 9 (1974) 3471]

MIT Bag Model

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[A. Chodos et al., Phys. Rev. D 9 (1974) 3471]

- Pressure outside the bag, i.e. of an ideal, relativistic, massless gas of bosons (pions):

$$\Omega = VT \int \frac{d^3p}{(2\pi)^3} \ln \left[1 - e^{-\beta p}\right]$$

$$= -\frac{VT^4}{6\pi^2} \int_0^\infty \frac{p^3 dp}{e^{\beta p} - 1} = -\frac{\pi^2 VT^4}{90}$$

$$P = -\frac{\partial \Omega}{\partial V} = \nu_b \frac{\pi^2 T^4}{90}$$

- Pressure inside the bag, i.e. of an ideal, relativistic, massless gas of fermions and bosons (quarks and gluons):

$$\Omega = -VT \int \frac{d^3p}{(2\pi)^3} \ln \left[1 + e^{-\beta p}\right]$$

$$= -\frac{VT^4}{6\pi^2} \int_0^\infty \frac{2p^3 dp}{e^{\beta p} + 1} = -\frac{7\pi^2 VT^4}{360}$$

$$P = -\frac{\partial \Omega}{\partial V} = \left(\nu_b + \frac{7}{4}\nu_f\right) \frac{\pi^2 T^4}{90} - B$$

[M. Le Bellac, Thermal Field Theory, Cambridge University Press (1996)]

MIT Bag Model

[A. Chodos et al., Phys. Rev. D 9 (1974) 3471]

- Phase transition between pion gas outside, $\nu_b = 3$, and the QGP inside the bag, $\nu_b = 2(N_c^2 - 1) = 16$ and $\nu_f = 2N_cN_f = 12$:

$$P_\pi = P_{QGP}$$

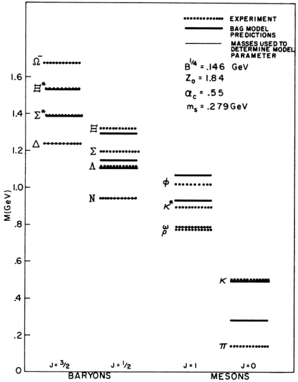
$$3\frac{\pi^2 T^4}{90} = 37\frac{\pi^2 T^4}{90} - B$$

- Critical temperature:

$$T_c = \left(\frac{45B}{17\pi^2}\right)^{1/4} \simeq 144 \text{ MeV}$$

with $B^{1/4} = 146$ MeV from original MIT fit of light hadron masses.

[M. Le Bellac, Thermal Field Theory, Cambridge University Press (1996)]



[T. DeGrand et al., Phys. Rev. D 12 (1975) 2060]

Connection of Statistical Bootstrap Model and MIT Bag Model

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- inconsistency of pointlike particles in the SBM was removed in 1980:

$$V \to V^{\mu} = Ap^{\mu}, \text{ with } A \equiv 1/4B$$

- energy density:

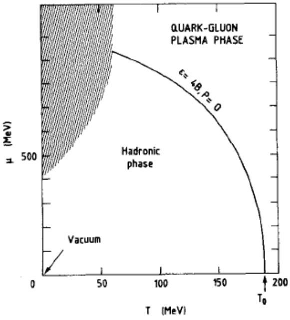
$$\varepsilon(T,\mu) = \frac{\varepsilon_{pt}(T,\mu)}{1+\varepsilon_{pt}(T,\mu)/4B}$$

  with ε_{pt} the fictitious point particle energy density, which diverges on the critical curve.

- on the critical curve, the average cluster mass and volume tend to infinity, while the energy density is now finite:

$$\varepsilon(T_c,\mu_c) = 4B$$

[R. Hagedorn and J. Rafelski, Phys. Lett. 97 B (1980) 136]



[R. Hagedorn, Quark Matter ’84, LNP 221 (1985), 53-76]

H-QM Helmholtz Research School Quark Matter Studies

II) Quantum Chromodynamics

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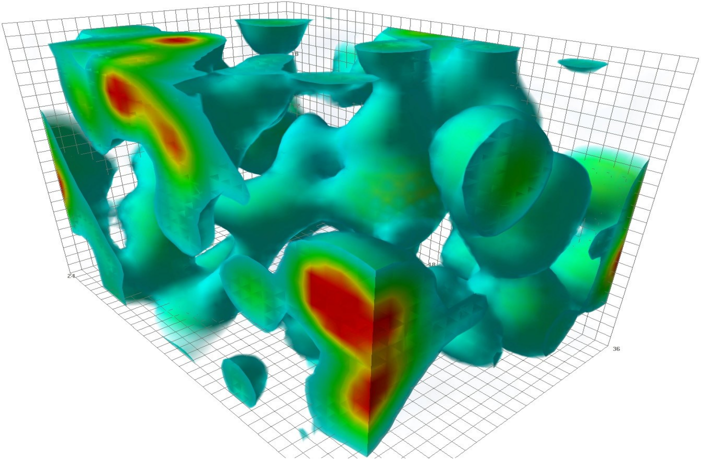

[http://www.physics.adelaide.edu.au/theory/staff/leinweber]

Quantum Chromodynamics

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QCD is a gauge field theory that describes the strong interactions of colored quarks and gluons and represents the SU(3) component of the SM:

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

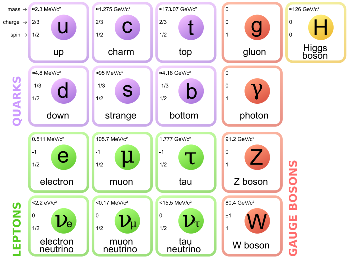
with field tensor

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_s f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu$$

and structure constants of the SU(3) group

$$[t^A, t^B] = i f_{ABC} t^C, \quad t^C \equiv \lambda^C/2$$

[J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012)]

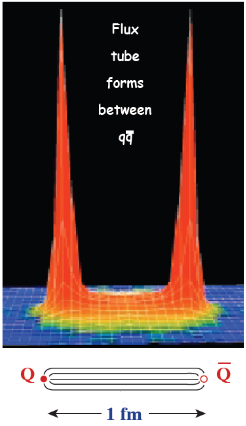


[http://en.wikipedia.org/wiki/Standard_Model]

Confinement

- confinement is the phenomenon that color charged particles cannot be isolated singularly, and therefore cannot be directly observed
- this is not proven analytically but verified by lattice QCD: when two quarks become separated, the gluon field forms a flux tube (string) between them ($F \approx 160$ kN)

  [http://en.wikipedia.org/wiki/Color_confinement]
- new quark-antiquark pair is produced when energetically favorable (string breaking)



[G. Bali et al., Phys. Rev. D 51 (1995) 5165, arXiv:9409005]

Asymptotic Freedom

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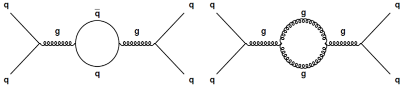
- interaction becomes asymptotically weaker as energy increases
- coupling constant $\alpha_s = g_s^2/4\pi^2$ as a function of momentum exchange $Q^2 \gg \mu^2$:

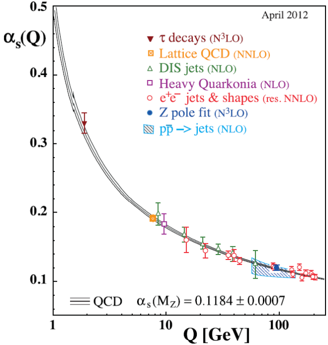
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + (\alpha_s(\mu^2)/12\pi)(11N_c - 2N_f)\ln(Q^2/\mu^2)}$$

[D. Griffiths, Introduction to Elementary Particles, Wiley, 1987]

- for $N_c = 3$ and $N_f = 6$ anti-screening dominates and coupling decreases



[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]



[J. Beringer et al. (PDG), Phys. Rev. D 86, 010001 (2012)]

H-QM Helmholtz Research School Quark Matter Studies

Chiral Symmetry

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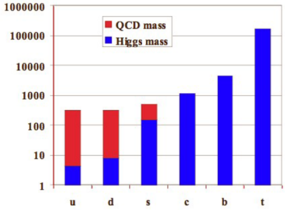
- QCD Lagrangian has chiral symmetry $SU(N_f)_L \times SU(N_f)_R$ in the limit of vanishing quark masses

- broken spontaneously by dynamical formation of a quark condensate $\langle \bar{\psi}_R \psi_L \rangle$: $SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$

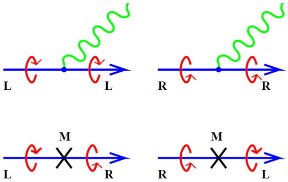
- broken explicitly by quark masses ($\psi_{L,R} = (1 \mp \gamma_5)\psi/2$):

$$\mathcal{L} = \bar{\psi}_L (i\not{D}) \psi_L + \bar{\psi}_R (i\not{D}) \psi_R$$

$$+ \bar{\psi}_L M \psi_R + \bar{\psi}_R M \psi_L$$



[B. Müller, arXiv: 0710.3366 [nucl-th]]



[T. Schaefer, Lecture on The Phases of QCD, NC State U.]

Chiral and Deconfinement Phase Transition

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Order parameter for chiral symmetry:

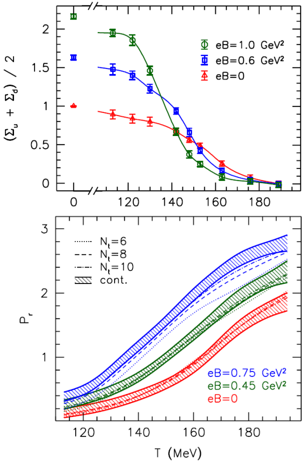
chiral condensate $\langle\bar{\psi}\psi\rangle$

- chiral symmetry: $\langle\bar{\psi}\psi\rangle = 0$
- chiral symmetry broken: $\langle\bar{\psi}\psi\rangle \neq 0$

Order parameter for confinement:

$$\text{Polyakov Loop } P = \mathrm{Tr}\exp\left[ig\int_0^{1/T} dx_0\, A_0(x_0)\right]$$

- confinement: $P = 0$
- deconfinement: $P \neq 0$



[G. Endrödi, arXiv: 1311.0648 [hep-lat]]

III) Quark Gluon Plasma

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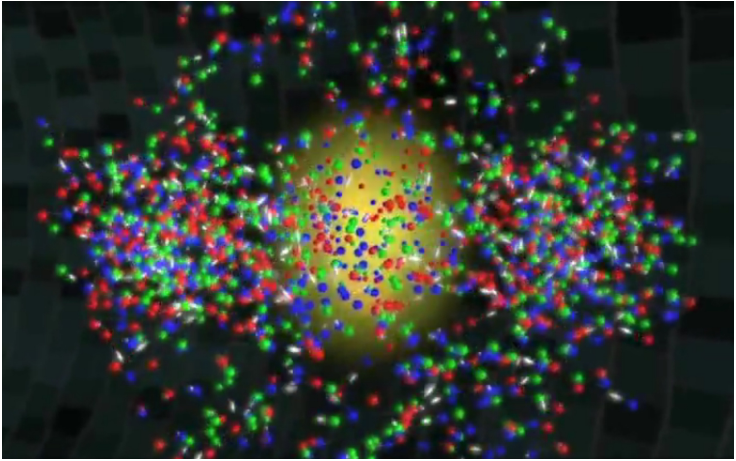


[www.bnl.gov/rhic/news2/]

What is QGP?

Definition used by STAR collaboration:

- QGP is a (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes

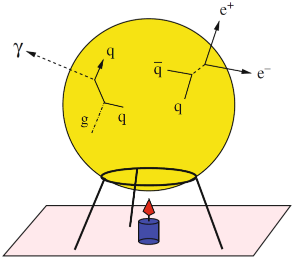
[STAR collaboration, nucl-ex/0501009]

Not demanded:

- that quarks and gluons in the produced matter are non- or only weakly interacting
- evidence for a first- or second order phase transition
- evidence for chiral symmetry restoration

Probing the QGP - Thermal Radiation

- the hot medium radiates electromagnetically, i.e. it emits photons and dileptons (e^+e^- and $\mu^+\mu^-$ pairs)
- their spectra can provide information about the very early stages and the deep interior of the QGP, since they leave the medium without modification
- Problem: photons and leptons can be formed anywhere and at any time - identifying the radiation emitted by the QGP is difficult



[H. Satz, Lect. Notes Phys. 785, 1 (2010)]

Probing the QGP - Quarkonia

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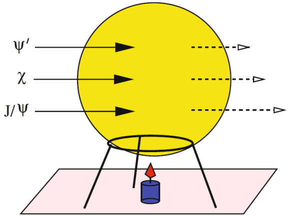
→ **talk by K. König on *Structure of quarkonium states and potential models*, 14.11.2013**

- quarkonia are bound states of two heavy quarks and represent 'external' probes for the QGP since they are produced by initial collisions
- since different quarkonia have different melting temperatures, depending on their binding energy and radius, they can be used as a thermometer for QGP

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

[L. Kluberg and H. Satz, arXiv:0901.3831]



[H. Satz, Lect. Notes Phys. 785, 1 (2010)]

Probing the QGP - Quarkonia

TECHNISCHE UNIVERSITÄT DARMSTADT

→ **talk by K. König on *Structure of quarkonium states and potential models*, 14.11.2013**

At high enough temperatures, quarkonia are dissolved by color screening:

- at $T = 0$ the potential energy of a quarkonium pair is given by:

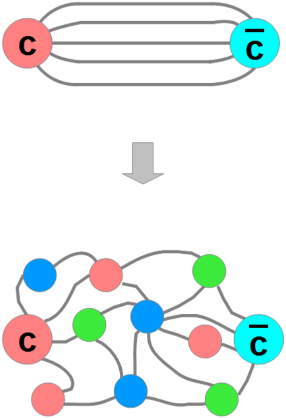
$$V(r) \simeq -\frac{\alpha_s}{r} + \sigma r$$

- at $T > T_c$ quarks and gluons in the QGP lead to color screening:

$$V(r) \simeq -\frac{\alpha_s}{r} e^{-r/\lambda_D}$$

- static color screening is only part of the picture of quarkonium melting, another important mechanism is ionization by absorption of thermal gluons

[B. Müller, Phys. Scr. T 158 (2013) 014004]



Probing the QGP - Quarkonia

TECHNISCHE UNIVERSITÄT DARMSTADT

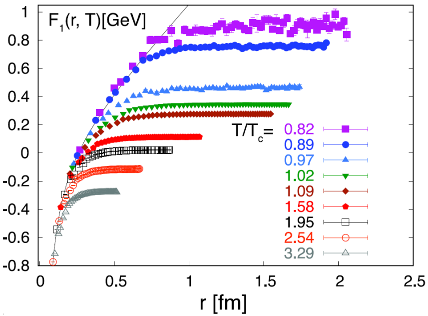
→ **talk by K. König on *Structure of quarkonium states and potential models*, 14.11.2013**

- maximum size of a bound state (Debye length λ_D) of two heavy quarks decreases with increasing temperature

- different charmonium states disappear sequentially as a function of their binding strength:

Bound state	χ_c	ψ'	J/ψ	$\Upsilon(2S)$	χ_b	$\Upsilon(1S)$
T_d	$\lesssim T_c$	$\lesssim T_c$	$\sim 1.2 T_c$	$\sim 1.2 T_c$	$\sim 1.3 T_c$	$\sim 2.0 T_c$

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]



[P. Petreczky, J. Phys. G 37 (2010) 094009, arXiv:1001.5284]

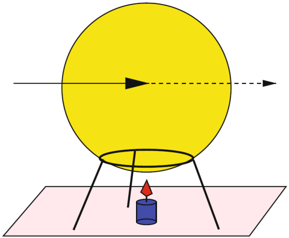
[P. Petreczky, arXiv:0906.0502]

Probing the QGP - Jets

The QGP can also be probed by using high energy partons that produce jets of elementary particles:

- high-momentum quarks and gluons are produced by partonic scatterings with large momentum transfer $Q \geq 1$ GeV, $\tau_{prod} \approx 1/p_T \leq 0.1$ fm/c
- they interact strongly with the medium and loose energy (jet quenching), $\Delta E \approx 1$ GeV/fm
- their cross-sections can be theoretically predicted by perturbative QCD

[D. d'Enterria, arXiv:0902.2011 [nucl-ex]]



[H. Satz, Lect. Notes Phys. 785, 1 (2010)]

Jets - Energy Loss Mechanisms

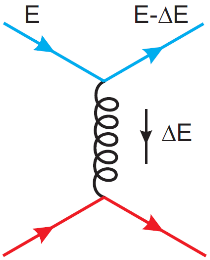
Collisional energy loss:

- elastic scatterings with partons of the QGP dominate at low particle momentum
- collisional energy loss for a parton of energy $E \gg M^2/T$:

$$\frac{\Delta E}{\Delta L} \approx \frac{1}{4} C_R \alpha_s (ET) m_D^2 \ln\left(\frac{ET}{m_D^2}\right)$$

- for a charm quark with $E = 20$ GeV, $M = 1.3$ GeV, $T = 0.4$ GeV, $C_R = (N_c^2 - 1)/2N_c = 4/3$ and $m_D = 1$ GeV: $\Delta E/\Delta L = 2.3$ GeV/fm

[D. d'Enterria, arXiv:0902.2011 [nucl-ex]]



[D. d'Enterria, arXiv:0902.2011 [nucl-ex]]

Jets - Energy Loss Mechanisms

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Radiative energy loss:

- a parton traversing the QGP loses energy mainly by medium-induced multiple gluon emission
- for thin media, $L \ll \lambda$, Bethe-Heitler regime:

$$\Delta E^{BH}/\Delta L \approx \alpha_s \hat{q}\, L \ln(E/(m_D^2 L))$$

- for $L \gg \lambda$, Landau-Pomeranchuk-Migdal regime:

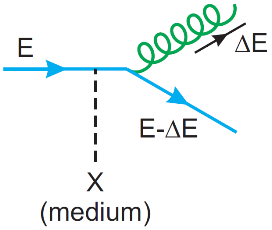
$$\Delta E^{LPM}/\Delta L \approx \alpha_s \hat{q}\, L, \qquad \text{for } \omega < \omega_c$$

$$\Delta E^{LPM}/\Delta L \approx \alpha_s \hat{q}\, L \ln(E/(\hat{q}L^2)), \qquad \text{for } \omega > \omega_c$$

with char. gluon radiation energy $\omega_c = \hat{q}L^2/2$

- for a gluon with $E = 20$ GeV, $\hat{q} = 2$ GeV^2/fm, $L = 6$ fm: $\Delta E/\Delta L \approx 10$ GeV/fm

[D. d'Enterria, arXiv:0902.2011 [nucl-ex]]



[D. d'Enterria, arXiv:0902.2011 [nucl-ex]]

What can we learn from Jet Quenching?

Parton energy loss $\Delta E(E, m, T, \alpha, L)$ provides information on:

- mean free path $\lambda = 1/(\rho\sigma)$, with ρ (≈ 15 fm^{-3}) the density of the medium and σ the integrated cross-section of particle-medium interaction (≈ 1.5 mb)
- opacity $N = L/\lambda$, i.e. the number of scatterings
- Debye mass $m_D(T) \sim g_s T$ (≈ 1 GeV), i.e. the inverse of the screening length, characterizes typical momentum exchanges
- transport coefficient $\hat{q} \equiv m_D^2/\lambda = m_D^2\rho\sigma$ (≈ 2 GeV^2/fm), encodes the scattering power of the medium, jet quenching parameter
- diffusion constant $D = 2T^2/\kappa \approx 2T^2/\hat{q}v$ with momentum diffusion coefficient κ
- initial gluon density dN^g/dy of the expanding plasma
- speed of sound $c_s = \beta\cos(\theta_M)$ for supersonic ($\beta > c_s$) partons, with Mach angle θ_M
- refractive index $n = \sqrt{\epsilon_r} = 1/(\beta\cos(\theta_c))$ for superluminal ($\beta > 1/n$) partons

[D. d'Enterria, arXiv:0902.2011 [nucl-ex]]

QGP in Heavy Ion Collisions

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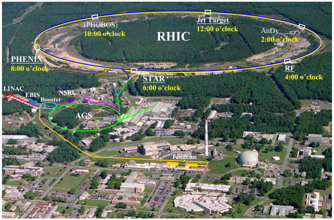
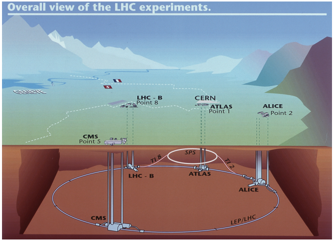
- first heavy ion beams at AGS (BNL) with $\sqrt{s_{NN}} = 5$ GeV and at SPS (CERN) with 18 GeV in the 80's
- it is not clear whether AGS could form deconfined matter, but SPS already hinted at the existence of a new state of matter
- first Au-Au collisions at 130 GeV in 2000 and at 200 GeV in 2001 at RHIC (BNL)
- first Pb beam at 2.76 TeV in november 2010 and (hopefully) 5.5 TeV from 2015 onwards

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]



[http://inspirehep.net/record/1086597]



[http://cds.cern.ch/record/40525]

Basics of Heavy Ion Collisions
Rapidity and Pseudorapidity

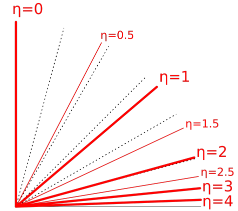
- for a particle with momentum p_z along the beam axis and energy E the rapidity is

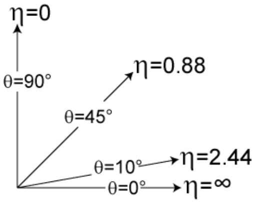
$$y = \tanh^{-1}(\beta_z) = \tanh^{-1}\left(\frac{p_z}{E}\right) = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

i.e. the rapidity of the boost along the beam axis from the lab frame to the frame of the particle

- pseudorapidity depends only on the polar angle (between the particle momentum and the beam axis) and not on its energy:

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] = \frac{1}{2}\ln\left(\frac{|p|+p_z}{|p|-p_z}\right)$$





[http://en.wikipedia.org/wiki/Pseudorapidity]

Basics of Heavy Ion Collisions
Elliptic Flow

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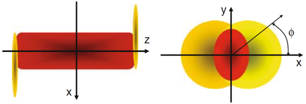
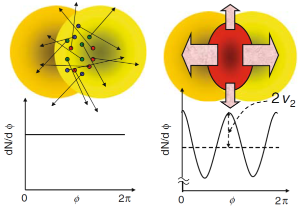
- elliptic flow is the second harmonic, v_2, in a Fourier expansion of the azimuthal momentum distribution in the transverse plane:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots\right]$$

- if $\lambda \gg L$, the azimuthal distribution of particles does not depend on ϕ on average due to the symmetry of the production
- if $\lambda \ll L$, hydrodynamics can be applied to describe the space-time evolution and the spatial asymmetry is converted via multiple collisions into an anisotropic momentum distribution

[J-Y. Ollitrault, Phys. Rev. D 48 (1993) 1132]





[T. Hirano et al., Lect. Notes Phys. 785, 139 (2010)]

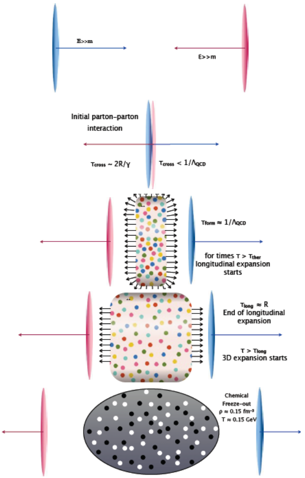
QGP in Heavy Ion Collisions - Estimating the Energy Density

- assuming that all available energy in the center-of-mass frame is dissipated, the maximum energy density is

$$\varepsilon \approx \frac{\sqrt{s_{NN}}\,A}{V} \approx \frac{\sqrt{s_{NN}}\,A}{4\pi\,(1.124\,A^{1/3})^3/3} \approx \frac{\sqrt{s_{NN}}}{5.94\,fm^3}$$

- SPS (18 GeV): $\varepsilon \approx 3$ GeV/fm^3
  RHIC (200 GeV): $\varepsilon \approx 34$ GeV/fm^3
  LHC (2760 GeV): $\varepsilon \approx 465$ GeV/fm^3
- real energy densites will be significantly smaller!
- lattice: $\varepsilon \approx 1$ GeV/fm^3 needed to create QGP

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]



[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]

QGP in Heavy Ion Collisions - Estimating the Energy Density

Energy density in the Bjorken scenario:

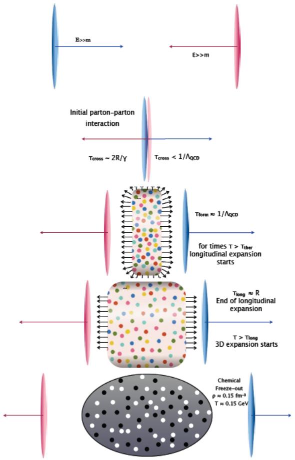
- the produced medium has cylindrical shape with length $2\Delta d$ and radius $R \approx 1.123\, A^{1/3}$ and contains particles with $\beta_z \leq \Delta d/\tau$
- since $\beta_z = \tanh(y) \approx y$ for $y \to 0$, this corresponds to a rapidity range $\Delta y = 2\Delta d/\tau$
- the total energy in the volume considered will be

$$E = \left|\frac{dE}{dy}\right|_{y=0} \frac{2\Delta d}{\tau}$$

- the energy density can be written as

$$\varepsilon(y) = \left|\frac{dE_T}{dy}\right| \frac{1}{\pi R^2 \tau} = \frac{dN}{dy} \frac{\langle m_T \rangle}{\tau \pi R^2}$$

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]



[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]

Initial Energy Density - RHIC

- the multiplicity of charged particles was measured at RHIC with $dN_{ch}/d\eta > 600$ for most central Au-Au collisions at 200 GeV at mid-rapidity

  [PHOBOS Collaboration, Phys. Rev. Lett. 85 (2000) 3100]
  [PHOBOS Collaboration, Phys. Rev. Lett. 88 (2002) 022302]
  [PHENIX Collaboration, Nucl. Phys. A 757 (2005) 184]
  [PHENIX Collaboration, Phys. Rev. C 71 (2005) 034908]

- with $dN/d\eta \sim (3/2)dN_{ch}/d\eta$ to include neutral pions, and using the Bjorken model, the initial energy density at mid-rapidity is

$$\varepsilon \approx \frac{dN}{d\eta}\frac{\langle m_T \rangle}{\tau \pi R^2} \approx 5 - 15\ \text{GeV/fm}^3$$

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]

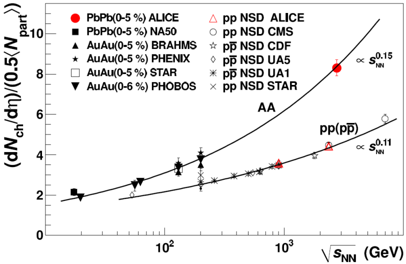


Fig.: Charged particle pseudo-rapidity density per participant pair

[ALICE Collaboration, Phys. Rev. Letters 105 (2010) 252301]

Initial Energy Density - LHC

- ALICE and ATLAS measured about 1600 charged particles per unit of pseudo-rapidity

  [ALICE Collaboration, Phys. Rev. Lett. 105 (2010) 252301]
  [ALICE Collaboration, Phys. Rev. Lett. 106 (2011) 032301]
  [ATLAS Collaboration, Phys. Lett. B 710 (2012) 363]

- the initial energy density at LHC is about three times larger than at RHIC:

$$\varepsilon \approx \frac{dN}{d\eta} \frac{\langle E_T \rangle}{\tau \pi R^2} \approx 15 - 30 \text{ GeV/fm}^3$$

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]

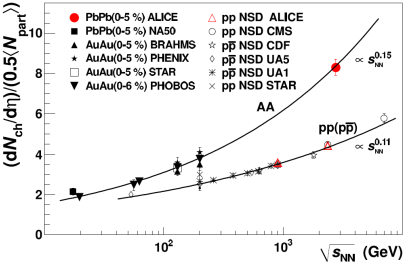


Fig.: Charged particle pseudo-rapidity density per participant pair

[ALICE Collaboration, Phys. Rev. Letters 105 (2010) 252301]

Initial Temperature - RHIC and LHC

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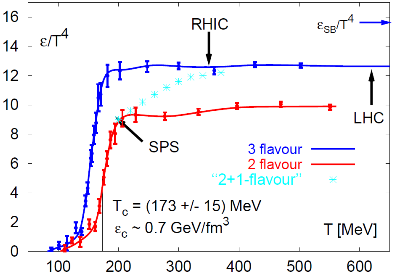
- assuming that the system quickly equilibrates, the initial temperature can be estimated from lattice QCD, assuming $\mu_B \approx 0$,

$$T^4[\mathrm{MeV}^4] \approx \frac{200^3 \times 10^3}{12.5} \times \varepsilon[\mathrm{GeV/fm}^3]$$

- estimate for initial temperature at RHIC top energies: $T = 240 - 320$ MeV, using $\varepsilon = 5 - 15$ GeV/fm^3
- estimate for initial temperature at LHC energy (2.76 TeV): $T = 310 - 370$ MeV, using $\varepsilon = 15 - 30$ GeV/fm^3,



[F. Karsch, E. Laermann, arXiv: 0305025]

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]

H-QM Helmholtz Research School Quark Matter Studies

Initial Temperature from Thermal Radiation - RHIC

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- PHENIX measured e^+e^- pairs with invariant masses < 300 MeV and $1 \leq p_T \leq 5$ GeV in Au-Au collisions at 200 GeV
  [PHENIX Collaboration, Phys. Rev. Lett. 104 (2010) 132301]
- the excess of the dielectron yield at most central collisions, when treated as internal conversion, agrees qualitatively with hydrodynamical models with an initial temperature of 300 to 600 MeV
- an inverse slope parameter of

$$T_{RHIC} = 221 \pm 19^{stat} \pm 19^{syst} \text{ MeV}$$

for 0-20% Au-Au collisions at 200 GeV was extracted

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]

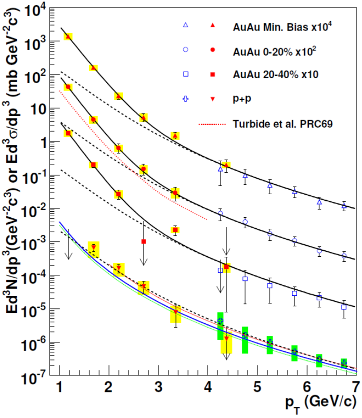


Fig.: Invariant yield of direct photons vs. p_T

[PHENIX Collaboration, Phys. Rev. Lett. 104 (2010) 132301]

Initial Temperature from Thermal Radiation - LHC

- Preliminary results from the first direct-photon measurement with real photons at ALICE show a slope parameter of

$$T_{LHC} = 304 \pm 51^{syst+stat}\ \text{MeV}$$

  for $0.8 < p_T < 2.2$ GeV/c at 2.76 TeV

- the initial temperature at LHC is at least 30-40% higher than at RHIC

[M. Wilde, Proc. Quark Matter 2012, arXiv:1210.5958]

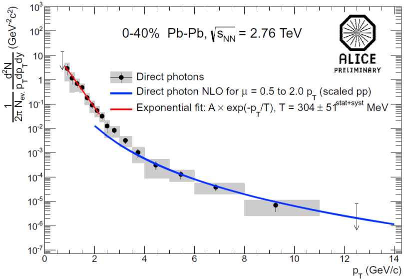


Fig.: Invariant yield of direct photons vs. p_T

[M. Wilde, Nucl. Phys. A 904-905 (2013) 573c]

Initial Temperature from Quarkonia

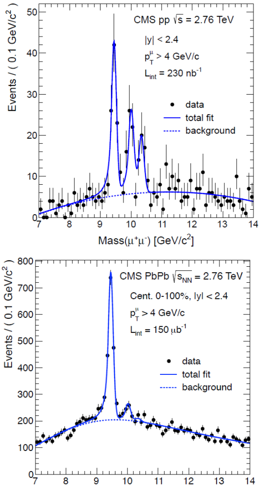
→ **talk by Almasi on Υ *production at RHIC and LHC*, 13.2.2014**

- results by CMS on the upsilon resonances (Υ(1S), Υ(2S),Υ(3S)) indicate a significant decrease of R_{AA} for Υ(2S) and Υ(3S)

  [CMS Collaboration, Phys. Rev. Lett. 107 (2011) 052302]
  [CMS Collaboration, JHEP 1205 (2012) 063]
  [CMS Collaboration, arXiv: 1208.2826]

- since $\sim$ 50% of the Υ(1S) production is due to feed-down, one expects $R_{AA} \sim 0.5$ when higher resonances are dissolved

- R_{AA} for Υ(1S) is about 0.41 for most central collisions, compatible with a formation of QGP at an initial temperature between 1.2 and 2.0 T_c, i.e. 200 and 400 MeV



[CMS Collaboration, arXiv: 1208.2826]

J/ψ as a Probe for Deconfinement

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$\rightarrow$ **talk by A. Rost on *Charmonia in the QGP*, 16.1.2014**

- PHENIX observed J/ψ suppression of about 40 to 80% in central Au-Au collisions at 200 GeV

  [PHENIX Collaboration, Journal of Physics G 34 (2007) S749]
  [PHENIX Collaboration, Phys. Rev. C 84 (2011) 054912]
  [PHENIX Collaboration, arXiv: 1208.2251]

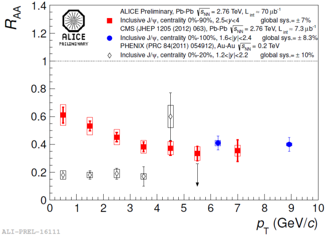
- since $\sim$ 40% of the J/ψ production is due to feed-down, it is unclear whether J/ψ is melt at RHIC energies

- $R_{AA}^{J/\psi}$ measured by ALICE is around 0.5 in most central Pb-Pb collisions, i.e. larger than at RHIC

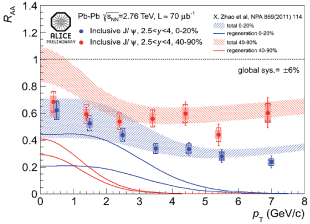
  [ALICE Collaboration, Phys. Rev. Lett. 109 (2012) 072301]

- this suggests J/ψ production by charm quark recombination in later stages of the QGP evolution and would be a direct probe for deconfinement

  [P. Braun-Munzinger and J. Stachel, Phys. Lett. B 490 (2000) 196]



[C. Suire, Hard Probes (2012), arXiv: 1208.5601]



[E. Scomparin, Quark Matter 2012, arXiv: 1211.1623]

Final Temperature from Chemical Freeze-Out

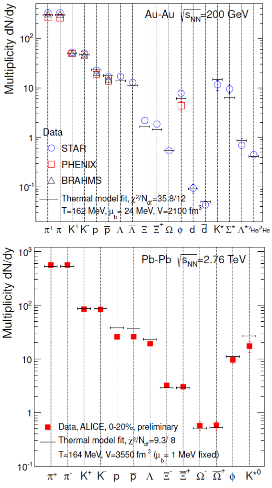
- hadron yield ratios can be successfully described by a statistical model where the expanding hot system hadronizes statistically:

$$n_i = \frac{N_i}{V} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1}$$

  with +/- for fermions/bosons, N_i hadrons of species i and degeneration factor g_i

  [A. Andronic and P. Braun-Munzinger, arXiv:hep-ph/0402291]

- only two parameters ar needed to predict the hadron yield ratios: T and μ_b (for zero total strangeness and isospin)
- similar freeze-out temperatures at RHIC and LHC of $T \approx 160$ MeV agree well with the phase transition temperature predicted by lattice QCD



[A. Andronic et al., arXiv: 1210.7724]

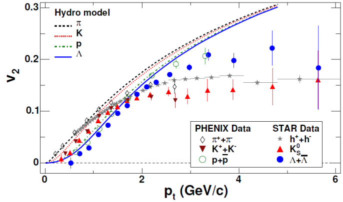
Elliptic Flow

Elliptic flow measurements have been one of the major observations at RHIC, evidencing that

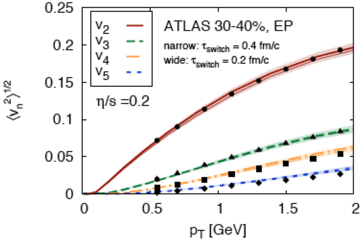
- the created matter equilibrates in an early stage of the collision, and then evolves hydrodynamically
- it behaves like a perfect fluid with very small ratio of shear viscosity over entropy density, $\eta/s \geq 1/4\pi \approx 0.08$

Analyses of event-by-event fluctuations of higher Fourier coefficients $v_n(p_T)$ yield $\eta/s \approx 0.12$ at RHIC and $\eta/s \approx 0.20$ at LHC

[C. Gale et al., Phys. Rev. Lett. 110 (2013) 012302]
[ALICE collaboration,Phys. Rev. Lett. 107 (2010) 252302]
[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]



[STAR Collaboration, Phys. Rev. C 72 (2005) 014904]



[B. Müller, Phys. Scr. T158 (2013) 014004]

Jet Quenching

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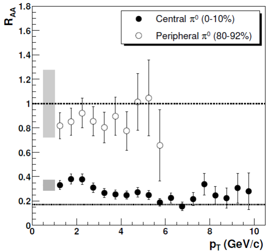
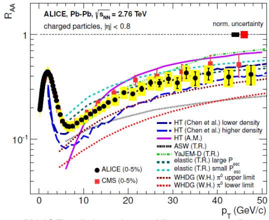
- suppression of high p_T hadrons and quenching of back-to-back hadron correlations were major discoveries at RHIC
- first LHC results indicate a strong suppression of charged particle production in Pb-Pb collisions and a characteristic centrality and p_T dependence
- above $p_T = 7$ GeV there is a significant rise in the nuclear modification factor, which reaches $R_{AA} \approx 0.4$ for $p_T > 30$ GeV, in agreement with models for radiative energy loss of gluons in QGP

[G. Martinez Garcia, arXiv: 1304.1452 [nucl-ex]]



[PHENIX collaboration, Phys. Rev. Lett. 91 (2003) 072301]



[ALICE collaboration, arXiv: 1208.2711]

Jet Quenching

- from R_{AA} one can approximately obtain the fraction of energy lost,

$$\varepsilon_{loss} = \Delta p_T / p_T \approx 1 - R_{AA}^{1/(n-2)} \approx 0.2$$

with $R_{AA} \approx 0.2$ and $n \approx 8$ as extracted from the Au-Au and p-p invariant mass spectra,

$$1/p_T dN/dp_T \propto p_T^{-n}$$

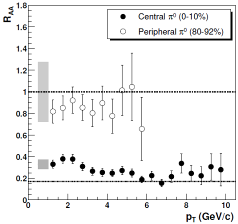
[PHENIX collaboration, Phys. Rev. C 76 (2007) 034904]

- at high p_T, suppression well reproduced by parton energy loss models: $dN^g/dy \approx 1400$, $\langle \hat{q} \rangle \approx 13$ GeV^2/fm and $T \approx 400$ MeV

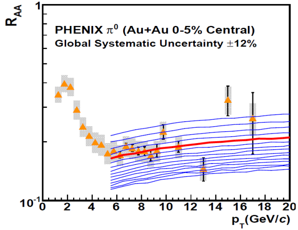
[D. d'Enterria, arXiv:0902.2011 [nucl-ex]]

- JET collaboration: $\langle \hat{q} \rangle \approx 1.1 \pm 0.3$ GeV^2/fm at RHIC, $\langle \hat{q} \rangle \approx 1.9 \pm 0.7$ GeV^2/fm at LHC

[JET collaboration, arXiv: 1312.5003]

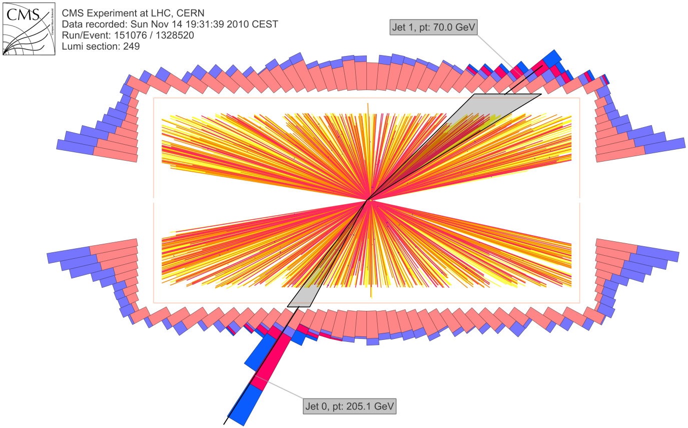


[PHENIX collaboration, Phys. Rev. Lett. 91 (2003) 072301]



[D. d'Enterria, arXiv:0902.2011 [nucl-ex]]

Asymmetry of Di-Jets



[http://www.lhc-facts.ch/img/news2010/]

Asymmetry of Di-Jets

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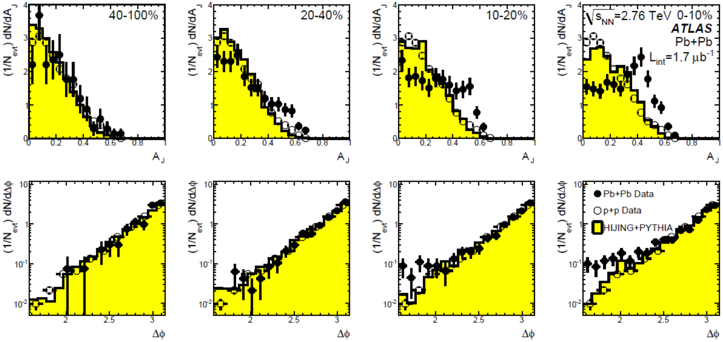

Top: Dijet asymmetry distribution as a function of collision centrality (left to right from peripheral to central events)
Bottom: distribution of the azimuthal angle between two jets

- an asymmetry, $A_J = (E_{T1} - E_{T2})/(E_{T1} + E_{T2})$, increasing with centrality, was observed between the transverse energies of the leading and second jets
- confirmation of large jet energy loss in a hot, dense medium

[ATLAS collaboration, Phys. Rev. Lett. 105 (2010) 252303]

Summary

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After more than a decade of experiments at RHIC and recently at LHC,
a consistent picture of the QGP as a strongly coupled gauge plasma has emerged:

- strong elliptic flow, indicating early thermalization at times less than 1 fm/c and very small ratio η/s of 0.12 at RHIC and 0.20 at LHC
- initial temperature extracted from thermal radiation is $T \approx 220$ MeV at RHIC and $T \approx 300$ MeV at LHC
- quarkonium suppression and regeneration signals deconfinement and temperatures of $T = 200 - 400$ MeV
- strong jet quenching, implying a very large parton energy loss in the medium and a high color opacity

Merry Christmas!

QGP Equation of State and Susceptibilities

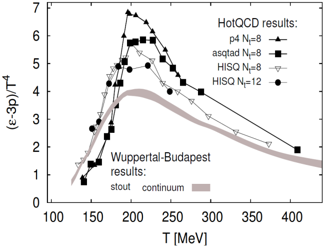
Equation of state:

- the Wuppertal-Budapest group obtained a value $\varepsilon - 3p \approx 4$ for the peak height of the trace anomaly

  [Y. Aoki et al., JHEP 0601 (2006) 089]
  [S. Borsanyi et al., JHEP 1011 (2010) 077]

- the hotQCD collaboration typically receives higher values

  [P. Petrecky, PoS LATTICE (2012) 069]

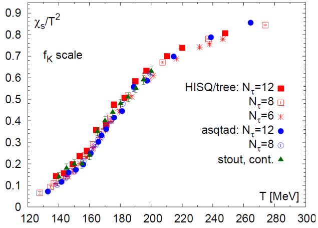


Susceptibilities:

- fluctuations of conserved charges are sensitive to underlying degrees of freedom and important probes for deconfinement

$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2 \rangle$$

[S. Borsanyi et al., JHEP 1201 (2012) 138]



[P. Arnold, PoS Confinement X (2012) 030]

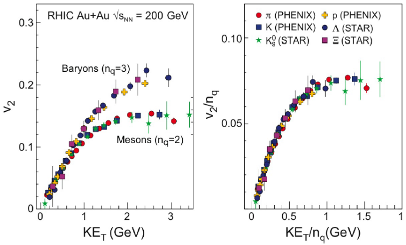
Elliptic Flow

Evidence that the medium is composed of deconfined, thermalized and collectively flowing quarks from hadron spectra:

- the elliptic flow of hadrons is by a factor 3/2 larger compared to mesons at $p_T = 2 - 3$ GeV/c
- well described by combination of hydrodynamics and models based on recombination of quarks from a thermally equilibrated partonic medium:

$$v_2^{(M)}(p_T) \approx 2v_2^{(q)}(p_T/2)$$
$$v_2^{(B)}(p_T) \approx 3v_2^{(q)}(p_T/2)$$

[R. J. Fries et al., Phys. Rev. C 68 (2003) 044902]



[B. Müller, arXiv: 0710.3366 [nucl-th]]