Dedicated to the Memory of J. Zimányi

The Origin of Thermal Hadron Production

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basic observation in all high energy multihadron production

thermal production pattern

Fermi, Landau, Pomeranchuk, Hagedorn

- species abundances $\sim$ ideal resonance gas at T_H
- universal $T_H \simeq 150 - 200$ MeV for all (large) $\sqrt{s}$
- thermal transverse momentum spectra with same T_H

caveats: baryon density, strangeness, jets, flow basic observation in all high energy multihadron production

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begin by summarizing experimental situation

in elementary collisions

1. Thermal Hadron Production

what is "thermal"?

- equal *a priori* probabilities for all states in accord with a given overall average energy $\Rightarrow$ temperature T;
- partition function of ideal resonance gas

$$\ln Z(T) = V \sum_i \frac{d_i}{(2\pi)^3} \phi(m_i, T)$$

Boltzmann factor $\phi(m_i, T) = 4\pi m_i^2 T K_2(m_i/T)$

- relative abundances $$\frac{N_i}{N_j} = \frac{d_i \phi(m_i, T)}{d_j \phi(m_j, T)}$$
- transverse momenta $$\frac{dN}{dp_T^2} \sim \exp -\frac{1}{T}\sqrt{m_i^2 + p_T^2}.$$

Abundances

e^+e^-, LEP Data [Becattini 1996]

Fit relative abundances to ideal resonance gas of all hadronic resonances, with $M \leq 1.7$ GeV, two parameters T and γ_s

$T = 169.9 \pm 2.6$ MeV

$\gamma_s = 0.691 \pm 0.053$

$\chi^2/\text{dof} = 17.2/12$

estimate systematic error by varying resonance gas scheme, contributing resonances

e^+e^- $\sqrt{s} = 91.2$ GeV				
species	measured			fit
π^+	8.53	$\pm$	0.40	8.72
π^0	9.18	$\pm$	0.82	9.83
K^+	1.18	$\pm$	0.052	1.06
K^0	1.015	$\pm$	0.022	1.01
η	0.934	$\pm$	0.13	0.908
ρ^0	1.21	$\pm$	0.22	1.16
K^{*+}	0.357	$\pm$	0.027	0.349
K^{*0}	0.372	$\pm$	0.027	0.343
η'	0.13	$\pm$	0.05	0.1070
p	0.488	$\pm$	0.059	0.484
ϕ	0.10	$\pm$	0.0090	0.167
Λ	0.185	$\pm$	0.0085	0.152
Ξ^-	0.0122	$\pm$	0.00079	0.011
Ξ^{*0}	0.0033	$\pm$	0.00047	0.00391
Ω	0.0014	$\pm$	0.00046	0.000782

$$T = 170 \pm 3 \pm 6 \text{ MeV}$$

similar analyses carried out for

- e^+e^- at $\sqrt{s} = 14,\ 22,\ 29,\ 35,\ 43$ GeV
- pp at $\sqrt{s} = 19.4,\ 23.8,\ 26.0,\ 27.4$ GeV
- $p\bar{p}$ at $\sqrt{s} = 200,\ 500,\ 900$ GeV
- π^+p at $\sqrt{s} = 21.7$ GeV
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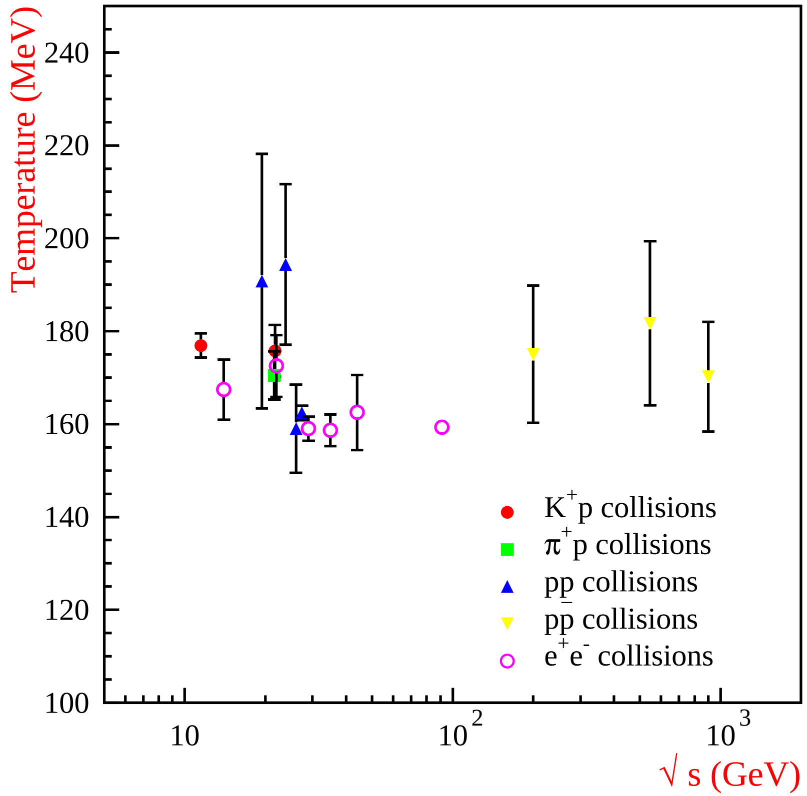
compilation Becattini 2006



Result:

$$T \simeq 170 \pm 20 \text{ MeV}$$

independent of
- collision energy
- collision configuration

Heavy ion collisions $\Rightarrow$ baryon density

- resonance gas at T, μ_B; $\mu_B \Downarrow$ for $\sqrt{s} \Uparrow$
- elementary high energy collisions $\mu_B \simeq 0$
- species abundances in high energy heavy ion collisions (peak SPS, RHIC)

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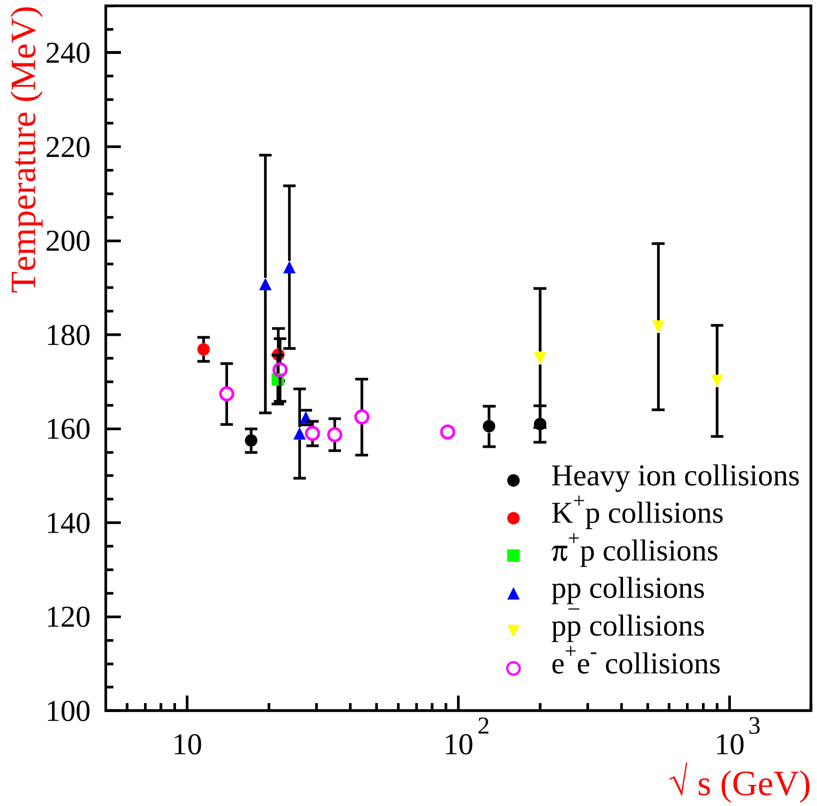

Result:

<u>same hadronization temperature</u>
for high energy heavy ion and elementary collisions,
independent of collision energy

Conclude:

Hadron abundances in all high energy collisions (e^+e^- annihilation, hadron-hadron interactions and heavy ion collisions) are those of an ideal resonance gas at a universal temperature

$$T_H \simeq 170 \pm 20 \text{ MeV.}$$

NB: Transverse momentum spectra in elementary collisions are in accord with such thermal behaviour.

return later to baryon number dependence & flow in heavy ion collisions

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WHY?

Why should high energy collisions produce a thermal medium?

Multiple parton interactions → <u>kinetic</u> thermalization?

nucleus-nucleus maybe; e^+e^-, hadron-hadron not

Is there another "<u>non-kinetic</u>" thermalization mechanism?

**Is there a <u>common</u> origin of thermal production
in all high energy collisions?**

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What does that mean?

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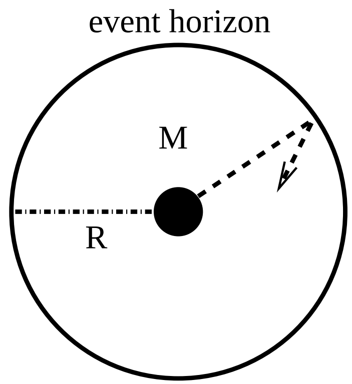
Conjecture: Colour confinement ∼ black hole physics

[Paolo Castorina, Dmitri Kharzeev, HS 2007]

2. Black Holes and Event Horizons

- black hole

  neutron star after gravitational collaps
  large mass M and compact size
  gravitation so strong that matter &
  light are confined $\Rightarrow$ event horizon R
  no communication with outside, but...



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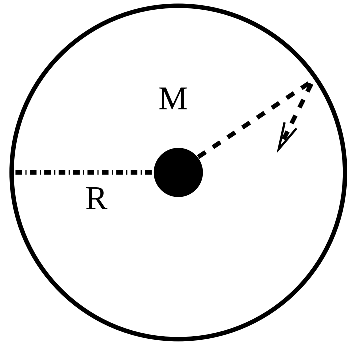
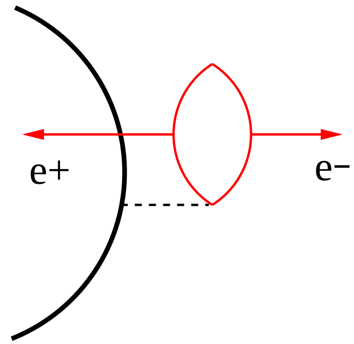


- **Hawking radiation** [Hawking 1975]

quantum effect $\sim$ uncertainty principle
vacuum fluctuation e^+e^- outside event horizon, with $\Delta E \Delta t \sim 1$
if in Δt, e^+ falls into black hole,
then e^- can escape; equivalent:
e^- tunnels through event horizon



- **Quantum Causality**

  no information about state of system beyond event horizon; e^+ on one side, e^- on the other: EPR

$\Rightarrow$ Hawking radiation must be thermal

$$\frac{dN}{dk} \sim \exp\{-\frac{k}{T_{BH}}\}$$

with black hole temperature $\qquad T_{BH} = \dfrac{\hbar}{8\pi c GM}$

relativistic quantum effect: disappears for $\hbar \to 0$ or $c \to \infty$

$\Rightarrow$ tunnelling through event horizon $\to$ thermal radiation

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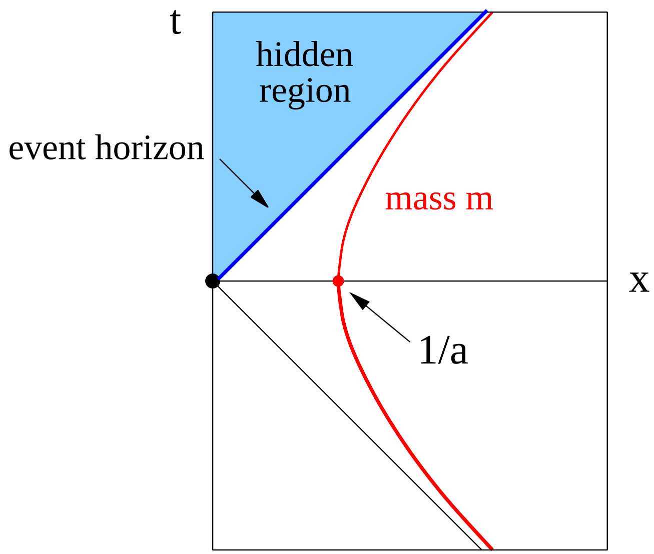
- Unruh relation [Unruh 1976]

  event horizon arises for systems in uniform acceleration mass m in uniform acceleration a

$$\frac{d}{dt}\frac{mv}{\sqrt{1-v^2}} = F$$



$v = dx/dt$, $F = ma$, $c = 1$

solution: hyperbolic motion

$$x = \frac{1}{a}\cosh a\tau$$

$$t = \frac{1}{a}\sinh a\tau$$

$\exists$ event horizon: m cannot reach hidden region
observer in hidden region cannot communicate with m

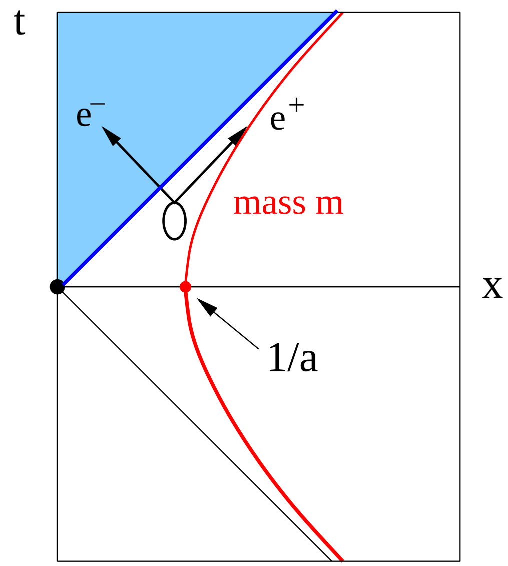
m passes through vacuum, can use part of acceleration energy to excite vacuum fluctuations on-shell

e^+ absorbed in detector on m

e^- disappears beyond event horizon

"quantum entanglement"

$\sim$ Einstein-Podolsky-Rosen effect



observer on m as well as observer in hidden region have incomplete information: $\Rightarrow$ each sees thermal radiation

observer on m:
physical vacuum = thermal medium of temperature T_U

Unruh temperature $\quad T_U = \dfrac{\hbar a}{2\pi c}$ again relativistic quantum effect for observer in hidden region, Unruh radiation:

passage of $m \Rightarrow$ thermal radiation of temperature T_U

Black hole event horizon $R = 2GM$ (Schwarzschild radius)

$$F = ma = G\frac{Mm}{R^2} \;\Rightarrow\; a = \frac{GM}{R^2} = \frac{1}{4GM}$$

$$\Rightarrow\; T_U = \frac{a}{2\pi} = \frac{1}{8\pi GM} = T_{BH}$$

recover Hawking result

for observer in hidden region, Unruh radiation:

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recover Hawking result

In general: [T. D. Lee 1986, Parikh & Wilczek 2000]

event horizon $\sim$ information transfer forbidden

$\Rightarrow$ quantum tunnelling $\sim$ thermal radiation

Relation to QCD?

Gravitation:

matter and light confined to restricted region of space ("black hole")

QCD:

coloured quarks and gluons confined to restricted region of space, colourless from the outside ("white hole")

Hadrons as black hole analogue in strong interaction physics?

[Recami & Castorina 1976, Salam & Strathdee 1978]

Schwarzschild radius of nucleon

$$R_g^n = 2\,G\,m \simeq 1.3 \times 10^{-38}\ \mathrm{GeV}^{-1} \simeq 3 \times 10^{-39}\ \mathrm{fm}$$

Volume of nucleon too big by 10^{100} to be a gravitational black hole

Gravitation $\rightarrow$ strong interaction: $Gm^2 \longrightarrow \alpha_s$, hence

$$R_s^n = \frac{2\alpha_s}{m} \simeq 1 \text{ fm}$$

if $\alpha_s \simeq 2 - 3$.

Hadron radius $\sim$ "strong" Schwarzschild radius

Hadrons $\sim$ "strong" black (or "white") holes
coloured inside, white outside

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Hadron radius ∼ "strong" Schwarzschild radius

Hadrons ∼ "strong" black (or "white") holes
coloured inside, white outside

More generally:

consider interacting hadrons, multihadron production, in the framework of black hole physics concepts

Black hole: event horizon for all interactions

White hole: event horizon only for strong interactions

3. Pair Production and String Breaking

Basic process: two-jet e^+e^- annihilation, cms energy $\sqrt{s}$:

$$e^+e^- \longrightarrow \gamma* \longrightarrow q\bar{q} \longrightarrow \text{ hadrons}$$

$q\bar{q}$ separate subject to constant confining force $F = \sigma$

initial quark velocity $\quad v_0 = \dfrac{p}{\sqrt{p^2 + m^2}} \; , \quad p \simeq \sqrt{s}/2$

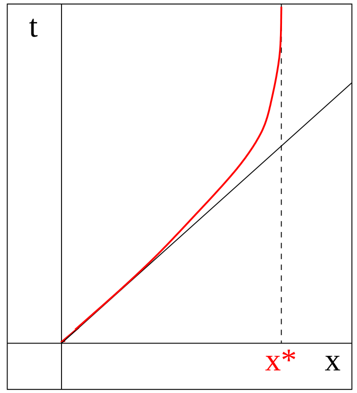
Solve $ma = \sigma$ (hyperbolic motion): [Hosoya 1979, Horibe 1979]

$$\tilde{x} = [1 - \sqrt{1 - v_0\tilde{t} + \tilde{t}^2}] \; , \; \tilde{x} = x/x_0 \; , \; \tilde{t} = t/x_0$$

with $$x_0 = \frac{m}{\sigma}\frac{1}{\sqrt{1 - v_0^2}} = \frac{m}{\sigma}\,\gamma = \frac{1}{a}\,\gamma$$

classical turning point $v(t^*) = 0$ at

$$x^* = x(t^*) = \frac{m}{\sigma}\,\gamma\,[1 - \sqrt{1-(v_0/2)^2}] \simeq \frac{\sqrt{s}}{2\sigma}$$



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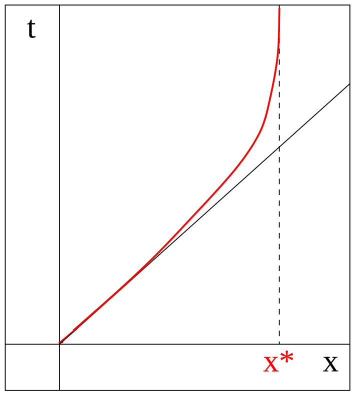
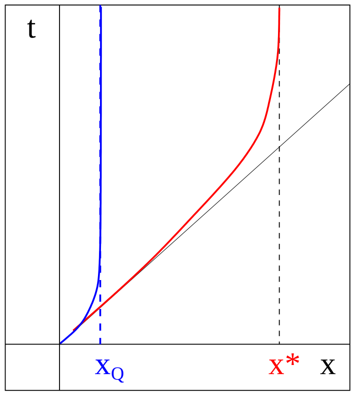


What's wrong?

classical event horizon

Strong field $\Rightarrow$ vacuum unstable
against pair production [Schwinger 1951]

when $\sigma x > \sigma x_Q \equiv 2m$
string connecting $q\bar{q}$ breaks

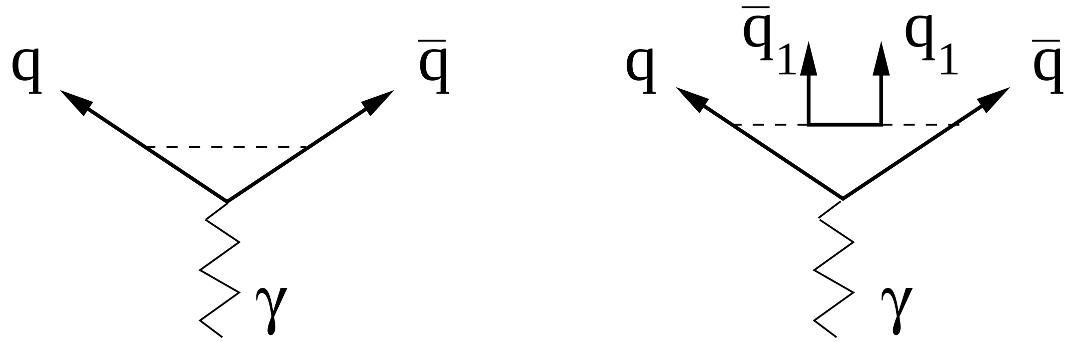


Result:

quantum event horizon

Hadron production in e^+e^- annihilation:

"inside-outside cascade" [Bjorken 1976]



$q\bar{q}$ **flux tube has thickness** $r_T \simeq \sqrt{\frac{2}{\pi\sigma}}$

$q_1\bar{q}_1$ **at rest in cms, but** $k_T \simeq \frac{1}{r_T} \simeq \sqrt{\frac{\pi\sigma}{2}}$

$q\bar{q}$ **separation at** $q_1\bar{q}_1$ **production** $\sigma x(q\bar{q}) = 2\sqrt{m^2 + k_T^2}$

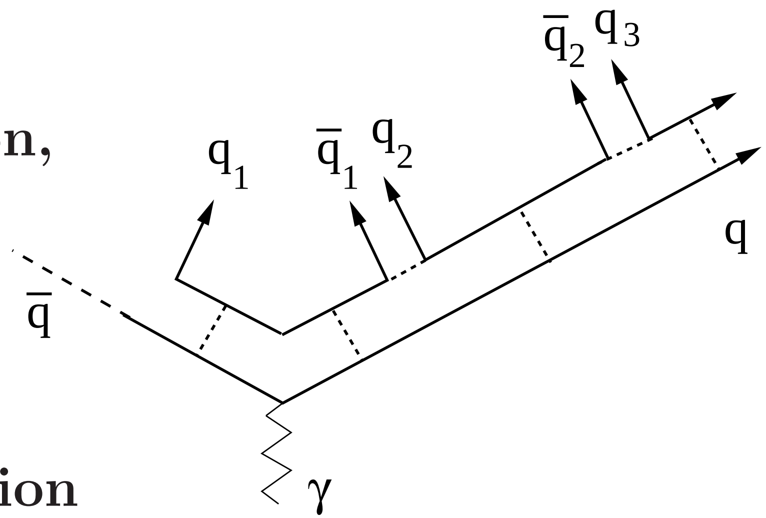
q_1 screens $\bar{q}$ from q, hence string breaking at

$$x_q \simeq \frac{2}{\sigma}\sqrt{m^2 + (\pi\sigma/2)} \simeq \sqrt{\frac{2\pi}{\sigma}} \simeq 1 \text{ fm}$$

new flux tubes $q\bar{q}_1$ and $\bar{q}q_1$
stretch $q_1\bar{q}_1$
to form new pair $q_2\bar{q}_2$

$$\sigma x(q_1\bar{q}_1) = 2\sqrt{m^2 + k_T^2}$$

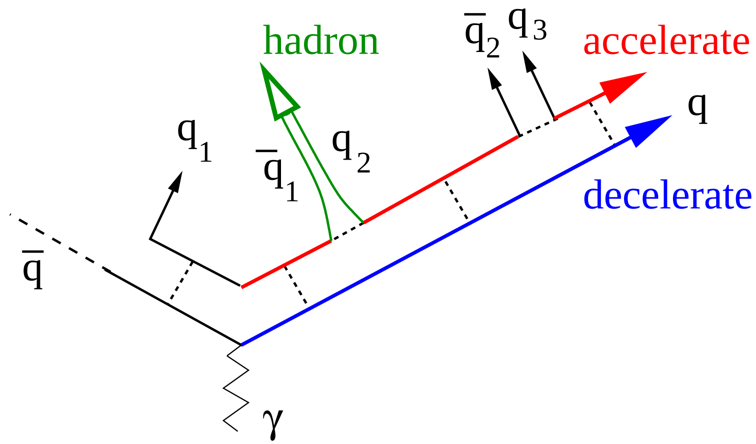
equivalent:
$\bar{q}_1$ reaches $q_1\bar{q}_1$ event horizon,
tunnels to become $\bar{q}_2$

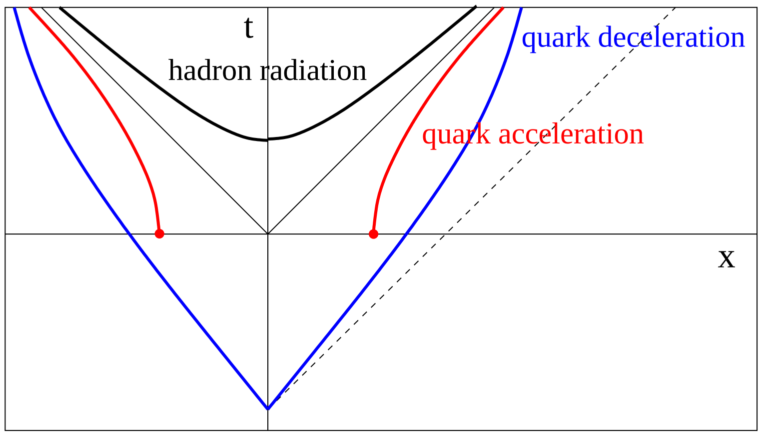


emission of hadron $\bar{q}_1 q_2$
as Hawking radiation

self-similar pattern:

- **screening**
- **string breaking**
- **tunnelling**
- **quark acceleration /deceleration**
- **Hawking radiation**





temperature of Hawking radiation: what acceleration?

$(\bar{q}_1 \longrightarrow \bar{q}_2 \longrightarrow \bar{q}_3 \longrightarrow \ldots)$

bring quark on-shell

$$v = 0 \rightarrow v = k_T/(m^2 + k_T^2)^{1/2} \simeq 1$$

in virtuality time $\Delta\tau = 1/\Delta E \simeq 1/2k_T$

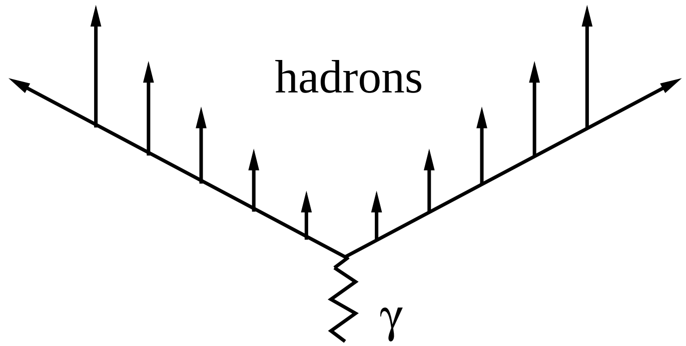
$$a = \frac{\Delta v}{\Delta \tau} \simeq 2k_T \simeq \sqrt{2\pi\sigma} \simeq 1.1 \text{ GeV}$$

$\Rightarrow$ temperature of hadronic Hawking radiation

$$\boxed{T_q = \frac{a}{2\pi} \simeq \sqrt{\frac{\sigma}{2\pi}} \simeq 180 \text{ MeV}}$$

determines: hadron species abundances, p_T spectra hadronization pattern:

hadron multiplicity?



thickness of classical "overstretched" string:

$$R_T^2 = \frac{2}{\pi\sigma} \sum_{k=0}^{K} \frac{1}{2k+1} \simeq \frac{2}{\pi\sigma} \ln 2K \simeq \frac{2}{\pi\sigma} \ln \sqrt{s}$$

quantum breaking at $x_q \sim r_T$, hence hadron multiplicity

$$\boxed{\nu(s) \simeq \frac{R_T^2}{r_T^2} \simeq \ln \sqrt{s}}$$

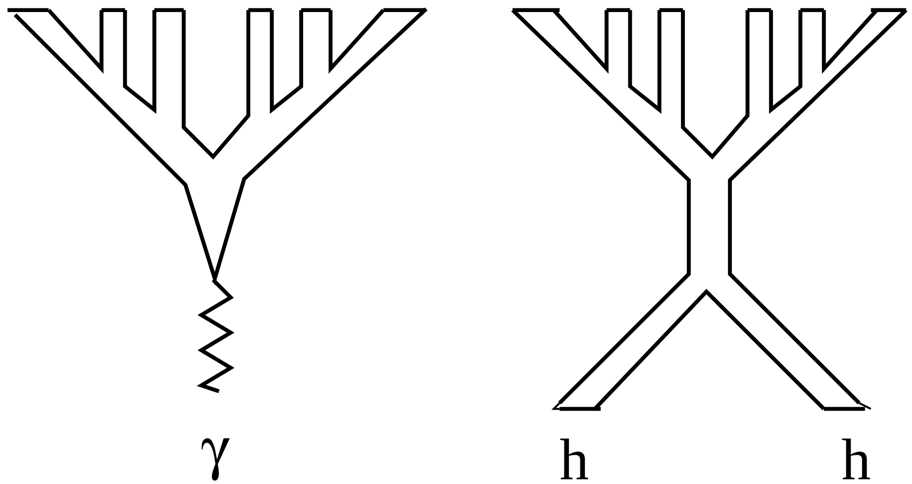
NB: parton evolution (minijets), multiple jets lead to stronger increase

parton saturation: see Kharzeev & Tuchin

generalize:

e^+e^- annihilation — **white hole creation**

hadron-hadron collision — **white hole fusion**



both → self-similar cascades

Heavy ion collisions ⇒

- **baryon number**
- **centrality ("spin")**

4. Charged and Rotating Black Holes

Black holes: three (& only three) observable properties

mass M, charge Q, angular momentum J

hence thermal Hawking radiation $\Rightarrow$ $T_H(M, Q, J)$

Origin of event horizon?

invariant space-time metric (time t, space r, latitude θ)

$$ds^2 = f_t(M, Q, J)\ dt^2 - f_r(M, Q, J)\ dr^2 - f_\theta(M, Q, J) d\theta^2$$

event horizon: $f_r \to \infty$

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event horizon: $f_r \to \infty$

- $Q = J = 0$: **Schwarzschild BH** $\qquad T_S(M) = \dfrac{1}{8\pi\, G\, M}$

- $Q \neq 0, J = 0$: Reissner-Nordström BH

$$T_{RN}(M,Q) = T_S(M)\left\{\frac{4\sqrt{1-Q^2/GM^2}}{(1+\sqrt{1-Q^2/GM^2})^2}\right\} < T_S(M)$$

smaller than $T_S(M)$ because Coulomb repulsion partially balances gravitational attraction

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- $Q = 0, J \neq 0$: Kerr BH $\quad (\rho = J/M)$

$$T_K(M,J) = T_S(M) \left\{ \frac{4\sqrt{1 - \rho^2/(GM)^2}}{(1 + \sqrt{1 - \rho^2/(GM)^2})^2} \right\} \;<\; T_S(M)$$

smaller than $T_S(M)$ because centrifugal force
partially balances gravitational attraction

normally $f_r \longrightarrow \infty \quad \Rightarrow \quad f_t \longrightarrow 0$

for rotating BH, two distinct solutions:

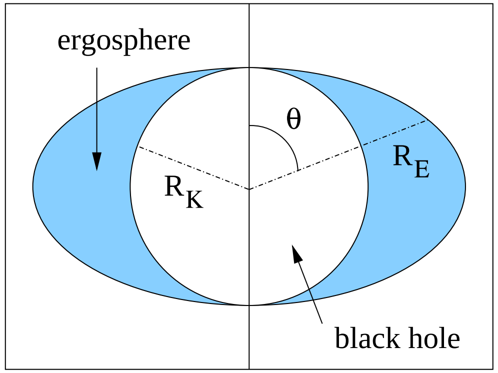
event horizon

$$f_r \longrightarrow \infty \quad \Rightarrow \quad R_K = GM\,(1 + \sqrt{1 - \rho^2/(GM)^2}\,)$$

ergosphere

$$f_t \longrightarrow 0 \quad \Rightarrow \quad R_E = GM\,(1 + \sqrt{1 - [\rho^2/(GM)^2]\cos^2\theta})$$

in ergosphere,
rotational drag
affects even light



5. Baryon Density and Non-Central Collisions

White holes: three (& only three) features observable in strong interactions:

$\sqrt{s}$, net baryon number, angular momentum

$\sqrt{s}$ determines classical event horizon, $\sim$ multiplicity

Hawking radiation at earlier quantum horizon,

$\Rightarrow T_H(\sigma)$, not $T_H(\sqrt{s})$

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angular momentum $\Rightarrow$ $T_H(\sigma, \text{centrality})$

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- Baryon Density

  Coulomb repulsion vs. gravitation $\Rightarrow$ baryon repulsion vs. vacuum pressure

Fermion pressure at $T = 0$ $\quad P = \left(\frac{d_f}{24\pi^2}\right)\mu^4$

against vacuum pressure $\quad B \sim \langle G^2_{\mu\nu} \rangle$

leads to $\quad \mu_0 = (2\pi^2 B)^{1/4}$

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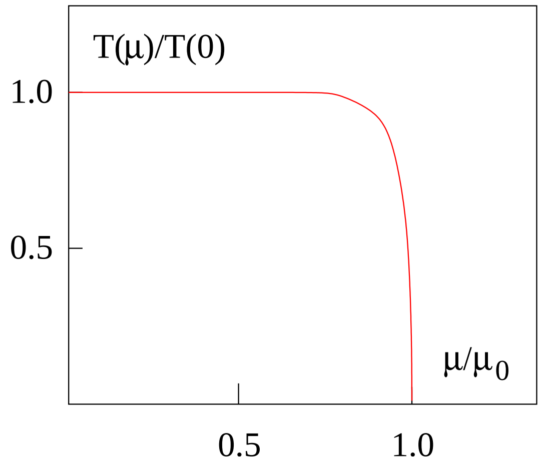
leads to $$\mu_0 = (2\pi^2 B)^{1/4}$$

and hence to Hawking hadronization temperature

$$T(\mu)/T_0 = \frac{\sqrt{1-(\mu/\mu_0)^4}}{(1+\sqrt{1-(\mu/\mu_0)^4})^2}$$

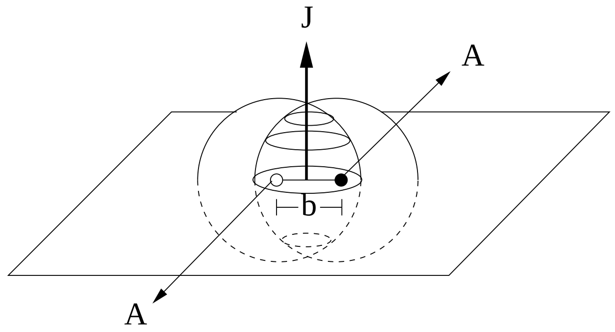


overly simplistic - include realistic baryon interaction

- **Angular Momentum**

  Non-central *AA* collision

  impact parameter *b*



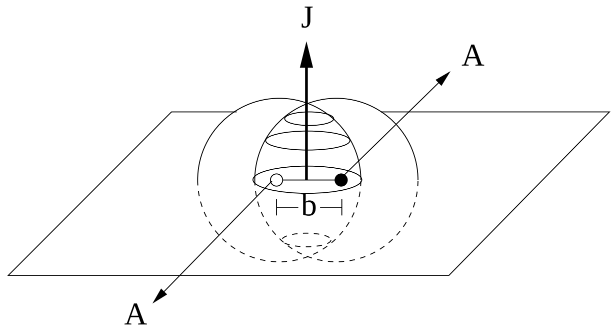
assume interaction region rotates

(collective effect ∼ hydro)

- <u>**Angular Momentum**</u>

  Non-central $\boldsymbol{AA}$ collision

  impact parameter $\boldsymbol{b}$

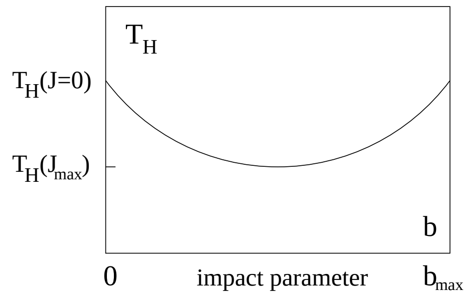


assume interaction region rotates

(collective effect $\sim$ hydro)

$\Rightarrow$ $\boldsymbol{T_H}$ decreases with centrality

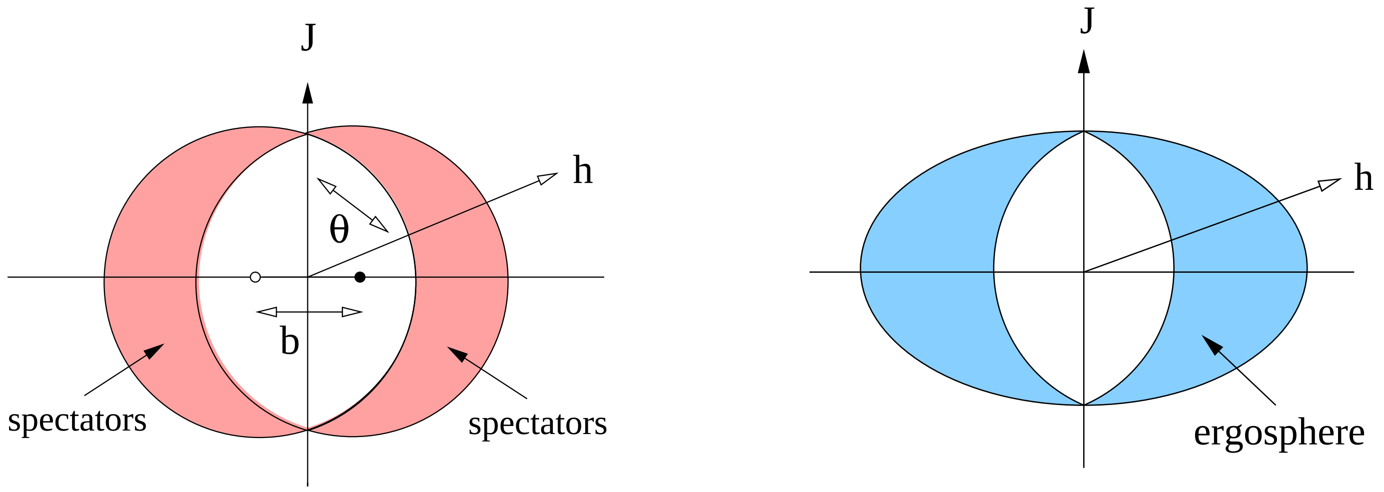
increases again when collectivity stops



test through species abundance ratios

ergosphere $R_E(J\cos\theta)$ $\longrightarrow$

azimuthal dependence of hadron spectra



along polar axis: no "flow", $T_H(J) < T_H(J=0)$

along equator: "flow", $T_H(J) < T_H(J=0)$

test in simultaneous study of species abundances and p_T spectra

5. Kinetic vs. Stochastic Thermalization

Kinetic thermalization:

time evolution of given non-equilibrium configuration
(two parallel colliding parton beams)
through multiple collisions
to a time-independent equilibrium state
(quark-gluon plasma)
requires

- **many constituents**
- **sufficiently large interaction cross sections**
- **sufficiently long time**

thermal hadron production in e^+e^-, $pp/p\bar{p}$?

Hagedorn: *the emitted hadrons are "born into equilibrium"*

Hawking radiation:

final state produced at random from the set of all states corresponding to temperature T_H determined by confining field

this set of all final states is same as that produced by kinetic thermalization

measurements cannot tell if the equilibrium was reached by thermal evolution or by throwing dice:

$\Rightarrow$ **Thermodynamic Equivalence Principle** $\Leftarrow$

6. Summary

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- Energy, baryon number and angular momentum of the QCD "black hole" provide the multiplicity of produced hadrons and the dependence of T_H on baryon density and collision centrality.
- The resulting scenario provides a common basis for thermal hadron production in QCD interactions, from e^+e^- annihilation to nuclear collisions.

NB:

In astrophysics/gravitation, Hawking radiation is not observed/observable ($T_{BH} \ll 2.7^\circ$K)

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Thermal hadron production:

first experimental confirmation of Hawking-Unruh radiation

God does play dice, but He sometimes throws them where they can't be seen.

Stephen Hawking