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

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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
- K^+p at $\sqrt{s} = 11.5,\ 21.7$ GeV

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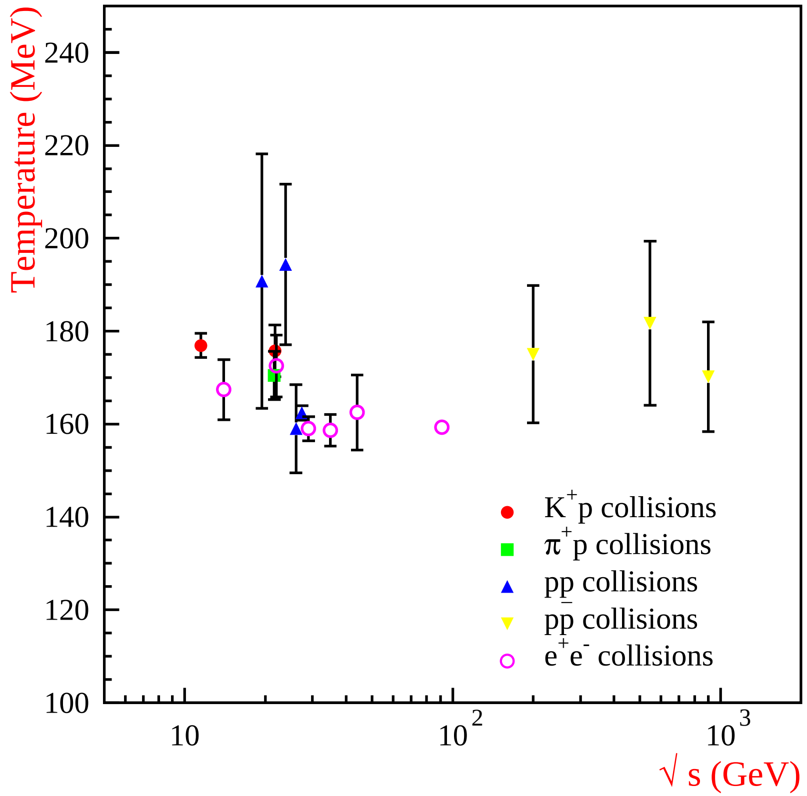
compilation **Becattini 2006**



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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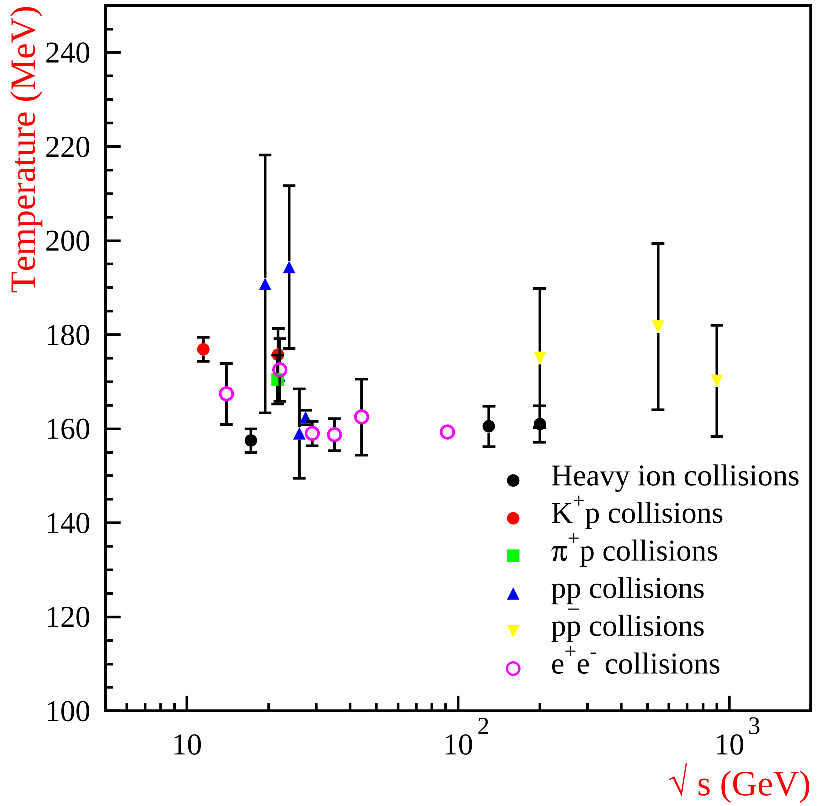
- species abundances in high energy heavy ion collisions (peak SPS, RHIC)

compilation Becattini 2006

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: Strangeness production in elementary collisions uniformly suppressed by $\gamma_s \simeq 0.5 - 0.6$

suppression weakened/removed in heavy ion collisions

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WHY?

Why should high energy collisions produce a thermal medium?

Multiple parton interactions $\longrightarrow$ kinetic thermalization?

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

Is there another "non-kinetic" thermalization mechanism?

Is there a common origin of thermal production in all high energy collisions?

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Passing colour charge disturbs vacuum, vacuum recovers by hadron production according to maximum entropy

What does that mean?

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What does that mean?

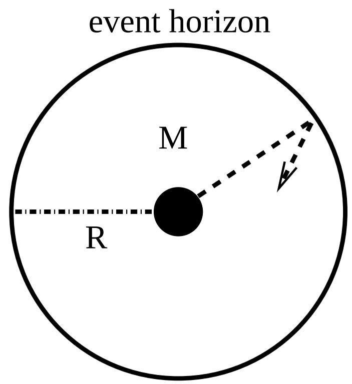
Conjecture: Colour confinement ∼ black hole physics

[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 ⇒ event horizon R
  no communication with outside, but...



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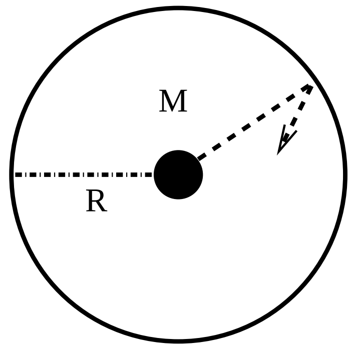
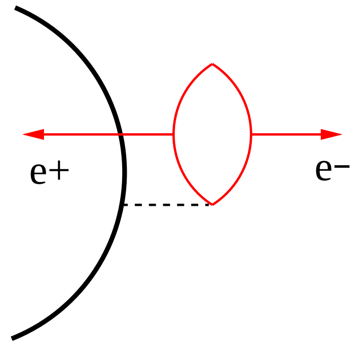


- Hawking radiation

[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



- <u>Quantum Causality</u>

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

⇒ Hawking radiation must be thermal

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

with black hole temperature $$T_{BH} = \frac{\hbar}{8\pi c G M}$$

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

⇒ tunnelling through event horizon → thermal radiation

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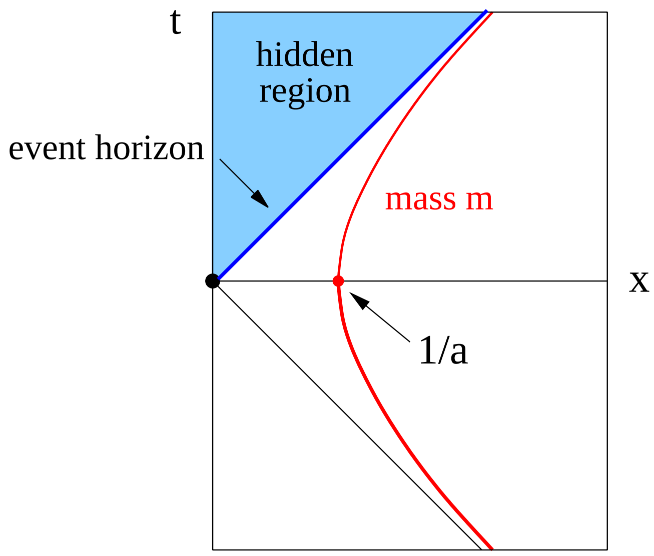
$\Rightarrow$ tunnelling through event horizon $\to$ thermal radiation

- 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

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

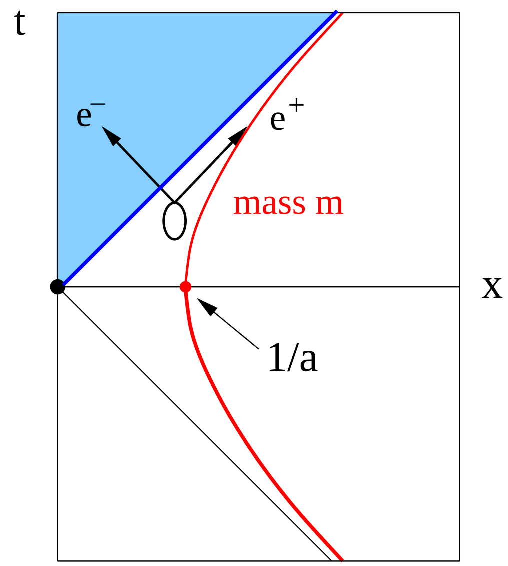
$$t = \frac{1}{a}\sinh a\tau$$

$\exists$ 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 $$T_U = \frac{\hbar a}{2\pi c}$$ 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:

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

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

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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 are confined to restricted region of space ("black hole")

QCD:

coloured quarks and gluons are confined to restricted region of space, colourless from the outside ("colour singlet")

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

But gravitation → strong interaction: $Gm^2 \rightarrow \alpha_s$, hence

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

if $\alpha_s \simeq 2 - 3$.

Hadron radius ∼ "strong" Schwarzschild radius

Hadrons ∼ "strong" black holes
coloured inside, colourless outside

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Hadron radius $\sim$ "strong" Schwarzschild radius

Hadrons $\sim$ "strong" black holes
coloured inside, colourless outside

More generally:

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

Black hole: event horizon for all interactions

Strong black hole: event horizon 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]

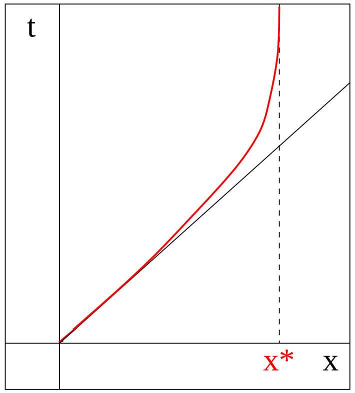
$$\tilde{x} = [1 - \sqrt{1 - v_0\tilde{t} + \tilde{t}^2}]\ ,\ \tilde{x} = x/x_0\ ,\ \tilde{t} = t/x_0$$

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**

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



$q\bar{q}$ **can separate arbitrarily far**
if $\sqrt{s}$ **is large enough**

What's wrong?

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

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

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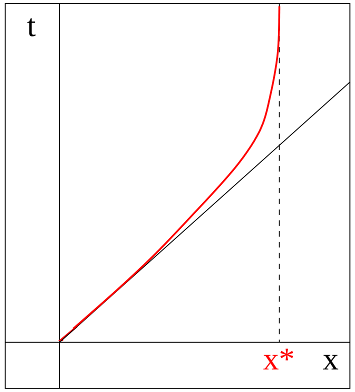
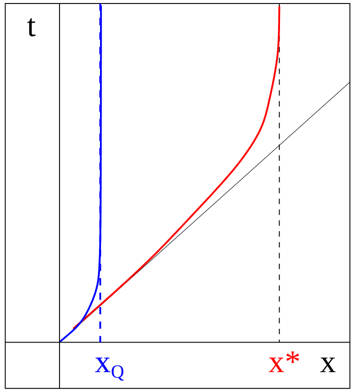


What's wrong?

classical event horizon

Strong field ⇒ vacuum unstable
against pair production [Schwinger 1951]

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

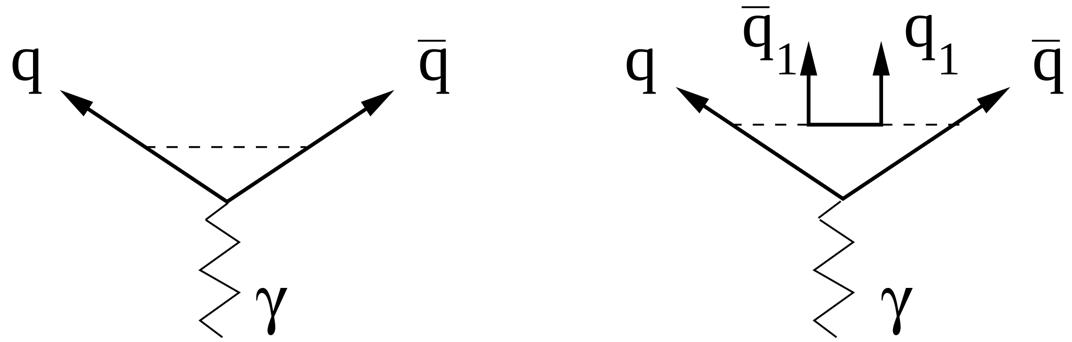


Result:

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

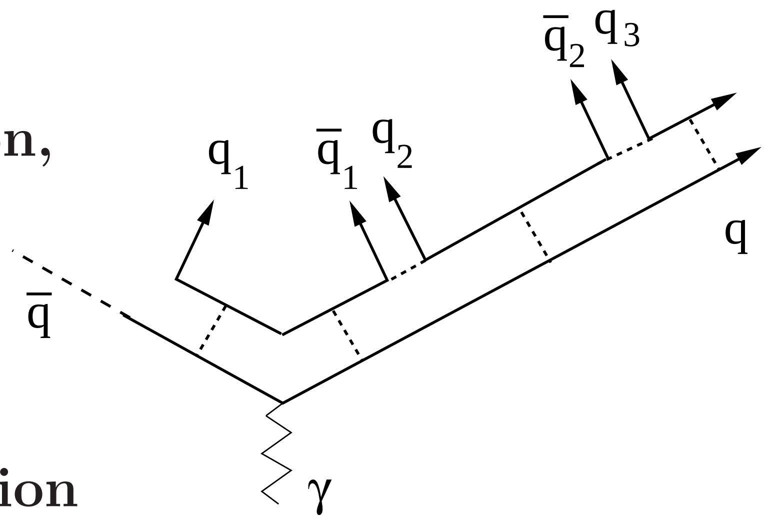
$$x_q \simeq \frac{2}{\sigma}\sqrt{m^2 + (\pi\sigma/2)} \simeq \sqrt{2\pi/\sigma} \simeq 1 \text{ fm}$$

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

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

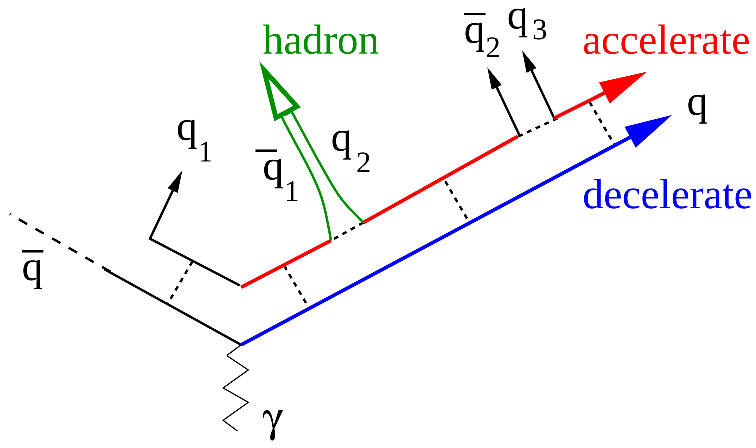
equivalent:
$\bar{q}_1$ reaches $q_1\bar{q}_1$ event horizon,
tunnels to become $\bar{q}_2$

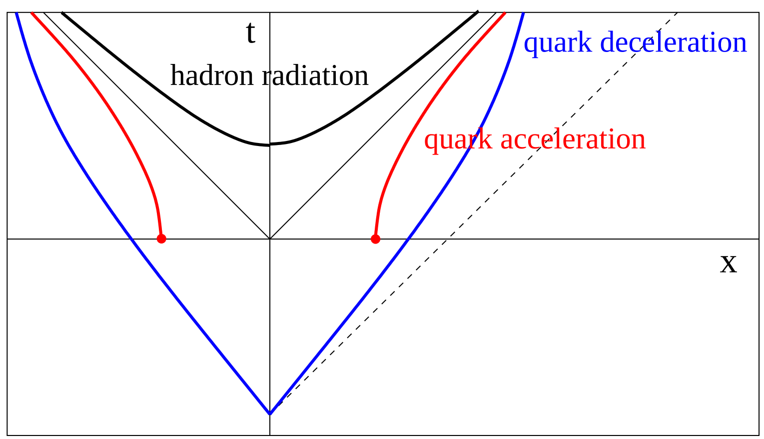
emission of hadron $\bar{q}_1 q_2$
as Hawking radiation



self-similar pattern:

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





temperature of Hawking radiation: what acceleration?

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

$$a = F/m \;\Rightarrow\; a_q = \frac{\sigma}{w_q} = \frac{\sigma}{\sqrt{m_q^2 + k_q^2}}$$

string breaking & thickness determine $k_q \simeq \sqrt{\pi\sigma/2}$

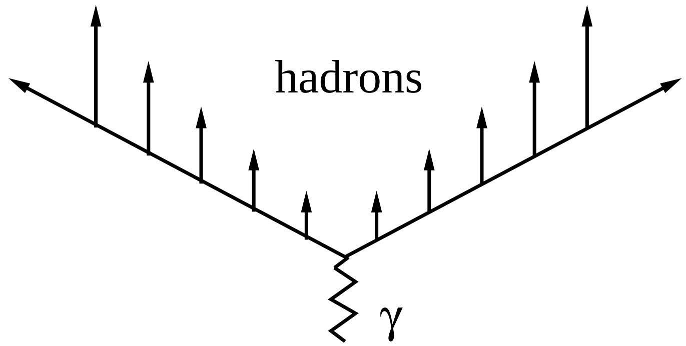
$$\Rightarrow \quad a_q \simeq \frac{\sigma}{\sqrt{m_q^2 + (\sigma/2\pi)}}$$

for light quarks, $m_q \ll \sqrt{\sigma} \simeq 420$ MeV, hence

$$\boxed{T = \frac{a}{2\pi} \simeq \sqrt{\frac{\sigma}{2\pi}} \simeq 170 \text{ MeV}}$$

temperature of hadronic Hawking-Unruh radiation in QCD hadronization pattern:

hadron multiplicity?



thickness of classical "overstretched" string:

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

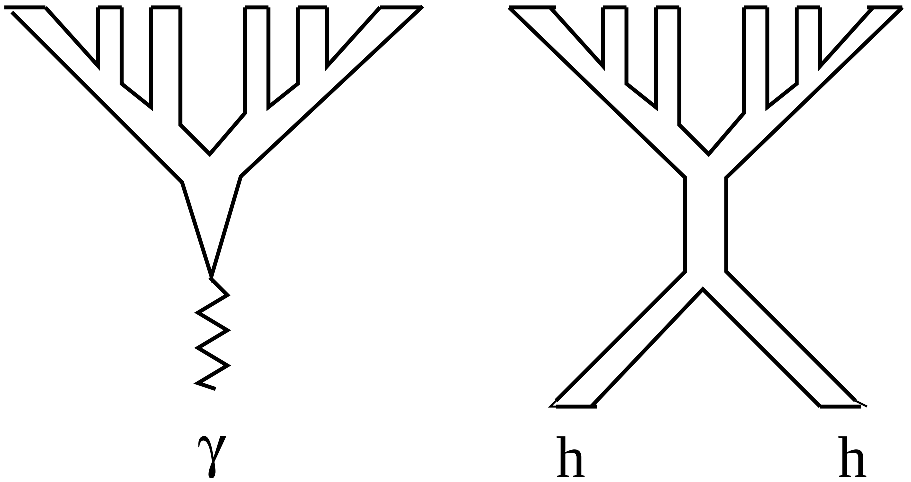
quantum breaking at $x_q \sim r_T$, hence hadron multiplicity

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

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

generalize:

e^+e^- annihilation	**hadron-hadron collision**
“black hole” creation	**“black hole” fusion**



both → self-similar cascades

Heavy ion collisions: interference between emitted hadrons

4. Strangeness Production

[Becattini, Castorina, Manninen, HS 2008]

Unruh temperature $\sim$ 1 / mass of secondary; e.g. :

spontaneous production in strong field $\mathcal{E}$ (Schwinger)

$$P(m.\mathcal{E}) \sim \exp\{-\pi m^2/e\mathcal{E}\}, \quad a = \frac{e\mathcal{E}}{m}$$

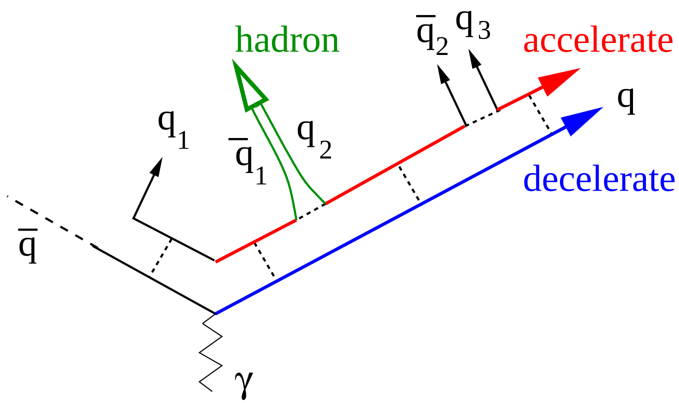
so that

$$P(m,\mathcal{E}) \sim \exp\{-m/T_U\}, \quad T_U = \frac{a_e}{2\pi} = \frac{e\mathcal{E}}{2\pi m}$$

we had for finite quark mass m_q

$$a_q \simeq \frac{\sigma}{\sqrt{m_q^2 + (\sigma/2\pi)}}$$

produced meson consists
of quarks $\bar{q}_1$ and q_2



meson containing two
different quark masses
will have average acceleration

$$\bar{a}_{12} = \frac{w_1 a_1 + w_2 a_2}{w_1 + w_2} = \frac{2\sigma}{w_1 + w_2}; \quad w_i \simeq \sqrt{m_i^2 + (\sigma/2\pi)}$$

leading to

$$T(12) \simeq \frac{a_{12}}{2\pi}$$

easily extended to baryons; result: five temperatures

$$T(00) = T(000);\ T(s0);\ T(ss) = T(sss);\ T(00s);\ T(0ss)$$

fully determined by σ and m_s

for $\sigma \simeq 0.17$ GeV^2 and $m_s \simeq 0.08$ GeV

obtain temperatures:

T	[GeV]
$T(00)$	0.164
$T(0s)$	0.156
$T(ss)$	0.148
$T(000)$	0.164
$T(00s)$	0.158
$T(0ss)$	0.153
$T(sss)$	0.148

does this work?

analyse all existing high energy e^+e^- data

hadron production data in e^+e^- annhilation exist at

$$\sqrt{s} = 14,\ \ 22,\ \ 29,\ \ 35,\ \ 43, 91, 180 \text{ GeV}$$

(PETRA, PEP, LEP)

example:

long-lived hadrons produced at LEP for $\sqrt{s} = 91.25$ GeV fit data in terms of σ and m_s

result:

$\sigma = 0.169 \pm 0.002$ GeV^2

$m_s = 0.083$ GeV

$\chi^2/\mathrm{dof} = 22/12$

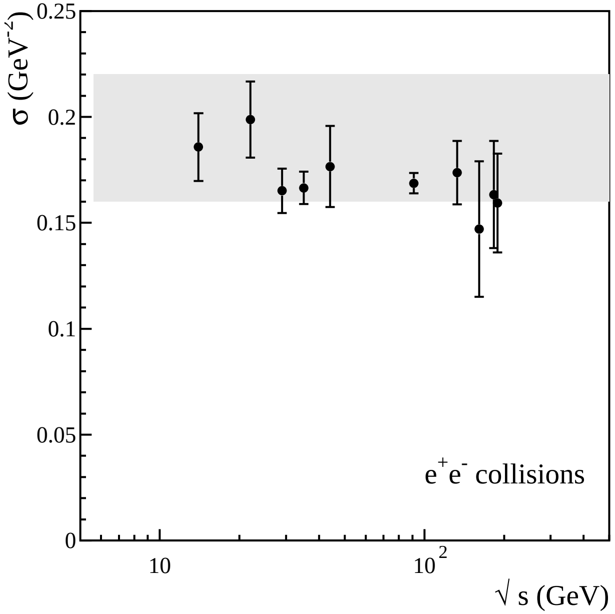
standard values:

$\sigma = 0.195 \pm 0.030$ GeV^2

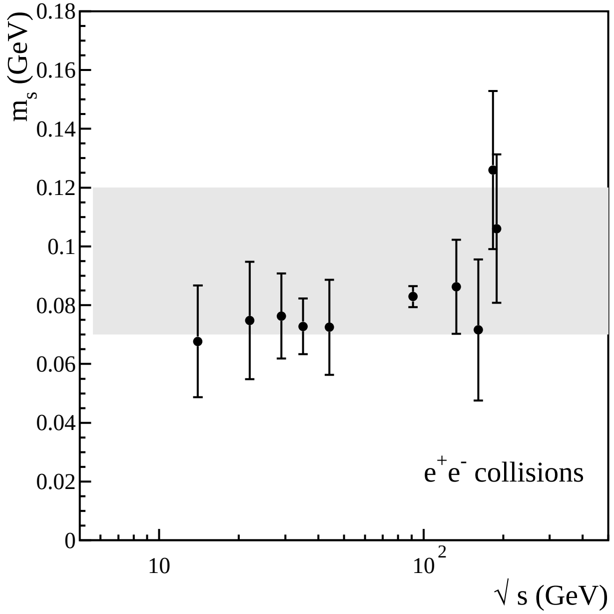
$m_s = 0.095 \pm 0.025$ GeV

perform analyses for all data

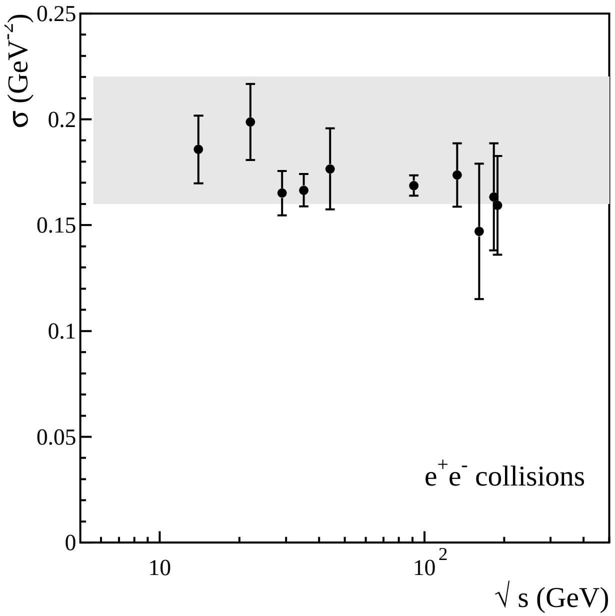
e^+e^- $\sqrt{s} = 91.2$ GeV				
species	measured			fit
π^+	8.50	$\pm$	0.10	8.44
π^0	9.61	$\pm$	0.29	9.81
K^+	1.127	$\pm$	0.026	1.055
K^0	1.038	$\pm$	0.001	1.015
η	1.059	$\pm$	0.996	0.910
ω	1.024	$\pm$	0.059	0.996
p	0.519	$\pm$	0.018	0.570
η'	0.166	$\pm$	0.047	0.108
ϕ	0.0977	$\pm$	0.0058	0.1164
Λ	0.1943	$\pm$	0.0038	0.1846
Σ^+	0.0535	$\pm$	0.0052	0.0428
Σ^0	0.0389	$\pm$	0.0041	0.0435
Σ^-	0.0410	$\pm$	0.0037	0.0390
Ξ^-	0.01319	$\pm$	0.0005	0.0126
Ω	0.00062	$\pm$	0.0001	0.0009

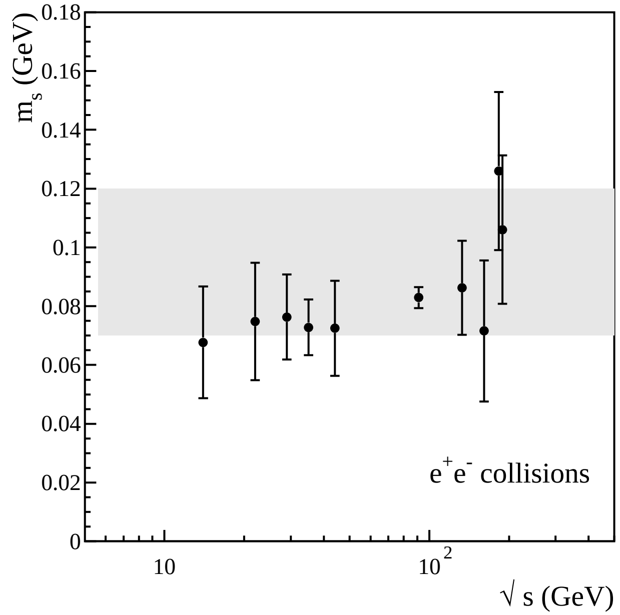


σ (GeV⁻²)
0.25
0.2
0.15
0.1
0.05
0
10
10²
√ s (GeV)
e⁺e⁻ collisions



m_s (GeV)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10
10²
√ s (GeV)
e⁺e⁻ collisions





Conclude

thermal hadron production in e^+e^- annihilation, includ'g strangeness suppression, is reproduced parameter-free as Hawking-Unruh radiation of QCD

$\Rightarrow$ $pp/p\bar{p}$ (straight-forward); heavy ions (interesting)

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:**

$\Rightarrow$ <u>Ergodic Equivalence Principle</u> $\Leftarrow$

gravitation $\sim$ acceleration **kinetic $\sim$ stochastic**

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- The corresponding hadronization temperature T_H is determined by quark acceleration and deceleration in the colour field at the (quantum) horizon.
- Strangeness suppression is provided by the modification of the Unruh temperature due to the strange quark mass.
- Given string tension σ and strange quark mass m_s, the resulting scenario provides a parameter-free description of thermal hadron production in elementary high energy interactions.

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

Stephen Hawking