16.8.13

# Hadrosynthesis and Quark Confinement

**Helmut Satz**

**Universität Bielefeld, Germany**

**Kolymbari, Crete** **August 28, 2013**

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) $\sqrt{s}$

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) $\sqrt{s}$

caveats

- strangeness suppression in elementary collisions
- strangeness suppression weakened/removed in nuclear collisions

## 1. Thermal Hadron Production

what is "thermal"?

- equal *a priori* probabilities for all states in accord with 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 $\phi(m_i, T) = 4\pi m_i^2 T K_2(m_i/T) \sim \epsilon^{-m_i/T}$;

- relative abundances $\dfrac{N_i}{N_j} = \dfrac{d_i \phi(m_i, T)}{d_j \phi(m_j, T)} \sim \epsilon^{-(m_i - m_j)/T}$

predicted in terms of temperature $T$

## 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 $\gamma_s$

$T = 169.9 \pm 2.6$ MeV

$\gamma_s = 0.691 \pm 0.053$

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

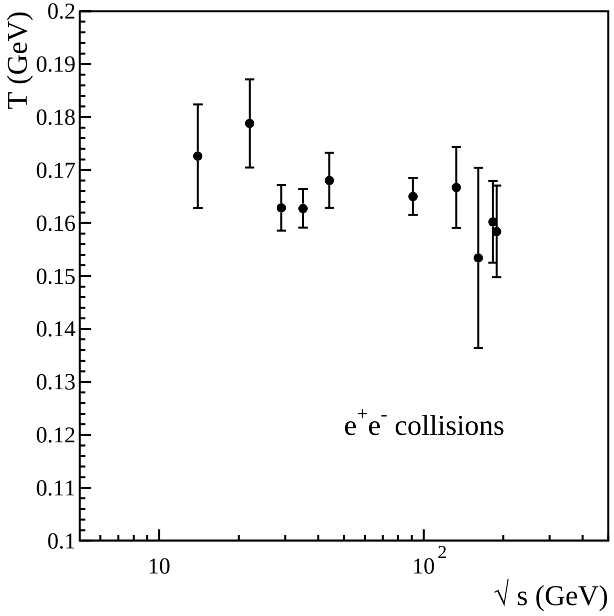
estimate systematic error by varying resonance gas scheme, contributing resonances

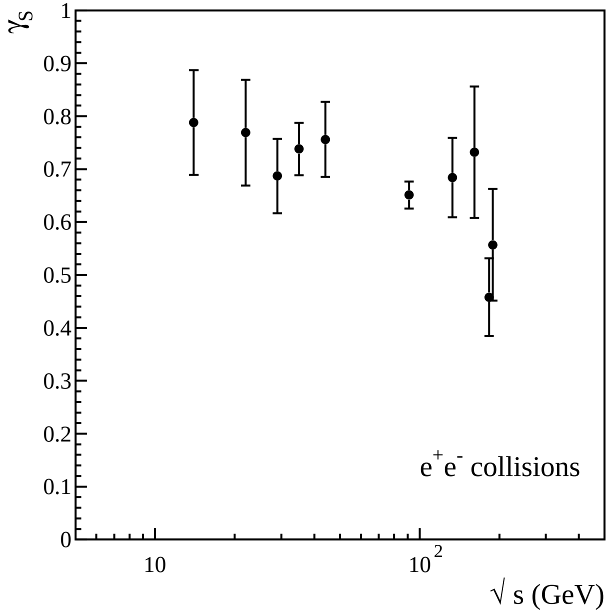
| $e^+e^-$ $\sqrt{s} = 91.2$ *GeV* | | | | |
|---|---|---|---|---|
| species | measured | | | fit |
| $\pi^+$ | 8.53 | $\pm$ | 0.40 | 8.72 |
| $\pi^0$ | 9.18 | $\pm$ | 0.82 | 9.83 |
| $K^+$ | 1.18 | $\pm$ | 0.052 | 1.06 |
| $K^0$ | 1.015 | $\pm$ | 0.022 | 1.01 |
| $\eta$ | 0.934 | $\pm$ | 0.13 | 0.908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

$$T = 170 \pm 10 \text{ MeV}, \ \gamma_s \simeq 0.7 \pm 0.1$$

similar analyses carried out for $e^+e^-$ at [Becattini et al., 2008]

$$\sqrt{s} = 14,\ 22,\ 29,\ 35,\ 43,\ 133,\ 161,\ 183\ \text{GeV}$$




$$T = 170 \pm 15\ \text{MeV},\ \gamma_s \simeq 0.7 \pm 0.15$$

**corresponding analyses for hadronic collisions**

- $pp$ at $\sqrt{s} = 19.4,\ 23.8,\ 26.0,\ 27.4$ GeV
- $p\bar{p}$ at $\sqrt{s} = 200,\ 500,\ 900$ GeV
- $\pi^+ p$ at $\sqrt{s} = 21.7$ GeV
- $K^+ p$ at $\sqrt{s} = 11.5,\ 21.7$ GeV

corresponding analyses for hadronic collisions

- $pp$ at $\sqrt{s} = 19.4,\ 23.8,\ 26.0,\ 27.4$ GeV
- $p\bar{p}$ at $\sqrt{s} = 200,\ 500,\ 900$ GeV
- $\pi^+ p$ at $\sqrt{s} = 21.7$ GeV
- $K^+ p$ at $\sqrt{s} = 11.5,\ 21.7$ GeV

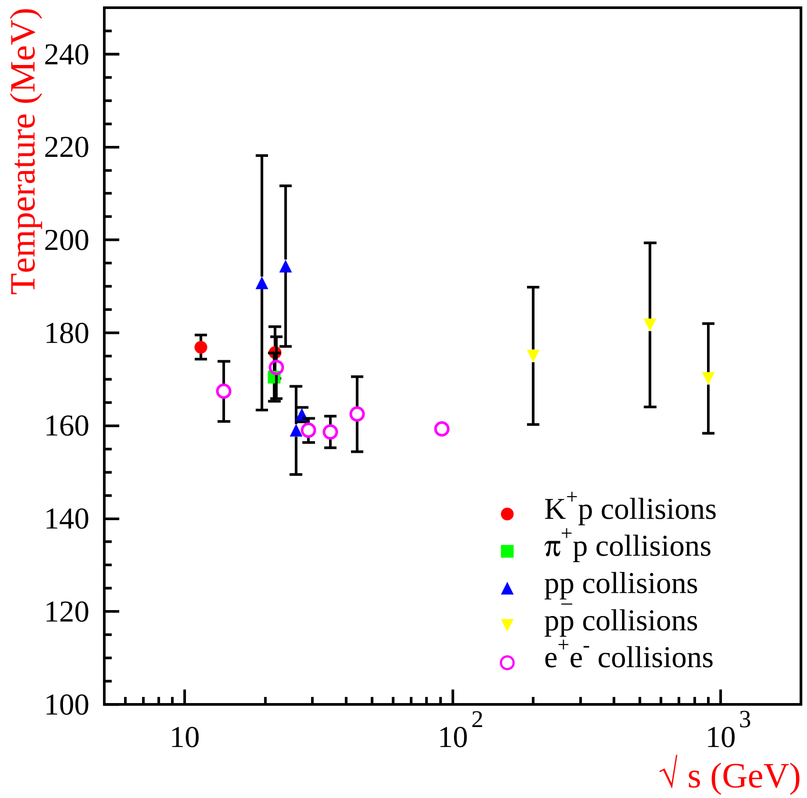
compilation Becattini 2006

Result:

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

$$\gamma_s \simeq 0.7 \pm 0.2 \text{ MeV}$$

independent of
- collision energy
- collision configuration



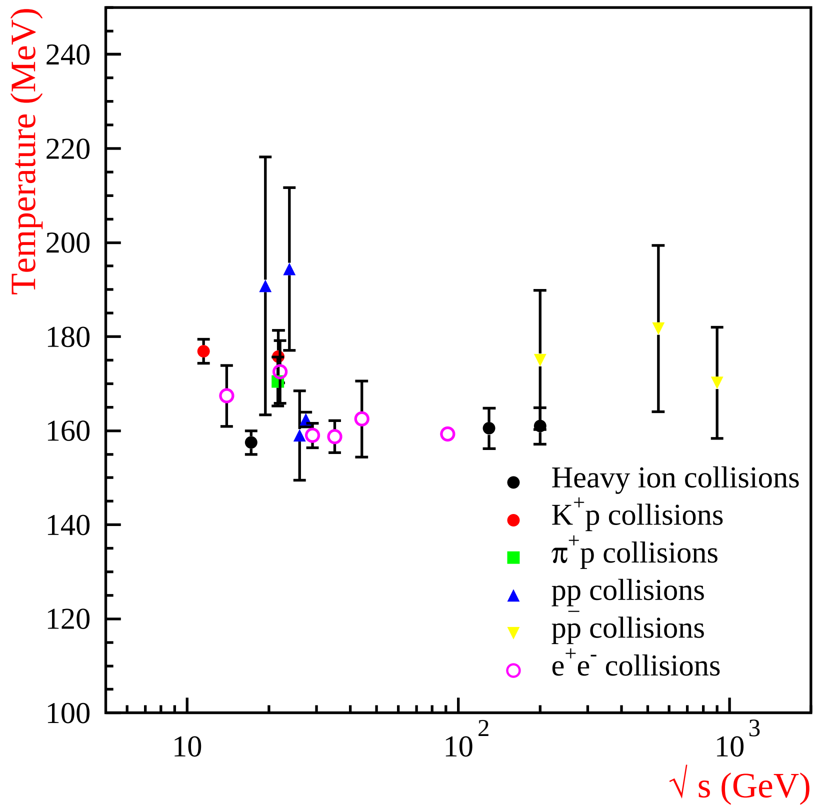
## Heavy ion collisions $\Rightarrow$ baryon density

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

# Heavy ion collisions ⇒ baryon density

- resonance gas at $T$, $\mu_B$;   $\mu_B \Downarrow$ for $\sqrt{s} \Uparrow$
- consider 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,
collision energy independent

<u>increased strangeness</u>
$\gamma_s \longrightarrow 0.8 - 1.0$ for high
energy heavy ion collisions

## 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**

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

**Strangeness production in elementary collisions is uniformly suppressed by $\gamma_s \simeq 0.6 - 0.7$**

**suppression weakened/removed in heavy ion collisions**

## 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**

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

**Strangeness production in elementary collisions is uniformly suppressed by $\gamma_s \simeq 0.6 - 0.7$**

**suppression weakened/removed in heavy ion collisions**

**WHY?**

- **Why do elementary high energy collisions produce a thermal medium?**

  **For nucleus-nucleus collisions possibly multiple parton interactions $\longrightarrow$ kinetic thermalization; $e^+e^-$, $pp/p\bar{p}$ not**

- **Is there another non-kinetic thermalization mechanism, providing a common origin of thermal production in all high energy collisions?**

- **Why is strangeness production universally suppressed in elementary collisions?**

- **Why no strangeness suppression in nuclear collisions?**

- **Why do elementary high energy collisions produce a thermal medium?**

  **For nucleus-nucleus collisions possibly multiple parton interactions $\longrightarrow$ kinetic thermalization; $e^+e^-$, $pp/p\bar{p}$ not**

- **Is there another non-kinetic thermalization mechanism, providing a common origin of thermal production in all high energy collisions?**

- **Why is strangeness production universally suppressed in elementary collisions?**

- **Why no strangeness suppression in nuclear collisions?**

**Conjecture:**

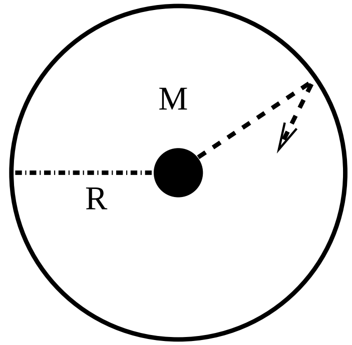
**physical vacuum $\sim$ event horizon for colored constituents**
**thermal hadron production $\sim$ Hawking-Unruh radiation of QCD**

[Paolo Castorina, Dmitri Kharzeev, HS 2007]

# 2. Black Holes and Event Horizons

- <u>black hole</u>

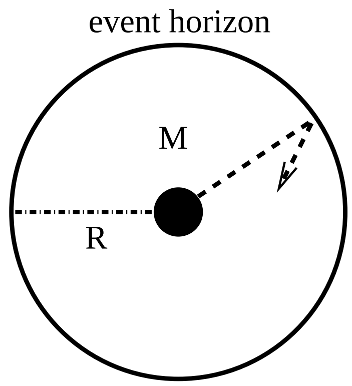
  neutron star after gravitational collaps
  large mass $M$ and compact size
  gravitation so strong that matter &
  light are confined $\Rightarrow$ event horizon $R$
  no communication with outside, but...



## 2. Black Holes and Event Horizons

- **black hole**

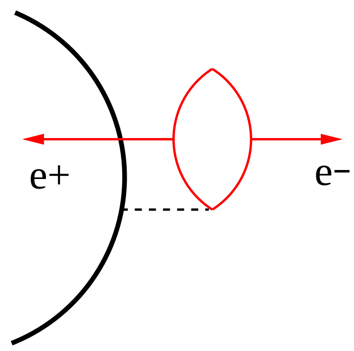
neutron star after gravitational collaps
large mass $M$ and compact size
gravitation so strong that matter &
light are confined $\Rightarrow$ event horizon $R$
no communication with outside, but...




- **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 $\Delta t$, $e^+$ 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

$\Rightarrow$ Hawking radiation must be thermal

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

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

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

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

- <u>Quantum Causality</u>

  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 $\quad T_{BH} = \frac{\hbar}{8\pi c GM}$

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

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

- <u>Unruh relation</u> [Unruh 1976]

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

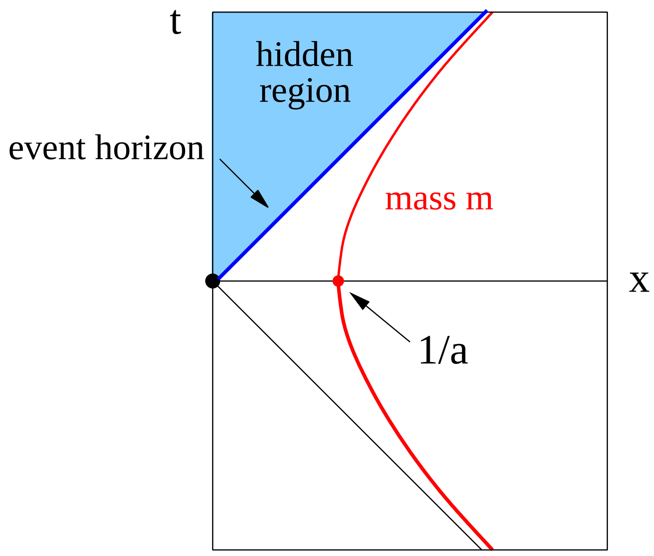
$$\frac{d}{dt}\frac{mv}{\sqrt{1-v^2}} = F$$

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

solution: hyperbolic motion

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

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

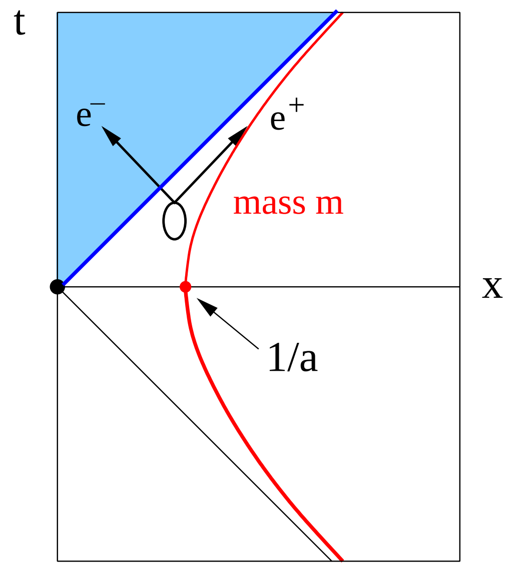



$\exists$ event horizon: $m$ cannot reach hidden region
observer in hidden region cannot communicate with $m$

$m$ 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 $m$ & observer in hidden region have incomplete information: $\Rightarrow$ each sees thermal radiation of

Unruh temperature $$T_U = \frac{\hbar a}{2\pi c} = \frac{\hbar F}{2m\pi c}$$

Applications:

- for $F = GMm/R^2$ and Schwarzschild $R = 2M$ recover Hawking temperature

$$T_U = \frac{a}{2\pi} = \frac{GM}{R^2} = \frac{1}{8\pi GM}$$

- for $F = e\mathcal{E}$ recover Schwinger mechanism for production of pair (mass $m$) in strong field $\mathcal{E}$

$$T_U = \frac{a}{2\pi} = \frac{e\mathcal{E}}{\pi m}$$

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

production probability $P(m, \mathcal{E})$

# 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]

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

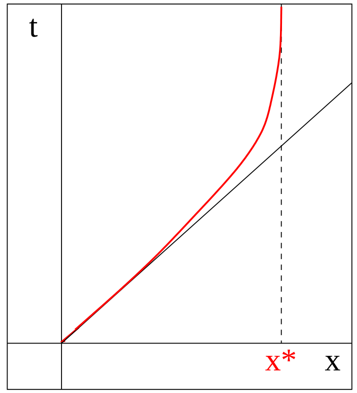
with $$x_0 = \frac{m}{\sigma}\frac{1}{\sqrt{1 - v_0^2}} = \frac{m}{\sigma}\,\gamma = \frac{1}{a}\,\gamma$$

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

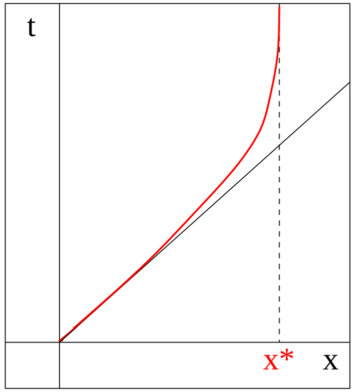
What's wrong?



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

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

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

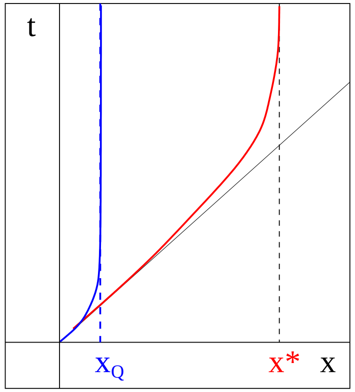



What's wrong?

classical 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

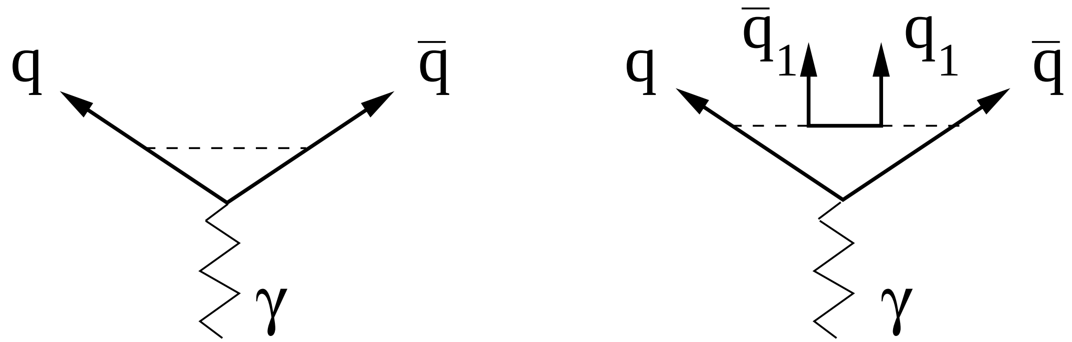



Result:

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

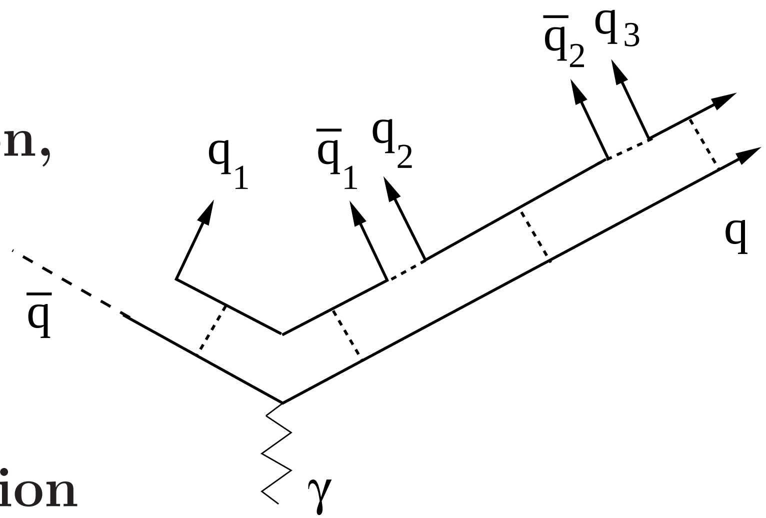
$$x_q \simeq \frac{2}{\sigma}\sqrt{m^2 + (\pi\sigma/2)} \simeq \sqrt{2\pi/\sigma} \simeq 1 \text{ fm}$$

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

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

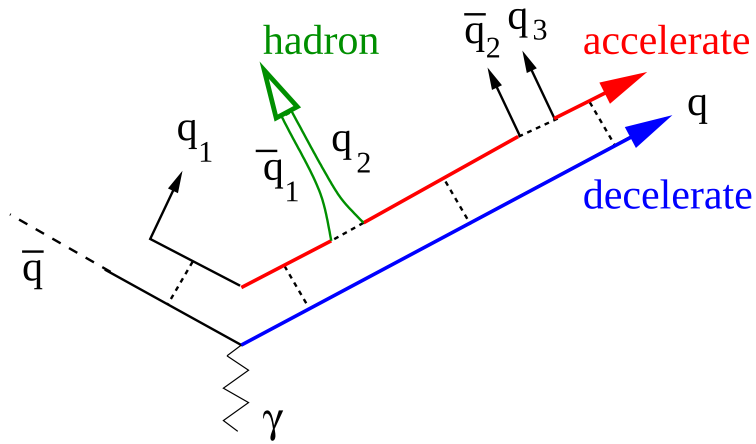
equivalent:
$\bar{q}_1$ reaches $q_1\bar{q}_1$ event horizon,
tunnels to become $\bar{q}_2$

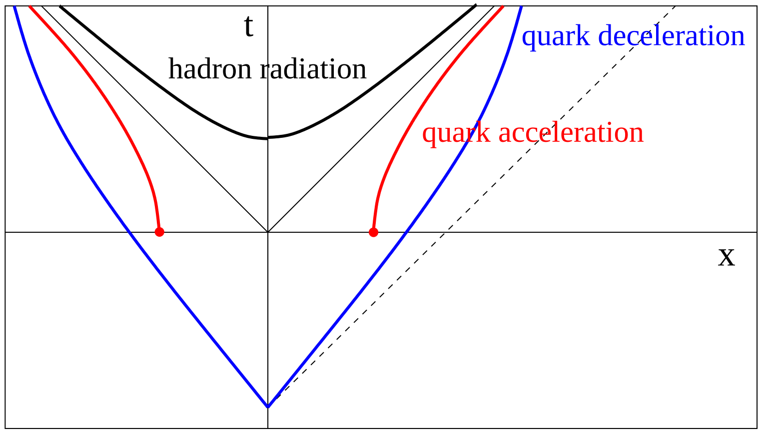
emission of hadron $\bar{q}_1 q_2$
as Hawking radiation



**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

# 4. Strangeness Production

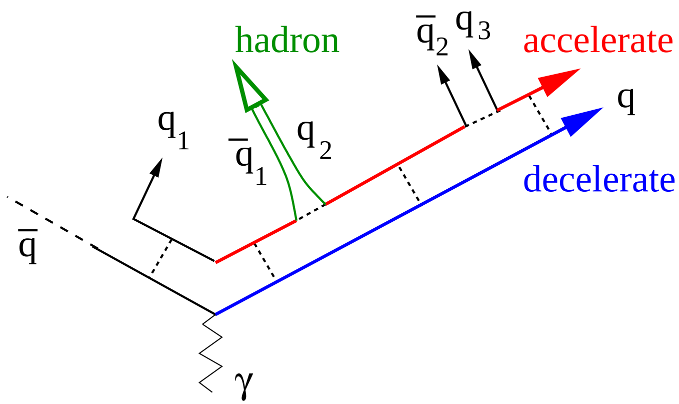
[Becattini, Castorina, Manninen, HS 2008]

Unruh temperature $\sim$ 1 / mass of secondary

we had for finite quark mass $m_q$

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

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 $\sigma$ 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 $\sigma$ and $m_s$

result:

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

$m_s = 0.083$ GeV

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

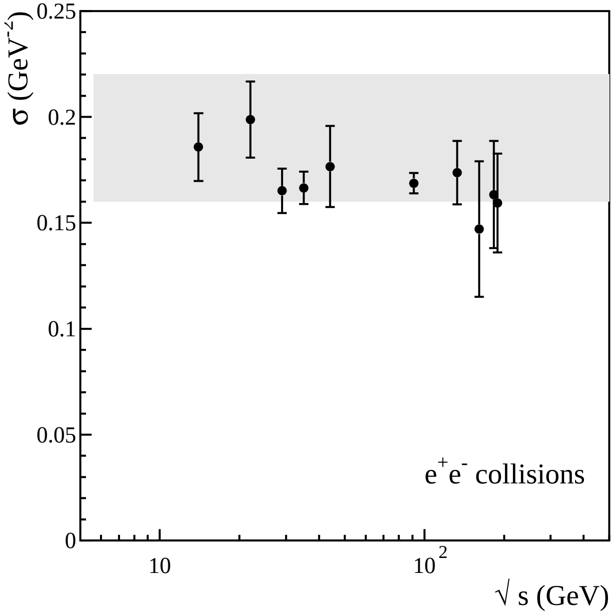
standard values:

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

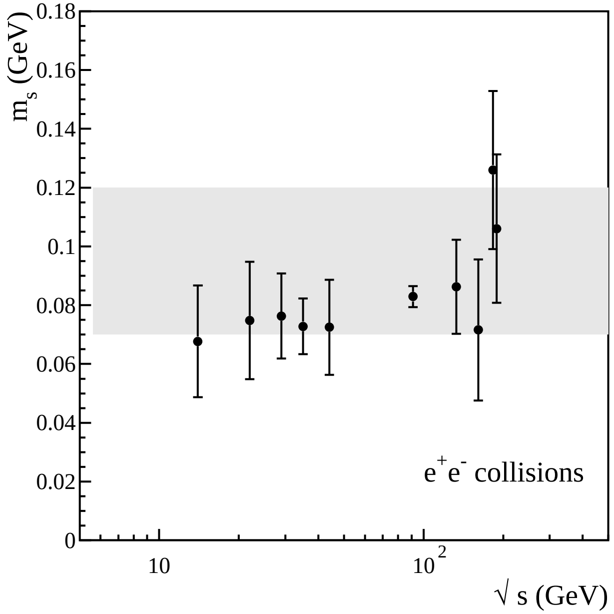
$m_s = 0.095 \pm 0.025$ GeV

perform analyses for all data

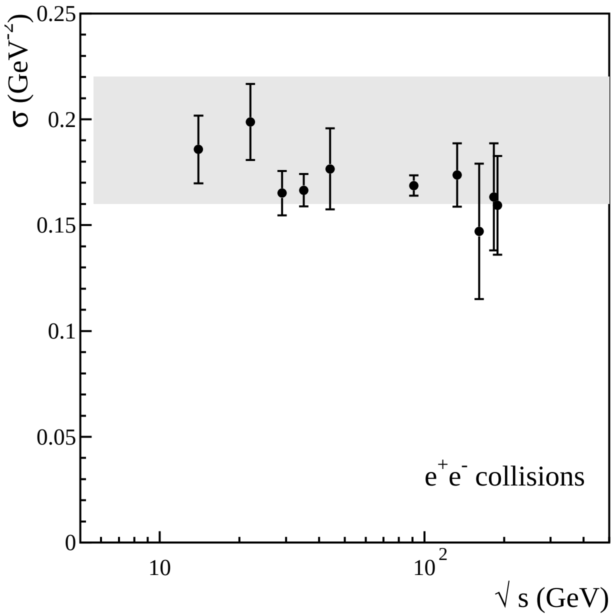
| $e^+e^-$ $\sqrt{s} = 91.2$ $GeV$ | | | | |
|---|---|---|---|---|
| species | measured | | | fit |
| $\pi^+$ | 8.50 | $\pm$ | 0.10 | 8.30 |
| $\pi^0$ | 9.61 | $\pm$ | 0.29 | 9.67 |
| $K^+$ | 1.127 | $\pm$ | 0.026 | 1.089 |
| $K^0$ | 1.038 | $\pm$ | 0.001 | 1.049 |
| $\eta$ | 1.059 | $\pm$ | 0.996 | 0.910 |
| $\omega$ | 1.024 | $\pm$ | 0.059 | 0.971 |
| $p$ | 0.519 | $\pm$ | 0.018 | 0.557 |
| $\eta'$ | 0.166 | $\pm$ | 0.047 | 0.096 |
| $\phi$ | 0.0977 | $\pm$ | 0.0058 | 0.1060 |
| $\Lambda$ | 0.1943 | $\pm$ | 0.0038 | 0.1891 |
| $\Sigma^+$ | 0.0535 | $\pm$ | 0.0052 | 0.0437 |
| $\Sigma^0$ | 0.0389 | $\pm$ | 0.0041 | 0.0444 |
| $\Sigma^-$ | 0.0410 | $\pm$ | 0.0037 | 0.0400 |
| $\Xi^-$ | 0.01319 | $\pm$ | 0.0005 | 0.01269 |
| $\Omega$ | 0.00062 | $\pm$ | 0.0001 | 0.00077 |

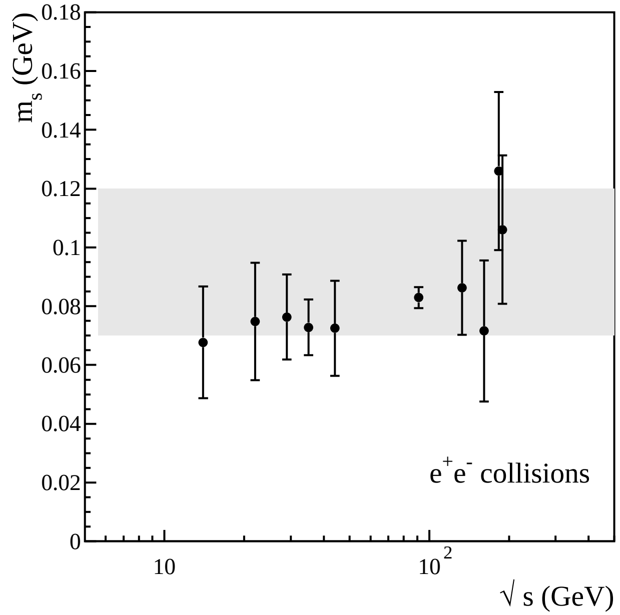


σ (GeV⁻²)
0.25
0.2
0.15
0.1
0.05
0
10
10²
√ s (GeV)
e⁺e⁻ collisions

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)**

## Heavy Ions

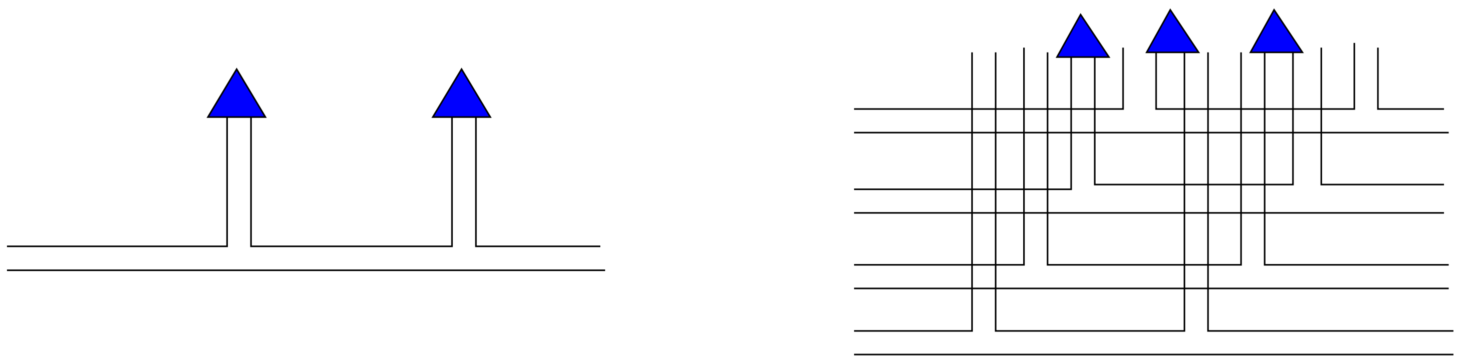
- elementary collisions

  sequential $q\bar{q}$ pair production $\Rightarrow$ independent hadron emission

- nuclear collisions

  superposition of $q\bar{q}$ pair production,

  interference, averaging



elementary nuclear

result: average temperature determined by averaged quark acceleration

$$\bar{a} = \frac{N_q w_q a_q + N_s w_s a_s}{N_q w_q + N_s w_s} = \left(\frac{\sigma}{w_q}\right) \frac{N_q + N_s}{N_q + N_s (w_s / w_q)} \simeq 0.97\ a_q$$

all hadrons acquire average temperature

$$T = \frac{\bar{a}}{2\pi} \simeq 160 \text{ MeV}$$

strangeness suppression removed

in high energy nuclear collisions

## 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**

## 6. Summary

- **The physical vacuum is an event horizon for coloured quarks and gluons; thermal hadrons are Hawking-Unruh radiation produced by quark tunnelling through event horizon.**

## 6. Summary

- **The physical vacuum is an event horizon for coloured quarks and gluons; thermal hadrons are Hawking-Unruh radiation produced by quark tunnelling through event horizon.**

- **The corresponding hadronization temperature $T_H$ is determined by quark acceleration and deceleration in the colour field at the (quantum) horizon.**

## 6. Summary

- The physical vacuum is an event horizon for coloured quarks and gluons; thermal hadrons are Hawking-Unruh radiation produced by quark tunnelling through event horizon.

- The corresponding hadronization temperature $T_H$ is determined by quark acceleration and deceleration in the colour field at the (quantum) horizon.

- Strangeness suppression arises through modified Unruh temperature for strange quark mass. In nuclear collisions, it is effectively removed by averaging.

## 6. Summary

- The physical vacuum is an event horizon for coloured quarks and gluons; thermal hadrons are Hawking-Unruh radiation produced by quark tunnelling through event horizon.

- The corresponding hadronization temperature $T_H$ is determined by quark acceleration and deceleration in the colour field at the (quantum) horizon.

- Strangeness suppression arises through modified Unruh temperature for strange quark mass. In nuclear collisions, it is effectively removed by averaging.

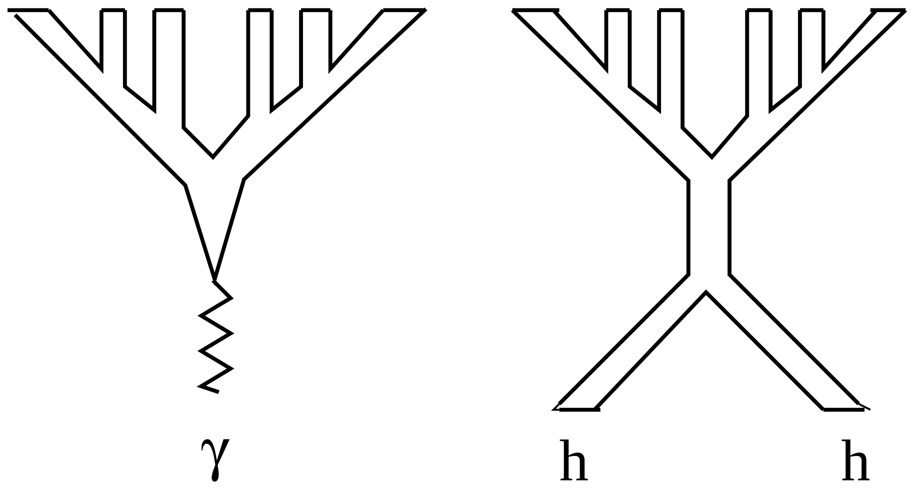
- Given string tension $\sigma$ and strange quark mass $m_s$, the resulting scenario provides a parameter-free description of thermal hadron production in all high energy interactions.

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

**Stephen Hawking**

**generalize:**

| | |
|---|---|
| **$e^+e^-$ annihilation** | **hadron-hadron collision** |
| **"black hole" creation** | **"black hole" fusion** |




**both → self-similar cascades**

**Heavy ion collisions: interference between emitted hadrons**