Event horizon in high energy hadroproduction

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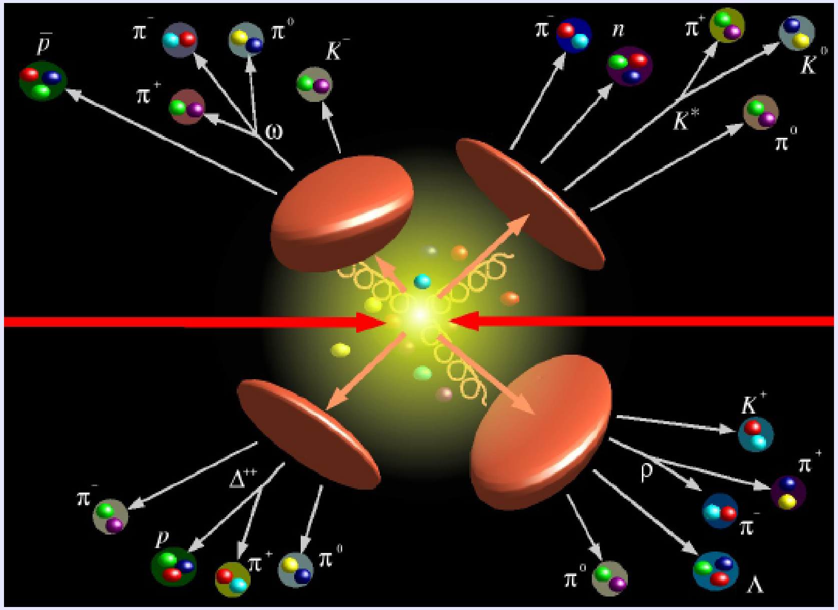
DUBNA

Phenomenological approach

- Thermal hadron production: open questions
- Event horizon and thermal spectrum
- Unruh effect
- Color event horizon and hadronization
- Answering a là Unruh to the open questions
- Conclusions

In modern view, the statistical model is a model of hadronization, describing the process of hadron formation at the scale where QCD is no longer perturbative



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 $T_H \simeq 165 \pm 15 Mev$ for all (large) $\sqrt{s}$

caveats

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

F. Becattini, Z. Phys. C69 (1996) 485.

F. Becattini, *Universality of thermal hadron production in pp, $p\bar{p}$ and e^+e^- collisions*, in *Universality features in multihadron production and the leading effect*, Erice 1966, World Scientific, Singapore (1998) 74-104; arXiv:hep-ph/9701275.

F. Becattini and G. Passaleva, Eur. Phys. J. C23 (2002) 551.

F. Becattini and U. Heinz, Z. Phys. C76 (1997) 268.

J. Cleymans et al., Phys. Lett. B 242 (1990) 111.

J. Cleymans and H. Satz, Z. Phys. C57 (1993) 135.

K. Redlich et al., Nucl. Phys. A 566 (1994) 391.

P. Braun-Munzinger et al., Phys. Lett. B344 (1995) 43.

F. Becattini, M. Gazdzicki and J. Sollfrank, Eur. Phys. J. C5 (1998) 143.

F. Becattini et al., Phys. Rev. C64 (2001) 024901.

P. Braun-Munzinger, K. Redlich and J. Stachel, in *Quark-Gluon Plasma 3*, Hwa and X.-N Wang (Eds.), World Scientific, Singapore 2003.

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

Particles and resonaces of PDG up to 2 Gev

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

$\gamma_s = 0.691 \pm 0.053$

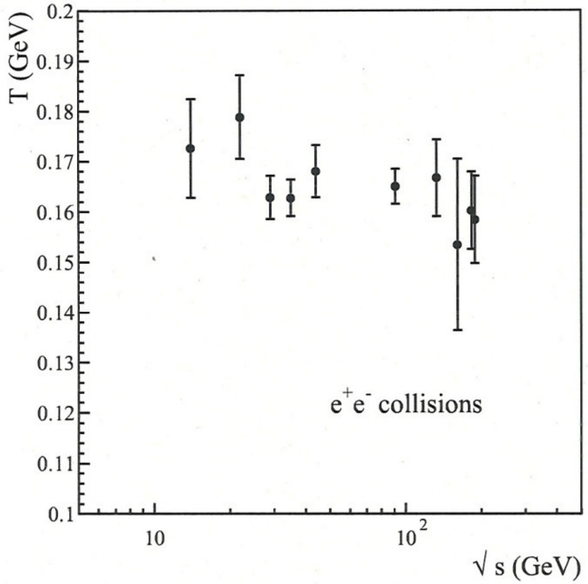
estimate systematic error by varying resonance gas scheme, contributing resonances

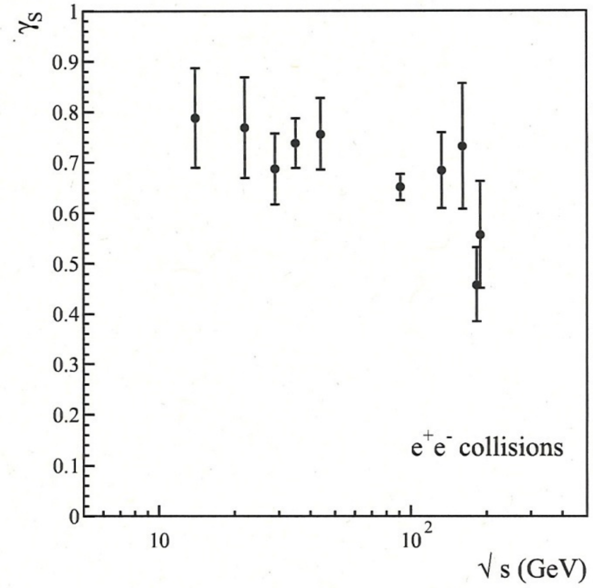
e^+e^- $\sqrt{s} = 91.2$ GeV				
species	measured			fit
π^+	8.53	$\pm$	0.40	8.72
π^0	9.18	$\pm$	0.82	9.83
K^+	1.18	$\pm$	0.052	1.06
K^0	1.015	$\pm$	0.022	1.01
η	0.934	$\pm$	0.13	0.908
ρ^0	1.21	$\pm$	0.22	1.16
K^{*+}	0.357	$\pm$	0.027	0.349
K^{*0}	0.372	$\pm$	0.027	0.343
η'	0.13	$\pm$	0.05	0.1070
p	0.488	$\pm$	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

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

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

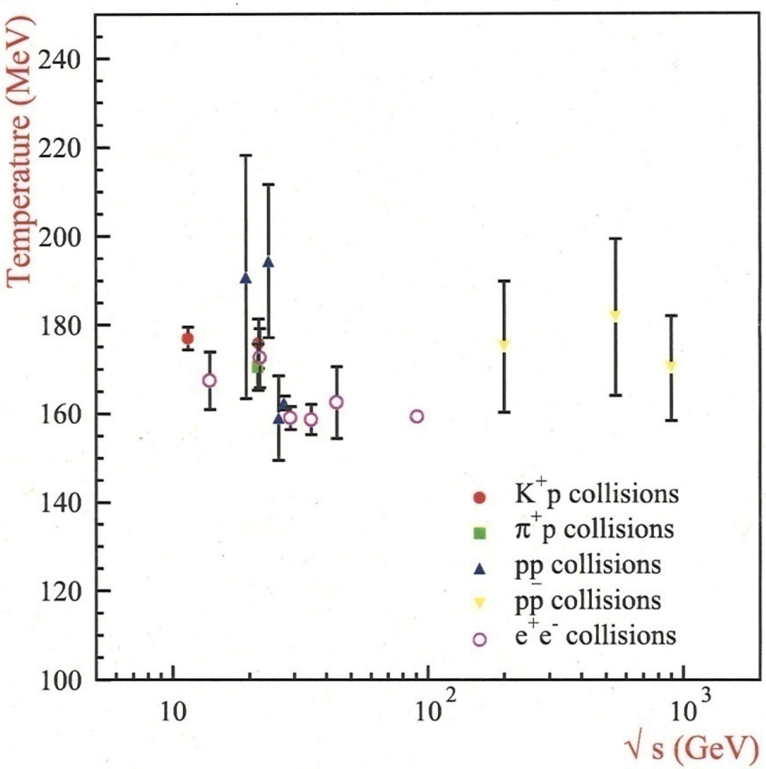
compilation **Becattini 2006**

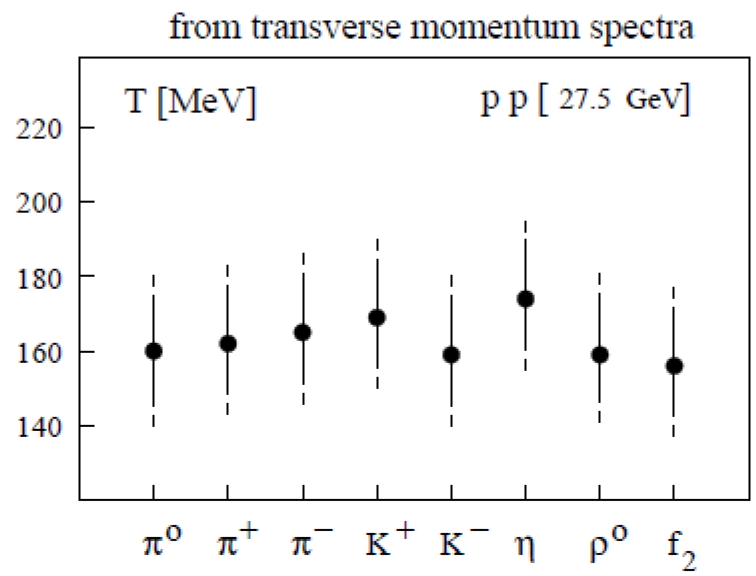
Result:

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

$$\gamma_s \simeq 0.7 \pm 0.2$$

independent of
- collision energy
- collision configuration





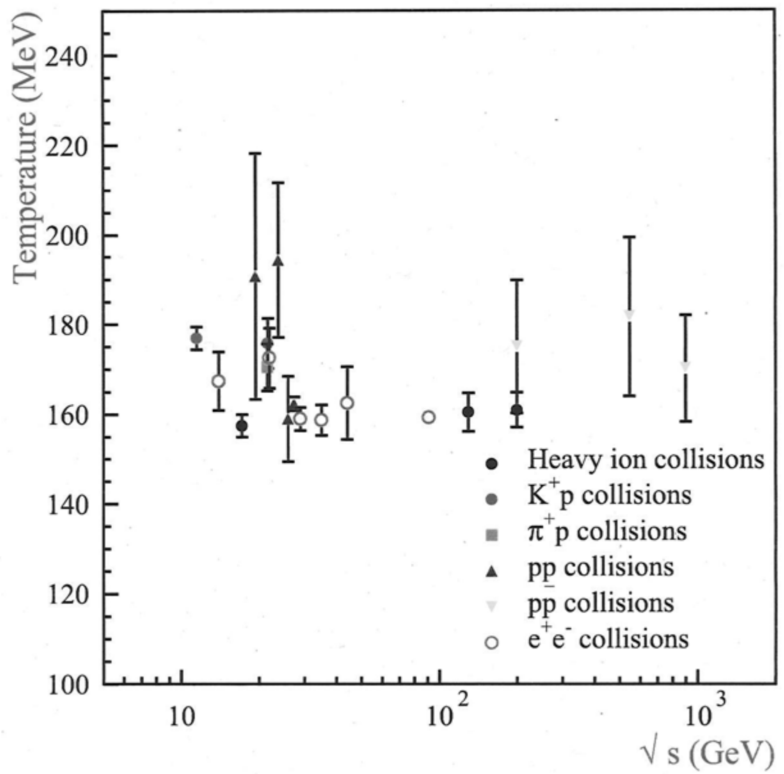
pp at $\sqrt{s} = 27.4$ GeV:

average $T = 163$ MeV

Heavy ion collisions ⇒ baryon density

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

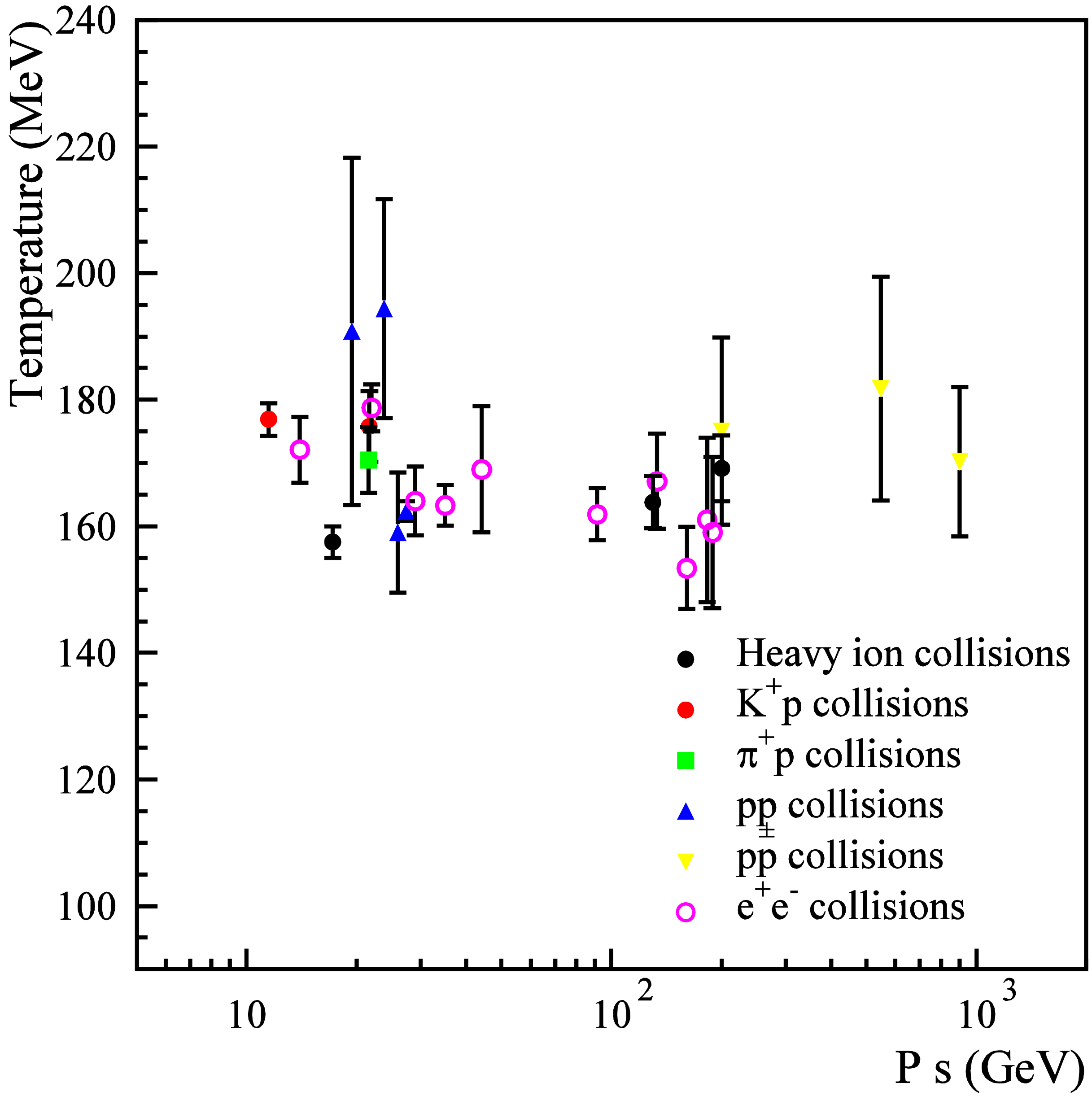
compilation Becattini 2006



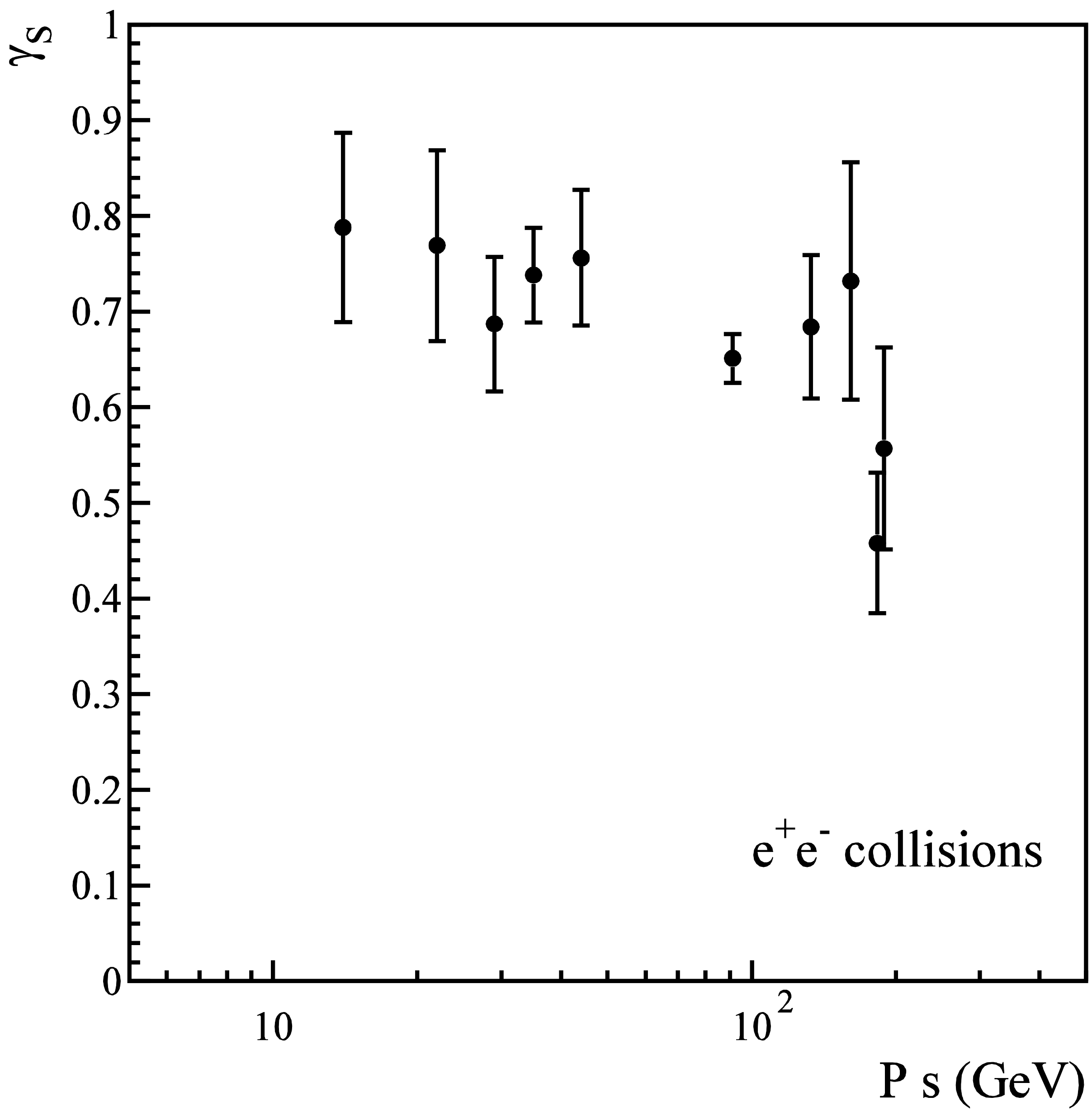
Result:

same hadronization temperature for high energy heavy ion and elementary collisions, collision energy independent

increased strangeness $\gamma_s \to 0.8 - 1.0$ for high energy heavy ion collisions



Temperature (MeV)
240
220
200
180
160
140
120
100
10
10^2
10^3
P s (GeV)
Heavy ion collisions
K+p collisions
π+p collisions
pp collisions
p̄p collisions
e+e- collisions



γ_S
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
10^2
P s (GeV)
e^+e^- 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 $\gamma_s \simeq 0.6 - 0.7$

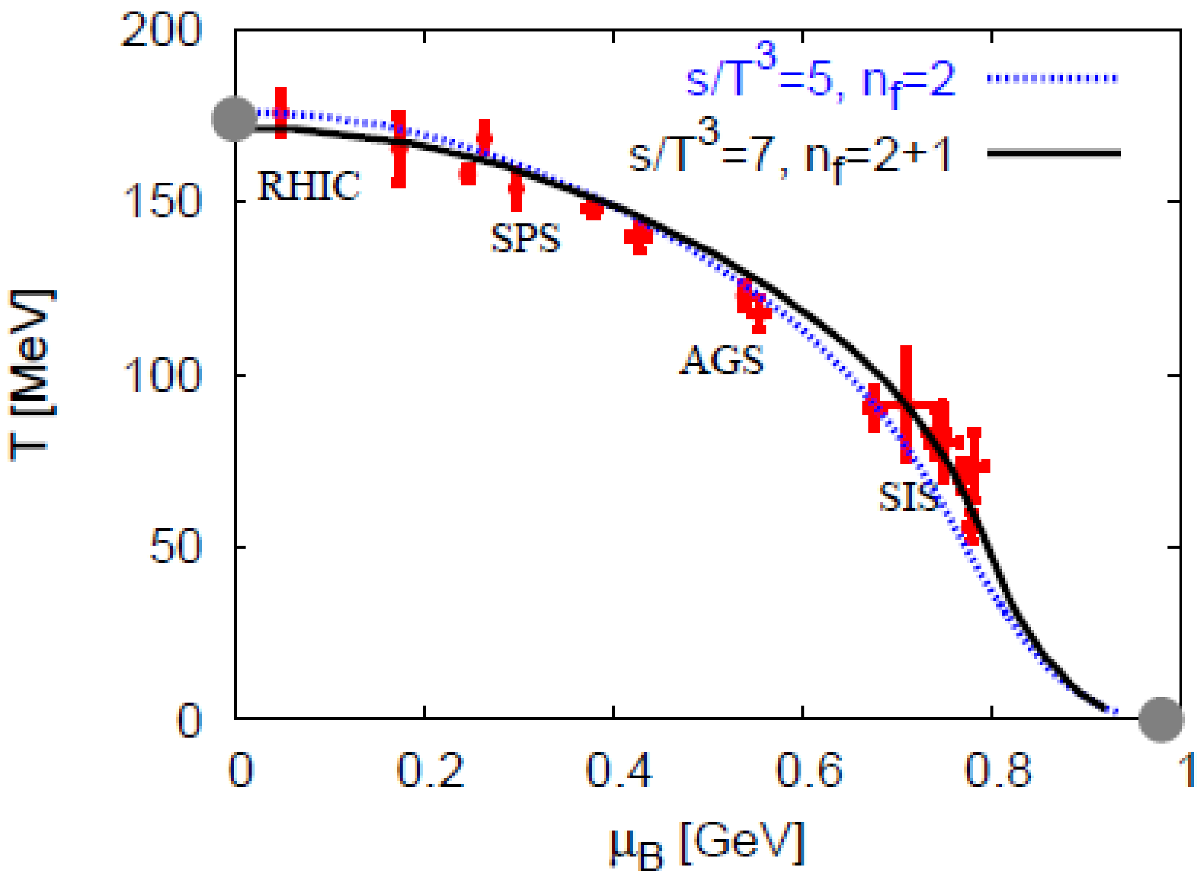
suppression weakened/removed in heavy ion collisions

WHY?

Freeze-out

s/T^3 = 7

Chemical freeze-out
The point where particle abundances freeze



J. Cleymans and K. Redlich, Phys. Rev. Lett. 81 (1998) 5284.

J. Cleymans and K. Redlich, Phys. Rev. C 61 (1999) 054908.

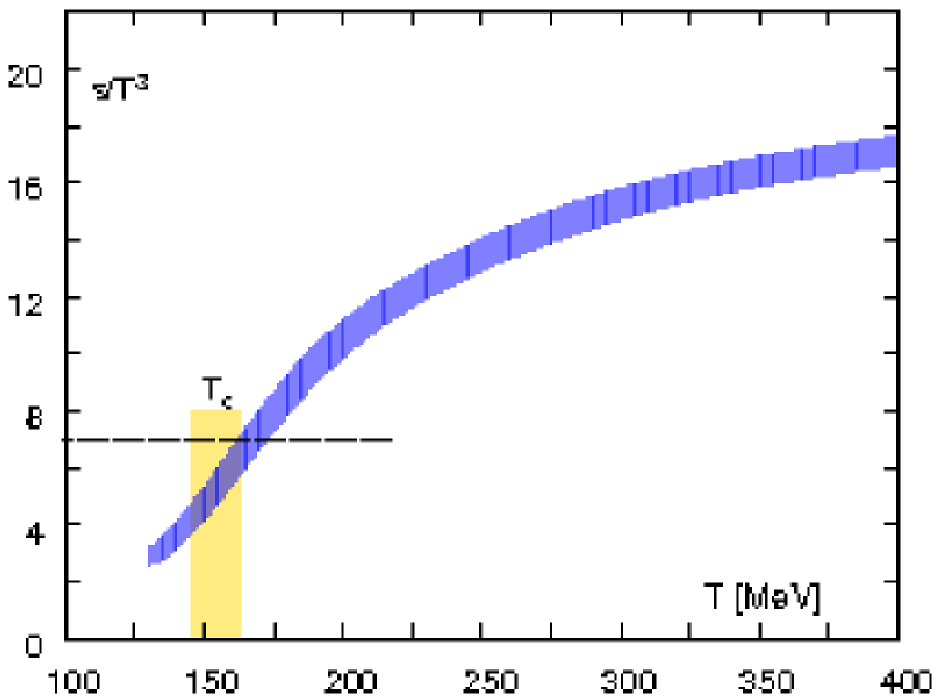
J. Cleymans et al., arXiv:hep-ph/0511094

P. Braun-Munzinger and J. Stachel, J. Phys. G 28 (2002) 1971.

V. Magas and H. Satz, Eur. Phys. J. C32 (2003) 115.

J. Cleymans et al., Phys. Lett. B 615 (2005) 50.

A. Tawfik, J. Phys. G 31 (2005) S1105; hep-ph/0507252 and hep-ph/050824.

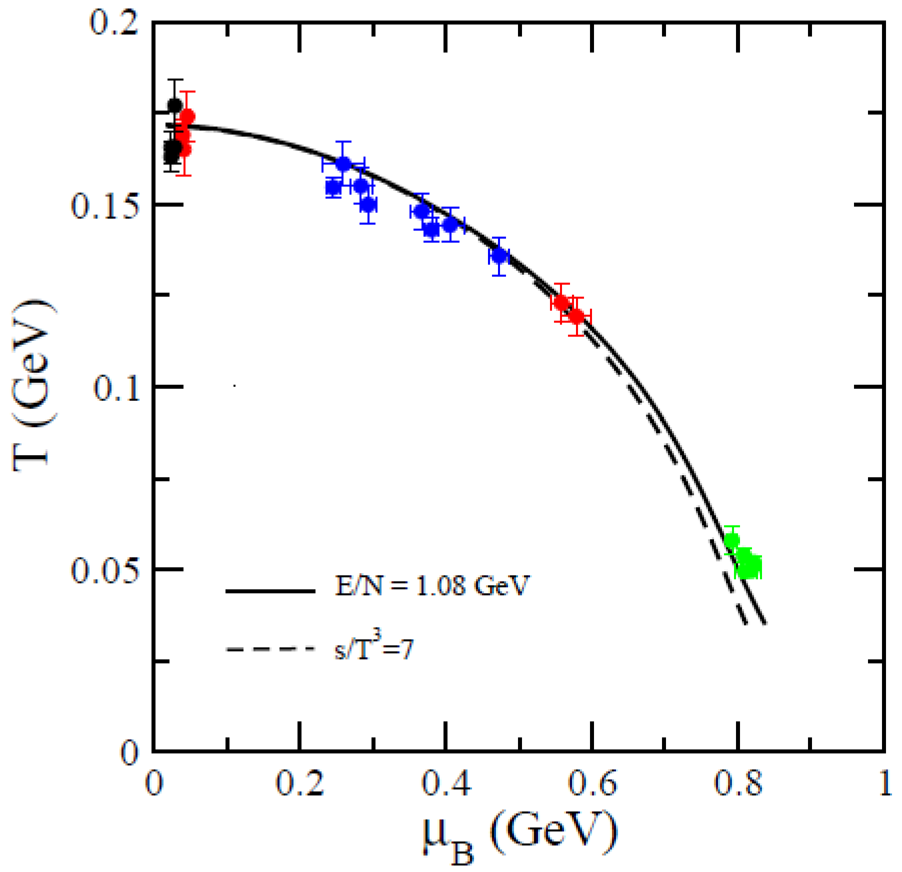


Lattice results for s/T^3 as function of the temperature

A. Bazazov et al. (HotQCD Collaboration), arXiv:1407.6387

At zero baryon density

Freeze-out
E/N = 1.08 Gev



WHY ?

Questions

1) ***Why do elementary high energy collisions***
show a statistical behavior?

2) ***Why is strangeness production universally suppressed***
in elementary collisions?

3) ***Why (almost) no strangeness suppression in nuclear collisions?***

4) ***Why hadron freeze-out for s/T^3 = 7 or E/N=1.08 Gev***

5) ***Why thermalization in so short time (0.5- 1 fm/c)***

Is there another non-kinetic mechanism providing a common origin of the statistical features?

Conjecture

Physical vacuum ⟷ **Event horizon for colored constituents**

↓

Thermal hadron production ⟷ **Hawking-Unruh radiation in QCD**

P.C., D.Kharzeev and H.Satz -- D.Kharzeev and Y.Tuchin (temperature)

Eur.Phys.J. C52 (2007) 187-201 **Nucl. Phys. A 753, 316 (2005)**

F.Becattini, P.C., J.Manninen and H.Satz (strangeness suppression in e+e-)

Eur.Phys.J. C56 (2008) 493-510

P.C. and H.Satz (strangeness enhancement in heavy ion collisions)

Adv.High Energy Phys. 2014 (2014) 376982

P.C., A. Iorio and H.Satz (entropy and freeze-out)

arXiv:1409.3104

Recall

$\Rightarrow$ Hawking radiation

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

with black hole temperature

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

relativistic quantum effect: disappears for

$\hbar \longrightarrow 0$ or $c \longrightarrow \infty$

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

ALMOST

M. K. Parikh and F. Wilczek, “Hawking radiation as tunneling,” Phys. Rev. Lett. 85 (2000) 5042

- Unruh relation [Unruh 1976]

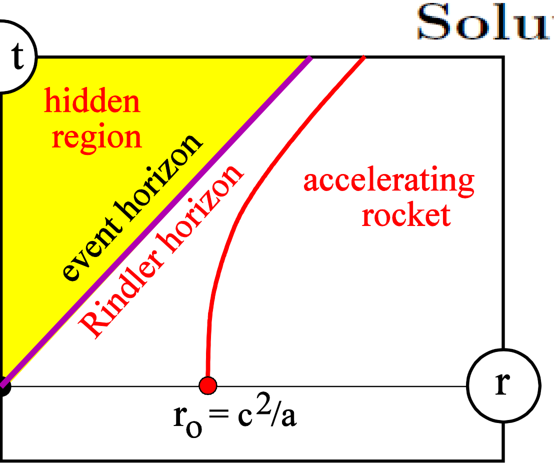
Event horizon arises for systems in uniform acceleration. For a mass m in uniform acceleration a

Rindler observer

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

where $v = dx/dt$, $F = ma$,

Solution: hyperbolic motion



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

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

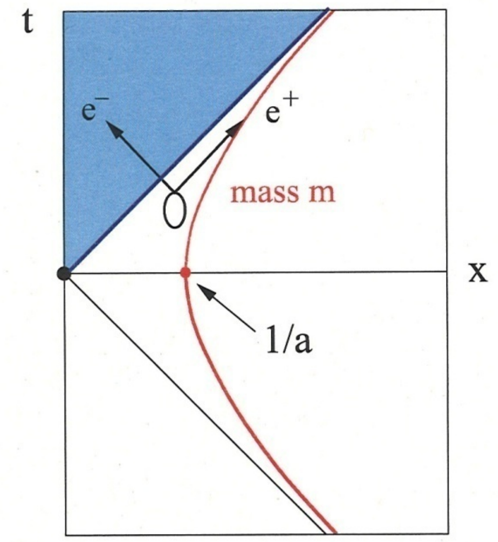
arXiv:0710.5373

The Unruh effect and its applications

Luis C. B. Crispino, Atsushi Higuchi, George E. A. Matsa

e^+ absorbed in detector on m

e^- disappears beyond event horizon



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

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

Unruh radiation via WKB method
D.A.Singleton http.//dx.doi.org.10.5772/53898

Hawking Radiation as Quantum Tunneling in Rindler Coordinate, Kim arXive 0710.0915

In QFT

Using the path-integral formulation of quantum field theory, an accelerated observer sees a thermal spectrum to a large class of interacting field theories

The n-point Green functions for an accelerated observer are exactly the same of the n-point Green functions of a Minkowski observer at temperature

$$T = \frac{a}{2\pi}$$

Acceleration radiation in interacting field theories

Phys. Rev. D **29**, 1656 (1984)

William G. Unruh and Nathan Weiss

arXiv:0710.5373

The Unruh effect and its applications

Luis C. B. Crispino, Atsushi Higuchi, George E. A. Matsa

Applications (elementary implementation)

Applications:

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

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

- 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 $P(m, \mathcal{E})$

R. Parentani, S. Massar . **Phys.Rev. D55 (1997) 3603-3613**

THE SCHWINGER MECHANISM, THE UNRUH EFFECT AND THE PRODUCTION OF ACCELERATED BLACK HOLES

R. Brout, R. Parentani, and Ph. Spindel, "Thermal properties of pairs produced by an electric field: A tunneling approach," Nucl. Phys. B 353 (1991) 209.

The correspondence with gravity

Unruh effect and the near horizon approximation

Rindler metric of an accelerated observer
(in spherical coordinates τ, χ, θ, ϕ)

$$ds^2 = \chi^2 a^2 d\tau^2 - d\chi^2 - \chi^2 cosh^2 a\tau (d\theta^2 + sin^2\theta d\phi^2)$$

Schwarzchild BH metric ; $\gamma = (1 - 2GM/r)$

$$ds^2 = \gamma dt^2 - \gamma^{-1} dr^2 - r^2 (d\theta^2 + sin^2\theta d\phi^2)$$

Coordinate transformation $\eta = \sqrt{\gamma}/k$,
where k = surface gravity and $r \to R = 2GM$

$$ds^2 = \eta^2 k^2 dt^2 - d\eta^2 - R^2 (d\theta^2 + sin^2\theta d\phi^2)$$

Uniform acceleration

↓

Event Horizon

↓

Universal thermal behavior

↓

In QCD ?

Confinement $V \rightarrow \sigma r$

Rindler force at large distances

D.Grumiller PRL105(2010)211303,
D.Grumiller and F.Preis ,arxiv 1107.2373

Rindler force at large distances in gravity?

effective field theory

Diffeomorphism invariance, spherical symmetry,local validity of Newton's law

$$g_{\alpha\beta}\, \mathrm{d}x^\alpha\, \mathrm{d}x^\beta = -K^2\, \mathrm{d}t^2 + \frac{\mathrm{d}r^2}{K^2}$$

$$K^2 = 1 - \frac{2M}{r} - \Lambda r^2 + 2ar$$

$$V^{\text{eff}} = -\frac{M}{r} + \frac{\ell^2}{2r^2} - \frac{M\ell^2}{r^3} - \frac{\Lambda r^2}{2} + ar\left(1 + \frac{\ell^2}{r^2}\right)$$

$$V^{QCD} = -\frac{\alpha_s}{r} + \sigma r$$

Effective Geometry in YM theories

- Electrodynamics in a non linear medium $\longrightarrow$ effective curved geometry

$L_{eff}(F)$, $F = F_{\mu\nu}F^{\mu\nu}$.

The low energy photons of a non linear electrodynamics do not propagate on the null cones of the flat metric but on the null cones on an effective metric generated by the self-interaction of the e.m. field

($' = d/dF$, $\eta_{\mu\nu}$ flat metric, Novello and Perez Bergliaffa 2003)

$$g_{\mu\nu} = \eta_{\mu\nu}L' - 4F_{\alpha\mu}F^{\alpha}_{\nu}L''$$

Analogue black holes for light rays in static dielectrics arXiv:1401.7544 Bittencourt et al.

• QCD **in vacuum** is non linear

$$L_{eff} = -\frac{1}{4}\frac{g^2}{g^2(g\sqrt{F})}F^a_{\mu\nu}F^{\mu\nu}_a$$

Abelian Configuration

Define $\bar{g} = g(g\sqrt{F})$, $\beta' = d\beta(\bar{g})/d\bar{g}$

$g_{\mu\nu} = \eta_{\mu\nu}[1 - \beta(\bar{g})/\bar{g}]+$

$4\beta(\bar{g})/\bar{g}[1 - \frac{5}{2}\beta(\bar{g})/\bar{g} + \frac{1}{2}\beta']F_{\alpha\mu}F^{\alpha}_{\nu}/F$

If $\beta < 0$ in the IR region, there are configuration with $B > E$ such that g_{oo} change sign.

QCD - Uniform acceleration $V \to \sigma r$

Pair Production and String Breaking

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

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

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

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

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

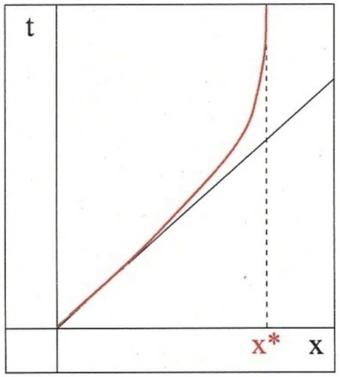
$$\tilde{x} = [1 - \sqrt{1 - v_0\tilde{t} + \tilde{t}^2}] \ , \ \tilde{x} = x/x_0 \ , \ \tilde{t} = t/x_0$$

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

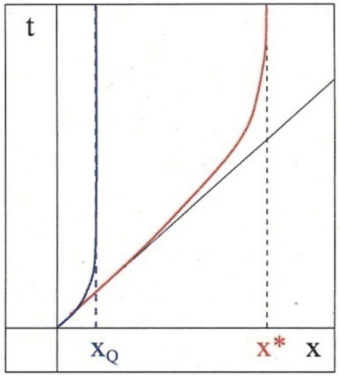


What's wrong?

classical 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

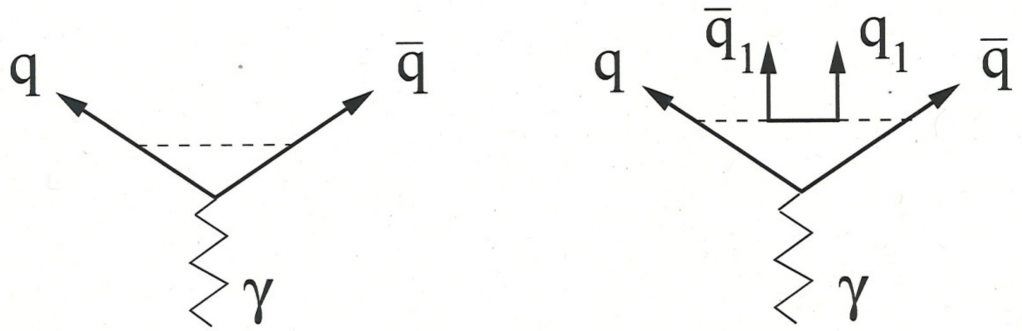


Result:

quantum event horizon

Hadron production in e^+e^- annihilation:

"inside-outside cascade" [Bjorken 1976]



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

M. Luscher, G. Munster and P. Weisz, Nucl. Phys. B180 (198

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

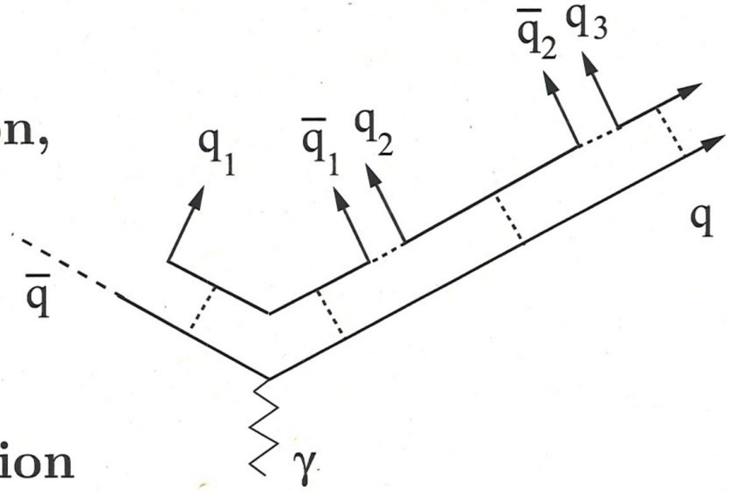
q_1 screens $\bar{q}$ from q, hence string breaking at

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

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

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

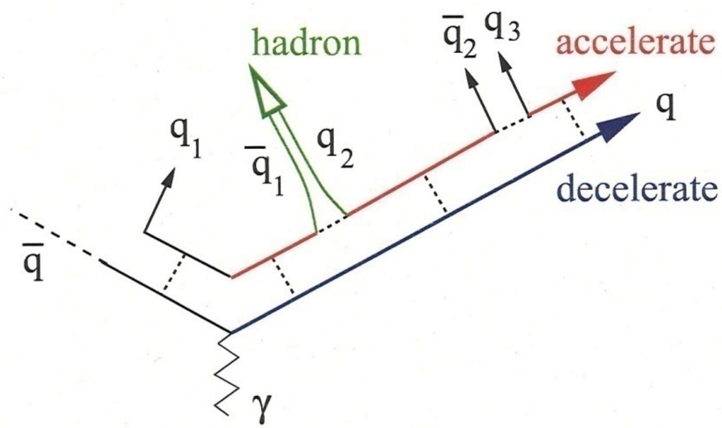
equivalent:
$\bar{q}_1$ reaches $q_1\bar{q}_1$ event horizon,
tunnels to become $\bar{q}_2$

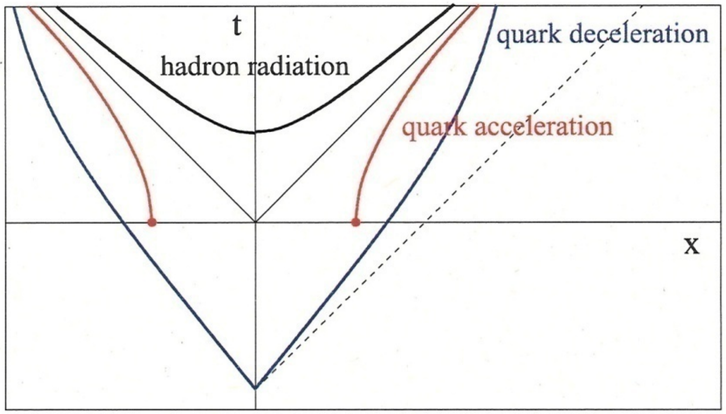


emission of hadron $\bar{q}_1q_2$
as Hawking radiation

self-similar pattern:

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





temperature of Hawking radiation: what acceleration?

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

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

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

Strangeness Production

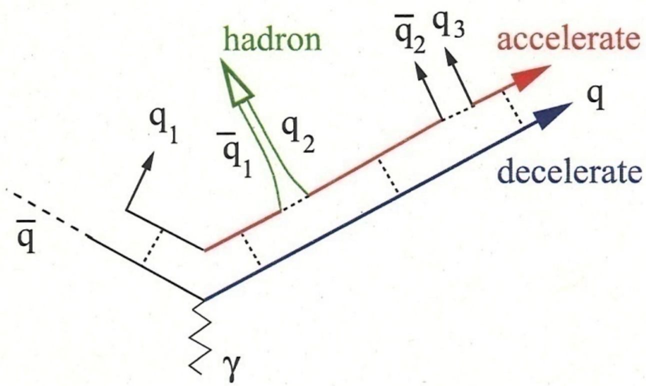
[Becattini, Castorina, Manninen, HS 2008]

Unruh temperature ~ 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 σ and m_s

TOY MODEL

Assume that there are only two species: scalar and electrically neutral mesons, "pions" with mass m_π, and "kaons" with mass m_k and strangeness $s = 1$

According to the statistical model with the γ_s suppression factor, the ratio N_k/N_π is given by

$$\frac{N_k}{N_\pi}\Big|^{stat}_{\gamma_s} = \frac{m_k^2}{m_\pi^2}\gamma_s \frac{K_2(m_k/T)}{K_2(m_\pi/T)} \tag{14}$$

because there is thermal equilibrium at temperature T.

6

On the other hand, in the H-U based statistical model there is no γ_s, $T_k = T(0s) \neq T_\pi = T(00) = T$ and therefore

$$\frac{N_k}{N_\pi}\Big|^{stat}_{H-U} = \frac{m_k^2}{m_\pi^2}\frac{T_k}{T_\pi}\frac{K_2(m_k/T_k)}{K_2(m_\pi/T_\pi)}. \tag{15}$$

which corresponds to a γ_s parameter given by

$$\gamma_s = \frac{T_k}{T_\pi}\frac{K_2(m_k/T_k)}{K_2(m_k/T_\pi)}. \tag{16}$$

For $\sigma = 0.2$ Gev^2, $m_s = 0.1$ Gev, $T_\pi = 178$ Mev and $T_k = 167$ Mev (see table I), the crude evaluation by eq.(16) gives $\gamma_s \simeq 0.73$.

Full analysis

for $\sigma \simeq 0.17\ \text{GeV}^2$ 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

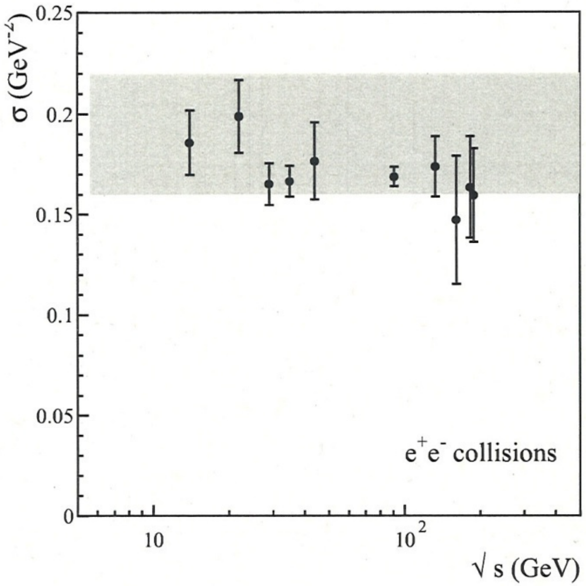
standard values:

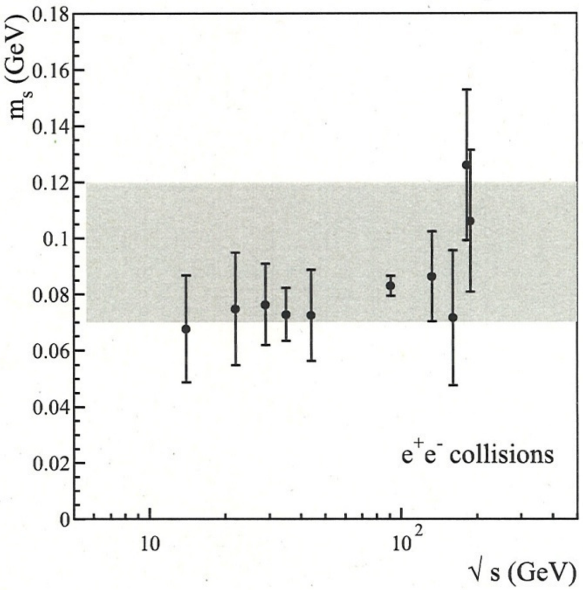
$\sigma = 0.195 \pm 0.030$ GeV^2

$m_s = 0.095 \pm 0.025$ GeV

perform analyses for all data

e^+e^- $\sqrt{s} = 91.2$ GeV				
species	measured			fit
π^+	8.50	$\pm$	0.10	8.30
π^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
η	1.059	$\pm$	0.996	0.910
ω	1.024	$\pm$	0.059	0.971
p	0.519	$\pm$	0.018	0.557
η'	0.166	$\pm$	0.047	0.096
ϕ	0.0977	$\pm$	0.0058	0.1060
Λ	0.1943	$\pm$	0.0038	0.1891
Σ^+	0.0535	$\pm$	0.0052	0.0437
Σ^0	0.0389	$\pm$	0.0041	0.0444
Σ^-	0.0410	$\pm$	0.0037	0.0400
Ξ^-	0.01319	$\pm$	0.0005	0.01269
Ω	0.00062	$\pm$	0.0001	0.00077





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)

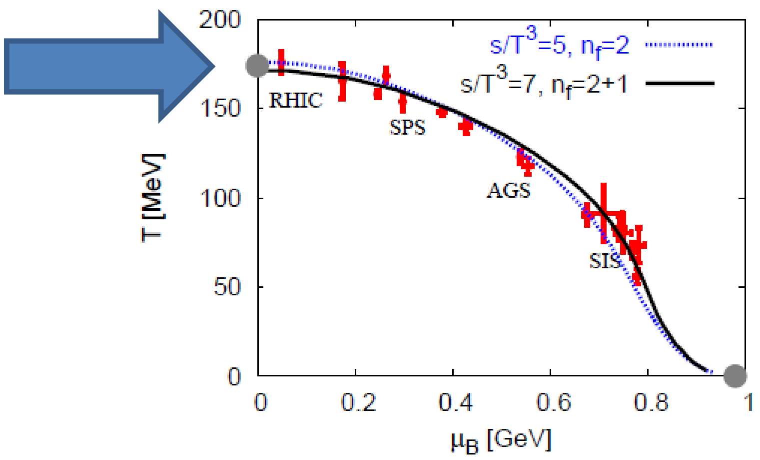
String breaking and E/N = 1.08 Gev

The energy of the pair produced by string breaking, i.e., of the newly formed hadron, is given by

$$E_h = \sigma R = \sqrt{2\pi\sigma}.$$

In the central rapidity region of high energy collisions, one has $\mu \simeq 0$, so that E_h is in fact the average energy $\langle E \rangle$ per hadron, with an average number $\langle N \rangle$ of newly produced hadrons. Hence we obtain

$$\frac{\langle E \rangle}{\langle N \rangle} = \sqrt{2\pi\sigma} \simeq 1.09 \pm 0.08,$$



Bekenstein-Hawking black-hole entropy

$$S_{\rm BH} = \frac{1}{4}\,\frac{A}{r_P^2}\,,$$

$r_P = \sqrt{\hbar G/c^3}$, the Planck length

On the other hand, there is no gravity involved in the hadronization process.

quantum particles relativistically accelerated by the strong force.

Rindler spacetime.

$$S = \frac{A}{4 r^2}$$

1) Valid for a Rindler horizon (constant acceleration)?

2) What is the scale r?

- Bekenstein-Hawking formula also holds for the Rindler spacetime,

  R. Laflamme, Phys. Lett. B **196** (1987) 449

- r is the typical (short) scale of quantum fluctuaction

  L. Bombelli, R. K. Koul, J. H. Lee and R. D. Sorkin, Phys. Rev. D 34, 373 (1986).

QFT

M.Srednicki PRL 71(1993)666

H.Terashima PRD 61(2000) 104016

Lambiase, Iorio, Vitiello Annals of Physics 309 (2004) 151

BRUTE FORCE…..

String breaking and $s/T^3 \approx 7$

$$S_h = \frac{1}{4}\,\frac{A_h}{r_T^2} = \frac{1}{4}\,\frac{4\pi R^2}{r_T^2}$$

$$r_T = \sqrt{2/\pi\sigma},$$

$$k_T = \sqrt{\pi\sigma/2}.$$

$$R = \sqrt{2\pi/\sigma}$$

$$S_h = \pi^3$$

$$\frac{s}{T_h^3} = \frac{S_h}{(4\pi/3)R^3T_h^3} = \frac{3\pi^2}{4} \simeq 7.4$$

Why? High speculative answer…

The deep meaning of the result

$$\frac{s}{T_h^3} = \frac{S_h}{(4\pi/3)R^3T_h^3} = \frac{3\pi^2}{4} \simeq 7.4$$

based on

$$S_h = \boxed{\frac{1}{4}}\frac{A_h}{r_T^2} = \boxed{\frac{1}{4}}\frac{4\pi R^2}{r_T^2}$$

Could be that the entanglement entropy density per unit horizon area is finite and universal (at least for $\mu \cong 0$). In QFT

$$S = \alpha \frac{A}{r^2{}_T}$$

QFT

- M.Srednicki PRL 71(1993)666
- H.Terashima PRD 61(2000) 104016
- Lambiase, Iorio, Vitiello , Annals of Physics 309 (2004) 151

$$\alpha \stackrel{?}{=} 1/4$$

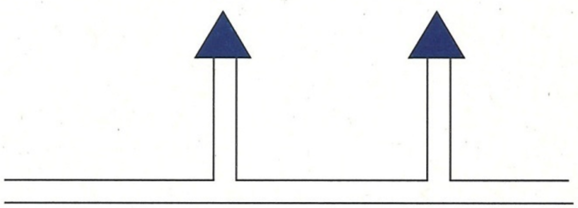
Heavy Ions

- elementary collisions

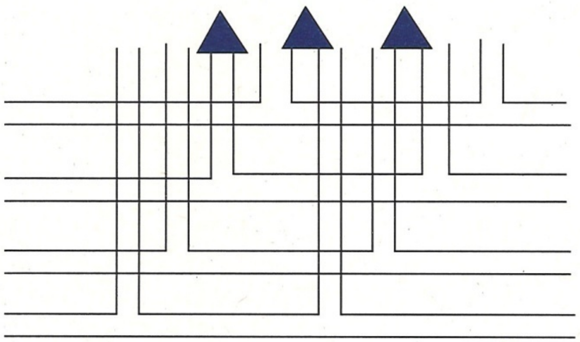
  sequential $q\bar{q}$ pair production $\Rightarrow$ independent hadron emission

- nuclear collisions

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

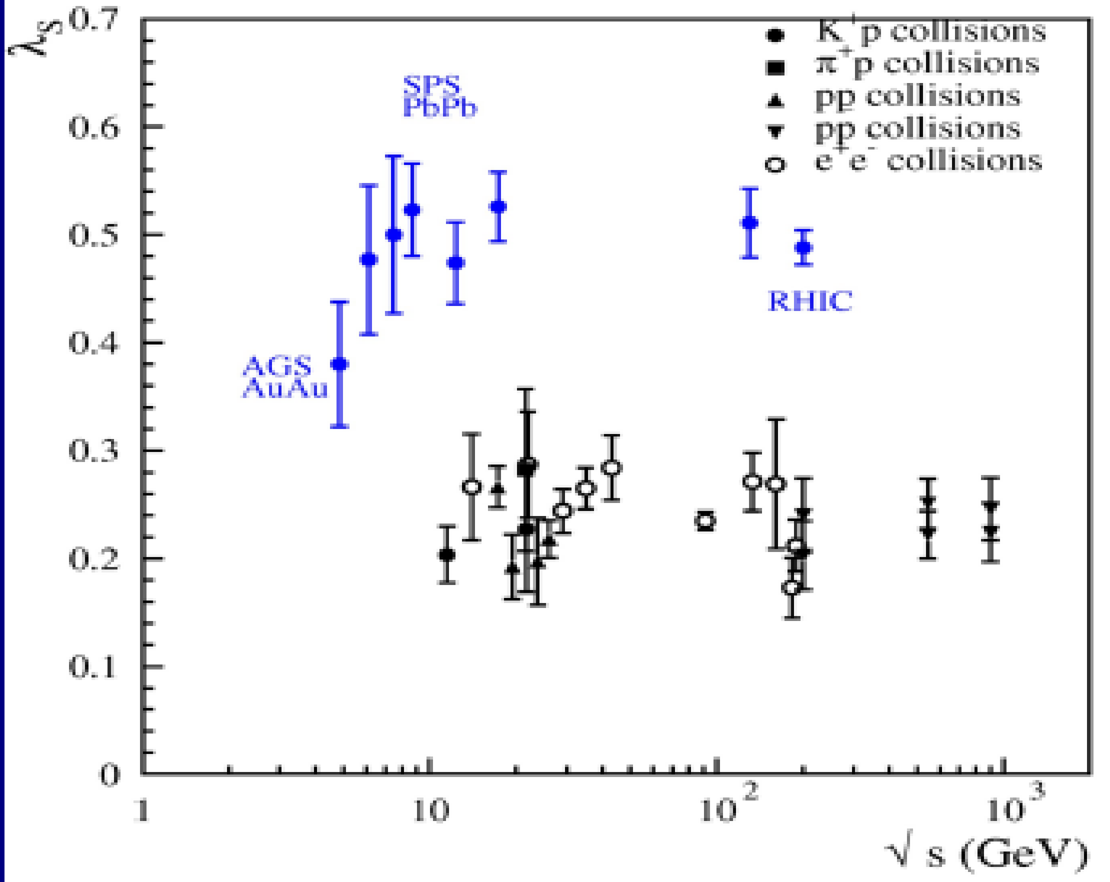


elementary



nuclear

Wroblewski ratio: current status



$$\lambda_s = \frac{2N_s}{N_l}$$

P.C. and H.Satz **- Adv.High Energy Phys. 2014 (2014) 376982**

Hawking-Unruh Hadronization and Strangeness Production in High Energy Collisions

In elementary collisions

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

- $\sigma = 0.169\ \mathrm{GeV}^2.$

  $m_s = 0.083\ \mathrm{Gev}$

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

TOY MODEL

Let us consider a high density system of quarks and antiquarks in a causally connected region. Generalizing our formulas in sec. 2, the average acceleration is given by

$$\bar{a} = \frac{N_l w_0 a_0 + N_s w_s a_s}{N_l w_0 + N_s w_s} \tag{17}$$

By assuming $N_l >> N_s$, after a simple algebra, the average temperature, $\bar{T} = \bar{a}/2\pi$, turns out to be

$$\bar{T} = T(00)[1 - \frac{N_s}{N_l}\frac{w_0 + w_s}{w_0}(1 - \frac{T(0s)}{T(00)})] + O[(N_s/N_l)^2] \tag{18}$$

Now in our world of "pions" and "kaons" one has $N_l = 2N_\pi + N_k$ and $N_s = N_k$ and therefore

$$\bar{T} = T(00)[1 - \frac{N_k}{2N_\pi}\frac{w_0 + w_s}{w_0}(1 - \frac{T(0s)}{T(00)})] + O[(N_k/N_\pi)^2]. \tag{19}$$

On the other hand, in the H-U based statistical calculation the ratio N_k/N_π depends on the equilibrium (average) temperature $\bar{T}$, that is

$$N_k/N_\pi = \frac{m_k^2}{m_\pi^2}\frac{K_2(m_k/\bar{T})}{K_2(m_\pi/\bar{T})}, \tag{20}$$

and, therefore, one has to determine the temperature $\bar{T}$ in such a way that eq.(19) and eq.(20) are self-consistent. This condition implies the equation

$$2\frac{[1-\bar{T}/T(00)]w_0}{[1-T(0s)/T(00)](w_s+w_0)} = \frac{m_k^2}{m_\pi^2}\frac{K_2(m_k/\bar{T})}{K_2(m_\pi/\bar{T})}, \tag{21}$$

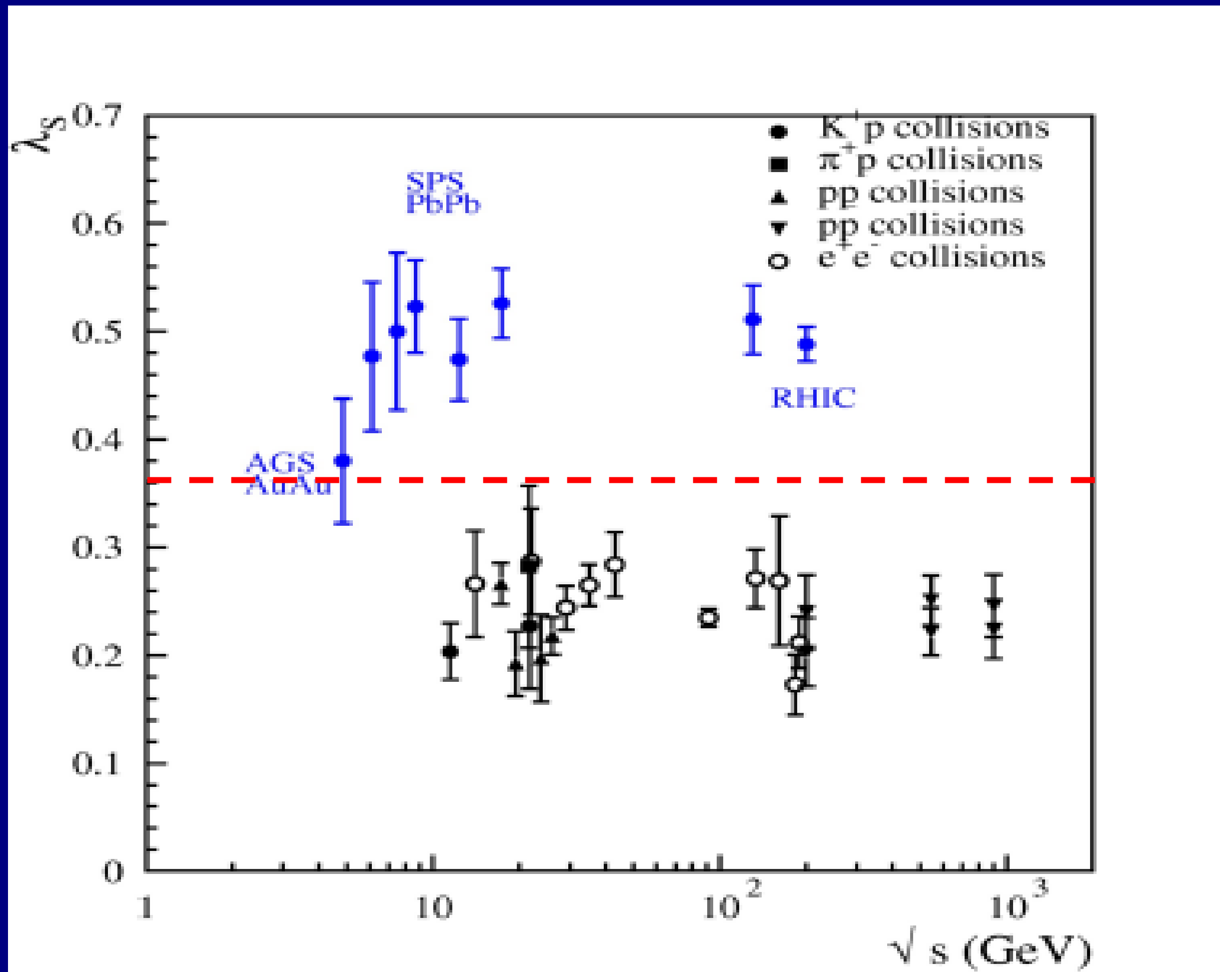
that can be solved numerically.

For $\sigma = 0.2$ Gev^2, $m_s = 0.1$ and the temperatures in table I, the average temperature turns out $\bar{T} = 174$ Mev and one can evaluate the Wroblewski factor defined by

$$\lambda = \frac{2N_s}{N_l} \tag{22}$$

where N_s is the number of strange and anti-strange quarks in the hadrons in the final state and N_l is the number of light quarks and antiquarks in the final state minus their number in the initial configuration.

Wroblewski ratio: current status



The Wrobleski factor increases from 0.25 in elementary collisions to 0.36 in the toy (pions and kaons) model.

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"*

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 σ and strange quark mass m_s, the resulting scenario provides a parameter-free description of thermal hadron production in all high energy interactions.

- **For** $\mu \cong 0$ **the Unruh mechanism explains the freeze-out criterium E/N = 1.08 Gev and suggests a possible understanding of s/T^3 = 7**

Fundamental Physics!

$$T \approx 170 Mev \Rightarrow a \approx 10^{34} cm/\sec^2$$

BH $M \approx 10^{11} Kg, R \approx 0.14 fm$

$$\rho \approx 10^{58} kg/m^3$$

$$\rho_{NS} \approx 10^{20} - 10^{19} kg/m^3$$

But there is more

$$S = \frac{1}{4}\frac{A}{r^2}$$

In string breaking

Hawking-Unruh radiation in a lab?

Gravity analogue **C. Barcelo, S. Liberati, and M. Visser, Living Rev. Rel.**

Lasers - Unruh, Schutzhold,…

Hawking-Unruh effect in Graphene - Lambiase-Iorio, PLB716,2012,334 and arxive 1308.0265.

High energy lab