Hadronization of quark gluon plasma (and gluon jets) and the role of the 0^{++} gb as primary hadron product.

P. Minkowski, ichep 2000, 27.07.2000

Topics: – QCD gb base condensates
$0^{++}, 0^{-+}, 2^{++}$ gb.

– fast transition from
$qgp \to gb(0^{++}) \to$ hadrons
$\pi^+\pi^-, \pi^0\pi^0, K\bar{K} \ldots$
$gb(0^{++}) \to \rho_V \rho_V \to \pi^+\pi^- e^+e^-_{(\gamma)}$

– further tests, conclusions.

QCD : base condensates

$q \times \bar{q}$ and $G \times G$ pairing.

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2 + 1 light flavors $u, d, s \rightarrow q_f$

$m_u : m_d : m_s \simeq 5.25 : 8.75 : 175$

$3 : 5 : 100$

$$\boxed{\mathcal{L} = \begin{array}{l} -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \bar{q}^{c'}_f \, i \gamma^\mu D(V)_{\mu c' c} \, q^c_f \\ \qquad - m_f \, \bar{q}^c_f \, q^c_f \\ -\frac{1}{2} \, tr \left(C(V) \right)^2 \\ + 2 \, tr \, \partial_\mu \bar{c} \, D^\mu(V) \, c \end{array}}$$

$C = \left(\partial_\mu V^{\mu a} \right) \frac{\lambda^a}{2}$; $c = c^a \frac{\lambda^a}{2}$ $\left(\neq \begin{array}{l} c \text{ color} \\ c \\ \text{ghost-f.} \end{array} \right)$

$V^\mu = V^{\mu a} \frac{\lambda^a}{2}$; $a = 1, \dots 8$ λ^a : color SU3 matrices

$D_\mu(V) q_f = \left(\partial_\mu + i g V_\mu \right) \cdot q_f$; $D_\mu(V) c = \partial_\mu c + i g \left[V_\mu , c \right]$

$$[D_\nu, D_\mu] = ig \frac{\lambda^a}{2} G^a_{\mu\nu}$$ field strength in $SU3_c$.

$$G^a_{\mu\nu} = \partial_\nu V^a_\mu - \partial_\mu V^a_\nu - g f^{abc} V^b_\nu V^c_\mu.$$

g: strong coupling constant $\to \varkappa = \frac{g^2}{16\pi^2} = \frac{\alpha_s}{4\pi}$

(exactly) two central anomalies:

energy momentum trace
$$\vartheta^\mu_\mu = -2b\left(\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu}\right) + m_f \bar{q}_f q_f.$$

$F^a_{\mu\nu} \sim g G^a_{\mu\nu}$

& ren. group invariant normalization
$$= -\frac{b_1}{8\pi^2} \frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + m_f \ldots$$

singlet (flavor) axial current divergence
$$\partial^\mu j^5_\mu = 2n_{f,l} \left(2\varkappa\, \varepsilon(\varkappa)\right)\left(\frac{1}{4} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}\right) - 2i m_f \bar{q}_f \gamma_5 q_f$$

$b_1 = \left(11 - \frac{2}{3} n_{fl}\right)$

$$\partial^\mu j^5_\mu = (2n_{fl}) \frac{1}{8\pi^2} \frac{1}{4} F^a_{\mu\nu} \tilde{F}^{\mu\nu a} - m_f \ldots$$

$b(\varkappa) = -\beta/g = b_1\varkappa + b_2\varkappa^2 + \ldots$ Callan-Symanzik rescaling function.

$\varepsilon(\varkappa) = \exp \int^{\varkappa} d\varkappa' \left[\gamma(j^{(5)}_\mu) / b\, \varkappa'\right]$; $\gamma(j^5_\mu)$ anomalous j_μ^5 dimension.

Properties of the ground state

condensates associated with the operators defining the central anomalies:

$$\mathcal{B}^2(x) = \frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} = \frac{1}{2}\left(\vec{B}^{a\,2} - \vec{E}^{a\,2}\right)$$

$$\mathcal{B}\tilde{\mathcal{B}}(x) = \frac{1}{4} F^a_{\mu\nu} \tilde{F}^{\mu\nu a} = \vec{B}^a \cdot \vec{E}^a$$

$$\underbrace{\langle\Omega | \mathcal{B}^2(x) | \Omega\rangle}_{} := \begin{Bmatrix} 0.125 \\ 0.250 \end{Bmatrix} \mathrm{GeV}^4$$

SVZ $c\bar{c}$-sum rules

heavy quark expansions.

> gluon pair condensation or (g-g) superconductivity

$$\langle\Omega | \mathcal{B}\tilde{\mathcal{B}}(x) | \Omega\rangle = 0$$

CP – Θ parameter.

$$\langle\Omega | \mathcal{T}_{\mu\nu} | \Omega\rangle = -P g_{\mu\nu} \;;\; P = \frac{g((t_1))}{32\pi^2} \langle \mathcal{B}^2\rangle_0 .$$

$$P = -\varepsilon = \begin{Bmatrix} 3.5\cdot 10^{-3} \\ 7.0\; 10^{-3} \end{Bmatrix} \mathrm{GeV}^4 = \begin{Bmatrix} 0.45 \\ 0.89 \end{Bmatrix} \mathrm{GeV}/\mathrm{fm}^3 .$$

$$\underbrace{\langle\Omega | -\bar{q}^c_u q^c_u | \Omega\rangle}_{} = \lim_{m_{u,d}\to 0} f_\pi^2 m_\pi^2 / (m_u + m_d)$$

> (q-q̄) pair condensation or superconductivity

$$= 0.011\ \mathrm{GeV}^3 = 1.375/\mathrm{fm}^3$$

$f_\pi = 93.2$ MeV; $m_u + m_d = 14$ MeV &

$$\langle\Omega | \bar{q}^c_f i\gamma_5 q^c_f | \Omega\rangle = 0 .$$

(at $T=0$)

$- \langle gb | \mathcal{B}^2(x) | \Omega \rangle$ breaking up (locally) one gluonpair.

0^{++} lowest in mass

$0^{++}, 2^{++}, 4^{++} \ldots$ S_0 series

L. Landau
C.N. Yang.

$\langle gb | \mathcal{B}\tilde{\mathcal{B}}(x) | \Omega \rangle$

0^{-+}

$0^{-+}, 2^{-+}, 4^{-+} \ldots$ A series

$\langle gb | \left(\vartheta_{\mu\nu} - \frac{1}{4} \delta_{\mu\nu} \vartheta^{\rho}_{\rho}(x) \right) | \Omega \rangle$

2^{++}

2^{++} $3^{++}, 4^{++}, 5^{++} \ldots$ S_2 series.

(helicity)

(similarly breaking up (locally) one $q\bar{q}$ pair)

$\langle \pi | \bar{q}^c_{f_2} i\gamma_5 q^c_{f_1}(x) | \Omega \rangle$
(K, $\bar{K}$, η, η')

0^{-+} lowest in mass $(\pi, K, \bar{K}, \eta)$ Goldstone modes.

0^{-+} (1^{+-}) 2^{-+} $(3^{+-}) \ldots$ pseudoscalar Regge trajectory (ies)

$\langle \rho \ldots | \bar{q}^c_{f_2} \gamma_\mu q^c_{f_1}(x) | \Omega \rangle$

1^{--} (2^{++}) 3^{--} (4^{++}) $5^{--} \ldots$ ρ - trajectory

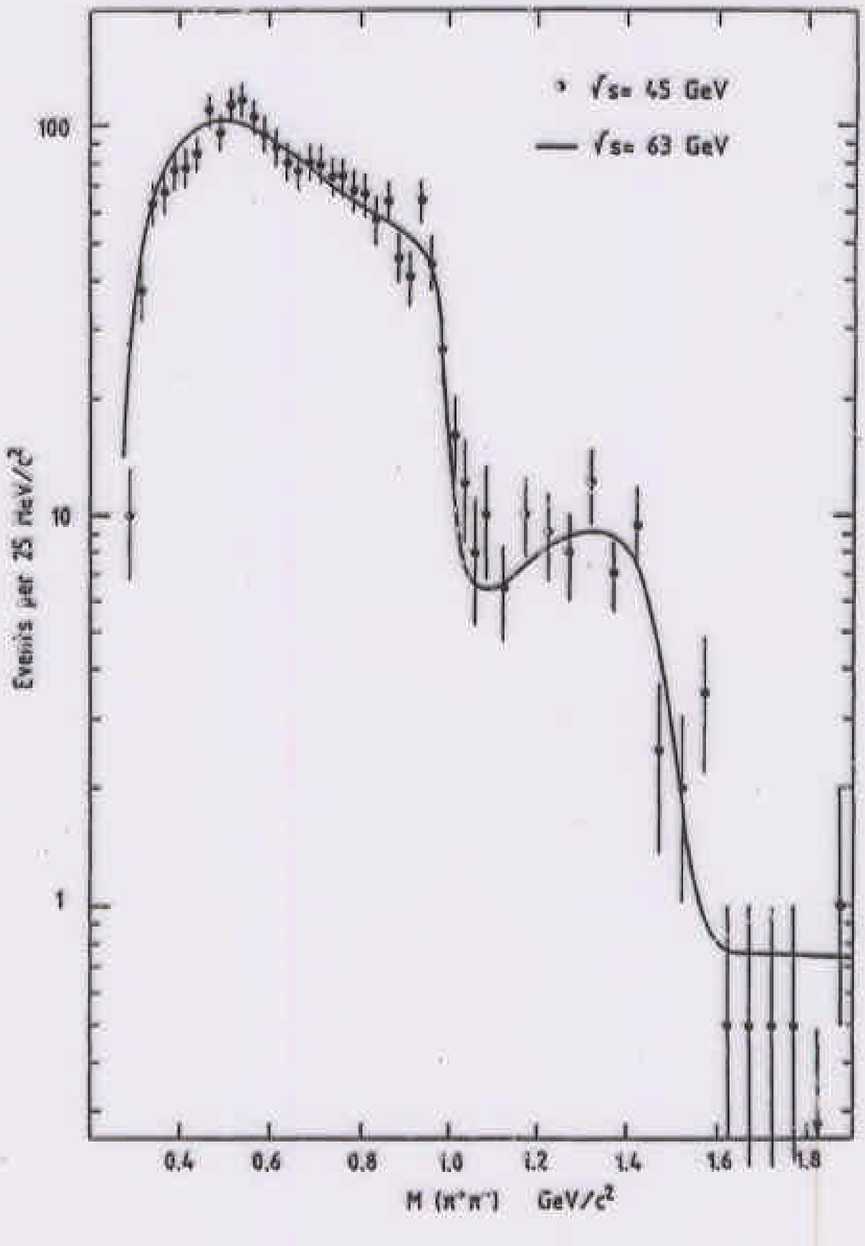


Figure 2: The mass spectrum of the $\sqrt{s}$=45 GeV exclusive $\pi^+\pi^-$ events (data points). The solid line represents the $\sqrt{s}$=63 GeV data, normalised to the same total number of events. No acceptance has been applied to either distribution [11, 17].

Hadronization of qgp. for $T \downarrow T_c(?)$

a) narrow 'melting' region
in thermal equilibrium (not $y, y_\perp$ distorted).
of gb (0^{++})

consider energy density in a given $t, \vec{x}$ frame
of gb (0^{++}) for $T < T_c(?)$.

- $$\varepsilon_{gb}(T) = \left(\frac{1}{2\pi}\right)^3 \int d^3p \, \frac{1}{e^{E/T} - 1}$$

with $m_{gb} \to m_{gb}(T)$ melting of
$\langle \Omega | B^2 | \Omega \rangle$ condensate.

$$\frac{B^2(T)}{B^2(0)} = 1 - \left(\frac{T}{T_c}\right)^4$$ g-l superconductivity

(2nd order) neglecting interactions
& conformal covariance of condensates (P.M.)

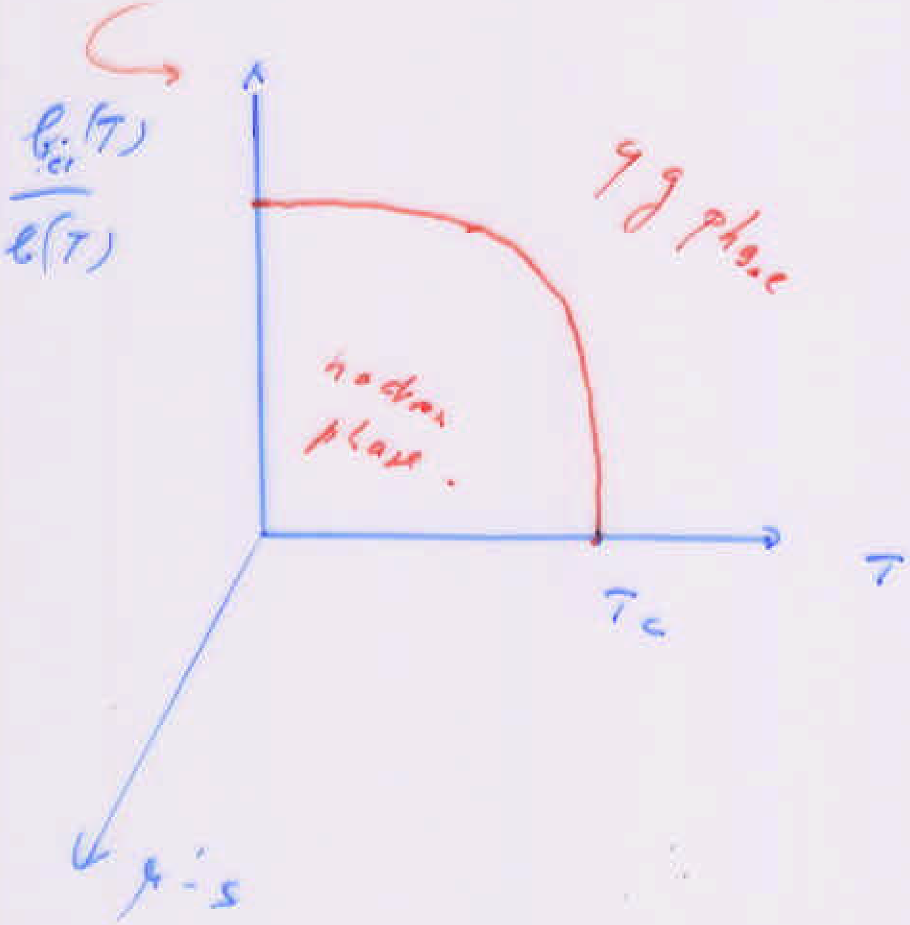
quasi-excitation
↓
$$m_{gb}(T) = m_{gb}(0)\left(1 - \left(T/T_c\right)^4\right)^{1/4}$$
$$\sim \sqrt{2}\, m_{gb}(0) \left(\frac{\Delta T}{T_c}\right)^{1/4}$$ near $T \to T_c$.

superconducting phase ↔ QGP.

$$\langle \Omega | \mathcal{B}^2(x) | \Omega \rangle \to \mathcal{B}_0^2$$

$$\frac{\mathcal{B}_{cr}^2(\cancel{\ }T)}{\mathcal{B}_0^2} + \frac{T^4}{T_0^4} = 1.$$

$\mathcal{B}^2(T) = b_{cr}^4$



$T^4, \ldots$

↔ conformal covariance.

$m_{gb}(T) \to m.$

$$\varepsilon_{gb}(T) = \frac{1}{16\pi^2} m_{gb}^4(T)$$

$$\sum_{n=1}^{\infty} \Big(K_4(n\beta m) - K_0(n\beta m) \Big).$$

only $n=1$ Boltzmann approx.

$$K_4(\xi) - K_0(\xi) \sim \begin{cases} \dfrac{48}{\xi^4} & \xi \to 0. \ (m \to 0) \\ \sqrt{32\pi}\, \dfrac{1}{\xi^{3/2}} e^{-\xi} & \xi \gg 1. \end{cases}$$

melting occurs upon the transition between the two asymptotic regimes $\xi \to \gg 1 \sim m(T) \to m_{gb}(0)$.

$$\sqrt{2}\,\frac{m_{gb}(0)}{T_c} \sim \frac{1.4\ \text{GeV}}{.17(5)\ \text{GeV}} \sim 8.$$

so $\cdot\ \xi \ll \underline{\underline{4}}$ in order to approach melting conditions.

$\hookrightarrow$ ajust to the sake of order of magnitude comparison

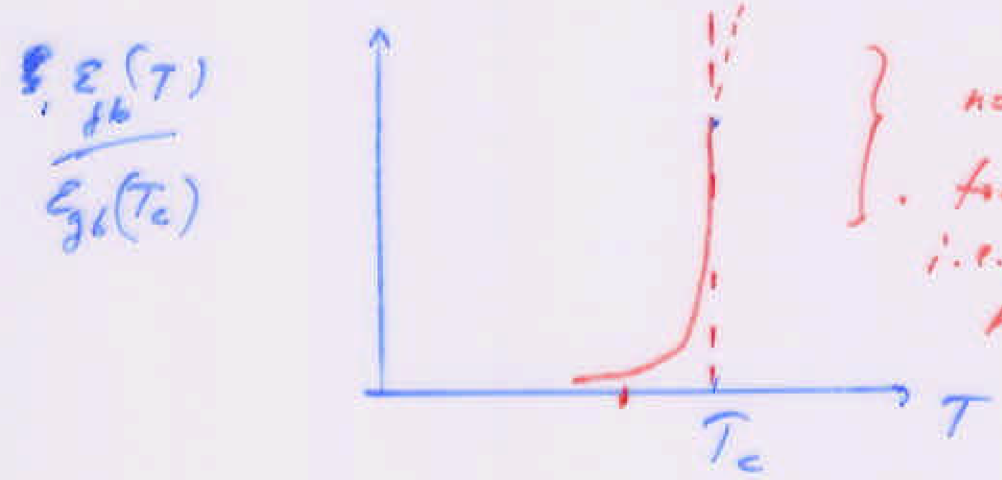
$$\to \sqrt{2}\,\frac{m_{gb}(0)}{T_c}\left(\frac{\Delta T}{T_c}\right)^{1/4} < 4$$

$$\underbrace{\sqrt{2}\,\frac{m_{gb}(0)}{T_c}}_{\sim 8}\left(\frac{\Delta T}{T_c}\right)^{1/4} < 4$$

$$\frac{\Delta T}{T_c} < \left(\frac{1}{2}\right)^4 = \frac{1}{16}.$$

as a condition for onset of melting.

this illustrates the 'sudden' onset of the transition from the quasi-excitations of massive $gb(0^{++})$ to the QGP.



no agreement yet for the region $T > T_c$ i.e. for plasma modes freezing.

$\Delta T_c \ll T_c$.
$\lesssim 10$ MeV

in the large mass scenario supported by lattice calculations $m_{gb}(0) \to 1.6$ GeV the transition would be sharper.

Further tests:

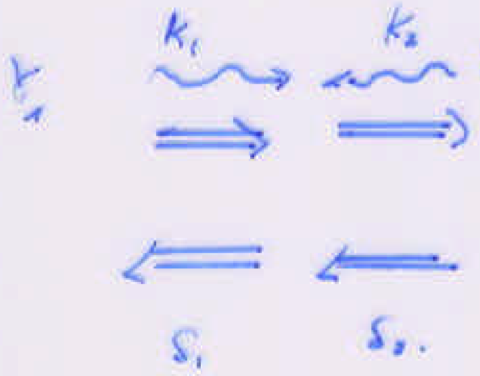
completion of the threefold
$gb(0^{++}, 0^{-+}, 2^{++})$

new clarification from L3 expt.:

$$e^+e^- \to e^+e^-[\gamma^*\gamma^*] \to e^+e^-[K_s K_s].$$

$$\gamma^*\gamma^* \to f_J(1760) \to K_s K_s$$

main helicity structure



$h = 2$

$J = 2.$

$h = -2$

$\gtrsim 75\%$ of the $K_s K_s$ signal in the 1760 MeV ($\sqrt{s}$) region.

$f_J(1760) <$ $f_2(1760)$ → main component. confirming BES result.

'$f_0(1760)$'

but unclear br$(f_2(1760) \to \pi\pi)$
not seen by Aleph.

$f_2(1760)$ is not easily interpretable as radial ($s\bar{s}$) excitation of $f_2'(1525)$

$\Delta m \sim 235$ MeV.

$$\Gamma_{\gamma\gamma}(f_2'(1525))\ Br(f_2' \to K\bar{K})$$

$$\sim (\alpha_s)^4 \qquad = (0.093 \pm 0.018 \pm 0.022)\ \text{keV}.$$

$\angle 3$ $\quad$ 2 : 9

$$\Gamma_{\gamma\gamma}(a_2) = 0.98 \pm 0.05 \pm 0.09\ \text{keV}.$$

$$a_2'(1765) : \Gamma_{\gamma\gamma}(a_2') \times Br(a_2' \to \pi^+\pi^-\pi^0) = 0.29 \pm 0.04 \pm 0.02\ \text{keV}.$$

$$\Delta m(a_2' - a_2) = 445\ \text{MeV}.$$

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hence $f_2(1760)$ could well have reduced $\gamma\gamma$ width through its $gb(2^{++})$ nature, and then a sizable br. fr. $\to \pi\pi$ follows.

$\to$ in $\gamma^*\gamma^* \to f_2'(1525)\ \&\ f_2(1760) \to X$ non trivial interference in resonance shapes.

$gb(0^{-+}) \leftrightarrow \eta(1440)$

L3 : $\gamma^*\gamma^* \to \eta(1440) \to K_S K^\pm \pi^\mp$

$$\Gamma_{\gamma\gamma}\big(\eta(1440)\big)\, Br\big(\eta(1440) \to K\bar{K}\pi\big)$$

small $Br \to \eta\pi\pi$ $\qquad = 0.234 \pm 0.055 \pm 0.017$ keV

$$\Gamma_{\gamma\gamma}\big(\eta'(958)\big)$$

$$= 4.17 \pm 0.10 \pm 0.27 \quad \text{keV.}$$

$gb(0^{++}) \to \begin{matrix}\pi\bar{\pi} \\ K\bar{K}\end{matrix}$ from 2 gluon hadronization

in central A+A collisions :

look at $(y, p_t)_k$ ordered pairs

$\to (p_k \pm p_{k+1})^2$ correlations.

Conclusions:

1) small event by event fluctuations in qgp induced products from central heavy ion collisions indicate fast hadronization (2nd order phase transition in thermodynamic terms)

2) at present the presence of primary gb(0^{++}) production in these circumstances is only indirectly supported by the $m(e^+e^-) \sim 400-600$ MeV enhancement * gb(0^{++}) $\to \pi^+\pi^- e^+e^-$ interpretation

3) $\gamma^*\gamma^* \to \eta(1440) \to K_s K^\mp \pi^\pm$ (L3)

$\gamma^*\gamma^* \to f_2(1760) \to K_s K_s$ (BES, Mark III)

also contribute at present only circumstantial evidence for gb(0^{-+}), gb(2^{++})

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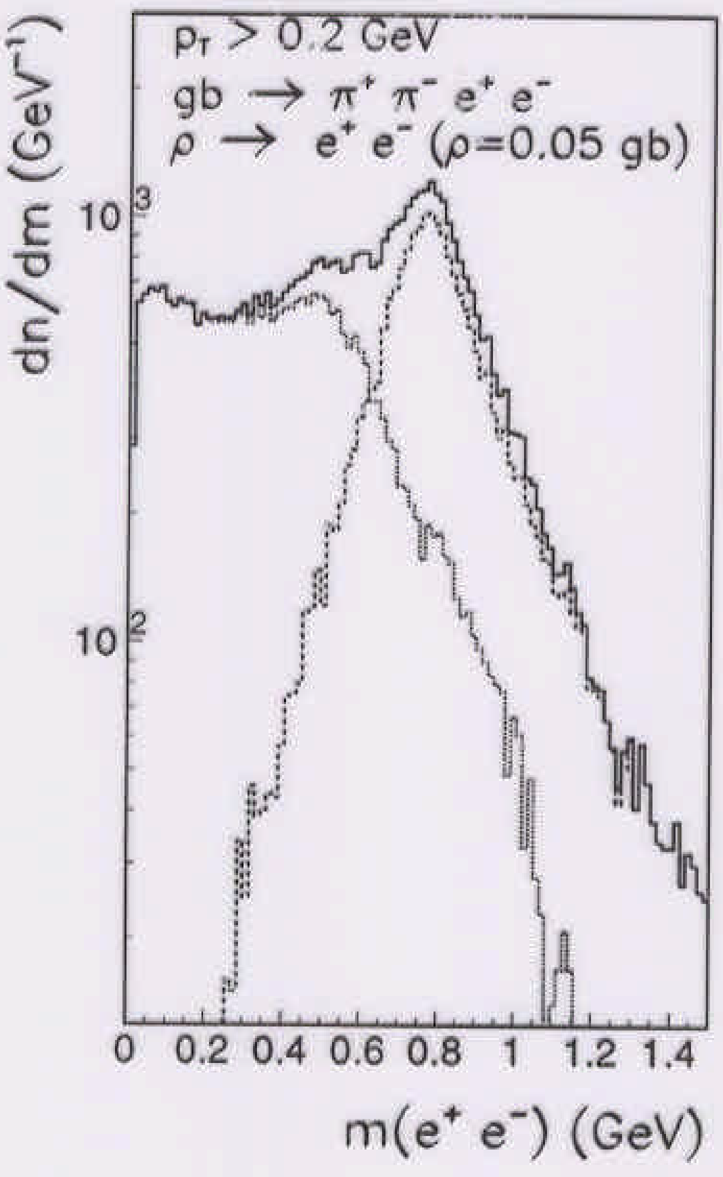

Figure 6: Invariant mass distribution of e^+e^- pairs resulting from the decay $\rho \to e^+e^-$ and from the assumed decay of the 0^{++} glueball state $0^{++} \to \pi^+\pi^-e^+e^-$. A cut on the transverse momentum of the dilepton pair of 0.2 GeV is imposed. In this calculation the products of production cross section times branching fraction into e^+e^- of the ρ^0 meson and the 0^{++} glueball state are in the ratio of 1 : 20.

LC2

4) two types of rapidity gaps can shed light on related hadronization of gluon jets

a) gap for low rapidities in the jet

b) 'gap' for fragmentation (high) rapidities in all jets including the gluon jet.