FINITE TEMPERATURE QCD: DI-MUON PRODUCTION & QUARKONIUM SURVIVAL

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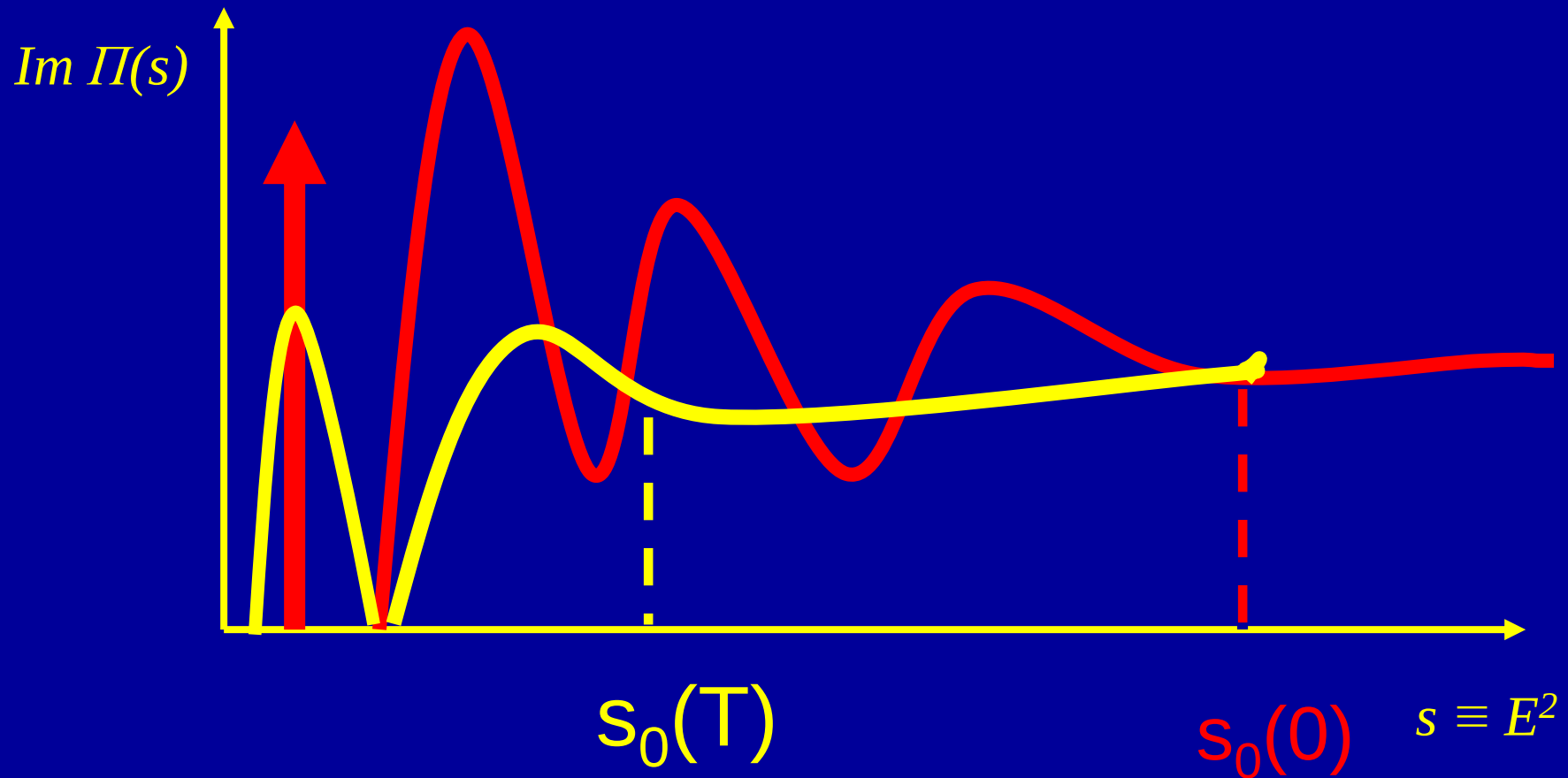
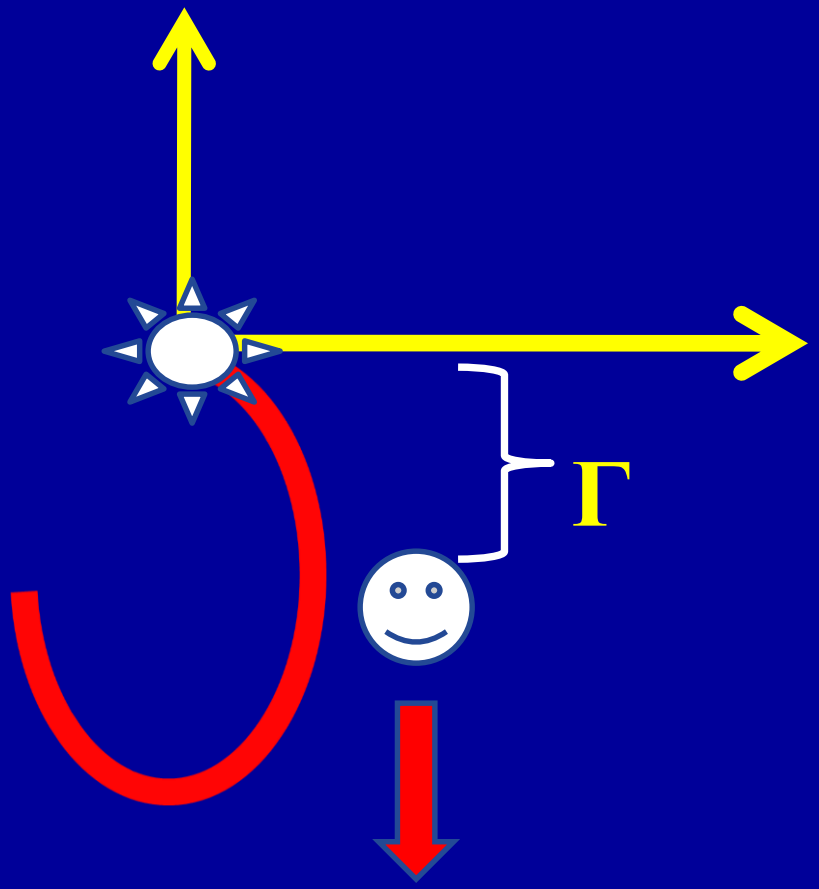
Rencontres de Moriond, QCD, La Thuile 2016

Realistic Spectral Function (T)



ORDER PARAMETERS

$S_0(T)$ & WIDTH(T) & COUPLING(T) [M(T)]



$\Gamma \rightarrow \Gamma(T)$

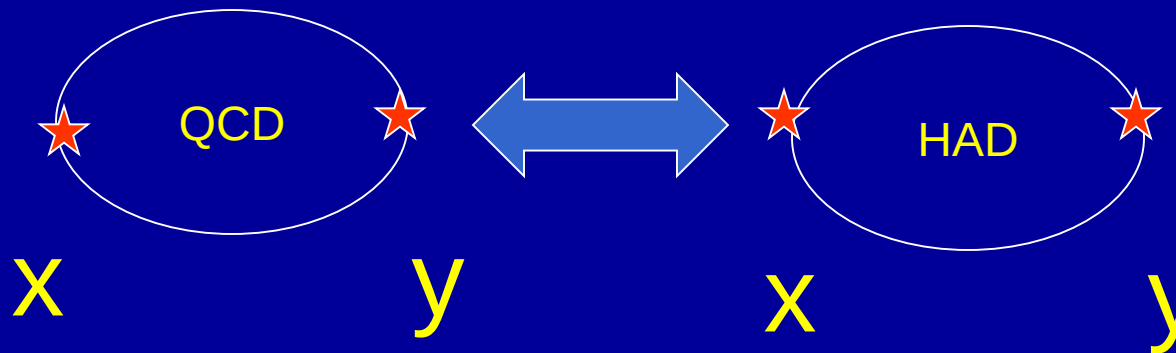
(CAD, M. Loewe, 1991)

Di-muon production in heavy ion collisions: spectrum distortion

Perfect agreement with NA60 data on di-muon production in In+In collisions (2006)

Predicted charmonium & bottonium survival beyond T_c (CAD et al. 2011)

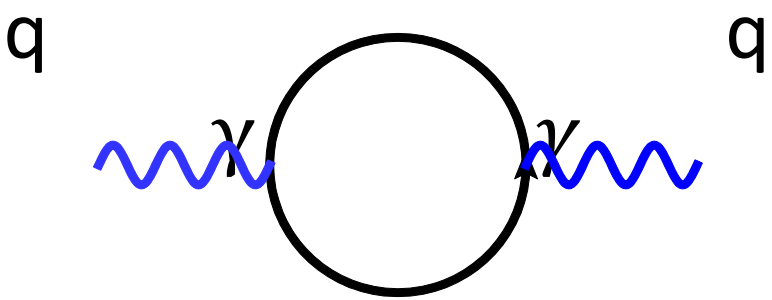
Confirmed by LQCD for bottonium (Aarts et al. 2011)



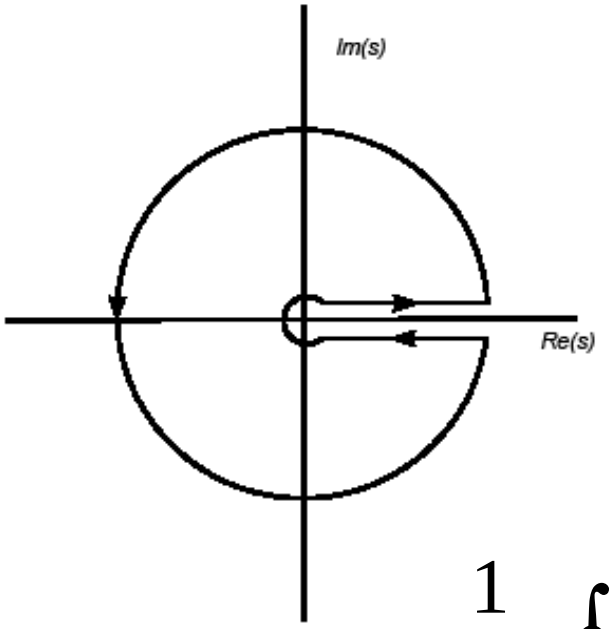
CAUCHY'S THEOREM IN THE COMPLEX ENERGY^2 PLANE

$$\Pi_{\mu\nu}(q^2) = i \int d^4x\, e^{iqx} \langle 0|T[V_\mu(x) V_\nu^\dagger(0)]|\rangle$$

$$V_\mu(x) =: \bar{q}^a(x)\, \gamma_\mu\, q^a(x) :$$



QUARK-HADRON DUALITY



$$\oint_C \Pi(s)\, ds = 0$$

$$-\frac{1}{2\pi i}\oint_{C(|s_0|)} ds\, \Pi(s) = \int_{s_{th}}^{s_0} ds\, \frac{1}{\pi}\, \mathrm{Im}\, \Pi(s)$$

$$-\frac{1}{2\pi i}\oint_{C(|s_0|)} ds\,\Pi_{QCD}(s) = \int_{s_{th}}^{s_0} ds\,\frac{1}{\pi}\,\mathrm{Im}\,\Pi(s)\,|_{HAD}$$

DOLAN-JACKIW (MATSUBARA)

$$S_F(T=0) = \frac{\not{k} + m}{k^2 - m^2 + i\epsilon}$$

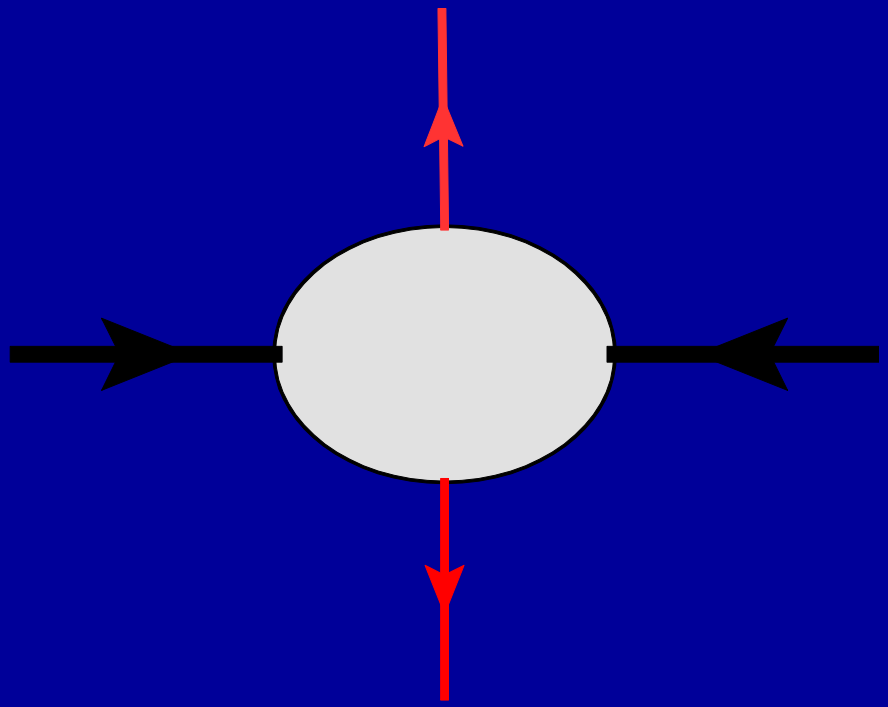
$$S_F(T) = (\not{k}+m)\left[\frac{1}{k^2 - m^2 + i\epsilon} + 2\,\pi\, i\, \delta(k^2 - m^2)\, n_F(|k_0|)\right]$$

$$n_F(z) = \frac{1}{e^{z/T} + 1}$$

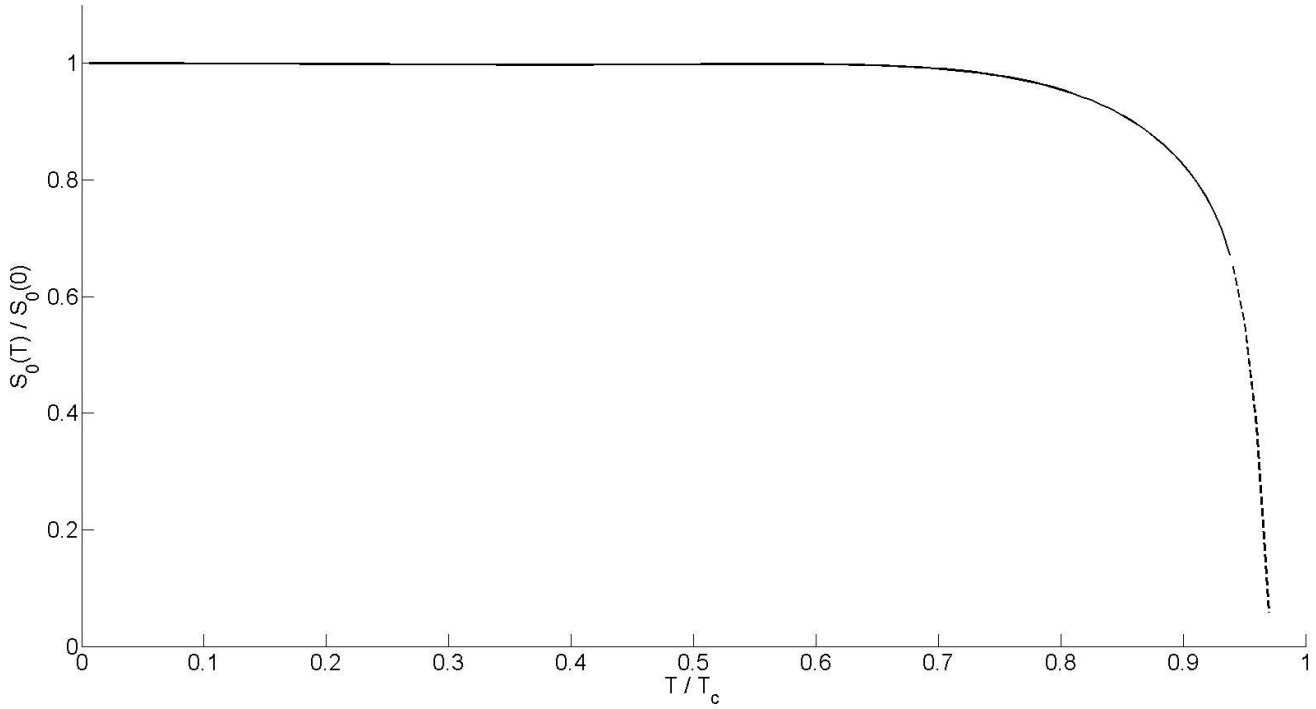
Di-muon Production in Heavy-Ion Collisions

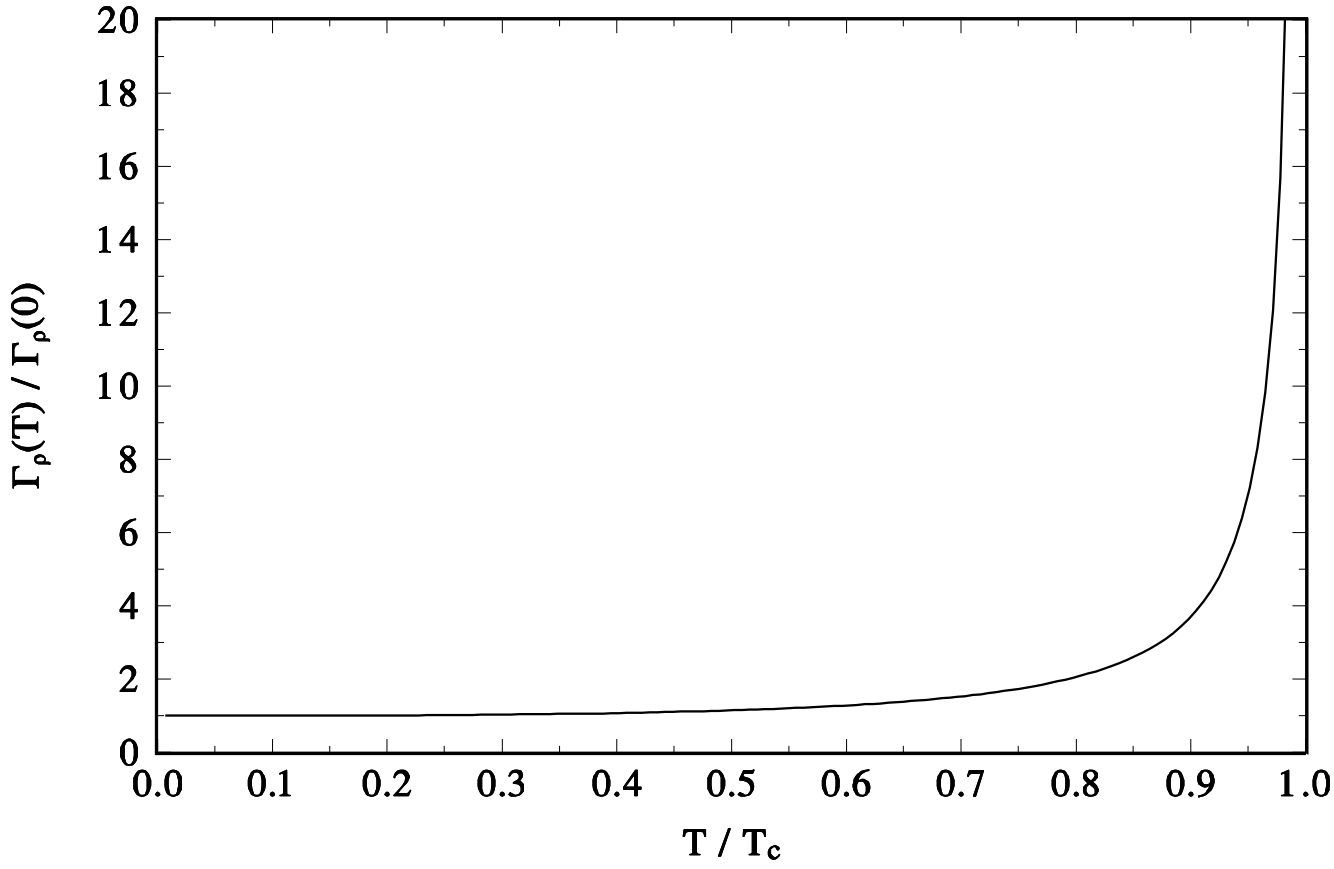
ρ- region

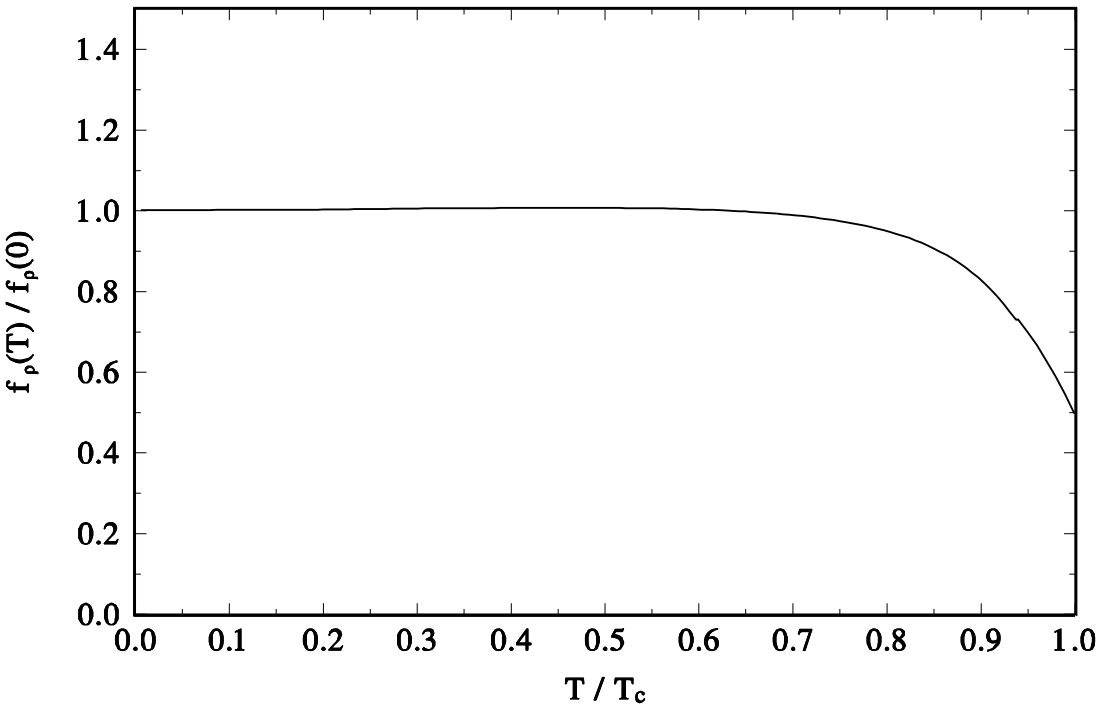
VECTOR CURRENT CORRELATOR



$$\frac{1}{\pi}\,\mathrm{Im}\Pi_0^{\mathrm{HAD}}(s) = \frac{1}{\pi}\frac{1}{f_\rho^2}\frac{M_\rho^3\Gamma_\rho}{(s-M_\rho^2)^2+M_\rho^2\Gamma_\rho^2},$$


1
0.8
0.6
0.4
0.2
0
$S_0(T) / S_0(0)$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
T / T_c

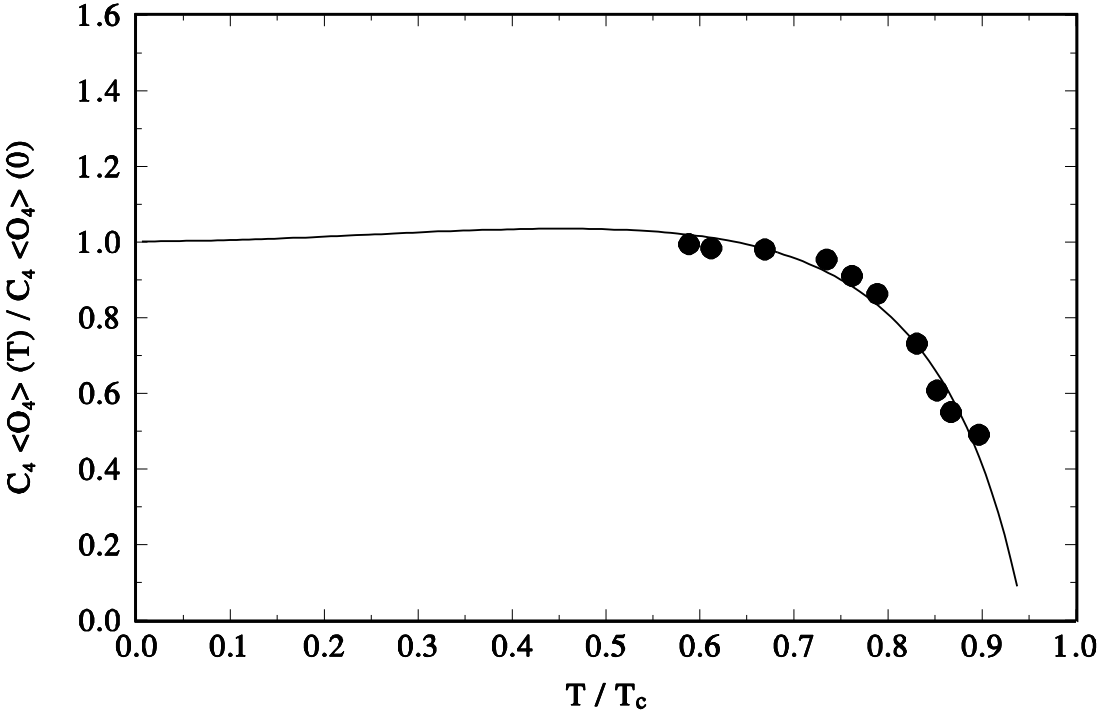

20
18
16
14
12
10
8
6
4
2
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Γρ(T) / Γρ(0)
T / Tc


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$f_\rho(T) / f_\rho(0)$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
T / T_c

CONFIRMATION FROM LQCD ???

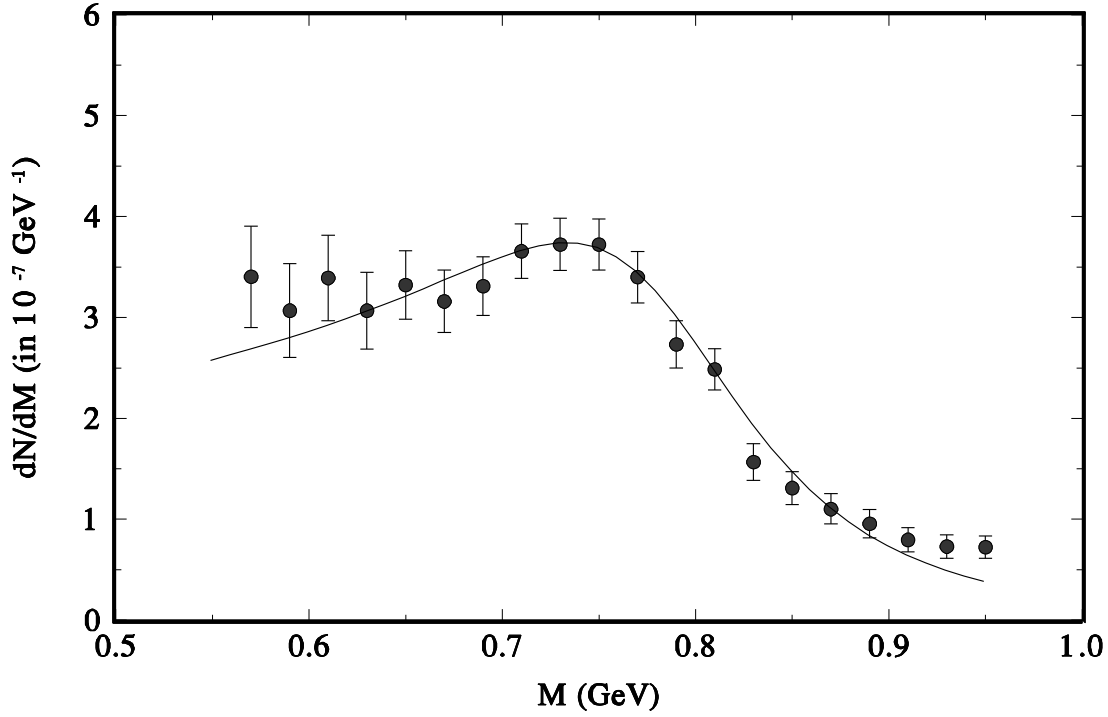
Operator Product Expansion

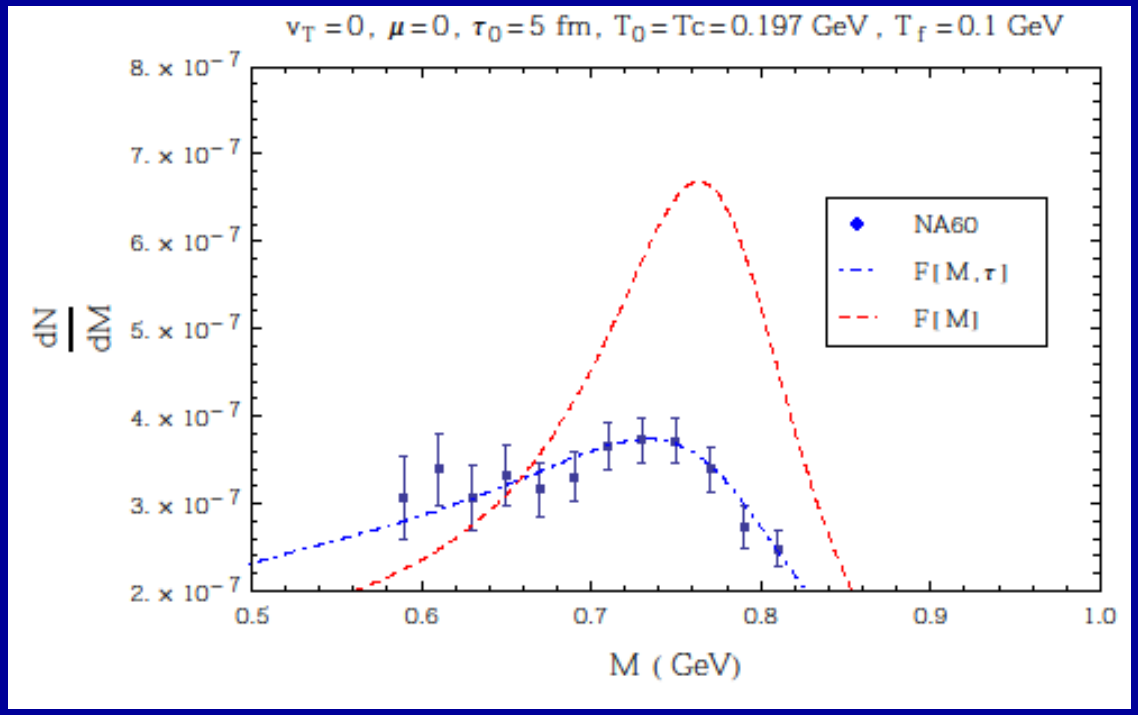
$$< 0|C_4\ O_4\ |0> \propto \quad \alpha_s < 0|G_{\mu\nu}\ G^{\mu\nu}\ |0>$$


1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
C4 <O4> (T) / C4 <O4> (0)
T / Tc

In + In (158 A GeV) $\rightarrow \mu^+ \mu^-$

(CERN NA60)

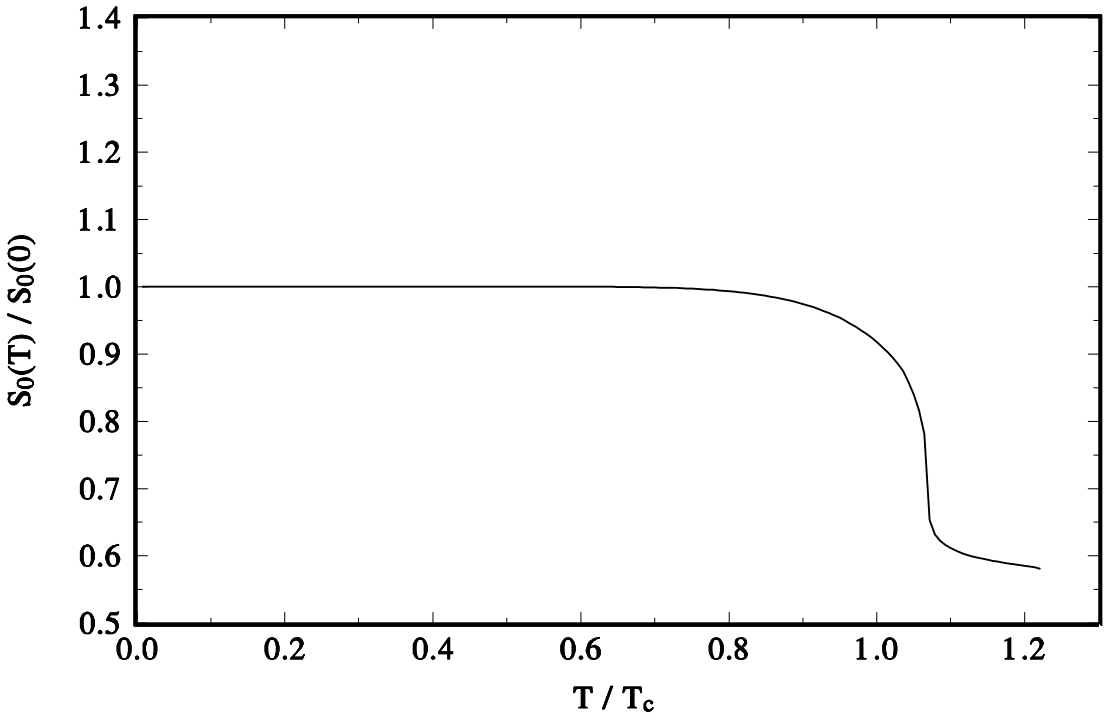



$v_T = 0$, $\mu = 0$, $\tau_0 = 5$ fm, $T_0 = Tc = 0.197$ GeV, $T_f = 0.1$ GeV
$8. \times 10^{-7}$
$7. \times 10^{-7}$
$6. \times 10^{-7}$
$5. \times 10^{-7}$
$4. \times 10^{-7}$
$3. \times 10^{-7}$
$2. \times 10^{-7}$
$\frac{dN}{dM}$
0.5
0.6
0.7
0.8
0.9
1.0
M (GeV)
NA60
F[M, τ]
F[M]

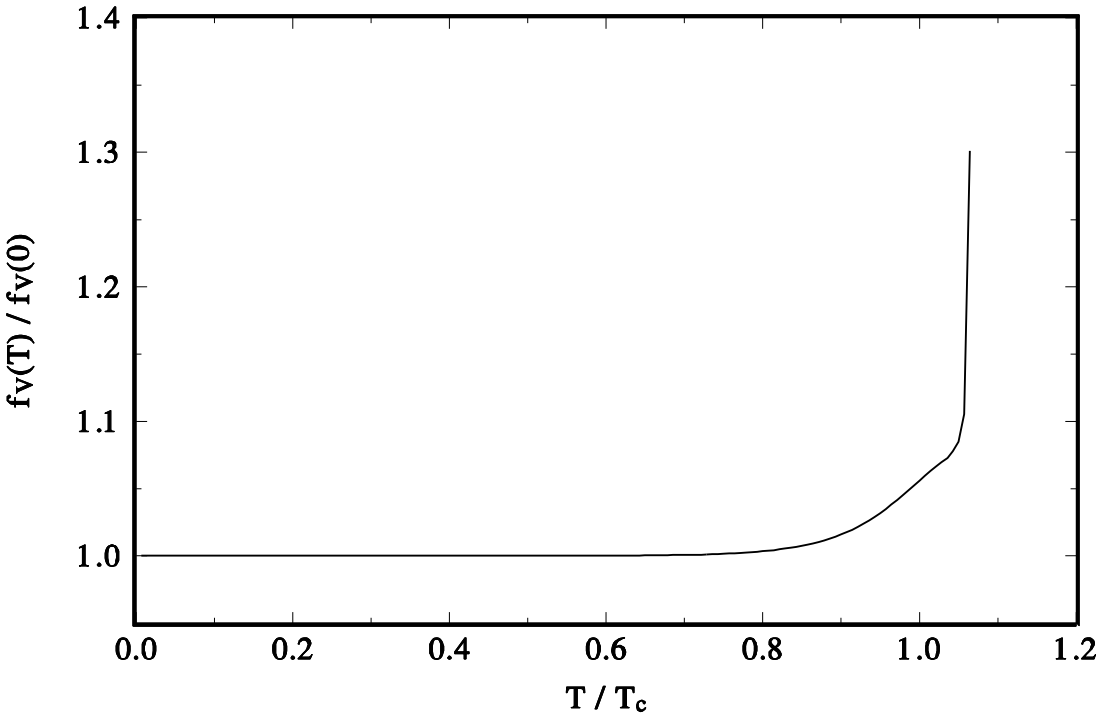
HEAVY-HEAVY QUARK HADRONS

J/ψ , η_c , χ_c

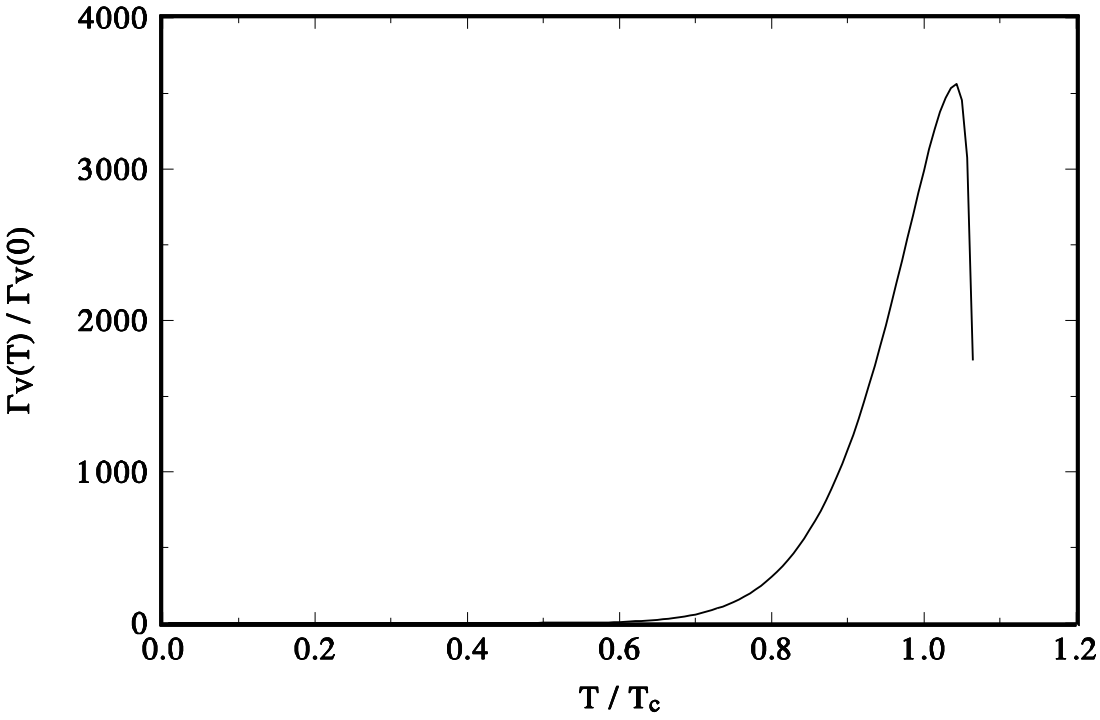
S_0 (T)



f_V (T)

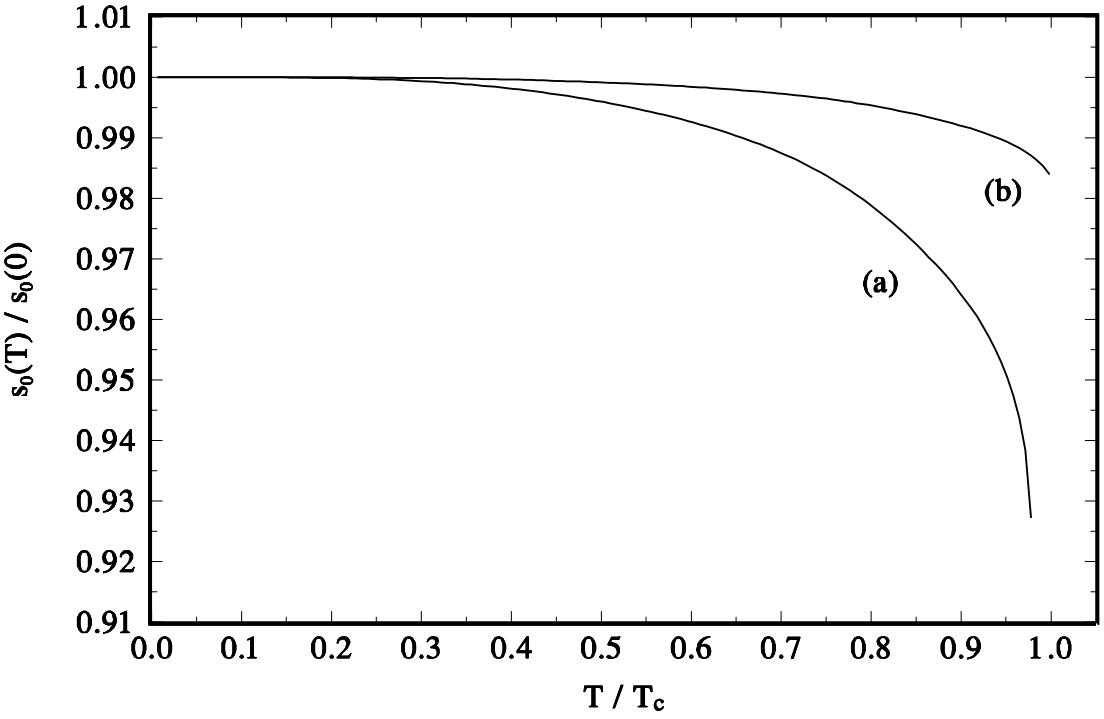


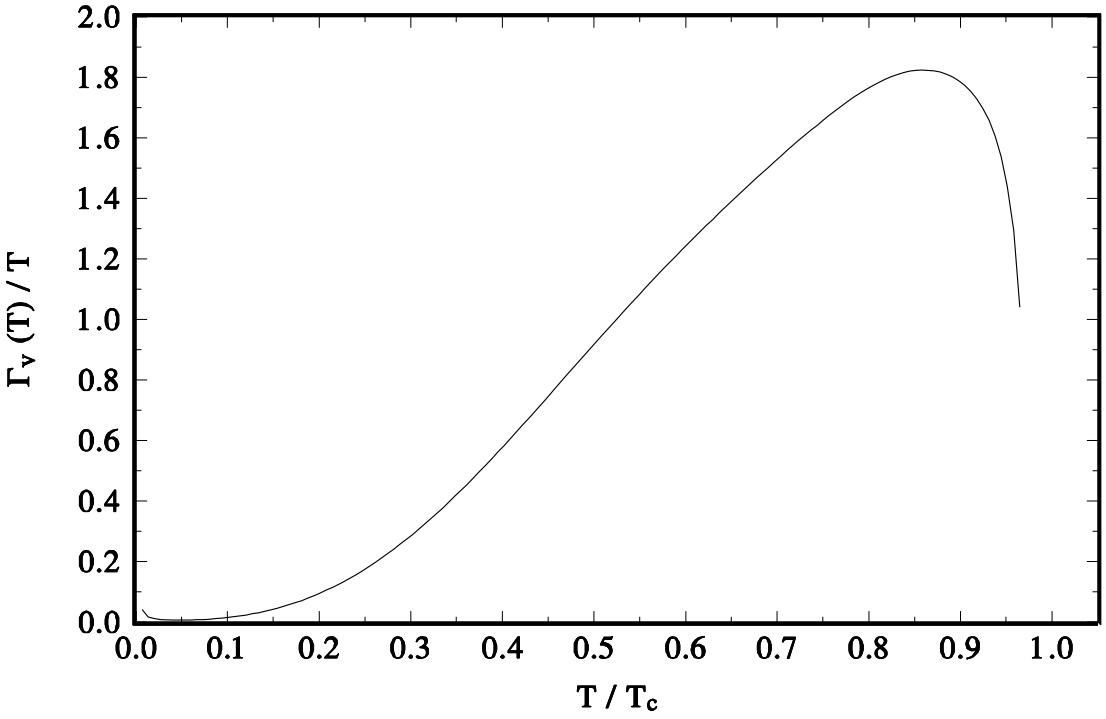
Γ_V (T)

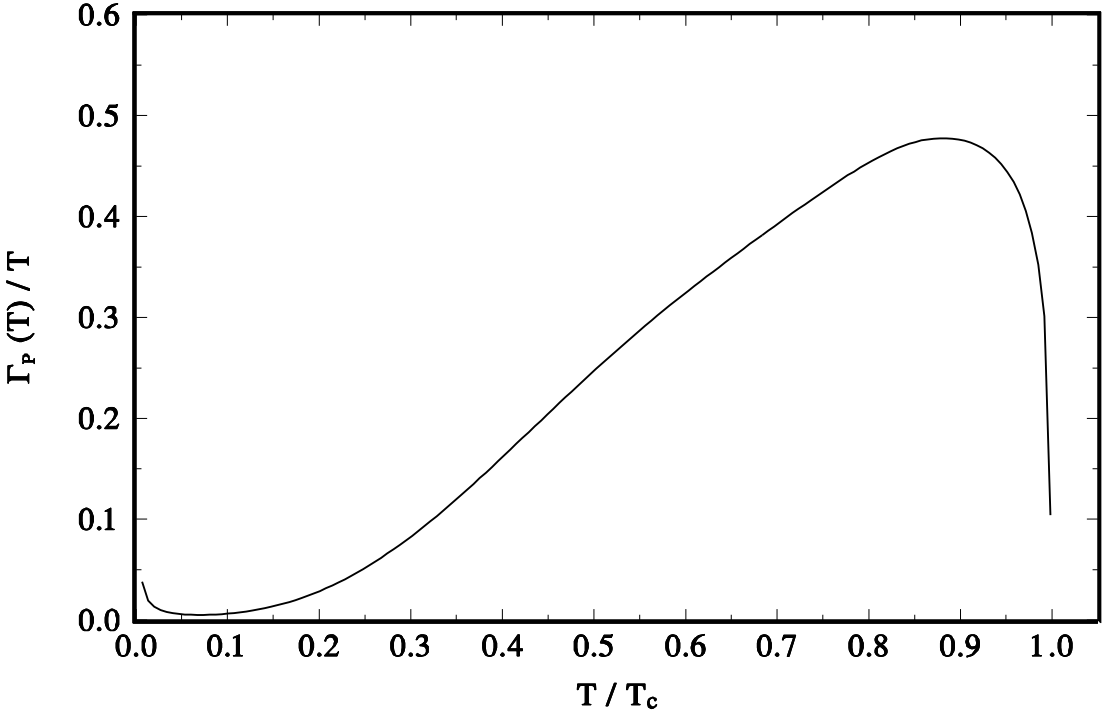


HEAVY-HEAVY QUARK HADRONS

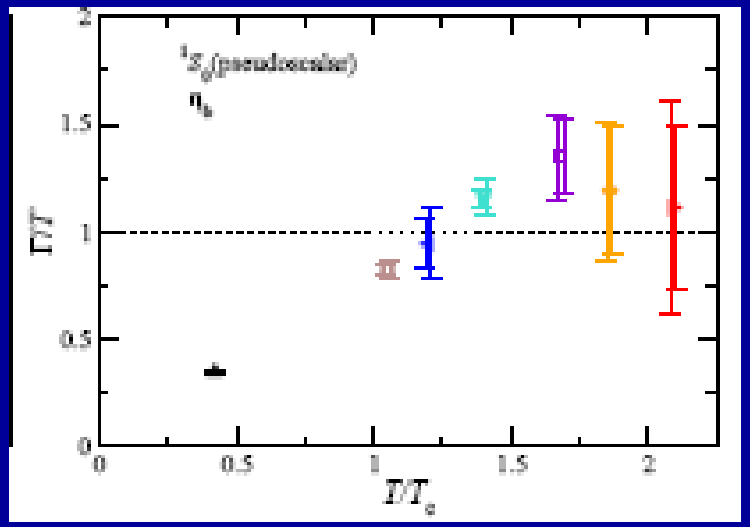
Υ , η_b

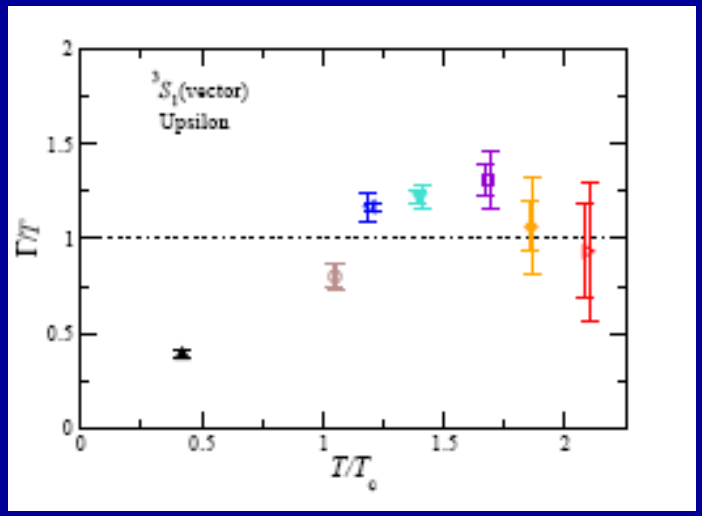

1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$s_0(T) / s_0(0)$
T / T_c
(a)
(b)

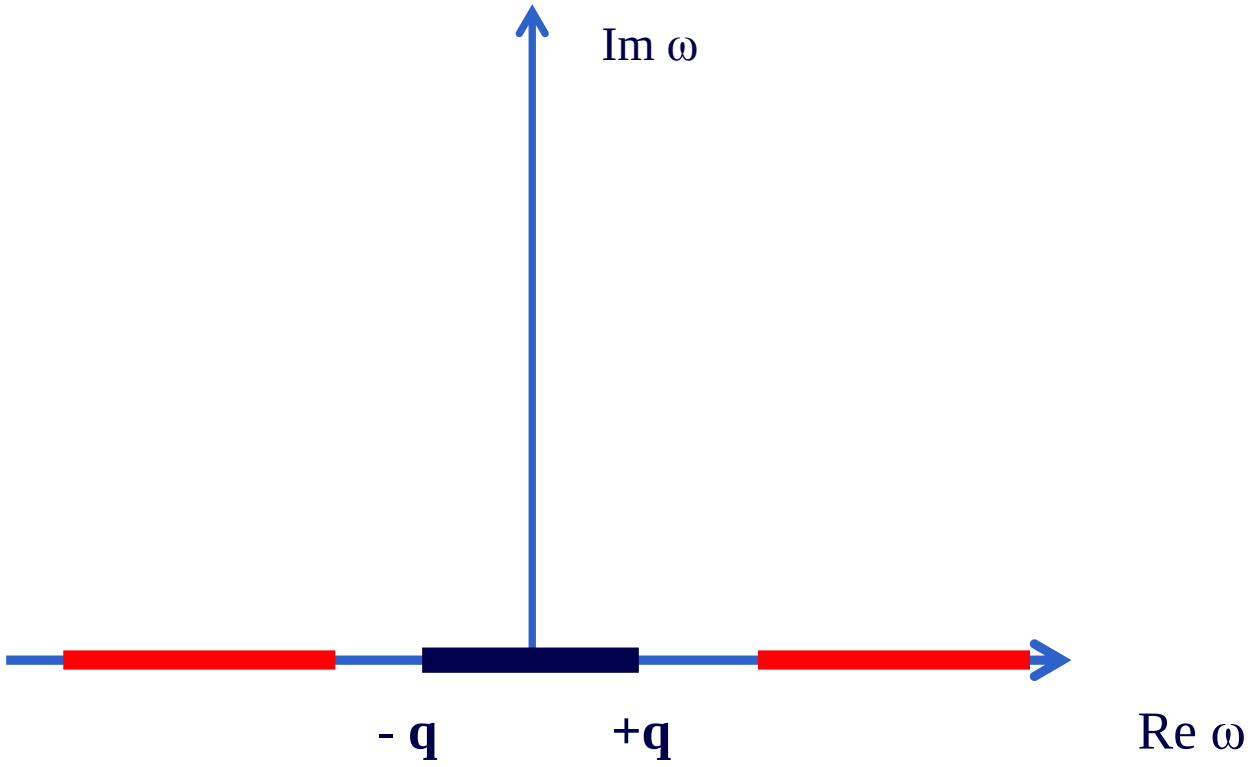

2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Γv (T) / T
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
T / Tc


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Γ_P (T) / T
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
T / T_c

CONFIRMATION FROM LQCD ???


$^1S_0$(pseudoscalar)
η_b
Γ/T
T/T_c
0
0.5
1
1.5
2


$^3S_1$(vector)
Upsilon
Γ/T
T/T_c
0
0.5
1
1.5
2


Im ω
- q
+q
Re ω

$$\mathrm{Im}\,\Pi(q^2,T) \propto \frac{\omega}{|\vec{q}|^3}\; F[n_F(T)]$$

$$-1 \le \frac{\omega}{|\vec{q}|} \le +1$$

$$\frac{\lim}{\substack{\omega \to 0 \\ |\vec{q}| \to 0}} \left(\frac{\omega}{|\vec{q}|^3}\right) = \frac{2}{3}\,\delta(\omega^2)$$

$$\mathrm{Im}\,\Pi^{+}(\omega, T) = \frac{1}{4\pi}\left[1 - 2n_F\left(\frac{\omega}{2T}\right)\right]$$

$$\mathrm{Im}\ \Pi^{-}(\omega, T) = \frac{4}{\pi}\delta(\omega^2)\int_0^{\infty} y n_F\left(\frac{y}{T}\right)dy = \frac{\pi}{3}T^2\delta(\omega^2)$$