DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN
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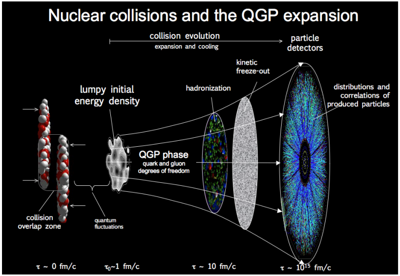
Di-Muon production in heavy ion collisions at LHC: A signal for Quark-Gluon deconfinement

Luis A. Hernandez and Prof. C. A. Dominguez

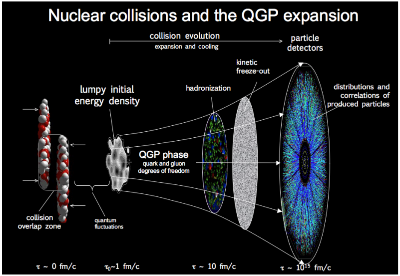
Department of Physics, University of Cape Town.

School of Subnuclear Physics.
Erice-Sicily, June 30 2015.



arXiv:0905.0174 by P. Sorensen

Electromagnetic probes.



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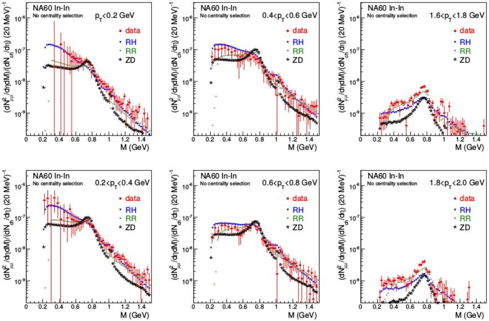

Eur. Phys. J. C **61**, 711 (2009) by R. Arnaldi, *et al.*

QCD Sum Rules.

The QCD Sum Rules are an analytical formalism, they include non-perturbative and perturbative information of QCD. Moreover, QCD Sum Rules are an excellent complement to numerical studies done with Lattice QCD.

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Operator Product Expansion (OPE).

The correlation function of these currents is introduced and treated in the framework of the OPE.

$$\Pi_0^{\mathsf{QCD}}(Q^2) = C_0\,\hat{I} + \sum_{N=1} \frac{C_{2N}(Q^2,\mu^2)}{Q^{2N}} \langle \hat{\mathcal{O}}_{2N}(\mu^2) \rangle \ .$$

OPE includes the short- and long-distance quark-gluon interaccions.

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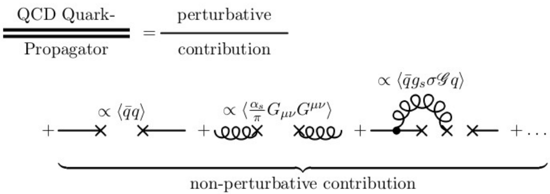

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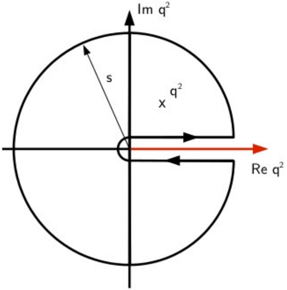
Cauchy's Theorem.



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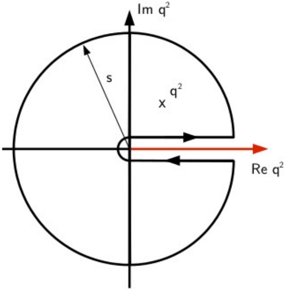

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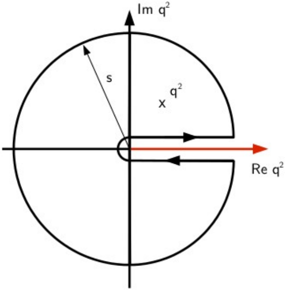

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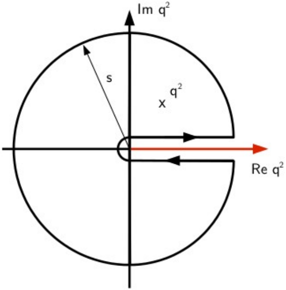

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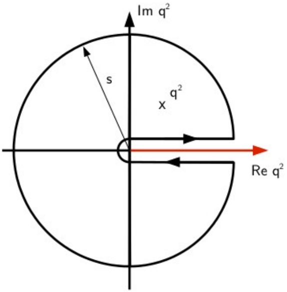

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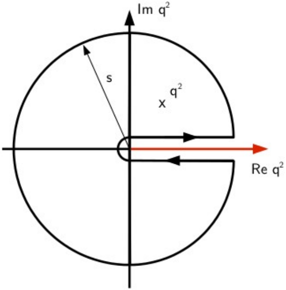

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Finite Energy QCD Sum Rules (FESR).

Time to join both sectors!!!

$$\int_0^{s_0} ds P(s) \frac{1}{\pi} \mathrm{Im}\Pi(s) = - \oint_{C(|s_0|)} ds P(s) \Pi^{OPE}(s).$$

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FESR.

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\end{aligned}$$

$$\begin{aligned}
(-1)^N C_{2N+2} \langle \widehat{O}_{2N+2} \rangle &= \int_0^{s_0} ds \; s^N \; \frac{1}{\pi} \mathrm{Im}\Pi^{HAD}(s) \\
&+ \frac{1}{2\pi i} \oint_{C(|s_0|)} ds \; s^N \; \Pi^{QCD}(s).
\end{aligned}$$

FESR at finite temperature.

- We work with QFT at finite temperature.

$$
\begin{aligned}
S_F(T=0) &= \frac{\not{k}+m}{k^2-m^2+i\epsilon}, \\
S_F(T) &= S_F(T=0) + 2\pi i \delta(k^2-m^2)(\not{k}+m) n_F(|k_0|), \\
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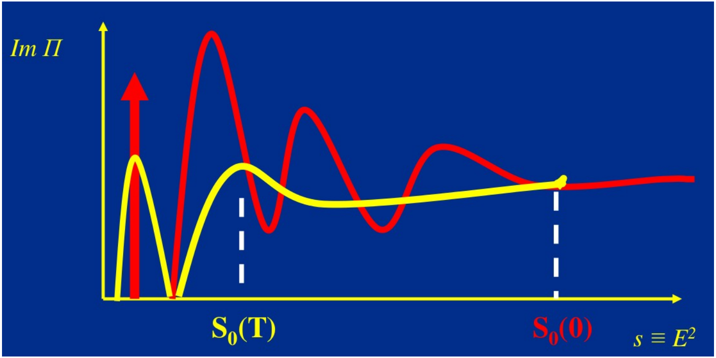
  Wilson coefficients acquire explicitly the thermal behavior.

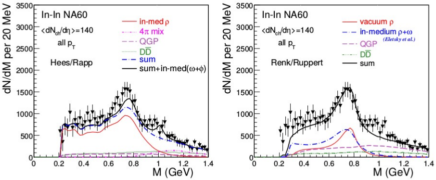
- Hadronic parameters develop thermal behaviour (Masses, coupling constants, resonance's widths).

- The parameter s_0 is thermal-dependent.



Qualitative parameter of deconfinement.

DIMUON PRODUCTION FROM IN-MEDIUM ρ DECAYS.



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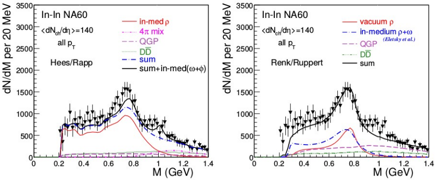

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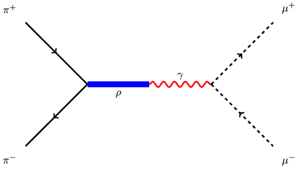

Vector Meson Dominance (VMD).

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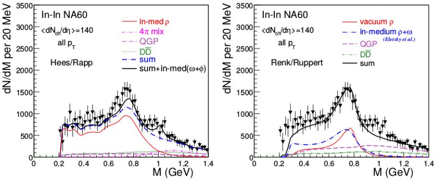

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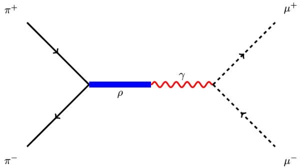

Vector Meson Dominance (VMD).

$\mathrm{Im}\Pi^{\mathrm{HAD}}(s)$ is related with the hadronic spectral function and the latter is well approximated by the Breit-Wigner form

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

Finite Sum Rules at finite temperture.

$$(-1)^{N-1}C_{2N}\langle O_{2N}\rangle = 8\pi^2\left[\int_0^{s_0} ds\ s^{N-1}\frac{1}{\pi}\mathrm{Im}\Pi^{\mathrm{HAD}}(s) - \frac{1}{2\pi i}\oint_{C(|s_0|)} ds\ s^{N-1}\Pi^{\mathrm{QCD}}(s)\right],$$

Dimuon production from in-medium ρ decays.

The solution from FESR for all hadronic parameters as a function of T are the following

$$
\begin{aligned}
\Gamma_\rho(T) &= \Gamma_\rho(0)[1-(T/T_c)^3]^{-1}, \\
M_\rho(T) &= M_\rho(0)[1-(T/T^*_M)^{10}], \\
f_\rho(T) &= f_\rho(0)[1-0.3901(T/T_c)^{10.75} \\
&+ 0.04155(T/T_c)^{1.27}].
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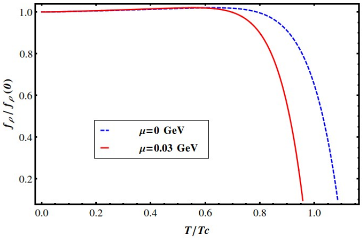
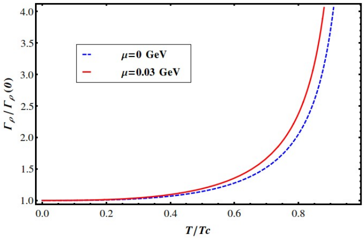


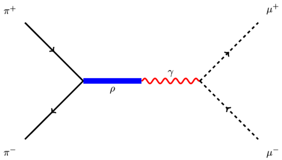
Temperature behaviour of f_ρ



Temperature behaviour of Γ_ρ

Dimuon production from in-medium ρ decays.

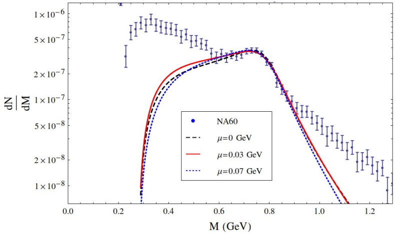
With the solution from the FESR, we proceed to compute the dimuon thermal rate in the hadronic phase originating from ρ decays. (We consider processes where pions annihilate into ρ which in turn decay into dimuons by means vector dominance.)



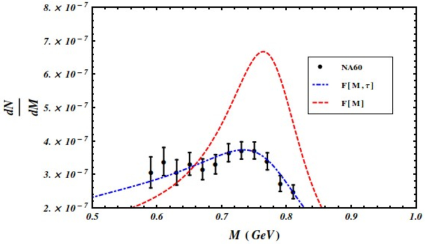
$$\frac{dN}{d^4x d^4K} = \frac{\alpha^2}{48\pi^4}\left(1+\frac{2m^2}{M^2}\right)\left(1-\frac{4m_\pi^2}{M^2}\right)\times\sqrt{1-\frac{4m^2}{M^2}}\,e^{-K_0/T}\mathcal{R}(K,T)\,\mathrm{Im}\Pi_0^{\mathrm{res}}(M^2),$$

DIMUON PRODUCTION FROM IN-MEDIUM ρ DECAYS.

Non-model dependence result but directly from the perturbative and non-perturbative QCD information.



Invariant dimuon mass distribution comparated to NA60 data.



(Linear scale) Invariant dimuon distribution around ρ-meson peak comparated to NA60 data.

Thank you!!!

For more information and details:

- A. Ayala and C. A. Dominguez and L. A. Hernandez and M. Loewe and M. J. Mizher, Phys. Rev. **D**88, 114028, (2013)
- A. Ayala and C. A. Dominguez and M. Loewe and Y. Zhang, Phys. Rev. **D**86, 114036, (2012)

Backup

- QCD Sum Rules was developed more than 30 years ago by Shifman, Vainshtein and Zakharov (SVZ).
- light-quark vector current correlator, which at $T = 0$ can be written as

$$\begin{aligned}\Pi_{\mu\nu}(q^2) &= i\int d^4x e^{iq\cdot x}\langle 0|T\left[\mathcal{V}_\mu(x)\mathcal{V}_\nu^\dagger(0)\right]|0\rangle \\ &= \left(-g_{\mu\nu} + q_\mu q_\nu\right)\Pi_1(q^2),\end{aligned}$$

  where $\mathcal{V}_\mu(x) = (1/2)[:\bar{u}(x)\gamma_\mu u(x) - \bar{d}(x)\gamma_\mu d(x):]$ is the conserved vector current and q_μ is the four-momentum transfer.
- In the thermal perturbative QCD sector, only one-loop contributions can be taken into account, since the problem of the appearance of two scales, i.e. the short-distance QCD scale and the critical temperature T_c, remains unsolved.

- $\Gamma_\rho(0) = 0.145\ GeV$, $M_\rho(0) = 0.776\ GeV$, $T_c = 0.197\ GeV$ and $f_\rho(0) = 5$
- In order to extend this analysis to finite chemical potencial we first incorporate the μ dependence into the pQCD sector, which involves a quark loop. This modifies the corresponding Fermi-Dirac distribution, splitting it into particle-antiparticle contributions. And we incorporate the μ dependence of the critical temperature T_c. For this, we use a Schwinger-Dyson approach, a parametrization for the crossover transition line between chiral-symmetry-restored and -broken phases.

$$T_c(\mu) = T_c(\mu = 0) - 0.218\mu - 0.139\mu$$

The rate is given by

$$\frac{dN}{d^4x d^4K}=\frac{\alpha^2}{48\pi^4}\left(1+\frac{2m^2}{M^2}\right)\left(1-\frac{4m_\pi^2}{M^2}\right)\times\sqrt{1-\frac{4m^2}{M^2}}e^{-K_0/T}\mathcal{R}(K,T)\mathrm{Im}\Pi_0^{\mathsf{res}}(M^2),$$

where N is the number of muon pairs per unit of infinitesimal space-time and energy-momentum volume, with x^μ the space-time coordinate and K^μ the four-momentum of the muon pairs, α is the electromagnetic coupling, m is the muon mass, m_π is the pion mass and M is the dimuon invariant mass. And

$$\begin{aligned}\mathcal{R} &= \frac{T/K}{1-e^{-K_0/T}} \\ &\times \ln\left[\left(\frac{e^{-E_{\mathsf{max}}/T}-1}{e^{-E_{\mathsf{min}}/T}-1}\right)\left(\frac{e^{E_{\mathsf{min}}/T}-e^{-K_0/T}}{e^{E_{\mathsf{max}}/T}-e^{-K_0/T}}\right)\right],\end{aligned}$$

with

$$E_{\text{max}} = \frac{1}{2}\left[K_0 + K\sqrt{1-4m_\pi^2/M^2}\right]$$
$$E_{\text{min}} = \frac{1}{2}\left[K_0 - K\sqrt{1-4m_\pi^2/M^2}\right].$$

In order to integrate the dimoun thermal rate, we use

$$d^4K = \frac{1}{2}dM^2 d^2K_\perp dy$$
$$d^4x = \tau d\tau d\eta d^2x_\perp,$$

where y and η are the momentum-space and coordinate-space rapidities, respectively and $\tau = \sqrt{t^2 - z^2}$. To relate the temperature change to the time evolution of the system, we neglect a possible small transverse expansion, assume it entirely longitudinal, and use the cooling law

$$T = T_0\left(\frac{\tau_0}{\tau}\right)^{v_s^2},$$

where $v_s^2 = 1/3$ is the square of the sound velocity for an ideal hadron gas. The evolution is taken down to a freeze-out temperature T_f. Also, we consider perfect correlation between η and y ($\eta = y$). The invariant mass distribution becomes

$$\frac{dN}{dMdy} = \Delta y M \int_{\tau_0}^{\tau_f} \tau d\tau \int d^2K_\perp \int d^2x_\perp \frac{dN}{d^4xd^4K}.$$