DI-MUON PRODUCTION IN HEAVY-ION COLLISIONS: A SIGNAL FOR QUARK-GLUON DECONFINEMENT

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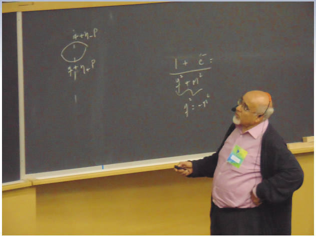
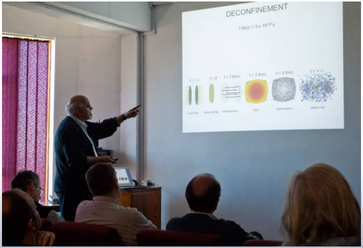
December 05, 2017
Loewe's fest (Conference on non perturbative QFT)

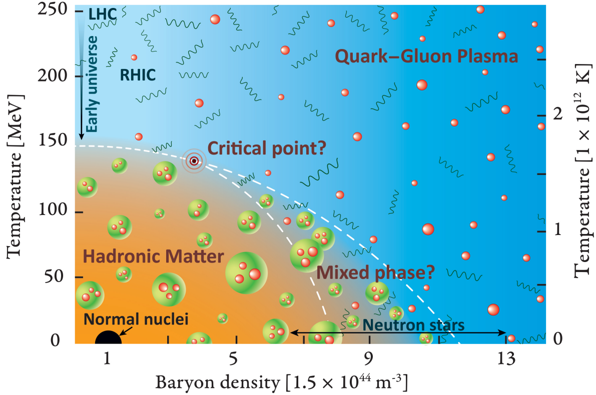
Pontificia Universidad Católica de Chile.

Happy birthday Marcelo!!!

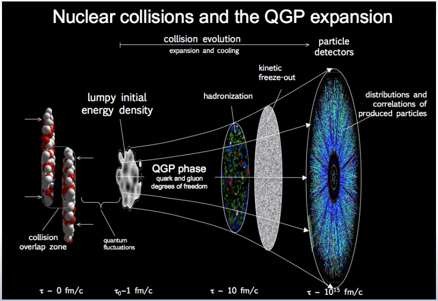




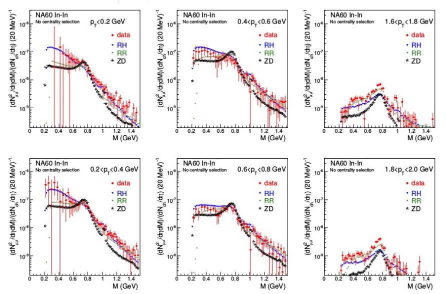
Strongly interacting matter in extreme conditions.



Electromagnetic probes.



arXiv:0905.0174 by P. Sorensen



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

QCD Sum Rules.

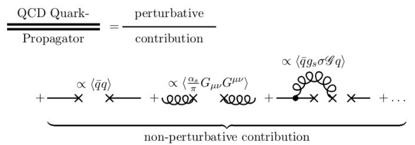
The QCD Sum Rules are an analytical formalism, they include non-perturbative and perturbative information of QCD.

Operator Product Expansion (OPE).

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

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

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



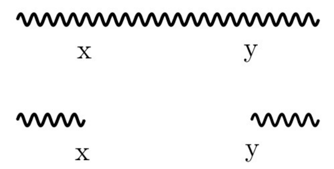
QCD Sum Rules.

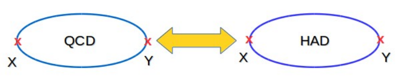
QCD information is then matched to a sum over hadronics states.
where

$$\Pi(q^2) = i \int d^4x e^{iqx} \langle 0| T(J(x) J^\dagger(0))|0\rangle.$$

Correlation function in QFT.

$$\langle 0| T(J(y) J^\dagger(x))|0\rangle.$$

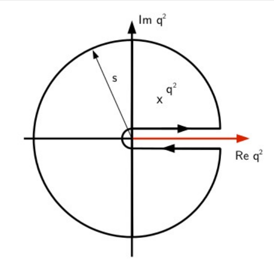




QCD Sum Rules.

$$\Pi_0^{QCD}(Q^2) \Leftrightarrow \Pi_0^{HAD}(Q^2)?$$

Cauchy's Theorem.



- The discontinuity across the real axis brings in the hadronic spectral function.
- Integration around the circle involves the QCD correlator.
- **The radius of the circle (typically named s_0) is the onset of pQCD**.

Finite Energy QCD Sum Rules (FESR).

FESR.

Time to join both sectors!!!

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

$$\begin{aligned}\int_0^{s_0} ds P(s) \frac{1}{\pi} \mathrm{Im}\Pi(s) &= -\oint_{C(|s_0|)} ds P(s) C_0 \hat{I} \\ &- \sum_{N=1} \oint_{C(|s_0|)} ds P(s) \frac{C_{2N}(Q^2,\mu^2)}{Q^{2N}} \langle \hat{O}_{2N}(\mu^2) \rangle .\end{aligned}$$

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

FESR at finite temperature.

- We work with QFT at finite temperature.

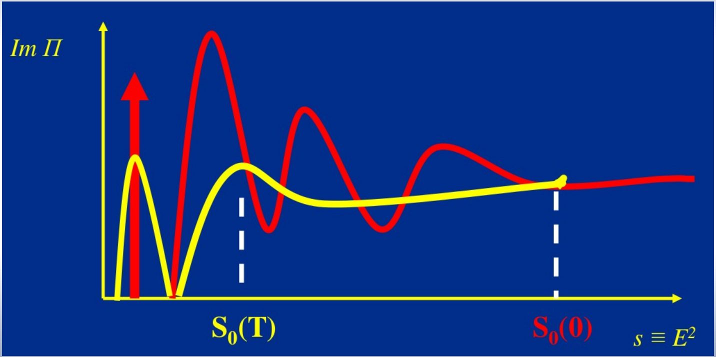
$$
\begin{aligned}
S_F(T=0) &= \frac{\not{k}+m}{k^2-m^2+i\epsilon}, \\
S_F(T) &= S_F(T=0) + 2\pi i\delta(k^2-m^2)(\not{k}+m)n_F(|k_0|), \\
D_B(T=0) &= \frac{i}{p^2-m^2+i\epsilon}, \\
D_B(T) &= D_B(T=0) + 2\pi\delta(p^2-m^2)n_B(|k_0|).
\end{aligned}
$$

  Wilson coefficients acquire explicitly the thermal behavior.

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

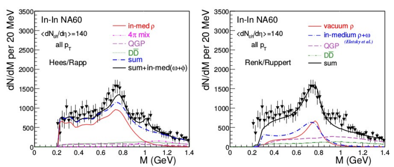
FESR at finite temperature.

- The parameter s_0 is thermal-dependent.



Qualitative parameter of deconfinement.

Di-muon production from in-medium ρ decays.



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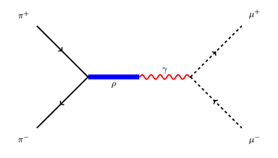


Vector Meson Dominance (VMD).

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

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

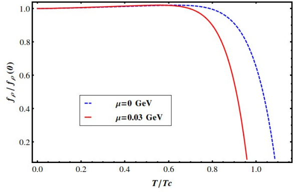
Finite Sum Rules at finite temperature.

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

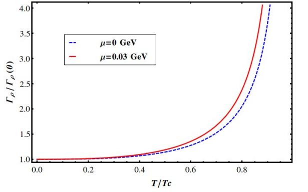
Di-muon production from in-medium ρ decays.

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

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



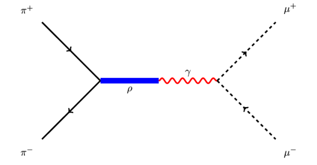
Temperature behaviour of f_ρ



Temperature behaviour of Γ_ρ

Di-muon production from in-medium ρ decays.

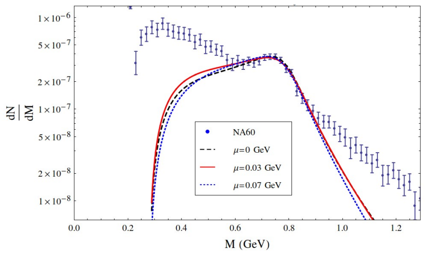
With the solution from the FESR, we proceed to compute the di-muon thermal rate in the hadronic phase originating from ρ decays. (We consider processes where pions annihilate into ρ which in turn decay into di-muon by means vector dominance.)



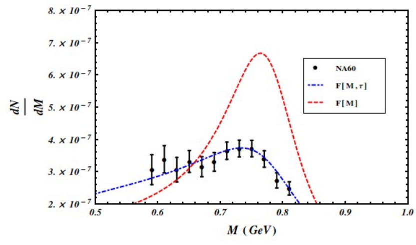
$$\frac{dN}{d^4xd^4K}=\frac{\alpha^2}{48\pi^4}\left(1+\frac{2m^2}{M^2}\right)\left(1-\frac{4m_\pi^2}{M^2}\right)\times\sqrt{1-\frac{4m^2}{M^2}}\,e^{-K_0/T}\mathcal{R}(K,T)\,\mathrm{Im}\Pi_0^{res}(M^2),$$

Di-muon production from in-medium ρ decays.

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



Invariant di-muon mass distribution compared to NA60 data.



(Linear scale) Invariant di-muon distribution around ρ-meson peak compared 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. D88, 114028, (2013)
- A. Ayala and C. A. Dominguez and M. Loewe and Y. Zhang, Phys. Rev. D86, 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

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

  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.

Backup

- $\Gamma_\rho(0) = 0.145\ GeV$, $M_\rho(0) = 0.776\ GeV$, $T_c = 0.197\ GeV$ and $f_\rho(0) = 5$
- In order to extend this analysis to finite chemical potential 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.

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

Backup

The rate is given by

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

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 di-muon invariant mass. And

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

Backup

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 di-moun 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

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

Backup

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

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