Searching for P- and CP-odd effects in heavy ion collisions

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Publications

Collaboration with A. Andrianov, V. Andrianov and X. Planells

Some publications:

- A. A. Andrianov, V. A. Andrianov, D. Espriu & X. Planells, Phys. Lett. B 710 (2012) 230.
- A. A. Andrianov, D. Espriu & X. Planells, Eur. Phys. J. C 73 (2013) 2294.
- A. A. Andrianov, D. Espriu & X. Planells, Eur. Phys. J. C 74 (2014) 2776.
- A. A. Andrianov, V. A. Andrianov, D. Espriu & X. Planells, Phys. Rev. D 90 (2014) 034024.

Outline

- Why P and CP might not be good symmetries in HIC
- Effective meson theory in a medium with LPB
- Possible Manifestations of P-odd effects in HIC
  - Dalitz decays in a P-odd environment
  - ρ broadening
  - In-medium $V \to \ell^+\ell^-$ decays
  - Observables sensitive to P-odd effects
- Conclusions

Why considering P- and CP- odd effects in HIC?

Parity is one of the well established global symmetries of strong interactions. Yet there are reasons to believe that it may be broken. No fundamental principle forbids spontaneous parity breaking for $\mu \neq 0$

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  - A.B. Migdal, Zh. Eksp. Teor. Fiz. 61 (1971);
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  - A. A. Andrianov & D. Espriu, Phys. Lett. B 663 (2008) 450;
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Effective theory studies indicate that this phase is a real possibility at 'moderate' densities (3 to 8 $\times \rho_N$).
Surely relevant in astrophysical contexts but might possibly be present in HIC too.
However this is not the topic of today's presentation...

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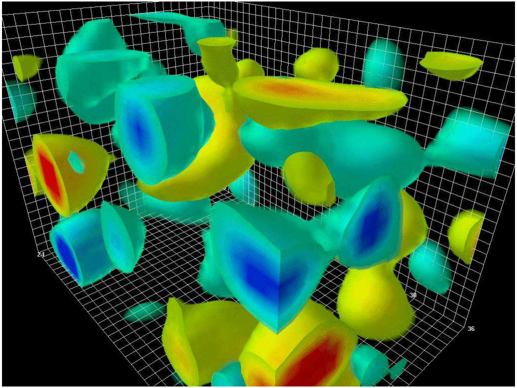
Violent local fluctuations in the topological charge may occur in a heavy ion collision



Lattice simulation of fluctuations in the local topological charge [Leinweber]

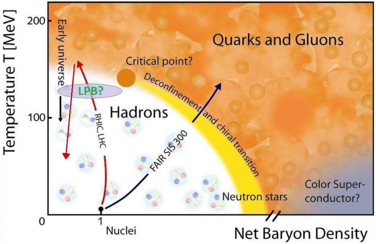
Motivation of local parity breaking

Local large fluctuations in the topological charge could exist in a hot environment and could generate a local imbalance of topological charge.

Temporarily, an effective CP- odd θ term may be generated.

For *peripheral* heavy ion collisions: may lead to the Chiral Magnetic Effect (CME): Large $\vec{B} \Rightarrow$ large $\vec{E} \Rightarrow$ charge separation.

For *central* collisions (and light quarks): may trigger an ephemeral phase with axial chemical potential $\mu_5 \neq 0$.



We will consider possible consequences in the hadronic phase.

Generating a chiral charge

Topological charge T_5 may arise in a finite volume due to quantum fluctuations in a hot medium due to sphaleron-like transitions

$$T_5 = \frac{1}{8\pi^2}\int_{\text{vol.}} d^3x \varepsilon_{jkl} \text{Tr}\left(G^j \partial^k G^l - i\frac{2}{3} G^j G^k G^l\right)$$

and survive for a sizeable lifetime in a heavy-ion fireball.
Introduce a topological chemical potential μ_θ into the QCD lagrangian via $\Delta\mathcal{L}_{top} = \mu_\theta \Delta T_5$

$$\Delta T_5 = T_5(t_f) - T_5(t_i) = \frac{1}{8\pi^2}\int_{t_i}^{t_f} dt \int_{\text{vol.}} d^3x \text{Tr}\left(G^{\mu\nu}\widetilde{G}_{\mu\nu}\right).$$

PCAC predicts the induced axial charge to be conserved during $\tau_{fireball}$ in the chiral ($m = 0$) limit:

$$\frac{d}{dt}\left(Q_5^q - 2N_f T_5\right) \simeq 0, \quad Q_5^q = \int_{\text{vol.}} d^3x \bar{q}\gamma_0\gamma_5 q = \langle N_L - N_R \rangle$$

Valid for lightest (u and d) quarks only.

Effective meson theory in a medium with LPB

We have two possible isospin structures for μ_5:

- Isosinglet pseudoscalar background ($T \gg \mu$) [RHIC, LHC]
- Isotriplet and/or isosinglet pseudoscalar background ($\mu \gg T$) [FAIR, NICA]

Only the first case will be considered in this talk.

We will now build an effective theory for mesons in a P- and CP-odd environment.
We will deal in turn with scalars and vector mesons.

The scalar sector can be estimated by using the spurion technique in the Lagrangian

$$D_\mu \Longrightarrow D_\mu - i\{\mu_5 \delta_{0\mu}, \cdot\} \qquad D = 2$$

and constructing a generalised sigma model with the light scalar mesons $\sigma, \vec{\pi}, \eta, \eta', \vec{a}_0$

Due to parity breaking there is mixing in the $\sigma - \eta - \eta'$ and $\vec{\pi} - \vec{a}_0$ channels.

The new eigenstates do not have a well defined parity. The resulting $J = 0$ eigenstates are all coupled to $\pi\pi$ due to the strong mixing with the σ, and *thermalize* in the HIC fireball.

In this case the most relevant operator has $D = 3$. P- and CP-odd effects will appear through the Chern-Simons term:

$$\Delta\mathcal{L} \simeq \varepsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left[\hat{\zeta}_\mu V_\nu V_{\rho\sigma}\right]$$

with $\hat{\zeta}_\mu = \partial_\mu \hat{a}(\vec{x}, t) = \delta_{\mu 0}\partial_0 \hat{a}(t)$ (for a spatially homogeneous, time dependent background).

We shall assume $\partial_0 \hat{a}(t) \sim \hat{\zeta} \propto \mu_5$.

Vector mesons will be introduced and treated in the conventional way using the Vector Meson Dominance model.

For vector mesons here will be no mixing (at this order) but a distortion of the spectrum.

Note the breaking of Lorentz symmetry in both cases.

Vector Meson Dominance bosonization:

$$\mathcal{L}_{\rm int} = \bar{q}\gamma_\mu \hat{V}^\mu q; \quad \hat{V}_\mu \equiv -eA_\mu Q + \frac{1}{2}g_\omega \omega_\mu \mathbb{I} + \frac{1}{2}g_\rho \rho^0_\mu \tau_3,$$

where $Q = \frac{\tau_3}{2} + \frac{1}{6}$, $g_\omega \simeq g_\rho \equiv g \simeq 6.$

Maxwell and mass terms

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} + \rho_{\mu\nu}\rho^{\mu\nu}\right) + \frac{1}{2}V_{\mu,a}(\hat{m}^2)_{a,b}V^\mu_b$$

$$\hat{m}^2 \simeq m_V^2 \begin{pmatrix} \frac{10e^2}{9g^2} & -\frac{e}{3g} & -\frac{e}{g} \\ -\frac{e}{3g} & 1 & 0 \\ -\frac{e}{g} & 0 & 1 \end{pmatrix}$$

P-odd interaction

$$\mathcal{L}_{P-odd}(k) = -\frac{1}{4}\varepsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}\left(\hat{\zeta}_\mu \hat{V}_\nu \hat{V}_{\rho\sigma}\right) = \frac{1}{2}\zeta\epsilon_{jkl}\, V_{j,a}\, N_{ab}\, \partial_k V_{l,b}$$

For an isosinglet pseudoscalar background:

$$(N^\theta_{ab}) \simeq \begin{pmatrix} \frac{10e^2}{9g^2} & -\frac{e}{3g} & -\frac{e}{g} \\ -\frac{e}{3g} & 1 & 0 \\ -\frac{e}{g} & 0 & 1 \end{pmatrix}, \quad \det\left(N^\theta\right) = 0$$

Simultaneous diagonalization of the matrices $\hat{m}^2, N$

$$N = \mathrm{diag}\left[0,\,1,\,1+\frac{10e^2}{9g^2}\right] \simeq \mathrm{diag}\,[0,\,1,\,1]$$

$$\hat{m}^2 = m_V^2\,\mathrm{diag}\left[0,\,1,\,1+\frac{10e^2}{9g^2}\right] \simeq \mathrm{diag}\,[0,\,1,\,1]$$

After diagonalization the photon itself is unaffected.

Vector mesons exhibit the following dispersion relation:

$$m_{V,\epsilon}^2 = m_V^2 - \epsilon\zeta|\vec{k}|,$$

where $\epsilon = 0, \pm 1$ is the meson polarization.

The position of the poles for $\pm$ polarized mesons is moving with wave vector $|\vec{k}|$.

Massive vector mesons split into three polarizations with masses $m_{V,+}^2 < m_{V,L}^2 < m_{V,-}^2$.

This splitting unambiguously signifies P breaking. Can it be measured?

Possible manifestations of P-odd effects in HIC

Look for e.m. probes $\Rightarrow$ 'anomalies' in dilepton production

$$\rho, \omega \to e^+ e^-.$$

The total dilepton production also receives potential contribution from the pseudoscalar Dalitz decays

$$\eta, \eta' \to \gamma e^+ e^-,$$

and the ω Dalitz decay

$$\omega \to \pi^0 e^+ e^-,$$

Results computed using PHENIX experimental cuts: $|y_{ee}| < 0.35$, $|\vec{p}_t^e| > 200$ MeV and gaussian M_{ee} smearing (width=10 MeV); and an effective temperature $T = 220$ MeV.

In fact dilepton production shows a number of anomalies...

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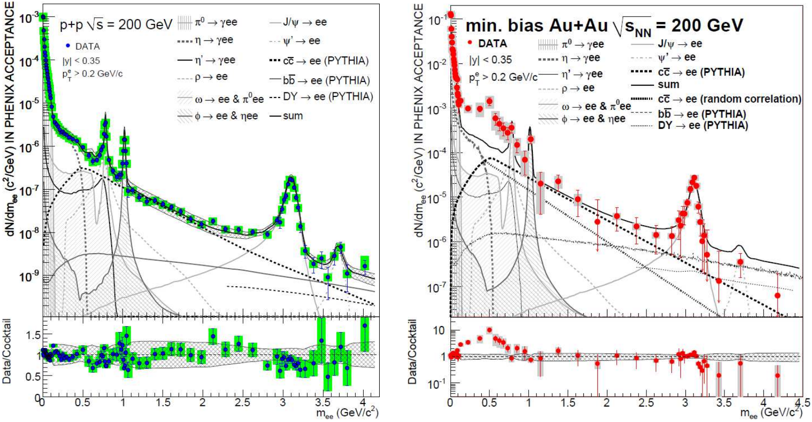
Manifestation of LPB in heavy ion collisions



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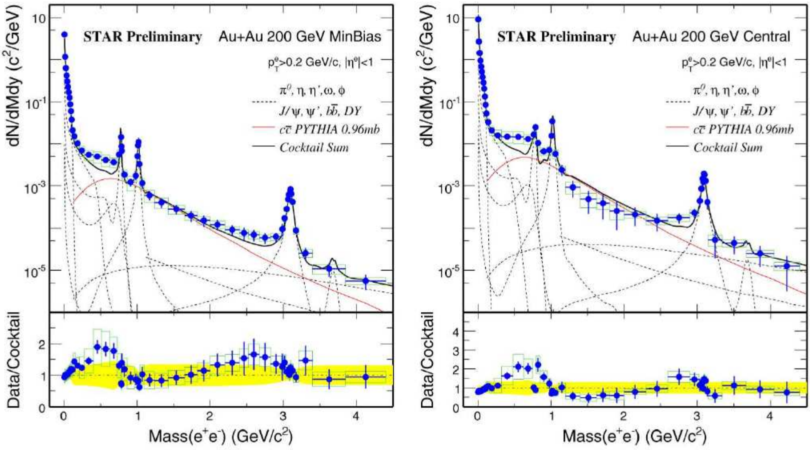
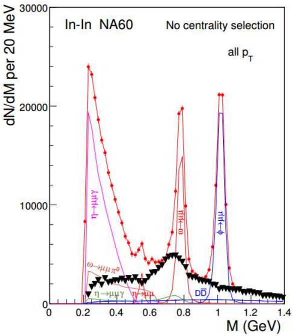
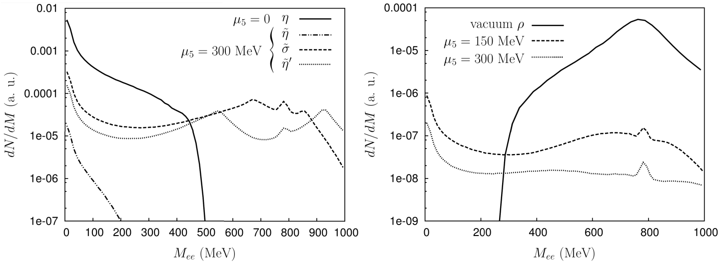


A large broadening of the ρ spectrum was measured by the NA60 collaboration several years ago



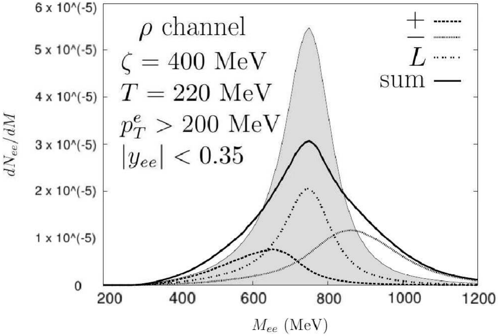
It is claimed that the broadening can be understood by 'conventional' physics...



Clearly insufficient to explain the enhancement in PHENIX in the region 200-500 MeV but it helps a little in STAR data.

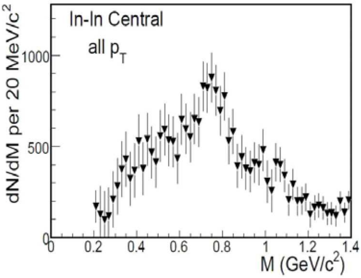
ρ broadening

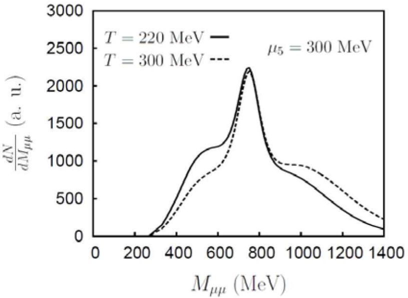
P-odd effects introduce broadening in a natural manner.



Polarization splitting in ρ spectral function for LPB $\zeta = 400$ MeV ($\mu_5 = 290$ MeV) compared with $\zeta = 0$ (shaded region).

And indeed the peculiar shape of the ρ spectrum measured by NA60 is grossly reproduced:

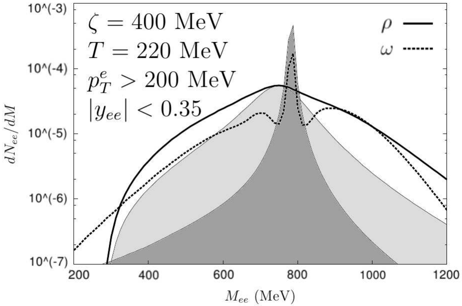




Only one parameter is fitted — the value of μ_5.

Putting together the ρ and ω mesons

In-medium ρ and ω channels (solid and dashed line) and their vacuum contributions (light and dark shaded regions) for $\mu_5 = 290$ MeV.



Enhancement of the dilepton yield that could (at least partly) explain the anomalous enhancement seen by PHENIX and STAR.

Angular analysis of $V \to \ell^+\ell^-$ decays

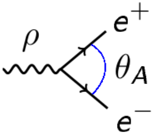
One of the clearest signals of P-odd effects is the separation between polarizations.

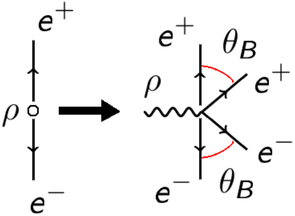
Is there any way to study these decays in order to separate the different polarizations?

It is well known that the angular distribution of leptons carries the information on the polarization. However, current angular distribution studies are not thought to detect possible P-odd effects.

We will define the two following angles:

Case A: θ_A is the angle between the two outgoing leptons in the laboratory frame.

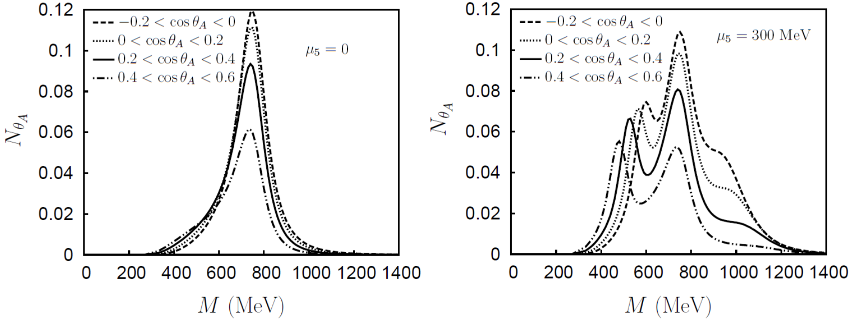




Case B: θ_B is the angle between one of the two outgoing leptons in the laboratory frame and the same lepton in the dilepton rest frame.

In order to isolate the transverse polarizations, we will perform different cuts for each angle and study the variations of the ρ (and ω) spectral function.

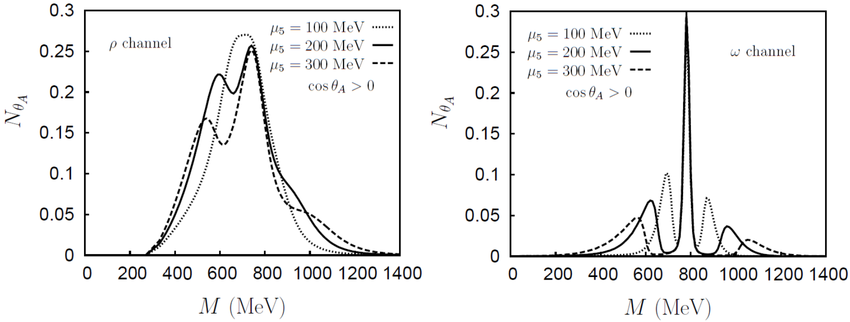
Angle θ_A between the two outgoing leptons in the laboratory frame.



ρ spectral function depending on the dielectron invariant mass M in vacuum ($\mu_5 = 0$) and in a parity-breaking medium with $\mu_5 = 300$ MeV for different ranges of θ_A.

Visible secondary peak in a P-odd medium! Important reduction of the number of events: the vacuum peak shows at most $\simeq 10\%$ of the events one would expect without any cut in θ_A.

If the secondary peak was found for a particular angular coverage, its position would be an unambiguous measurement of μ_5.

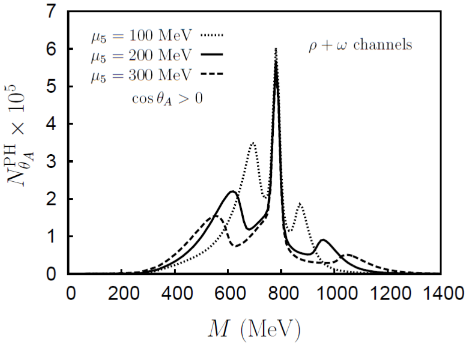


ρ and ω spectral functions depending on the invariant mass M and integrating $\cos\theta_A \geq 0$ for $\mu_5 = 100, 200$ and 300 MeV.

The vacuum ρ peak hides the secondary one for $\mu_5 \simeq 100$ MeV due to its large width. For ω, all the peaks are visible.

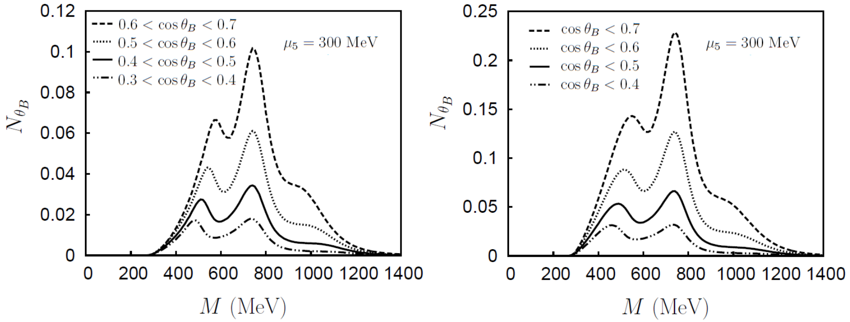
Angular analysis of $V \to \ell^+\ell^-$ decays
CASE A

We also present the combination of the ρ and ω channels. In this case, the total production is normalized to PHENIX data.



Combination of ρ and ω spectral functions depending on the invariant mass M and integrating $\cos\theta_A \geq 0$ for $\mu_5 = 100, 200$ and 300 MeV.

Angle θ_B between one of the two outgoing leptons in the laboratory frame and the same lepton in the dilepton rest frame.



ρ spectral function depending on the invariant mass M for different ranges of θ_B for fixed $\mu_5 = 300$ MeV.

The main difference with θ_A is a slightly smaller number of events. The rest of the analysis is completely equivalent.

Conclusions

- P- and CP-odd effects not forbidden by any physical principle in QCD at finite temperature/density.
- Topological fluctuations transmit their influence to hadronic physics via an axial chemical potential.
- P- breaking leads to unexpected modifications of the in-medium properties of scalar and vector mesons.
- LPB has an influence on the observed dilepton spectrum in the LMR of PHENIX and STAR.
- Some observables may allow us to establish P- and CP-breaking unambiguously.

Experimental collaborations should check this possibility.

Thank you for your attention!

Why lightest quarks?

The characteristic left-right oscillation time is governed by inverse quark masses.

- For u, d quarks $1/m_q \sim 1/5 \text{ MeV}^{-1} \sim 40 \text{ fm} \gg \tau_{\text{fireball}}$ and the left-right quark mixing can be neglected.
- For s quark $1/m_s \sim 1/150 \text{ MeV}^{-1} \sim 1 \text{ fm} \ll \tau_{\text{fireball}}$ and $\langle Q_5^s \rangle \simeq 0$ due to left-right oscillations.

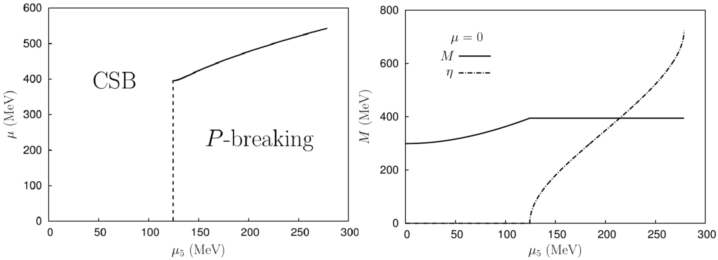
For u, d quarks QCD with a background topological charge leads to the generation of an axial chemical potential μ_5, conjugate to Q_5^q

$$\langle \Delta T_5 \rangle \simeq \frac{1}{2N_f} \langle Q_5^q \rangle \iff \mu_5 \simeq \frac{1}{2N_f} \mu_\theta,$$

$$\Delta \mathcal{L}_{top} = \mu_\theta \Delta T_5 \iff \Delta \mathcal{L}_q = \mu_5 Q_5^q$$

Large enough values of μ_5 trigger the appeareance of a a pseudoscalar isosinglet condensate.

E.g. in the Nambu-Jona-Lasinio model [AEP 1310.4416]:



Angular analysis of $V \to \ell^+\ell^-$ decays

The $L, \pm$ contribution for vector mesons decaying into leptons before applying experimental cuts is given by:

$$\frac{dN^{\epsilon}_{ee}}{dM} \simeq c_V \frac{\alpha^2 \Gamma_V m_V^2}{3\pi^2 g^2 M^2} \left(\frac{M^2 - n_V^2 m_\pi^2}{m_V^2 - n_V^2 m_\pi^2} \right)^{3/2}$$

$$\times \sum_{\epsilon} \int_M^\infty dk_0 \frac{\sqrt{k_0^2 - M^2}}{e^{k_0/T} - 1} \frac{m^4_{V,\epsilon}}{\left(M^2 - m^2_{V,\epsilon} \right)^2 + m^4_{V,\epsilon} \frac{\Gamma_V^2}{m_V^2}},$$

where $n_V = 2, 0$; $|\vec{k}| = \sqrt{k_0^2 - M^2}$ and $M^2 > n_V^2 m_\pi^2$. c_V absorbs combinatorial factors different for ρ and ω, μ and finite volume suppression. Empirically for $\mu_5 = 0$ the ratio $c_\rho / c_\omega \sim 10$ holds.

LPB polarization analysis

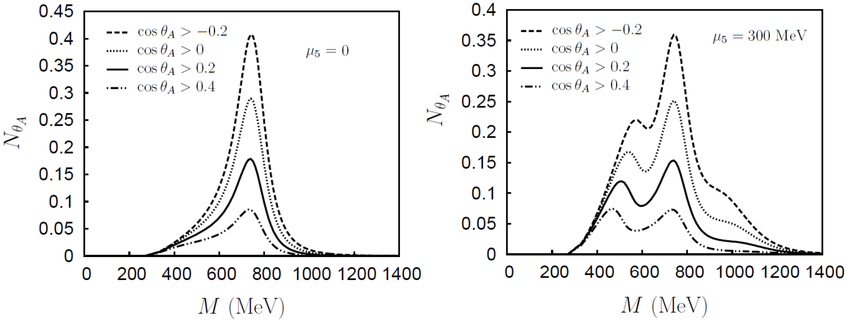
We will perform a two-dimensional study of the decay product with the dielectron invariant mass M_{ee} and one of the angles θ_A or θ_B

The overall constants c_V are chosen so that after integrating the entire phase space (except for experimental cuts) the total production at the vacuum resonance peak is normalized to 1:

$$N_\theta = \frac{\int_{\Delta\theta} \frac{dN}{dMd\cos\theta}(M, \cos\theta)\, d\cos\theta}{\int_{-1}^{+1} \frac{dN}{dMd\cos\theta}(M = m_V, \cos\theta)\, d\cos\theta}.$$

This choice will help us to quantify the number of events found when the phase space is restricted by our own cuts in θ.

Dealing with quantities smaller than 10% may be tricky. The main information is focused in $\cos\theta_A \approx 1$ so we integrate up to this value in wider bins.



ρ spectral function depending on the dielectron invariant mass M in vacuum ($\mu_5 = 0$) and in a parity-breaking medium with $\mu_5 = 300$ MeV for different ranges of θ_A.

Optimization process required in every different experiment.

Little relevance of setting individual cuts in the lepton rapidity (as opposed to the pair = vector meson)