PASSING THE BOUNDARY BETWEEN THE PARITY BREAKING MEDIUM AND VACUUM BY VECTOR PARTICLES

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- Introduction.
- The statement of the problem.
- Two vacua. Bogolubov transformation.
- Classical solutions.
- Spatial CS vector (axion stars).
- Time-like CS vector (collision of heavy ions).
- Conclusion.

Dark Energy

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Fermi-LAT, PAMELA, AMS-2: anomalous excess of e^+e^-.

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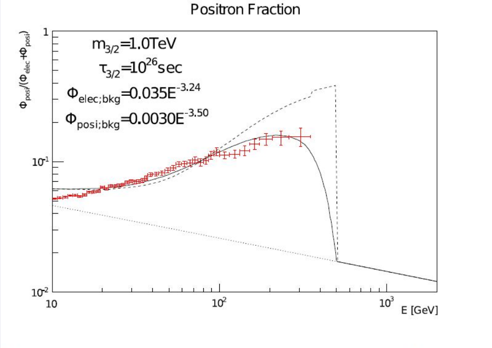
arXiv:1304.1483 [hep-ph]



l: *The positron fraction expected in the decaying gravitino dark matter*

Introduction

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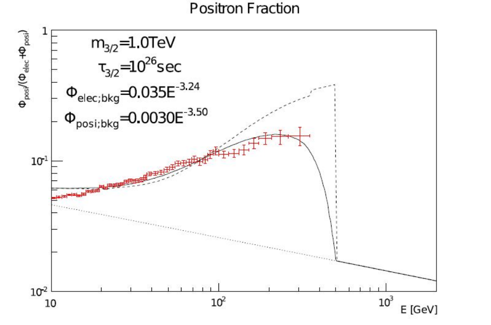

l: The positron fraction expected in the decaying gravitino dark matter

Heavy ion physics

NA60, PHENIX: abnormal yield of lepton pairs (e, μ)

The statement of the problem

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4}\,F^{\alpha\beta}(x)F_{\alpha\beta}(x) - \frac{1}{4}\,F^{\mu\nu}(x)\widetilde{F}_{\mu\nu}(x)\,a_{c\ell}(x) \\
&+ \frac{1}{2}\,m^2\,A_\nu(x)A^\nu(x) + A^\mu(x)\,\partial_\mu B(x) + \frac{1}{2}\,\varkappa\,B^2(x),
\end{aligned}
$$

$$\mathcal{L} = -\tfrac{1}{4} F^{\alpha\beta}(x) F_{\alpha\beta}(x) - \tfrac{1}{4} F^{\mu\nu}(x) \widetilde{F}_{\mu\nu}(x)\, a_{c\ell}(x) + \tfrac{1}{2} m^2 A_\nu(x) A^\nu(x) + A^\mu(x)\, \partial_\mu B(x) + \tfrac{1}{2} \varkappa B^2(x),$$

We consider a slowly varying classical pseudoscalar background of the kind,

$$a_{c\ell}(x) = \zeta_\lambda x^\lambda\, \theta(-\zeta \cdot x)$$

$$\begin{cases} \Box A^\nu(x) + m^2 A^\nu(x) = \varepsilon^{\nu\alpha\rho\sigma} \zeta_\alpha\, \partial_\rho A_\sigma(x) & \text{for } \zeta \cdot x < 0; \\ \Box A^\nu(x) + m^2 A^\nu(x) = 0 & \text{for } \zeta \cdot x > 0. \end{cases}$$

Construction of the chiral polarization vectors

$$S^{\nu}_{\lambda} = \delta^{\nu}_{\lambda}\,\mathtt{D} + k^{\nu}\,k_{\lambda}\,\zeta^2 + \zeta^{\nu}\,\zeta_{\lambda}\,k^2 - \zeta\cdot k\,(\zeta_{\lambda}\,k^{\nu} + \zeta^{\nu}\,k_{\lambda}); \quad \mathtt{D} \equiv (\zeta\cdot k)^2 - \zeta^2\,k^2$$

Transversal polarizations are,

$$\boldsymbol{\pi}^{\mu\nu}_{\pm} \equiv \frac{S^{\mu\nu}}{2\,\mathtt{D}} \pm \frac{i}{2}\,\varepsilon^{\mu\nu\alpha\beta}\,\zeta_{\alpha}\,k_{\beta}\,\mathtt{D}^{-\frac{1}{2}}; \quad \varepsilon^{\mu}_{\pm}(k) = \boldsymbol{\pi}^{\mu\lambda}_{\pm}\,\epsilon^{(0)}_{\lambda}$$

Scalar and longitudinal polarizations,

$$\varepsilon^{\mu}_{S}(k) \equiv \frac{k^{\mu}}{\sqrt{k^2}}, \qquad \varepsilon^{\mu}_{L}(k) \equiv \left(\mathtt{D}\,k^2\right)^{-\frac{1}{2}}\left(k^2\,\zeta^{\mu} - k^{\mu}\,\zeta\cdot k\right)$$

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Spatial CS vector. $\zeta_{\mu} = (0, -\zeta_x, 0, 0)$

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Spatial CS vector. $\zeta_{\mu} = (0, -\zeta_x, 0, 0)$: dispersion laws

$$\begin{cases} k_{1L} = k_{10} = \sqrt{\omega^2 - m^2 - k_{\perp}^2} \\ k_{1\pm} = \sqrt{\omega^2 - m^2 - k_{\perp}^2 \mp \zeta_x\sqrt{\omega^2 - k_{\perp}^2}} \end{cases}$$

$\hat{k} = (\omega, k_2, k_3),\ \hat{x} = (x_0, x_2, x_3) : \hat{k}\cdot\hat{x} = -\omega x_0 + k_2 x_2 + k_3 x_3 .$

Proca-Stückelberg solution

$$A^{\mu}_{\mathrm{PS}}(x) = \int \mathrm{d}\hat{k}\,\theta(\omega^2 - k_{\perp}^2 - m^2) \sum_{r=1}^{3} \left[\mathbf{a}_{\hat{k},r}\, u^{\mu}_{\hat{k},r}(x) + \mathbf{a}^{\dagger}_{\hat{k},r}\, u^{\mu\,*}_{\hat{k},r}(x) \right]$$

$$u^{\nu}_{\hat{k},r}(x) = [\,(2\pi)^3\, 2k_{10}\,]^{-1/2}\, e^{\nu}_{r}(\hat{k})\, \exp\{\, i\, k_{10} x_1 + i\, \hat{k}\cdot\hat{x}\} \qquad (\, r = 1, 2, 3\,)$$

Chern-Simons solution

$$A^{\nu}_{\mathrm{CS}}(x) = \int \mathrm{d}\hat{k} \sum_{A=\pm,L} \theta(k_{1A}^2(\omega, k_{\perp})) \left[c_{\hat{k},A}\, v^{\nu}_{\hat{k}\,A}(x) + c^{\dagger}_{\hat{k},A}\, v^{\nu *}_{\hat{k}\,A}(x) \right]$$

$$v^{\nu}_{\hat{k}\,A}(x) = \left[\,(2\pi)^3\, 2k_{1A}\,\right]^{-\frac{1}{2}} \varepsilon^{\nu}_{A}(k)\ \exp\{\, i k_{1A}\, x_1 + i\hat{k}\cdot\hat{x}\} \quad (A = L, \pm)$$

$$\left[\, A^{\mu}_{\mathrm{PS}}(x) - A^{\mu}_{\mathrm{CS}}(x)\,\right] |_{\zeta\cdot x=0} = 0$$

Bogolubov Transformations

$$v^{\nu}_{\hat{k},A}(\hat{x}) = \sum_{s=1}^{3} \left[\alpha_{sA}(\hat{k})\, u^{\nu}_{\hat{k},s}(\hat{x}) - \beta_{sA}(\hat{k})\, u^{\nu *}_{\hat{k},s}(\hat{x})\right]$$

relations between the creation-destruction operators are,

$$\mathbf{a}_{\hat{k},\,r} = \sum_{A=\pm,L} \left[\alpha_{rA}(\hat{k})\, c_{\hat{k},A} - \beta^{*}_{rA}(\hat{k})\, c^{\dagger}_{\hat{k},A}\right]$$

$$c_{\hat{k},A} = \sum_{r=1}^{3} \left[\alpha^{*}_{Ar}(\hat{k})\, \mathbf{a}_{\hat{k},\,r} + \beta^{*}_{Ar}(\hat{k})\, \mathbf{a}^{\dagger}_{\hat{k},\,r}\right]$$

There are two different Fock vacua,

$$\mathbf{a}_{\hat{k},\,r}|0\rangle = 0 \qquad\qquad c_{\hat{k},A}\,|\,\Omega\,\rangle = 0$$

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There are two different Fock vacua,

$$\mathbf{a}_{\hat{k},\,r}|0\rangle = 0 \qquad c_{\hat{k},A}\,|\,\Omega\,\rangle = 0$$

$$\langle\, 0 \,|\, \mathbf{a}_{\hat{p},s}\, c^{\dagger}_{\hat{k},A}\,|\, 0\,\rangle = \delta(\hat{k} - \hat{p})\,\alpha_{As}(\hat{k})$$

The latter quantity can be interpreted as the relative probability amplitude that particle is transmitted from the left face to the right face.

Vacuum as a coherent state

$$|0\rangle_{\hat{k}} = \sum_{p,m,l=0}^{\infty} f_{pml} \frac{(c^{\dagger}_{\hat{k},+})^p (c^{\dagger}_{\hat{k},-})^m (c^{\dagger}_{\hat{k},L})^l}{\sqrt{p!m!l!}} \,|\,\Omega\,\rangle_{\hat{k}}$$

To find f_{pml} we use the equality $\mathbf{a}_{\hat{k},r}|0\rangle_{\hat{k}} = 0$.

Vacuum as a coherent state

$$|0\rangle_{\hat{k}} = \sum_{p,m,l=0}^{\infty} f_{pml} \frac{(c^{\dagger}_{\hat{k},+})^p (c^{\dagger}_{\hat{k},-})^m (c^{\dagger}_{\hat{k},L})^l}{\sqrt{p!m!l!}} \mid \Omega \rangle_{\hat{k}}$$

To find f_{pml} we use the equality $\mathbf{a}_{\hat{k},r}|0\rangle_{\hat{k}} = 0$.

$$|0\rangle_{\hat{k}} = \exp\left[\frac{\beta^*_{r+}(\hat{k})}{2\alpha_{r+}(\hat{k})}(c^{\dagger}_{\hat{k},+})^2 + \frac{\beta^*_{r-}(\hat{k})}{2\alpha_{r-}(\hat{k})}(c^{\dagger}_{\hat{k},-})^2 + \frac{\beta^*_{rL}(\hat{k})}{2\alpha_{rL}(\hat{k})}(c^{\dagger}_{\hat{k},L})^2\right] \mid \Omega \rangle_{\hat{k}}$$

$$\mid \Omega \rangle_{\hat{k}} = \exp\left[\frac{-\beta^*_{A1}(\hat{k})}{2\alpha^*_{A1}(\hat{k})}(\mathbf{a}^{\dagger}_{\hat{k},1})^2 + \frac{-\beta^*_{A2}(\hat{k})}{2\alpha^*_{A2}(\hat{k})}(\mathbf{a}^{\dagger}_{\hat{k},2})^2 + \frac{-\beta^*_{A3}(\hat{k})}{2\alpha^*_{A3}(\hat{k})}(\mathbf{a}^{\dagger}_{\hat{k},3})^2\right] |0\rangle_{\hat{k}}$$

Vacuum as a coherent state

In the correct normalization, $\langle 0|0\rangle = 1$, $\langle\Omega|\Omega\rangle = 1$.
Going to the continuum limit for $\hat{k}$,

$$|0\rangle = \exp\left[\int\left(\sum_{A=\pm,L}\frac{\beta^*_{rA}(\hat{k})}{2\alpha_{rA}(\hat{k})}(c^\dagger_{\hat{k},A})^2\theta(k^2_{1A}(\hat{k}))\right)d\hat{k}\right]|\,\Omega\,\rangle$$

$$|\,\Omega\,\rangle = \exp\left[\int\theta(\omega^2-m^2-k^2_\perp)\left(\sum_{r=1,2,3}\frac{-\beta^*_{Ar}(\hat{k})}{2\alpha^*_{Ar}(\hat{k})}(\mathbf{a}^\dagger_{\hat{k},r})^2\right)d\hat{k}\right]|0\rangle$$

Classical solutions

$\zeta_\mu = (0, -\zeta, 0, 0)$

$$\Box A^\nu + m^2 A^\nu + \zeta \varepsilon^{1\nu\sigma\rho} \theta(-x_1) \partial_\sigma A_\rho = 0$$

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A_1 may be found in the whole space,

$$A_1 = \int \frac{d\hat{k}}{(2\pi)^3} \; (\tilde{u}_{1\rightarrow}(\omega, k_2, k_3) e^{ik_{10}x_1} + \tilde{u}_{1\leftarrow}(\omega, k_2, k_3) e^{-ik_{10}x_1}) e^{i\hat{k}\hat{x}}$$

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Solution for A_ν ($\nu = 0, 2, 3$)

$$A_\nu = \int \frac{d\hat{k}}{(2\pi)^3} \; \tilde{A}_\nu e^{i\hat{k}\hat{x}}$$

$$\tilde{A}_\nu = \begin{cases} \tilde{u}_{\nu\rightarrow}(\omega, k_2, k_3)e^{ik_{10}x_1} + \tilde{u}_{\nu\leftarrow}(\omega, k_2, k_3)e^{-ik_{10}x_1}, \; x_1 > 0 \\ \sum_A \left[\tilde{v}_{\nu A\rightarrow}(\omega, k_2, k_3)e^{ik_{1A}x_1} + \tilde{v}_{\nu A\leftarrow}(\omega, k_2, k_3)e^{-ik_{1A}x_1}\right], \; x_1 < 0 \end{cases}$$

After the integration of the field equations over x_1 from $-\varepsilon$ to ε,

$$-k_{10}^2\left(-\frac{\tilde{u}_{0\rightarrow}-\tilde{u}_{0\leftarrow}}{ik_{10}}+\sum_A\frac{\tilde{v}_{0A\rightarrow}-\tilde{v}_{0A\leftarrow}}{ik_{1A}}\right)=i\zeta\left(k_2\sum_A\frac{\tilde{v}_{3A\rightarrow}-\tilde{v}_{3A\leftarrow}}{ik_{1A}}-k_3\sum_A\frac{\tilde{v}_{2A\rightarrow}-\tilde{v}_{2A\leftarrow}}{ik_{1A}}\right)$$

$$-k_{10}^2\left(-\frac{\tilde{u}_{2\rightarrow}-\tilde{u}_{2\leftarrow}}{ik_{10}}+\sum_A\frac{\tilde{v}_{2A\rightarrow}-\tilde{v}_{2A\leftarrow}}{ik_{1A}}\right)=-i\zeta\left(k_3\sum_A\frac{\tilde{v}_{0A\rightarrow}-\tilde{v}_{0A\leftarrow}}{ik_{1A}}+\omega\sum_A\frac{\tilde{v}_{3A\rightarrow}-\tilde{v}_{3A\leftarrow}}{ik_{1A}}\right)$$

$$-k_{10}^2\left(-\frac{\tilde{u}_{3\rightarrow}-\tilde{u}_{3\leftarrow}}{ik_{10}}+\sum_A\frac{\tilde{v}_{3A\rightarrow}-\tilde{v}_{3A\leftarrow}}{ik_{1A}}\right)=i\zeta\left(\omega\sum_A\frac{\tilde{v}_{2A\rightarrow}-\tilde{v}_{2A\leftarrow}}{ik_{1A}}+k_2\sum_A\frac{\tilde{v}_{0A\rightarrow}-\tilde{v}_{0A\leftarrow}}{ik_{1A}}\right)$$

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$$-k_{10}^2\left(-\frac{\tilde{u}_{3\rightarrow}-\tilde{u}_{3\leftarrow}}{ik_{10}}+\sum_A \frac{\tilde{v}_{3A\rightarrow}-\tilde{v}_{3A\leftarrow}}{ik_{1A}}\right)=i\zeta\left(\omega\sum_A \frac{\tilde{v}_{2A\rightarrow}-\tilde{v}_{2A\leftarrow}}{ik_{1A}}+k_2\sum_A \frac{\tilde{v}_{0A\rightarrow}-\tilde{v}_{0A\leftarrow}}{ik_{1A}}\right)$$

Moreover, all contributions from different polarizations to A are continuous,

$$\tilde{u}_{\nu\rightarrow}^{(A)}+\tilde{u}_{\nu\leftarrow}^{(A)}=\tilde{v}_{\nu A\rightarrow}+\tilde{v}_{\nu A\leftarrow} \qquad (A=\pm,L).$$

Matching conditions

$$\tilde{u}_{\nu\rightarrow}^{(A)}=\frac{1}{2}\left(\tilde{v}_{\nu A\rightarrow}\left(\frac{k_{1A}+k_{10}}{k_{10}}\right)-\tilde{v}_{\nu A\leftarrow}\left(\frac{k_{1A}-k_{10}}{k_{10}}\right)\right)$$
$$\tilde{u}_{\nu\leftarrow}^{(A)}=\frac{1}{2}\left(-\tilde{v}_{\nu A\rightarrow}\left(\frac{k_{1A}-k_{10}}{k_{10}}\right)+\tilde{v}_{\nu A\leftarrow}\left(\frac{k_{1A}+k_{10}}{k_{10}}\right)\right)$$

Escaping from the parity-breaking medium

Using the relations obtained before, it is possible to find, which part is reflected

$$\tilde{v}_{\nu L\leftarrow} = 0$$

$$\tilde{v}_{\nu\pm\leftarrow} = \frac{k_{1\pm} - k_{10}}{k_{1\pm} + k_{10}} \tilde{v}_{\nu\pm\rightarrow}$$

and which pass through the boundary,

$$\tilde{u}^{(L)}_{\nu\rightarrow} = \tilde{v}_{\nu L\rightarrow}$$

$$\tilde{u}^{(\pm)}_{\nu\rightarrow} = \frac{2k_{1\pm}}{k_{10} + k_{1\pm}} \tilde{v}_{\nu\pm\rightarrow}$$

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The dispersion laws in terms of invariant mass are $M^2 = k_\mu k^\mu$:

$$\begin{cases} k_{1L} = \sqrt{\frac{(M^2 - m^2)^2}{\zeta^2} - m^2} \\ k_{1\pm} = \sqrt{\frac{(M^2 - m^2)^2}{\zeta^2} - M^2} \end{cases}$$

Reflection coefficient

$$k_{ref} = \frac{\left|\sqrt{\frac{(M^2-m^2)^2}{\zeta^2} - M^2} - \sqrt{\frac{(M^2-m^2)^2}{\zeta^2} - m^2}\right|}{\left|\sqrt{\frac{(M^2-m^2)^2}{\zeta^2} - M^2} + \sqrt{\frac{(M^2-m^2)^2}{\zeta^2} - m^2}\right|}$$

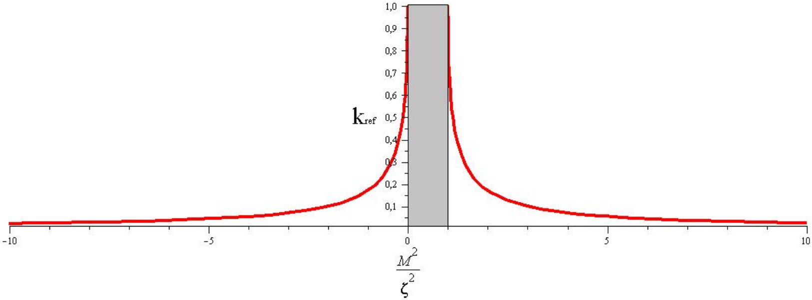


Figure : The coefficient of reflection from the boundary for photons escaping from the broken-parity medium. The kinematically forbidden domain of invariant mass values is hatched.

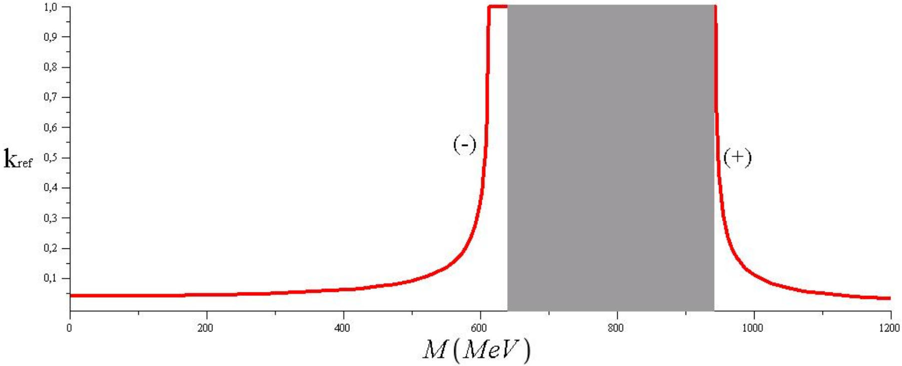
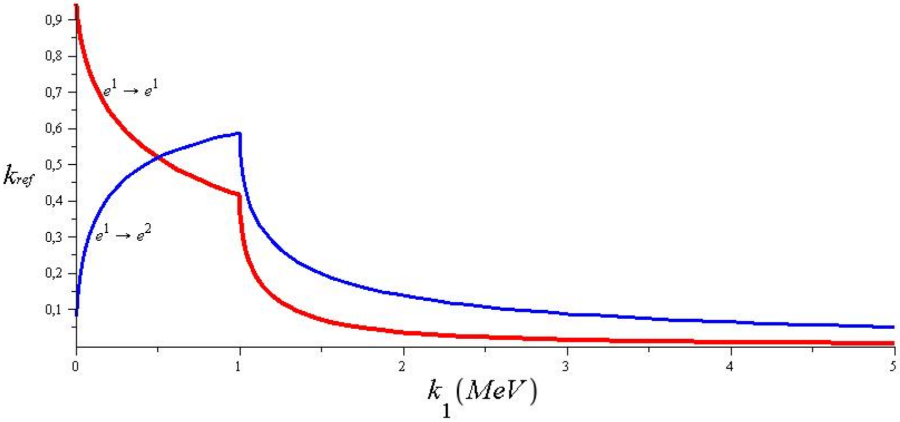


Figure : The coefficient of reflection from the boundary for vector mesons escaping from the broken-parity medium. The kinematically forbidden domain of invariant mass values is hatched. We take $\zeta = 300 MeV$

Entrance

$$k^{e^1\to e^1} = \frac{1}{2}\left(\frac{k_{10}-k_{1+}}{k_{10}+k_{1+}} + \frac{k_{10}-k_{1-}}{k_{10}+k_{1-}}\right); \qquad k^{e^1\to e^2} = \frac{1}{2}\left(\frac{k_{10}-k_{1+}}{k_{10}+k_{1+}} - \frac{k_{10}-k_{1-}}{k_{10}+k_{1-}}\right).$$



Time-like CS vector

$\zeta_\mu = (\zeta, 0, 0, 0)$

$$\Box A^\nu + m^2 A^\nu + \zeta\theta(-x_1)\varepsilon^{0\nu\sigma\rho}\partial_\sigma A_\rho = 0.$$

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$$\Box A^\nu + m^2 A^\nu + \zeta\theta(-x_1)\varepsilon^{0\nu\sigma\rho}\partial_\sigma A_\rho = 0.$$

$$k_{ref} = \left|\frac{k_{1A} - k_{10}}{k_{1A} + k_{10}}\right|$$

Dispersion laws

$$\begin{cases} k_{1L} = k_{10} = \sqrt{\omega^2 - m^2 - k_\perp^2} \\ k_{1-} = \sqrt{\omega^2 - m^2 - k_\perp^2 + \frac{\zeta^2}{2} + \zeta\sqrt{\omega^2 - m^2 + \frac{\zeta^2}{4}}} \\ k_{1+} = \sqrt{\omega^2 - m^2 - k_\perp^2 + \frac{\zeta^2}{2} - \zeta\sqrt{\omega^2 - m^2 + \frac{\zeta^2}{4}}} \end{cases}$$

In terms of invariant mass,

$$k_{ref} = \frac{\left|\sqrt{\frac{(M^2-m^2)^2}{\zeta^2} - k_\perp^2} - \sqrt{\frac{(M^2-m^2)^2}{\zeta^2} + (M^2 - m^2) - k_\perp^2}\right|}{\left|\sqrt{\frac{(M^2-m^2)^2}{\zeta^2} - k_\perp^2} + \sqrt{\frac{(M^2-m^2)^2}{\zeta^2} + (M^2 - m^2) - k_\perp^2}\right|}$$

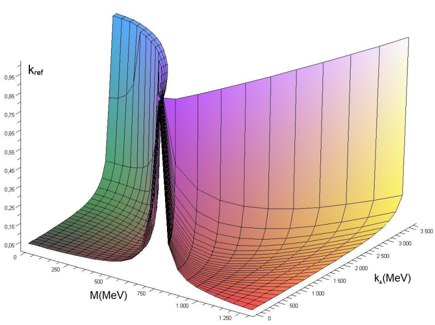

Figure : The reflection coefficient for vector mesons escaping. The kinematically forbidden domain of invariant mass values is hatched. Two views at the three-dimensional graph are represented. For the vector meson we take $\zeta = 300 MeV$.

Problem with the gauge invariance

$$\int d^3x \zeta_\mu A_\nu \partial_\rho A_\sigma \varepsilon^{\mu\nu\rho\sigma}$$

Solution of this problem

$$\zeta_\mu = (\zeta\theta(-x_1), -\zeta t\delta(x_1), 0, 0)$$

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Solution of this problem

$$\zeta_\mu = (\zeta\theta(-x_1), -\zeta t\delta(x_1), 0, 0)$$

Matching conditions

transversal polarization,

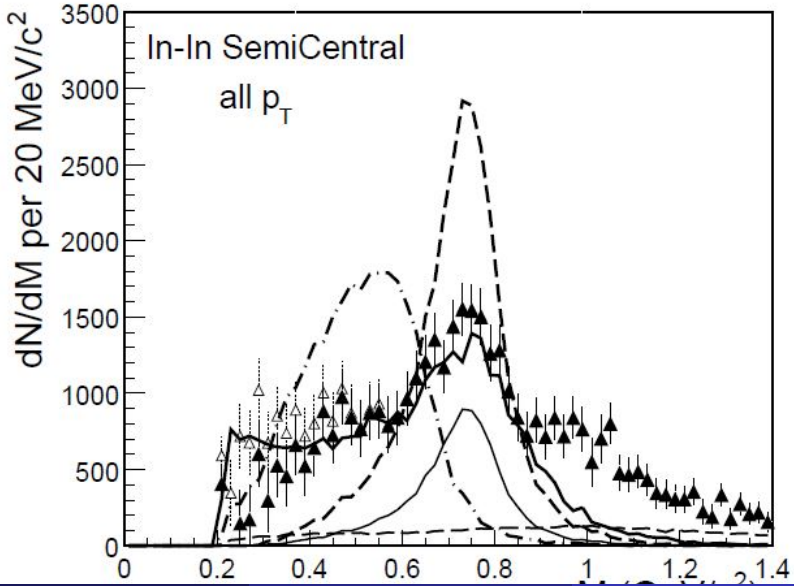
$$\begin{cases} (\tilde{u}^{(\pm)}_{0\leftarrow} - \tilde{v}^{(\pm)}_{0\leftarrow}) = \frac{i\zeta}{2k_{10}\omega^2} C_\pm(k_2, k_3) \\ \partial_1 \tilde{A}_1 - \text{continuous} \\ \tilde{u}^{(\pm)}_{0\leftarrow} + \tilde{u}^{(\pm)}_{0\rightarrow} = \frac{C_\pm(k_2,k_3)}{k_3(k_2 - k_3 C_{2A})} + C_{u\pm}(k_2, k_3) \\ \tilde{v}_{3\pm\rightarrow} + \tilde{v}_{3\pm\leftarrow} = \frac{C_\pm(k_2,k_3)}{\omega(k_2 - k_3 C_{2A})} \end{cases}$$

longitudinal,

$$\begin{cases} \tilde{u}^{(L)}_{0\leftarrow} = \tilde{v}^{(L)}_{0\leftarrow} \\ \partial_1 \tilde{A}_1 - \text{continuous} \\ \tilde{u}^{(L)}_{0\leftarrow} + \tilde{u}^{(L)}_{0\rightarrow} = C_{uL}(k_2, k_3) \\ \tilde{v}_{3L\rightarrow} + \tilde{v}_{3L\leftarrow} = \frac{C_L(k_2,k_3)}{\omega} \end{cases}$$

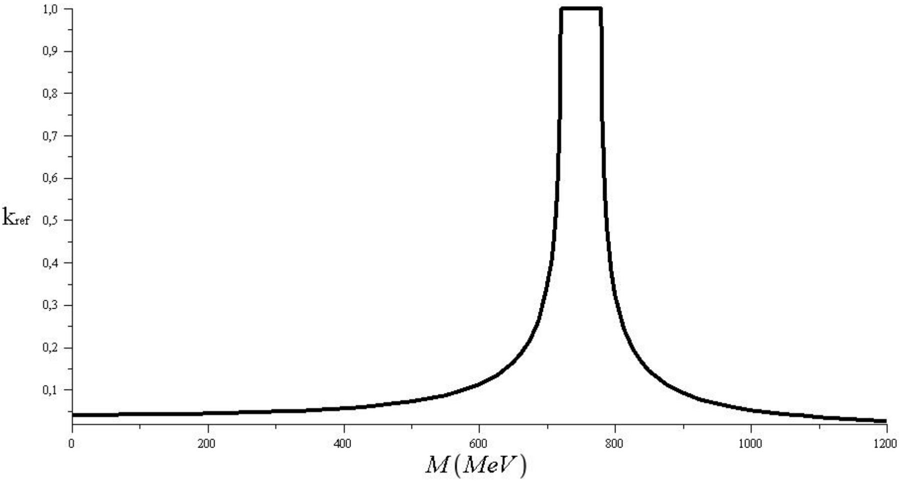
Conclusion

- The main results for the spatial CS vector:
  * The expression that relates two different physical vacua was found. It was shown that each of this vacua can be presented as a coherent state in terms of another one;
  * The relations that can be used to calculate the passage through or reflection of incoming and outgoing particles of any polarization are obtained;
  * In particular, it was shown that transverse polarizations undergo strong reflection up to total internal one at certain frequencies;
  * When a medium with broken parity is irradiated with photons, an additional rotation of circular polarizations can occur at the reflection from the interface.
- For time-like CS vector:
  * Reflection coefficients;
  * The gauge invariance can be restored.


In-In SemiCentral
all p_T
dN/dM per 20 MeV/c^2
3500
3000
2500
2000
1500
1000
500
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4

to 9

$$\left\{\begin{array}{c}
\tilde{v}_{2-\leftrightarrows} = \frac{k_2 k_3 - i\omega\sqrt{\omega^2 - k_\perp^2}}{\omega^2 - k_2^2}\tilde{v}_{3-\leftrightarrows} \\
\tilde{v}_{2+\leftrightarrows} = \frac{k_2 k_3 + i\omega\sqrt{\omega^2 - k_\perp^2}}{\omega^2 - k_2^2}\tilde{v}_{3+\leftrightarrows} \\
\tilde{v}_{2L\leftrightarrows} = \frac{k_2}{k_3}\tilde{v}_{3L\leftrightarrows} \\
\\
\tilde{v}_{0-\leftrightarrows} = -\frac{\omega k_3 - ik_2\sqrt{\omega^2 - k_\perp^2}}{\omega^2 - k_2^2}\tilde{v}_{3-\leftrightarrows} \\
\tilde{v}_{0+\leftrightarrows} = -\frac{\omega k_3 + ik_2\sqrt{\omega^2 - k_\perp^2}}{\omega^2 - k_2^2}\tilde{v}_{3+\leftrightarrows} \\
\tilde{v}_{0L\leftrightarrows} = -\frac{\omega}{k_3}\tilde{v}_{3L\leftrightarrows}
\end{array}\right. \tag{2}$$


1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
kref
0
200
400
600
800
1000
1200
M(MeV)