Dilepton production and anisotropy in πN collisions

NSTAR2019

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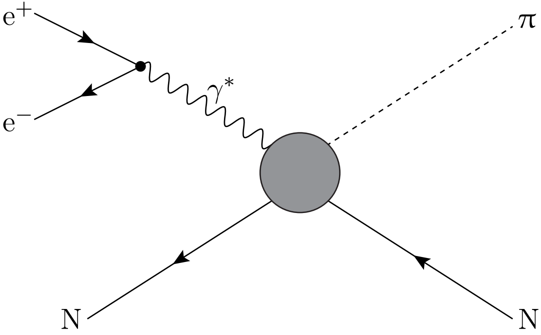
June 12, 2019

πN-collision



- Studied at HADES (GSI, Darmstadt, Germany)

  See also talk by B. Ramstein (Wednesday)

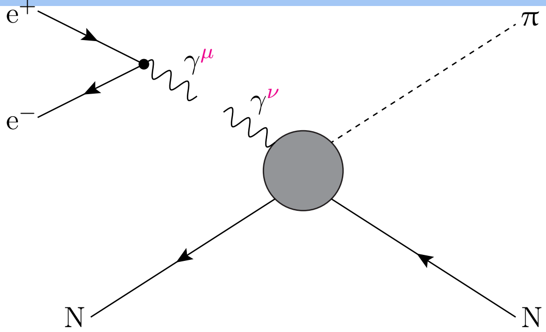
Spin density matrix

- Spin-1/2 case: $\rho = \frac{1}{2}\left(\mathbb{1} + \vec{\mathcal{P}} \cdot \vec{\sigma}\right)$
- Spin-1 case: $\rho = \frac{1}{3}\left[1 + \vec{\mathcal{P}} \cdot \vec{\mathcal{S}} + \sqrt{\frac{3}{2}}\mathcal{T}_{jk}\left(\mathcal{S}_j\mathcal{S}_k + \mathcal{S}_k\mathcal{S}_j\right)\right]$

$$\mathcal{T}_{jk} = \sqrt{\frac{3}{8}}\left(\langle \mathcal{S}_j\mathcal{S}_k + \mathcal{S}_k\mathcal{S}_j\rangle - \frac{4}{3}\delta_{jk}\right)$$

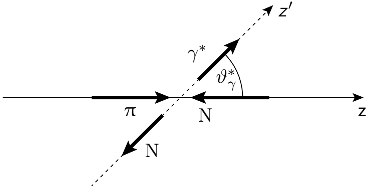
$$\vec{\mathcal{P}} = \langle\vec{\sigma}\rangle$$

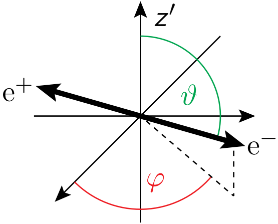
$$\vec{\mathcal{P}} = \langle\vec{\mathcal{S}}\rangle$$



- $\mathcal{M}(\lambda) = \epsilon_\mu(\lambda)\mathcal{L}^\mu\mathcal{H}^\nu\epsilon^*_\nu(\lambda)$
- $|\mathcal{M}|^2 = \sum_{\text{pol}}\sum_{\lambda,\lambda'} \epsilon_\mu(\lambda)\mathcal{L}^\mu\mathcal{H}^\nu\epsilon^*_\nu\epsilon_{\nu'}(\lambda')\mathcal{H}^{\nu'}\mathcal{L}^{*\mu'}\epsilon^*_{\mu'}$
- $\mathcal{L}^{\mu\nu} = \sum_{\text{pol}}\mathcal{L}^\mu\mathcal{L}^{*\nu} \quad \mathcal{H}^{\mu\nu} = \sum_{\text{pol}}\mathcal{H}^\mu\mathcal{H}^{*\nu}$
- $\rho^{\text{prod}}_{\lambda\lambda'} = \epsilon^*(\lambda)_\mu\mathcal{H}^{\mu\nu}\epsilon(\lambda')_\nu \quad \rho^{\text{decay}}_{\lambda'\lambda} = \epsilon^*(\lambda')_\mu\mathcal{L}^{\mu\nu}\epsilon(\lambda)_\nu$
- $|\mathcal{M}|^2 = \mathcal{L}^{\mu\nu}\mathcal{H}_{\mu\nu} = \sum_{\lambda\lambda'}\rho^{\text{prod}}_{\lambda\lambda'}\rho^{\text{decay}}_{\lambda'\lambda}$

Decay Matrix





- $\mathcal{L}^{\mu} \quad = e\bar{\mathrm{u}}(p_-, s)\gamma^{\mu}\mathrm{v}(p_+, s')$
- $\rho^{\text{decay}}_{\lambda'\lambda} \quad \approx e^2 \mathcal{T}r \left\{ \not{\epsilon}(\lambda')(\not{p}_+)\not{\epsilon}^*(\lambda)(\not{p}_-) \right\}$
- $\rho^{\text{decay}}_{\lambda'\lambda} \quad \approx 4q^2 \begin{pmatrix} 1+\cos^2\vartheta & -\frac{\sqrt{2}}{2}e^{i\varphi}\sin 2\vartheta & e^{2i\varphi}\sin^2\vartheta \\ -\frac{\sqrt{2}}{2}e^{-i\varphi}\sin 2\vartheta & 2(1-\cos^2\vartheta) & \frac{\sqrt{2}}{2}e^{i\varphi}\sin 2\vartheta \\ e^{-2i\varphi}\sin^2\vartheta & \frac{\sqrt{2}}{2}e^{-i\varphi}\sin 2\vartheta & 1+cos^2\vartheta \end{pmatrix}_{\lambda'\lambda}$

Anisotropy Coefficients

- $|\mathcal{M}|^2 \propto \mathcal{N}\left(1+\lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi + \lambda_\varphi^\perp \sin^2\vartheta \sin 2\varphi + \lambda_{\vartheta\varphi}^\perp \sin 2\vartheta \sin\varphi\right)$
- $\lambda_\vartheta = \frac{1}{\mathcal{N}}\left(\rho^{\mathrm{prod}}_{-1,-1} + \rho^{\mathrm{prod}}_{+1,+1} - 2\rho^{\mathrm{prod}}_{0,0}\right)$
- $\lambda_\varphi = 2\frac{1}{\mathcal{N}}\mathcal{Re}\left(\rho^{\mathrm{prod}}_{-1,+1}\right)$
- $\lambda_{\vartheta\varphi} = \frac{\sqrt{2}}{\mathcal{N}}\mathcal{Re}\left(\rho^{\mathrm{prod}}_{0,+1} - \rho^{\mathrm{prod}}_{-1,0}\right)$
- $\lambda_\varphi^\perp = \frac{2}{\mathcal{N}}\mathcal{Im}\left(\rho^{\mathrm{prod}}_{-1,+1}\right)$
- $\lambda_{\vartheta\varphi}^\perp = \frac{\sqrt{2}}{\mathcal{N}}\mathcal{Im}\left(\rho^{\mathrm{prod}}_{0,+1} - \rho^{\mathrm{prod}}_{-1,0}\right)$
- $\mathcal{N} = \rho^{\mathrm{prod}}_{-1,-1} + \rho^{\mathrm{prod}}_{+1,+1} + 2\rho^{\mathrm{prod}}_{0,0}$

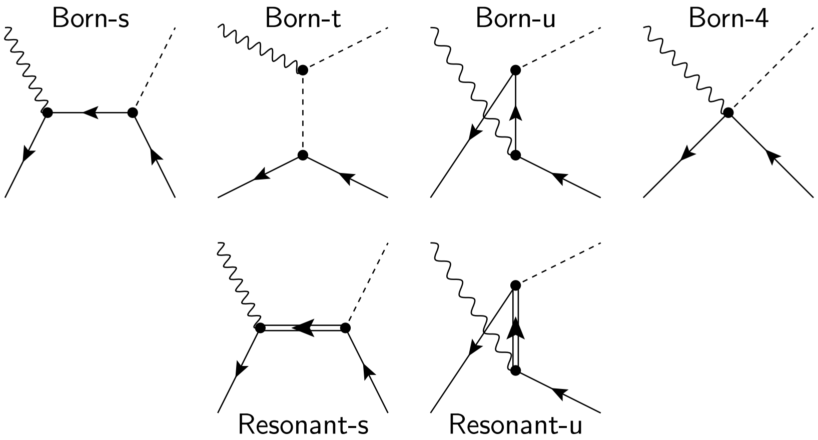
Anisotropy Coefficients

- $|\mathcal{M}|^2 \propto \mathcal{N}\left(1+\lambda_\vartheta\cos^2\vartheta+\lambda_\varphi\sin^2\vartheta\cos 2\varphi+\lambda_{\vartheta\varphi}\sin 2\vartheta\cos\varphi+\lambda_\varphi^\perp\sin^2\vartheta\sin 2\varphi+\lambda_{\vartheta\varphi}^\perp\sin 2\vartheta\sin\varphi\right)$
- $\lambda_\vartheta = \frac{1}{\mathcal{N}}\left(\rho^{\text{prod}}_{-1,-1}+\rho^{\text{prod}}_{+1,+1}-2\rho^{\text{prod}}_{0,0}\right)$
- $\lambda_\varphi = 2\frac{1}{\mathcal{N}}\mathcal{R}e\left(\rho^{\text{prod}}_{-1,+1}\right)$
- $\lambda_{\vartheta\varphi} = \frac{\sqrt{2}}{\mathcal{N}}\mathcal{R}e\left(\rho^{\text{prod}}_{0,+1}-\rho^{\text{prod}}_{-1,0}\right)$
- $\lambda_\varphi^\perp = \frac{2}{\mathcal{N}}\mathcal{I}m\left(\rho^{\text{prod}}_{-1,+1}\right)$
- $\lambda_{\vartheta\varphi}^\perp = \frac{\sqrt{2}}{\mathcal{N}}\mathcal{I}m\left(\rho^{\text{prod}}_{0,+1}-\rho^{\text{prod}}_{-1,0}\right)$
- $\mathcal{N} = \rho^{\text{prod}}_{-1,-1}+\rho^{\text{prod}}_{+1,+1}+2\rho^{\text{prod}}_{0,0}$

Anisotropy Coefficients

- $\lambda_\vartheta = \frac{1}{\mathcal{N}} \left(\rho^{\text{prod}}_{-1,-1} + \rho^{\text{prod}}_{+1,+1} - 2\rho^{\text{prod}}_{0,0} \right)$
- $\Sigma_\perp = \rho^{\text{prod}}_{-1,-1} + \rho^{\text{prod}}_{+1,1} \quad \Sigma_\parallel = 2\rho^{\text{prod}}_{0,0}$
- $\lambda_\vartheta = \frac{\Sigma_\perp - \Sigma_\parallel}{\Sigma_\perp + \Sigma_\parallel}$
- Interpretation of λ_ϑ:
- $\lambda_\vartheta = +1 \rightarrow$ completely transversely polarised photon
- $\lambda_\vartheta = -1 \rightarrow$ completely longitudinally polarised photon

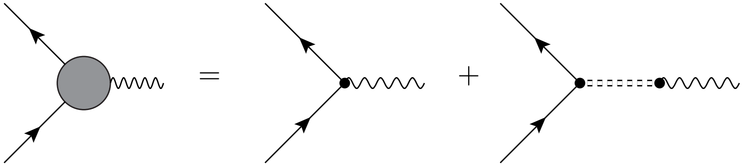
Hadronic Interactions



Vector Meson Dominance Model

- J. J. Sakurai proposed intermediate vector mesons Ann. Phys., 11 (1960)
- $\mathscr{L}^1_{\rho\gamma\pi} = -\frac{em_\rho^2}{g_\rho}\rho^0_\mu A^\mu - g_{\rho\pi\pi}\rho^0_\mu J^\mu$

- Refined by N. M. Kroll, T. D. Lee, and B. Zumino Phys. Rev., 157 (1967)
- $\mathscr{L}^2_{\rho\gamma\pi} = -\frac{e}{2g_\rho}F^{\mu\nu}\rho^0_{\mu\nu} - g_{\rho\pi\pi}\rho^0_\mu J^\mu - eJ_\mu A^\mu$
- because in p-space $\mathscr{L}^2_{\rho\gamma} = -\frac{e}{g_\rho}p^2 A^\mu \rho_\mu$



Interactions

- Substitute derivative in kinetic terms with covariant derivatives
- e.g. $\partial_\mu \vec{\pi} \to D_\mu \vec{\pi} = \partial_\mu \vec{\pi} - g_{\rho\pi\pi} \vec{\rho}_\mu \times \vec{\pi}$
- $\mathscr{L}_{\pi NN} = -\frac{f_{\pi NN}}{m_\pi} \overline{\psi}_N \gamma^5 \gamma^\mu \vec{\tau} \psi_N \cdot \partial_\mu \vec{\pi}$
- $\mathscr{L}_{\rho NN} = \frac{g_\rho}{2} \overline{\psi}_N \left(\vec{\not{\rho}} - \kappa_\rho \frac{\sigma_{\mu\nu}}{4 m_N \vec{\rho}^{\mu\nu}} \right) \cdot \vec{\tau} \psi_N$
- $\mathscr{L}_{\pi\pi\rho} = -g_{\pi\pi\rho} [(\partial^\mu \vec{\pi}) \times \vec{\pi}] \vec{\rho}_\mu$
- $\mathscr{L}_{\pi NN\rho} = -\frac{g_\rho f_{\pi NN}}{m_\pi} \overline{\psi}_N \gamma_5 \gamma^\mu \vec{\tau} \psi \cdot (\vec{\rho}_\mu \times \vec{\pi})$

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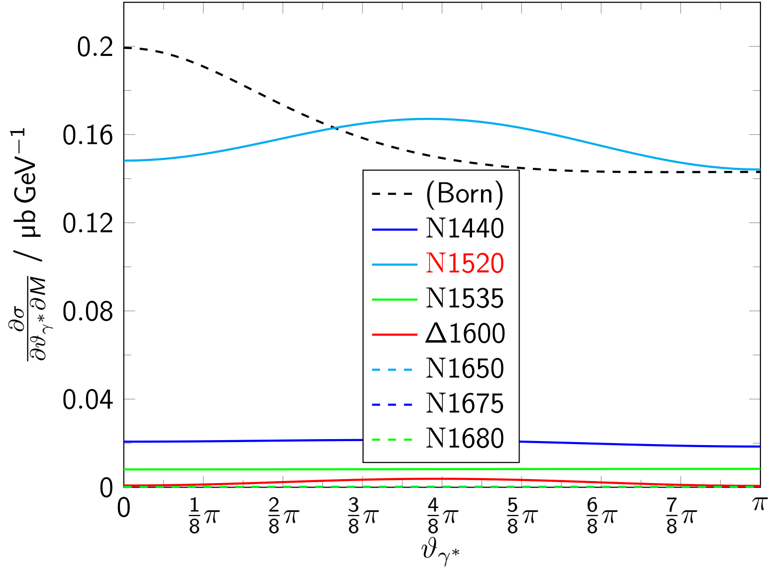
- $\mathscr{L}_{\rho\mathrm{NR}_{1/2}} = \frac{g_{\rho\mathrm{NR}}}{2m_\rho}\overline{\psi}_\mathrm{R}\vec{T}\sigma^{\mu\nu}\tilde{\Gamma}\psi_\mathrm{N}\cdot\vec{\rho}_{\mu\nu} + \text{h.c.}$
- $\mathscr{L}_{\pi\mathrm{NR}_{1/2}} = -\frac{g_{\pi\mathrm{NR}}}{m_\pi}\overline{\psi}_\mathrm{R}\Gamma\gamma^{\mu}\vec{T}\psi_\mathrm{N}\cdot\partial_\mu\vec{\pi} + \text{h.c.}$
- $\mathscr{L}_{\rho\mathrm{NR}_{3/2}} = -i\frac{g_{\rho\mathrm{NR}}}{m_\rho}\overline{\psi}^{\mu}_\mathrm{R}\vec{T}\gamma^{\nu}\tilde{\Gamma}\psi_\mathrm{N}\cdot\vec{\rho}_{\mu\nu} + \text{h.c.}$
- $\mathscr{L}_{\pi\mathrm{NR}_{3/2}} = \frac{g_{\pi\mathrm{NR}}}{m_\pi}\overline{\psi}^{\mu}_\mathrm{R}\Gamma\vec{T}\psi_\mathrm{N}\cdot\partial_\mu\vec{\pi} + \text{h.c.}$
- $\mathscr{L}_{\rho\mathrm{NR}_{5/2}} = -\frac{g_{\rho\mathrm{NR}}}{(2m_\rho)^4}\overline{\psi}^{\mu\nu}_\mathrm{R}\vec{T}\tilde{\Gamma}\gamma^{\rho}(\partial_\mu\psi_\mathrm{N})\cdot\vec{\rho}_{\rho\nu} + \text{h.c.}$
- $\mathscr{L}_{\pi\mathrm{NR}_{5/2}} = -\frac{g_{\pi\mathrm{NR}}}{m_\pi^4}\overline{\psi}^{\mu\nu}_\mathrm{R}\Gamma\vec{T}\psi_\mathrm{N}\partial_\mu\partial_\nu\vec{\pi} + \text{h.c.}$
- $\Gamma = \gamma^5$ for resonances with $J^P \in \{1/2^+, 3/2^-, 5/2^+\}$ and $\Gamma = 1$ otherwise, and $\tilde{\Gamma} = \gamma^5\Gamma$

Particles

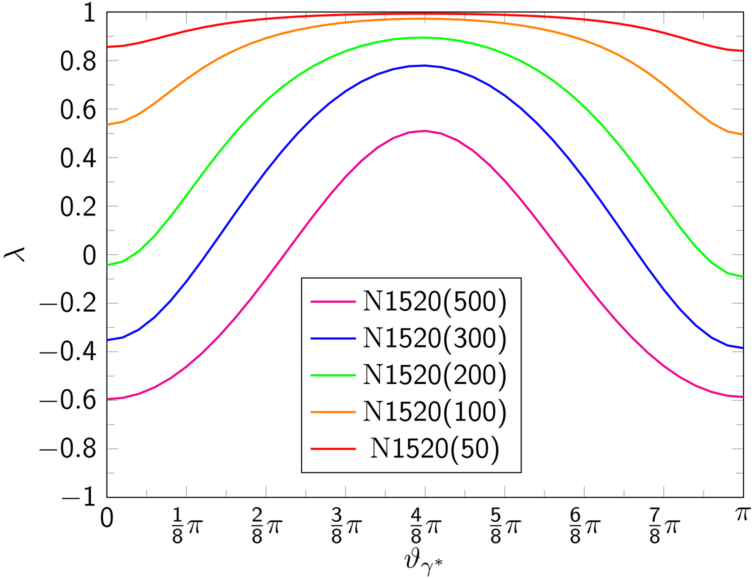
particle (J^P)	mass[1] / GeV	width[1] / GeV	BR[1] $\to \pi N$	BR[2] $\to \rho N$
N1440 ($1/2^+$)	1.440	0.350	0.650	0.005
N1520 ($3/2^-$)	1.515	0.110	0.600	0.120
N1535 ($1/2^-$)	1.530	0.150	0.420	0.030
Δ1600 ($3/2^+$)	1.570	0.250	0.160	0.050
Δ1620 ($1/2^-$)	1.610	0.130	0.300	0.430
N1650 ($1/2^-$)	1.650	0.125	0.600	0.070
N1675 ($5/2^-$)	1.675	0.145	0.400	0.005
N1680 ($5/2^+$)	1.685	0.120	0.650	0.120

[1] PDG 2019 [2] Bonn-Gatchina PWA of the vector mesons production data (ECT-Trento 2017)

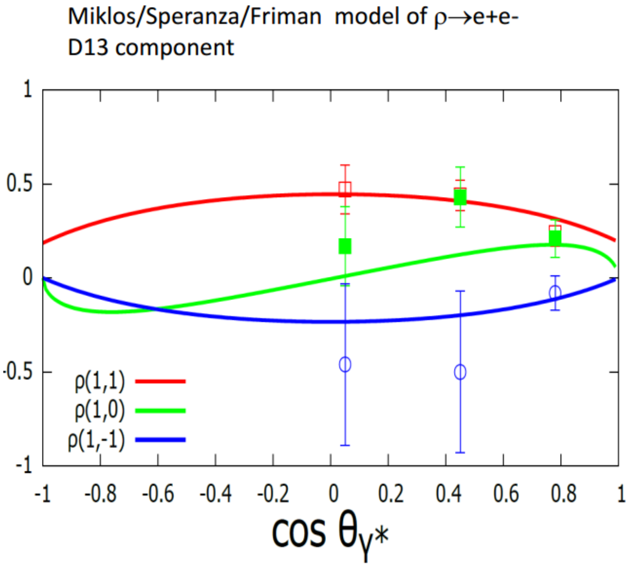
Cross Sections $\sqrt{s} = 1.49$ GeV



See also talk by P. Salabura (Thursday 11.15)


1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
λ
0
$\frac{1}{8}\pi$
$\frac{2}{8}\pi$
$\frac{3}{8}\pi$
$\frac{4}{8}\pi$
$\frac{5}{8}\pi$
$\frac{6}{8}\pi$
$\frac{7}{8}\pi$
π
ϑ_{γ^*}
N1520(500)
N1520(300)
N1520(200)
N1520(100)
N1520(50)

Preliminary:



Summary & Outlook

- Our model gives a nice prediction for experimental results
- Dominant $\sqrt{s} = 1.49\,\text{GeV}$ resonance: N1520 (matches PWA)

- Include form factors to handle new pion beam: $\sqrt{s} = 1.7\,\text{GeV}$
- Include ω
- Purely hadronic interactions: $\pi\text{N} \rightarrow \text{N}\pi\pi$