LIGHT MESON EMISSION IN (ANTI)PROTON INDUCED REACTIONS

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Résumé

The aim of this talk is to suggest possible mechanism of reactions induced by high energy antiprotons, involving the detection of one or few mesons. The cross section can be calculated, on the basis of factorized formulas.

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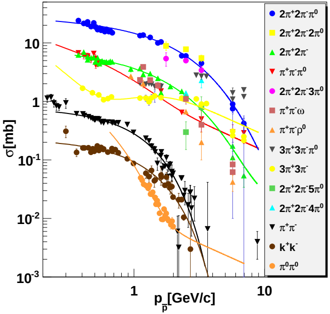
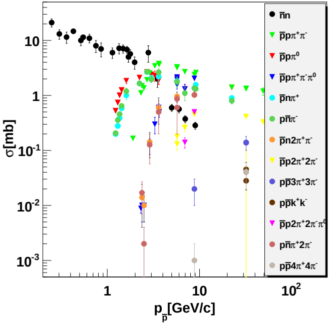
Content

- An extension of the QED 'return to resonance' mechanism to light meson emission (π, ρ) in (anti)proton collisions with a hadronic target (nucleon or nucleus) is proposed.
- The cross section and the multiplicity distributions are calculated.
- Applications
  - production of (anti)neutron beams
  - high multplicity particle production

$\bar{p}p$ induced cross sections

A. Dbeyssi, ETG, Prob.At.Sci.Technol. 2012N1 (2012) 84



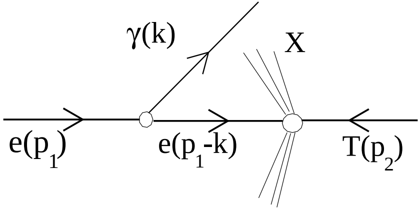


The quasi-real electron method is extended to the collinear emission of a light meson from a (anti)proton beam to calculate the cross section for single and multi pion production.

E.A. Kuraev, E.S. Kokoulina, E.T-G, arXiv :1306.5169 [hep-ph], *to appear in Phys.Part.Nucl.Lett.*

"Quasi-Real Electron" mechanism in QED

V.N. Baier, V.S. Fadin and V.M. Katkov (1973)

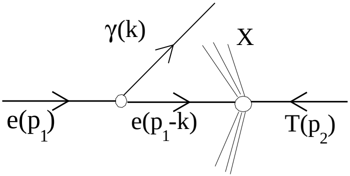


$$e(p_1) + T(p_2) \to e(p_1 - k) + \gamma(k) + X$$

- The emission of a hard real photons by electron (positron) beams at e^+e^- colliders (the virtual electron remains almost on mass shell) enhances the cross section (return-to-resonance mechanism).
- Effective method for studying narrow resonances.
- Properties of the cross section :
  - Factorization
  - Logarithmic enhancement

Quasi-real electron method

$$e(p_1) + T(p_2) \to e(p_1 - k) + \gamma(k) + X$$



The virtual electron after the hard (collinear) photon emission is almost on mass shell.

$$\mathcal{M}_\gamma(p_1, p_2) = e\overline{T}(p_2)\frac{\hat{p_1} - \hat{k} + m}{-2p_1 k}\hat{\varepsilon}(k)u(p_1).$$

Factorization of the matrix element : $|(p_1 - k)^2 - m^2| \ll 2p_1 p_2$

$$\sum |\mathcal{M}_\gamma|^2 = e^2 \left[\frac{E_{p_1}^2 + E_{\vec{p_1}-\vec{k}}^2}{\omega(E_{p_1} - \omega)(kp_1)} - \frac{m^2}{(kp_1)^2}\right] \sum |\bar{T}(p_2)u(p_1 - k)|^2.$$

$\sum |\bar{T}(p_2)u(p_1 - k)|^2$: Born matrix element squared with shifted argument.

Quasi-real electron method

$$e(p_1) + T(p_2) \to e(p_1 - k) + \gamma(k) + X$$

- The unpolarized cross section can be factorized :
  $d\sigma_\gamma^{eT\to eT\gamma}(s,x) = d\sigma(\bar{x}s)dW_\gamma(x),\ s = (p_1+p_2)^2,\ \bar{x} = 1-x,$
  $$dW_\gamma(x) = \frac{\alpha}{\pi}\frac{dx}{x}\left[(1-x+\frac{1}{2}x^2)\ln\frac{E^2\theta_0^2}{m_e^2} - (1-x)\right],$$
  $x = \frac{\omega}{E},\ \theta < \theta_0 \ll 1,\ \frac{E\theta_0}{m_e} \gg 1,$
- The initial electron transforms into an electron (with energy fraction $1-x$) + a hard photon(x), emitted at $\theta < \theta_0$
- $\bar{x}s > s_{thr}$, where s_{thr} is the threshold energy of process without photon emission.
- Logarithmic enhancement originates from the small values of the mass of the intermediate electron, which is almost on mass shell.
  This justifies also the name of Quasi Real Electron (QRE) method.

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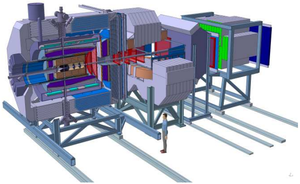
Extension to QCD : light meson emission

Extension of the QRE method to light meson emission (π, ρ) in (anti)proton collisions with a hadronic target (nucleon or nucleus). (Example)

$$p(\bar{p})+p \to n(\bar{n})+p+\pi^+(\pi^-)+N_\pi,$$



- Detection of charged pion and ρ mesons,
- Magnetic deviation of charged meson,

Large production of anti-neutrons

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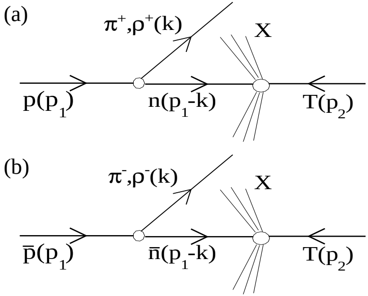
QR method in hadron physics

$$p + T \to n + T + h^+; \ \bar{p} + T \to \bar{n} + T + h^-$$



$h = \rho$ or π, T any target (p, n, nucleus..).

Factorization of the cross section ($x = E_h/E$; $\bar{x} = 1 - x$) :

$$\begin{aligned} d\sigma^{pT \to h_+ X}(s, x) &= \sigma^{nT \to X}(\bar{x}s) dW^{h_+}(x), \\ d\sigma^{\bar{p}T \to h_+ X}(s, x) &= \sigma^{\bar{n}T \to X}(\bar{x}s) dW^{h_-}(x), \\ d\sigma^{pT \to h_0 X}(s, x) &= \sigma^{pT \to X}(\bar{x}s) dW^{h_0}(x). \end{aligned}$$

QRE method in hadron physics

- The cross sections are :

$$
\begin{aligned}
d\sigma^{pT\to h_+X}(s,x) &= \sigma^{nT\to X}(\bar{x}s)dW^{h_+}(x),\\
d\sigma^{\bar{p}T\to h_+X}(s,x) &= \sigma^{\bar{n}T\to X}(\bar{x}s)dW^{h_-}(x),\\
d\sigma^{pT\to h_0X}(s,x) &= \sigma^{pT\to X}(\bar{x}s)dW^{h_0}(x).
\end{aligned}
$$

- Following the QED result :

$$
\begin{aligned}
\frac{dW^i_\rho(x)}{dx} &= \frac{g^2}{4\pi^2}\frac{1}{x}\sqrt{1-\frac{m_\rho^2}{x^2E^2}}\left[\left(1-x+\frac{1}{2}x^2\right)L-(1-x)\right]\\
L &= \ln\left(1+\frac{E^2\theta_0^2}{M^2}\right), \rho^i=\rho^+,\rho^-,\rho^0,
\end{aligned}
$$

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Pion hard photon emission

$$\frac{dW^{\pi}}{dx} = \sum |\mathcal{M}_{pn}(p_1, p_1 - k)|^2 \frac{d^3 k}{16\omega\pi^3},$$

with

$$\sum |\mathcal{M}_{pn}(p_1, p_1 - k)|^2 = \frac{g^2}{[m_\pi^2 - 2(p_1 k)]^2} Tr(\hat{p}_1 - \hat{k} + M)\gamma_5(\hat{p}_1 + M)\gamma_5$$

$$= \frac{4(p_1 k)g^2}{[m_\pi^2 - 2(p_1 k)]^2},$$

.

$$(p_1 k) = E\omega(1 - bc), 1 - b^2 \approx \frac{m_\pi^2}{\omega^2} + \frac{M^2}{E^2}$$

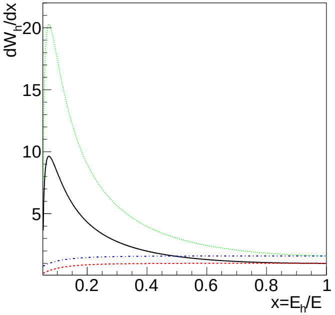
Angular integration for $1 - (\theta_0^2/2) < c < 1,\ c = \cos(\vec{k}, \vec{p}_1)$:

$$\frac{dW_\pi^i(x)}{dx} = \frac{g^2}{8\pi^2}\sqrt{1 - \frac{m_\pi^2}{x^2 E^2}}\left[L + \ln\frac{1}{d(x)} + \frac{m_\pi^2}{x d(x) M^2}\right],$$

$$x = \frac{E_\pi}{E} > \frac{m_\pi}{E},\quad d(x) = 1 + \frac{m_\pi^2 \bar{x}}{M^2 x^2},\quad \bar{x} = 1 - x,$$

$g = g_{\rho pp} = g_{\pi pp} \approx 6$ is the strong coupling constant.

dW_h/dx for ρ- and π-meson production- *"not normalized probability"*



$\theta_0 = 10^\circ$ *for* ρ- *meson*

$\theta_0 = 10^\circ$ *for* π*-meson*

$\theta_0 = 20^\circ$ *for* ρ- *meson*

$\theta_0 = 20^\circ$ *for* π*-meson*

Integrated probabilities

$$W_i = \int_{x_t^i}^{1} \frac{dW_i}{dx} dx$$

$x_t^i = E_{th}^i/E$, E_{th} is the threshold value of the energy of the detected particle, $i = \rho, \pi$:

$$W_i = \frac{g^2}{4\pi^2}(A^i L + B^i),$$

$$A^\rho = I_0(x_t^\rho) - I_1(x_t^\rho) + \frac{1}{2} I_2(x_t^\rho), \quad B^\rho = -I_0(x_t^\rho) + I_1(x_t^\rho),$$

$$A^\pi = \frac{1}{2} I_1(x_t^\pi); \quad B^\pi = I_1(x_t^\pi),$$

with $I_n(z) = \int_z^1 \frac{dx}{x} x^n \sqrt{1 - \left(\frac{z}{x}\right)^2}$

$$I_0(z) = \frac{1}{2} \ln \frac{1+r}{1-r} - r, \quad I_1(z) = r + z \arcsin(z);$$

$$I_2(z) = \frac{1}{2} r - \frac{z^2}{4} \ln \frac{1+r}{1-r};$$

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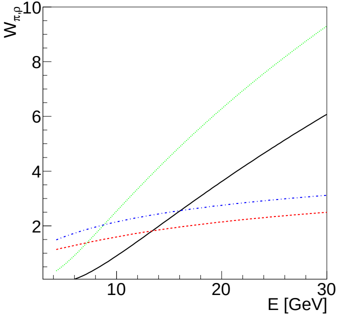
Integrated "probabilities"



$\theta_0 = 10^\circ$ *for ρ- meson*
$\theta_0 = 10^\circ$ *for π-meson*
$\theta_0 = 20^\circ$ *for ρ- meson*
$\theta_0 = 20^\circ$ *for π-meson*

- The integrated quantities W_i, $i = \rho, \pi$ may exceed unity, violating unitarity.
- Virtual correction for the probability of emission of n "soft" photons (emission and absorption of the off-mass shell meson).
- Poisson formula for n soft photons : $W_n = (a^n/n!)e^{-a}$ (a : probability of emission of a single soft photon).

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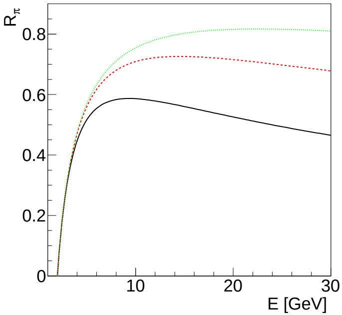
Renormalization factor

A general factor $P_\pi = e^{-W_\pi}$, takes into account virtual corrections.

$$\sigma(s) \to \sigma(s) \times \mathcal{R}_\pi, \; \mathcal{R}_\pi = P_\pi \sum_{k=0}^{k=n} \frac{W_\pi^k}{k!}. \qquad (2)$$



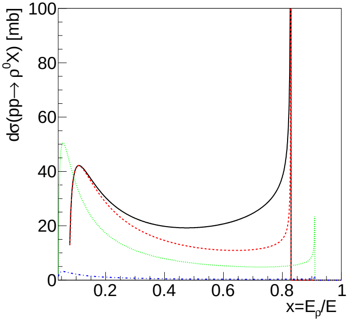
Probability of emission of 2, 3, 4 pions, for $\theta_0 = 10^\circ$

Annihilation into two pions $\bar{p} + p \to \pi^+ + \pi^- + X$

$$
\begin{aligned}
d\sigma^{p\bar{p}\to\rho^0 X} &= 2\frac{dW_\rho(x)}{dx}\sigma^{p\bar{p}\to X}(\bar{x}s) \times P_\rho, \\
P_\rho &= e^{-W_\rho};\ W_\rho = \int_{x_t}^{1} \frac{dW_\rho}{dx};
\end{aligned}
$$

- The factor of two takes into account the emission along each of the initial particles.
- P_ρ is a survival factor which takes into account virtual radiative corrections.

Annihilation into two pions $\bar{p} + p \to \pi^+ + \pi^- + X$



$E = 10\ GeV\ and\ \theta_0 = 10^\circ$

$E = 10\ GeV\ and\ \theta_0 = 20^\circ$

$E = 20\ GeV\ and\ \theta_0 = 10^\circ$

$E = 20\ GeV\ and\ \theta_0 = 20^\circ$

The characteristic peak at $x = x_{max}$ *is known in QED :* $e^+ + e^- \to \mu^+ + \mu^- + \gamma$ *: threshold effect, corresponding to the creation of a muon pair, where* $x_{max} = 1 - 4M_\mu^2/s$, M_μ *is the muon mass.*

Annihilation into three pions $\bar{p}+p\to\pi^{+}+\pi^{-}+\pi^{0}+X$

Three pion production, assuming that the process occurs through a $\pi^0\rho^0$ initial state emission :

$$d\sigma(p,\bar{p})^{p\bar{p}\to\pi\rho X}=$$

$$dW_\rho^0(x_\rho)dW_\pi^0(x_\pi)[d\sigma(p-p_\rho,\bar{p}-p_\pi)^{p\bar{p}\to X}+$$

$$d\sigma(p-p_\pi,\bar{p}-p_\rho)^{p\bar{p}\to X}]P_\pi P_\rho,$$

implying the subsequent decay $\rho^0\to\pi^+\pi^-$.

Predictions for cross sections

- The cross sections for the interaction of high energy (anti)neutron beams with hadrons can be derived by (anti)proton, with the emission of the charged meson.

$$\sigma^{nT\to X}(\bar{x}s) = \frac{d\sigma^{pT\to h^+X}/dx}{dW_+(x)/dx},$$

- Total cross section for $\bar{n}p \to X$ from the total cross section of $\bar{p}p \to \bar{n}h_-p \approx 1$ mb :

$$P_\pi W_\pi(E_1, \theta_0)\sigma^{\bar{n}p\to X}(E - E_1) = \sigma^{\bar{p}p\to\pi X}(E)$$

Literature

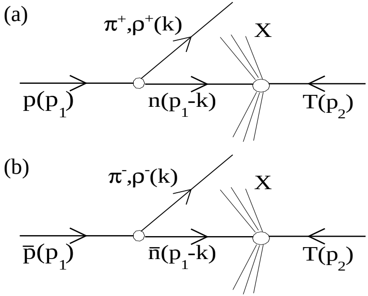
- The gluon dominance model predicts the ratio of inelastic CE to total inelastic cross section in pp scattering $\approx 40\%$, in reasonable agreement with the experimental data.
- Probabilities to create a π or ρ-meson by a proton, in infinite momentum reference frame (Altarelli,1977).
- Emission of (polarized) ρ-meson by quark and the ρ meson production in quark-antiquark annihilation (Teryaev, 1982).
- Description in terms of a single pseudoscalar meson π^+, K^+ exchange : information on the strange meson-baryon constant can be extracted.

Conclusion

- The QRE method has been extended to light meson emission from an (anti)proton beam. Cross section for multi-pion emission have been predicted for present and planned hadron facilities.
- Collinear light meson emission for producing secondary (anti)neutron beams, at a high energy (anti)proton accelerator.
- The gluon dominance model predicts the ratio of inelastic CE to total inelastic cross section in *pp* scattering $\approx 40\%$, in reasonable agreement with the experimental data.
- Collinear light meson emission in (anti)proton-proton collisions is a source of high multiplicities pion events. The emission of hadrons in initial as well as in final states must be taken into account.

The matrix element

$$p + T \to n + T + h^+;\ \bar{p} + T \to \bar{n} + T + h^-$$



$h = \rho$ or π, T any target (p, n, nucleus..).
The matrix element for collinear $\pi(\rho)$ emission is :

$$\mathcal{M}^{h_+}_{pT}(p_1, p_2)) = \mathcal{M}_{nT}(p_1 - k, p_2) T^{pn}_{h_+}(p_1, p_1 - k);$$

$$\mathcal{M}^{h_-}_{\bar{p}T}(p_1, p_2)) = \mathcal{M}_{\bar{n}T}(p_1 - k, p_2) T^{\bar{p}\bar{n}}_{h_-}(p_1, p_1 - k).$$

$$T^{pn}_h = \frac{g}{m_h^2 - 2p_1 k} \bar{u}_n(p_1 - k)\gamma_5(\hat{\epsilon}) u_p(p_1).$$