$\pi^+\pi^-$ production in (anti)proton-proton collisions in the kinematical domain relevant for PANDA

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Motivation

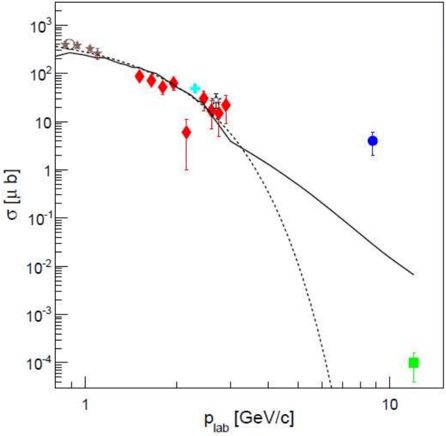
- The reaction $\bar{p}p \to e^+e^-$ allows to measure electromagnetic proton form factors.
- Important simulation work is under way.
- The reaction $\bar{p}p \to \pi^+\pi^-$ is the main background :
  - has a large cross section,
  - contains information on the quark content of the proton
  - allow to test different QCD models

It is necessary to fully understand the process $\bar{p}p \to \pi^+\pi^-$ at PANDA energies.

Situation of data

$\bar{p}p \to \pi^+\pi^-$ experimental data

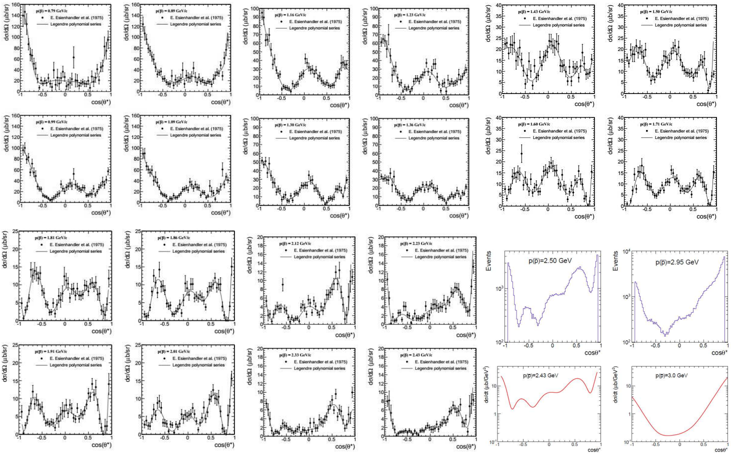
- Total cross section.



- Data from :
  ○ NPB 411 :3(1994)
  NPB 172 :302(1980)
  NPB 517 :3(1998)
  NPB 51 :29(1973)
  PRD 4 :2658(1971)
  ⋆ PLB 25 :486(1967)
  NPB 284 :643(1987)
  solid line Generator
  dash line A Dbeyssi, PhD, Orsay (2013)

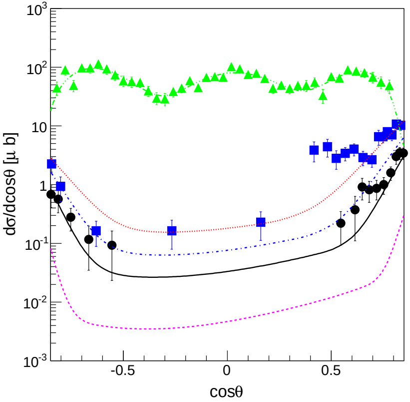
Differential cross section : Low energy range

(0.79-2.43GeV/c NPB 96 :09(1975) & 2.5-3.0GeV/c)



- Complete data sets
- Oscillatory behavior
- Fit by Legendre polynomes

Differential cross section : higher energy range



Data from :
$P_{Lab} = 1.7\text{GeV}/c$, NPB 96 :109(1975)
$P_{Lab} = 5\text{GeV}/c$, NPB 60 :173(1973)
$P_{Lab} = 6.21\text{GeV}/c$, NPB 116 :51(1976)
Generator $P_{Lab} = 3\text{GeV}/c$
Generator $P_{Lab} = 10\text{GeV}/c$

- Incomplete angular distributions
- Mostly forward/backward data
- Some measurements at $\cos\theta = 0$

Modelization of the reaction $\bar{p}p \to \pi^+\pi^-$ in Panda Root

Generators :

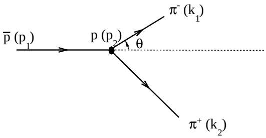
- Dual Parton Model(generic annihilation background in $\bar{p}p$ annihilation)
- Phase Space Model(flat distribution in $\cos\theta$)
- EvtGen (generate benchmark reactions by user) : twoPionGen (*M. Zambrana et al.*)
  - Legendre polynomials (low energy region : $0.79 \leq p_{\bar{p}} <$ 2.43 GeV) ;
  - Interpolation (intermediate energy region : 2.43 GeV $\leq p_{\bar{p}} <$ 5 GeV)
  - Regge theory (high energy region : 5 GeV $\leq p_{\bar{p}} <$ 12 GeV)

My study of the reaction $\bar{p} + p \to \pi^- + \pi^+$

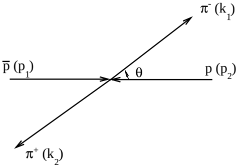
- Kinematics :

$$\bar{p}(p_1) + p(p_2) \to \pi^-(k_1) + \pi^+(k_2)$$

In Lab System



In CM System



particle	Momentum	Lab	CMS
$\bar{p}$	p_1	$(E_\ell, \vec{p}_\ell)$	$(E_1, \vec{p}_1)$
p	p_2	$(M_p, 0)$	$(E_2, \vec{p}_2)$
π^-	k_1	$(\epsilon_1, \vec{k}_1^\ell)$	$(\varepsilon_1', \vec{k}_1)$
π^+	k_2	$(\epsilon_2, \vec{k}_2^\ell)$	$(\varepsilon_2', \vec{k}_2)$

Table 1. Notation of four-momenta in different reference frames.

- The (s-, t- , u-) Mandelstam variables :

$$s = (p_1 + p_2)^2 = (k_1 + k_2)^2$$
$$t = (p_1 - k_1)^2 = (k_2 - p_2)^2$$
$$u = (p_1 - k_2)^2 = (k_1 - p_2)^2$$

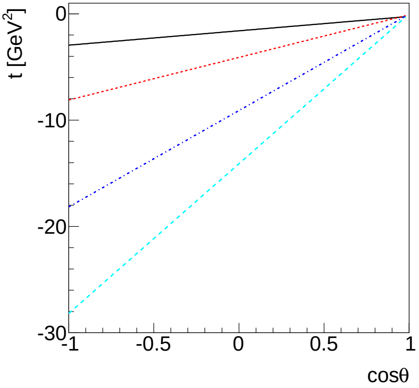
- Finally, we get the relation between t and s, and $cos\theta$
  In CM system :

$$t = M_p^2 + m_\pi^2 - 2E_1^2(1 - \beta_p\beta_\pi \cos\theta)$$
$$\beta_p = \sqrt{1 - \frac{4M_p^2}{s}}$$
$$\beta_\pi = \sqrt{1 - \frac{4m_\pi^2}{s}}$$
$$s = 4E_1^2$$

Dependence of t on $\cos\theta$

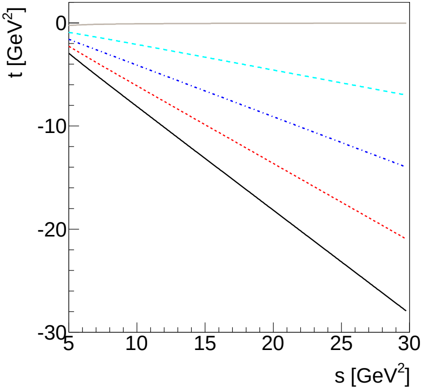
In PANDA, $p_{Lab} > 1.5$ GeV, $s > 5.08$ GeV^2

- The range of $\cos\theta$: -1 $< \cos\theta <$ 1
- Different values of s : $s =$ 5. 10, 20, 30 GeV^2



Dependence of t on s

- The range of s : 5 - 30 GeV^2
- Different values of $\cos\theta$: $\cos\theta$ = -1, -0.5, 0, 0.5, 1



Relation between CM system and Lab system

- The Mandelstam variables s, t, u and the scalars (i.e., the masses of particles) are kinematical invariants,
- So the relations between two systems of $\cos\theta$:

$\epsilon^{\pm}$ is the energy of π^{-} in lab system(E) :

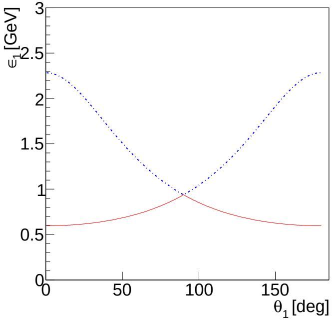
$$\epsilon_1^{\pm} = \frac{MW^2 \pm \sqrt{p_\ell^2 \cos^2\theta_\ell \left[W^2(M_p^2 - m_\pi^2) + m_\pi^2 p_\ell^2 \cos^2\theta_\ell\right]}}{(W^2 - p_\ell^2 \cos^2\theta_\ell)}$$

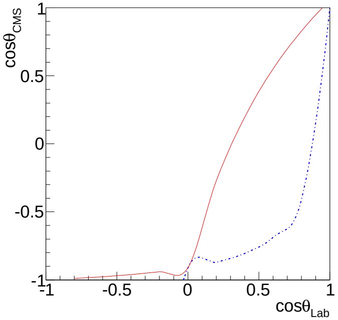
$$W = E_\ell + M_p$$

$$\cos\theta_{CMS} = \frac{E_1^2 - E_\ell \epsilon^{\pm}(1 - \beta_p^\ell \beta_\pi^\ell \cos^2\theta_{Lab})}{E_1^2 \beta_p \beta_\pi}$$

Relation between CM system and Lab system

plots of $\epsilon_1^{\pm}$ and $\cos\theta$





Crossing symmetry : from annihilation (σ^a) to elastic scattering (σ^s)

$$\bar{p}(p_1) + p(p_2) \to \pi^-(k_1) + \pi^+(k_2)$$

Crossed reactions : elastic $\pi^\pm p \to \pi^\pm p$ scattering :

1. $\pi^-(-k_2) + p(p_2) \to \pi^-(k_1) + p(-p_1), \; p_1 \to -k_2$
2. $\pi^+(-k_1) + p(p_2) \to p(-p_1) + \pi^+(k_2), \; p_1 \to -k_1$

1.

$$s_s = (-k_2 + p_2)^2 \to t_a$$
$$t_s = (-k_2 - k_1)^2 \to s_a$$
$$u_s = (-k_2 + p_1)^2 \to u_a$$

2.

$$s_s = (-k_1 + p_2)^2 \to u_a$$
$$t_s = (-k_1 + p_1)^2 \to t_a$$
$$u_s = (-k_1 - k_2)^2 \to s_a$$

Crossing symmetry

$$s_a = 4E^2 = 4(M^2 + |\vec{p}_a|^2)$$

$$s_s = m^2 + M^2 + 2E_2'\epsilon_2' + 2|k_s|^2$$

$$\sigma^a = \frac{1}{4}\frac{|\mathcal{M}_{(a)}|^2}{64\pi^2 s}\frac{|\vec{k}_a|}{|\vec{p}_a|}$$

$$\sigma^s = \frac{1}{2}\frac{|\mathcal{M}_{(s)}|^2}{64\pi^2 s}\frac{|\vec{k}_s|}{|\vec{p}_s|}$$

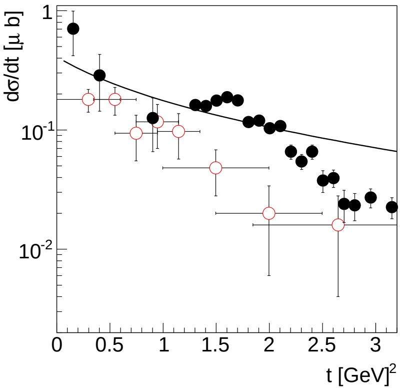
From equality of $s_a = s_s$, get k_s

$$|\vec{k}_s|^2 = \frac{1}{4s}\left[m^4 - 2m^2(M^2 + s) + (M^2 - s)^2\right]$$

Then the cross sections are related by :

$$\sigma^a = \frac{1}{2}\frac{|\vec{k}_s|^2}{|p_a|^2}\sigma^s = f\sigma^s$$

Crossing symmetry



$$\sigma^a = \frac{1}{2}\frac{|\vec{k}_s|^2}{|p_a|^2}\sigma^s = f\sigma^s$$

when t is small,

$$\sigma^s \simeq const \cdot s^{-2}$$

$$\sigma^s(s) = \sigma^s(s_1)\cdot\frac{s^{-2}}{s_1^{-2}}$$

$$\sigma^a(s) = f\sigma^s(s_1)\cdot\frac{s^{-2}}{s_1^{-2}}$$

Data for $\bar{p}+p\to\pi^-+\pi^+$ (red empty circles) at 6.2 GeV/c, $\pi^-+p\to\pi^-+p$(black solid circles) at 6.73 GeV/c.$f=0.589$

conclusion and perspective

- Finalize the collection of data, on annihilation and scattering
- Calculate simple t- u- s- channel diagrams and compare with data
- Refine the models (Regge exchange, off-shell..)
- Understand the change of regime from Legendre polynomes to Regge-type angular distributions