



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

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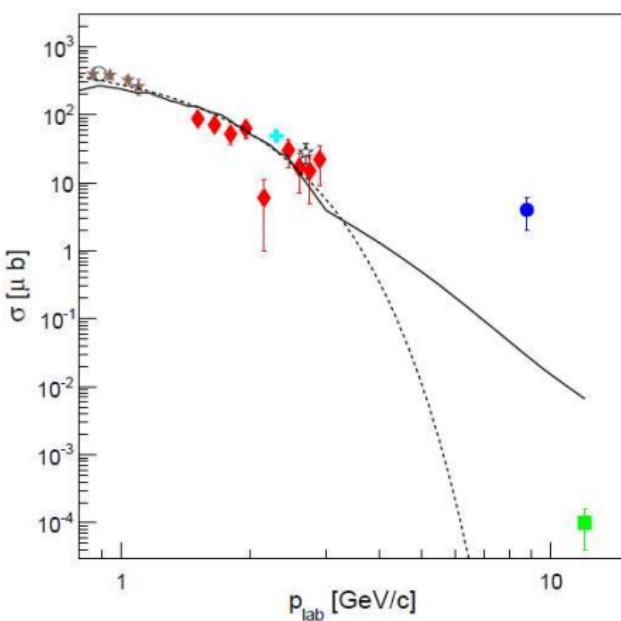
Motivation

- ▶ The reaction $\bar{p}p \rightarrow e^+e^-$ allows to measure electromagnetic proton form factors.
- ▶ Important simulation work is under way.
- ▶ The reaction $\bar{p}p \rightarrow \pi^+\pi^-$ is the main background :
 - ▶ has a huge 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 $\bar{p}p \rightarrow \pi^+\pi^-$ at PANDA energies.

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

Total cross section



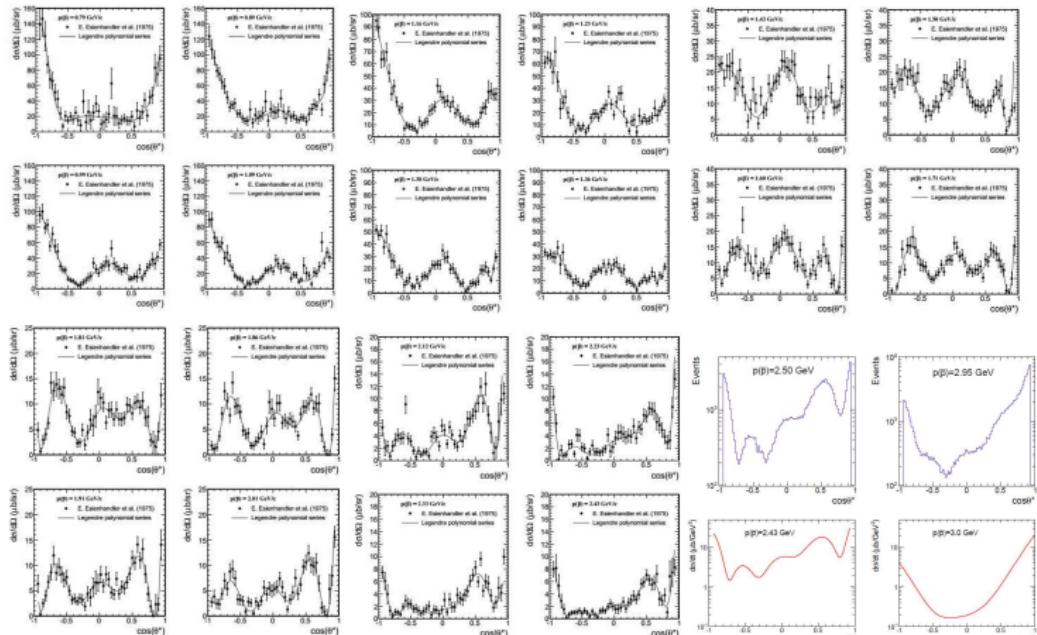
Data from :

- 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 (M. Zambrana)*dashed line* : A. Dbeysi,
PhD, Orsay (2013)

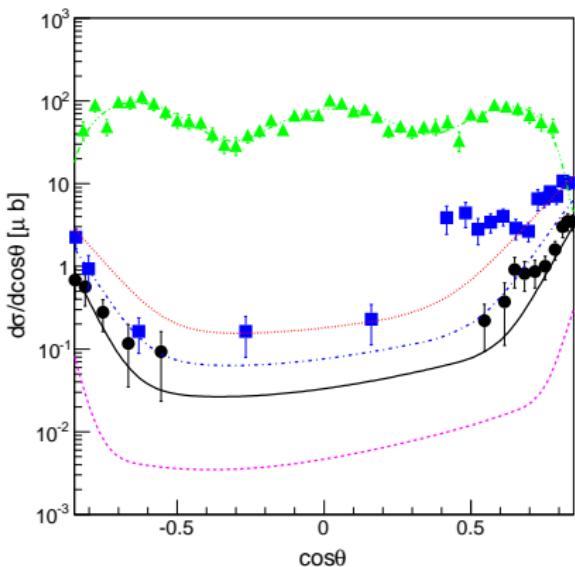
Differential cross section : Low energy range

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



- ▶ Complete data sets
- ▶ Oscillatory behavior
- ▶ Fit by Legendre polynomials

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 $\cos\theta = 0$

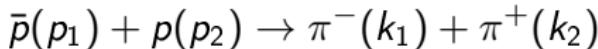
Modelization of the reaction $\bar{p}p \rightarrow \pi^+\pi^-$ in Panda Root

Generators :

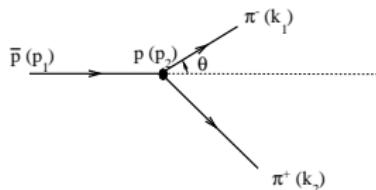
- ▶ Dual Parton Model (generic annihilation background in $\bar{p}p$ annihilation)
- ▶ FTF (Hadronic interaction model in GEANT4)
- ▶ Phase Space Model(flat distribution in $\cos\theta$)
- ▶ EvtGen (generate benchmark reactions by user) :
twoPionGen (*M. Zambrana et al.*)
 - ▶ Legendre polynomials (low 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 $\bar{p} + p \rightarrow \pi^- + \pi^+$

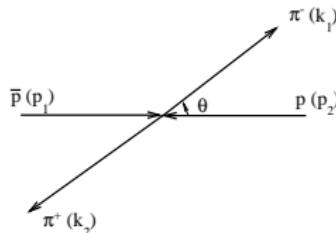
► Kinematics :



In Lab System



In CM System



particle	Momentum	Lab	CMS
\bar{p}	p_1	(E_ℓ, \vec{p}_ℓ)	(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 :

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

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

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

- Relation between t , s , and $\cos\theta$

In CM system :

$$t = M_p^2 + m_\pi^2 - 2E_1^2(1 - \beta_p\beta_\pi \cos\theta)$$

$$\beta_p = \sqrt{1 - \frac{4M_p^2}{s}}$$

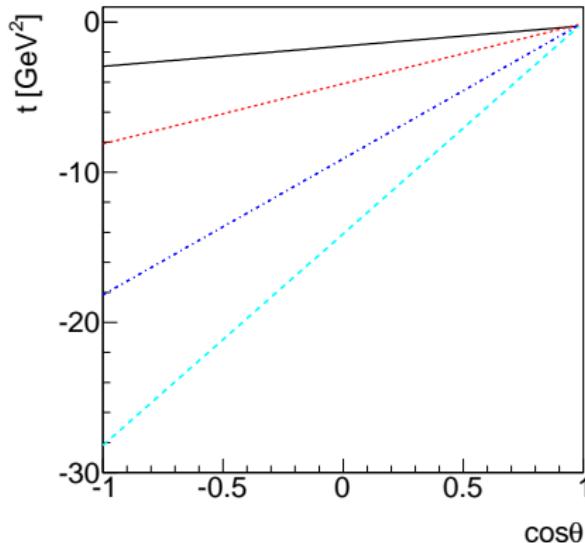
$$\beta_\pi = \sqrt{1 - \frac{4m_\pi^2}{s}}$$

$$s = 4E_1^2$$

Dependence of t on $\cos\theta$

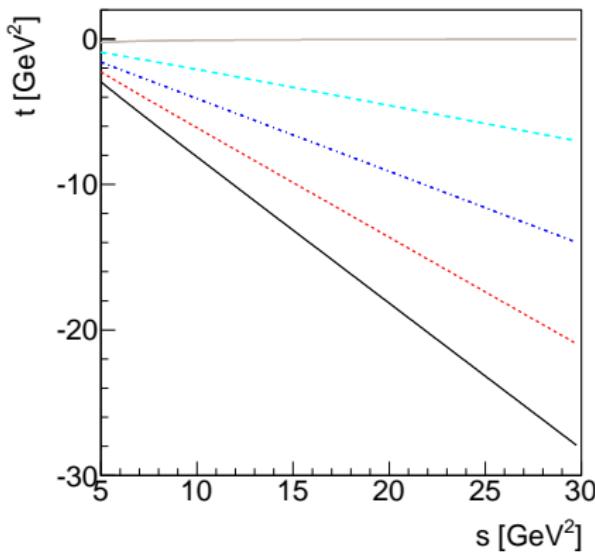
In PANDA, $p_{Lab} > 1.5 \text{ GeV}$, $s > 5.08 \text{ GeV}^2$

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



Dependence of t on s

- ▶ The range of s : 5 - 30 GeV^2
- ▶ Different values of $\cos\theta$: $\cos\theta = -1, \textcolor{red}{-0.5}, \textcolor{blue}{0}, \textcolor{teal}{0.5}, 1$



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 $\cos \theta$:
 ϵ^\pm is the energy of π^- in lab system(E) :

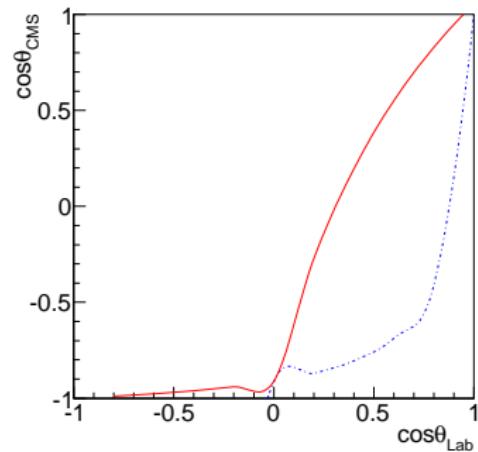
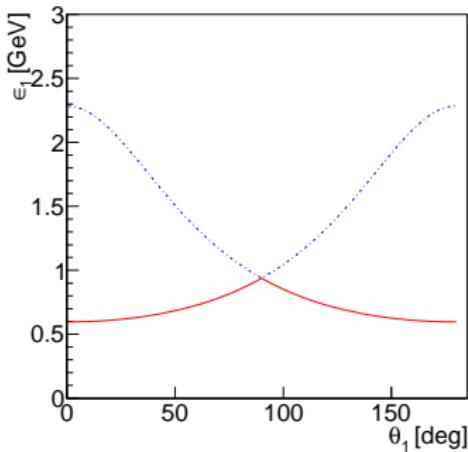
$$\epsilon_1^\pm = \frac{MW^2 \pm \sqrt{p_\ell^2 \cos^2 \theta_\ell [W^2(M_p^2 - m_\pi^2) + m_\pi^2 p_\ell^2 \cos^2 \theta_\ell]}}{(W^2 - p_\ell^2 \cos^2 \theta_\ell)}$$

$$W = E_\ell + M_p$$

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

Relation between CM system and Lab system

plots of ϵ_1^\pm and $\cos\theta$



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

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

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

$$1. \pi^-(-k_2) + p(p_2) \rightarrow \pi^-(k_1) + p(-p_1), \quad p_1 \rightarrow -k_2$$

$$s_s = (-k_2 + p_2)^2 \rightarrow t_a$$

$$t_s = (-k_2 - k_1)^2 \rightarrow s_a$$

$$u_s = (-k_2 + p_1)^2 \rightarrow u_a$$

$$2. \pi^+(-k_1) + p(p_2) \rightarrow p(-p_1) + \pi^+(k_2), \quad p_1 \rightarrow -k_1$$

$$s_s = (-k_1 + p_2)^2 \rightarrow u_a$$

$$t_s = (-k_1 + p_1)^2 \rightarrow t_a$$

$$u_s = (-k_1 - k_2)^2 \rightarrow s_a$$

Crossing symmetry

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

$$s_s = m^2 + M^2 + 2E'_2\epsilon'_2 + 2|k_s|^2$$

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

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

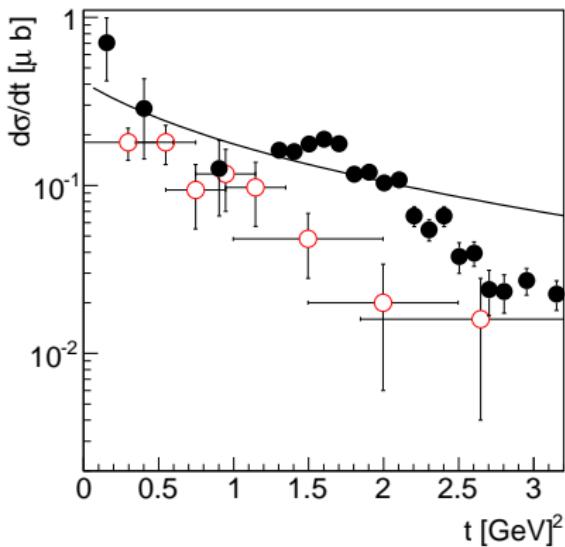
From equality of $s_a = s_s$, get k_s

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

Then the cross sections are related by :

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

Crossing symmetry



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

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

when t is small,

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

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

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

Conclusions and Perspectives

- ▶ 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 polynomials to Regge-type angular distributions in the 2-3 GeV/c p_{Lab} region