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Elastic $\bar{p}p$ collisions: a complete set of experiments and reconstruction of the scattering matrix

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Outline

- ***Physics motivation***
  - **Direct reconstruction of the scattering matrix elements.**
  - **Investigation of spin-effects in the extraction of forward scattering amplitude.**

- ***Preliminary results***
  - **Phenomenological parameterizations of the amplitudes for elastic proton-antiproton collisions.**
  - **Dependences on t-invariant for elastic proton-antiproton scattering for:**
    - **Differential cross-section**
    - **Polarization**
    - **Elements of the spin-correlation and depolarization tensors**
    - **Wolfenstein parameters**

- ***Summary and plans***

Physics motivation

- **Definition of the scattering matrix is the main goal of the complete experiment with proton-proton and/or proton-antiproton scattering**
  - The method of the direct reconstruction is valid at any initial energies

- **Scattering amplitudes**
  - Additional new experiments are necessary in particular with proton-antiproton beams in order to
    - **obtain important information about helicity amplitudes;**
    - **cancel some uncertainties in the phenomenological parameterizations of amplitudes;**
    - **improve the precision of the experimental data**
  - Many analytic parameterizations are very close for high energies, it turns that they may be differ markedly at low and medium energy. Therefore new experiments are necessary at wide energy region, in particular at low and medium energies.

- **Elastic scattering is (in some sense) one of the most fundamental type of reaction (but it's also the most difficult to understand theoretically).**

$pp/\bar{p}p$ -scattering: amplitude parameterization

- ***Analytical*** **phenomenological parameterization is used for proton-proton non-spin flip amplitude**

R.N.J. Phillips and V. Barger, Phys.Lett. ***46B*** *(1973) 412.*
J.J. Aubert et al. Phys.Lett. ***58B*** *(1975) 233.*

$$\Phi_1 \propto F_0^{(j)},$$

$$F_0^{(j)} = \begin{cases} \sqrt{A}\exp\left(\tfrac{1}{2}Bt\right) + \sqrt{C}\exp\left(\tfrac{1}{2}Dt + i\varphi\right), \ j=1 \\ i\sqrt{A}\exp\left[\left(\tfrac{1}{2}B + \alpha' \ln S - i\alpha' \tfrac{\pi}{2}\right)t\right] + \left(\dfrac{\sqrt{C_0}}{S} - i\sqrt{C_\infty}\right)\exp\left(\tfrac{1}{2}Dt\right), \ j=2. \end{cases}$$

- **I-st method for amplitude parameterization in proton-antiproton collisions:**
  - **the same functions is used for parameterization of the proton-antiproton non-spin flip amplitude**
  - **We have to use**
    - **derivative relations** $\Phi_5 \propto F_1 \propto \dfrac{\partial F_0}{\partial\left(\sqrt{t}\right)}; \Phi_4 \propto F_2 \propto \dfrac{\partial^2 F_0}{\partial\left(\sqrt{t}\right)^2}.$
    - **some additional suggestions**

1-st version	2-d version
$\Phi_1 = \Phi_3$	
$\Phi_2 = 0$	$\Phi_2 = -\Phi_4$

in order to calculate (spin-dependent) observables

See also

S.B.Nurushev, V.A.Okorokov et al. **"Elastic pp scattering at RHIC: a complete set of experiments".** *Proceedings of the SPIN-2001 Workshop, E1,2-2002-103, JINR, Dubna, 2002, pp.302-304.*

Spin-dependent observables

The differential cross-section, polarization, elements of the spin tensors and Wolfenstein parameters are under study for elastic proton-antiproton scattering at low and medium energies.

1-st version

$$\left.\begin{aligned}
& d\sigma/dt \equiv \sigma_0 = |F_0|^2; \\
& P\sigma_0 = \mathrm{Im}\left[(2F_0 - F_2)^* F_1\right]; \\
& (1-D_{nn})\sigma_0 = 1/2|F_0|^2; \\
& (1-C_{nn})\sigma_0 = 1/2\left[|F_0|^2 + |F_0+F_2|^2\right]; \\
& D_t = C_{nn}; \\
& C_{kp}\sigma_0 = 1/4\left[-|F_0|^2 + |F_0-F_2|^2\right]\sin\theta - \mathrm{Re}\left(F_1^* F_2\right)\cos\theta; \\
& R\sigma_0 = |F_0|^2\cos(\theta/2) - \mathrm{Re}\left[F_1^*(2F_0+F_2)\right]\sin(\theta/2); \\
& A\sigma_0 = 1/2\left[2|F_0|^2 - |F_2|^2\right]\sin(\theta/2) + \mathrm{Re}\left[F_1^*(2F_0+F_2)\right]\cos(\theta/2); \\
& R'\sigma_0 = -|F_0|^2\sin(\theta/2) - \mathrm{Re}\left[F_1^*(2F_0+F_2)\right]\cos(\theta/2); \\
& A\sigma_0 = 1/2\left[2|F_0|^2 - |F_2|^2\right]\cos(\theta/2) + \mathrm{Re}\left[F_1^*(2F_0+F_2)\right]\sin(\theta/2).
\end{aligned}\right\}(1)$$

2-d version

$$\left.\begin{aligned}
& d\sigma/dt \equiv \sigma_0 = |F_0|^2; \\
& P\sigma_0 = 2\,\mathrm{Im}\left[(F_0 - F_2)^* F_1\right]; \\
& D_{nn} \equiv 1; \\
& (1-C_{nn})\sigma_0 = |F_0+F_2|^2; \\
& D_t = C_{nn}; \\
& C_{kp} \equiv 0; \\
& R\sigma_0 = \left(|F_0|^2 - |F_2|^2\right)\cos(\theta/2) - 2\,\mathrm{Re}\left[F_1(F_0+F_2)^*\right]\sin(\theta/2); \\
& A\sigma_0 = \left[|F_0|^2 - |F_2|^2\right]\sin(\theta/2) + \mathrm{Re}\left[F_1(F_0+F_2)^*\right]\cos(\theta/2); \\
& R'\sigma_0 = -\left(|F_0|^2 - |F_2|^2\right)\sin(\theta/2) + \mathrm{Re}\left[F_1^*(F_0+F_2)\right]\cos(\theta/2); \\
& A\sigma_0 = \left[|F_0|^2 - |F_2|^2\right]\cos(\theta/2) - 2\,\mathrm{Re}\left[F_1^*(F_0+F_2)\right]\sin(\theta/2).
\end{aligned}\right\}(2)$$

θ **is the scattering angle in center-of-mass system of proton-proton (antiproton) collisions**

$\bar{p}p$ - scattering: amplitude parameterization

II-st method for amplitude parameterization in proton-antiproton collisions:

cross-symmetry relations are used for definition proto-antiproton helicity amplitudes via helicity amplitudes of the proton-proton scattering .

Preliminary results

1-st version

$$\left.\begin{aligned}
\bar{\Phi}_1 &= 1/2\left[2\Phi_1 \sin^2\psi + \left(1+\cos^2\psi\right)\Phi_4\right];\\
\bar{\Phi}_2 &= 1/2\sin^2\psi\left[2\Phi_1 - \Phi_4\right];\\
\bar{\Phi}_3 &= 1/2\left[-\Phi_4 \sin^2\psi - 2\Phi_1 \cos^2\psi\right];\\
\bar{\Phi}_4 &= 1/2\left[\Phi_4 \sin^2\psi + 2\Phi_1 \cos^2\psi\right] + 2\Phi_5 \sin\psi;\\
\bar{\Phi}_5 &= 1/2\cos\psi\left[\sin\psi\left(2\Phi_1 - \Phi_4\right) + 2\Phi_5\right];\\
\bar{\Phi}_6 &= 1/2\cos\psi\left[2\Phi_5 - \sin\psi\left(2\Phi_1 - \Phi_4\right)\right].
\end{aligned}\right\}(II.1)$$

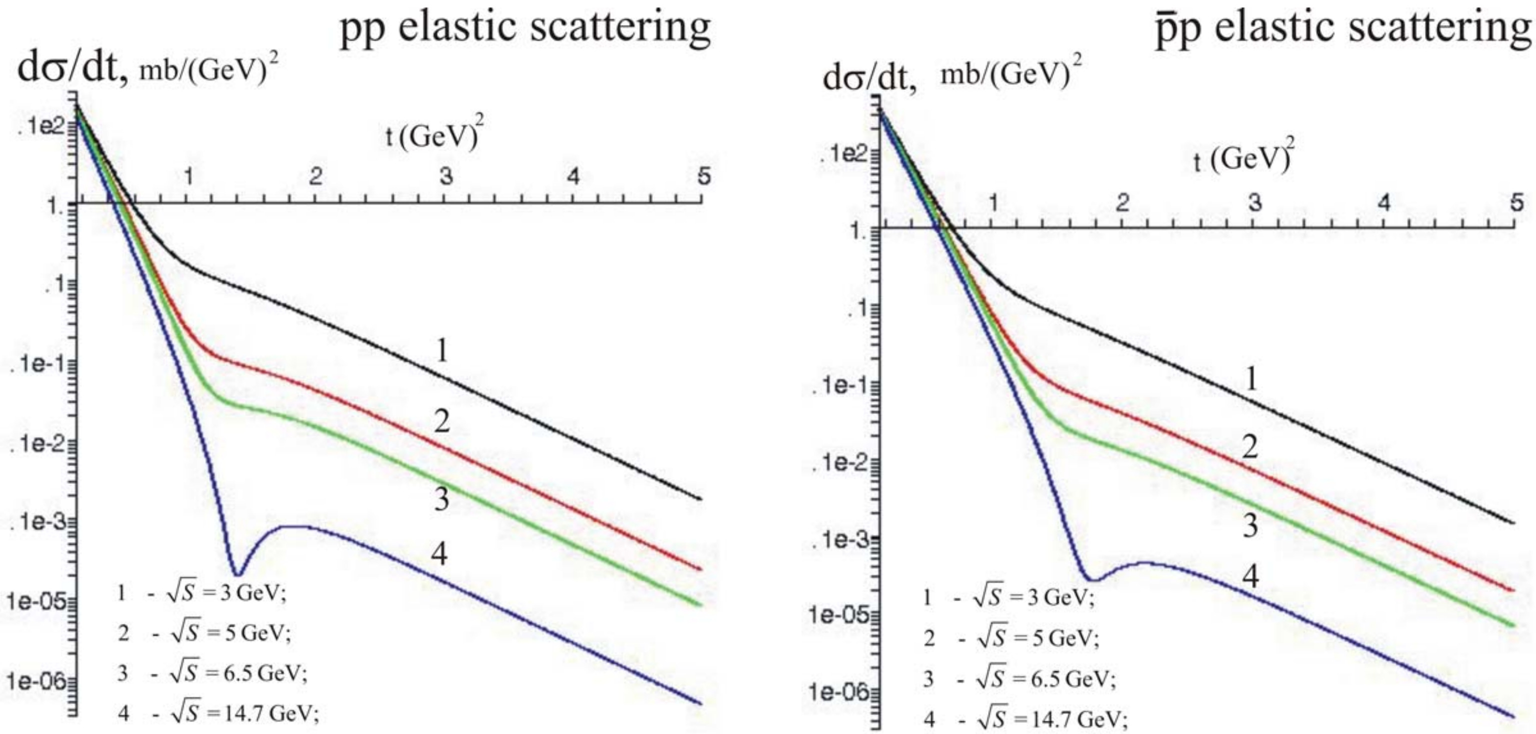
2-d version

$$\left.\begin{aligned}
\bar{\Phi}_1 &= \Phi_1 \sin^2\psi + \Phi_4 \cos^2\psi;\\
\bar{\Phi}_2 &= \Phi_1 \sin^2\psi + \Phi_4 \cos^2\psi;\\
\bar{\Phi}_3 &= -\left[\Phi_4 \sin^2\psi + \Phi_1 \cos^2\psi\right];\\
\bar{\Phi}_4 &= \Phi_4 \sin^2\psi + \Phi_1 \cos^2\psi + 2\Phi_5 \sin\psi;\\
\bar{\Phi}_5 &= \cos\psi\left[\sin\psi\left(\Phi_1 - \Phi_4\right) + \Phi_5\right];\\
\bar{\Phi}_6 &= \cos\psi\left[\Phi_5 - \sin\psi\left(\Phi_1 - \Phi_4\right)\right].
\end{aligned}\right\}(II.2)$$

$$\cos\psi = -\sqrt{\frac{St}{\left(S-4m_p^2\right)\left(t-4m_p^2\right)}};\ \sin\psi = \frac{m_p\sqrt{S-4m_p^2}}{\sqrt{t\left(t-4m_p^2\right)}}\sin\theta.$$

we obtain analytical expressions for all amplitudes for proton-antiproton collisions via known amplitudes of the proton-proton scattering and can study different spin-dependent observables.

$pp\,/\,\bar{p}p$ -scattering: differential cross-sections



- **t-dependences of differential cross-section are similar for proton-proton and proton-antiproton collisions** (according with our similar amplitude parameterizations for proton-proton and proton-antiproton scatterig)
- **there is good agreement our parameterization with other parameterizations in framework Regge model and with experimental data**

  W. Rarita et al. Phys.Rev. ***165*** *(1968) 1615.*

  D.A. Austin et al. Phys.Rev.D ***2*** *(1970) 2613.*

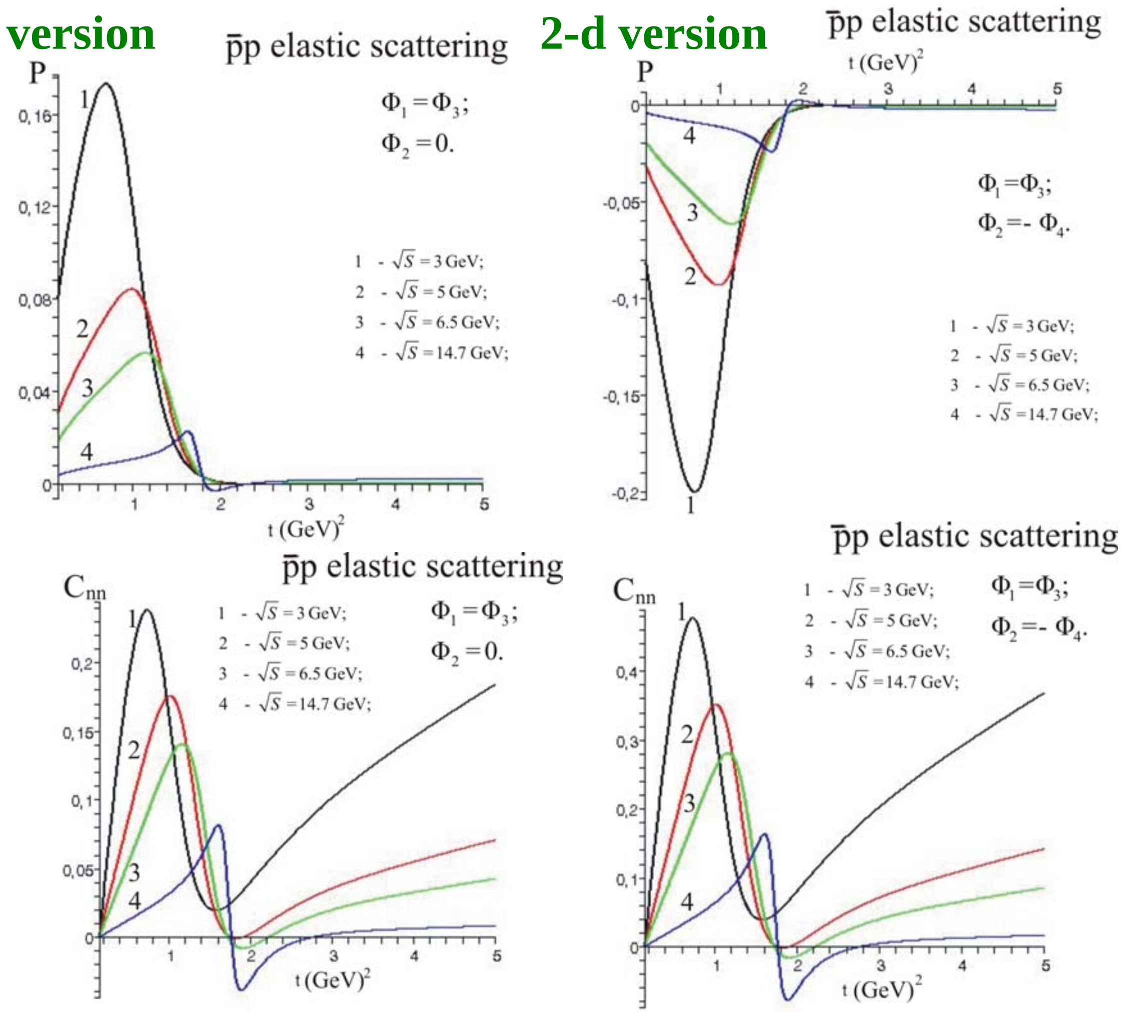
Polarization and C_{nn} vs t-invariant

Polarization has opposed sign for the 1-st and 2-d versions.

Absolute value of polarization decreases with initial energy increasing - correct energy dependence at qualitative level.

C_{nn} shows complex t-dependence.

Maximum of the nontrivial element of spin-correlation tensor C_{nn} decreases with initial energy increasing just as does the maximum of the polarization P.



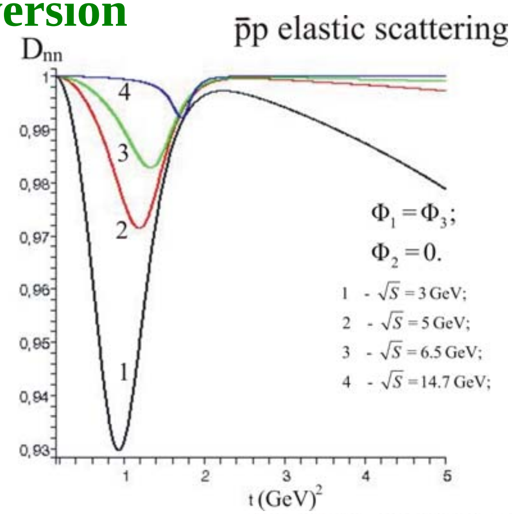
D_{nn} and C_{kp} parameters vs t-invariant

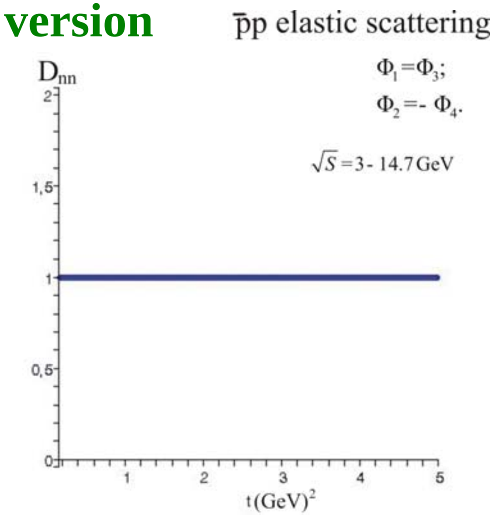
1-st version

2-d version

The value of element D_{nn} (D) of the depolarization tensor increases with energy increasing for the 1-st version.
Dependence of the Dnn (D) for proton-antiproton collisions has similar behavior as for pp-collisions at low energy.

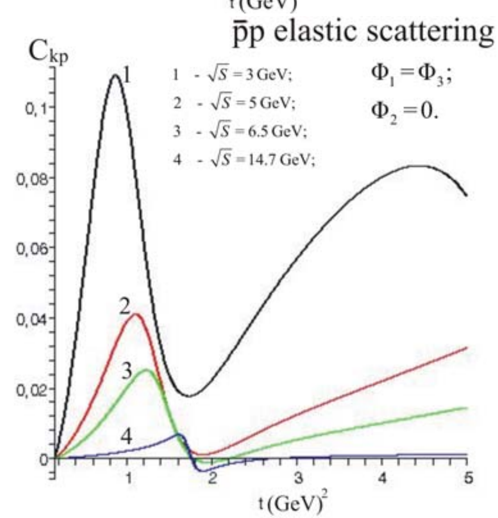
*S.B. Nurushev ZEPT **37** (1959) 301; S.B. Nurushev et al. ZEPT **46** (1964) 50.*

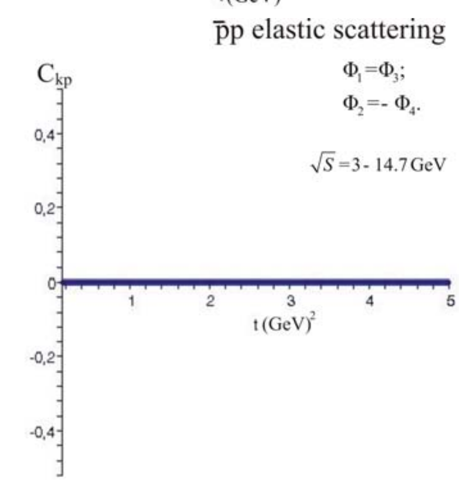




Maximum of the nontrivial element of spin-correlation tensor C_{kp} decreases with initial energy increasing just as does the maximum of the polarization P for the 1-st version.

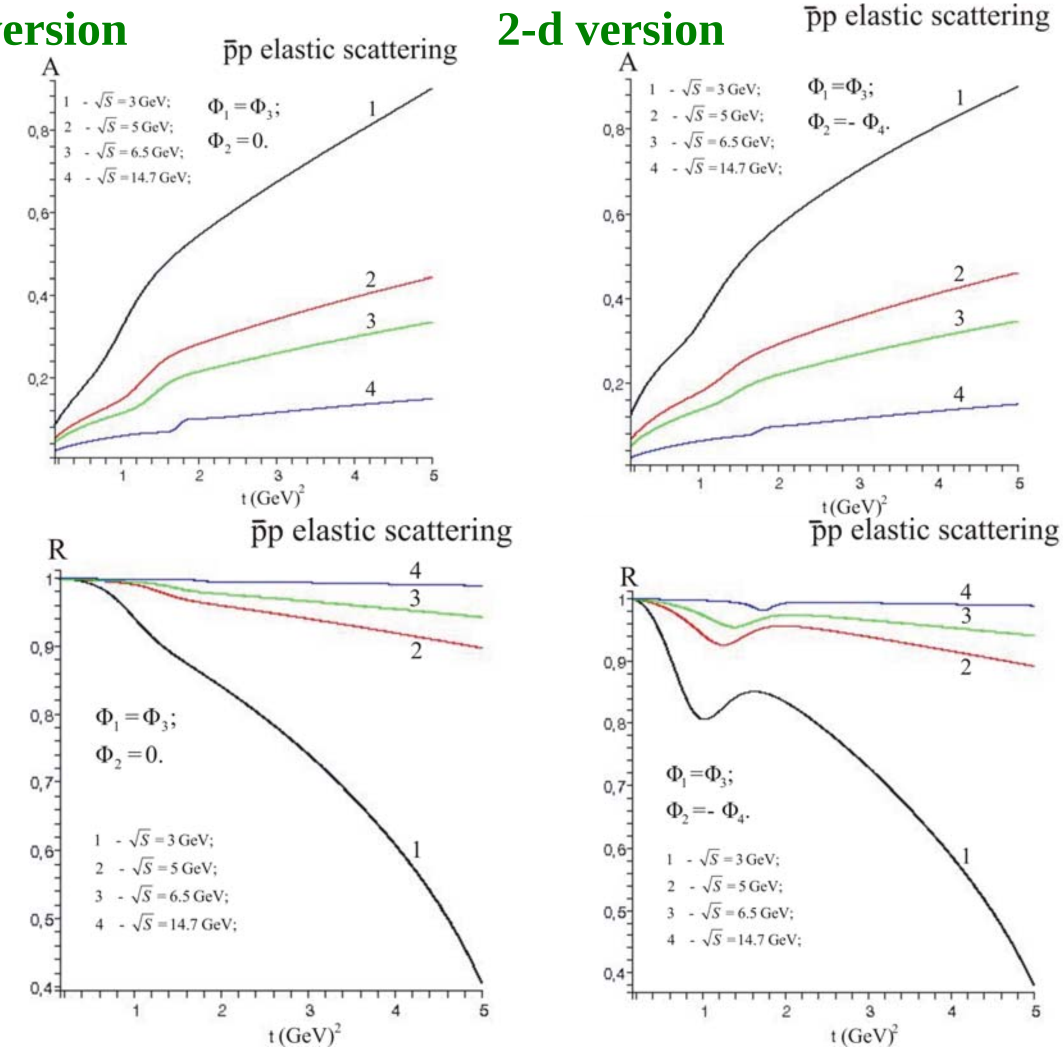
C_{kp} shows trivial value for the 2-d version.





Wolfenstein parameters (1): A & R

1-st version **2-d version**



The A parameter shows very similar t-dependences for both 1-st and 2-d versions. The A increases with t value increasing.

These Wolfenstein parameters show opposed energy dependence on each other for both 1-st and 2-d versions. Indeed, the value of the A parameter decreases with initial energy increasing. On the opposite side, R parameter increases with energy increasing.

The dependences of the R parameter on t-invariant differ for various versions at the same initial energy. This distinction is observed at low energy more clearly.

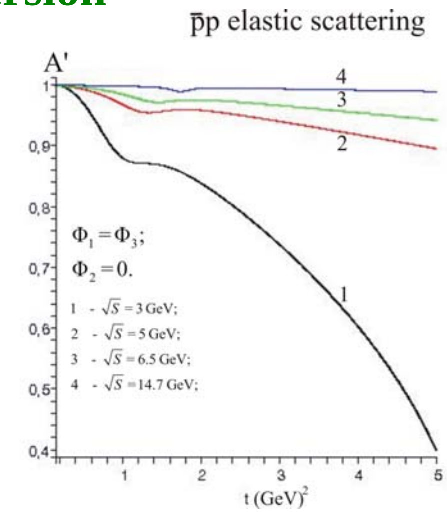
Wolfenstein parameters (2): A’ & R’

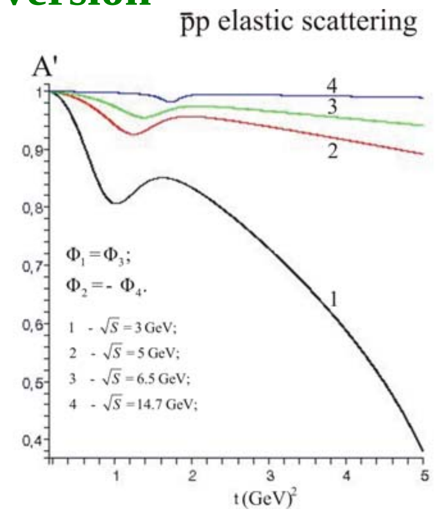
1-st version | **2-d version**

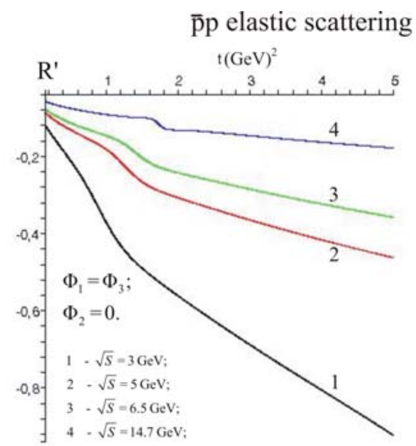
t-dependences are similar for the A’ parameter for both 1-st and 2-d version.

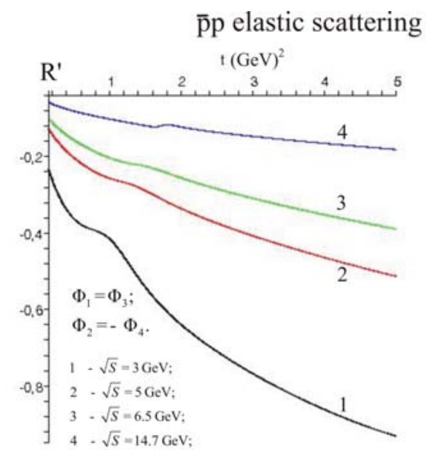
**Second pair of Wolfenstein parameters show opposed energy dependence of the absolute value for each other for both 1-st and 2-d versions as well as the first pair of Wolfenstein parameters:
the value of the A’ parameter increases with initial energy increasing. On the opposite side, absolute value of the R’ parameter decreases with energy increasing.**

R’ parameter is negative for considering domain of t-invariant and t-dependences are very similar for both versions for R’.









Summary & plans

- Two variants are suggested for analytical parameterization of the helicity amplitudes for elastic proton-antiproton collisions.
- The t-dependences of the differential cross-section and some spin-dependent parameters are investigated for elastic proton-antiproton scattering at low and medium energies.
  - correct energy dependences are obtained for polarization and C_{nn} at qualitative level at least.
  - absolute values decrease at initial energy increasing for the all spin-dependent parameters with the exception two Wolfenstein parameters, namely R and A'.

- We suggest to measure differential cross-section and Wolfenstein parameters in three-scattering experiments for proton-antiproton collisions (PAX Collaboration) in order to define arbitrary constants for amplitudes F_1 and F_2.
- We plan to continue study both variants of the analytical parameterization of amplitudes and spin-dependent parameters for both proton-proton and proton-antiproton scattering in wide energy domain.