Constraints on $\bar{N}N$ interaction from the process $e^+e^- \to N\bar{N}$ near threshold

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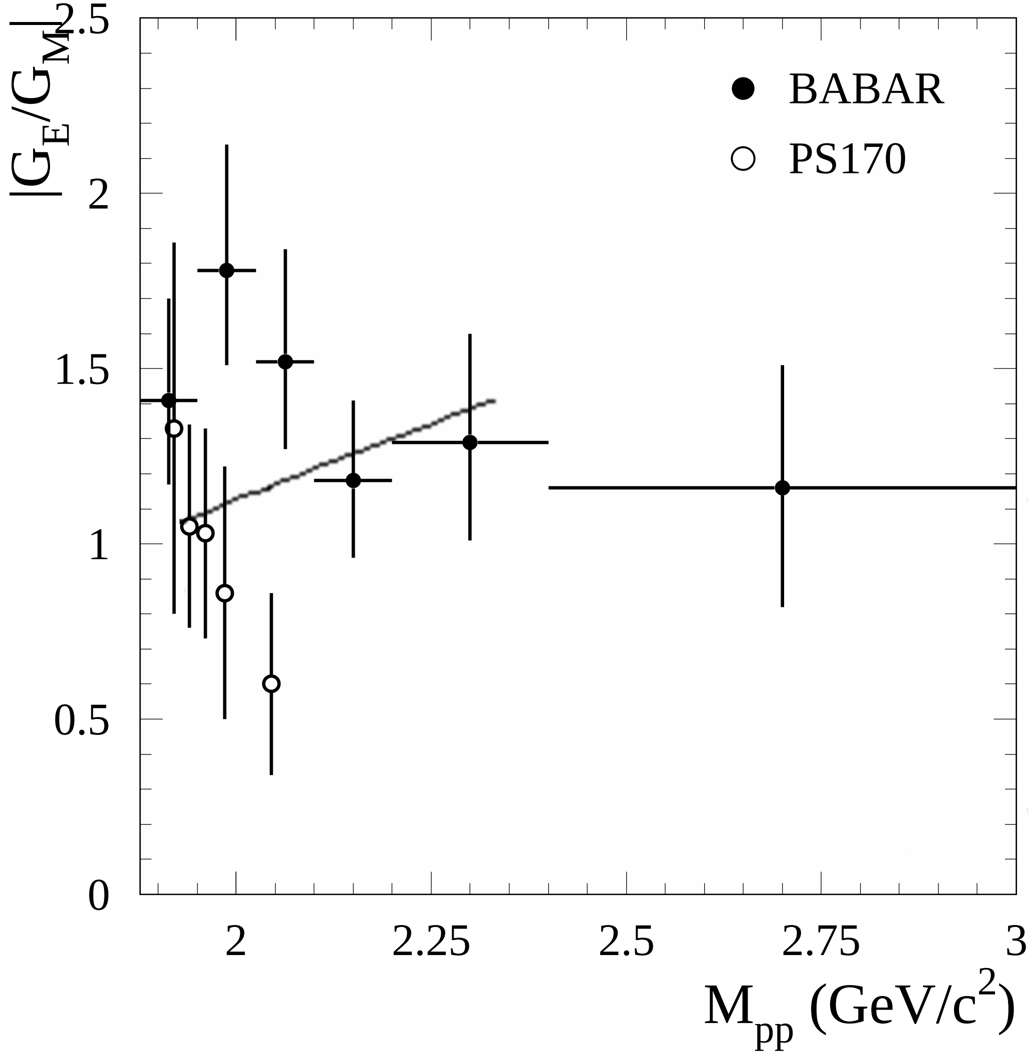


R.Bijker, F.Jachello, Phys.Rev. C69 (2004)

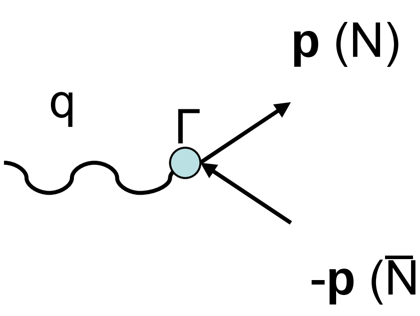
$T_p \approx 210$ MeV

Ratio of electric and magnetic form factors in the threshold region.

$$G_E = F_1 + F_2 \frac{q^2}{4m_p^2},$$

$$G_M = F_1 + F_2.$$

$$\Gamma^\mu = F_1\gamma^\mu - \frac{F_2}{2m_p}\sigma^{\mu\nu}q_\nu$$



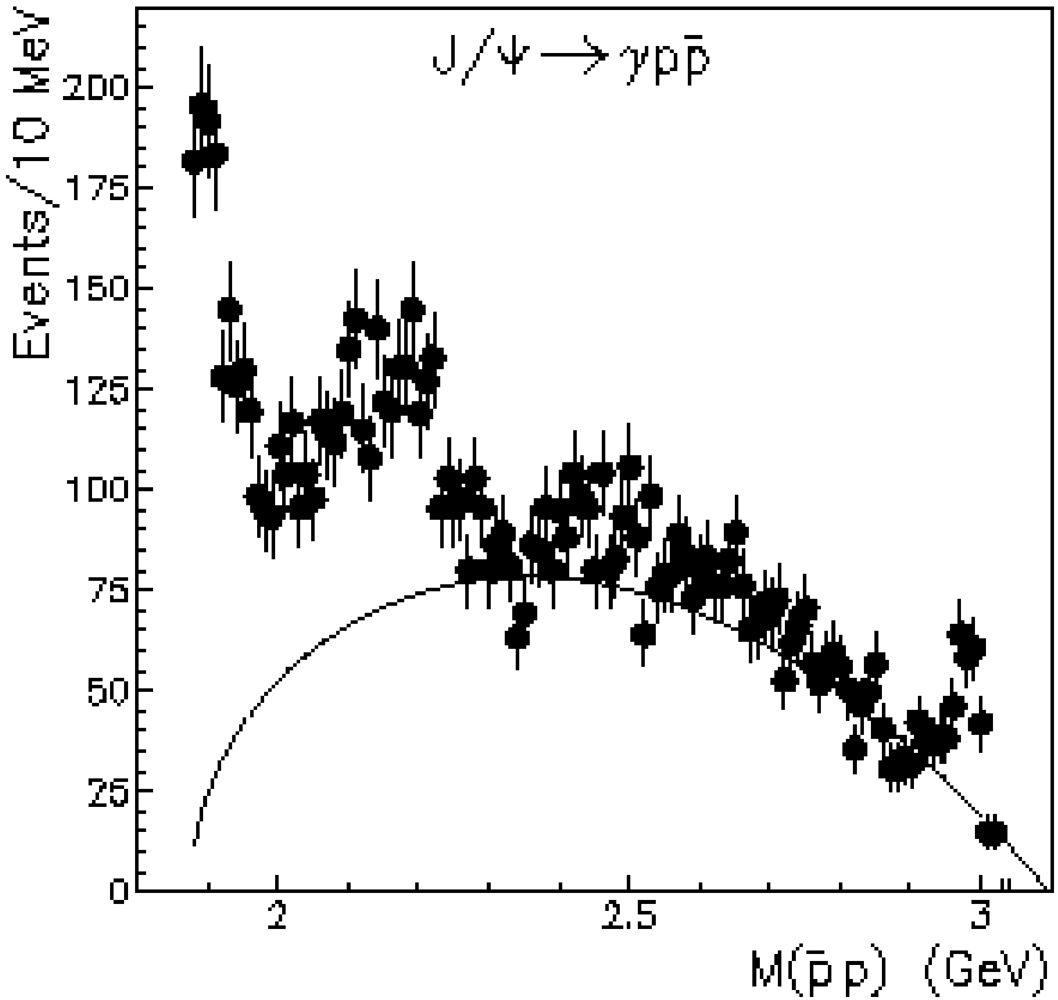


FIG. 4. The $p\bar{p}$ mass spectrum from the decay $J/\Psi \to \gamma p \bar{p}$. The circles show experimental results of the BES Collaboration [1], while the solid line is the spectrum obtained from Eq. (4) by assuming a constant reaction amplitude A.

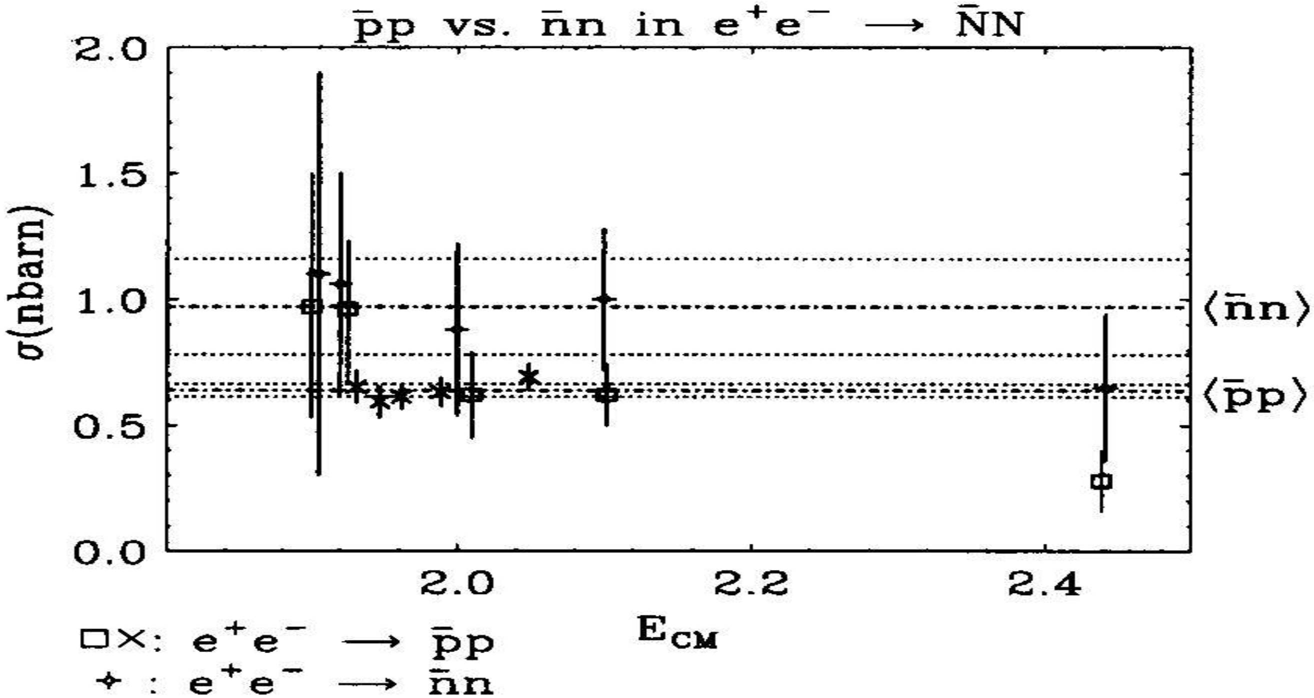
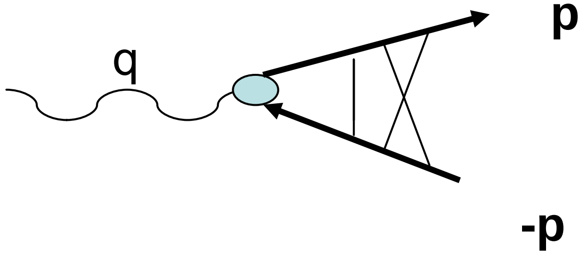


Figure 1. *Comparison of the cross sections for* $e^+e^- \longrightarrow \bar{n}n$ *and* $\bar{p}p$ *in the threshold region* $E_{CM} \sim 2$ *GeV. In the case of* $e^+e^- \longrightarrow \bar{p}p$*, the direct-channel data are combined with the data for the time-reversed reaction* $\bar{p}p \longrightarrow e^+e^-$ *(marked by* $\times$*). The dash-dotted and dotted lines denote the average and 1-*σ *error bars, respectively, for the* $\bar{p}p$ *and* $\bar{n}n$ *data sets.*

General features of the process



P $\bar{\text{P}}$ formation scale

$$\lambda \approx 1/q \approx 1/2m_p \approx 0.1 \text{ fm}$$

At distances 0.1 < r < 1.4 fm there is a strong interaction between slowly moving P and Pbar. This scale corresponds to the energies starting from few ten's MeV. *Strong final state interaction in this energy scale is very likely responsible for the energy dependence of the form factors near threshold.*

QUANTUM NUMBERS of P Pbar state

PHOTON

J=1, P=-1, C=-1

P Pbar Isospin not fixed I=0,1

$$\text{P} = (-1)^{L+1}, \quad \text{C} = (-1)^{L+S}, \quad \mathbf{J} = \mathbf{L} + \mathbf{S}$$

L - even S = 1 $^3S_1 + ^3D_1$

Elementary amplitude of N Nbar production

In the units of e^2/q^2

$$\boldsymbol{\varepsilon}_\mu^\dagger \cdot \boldsymbol{T}_{\mu\lambda}(\boldsymbol{p}) = \boldsymbol{\varepsilon}_\mu^\dagger \left(\frac{1}{3}\left[(2E+M)\tilde{F}_1 + \frac{E^2+2ME}{M}\tilde{F}_2) \right] \mathbf{e}_\lambda + \frac{E\tilde{F}_2 - M\tilde{F}_1}{3M(E+M)}\left(3\boldsymbol{p}(\mathbf{e}_\lambda \cdot \boldsymbol{p}) - \boldsymbol{p}^2 \mathbf{e}_\lambda\right)\right)$$

M – proton mass, *E* – nucleon energy, $\mathbf{e}_\lambda$ - polarization of virtual photon

$\boldsymbol{\varepsilon}_\mu^\dagger$ - spin-1 function of N Nbar pair

$\tilde{F}_1$ and $\tilde{F}_2$ -Dirac form factors responsible for short distance behavior

$\tilde{F}_1$ and $\tilde{F}_2$ *are the smooth functions, nearly constants in threshold region*

Accounting for N Nbar interaction

$$\boldsymbol{\varepsilon}_\sigma^\dagger \cdot \boldsymbol{T}_\lambda(\boldsymbol{p}) \to T_{\sigma\lambda}^I = \int d^3p' \boldsymbol{\Psi}_{\boldsymbol{p}\sigma}^{I(-)\dagger}(\boldsymbol{p}') \cdot \boldsymbol{T}_\lambda(\boldsymbol{p}')$$

I – is the isospin of N Nbar pair

$\psi_{\boldsymbol{p}\sigma}^{I(-)\dagger}(\boldsymbol{r})$ - N Nbar scattering state with asymptotic behaviour

$$\boldsymbol{\Psi}_{\boldsymbol{p}\sigma}^{I(-)\dagger}(\boldsymbol{r})\Big|_{r\to\infty} \to e^{-i\boldsymbol{pr}+i\eta\ln(pr(1-\cos\theta))}\boldsymbol{\varepsilon}_\sigma^\dagger + \frac{e^{ipr+i\eta\ln 2pr}}{r} f_{\sigma\sigma'}^I \boldsymbol{\varepsilon}_{\sigma'}^\dagger.$$

$$\eta = \frac{e^2}{\hbar v}.$$

For p pbar production $\quad T^p = T^1 + T^0$

For n nbar production $\quad T^p = T^1 - T^0$

$$\Psi_{p\sigma}^{I(-)\dagger}(\boldsymbol{r})\hat{H} = (E - M)\Psi_{p\sigma}^{I(-)\dagger}(\boldsymbol{r}), \quad \hat{H} = \frac{\boldsymbol{p}^2}{M} + U(\boldsymbol{r}) - iW(\boldsymbol{r})$$

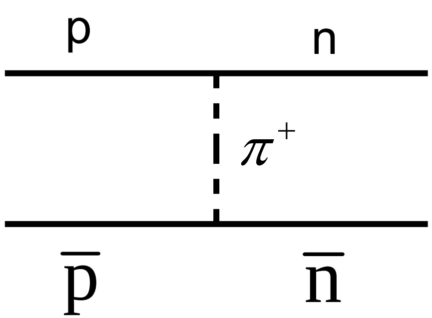
Paris N Nbar potential, Phys.Rev. C50 (1994) 2710

Phys. Rev. C59 (1999) 2313

Real part - meson exchange for r > 0.84 - 1 fm and fit

$$a_0 + a_1 r + a_2 r^2 + a_3 r^3 \text{ or } b_0 + b_1 r + b_2 r^2$$

for r < 0.84 - 1 fm. In both I=0,1 channels



Coupled channels

Imaginary part $W(r) \sim \frac{K_0(2Mr)}{r} g_C (1 + f_C T_{lab})$

Production amplitude becomes

$$T^{I}_{\sigma\lambda} = G^{I}_{0}\delta_{\sigma\lambda} - \sqrt{4\pi}G^{I}_{2}\langle 2m,1\sigma \mid 211\lambda\rangle Y^{*}_{2m}(\hat{\boldsymbol{p}})$$

S-wave D-wave

Electromagnetic form factors

$$G^{I}_{E} = G^{I}_{0} + \sqrt{2}G^{I}_{2}\frac{\mathrm{Q}}{2\mathrm{M}}, \quad \mathrm{G}^{\mathrm{I}}_{\mathrm{M}} = G^{I}_{0} - \frac{G^{I}_{2}}{\sqrt{2}}$$

$$G^{p}_{E} = G^{1}_{E} + G^{0}_{E}, \qquad G^{p}_{M} = G^{1}_{M} + G^{0}_{M}$$

$$G^{n}_{E} = G^{1}_{E} - G^{0}_{E}, \qquad G^{n}_{M} = G^{1}_{M} - G^{0}_{M}$$

With these form factors the cross section p pbar or n nbar production has the usual form

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4Q^2}\left[|G_M^p(Q^2)|^2 \left(1+\cos^2\theta\right) + \tfrac{4M^2}{Q^2} |G_E^p(q^2)|^2 \sin^2\theta \right]$$

where $\beta = \frac{v}{c}$ and *C* is the Coulomb distortion factor.

We omitted here effects of Coulomb-nuclear interference.

The amplitude depends on the wave function at short distances

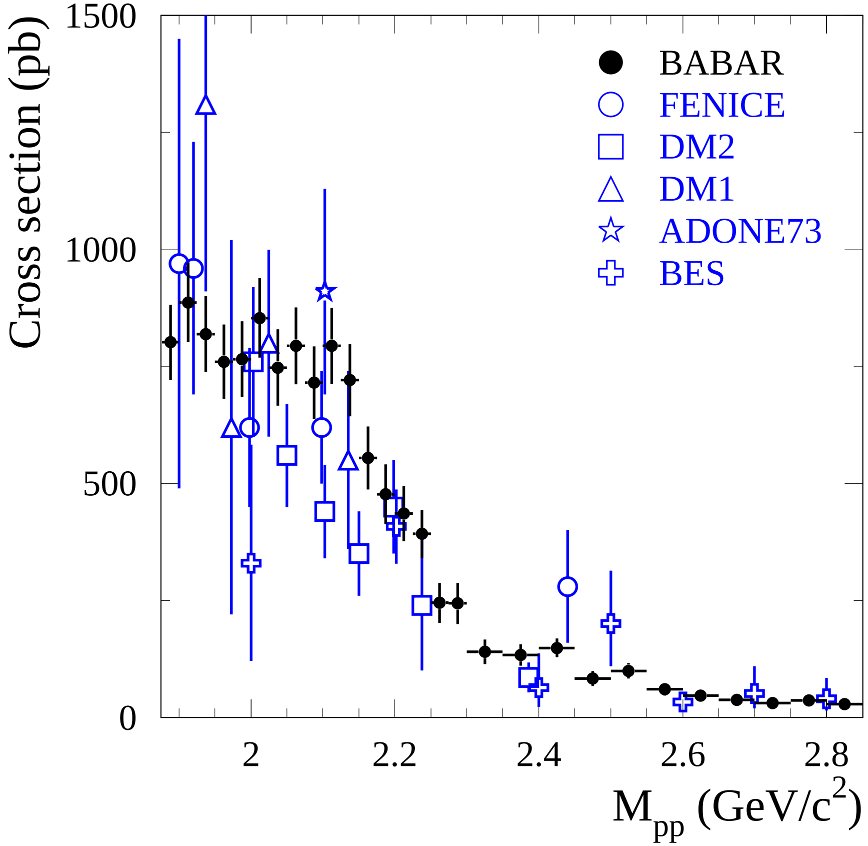
$$T^{I}_{\mu\lambda} \sim \boldsymbol{\Psi}^{I(-)\dagger}_{p\sigma}(\boldsymbol{r}=\boldsymbol{0}) \cdot \frac{1}{3}\left[(2E+M)\tilde{F}_1 + \frac{E^2+2ME}{M}\tilde{F}_2) \right] \mathbf{e}_{\lambda}$$

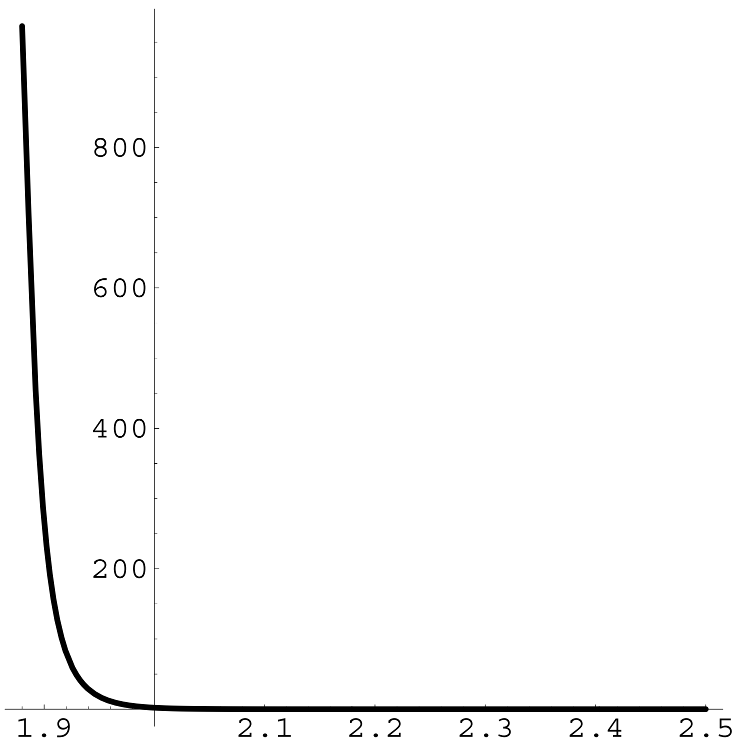
The second term $\sim \nabla_i \nabla_j \boldsymbol{\Psi}^{I(-)\dagger}_{p\sigma}(\boldsymbol{r}=\boldsymbol{0})$

The process is sensitive to the short distance behavior of N Nbar wave function and N Nbar potential.

It is not obvious that a pure phenomenological potential constructed to reproduce scattering phases in several partial waves in the restricted energy region will reproduce correctly the short range behavior of the N Nbar wave function.

A calculation with original Paris N Nbar potential





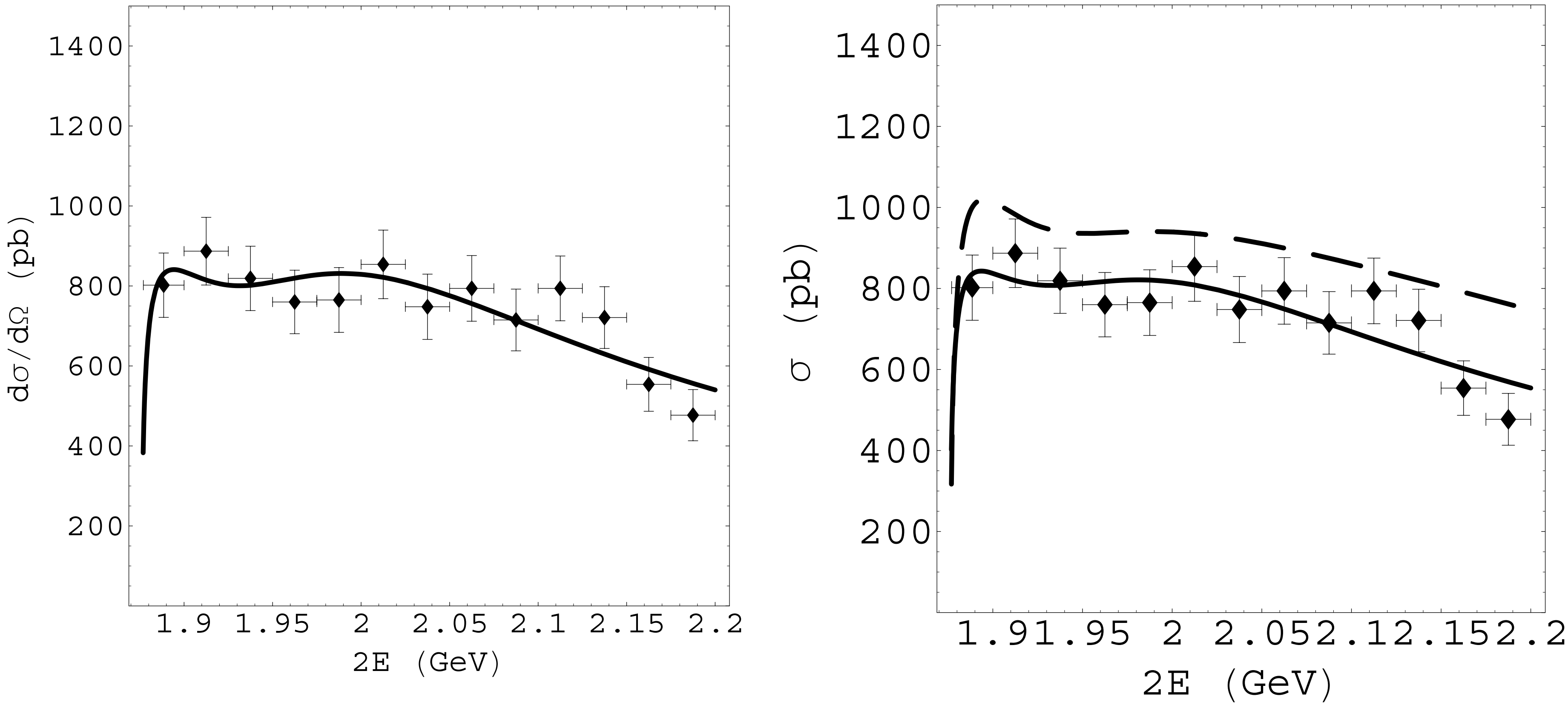
The only sensitive parameter in N Nbar potential is in the absorptive part of the potential

$$W(r) \sim \frac{K_0(2Mr)}{r} g_C (1 + f_C T_{lab})$$

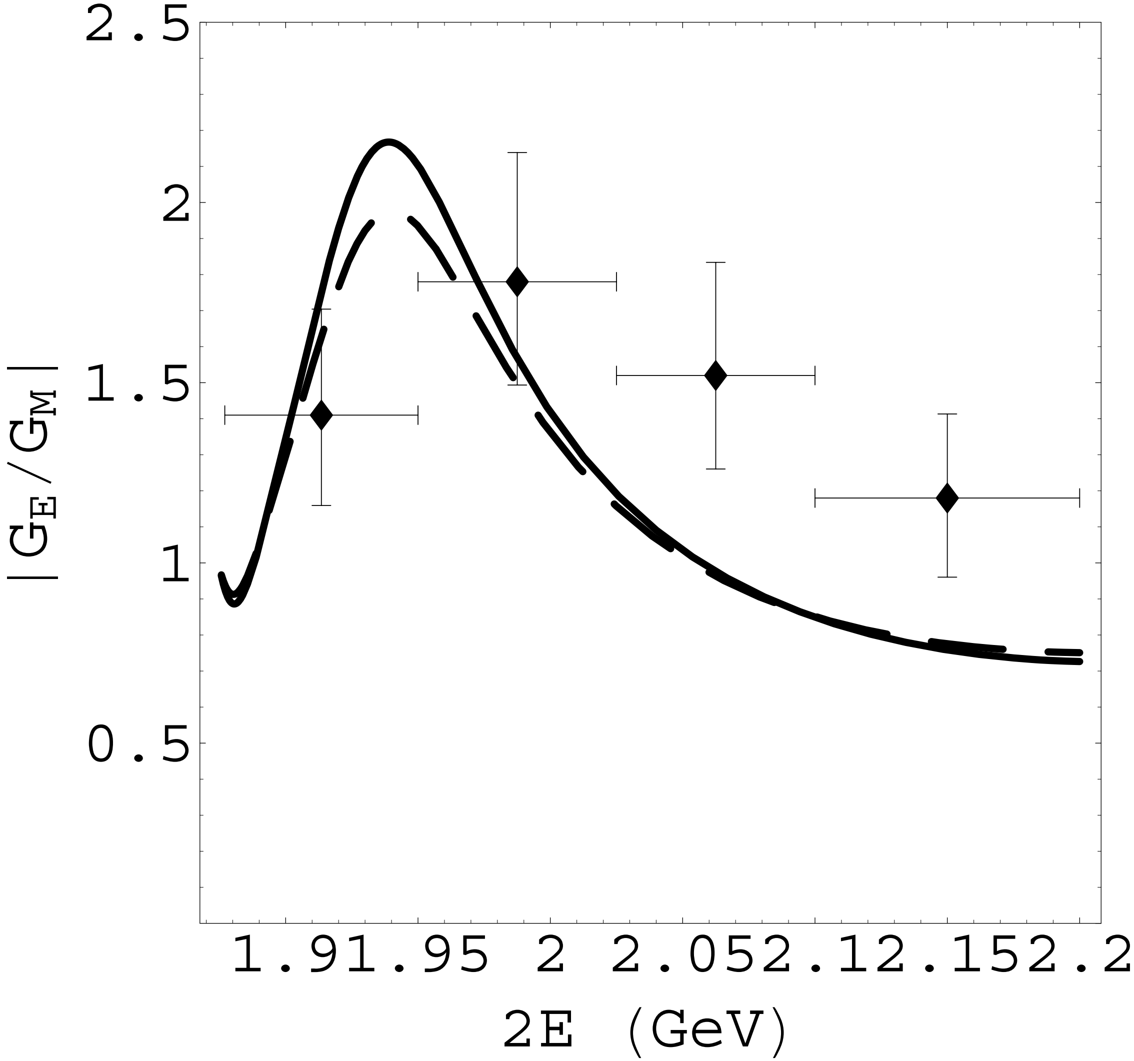
f_C is responsible for absorption rate at different energies. It is the same for all partial waves, which is probably oversimplified assumption. The coefficient is not well defined from the data. In two versions of the potential (1994) and (1999) it differs by factor ~2.

In our process we have s- and d-waves only and sensitivity to this coefficient is much higher due to short range origin of the process.

Only when we reduced f_C by factor ~10 in both isospin channels we were able to reproduce the energy dependence of the cross section



Without any additional fit we were able to reproduce the ratio of the proton electric and magnetic form factors.



Summary

- We developed an approach to account for final state interaction (FSI) in P Pbar production near threshold.
- The effects of FSI are considerable; they lead to strong energy dependence near threshold.
- The process is sensitive to short range behavior of the N Nbar potential. It gives an additional constraint on the parameters of the potential.

- There is an indication that the energy dependence of the absorptive part of the Paris N Nbar potential is too strong for s- and d-waves in J=S=1 channel.