$e^-e^+ \to \overline{N}N$ at Threshold and Proton Form Factor

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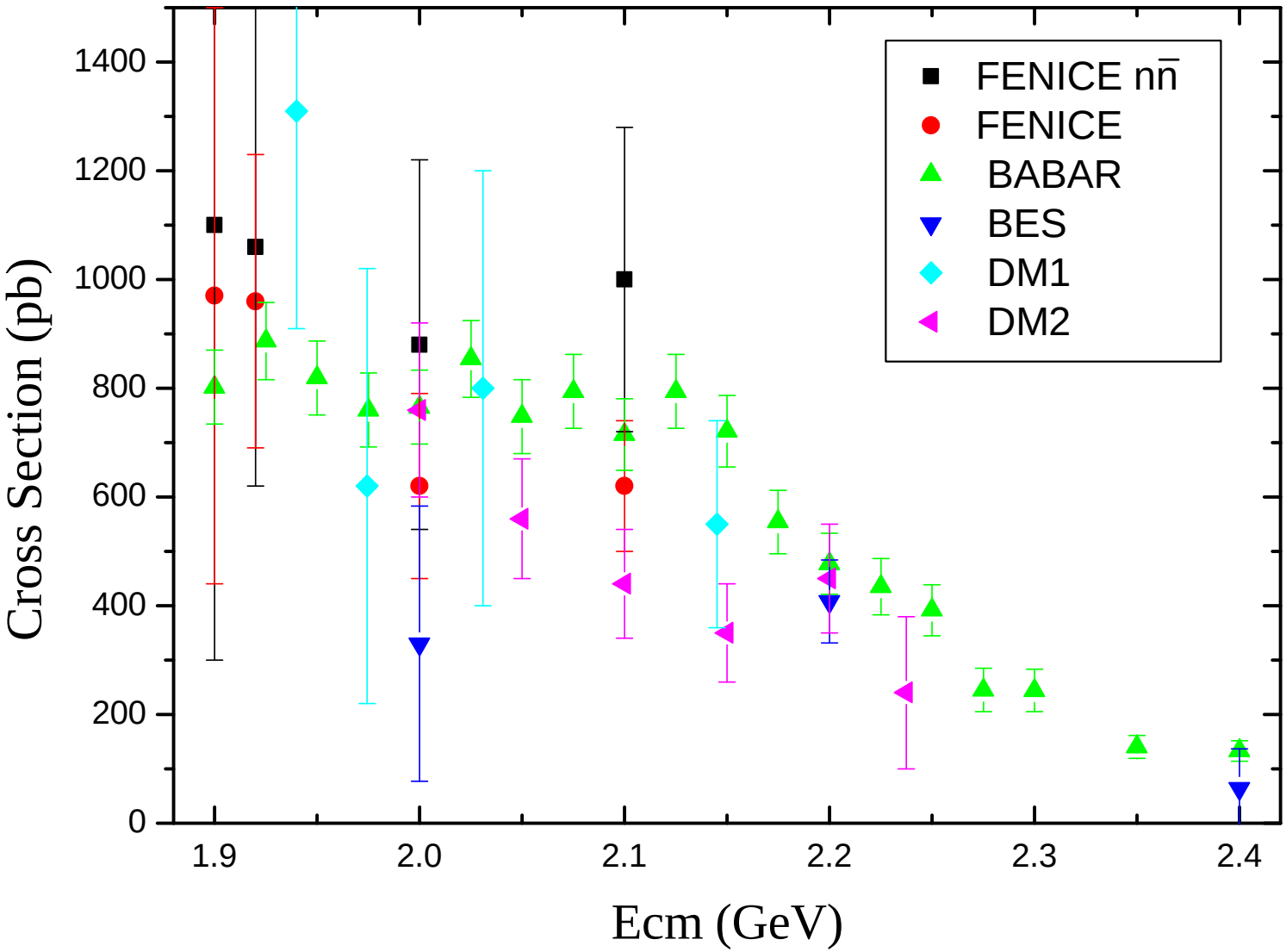
- Data of $e^- e^+ \longrightarrow \overline{N} N$ at Threshold
- One-Step Process
- Two-Step Process with $\rho(2000)$ and $\omega(1900)$
- Two-Step Process with $\rho(2000)$, $\omega(1900)$ and $\rho(1700)$
- Remarks

Data of $e^-e^+ \to \overline{N}N$ Cross Sections



Data of $e^-e^+ \to \overline{N}N$ Cross Sections

- The combined data at threshold indicate that

$$\frac{\sigma(e^+e^- \to \bar{p}p)}{\sigma(e^+e^- \to \bar{n}n)} < 1 \tag{1}$$

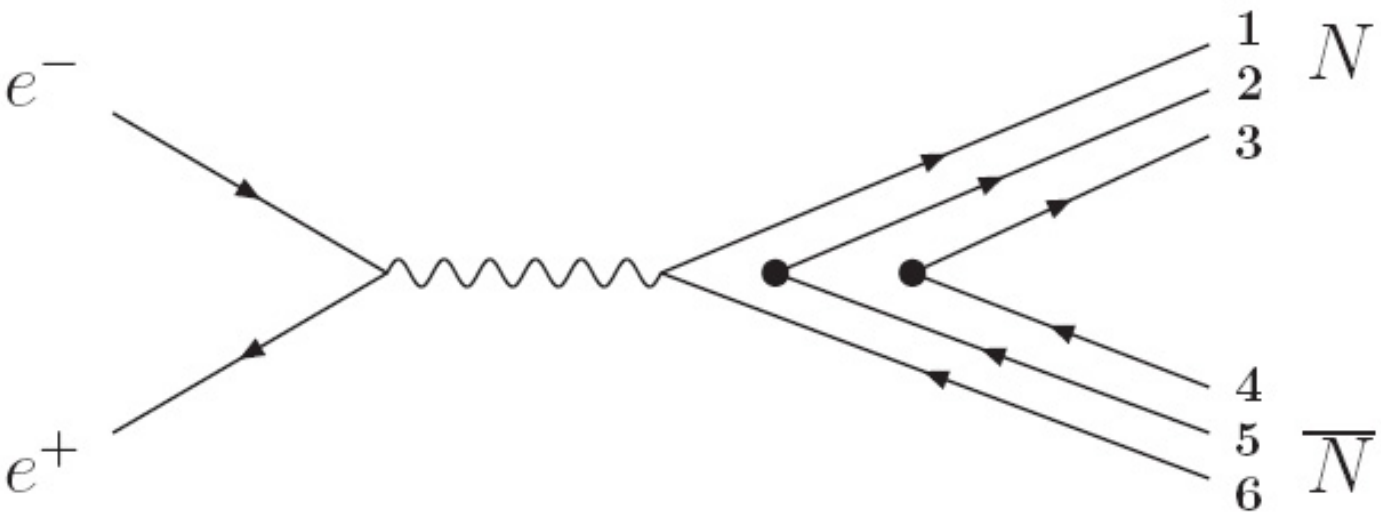
- It is puzzling!
- We expect that the u quark contribution dominates in the proton and the d quark in the neutron, so that

$$\frac{\sigma(e^+e^- \to \bar{p}p)}{\sigma(e^+e^- \to \bar{n}n)} \gg 1 \tag{2}$$

at large momentum transfers.

One-Step Process in $^3P_0$ Model

One-step process in which the primary $\overline{q}q$ pair is directly dressed by additional $\overline{q}q$ pairs to form a hadron pair,



Transition amplitude

$$T_{e^+e^-\to\overline{N}N} = \langle \overline{N}N|V_{^3P_0}|\overline{q}q\rangle\langle\overline{q}q|T|e^+e^-\rangle \qquad (3)$$

One-Step Process in $^3P_0$ Model

$^3P_0$ Vertex: $V_{^3P_0} = V_{25}V_{34}$ with

$$V_{ij} = \lambda\, \vec{\sigma}_{ij} \cdot (\vec{p}_i - \vec{p}_j)\, \hat{F}_{ij}\, \hat{C}_{ij}\, \delta(\vec{p}_i + \vec{p}_j) \tag{4}$$

- $\vec{p}_i$ and $\vec{p}_j$ are the momenta of quark and antiquark created out of the vacuum;
- Spin Operator: $\vec{\sigma}_{ij} = (\vec{\sigma}_i + \vec{\sigma}_j)/2$;
- Flavor and Color Operators: $\hat{F}_{ij}$ and $\hat{C}_{ij}$, projecting a quark-antiquark pair to the respective vacuum quantum numbers.

One-Step Process in $^3P_0$ Model

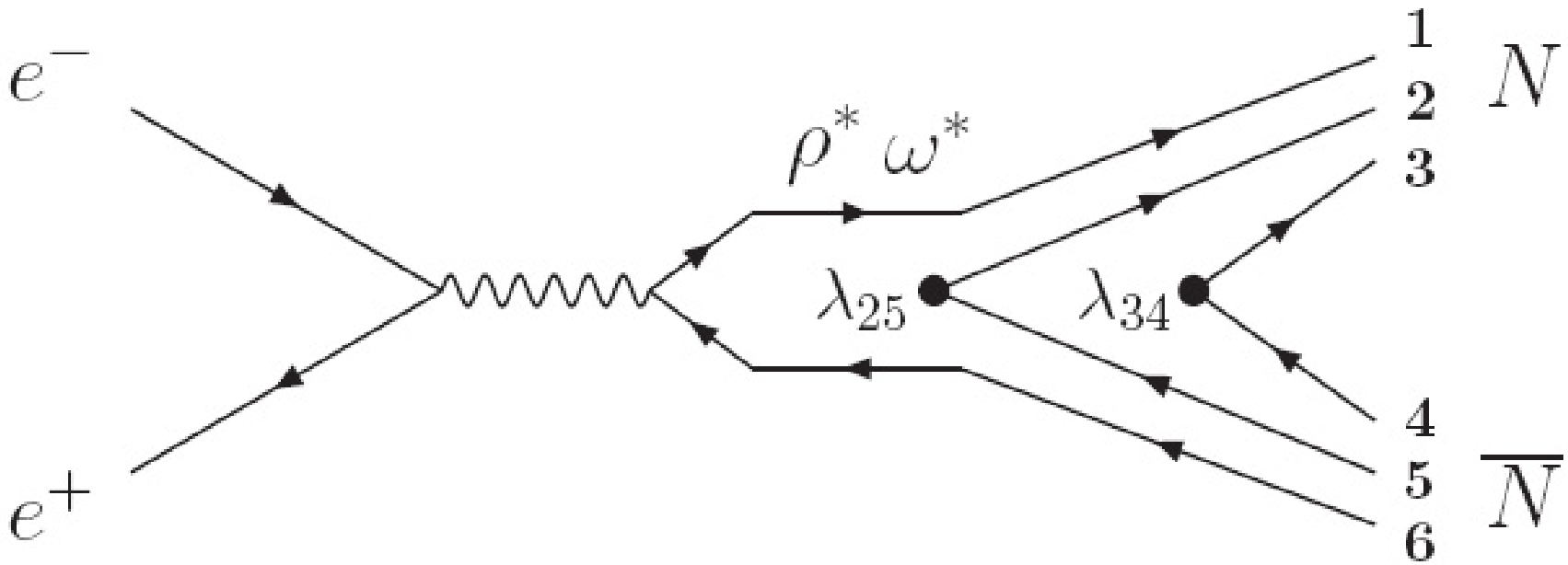
- Radial wave function of nucleons takes the Gaussian form with size parameters $a_{\rho(\lambda)} = 1.5 \sim 2.0$ GeV^{-1}, see PRD34.2809, D47.1994, D75.094017
- $a_{\rho(\lambda)} = 1.5 \sim 2.0$ GeV^{-1} corresponds to a nucleon radius $R = 0.3 \sim 0.4$ fm.
- At E_{cm} around 2 GeV the $^3P_0$ model gives

$$\frac{\sigma(e^+e^- \to \overline{p}p)}{\sigma(e^+e^- \to \overline{n}n)} \approx 3 \tag{5}$$

- The one-step process can NOT be dominant for $e^+e^- \to \overline{N}N$ at threshold in the $^3P_0$ model.

Two-Step Process in $^3P_0$ Model

Two-step process in which the primary $\overline{q}q$ pair forms first a vector meson which in turn decays into a hadron pair,



$$T_{e^+e^-\to\overline{N}N} = \langle \overline{N}N|V_{^3P_0}|\rho^*\rangle\langle\rho^*|G|\rho^*\rangle\langle\rho^*|\overline{q}q\rangle\langle\overline{q}q|T|e^+e^-\rangle$$

$^3P_0$ Vertex: $V_{^3P_0} = V_{25}\ \frac{1}{\Delta E}\ V_{34}$

Two-Step Process in $^3P_0$ Model

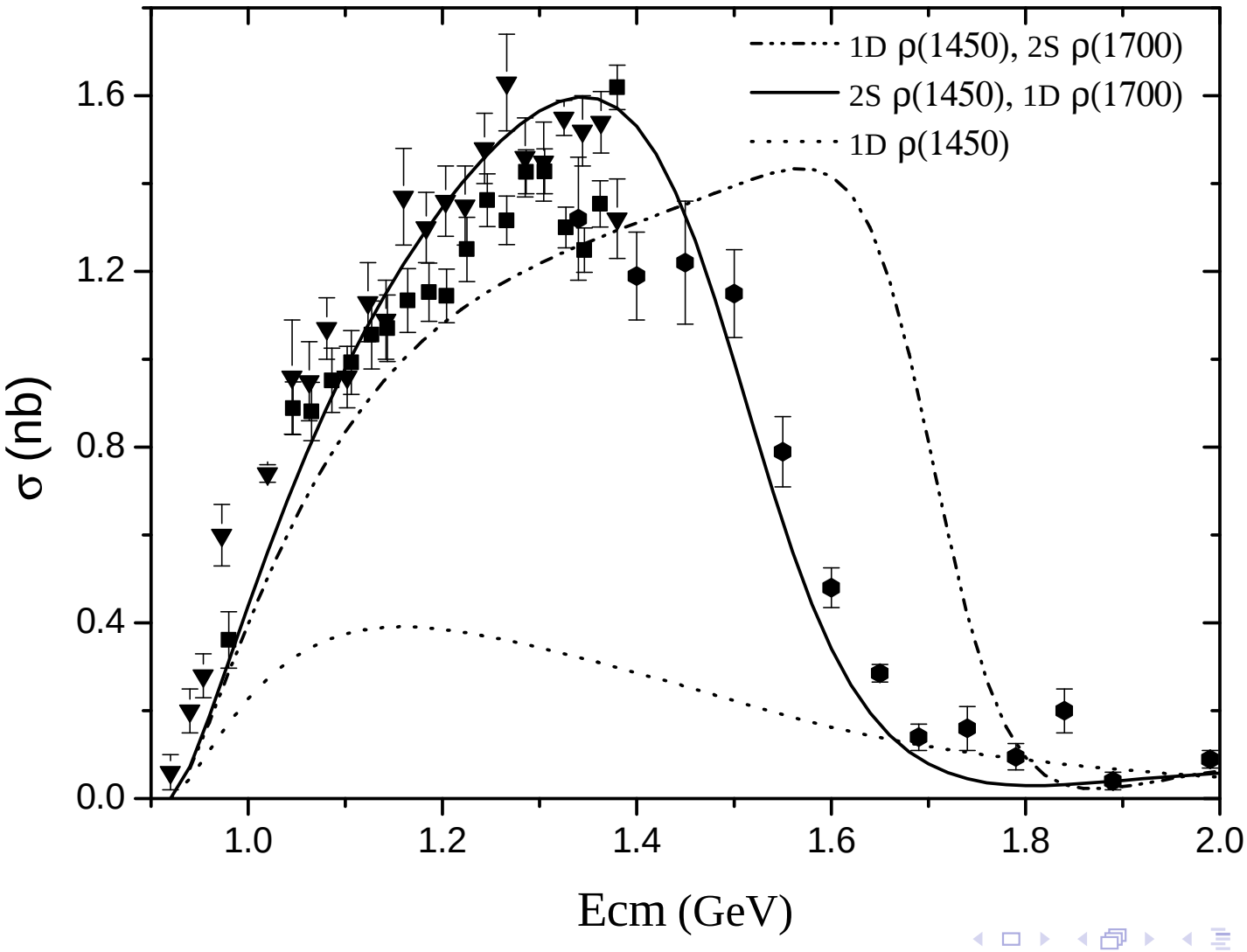
- $1/\Delta E$, accounting for the energy propagation between the two $q\bar{q}$ vertices, is simply set by associating an equal share of Ecm to each valence quark (PLB331.8, PLB354.24, PRD71.025204);
- Radial wave function of nucleon takes the Gaussian form with the size parameter $a = 2.0$ GeV^{-1}
- Radial wave function of intermediate mesons takes the Gaussian form with the size parameter b fixed to be 3.85 GeV^{-1} by the process $\rho \longrightarrow e^- e^+$
- $\lambda_{25} = 1.0$, the one for $\rho \longrightarrow \pi\pi$;
- $\lambda_{34} = 2.6$ (arguable!), the one for $\Sigma(1385) \longrightarrow \Lambda\pi$.

Candidates of Intermediate Mesons

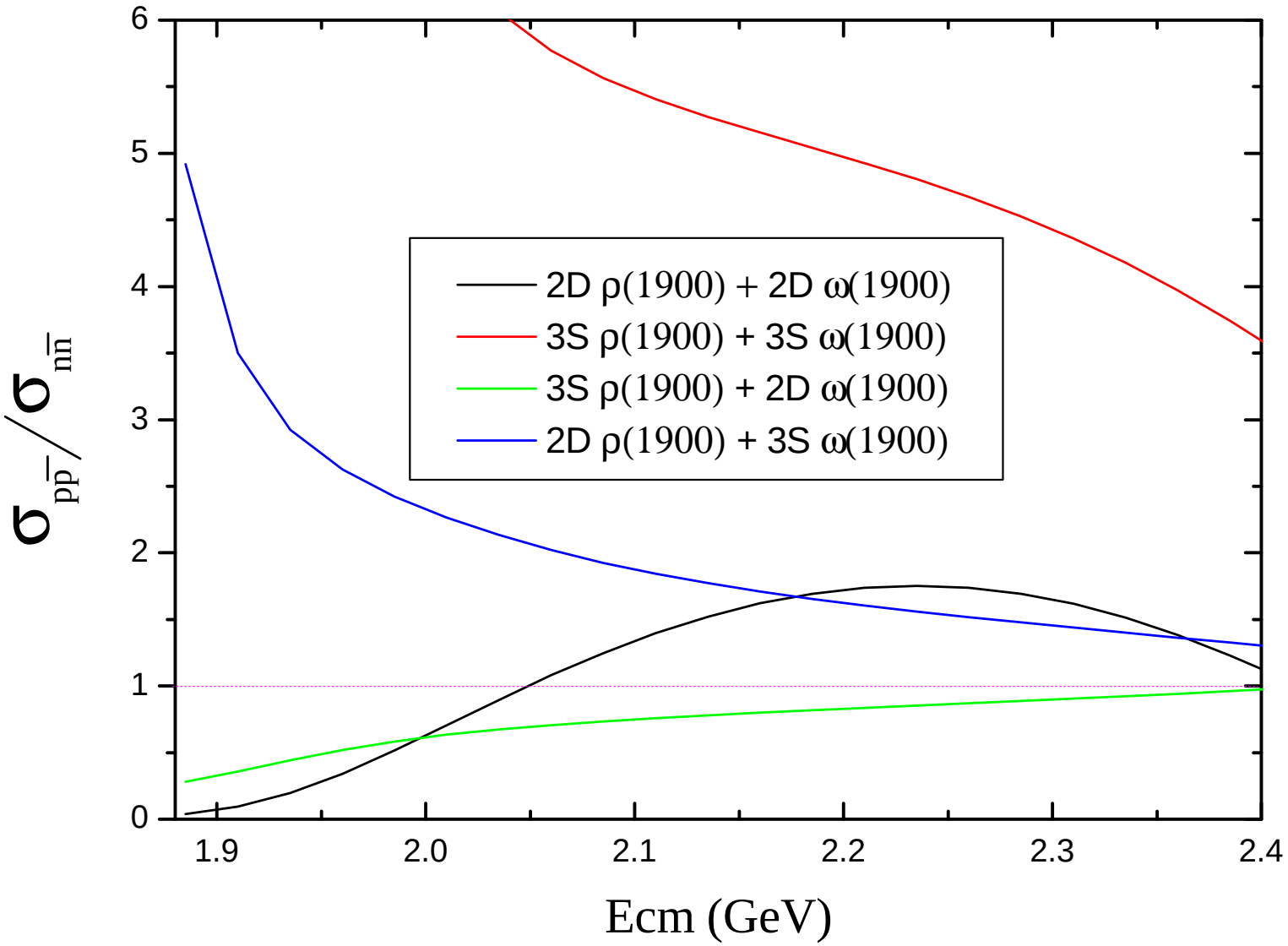
1S	$\rho(770)$	$\omega(782)$
2S	$\rho(1450)$	$\omega(1420)$
1D	$\rho(1700)$	$\omega(1650)$
3S or 2D	$\rho(2000)$	$\omega(1930)$

- $\rho(2000)$ ($\Gamma = 300$ MeV) taken from NPA662.319(2000);
- $\omega(1930)$ ($\Gamma = 150$ MeV) taken from PLB507.23(2001);
- Data of $e^-e^+ \to \pi\omega$ indicate that $\rho(1425)$ and $\rho(1700)$ are dominantly $2S$ and $1D$ states, respectively.

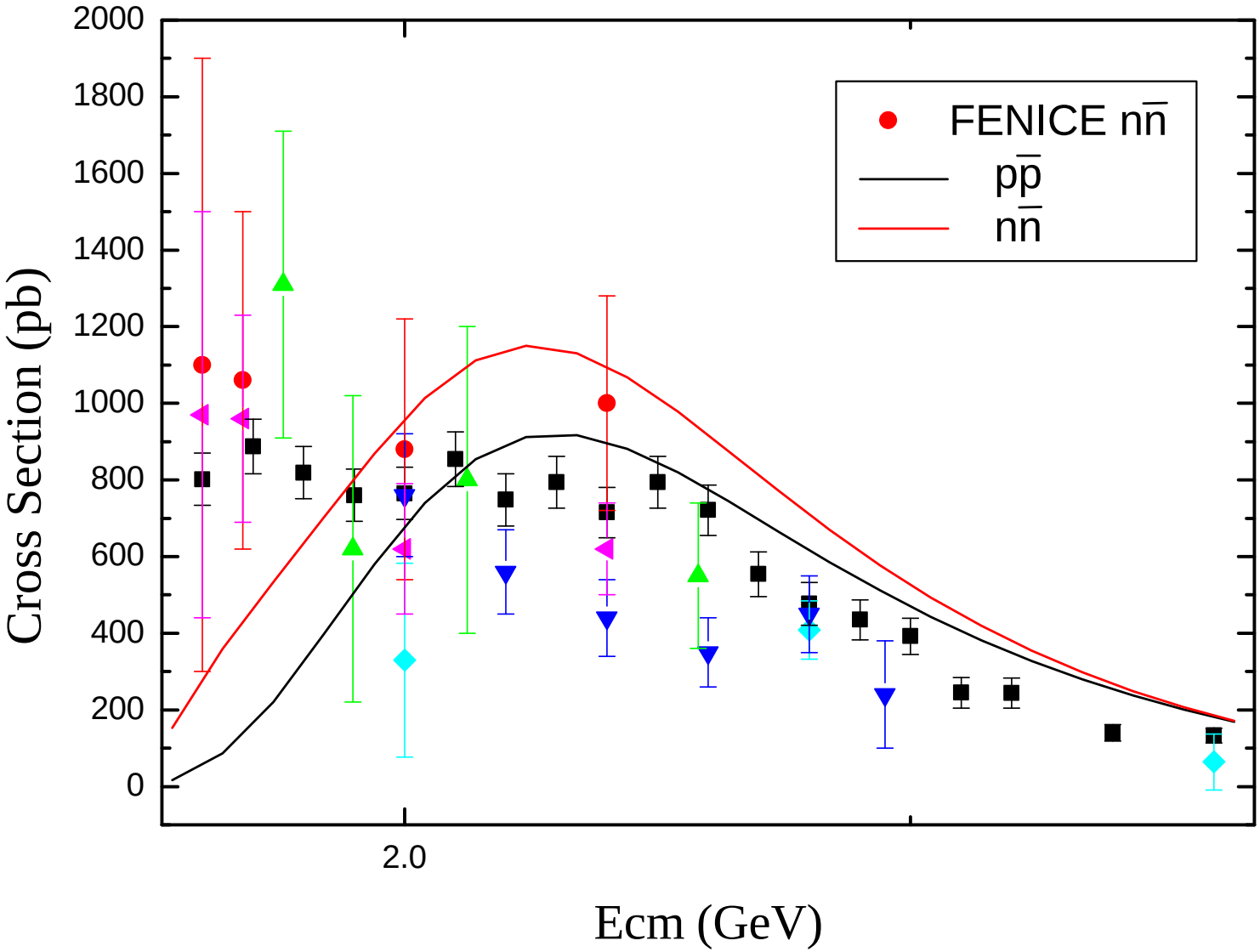
$e^-e^+ \to \pi\omega$ in $^3P_0$ Model with ρ, $\rho(1450)$ and $\rho(1700)$ (PRC79.025201)



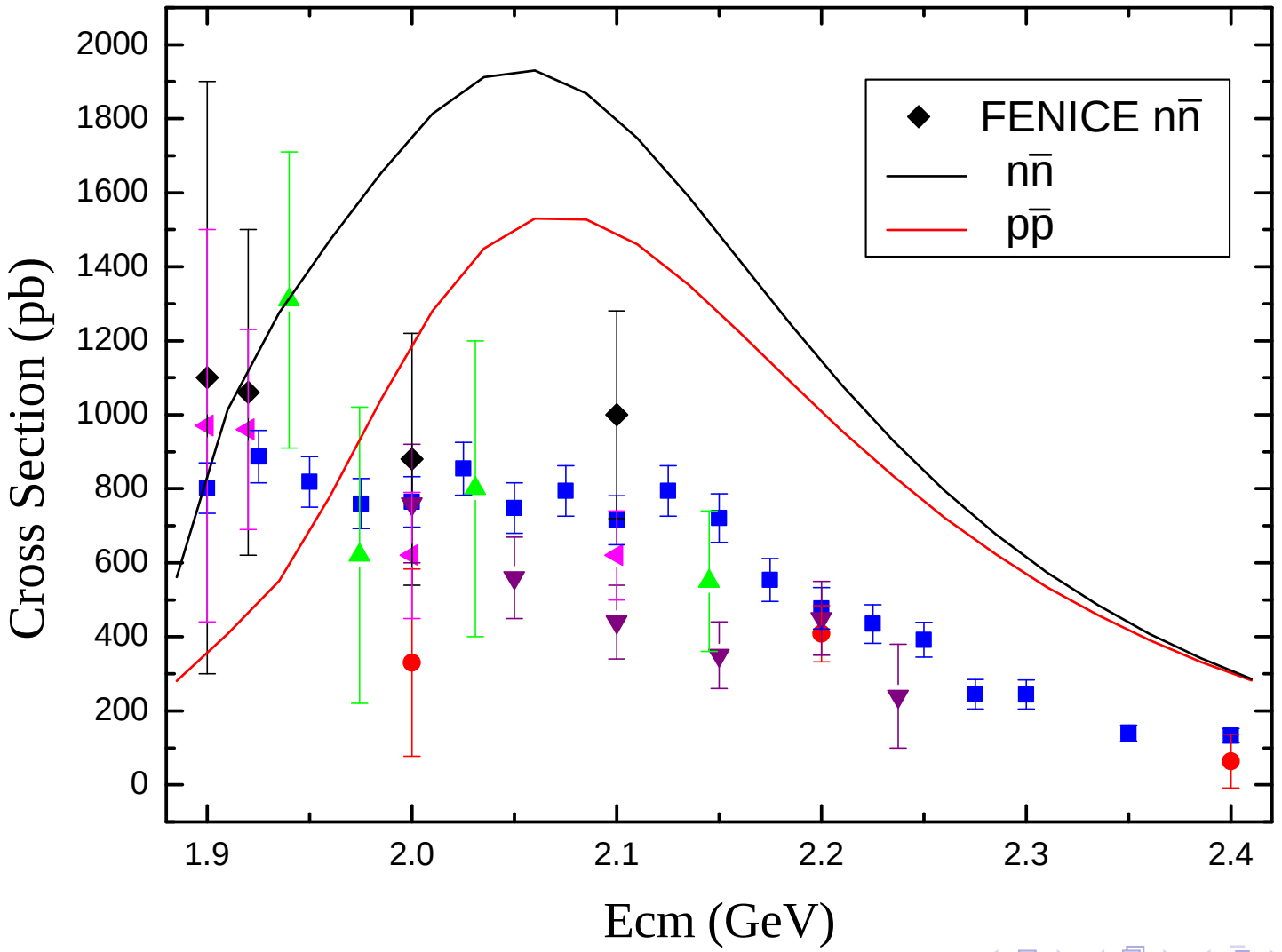
$\sigma_{e^-e^+\to\bar{p}p}/\sigma_{e^-e^+\to\bar{n}n}$ with $3S$ $\rho(2000)$ and $2D$ $\omega(1930)$



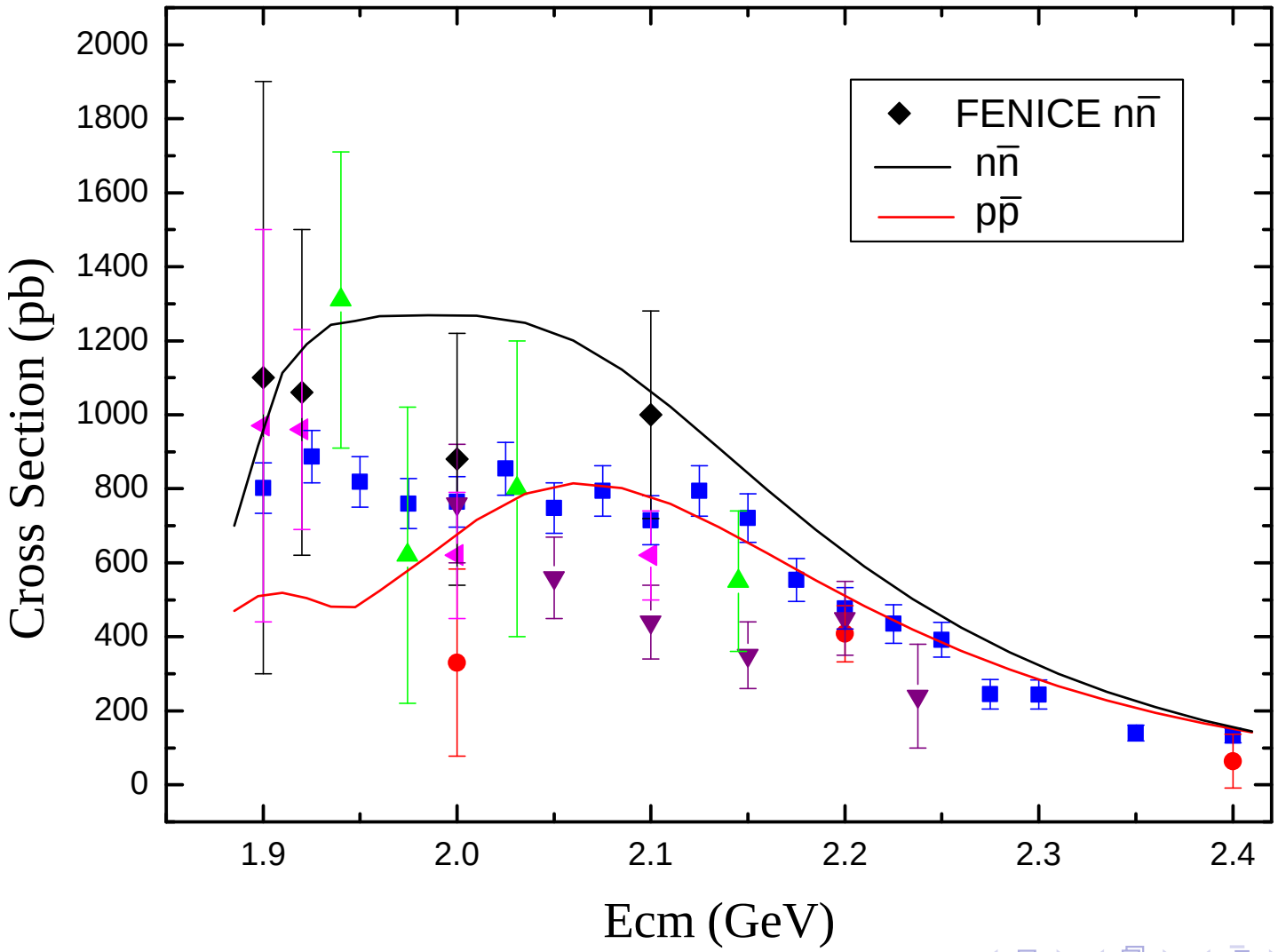
$\sigma_{e^-e^+\to\bar{p}p(\bar{n}n)}$ with $3S$ $\rho(2000)$ and $2D$ $\omega(1930)$



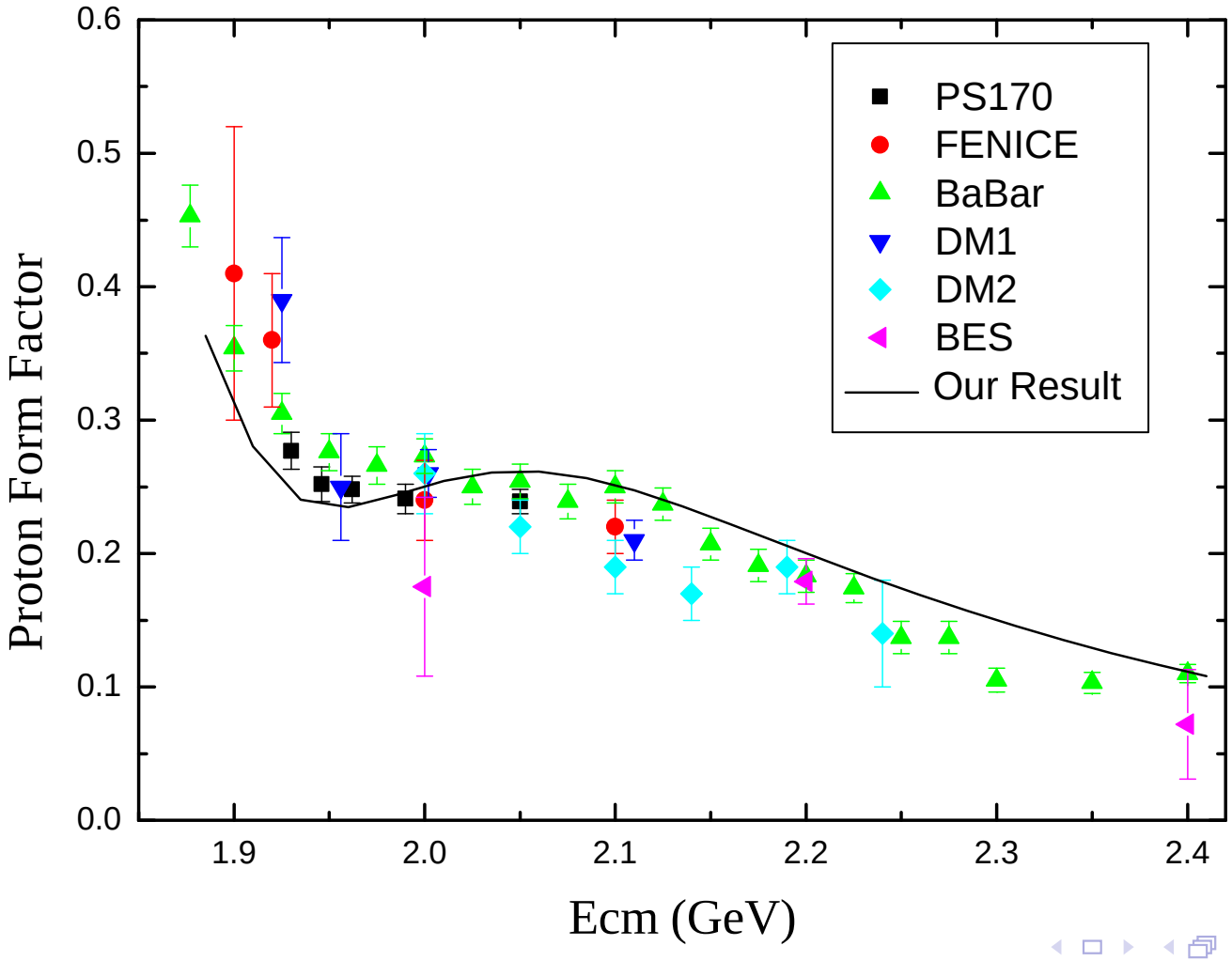
$\sigma_{e^-e^+\to\bar{p}p\,(\bar{n}n)}$ with $3S$ $\rho(2000)$, $2D$ $\omega(1930)$ and $1D$ $\rho(1700)$



$\sigma_{e^-e^+\to\bar{p}p\,(\bar{n}n)}$ with $3S(50\%)+2D(50\%)$ $\rho(2000)$, $2D$ $\omega(1930)$ and $1D$ $\rho(1700)$



Proton effective form factor with $3S(50\%) + 2D(50\%)$ $\rho(2000)$, $2D$ $\omega(1930)$ and $1D$ $\rho(1700)$



Discussion and Conclusions

- The reactions $e^+e^- \longrightarrow \overline{N}N$ are studied in the $^3P_0$ non-perturbative quark model. The results are promising;
- The work suggests that the two-step process is dominant over the one-step one;
- A D-wave $\omega(1930)$ is strongly favored by experimental data;
- $\rho(2000)$ might be a mixture of S and D waves.

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