Proton pair production cross sections at BESIII

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On behalf of BESIII Collaboration

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Outline

■ Introduction
  ➢ BEPCII and BESIII
  ➢ BESIII data samples
  ➢ Nucleon Electromagnetic Form Factors

■ Measurement of Proton Form Factors at BESIII
  ➢ Cross section and effective FFs
  ➢ Electromagnetic FFs ratio

■ Summary and Prospect
Beijing Electron Positron Collider

$E_{\text{beam}}$: 1.0-2.3 GeV
$\sigma_E$: $5.16 \times 10^{-4}$
$L$: $0.85 \times 10^{33}$ cm$^{-2}$s$^{-1}$ @3770
BEijing Spectrometer III

Main Drift Chamber
Small cell, 43 layer
\( \sigma_{xy} = 130 \, \mu m, \frac{dE}{dx} \sim 6\% \)
\( \sigma_p/p = 0.5\% \) at 1 GeV

Time Of Flight
Plastic scintillator
\( \sigma_T \) (barrel): 80 ps
\( \sigma_T \) (endcap): 110 ps

Muon Counter
Resistive plate chamber
Barrel: 9 layers
Endcaps: 8 layers
\( \sigma_{\text{spatial}} \): 1.48 cm

Electromagnetic Calorimeter
CsI(Tl): \( L = 28 \, \text{cm} \) (15\( X_0 \))
Energy range: 0.02-2 GeV
Barrel \( \sigma_E \): 2.5\%, \( \sigma_l \): 6 mm
Endcap \( \sigma_E \): 5.0\%, \( \sigma_l \): 9 mm

SC Magnet 1.0 T
### BESIII data samples

#### Data taken in BEPCII till May 2015:

<table>
<thead>
<tr>
<th>Taking data</th>
<th>Total Num. / Lum.</th>
<th>Taking time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$</td>
<td>225+1086 M</td>
<td>2009+2012</td>
</tr>
<tr>
<td>$\psi(2S)$</td>
<td>106+350 M</td>
<td>2009+2012</td>
</tr>
<tr>
<td>$\psi(3770)$</td>
<td>2916 pb$^{-1}$</td>
<td>2010~2011</td>
</tr>
<tr>
<td>$\tau$ scan</td>
<td>24 pb$^{-1}$</td>
<td>2011</td>
</tr>
<tr>
<td>$Y(4260)/Y(4230)/Y(4360)/\text{scan}$</td>
<td>806/1054/523/488 pb$^{-1}$</td>
<td>2012~2013</td>
</tr>
<tr>
<td>$4600/4470/4530/4575/4420$</td>
<td>506/100/100/42/993 pb$^{-1}$</td>
<td>2014</td>
</tr>
<tr>
<td>$J/\psi$ line-shape scan</td>
<td>100 pb$^{-1}$</td>
<td>2012</td>
</tr>
<tr>
<td>R scan (2.23, 3.40) GeV</td>
<td>12 pb$^{-1}$</td>
<td>2012</td>
</tr>
<tr>
<td>R scan (3.85, 4.59) GeV</td>
<td>795 pb$^{-1}$</td>
<td>2013~2014</td>
</tr>
<tr>
<td>R scan (2.0, 3.08) GeV</td>
<td>$\sim$525 pb$^{-1}$</td>
<td>2014~2015</td>
</tr>
</tbody>
</table>

The red color marks the data sets used in proton form factor analysis.
The universe is commonly defined as the totality of everything that exists, including all matter and energy.

Ordinary matter (4%) is made of protons, neutrons and electrons, bound together by nuclear and electromagnetic forces into atoms and molecules.

NEFFs are among the most basic observables of the nucleon, and intimately related to its internal structure and dynamics.

NEFFs are semi-empirical formula in effective quantum field theories which help describe the spatial distributions of electric charge and current.
The FFs are measured in space-like (SL) region or time-like (TL) region. The proton electromagnetic vertex $\Gamma_\mu$ describing the hadron current

\[ k_\mu = (E_e, k_e) \]
\[ j_\mu = \langle e | \gamma_\mu | e \rangle \]
\[ k'_\mu = (E'_e, k'_e) \]
\[ P_\mu = (E_p, \vec{p}) \]
\[ P'_\mu = (E'_p, \vec{p}') \]

\[ \Gamma_\mu(p', p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_\mu v q^\nu}{2m_p} F_2(q^2) \]

\[ G_E(q^2) = F_1(q^2) + \tau \kappa_p F_2(q^2) \]

\[ G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2) \]

\[ \tau = \frac{q^2}{4m_p^2}, \quad \kappa_p = \frac{g_p - 2}{2} = \mu_p - 1 \]

At $q^2 = 0$,
proton: $F_1 = F_2 = 1$, $G_E = 1$, $G_M = \mu_p$
neutron: $F_1 = 0$, $F_2 = 1$, $G_E = 1$, $G_M = \mu_n$

$G_E$ and $G_M$ can be interpreted as Fourier transforms of spatial distributions of charge and magnetization of nucleon in the Breit frame

\[ i.e \rho(\vec{r}) = \int \frac{d^3q}{2\pi^3} e^{-i\vec{q} \cdot \vec{r}} \frac{M}{E(\vec{q})} G_E(\vec{q}^2) \]
# NEFFs in Time-like region

- Previous experimental results from scan method and ISR method:

<table>
<thead>
<tr>
<th>Process</th>
<th>Date</th>
<th>Experiment</th>
<th>$q^2$ (GeV^2/c^4)</th>
<th>$q^2$ point</th>
<th>Event</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow p\bar{p}$</td>
<td>1972</td>
<td>FENICE/ADONE [17]</td>
<td>4.3</td>
<td>1</td>
<td>27</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>1979</td>
<td>DM1/ORSAY-DCI [18]</td>
<td>3.75-4.56</td>
<td>4</td>
<td>70</td>
<td>25.0%</td>
</tr>
<tr>
<td></td>
<td>1983</td>
<td>DM2/ORSAY-DCI [19]</td>
<td>4.0-5.0</td>
<td>6</td>
<td>100</td>
<td>19.6%</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>FENICE/ADONE [20]</td>
<td>3.6-5.9</td>
<td>5</td>
<td>76</td>
<td>19.3%</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>BES/BEPC [21]</td>
<td>4.0-9.4</td>
<td>10</td>
<td>80</td>
<td>21.2%</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>CLEO/ [22]</td>
<td>13.48</td>
<td>1</td>
<td>16</td>
<td>33.3%</td>
</tr>
<tr>
<td>$p^+p^- \rightarrow e^+e^-$</td>
<td>1976</td>
<td>PS135/CERN [24]</td>
<td>3.52</td>
<td>1</td>
<td>29</td>
<td>15.7%</td>
</tr>
<tr>
<td></td>
<td>1994</td>
<td>PS170/CERN [25]</td>
<td>3.52-4.18</td>
<td>9</td>
<td>3667</td>
<td>6.1%</td>
</tr>
<tr>
<td></td>
<td>1993</td>
<td>E760/Fermi [26]</td>
<td>8.9-13.0</td>
<td>3</td>
<td>29</td>
<td>33.8%</td>
</tr>
<tr>
<td></td>
<td>1999</td>
<td>E835/Fermi [27]</td>
<td>8.84-18.4</td>
<td>6</td>
<td>144</td>
<td>10.3%</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \gamma + p\bar{p}$</td>
<td>2006</td>
<td>Babar/SLAC-PEP II [30]</td>
<td>3.57-19.1</td>
<td>38</td>
<td>3261</td>
<td>9.8%</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>Babar/SLAC-PEP II [31]</td>
<td>3.57-19.1</td>
<td>38</td>
<td>6866</td>
<td>6.7%</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>Babar/SLAC-PEP II [32]</td>
<td>9.61-36.0</td>
<td>8</td>
<td>140</td>
<td>18.4%</td>
</tr>
</tbody>
</table>
NEFFs in Time-like region

- Still questions left on the proton FFs
  - Steep rise toward threshold
  - Two rapid decreases of the FF near 2.25 and 3.0 GeV
  - The asymptotic values for SL and TL FFs should be identical at high energies, while $G_M$ is larger than SL quantities (i.e. at $|q^2|=3.08^2$ GeV$^2$, $|G_{TL}|=0.031$, and $|G_{SL}|=0.011$)

- Electromagnetic FF ratio
  - Poor precision (11%, 43%) and limited energy range (1.92, 2.7) GeV
  - disagreement of $|G_E/G_M|$ ratio between PS170 and BaBar
Reconstruction of $e^+e^- \rightarrow p\bar{p}$ at BESIII

**Event selection**

- **Good charged tracks**
  - $|R_{xy}| < 1$ cm, $|R_z| < 10$ cm
  - $|\cos\theta| < 0.93$

- **Particle identification**
  - $dE/dx + \text{Tof}$
  - $\text{Prob}(p) > \text{Prob}(K/\pi)$
  - For proton track, require $E/p < 0.5$, $\cos\theta < 0.8$

- $N_{\text{char}} = 2$ & $N_p = N_{\bar{p}} = 1$
- $|\text{tof}_p - \text{tof}_{\bar{p}}| < 4$ ns
- Two tracks angle $> 179^\circ$
- Momentum window cut for proton and anti-proton
**Background analysis**

- **Beam associated background**: interaction between beam and beam pipe, beam and residual gas and the Touschek effect.

- A special data sample, with separated beam condition, are used to study such background.

- **The physical background** from the processes with two-body in the final state, or with multi-body include \( p\bar{p} \) in the final states.

<table>
<thead>
<tr>
<th>Bkg.</th>
<th>( N_{gen}^{MC} \times 10^6 )</th>
<th>( N_{sur}^{MC} )</th>
<th>( \sigma ) (nb)</th>
<th>( N_{uplimit}^{MC} )</th>
<th>( N_{nor}^{MC} )</th>
<th>( N_{gen}^{MC} \times 10^6 )</th>
<th>( N_{sur}^{MC} )</th>
<th>( \sigma ) (nb)</th>
<th>( N_{uplimit}^{MC} )</th>
<th>( N_{nor}^{MC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c^+c^- )</td>
<td>9.6</td>
<td>0</td>
<td>1435.01</td>
<td>&lt; 0.96</td>
<td>0</td>
<td>39.9</td>
<td>1</td>
<td>756.86</td>
<td>&lt; 2.54</td>
<td>1</td>
</tr>
<tr>
<td>( \mu^+\mu^- )</td>
<td>0.7</td>
<td>0</td>
<td>17.41</td>
<td>&lt; 0.16</td>
<td>0</td>
<td>1.5</td>
<td>0</td>
<td>8.45</td>
<td>&lt; 0.42</td>
<td>0</td>
</tr>
<tr>
<td>( \gamma\gamma )</td>
<td>1.9</td>
<td>0</td>
<td>70.44</td>
<td>&lt; 0.24</td>
<td>0</td>
<td>4.5</td>
<td>0</td>
<td>37.05</td>
<td>&lt; 0.62</td>
<td>0</td>
</tr>
<tr>
<td>( \pi^+\pi^- )</td>
<td>0.1</td>
<td>0</td>
<td>0.17</td>
<td>&lt; 0.01</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>&lt; 0.11</td>
<td>&lt; 0.02</td>
<td>0</td>
</tr>
<tr>
<td>( K^+K^- )</td>
<td>0.1</td>
<td>0</td>
<td>0.14</td>
<td>&lt; 0.008</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>0.003</td>
<td>&lt; 0.02</td>
<td>0</td>
</tr>
<tr>
<td>( p\bar{p}\pi^0 )</td>
<td>0.1</td>
<td>0</td>
<td>&lt; 0.1</td>
<td>&lt; 0.006</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>&lt; 0.1</td>
<td>&lt; 0.07</td>
<td>0</td>
</tr>
<tr>
<td>( p\bar{p}\pi^0\pi^0 )</td>
<td>0.1</td>
<td>0</td>
<td>&lt; 0.1</td>
<td>&lt; 0.006</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>&lt; 0.1</td>
<td>&lt; 0.07</td>
<td>0</td>
</tr>
<tr>
<td>( \Lambda\bar{\Lambda} )</td>
<td>0.1</td>
<td>0</td>
<td>&lt; 0.4</td>
<td>&lt; 0.02</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>0.002</td>
<td>&lt; 0.001</td>
<td>0</td>
</tr>
</tbody>
</table>
σ_{Born} = \frac{N_{obs} - N_{bkg}}{L \cdot \varepsilon \cdot (1+\delta)}

- $N_{obs}$: the observed number of signal in data
- $N_{bkg}$: the number of background evaluated from MC
- $L$: the integral luminosity
- $\varepsilon$: detection efficiency by MC sample, with Conexc generator
- $(1+\delta)$: radiative correction factor
Extraction of the effective FF

**Effective FF**

- Assuming $|G_E| = |G_M| = |G_{\text{eff}}|$, (which holds at $p\bar{p}$ mass threshold)

$$\sigma = \frac{\pi \alpha^2}{3m_p^2 \tau} \left[1 + \frac{1}{2\tau}\right] |G_{\text{eff}}|^2$$

- After taking natural units: $1m = 5.0677 \times 10^{15}$ GeV$^{-1}$

$$G_{\text{eff}} = \sqrt{\frac{\sigma_{\text{Born}}}{86.83 \cdot \beta_s (1 + \frac{2m_p^2}{s})}}$$

![Graph showing form factor vs. $M_{pp}$](image1)

![Graph showing form factor vs. $M_{pp}$](image2)
Extraction of electromagnetic $|G_E/G_M|$ ratio

- Angular analysis to extract the $em$ FFs:
  \[
  \frac{d\sigma}{d\Omega}(q^2) = \frac{\alpha^2\beta}{4s} |G_M(s)|^2 \left[ (1 + \cos^2\theta_p) + R_{em} \frac{1}{\tau} \sin^2\theta_p \right]
  \]
  \[
  R_{em} = \frac{G_E(q^2)}{G_M(q^2)}
  \]
  \[
  \theta: \text{polar angle of proton at the c.m.system}
  \]

- Fit function:
  \[
  \frac{dN}{d\cos\theta_p} = N_{\text{norm}} \left[ (1 + \cos^2\theta_p) + R_{em} \frac{1}{\tau} \sin^2\theta_p \right]
  \]
  \[
  N_{\text{norm}} = \frac{2\pi\alpha^2\beta L}{4s} \left[ 1.94 + 5.04 \frac{m_p^2}{s} R^2 \right] G_M(s)^2
  \]
  is the overall normalization

\[
\begin{align*}
\sqrt{s} &= 2232.4 \text{ MeV} \\
\sqrt{s} &= 2400.0 \text{ MeV} \\
\sqrt{s} &= (3050.0, 3080.0) \text{ MeV}
\end{align*}
\]
Extraction of electromagnetic $|G_E/G_M|$ ratio

- Method of Moment
  
  ➢ Second Moment of $\cos \theta_p$: $\langle \cos^2 \theta_p \rangle = \frac{1}{N_{\text{norm}}} \int \cos^2 \theta_p \frac{d\sigma}{d\Omega} d\cos \theta_p$

  ➢ The estimator of $\langle \cos^2 \theta_p \rangle$: $\langle \cos^2 \theta_p \rangle = \frac{\cos^2 \theta_p}{\varepsilon_i} = \frac{1}{N} \sum_{i=1}^{N} \cos^2 \theta_p / \varepsilon_i$

  ➢ Extract $|G_E/G_M|$ ratio: $R = \sqrt{\frac{s}{4m_p^2} \frac{\langle \cos^2 \theta_p \rangle - 0.243}{0.108 - 0.648\langle \cos^2 \theta_p \rangle}}$

  ➢ Uncertainty of $\langle \cos^2 \theta_p \rangle$: $\sigma_{\langle \cos^2 \theta_p \rangle} = \sqrt{\frac{1}{N-1} \left[ \langle \cos^4 \theta_p \rangle - \langle \cos^2 \theta_p \rangle \right]}$

- Results on $|G_E/G_M|$ ratio:

| $\sqrt{s}$ (MeV) | $|G_E/G_M|$ | $|G_M|$ ($\times 10^{-2}$) | $\chi^2/ndf$ |
|-----------------|-------------|----------------|--------------|
| $2232.4$         | $0.87 \pm 0.24 \pm 0.05$ | $18.42 \pm 5.09 \pm 0.98$ | $1.04$ |
| $2400.0$         | $0.91 \pm 0.38 \pm 0.12$ | $11.30 \pm 4.73 \pm 1.53$ | $0.74$ |
| $(3050.0, 3080.0)$ | $0.95 \pm 0.45 \pm 0.21$ | $3.61 \pm 1.71 \pm 0.82$ | $0.61$ |

Fit on $\cos \theta_p$

*method of moment*

| $\sqrt{s}$ (MeV) | $|G_E/G_M|$ | $|G_M|$ ($\times 10^{-2}$) | $\chi^2/ndf$ |
|-----------------|-------------|----------------|--------------|
| $2232.4$         | $0.83 \pm 0.24$ | $18.60 \pm 5.38$ | - |
| $2400.0$         | $0.85 \pm 0.37$ | $11.52 \pm 5.01$ | - |
| $(3050.0, 3080.0)$ | $0.88 \pm 0.46$ | $3.34 \pm 1.72$ | - |

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The proton effective FFs are measured at 12 c.m. energies. The Born cross sections and effective FFs are in good agreement with previous experiments, improving the overall uncertainty by ~30%.

The $|G_E/G_M|$ ratio are extracted at three energy points, with uncertainty in 25% and 50% (dominated by statistics).

The $|G_E/G_M|$ ratio are close to unity and consistent with BaBar results in the same $q^2$ region, indicates the data are consistent with the assumption $|G_E| = |G_M|$ within uncertainties.

At BEPCII, a new scan with c.m. energy in 2.0 GeV and 3.1 GeV is ongoing, which suggest precision measurement of proton form factor reveal two steps around 2.25 and 3.0 GeV improve the $|G_E/G_M|$ ratio uncertainty
NEFFs in Space-like region

- Nucleon Electromagnetic FFs (NEFF) in Space-like region

- Unpolarized electron-proton elastic
  - In one-photon exchange approximation,
    \[
    \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \frac{1}{1+\tau} \left[ G_E^2 + \frac{\tau}{\varepsilon} G_M^2 \right], \quad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta_e/2)}
    \]
    is the longitudinal polarization of photon.
  - Rosenbluth Separation: \( \sigma_R = \frac{\varepsilon}{\tau} G_E^2 + G_M^2 \)

- Polarized electron-proton elastic scattering
  - Longitudinally polarized electron beam
  - Recoil proton polarization:
    \[
    \frac{G_E}{G_M} = - \frac{P_t}{P_1} \frac{E_e + E_{\text{beam}}}{2M_p} \tan \frac{\theta}{2}
    \]

- The two-photon exchange contribution