Proton pair production cross sections at BESIII

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On behalf of BESIII Collaboration

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Outline

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Beijing Electron Positron Collider

E_{beam}: 1.0-2.3 GeV

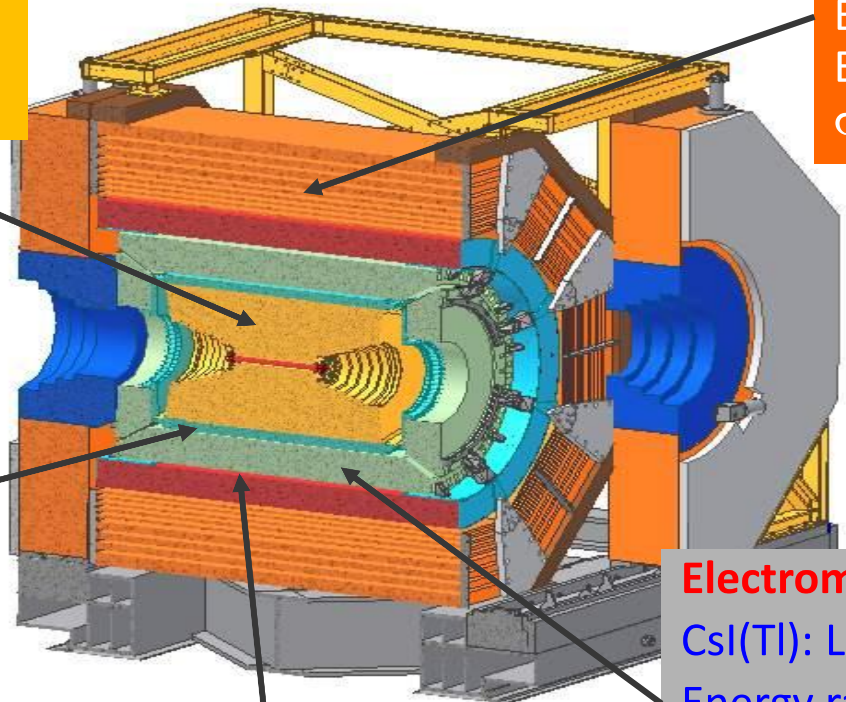
σ_E: 5.16×10^{-4}

L: 0.85×10^{33} $cm^{-2}s^{-1}$ @3770

BEijing Spectrometer III

Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm, dE/dx~6%
σ_p/p = 0.5% at 1 GeV

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



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

SC Magnet 1.0T

Electromagnetic Calorimeter
CsI(Tl): L=28 cm (15X_0)
Energy range: 0.02-2GeV
Barrel σ_E 2.5%, σ_l 6mm
Endcap σ_E 5.0%, σ_l 9mm

BESIII data samples

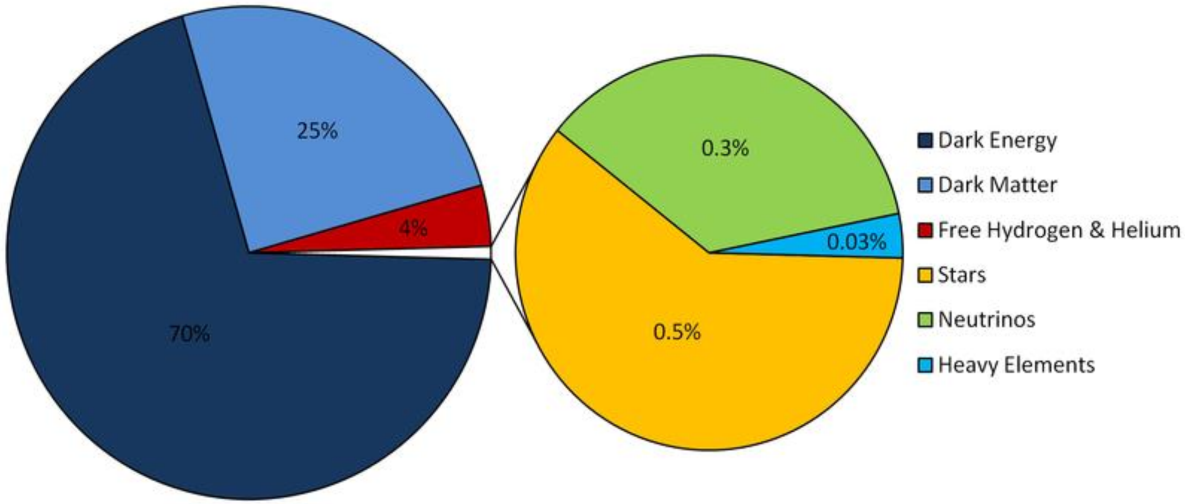
- Data taken in BEPCII till May 2015:

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

The red color marks the data sets used in proton form factor analysis.

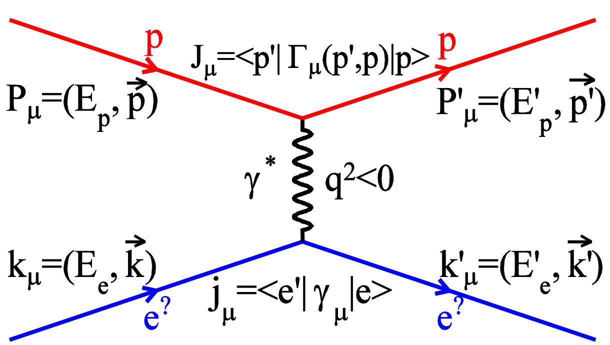
Nucleon Electromagnetic FFs

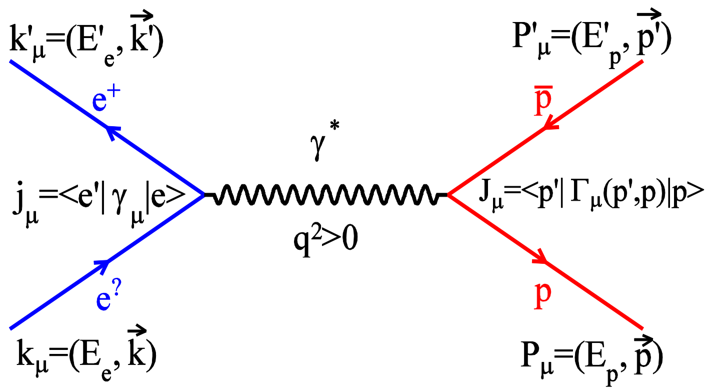
- The universe is commonly defined as the totality of everything that exists, including all matter and energy.
- Ordinary matter (4%) is made of protons, neutrons and electrons, bound together by nuclear and electromagnetic forces into atoms and molecules.
- NEFFs are among the most basic observables 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.



Nucleon Electromagnetic FFs

- The FFs are measured in space-like (SL) region or time-like (TL) region. The proton electromagnetic vertex Γ_μ describing the hadron current





- $\Gamma_\mu(p',p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p} F_2(q^2)$
- $G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$
- $G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$
- $\tau = \frac{q^2}{4m_p^2}$, $\kappa_p = \frac{g_p - 2}{2} = \mu_p - 1$
- 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 $\rho(\vec{r}) = \int \frac{d^3q}{2\pi^3} e^{-i\vec{q}\cdot\vec{r}} \frac{M}{E(\vec{q})} G_E(\vec{q}^2)$

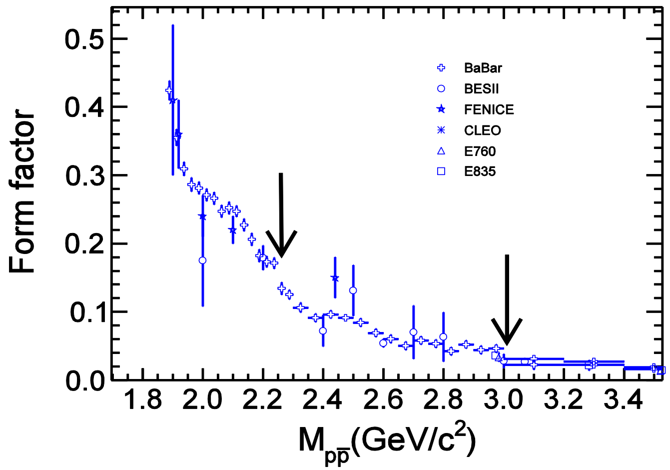
NEFFs in Time-like region

- Previous experimental results from scan method and ISR method:

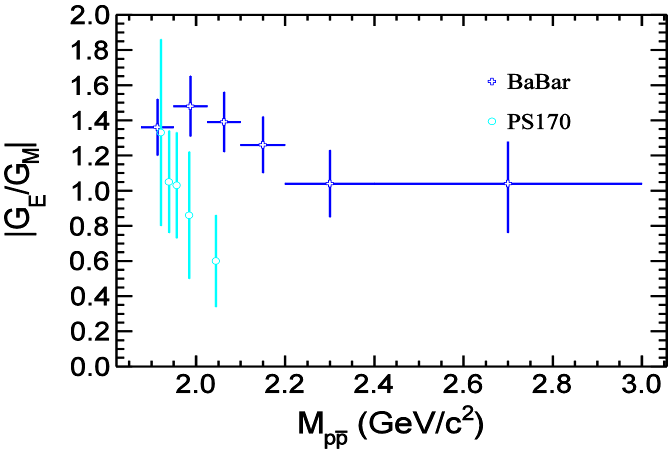
Process	Date	Experiment	q^2 (GeV^2/c^4)	q^2 point	Event	Precision
$e^+e^- \to p\bar{p}$	1972	FENICE/ADONE [17]	4.3	1	27	15%
	1979	DM1/ORSAY-DCI [18]	3.75-4.56	4	70	25.0%
	1983	DM2/ORSAY-DC1 [19]	4.0-5.0	6	100	19.6%
	1998	FENICE/ADONE [20]	3.6-5.9	5	76	19.3%
	2005	BES/BEPC [21]	4.0-9.4	10	80	21.2%
	2006	CLEO/ [22]	13.48	1	16	33.3%
$p^+p^- \to e^+e^-$	1976	PS135/CERN [24]	3.52	1	29	15.7%
	1994	PS170/CERN [25]	3.52-4.18	9	3667	6.1%
	1993	E760/Fermi [26]	8.9-13.0	3	29	33.8%
	1999	E835/Fermi [27]	8.84-18.4	6	144	10.3%
	2003	E835/Fermi [28]	11.63-18.22	4	66	21.1%
$e^+e^- \to \gamma + p\bar{p}$	2006	BaBar/SLAC-PEPII [30]	3.57-19.1	38	3261	9.8%
	2013	BaBar/SLAC-PEPII [31]	3.57-19.1	38	6866	6.7%
	2013	BaBar/SLAC-PEPII [32]	9.61-36.0	8	140	18.4%

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 $|G_{SL}|=0.011$)



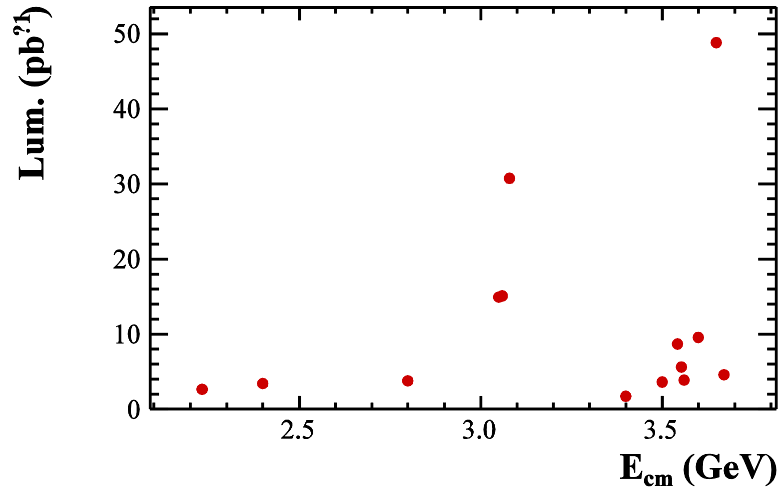
- Electromagnetic FF ratio
  - ➢ Poor precision (11%, 43%) and limited energy range (1.92, 2.7) GeV
  - ➢ disagreement of $|G_E/G_M|$ ratio between PS170 and BaBar



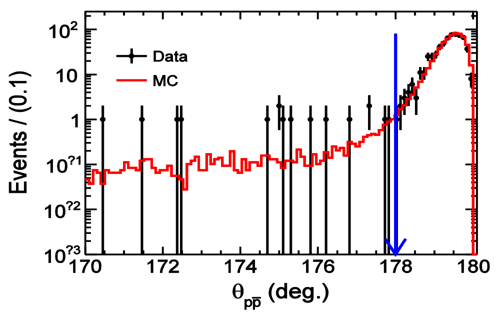
Reconstruction of $e^+e^- \to p\bar{p}$ at BESIII

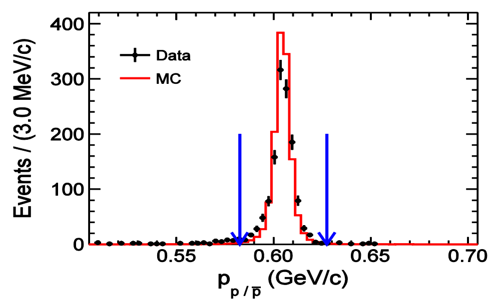
Event selection

- Good charged tracks
  - $|R_{xy}| < 1$ cm, $|R_z| < 10$ cm
  - $|\cos\theta| < 0.93$
- Particle identification
  - dE/dx + Tof
  - Prob(p) > Prob(K/ π)
  - For proton track, require E/p < 0.5, cosθ < 0.8



- $N_{char} = 2$ & $N_p = N_{\bar{p}} = 1$
- $|tof_p - tof_{\bar{p}}| < 4$ ns
- Two tracks angle > 179^o
- Momentum window cut for proton and anti-proton





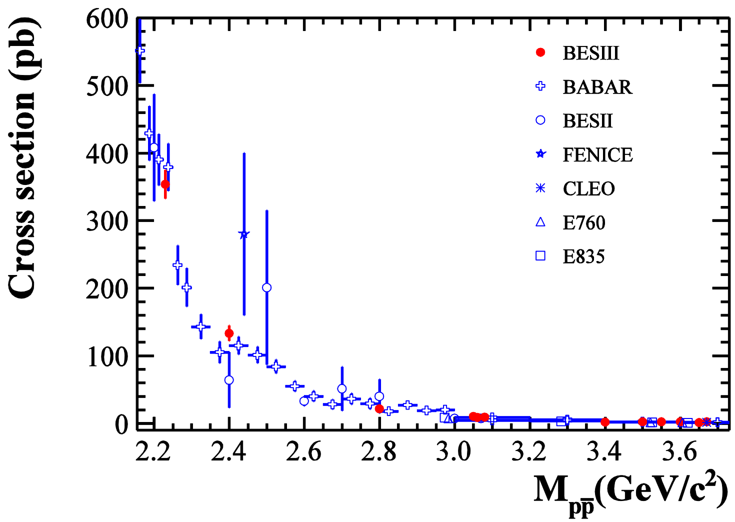
Background analysis

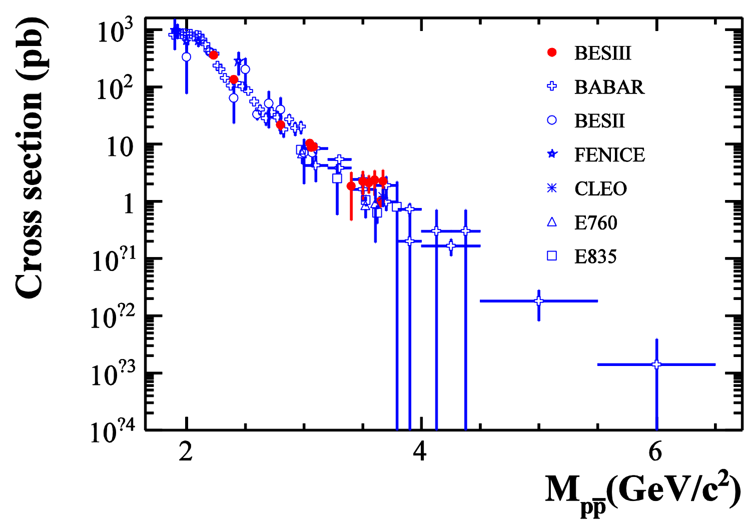
- Beam associated background: interaction between beam and beam pipe, beam and residual gas and the Touschek effect.
- A special data sample, with separated beam condition, are used to study such background.
- The physical background from the processes with two-body in the final state, or with multi-body include $p\bar{p}$ in the final states.

	$\sqrt{s} = 2232.4$ MeV (2.63 pb^{-1})					$\sqrt{s} = 3080.0$ MeV (30.73 pb^{-1})				
Bkg.	N^{MC}_{gen} ($\times 10^6$)	N^{MC}_{sur}	σ (nb)	$N^{MC}_{uplimit}$	N^{MC}_{nor}	N^{MC}_{gen} ($\times 10^6$)	N^{MC}_{sur}	σ (nb)	$N^{MC}_{uplimit}$	N^{MC}_{nor}
e^+e^-	9.6	0	1435.01	< 0.96	0	39.9	1	756.86	< 2.54	1
$\mu^+\mu^-$	0.7	0	17.41	< 0.16	0	1.5	0	8.45	< 0.42	0
$\gamma\gamma$	1.9	0	70.44	< 0.24	0	4.5	0	37.05	< 0.62	0
$\pi^+\pi^-$	0.1	0	0.17	< 0.01	0	0.1	0	< 0.11	< 0.02	0
K^+K^-	0.1	0	0.14	< 0.008	0	0.1	0	0.093	< 0.02	0
$p\bar{p}\pi^0$	0.1	0	< 0.1	< 0.006	0	0.1	0	< 0.1	< 0.07	0
$p\bar{p}\pi^0\pi^0$	0.1	0	< 0.1	< 0.006	0	0.1	0	< 0.1	< 0.07	0
$\Lambda\bar{\Lambda}$	0.1	0	< 0.4	< 0.02	0	0.1	0	0.002	< 0.001	0

Measurement of Proton Form Factors

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





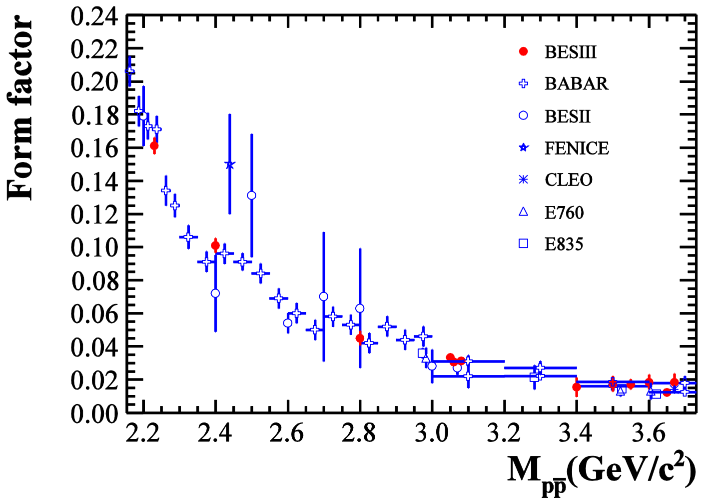
Extraction of the effective FF

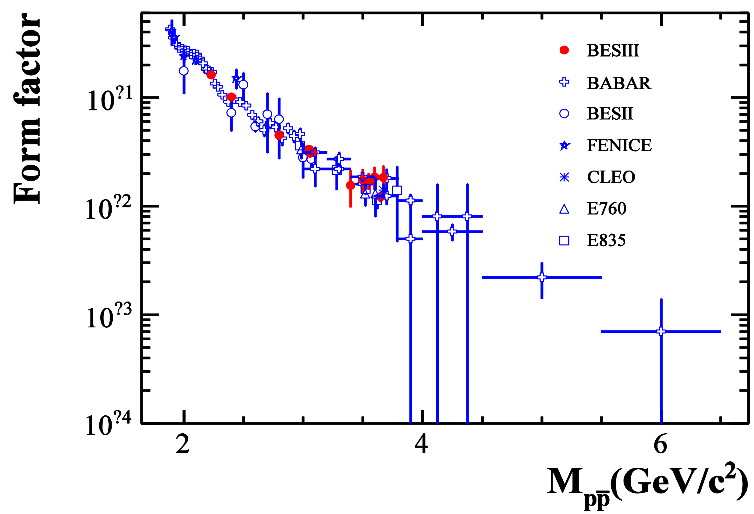
- Effective FF
  - Assuming $|G_E|=|G_M|=|G_{eff}|$, (which holds at $p\bar{p}$ mass threshold)

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

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

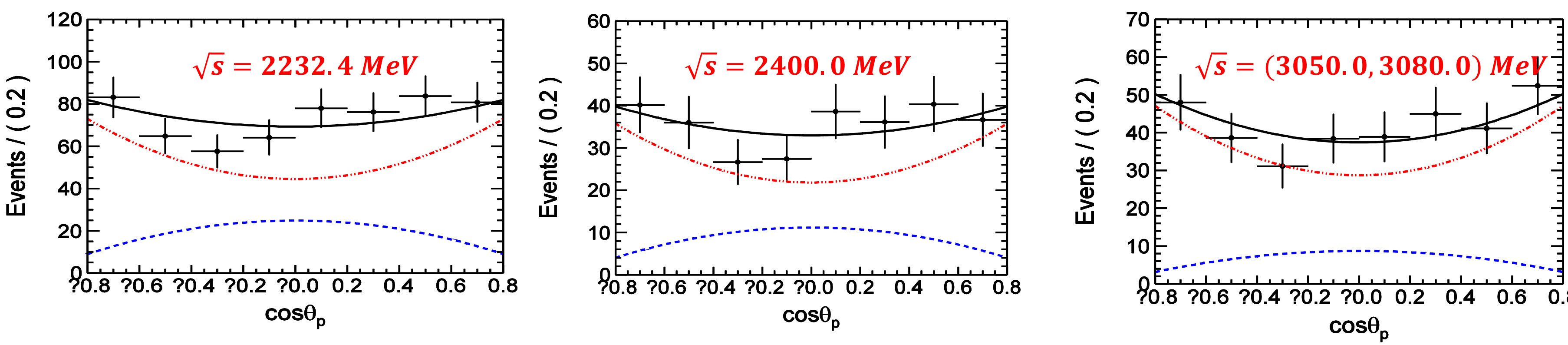
$$G_{eff} = \sqrt{\frac{\sigma_{Born}}{86.83\cdot\frac{\beta}{s}(1+\frac{2m_p^2}{s})}}$$





Extraction of electromagnetic $|G_E/G_M|$ ratio

- Angular analysis to extract the em FFs:
  - $\frac{d\sigma}{d\Omega}(q^2) = \frac{\alpha^2\beta}{4s}|G_M(s)|^2\left[\left(1+\cos^2\theta_p\right) + R_{em}^2\frac{1}{\tau}\sin^2\theta_p\right]$
  - $R_{em} = G_E(q^2)/G_M(q^2)$
  - θ: polar angle of proton at the c.m.system
- Fit function:
  - $\frac{dN}{d\cos\theta_p} = N_{norm}\left[\left(1+\cos^2\theta_p\right) + R_{em}^2\frac{1}{\tau}\sin^2\theta_p\right]$
  - $N_{norm} = \frac{2\pi\alpha^2\beta L}{4s}\left[1.94 + 5.04\frac{m_p^2}{s}R^2\right]G_M(s)^2$ is the overall normalization

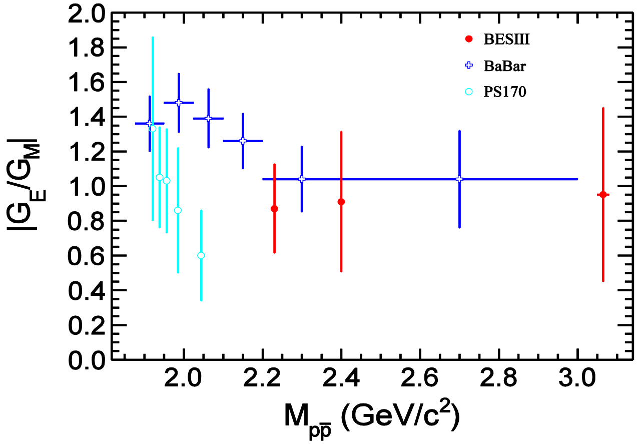


Extraction of electromagnetic $|G_E/G_M|$ ratio

- **Method of Moment**
  - Second Moment of $\cos\theta_p$: $\langle\cos^2\theta_p\rangle = \frac{1}{N_{norm}}\int \cos^2\theta_p \frac{d\sigma}{d\Omega} d\cos\theta_p$
  - The estimator of $\langle\cos^2\theta_p\rangle$: $\langle\cos^2\theta_p\rangle = \overline{\cos^2\theta_p} = \frac{1}{N}\sum_{i=1}^{N}\cos^2\theta_p/\varepsilon_i$
  - 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 $\langle\cos^2\theta_p\rangle$: $\sigma_{\langle\cos^2\theta_p\rangle} = \sqrt{\frac{1}{N-1}[\langle\cos^4\theta_p\rangle - \langle\cos^2\theta_p\rangle]}$

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

$\sqrt{s}$ (MeV)	$\lvert G_E/G_M\rvert$	$\lvert G_M\rvert$ ($\times 10^{-2}$)	χ^2/ndf
	Fit on $\cos\theta_p$		
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
	method of moment		
2232.4	0.83 ± 0.24	18.60 ± 5.38	-
2400.0	0.85 ± 0.37	11.52 ± 5.01	-
(3050.0, 3080.0)	0.88 ± 0.46	3.34 ± 1.72	-



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Conclusion and Prospect

- 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

Thank you!

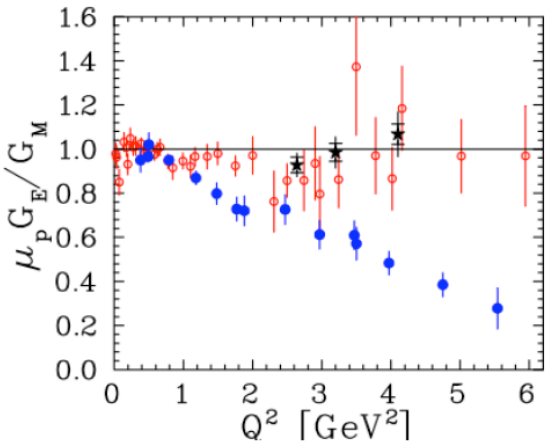
NEFFs in Space-like region

- Nucleon Electromagnetic FFs (NEFF) in Space-like region
- Unpolarized electron-proton elastic
  - In one-photon exchange approximation,

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[G_E^2 + \frac{\tau}{\varepsilon}G_M^2\right)\frac{1}{1+\tau}, \quad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)} \text{ is}$$

the longitudinal polarization of photon.

  - Rosenbluth Separation: $\sigma_R = \frac{\varepsilon}{\tau}G_E^2 + G_M^2$



Solid circle: recoil polarization
Open circle: Rosenbluth separation

- Polarized electron-proton elastic scattering
  - Longitudinally polarized electron beam
  - Recoil proton polarization:
  - $\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e+E_{beam}}{2M_p}\tan\frac{\theta}{2}$
- The two-photon exchange contribution