Measurement of Proton Electromagnetic Form Factors in $e^+e^- \to p\bar{p}$ in energy region 2.0 - 3.08 GeV

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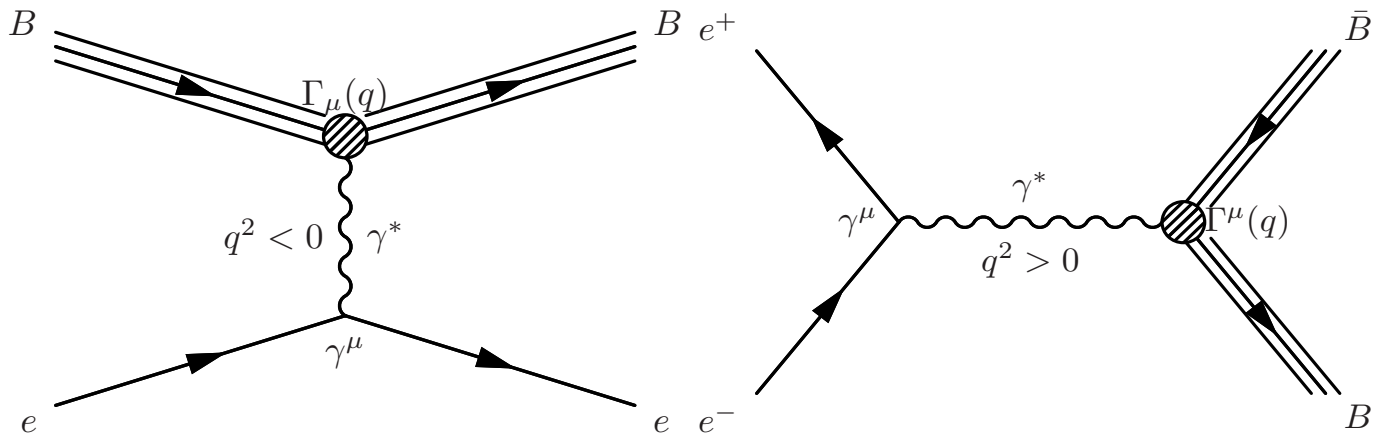
Preliminary Result Application

Motivation I: Internal structure and proton radius

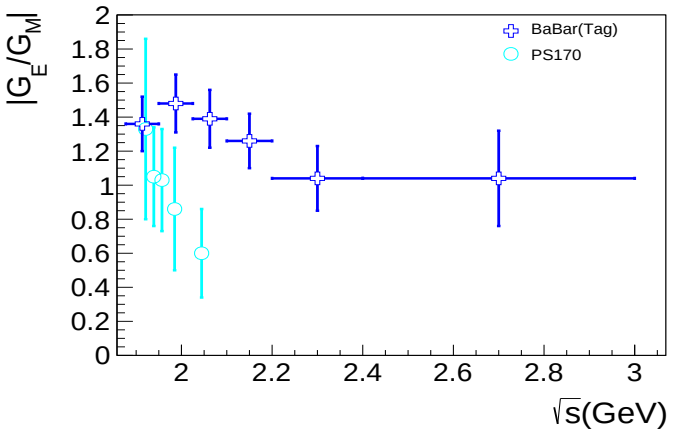
- The internal structure of hadrons are not well understood.
- Form factors (FF) are fundamental hadron structure observables, describe dynamical properties of hadrons Nature **466**, 213 (2010).
  - At low q^2: charge distribution and magnetization.
  - At higher q^2: dynamics, quark distribution.
    Vector current, two FFs (2S+1):



- The precise measurement of FFs in the TL region may also have a very positive impact on theoretical estimates of the proton radius Eur. Phys. J. A (2012) **48**: 151, Phys. Rev. Lett. **114**, 232301 (2015), Phys. Rep. **550-551**, 1 (2015).

Motivation II: Expected theory and remaining puzzles

- The extrapolation to $q^2 = 0$ in the SL region can be improved with an interpolation with TL constraints through the use of dispersion analysis when determining the charge and magnetic radii.
- From threshold to 3 GeV, it is expected to observe complex effects Phys. Rev. Lett. **114**, 232301 (2015):
  - Highly relativistic formation picture expressed in terms of quarks and gluons coexists,
  - Non-relativistic interactions of two slow hadrons leaving the formation zone.
- Reveal the structure around 2.25 GeV and 3.0 GeV observed by BABAR Phys. Rev. D **87**, 092005 (2013) and Phys. Rev. D **88**, 072009 (2013).
- Clarify whether the $|G_E/G_M|$ consistent with BABAR Phys. Rev. D **87**, 092005 (2013) or PS170 Nucl. Phys. **B411** (1994) 3.



Disagreement between BABAR and PS170.

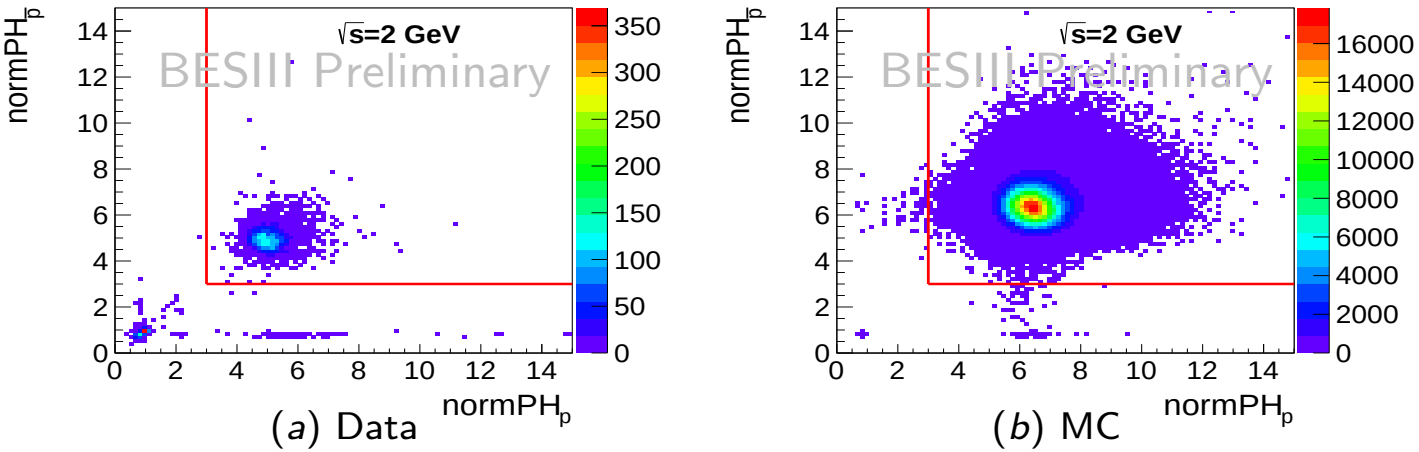
Method

- Particle identification
  - At (2.0, 2.05, 2.1, 2.125, 2.15) GeV, use dE/dx, normalized pulse height:

    $$normPH > (3.0, 2.5, 2.0, 1.8, 1.7).$$

  - At (2.175∼3.08) GeV, use dE/dx and TOF

    $$Prob(p) > Prob(e, \pi, K)$$



(a) Data (b) MC

- Momentum separation for p and $\bar{p}$:
  Signal region:

  $$p_{mean} - 4\sigma < p_{cm}(p, \bar{p}) < p_{mean} + 3\sigma$$

  p_{mean} and σ are from double gaussian fit to momentum of MC.

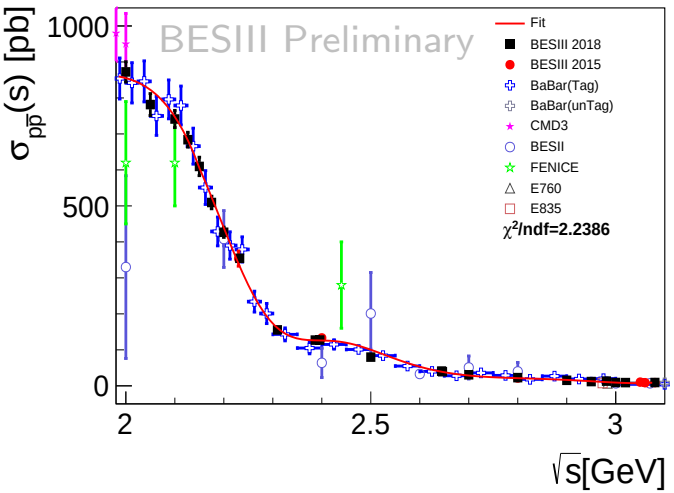
Cross section of $e^+e^- \to p\bar{p}$ and effective form factor

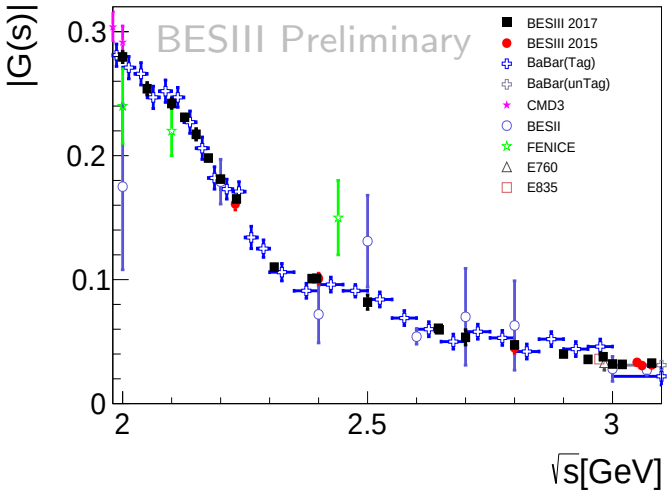
- $1.034 \sim 157.204$ pb^{-1}, from 22 energy points $2.0 \sim 3.08$ GeV.
- **Strategy**:
  - In TL region:

$$\frac{d\sigma_{p\bar{p}}(s)}{d\Omega} = \frac{\alpha^2\beta C}{4s}[|G_M(s)|^2(1+cos^2\theta_p) + \frac{4m_p^2}{s}|G_E(s)|^2 sin^2\theta_p]$$

  - Assume $|G(s)| = |G_E(s)| = |G_M(s)|$, the effective FF is

$$|G(s)| = \sqrt{\frac{\sigma_{p\bar{p}}(s)}{\frac{4\pi\alpha^2\beta(s)C(s)}{3s}(1+\frac{2m_p^2}{s})}}$$





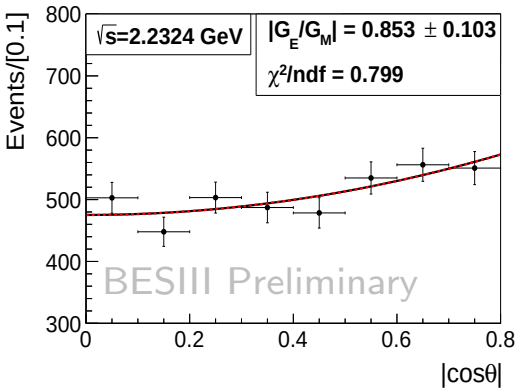
Measurement of $|G_E/G_M|$ and magnetic FF

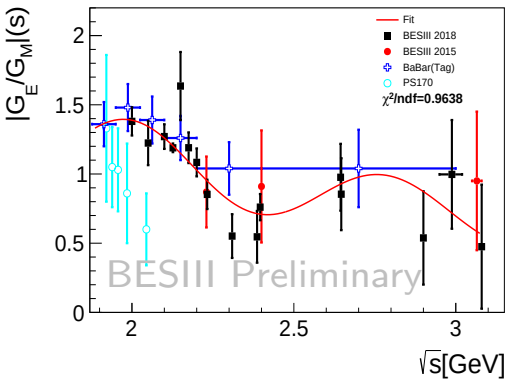
- **Strategy**:
  - Fit on the polar angular distribution of proton:

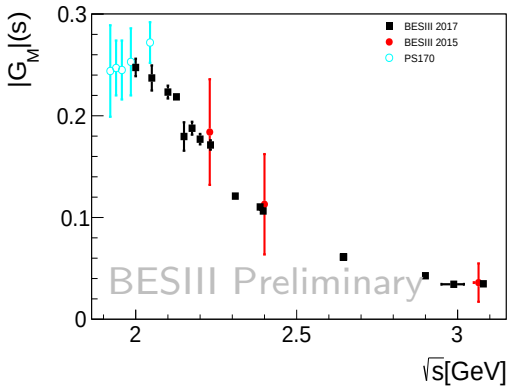
$$\frac{dN}{\epsilon(1+\delta)\times d\cos\theta_p} = \frac{\mathcal{L}\hbar c\pi\alpha^2\beta(s)C(s)}{2s}|G_M(s)|^2[(1+\cos^2\theta_p) + \frac{4m_p^2}{s}|\frac{G_E}{G_M}|(s)^2(1-\cos^2\theta_p)]$$

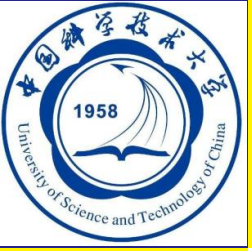
  - $|G_M|$ can be extracted from formula below:

$$|G_M(s)| = \sqrt{\frac{\sigma_{p\bar{p}}(s)}{\frac{4\pi\alpha^2\beta(s)C(s)}{3s}(1+\frac{2m_p^2}{s}|\frac{G_E}{G_M}|(s)^2)}}$$









Summary

- 0.688 fb^{-1}, 22 energies, 2.0 to 3.08 GeV,
- Uncertainty:
  σ_{born}: 3.0% $\sim$ 23.5%, |G|: 1.7% $\sim$ 11.8%, $|G_E/G_M|$: $\sim$10% for lower energy points, $|G_M|$: 1.8% $\sim$ 3.6%.
- Time-like region, an unprecedented accuracy
  Especially $|G_E/G_M|$ providing an uncertainty comparable to the space-like region for the first time.
- The structures in the σ_{born}:
  3.0 GeV: not be observed, 2.25 GeV: cannot be resolved.
- Our measurement of $|G_E/G_M|$ strongly favors BABAR's compared to that of PS170.