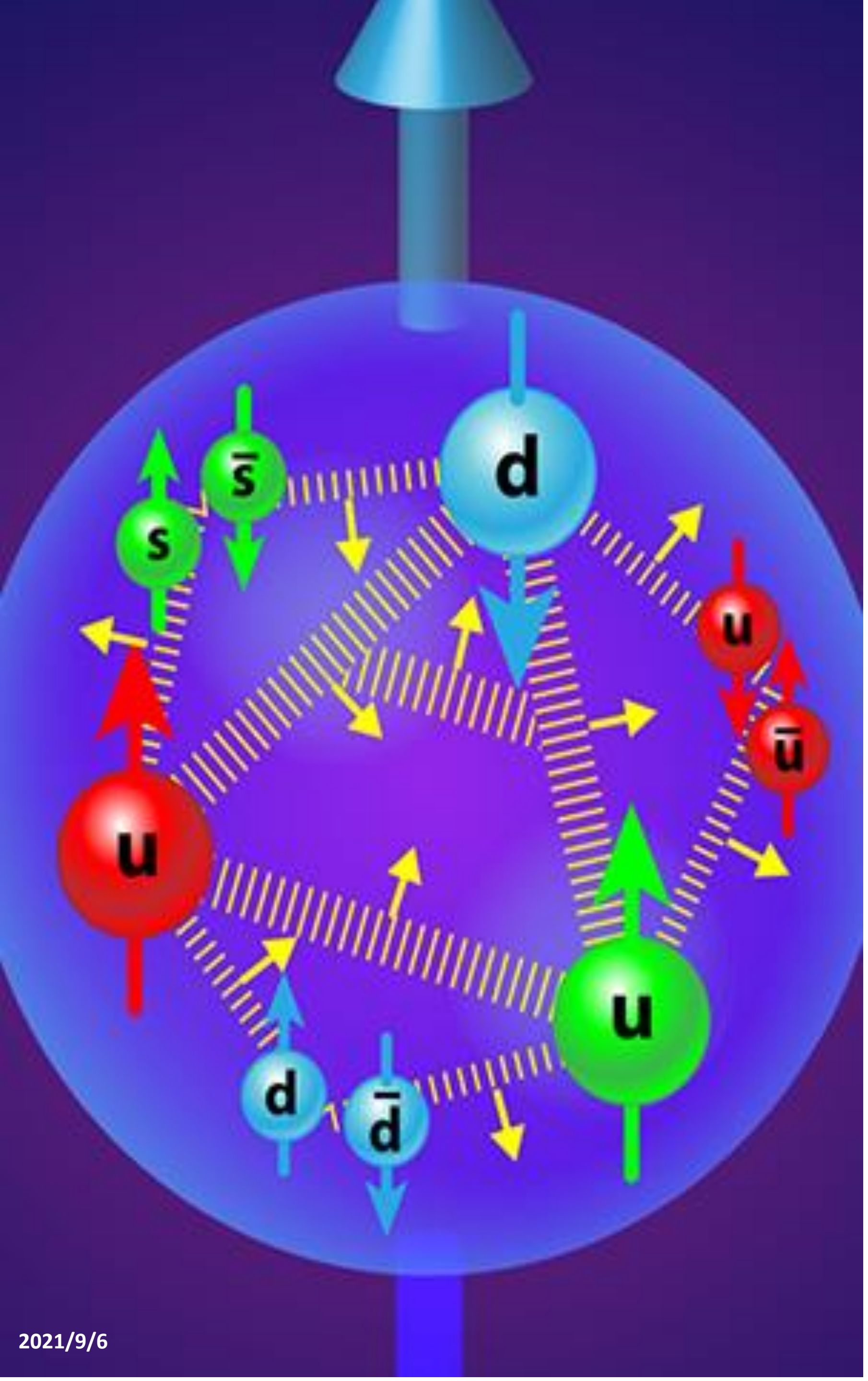

Recent result of nucleon time-like form factors at BESIII

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(On behalf of BESIII collaboration)

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05/09/2021-10/09/2021

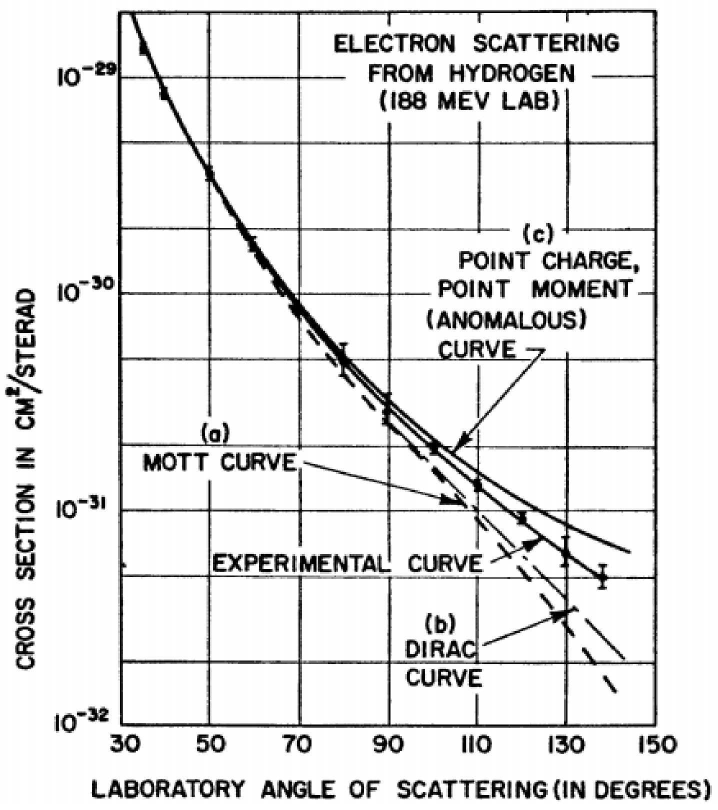
Outline

- Introduction
  - Nucleon Form Factors
  - The BESIII Experiment
- Nucleon EMFFs at BESIII
  - Status of Proton EMFFs Measurements at BESIII
  - Status of Neutron EMFFs Measurement at BESIII
- Summary and Perspectives

Nucleon Electromagnetic Form Factors

Nobel Prize in 1961

Rev. Mod. Phys. 30 (1958) 482



Reveals the internal structure inside the nucleon

Electron-proton elastic scattering

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E} \frac{1}{1+\tau} [G_E^2 + \frac{\tau}{\epsilon} G_M^2]$$

$$\tau = \frac{Q^2}{4m_p^2}, \quad Q^2 = -q^2, \quad \epsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta_e}{2}}$$

- Form factors: describing the internal structure/shape of the non-point-like particle
- Spin-$\frac{1}{2}$ baryons: two Form Factors (Electro and Magnetic, EMFFs)
- Assuming one photon exchange, hadronic current:

$$j_p^\mu = \bar{u}(p_2)\left[\gamma^\mu F_1(q^2) + \frac{i\kappa\sigma^{\mu\nu}q_\nu}{2m_p} F_2(q^2)\right] u(p_1)$$

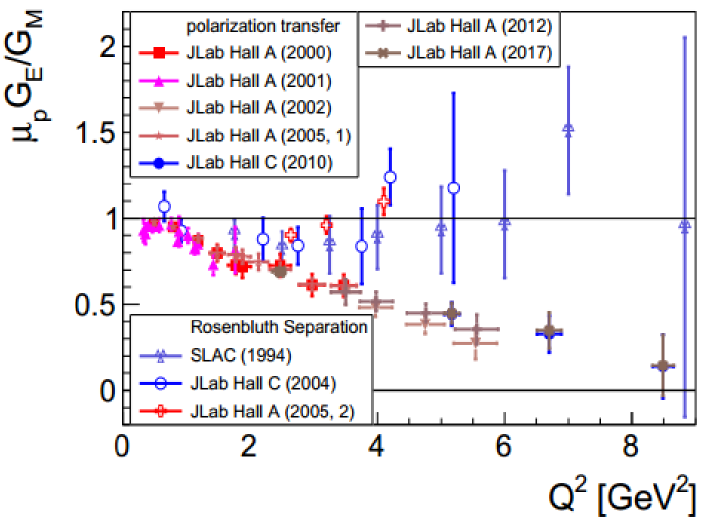
- Sachs Form Factors: $G_E(q^2) = F_1(q^2) + \frac{\kappa q^2}{4m_p^2} F_2(q^2)$

$$G_M(q^2) = F_1(q^2) + \kappa F_2(q^2)$$

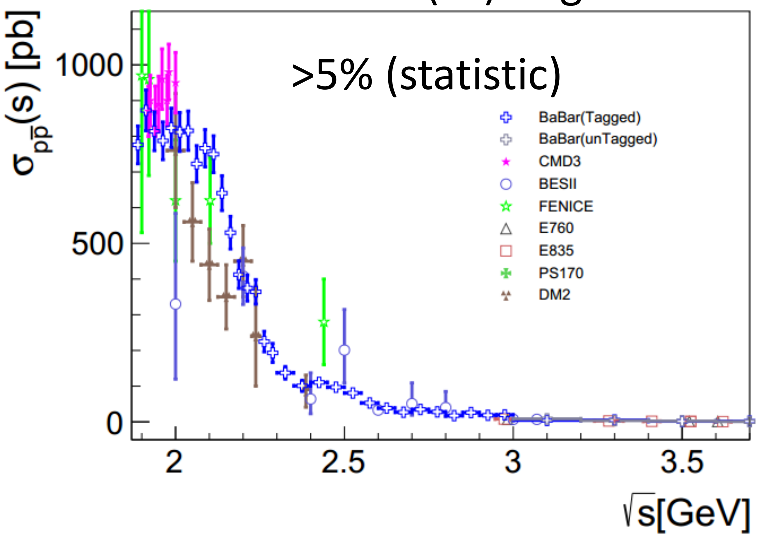
κ is the anomalous magnetic moment

Early Measurements of Proton EMFFs in SL and TL

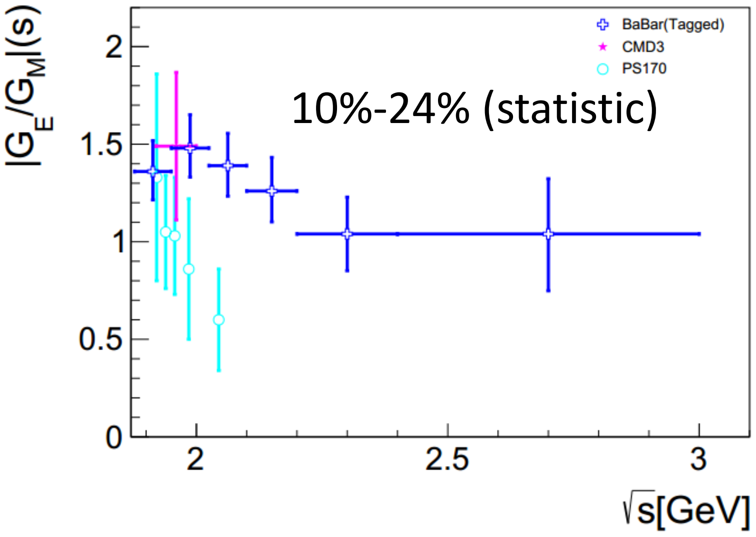
Space-like (SL) region

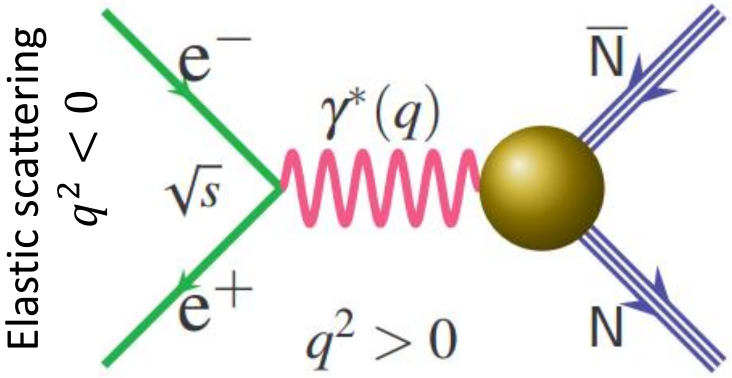


Time-like (TL) region



Time-like (TL) region

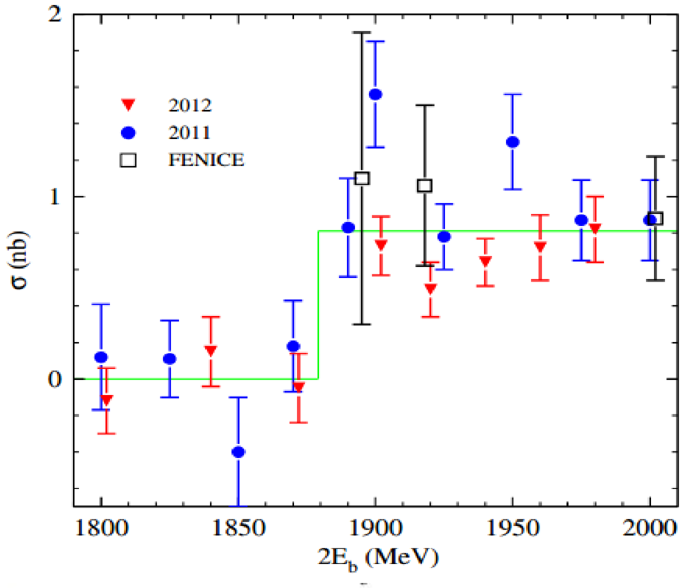


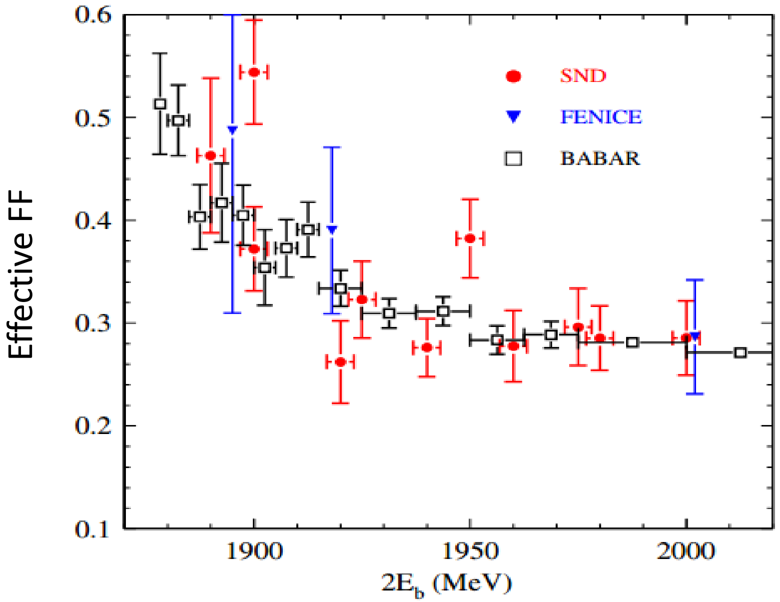


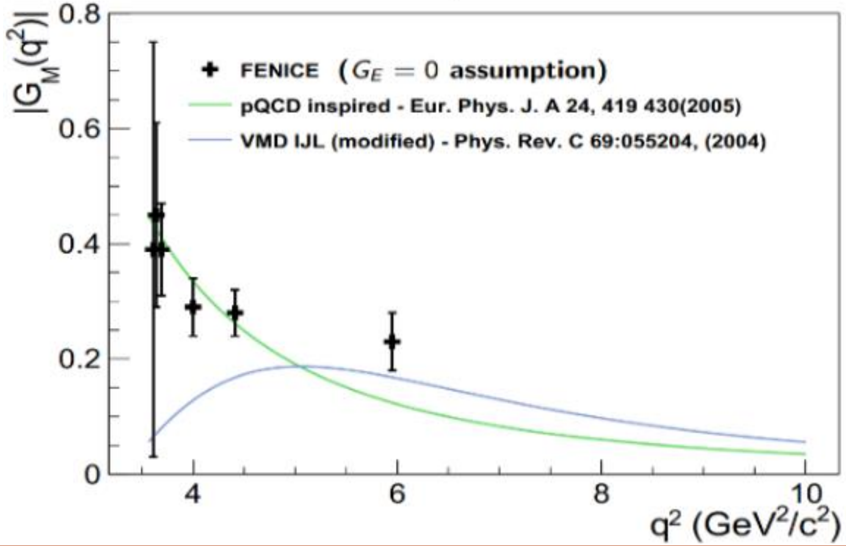
Annihilation

- The precision of SL result is much better than the TL results
- The trends of Rosenbluth Separation results and Polarization transfer results are different
- $|G_E/G_M|$ is different from Babar and CMD3
- More precision knowledge of proton FFs in TL region is very urgent

Early Measurements of Neutron EMFFs in TL



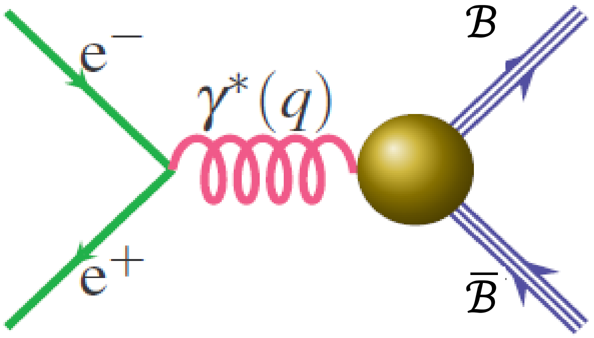




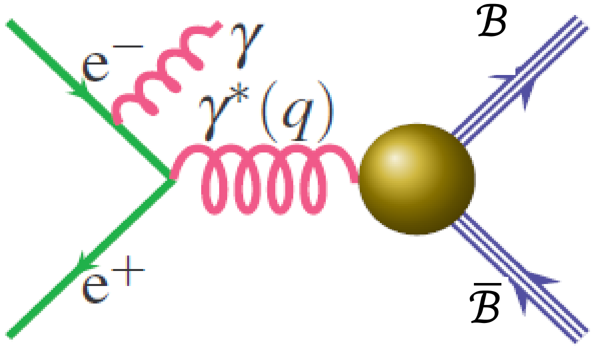
- Very limited data for the TL neutron EMFFs measurements
- Sharp jumping of the cross section at $n\bar{n}$ threshold
- No ratio of the EMFFs or individual EMFFs measurement

Methods to Measure the EMFFs at an e^+e^- Collider

Direct annihilation



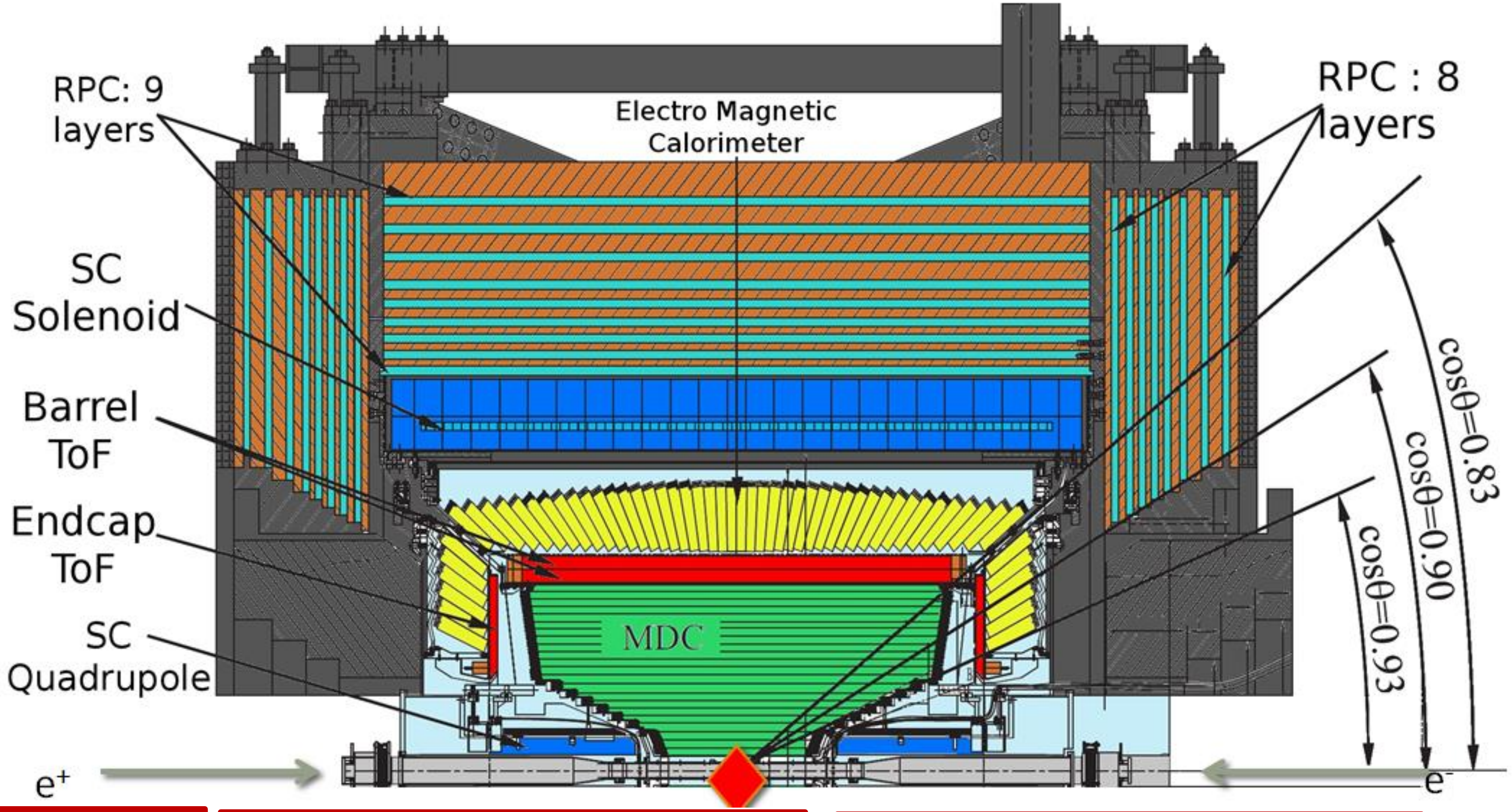
Initial State Radiation



	Energy Scan (Direct annihilation)	Initial State Radiation
E_{beam}	discrete	Fixed
L	Low at each beam energy	High at one beam energy
σ	$\frac{d\sigma_{p\bar{p}}}{d(cos\theta)} = \frac{\pi\alpha^2\beta C}{2q^2}[\lvert G_M\rvert^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}\lvert G_E\rvert^2\sin^2\theta]$ $C = \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}$ for charged final particles, 1 for neutral	$\frac{d\sigma_{\gamma p\bar{p}}}{dq^2 d(\cos\theta_\gamma)} = \frac{1}{s}W(s,x,\theta_\gamma)\sigma_{p\bar{p}}(q^2)$ $W(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2})$
q^2	Single at each beam energy, $q^2 = 4E_{beam}^2$	From threshold $M_{p\bar{p}}^2$ to $4E_{beam}^2$

Both techniques can be used at BESIII

BESIII Spectrometer



MDC

$\frac{\delta p}{p} < 0.5\%$ @ 1GeV/c

$\frac{\delta(dE/dx)}{dE/dx} < 6\%$

TOF

$\delta t = 70$ ps in Barrel

$\delta t = 60$ ps in Endcap after upgrade

EMC

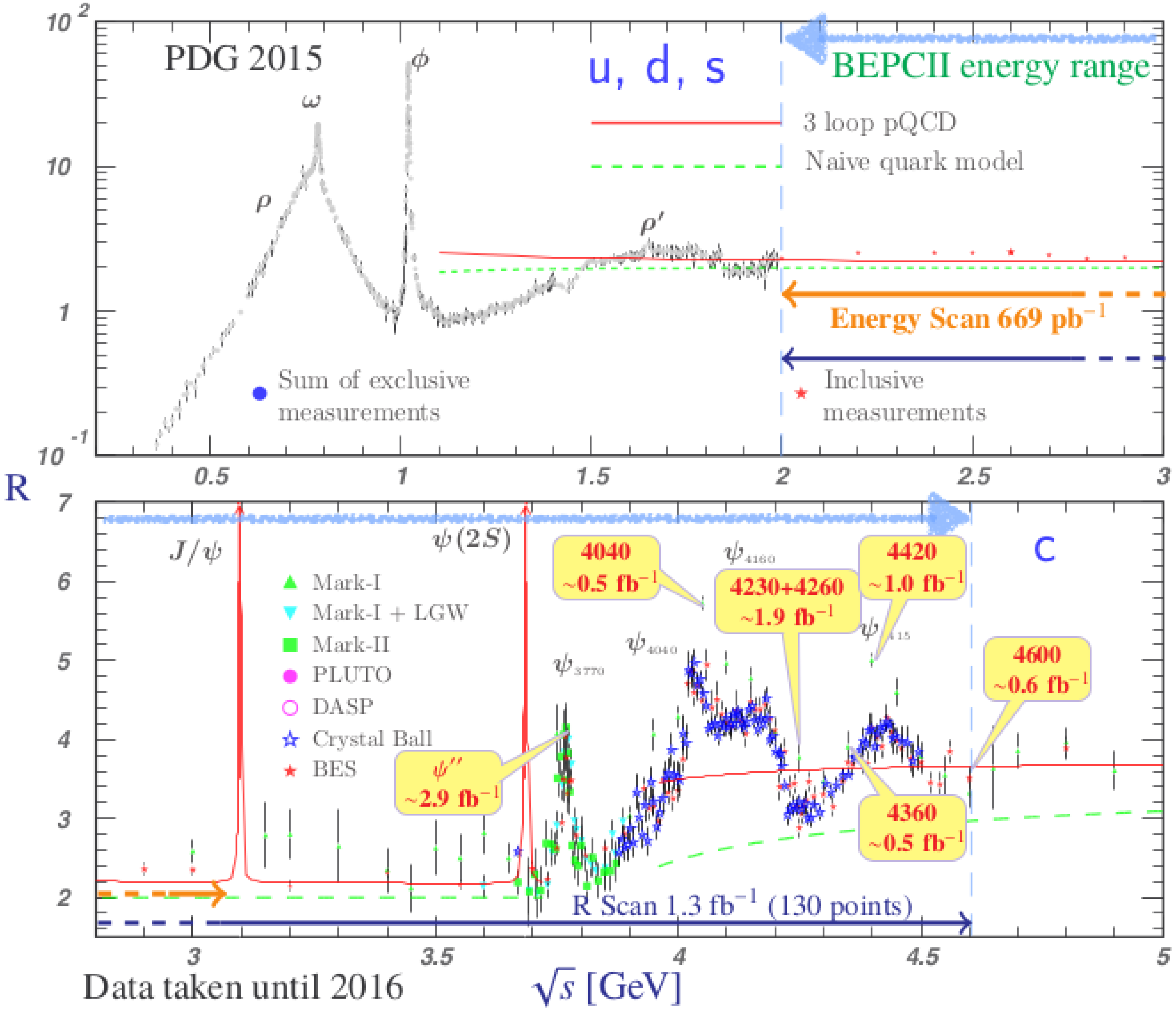
$\frac{\delta E}{E} < 2.5\%$ @ 1GeV

$\delta z = 0.6/\sqrt{E}$ cm

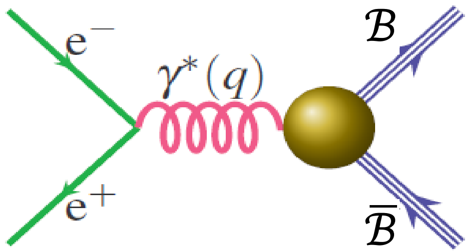
MUC

$\delta(xy) < 2$ cm

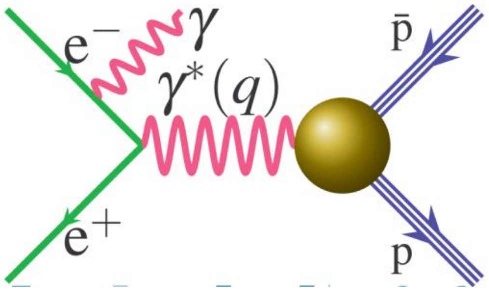
Data Sets for Nucleon EMFFs Measurments



Proton and Neutron EMFFs
From energy scan data
(2.0-3.08) GeV: 669 pb^{-1}



Proton EMFFs
From resonances data with ISR
$L_{int}(\geq \psi''): 7.5\ fb^{-1}$

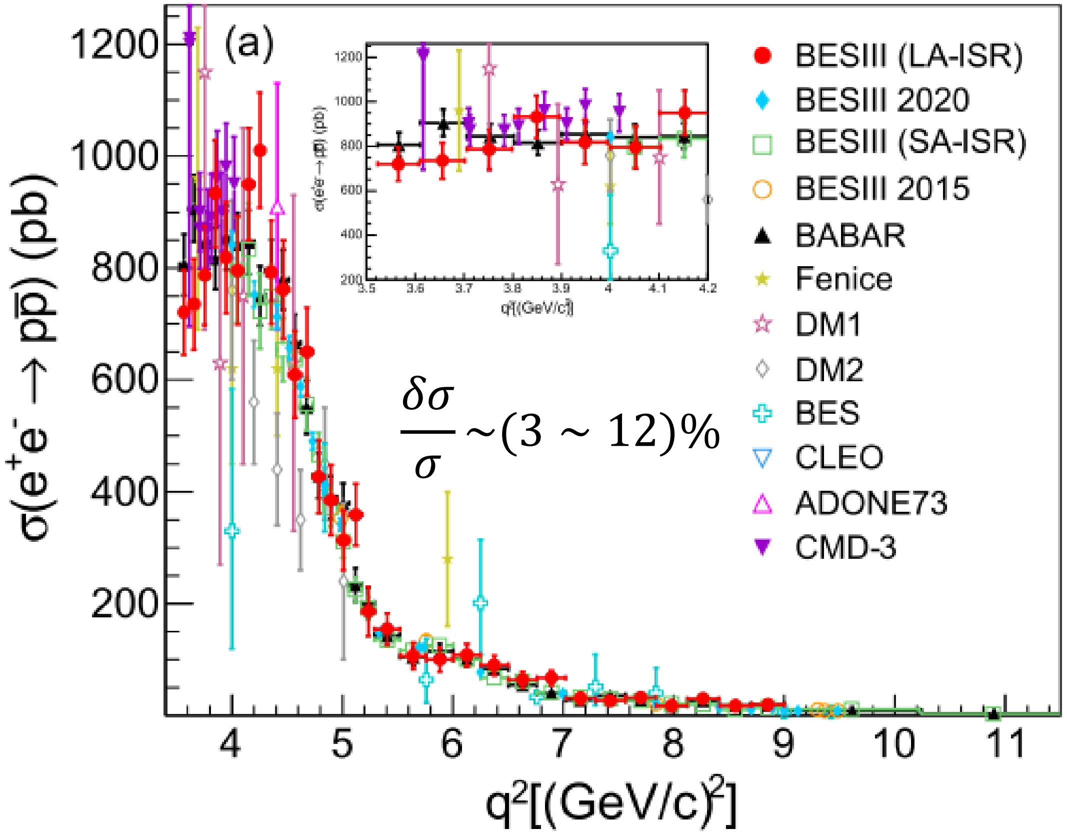


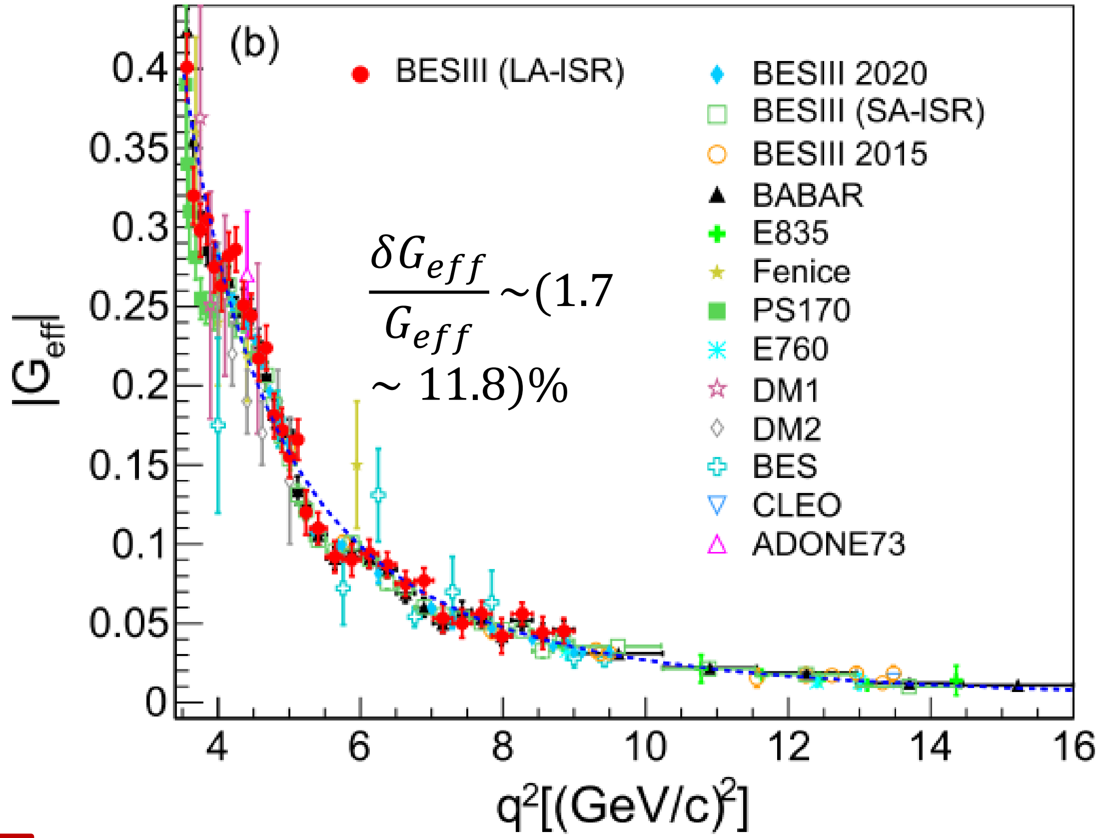
Measuring Proton EMFFs with Different Methods

Three different analyses to analyze proton EMFFs at BESIII

- **Direct process $e^+e^- \to p\bar{p}$**
  - data sets 2.00 - 3.08 GeV (669 pb^{-1})
  - Large statistics, most precise measurement for the proton time-like EMFFs
  - Relative better uncertainty of the ratio of EMFFs (or individual FFs)
  - Difficult to access the $p\bar{p}$ threshold
- **ISR process $e^+e^- \to p\bar{p}\gamma_{ISR}$**
  - data sets at 3.773-4.600 GeV (7.5 fb^{-1})
  - **tagged (Large Angle-ISR)** or **untagged (Small Angle-ISR) methods**
  - Low statistics due to the suppress factor of $\frac{\alpha}{\pi} \sim 0.0025$
  - Large $p\bar{p}$ invariant mass range up to 3.8 GeV/c^2 (ISR-untagged)
  - Only method to access the $p\bar{p}$ threshold at e^+e^- collider experiment (ISR-tagged)
  - Full proton angular distribution, better precision of the ratio of EMFFs (ISR-tagged)

Born Cross Section of $e^+e^- \to p\bar{p}$ and Proton Effective FF





Direct process with scan data:

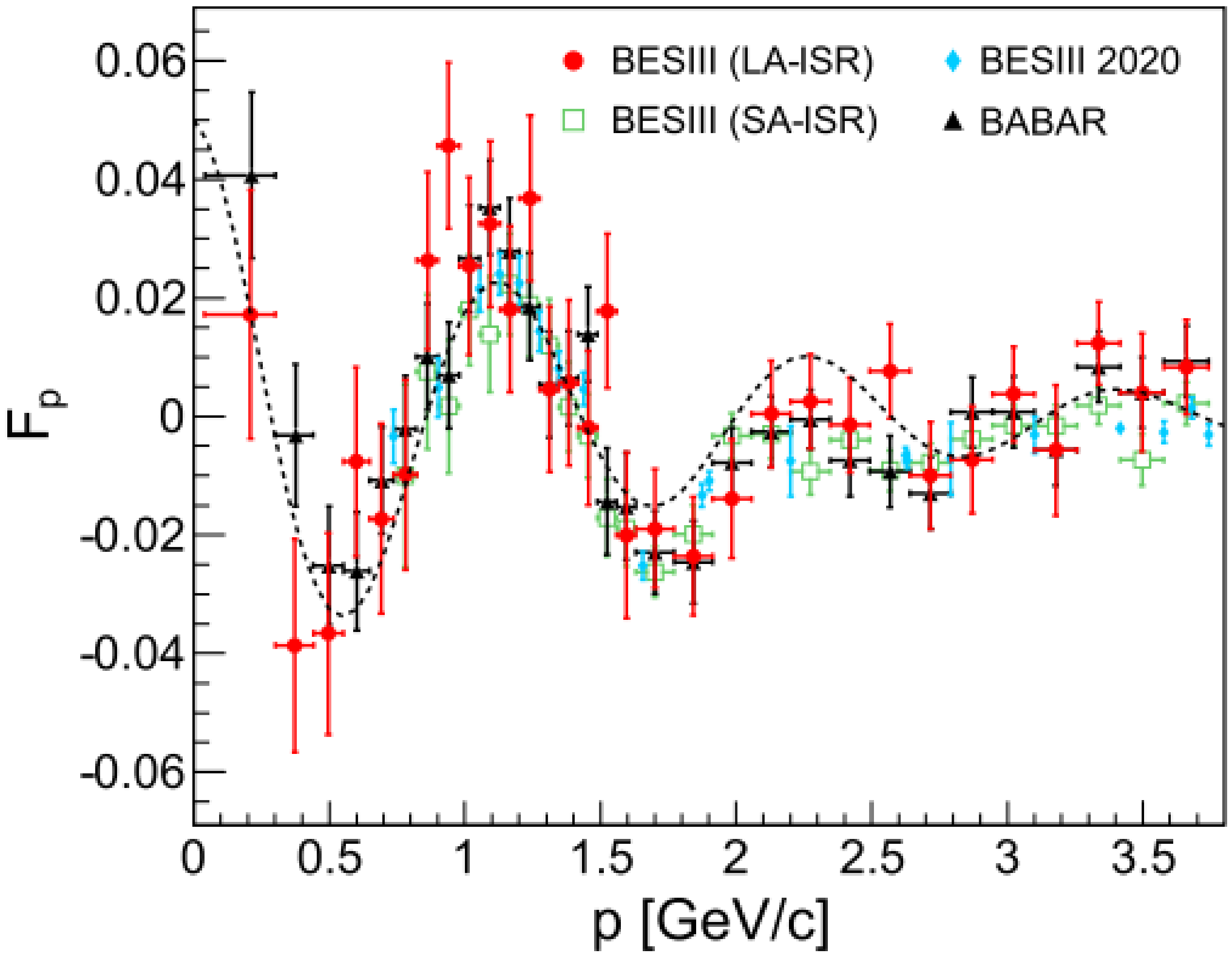
- $\sqrt{s} = 2.232 - 3.671$ GeV, 157 pb^{-1}, PRD 91, 112004
- $\sqrt{s} = 2.000 - 3.080$ GeV, 669 pb^{-1}, PRL 124, 042001
- Most precise measurement, i.e. at $\sqrt{s} = 2.125$ GeV, $\frac{\delta\sigma}{\sigma}$~0.45%

ISR process $e^+e^- \to p\bar{p}\gamma_{ISR}$

LA-ISR: $\sqrt{q^2} = 1.876 - 3.000$ GeV/c^2, PLB 817, 136328

SA-ISR: $\sqrt{q^2} = 2.000 - 3.800$ GeV/c^2, PRD 99, 092002

Oscillation Structure of $|G_{eff}|$

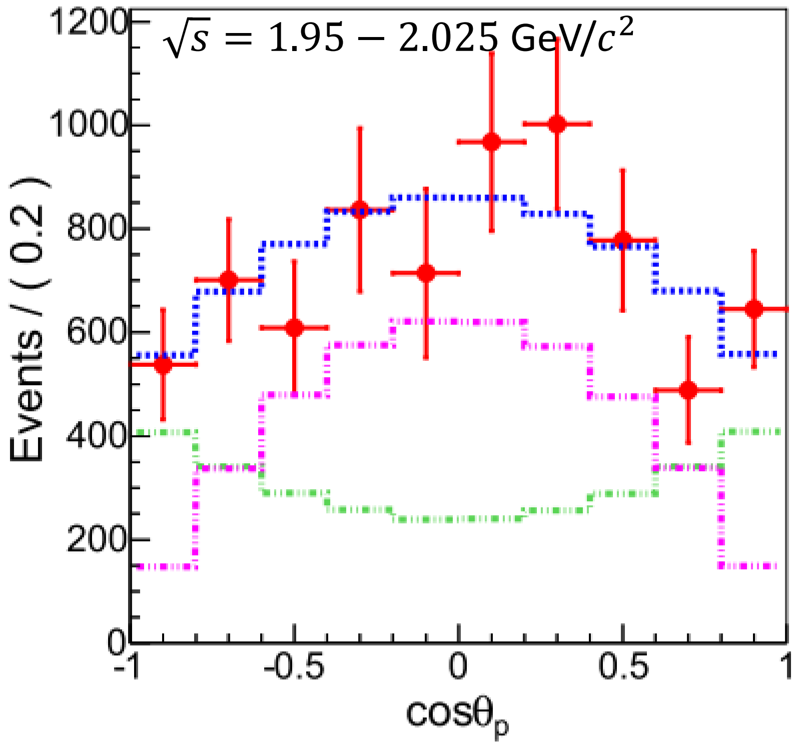


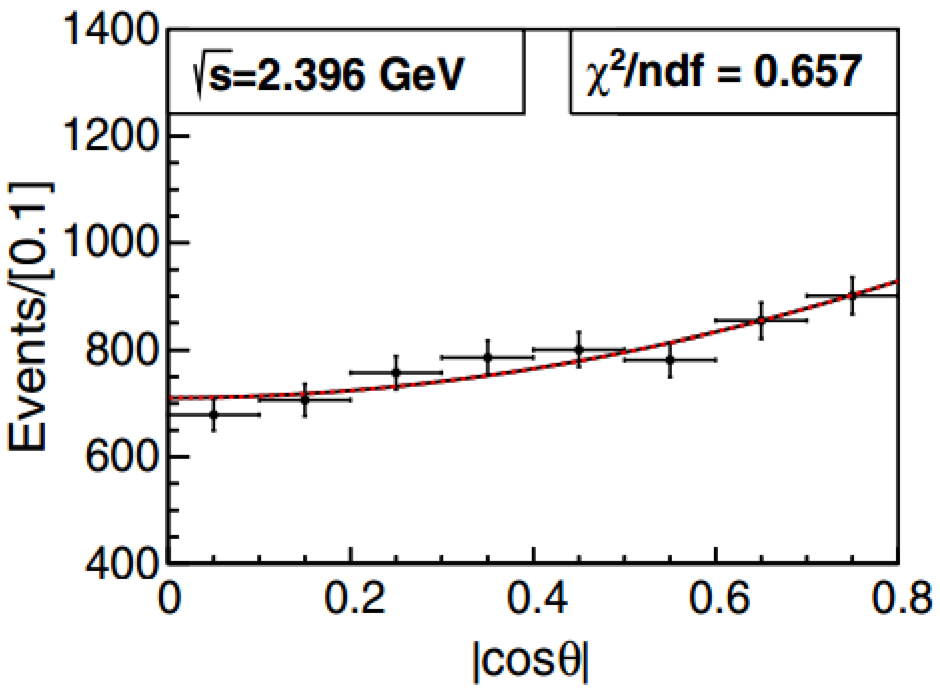
- Confirm the oscillation behavior observed from Babar data

- Possible explanations:
  - interference effects from final state re-scattering [1]
  - resonant structure [2]

[1] A. Bianconi, E. Tomasi-Gustafsson, Phys. Rev. C 93, 035201 (2016).
[2] I. T. Lorenz, F. W. Hammer, U. G. Meißner, Phys. Rev. D 92, 034018 (2015)

Ratio of Proton EMFFs and Individual EMFFs





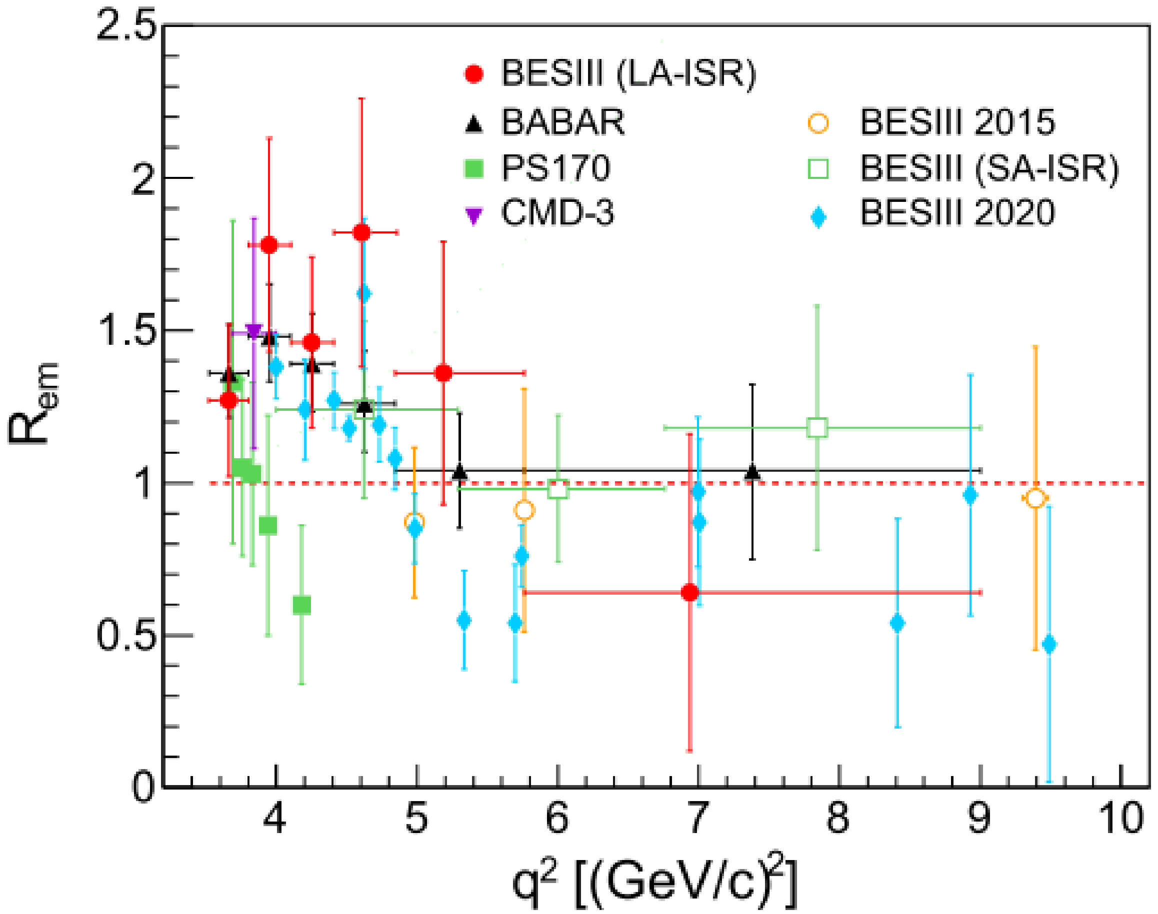
- ISR process:

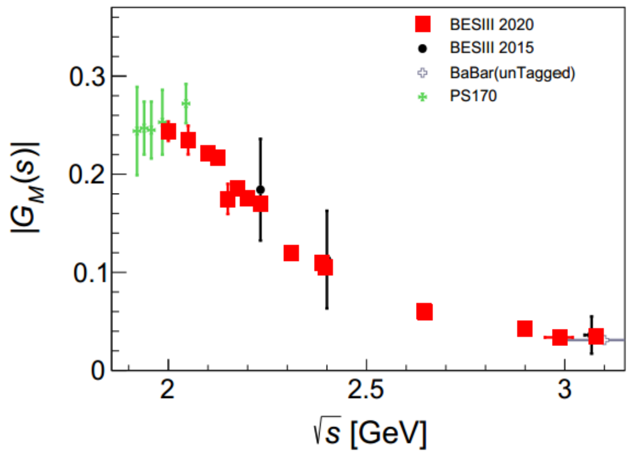
$$\frac{dN}{dcos\theta_p} = A[F_M(\cos\theta_p, M_{p\bar{p}}) + \frac{|R_{EM}|^2}{2\tau} F_E(cos\theta_p, M_{p\bar{p}})]$$

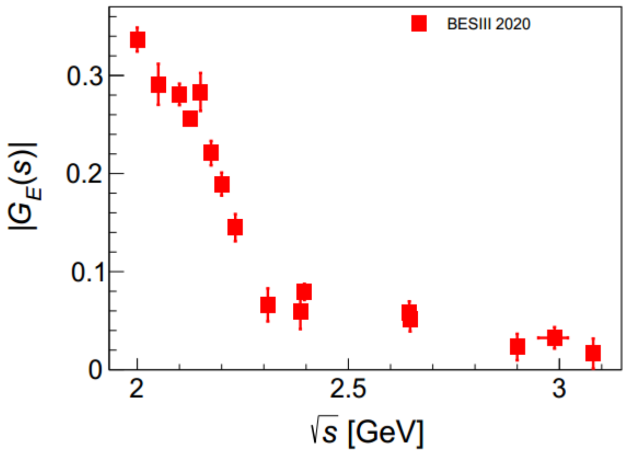
- Direct process:

$$\frac{d\sigma}{dcos\theta_p} = \frac{\pi\alpha^2\beta C}{2s} |G_M| [(1 + \cos^2\theta_p) + \frac{|R_{EM}|^2}{\tau} \sin^2\theta_p]$$

Ratio of Proton EMFFs and Individual EMFFs

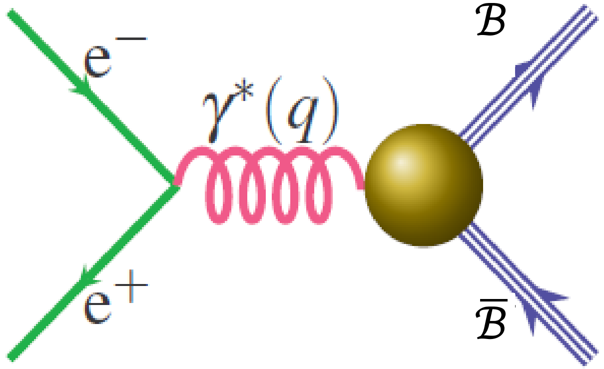


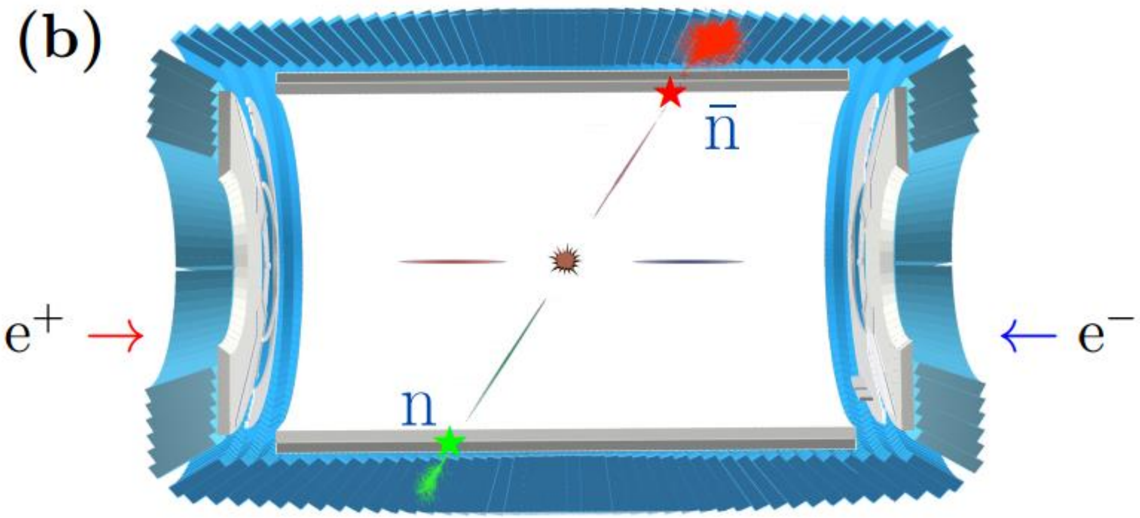




- Precision of the measurements of $|R_{EM}|$ and $|G_M|$ improved significantly
- $|G_E|$ measured for the first time
- At $\sqrt{s} = 2.125$ GeV, $\frac{\delta|R_{EM}|}{|R_{EM}|} \sim 3.4\%$
- The trend of proton EMFFs R_{EM}: BESIII result favors Babar result

Measurement of Neutron EMFFs at BESIII

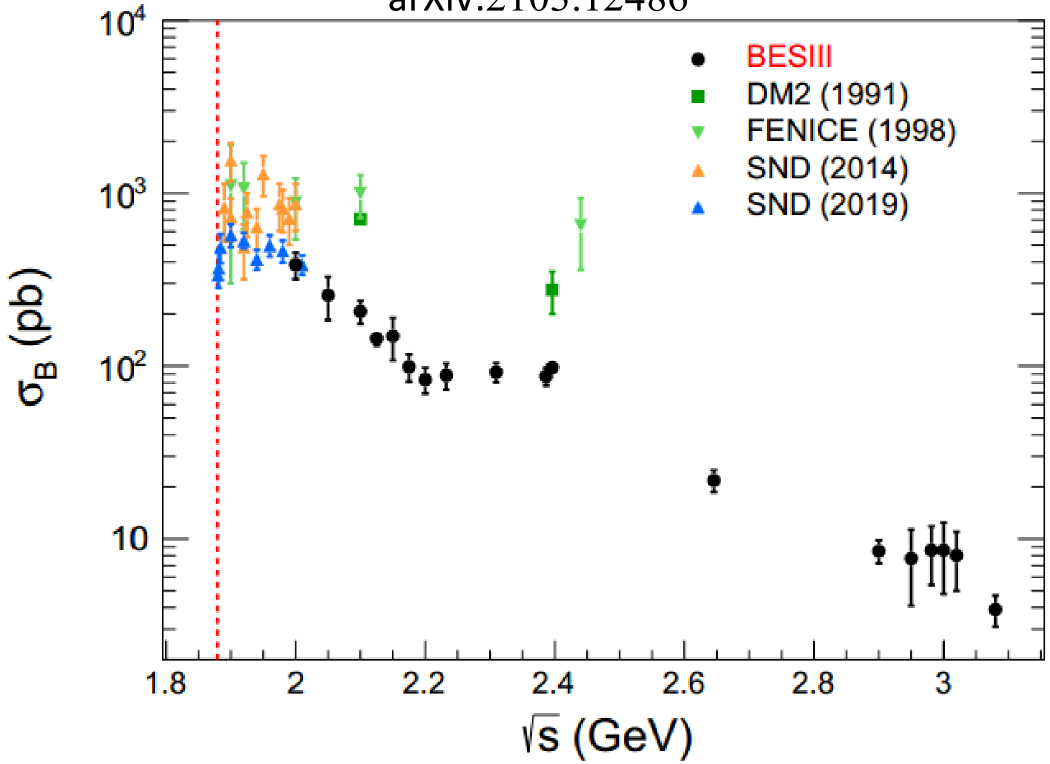


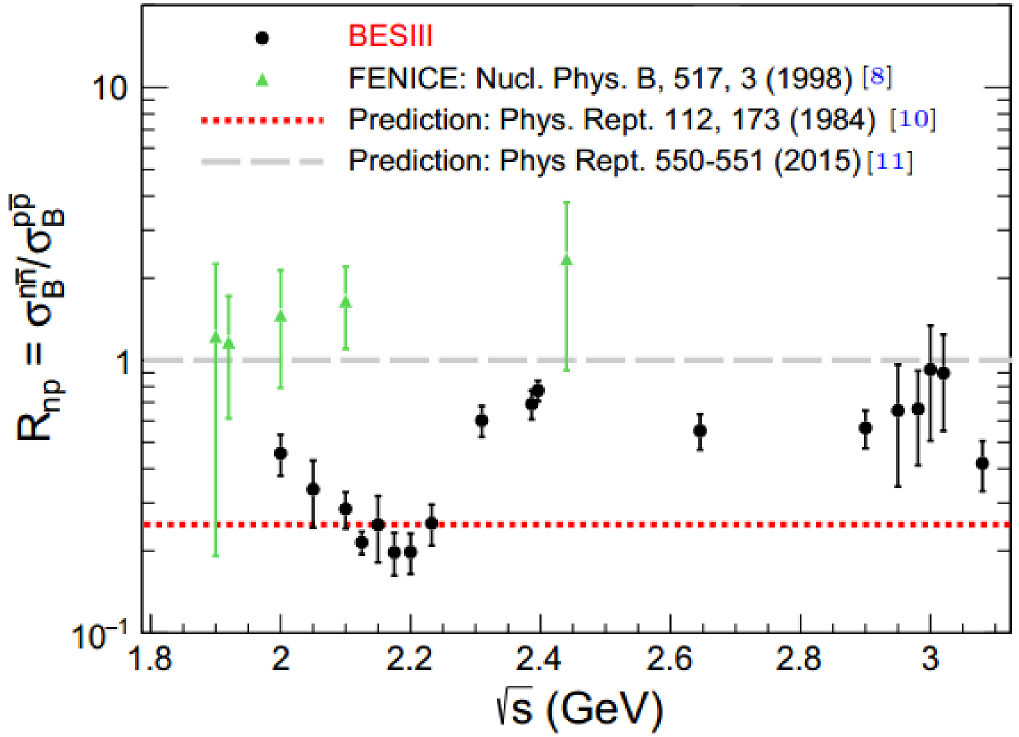


- Direct process $e^+e^- \to n\bar{n}$ with data sets at 2.00-3.08 GeV (669 pb^{-1})
- Difficult with the pure neutral channel at BESIII
- Information from EMC and/or TOF only
- Sophisticated background suppression

Born Cross Section of $e^+e^- \to n\bar{n}$

arXiv:2103.12486

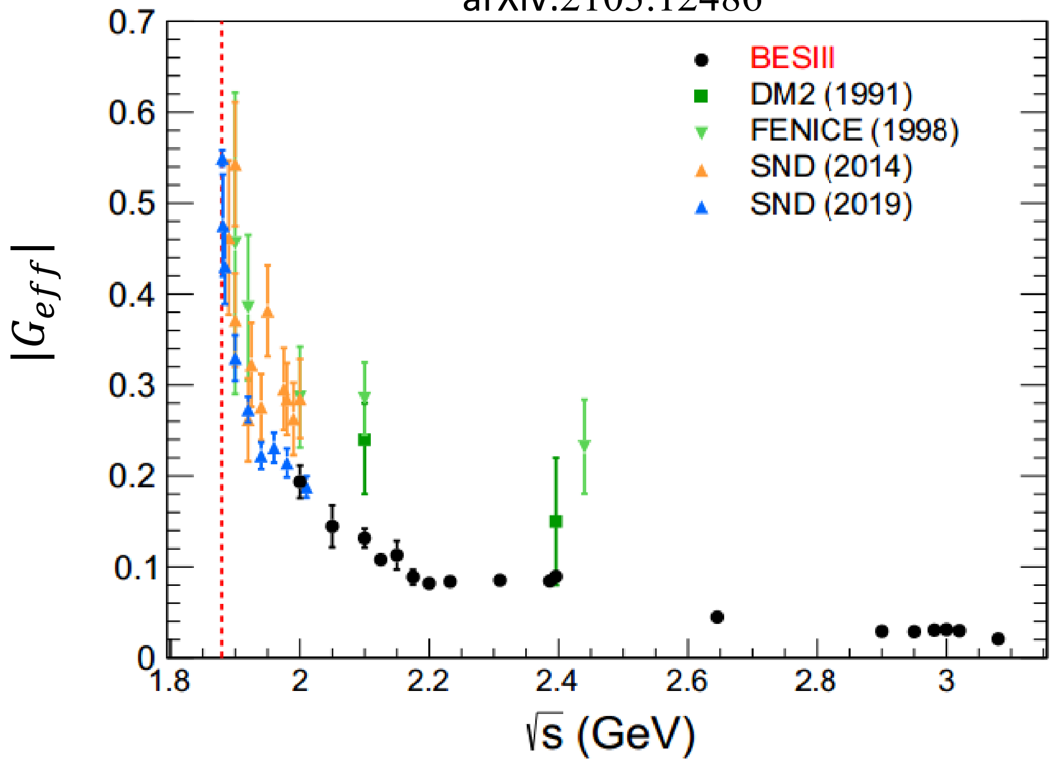


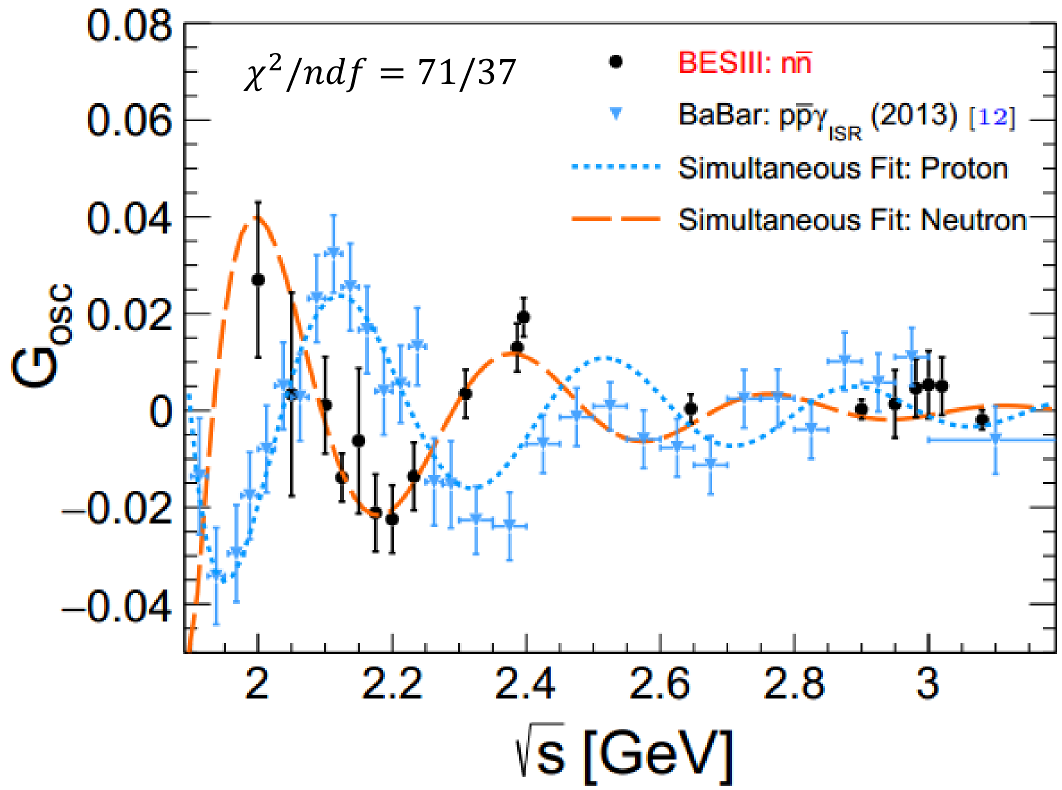


- ✓ Precision of σ_B and $|G_{eff}|$ are very much improved. At $\sqrt{s} = 2.125$ GeV, 679 events collected, $\frac{\delta\sigma_B^{stat.}}{\sigma_B} = 4.15\%$
- ✓ Systematically below all other previously results above 2 GeV, while still in agreement within 2σ
- ✓ $R_{np} = \frac{\bar{\sigma}_B^{n\bar{n}}}{\bar{\sigma}_B^{p\bar{p}}}$ inconsistent with FENICE result, clarifies the photon-nucleon interaction puzzle which persisted for over 20 years.

Neutron Effective FF and Oscillation Structure

arXiv:2103.12486





- ✓ $|G_{eff}|$ is measured over a large energy range with unprecedented precision
- ✓ The oscillation structure is also observed, but with orthogonal periodic behavior compared with that of proton. Very interesting!

$$F_{osc}^{n,p} = A^{n,p} \exp(-B^{n,p} \cdot p) \cos(C \cdot p + D^{n,p})$$

Fit G_{osc} simultaneously with the same frequency (C), a phase difference of $\Delta D = |D_p - D_n| = (123 \pm 12)^\circ$

Summary and Perspective

- Both direct and ISR analyses of Nucleon EMFFs are finished at BESIII, and provide complementary results
- The precision of nucleon EMFFs in the TL region are improved significantly
- Oscillation structure are both observed on $|G_{eff}|$ spectrums of Proton and Neutron

- The precision of nucleon EMFFs, especially the ratio or individual FFs, is still not good for the threshold region ($q^2 \sim 2.0\ GeV/c^2$)
- The ISR process (LA-ISR) offers unique way to access the $N\bar{N}$ threshold region, and to obtain full angular distribution
- More large data sets ($\sim 22\ fb^{-1}$) accumulated at BESIII, which can be analyzed not only for nucleon EMFFs, but also for other baryon channels

Thank you for your attention!