Recent result of nucleon time-like form factors at BESIII

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Strong Interaction at Low Energy

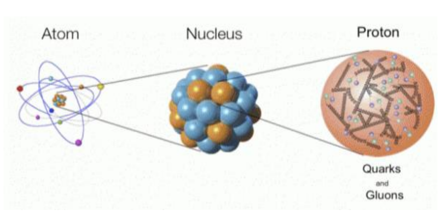
The standard model of particle physics is a well-tested theoretical framework,

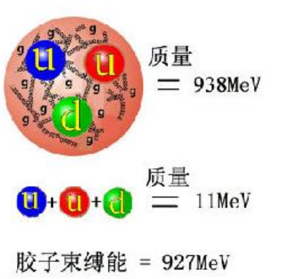
However, the SM has a number of issues need further investigation:

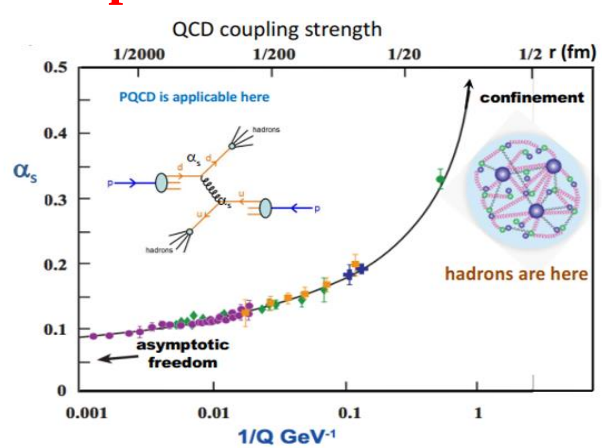
- ☐ **The nature of quark confinement**
- ☐ Matter-antimatter asymmetry of the Universe
- ☐ Gravity, dark matter, numbers of flavors, etc.

Nucleons are composite objects with inner structure. At low Q, perturbative QCD not possible (expansion of coupling constant α_s)

⇒ Nucleon structure must be measured in experiments!

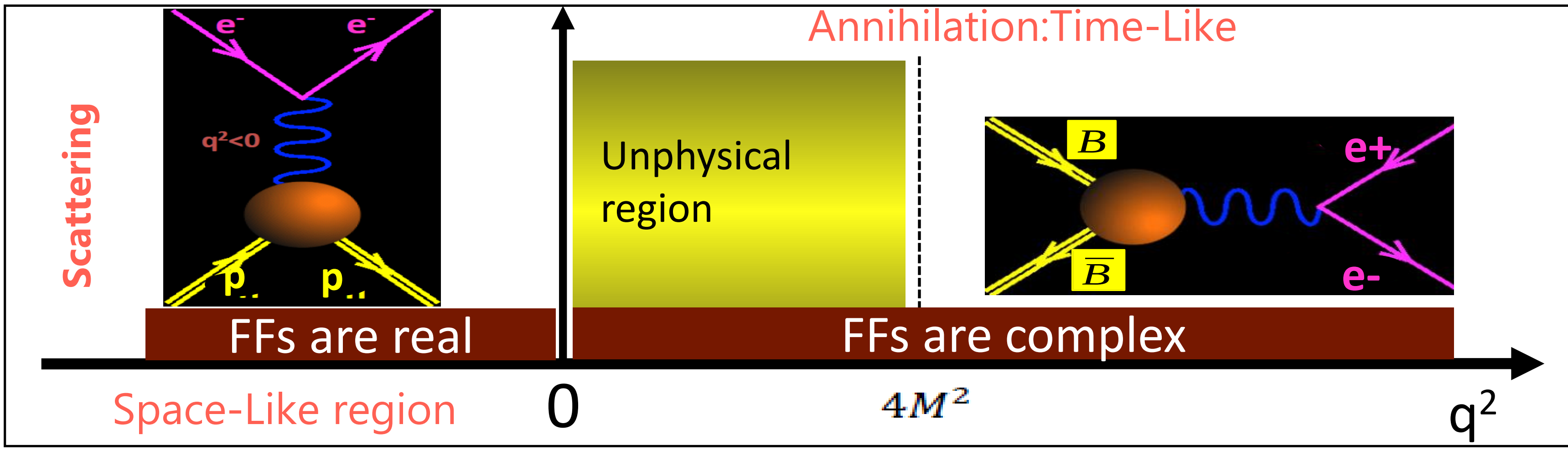






Electromagnetic Form Factors

- **Fundamental properties of the nucleon**
  - **Connected to charge, magnetization distribution**
  - **Crucial testing ground for models of the nucleon internal structure**



The nucleon electromagnetic vertex Γ_μ describing the hadron current:

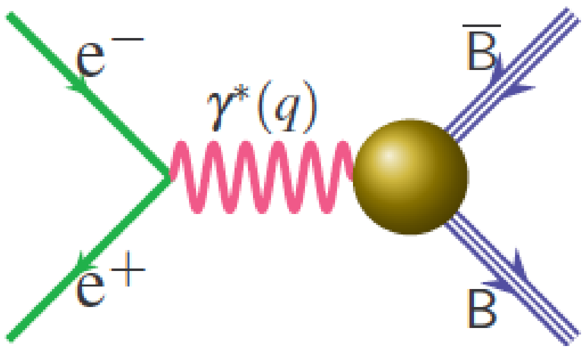
$$\Gamma_\mu(p', p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p} F_2(q^2)$$

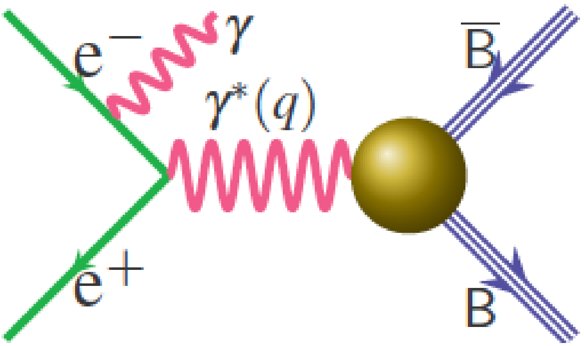
Sachs FFs: $G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$, $G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$

Normalization of FF: $q^2 = 0$: $G_E = Z$, $G_M = \mu_N$

$q^2 = 4m_N^2$: $G_E = G_M$

Experimental Access of Time-like Form Factors





	Energy Scan	Initial State Radiation
E_{beam}	discrete	fixed
$\mathcal{L}$	low at each beam energy	high at one beam energy
σ	$\frac{d\sigma_{p\bar{p}}}{d(\cos\theta)} = \frac{\pi\alpha^2\beta C}{2q^2}[\lvert G_M\rvert^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}\lvert G_E\rvert^2\sin^2\theta]$	$\frac{d^2\sigma_{p\bar{p}\gamma}}{dq^2 d\theta_\gamma} = \frac{1}{s}W(s,x,\theta_\gamma)\sigma_{p\bar{p}}(q^2)$ $W(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2})$
q^2	single at each beam energy	from threshold to s

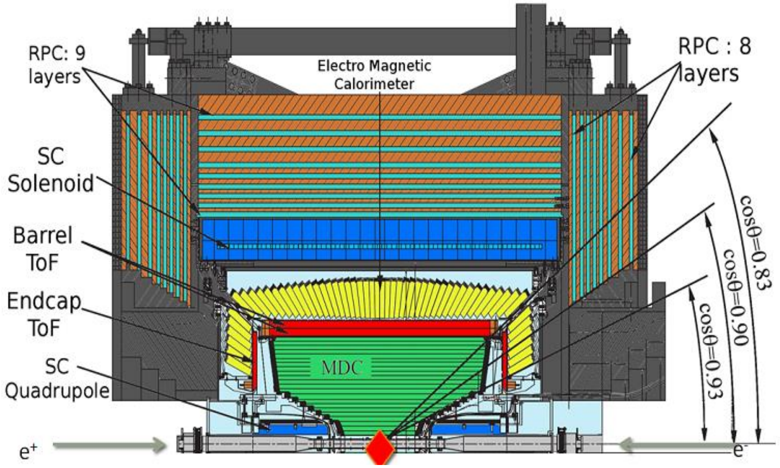
Both techniques, energy scan and initial state radiation. can be used at BESIII

$\sim \frac{1}{400}$

BEPCII/BESIII: a τ-charm factory

Electromagnetic Calorimeter
CsI(Tl): L=28 cm
Barrel σ_E=2.5%
Endcap σ_E=5.0%

Muon Counter
RPC
Barrel: 9 layers
Endcap: 8 layers
$\sigma_{spatial}$: 1.48 cm



Ecm= 2.0-4.6 GeV (2.0-4.95 GeV since 2019)

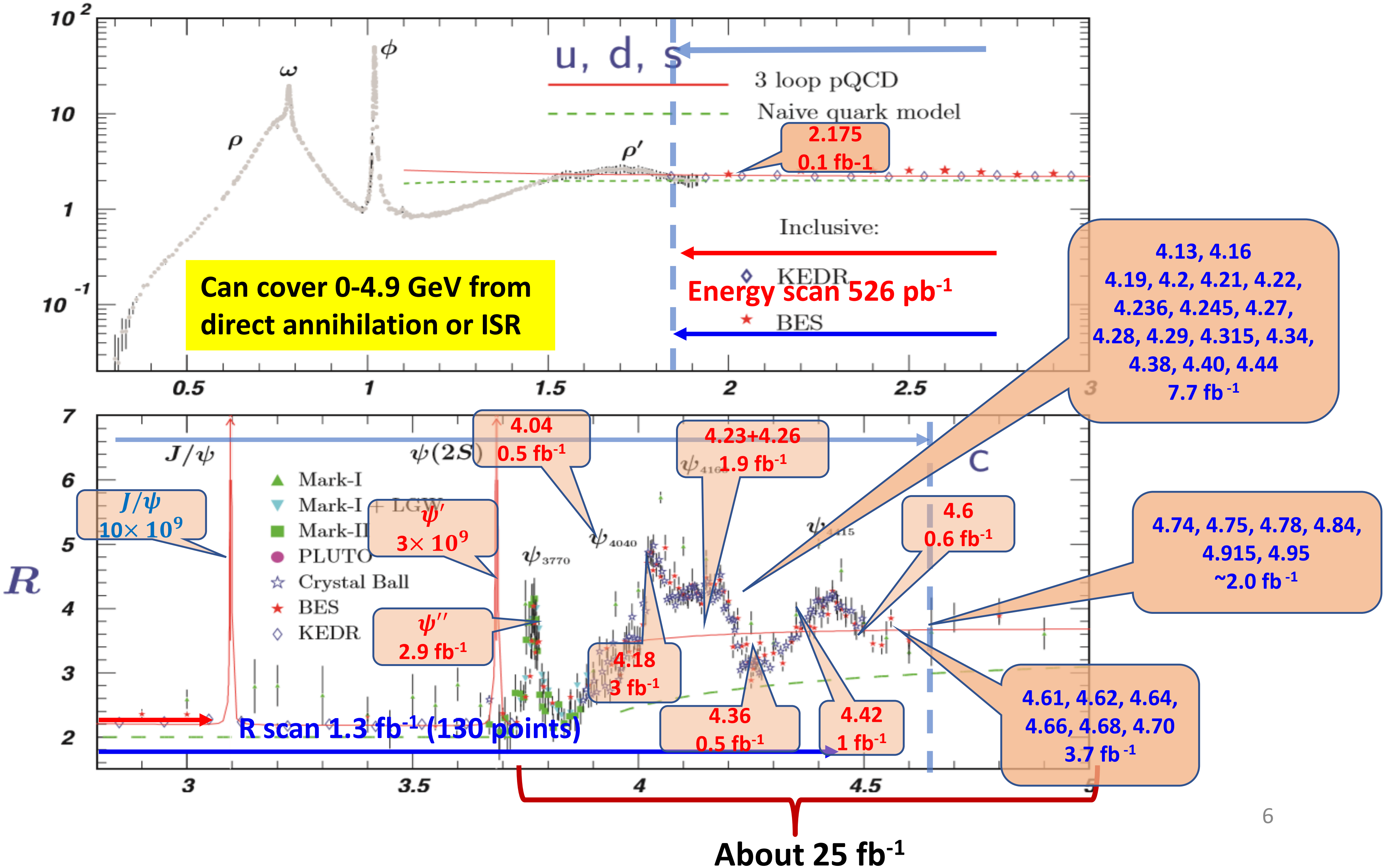
Energy spread: $\Delta E \approx 5 \times 10^{-4}$

Peak luminosity in continuously operation @Ecm= 3.77 GeV: 1.0×10^{33} $cm^{-2}s^{-1}$

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

Time Of Flight
Plastic scintillator
σ_T(barrel): 80 ps
σ_T(endcap): 110 ps
(update to 65 ps with MRPC)

Data Samples Collected at BESIII



Baryon Pair Production

- The Born cross section for $e^+e^- \to \gamma^* \to B\bar{B}$ (B is spin 1/2 baryon):

$$\sigma_{B\bar{B}}(q) = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q)|^2 + \frac{1}{2\tau}|G_E(q)|^2\right]$$

- At threshold: $G_M = G_E = G$, $\tau = \frac{s}{4m_B^2} = 1$

- The $\sigma_{B\bar{B}}(q)$ becomes:

$$\sigma_{B\bar{B}}(q) = \frac{2\pi\alpha^2 C\beta}{q^2}|G|^2 = \frac{2\pi\alpha^2 C\beta}{s}|G|^2$$

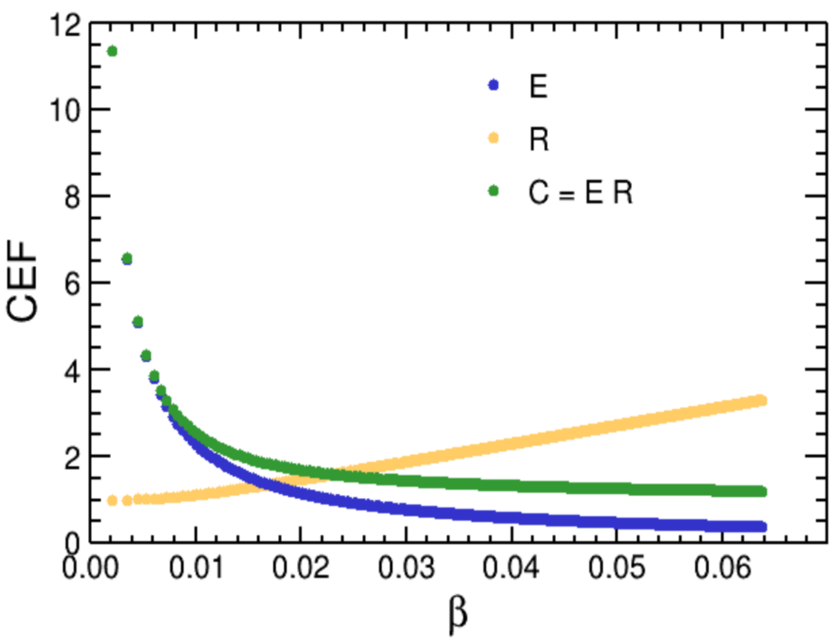
  - **C: Coulomb Enhancement factor (CEF)**
  - $\beta = \sqrt{1 - 4m_B^2/s}$ (vanish at threshold)
  - G: form factor

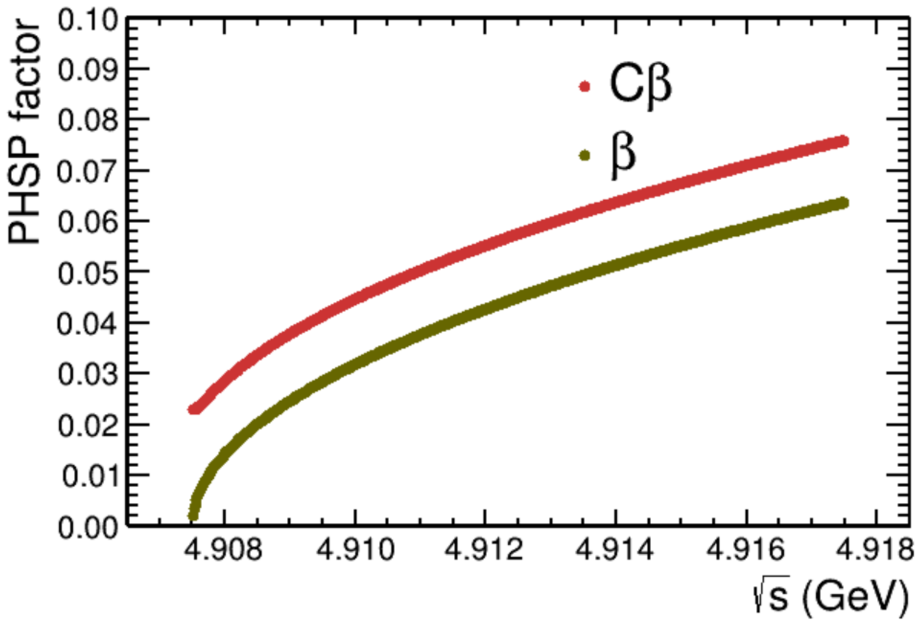
Coulomb Enhancement Factor

- C = E·R (for charged baryon)
  - $\mathrm{E} = \pi\alpha F/\beta$, $\mathrm{R} = \frac{1}{1-e^{-\frac{\pi\alpha F}{\beta}}}$,
  - F= $1+\beta^2$ or $\sqrt{1-\beta^2}$

- $\sigma_{B\bar{B}}(q) = \frac{2\pi\alpha^2 C\beta}{s}|G|^2$

C will lead to a non-zero Born cross section at threshold

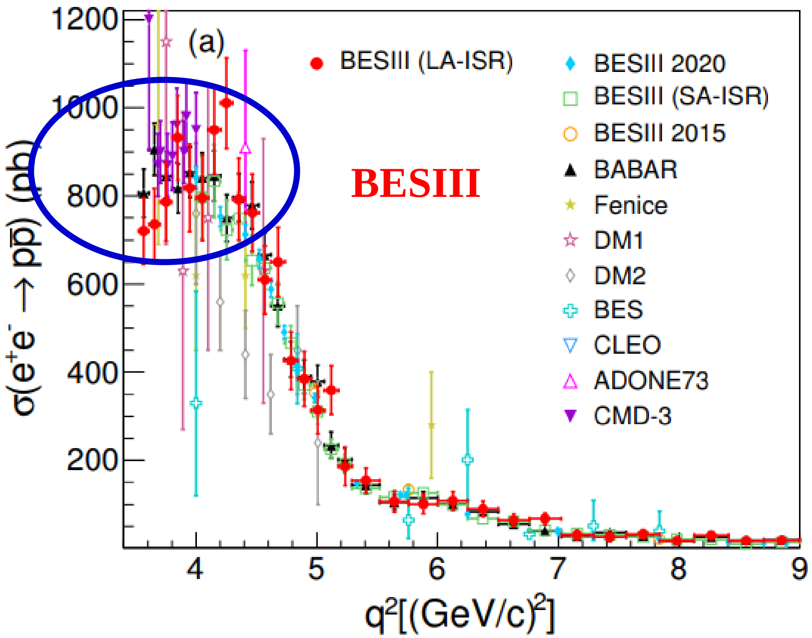


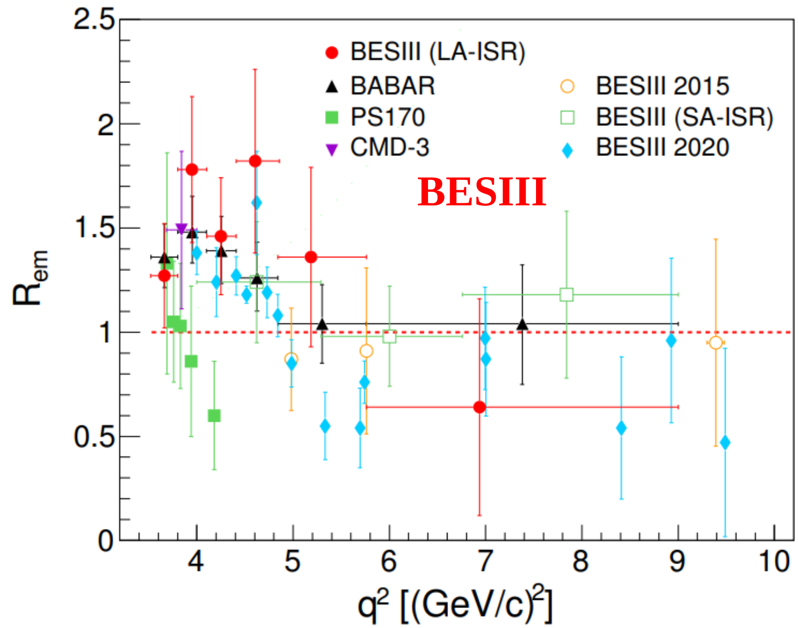


Proton Form Factors at BESIII

SA-ISR: PRD 99, 092002 (2019)
LA-ISR: PLB 817, 136328 (2019)

- **ISR method** with detected photon and undetected using 7.5 fb^{-1} integrated luminosity.



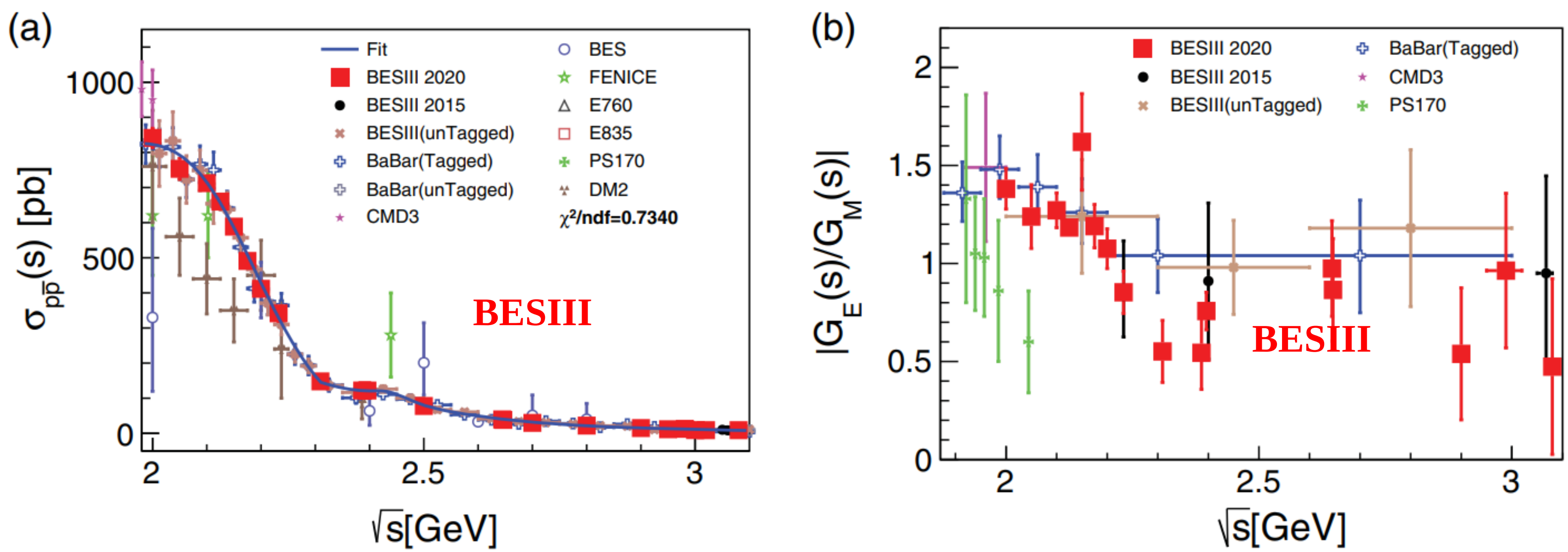


- From threshold to q^2=4.0 GeV^2, average cross section 840 pb
- Point-like cross section at threshold, $\sigma_{\mathrm{point}} = \frac{\pi\alpha^2}{3m^2\tau}\left[1+\frac{1}{2\tau}\right] = 845\ \mathrm{pb}$

Proton Form Factors at BESIII

PRL 124, 042001 (2020)
PRD 91, 112004 (2015)

- Scan technique from 2.0 to 3.08 GeV, using 688.5 pb^{-1} integrated luminosity.
- $|G_E/G_M|$, $|G_M|$ are determined with **high accuracy**, comparable to data in SL.
- $|G_E|$ is measured for the first time.

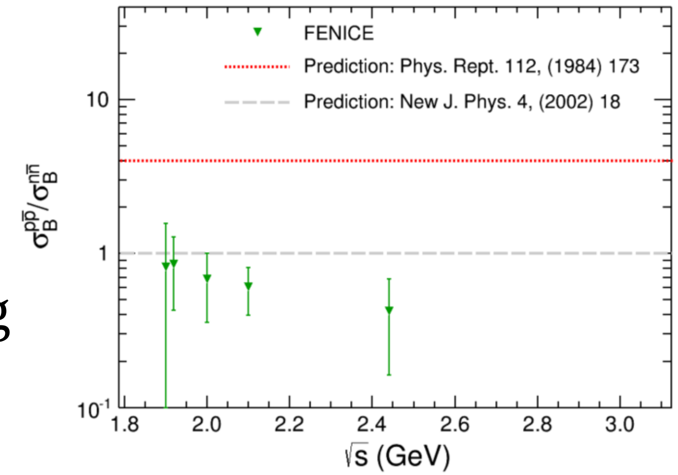


Neutron Form Factors

- Measurements on Neutron FFs are rare. Data from the FENICE indicates

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

A. Antonelli et al., Nucl. Phys. B 517, 3 (1998)

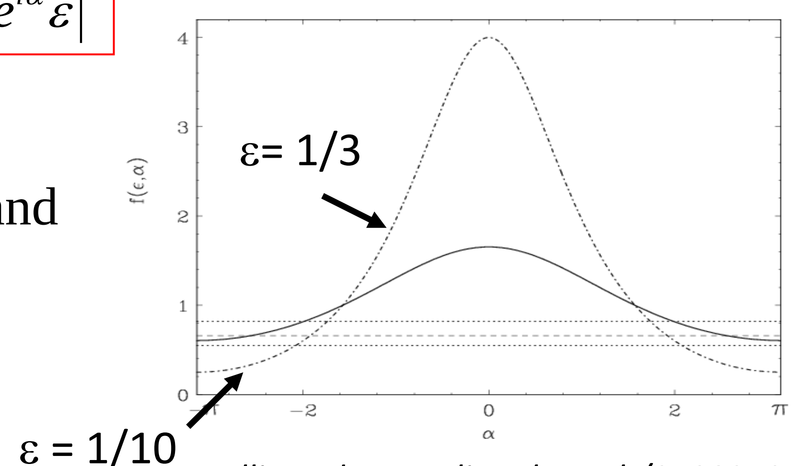


- An intermediate coherent isovector state serving as an intermediary between e^+e^- and $N\bar{N}$

$$\boxed{f = \frac{\sigma(e^+e^- \to p\overline{p})}{\sigma(e^+e^- \to n\overline{n})} = \left|\frac{A_1 + e^{i\alpha}A_0}{A_1 - e^{i\alpha}A_0}\right|^2 = \left|\frac{1+e^{i\alpha}\varepsilon}{1-e^{i\alpha}\varepsilon}\right|^2}$$

A_1 and A_0 are I = 1 and 0 amplitudes, and dominated by single states ρ, ω, ϕ

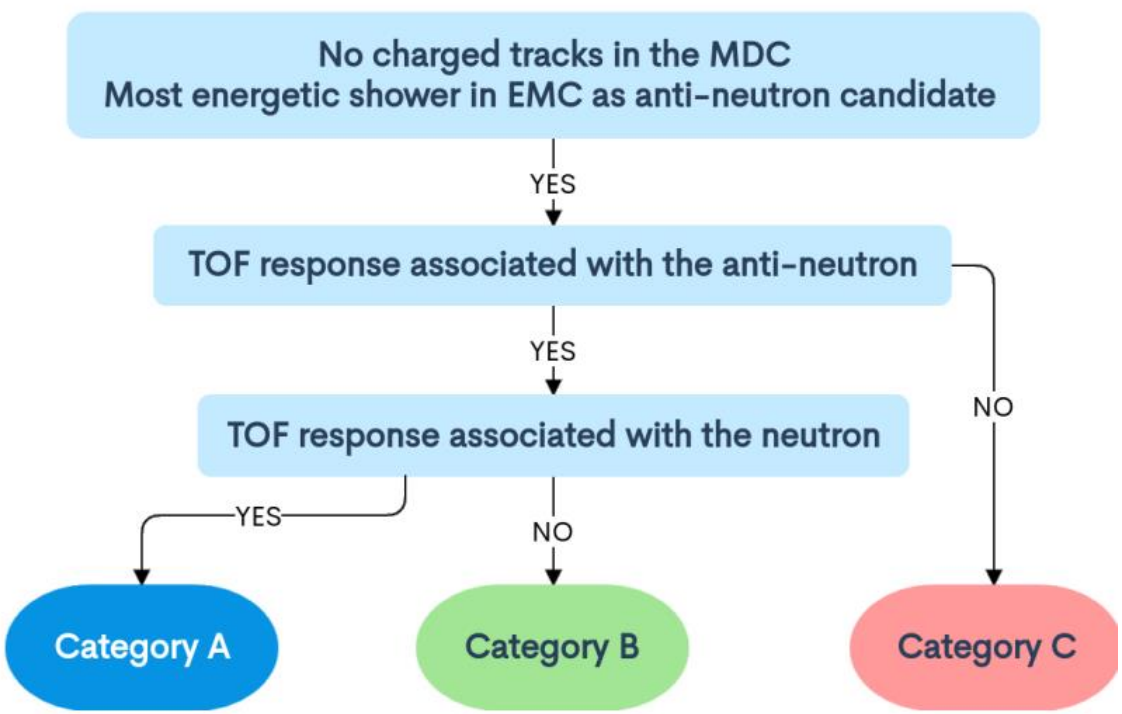
$\varepsilon = A_0/A_1$



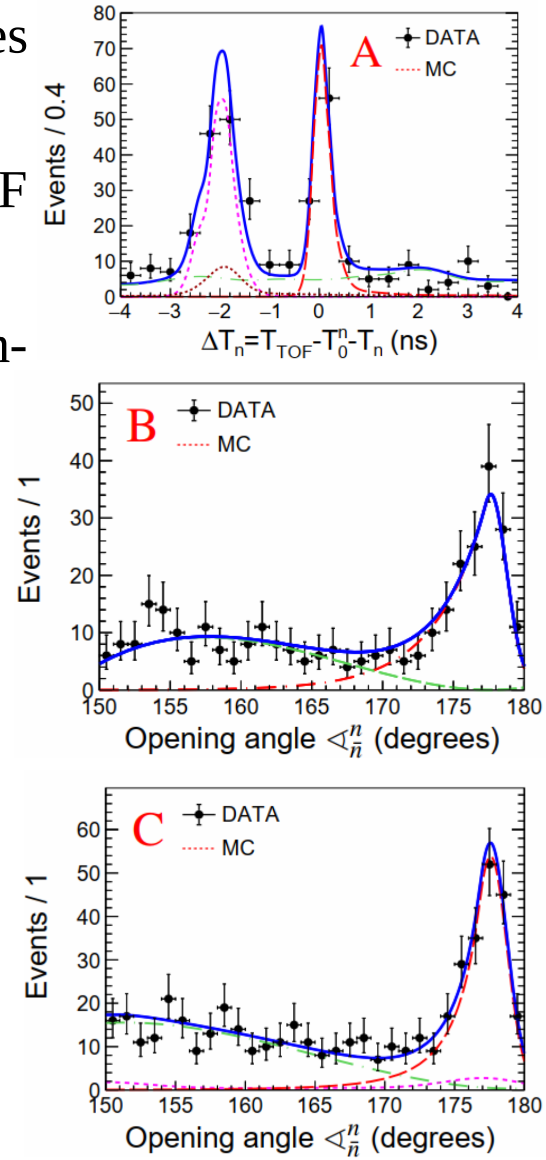
J. Ellis and M. Karliner hep-ph/0108259

Neutron Form Factors at BESIII

- **High luminosity** 18 data sets at center-of-mass energies between 2.0 and 3.08 GeV, 647.9 pb^{-1}
- **Pure neutral** channel $e^+e^- \to n\bar{n}$, only EMC and/or TOF information
- Sophisticated **background suppression**: $e^+e^- \to \gamma\gamma$, beam-associated

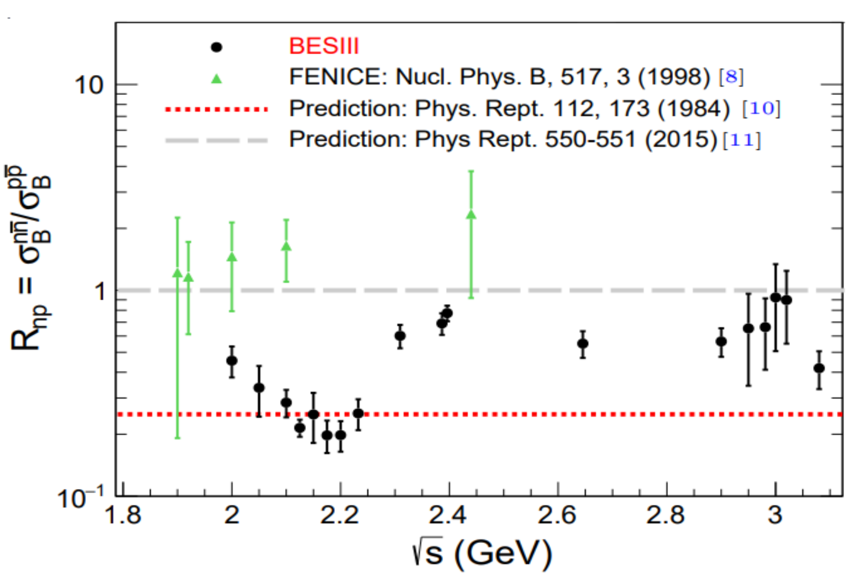


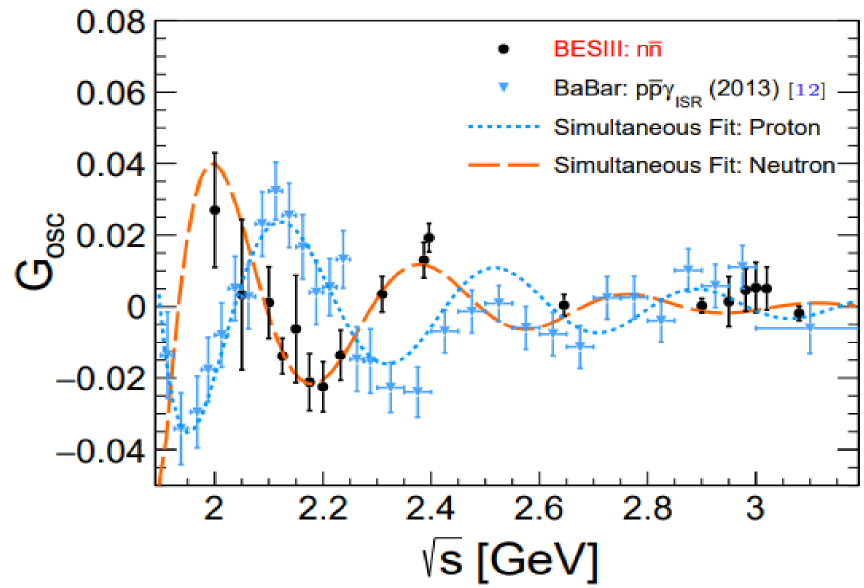
Nat. Phys. 17, 1200–1204 (2021)



Neutron Form Factors at BESIII

- Clarify the "puzzle" that photon-neutron coupling larger than photon-proton coupling existing over 20 years.
- Oscillation of FF observed in neutron data, with same frequency, but orthogonal phase





Results from three Methods

- Born cross section and effective form factor

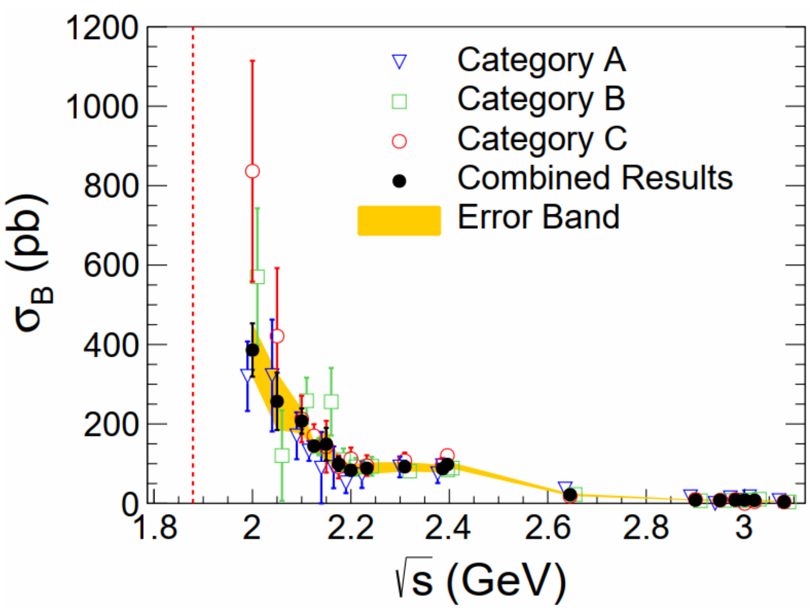
$$\sigma_B^i = \frac{\mathcal{N}_i^s}{\mathcal{L}_{\rm int}\varepsilon_i(1+\delta)}, \qquad |G^i| = \sqrt{\frac{\sigma_B^i}{\frac{4\pi\alpha_{em}^2\beta}{3q^2}\left(1+\frac{1}{2\tau}\right)}}$$

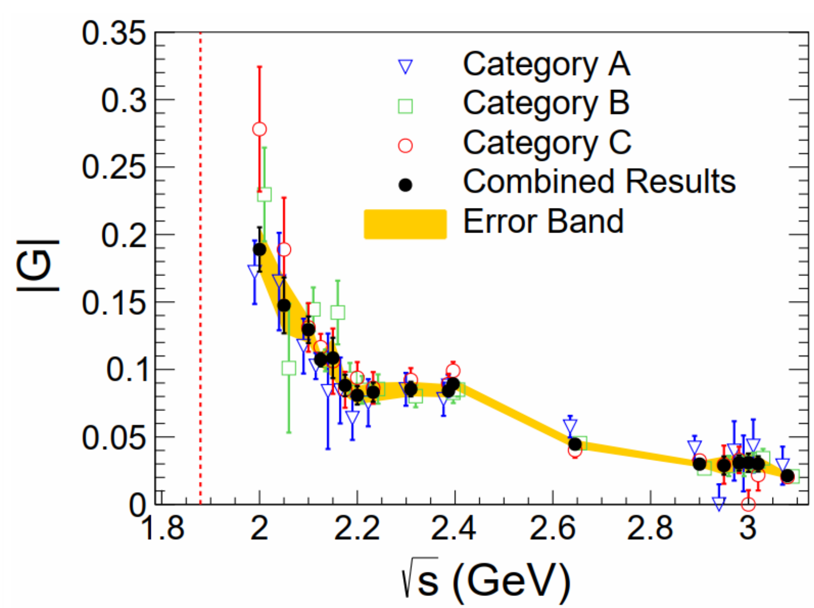
- Consistent results from three methods

Unc.

Cor. Matrix

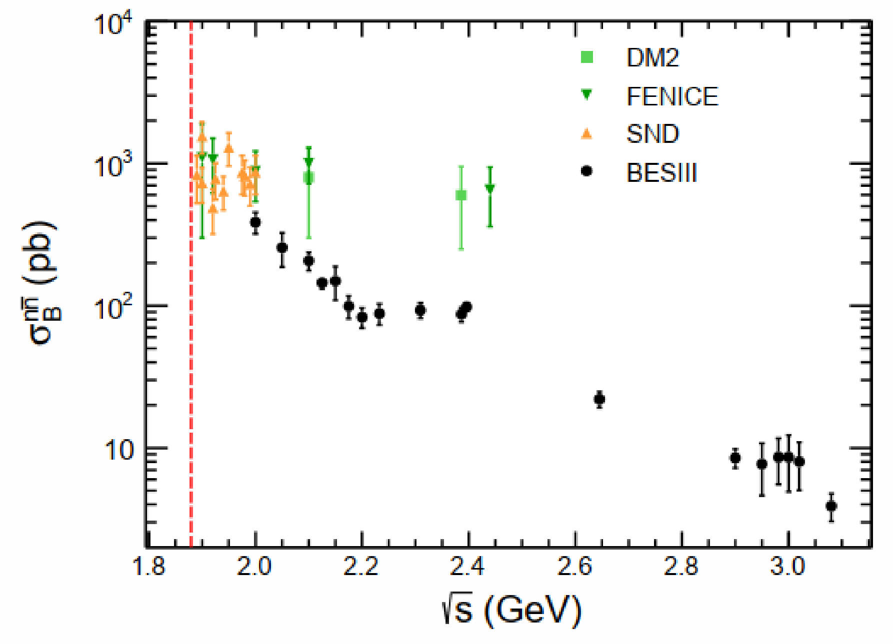
$$\sigma_B = \sum_i w_i \sigma_B^i, \qquad \Delta\sigma_B = \sqrt{\frac{1}{\sum_i \sum_j W_{i,j}}}, \qquad w_i = \frac{\sum_j W_{i,j}}{\sum_i \sum_j W_{i,j}}, \qquad W = [\boldsymbol{\Delta\sigma^T \rho \Delta\sigma}]^{-1}$$

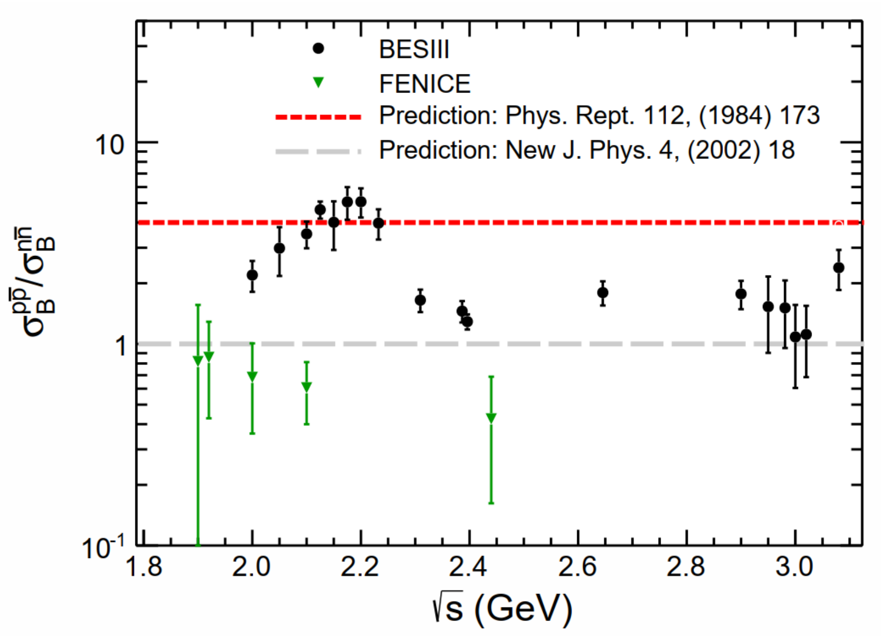




Combined Results

- $\Delta\sigma_{\mathrm{B}}^{min}$~8% @ 2.396 GeV， total No. of signal~2300
- Deviated from FENICE results by 2σ
- Using proton pair production as input => $\boldsymbol{\sigma_B^{p\bar{p}}/\sigma_B^{n\bar{n}} \in (1,4)}$



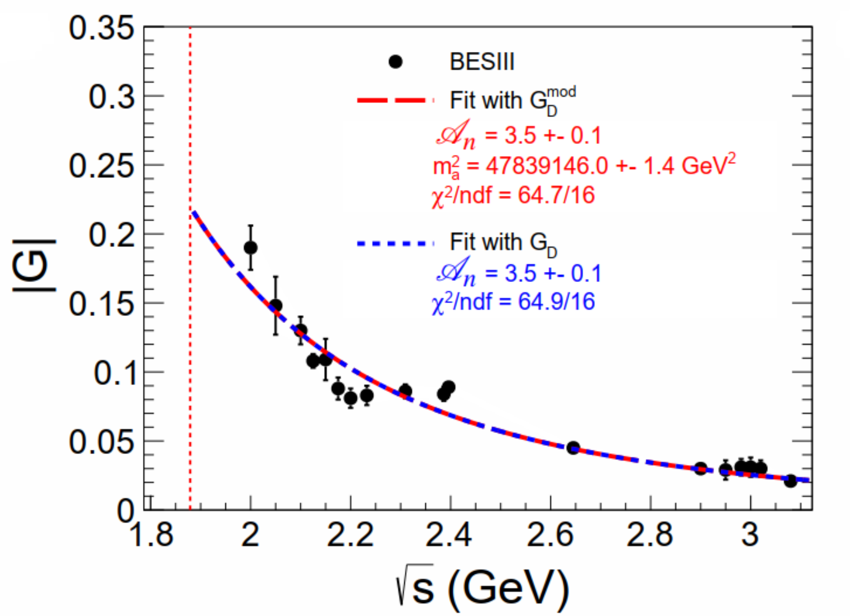


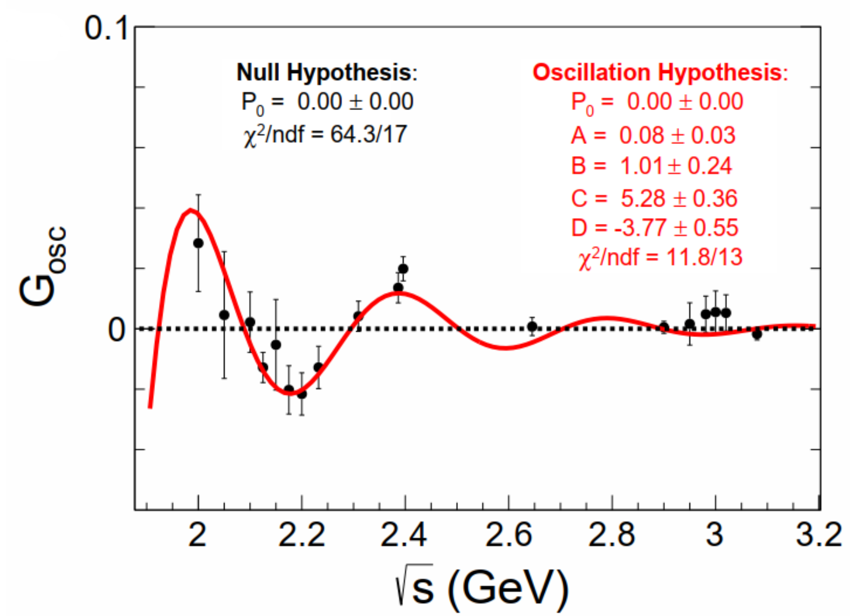
Oscillation in reduced-G_{eff}

- Babar observed the oscillation in proton G_{eff}
- Similar oscillation structure in neutron G_{eff} after subtracting the dipole structure

$$G_{osc}(q^2) = |G_n| - G_{D^*}, \qquad G_{D^*} = G_D \cdot \frac{1}{1+\frac{q^2}{m_a^2}}, \qquad G_D = \frac{\mathscr{A}_n}{\left(1-\frac{q^2}{0.71(\mathrm{GeV}^2)}\right)^2},$$

$$F_{osc}^{n,p} = A^{n,p} \cdot \exp\left(-B^{n,p} \cdot p\right) \cdot \cos\left(C \cdot p + D^{n,p}\right), \qquad p \equiv \sqrt{E^2 - m_{n,p}^2}, \qquad E \equiv \frac{q^2}{2m_{n,p}} - m_{n,p}$$

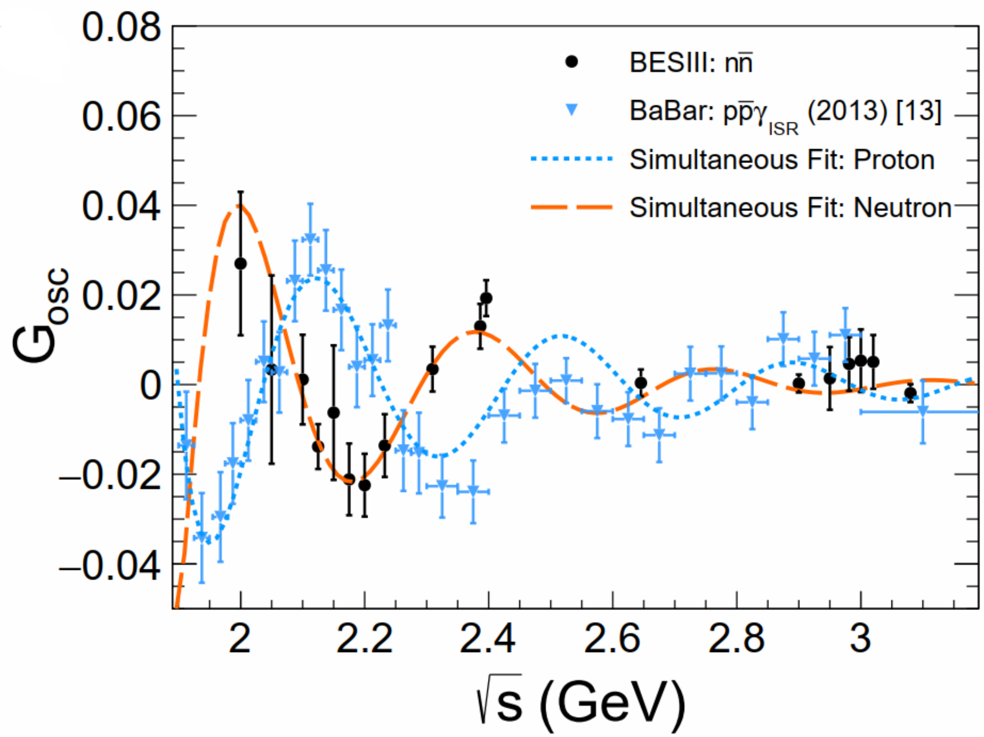




Oscillation in reduced-G_{eff}

- Simultaneously fit the oscillation structure for proton and neutron (share frequency C)

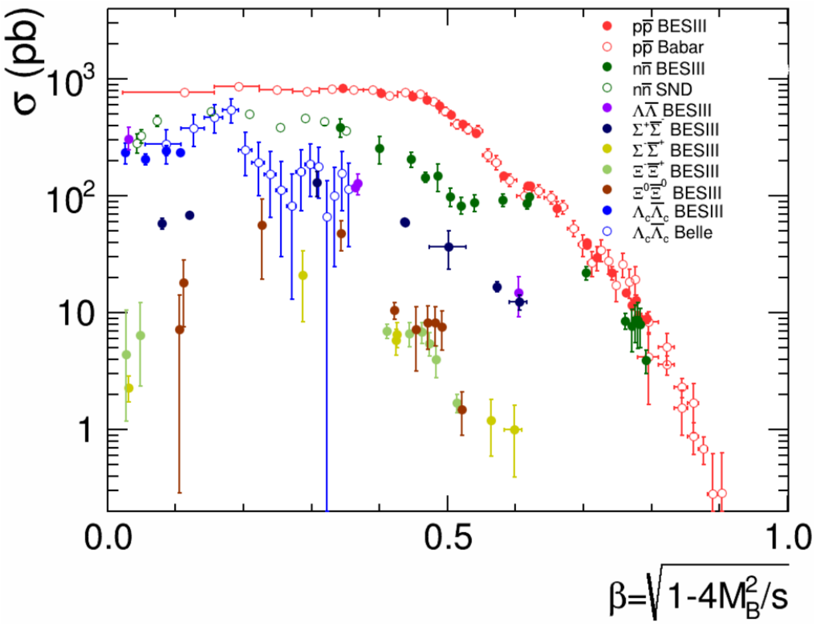
$$F_{osc}^{n,p} = A^{n,p} \cdot \exp\left(-B^{n,p} \cdot p\right) \cdot \cos\left(C \cdot p + D^{n,p}\right), \qquad p \equiv \sqrt{E^2 - m_{n,p}^2}, \qquad E \equiv \frac{q^2}{2m_{n,p}} - m_{n,p}$$

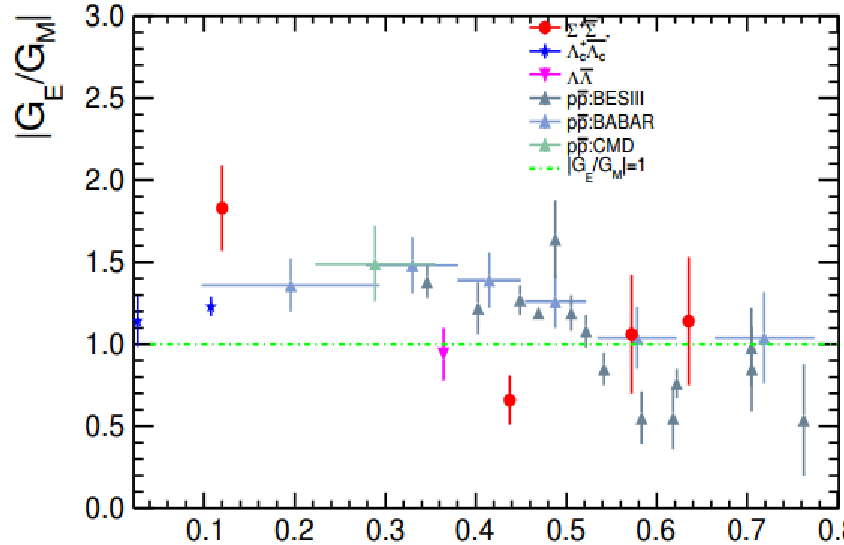


$$C = (5.55 \pm 0.28)\ \mathrm{GeV}^{-1}$$

$$\Delta D = \left|D_p - D_n\right| = (125 \pm 12)^\circ$$

Baryon EMFFs





G.S.Huang, R.B. Ferroli,
Natl.Sci.Rev. 8 (2021) 11, nwab187

- Abnormal threshold effects observed in various baryon pair production: $p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Lambda_c^+\bar{\Lambda}_c^-$ …
- Oscillation structures observed in $p\bar{p}$, $n\bar{n}$
- $|G_E/G_M|$ ratio significantly larger than 1 at low beta for p, Λ_c^+, Σ^+, indicating large D-wave near threshold
- Relative phase angle of form factor $\Delta\phi(\sin\Delta\phi)$ measured for Λ, Λ_c^+

Summary

- The neutron pair productions measured at BESIII with improved precision.
- Interesting effects observed in the reduced effective form factors of nucleon.
- More theoretical discussions are desirable.

Thank you!