Study of Baryon form factors at BESIII

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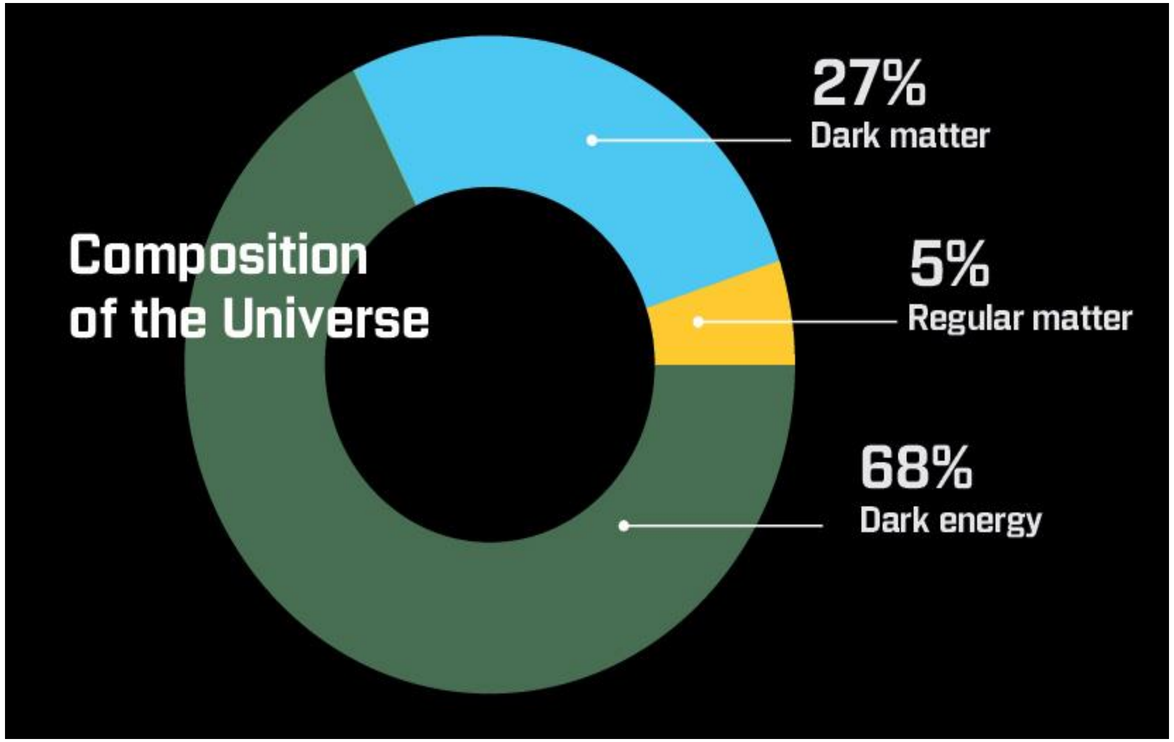
Outline

- Introduction
- Baryon Form factors
  - Nucleon form factors
  - Hyperon form factors
- Summary and prospect

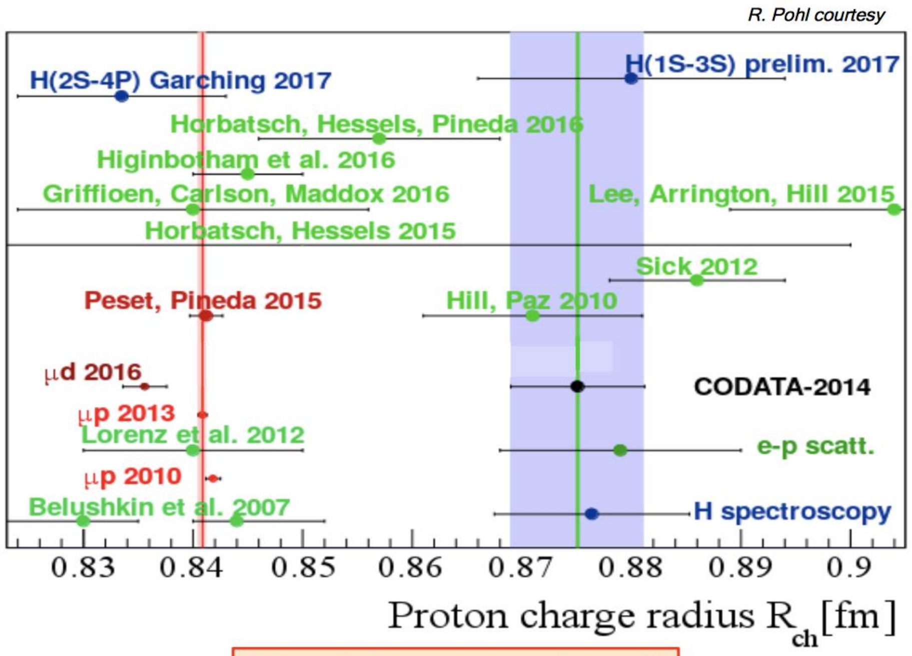
Composition of the Universe



NASA

- Nucleon is the dominant component of visible universe (>99%)

Proton Radius Confusion



Need for more data !!

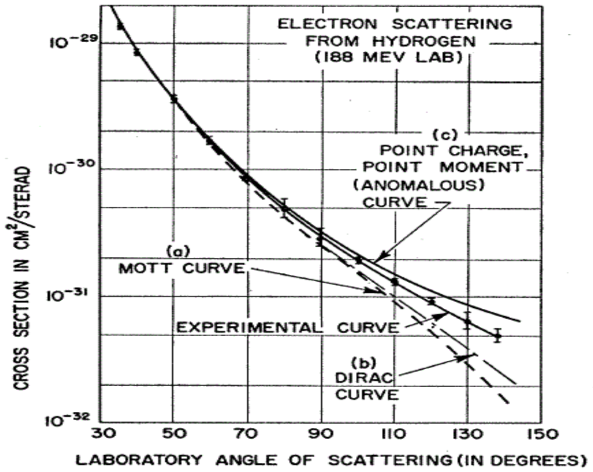
- Probe nucleon charge radius:

$G_E(Q^2) = 1 - \frac{1}{6} r_E^2 Q^2 + \cdots$ （Q：four momentum transfer）

Nucleon Electromagnetic Form Factor (NEFF)

- Elastic scattering of electron and proton (Hofstadter, Nobel Prize 1961)
  - Theoretically, differential cross section is:

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}=\left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left(1+2\tau\tan^2\frac{\theta}{2}\right)F(q^2)$$



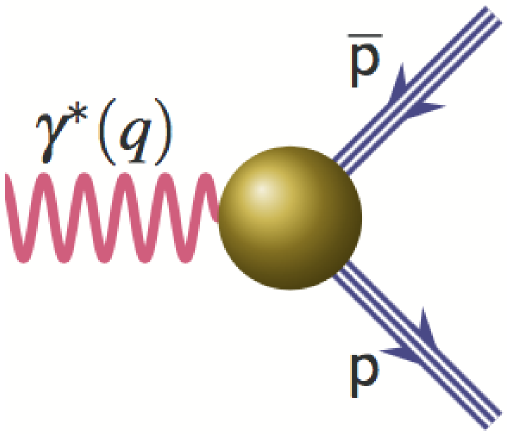
- The nucleon electromagnetic vertex Γ_μ describing the hadron current:

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

- Sachs FFs:

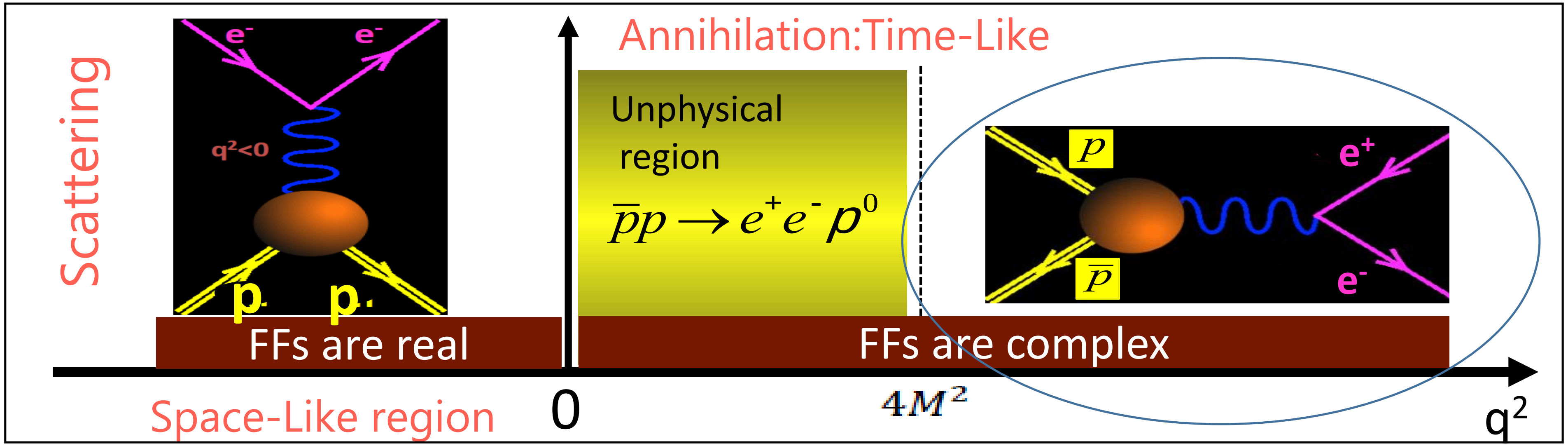
Electric FF: $G_E(q^2)=F_1(q^2)+\tau\kappa_p F_2(q^2)$

Magnetic FF: $G_M(q^2)=F_1(q^2)+\kappa_p F_2(q^2)$



$$\tau=\frac{q^2}{4m^2},\qquad \kappa=\frac{g-2}{2},\qquad g=\frac{\mu}{J}$$

Playground of EMFFs



- **In SL**, FFs are real.
  - Encode information about charge distribution of the nucleon
- **In TL**, FFs are complex, $|G_E/G_M|$ and $\Delta\Phi$.
  - Can be related to the time evolution of the EM charges within the nucleon
- BESIII has access to the FFs in TL

Measurement techniques for baryon FF

	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

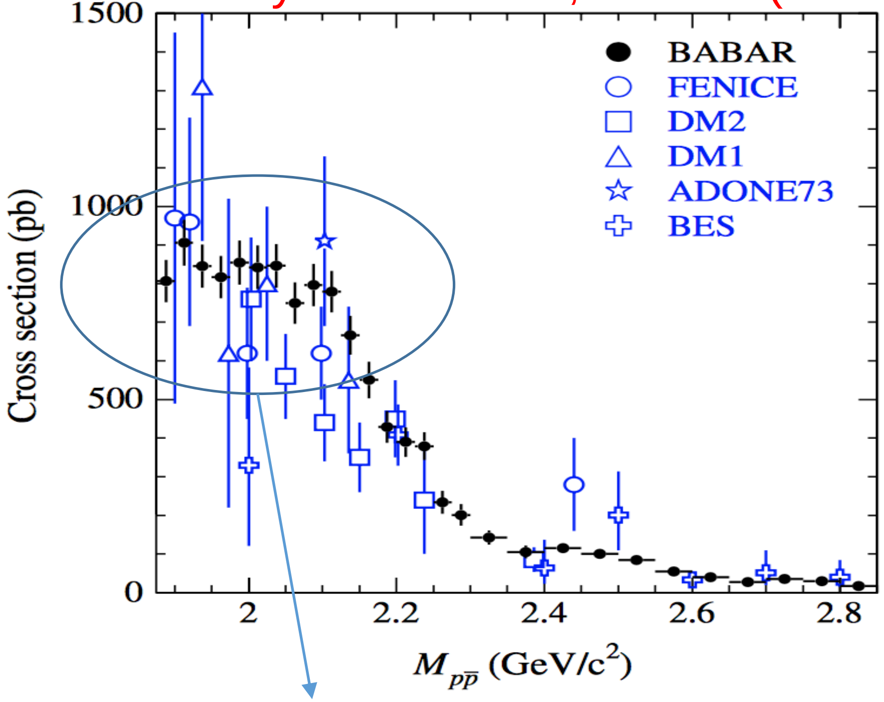
$\sim \frac{1}{400}$

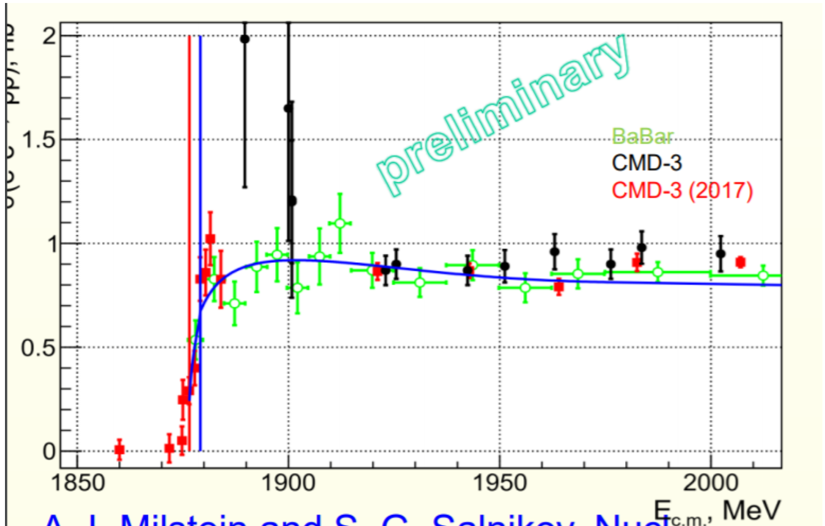
Both techniques, energy scan and initial state radiation. can be used at BESIII

Status on proton FFs

- Still mystery on proton cross section line-shape

Phys. Rew. D 87, 092005 (2013)





A. I. Milstein and S. G. Salnikov, Nucl. Phys. A 977 , 60 (2018)

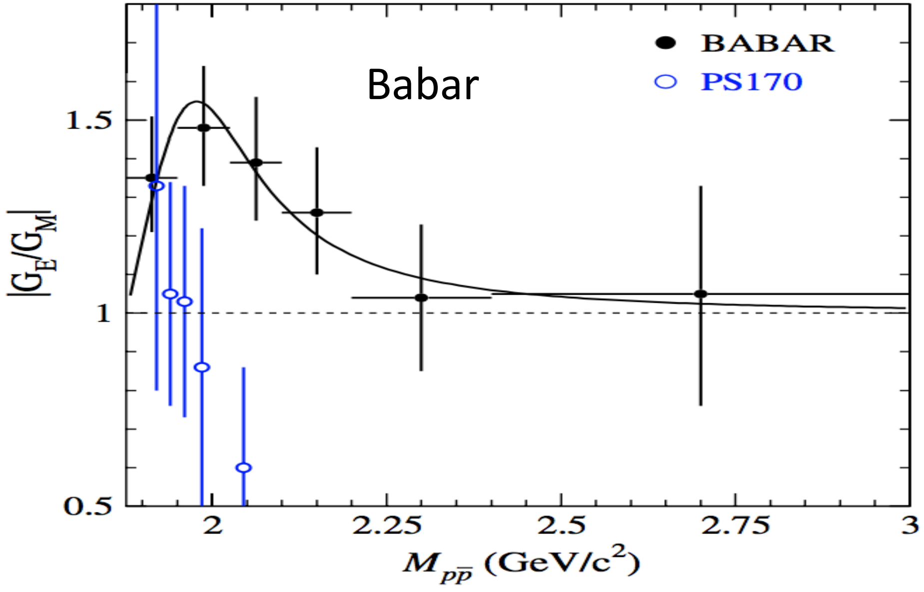
- Point-like cross section near threshold,
- $\sigma_{\text{point}} = \frac{\pi\alpha^2}{3m^2\tau}[1 + \frac{1}{2\tau}]$

- The e+e- → ppbar cross section shows an exponential growth in 1 MeV interval above threshold.

Status on proton FFs

- Inconsistence on $|G_E/G_M|$ of proton & poor precision

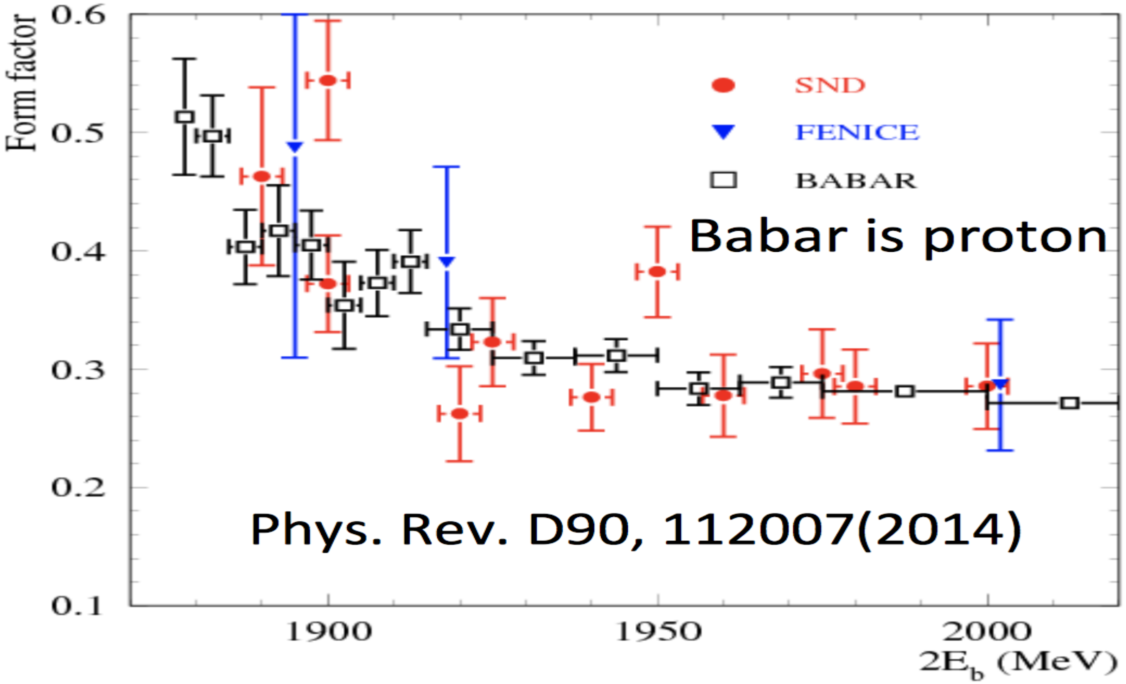
Phys. Rew. D 87, 092005 (2013)



- pQCD predictes a continuous transition and SL-TL equality at high Q^2
- SL best accuracy in $Q^2(0.5, 8.5)$ GeV^2: 1.7%
- TL accuracy before BESIII: exceeding 20%

Status on neutron FFs

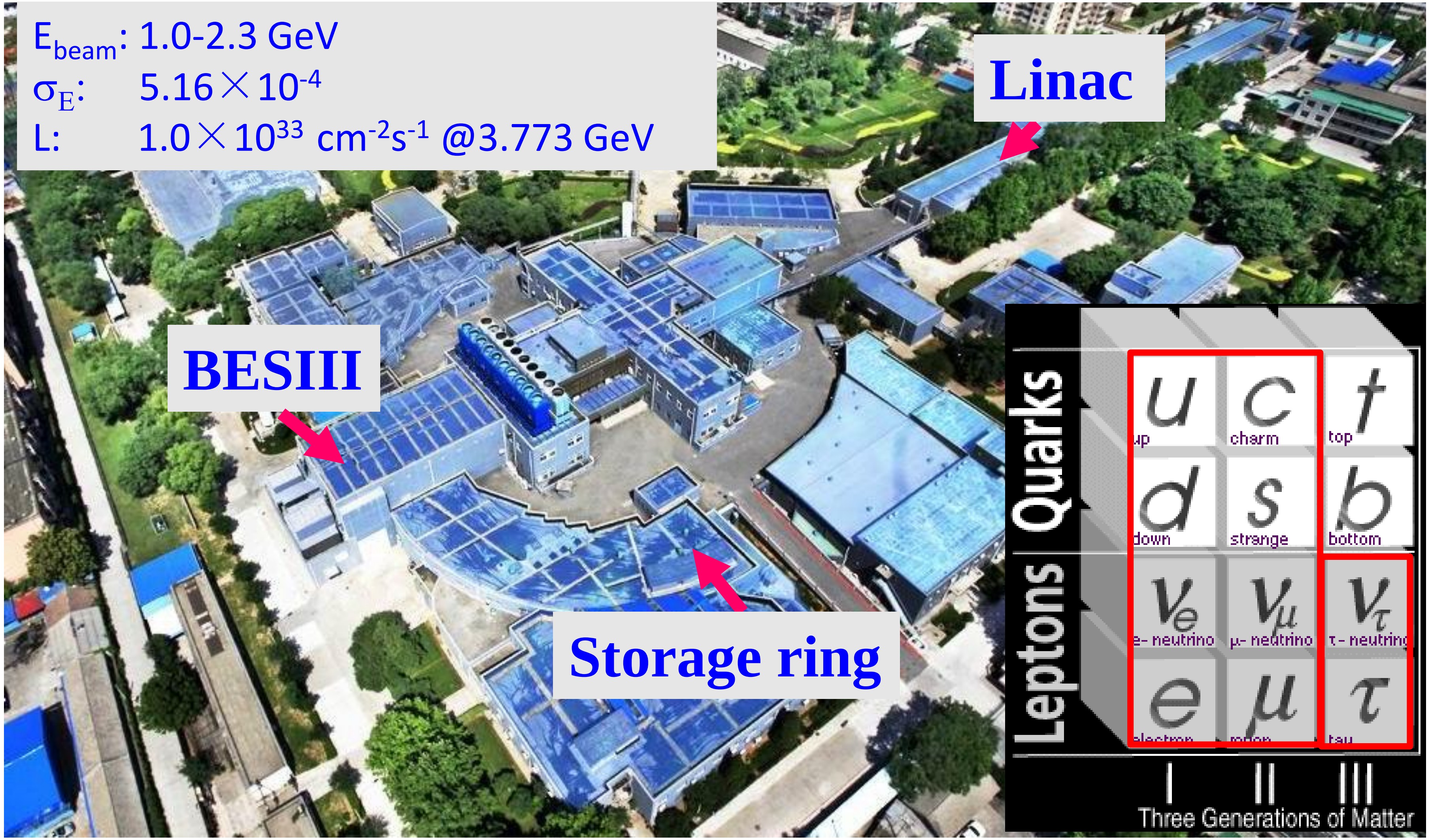
- Poor precision, limited q^2 range in neutron FF



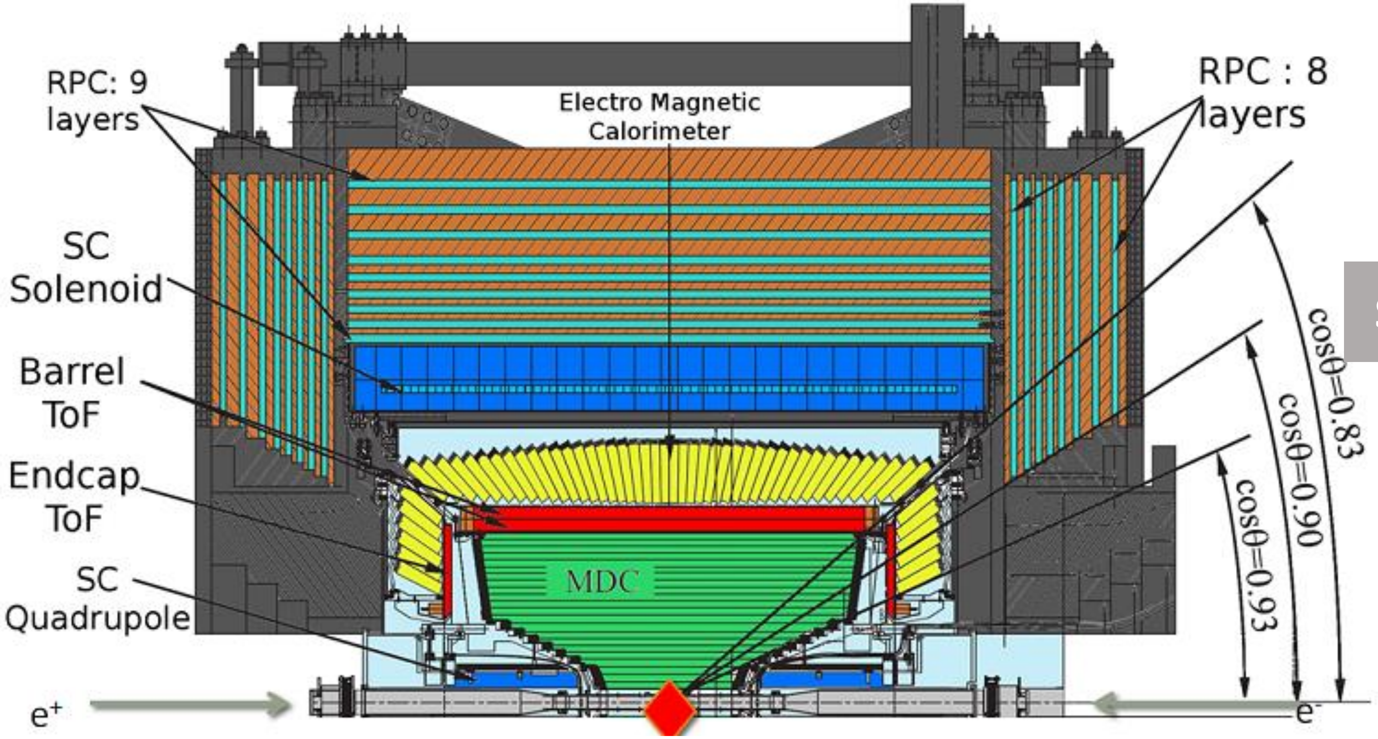
- pQCD prediction[1]: $|\frac{G_M^n}{G_M^p}|^2 \approx (\frac{q_d}{q_u})^2 = 0.25$
- VMD prediction[2]: $|\frac{G_M^n}{G_M^p}|^2 \approx 1$

[1] V. L. Chernyak and I. R. Zhitnitsky, Nucl. Phys. B 246 (1984) 52.
[2] J. G. Körner and m. Kuroda, Phys. Rev. D 16 (1988) 2165.

Beijing Electron Positron Collider (BEPCII)



BESIII detector



SC Magnet 1.0T

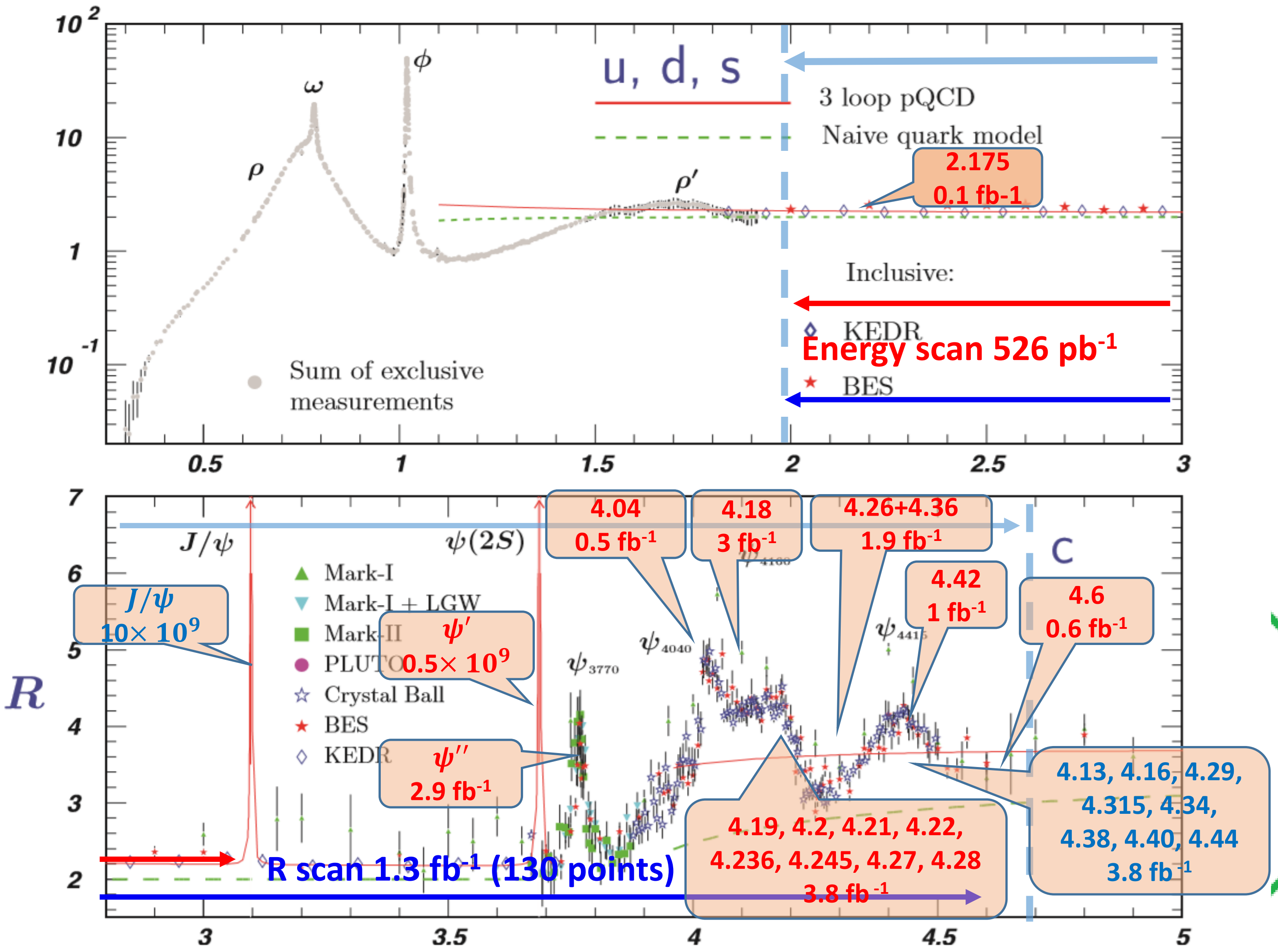
Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm, dE/dx~6%
σ_p/p = 0.5% at 1 GeV

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

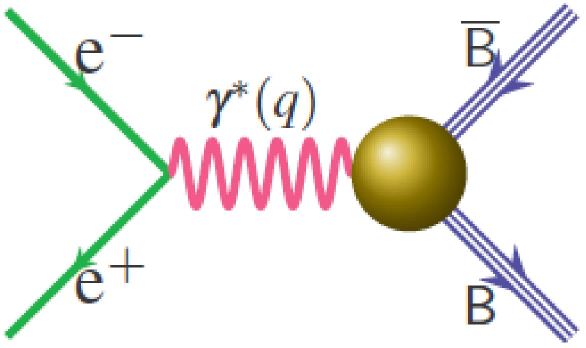
Electromagnetic Calorimeter
CsI(Tl): L=28 cm ($15X_0$)
Energy range: 0.02-2GeV
Barrel σ_E 2.5%, σ_l 6mm
Endcap σ_E 5.0%, σ_l 9mm

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

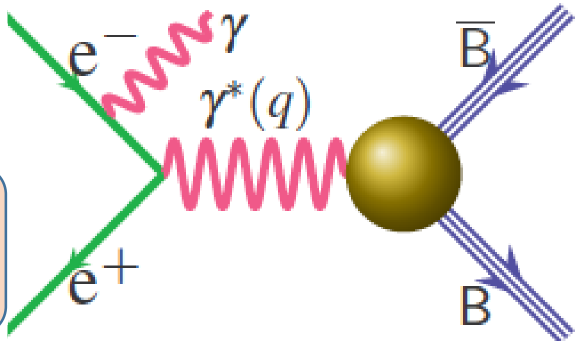
BESIII data samples



Scan technique



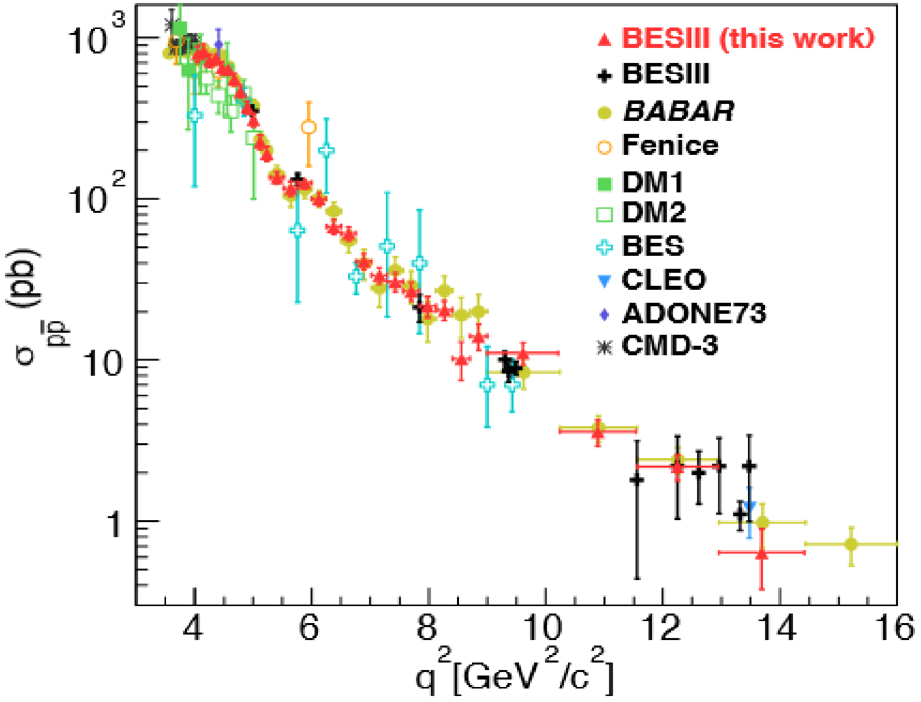
ISR technique

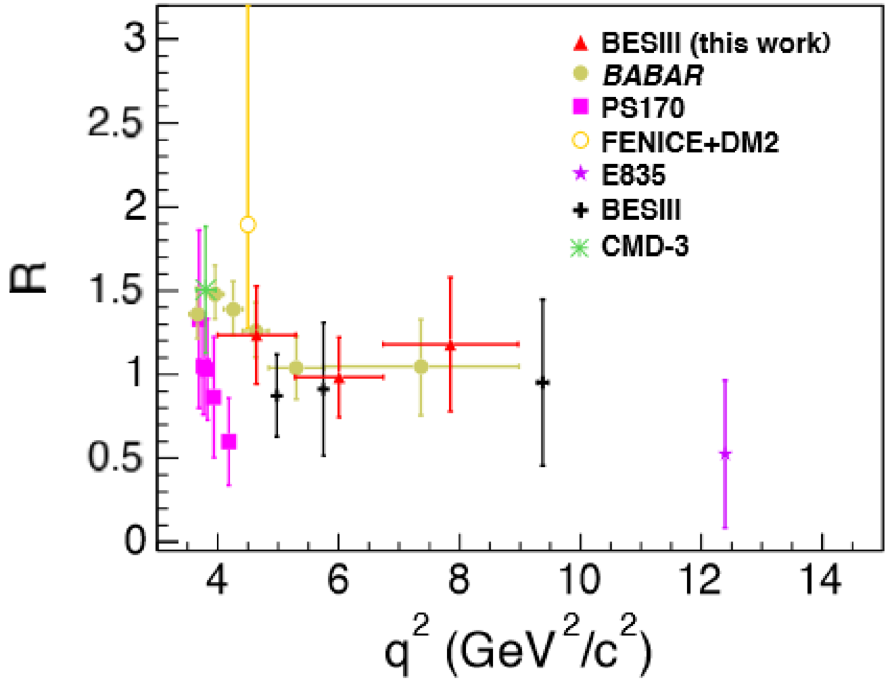


Proton FFs with ISR technique

Phys. Rev. D99, 092002 (2019)

- Combined seven data samples (7.4 fb^{-1})



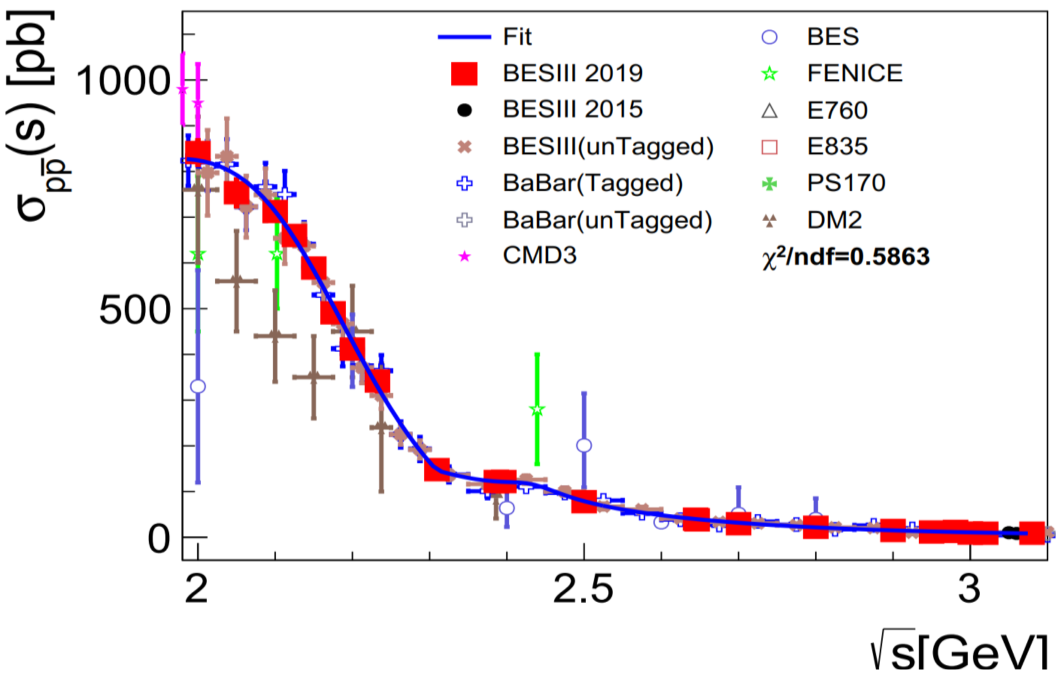


- Precision on $|G_{eff}|$: 4.1%-28.7%(untagged)
- Precision $|G_E/G_M|$ ratio: 23.0%-31.4%(untagged)
- Confirm Babar's result on $|G_E/G_M|$ above threshold

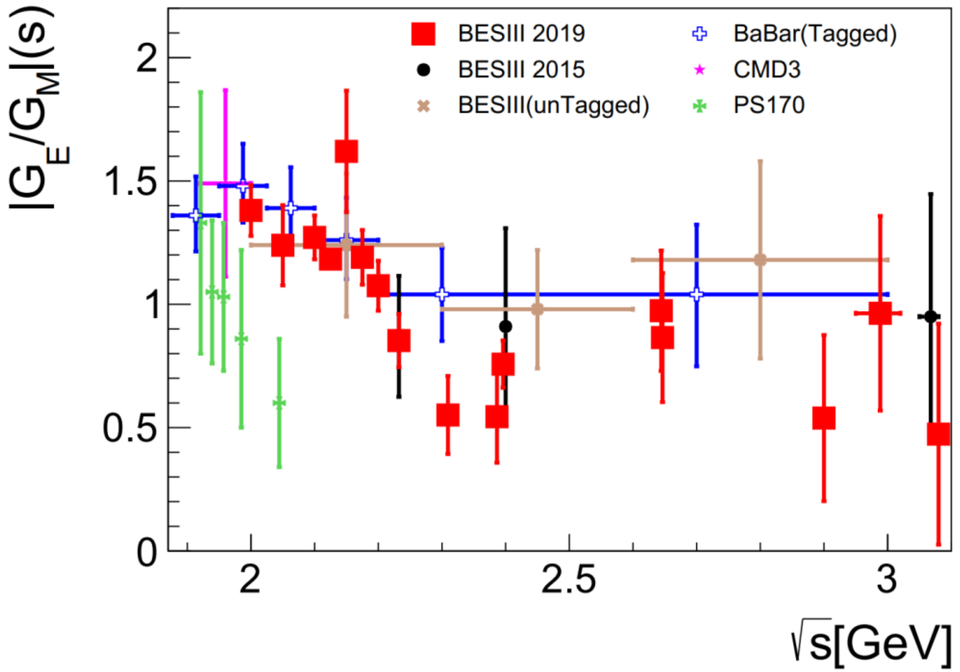
Proton FFs with scan technique

arxiv:1905.09001 (submit to PRL)

- Precise measurement of cross section $e^+e^- \to p\bar{p}$ at 22 points from 2.0 to 3.08 GeV, 688.5 pb^{-1}
- $|G_E/G_M|$, $|G_M|$ are determined with high accuracy, with uncertainty comparable to data in SL
- $|G_E|$ is measured for the first time



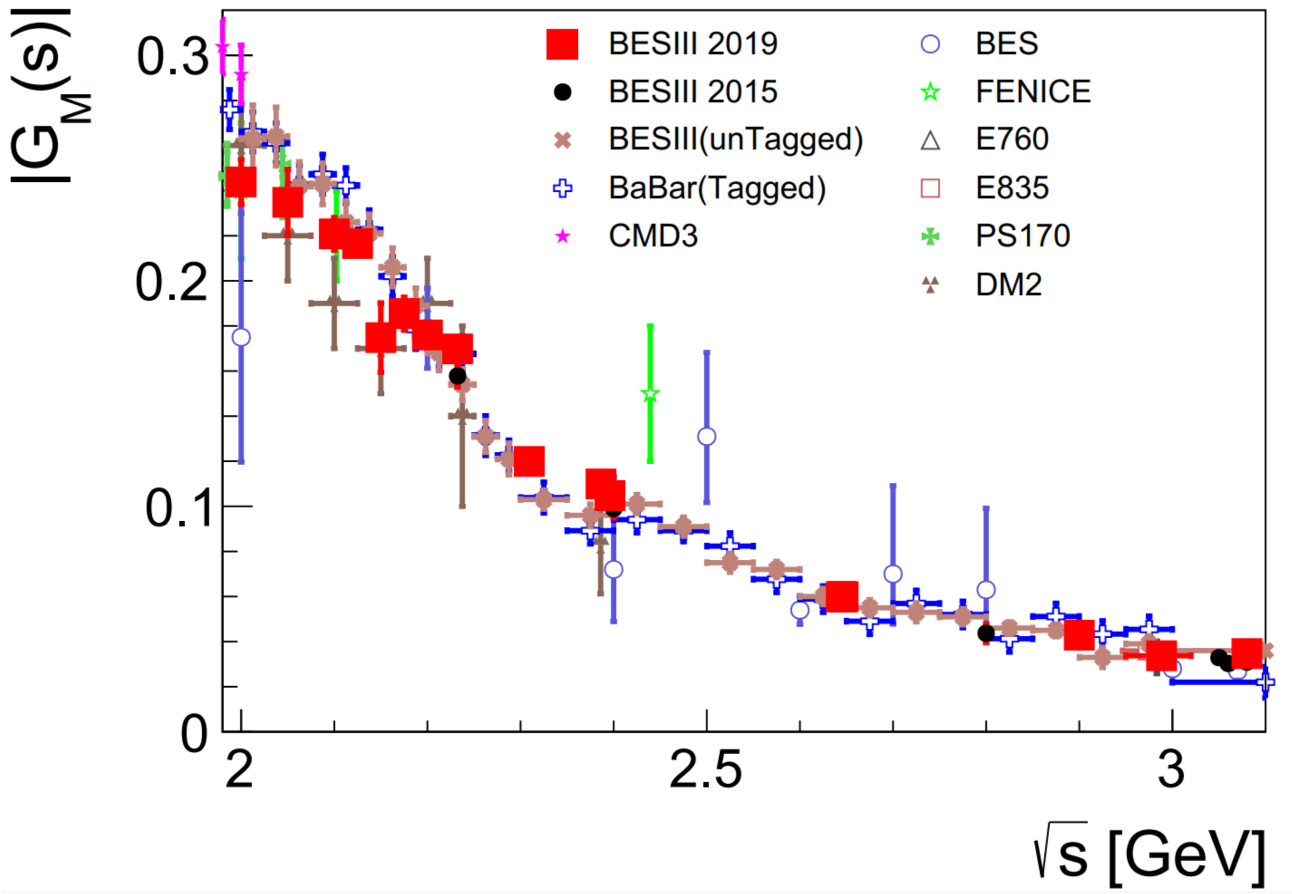
Best precision on σ: 3% (systematic dominant)



Best precision on $|G_E/G_M|$: 3.4% (statistical dominant)

Proton FFs with scan technique

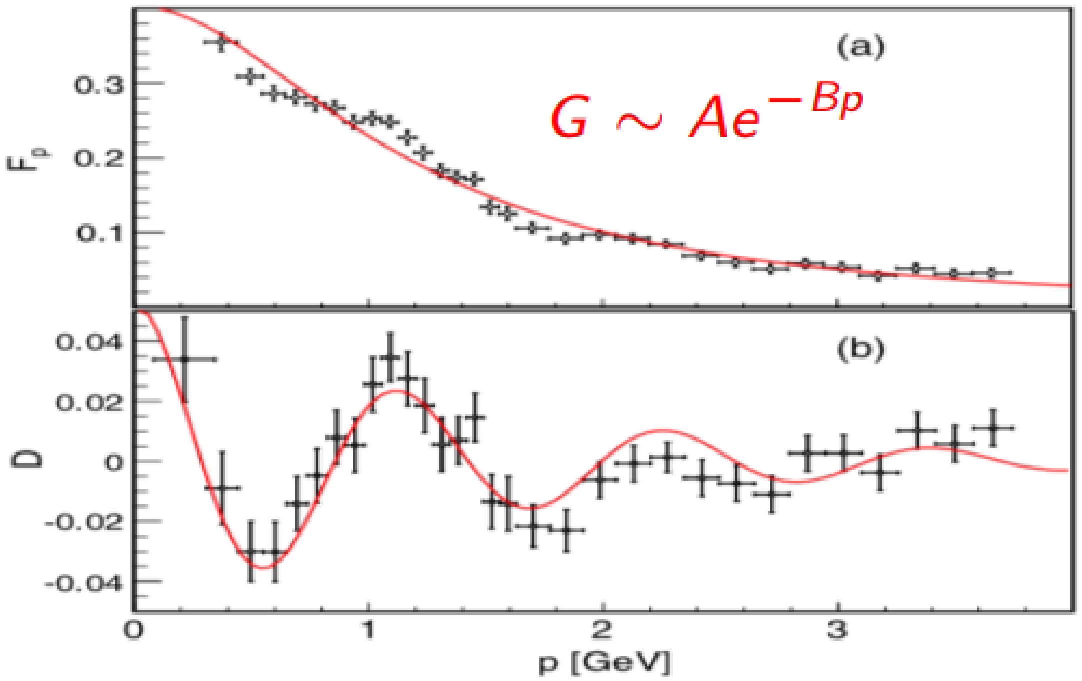
arxiv:1905.09001 (submit to PRL)

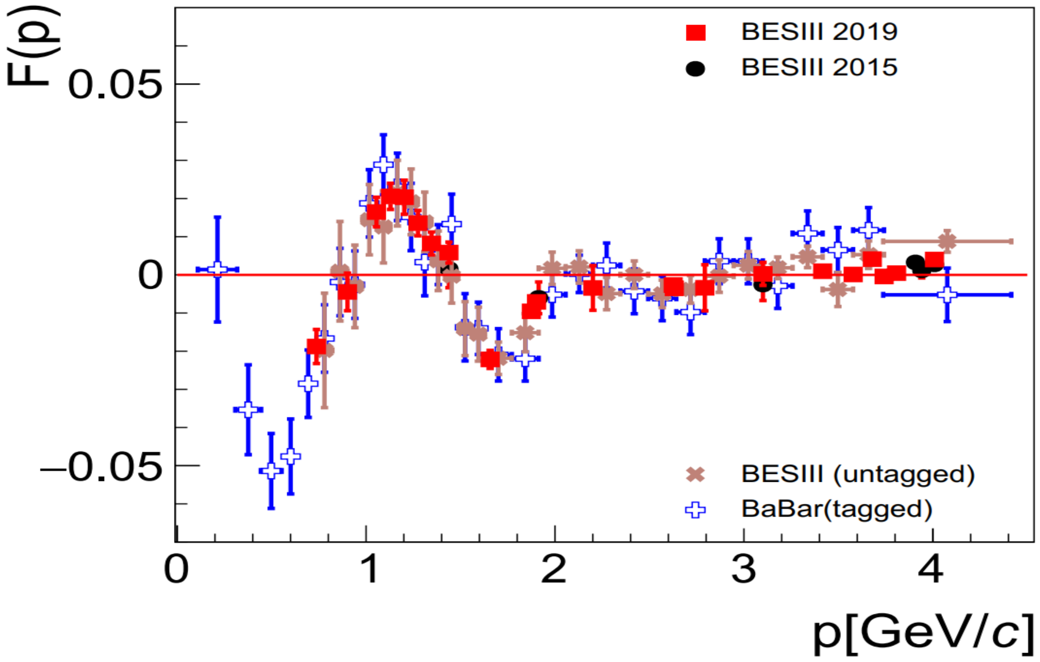


- Hypothesis on other results: $|G_E|=|G_M|$
- First line-shape of $|G_M|$ without hypothesis, achieved by BESIII scan data.

Oscillation structures ?

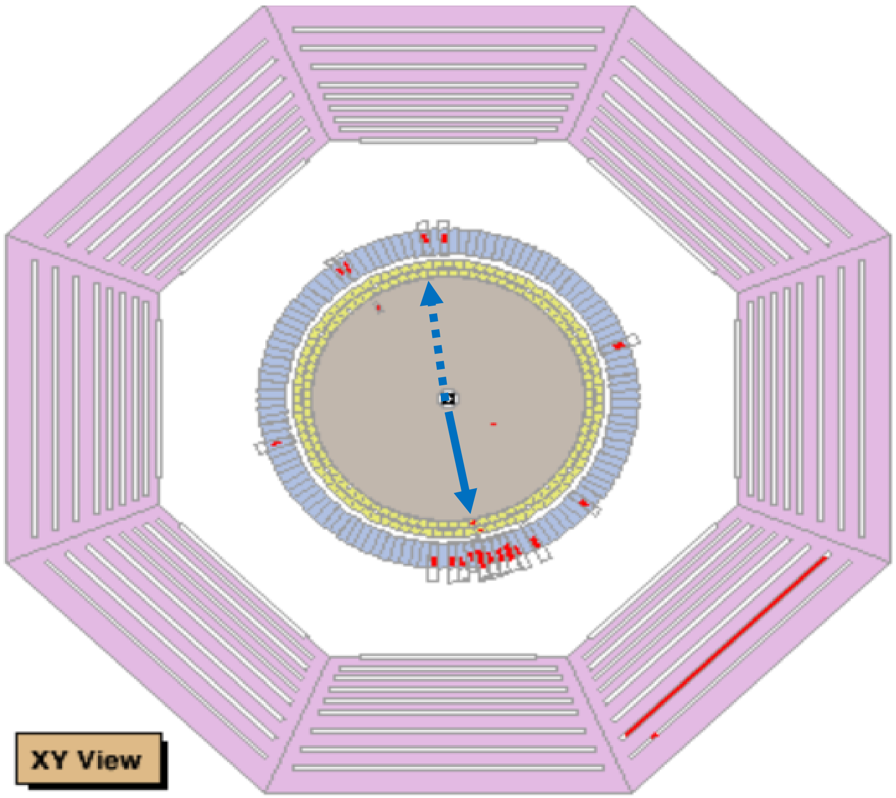
PRL. 114, 232301 (2015)



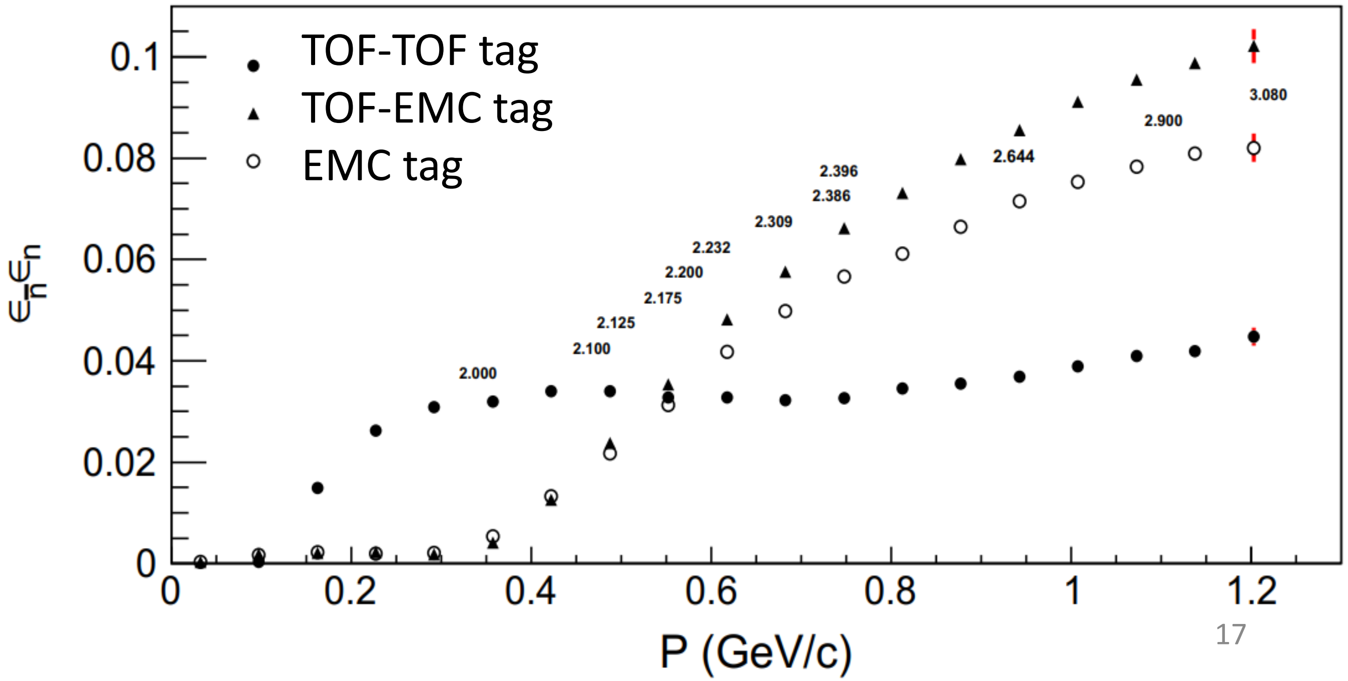


- Oscillating structures observed in the EFF minus modified dipole parameterization in Babar.
  - Rescattering process in final state
  - Independent resonant structure

Neutron form factors at BESIII

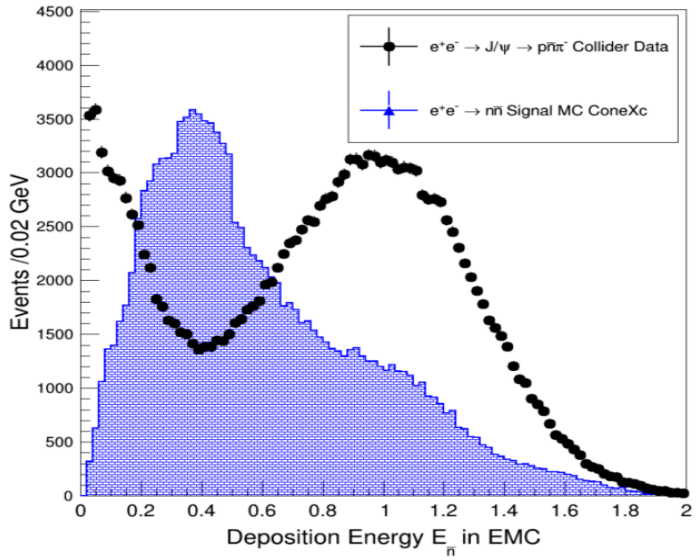


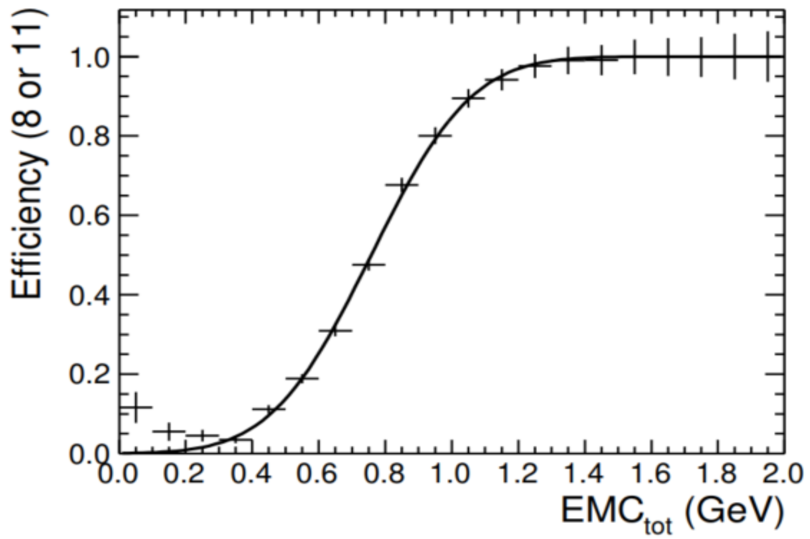
- Analysis Challenges: Reconstruction of $e^+e^- \to n\bar{n}$
  - No MDC signal
  - Low EMC efficiency,
  - No TOF reconstruction



Neutron form factors at BESIII

Analysis Challenges: Insufficient MC simulation

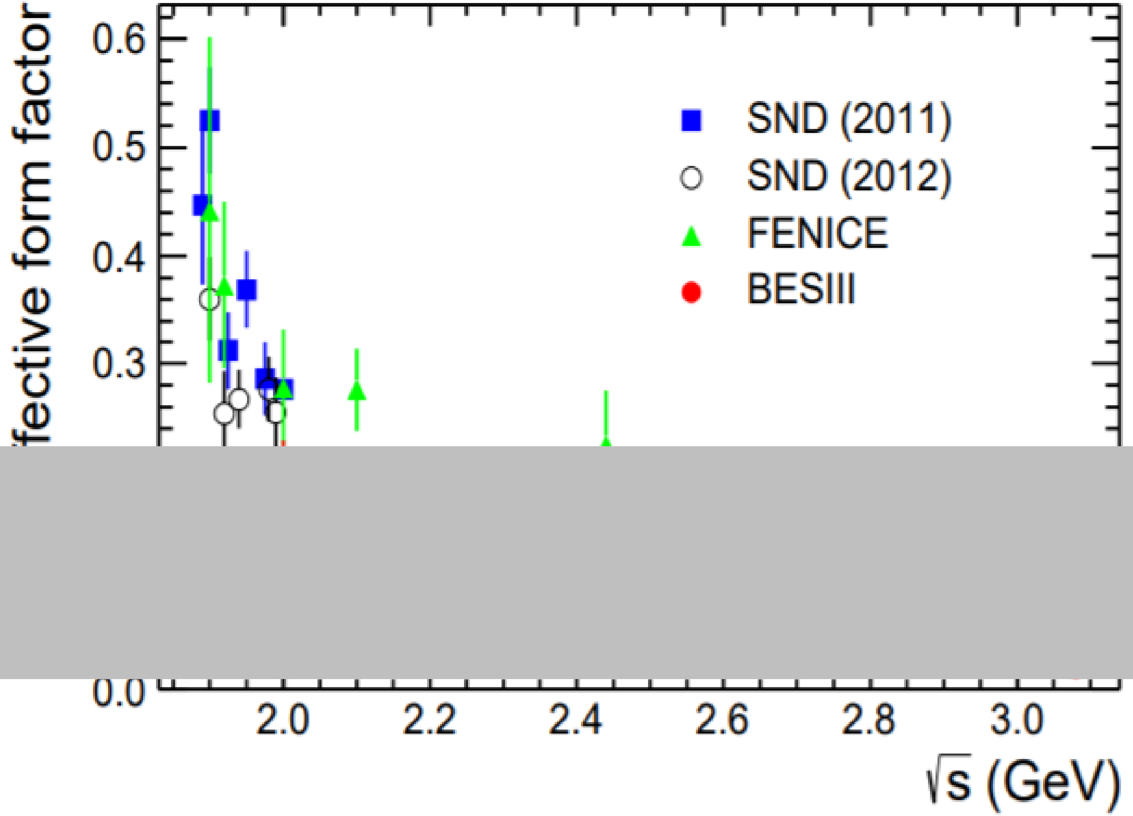




- Corrections need to be applied for MC efficiency:
  - $C_{data/MC}$: correction due to data/MC difference
  - C_{trg}: trigger efficiency correction (in dependence of total deposition energy)

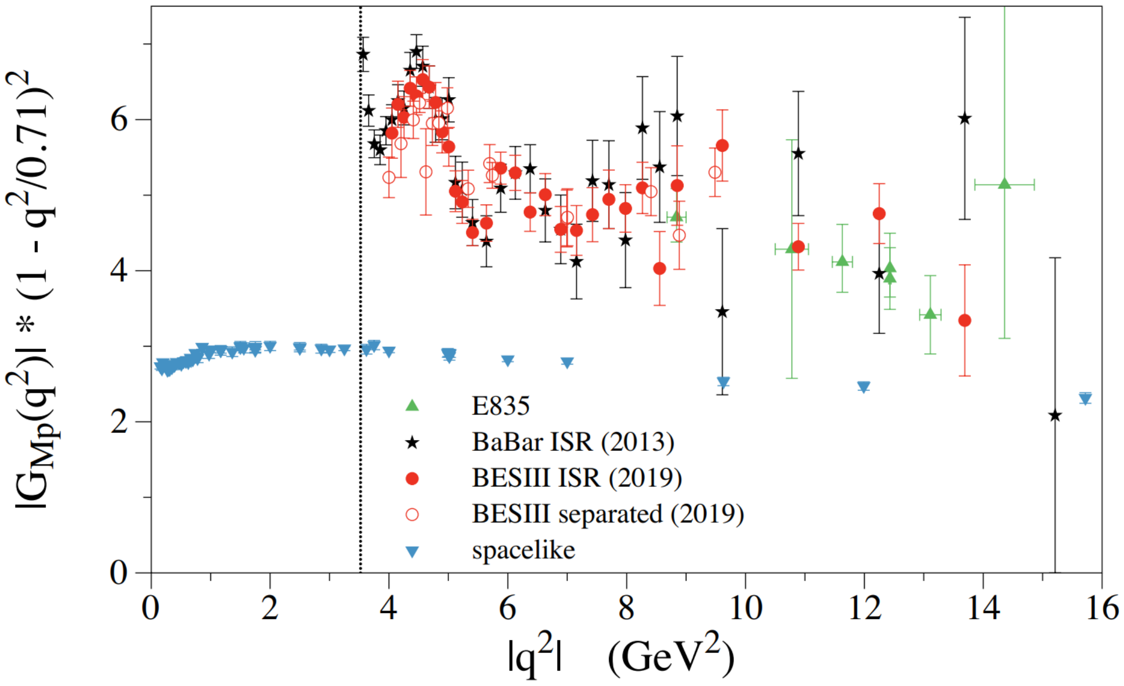
Neutron form factors at BESIII

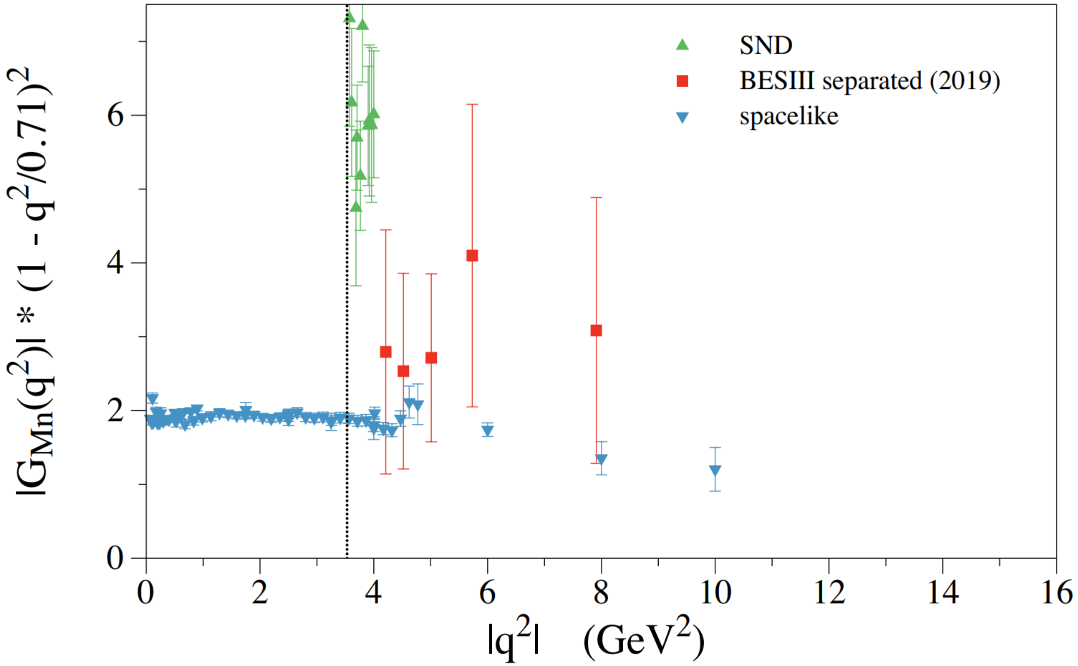
$$\sigma^{Born}_{N\bar{N}}(q^2) = \frac{N_{data}}{\mathcal{E}_{MC}\times\mathcal{E}_{cor}\times\mathcal{L}_{int}\times(1+\delta)} \qquad \mathcal{E}_{cor} = \mathcal{C}_{data/MC}\times\mathcal{C}_{trg}$$



Comparison with Space-Like Results

- pQCD predicted asymptotic behavior of FFs



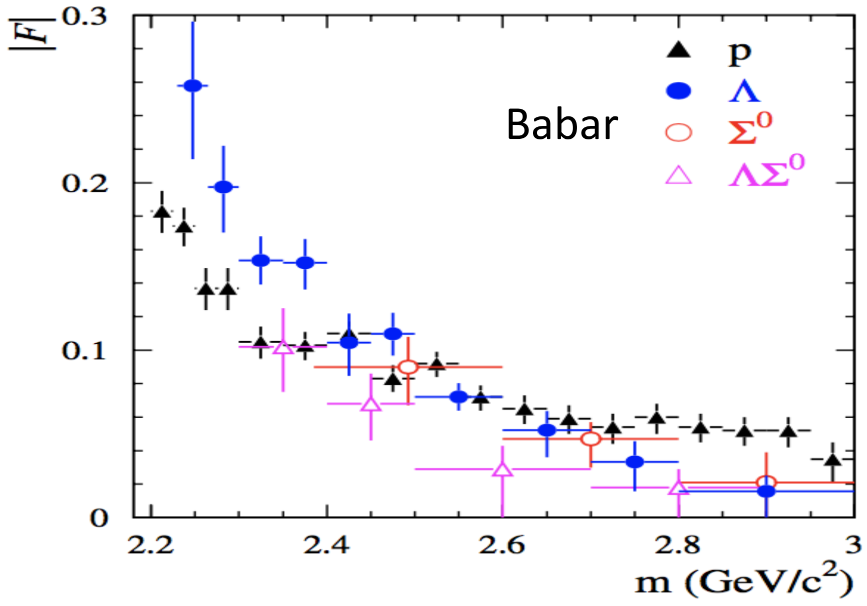


Figures from Prof. Vanderhaeghen

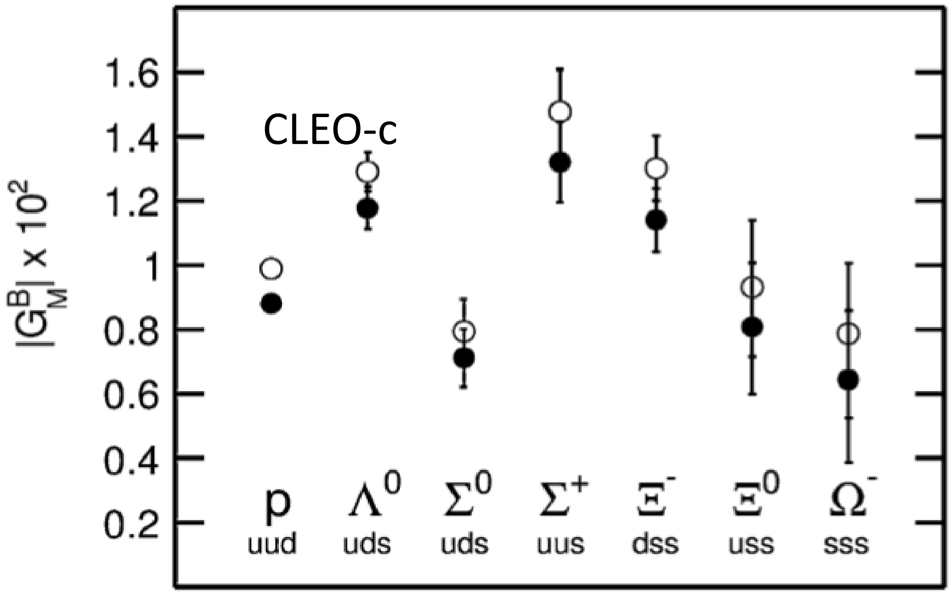
Status on hyperon FFs

- Rare experimental results on Hyperon FF

Phys. Rev. D **76,** 092006 (2007)



Phys. Lett. B 739 (2014) 90–94

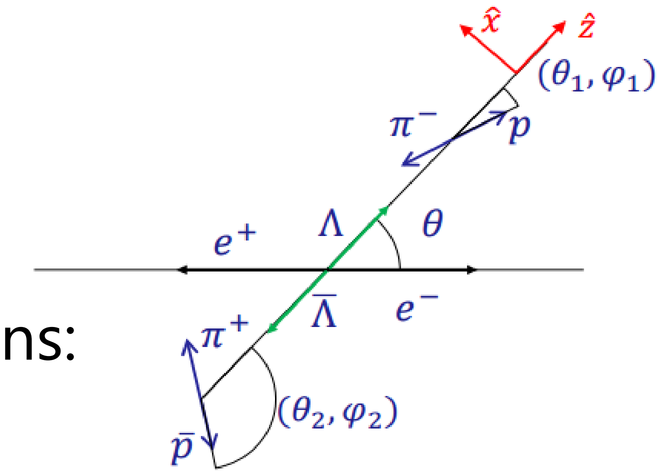


q^2=14.2 GeV^2

- diquark correlation evidence
- favor spin–isospin singlet

Relative phase of baryon

- Complex form of FFs:
  - $G_E = |G_E|e^{i\Phi_E}$, $G_M = |G_M|e^{i\Phi_M}$
  - Relative phase: $\Delta\Phi = \Phi_E$-Φ_M
- A non-zero phase has polarization effect on the Baryons:
  - $P_y \propto \sin\Delta\Phi$



- The angular distribution of daughter baryon from Hyperon weak decay is:
  - $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda \boldsymbol{P_y} \cdot \hat{\boldsymbol{q}}$
  - α_Λ: asymmetry parameter
  - $\hat{q}$: unit vector along the daughter baryon in hyperon rest frame

With hyperon weak decay to B+P, the polarization of hyperon can be measurement, so does the relative phase between G_E and G_M !

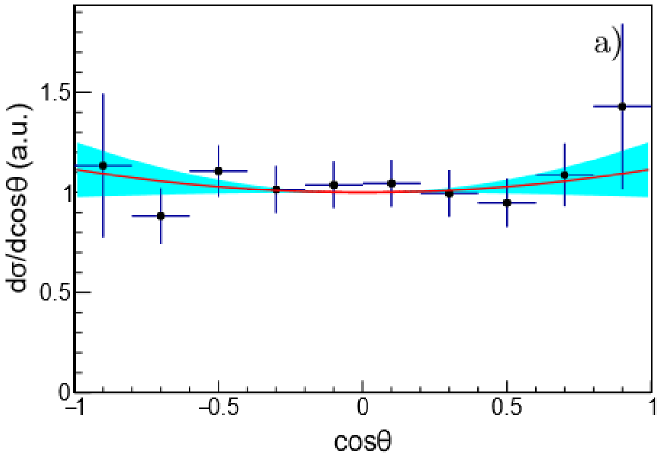
Complete measurement of Λ EMFFs

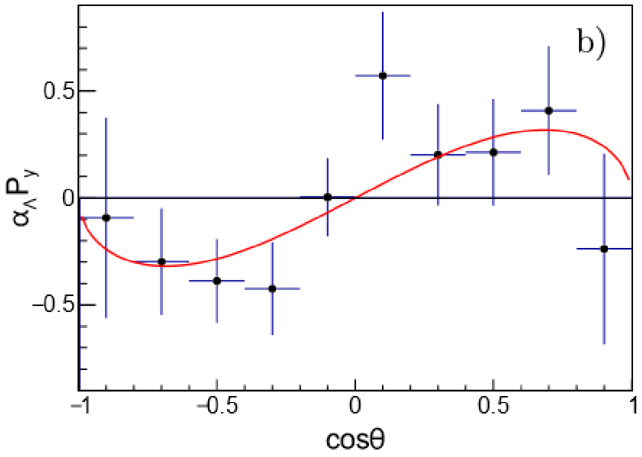
[arXIv: 1903.09421](https://arxiv.org/abs/1903.09421) (submit to PRL)

- An event of the reaction $e^+e^- \rightarrow \Lambda(\rightarrow p\pi^-)\overline{\Lambda}(\rightarrow \bar{p}\pi^+)$ is specified by the five dimensional vector $\xi = (\theta, \Omega_1, \Omega_2)$, the differential cross section is:

$$\begin{aligned}\mathcal{W}(\xi) = &\mathcal{T}_0(\xi) + \eta\,\mathcal{T}_5(\xi)\\ &-\alpha_\Lambda^2\left(\mathcal{T}_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\,\mathcal{T}_2(\xi) + \eta\,\mathcal{T}_6(\xi)\right)\\ &+\alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\mathcal{T}_3(\xi) - \mathcal{T}_4(\xi)\right).\end{aligned}$$

Phys.Lett. B772 (2017) 16-20





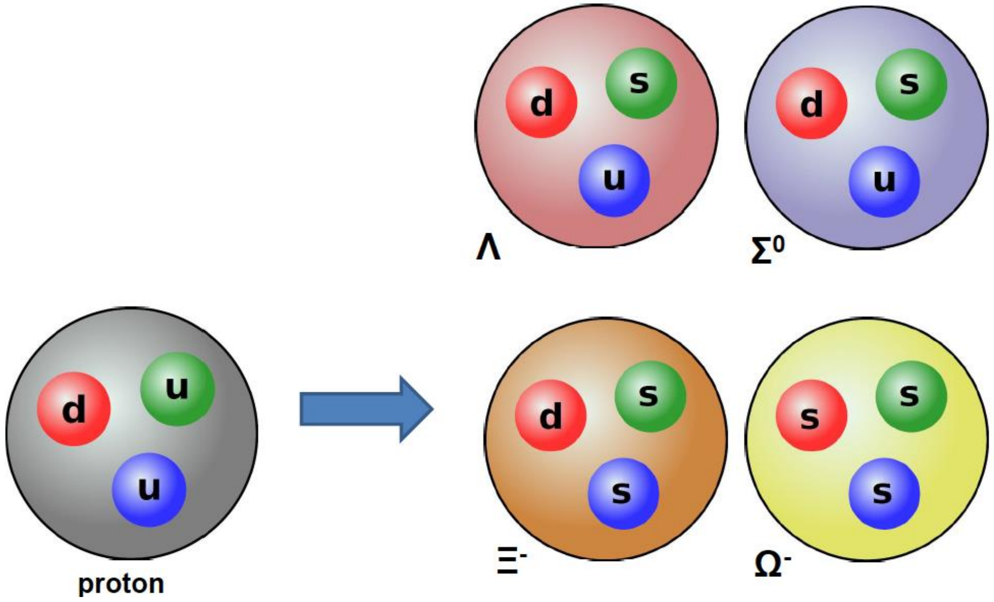
$$\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14(stat.) \pm 0.02(sys.)$$

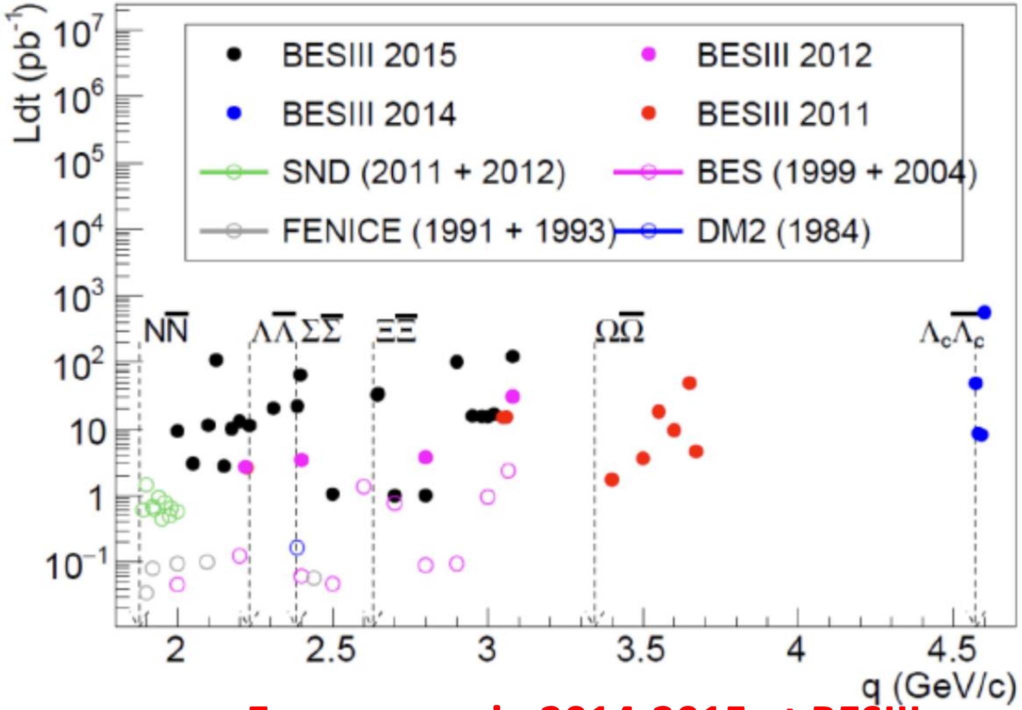
$$\Delta\Phi = 37^\circ \pm 12^\circ(stat.) \pm 6^\circ(sys.)$$

Fit data by Maximum Log Likelihood

Threshold effect

- Hyperon pair production:
  - Possibility to reconstruct hyperon pair production much close to threshold than the proton



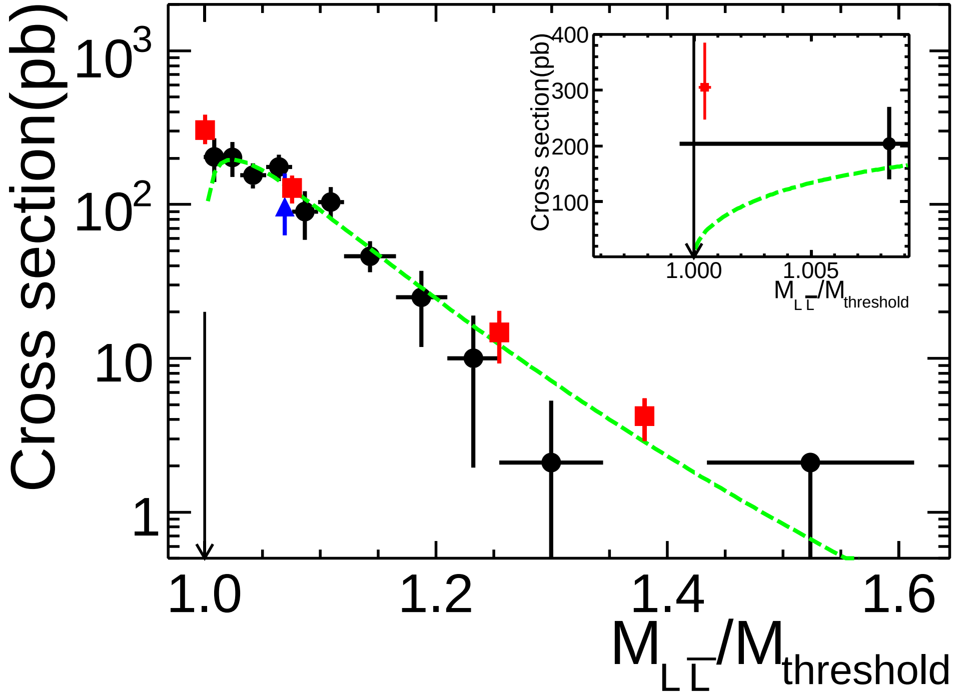


Energy scan in 2014-2015 at BESIII

Measurement of $e^+e^- \to \Lambda\bar{\Lambda}$ at $\sqrt{s}$ =2.2324 GeV

Phys. Rev. D 97, 032013 (2018)

- Near threshold production ($2M_\Lambda$ +1.0 MeV) and small PHSP in $\Lambda/\bar{\Lambda}$ decays
- Indirect search for antiproton in $\boldsymbol{\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+}$
- Search for mono-energetic π^0 in $\boldsymbol{\bar{\Lambda} \to \bar{n}\pi^0}$



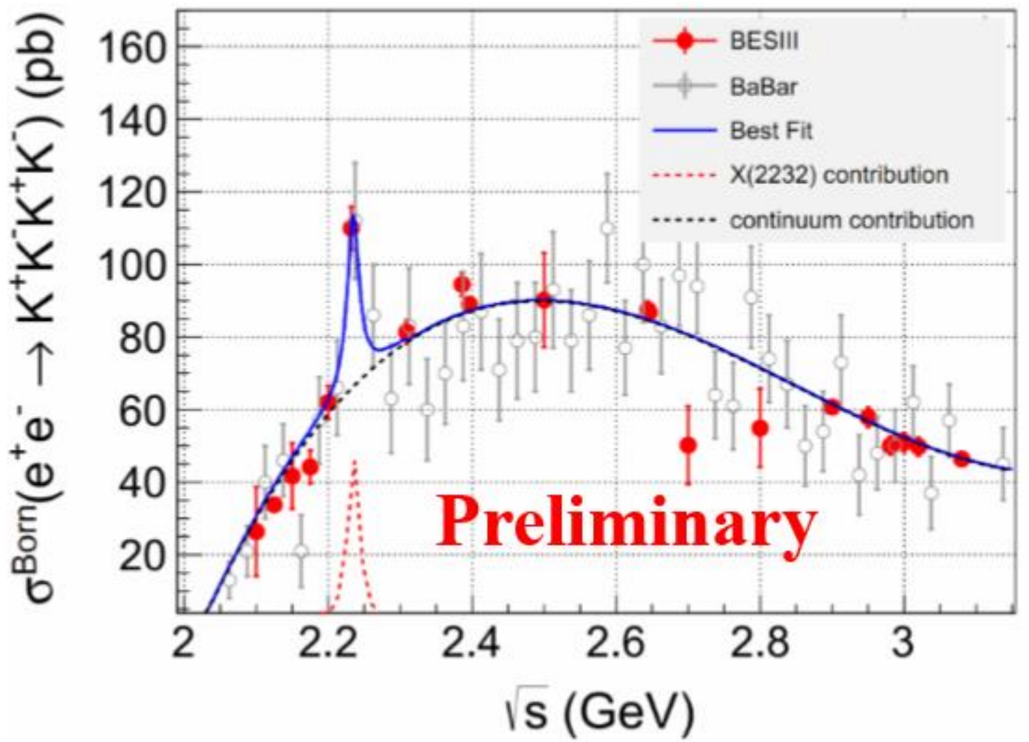
- The anomalous behavior differing from the pQCD prediction at threshold is observed.

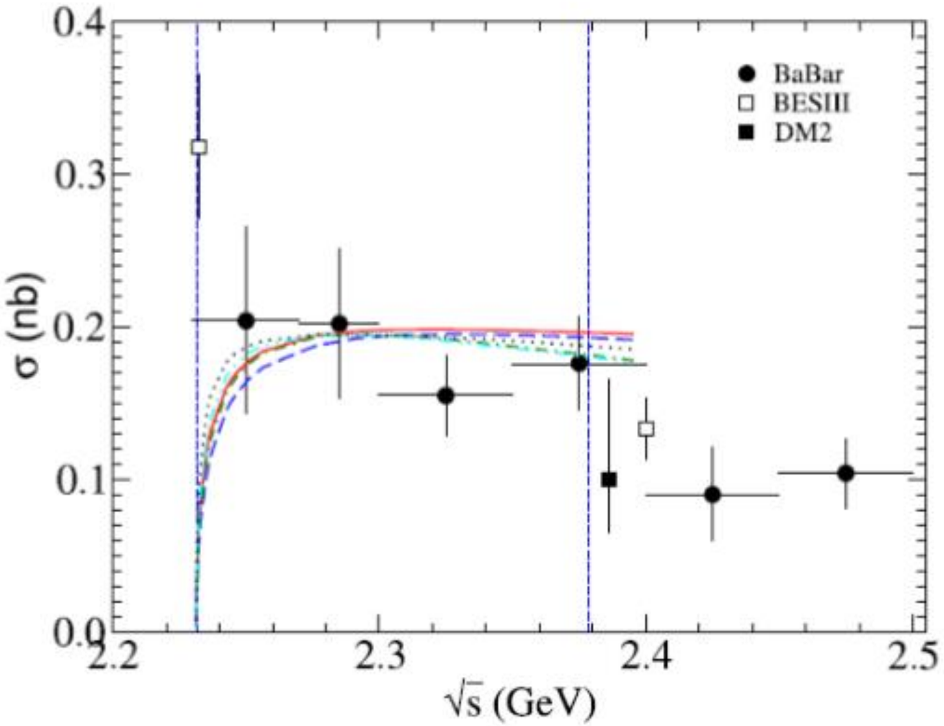
•Recalling the baryon pair production cross section:

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

•The Columb correction factor C=$\frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}$(Q), cancel the β for a charged $B\bar{B}$ pair, equals to 1 for a neutral $B\bar{B}$ pair

A possible resonance around $\Lambda\bar{\Lambda}$ resonance?

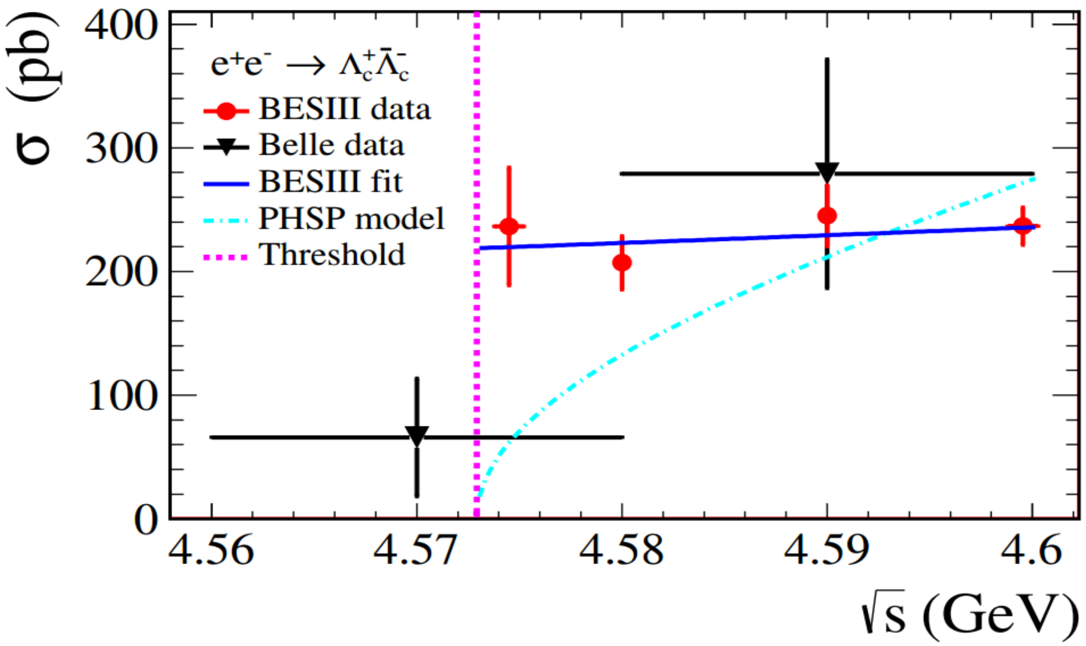


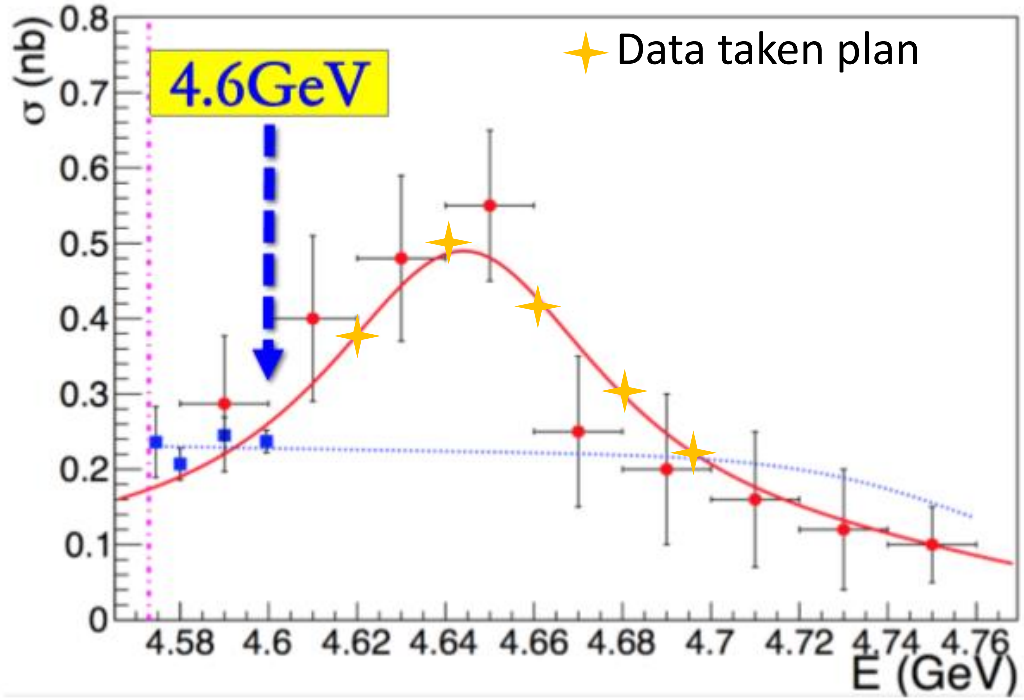


- A hint for resonance around $\Lambda\bar{\Lambda}$ threshold in $e^+e^- \to KKKK$ cross section
  - Mass=2232$\pm$3.5 MeV， width=20 MeV

$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ near kinematic threshold

Phys. Rev. Lett. 120, 132001 (2018)

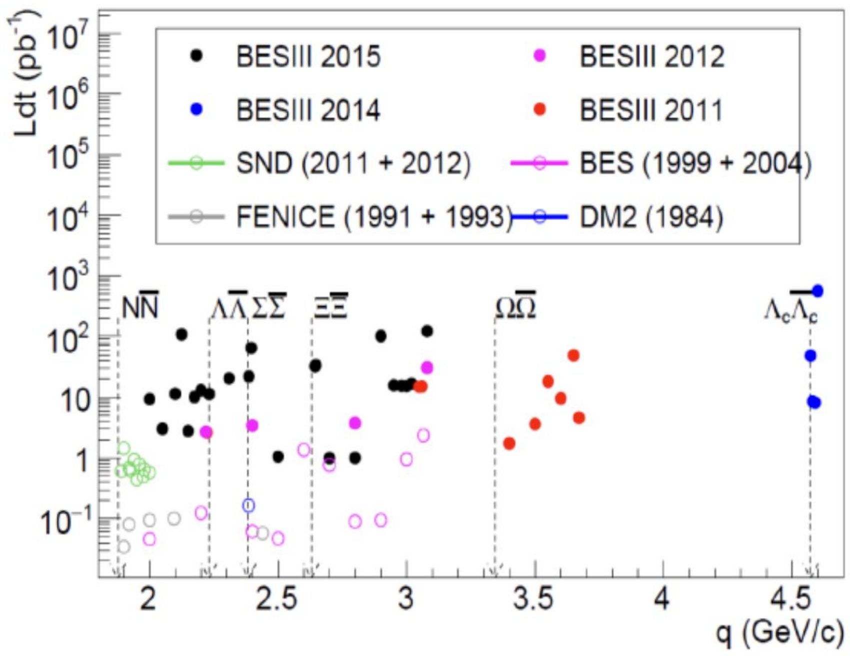




- Ten modes of Λ_c^+ ($\bar{\Lambda}_c^-$) are reconstructed
- Measurement of the Born cross section at 4 energy points below 4.6 GeV with **unprecedented statistical accuracy** (~1.3% at 4.6 GeV)

Summary and discussion

- Nucleon FFs is measured with scan and ISR techniques at BESIII
  - Answered the remaining questions on proton FFs
  - Precise measurement on neutron FFs is ongoing
- With the large data set, more precise results on Hyperon FFs are expected on BESIII.
  - More precise cross section line-shape
  - Test on threshold effect
  - Complete determination of G_E and G_M



Energy scan in 2014-2015 at BESIII

Thank you for your attention!