Baryon time-like form factors

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on behalf of BESIII Collaboration

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Outline

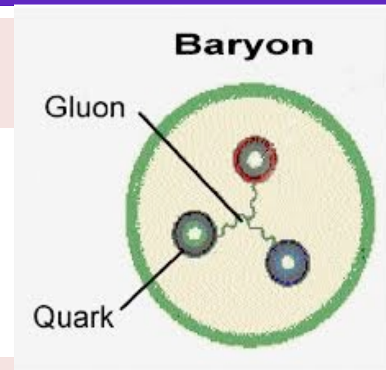
- Definition of baryon form factors (FFs)
- BEPCII & BESIII detector
- Status of baryon FFs measurements
  - Proton FFs
  - $\Lambda_c^+\bar{\Lambda}_c^-$ FFs } At threshold
  - $\Lambda\bar{\Lambda}$ FFs } At threshold
  - Status of neutron FFs
- Summary

Form factors

Baryons have structure

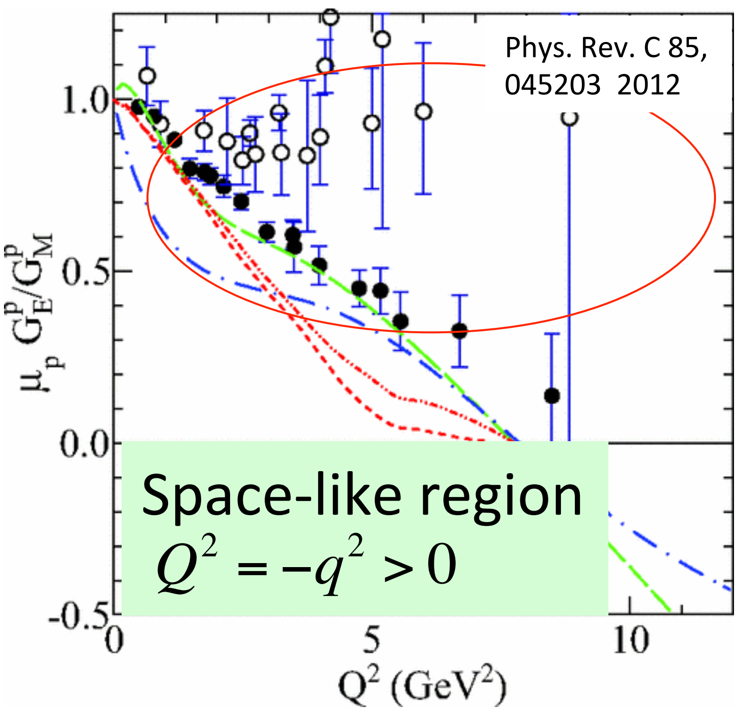
FFs describe Baryon' internal structure

Understanding hadrons' structure helps to **understand QCD**

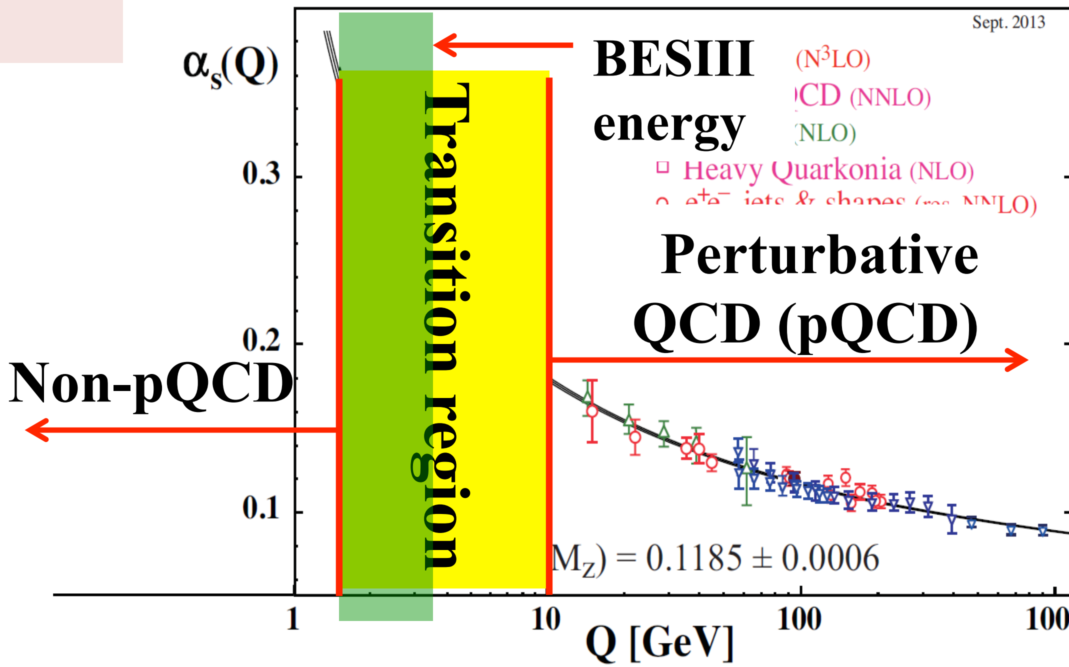


FFs help understand strong interaction

Inputs to QCD models

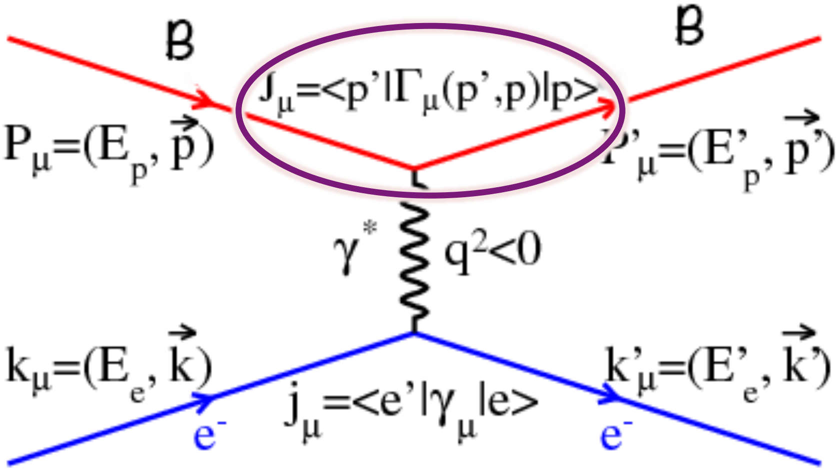


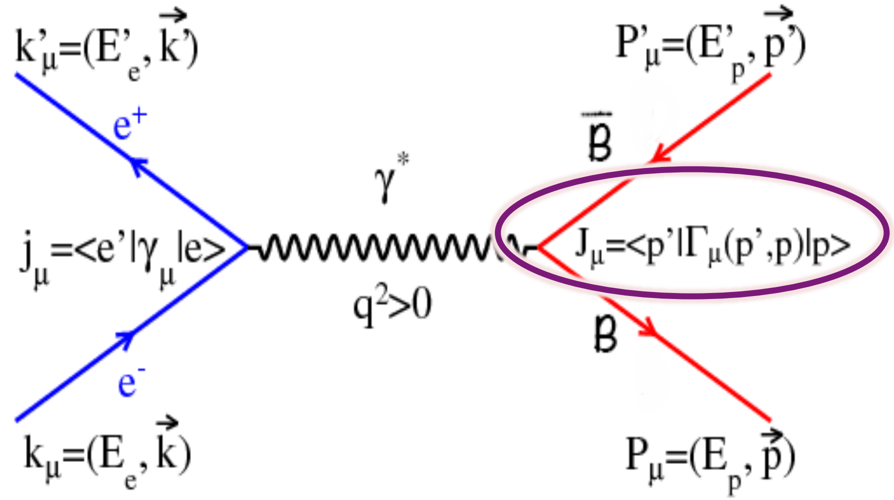
Space-like region $Q^2 = -q^2 > 0$



Time-like region $Q^2 = q^2 > 0$

Dirac FF and Pauli FF





Elastic scattering:

Space-like (SL) region, $q^2 < 0$

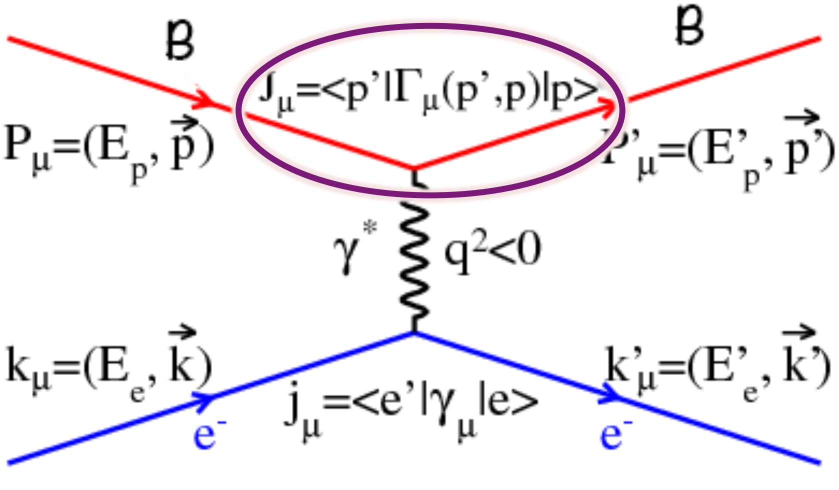
Annihilation:

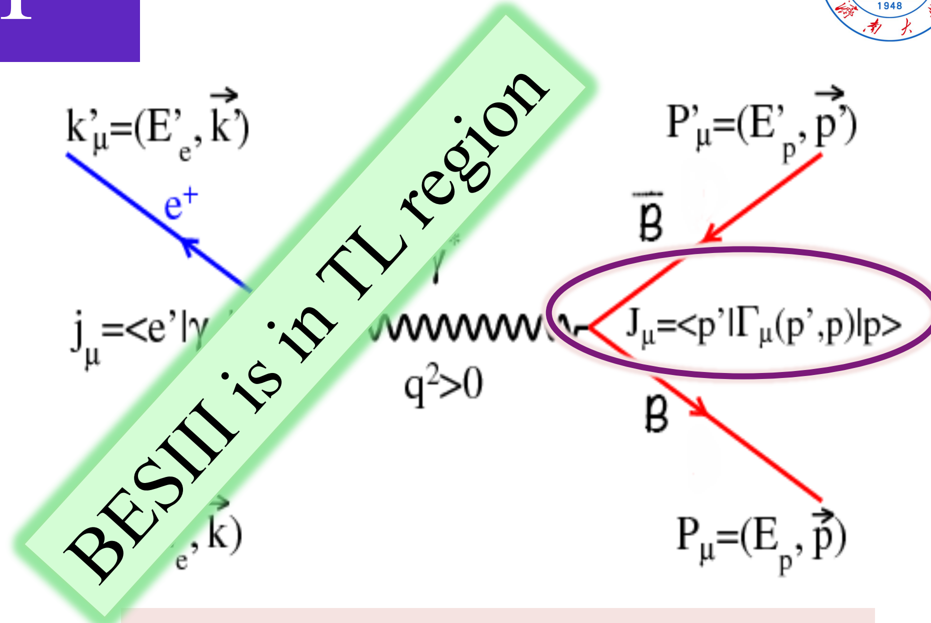
Time-like (TL) region, $q^2 > 0$

Baryon vertex: $$\Gamma_\mu = \gamma^\mu F_1\left(q^2\right) + \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \kappa F_2\left(q^2\right)$$

$F_1\left(q^2\right)$: Dirac FF, $F_2\left(q^2\right)$: Pauli FF

Dirac FF and Pauli FF





Elastic scattering:

Space-like (SL) region, $q^2 < 0$

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$F_1\left(q^2\right)$: Dirac FF, $F_2\left(q^2\right)$: Pauli FF

EM FFs and TL angular distribution

EM FFs:

$$G_E(q^2) = F_1(q^2) + \tau\kappa F_2(q^2), \quad \tau = \frac{q^2}{4M_B^2}$$

Electric

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

Magnetic

How to measure them? → Angular analysis

TL:

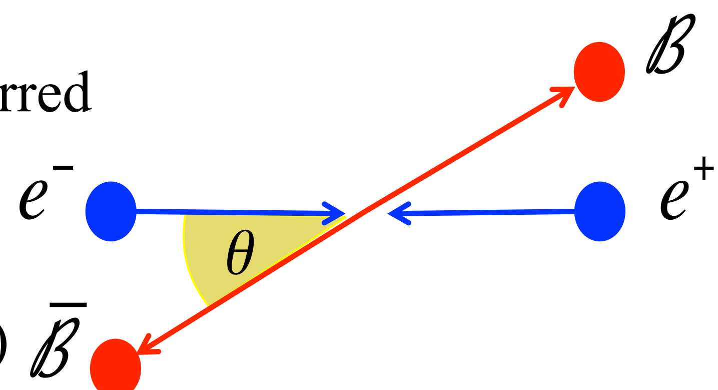
$$\frac{d\sigma_{born}}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[\frac{1}{\tau}\sin^2\theta |G_E|^2 + (1+\cos^2\theta)|G_M|^2\right]$$

$\beta = \sqrt{1-1/\tau}$

C : Coulomb correction

function of s and θ :

- $s = q^2$: 4-momentum transferred by the virtual photon
- θ : polar angle of baryon in CM (center-of-mass system)



Ratio of EM FFs and effective FFs

Angular distribution written as function of EM FFs ratio:

$$\frac{d\sigma_{born}}{d\Omega} = \frac{\alpha^2 \beta C}{4s} \left| G_M(s) \right| \left[\left(1 + \cos^2\theta \right) + R_{EM}^2 \frac{1}{\tau} \sin^2\theta \right]$$

Ratio of EM FFs:

$$R_{EM} = \left| G_E(s) / G_M(s) \right|$$

Born cross section:

$$\sigma_{born} = \frac{4\pi\alpha^2 \beta C}{3s} \left[\left| G_M \right|^2 + \frac{1}{2\tau} \left| G_E \right|^2 \right]$$

Assume: $|G| = |G_E| = |G_M|$

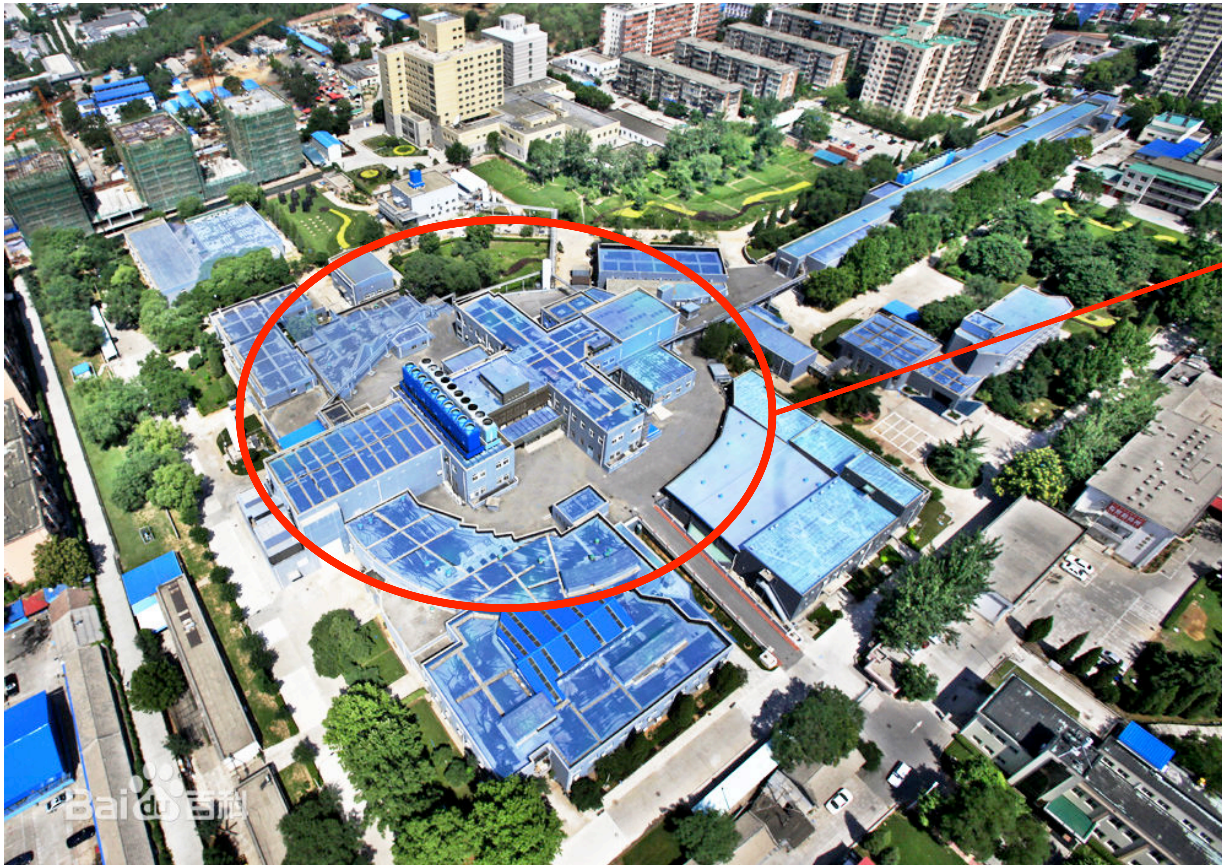
EF FFs:

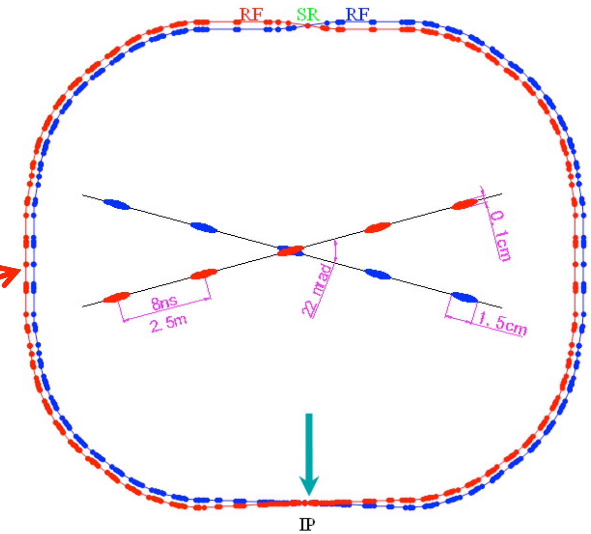
$$\left| G(s) \right| = \sqrt{\sigma_{born} \Big/ \left[\frac{4\pi\alpha^2 \beta C}{3s} \left(1 + \frac{1}{2\tau} \right) \right]}$$

Above baryon threshold: C=1

All formula valid for spin 1/2

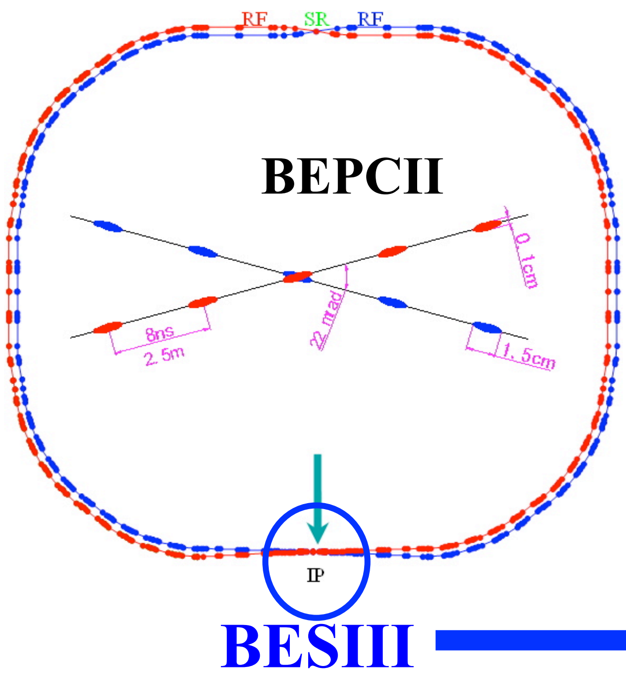
BEPCII (Beijing Electron Positron Collider II)

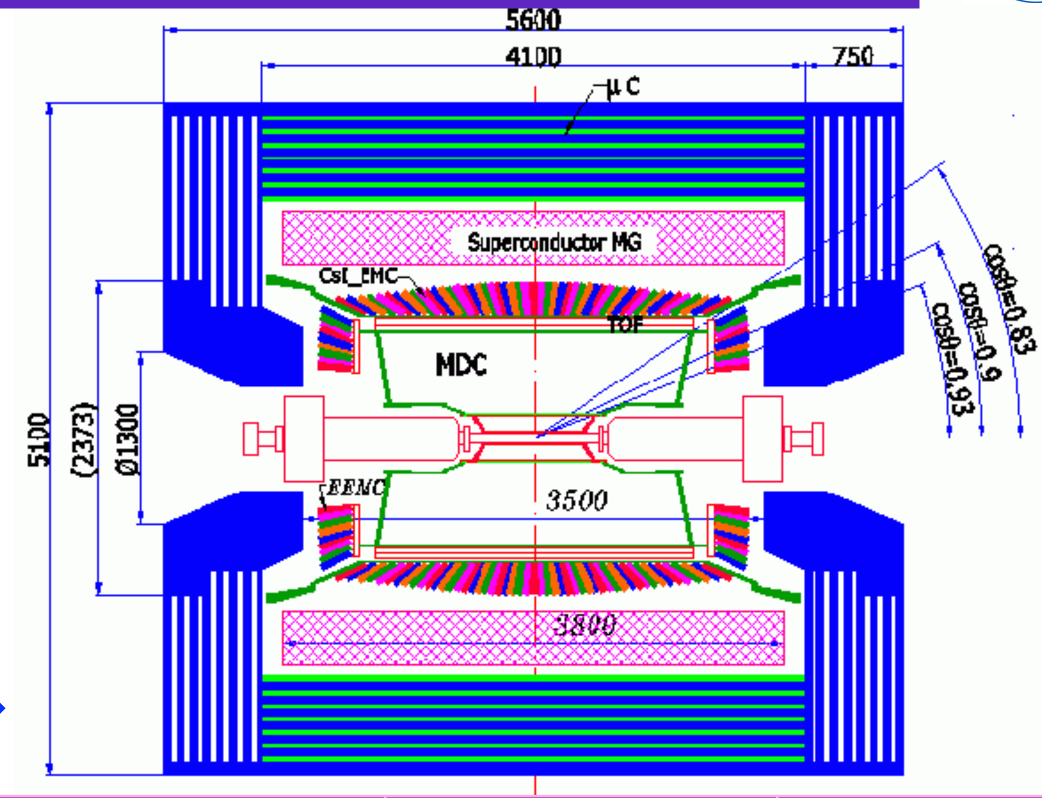




- Runs started in 2009
- CM energy: **2.0 – 4.6 GeV**
- "τ-charm factory"
- Peak instantaneous luminosity:
  - 1×10^{33} cm^{-2}s^{-1} (designed)
  - **1×10^{33} cm^{-2}s^{-1} (achieved)**
- Energy spread: 5.16×10^{-4}

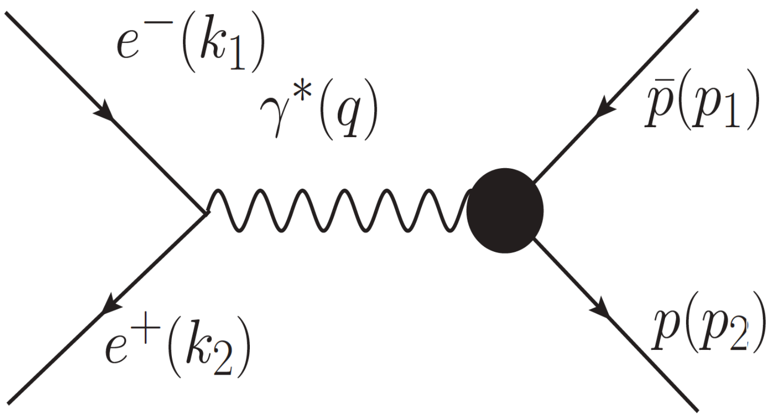
BESIII (BEijing Spectrometer III) at BEPCII





	MDC	TOF	EMC	MUC
Sub-detectors	Main Drift Chamber	Time of Flight	Electromagnetic Calorimeter	Muon Counter
Resolution	115μm(wire), < 5% (dE/dx)	68ps (Barrel), 70ps (Endcap)	2.3% (energy)	

Proton FFs in $e^+e^- \to p\bar{p}$



Energy scan method

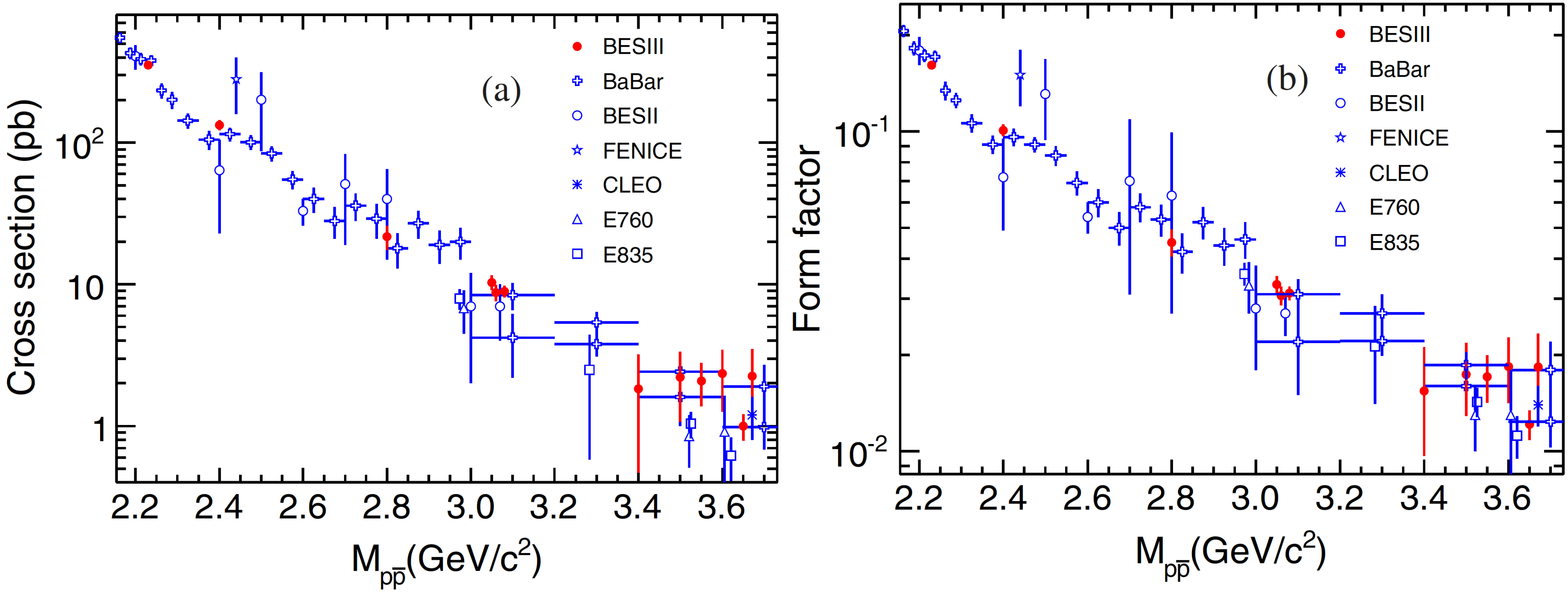
Following studies are based on **scan data**

Proton FFs at BESIII in $e^+e^- \to p\bar{p}$

Phys. Rev. D 91, 112004 (2015)

$$E_{CM} = 2.2324 - 3.671\ \text{GeV} \quad L_{\text{int}} = 156.94\,pb^{-1}\ \ 2011-2012$$

Born cross section at 12 CM | **EF FFs at 12 CM energy points**

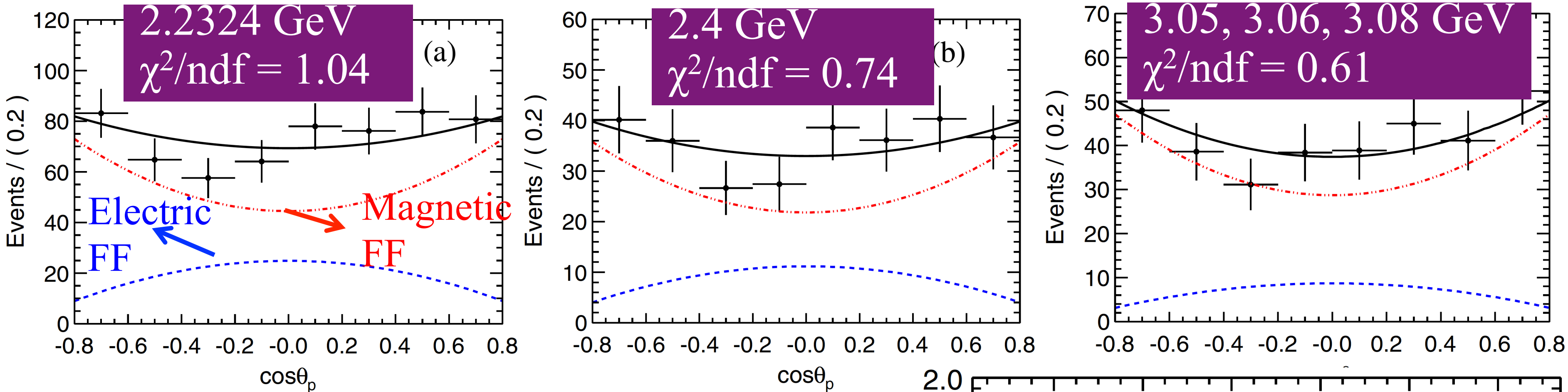


- **Consistent** with previous measurements
- Uncertainty **improved** by **~30%** compared to Babar

Proton FFs at BESIII in $e^+e^- \to p\bar{p}$

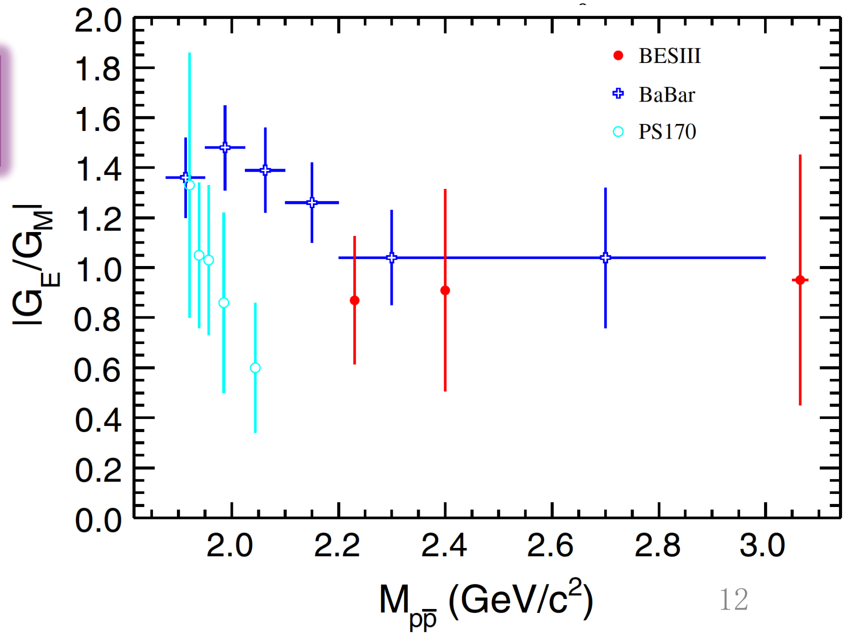
Phys. Rev. D 91, 112004 (2015)

R_{EM} at 3 points: 2.2324, 2.4, combined 3.05, 3.06 and 3.08 GeV



R_{EM}s are extracted from the fit

- **Inconsistent** between **Babar** and **PS170**
- **BESIII consistent with Babar** in the same q^2 region
- Close to 1

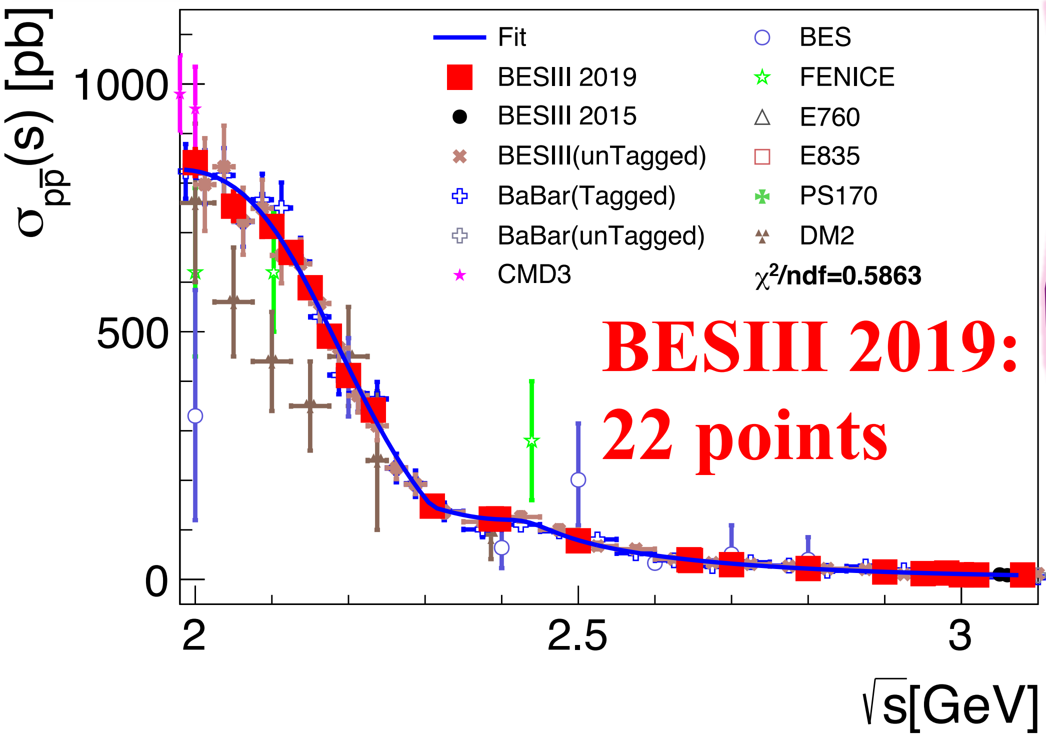


Proton FFs at BESIII in $e^+e^- \to p\bar{p}$

arXiv: 1905.09001

$$E_{CM} = 2.0 - 3.08 \text{ GeV} \quad L_{\text{int}} = 688.5 pb^{-1} \quad 2015$$

$$\sigma_{p\bar{p}}(s)$$



$\sqrt{s} \le 2.2324\text{GeV}$:

$$\frac{e^{a_0}\pi^2\alpha^3}{s\left[1-e^{-\frac{\pi\alpha_s(s)}{\beta(s)}}\right]\left[1+\left(\frac{\sqrt{s}-2m_p}{a_1}\right)^{a_2}\right]}$$

$\sqrt{s} > 2.2324\text{GeV}$:

$$\frac{2\pi\alpha^2\beta(s)C\left[2+\left(\frac{2m_p}{\sqrt{s}}\right)^2\right]e^{2a_3}}{3s^5\left[4\ln^2\left(\frac{\sqrt{s}}{a_4}\right)+\pi^2\right]^2}$$

- **Consistent** with previous experiments
- The **most precise** results until now 3.0-23.5% with **systematic uncertainty dominated**

Proton FFs at BESIII in $e^+e^- \to p\bar{p}$

arXiv: 1905.09001

$E_{CM} = 2.0 - 3.08$ GeV $L_{\text{int}} = 688.5 pb^{-1}$ 2015

$\sigma_{p\bar{p}}(s)$

Fit function:

Strong interaction effects considered **near threshold**

Normalization constant:

$a_0 = 0.82 \pm 0.11, a_3 = 4.02 \pm 1.22$

QCD parameter near threshold:

$a_1 = 0.35 \pm 0.02$

$\sigma_{p\bar{p}}$ power-law dependence, related to valence quarks:

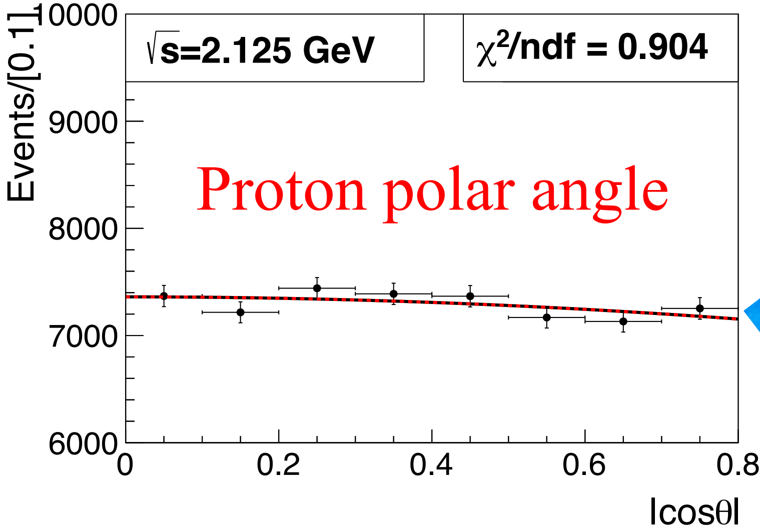
$a_2 = 4.26 \pm 0.59$

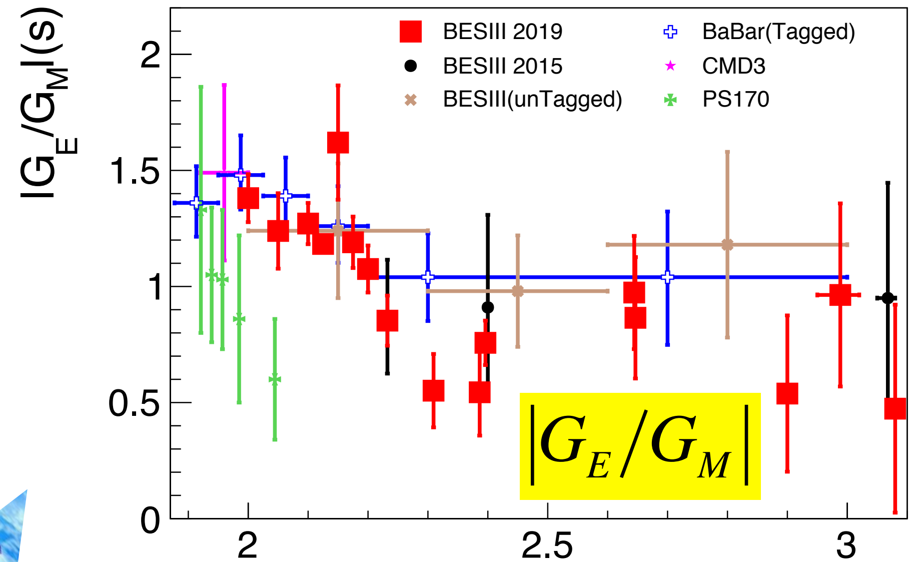
QCD parameter in Λ_{QCD} continuum region:

$a_4 = 0.49^{+0.98}_{-0.49}$

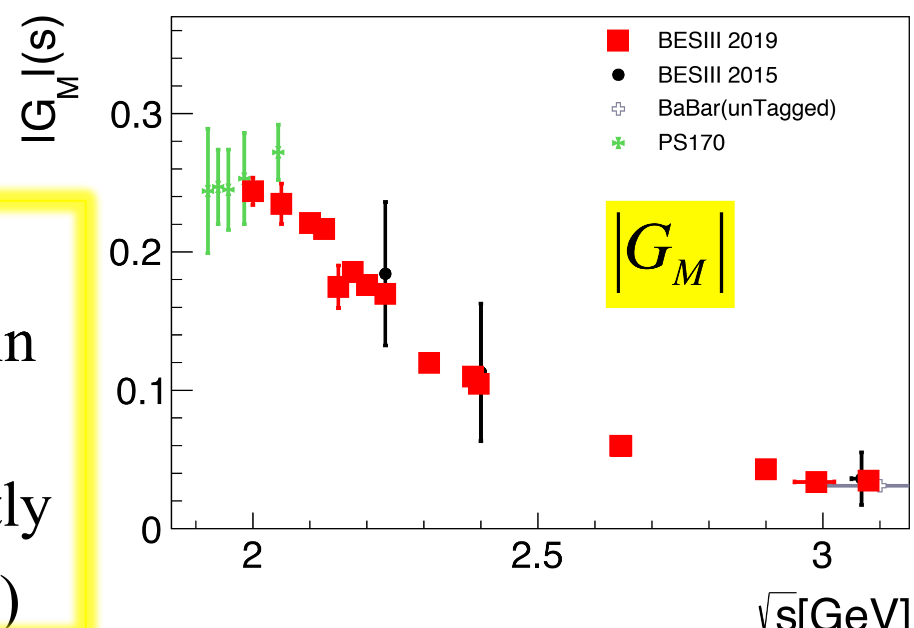
Proton FFs at BESIII in $e^+e^- \to p\bar{p}$

arXiv: 1905.09001





16 points out of 22, including combining 4 at 2.981-3.02 GeV

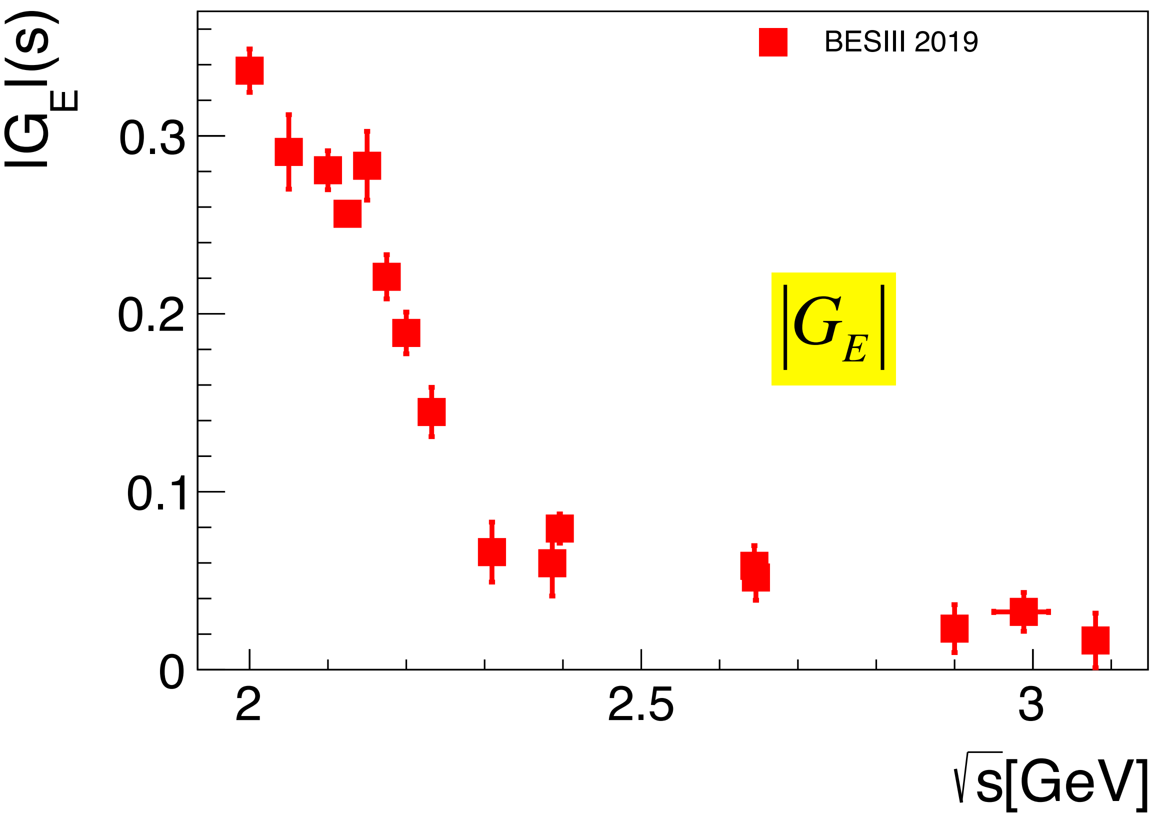


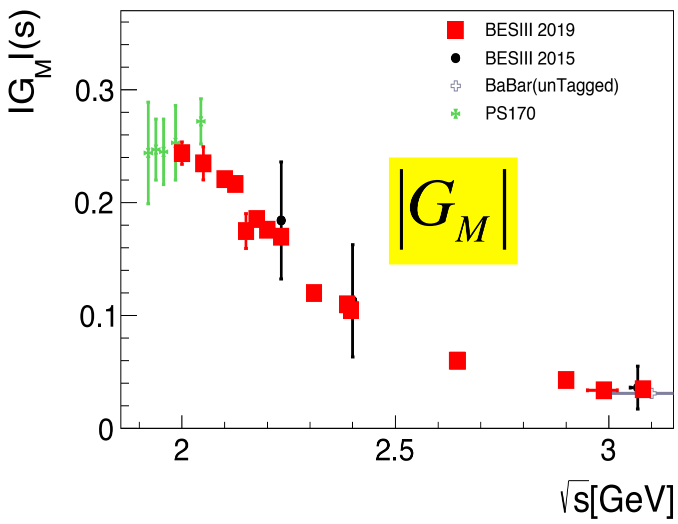
First time:

1. Precision **comparable** to data in SL region
2. $|G_M|$ over wide range with greatly **improved accuracy** (1.8-3.6%)

Proton FFs at BESIII in $e^+e^- \to p\bar{p}$

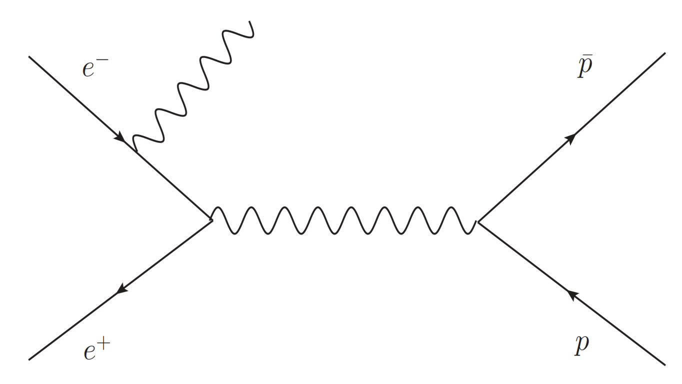
arXiv: 1905.09001





First time: 3. $|G_E|$ is **measured**

Proton FFs in ISR process



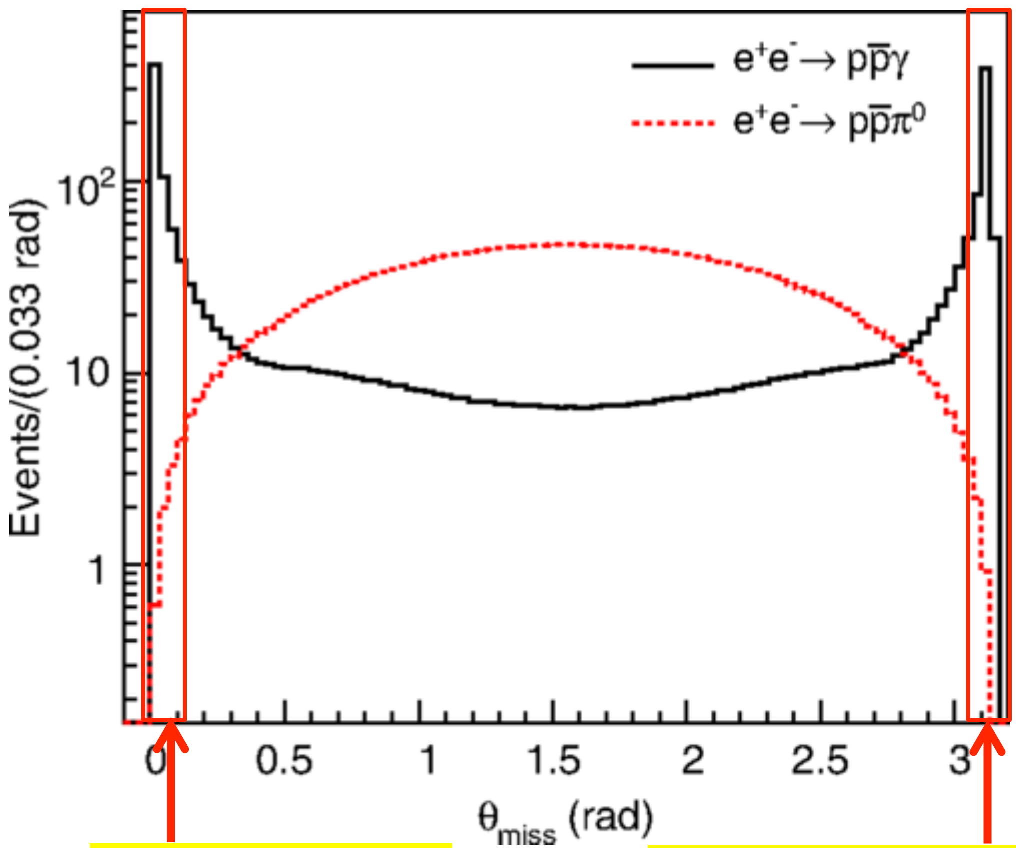
Untagged method (Phys. Rev. D 99, 092002 (2019))

Datasets using:

E_{cm} (GeV)	3.773	4.009	4.230	4.260	4.360	4.420	4.600
Taking time	2010-2011	2011	2013	2013	2013	2014	2014
Lumi. (pb^{-1})	2917.00	481.96	1047.34	825.67	539.84	1028.89	566.93

Proton FFs at BESIII with ISR (Untagged)

Phys. Rev. D 99, 092002 (2019)



$\theta_{miss} < 0.125$ $\theta_{miss} > \pi - 0.125$

θ_{miss} : polar angle of miss momentum

$\vec{p}_{miss}$: miss momentum

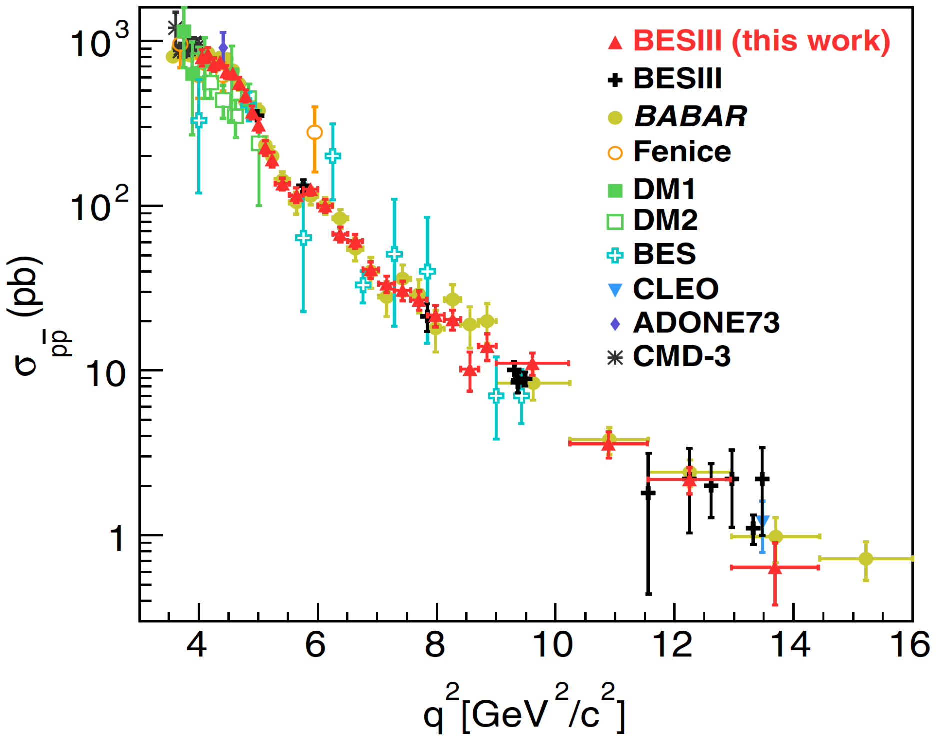
$$\vec{p}_{miss} = \vec{p}_{e^+} + \vec{p}_{e^-} - \vec{p}_p - \vec{p}_{\bar{p}}$$

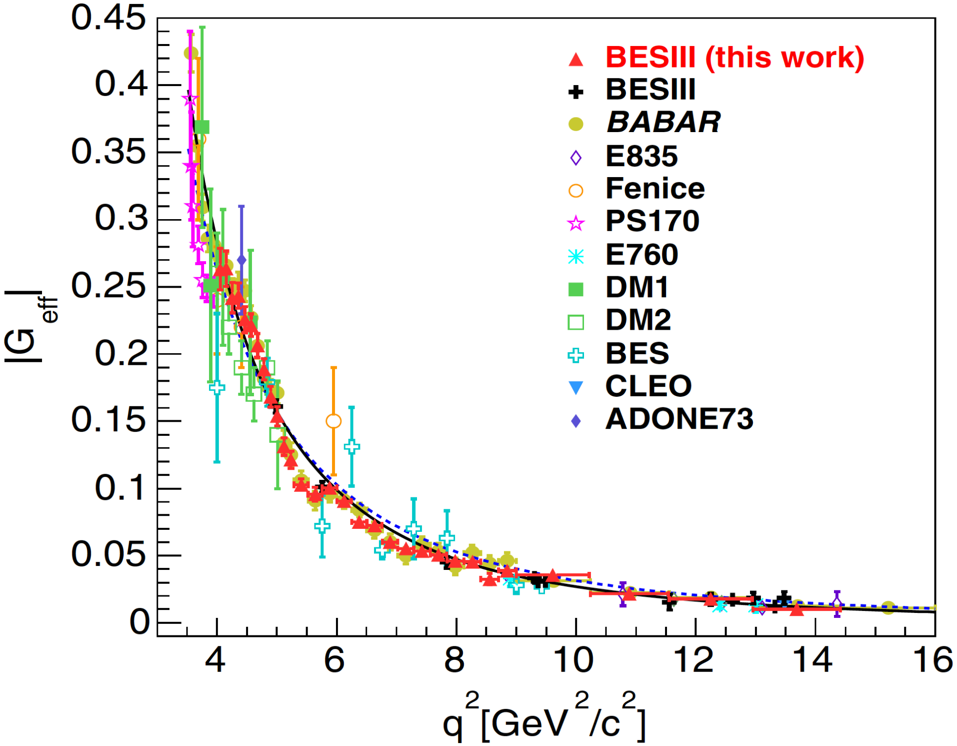
- Out of BESIII detector coverage: **untagged**
- Taking **large fraction** of ISR events

Proton FFs at BESIII with ISR (Untagged)

Phys. Rev. D 99, 092002 (2019)

Born cross section (left) and EF FF (right) at **30** intervals

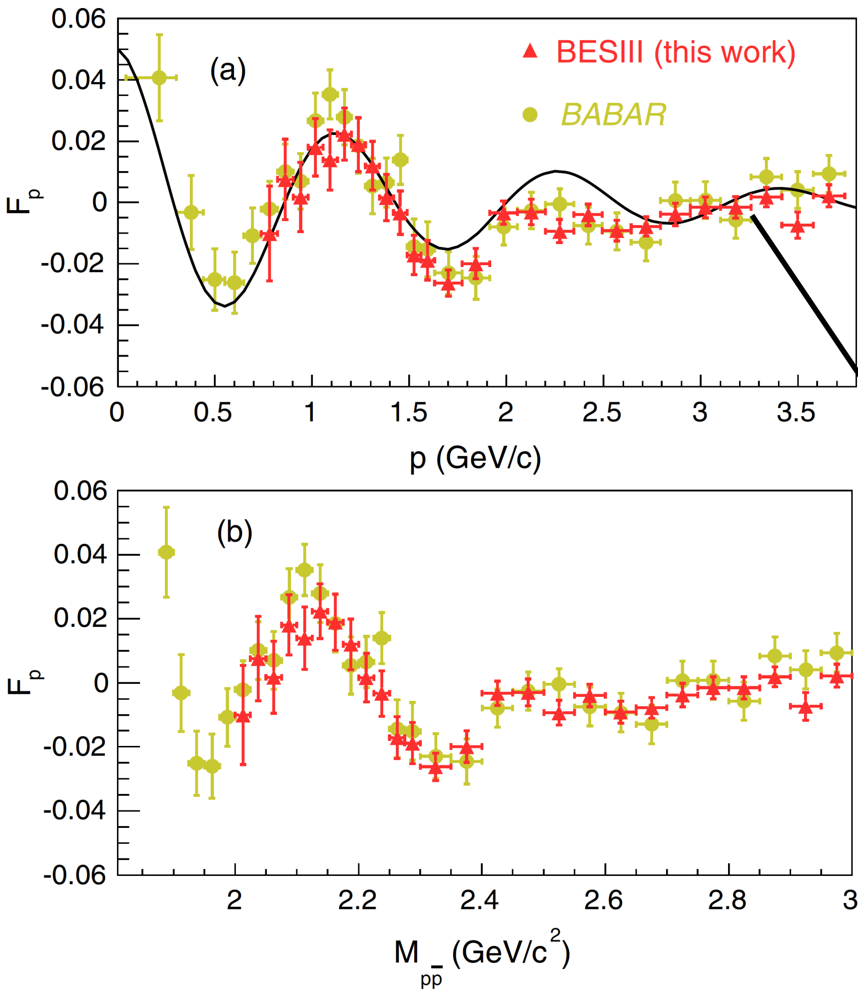




- **Consistent** with previous measurements
- Structures seen by Babar are **reproduced**

Proton FFs at BESIII with ISR (Untagged)

Phys. Rev. D 99, 092002 (2019)



Oscillation found in EF FF

- Especially more **obvious** in function of relative momentum of p and $\bar{p}$
- And **also** invariant mass of $p\bar{p}$
- After **subtraction** of smooth function

Black curve:

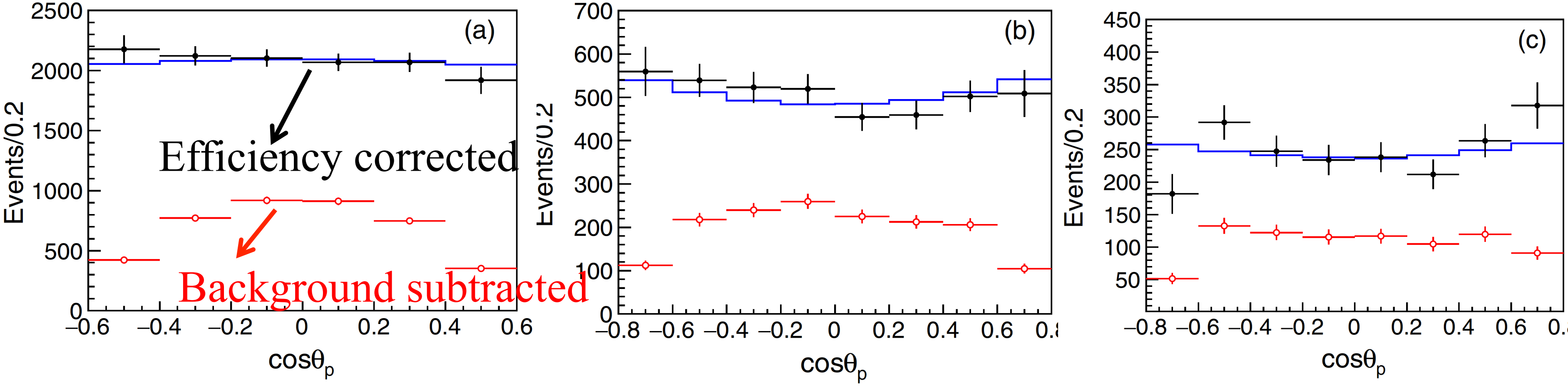
$$F_p = A^{osc}\exp\left(-B^{osc}p\right)\cos(C^{osc}p + D^{osc})$$

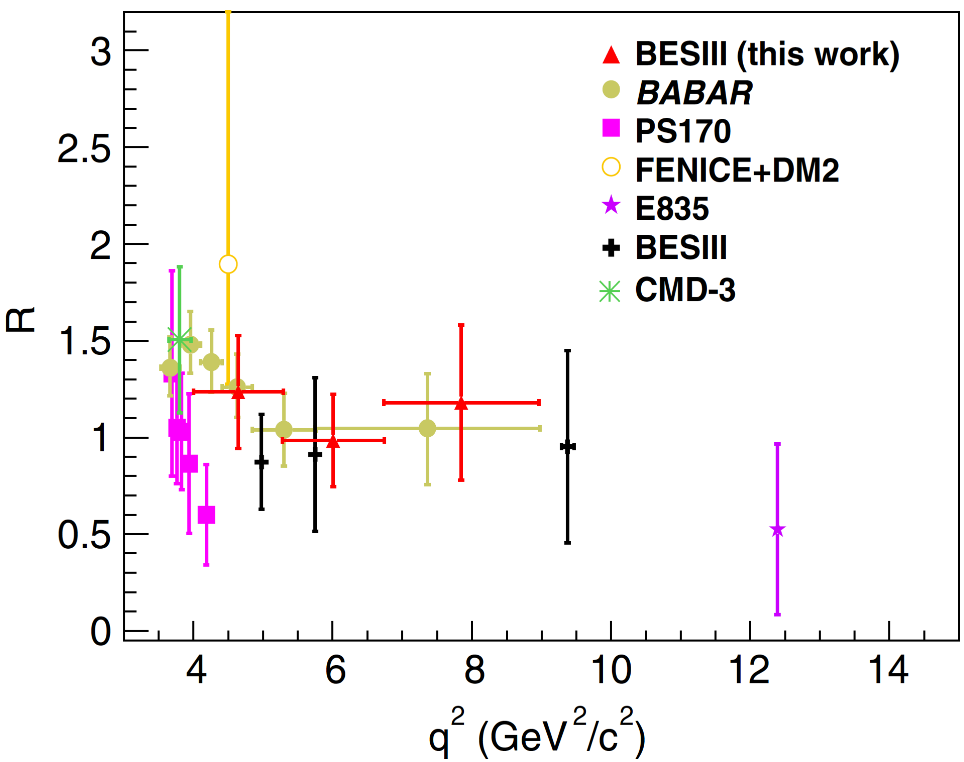
Origin of oscillation:

- Interference effect involving **rescattering** processes
- Or independent **resonant** structure
- Or **other** reasons

Proton FFs at BESIII with ISR (Untagged)

Phys. Rev. D 99, 092002 (2019)





R_{EM} at **3** intervals (GeV):
[2.0-2.3], [2.3-2.6], [2.6-3.0]

Measurements below 2 GeV will be **further** studied using data bellow 3.773 GeV

Hyperon form factors

Measurements at threshold

Baryon born cross section:

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

- $\beta = \sqrt{1-4m^2/s}$
- Neutral: $C = 1$
- Charged: $C = \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\pi\alpha/\beta)}$

Expecting at threshold:

- For neutral baryon, cross section should almost vanish
  - And increases with $\sqrt{s}$
- For charged baryon, cross section is non-zero

Measurements near threshold:

- Help to understand the Coulomb factor when baryon pair produced, which is not as expected presently in many cases
  - And this factor may connect to the dark matter search
- More deeply to understand the baryon structure

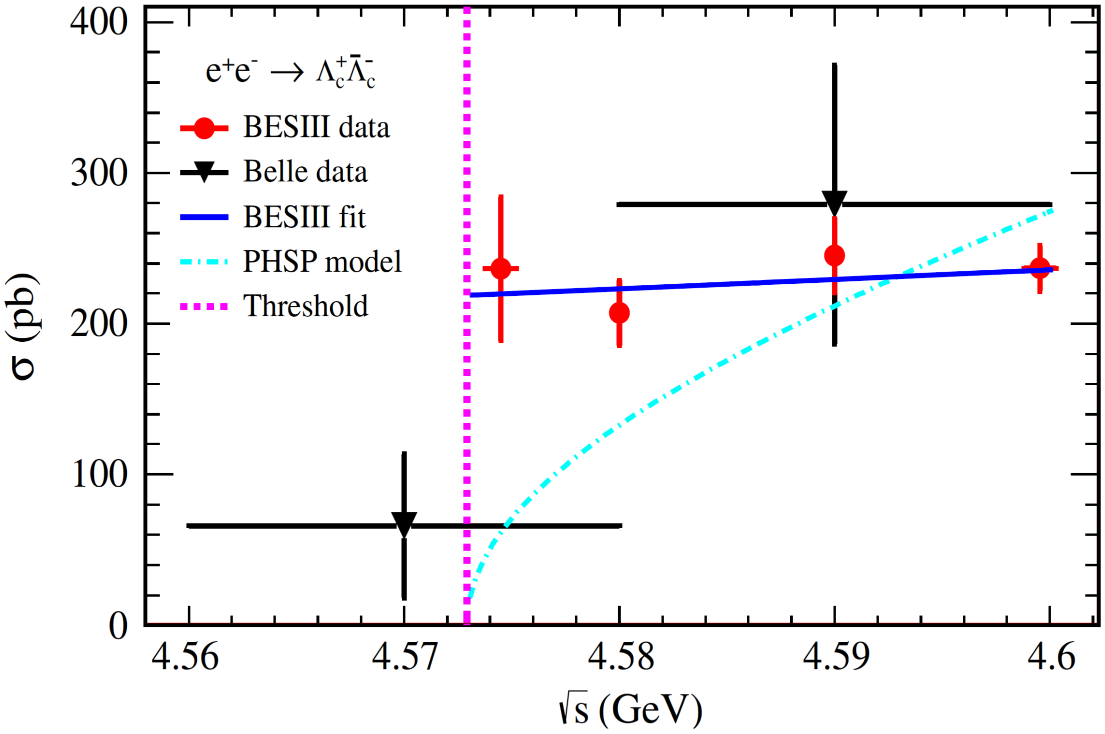
$\Lambda_c^+\bar{\Lambda}_c^-$ FFs near threshold at BESIII

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

$$E_{CM} = 4.5745, 4.5800, 4.5900, 4.5995\,\text{GeV} \quad 2011-2014$$

1.6 MeV above Λ_c

Have $|G_E/G_M|$ measured in this analysis



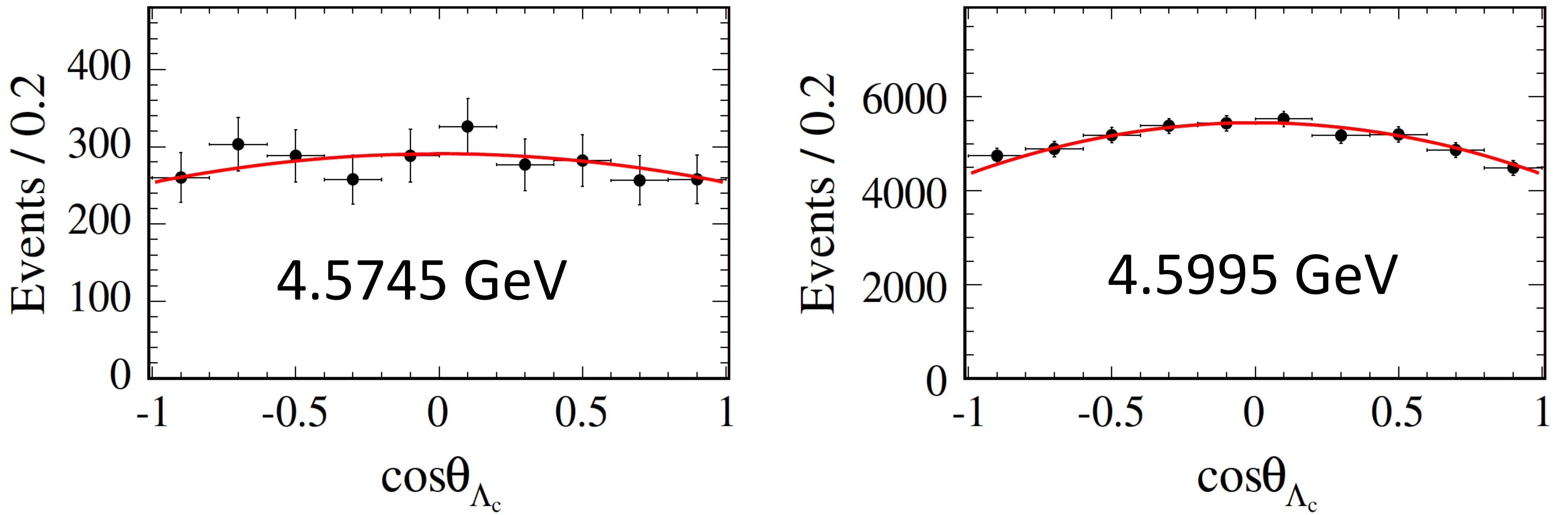
Largely improved precisions

Highlights enhanced cross section near threshold

Indicates complex Λ_c production behavior

$\Lambda_c^+\bar{\Lambda}_c^-$ FFs near threshold at BESIII

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



GeV	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4.5745	-0.13 ± 0.12 ± 0.08	1.14 ± 0.14 ± 0.07
4.5995	-0.20 ± 0.04 ± 0.02	1.23 ± 0.05 ± 0.03

$$f(\theta_{\Lambda_c}) \propto (1+\alpha_{\Lambda_c}\cos^2\theta_{\Lambda_c})$$

$$\lvert G_E/G_M \rvert^2 (1-\beta^2) = (1-\alpha_{\Lambda_c})/(1+\alpha_{\Lambda_c})$$

$\lvert G_E/G_M \rvert$ of Λ_c is the **first** measurement

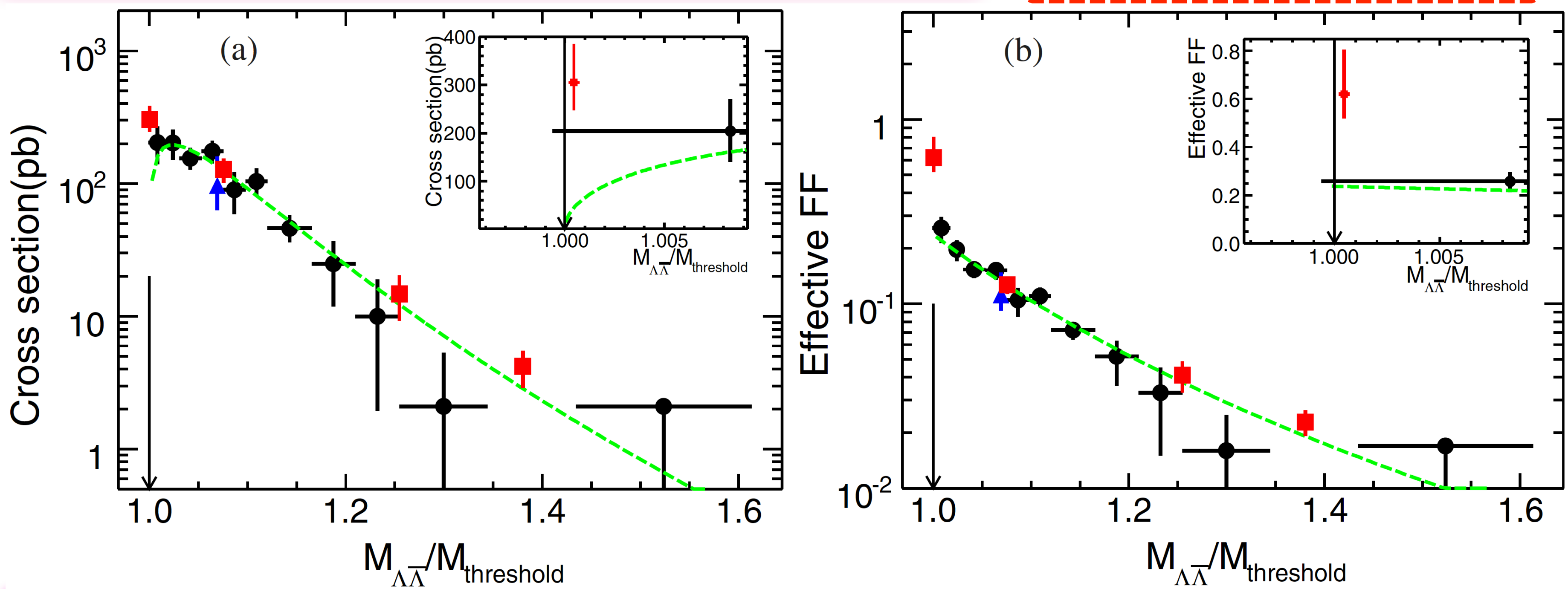
Provide import **insights** into Λ_c production mechanism

$\Lambda\bar{\Lambda}$ FFs near threshold at BESIII

Phys. Rev. D 97, 032013 (2018)

$E_{CM} = 2.2324, 2.4, 2.8, 3.08$ GeV

2.2324 GeV
1.0 MeV above Λ



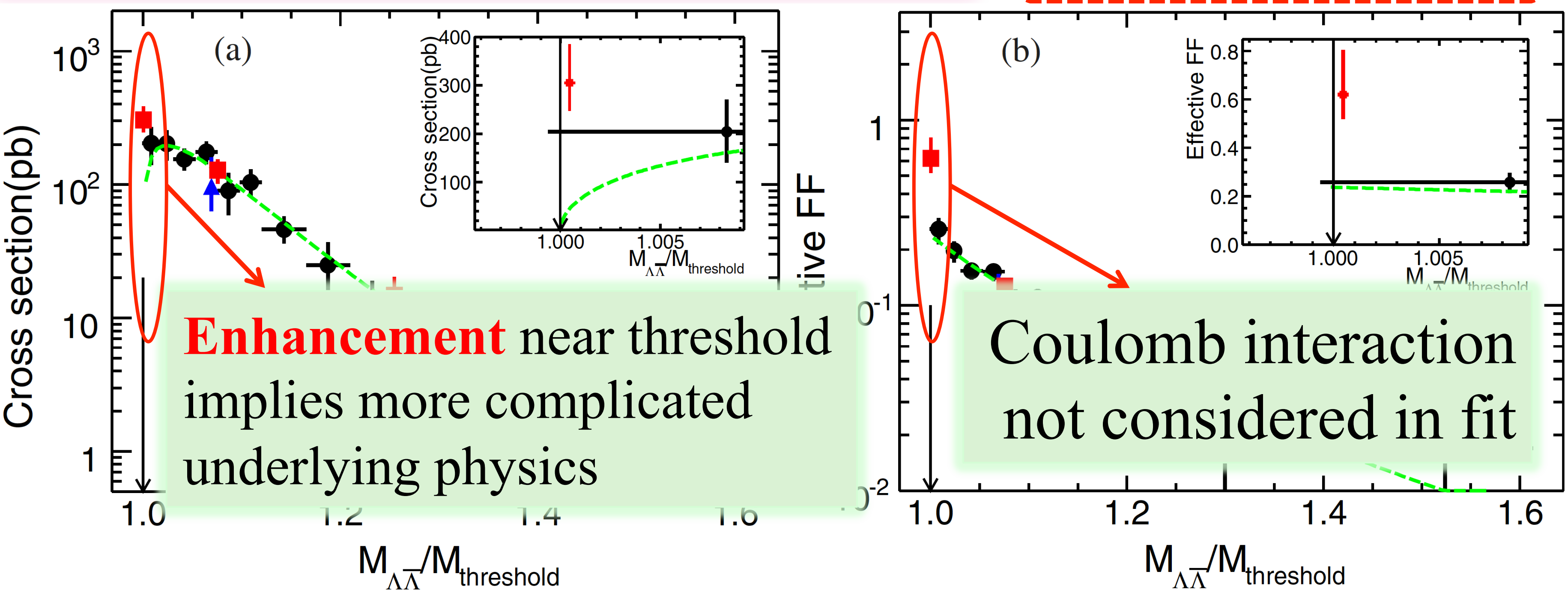
- Results **consistent** with previous measurements, with **improved** precision
- Cross section and EF FFs are measured **near threshold**
  - **Helpful** in understanding the mechanism of baryon production

$\Lambda\bar{\Lambda}$ FFs near threshold at BESIII

Phys. Rev. D 97, 032013 (2018)

$$E_{CM} = 2.2324, 2.4, 2.8, 3.08 \text{ GeV}$$

2.2324 GeV
1.0 MeV above Λ



Enhancement near threshold implies more complicated underlying physics

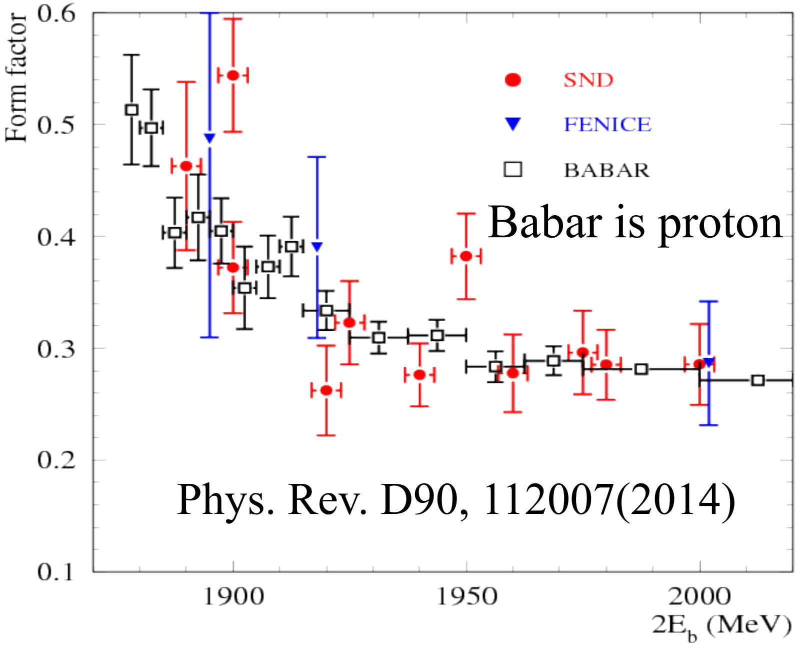
Coulomb interaction not considered in fit

- Results **consistent** with previous measurements, with **improved** precision
- Cross section and EF FFs are measured **near threshold**
  - **Helpful** in understanding the mechanism of baryon production

Other results on baryon FFs

Neutron FFs at BESIII

- The first results obtained by FENICE 20 years ago
- Confirmed by SND recently in 2014
- Compared to the proton FFs from Babar
  - Similar distributions of proton and neutron



Prospects at BESIII: with data scanned in 2015

- First measurement at BESIII
- Between 2 and 3.08 GeV
- **High statistics**

Summary

- BESIII already had important results on baryon FFs measurements
- **Proton FFs:**
  - **Published** on scan and ISR untagged method
  - **Consistent** with previous measurements with **improved precisions**
- **Hyperon FFs:**
  - **Neutral** Λ and **charged** $\Lambda_c^{\pm}$ nearby **threshold**
  - **Enhanced** cross section and FFs near threshold implies complicated underlying physics
- **Coming results:**
  - On **neutron**, Σ and ……

Thank you for your attention!

Back-up

Measurements of baryon FFs

Electromagnetic FFs:

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4M_B} F_2(q^2)$$ Electric

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$ Magnetic

How to measure? ⟵ Angular analysis

SL:

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

$$\varepsilon = 1 \Big/ \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]$$

$$\tau = q^2 / (4M_B^2)$$

TL:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta \zeta}{4q^2} \left[\frac{1}{\tau}\sin^2\theta |G_E|^2 + (1+\cos^2\theta)|G_M|^2\right]$$

$$\beta = \sqrt{1 - 1/\tau}$$

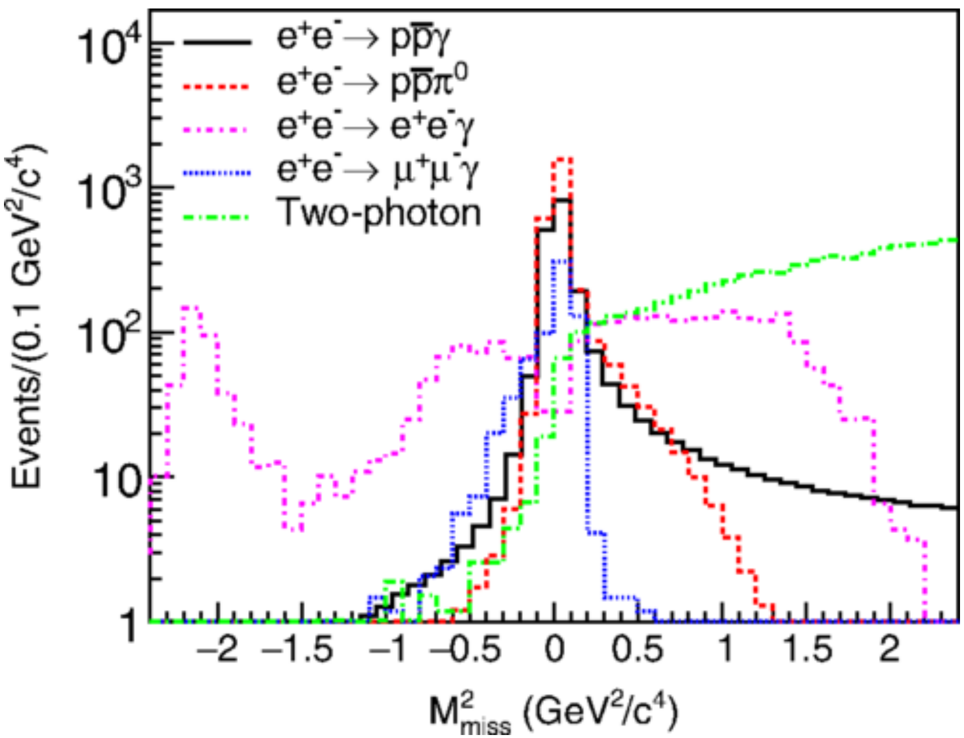
ζ : Coulomb correction

Results of proton form factors using data at 2.0-3.08 GeV arxiv:1905.09001

$\sqrt{s}$[GeV]	$\mathcal{L}$[pb^{-1}]	N_{obs}	σ_{Born}[pb]	$\lvert G_E/G_M \rvert$	$\lvert G_E \rvert[10^{-2}]$	$\lvert G_M \rvert[10^{-2}]$
2.0000	10.074 ± 0.067	5321	$841.3 \pm 11.5 \pm 24.8$	$1.38 \pm 0.10 \pm 0.03$	$33.66 \pm 1.23 \pm 0.31$	$24.38 \pm 0.99 \pm 0.26$
2.0500	3.343 ± 0.027	1703	$753.4 \pm 18.3 \pm 23.5$	$1.24 \pm 0.16 \pm 0.04$	$29.10 \pm 2.08 \pm 0.40$	$23.48 \pm 1.43 \pm 0.42$
2.1000	12.167 ± 0.085	5993	$712.6 \pm 9.2 \pm 21.4$	$1.27 \pm 0.09 \pm 0.02$	$28.07 \pm 1.10 \pm 0.31$	$22.08 \pm 0.74 \pm 0.17$
2.1250	108.490 ± 0.970	50312	$660.0 \pm 3.0 \pm 19.7$	$1.18 \pm 0.04 \pm 0.01$	$25.62 \pm 0.49 \pm 0.18$	$21.65 \pm 0.31 \pm 0.13$
2.1500	2.841 ± 0.024	1189	$588.8 \pm 17.1 \pm 17.8$	$1.62 \pm 0.24 \pm 0.06$	$28.32 \pm 1.89 \pm 0.46$	$17.48 \pm 1.51 \pm 0.37$
2.1750	10.625 ± 0.091	3762	$491.0 \pm 8.0 \pm 14.8$	$1.19 \pm 0.12 \pm 0.02$	$22.08 \pm 1.28 \pm 0.28$	$18.55 \pm 0.75 \pm 0.16$
2.2000	13.699 ± 0.092	4092	$411.6 \pm 6.4 \pm 12.3$	$1.08 \pm 0.10 \pm 0.02$	$18.93 \pm 1.20 \pm 0.28$	$17.60 \pm 0.63 \pm 0.12$
2.2324	14.501 ± 0.090	3644	$341.9 \pm 5.7 \pm 10.1$	$0.85 \pm 0.11 \pm 0.03$	$14.48 \pm 1.39 \pm 0.42$	$16.98 \pm 0.57 \pm 0.17$
2.3094	21.089 ± 0.143	2336	$148.0 \pm 3.1 \pm 5.7$	$0.55 \pm 0.16 \pm 0.02$	$6.61 \pm 1.72 \pm 0.25$	$11.99 \pm 0.44 \pm 0.14$
2.3864	22.549 ± 0.176	1851	$122.0 \pm 2.8 \pm 3.6$	$0.54 \pm 0.19 \pm 0.02$	$5.98 \pm 1.87 \pm 0.19$	$10.99 \pm 0.44 \pm 0.07$
2.3960	66.869 ± 0.475	5514	$121.9 \pm 1.6 \pm 3.6$	$0.76 \pm 0.10 \pm 0.02$	$7.93 \pm 0.86 \pm 0.21$	$10.48 \pm 0.27 \pm 0.07$
2.5000	1.098 ± 0.009	55	$77.9 \pm 10.5 \pm 4.1$	–	–	–
2.6444	33.722 ± 0.216	867	$39.7 \pm 1.3 \pm 1.2$	$0.97 \pm 0.24 \pm 0.05$	$5.84 \pm 1.13 \pm 0.24$	$5.99 \pm 0.37 \pm 0.11$
2.6464	34.003 ± 0.282	838	$38.2 \pm 1.3 \pm 1.2$	$0.87 \pm 0.27 \pm 0.04$	$5.18 \pm 1.30 \pm 0.21$	$5.99 \pm 0.37 \pm 0.11$
2.7000	1.034 ± 0.007	20	$29.8 \pm 6.7 \pm 1.6$	–	–	–
2.8000	4.761 ± 0.028	68	$22.0 \pm 2.7 \pm 1.0$	–	–	–
2.9000	105.253 ± 0.905	1010	$15.0 \pm 0.5 \pm 0.5$	$0.54 \pm 0.34 \pm 0.03$	$2.31 \pm 1.39 \pm 0.11$	$4.29 \pm 0.21 \pm 0.06$
2.9500	15.942 ± 0.143	118	$11.7 \pm 1.1 \pm 0.4$	$0.96 \pm 0.39 \pm 0.06$	$3.25 \pm 1.09 \pm 0.17$	$3.37 \pm 0.28 \pm 0.06$
2.9810	16.071 ± 0.096	131	$12.9 \pm 1.1 \pm 0.5$			
3.0000	15.881 ± 0.110	92	$9.2 \pm 1.0 \pm 0.3$			
3.0200	17.290 ± 0.123	97	$9.0 \pm 0.9 \pm 0.3$			
3.0800	157.204 ± 0.943	858	$9.0 \pm 0.3 \pm 0.3$	$0.47 \pm 0.45 \pm 0.04$	$1.64 \pm 1.53 \pm 0.12$	$3.47 \pm 0.18 \pm 0.03$

Proton FFs at BESIII with ISR (Untagged)

Phys. Rev. D 99, 092002 (2019)



$\sqrt{s} > 4\text{GeV}$:

$-0.1 < M^2_{miss} < 0.2\,\text{GeV}^2/c^2$

$\sqrt{s} = 3.773\text{GeV}$:

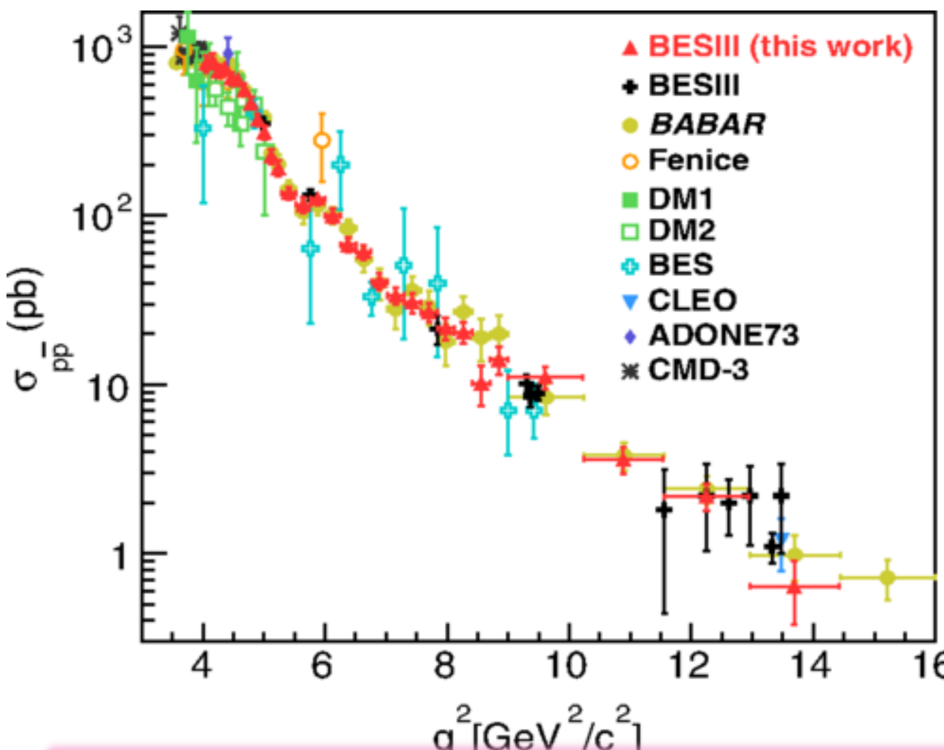
$-0.02 < M^2_{miss} < 0.10\,\text{GeV}^2/c^2$

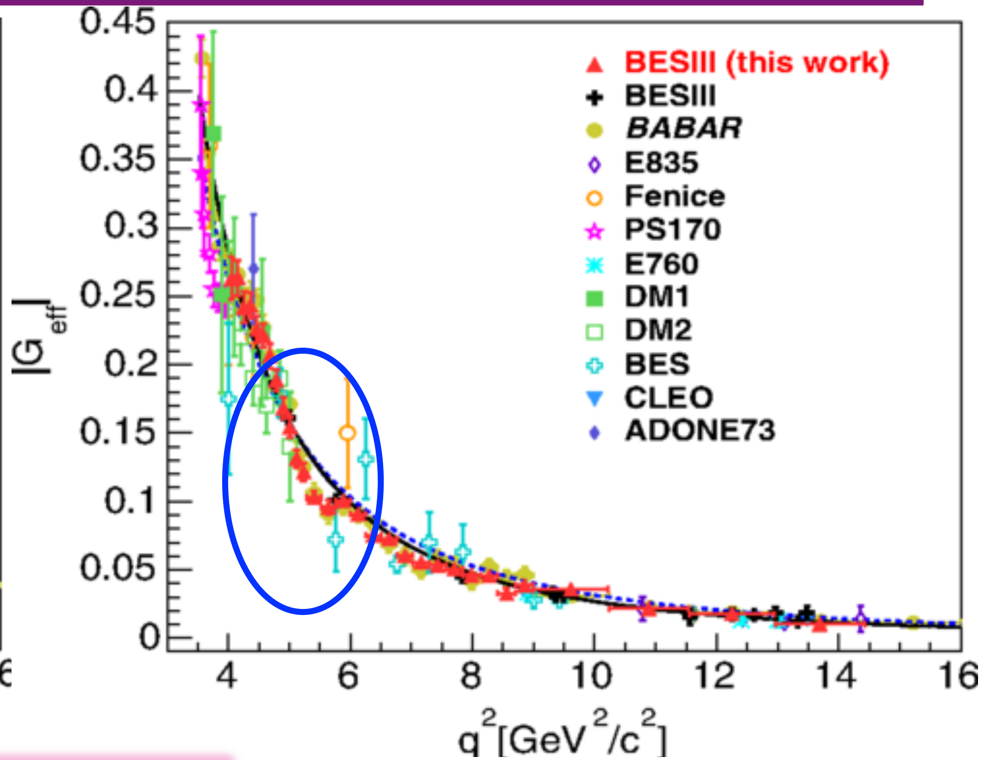
$$M^2_{miss} = \left(p_{e^+} + p_{e^+} - p_p - p_{\bar{p}}\right)^2$$

Proton FFs at BESIII with ISR (Untagged)

Phys. Rev. D 99, 092002 (2019)

Born cross section (left) and EF FF (right) at **30** intervals





- Dashed blue curve, fit using QCD inspired parameterization

$$|G_{\rm eff}| = \frac{\mathcal{A}_{\rm QCD}}{q^4[\log^2(q^2/\Lambda^2_{\rm QCD}) + \pi^2]}$$

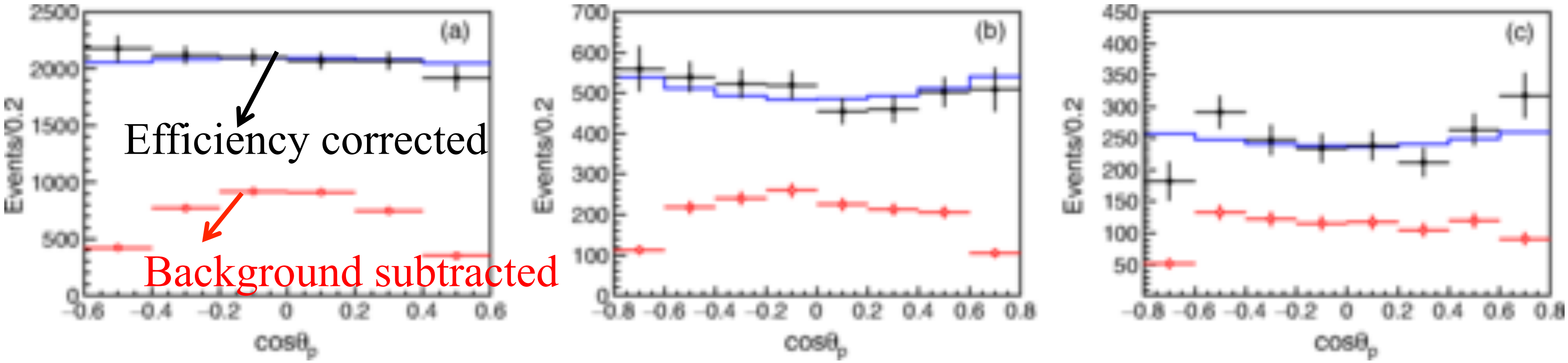
- Solid black curve, fit using systematic sinusoidal modulation

$$|G_{\rm eff}| = \frac{\mathcal{A}}{(1 + q^2/m_a^2)[1 - q^2/q_0^2]^2}$$

$$q_0^2 = 0.71\ ({\rm GeV}/c)^2,$$

Proton FFs at BESIII with ISR (Untagged)

Phys. Rev. D 99, 092002 (2019)



$$\frac{dN}{d\cos\theta_p} = A\left(H_M\left(\cos\theta_p, M_{p\bar{p}}\right) + R^2 H_E\left(\cos\theta_p, M_{p\bar{p}}\right)\right)$$

$H_M\left(\cos\theta_p, M_{p\bar{p}}\right), H_E\left(\cos\theta_p, M_{p\bar{p}}\right)$

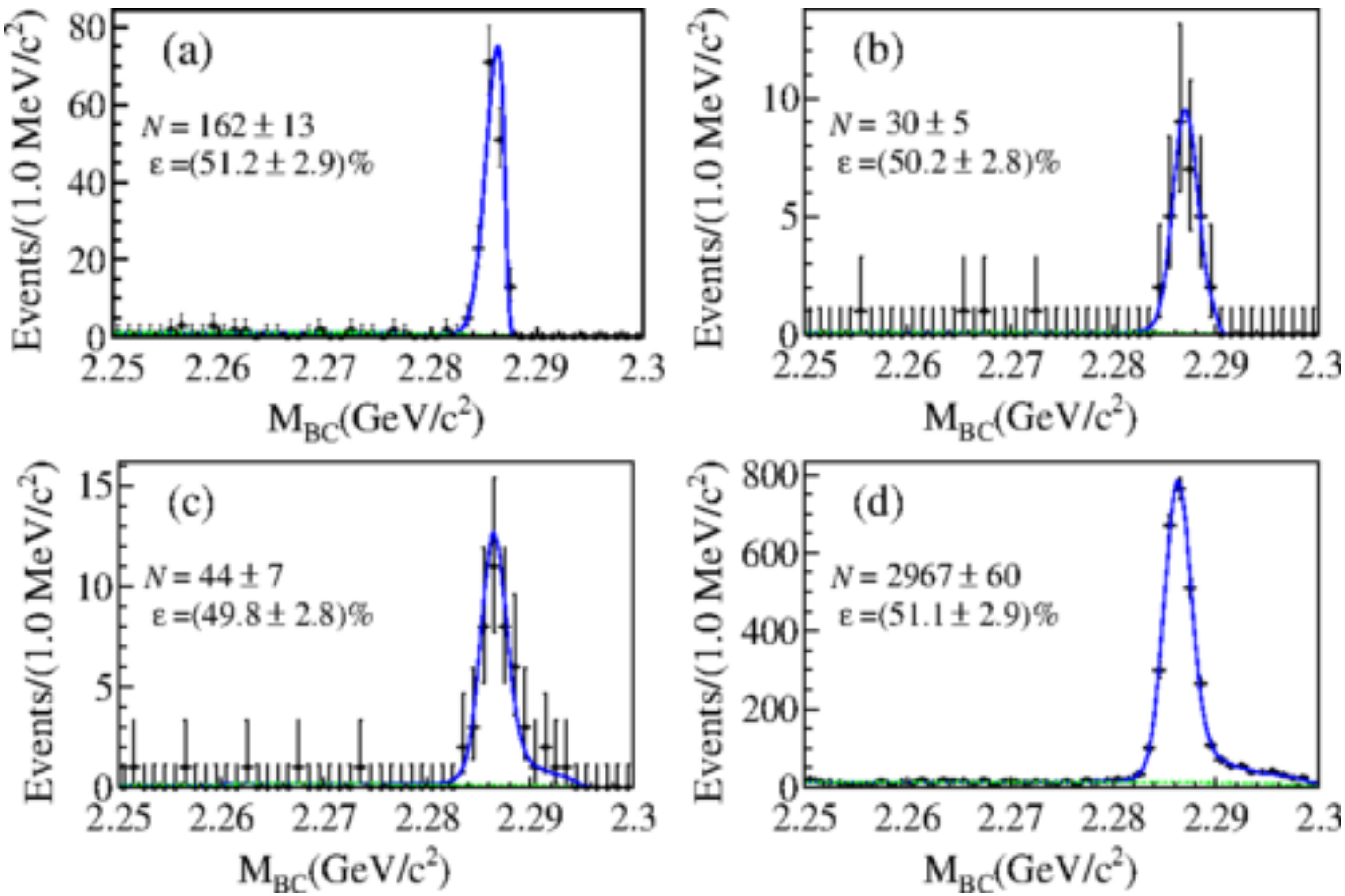
are obtained by MC by set $G_E = 0$ and $G_M = 0$,respectively.

- Denote magnetic and electric contributions to angular distribution

$\Lambda_c^+\bar{\Lambda}_c^-$ FFs near threshold at BESIII

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

Decay modes: $\Lambda_c^+ \to pK^-\pi^+, pK_S^0, \Lambda\pi^+, pK^-\pi^+\pi^0, pK_S^0\pi^0, \Lambda\pi^+\pi^0, pK_S^0\pi^+\pi^-, \Lambda\pi^+\pi^+\pi^-, \Sigma^0\pi^+, \Sigma^+\pi^+$



$$M_{BC} = \sqrt{E_{beam}^2 - p_{\Lambda_c}^2}$$