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SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Cluster of Excellence
PRISMA
Precision Physics, Fundamental Interactions and Structure of Matter

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

BES III measurements of baryon electromagnetic form factors

Christoph Rosner
On behalf of the BESIII Collaboration

QWG2022
26. – 30. 9. 2022

Outline

- Introduction:
  - Baryon electromagnetic form factors (FFs)
  - BESIII experiment and data set

- Proton FF results from BESIII
- Neutron FF results from BESIII
- Hyperon FF results from BESIII

- Summary

Baryon Structure Investigation

- Baryons possess a complex inner structure and dynamic
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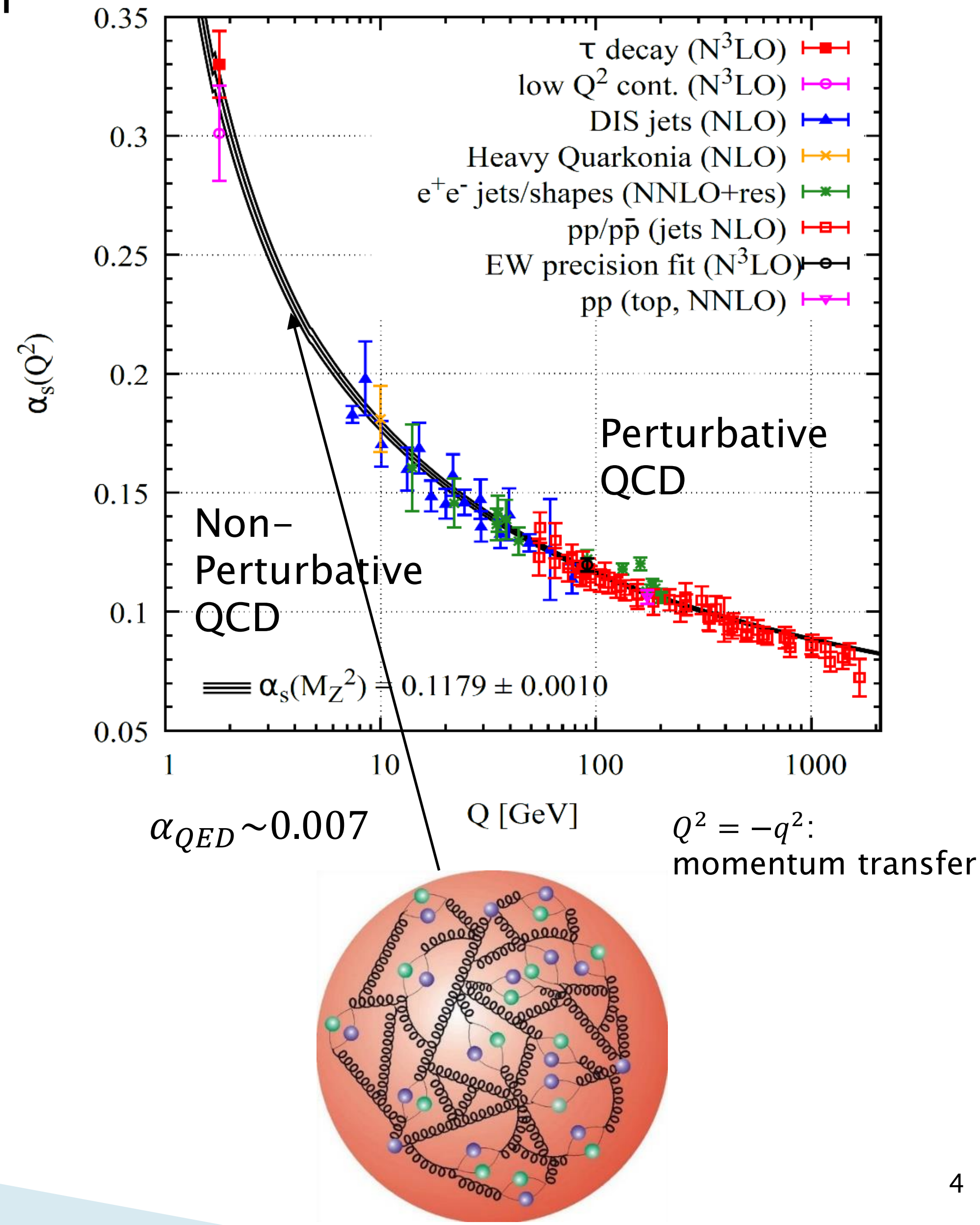
- Strong coupling constant $\alpha_s(Q^2)$ large at

  low momentum transfer Q^2

  ⇕

  large distances

Non-perturbative regime of QCD



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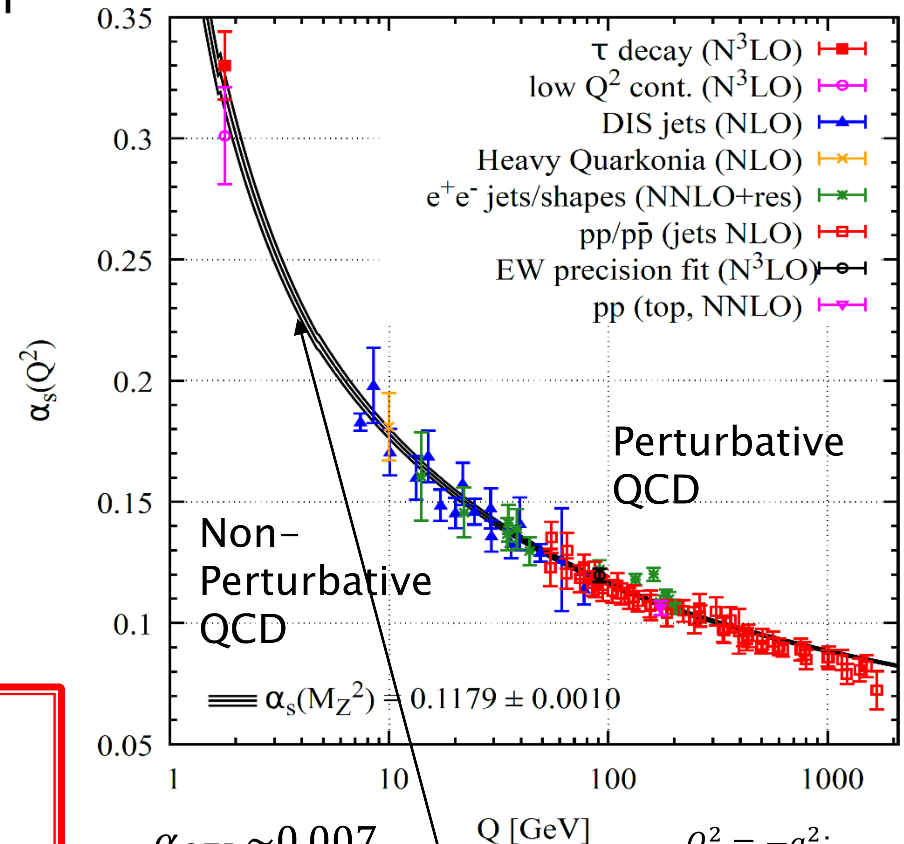
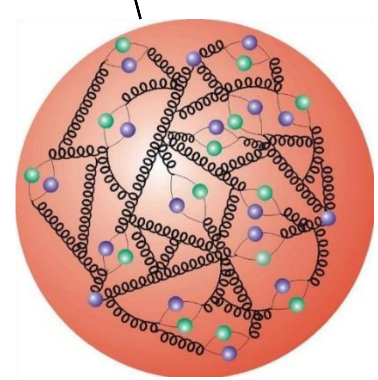


$\alpha_{QED} \sim 0.007$

$Q^2 = -q^2$: momentum transfer

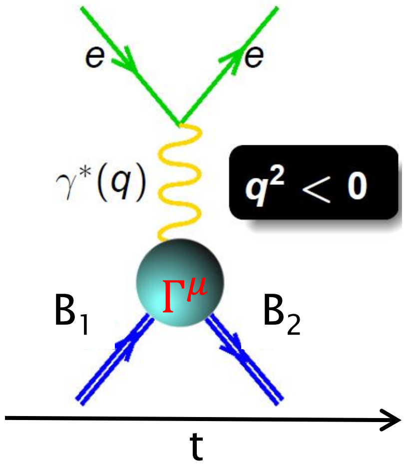


Form factors as:

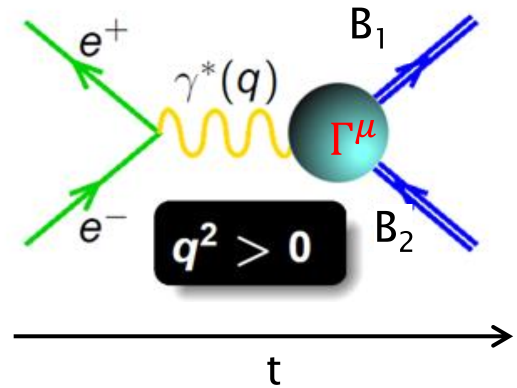
- Simplest observable of the complex inner structure and dynamics of baryons
- Testing ground for our understanding of non-perturbative QCD

Electromagnetic Form Factors

Baryon with spin s has (2s+1) Electromagnetic (EM) FFs:



Unphysical region



Spacelike region: Scattering

Timelike region: Annihilation

$Q^2 = -q^2$ FFs real

0

$4M_N^2$

FFs complex

Momentum transfer q^2

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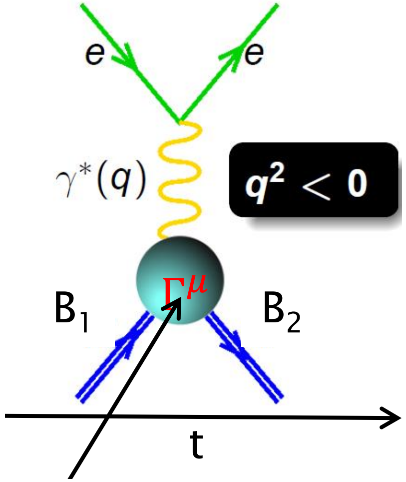

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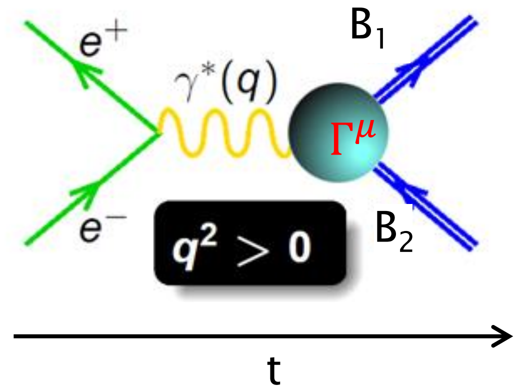

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$$\Gamma^\mu = \gamma^\mu F_1^N(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M_N} F_2^N(q^2)$$

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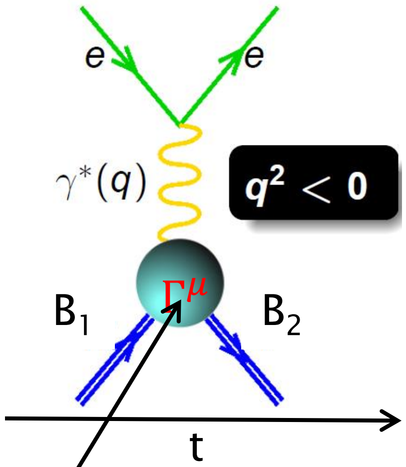

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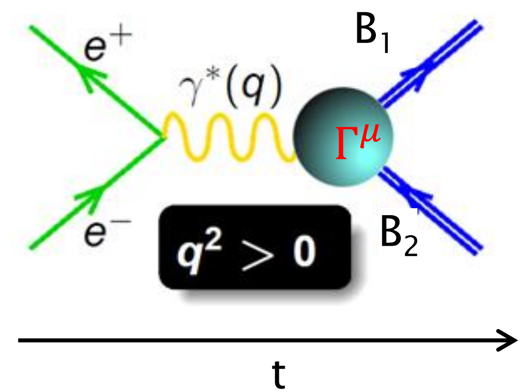

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<u>Formfactor definitions:</u>

Dirac: $F_1^N(q^2)$

Pauli: $F_2^N(q^2)$

Sachs FFs: $G_M^N = F_1^N + F_2^N$

$G_E^N = F_1^N + \frac{q^2}{4M_N^2} F_2^N$

<u>Asymptotic behaviour and boundary conditions:</u>

$$|G_{M,E}(-\infty)| = |G_{M,E}(+\infty)|$$

$$|G_M(4M^2)| = |G_E(4M^2)|$$

$$F_1(0) = Q, F_2(0) = 0$$

Timelike Form Factors

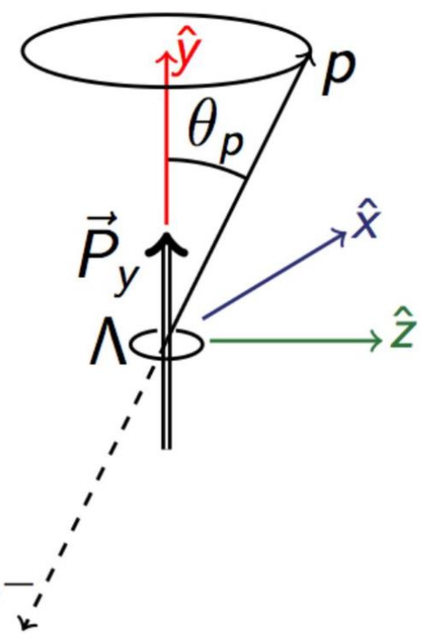
- TL FFs: Complex functions of momentum transfer:
  $G_E(q^2) = |G_E(q^2)| \cdot e^{i\phi_E}$, $G_M(q^2) = |G_M(q^2)| \cdot e^{i\phi_M}$

- FF Modulus $|G_{E,M}|$ and ratio $R = |G_E/G_M|$ accessible from baryon scattering angle

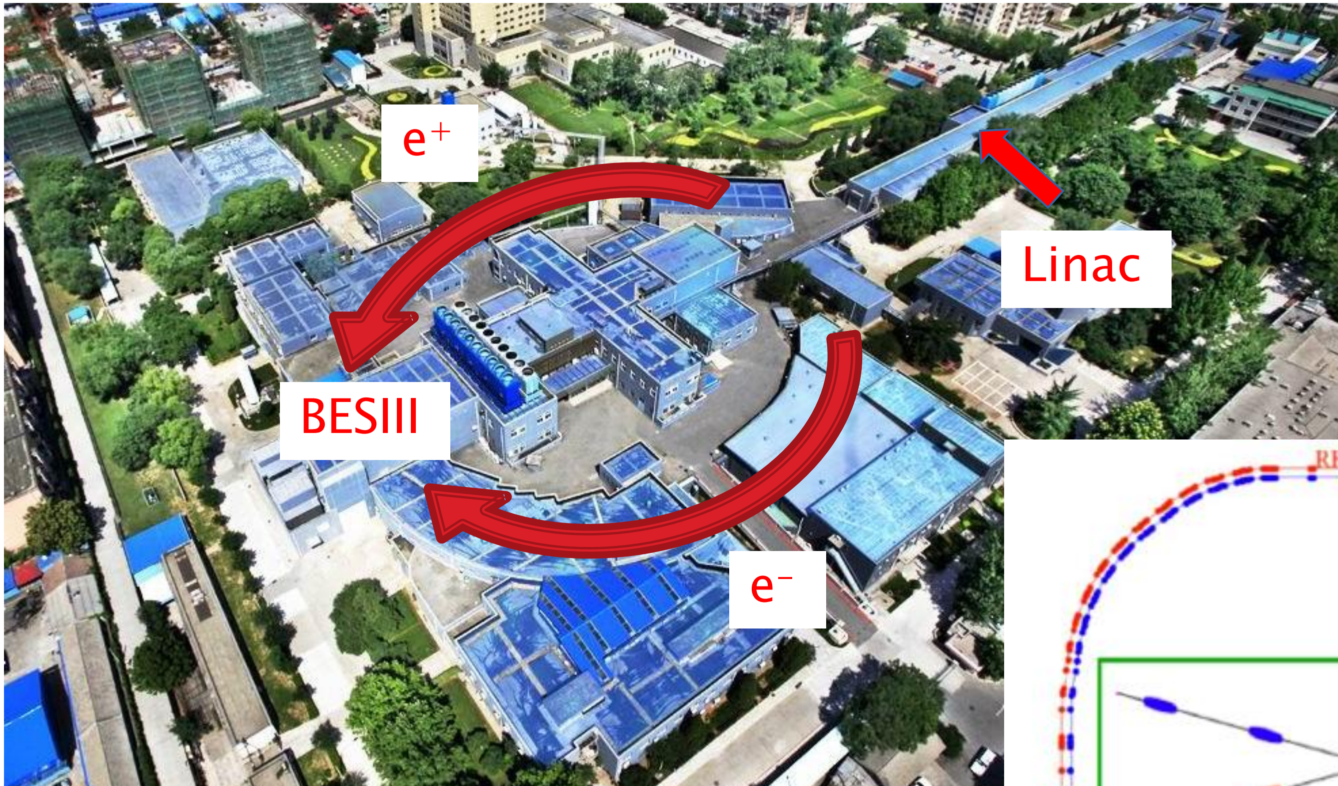
  ⇒ angular analysis

- Phase $\Delta\phi(q^2) = \phi_M(q^2) - \phi_E(q^2)$ between $G_E(q^2)$ and $G_M(q^2)$

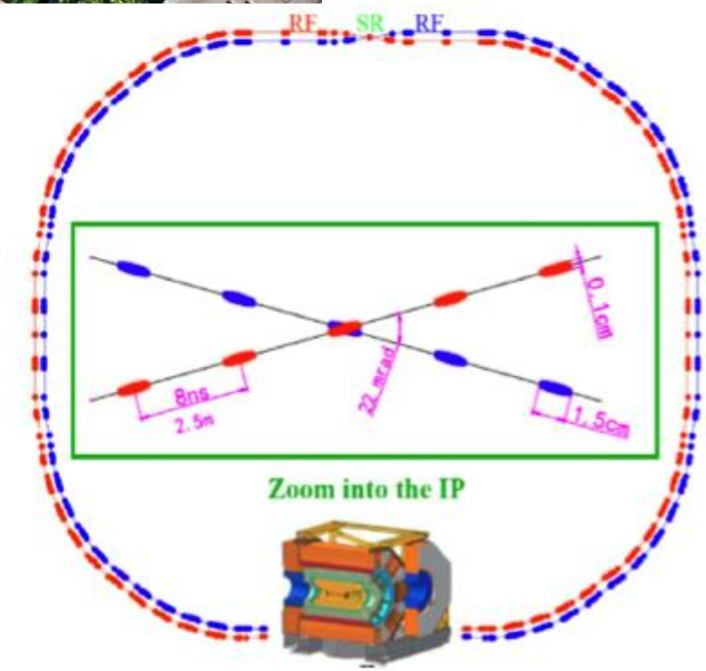
- For hyperons: $\Delta\phi$ accessible in weak, parity violating decays through polarization of final state



Beijing Electron Positron Collider



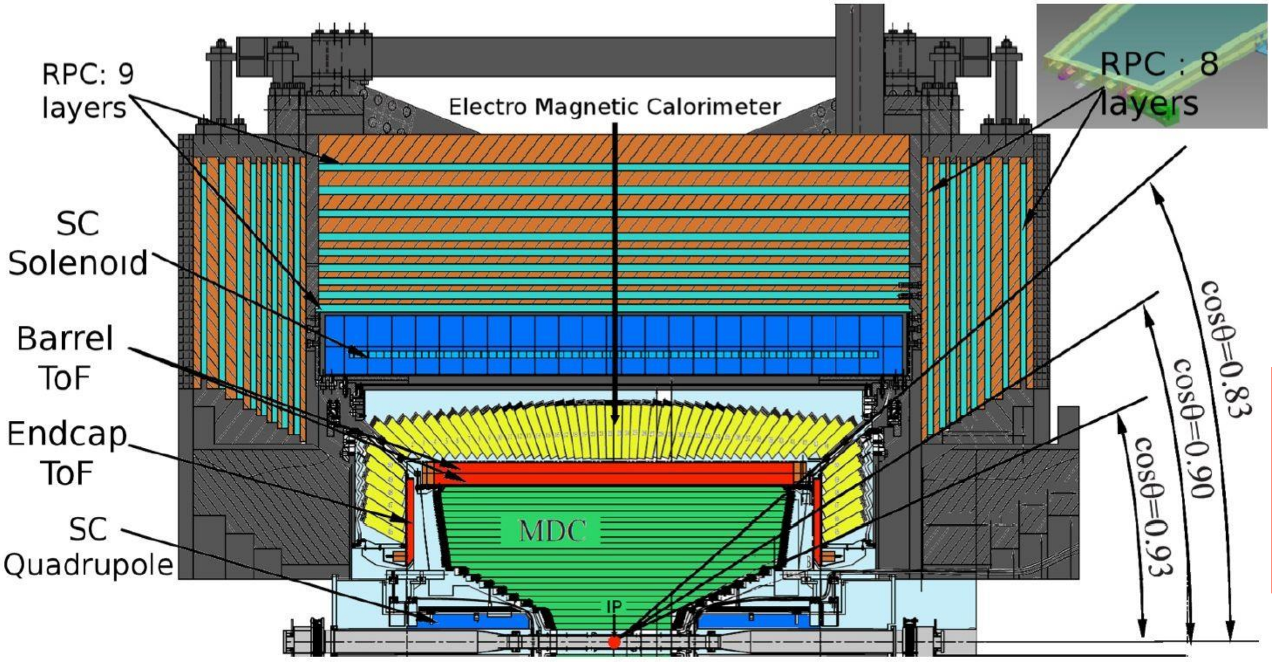
- start of construction 2004
- Data taking since 2009



- CMS energy: 2.0 – 4.95 GeV
- Optimised for τ–charm region
- Crossing angle: 11 mrad
- Design luminosity: 10^{33} cm^{-2} s^{-1} (Achieved in 2016)

BESIII Detector

1 Tesla solenoid magnet



Muon Counter:

- Resistive plate chamber
- 9 layers (Barrel), 8 layers (Endcap)
- $\sigma_{xy} = 1.48$ cm

Time of Flight:

- Plastic scintillator
- $\sigma_T = 68\ ps$ (Barrel)
- $\sigma_T = 60\ ps$ (Endcap)

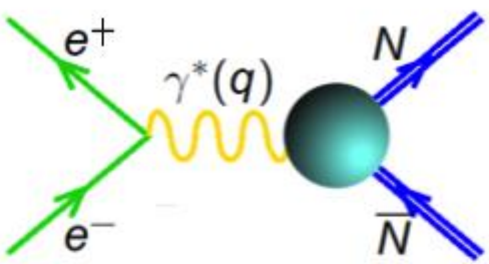
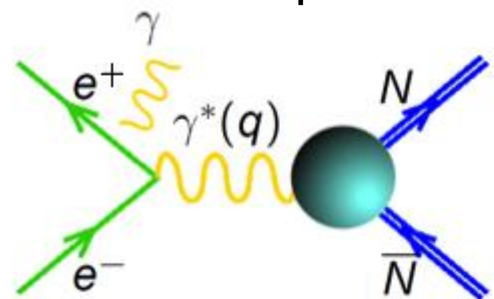
Main Drift Chamber:

- Small cell, 43 layers
- $\sigma_{xy} \approx 130\ \mu m, \frac{\sigma_{dE/dx}}{dE/dx} \approx 6\%$
- $\frac{\sigma_p}{p} \approx 0.5\%$ at 1 GeV/c

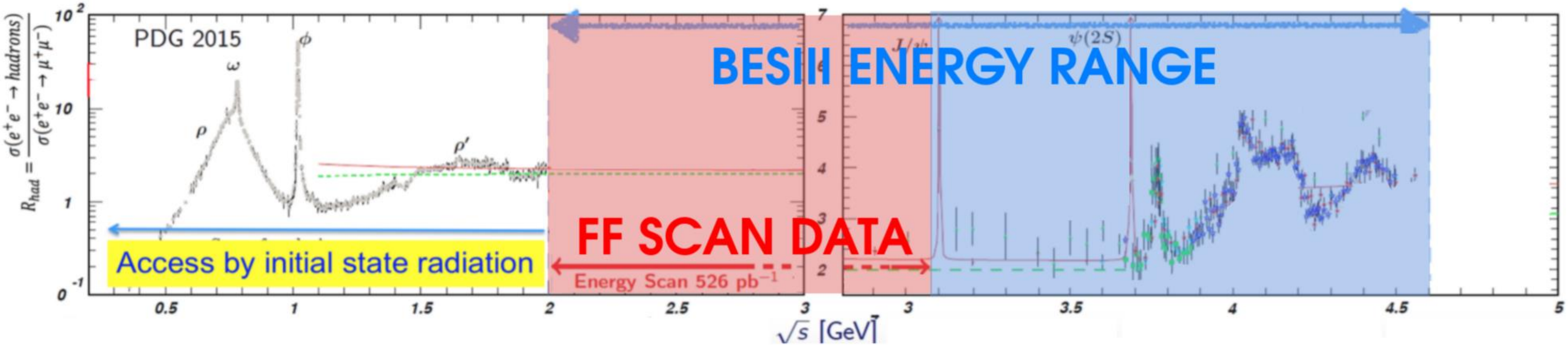
Electromagnetic Calorimeter:

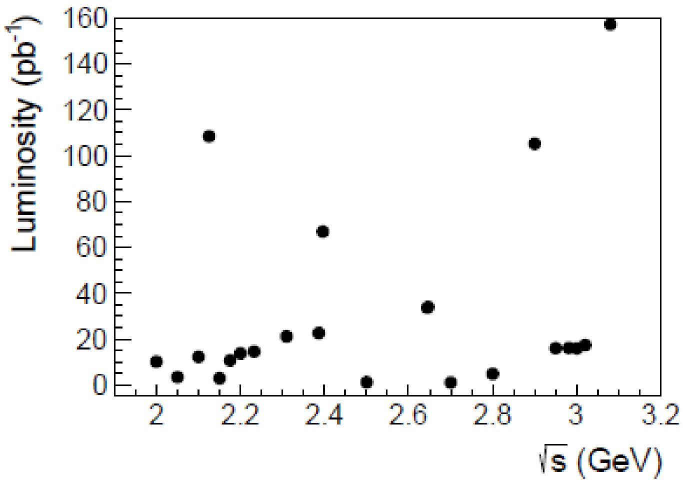
- CsI(Tl), Barrel + Endcap
- $\frac{\sigma_E}{E} < 2.5\%$ at 1 GeV/c
- $\sigma_x < 6$ mm at 1GeV/c

How to measure FFs at BESIII

Energy scan		ISR technique
		
$\frac{d\sigma_{p\bar{p}}(s)}{d\cos\theta_p} = \frac{2\pi\alpha^2\beta C}{4s}\left[\lvert G_M(s)\rvert^2(1+\cos^2\theta_p) + \frac{4m_p^2}{s}\lvert G_E(s)\rvert^2\sin^2\theta_p\right]$	<u>**Cross section**</u>	$\frac{d^2\sigma_{p\bar{p}\gamma}}{dxd\theta_\gamma} = W(s,x,\theta_\gamma)\sigma_{e^+e^-\to p\bar{p}}(s),$ $W^{LO}(x,\theta_\gamma) = \frac{\alpha}{\pi x}(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2})$
Discrete energy scan points	<u>**Beam energy**</u>	Fixed energy (resonance)
Good luminosity, but dedicated data necessary	<u>**Luminosity**</u>	Low effective luminosity due to radiator function

BESIII Data Sets





- Rich physics programm: charm physics, charmonium spectroscopy, light hadrons, …
- Worlds largest dataset at resonances J/ψ, ψ', ψ''
- Dedicated scan data set taken in 2015, main purpose: determination of baryon FFs
- 22 energy points between 2.0 and 3.08 GeV, total luminosity: 651 pb^{-1} → Worlds largest in this off-resonance region

Proton form factor measurements

Proton effective FF

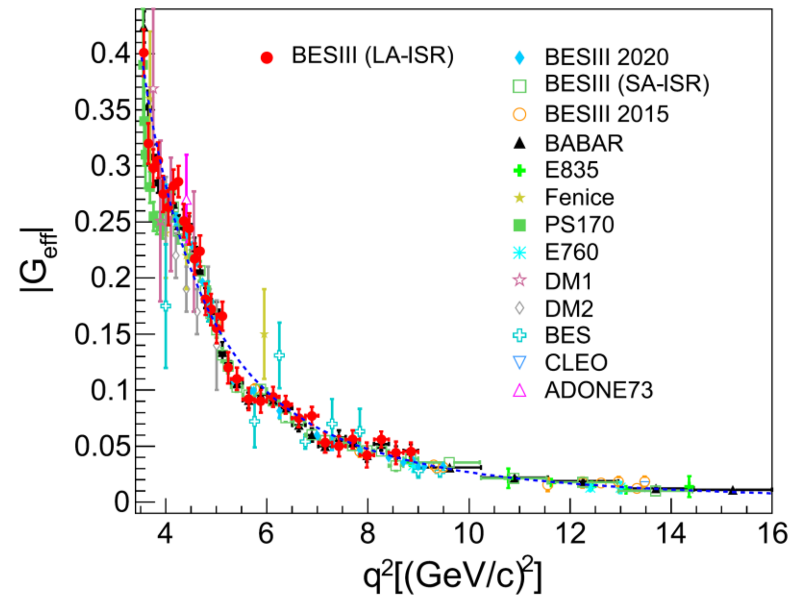
$$\sigma_{born} = \frac{N_{sel}}{\varepsilon \cdot (1+\delta) \cdot L}$$

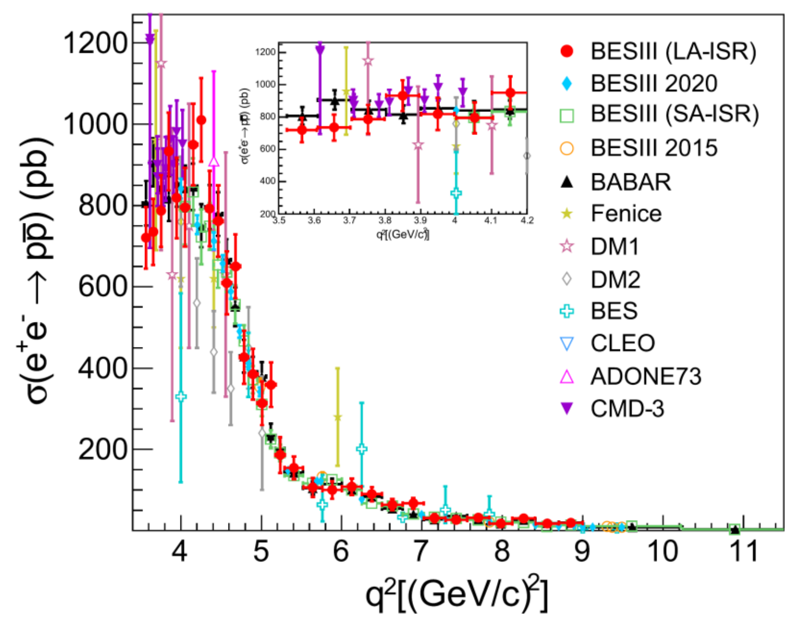
$$|G_{eff}| = \sqrt{\frac{3q^2}{4\pi\alpha^2\beta C} \cdot \frac{\sigma_{born}}{1+1/2\tau}}$$

With selected events, efficiency, radiative correction factor, luminosity

- BESIII results both from direct scan:
  - PRD 91, 112004 (2015): 157 pb^{-1} at 2.23– 3.67 GeV
  - PRL 124, 042001 (2020): 669 pb^{-1} at 2.0– 3.08 GeV

  and initial state radiation:
  - PRD 99, 092002 (2019): 7.4 fb^{-1} at 3.77– 4.60 GeV
  - PLB 817, 136328 (2021): 7.4 fb^{-1} at 3.77– 4.60 GeV





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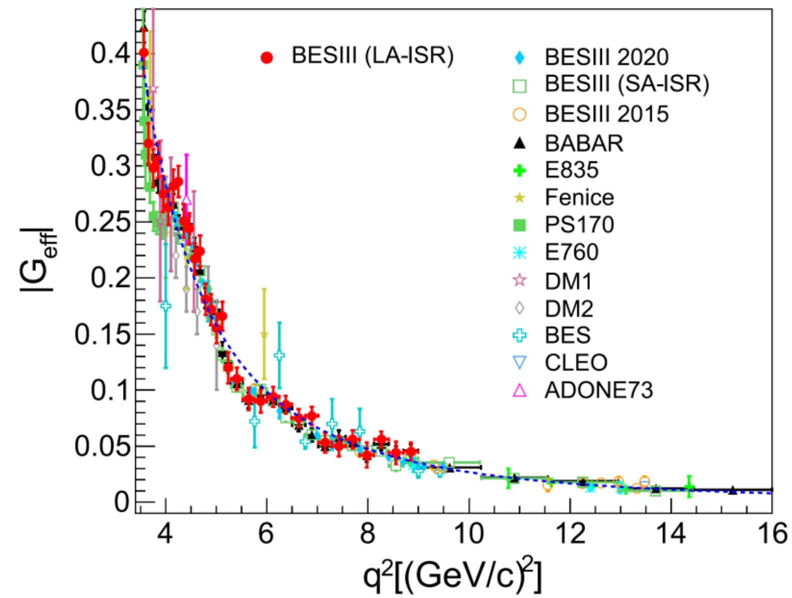

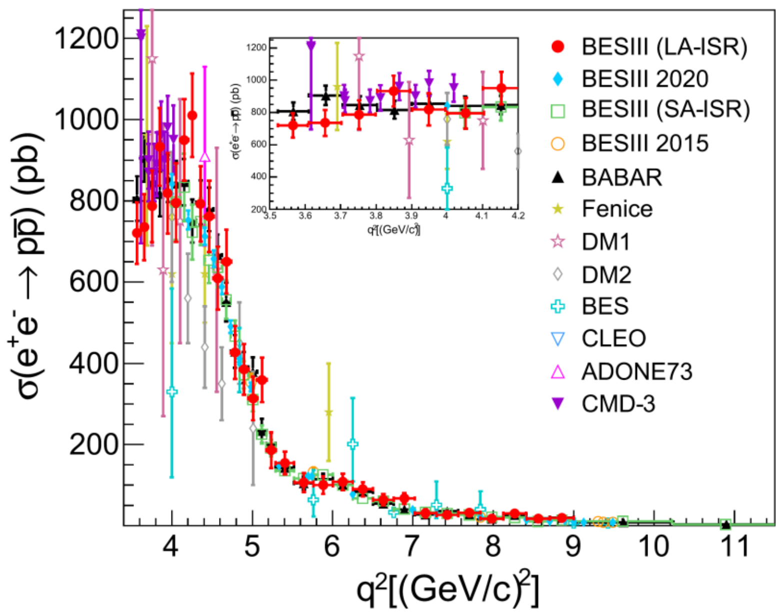

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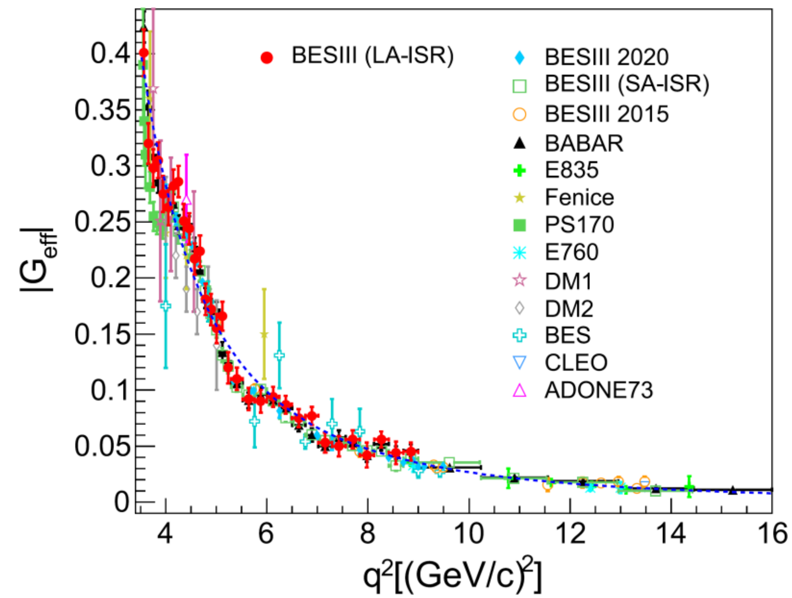
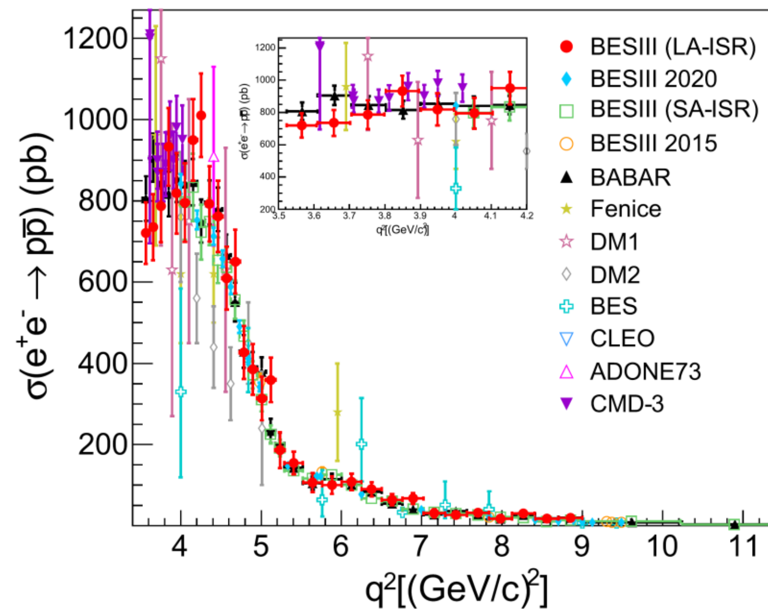
- Good agreement with previous experiments
- Most precise uncertainty between 2–4% for high luminosity data points
- BaBar: 9.4% –26.9%
- Dominated by systematics for lower energies

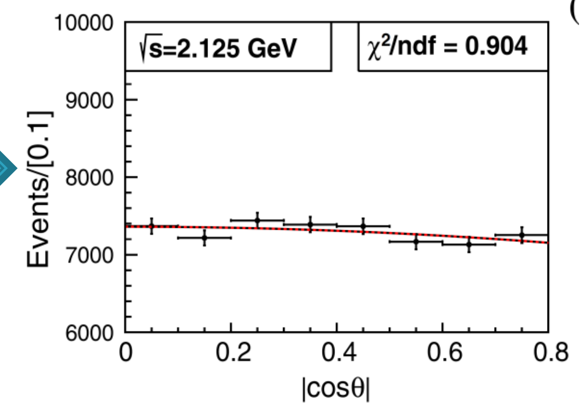




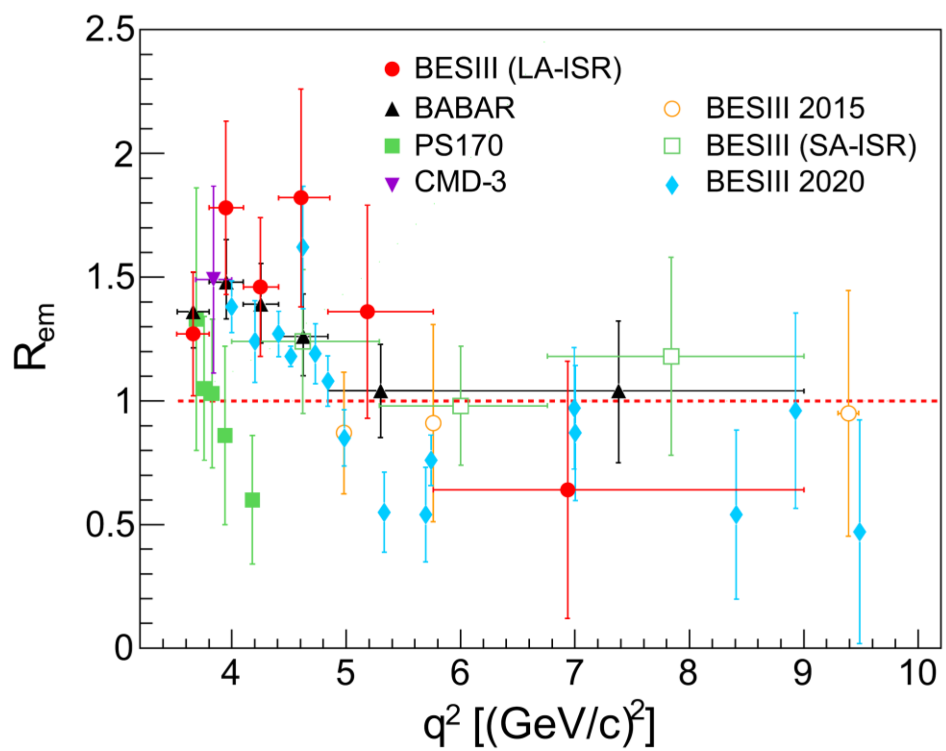
Proton FF results

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4E_{cm}^2}\left(\left(1+\cos^2\theta_p\right)|G_M|^2 + \frac{1}{\tau}\left(\sin^2\theta_p\right)|G_E|^2\right)$$

fit



- Uncertainty for R: 3.5% (2.125 GeV) and 96.0% (3.08 GeV)
- ~10% uncertainty for most lower energy points (up to 2.2324 GeV)
- Comparable to spacelike region
- All BESIII results favour BaBar result over PS170



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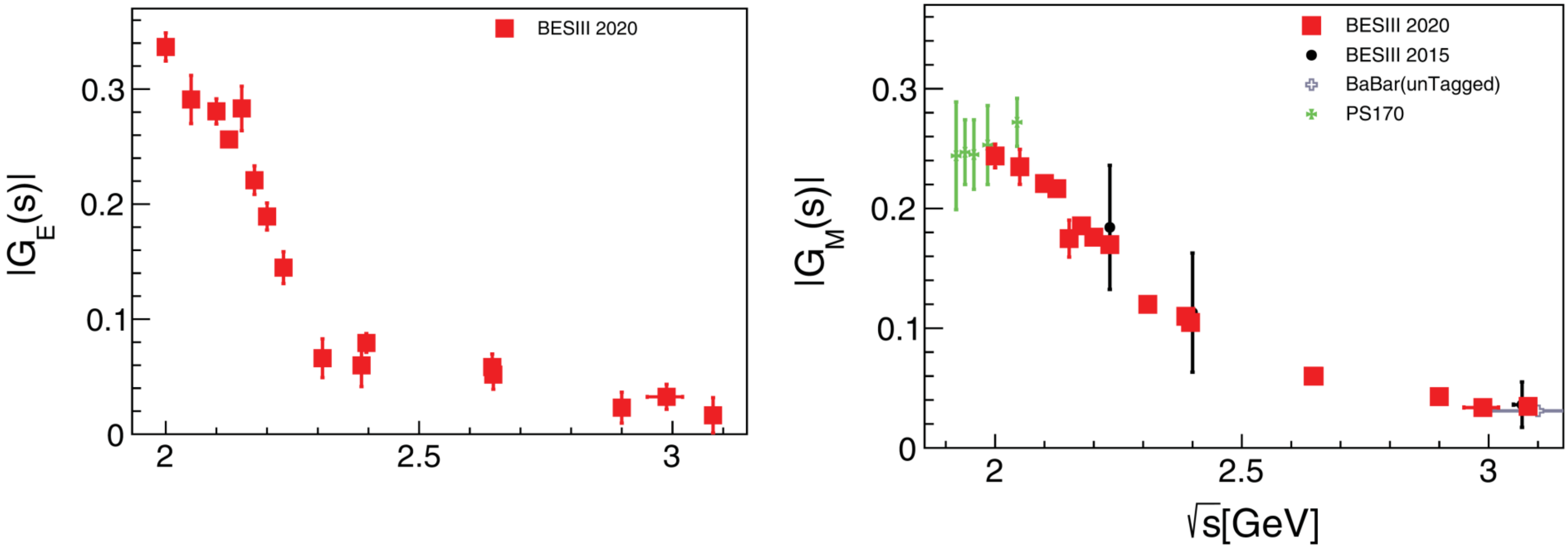
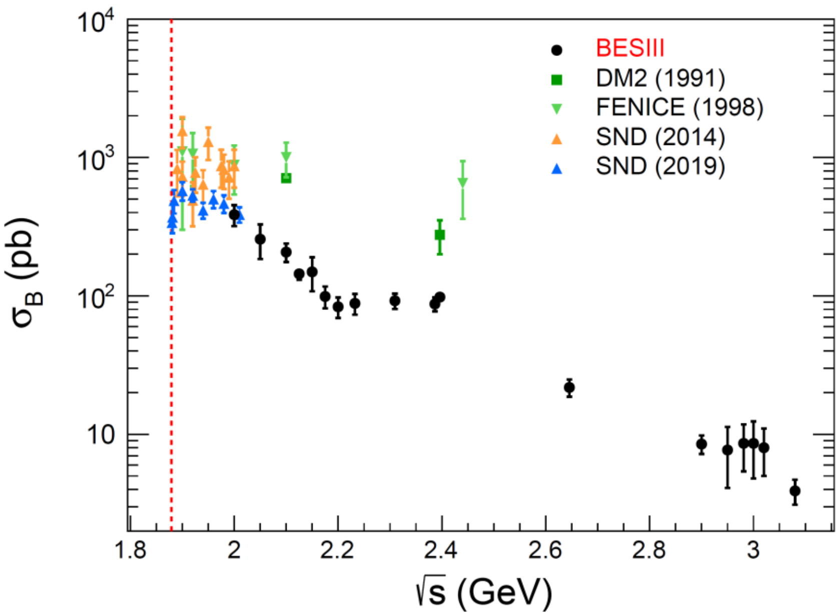
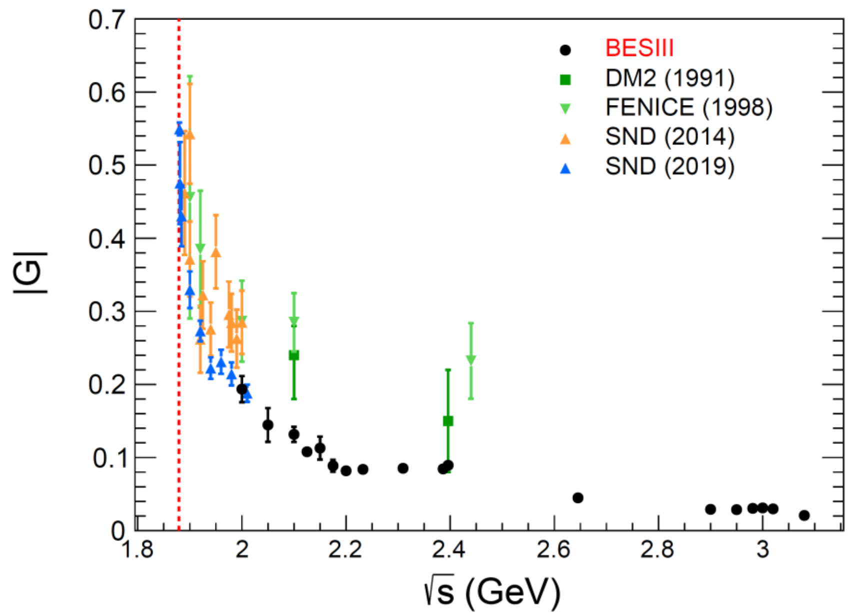


- Uncertainty for $|G_E|$: 1.9% – 83.2%
- Uncertainty for $|G_M|$: 1.3% – 9.8%
- First measurements of $|G_M|$ over wide kinematical range, vastly improved accuracy
- First separate extraction of $|G_M|$ and $|G_E|$

Neutron form factor measurements

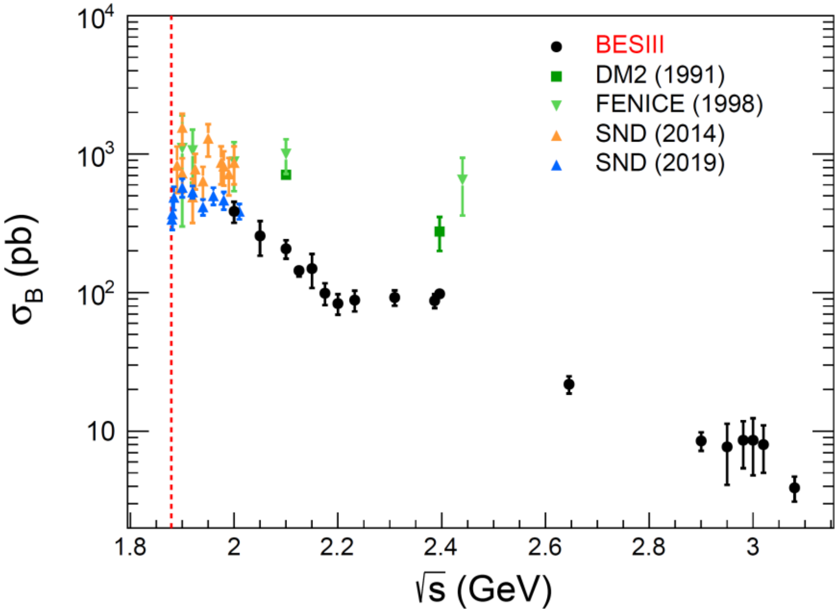
Neutron effective FF

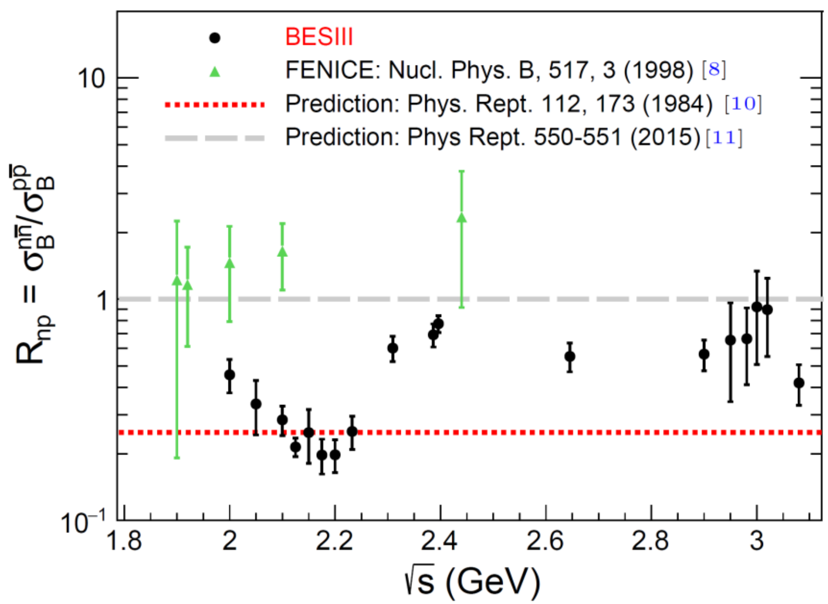




- First measurement of $\sigma_B(e^+e^- \to n\bar{n})$ over wide kinematical range
- Lowest uncertainty: 8.1% at 2.396 GeV → unprecedented precision
- Agreement with SND at low CM energies
- Tension between BESIII and Fenice results (~2σ)

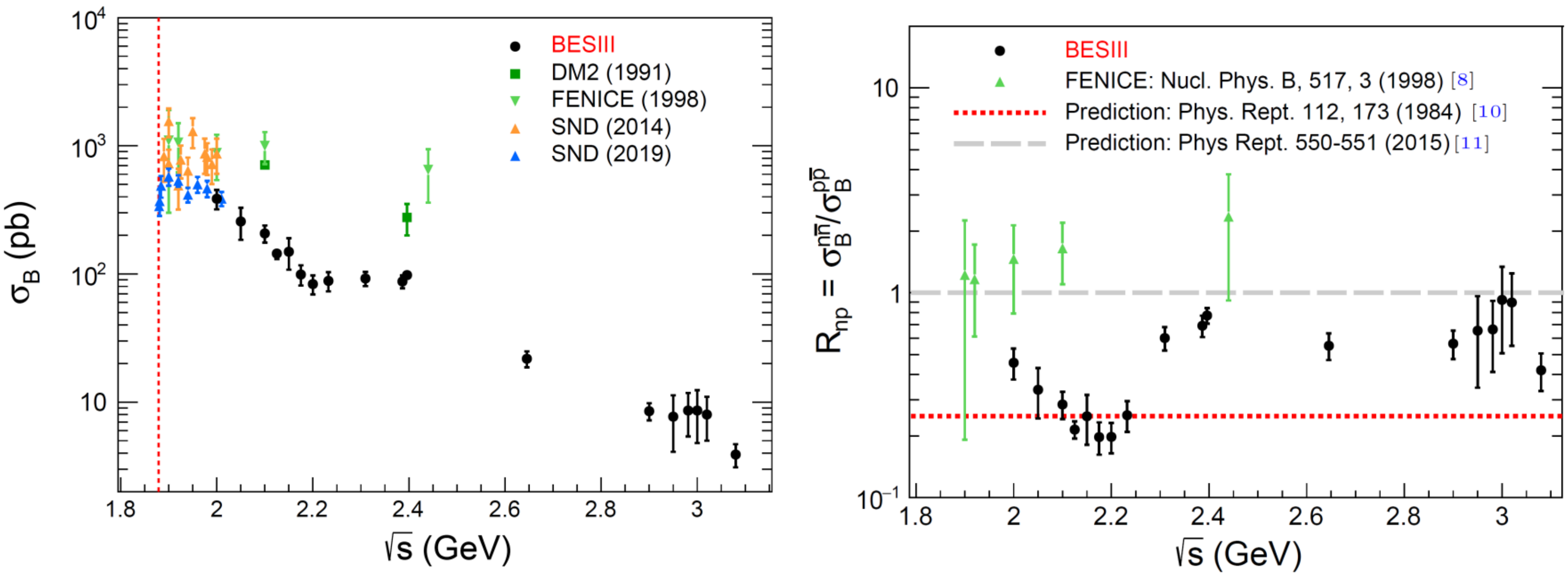
Neutron effective FF





- Unlike Fenice result: $R_{np} = \sigma_B^{n\bar{n}}/\sigma_B^{p\bar{p}} < 1$
  → Coupling of virtual photon to proton stronger than neutron in agreement with expectation
- Solves the 20 years old photon-nucleon interaction puzzle

Neutron effective FF



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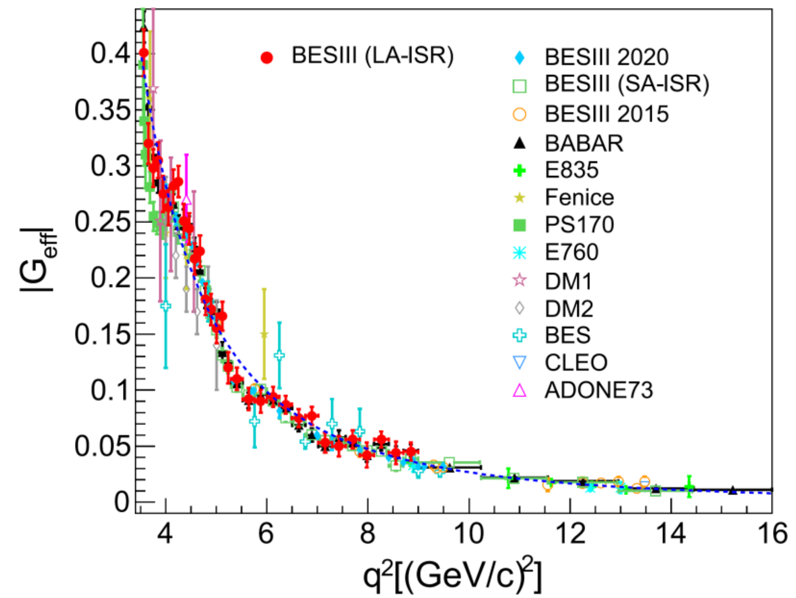
Measured for the first time: Form factor ratio and $|G_M|^2$

to be published soon

Periodic structures

- $|G_{eff}|$ follows Dipole behaviour:

$$|G_{eff}| = \frac{\mathcal{A}}{(1+\frac{s}{m_a^2})\left[1-\frac{s}{0.71(GeV/c)^2}\right]^2},$$



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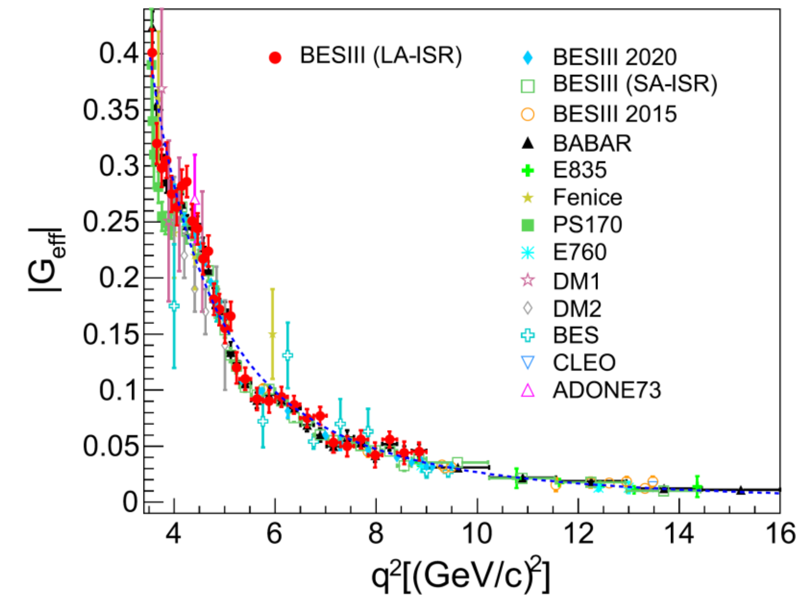
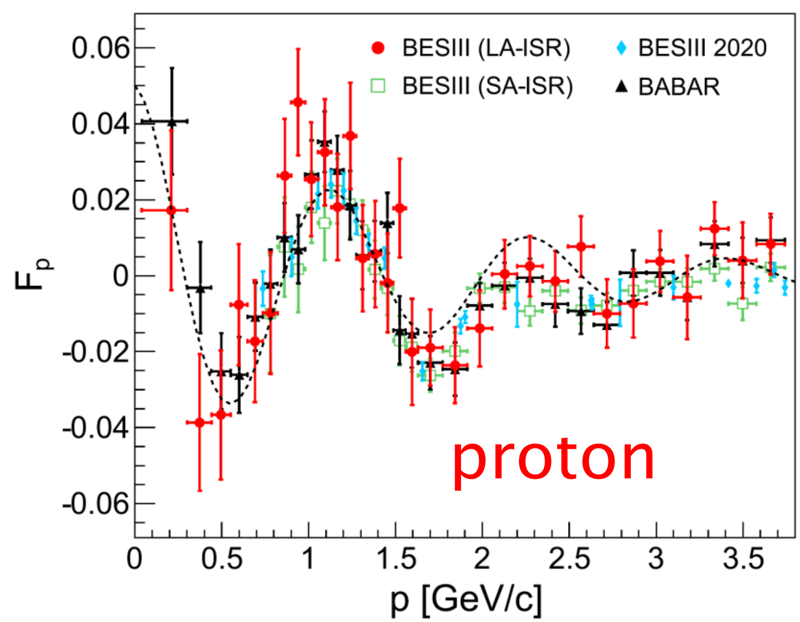
- Periodic structure in residuals, first seen in BaBar data

$$G_{osc}(p) = b_0^{osc} e^{-b_1^{osc} p} \cos(b_2^{osc} p + b_3^{osc})$$

- For proton: Confirmed independently by three BESIII analyses





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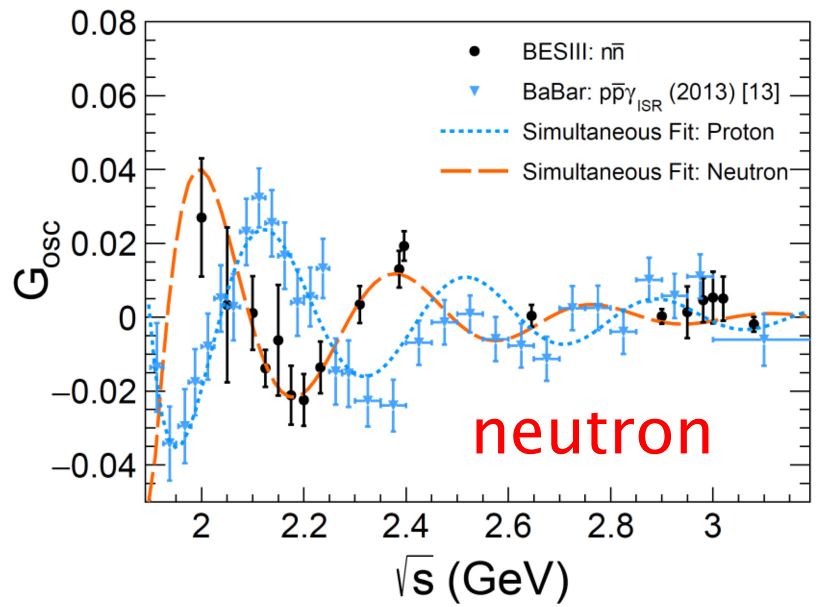
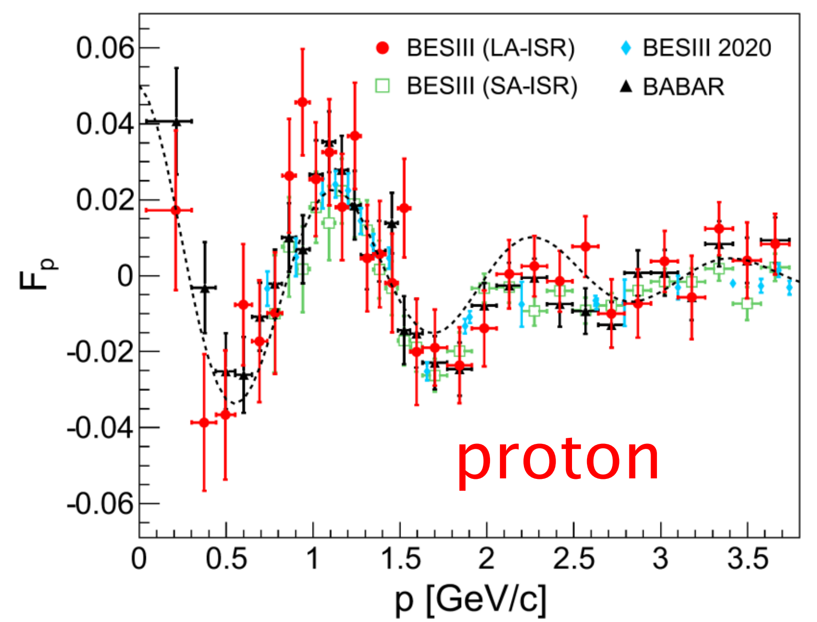
- For proton: Confirmed independently by three BESIII analyses
- First time seen in neutron data (simultaneous fit), phase shift: $(123 \pm 12)^\circ$
- Possible causes still debated, e. g.:
  - Interference effects in final state
    PRC 103 3, 035203 (2021)
  - Resonant structures
    PRD 92 3, 034018 (2015)





Hyperon Form factor measurements

Hyperon Form Factors at BESIII

- Measurements of $e^+e^- \to B\bar{B}$ with $B = \Lambda, \Sigma, \Xi, \Lambda_c^+$ at BESIII using the scan technique

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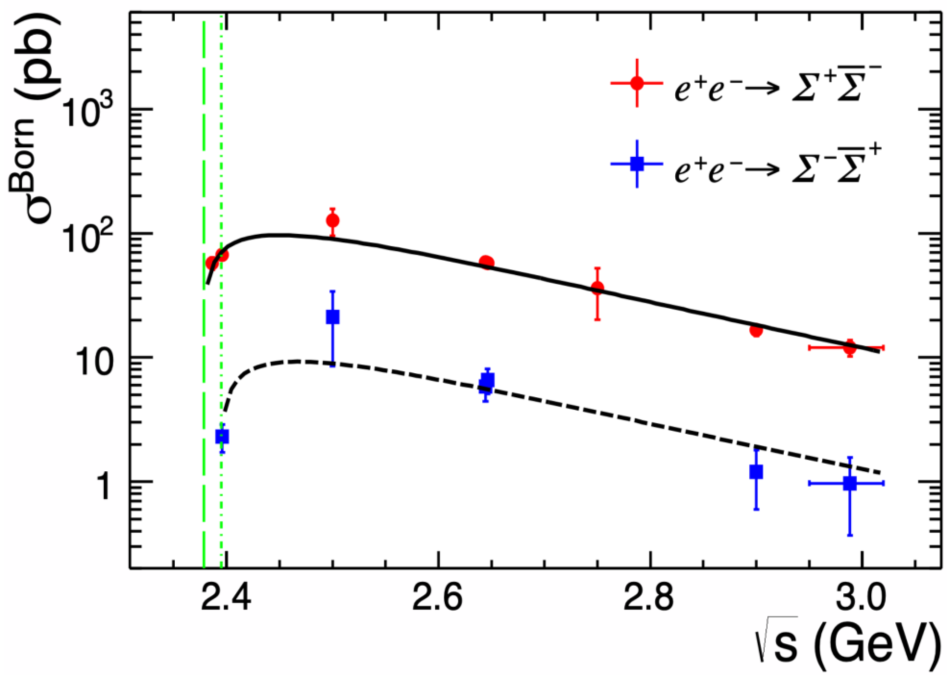
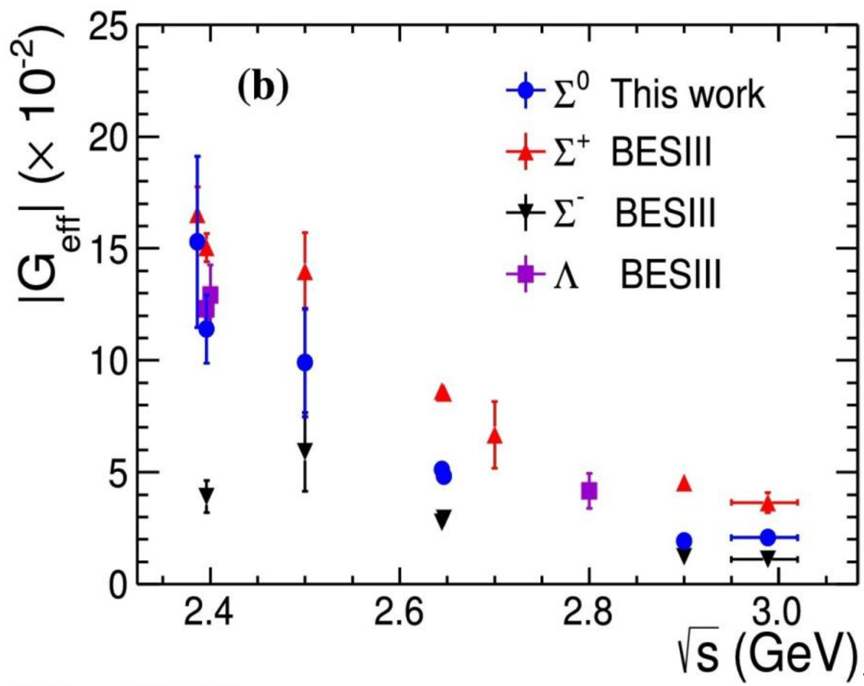
- First measurement in off-resonance region





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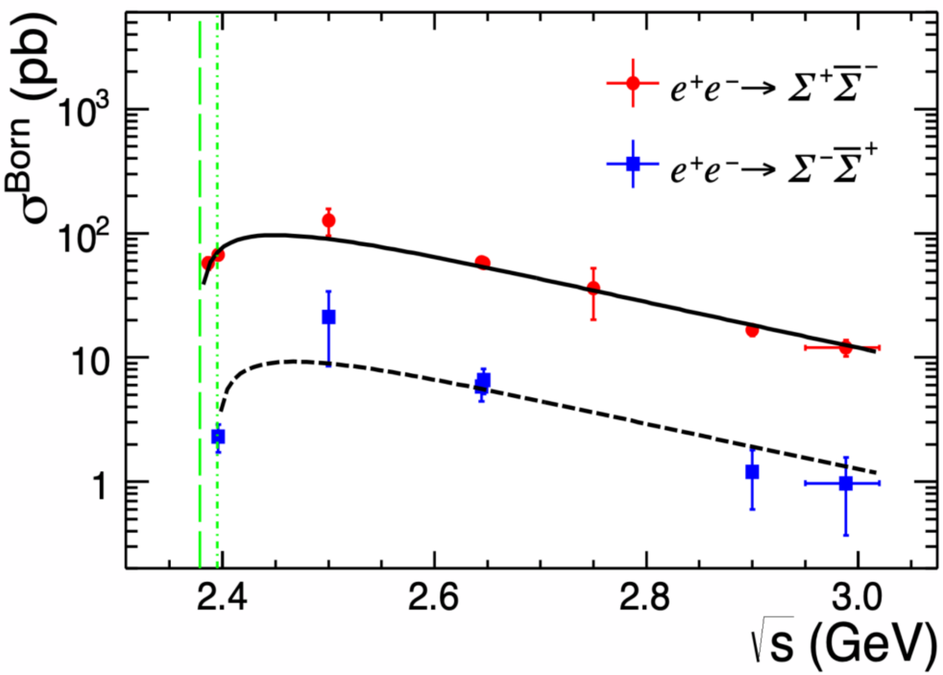
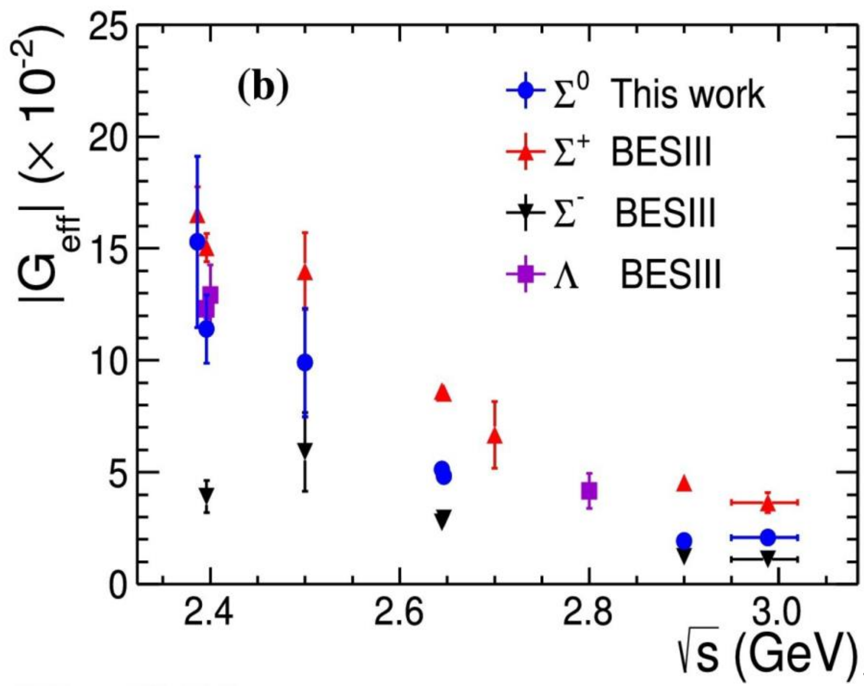
- First measurement in off-resonance region
- Eff. FF ratio of Λ/Σ^+ as expected, but Σ^+/Σ^- cross section ratio ~9, significantly above expectation from SU(3) symmetry breaking (10%–30%)





Hyperon Form Factors at BESIII

- Measurements of $e^+e^- \to B\bar{B}$ with $B = \Lambda, \Sigma, \Xi, \Lambda_c^+$ at BESIII using the scan technique

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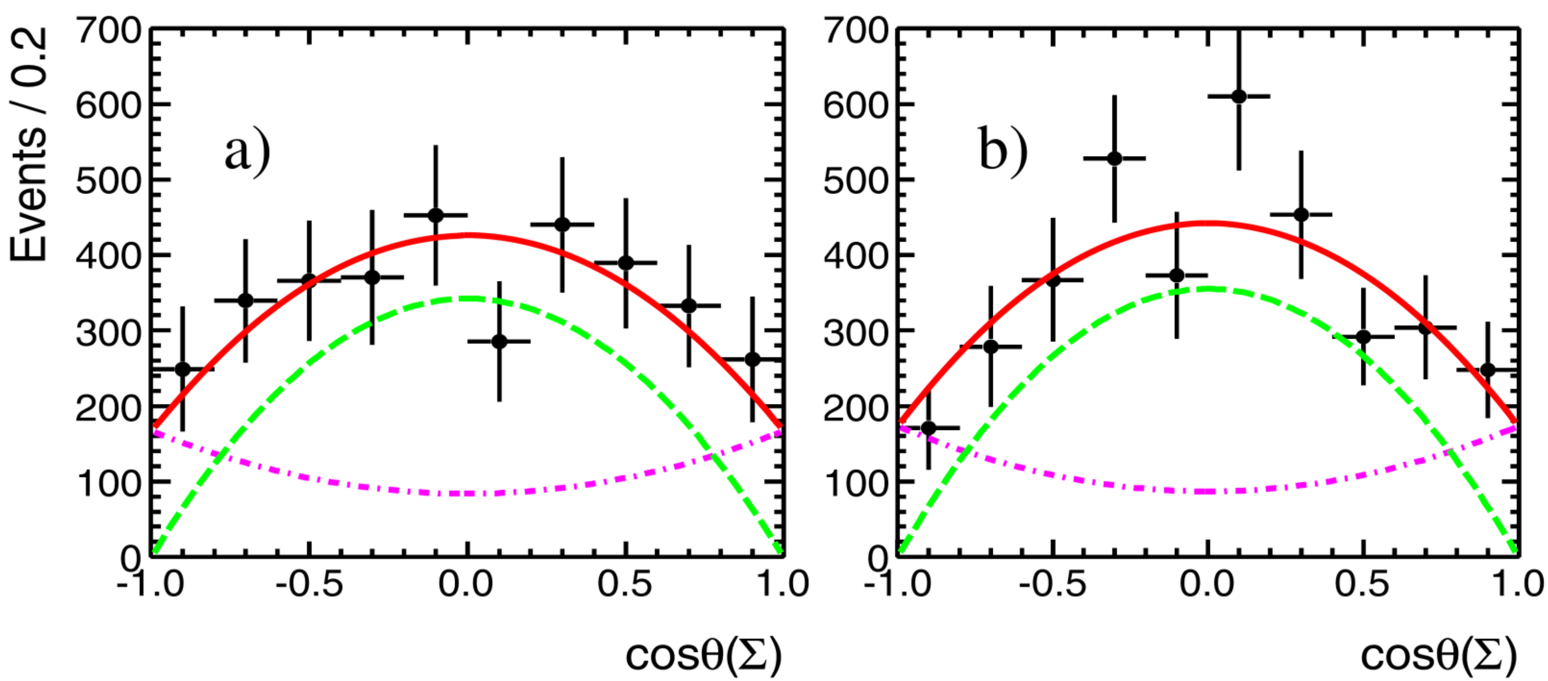
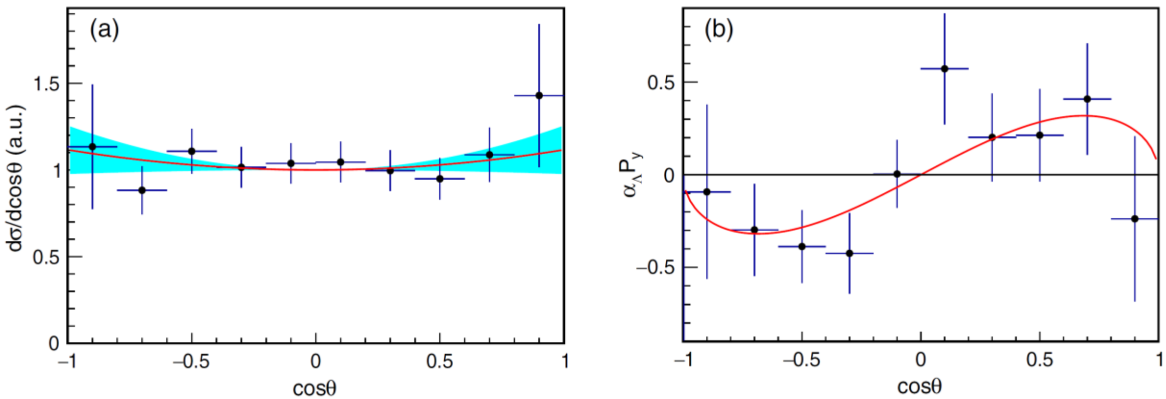
- $e^+e^- \longrightarrow \Sigma^+\bar{\Sigma}^-, \Sigma^-\bar{\Sigma}^+, \Sigma^0\bar{\Sigma}^0$: cross section measured from 2.3864 to 3.02 GeV
- First measurement in off-resonance region
- Eff. FF ratio of Λ/Σ^+ as expected, but Σ^+/Σ^- cross section ratio ~9, significantly above expectation from SU(3) symmetry breaking (10%–30%)
- Σ^+: $|G_E/G_M|$ measured to be 1.83±0.26 at 2.396 GeV → significantly above 1



Λ form factors at BESIII

- First complete measurement of Λ form factors at 2.396 GeV by BESIII



- $R = |G_E/G_M| = \mathbf{0.96 \pm 0.14 \pm 0.02}$
- $\Delta\Phi = \mathbf{37^o \pm 12^o \pm 6^o}$
- $\sigma = 118.7 \pm 5.3 \pm 5.1$ pb

- Most precise result on $|G_E/G_M|$ and σ_{born}
- First conclusive result on phase between G_E and G_M

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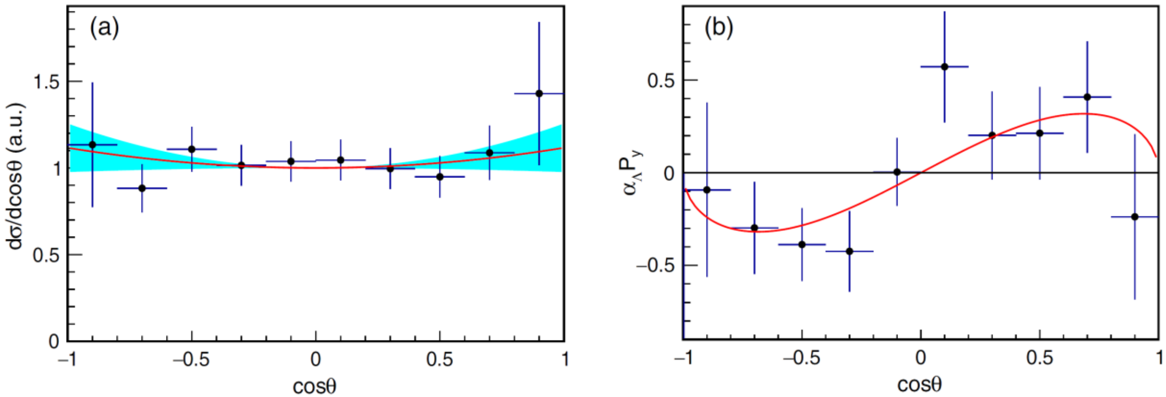

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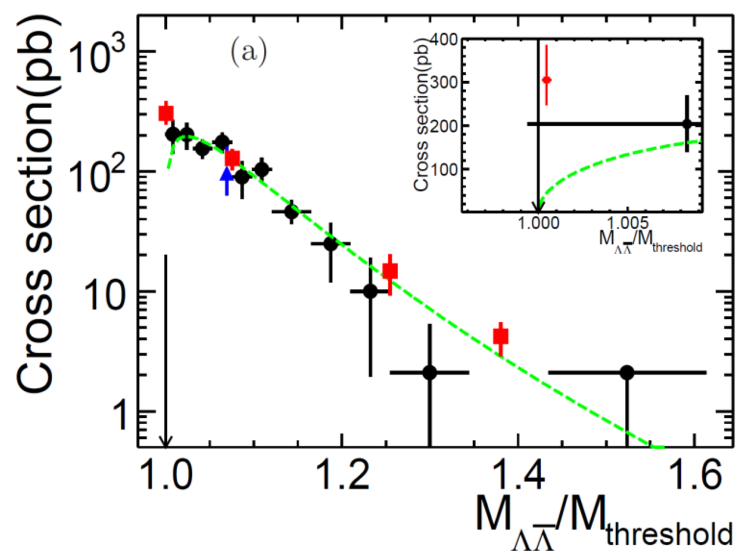
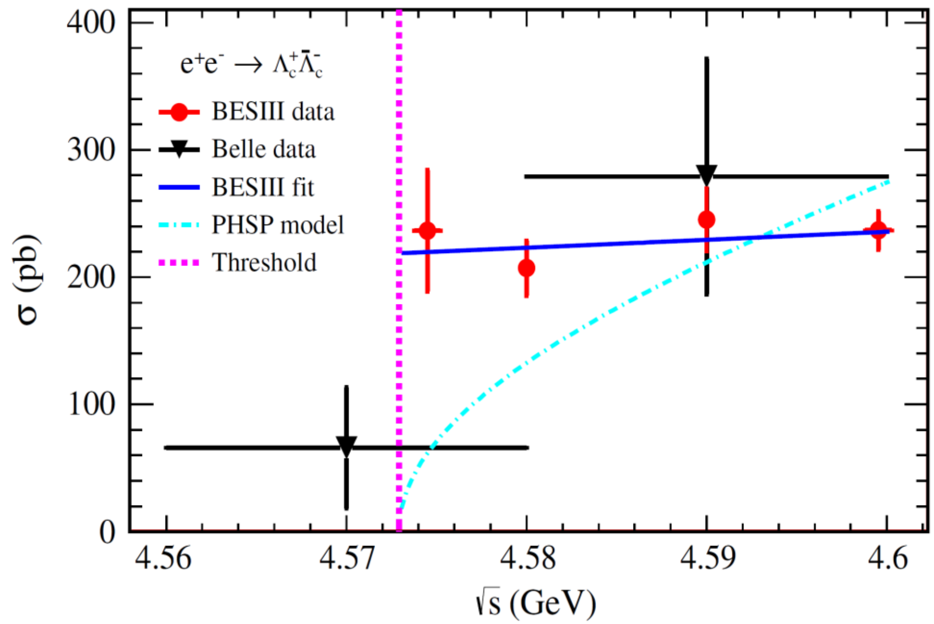


- Most precise result on $|G_E/G_M|$ and σ_{born}
- First conclusive result on phase between G_E and G_M
- Anomalous behaviour of σ_{born} near threshold compared to pQCD prediction

Λ_c^+ form factors at BESIII

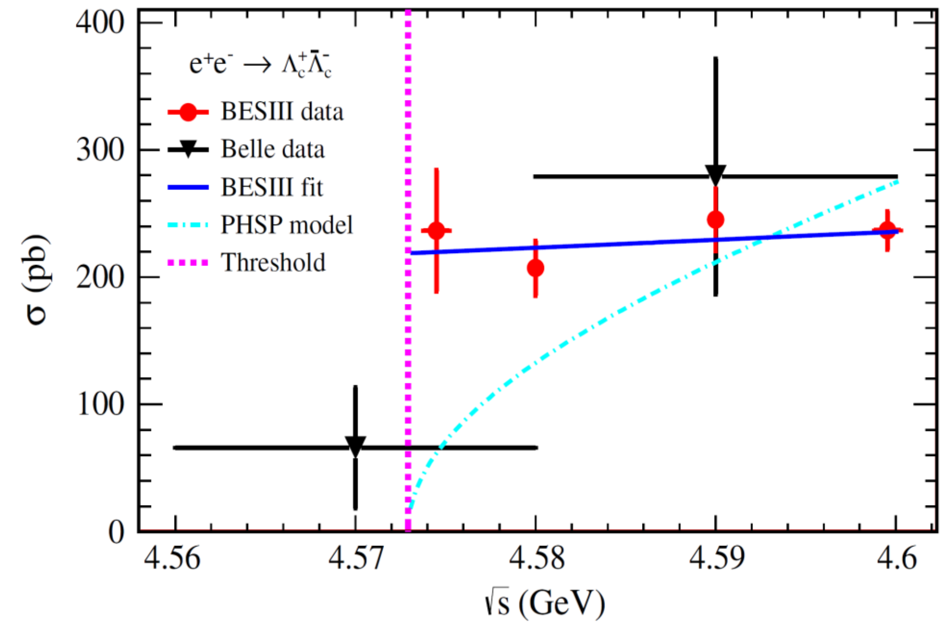
- ECM = 4.5745, 4.58, 4,59, 4.5995 GeV
- Just 1.6 MeV over threshold

- First direct measurement of Λ_c^+ form factors

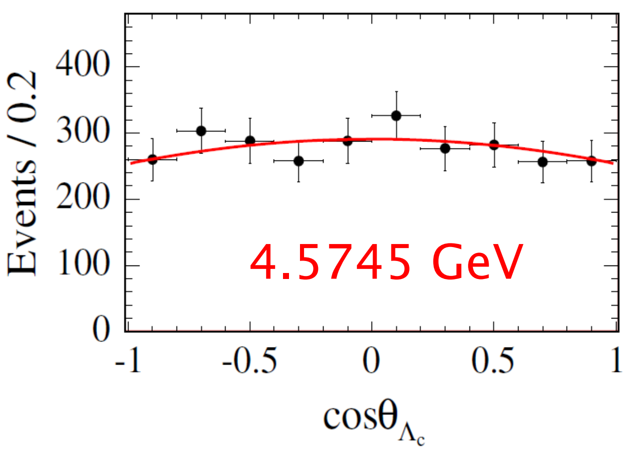


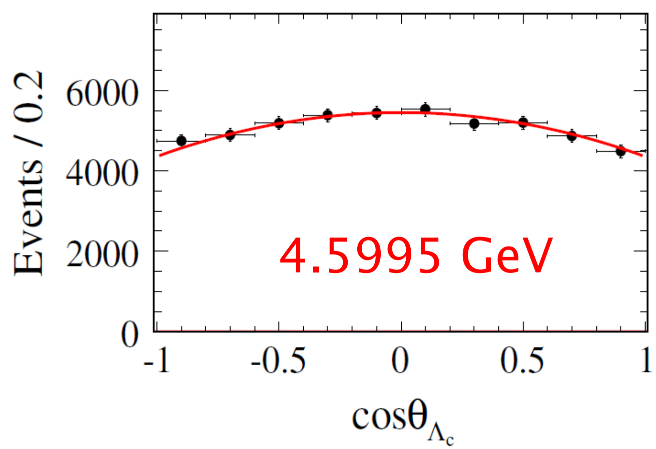
Λ_c^+ form factors at BESIII

- ECM = 4.5745, 4.58, 4,59, 4.5995 GeV
- Just 1.6 MeV over threshold
- First direct measurement of Λ_c^+ form factors
- $|G_E/G_M|$ extracted at two energy points

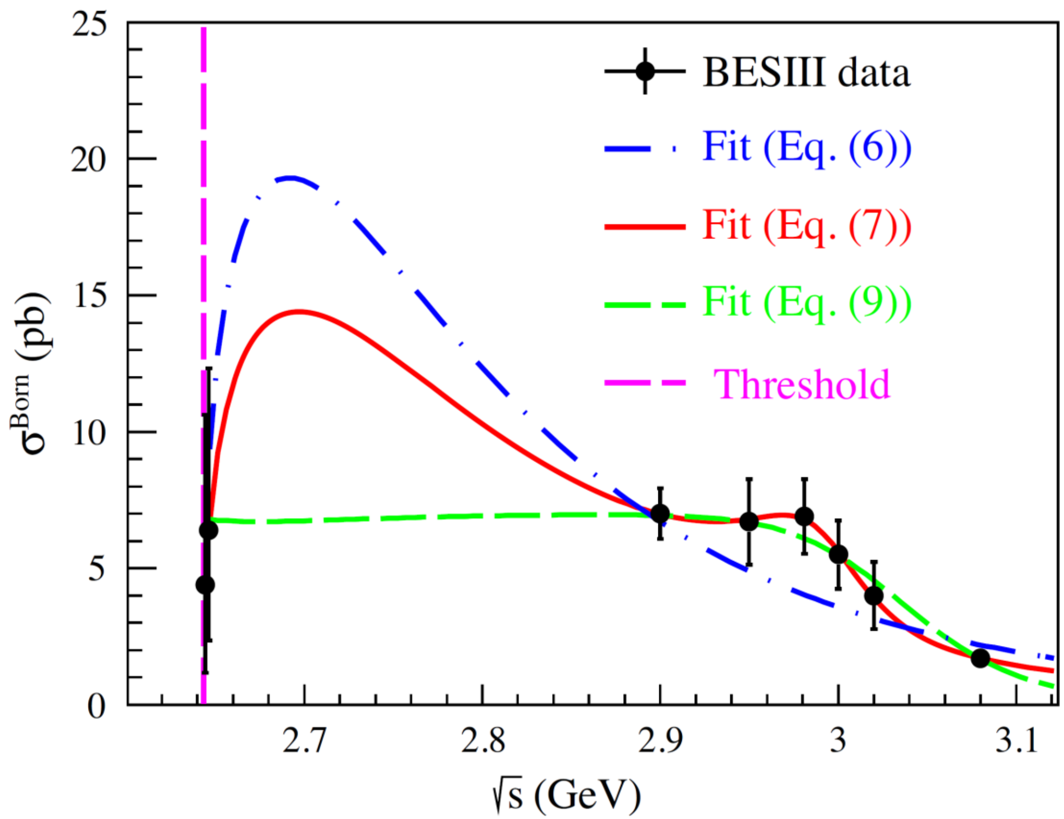


$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$



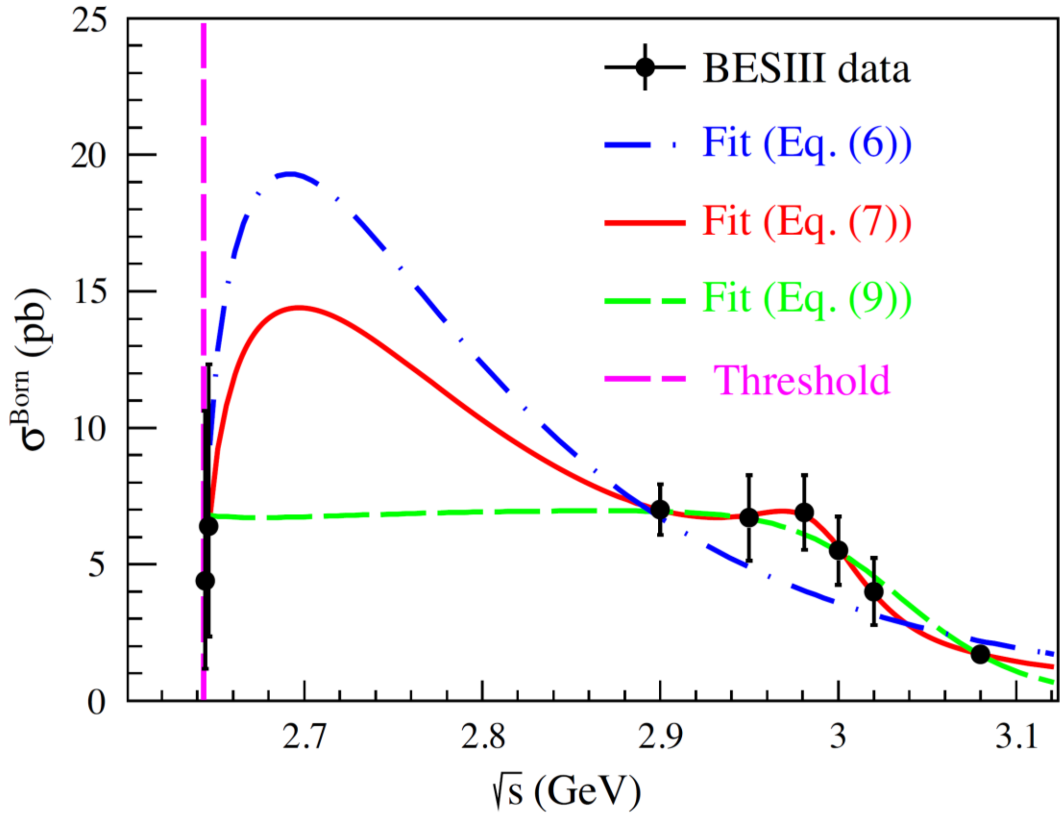


Ξ form factors at BESIII



- First measurement of the process $e^+e^- \to \Xi^-\bar{\Xi}^+$
- Cross section and eff. FF measured from close to threshold (2.644 GeV) up to 3.08 GeV

Ξ form factors at BESIII



- First measurement of the process $e^+e^- \to \Xi^-\bar{\Xi}^+$
- Cross section and eff. FF measured from close to threshold (2.644 GeV) up to 3.08 GeV

Further hyperon analysis in pipeline, e.g. $e^+e^- \to \Omega^-\bar{\Omega}^+$. Stay tuned!

Summary

- BESIII: excellent facility to study baryon EM FFs in the TL region
- Both direct scan and ISR technique employed
- Nucleon FFs: high precision results from scan measurement:
  - σ_B, $|G_{eff}|$, R_{EM}, and $|G_M|$ extracted for both proton and neutron over wide range of q^2, unprecedented accuracy
  - First separate extraction of $|G_E|$ and $|G_M|$ of proton and neutron in time-like region
- Observation of new, unexpected periodic structures in nucleon FFs
- First time results for many hyperon final states such as $\Lambda, \Sigma, \Xi, \Lambda_c^+$:
  - First complete measurement of Λ FFs at 2.396 GeV, including phase between G_E and G_M
  - First direct measurement of Ξ and Λ_c^+ FFs
  - First measurement of $|G_E/G_M|$ for Σ^+ and Λ_c^+
  - More results yet to come

Thank You!