Baryon Form Factors with BESIII

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on behalf of the BESIII Collaboration

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Outline

Motivation

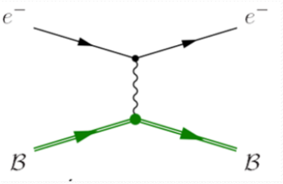
Electromagnetic Form Factors

- The nucleons are the fundamental building blocks of matter
- Clearly understanding nucleons structure is critical to the understanding of the world
- EM FFs are key ingredients to describe the internal structure
- EM FFs provide the most direct access to the spatial charge and magnetization distributions

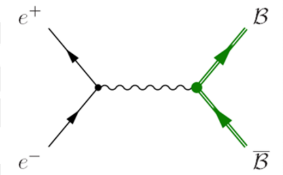
Baryon electromagnetic form factors

could be studied in:

- Space-like:
  - elastic scattering $e^- B \to e^- B$
  - momentum transfer squared $q^2 < 0$
  - FFs are real as function of q^2

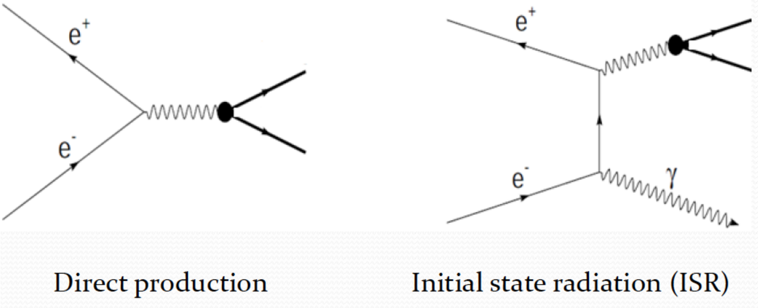


- Time-like:
  - $e^+ e^- \leftrightarrow B\bar{B}$
  - momentum transfer squared $q^2 > 0$
  - FFs are complex as function of q^2



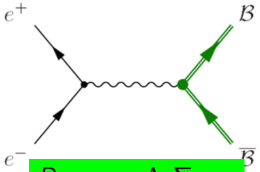
We can measure baryon time-like EM FFs in BESIII

Two methods



	Energy Scan	Initial State Radiation
Data sample	A series of $\sqrt{s}$	one $\sqrt{s}$
q^2 range	single at each beam energy	from threshold to $\sqrt{s}$
Integrated Lum.	low at each beam energy	high at one energy beam energy
	this talk	in progress

Measurement of TL EM FFs



- Differential cross section:
  $\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4q^2}[|G_M(q^2)|^2(1+cos^2\theta) + \frac{1}{\tau}|G_E(q^2)|^2(sin^2\theta)]$
- Born cross section:
  $\sigma(q^2) = \frac{4\alpha^2 \beta C}{3q^2}[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2]$
- Effective FFs: $|G(q^2)| = \sqrt{\frac{\sigma}{\frac{4\alpha^2\beta C}{3q^2}(1+\frac{1}{2\tau})}}$

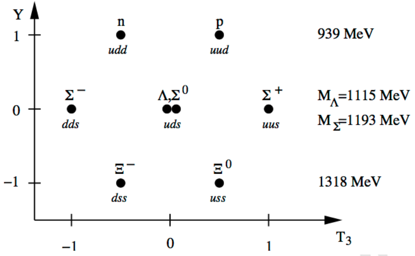
$\tau = q^2/(4m_B^2)$, θ is the polar angle of baryon in the CM

- $R = |G_E/G_M|$ measurement
- Angular dependence: $\frac{d\sigma}{dcos\theta} = N[(1+cos^2\theta) + \frac{R^2}{\tau}(1-cos^2\theta)]$
  N is the overall normalization.

- All the formulas are valid
  - for the baryons with spin=1/2
  - assuming one photon exchange domination

Hyperon electromagnetic form factors

- Hyperons unstable → cannot serve as target
- Only Time-Like hyperon EM FFs are experimentally accessible.
- e+e- -collisions are currently the best way to study hyperon structure.
- Difference between nucleon and hyperon EM FFs provides a powerful test of SU(3) symmetry

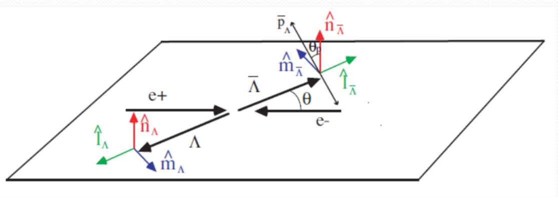


Polarization effect in the $e^+e^- \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$

In the time-like region:

- $G_E(q^2) = |G_E(q^2)|e^{i\Phi_E}$
- $G_M(q^2) = |G_M(q^2)|e^{i\Phi_M}$
- Relative phase: $\Delta\Phi = \Phi_M - \Phi_E$

A nonzero relative phase leads to polarization P_n of the outgoing baryons.

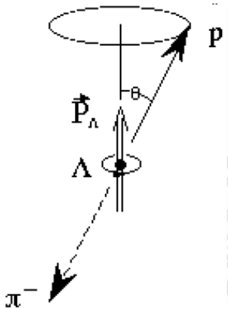


- The n is the normal to the production plane, $\hat{n} = \hat{e}_{e^+} \times \hat{e}_{\bar{\Lambda}}$
- $\hat{l}$ is $\Lambda(\bar{\Lambda})$ momenta direction in $c.m.$ frame
- $\hat{m} = \hat{n} \times \hat{l}$

- $P_n = \frac{sin2\theta Im[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1+cos^2\theta)+\frac{1}{\tau}|G_E(q^2)|^2 sin^2\theta} \Longrightarrow$ gives modulus of $\Delta\Phi$
- $C_{lm} = \frac{sin2\theta Re[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1+cos^2\theta)+\frac{1}{\tau}|G_E(q^2)|^2 sin^2\theta} \Longrightarrow$ gives sign of $\Delta\Phi$

Measure the Λ polarization

- The differential cross section of the decay proton angle:
  $\frac{d\sigma}{dcos\theta_p} = \frac{1}{2}(1 + \alpha_\Lambda P_n cos\theta_p)$
- The polarization can be extracted by:
  $P_n = \frac{3}{\alpha_\Lambda} < cos\theta_p >$
- The spin correlation of the Λ and $\bar{\Lambda}$:
  $C_{lm} = (\frac{9}{\alpha\bar{\alpha}}) < cos\theta_{pl} cos\theta_{\bar{p}m} >$
- α is the asymmtery parameter,
  $\alpha_\Lambda = 0.64, \alpha_{\bar{\Lambda}} = -0.64$

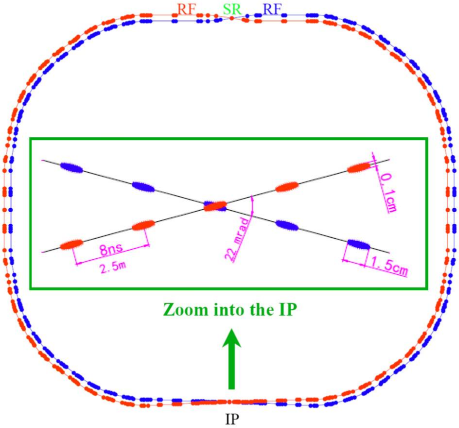


Hence, the phase between the form factors would be known.

BEPCII and BESIII

BEPCII and BESIII

BEPCII storage rings



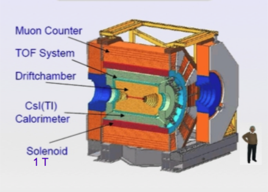
Double-ring e^+e^- collider:

- Beam energy: 1.0-2.3GeV
- Crossing angle: ± 11 mrad
- Design Luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$
- Achieved: $8.5 \times 10^{32} cm^{-2} s^{-1}$
- Energy spread: 5.16×10^{-4}
- Optimum energy: $1.89 GeV$

BESIII detector

BESIII detector:

- MDC: main drift chamber (40% He + 60% propane)
- TOF: time of flight (two layers plastic scintillators)
- EMC: electromagnetic calorimeter (CsI(TI))
- MUC: muon system (resistive plate chambers)

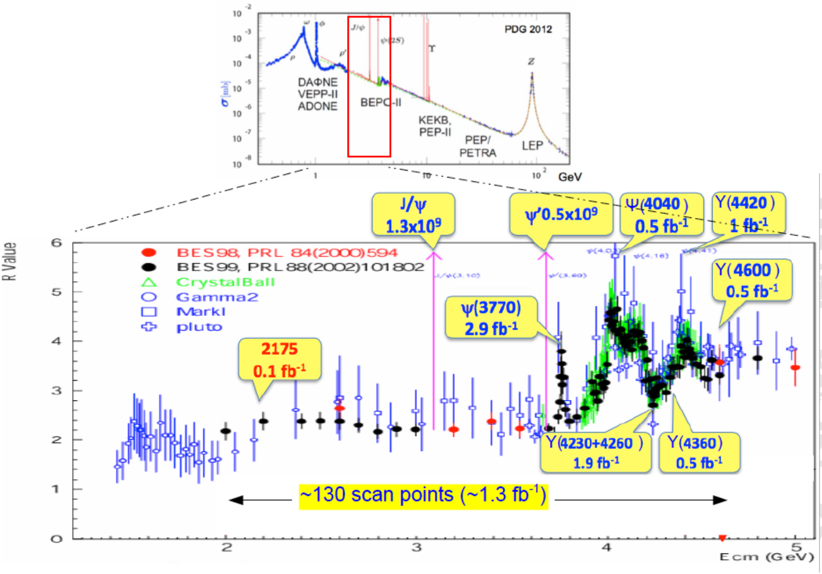


Performance:

Expt.	MDC Wire resolution	MDC dE/dx resolution	EMC Energy resolution
CLEO	$110\,\mu m$	5%	2.2 – 2.4%
BABAR	$125\,\mu m$	7%	2.67%
Belle	$130\,\mu m$	5.6%	2.2%
BESIII	$115\,\mu m$	$< 5\%$	2.3%

Expt.	TOF time resolution
CDF	100 ps
Belle	90 ps
BESIII	68 ps (Barrel) 100 ps (ETOF)

The BESIII data sample



The small and big scan

Mentioned in this talk.

Small scan at 2011/2012. $\sim$157pb^{-1}

$E_{cm}(GeV)$	Luminosity(pb^{-1})	Used for
2.2324	2.6	Proton FFs Λ FFs
2.4	3.4	Proton FFs Λ FFs
2.8	3.8	Proton FFs Λ FFs
3.05	14.9	Proton FFs
3.06	15.1	Proton FFs
3.08	30.7	Proton FFs Λ FFs
3.4 3.5 3.542 3.6 3.65 3.671	1.7 3.6 18.2 9.6 48.8 4.6	Proton FFs

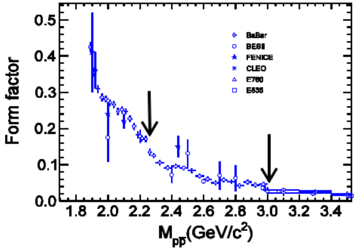
Big scan at 2014/2015. $\sim$525pb^{-1}

$E_{cm}(GeV)$	Luminosity(pb^{-1})	Purpose
2.0	9.3	Nucleon FFs
2.1	11.3	Nucleon FFs
2.15	2.8	Y(2175)
2.175	10.1	Y(2175)
2.2	13.0	Nucleon FFs & Y(2175)
2.2324	11.2	Hyp Threshold ($\Lambda\bar{\Lambda}$)
2.3094	20.5	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^0\bar{\Lambda}$)
2.3864	22.1	Hyp FFs Hyp Threshold ($\Sigma^0\bar{\Sigma}^0$)
2.396	64.8	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^-\bar{\Sigma}^+$)
2.5	1.0	R scan
2.6444	66.3	Nucleon & Hyp FFs Hyp Threshold ($\Xi^-\bar{\Xi}^+$)
2.7	1.0	R scan
2.8	1.0	R scan
2.9	102.1	Nucleon & Hyp FFs
2.95	15.7	$m_{p\bar{p}}$ step
2.981	15.4	η_c, $m_{p\bar{p}}$ step
3.0	15.3	$m_{p\bar{p}}$ step
3.02	16.6	$m_{p\bar{p}}$ step
3.08	123.0	Nucleon FFs

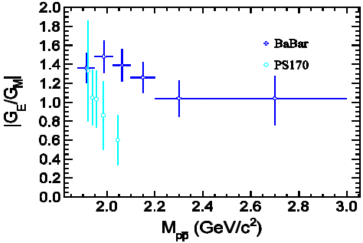
Nucleon Electromagnetic FFs

Experimental status of proton EM FFs

- EM FFs
  - Steep rise towards threshold
  - Two rapid decreases



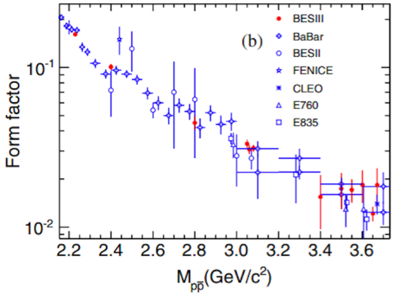
- FFs ratio
  - Only two experiments, BaBar and PS170
  - Inconsistent results
  - Poor precision and limited energy range

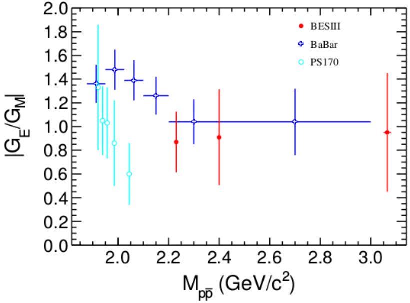


Proton FFs from 2012 scan

Phys. Rev. D 91, 112004 (2015)

- Uncertainty in effective FFs improved by 30%
- The $R = |G_E/G_M|$ ratio are close to unity
- Consistent with BaBar results in the same q^2 region



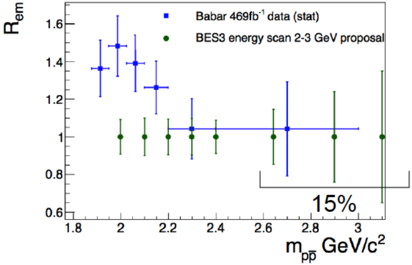


Proton FFs: prospects from 2015 scan

From proposal

E_{cm} (GeV)	Luminosity (pb^{-1})	$\delta R_{em}/R_{em}$	$\delta G_M/G_M$	$\delta G_E/G_E$
2.0	8.95	9.2%	3%	9%
2.1	10.8	10%	3%	10%
2.2	13	9.5%	3%	11%
2.3084	20	9.7%	3%	10%
2.3950	35	8.8%	3%	9%
2.644	65	14.6%	5%	16%
2.9	100	24%	6%	25%
3.1	150	$\sim 35\%$	8.5%	35%

15% (last three energy points, bracketed)

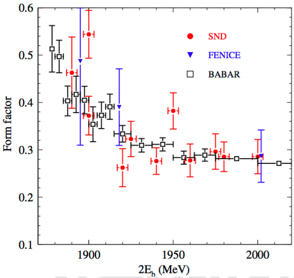


- Expected statistical accuracies for R between the 9% and 35%.
- Combination of the last three energy points would lead to 15% accuracy in R.
- Expected statistical accuracies for $|G_M|$ between 3 to 9%, 9 to 35% for $|G_E|$

Neutron EM FFs

Two measurements

- FENICE with 74 $e^+e^- \to n\bar{n}$ events
- recently confirmed by SND
- from $n\bar{n}$ threshold up to 2GeV
- Compare with proton FFs (BaBar)
  - both increase near threshold
  - close to each other



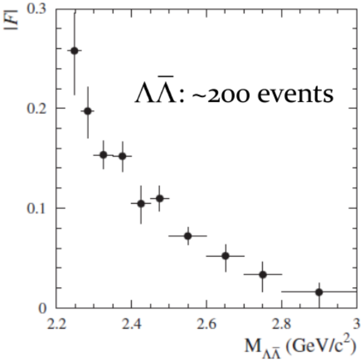
BESIII: Based on the new scan data in 2-3.1GeV:

- Extract EM FFs in wide q^2 region
- Measure R for the first time

Hyperon Electromagnetic FFs

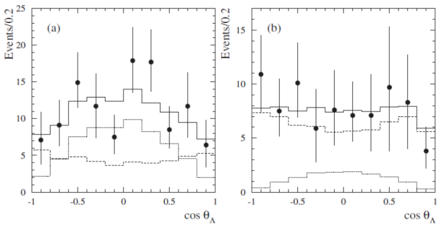
Experimental status

- Babar Collaboration:



Phys. Rev. D76, 092006(2007)

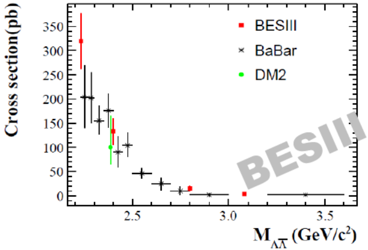
- $e^+e^- \to \gamma\Lambda\bar{\Lambda}$
- Based on very little data.
- Total error on the G_E/G_M ratio 33-100%.

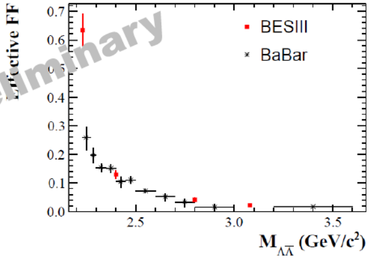


- Λ polarization: $-0.22 < P_n < 0.28$
- Relative phase: $-0.76 < sin\phi < 0.98$

- CLEO-c: $\Lambda\bar{\Lambda}$ @3.773GeV: $\sim$ 105 events
  Phy. Lett. B739(2014)

$e^+e^- \to \Lambda\bar{\Lambda}$ from 2012 scan





- Cross section does not vanish at threshold
- Suggested explanation Coulomb interaction at quark level
- Data sample is too small to extract angular distributions
  - model dependent efficiencies → the biggest contribution to the systematic uncertainty

Hyperon FFs: expectation from 2015 scan

For $\Lambda\bar{\Lambda}$, we could give angular distribution
$\rightarrow$ model dependence of efficiencies gone
$\rightarrow$ get rid of the biggest source of systematic uncertainties

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We shall also be able to measure $e^+e^- \rightarrow \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0, \Sigma^+\bar{\Sigma}^-, \Sigma^-\bar{\Sigma}^+$.....

- Determine FFs, R and polarization at single energy points
- Measure effective FFs with possible energy points

Summary

- 2012 scan:
  - The proton form factors and their ratio have been measured.
  - Preliminary results of Λ just released.
- 2015 scan:
  - Proton FFs will be significantly improved
  - BESIII's first result of neutron FFs will come
  - Possible to measure relative phase of Λ
  - More and better measurements of baryon FFs will come
- Measurements by ISR also in progress

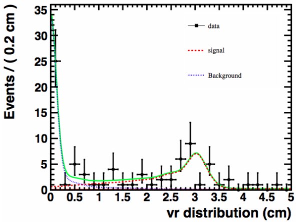
Thank you!

backups

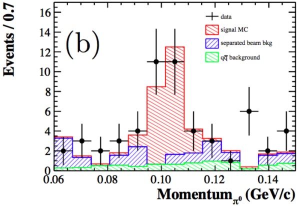
$e^+e^- \to \Lambda\bar{\Lambda}$ at $\sqrt{s} = 2232.4$ MeV

BESIII has collected data at $\sqrt{s} = 2232.4$ MeV, which is only 1.0 MeV above $\Lambda\bar{\Lambda}$ threshold. Two seperate analysis:

- Reconstruct $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$
  - The momentum of final states are too low to leave message in the detector.
  - Antiproton interacting on the beam pipe will produce secondary particles, whose vertex is around 3 cm.
  - $N_{\Lambda\bar{\Lambda}} = 43 \pm 7$



- Reconstruct $\bar{\Lambda} \to \bar{n}\pi^0$
  - The final states of π^0 has a mono-momentum around 105 MeV.
  - $N_{\Lambda\bar{\Lambda}} = 22 \pm 6$



Results of cross section

- Data at $\sqrt{s} = 2400.0$, 2800.0 and 3080.0 MeV are also used to study $e^+e^- \to \Lambda\bar{\Lambda}$, with $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$.

$\sqrt{s}$ (MeV)	Reconstruction	σ_{Born} (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)
2232.4	$\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$	$325 \pm 53 \pm 46$	
	$\bar{\Lambda} \to \bar{n}\pi^0$	$300 \pm 100 \pm 40$	
	combined	320 ± 58	63.4 ± 5.7
2400.0		$133 \pm 20 \pm 19$	$12.93 \pm 0.97 \pm 0.92$
2800.0		$15.3 \pm 5.4 \pm 2.0$	$4.16 \pm 0.73 \pm 0.27$
3080.0		$3.9 \pm 1.1 \pm 0.5$	$2.21 \pm 0.31 \pm 0.14$