Baryon Time-Like Form Factors at BESIII

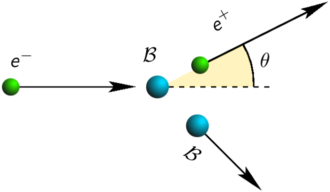
Yadi Wang
on behalf of the BESIII Collaboration
2013-09-11

Outline

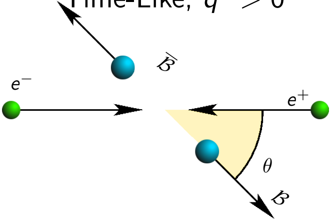
- Definitions of Baryon Form Factors (FFs)
- A brief introduction of BESIII detector at BEPCII
- Status of Baryons Time-Like FFs and prospects at BESIII
    - Proton FFs
    - Neutron FFs
    - Other hyperons ($\Lambda, \Sigma, \Lambda_c$) FFs
- Summary

Definitions of Baryon Form Factors (FFs)

Space-Like, $q^2 < 0$



Time-Like, $q^2 > 0$



Elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E_e' \cos^2\frac{\theta}{2}}{4E_e^3 \sin^4\frac{\theta}{2}} \left[G_E^2 - \tau\left(1 + 2(1-\tau)\tan^2\frac{\theta}{2}\right) G_M^2 \right] \frac{1}{1-\tau}, \quad \tau = \frac{q^2}{4M_B^2}$$

Annihilation

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

Coulomb correction $\mathcal{C}$

$q^2 \to \pm\infty$ (analyticity) $\Longrightarrow G_{E,M}(-\infty) = G_{E,M}(+\infty)$

How to measure TL FFs

$e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$, the angular distributions at certain q^2

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

q^2: 4-momentum transfered by the virtual photon

θ: polar angle of proton or baryon in CM

Or the ratio of them:

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

The absolute value can be get from

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

Cross Section

Or write in partial waves

$$\sigma = 2\pi\alpha^2\beta\frac{4M^2}{(q^2)^2}\left[\mathcal{C}|G_S(4M^2)|^2 + 2|G_D(q^2)|^2\right]$$

$\mathcal{C}$ is only for S-wave. $G_S = \frac{2G_M\sqrt{q^2/4M^2}+G_E}{3}$, $G_D = \frac{G_M\sqrt{q^2/4M^2}-G_E}{3}$

At threshold, why $G_E(4M^2) = G_M(4M^2)$?

- if we assume only S-wave,
  $G_D(4M^2) = 0 \Longrightarrow G_E(4M^2) = G_M(4M^2)$
  Also a conclusion from analyticity.
- EM current, F_1 and F_2 (assumed analytic functions)
  $\Gamma_\mu = e\bar{\mu}(p')\left[F_1(q^2)\gamma_\mu + \frac{\kappa}{2M_N}F_2(q^2)i\sigma_{\mu\nu}q^\nu\right]u(p)e^{iqx}$
  $G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2,\ G_M = F_1 + \kappa F_2 \Longrightarrow G_E(4M^2) = G_M(4M^2)$

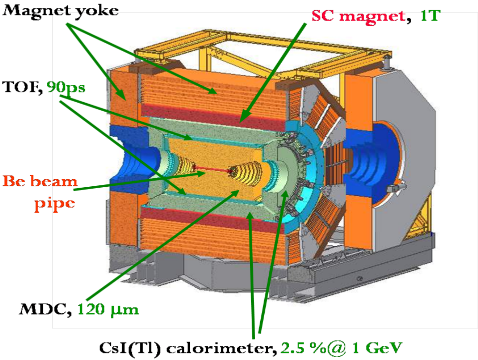
Cross section

For Charged leptons at threshold (S-wave):

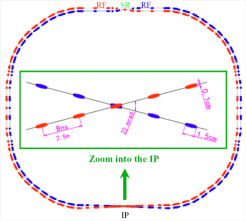
- $\mathcal{C} = \frac{\pi\alpha/\beta}{1-exp(-\pi\alpha/\beta)} \xrightarrow[\beta\to 0]{} \frac{\pi\alpha}{\beta} \longrightarrow \sigma = \frac{\pi^2\alpha^3}{2M^2}|G_S(4M^2)|^2$
- **Few MeV above threshold,** $\mathcal{C} \sim 1 \longrightarrow \sigma(q^2) \propto \beta|G_S(q^2)|^2$
- *Is it true for Charged Baryons ???*

For neutral baryons, in principle no Coulomb correction, $\mathcal{C} = 1.$

BESIII Detector



BEPCII



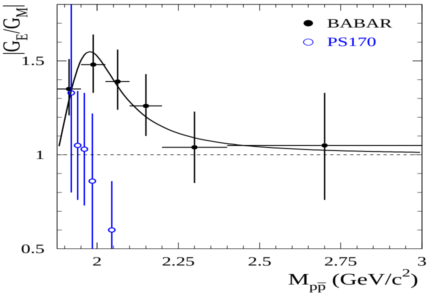
- Beam energy: $1.0 - 2.3$ GeV
- Peak Luminosity:
  1×10^{33} cm^{-2}s^{-1} (Designed),
  0.65×10^{33} cm^{-2}s^{-1} (Achieved).
- Beam energy measurement:
  Compton backscattering technique.
- $\delta E/E \sim 5 \times 10^{-5} \rightarrow \delta E \sim 50$ KeV at $E \sim m_\tau$.

BESIII data taking status and plan

dataset	Previous data	BESIII present & future	Goal
J/ψ	BESI: 58 M	1.2 B 20*BESII	10 B
ψ'	CLEO: 28 M	0.5 B 20*CLEOc	3 B
ψ''	CLEO: 0.8/fb	2.9/fb 3.5*CLEOc	20/fb
$\psi(4040)$/ $\psi(4160)$/ $\psi(4260)$/ $\psi(4360)$	CLEO: 0.6/fb @$\psi(4160)$	2011: 0.4/fb @$\psi(4040)$ 2013: 2/fb @4260, 0.5/fb @4360 Data for lineshape	5-10 /fb
R scan	BESII	2012: R @ 2.23, 2.4, 2.8, 3.4GeV 25/pb τ 2013-2014:high mass resonance? R measurement?	
J/ψ lineshape		2012: 16 points	finished
ψ'' lineshape		in the future	
$2-4$ GeV		in the future	

G_E/G_M of proton

Phys. Rev. D 87, 092005 (2013)



- Maximum at 2 GeV/c^2
- $G_E > G_M$ for all $M_{p\bar{p}}$ ($\neq$ space-like),
  Babar inconsistent with PS170
- Consistent with $|G_E/G_M| = 1$ at large $M_{p\bar{p}}$

$M_{p\bar{p}}$, GeV/c^2	N	N_{bkg}	$\|G_E/G_M\|$
1.877–1.950	1162	19 ± 10	$1.36^{+0.15+0.05}_{-0.14-0.04}$
1.950–2.025	1290	53 ± 16	$1.48^{+0.16+0.06}_{-0.14-0.05}$
2.025–2.100	1328	63 ± 14	$1.39^{+0.15+0.07}_{-0.14-0.07}$
2.100–2.200	1444	118 ± 28	$1.26^{+0.14+0.10}_{-0.13-0.09}$
2.200–2.400	1160	126 ± 26	$1.04^{+0.16+0.10}_{-0.16-0.10}$
2.400–3.000	879	122 ± 22	$1.04^{+0.24+0.15}_{-0.25-0.15}$

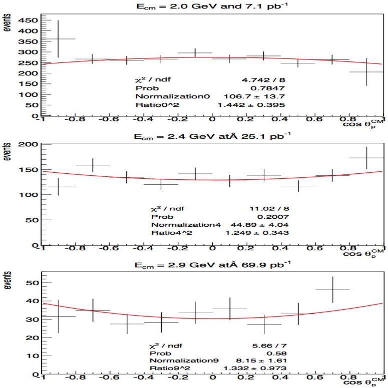
10% – 24% (statistical error) @ BABAR

10% expected @ BESIII

Feasible study at BESIII

$$\frac{d\sigma}{d\Omega}(q^2,\theta) = \frac{\alpha^2\beta\mathcal{C}}{4q^2}|G_M(q^2)|^2\left[(1+cos^2\theta)+R^2_{EM}\frac{1}{\tau}sin^2\theta\right]$$

Babayaga_phase generator + detector simulation + event selection's efficiency + ISR



Proposals have been made.

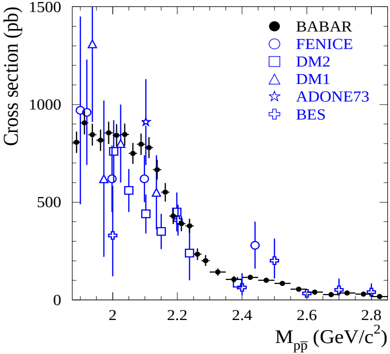
E_{cm} (GeV)	Luminosity (pb^{-1})	T_{beam} (day)
2.0	9.0	14.8
2.15	2.7	2.3
2.1	10.8	15.3
2.175	5.3	4.5
2.2	2.1	1.8
2.23	4.0	3.4
2.981	79.0	14.5
2.3	9.80	7.9
2.4	16.0	6.9
2.5	29.4	18.9
2.6	25.7	7.0
2.7	33.3	10.5
2.8	39.6	10.8
2.9	50.4	9.3

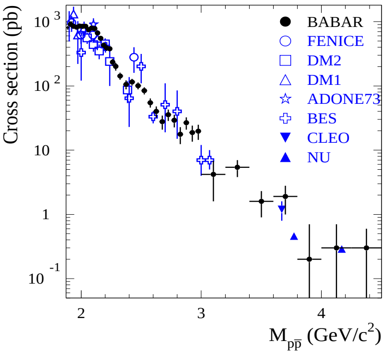
24% (stat.) @ BABAR → 10% (expected) @ BESIII

Structures on $M(p\bar{p})$?

Interesting steps appeared around 2.2 GeV and 3.0 GeV.

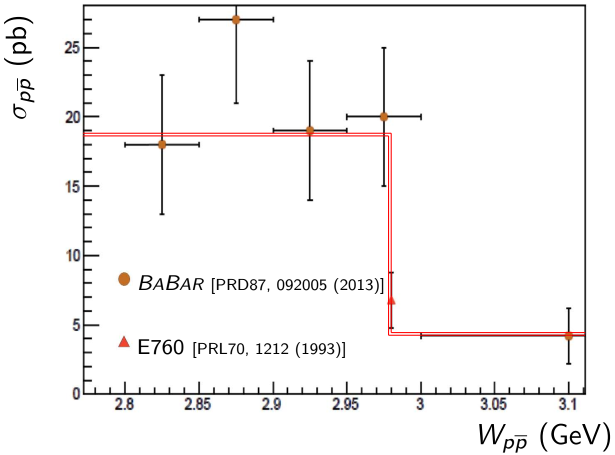
Phys. Rev. D 87, 092005 (2013)





With the high luminosity at BESIII, these structures are under investigation.

A step at 3.0 GeV?



Is it true there is a steep step around 3.0 GeV?

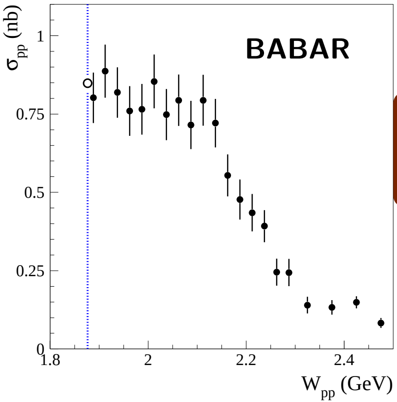
BESIII is measuring this step with enough accuracy.

At $p\bar{p}$ threshold ($q^2 = 4M_p^2$)

For Charged leptons at threshold (S-wave) $\rightarrow p\bar{p}$:

$$\mathcal{C} = \frac{\pi\alpha/\beta}{1-exp(-\pi\alpha/\beta)} \xrightarrow[\beta\to 0]{} \frac{\pi\alpha}{\beta}$$

$$\sigma = \frac{\pi^2\alpha^3}{2M^2}|G_S(4M^2)|^2 = 0.85|G_S(4M^2)|^2 \ \textbf{nb}$$

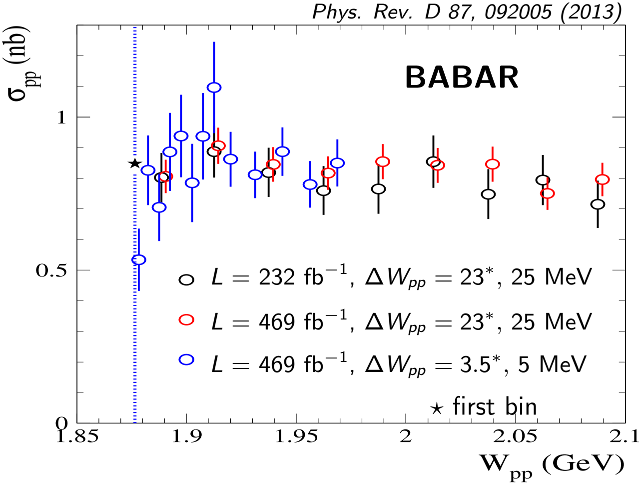


Phys. Rev. D 73, 012005 (2006)

$\sigma(e^+e^- \rightarrow p\bar{p})(4M_p^2) = 0.83 \pm 0.05$ **nb**

$G^p(4M_p^2) = 0.99 \pm 0.04(stat.) \pm 0.03(syst.)$

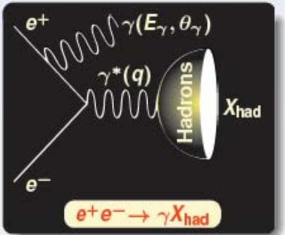
At $q^2 = 4M_p^2$ protons behave as point-like fermions!?



With more L and smaller binning, the result changed somewhat.

Results from BESIII needed (from ISR process).

Measurement of proton TL FFs from ISR



- $\dfrac{d^2\sigma}{dE_\gamma d\theta_\gamma} = W(E_\gamma, \theta_\gamma) \cdot \sigma_{e^+e^- \to X_{had}}(s)$
- $W(E_\gamma, \theta_\gamma) = \dfrac{\alpha}{\pi x}\left(\dfrac{2 - 2x + x^2}{\sin^2\theta_\gamma}\right)$

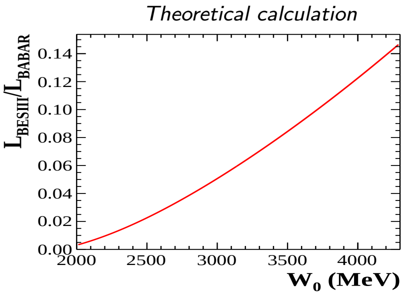
- $s = q^2$, q .... X_{had} momentum
- E_γ, θ_γ ... CM γ energy, scatt. ang.
- E_{CM} .... CM e^+e^- energy
- $x = E_\gamma / 2E_{CM}$

ISR versus c.m.

- All q at the same time $\Longrightarrow$ Better Control on systematics
- c.m. boost $\Longrightarrow$ at threshold efficiency $\neq 0 + \sigma_W \sim 1$ MeV
- Detected ISR $\gamma \Longrightarrow$ full $p\bar{p}$ angular coverage

ISR: BESIII vs BABAR for $\sigma(p\bar{p})$

$$L_{ISR}(W_0, E_\gamma) = \beta \frac{dE_\gamma}{E_\gamma}\left[1 - \frac{dE_\gamma}{E_\gamma} + \frac{1}{2}\left(\frac{dE_\gamma}{E_\gamma}\right)^2\right] \times dW \times L_0(W_0)$$

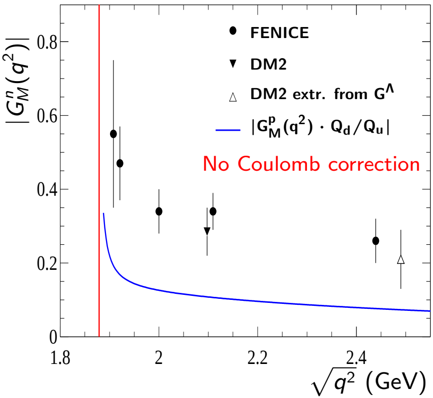


- $R_{EM} = G_E/G_M$ shape;
- Steps around 2.2 and 3.0 GeV;
- Threshold study.

To get the same result as BABAR, the luminosity needed at BESIII:

$E_{cm} = 10579$ MeV BABAR energy	$L = 450\ fb^{-1}$
$E_{cm} = 4260$ MeV	$L = 64.8\ fb^{-1}$
$E_{cm} = 4040$ MeV	$L = 56.6\ fb^{-1}$
$E_{cm} = 3770$ MeV	$L = 47.0\ fb^{-1}$
$E_{cm} = 3686$ MeV	$L = 44.1\ fb^{-1}$
$E_{cm} = 3100$ MeV	$L = 25.6\ fb^{-1}$
$E_{cm} = 2232$ MeV	$L = 4.8\ fb^{-1}$

G_M of neutron



Few results from Fenice with 74 signal events (0.4 pb^{-1}) from $e^+e^- \to n\bar{n}$

G_M^n / G_M^p

- Data ~ 1.5;
- Naively $\sim |Q_d/Q_u| = 1/2$;
- pQCD $\sim< 1$;
- Soliton models ~ 1;
- VMD $\sim\gg 1$.

$E \sim (2M_n - 3.0)$ GeV. Good detection performance for neutron.
SND, BESIII, and CMD2(?) can do this.

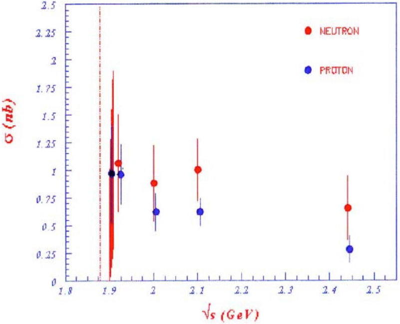
$\sigma(n\bar{n})$

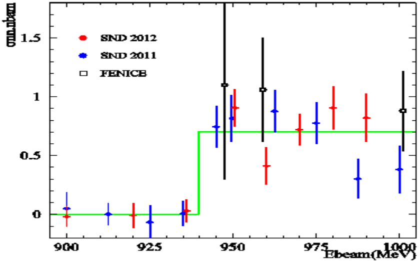
At threshold only S-wave:

$$\sigma = \frac{\pi^2\alpha^3\beta\mathcal{C}}{2M^2}|G_S(4M^2)|^2, \qquad \mathcal{C}=1, \beta\sim 0 \to \sigma \sim 0$$

$e^+e^- \to n\bar{n}$ **(FENICE)**

Nucl.Phys.B517,3(1998)

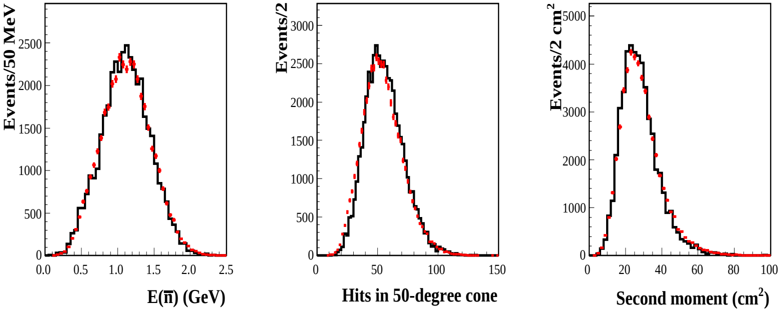




- SND preliminary result (ref. T.V.Dimova's report)
- Non-zero at threshold?
- $\sigma(n\bar{n}) \geq \sigma(p\bar{p})$?

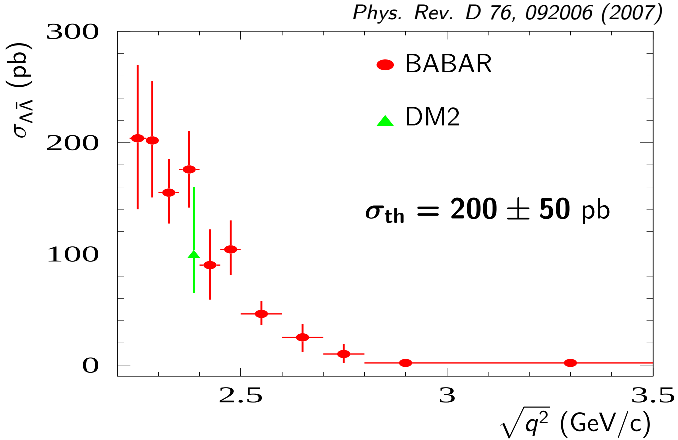
n and $\bar{n}$ identification at BESIII

$J/\psi \to n\bar{n}$. *Phys.Rev.D 86(5),032014 (2012)*



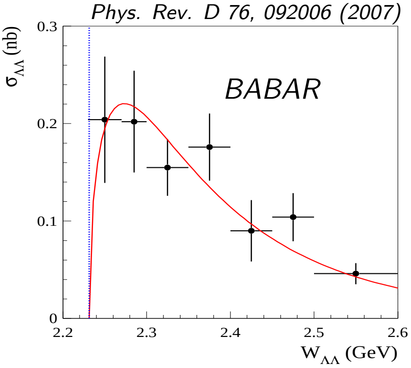
- Ref. to "Study of $J/\psi \to p\bar{p}$ and $J/\psi \to n\bar{n}$" paper at BESIII.
- Excellent selection of neutron and anti-neutron with EMC.
- Accurate measurement of $e^+e^- \to n\bar{n}$ is going on. New results will come.

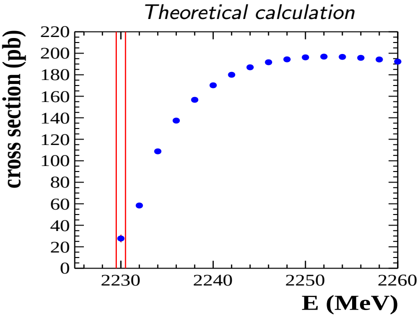
$\sigma(\Lambda\bar{\Lambda})$ at threshold similar with $\sigma(n\bar{n})$



Like a remnant of Coulomb interactions at quark level? $\Rightarrow$ $\mathcal{C} \propto \beta^{-1}$ as $\sqrt{q^2} \to 2M_{\mathcal{B}^0}$ $\Rightarrow$ For any neutral baryon $\sqrt{\sigma_{B\bar{B}}} \propto \frac{|G_B|}{M_B}$???

$\sigma(\Lambda\bar{\Lambda})$ at threshold similar with $\sigma(n\bar{n})$



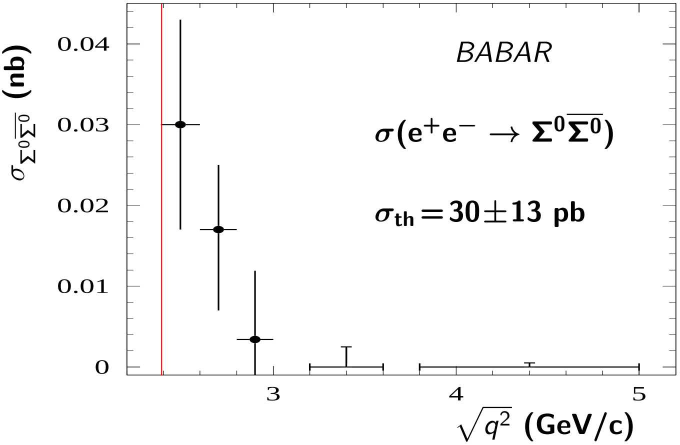


Considering beam energy spread, theoretically the cross section at threshold is about 20 pb.

BESIII has already collected data at threshold and above. The analysis is on progress.

No Coulomb correction at hadron level: $\mathcal{C} = 1$

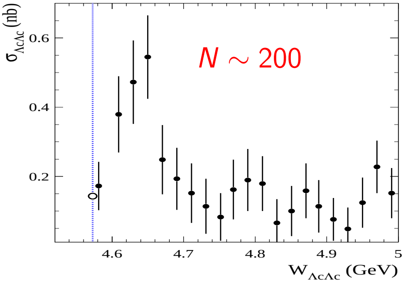
Phys. Rev. D 76, 092006 (2007)



$\sigma(\Lambda_c^+\Lambda_c^-)$ at threshold

Like $p\bar{p}$, partial wave FFs: $G_s = \frac{2G_M\sqrt{q^2/4M^2}+G_E}{3}$, $G_D = \frac{G_M\sqrt{q^2/4M^2}-G_E}{3}$
At threshold, only S-wave: $\sigma = \frac{\pi^2\alpha^3}{2M^2}|G_S(4M^2)|^2 = 0.15|G_S(4M^2)|^2$ nb

[Belle PRL101, 172001]



$\sigma(\Lambda_c^+\Lambda_c^-) \sim 0.15$ **nb** $\rightarrow$
point-like at threshold?

Belle ISR:
$Br(\Lambda_c^+ \rightarrow pK_s^0, pK^-\pi^+, \Lambda\pi^+) = 6.9\%$

BESIII	ϵB (%)
pK_s	0.4
$pK^-\pi^+$	1.8
$\Lambda\pi^+$	0.3
total	2.5

So, assume $\sigma = 0.14$ nb, $L \sim 70$ nb^{-1}, we will have $N = \epsilon B \sigma L = 2100$ at BESIII.

Summary

- Review of puzzles of baryons form factors;
  - Proton: G_E/G_M, structures on total cross sections, G_S at threshold;
  - Neutron: G_M, total cross section;
  - Hyperon $(\Lambda, \Sigma, \Lambda_c)$: threshold of total cross section
- Proposals for the next running period:
  - $2 \sim 4.5$ GeV;
- BESIII will present soon new, interesting results on baryon form factors!

Thanks for your attention!