BESIII SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

HIM Helmholtz-Institut Mainz

PRISMA Cluster of Excellence

Hadron Form Factors at BESIII

(focused on Baryon)

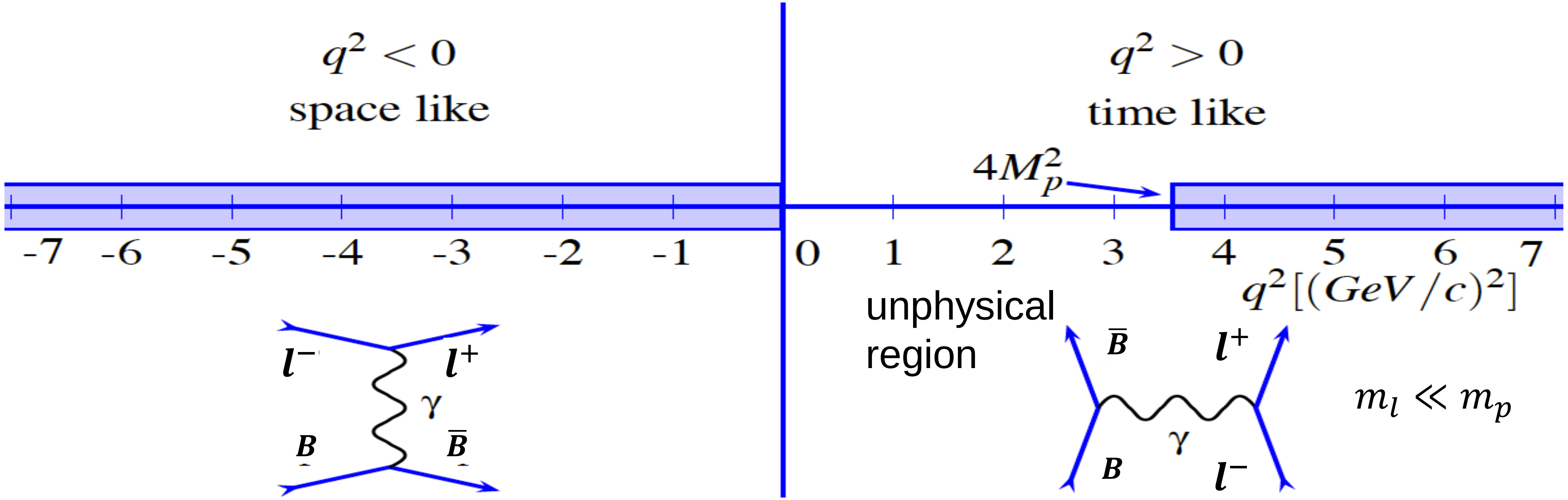
YADI WANG (HELMHOLTZ-INSTITUT MAINZ)

ON BEHALF OF BESIII

PHIPSI15, SEP. 23-26, 2015 @ USTC, HEFEI (CHINA)

Hadron Form Factors

All **hadronic structure** and **strong interactions** in form factors but subject to QED corrections.
Hadronic vector current: (2s+1) form factors. For baryons with ½ spin, two electromagnetic FFs.



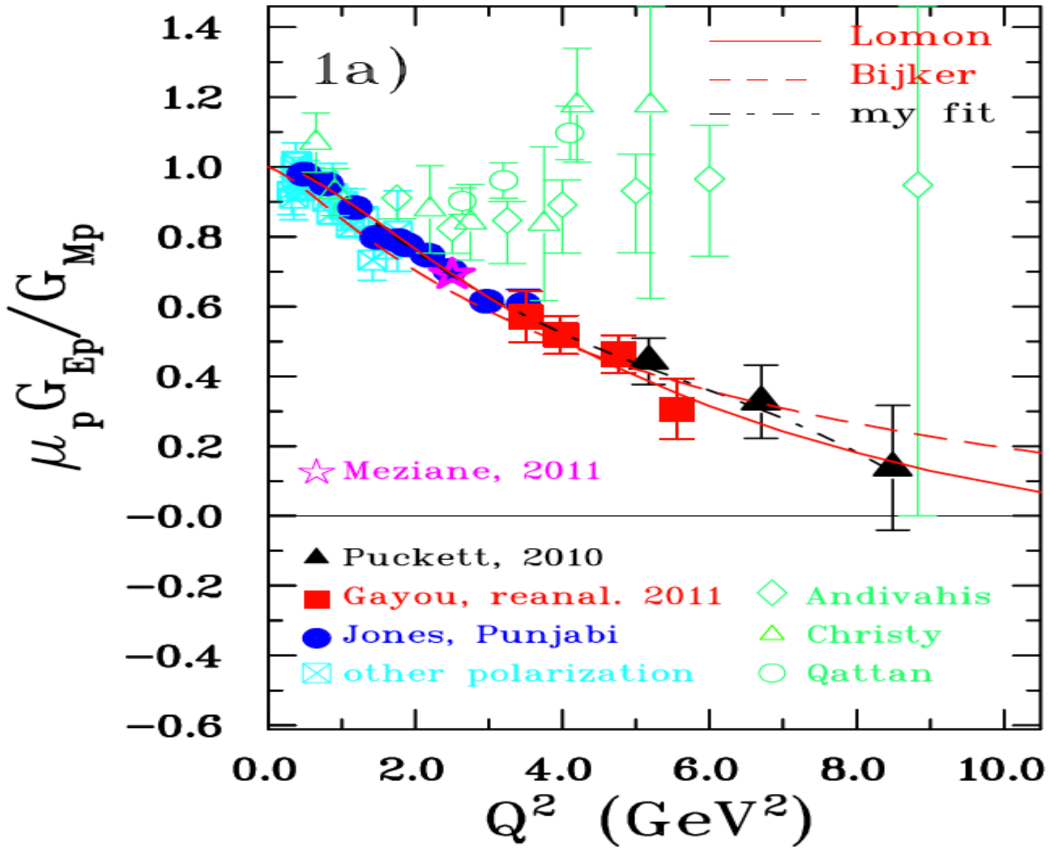
Form Factor real
cross section (Rosenbluth)
no single spin observables
double spin observables

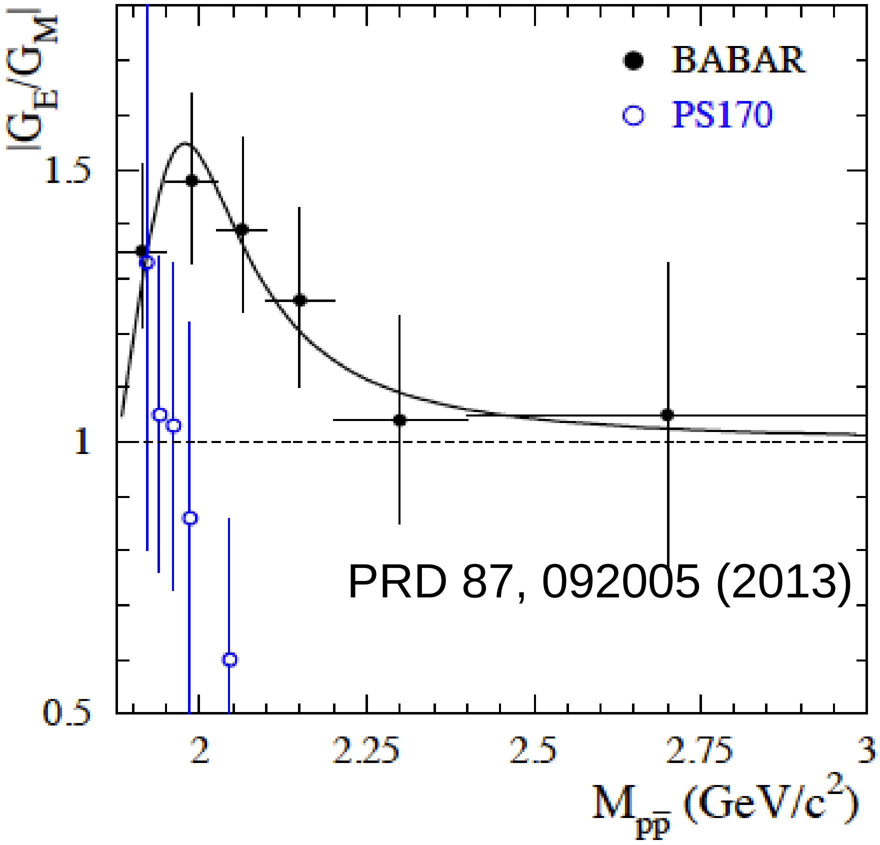
dispersion relations ⟷

Form Factor complex
cross section (angular Distr.)
single spin observables (P_y)
double spin observables

- **Fundamental properties of hadrons**
  - Contain information on charge, magnetization distribution
  - Crucial testing ground for models of hadron internal structure
  - Necessary input for experiments probing hadronic structure, or trying to understand modification of hadronic structure in hadronic medium
- **Driving renewed activity on theory side:**
  - Models trying to explain FFs of Nucleons
  - Trying to explain data at both low and high q^2
  - Progress on QCD based calculations

Rossenbluth separation on Space-like data Fit angular distr. of Time-like data





(q^2 < 0): precision of order %

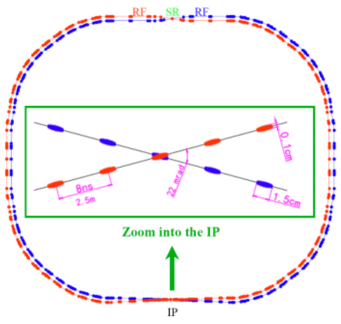
(q^2 > 0): precision >20%

time like EM form factor: badly known

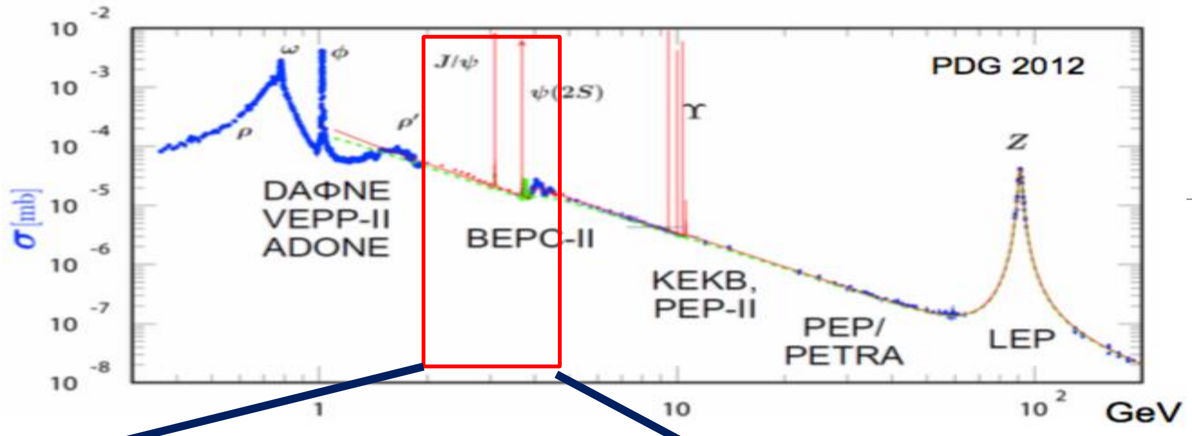
Outline

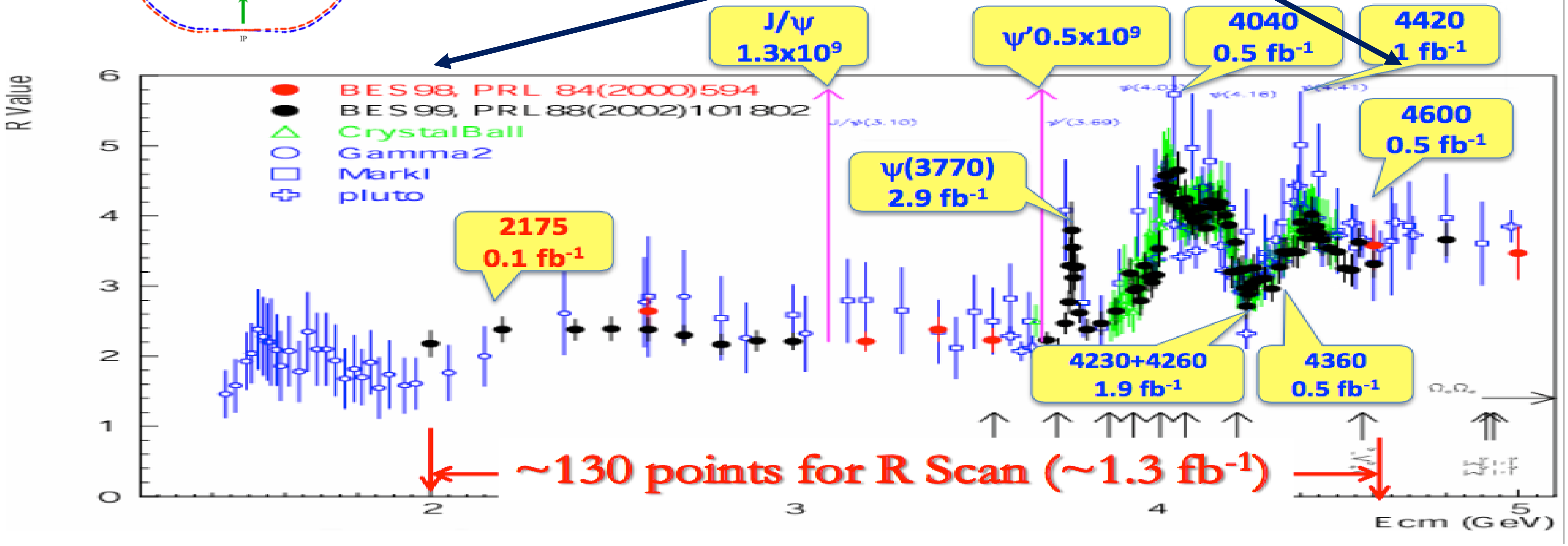
- BESIII detector at BEPC;
- Proton FFs;
- Neutron FFs;
- Λ FFs;
- Λ_C FFs;
- Other hyperons FFs;
- Summary.

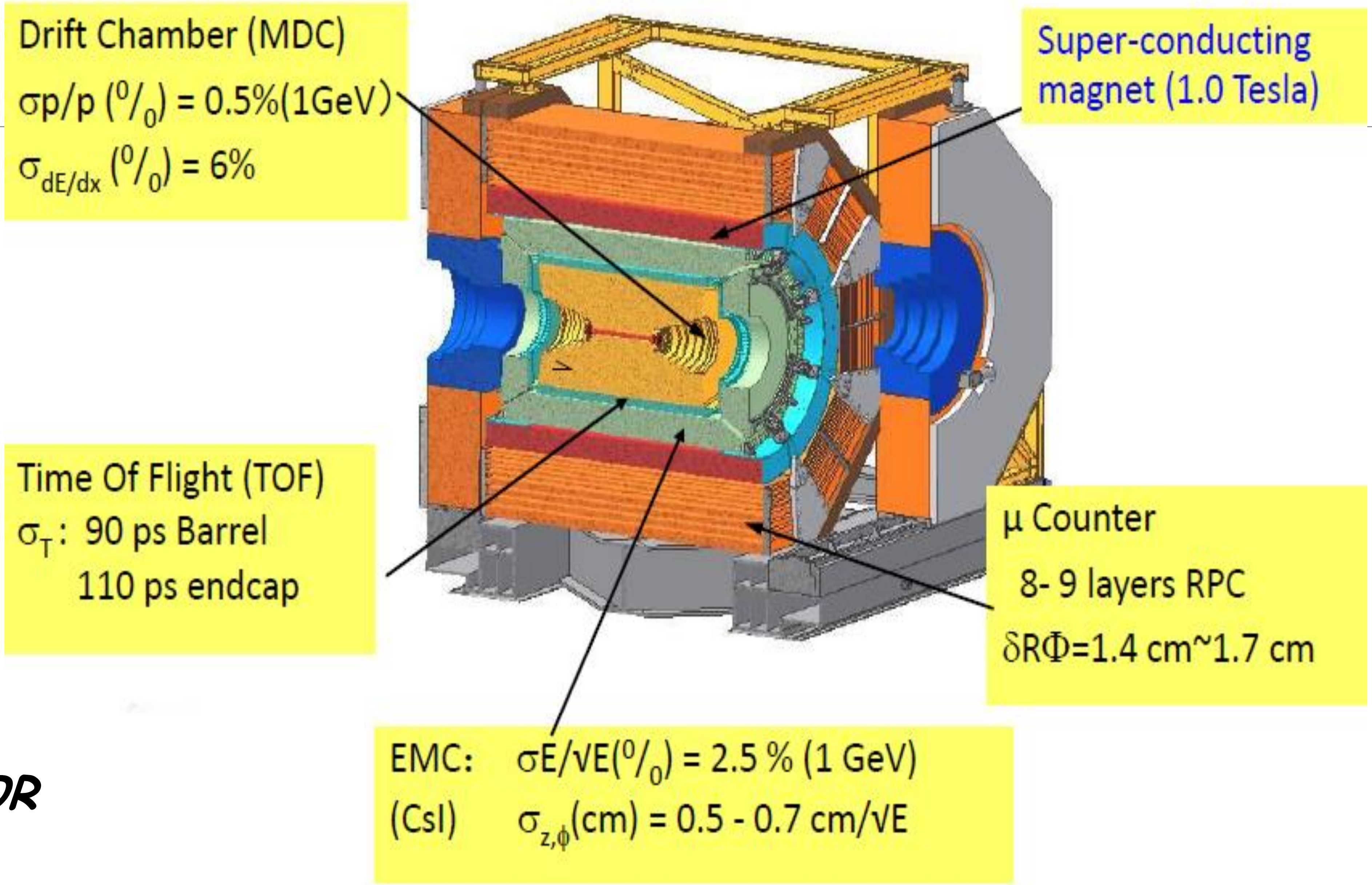
Data Samples at BESIII



e+e- collider



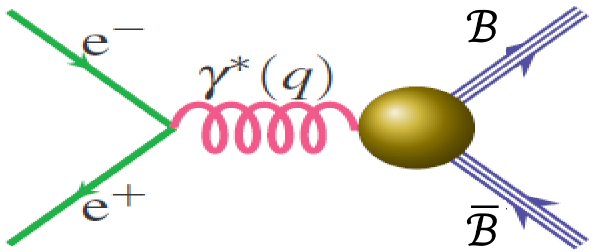




BESIII DETECTOR

Baryon EM FFs at BESIII

Direct annihilation



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

Effective form factor $\sigma \propto G(q^2)$

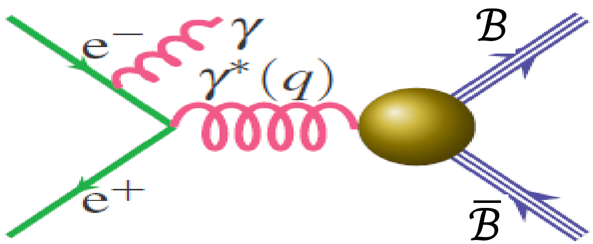
$$|G(q^2)| = \sqrt{\frac{\sigma^{Born}_{B\bar{B}}(q^2)}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta C}{3q^2})}}$$

Separation of $|G_E|$ and $|G_M|$ through angular analysis:

$$\frac{d\sigma^{Born}_{B\bar{B}}}{d\Omega_{CM}} = \frac{\alpha^2\beta C}{4q^2}\left[(1+\cos^2\theta^{CM}_B)|G_M|^2 + \frac{1}{\tau}|G_E|^2\sin^2\theta^{CM}_B\right]$$

$$\tau = \frac{q^2}{4M_B^2}, \beta = \sqrt{1-1/\tau},$$

Initial State Radiation



$$\frac{d^2\sigma_{B\bar{B}\gamma}}{dx\,d\theta_\gamma} = W(s,x,\theta_\gamma)\sigma^{Born}_{B\bar{B}}(q^2)$$

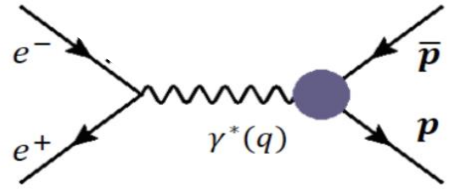
$$W_{LO}(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2}\right)$$

$$x = 1 - q^2/s = 2E_\gamma/\sqrt{s}$$

$$C = \begin{cases} \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}, \textit{at threshold } \frac{\pi\alpha}{\beta} \text{ a jump at threshold for charged} \\ 1, \text{ for a neutral } B\bar{B} \text{pair, } \sigma \to 0 \end{cases}$$

assuming coulomb acts after $B\bar{B}$ pair are built and they are as point-like particles.

Proton Form Factors with data 2012



Analysis based on 157 pb^{-1} collected at 12 scan points between 2.22 – 3.71 GeV in 2011 and 2012

Analysis features:

- p and $\bar{p}$ from vertex, in time, back to back, $E_{p,p} = E_{CM}/2$
- Efficiencies 60% (2.23 GeV) … 3% (~4 GeV)
- Radiative corrections from ConExc (NLO in ISR)
- Normalization to $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \gamma\gamma$ (Babayaga 3.5)

$$\sigma_{\text{Born}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{L \cdot \varepsilon \cdot (1+\delta)}$$

$$|G| = \sqrt{\frac{\sigma_{born}}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta C}{3E_{CM}^2})}}$$

N_{obs} : observed signal events

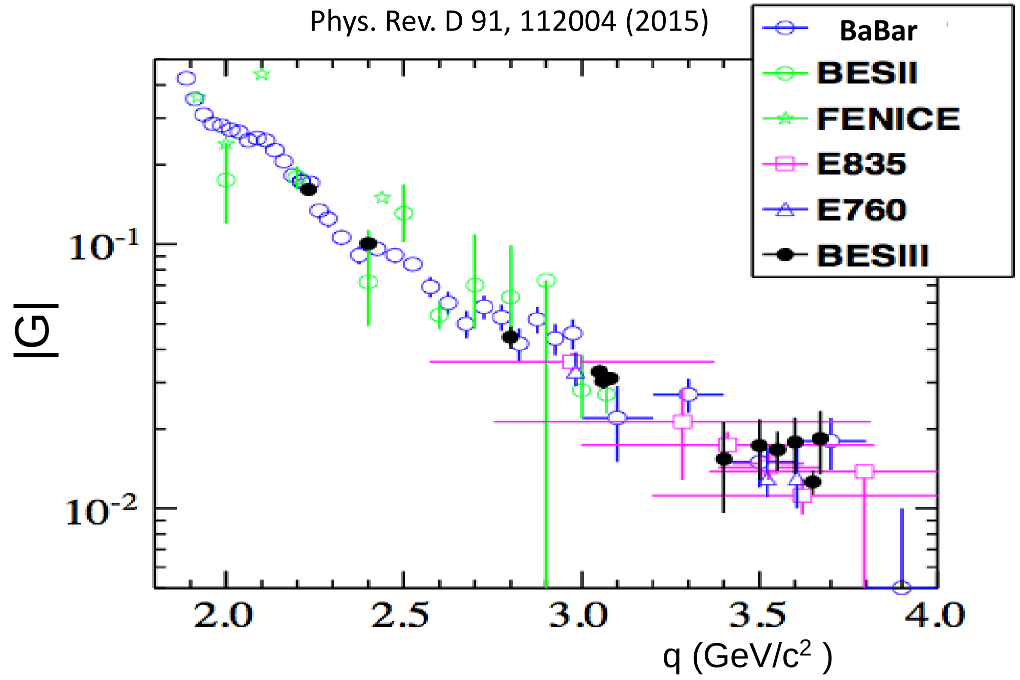
L : integrated luminosity

N_{bkg} : estimated background (from MC)

ε : detection efficiency (from MC)

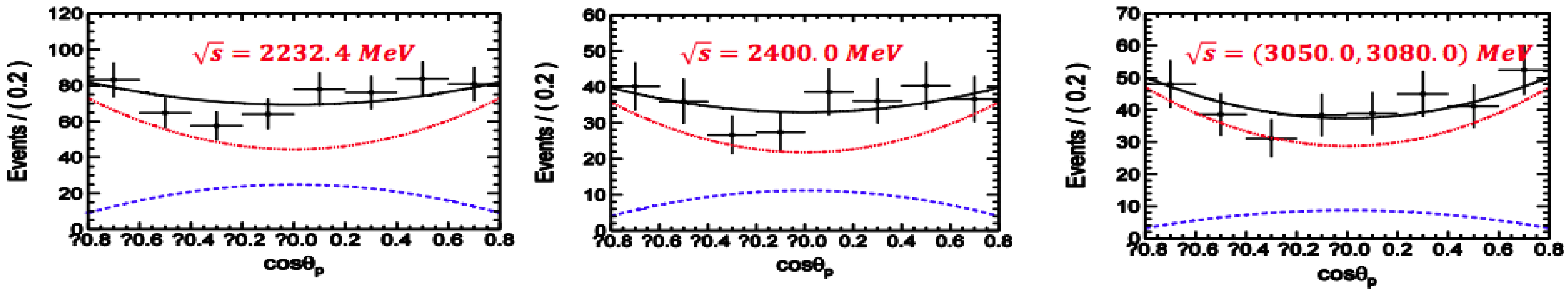
1 +δ: radiative factor (from MC)

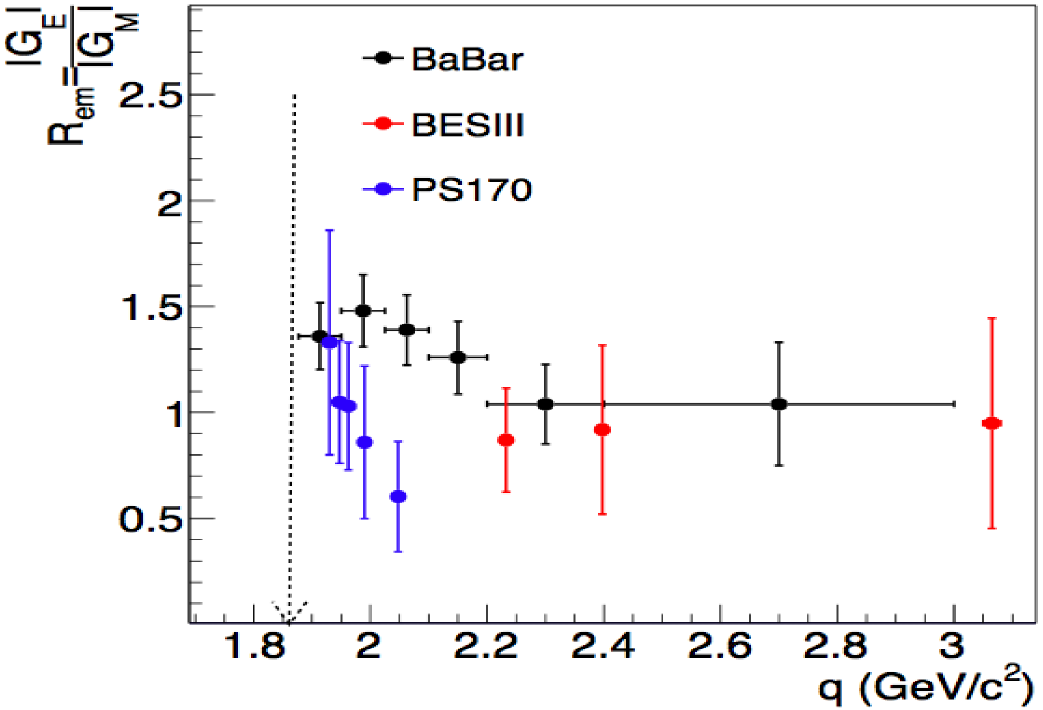
Phys. Rev. D 91, 112004 (2015)



- ***Effective FF consistent with Babar.***
- ***Overall uncertainty improvement by 30%.***
- ***No steps observed in cross section.***

- Angular analysis to extract the em FFs:
  - $\frac{d\sigma}{d\Omega}(q^2) = \frac{\alpha^2\beta}{4s}|G_M(s)|^2\left[(1+\cos^2\theta_p) + R_{em}^2\frac{1}{\tau}\sin^2\theta_p\right]$
  - $R_{em} = |G_E(q^2)|/|G_M(q^2)|$
  - θ: polar angle of proton at the c.m.system
- Fit function:
  - $\frac{dN}{d\cos\theta_p} = N_{norm}\left[(1+\cos^2\theta_p) + R_{em}^2\frac{1}{\tau}\sin^2\theta_p\right]$
  - $N_{norm} = \frac{2\pi\alpha^2\beta L}{4s}\left[1.94 + 5.04\frac{m_p^2}{s}R^2\right]G_M(s)^2$ is the overall normalization





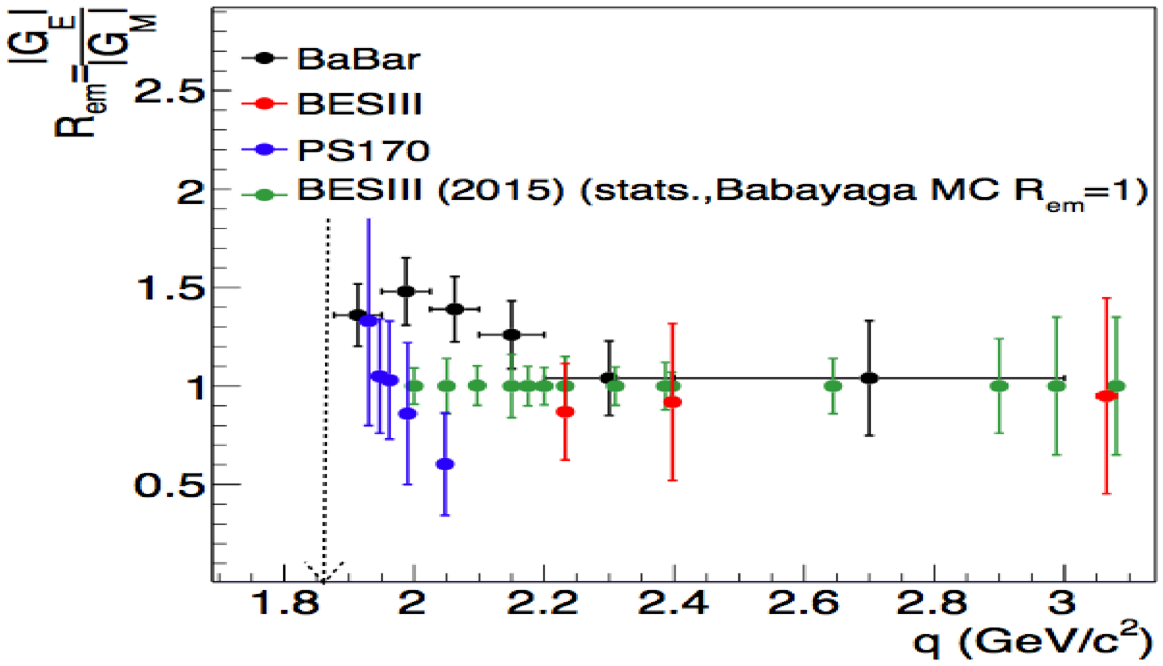
- R_{em} *consistent with BaBar and R=1.*
- *$|G_M|$ extracted for first time!*

fitting method and method of moments

$$\langle\cos^2\theta_p\rangle = \frac{1}{N_{\text{norm}}}\int \frac{2\pi\alpha^2\beta C}{4s}\cos^2\theta_p[(1+\cos^2\theta_p)|G_M|^2 + \frac{4m_p^2}{s}(1-\cos^2\theta_p)|R^2|G_M|^2]d\cos\theta_p.$$

$\sqrt{s}$ (MeV)	$\lvert G_E/G_M\rvert$	$\lvert G_M\rvert$ ($\times10^{-2}$)
		Fit on $\cos\theta_p$
2232.4	$0.87\pm0.24\pm0.05$	$18.42\pm5.09\pm0.98$
2400.0	$0.91\pm0.38\pm0.12$	$11.30\pm4.73\pm1.53$
(3050.0, 3080.0)	$0.95\pm0.45\pm0.21$	$3.61\pm1.71\pm0.82$
		Method of moments
2232.4	0.83 ± 0.24	18.60 ± 5.38
2400.0	0.85 ± 0.37	11.52 ± 5.01
(3050.0, 3080.0)	0.88 ± 0.46	3.34 ± 1.72

Prospects for $e^+e^- \to p\bar{p}$

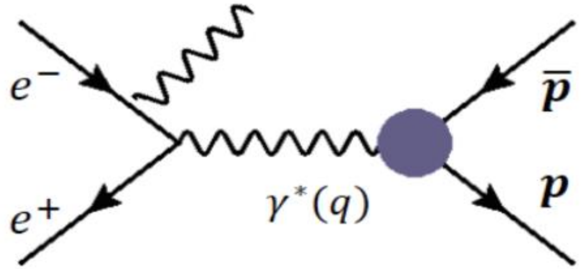


- ✓ Expected statistical accuracies based on $R_{em}=|G_E|/|G_M|=1$ between 9% and 35% (similar to space-like region for the same q^2-region)
- ✓ Expected accuracies for $|G_M|$ between 3% to 9%, 9% to 35% for $|G_E|$

2015 data

E_{cm} (GeV)	L_{online} (pb-1)		
2.0000	**9.306**	123	XS, Nucleon FFs
2.0500	3.01784	42	XS
2.1000	**11.34794**	104	XS, Nucleon FFs
2.1500	2.775088	28	XS
2.1750	**10.05633**	102	XS
2.2000	**13.00509**	114	XS, Nucleon FFs
2.2324	**11.24757**	111	XS, Nucleon FFs
2.3094	**20.481**	137.5	XS, Nucleon FFs
2.3864	**22.05922**	89	XS, Nucleon FFs
2.3960	**64.84102**	222.5	XS, Nucleon FFs
2.5000	1.04406	5	XS
2.6444	**32.530**	115	XS, Nucleon FFs
2.6464	**33.730**	112	XS, Nucleon FFs
2.7000	0.987445	4	XS
2.8000	0.996496	4	XS
2.9000	**102.096**	214	XS, Nucleon FFs
2.9500	15.696	25	XS
2.9810	15.391	22	XS
3.0000	15.269	21	XS
3.0200	16.605	22	XS
3.0800	**123.024**	194	XS, Nucleon FFs

Prospects of $e^+e^- \to p\bar{p}\gamma_{ISR}$



- Continuous q^2-range available: $m^2_{th} < q^2 < s$
- Full angular distribution in hadronic center-of-mass
- Detection efficiency independent of q^2 and hadronic angular distribution
- Acceptance at threshold $\neq 0$

Data samples (ECM): ψ(3770),ψ(4040), Y(4230), Y(4260), Y(4360), Y(4420), Y(4600). Total: 7.4 fb^{-1}

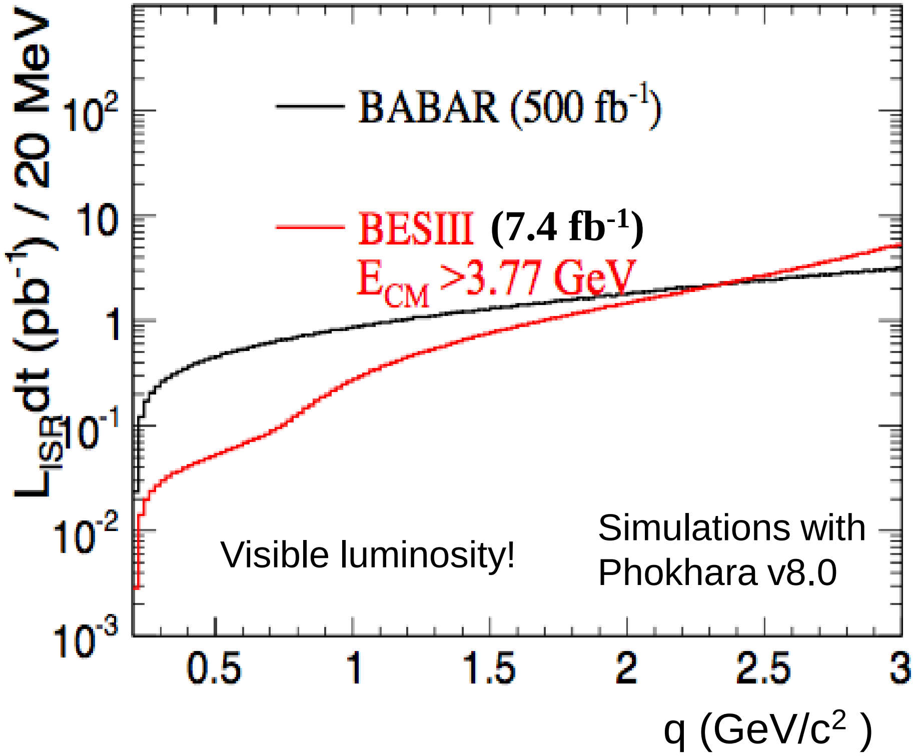
Analysis for each E_{CM} and q, then combine statistics

- ISR kinematics: photon and $p\bar{p}$-system with small opposite polar angles

Efficiencies: ~20% -γ-untagged, ~6% γ-tagged analysis

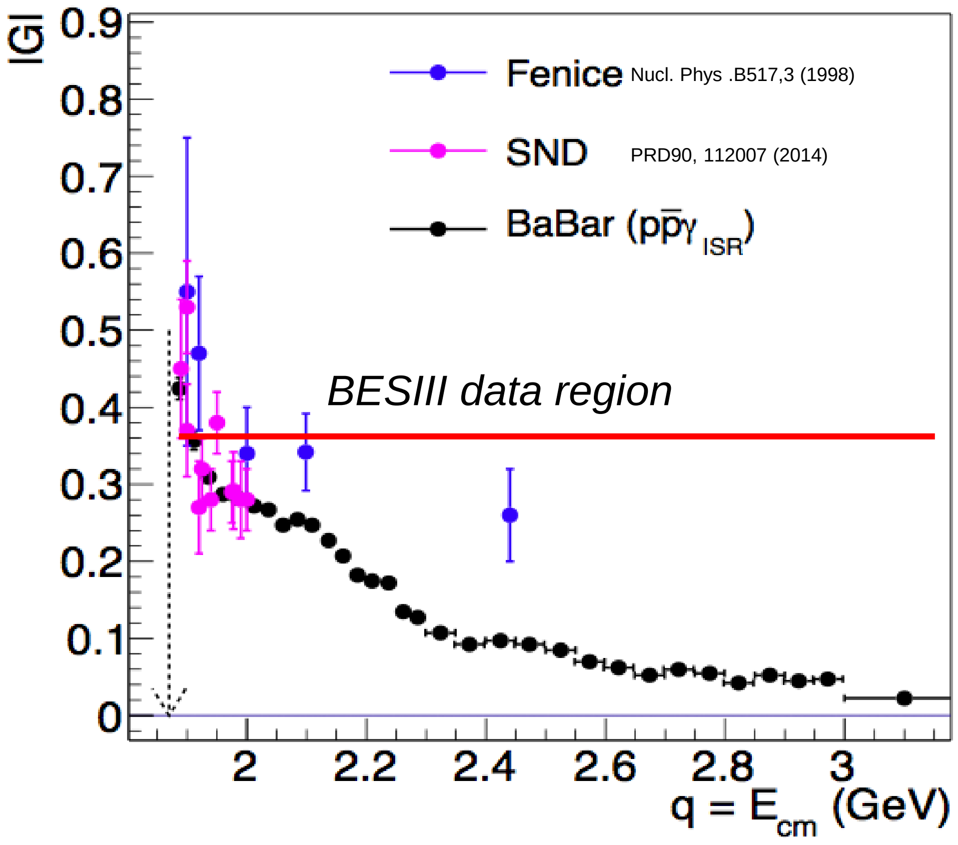
- From 2.0 GeV up, ISR analysis possible

Final statistics competitive with BaBar



simulation for $\mu^+\mu^-\gamma_{ISR}$
beheavior of $p\bar{p}\gamma_{ISR}$ very similar

Prospects for $e^+e^- \to n\bar{n}/n\bar{n}\gamma_{ISR}$



Only two direct measurements of neutron effective FF

Very challenging: energies of $n, \bar{n}$ are not fully deposited in EMC, bkg from γ, K_L^0, beam, ...

BESIII sub-detector

EMC calorimeter

CsI(Tl): $15X_0$, λ_I= 171.5 g/cm^2, ρ = 4.53 g/cm^3

→ 52% $n, \bar{n}$ interact in EMC

MUC: Iron + resistive plates (under study)

λ_I = 132.1 g/cm^2, ρ = 7.874 g/cm^3, 56 cm Fe thickness in barrel → ~96 % $n, \bar{n}$ interact in MUC

Expect the first measurement of R_{EM} with BESIII unprecedented statistics

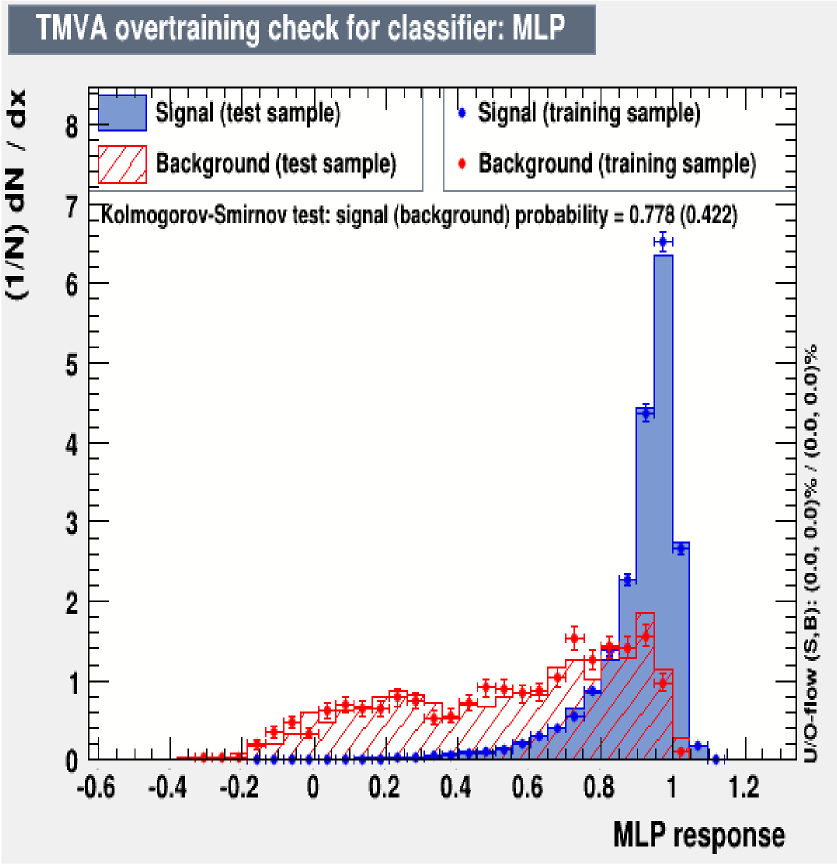
Prospects for $e^+e^- \to n\bar{n}/n\bar{n}\gamma_{ISR}$

Strategy:

➢First identification of $\bar{n}$ and γ_{ISR}:

➢EMC shower information (for $e^+e^- \to n\bar{n}\gamma_{ISR}$ Neural Network) for neutron identification

➢event kinematics (geometry)



$e^+e^- \to n\bar{n}$

➢$\boldsymbol{n/\bar{n}}$detection efficiencies of ~20/30% (efficiencies up to % level)

➢Main background from beam background processes

- Unprecedented statistics above 2.0 GeV (~300 evts at 2.4 GeV)

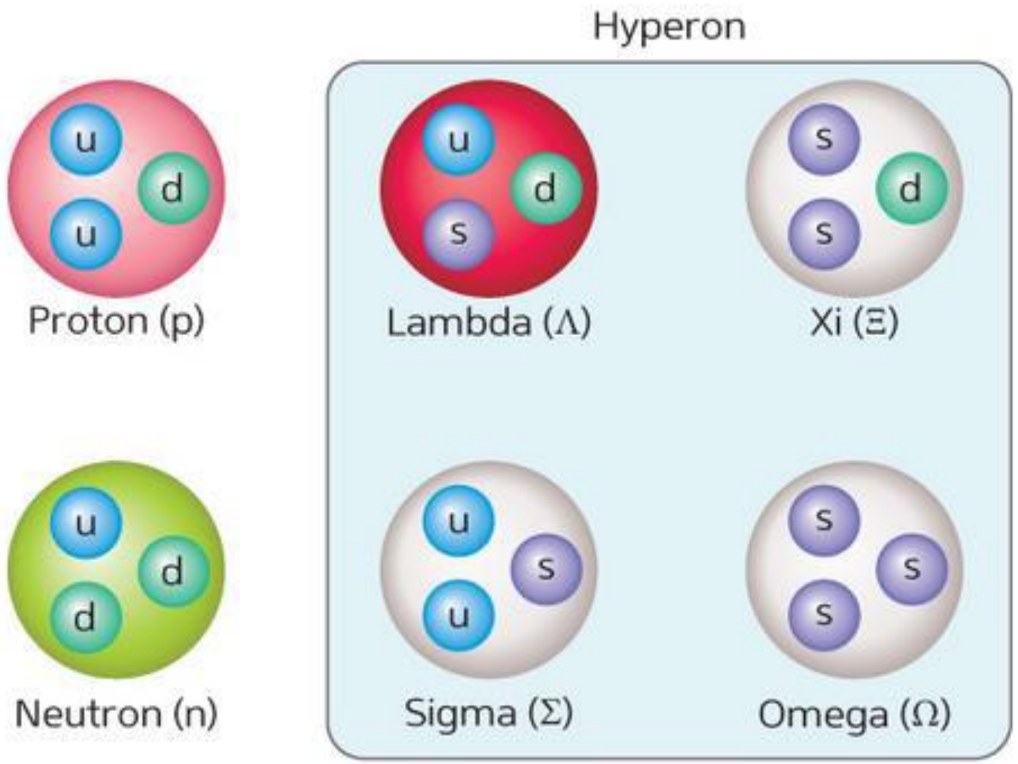
$e^+e^- \to n\bar{n}\gamma_{ISR}$

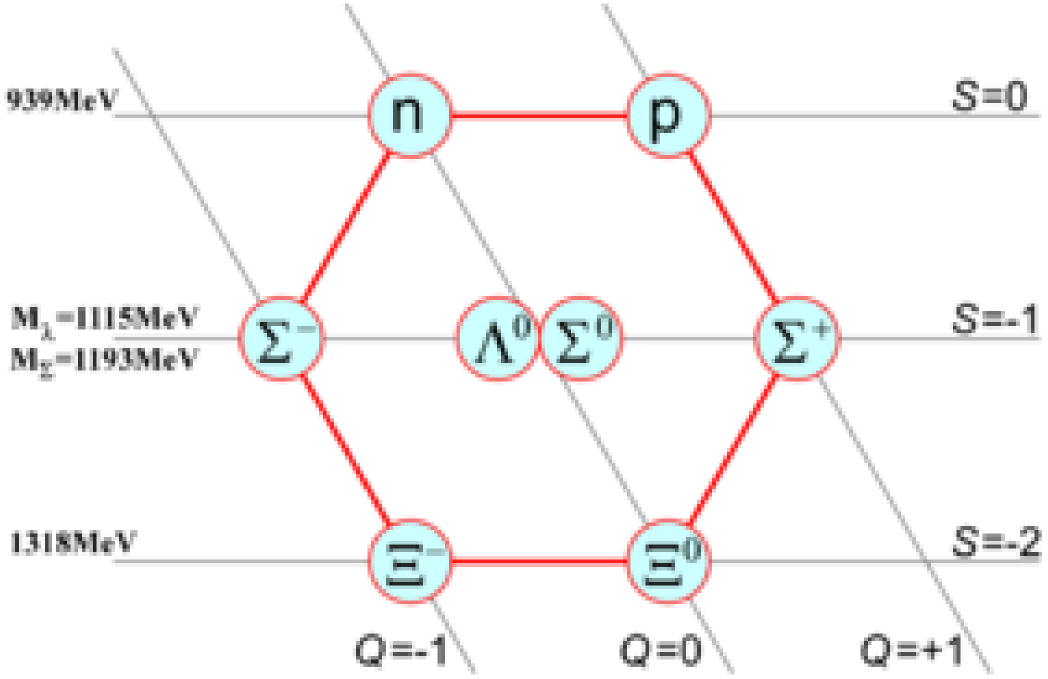
➢ Only tagged analysis possible (efficiencies at per mil level)

➢ Increase detection efficiency using TOF, MUC

➢ Main background from $e^+e^- \to n\bar{n}\pi^0$ and $e^+e^- \to \gamma\gamma\gamma$

“What happens with the baryon structure when a light quark is replaced by a heavier one?”





Status of $e^+e^- \to \Lambda\bar{\Lambda}$ FFs

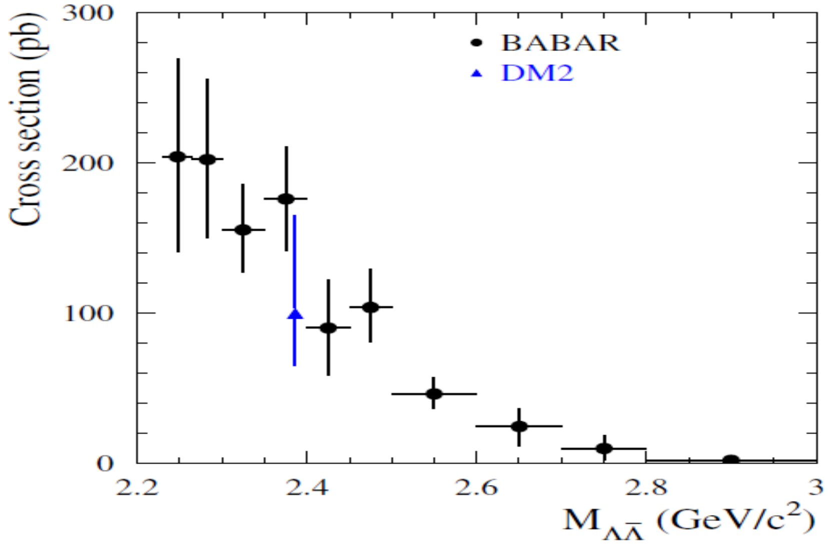
- From Babar, $e^+e^- \to \Lambda\bar{\Lambda}$ measured from threshold to 2.27 GeV, non-zero cross section $(204 \pm 60 \pm 20)$ pb.

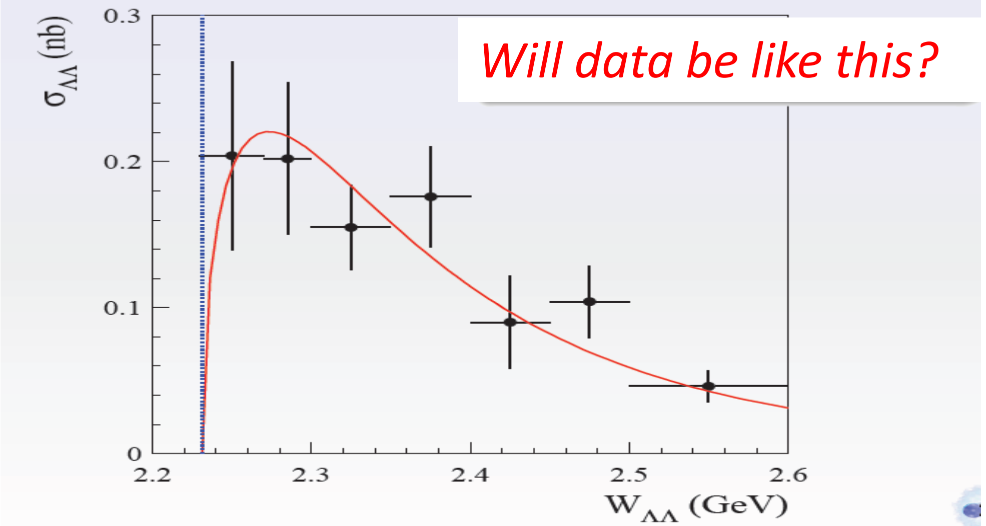
$$\sigma_{B\bar{B}}(q^2) = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right]$$

Coulomb factor C= 1 for neutral $B\bar{B}$ pair assuming coulomb acts after $B\bar{B}$ pair are built and they are as neutral point-like particles.

- Expected to increase with the velocity near the threshold starting from ZERO.

- $G_E = |G_E(q)|e^{i\Phi_E}, G_M = |G_M(q)|e^{i\Phi_M}$, relative phase $\Phi = \Phi_M - \Phi_E$ can be extracted from $\boldsymbol{\Lambda}/\bar{\boldsymbol{\Lambda}}$ polarization.





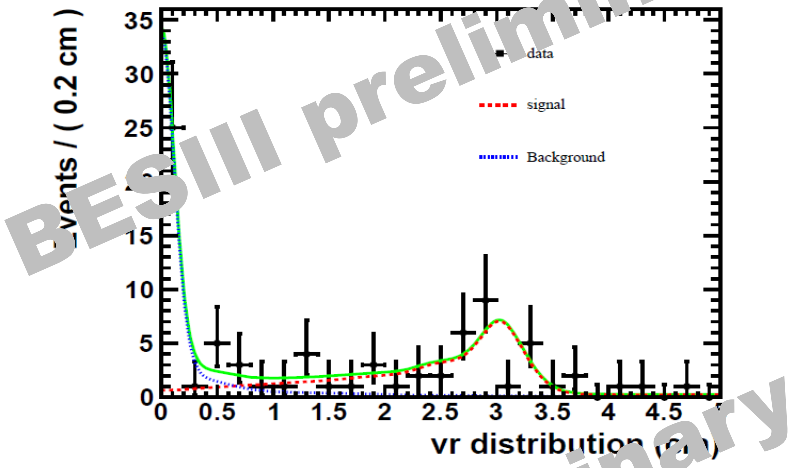
Will data be like this?

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

Data $\sqrt{s}$ =2232.4 MeV, 1.0 MeV above $\Lambda\bar{\Lambda}$ threshold.

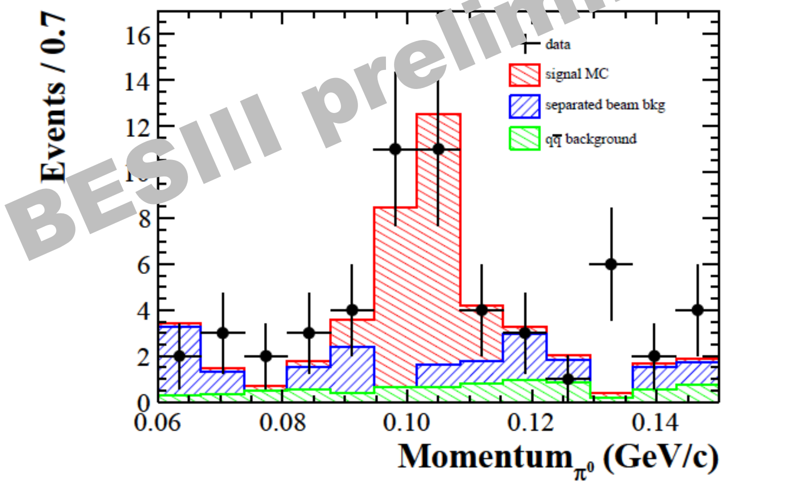
Strategy for $e^+e^- \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

i) The momentum of final states are too low to leave message in the detector.
ii) Antiproton interacting on the beam pipe will produce secondary particles, whose vertex is around 3 cm.
iii) The yield of $\Lambda\bar{\Lambda}$ events is 43 ± 7.



Strategy for $e^+e^- \to \Lambda\bar{\Lambda}, \bar{\Lambda} \to \bar{n}\pi^0$.

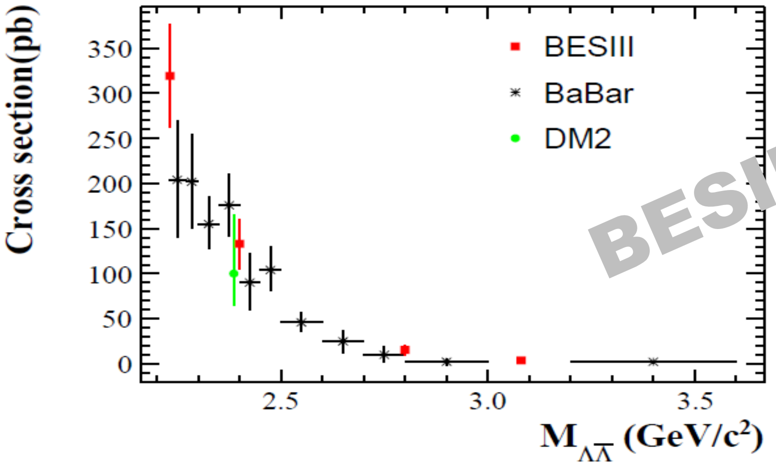
i) Multiply Variable Analysis tool (Boosted Decision Tree) is applied to separated from large background.
ii) The final states of π^0 has a mono-momentum around 105 MeV.
iii) The yield of $\Lambda\bar{\Lambda}$ events is 22 ± 6.

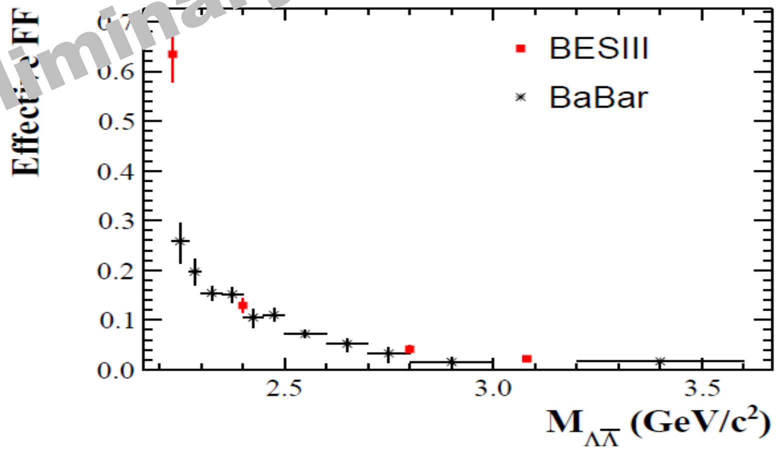


$e^+e^- \to \Lambda\bar{\Lambda}$ FFs from 2012 data

$\sqrt{s}$ (MeV)	Reconstruction	σ_{Born} (pb)	$\|G\|$ ($\times 10^{-2}$)
2232.4	$\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$	$325 \pm 53 \pm 46$	
	$\bar{\Lambda} \to \bar{n}\pi^0$	$(3.0\pm1.0\pm0.4)\times10^2$	
	combined	$\boxed{320 \pm 58}$	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		$3.9 \pm 1.1 \pm 0.5$	$2.21 \pm 0.31 \pm 0.14$

Surprisingly, large cross section near threshold!





BESIII preliminary

Cross section does not vanish at threshold ⟶ Coulomb interaction at quark level?

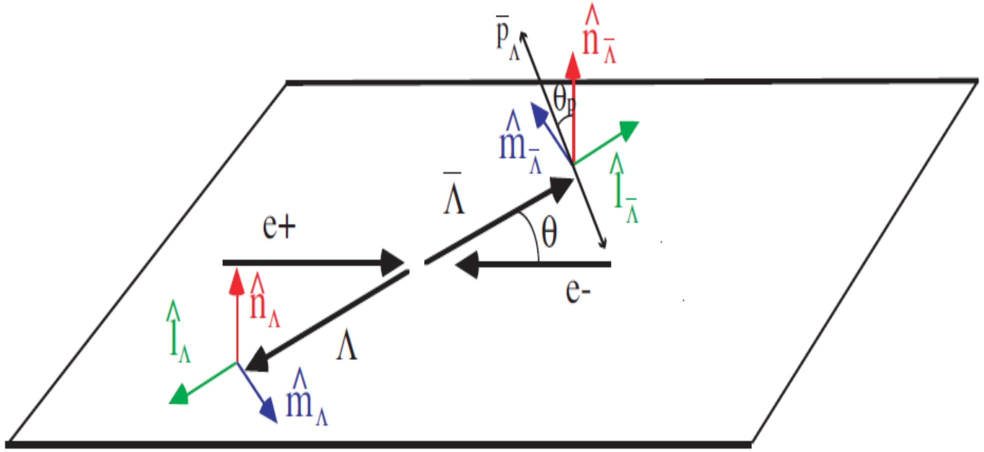
Will be clarified with more data of 2015?

Prospects of $\Lambda\bar{\Lambda}$ FFs

Parity violating decay: $\Lambda \rightarrow p\pi$, emission of proton depends on Λ- polarisation

$$\frac{dN}{d\cos\theta_p} \propto 1 + \alpha_\Lambda P_n \cos\theta_p$$

(*) Angle between proton and polarization axis in mother's rest frame



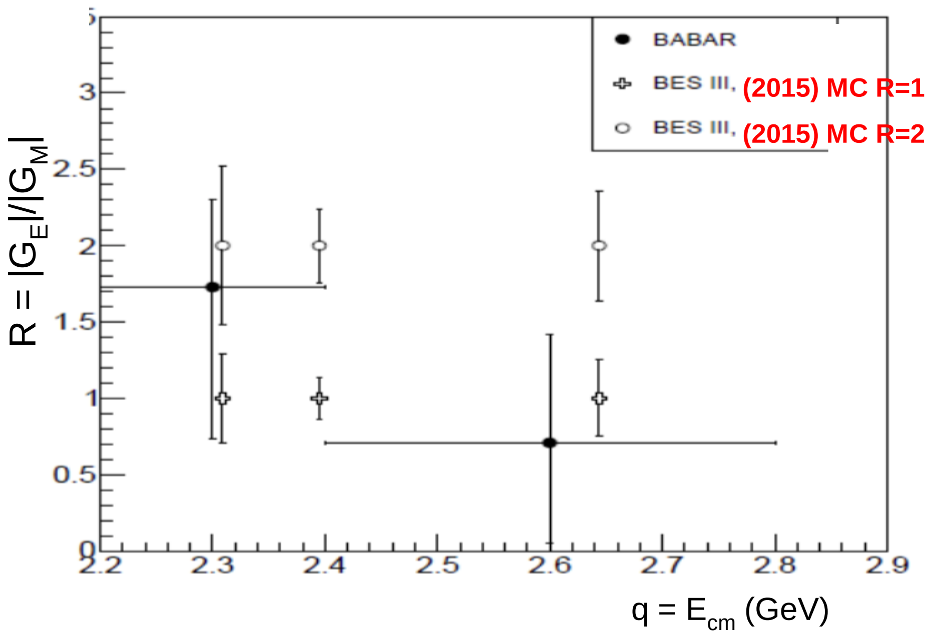
Imaginary part of FFs leads to polarization observables:

$$P_n = -\frac{\sin 2\theta_\Lambda \sin\Delta\phi / \tau}{R\sin^2\theta_\Lambda / \tau + (1+\cos^2\theta_\Lambda)/R} = \frac{3}{\alpha_\Lambda}\langle\cos\theta_p\rangle$$

From BESIII 2015 data: 15 points above $\Lambda\bar{\Lambda}$ threshold!

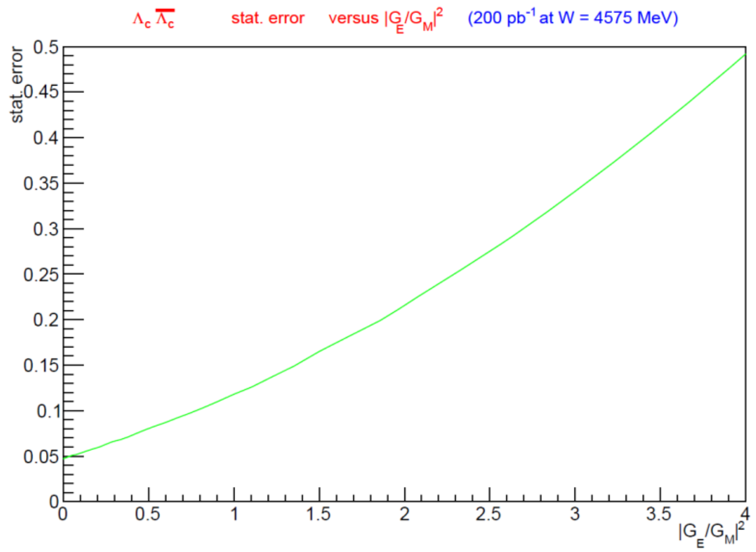
Expected statistical accuracies for P_n between 6% and 17%

Expected statistical accuracies for $R = |G_E|/|G_M| = 1$ between 14% and 29%



<u>Complete determination of TL FFs possible!!</u>

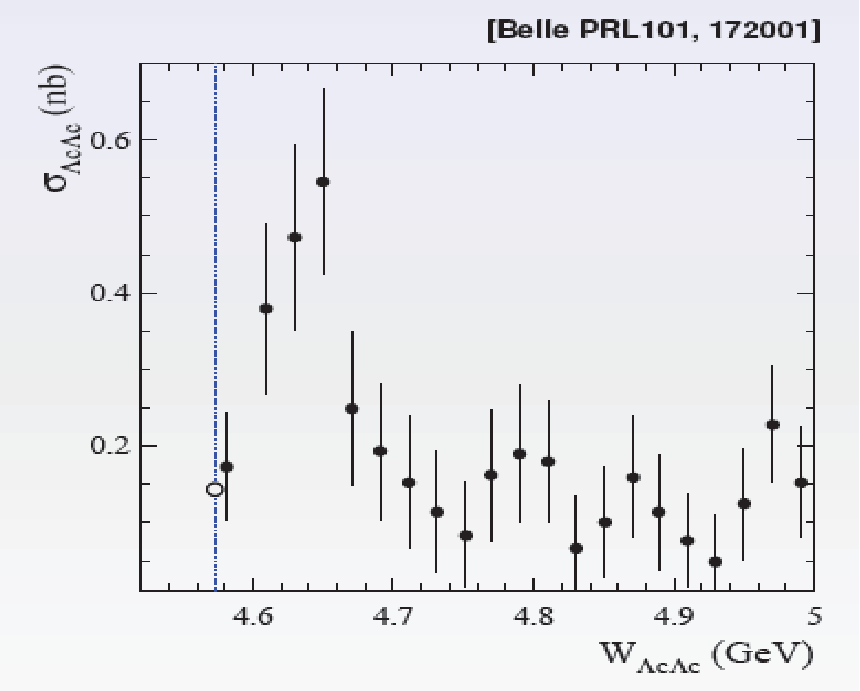
Prospects for $\Lambda_c\overline{\Lambda_c}$ at threshold



G_E and G_M in S/D wave form: $\sqrt{\tau}\, G_E = G_S - 2G_D$, $G_M = G_S + G_D$

At threshold, only S wave in principle.

$$\sigma = \frac{\pi^2\alpha^3}{2M^2}|G_S(4M^2)|^2 = 0.15|G_S(4M^2)|^2 \text{ nb}$$



Belle ISR process with $\Lambda_C \to pK_s, pK^-\pi^+, \Lambda\pi^+$

$\sigma_{M_0} = 0.15\, nb \;\to no\ D\ wave?$

- Assuming the same total number of events, the statistical error in retreiving $|G_E|/|G_M|$, from the angular distribution depends almost linearly on $|G_E|^2/|G_M|^2$

- W=4.575GeV at BESIII,

  L = 42 pb^{-1} → dR/R~23% (done)

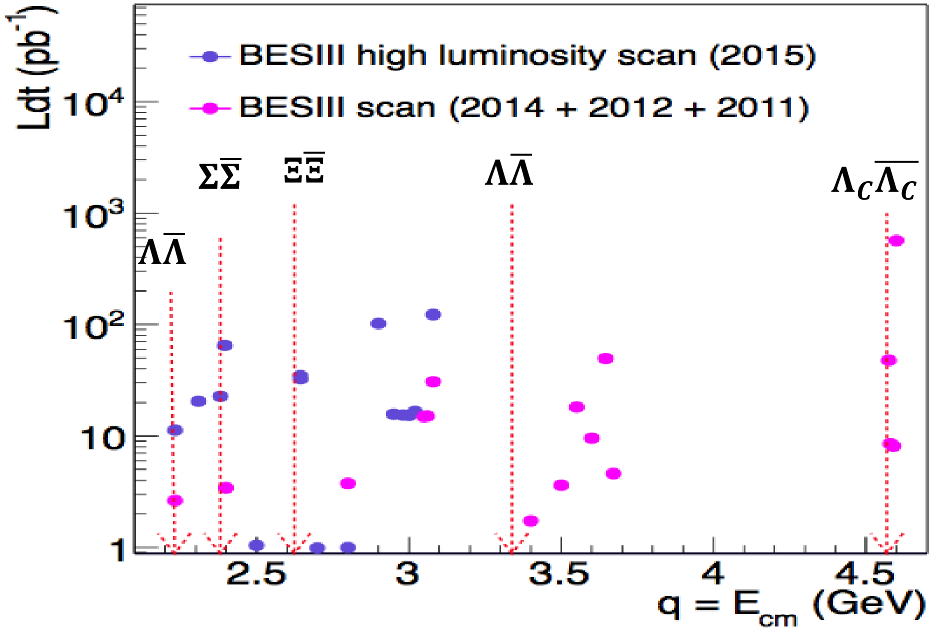
  Assuming R~2 (like BaBar)

  L=200 pb^{-1} → dR/R~10%

Proposal have been made to collect more L_{int}

Prospects for other hyperon TL-FFs (2015, 2014, 2011 data)

$e^+e^- \rightarrow \Lambda\overline{\Sigma^0}, \overline{\Sigma^0}\Sigma^0$ previously measured by BaBar, no R_{em} extraction possible



$e^+e^- \rightarrow \Lambda\overline{\Sigma^0}, \overline{\Sigma^0}\Sigma^0, \overline{\Sigma^-}\Sigma^+, \overline{\Sigma^+}\Sigma^-, \overline{\Xi^0}\Xi^0, \overline{\Xi^+}\Xi^-, \overline{\Omega^+}\Omega^-$:

measurements of effective FF and R_{em} and relative phase $\Delta\Phi$ at single energy points possible

$e^+e^- \rightarrow \overline{\Lambda_c^-}\Lambda_c^+$:

measurements of effective FF,

R_{em} and $|G_M|$ at threshold possible

$E_{e^+e^-}$ (GeV)	L (pb^{-1})	$\epsilon_{\Lambda\bar{\Sigma}^0}$ (%)	$\sigma_{\Lambda\bar{\Sigma}^0}$ (pb)	$N_{\Lambda\bar{\Sigma}^0}$	$\epsilon_{\Sigma^0\bar{\Sigma}^0}$ (%)	$\sigma_{\Sigma^0\bar{\Sigma}^0}$ (pb)	$N_{\Sigma\bar{\Sigma}^0}$
2.309	20	4	374	123			
2.386	20	8	40	26	4	351	115
2.395	55	8	40	72	7	100	158
2.644	65	15	6	24	15	25	100
2.9	100	17	2	14	17	3.4	24
2.981	15	17	1.5	1.6	17	3.0	3

10 fold more events of the world data could be get!!!

Summary

- BESIII excellent laboratory for hadron form factor measurements: scan data + ISR tecnique.
- Proton Form Factors and their ratio have been measured using a small amount of data.
- Results on $\Lambda\bar{\Lambda}$ just released.
- New high statistics data between 2.0 and 3.1 GeV will significantly improve FFs measurements for $p, n, \Lambda, \Xi, \Omega, \Sigma, \Lambda_c$. Also from ISR measurements exciting results for nucleon FFs expected.
- Other related topics being studied (not reviewed here):
  - ISR technique allows access to energies below 2 GeV: the first result is the charged pion (see Yaqian Wang's report)
  - Space-like transition FFs of mesons (di-γ contributions to (g_μ-2) (see Christoph Redmer's report))

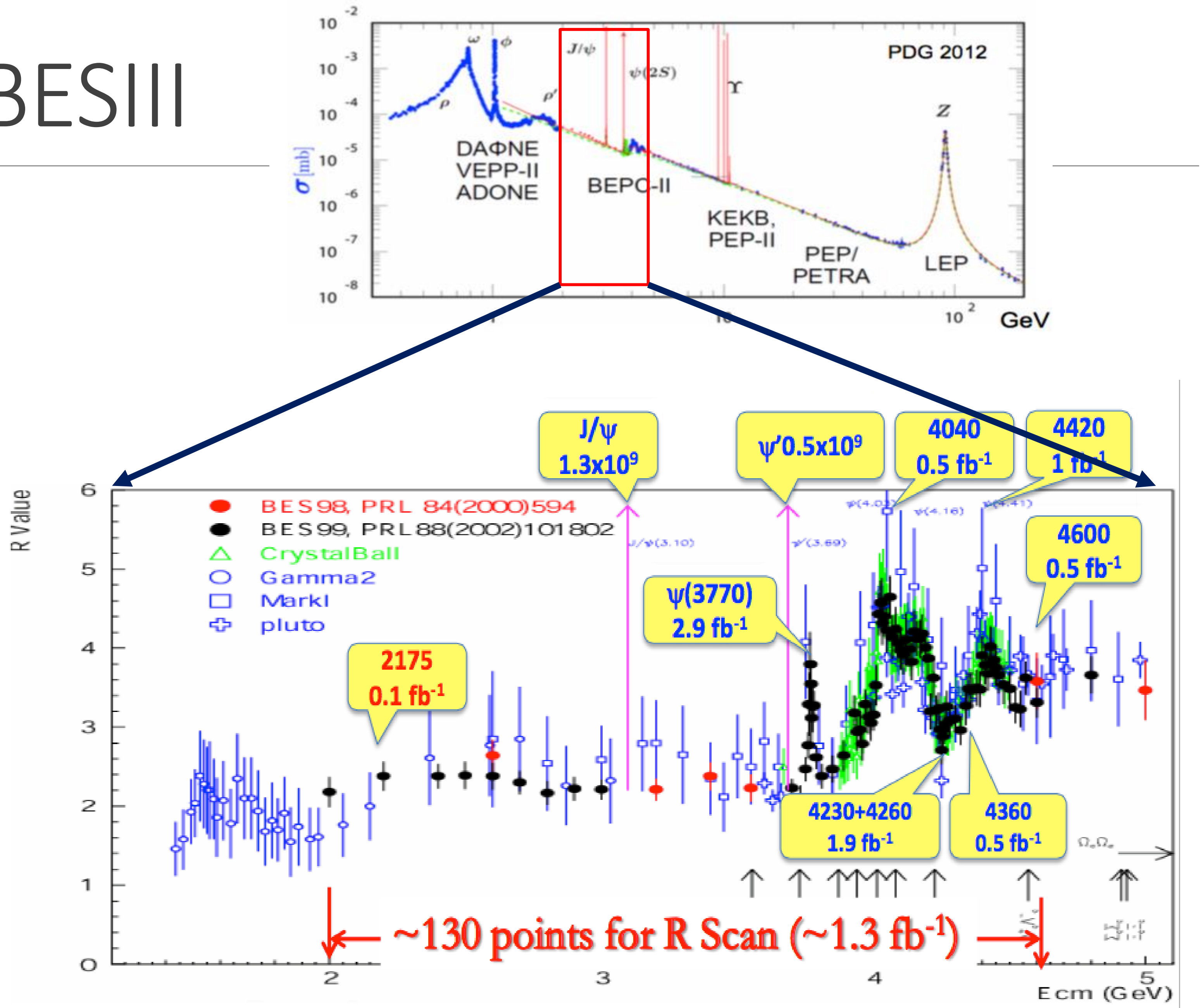
BESIII

THANKS FOR YOUR ATTENTION!

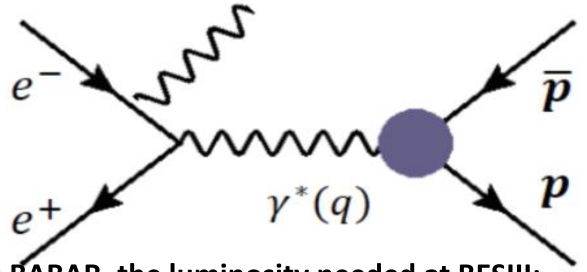
Time-like FFs at BESIII

Data collected at BESIII

Data sample	Lint	Energy
J/ψ	~0.45 fb-1	3.097
ψ’	~0.8 fb	3.686
ψ’’	2.9 fb-1	3.773
xyz	(0.5+1.9+0.5+ 1.0+0.5) fb^{-1}	(4.2-4.6)
scan	~12 pb^{-1}	2.23, 2.4, (3.05-3.08)
	0.85 fb^{-1}	(3.85-4.60)
	525.5 pb^{-1}	2.00-3.08



Prospects of $e^+e^- \to p\bar{p}\gamma_{ISR}$



- Continuous q^2-range available: $m^2_{th} < q^2 < s$
- Full angular distribution in hadronic center-of-mass
- Detection efficiency independent of q^2 and hadronic angular distribution
- Acceptance at threshold $\neq 0$

Data samples (ECM): ψ(3770),ψ(4040), Y(4230), Y(4260), Y(4360), Y(4420), Y(4600). Total: 7.4 fb-1

Analysis for each E_{CM} and q, then combine statistics

- ISR kinematics: photon and pp-system with small opposite polar angles

Efficiencies: ~20% -γ-untagged, ~6% γ-tagged analysis

- From 2.1 GeV up untagged-photon analysis possible

Final statistics competitive with BaBar

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

E=10579 MeV	L=450 pb^{-1}
E=4260 MeV	L = 64.8 pb^{-1}
E=4040 MeV	L = 56.6 pb^{-1}
E=3770 MeV	L = 47.0 pb^{-1}
E=3686 MeV	L = 44.1 pb^{-1}
E=3100 MeV	L = 25.6 pb^{-1}
E=2232 MeV	L = 4.8 pb^{-1}

Theoretical calculation