Proton Form Factors at BESIII

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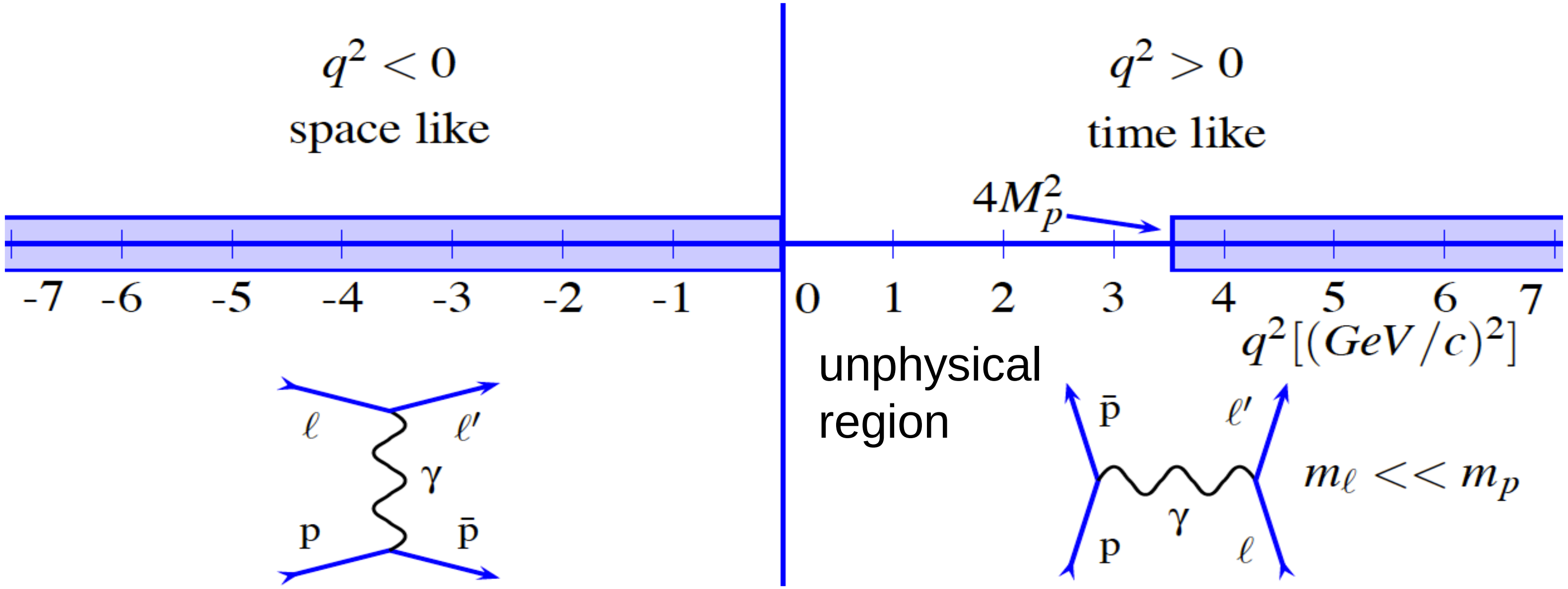
Outline

- Introduction
- BESIII detector at BEPC;
- Proton FFs
  - with 2012 scan data
  - with $\psi(3773)$ and XYZ data in ISR mode
  - MC simulated with 2014 scan data
- Summary.

Hadron Form Factors

Fundamental properties of hadrons about charge, magnetization distribution, internal structure.
Necessary input for physics. Driving renewed activities on theory side.

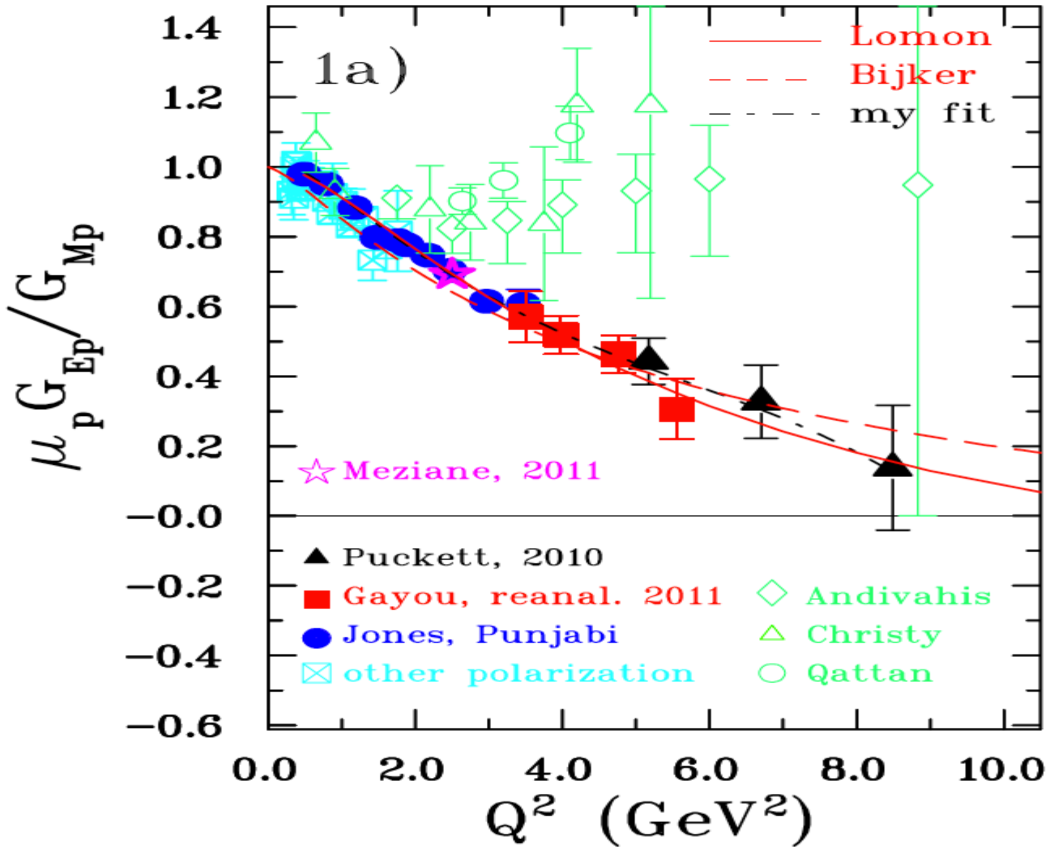


Form Factor real
cross section (Rosenbluth)
no single spin observables
double spin observables

dispersion relations ⟷

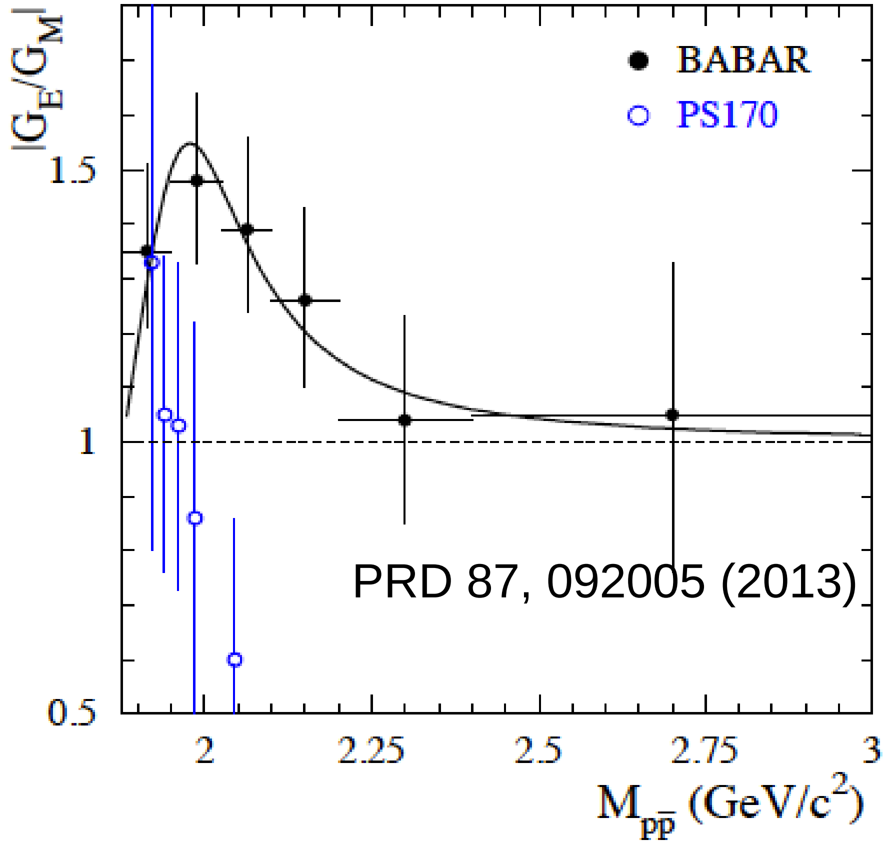
Form Factor complex
cross section (angular Distr.)
single spin observables (P_y)
double spin observables

Rossenbluth separation on Space-like data



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

Fit angular distr. of Time-like data



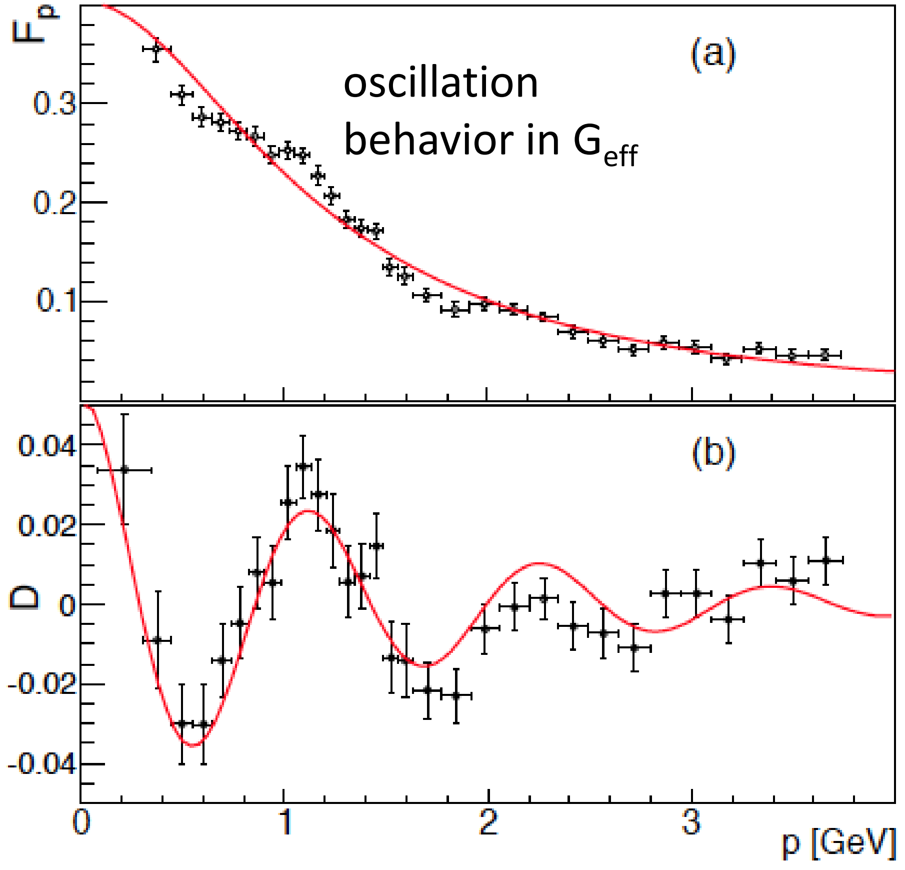
($q^2 > 0$): precision >20%

time like EM form factor: badly known

Periodic structures in TL proton FFs

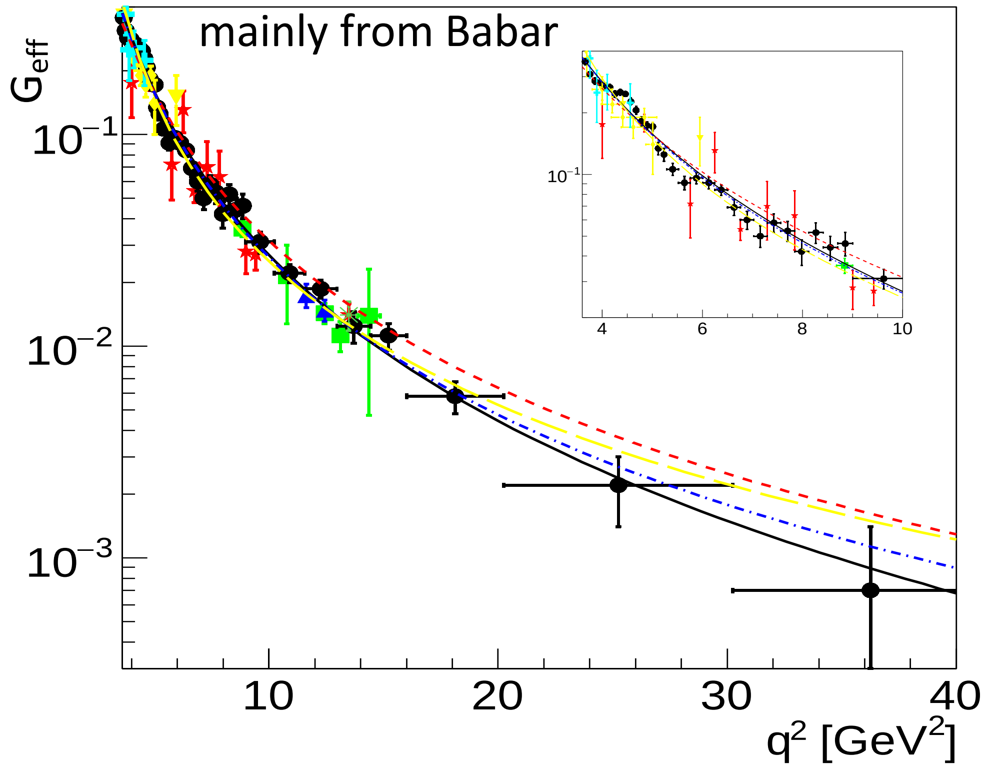
Phys. Rev. Lett. 114,232301 (2015), arXiv:1510.06338[nucl-th]

Andrea Bianconi, Egle Tomasi-Gustafsson



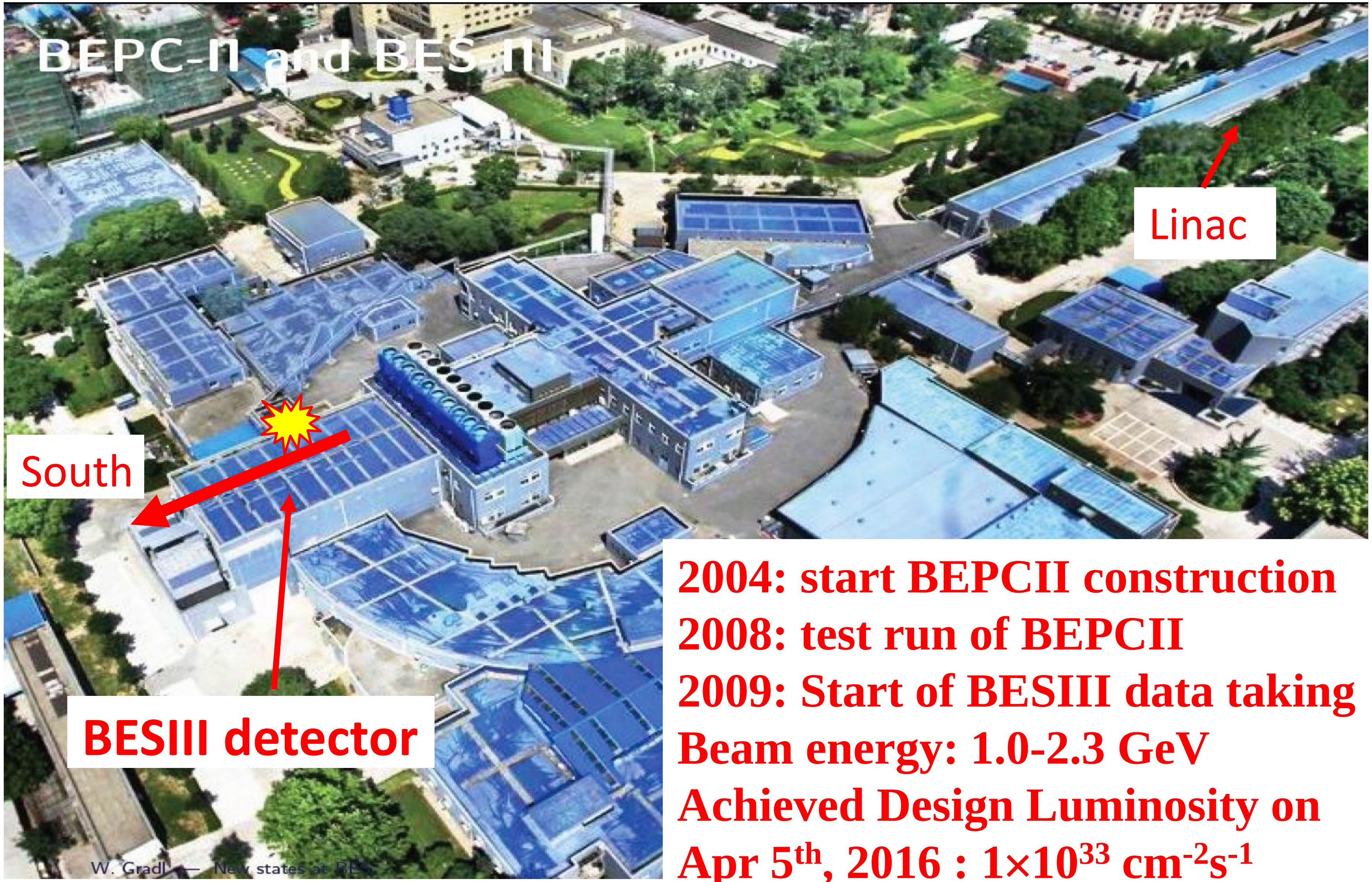
$$F_{osc}(p) \equiv A \exp(-Bp) \cos(Cp + D).$$

with world data
mainly from Babar



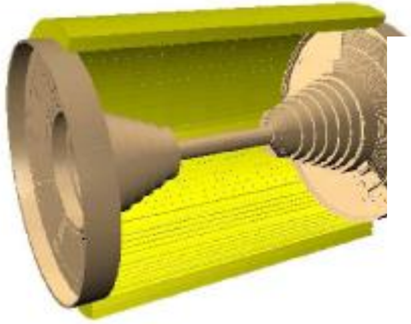
- ✓ A possible presence of an imaginary part associated to rescattering processes.
- ✓ A relative distance of 0.7–1.5 fm between the centers of the forming hadrons.

Beijing Electron Positron Collider (BEPC)



2004: start BEPCII construction
2008: test run of BEPCII
2009: Start of BESIII data taking
Beam energy: 1.0-2.3 GeV
Achieved Design Luminosity on Apr 5th, 2016 : 1×10^{33} cm^{-2}s^{-1}

MDC



R inner: 63mm ;

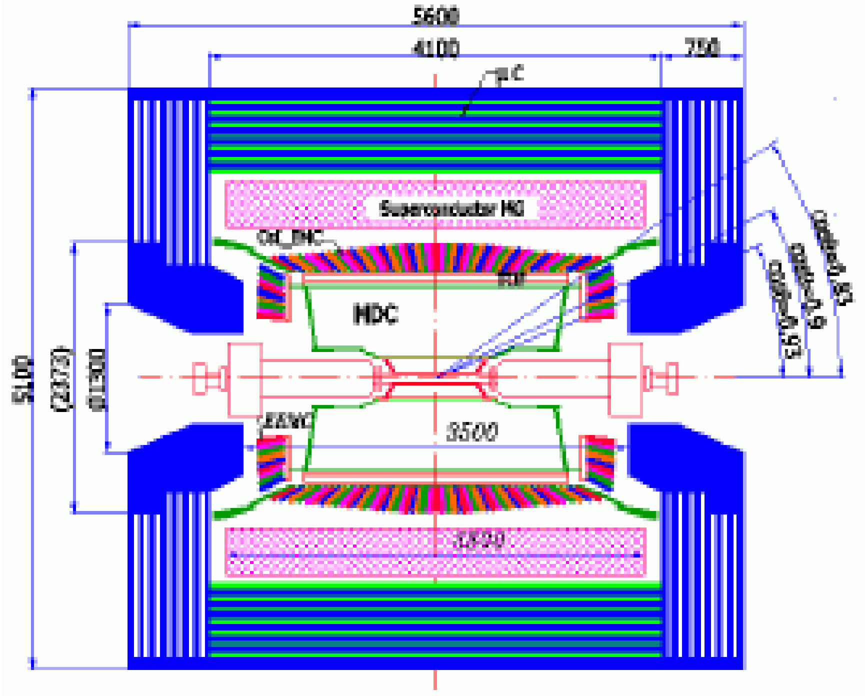
R outer: 810mm

Length: 2582 mm

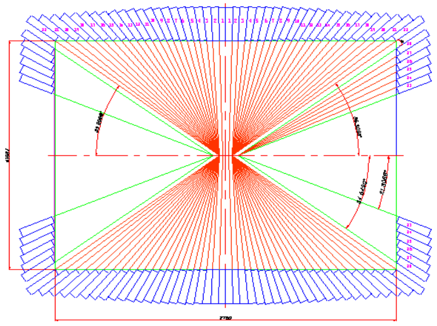
Layers: 43

σ_{xy}=130 μm, dE/dx~6

σ_p/p = 0.5% at 1 GeV



CsI(Tl) EMC



Crystals: 28 cm(15 X_0)

Barrel: |cosθ|<0.83

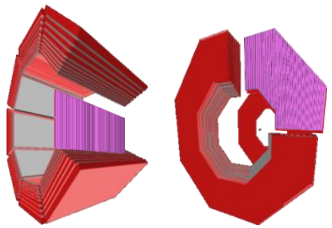
Endcap:

0.85 < |cosθ| < 0.93

Barrel σ_E 2.5%, σ_l 6m

Endcap σ_E 5.0%, σ_l 9mm

RPC MUC



BMUC: 9 layers – 72 modules

EMUC: 8 layers – 64 modules

$\sigma_{spatial}$: 1.48 cm

TOF

BTOF: two layers

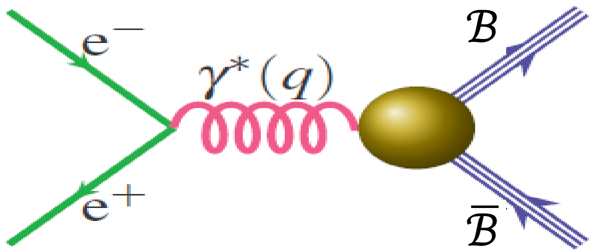
ETOF: 48 crys. for each

σ_T(barrel): 80 ps

σ_T(endcap): 110 ps

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 $\sigma \propto G(q^2)$

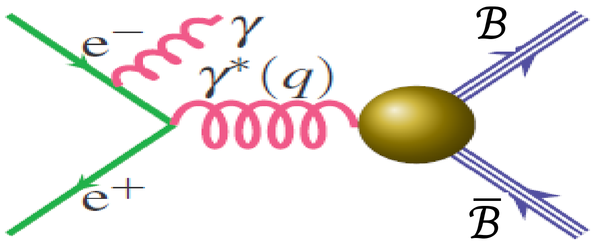
$$|G(q^2)| = \sqrt{\frac{\sigma^{Born}_{B\bar{B}}(q^2)}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta C}{3q^2})}}$$

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



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

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

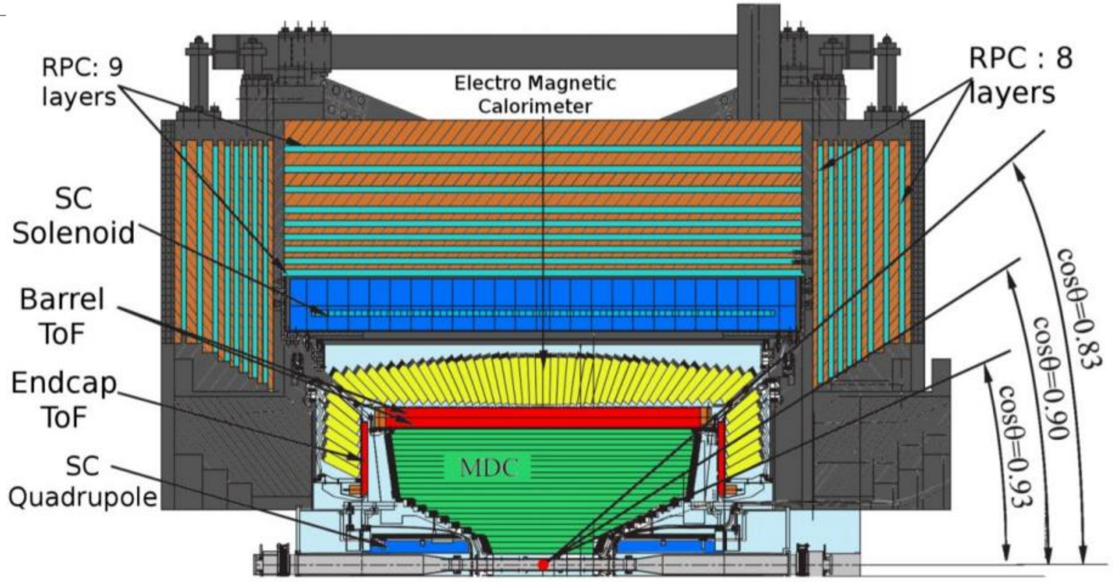
$$x = 1 - q^2/s = 2E_\gamma/\sqrt{s}$$

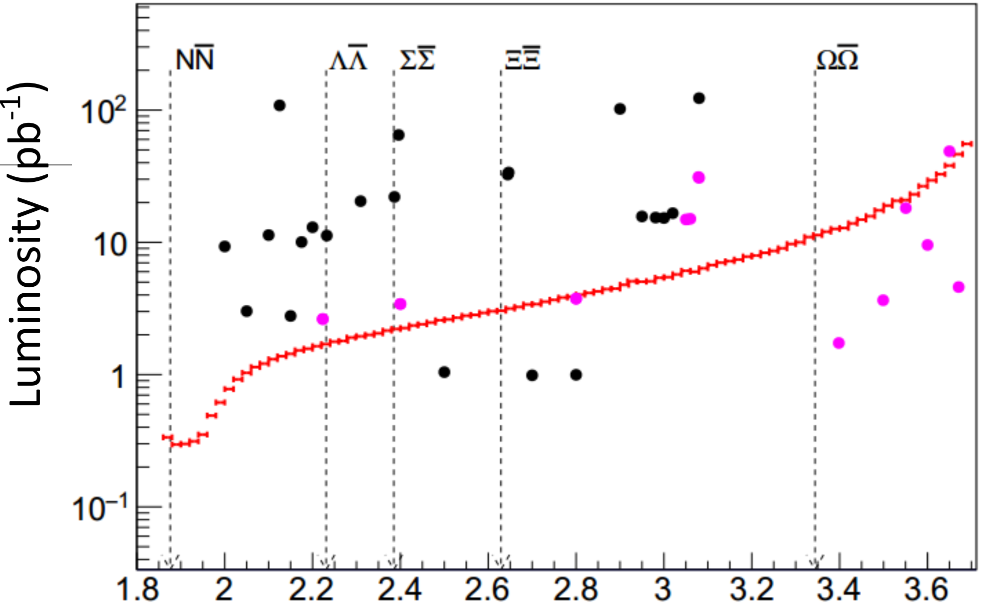
C= $\frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}$, *at threshold* $\frac{\pi\alpha}{\beta}$ a jump at threshold for charged

1, for a neutral $B\bar{B}$ pair, $\sigma \to 0$

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

Comparison between scan and ISR





Red line is the luminosity of $p\bar{p}\gamma_{ISR}$ out of 7.4 fb^{-1} dataset at high energy (ψ(3773), XYZ)

- E_{beam} discrete → q^2 fixed
  - q very precise ~ 0.1 MeV, ideal for threshold studies
- ‘High‘ cross section (~pb)
  - Low integrated luminosity enough for high statistics
- High geometrical acceptance
  - High detection efficiency

- E_{beam} fixed → Continuous q^2-range depends on the ISR
  - Acceptance at threshold ≠ 0
  - $m^2_{th} < q^2 < s$
- ‘Small‘ cross section (~10^{-3} pb)
  - High luminosities needed
- Small geometrical acceptance: ISR emitted at very large or very small polar angles

Proton Form Factors with scan data 2012

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

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

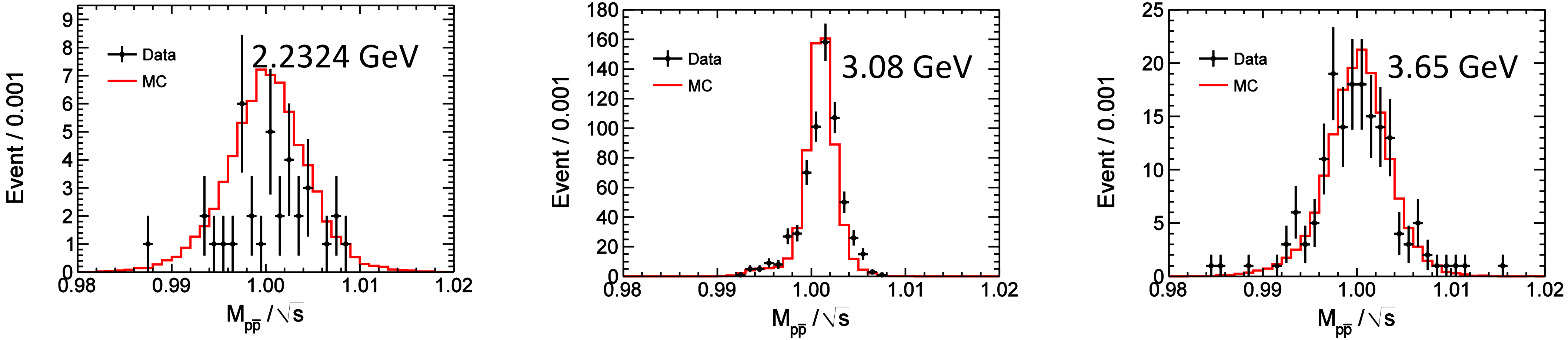
$$|G| = \sqrt{\frac{\sigma_{born}}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta C}{3E_{CM}^2})}}$$

Analysis features:

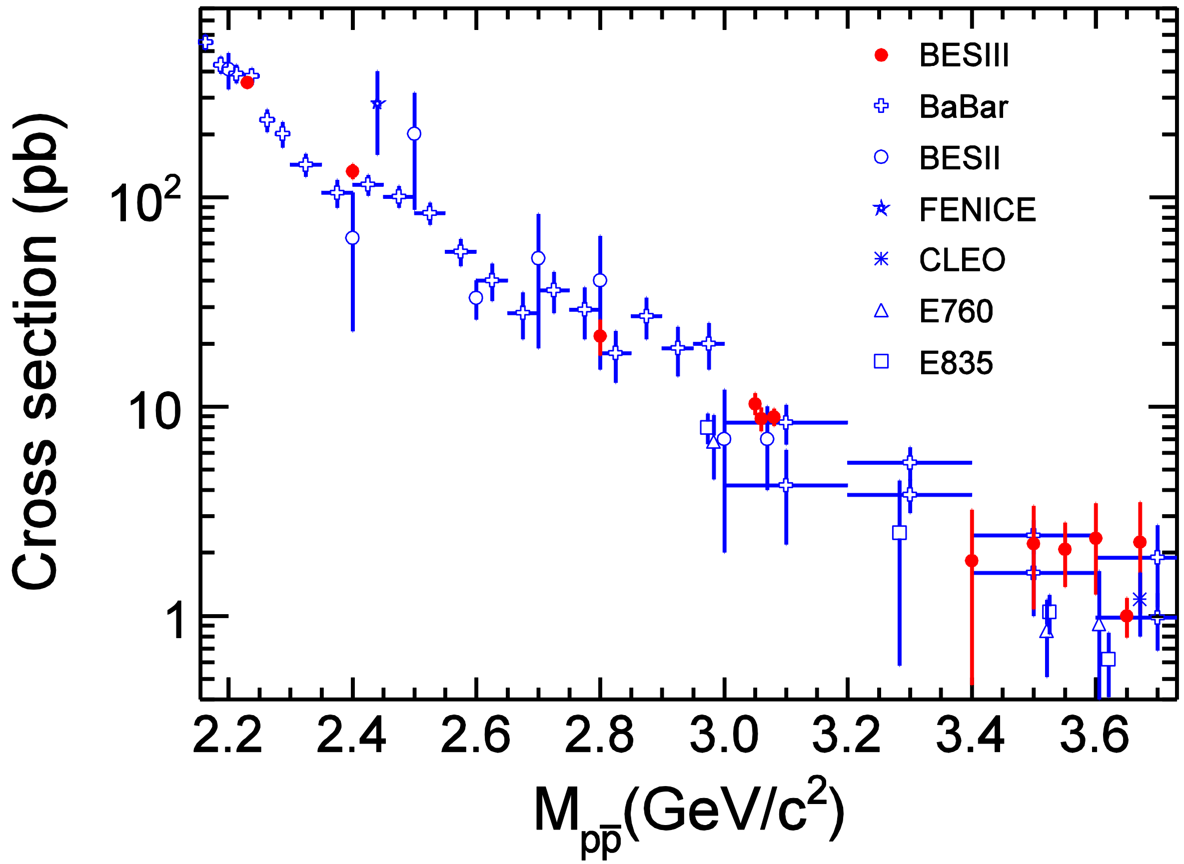
- p and $\bar{p}$ from vertex, in time, back to back, $E_{p,p} = E_{CM}/2$
- $\varepsilon\times(1+\delta) \sim$ 50%-60%
- Radiative corrections from ConExc (NLO in ISR)
- bkg normalized according to MC calculation

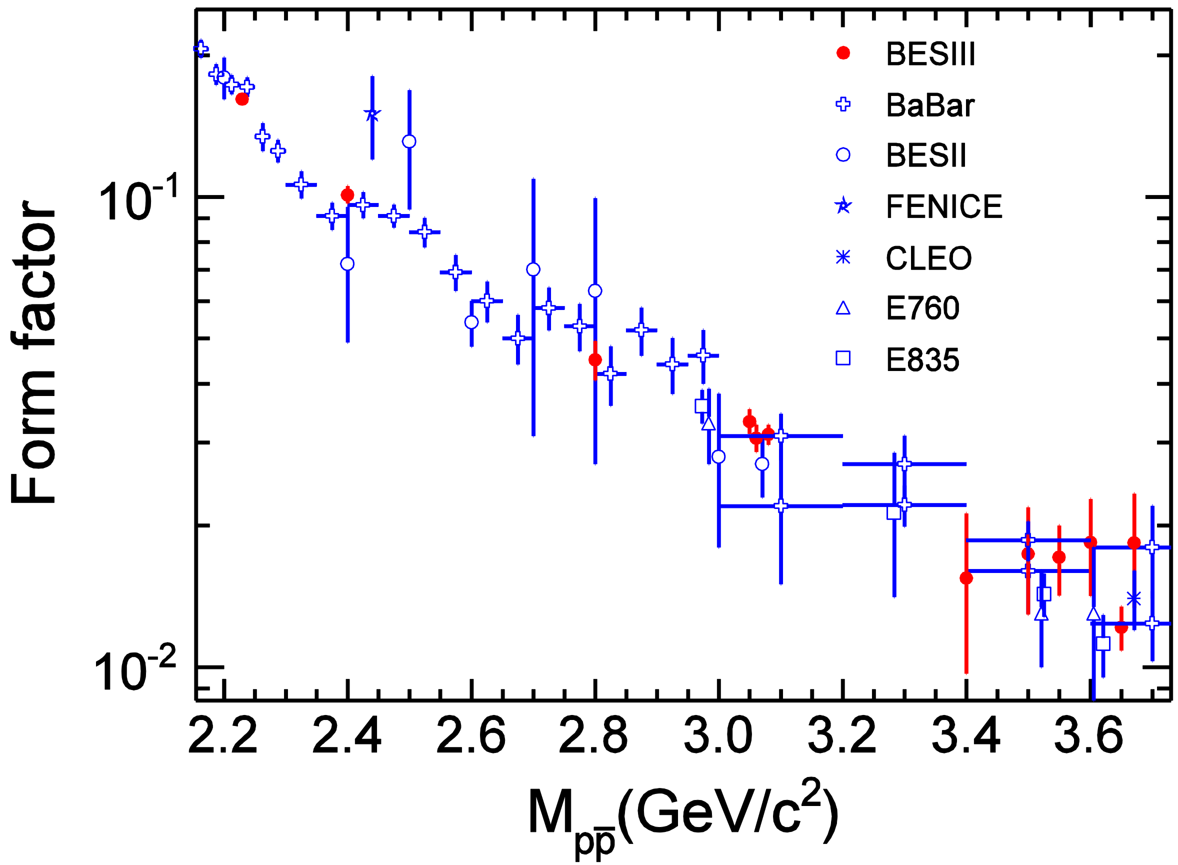
N_{obs}: observed signal events
L : integrated luminosity
N_{bkg}: estimated background from MC (beam associated bkg, physical bkg, e.g., bhabha, dimu, $p\bar{p}\pi^0$)
ε: detection efficiency (from MC)
1+δ: radiative factor (from MC)

bkg level very low



Phys. Rev. D 91, 112004 (2015)





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

Angular analysis to extract the EM FFs

- Angular analysis to extract the EM FFs:

$$\frac{d\sigma}{d\Omega}(q^2) = \frac{\alpha^2\beta}{4s}|G_M(s)|^2[(1 + cos^2\theta_p) + R_{EM}^2\frac{1}{\tau}sin^2\theta_p]$$

$R_{EM} = |G_E(q^2)|/|G_M(q^2)|$

θ: polar angle of the proton at the c.m. system

- Fit function:

$$\frac{dN}{dcos\theta_p} = N_{norm}[(1 + cos^2\theta_p) + R_{EM}^2\frac{1}{\tau}sin^2\theta_p]$$

$N_{norm} = \frac{2\pi\alpha^2\beta L}{4s}[1.94 + 5.04\frac{m_p^2}{s}R^2]G_M^2(s)$ is the overall normalization in $|cos\theta_p| < 0.8$

Method of Moment to extract the EM FFs

$$R = \sqrt{\tau \frac{y_4 - y_2 < \cos^2\theta >}{< \cos^2\theta > y_1 - y_3}}$$

$$G_M = \sqrt{\frac{N_{norm}}{N_1(y_2 + \frac{R^2}{\tau} y_1)}}$$

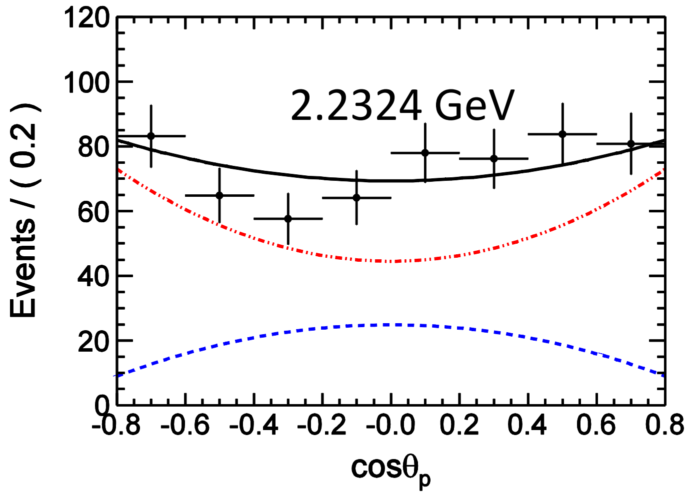
$$< \cos^2\theta >= \frac{N_1}{N_{norm}} \int_{xmin}^{xmax} \cos^2\theta \left\{ [(1+\cos^2\theta)]|G_M|^2 + \frac{1}{\tau}(1-\cos^2\theta)R^2 \right.$$

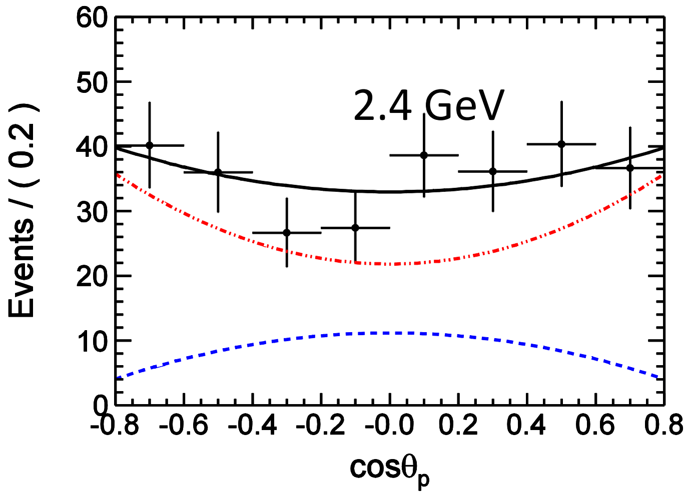
$$N_{norm} = \int_{xmin}^{xmax} \left\{ [(1+\cos^2\theta)]|G_M|^2 + \frac{1}{\tau}(1-\cos^2\theta)R^2|G_M|^2 \right\} d\cos\theta$$

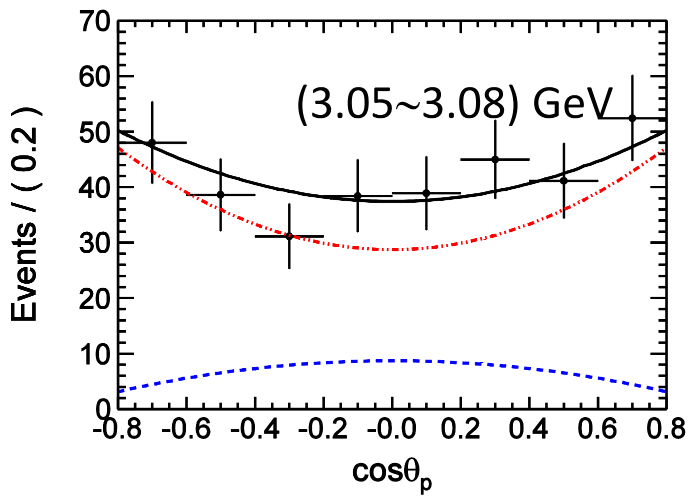
$$N_1 = \frac{L(1+\delta)\hbar c \pi \alpha^2 \beta C}{2s}$$

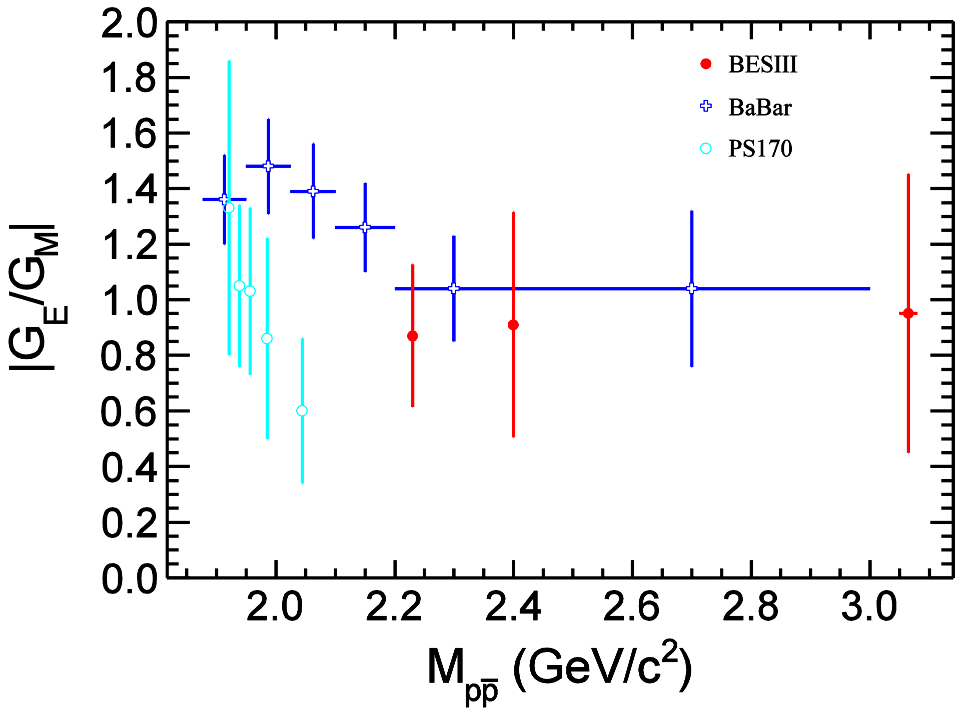
$$y_1 = \int_{xmin}^{xmax} (x - \frac{x^3}{3})dx, \quad y_2 = \int_{xmin}^{xmax} (x + \frac{x^3}{3})dx, \quad y_3 = \int_{xmin}^{xmax} (\frac{x^3}{3} - \frac{x^5}{5})dx, \quad y_4 = \int_{xmin}^{xmax} (\frac{x^3}{3} + \frac{x^5}{5})dx$$

Both methods in essence use the angular distribution of proton.





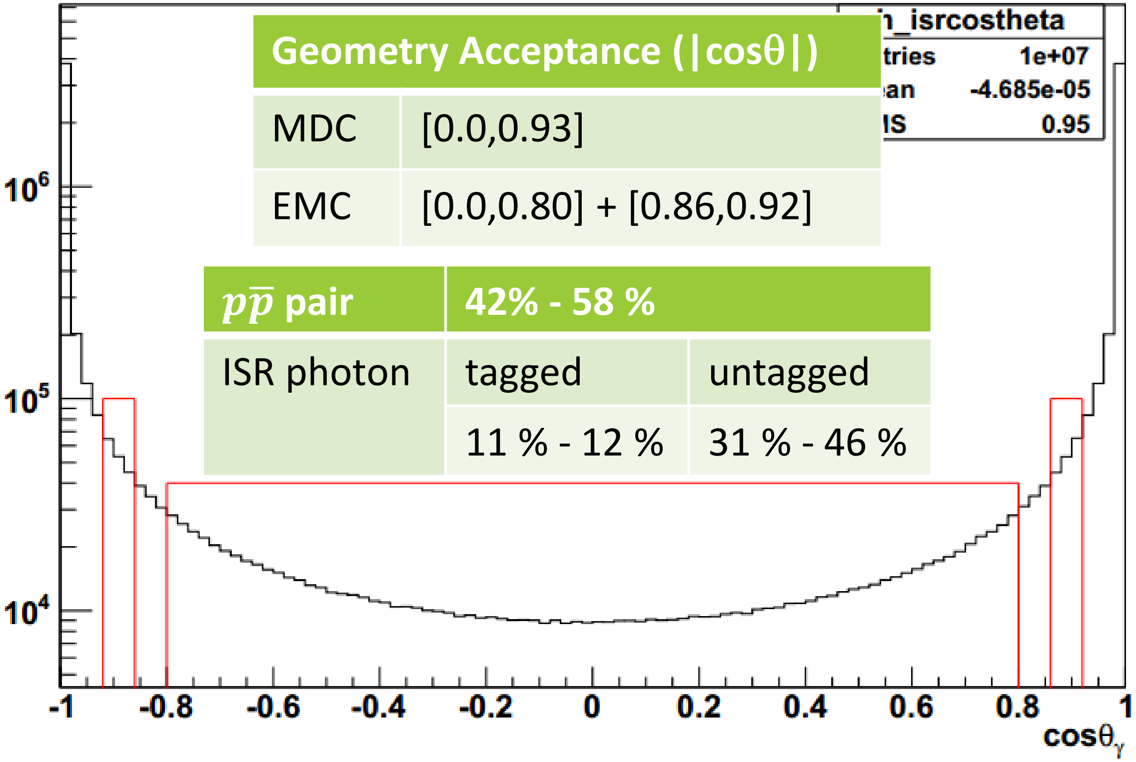




$\sqrt{s}$ (MeV)	$\lvert G_E/G_M \rvert$	$\lvert G_M \rvert$ ($\times 10^{-2}$)
		Fit on $\cos\theta_p$
2232.4	$0.87 \pm 0.24 \pm 0.05$	$18.42 \pm 5.09 \pm 0.98$
2400.0	$0.91 \pm 0.38 \pm 0.12$	$11.30 \pm 4.73 \pm 1.53$
(3050.0, 3080.0)	$0.95 \pm 0.45 \pm 0.21$	$3.61 \pm 1.71 \pm 0.82$
		Method of moments
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

- *R_{EM} consistent with BaBar and R=1.*
- *$\lvert G_M \rvert$ extracted for first time!*

ISR tagged and untagged



Geometry Acceptance (|cosθ|)	
MDC	[0.0,0.93]
EMC	[0.0,0.80] + [0.86,0.92]

$p\bar{p}$ pair	42% - 58 %	
ISR photon	tagged	untagged
	11 % - 12 %	31 % - 46 %

Two kinds of analysis:

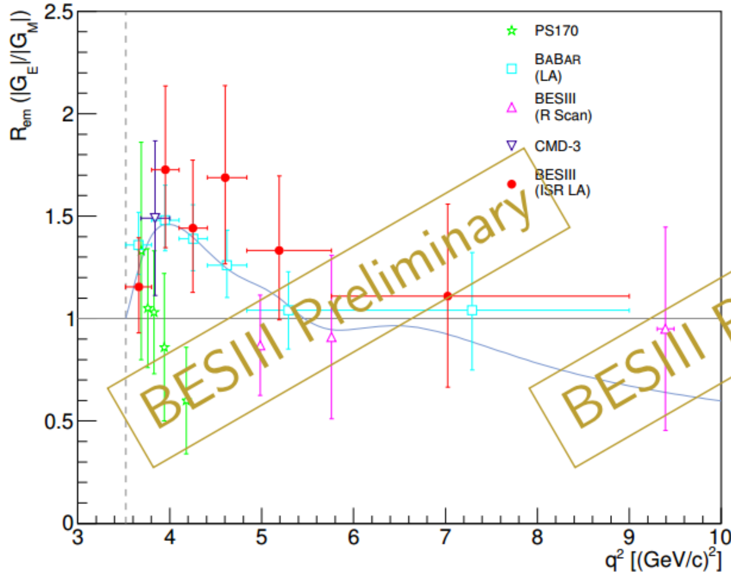
- photon detected (tagged analysis, ~12% of events)
- photon outside detector (untagged analysis, ~41% of events)

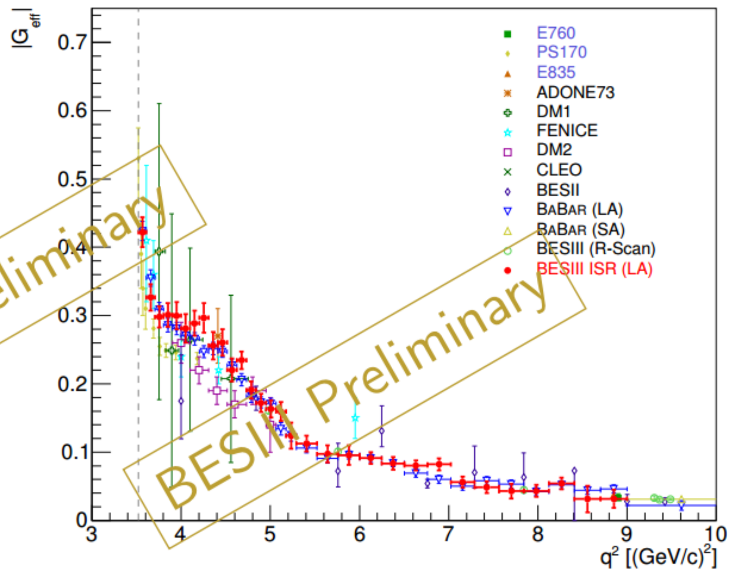
FFs with $e^+e^- \to p\bar{p}\gamma_{ISR}$ tagged

ψ′′	2.9 fb^{-1}	3.773
ψ(4040)	0.5 fb^{-1}	4.009
Y(4260)	1.9 fb^{-1}	4.23 and 4.26
Y(4360)	0.5 fb^{-1}	4.36
Y(4420)	1.0 fb^{-1}	4.42
Y(4600)	0.5 fb^{-1}	4.60

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

- Two charged tracks in MDC.
- The photon with the highest energy in EMC tagged as ISR photon.
- ISR kinematics: photon and $p\bar{p}$-system with small opposite polar angles
- From 2.0 GeV up, ISR analysis possible
- Background studied and substracted with data and MC



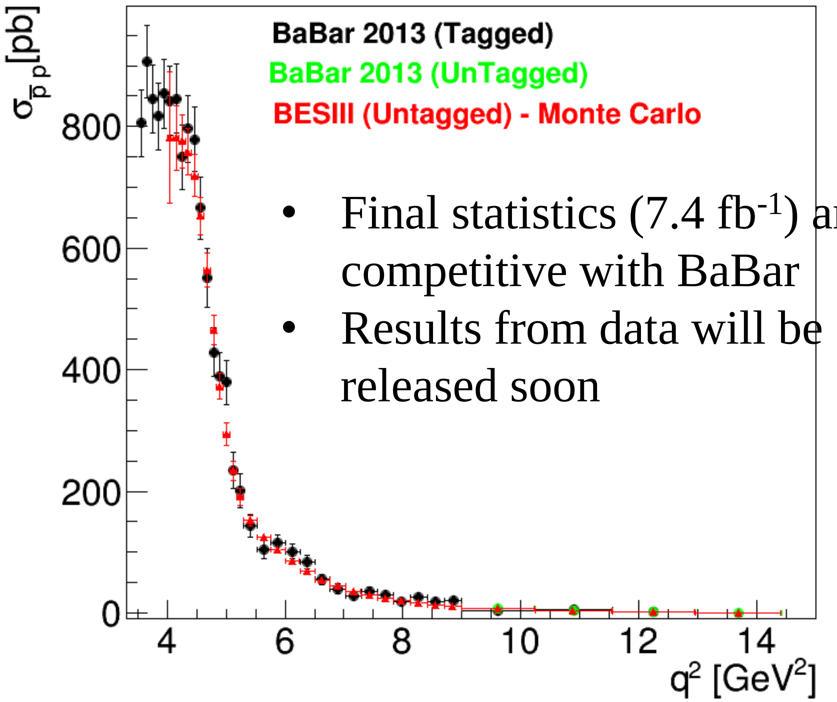


- ✓ Cross section (G_{eff}) in 31 mass intervals. Stat. ~ 5% - 32%
- ✓ R in 6 mass intervals. Stat. ~ 16% - 34%
- ✓ Consistent result with previous results
- ✓ **Final statistics competitive with BaBar**
- ✓ Cross section at threshold
- ✓ Systematic error included

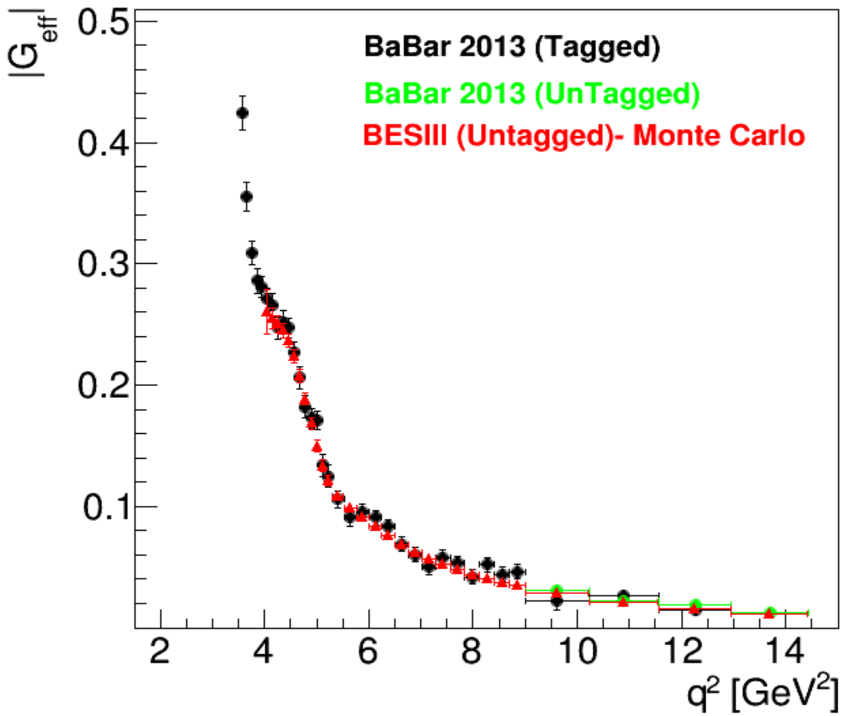
FFs with $e^+e^- \to p\bar{p}\gamma_{ISR}$ tagged

- Two charged tracks from vertex and with opposite charge
- Identification of non-detected photon based on missing momentum and missing mass
- Background channels are almost suppressed
- Background evaluation and subtraction
- Signal efficiency ~16%

The same datasets as ISR tagged are used



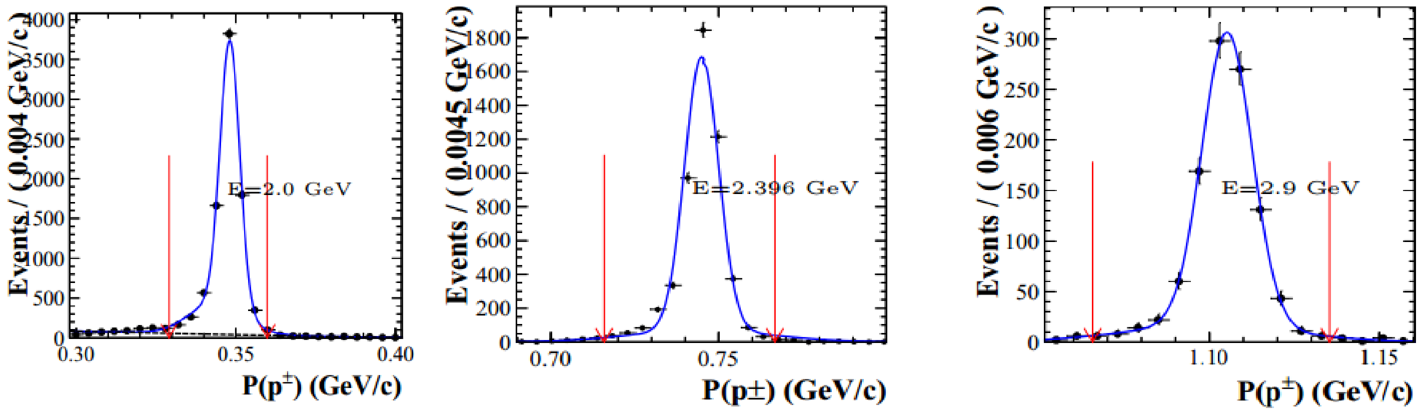
- Final statistics (7.4 fb^{-1}) are competitive with BaBar
- Results from data will be released soon



MC study of 2015 scan data

- Similar strategy as 2012 data is used:
- Two charged tracks in MDC with opposite charge
- PID to veto bkg from other two body decays
- EMC information used to veto bhabha: E/p
- Vertex fit to improve momentum resolution

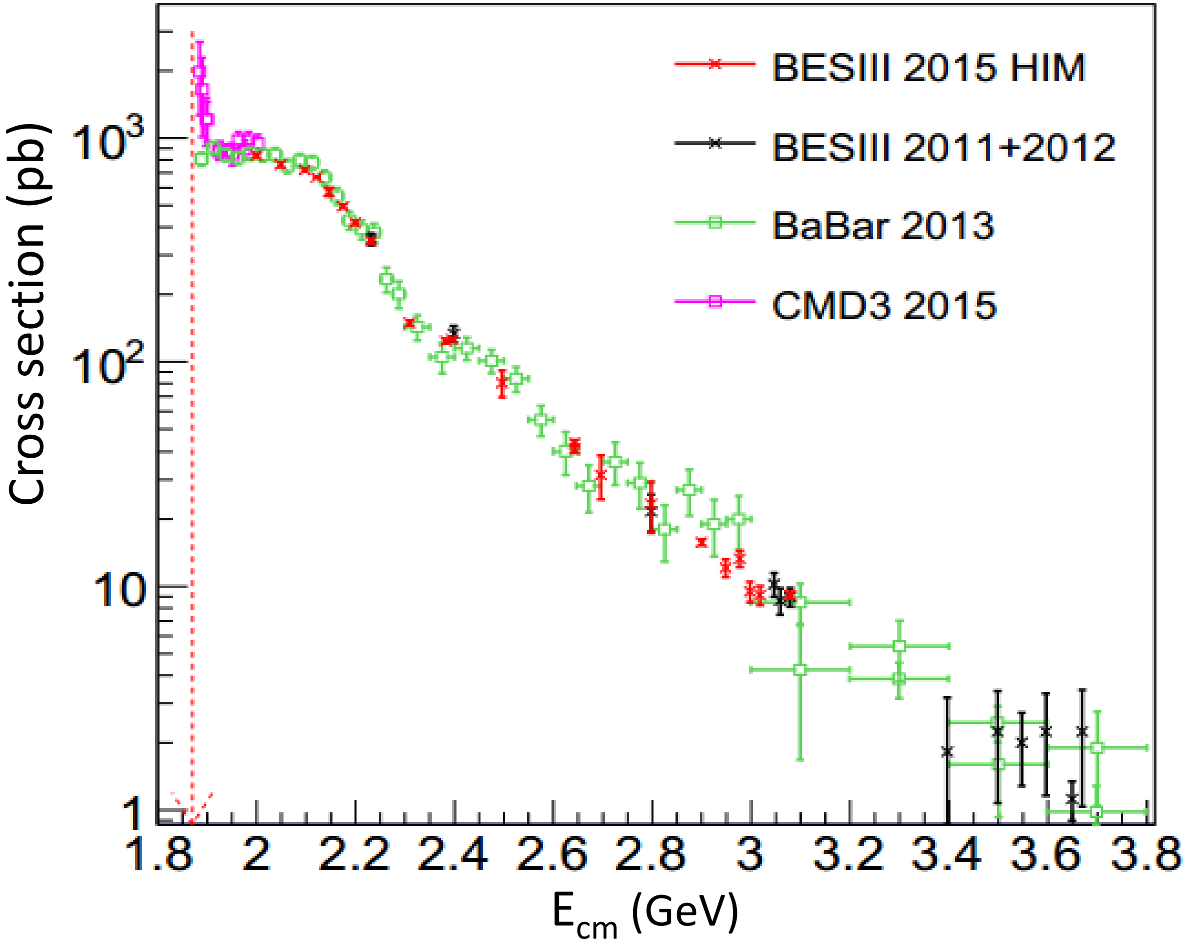
MC study with the same luminosity as 2014 data



- Count or fit momentum distribution to get N_{obs}

Energy (GeV)	$Time_{online}$	Luminosity (pb^{-1})
2.0	123 : 01 : 09	$10.074 \pm 0.005 \pm 0.067$
2.05	42 : 25 : 51	$3.343 \pm 0.003 \pm 0.027$
2.1	104 : 54 : 20	$12.167 \pm 0.006 \pm 0.085$
2.12655	~ 21 days	$108.49 \pm 0.02 \pm 0.97$
2.15	28 : 23 : 23	$2.841 \pm 0.003 \pm 0.024$
2.175	102 : 12 : 30	$10.625 \pm 0.006 \pm 0.091$
2.2	113 : 49 : 35	$13.699 \pm 0.007 \pm 0.092$
2.2324	111 : 27 : 27	$11.856 \pm 0.007 \pm 0.087$
2.3094	137 : 27 : 51	$21.089 \pm 0.009 \pm 0.143$
2.3864	89 : 43 : 45	$22.549 \pm 0.010 \pm 0.176$
2.396	222 : 28 : 34	$66.869 \pm 0.017 \pm 0.475$
2.5	5 : 04 : 12	$1.098 \pm 0.002 \pm 0.009$
2.6444	115 : 24 : 39	$33.722 \pm 0.013 \pm 0.216$
2.6464	112 : 05 : 06	$34.003 \pm 0.013 \pm 0.282$
2.700	3 : 44 : 55	$1.034 \pm 0.002 \pm 0.007$
2.800	3 : 57 : 22	$1.008 \pm 0.002 \pm 0.007$
2.900	214 : 01 : 57	$105.253 \pm 0.025 \pm 0.905$
2.950	25 : 35 : 22	$15.942 \pm 0.010 \pm 0.143$
2.981	22 : 25 : 15	$16.071 \pm 0.010 \pm 0.095$
3.000	20 : 53 : 33	$15.881 \pm 0.010 \pm 0.110$
3.020	22 : 22 : 02	$17.290 \pm 0.011 \pm 0.123$
3.080	194 : 48 : 13	$126.185 \pm 0.029 \pm 0.921$
Separated-beam2.2324	39 : 40 : 04	–
Separated-beam2.6444	38 : 43 : 45	–

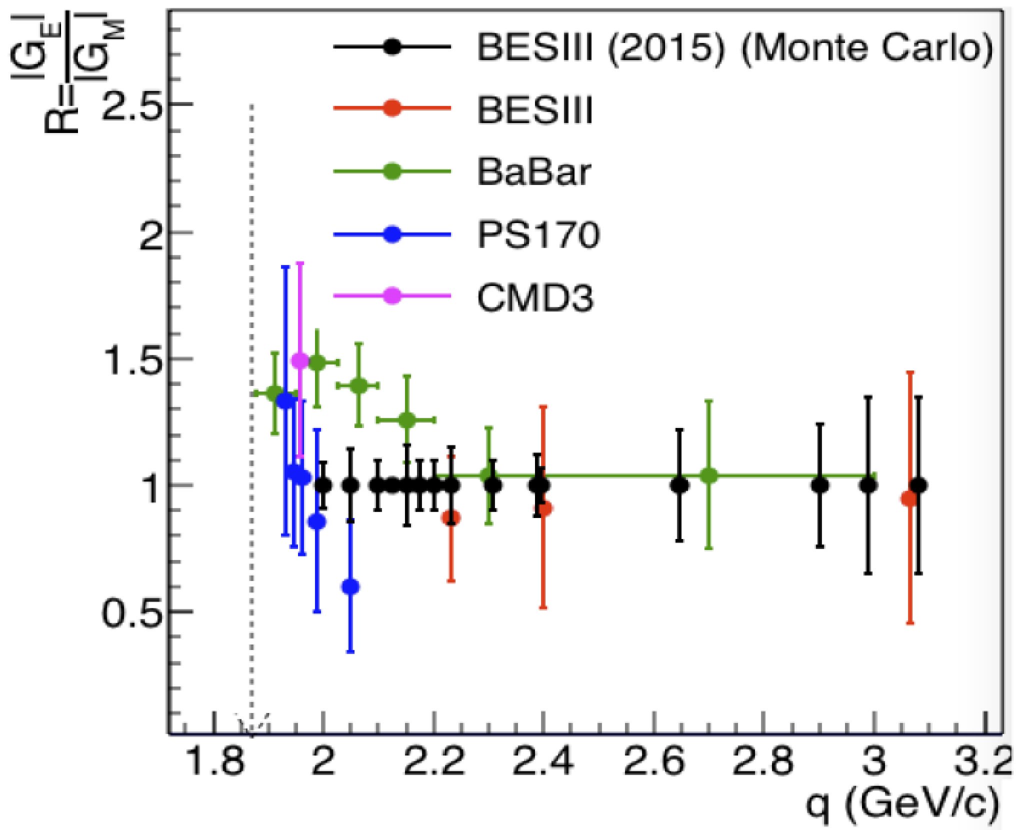
MC study with the same luminosity as 2015 data

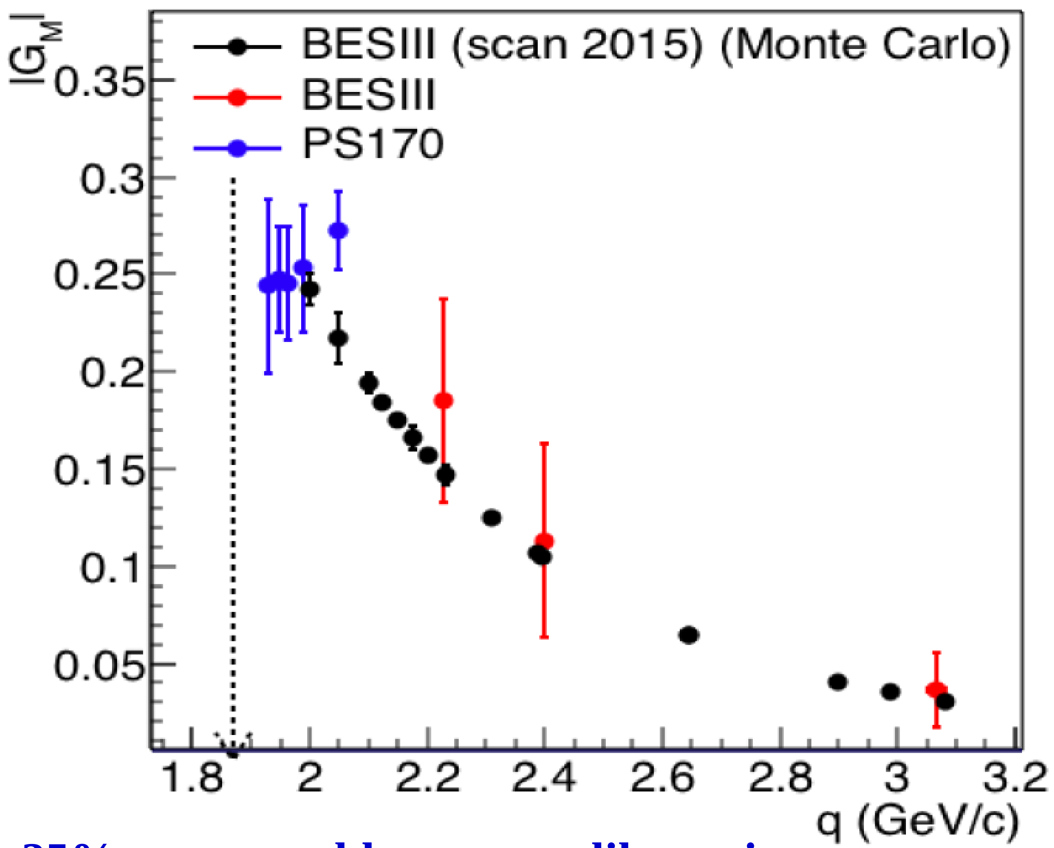


Unprecedented accuracies above 2.0 GeV: 0.5% @ 2.125 GeV; 26% @ 2.8 GeV

‘2015 HIM‘ based on simulation with Phokhara v9.1 [arXiv: 1407.7995v2]. Default FFs model based on Babar results.

MC study with the same luminosity as 2015 data





Assuming R ~ 1, then: **precision expected for R ~ 9% - 35%, comparable as space-like region**

precision expected for G_M ~ 1% ~ 9%, for G_E 3% ~ 35% (first time!).

possible extraction of the forward-backward asymmetry (2γ–contribution,…)

periodic structure of TL FFs?

Summary

- Proton FFs measurement with 2012 scan data at BESIII
  - Published

- Proton FFs measurement with $\psi(3773)$ and XYZ data at BESIII
  - ISR tagged in memo stage
  - ISR untagged in memo stage

- Proton FFs measurement with 2014 scan data at BESIII is going on
  - under working

Prospects on proton FFs

Hot topics in EM Form Factor research: G_E/G_M, charge radius, unphysical region, threshold behavior, radiative corrections, two-photon exchange, large Q2, interference

SND, CMD at VEPP-2000
e^+e^- collider

$|G_E^N|/|G_M^N|$, $|G_{eff}^N|$ (scan)
$q^2 \leq (4.0\ \text{GeV})^2$

BESIII at BEPCII
e^+e^- collider

$|G_E^B|$, $|G_M^B|$, G_E^Λ/G_M^Λ phase (scan and ISR)
$q^2 \leq (3.5\ \text{GeV})^2$

PANDA at FAIR
$p\bar{p}$ collider

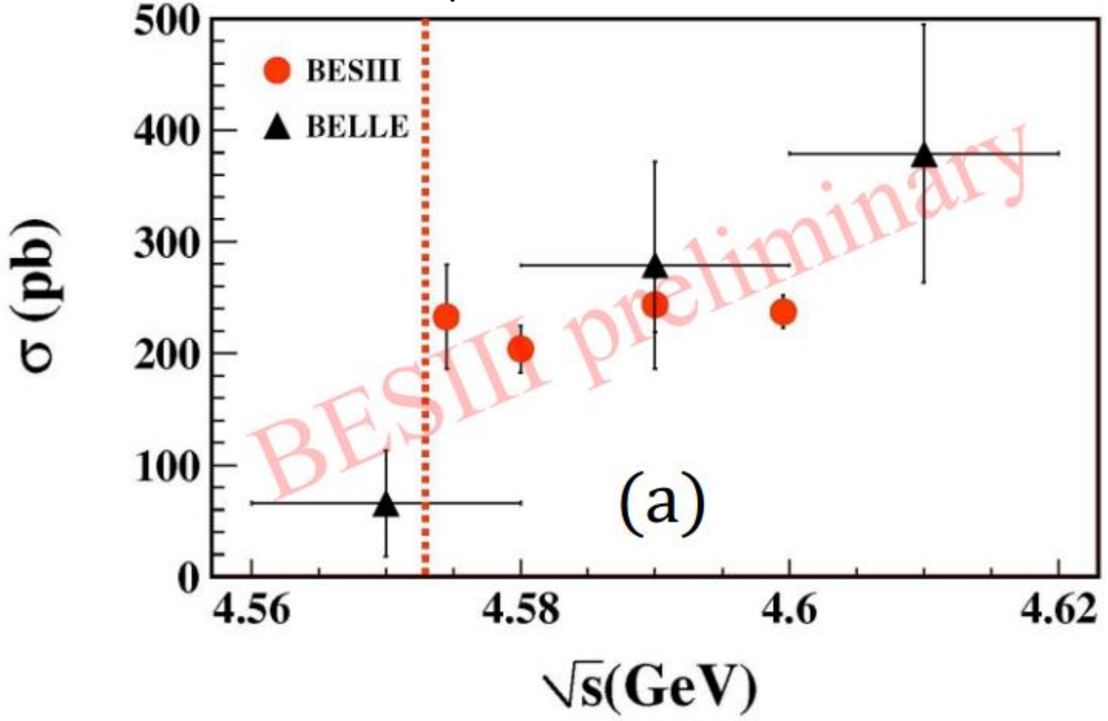
$|G_E^p|$, $|G_M^p|$, G_E^p/G_M^p phase (?)
$(2.4\ \text{GeV})^2 \leq q^2 \leq (3.7\ \text{GeV})^2$

Belle II at SuperKEKB
e^+e^- collider
$q^2 \leq (4.5\ \text{GeV})^2$

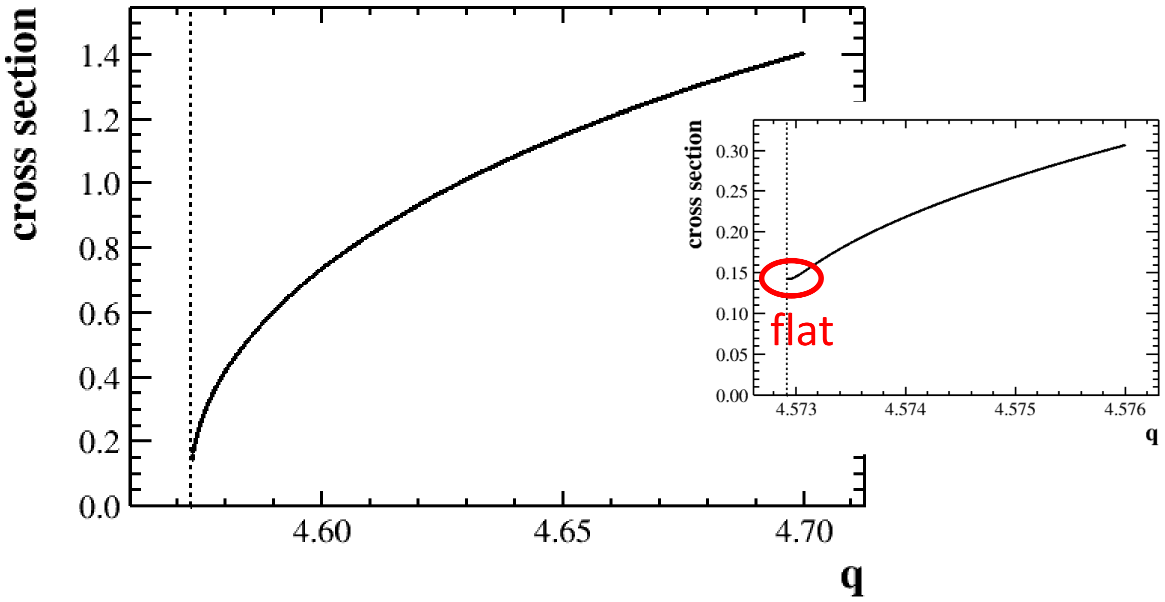
?

A few words about other baryon pairs, similar to $p\bar{p}$

experimental results

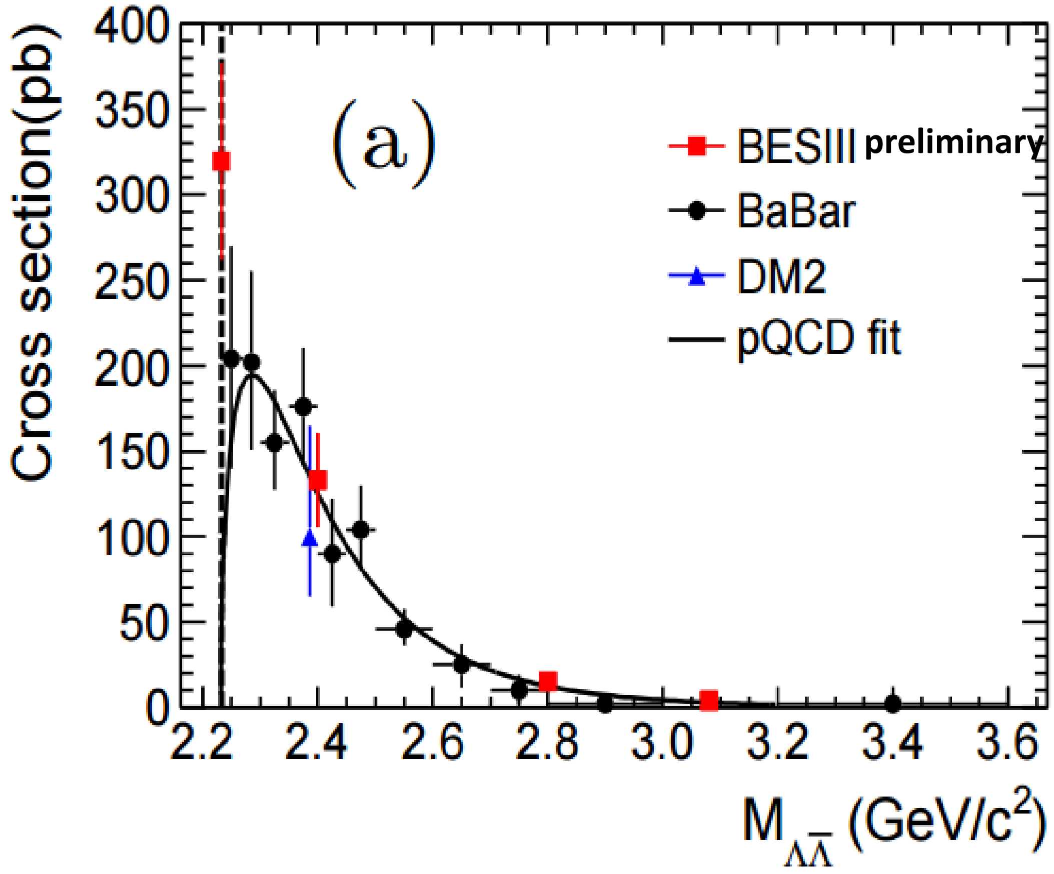


simple theoretical calculations



The cross section near threshold does not increase , but flat.
Bayron FFs or a new Coulomb factor may interpret?

A few words about other baryon pairs, similar to $n\bar{n}$



Cross section at threshold is non-zero outside of error!

Bayron FFs or a new Coulomb factor (taking into account the quark effect) may interpret?

Thanks for your attention!