# Baryon EM Form Factors in BESIII

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on behalf of BESIII-Collaboration

Outline:

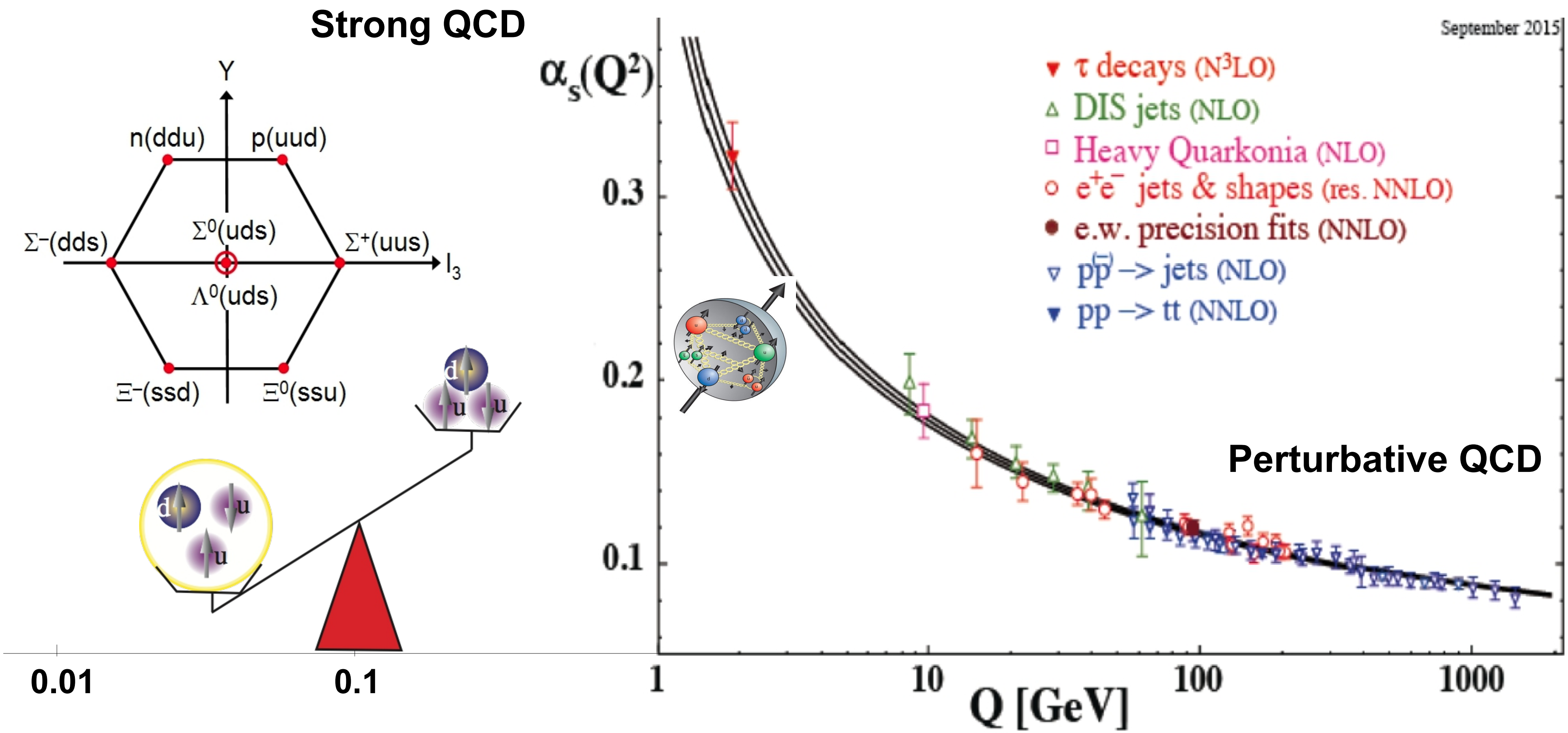
- Introduction
- Experiment
- $e^+e^- \rightarrow p\bar{p}$
- $e^+e^- \rightarrow \Lambda\bar{\Lambda}$
- Prospects and Summary

**Moriond QCD 2016**
**La Thuile, March 19th – 26th, 2016**

# Introduction

# Structure of Baryons

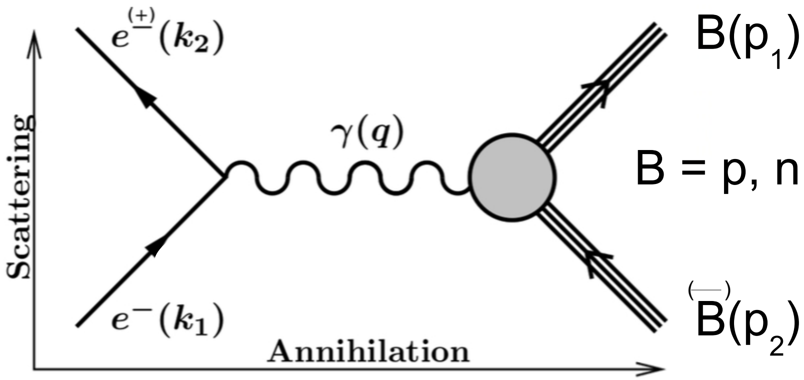
- **Baryons**: **non-perturbative** systems composed of **confined quaks and gluons**




- **Interactions** in terms of **non-perturbative** (long-distance) **functions:**
  **Form Factors**, **G**eneralized **P**arton **D**istributions, **G**eneralized **D**istribution **A**mplitudes, **F**ragmentation **F**unctions, **P**arton **D**istribution **A**mplitudes, **T**ransverse **M**omentum **D**ependence, **T**ransition **D**istribution **A**mplitudes...

# Electro-magnetic Form Factors (FFs)

- Assumption: FFs analytic functions of $q^2$




$$\Gamma^\mu(p_1,p_2) = \gamma^\mu \boldsymbol{F_1(q^2)} + \frac{i\sigma^{\mu\nu}q_\nu}{2M}\boldsymbol{F_2(q^2)}$$

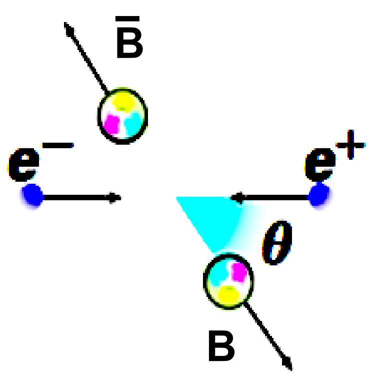
$$F_1(0) = Q; F_2(0) = K$$

$$\boldsymbol{G_M(q^2)} = F_1(q^2) + F_2(q^2)$$

$$\boldsymbol{G_E(q^2)} = F_1(q^2) + \frac{q^2}{4M}F_2(q^2)$$

- Experimental access: **angular analysis**

**Direct annihilation** ($q^2 > 0$): (1 photon exchange)



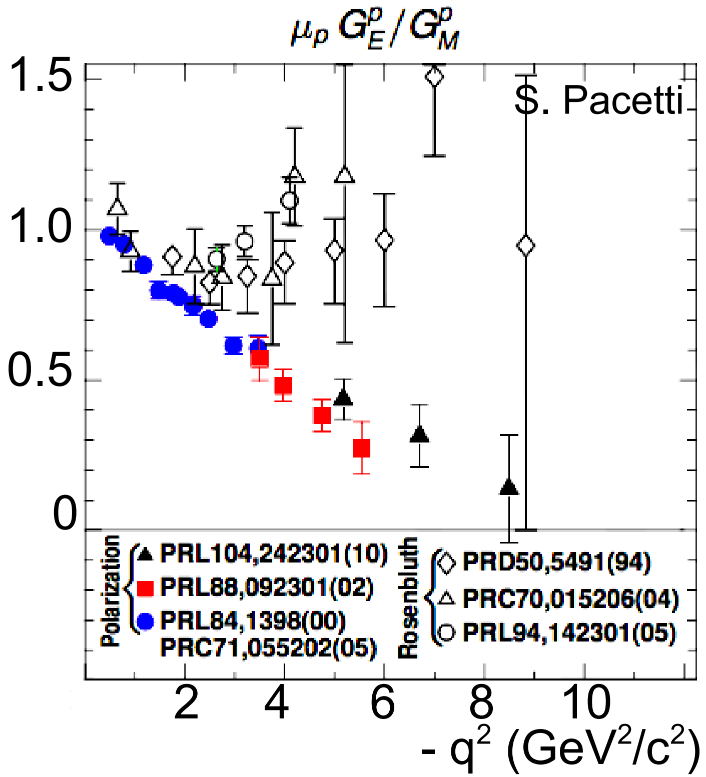

$$\frac{d\sigma^{Born}}{d\Omega} = \frac{\alpha^2\beta C}{4q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{4M^2}{q^2}\sin^2\theta|G_E|^2\right]$$

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

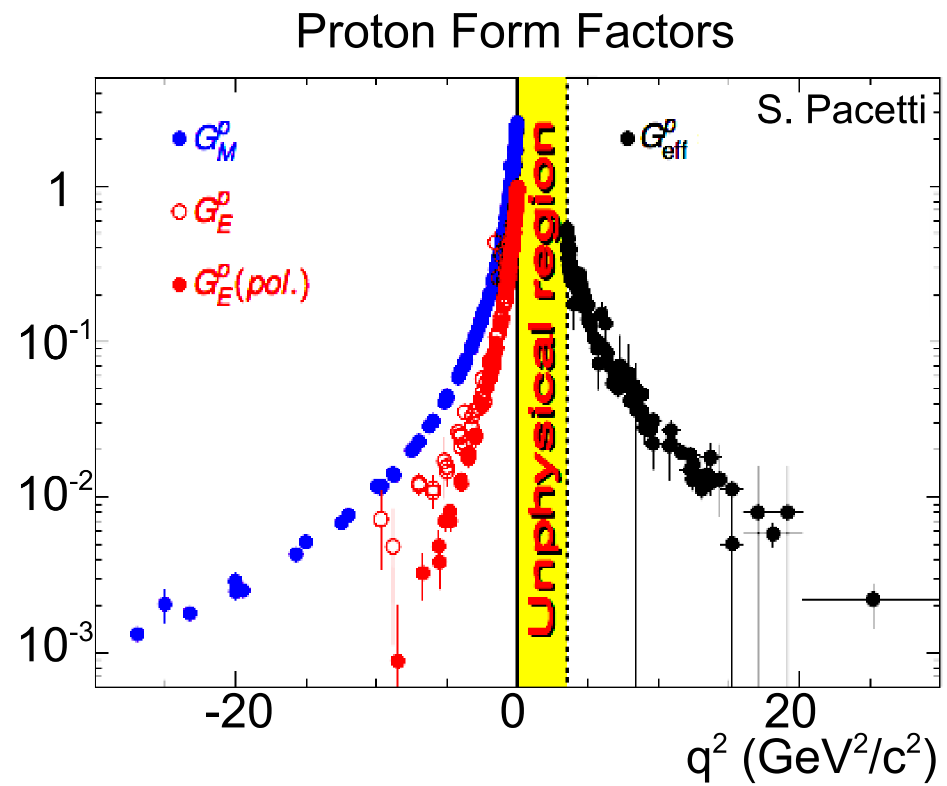
Effective FF: $$|G| = \sqrt{\frac{\sigma^{Born}(q^2)}{(1+\frac{2M^2}{q^2})(\frac{4\pi\alpha^2\beta C}{3q^2})}}$$

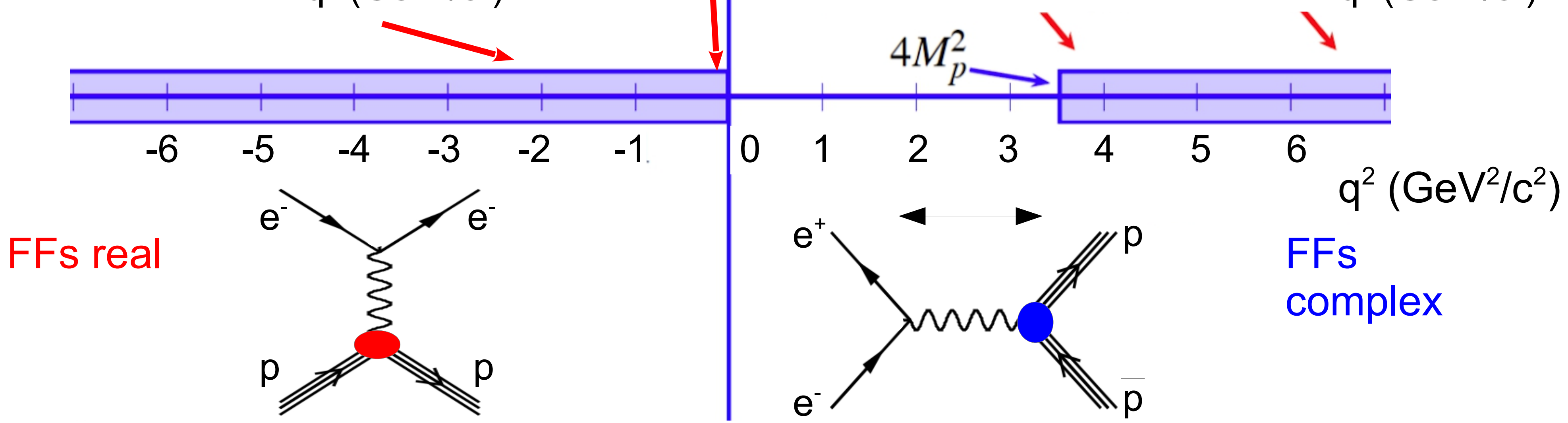
**Elastic Scattering** ($q^2 \leq 0$) : Rosenbluth separation, polarization transfer

# Electro-magnetic Form Factors (FFs)

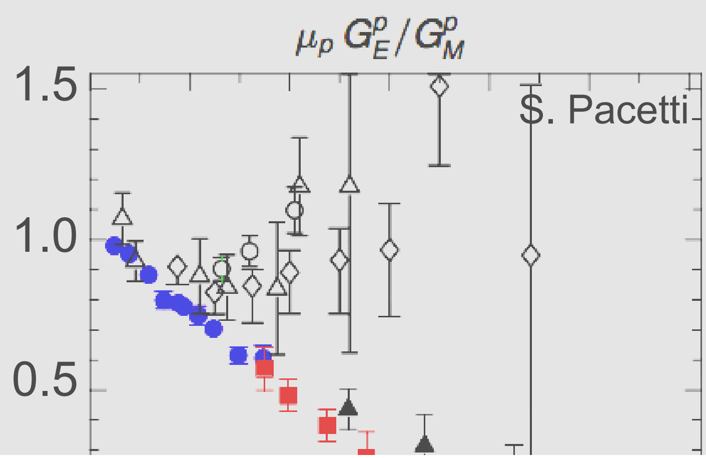




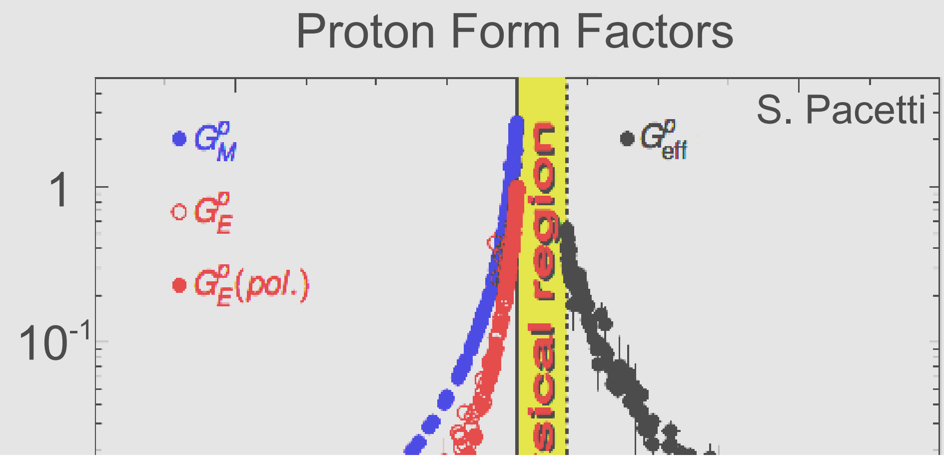


# Electro-magnetic Form Factors (FFs)

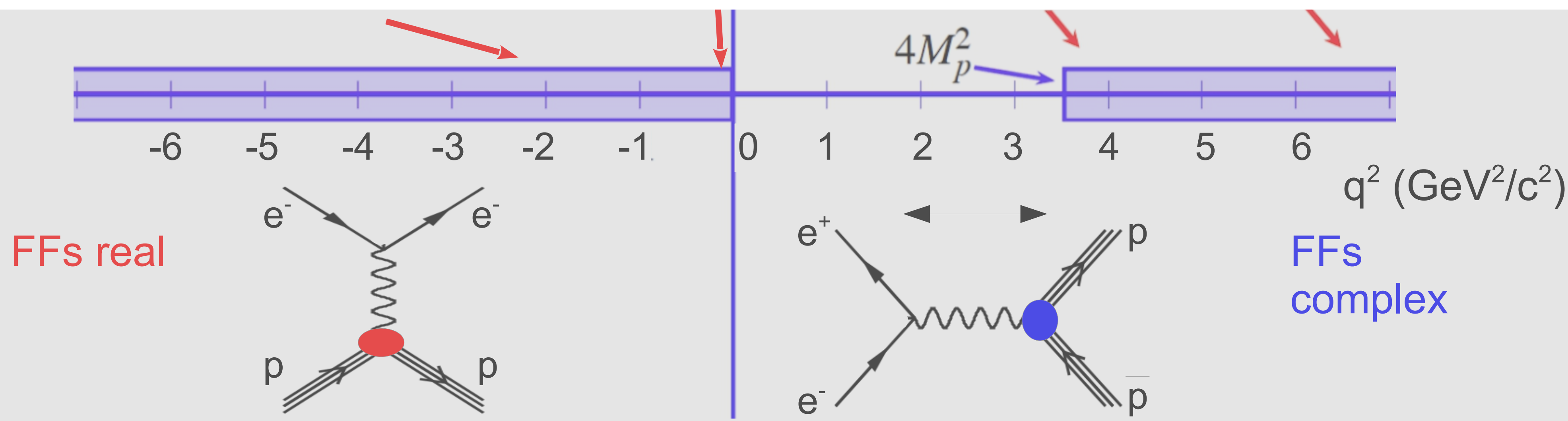







**Hot Topics** in Form Factor Research:

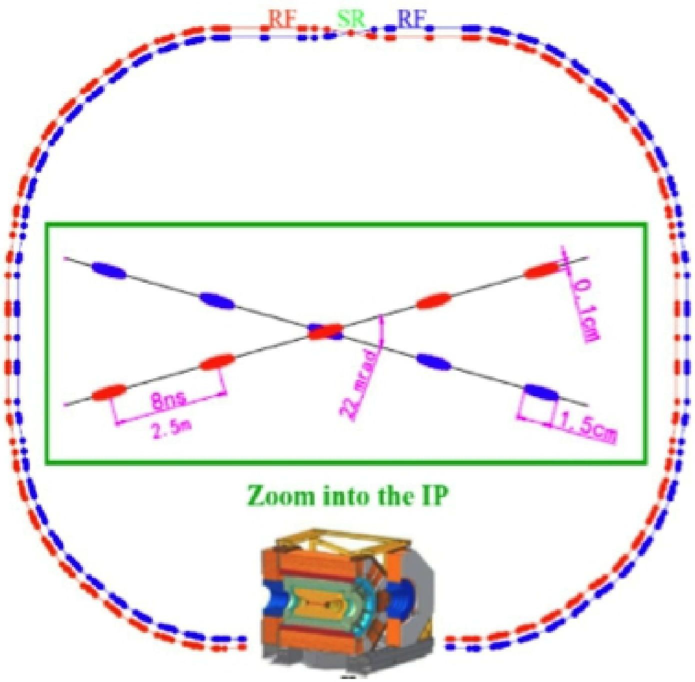
$G_E/G_M$, Charge Radius, Unphysical Region, Threshold Behaviour, Radiative Corrections, Two-Photon Exchange, Large $Q^2$)



# BESIII@BEPCII

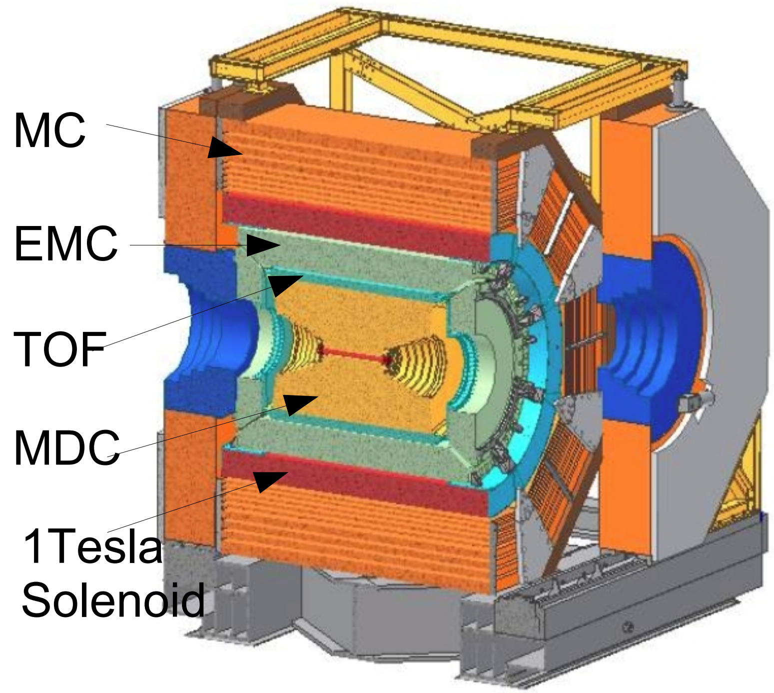
# BESIII @ BEPCII

**Double ring e+e- collider:**



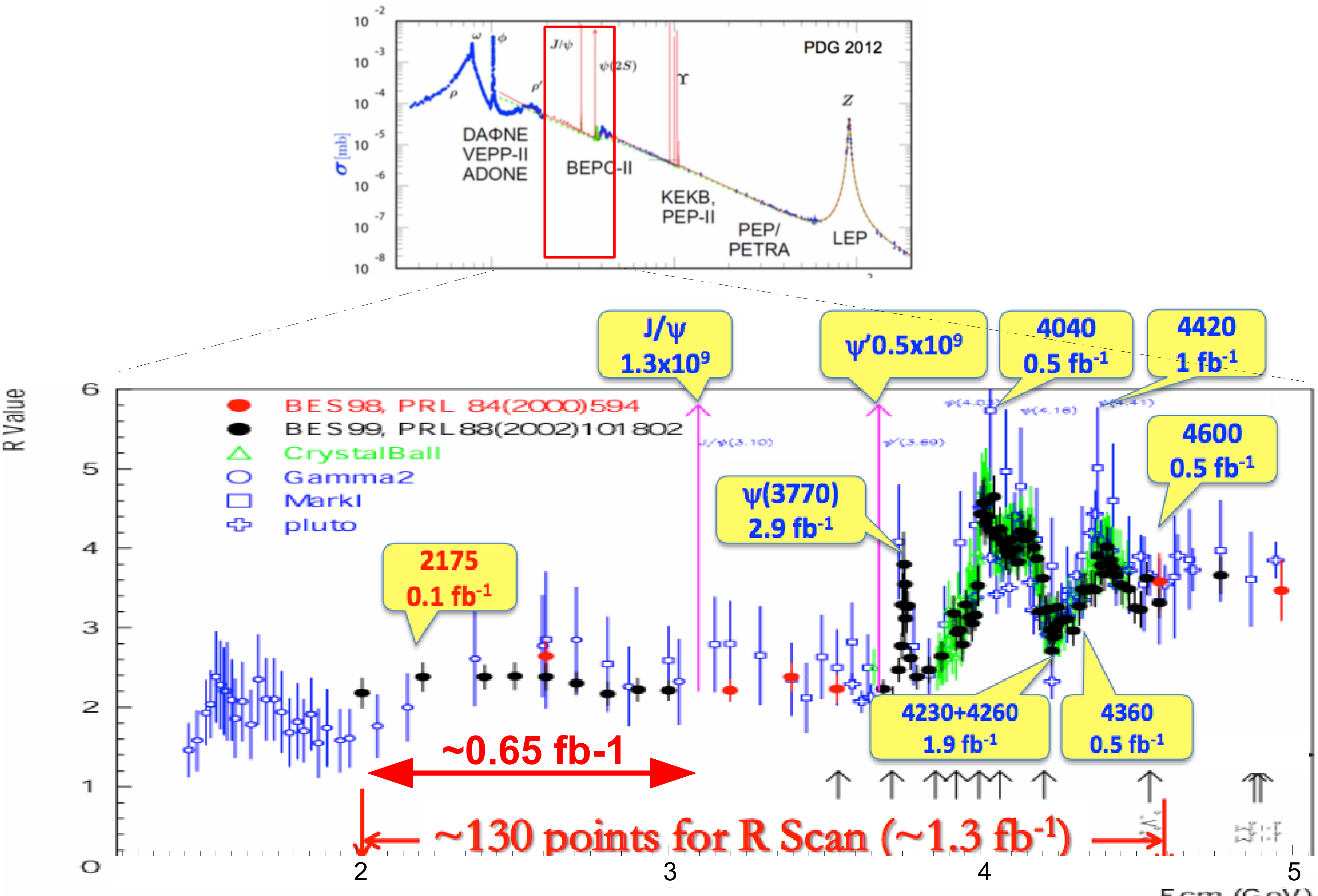

- **Beam energy: 1.0 – 2.3 GeV**
- Design luminosity: $10^{33}$ $cm^{-2}$ $s^{-1}$
- Energy spread: $5.16 \cdot 10^{-4}$
- Number of bunches: 93
- Total current: 0.91 A
- Bunch length: 1.5 cm

**Multi-purpose detector:**




- **Main Drift Chamber**
  $\sigma(p)/p < 0.5$ % for 1 GeV tracks,
  $\sigma(dE/dx)/dE/dx < 6\%$, $\sigma(xy) = 130$ μm
- **Time of Flight** $\sigma(t) \sim 90$ ps
- **EMCalorimeter** $\sigma(E)/E < 2.5$ %,
  $\sigma(x) < 6$mm for 1 GeV e-
- **Muon Counter** $\sigma(xy) < 2$ cm

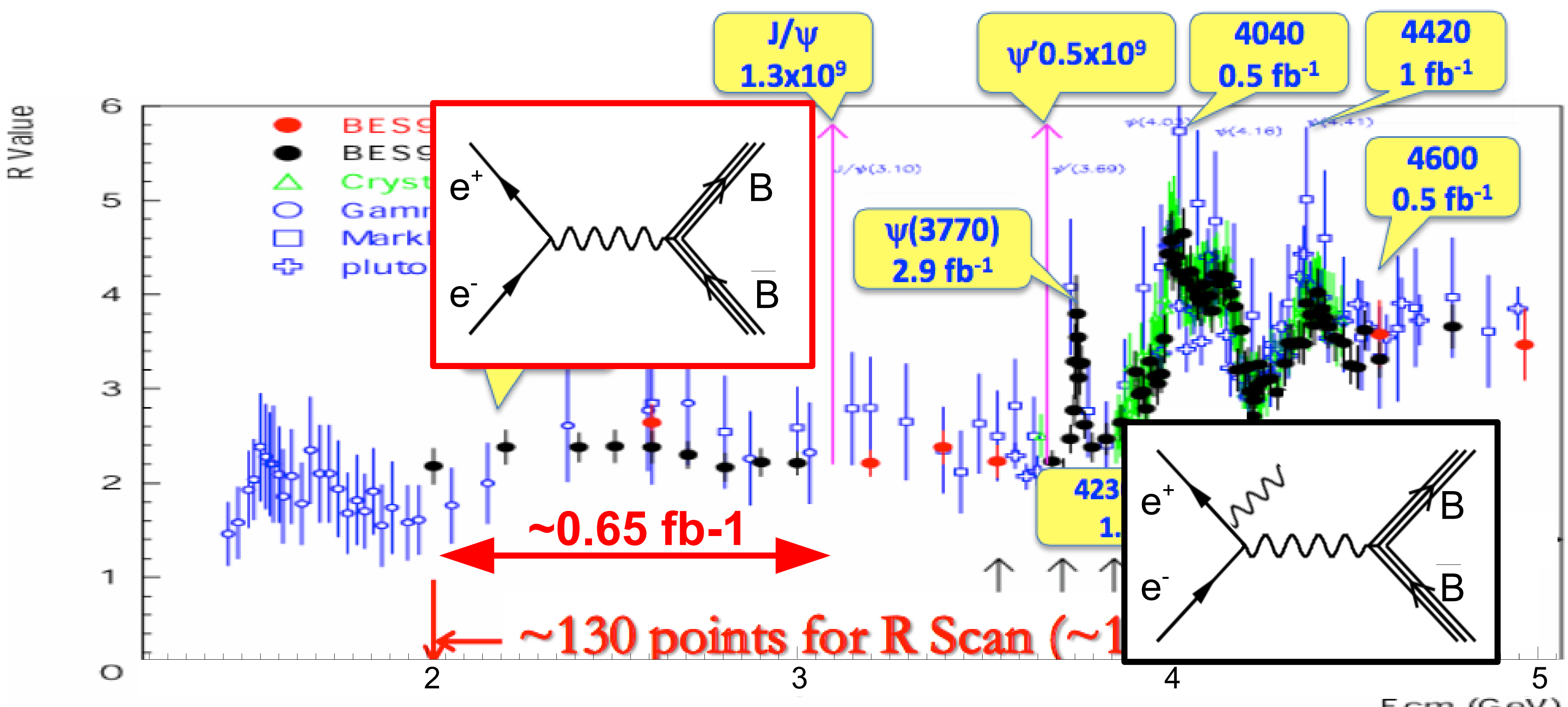
# BESIII Data Samples



# BESIII Data Samples for Baryon FFs

**In 2015 world largest scan data sample between 2 and 3.08 GeV!!**

**World largest J/Psi, Psi(2S), Psi(3770, Y(4260)...**
**produced directly in e+e- collisions**

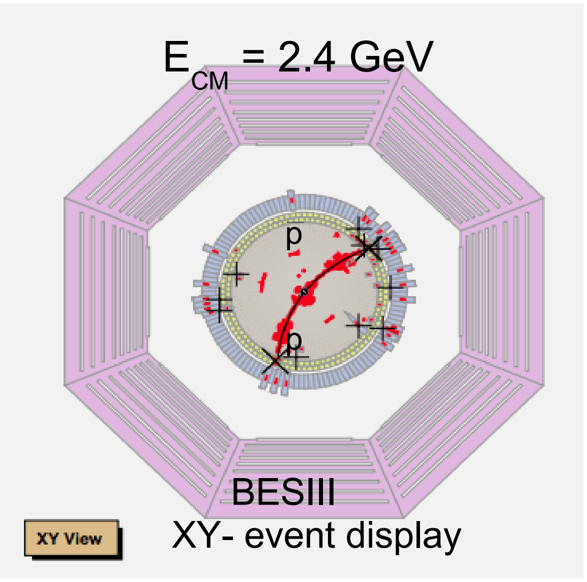


# Baryon FFs Measurements in BESIII

# $e^+e^- \to p\bar{p}$ Phys. Rev. D91, 112004 (2015)

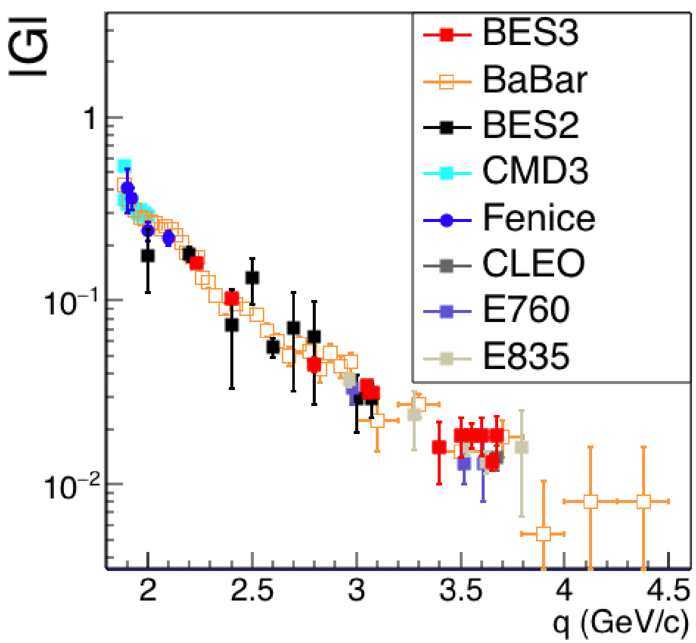
Based on **157 pb$^{-1}$** collected in 12 scan points between **2.22 – 3.71 GeV** in 2011/2012

- p and $\bar{p}$ from vertex, in time, back to back, $E_{p,\bar{p}} = E_{CM}/2$
- Background negligible or subtracted
- Efficiencies between 60% and 3%
- Radiative corrections up to LO in ISR (ConExc)
- Normalization to $e^+e^-\to e^+e^-$, $e^+e^-\to \gamma\gamma$ (Babayaga 3.5)




From $\sigma^{Born}(ee \to p\bar{p})$ extract effective form factor:

$$\sigma^{\rm Born} = \frac{N_{\rm obs} - N_{\rm bkg}}{L \cdot \epsilon (1+\delta)} \longrightarrow |G| = \sqrt{\frac{\sigma^{Born}(q^2)}{(1+\frac{2M^2}{q^2})(\frac{4\pi\alpha^2\beta C}{3q^2})}}$$




**Overall uncertainty improved by 30%**

**No steps observed in cross section**

→ Steep rise at threshold

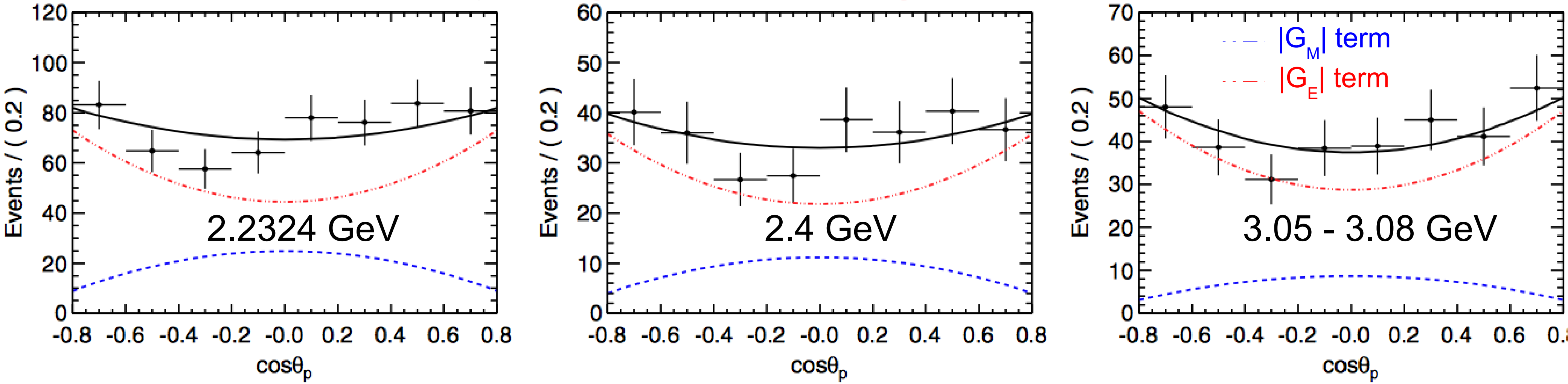
→ Asymptotic behavior in SL and TL regions differ:

$|G_M^{TL}(10\ GeV^2)| = 2|G_M^{SL}(10\ GeV^2)|$

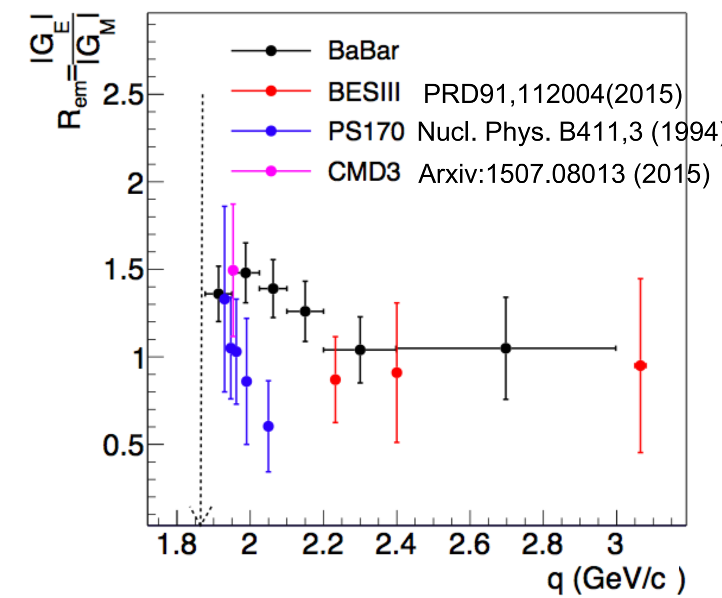
# $e^+e^- \to p\bar{p}$ Phys. Rev. D91, 112004 (2015)

From proton angular distribution extract $\mathbf{R_{em} = |G_E|/|G_M|}$ **and** $\mathbf{|G_M|}$**:**

$$\frac{dN}{d\cos\theta_p} = N_{\rm norm}[(1+\cos^2\theta) + R^2_{\rm em}\cdot\frac{4M^2}{q^2}\sin^2\theta]$$




| $\sqrt{s}$ (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) | $0.95 \pm 0.45 \pm 0.21$ | $3.61 \pm 1.71 \pm 0.82$ |




**$\mathbf{R_{em} = |G_E|/|G_M|}$ consistent with 1**

**$\mathbf{|G_M|}$ (and $\mathbf{|G_E|}$) extracted for first time**

→ Precision between 11% and 28%

→ Strong tension between Babar and PS170

# $e^+e^- \to \Lambda\bar{\Lambda}$ (BESIII Preliminary!!)

Based on 40.5 $pb^{-1}$ collected in 4 scan points between 2.2324 – 3.08 GeV in 2012

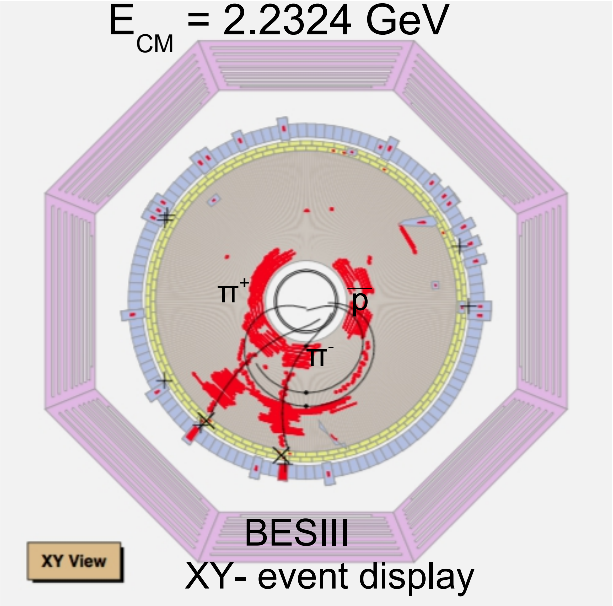
- at $E_{CM}$ = 2.2324 GeV (**1 MeV from threshold!!**)

  From $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ ($BR_{p\pi}$ = 64%)

  - well defined $p_{\pi+}$ and $p_{\pi-}$ and possible $\bar{p}$-annihilation

  From $\bar{\Lambda} \to \bar{n}\pi^0$ ($BR_{n\pi 0}$ = 36%)

  - $\bar{n}$-annihilation and well defined $p_{\pi 0}$




- at $E_{CM}$ ≥ 2.4 GeV, from $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$
  - p, $\bar{p}$, $\pi^-$ and $\pi^+$ from interaction vertex, in time, $\Lambda\bar{\Lambda}$ back to back, $E_{\Lambda,\bar{\Lambda}} = E_{CM}/2$ ...

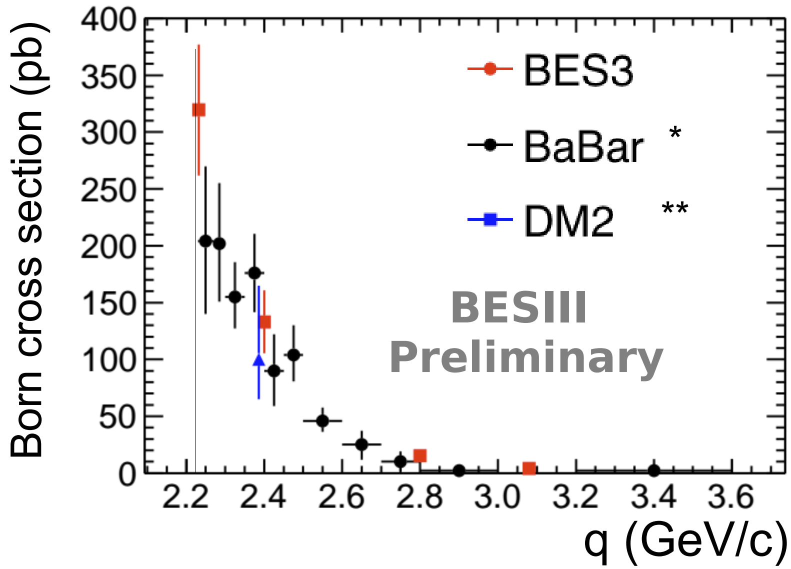
Results:

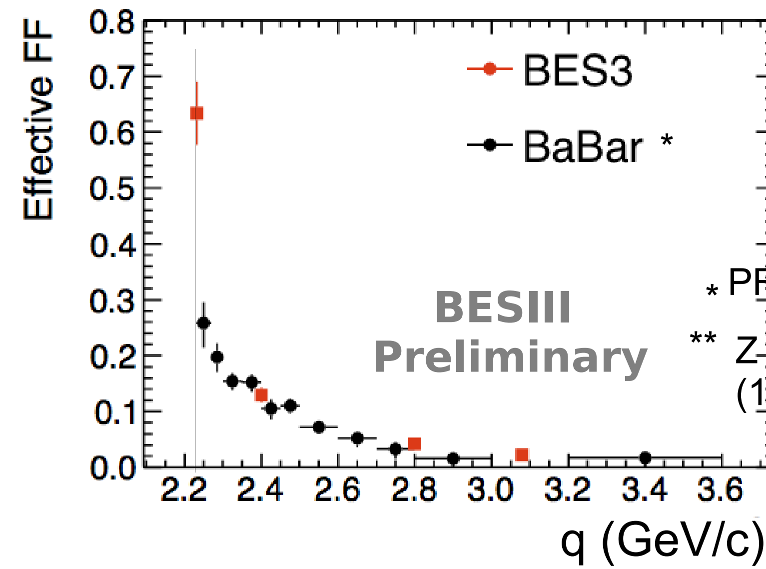
| $\sqrt{s}$ (GeV) | Channel | $\sigma^{\text{Born}}$(pb) | $\lvert G\rvert$ ($\times 10^{-2}$) |
|---|---|---|---|
| 2.2324 | $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$ | $325 \pm 53 \pm 46$ | |
| | $\bar{\Lambda} \to \bar{n}\pi^0$ | $300 \pm 100 \pm 40$ | |
| | combined | $318 \pm 47 \pm 37$ | $63.2 \pm 4.7 \pm 3.7$ |
| 2.4000 | $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$ | $133 \pm 20 \pm 19$ | $12.9 \pm 1.0 \pm 0.9$ |
| 2.8000 | | $15.3 \pm 5.4 \pm 2.0$ | $4.2 \pm 0.7 \pm 0.3$ |
| 3.0800 | | $3.9 \pm 1.1 \pm 0.5$ | $2.21 \pm 0.31 \pm 0.14$ |

# $e^+e^- \to \Lambda\bar{\Lambda}$ (BESIII Preliminary!!)

No Coulomb term for neutral baryon pairs → cross section should vanish at threshold

$$\sigma^{Born}(q^2) = \frac{4\pi\alpha^2\beta}{3q^2}\left[|G_M(q^2)|^2 + \frac{2M^2}{q^2}|G_E(q^2)|^2\right]$$




* PRD76,092006 (2007)

** Z. Phys C48, 23 (1990)

**Precision increased by at least 10% for low $q^2$ and even more above 2.4 GeV**

→ Origin of unexpected behavior? Coulomb interaction at quark level?(***)

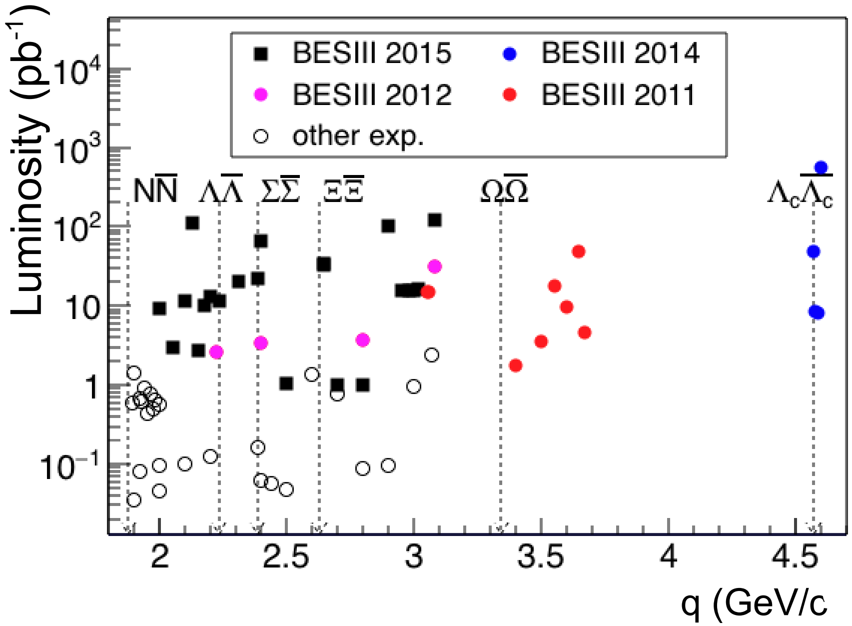
→ Precison measurement forseen by BESIII with 2015 data

*** Eur. Phys. J. A39:315-321(2009)

# Prospects and Summary

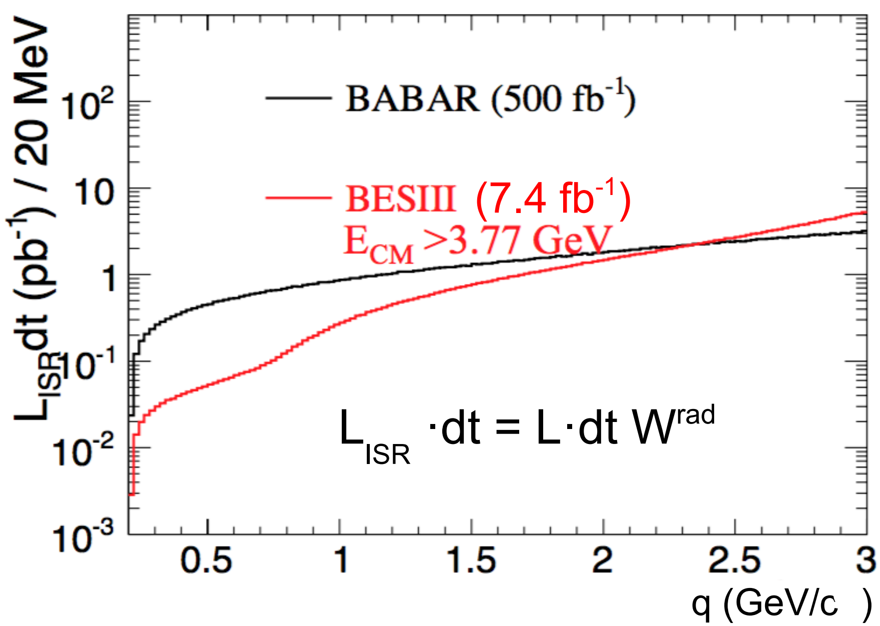
# Prospects in BESIII

**From energy scan**




- Protons: 9 to 35% accuracy on $R^p$, 3 – 9% on $|G^p_M|$
- Neutrons: unprecedented statistics. Possible measurement of |G| and $R^n$
- Hyperons: full determination of Λ-FFs. 14 – 29% accuracy for $R^\Lambda$, 6 - 17% for $P_\Lambda$. Similar for other hyperons
- $\Lambda_c$ : 13% accuracy for $R^{\Lambda c}$ at threshold

**From initial state radiation**




- Visible luminosity comparable to BaBar's
- Protons: Tagged and untagged photon analysis possible. Expected accuracies on $R^p$ between 10-40%
- Neutrons: only tagged photon analysis. Extraction of |G| from threshold to 3.0 GeV possible

# Summary

- BESIII excellent laboratory for Baryon form factor measurements: **energy scan + initial state radiation**

- **Proton Form Factors** have been measured using a fraction of available scan data

- Preliminary results on **Λ cross section** based on fraction of scan data just released

- **High statistics energy scan between 2.0 and 3.08 GeV will significantly improve FFs measurements for protons, neutrons, lambdas and other hyperons**

- **Very exciting results from ISR on nucleon FFs expected very soon!**

**Thank you!**

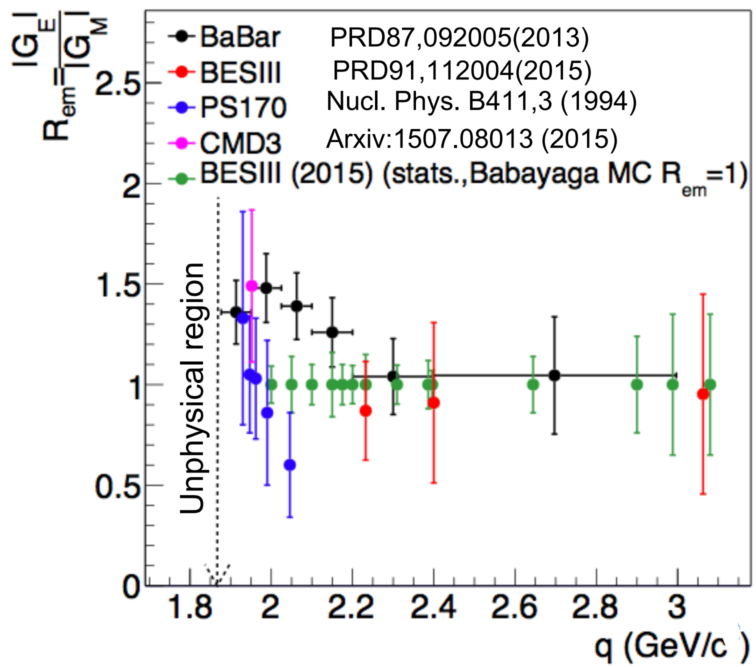
# Backup

# Prospects for $e^+e^- \rightarrow p\bar{p}$, $p\bar{p}\gamma_{ISR}$

**$e^+e^- \rightarrow p\bar{p}$**

**BESIII 2015: 21 scan points between 2.0 and 3.08 GeV (552 $pb^{-1}$)**

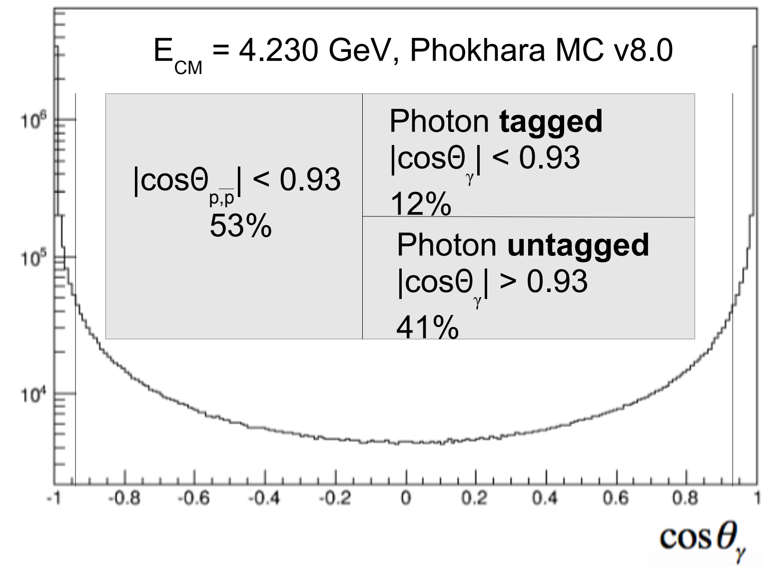
- Expected statistical **accuracies or $R_{em}=|G_E|/|G_M|=1$** between **9 % and 35%** (similar to space-like region for same $q^2$-region)
- Expected **accuracies for $|G_M|$ between 3 to 9%, 9 to 35 % for $|G_E|$**




**$e^+e^- \rightarrow p\bar{p}\gamma_{ISR}$**

**Data samples (ECM): ψ(3770),ψ(4040), 4230, 4260, 4360, 4420, 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 2.1 GeV up untagged-photon analysis possible
- Remaining $e^+e^- \rightarrow p\bar{p}\pi^0$ subtracted from data
- **Final statistics competitive with BaBar**



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

**Only two direct measurements of neutron effective FF**

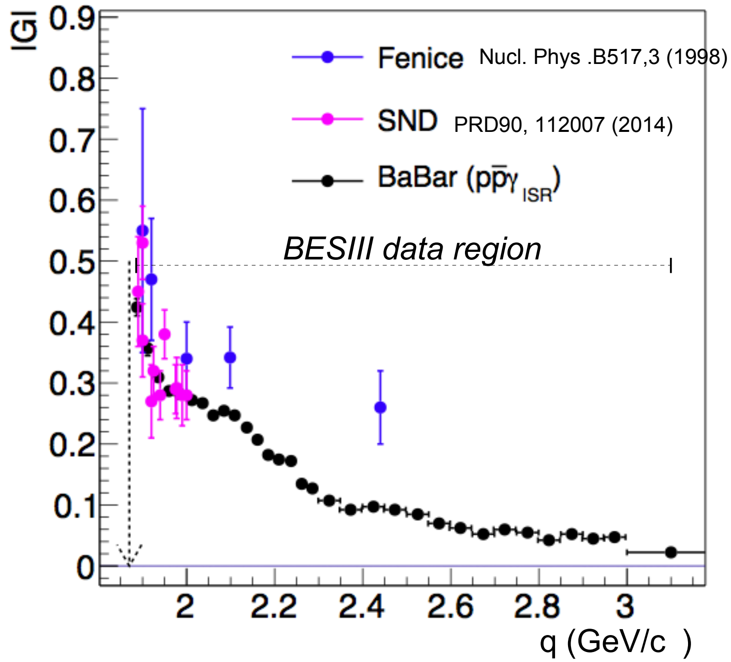
BESIII data cover wide range (1.87 – 3.08 GeV) with unprecedented statistics

→ **measurement of cross section and |G| in wide $q^2$-region**

→ **could provide the first measurement of $R_{em}$**

Strategy:

- First identification of $\bar{n}$ and $\gamma_{ISR}$: EMC shower information
- neutron identification
- event kinematics (geometry)




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

- $\bar{n}$/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 mille level)
- Increase detection efficiency using TOF, MUC
- Main background from $e^+e^- \to n\bar{n}\pi^0$ and e+e- → γγ(γ) (Neural Network)

**BESIII**

EMC calorimeter
CsI(Tl): $15X_0$ ,
$\lambda_I$ = 171.5 g/cm$^2$, ρ = 4.53 g/cm$^3$
→ 52% n/$\bar{n}$ interact in EMC

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

# Prospects for $e^+e^- \rightarrow$ Hyperons

**From 2015 scan full determination of lambda- FFs possible:**

- Imaginary part of FFs leads to polarization observables:

Parity violating decay: $\Lambda \rightarrow p\pi$

$$\frac{dN}{d\cos\theta_p} \propto 1+\alpha_\Lambda P_n \cos\theta_p \quad \text{and} \quad P_n = -\frac{\sin 2\theta \sin\Delta\phi/\tau}{R\sin^2\theta/\tau+(1+\cos^2\theta)/R} = \frac{3}{\alpha_\Lambda}\langle\cos\theta_p\rangle$$

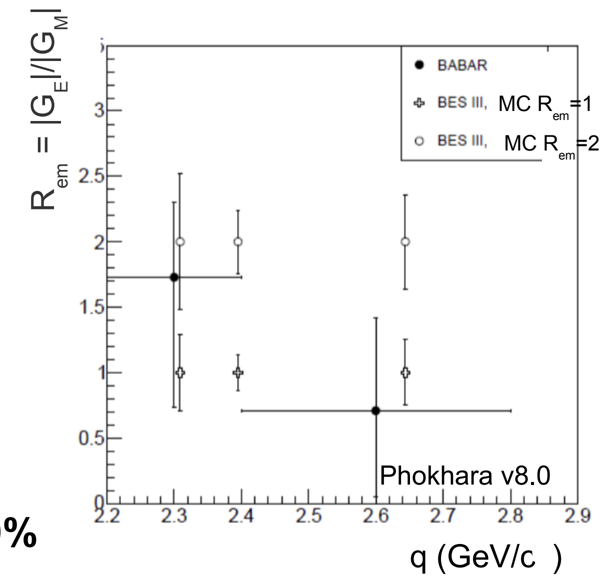
$\Theta_p$ : Angle between proton and polarization axis in $\Lambda$-CM

$\Theta_\Lambda$: $\Lambda$ polar angle in CM

$\Phi$ : relative phase between $G_E$ and $G_M$

**Expected statistical accuracies for $P_n$ between 6 and 17%**

**Expected statistical accuracies for $R_{em} = |G_E|/|G_M| = 1$ between 14 and 29%**



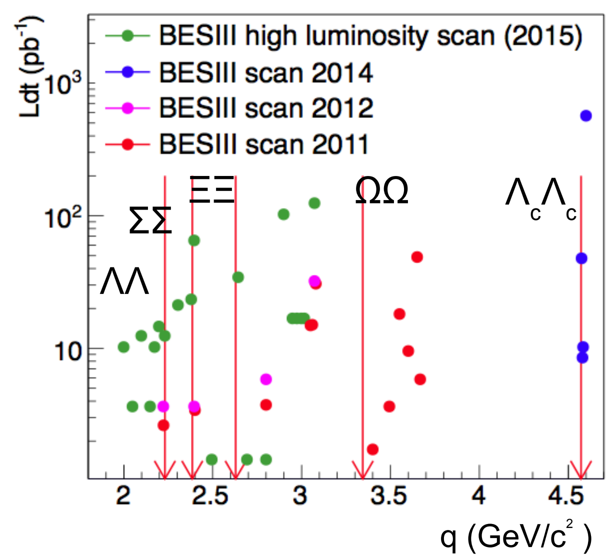

- Also available from threshold (2015, 2014, 2011 data):

$ee \rightarrow \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0, \Sigma^-\bar{\Sigma}^+, \Sigma^+\bar{\Sigma}^-, \Xi^0\bar{\Xi}^0, \Xi^+\bar{\Xi}^-, \Omega^+\bar{\Omega}^-, \bar{\Lambda}_c^-\Lambda_c^+$

measurements of effective FF and $R_{em}$ and $P_n$ at single energy points possible

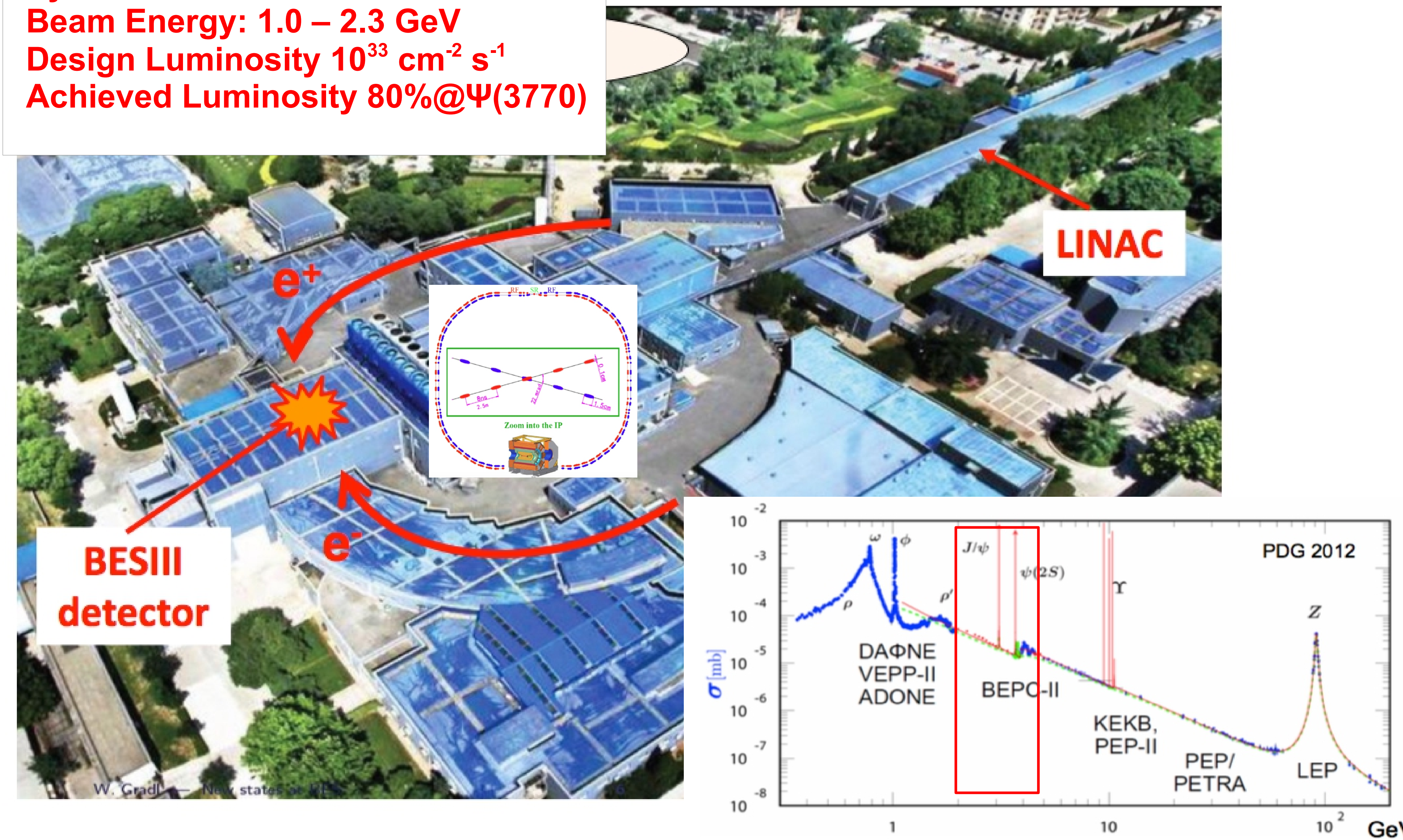
$ee \rightarrow \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$ previously measured by BaBar, no $R_{em}$ extraction possible

measurements of effective FF, $R_{em}$ and $|G_M|$ at threshold possible



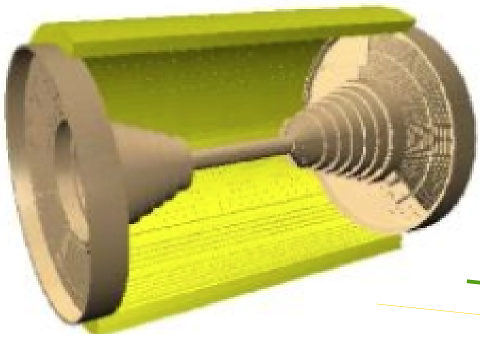
# BEPCII Collider

**Symmetric $e^+e^-$-collider**
**Beam Energy: 1.0 – 2.3 GeV**
**Design Luminosity $10^{33}$ $cm^{-2}$ $s^{-1}$**
**Achieved Luminosity 80%@Ψ(3770)**



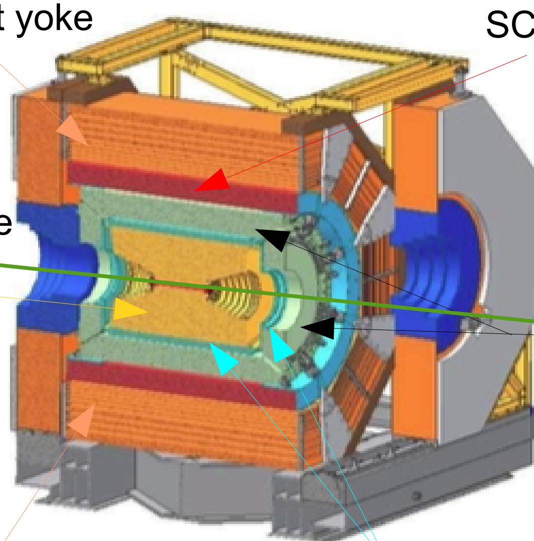
# BESIII Detector

## MDC

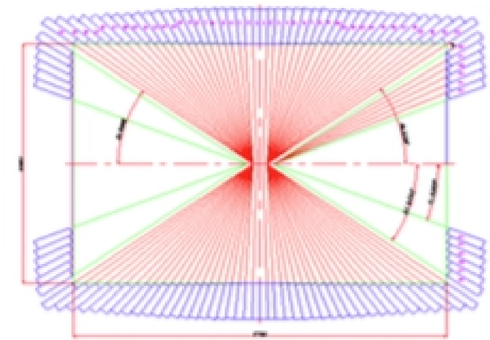


R inner: 63mm
R outer: 810 mm
Length: 2582 mm
43 Layers

$\sigma(p)/p = 0.5\%$
$\sigma_{dE/dx} = 6.0\%$



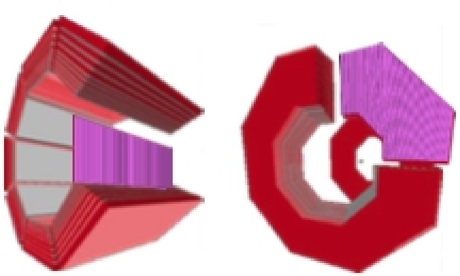

## CsI(Tl) EMC



6240 CsI(Tl) crystals: 28cm (**$15X_0$**)
Barrel: |cosΘ|<0.83
Endcap: 0.85 < |cosΘ| <0.93

$\sigma(E)/E = 2.5\%$
$\sigma_{Z,\Phi}(E) = 0.5 - 0.7$ cm

## RPC MUC



8 – 9 layers of RPC
p>400 MeV/c
$\delta R\Phi = 1.4 \sim 1.7$ cm

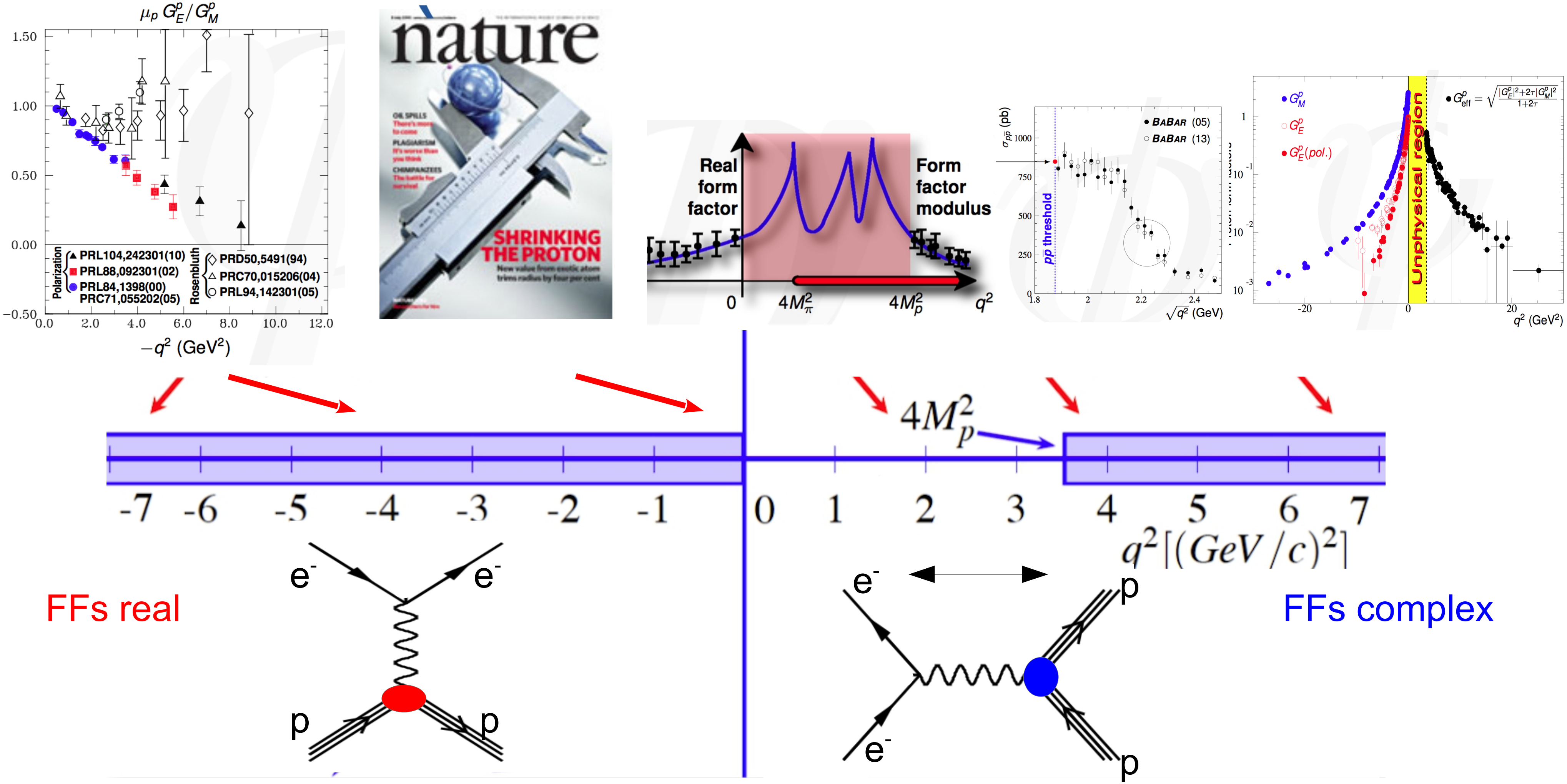
## TOF

BTOF: two layers;
ETOF: 48 crys. for each

$\sigma(t) = 80$ps (barrel)
$\sigma(t) = 120$ps (endcap)

# Electro-magnetic Form Factors (FFs)

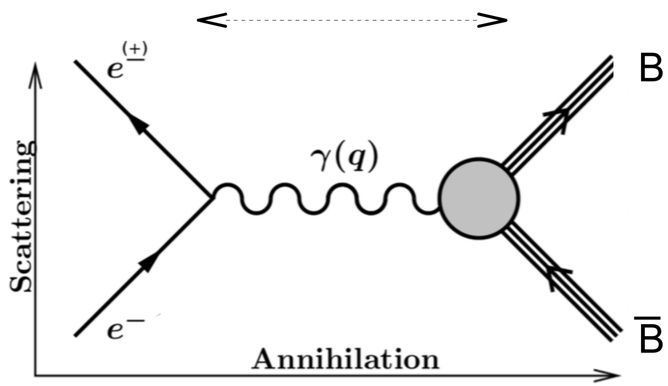
EM processes: all **hadronic structure** and **strong interactions** in FFs but subject to QED



# 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 spin 1/2-baryons 2 electromagnetic FFs:




B = p, n, Λ, Σ ...

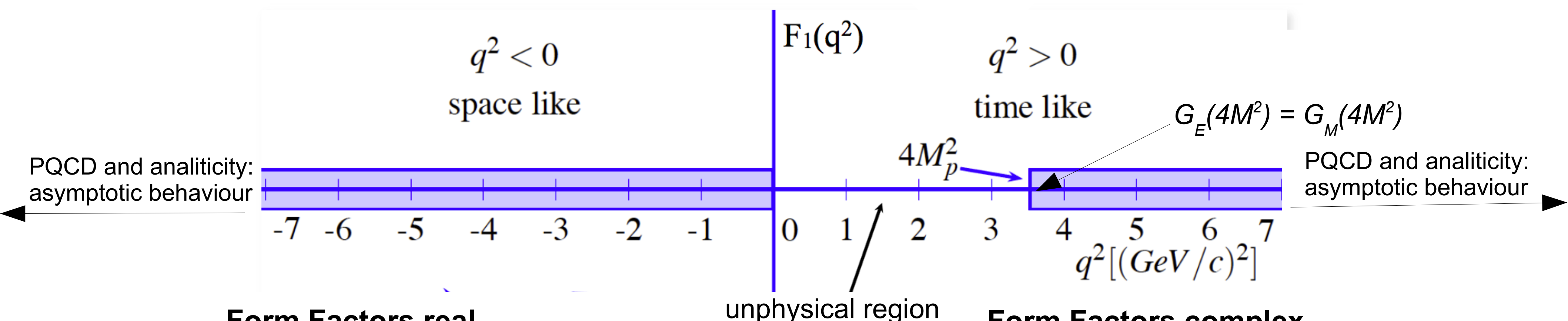
Vector current. Dirac and Pauli FFs:

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

Sachs parametrization:

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4M_B}F_2(q^2)$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$




**Form Factors real**

cross section (Rosenbluth)
no single spin observables
double spin observables

connected by dispersion relations

**Form Factors complex**

cross section (angular Distr.)
single spin observables ($P_y$)
double spin observables

# $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$ arXiv:1507.08188 (submitted to PLB)

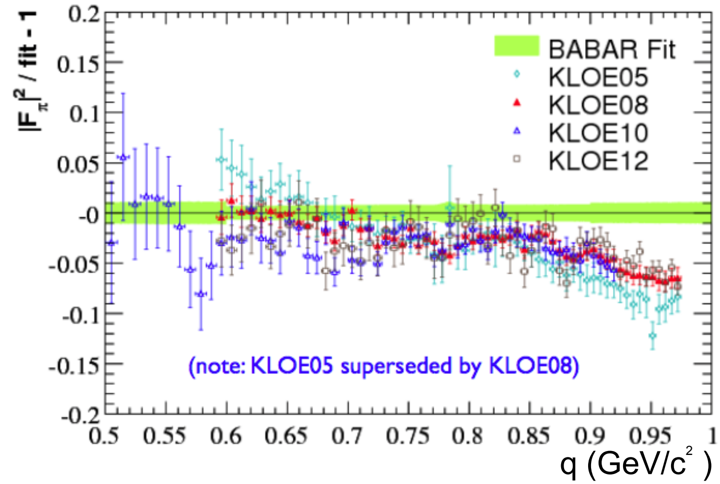
- Goal: **hadronic vacuum polarization contribution to $a_\mu = \frac{(g_\mu - 2)}{2}$**

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{hadr}$$

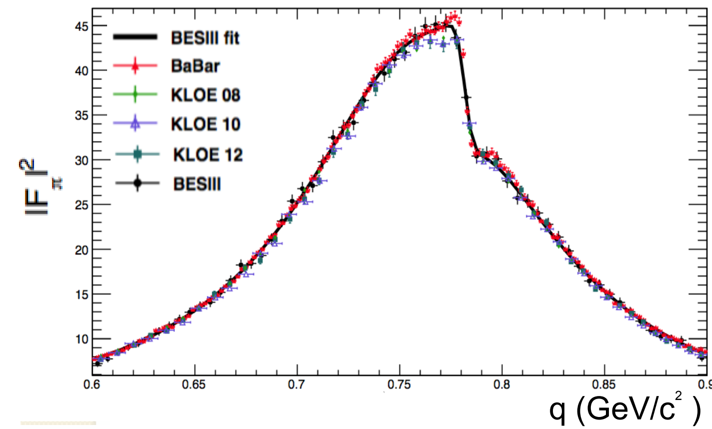
→ most relevant contribution to $a_\mu^{hadr}$ below 1 GeV: $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$

$$|F_\pi|^2(q^2) = \frac{3q^2}{\pi\alpha^2\beta^3}\sigma^{dressed}_{\pi^+\pi^-}(q^2)$$

Disagreement between existing measurements limits knowledge of $a_\mu$




- Features of BESIII analysis:
  - 2.9 fb-1 from Ψ(3770)
  - studied range between 600 – 900 MeV
  - only tagged analysis possible below 1 GeV
  - main background from $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$ prefectly understood (<1‰ )
  - luminosity from BhaBha events → 0.5% accuracy (Babayaga NLO)
  - FF fit function: Gounaris-Sakurai parametrization
  - radiative corrections from Phokhara v8.0



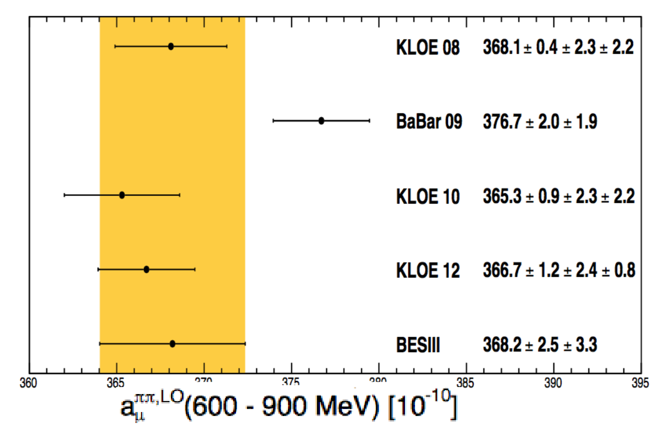

**Syst. uncertainty in cross section 0.9%**

**Compatible with prev. measurements (1σ)**

**More than 3σ deviation wrt $(g_\mu-2)^{SM}$ prediction confirmed**

**Data from untagged analysis and above Ψ(3770) will be used**

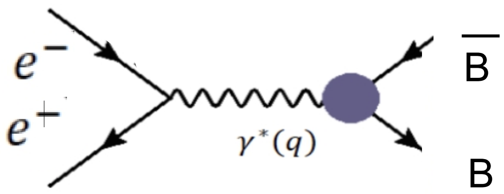
**Analysis will be extended below 600 MeV and above 900 MeV**



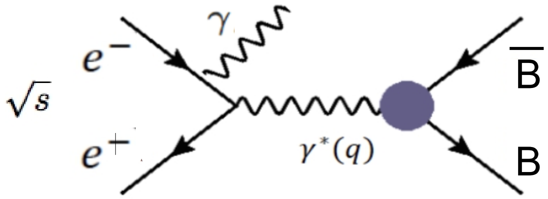
# Baryon EM FFs in BESIII

- BESIII @ BEPCII: e+e- -annihilation: access to **time-like form factors** from

**Direct annihilation**




**Initial State Radiation**




B = p, n, $\Lambda$, $\Sigma$ ...

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

Coulomb correction factor:

$$C = \frac{\pi\alpha}{\beta(1 - exp(\pi\alpha/\beta))}$$ (if $q_B \neq 0$), $C = 1$ (if $q_B = 0$)

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

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

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

**Effective form factor (assume $|G_E| = |G_M|$):**

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

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

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

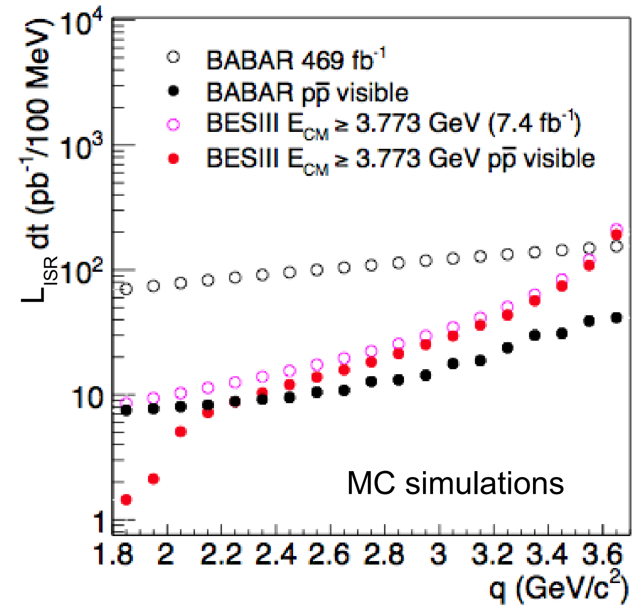
with $\tau = \frac{q^2}{4M_B^2}, \beta = \sqrt{1 - 1/\tau}$

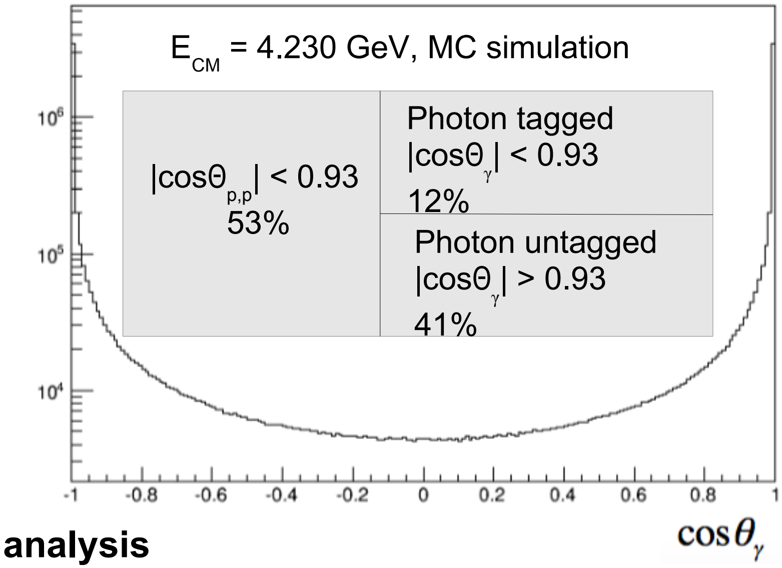
# Prospects for $e^+e^- \to p\bar{p}\gamma_{ISR}$

Available data samples ($E_{CM}$): ψ'',ψ(4040), Y(4230), Y(4260), Y(4360), Y(4420), Y(4600). Total: 7.4 fb-1

Strategy: for each $E_{CM}$ tagged and untagged analysis

- dN(ppγ)/dq
- Efficiencies, background, radiative factor, (functions dependent on q)
- Add all corrected data from different $E_{CM}$ for each q-bin
- Normalize with $L_{ISR}$
- Born cross section, Effective form factor
- Angular analysis: **Extraction of R and $|G_{E,M}|$**




**For q > 2.1 GeV**: **Large efficiencies (~20%) from untagged photon analysis** provide large statistics and **better $|G_E|/|G_M|$ accuracies**

**For q < 2.1 GeV**: **Only tagged measurement possible** for $E_{CM} \geq 3.773$ GeV.

Low efficiencies (~6%), lower statistics than BaBar. Perhaps untagged analysis of J/ψ and ψ(3686) possible ?!

# Electromagnetic Form Factors

- **Dispersion relations connect space and time-like regions**
- **Perturbative QCD constrains the asymptotic behaviour** [Matveev,Muradyan,Tevkheldize,Farrar, Brodsky-Lepage,... ]

$$F_i(q^2) \rightarrow (-q^2)^{-(i+1)} \left[ \ln \left( \frac{-q^2}{\Lambda^2_{\mathrm{QCD}}} \right) \right]^{-2.173_5}$$

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

(analiticty)

**Why time-like (TL) form factors (FFs)?**

- **To test theory relations beween space-like and time-like processes**
- **Precise knowledge of FFs needed** by many experiments and phenomenological models
- **To test pQCD** expanding the $Q^2$ kinematical domain up to soft-hard transition region (10 – 15 $(\mathrm{GeV}/c)^2$)