Hadron Form Factors in BESIII

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on behalf of BESIII-Collaboration

Outline:
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• Motivation
• Nucleon Electromagnetic Form Factors
• Hyperon Electromagnetic Form Factors
• Pion Form Factor
• Summary

HADRON2015
September 13th – 18th, 2015, Newport News
Double ring e+e- collider:

- Beam energy: 1.0 – 2.3 GeV
- Crossing angle: 22 mrad
- Design Luminosity at \(\Psi(3770)\): \(10^{33} \text{ cm}^2 \text{ s}^{-1}\), 85% achieved
- Optimum energy: 1.89 GeV
- Energy spread: \(5.16 \cdot 10^{-4}\)
- Number of bunches: 93
- Bunch length: 1.5 cm
- Total current: 0.91 A

TOF: time of flight (two layers plastic scintillator): \(\sigma(t) \sim 90\) ps

EMC: Cs I(Tl), barrel+2 end caps:
\[
\sigma(E)/E < 2.5\% , \sigma(x) < 6\text{mm for 1 GeV e-}
\]

MDC: main drift chamber (He 60% + propane 40%):
\[
\begin{align*}
\sigma(p)/p &< 0.5\% \text{ for 1GeV tracks, } \\
\sigma(dE/dx)/(dE/dx) &< 6\%
\end{align*}
\]

MUC: time of flight (RPC): \(\sigma(xy) < 2\text{ cm}\)
BESIII Data Samples

~130 scan points (~1.3 fb⁻¹)

J/ψ 1.3x10⁹
ψ' 0.5x10⁹
ψ(3770) 2.9 fb⁻¹
4230+4260 1.9 fb⁻¹
4360 0.5 fb⁻¹
4040 0.5 fb⁻¹
4420 1 fb⁻¹
4600 0.5 fb⁻¹

2175 0.1 fb⁻¹

R Value

E cm (GeV)
Motivation
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 2 electromagnetic FFs:

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

\[ G_M(q^2) = F_1(q^2) + F_2(q^2) \]

Sachs parametrization:

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

Vector current. Dirac and Pauli FFs:

\[ F_1(q^2) = \text{cross section (Rosenbluth)} \]

\[ \text{no single spin observables} \]

\[ \text{double spin observables} \]

\[ F_2(q^2) = \text{cross section (angular Distr.)} \]

\[ \text{single spin observables (P_y)} \]

\[ \text{double spin observables} \]

Form Factors real

Form Factors complex

unphysical region

PQCD and analiticity: asymptotic behaviour

B = p, n, Λ, Σ ...

PQCD and analiticity: asymptotic behaviour
Hadron Form Factors

- **Fundamental properties of hadrons**
  - Contain information on charge, magnetization distribution
  - Connected to distribution, dynamics of quarks
  - 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 all four EM FFs of Nucleons
  - Trying to explain data at both low and high $q^2$
  - Progress on QCD based calculations
  - ...
Baryon EM FFs in BESIII

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

Direct annihilation

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

Coulomb correction factor:
\[
C = \frac{\pi\alpha}{\beta(1 - \exp(\pi\alpha/\beta))} \quad (\text{if } q_B \neq 0), \; C = 1 \; (\text{if } q_B = 0)
\]

Effective form factor (assume \(|G_E| = |G_M|\)):
\[
|G(q^2)| = \sqrt{\frac{\sigma_{BB}^{\text{Born}}(q^2)}{1 + \frac{1}{2\tau}}} \left( \frac{4\pi\alpha^2\beta C}{3q^2} \right)
\]

Separation of \(|G_E|\) and \(|G_M|\) through angular analysis:
\[
\frac{d\sigma_{BB}^{\text{Born}}}{d\Omega_{CM}} = \frac{\alpha^2\beta C}{4q^2} \left[ (1 + \cos^2\theta_B^{CM})|G_M|^2 + \frac{1}{\tau}|G_E|^2\sin^2\theta_B^{CM} \right]
\]

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

Initial State Radiation

\[
\frac{d^2\sigma_{BB\gamma}}{dx d\theta_{\gamma}} = W(s, x, \theta_{\gamma})\sigma_{BB}^{\text{Born}}(q^2)
\]

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

\[x = 1 - q^2/s = 2E_{\gamma}/\sqrt{s}\]
Data Samples for Hadron FFs

Data available for Hadron FFs measurements:

- High accuracy in $q^2$
- High geometrical acceptance for hadron pair (93%)
- Low background

Complementary approaches:

- 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 $\neq 0$
Nucleon EM FFs in BESIII
Analysis based on 157 pb\(^{-1}\) collected in 12 scan points between 2.22 – 3.71 GeV in 2011 and 2012

- Main features:
  - p and \(\bar{p}\) from vertex, in time, back to back, \(E_{p,\bar{p}} = E_{CM}/2\)
  - Background negligible, \(~4\) GeV Bhabha subtracted
  - 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)

No steps observed in cross section. Overall uncertainty improvement by 30%

\[
R_{em} = \frac{|G_E|}{|G_M|} \text{ and } |G_M| \text{ for three } E_{CM}. R_{em} \text{ consistent with BaBar and } R=1. |G_M| \text{ extracted for first time!}
\]
Prospects for $e^+e^- \rightarrow p\bar{p}, p\bar{p}\gamma_{\text{ISR}}$

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

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

- Expected statistical accuracies or $R_{\text{em}} = |G_E|/|G_M| = 1$ 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 $|G_E|$

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

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

- Analysis for each $E_{\text{CM}}$ and $q$, then combine statistics
- ISR kinematics: photon and $p\bar{p}$-system with small opposite polar angles
- Efficiencies: $\sim 20\%$ -$\gamma$-untagged, $\sim 6\%$ $\gamma$-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 $e^+e^- \rightarrow n\bar{n}$, $n\bar{n}\gamma_{ISR}$

**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)

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

- $\bar{n}/n$ 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)

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

- Only tagged analysis possible (efficiencies at per mille level)
- Increase detection efficiency using TOF, MUC
- Main background from $e^+e^- \rightarrow n\bar{n}\pi^0$ and $e^+e^- \rightarrow \gamma\gamma(\gamma)$ (Neural Network)
Hyperon EM FFs in BESIII
Analysis based on 40.5 pb$^{-1}$ collected in 4 scan points between 2.2324 – 3.08 GeV in 2012 test run

- at $E_{CM} = 2.2324$ GeV ($m_{\Lambda \Lambda}^{th} = 2.2317$ GeV)
  - From $\Lambda \rightarrow p\pi^{-}$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^{+}$ (BR$_{p\pi} = 64\%$)
    - well defined $p_\pi$, possible $\bar{p}$-annihilation
  - From $\bar{\Lambda} \rightarrow \bar{p}\pi^{0}$ (BR$_{n\pi^{0}} = 36\%$)
    - $n$-annihilation in EMC (Neural Network), well defined $p_{\pi^{0}}$

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

Current results improve uncertainty by at least 10\% for low $q^{2}$ and even more for $E_{CM} > 2.4$ GeV

Cross section does not vanish at threshold!!

Coulomb interaction at quark level?

Cross section does not vanish at threshold!!

Coulomb interaction at quark level?
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: $\Lambda \rightarrow p\pi$

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

$\Theta_\Lambda$: Angle between proton and polarization axis in $\Lambda$-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):

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

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

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

Measurements of effective FF $R_{em}$ and $|G_M|$ at threshold possible
Pion FF in BESIII
\( e^+e^- \rightarrow \pi^+\pi^-\gamma_{\text{ISR}} \)

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

\[ \alpha_{\mu}^{\text{SM}} = \alpha_{\mu}^{\text{QED}} + \alpha_{\mu}^{\text{weak}} + \alpha_{\mu}^{\text{hadr}} \]

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

\[ |F_\pi|^2(q^2) = \frac{3g^2}{\pi\alpha^2\beta_3} \sigma_{\pi^+\pi^-}^{\text{dressed}}(q^2) \]

Disagreement between existing measurements limits knowledge of \( \alpha_\mu \)

**Features of BESIII analysis:**

- 2.9 fb\(^{-1}\) from \( \Psi(3770) \)
- studied range between 600 – 900 MeV
- only tagged analysis possible below 1 GeV
- main background from \( e^+e^- \rightarrow \mu^+\mu^-\gamma_{\text{ISR}} \) perfectly understood (<1%)
- luminosity from BhaBha events \( \rightarrow 0.5\% \) 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 (1\σ)

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

Data from untagged analysis and above \( \Psi(3770) \) will be used

Analysis will be extended below 600 MeV and above 900 MeV
Summary
Summary & Outlook

- BESIII excellent laboratory for hadron form factor measurements: scan data + ISR technique
- Proton Form Factors and their ratio have been measured using a small amount of data
- Preliminary results on Λ just released
- New high statistics data between 2.0 and 3.1 GeV will significantly improve FFs measurements for protons, neutrons, lambdas and other hyperons. Also from ISR measurements exciting results for nucleon FFs expected
- ISR technique allows access to energies below 2 GeV: the first result is the charged pion, more to come
- Other related topics being studied (not reviewed here):
  - Baryon production threshold measurements
  - Space-like transition FFs of mesons (light-by-light contributions to $(g_\mu - 2)$ )

Thank you!
Backup
Symmetric e^+e^--collider
Beam Energy: 1.0 – 2.3 GeV
Design Luminosity $10^{33}$ cm$^{-2}$ s$^{-1}$
Achieved Luminosity 70%@Ψ(3770)
BESIII Detector

MDC
- Beam pipe
- Magnet yoke
- SC Magnet (1 T)
- 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: 28 cm ($15X_0$)
- Barrel: $|\cos\Theta| < 0.83$
- Endcap: $0.85 < |\cos\Theta| < 0.93$
- $\sigma(E)/E = 2.5\%$
- $\sigma_{z,\phi}(E) = 0.5 - 0.7$ 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)
Experimental Situation: proton FFs

- Initial direct measurements of $\sigma_{\text{Born}}^{\text{ee} \rightarrow \text{pp}}$ had very poor statistics → only extraction of effective form factor, $|G|$, possible

\[ |G| = \sqrt{\frac{\sigma_{\text{Born}}}{(1 + \frac{1}{2t})(\frac{4\pi\alpha^2\beta C}{3E_{\text{CM}}^2})}} \]  

(Assumption: $|G| = |G_E| = |G_M|$)

New measurements by BaBar (ISR) and pp-experiments:
- Steep rise at threshold
- Steps near 2.25 and 3.0 GeV
- Asymptotic behavior in SL and TL regions differ:
  - $|G_M^{\text{TL}}(10 \text{ GeV}^2)| = 2|G_M^{\text{SL}}(10 \text{ GeV}^2)|$

- Only BaBar and PS170 with statistics for angular analysis → extraction of $R = \frac{|G_E|}{|G_M|}$ possible
  - Precision between 11% and 43%, (<1% precision in SL)
  - Strong tension between Babar and PS170
  - No individual determination of $G_E$ and $G_M$
$e^+e^- \rightarrow p\bar{p}$ (Phys. Rev. D91, 112004)

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

- Selection:
  - Only 2 oppositely charged tracks in detector:
    - identified as p and $p$: $dE/dx + \text{Tof} + E/p < 0.5$
    - from interaction vertex: $|R_{xy}| < 1 \text{cm}$, $|R_z| < 10 \text{ cm}$
    - same time of flight window: $|\text{tofp} - \text{tofp}| < 4 \text{ns}$
    - back to back signature
    - sharing $E_{cm}$
    - for $E_{cm} > 2.4 \text{ GeV}$ low polar angles rejected (Bhabha)

- Background:
  - Beam background, $ee \rightarrow$ two-body and multi-body with $p$ and $p \rightarrow$ negligible
  - Only remaining Bhabha at $E_{cm} > 3.40 \text{ GeV}$ corrected for

![Event display (XY-view)](image)
$e^+e^- \rightarrow p\bar{p}$ (Phys. Rev. D91, 112004)

- Results:
  - from $\sigma_{\text{Born}} (ee\rightarrow pp)$ measurement, extraction of effective form factor, $|G|:
    \[ \sigma_{\text{Born}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{L \cdot \epsilon \cdot (1 + \delta)} \]
    \[ |G| = |G_E| = |G_M| = \sqrt{\frac{\sigma_{\text{Born}}}{(1 + \frac{1}{2\tau})(\frac{4\pi \alpha^2 \beta C}{3E_{CM}^2})}} \]
    
    $N_{\text{obs}}$: observed signal events
    $L$: integrated luminosity
    $N_{\text{bkg}}$: estimated background (from MC)
    $\epsilon$: detection efficiency (from MC)
    $1 + \delta$: radiative factor (from MC)

    Agreement with previous measurements and overall uncertainty improved by 30%

  - from proton angular distribution in CM: extraction of $R = |G_E|/|G_M|$ and $|G_M|:
    - fit differential cross section with:
      \[ \frac{dN}{\epsilon \cdot d\cos \theta_p} = N_{\text{norm}} \left[ (1 + \cos^2 \theta_p) + R^2 \frac{1}{\tau} \sin^2 \theta_p \right] \]
      \[ N_{\text{norm}} = \frac{2\pi \alpha^2 \beta L}{4s} \left[ 1.94 + 5.04 \frac{m_p^2}{s} R^2 \right] \cdot |G_M|^2 \]
    - from second moment of $\cos \theta_p$:
      \[ R = \sqrt{s \frac{\langle \cos^2 \theta_p \rangle - 0.243}{4m_p^2 \cdot 0.108 - 0.648 \langle \cos^2 \theta_p \rangle}} \]
      \[ \sigma_R = \frac{0.0741}{R(0.167 - \langle \cos^2 \theta \rangle)^2} \frac{s}{4m_p^2} \sigma_{\langle \cos^2 \theta_p \rangle} \]
Extraction of electromagnetic $|G_E/G_M|$ ratio

- Angular analysis to extract the em FFs:
  - $\frac{d\sigma}{d\Omega}(q^2) = \frac{\alpha^2\beta}{4s} |G_M(s)|^2 \left[(1 + \cos^2\theta_p) + R_{em}^2 \frac{1}{\tau} \sin^2\theta_p\right]$
  - $R_{em} = \frac{G_E(q^2)}{G_M(q^2)}$
  - $\theta$: polar angle of proton at the c.m. system

- Fit function:
  - $\frac{dN}{d\cos\theta_p} = N_{\text{norm}} \left[(1 + \cos^2\theta_p) + R_{em}^2 \frac{1}{\tau} \sin^2\theta_p\right]$
  - $N_{\text{norm}} = \frac{2\pi\alpha^2\beta L}{4s} \left[1.94 + 5.04 \frac{m_p^2}{s} R^2\right] G_M(s)^2$ is the overall normalization

Graphs:

- $G_E/G_M = 0.87 \pm 0.24$
- $A = 585 \pm 24$
- $\chi^2$/Bin = 1.04

- $G_E/G_M = 0.91 \pm 0.38$
- $A = 281 \pm 17$
- $\chi^2$/Bin = 0.74

- $G_E/G_M = 0.95 \pm 0.45$
- $A = 333 \pm 18$
- $\chi^2$/Bin = 0.61

Energy ranges:

- $2.2324$ GeV
- $2.40$ GeV
- $3.05-3.08$ GeV
**Extraction of electromagnetic $|G_E/G_M|$ ratio**

- **Method of Moment**
  
  - Second Moment of $\cos^2 \theta_p$: \( \langle \cos^2 \theta_p \rangle = \frac{1}{N_{\text{norm}}} \int \cos^2 \theta_p \frac{d\sigma}{d\Omega} d\cos \theta_p \)
  
  - The estimator of $\langle \cos^2 \theta_p \rangle$: \( \langle \cos^2 \theta_p \rangle = \frac{\cos^2 \theta_p}{1} = \frac{1}{N} \sum_{i=1}^{N} \cos^2 \theta_p / \varepsilon_i \)

- Extract $|G_E/G_M|$ ratio: \( R = \sqrt{\frac{s}{4m_p^2} \frac{\langle \cos^2 \theta_p \rangle - 0.243}{0.108 - 0.648 \langle \cos^2 \theta_p \rangle}} \)

- Uncertainty of $\langle \cos^2 \theta_p \rangle$: \( \sigma_{\langle \cos^2 \theta_p \rangle} = \frac{1}{\sqrt{N-1}} [\langle \cos^4 \theta_p \rangle - \langle \cos^2 \theta_p \rangle] \)

- **Results on $|G_E/G_M|$ ratio:**


| \( \sqrt{s} \) (MeV) | $|G_E/G_M|$ | $|G_M| \times 10^{-2}$ | \( \chi^2/n_{dof} \) |
|-----------------|-----------------|-----------------|-----------------|
| Fit on $\cos \theta_p$ |
| 2232.4          | 0.87 ± 0.24 ± 0.05 | 18.42 ± 5.09 ± 0.95 | 1.04 |
| 2400.0          | 0.91 ± 0.38 ± 0.12 | 11.30 ± 4.73 ± 1.53 | 0.74 |
| (3050.0, 3080.0) | 0.95 ± 0.45 ± 0.21 | 3.61 ± 1.71 ± 0.82 | 0.61 |
| method of moment |
| 2232.4          | 0.88 ± 0.24      | 18.60 ± 5.38      | - |
| 2400.0          | 0.88 ± 0.37      | 11.52 ± 5.01      | - |
| (3050.0, 3080.0) | 0.88 ± 0.46      | 3.34 ± 1.72       | - |

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Proton threshold

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

\[ \sigma_{pp} \]

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

Results from BESIII needed (from ISR process).
**Prospects for** $e^+e^- \to p\bar{p}\gamma_{\text{ISR}}$

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

**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 $E_{\text{CM}} \geq 3.773$ GeV. Low efficiencies (~6%), lower statistics than BaBar. Perhaps untagged analysis of $J/\psi$ and $\psi(3686)$ possible ?!

**dN(ppγ)/dq**

Efficiencies, background, radiative factor, (functions dependent on $q$)

Add all corrected data from different $E_{\text{CM}}$ for each $q$-bin

Normalize with $L_{\text{ISR}}$

Born cross section, Effective form factor

Angular analysis: Extraction of $R$ and $|G_{E,M}|$

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

**For** $E_{\text{CM}} = 4.230$ GeV, MC simulation

| $|\cos \theta_{pp}| < 0.93$ | Photon tagged |
|-------------------------------|----------------|
| 53%                           | $|\cos \theta_{\gamma}| < 0.93$ | 12% |

| $|\cos \theta_{\gamma}| > 0.93$ | Photon untagged |
|-------------------------------|----------------|
| 41%                           | $|\cos \theta_{pp}| > 0.93$ |
Analysis based on 40.5 pb$^{-1}$ collected in 4 scan points between 2.2324 – 3.08 GeV in 2012

- Selection at $E_{CM} = 2.2324$ GeV ($m_{\Lambda\Lambda} = 2.2317$ GeV)
  - Reconstruction of $ee \rightarrow \Lambda\bar{\Lambda}$ from $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ (BR 64%)
    - only pi and pi in detector
    - pion-momentum well defined
    - Anti-proton annihilation---> secondary particles $|R| \sim 3$ cm
  - $43 \pm 7$ events observed

- Reconstruction of $ee \rightarrow \Lambda\bar{\Lambda}$ from $\Lambda \rightarrow n\pi^0$ (BR 36%)
  - Multivariate Analysis (boosted decision tree) to identify n
  - $p_{\pi^0}$ well defined
  - $22 \pm 6$ events observed

- At $E_{CM} = 2.4, 2.8$ and 3.08 GeV
  - Reconstruction of $ee \rightarrow \Lambda\bar{\Lambda}$ from $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$
  - Only 4 oppositely charged tracks in detector:
    - identified as $p, \bar{p}, \pi^-$ and $\pi^+$
    - from interaction vertex
    - $\Lambda\bar{\Lambda}$ invariant mass cut
    - $\Lambda\bar{\Lambda}$ back to back signature
    - sharing $E_{CM}$
\( e^+e^- \rightarrow \Lambda\bar{\Lambda} \) (BESIII Preliminary!!)

- Results:
  - from \( \sigma_{\text{Born}} (ee\rightarrow \Lambda\bar{\Lambda}) \) measurement, extraction of effective form factor, \(|G| :\)

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

\[
|G| = |G_E| = |G_M|
\]

\[
|G| = \sqrt{\frac{\sigma_{\text{Born}}}{(1 + \frac{1}{2\tau})(\frac{4\pi\alpha^2\beta}{3E^2})}}
\]

Cross section expected to vanish at threshold \((q = 2m_\Lambda)\): 

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

with \( \beta = \sqrt{1 - 4m_\Lambda^2/q^2} \)

| \( \sqrt{s} \) GeV | Reconstruction | \( \sigma_{\text{Born}} \) (pb) | \( |G| \) (\( \times 10^{-2} \)) |
|-----------------|-----------------|------------------|-----------------|
| 2.2324          | \( \Lambda \rightarrow pn^- \), \( \Lambda \rightarrow \bar{p}n^+ \) \( \Lambda \rightarrow \bar{n}n^0 \) combined | \( 325 \pm 53 \pm 46 \) | \( 63.4 \pm 5.7 \) |
| 2.40            |                 | \( 133 \pm 20 \pm 19 \) | \( 12.93 \pm 0.97 \pm 0.92 \) |
| 2.80            |                 | \( 15.3 \pm 5.4 \pm 2.0 \) | \( 4.16 \pm 0.73 \pm 0.27 \) |
| 3.08            |                 | \( 3.9 \pm 1.1 \pm 0.5 \) | \( 2.21 \pm 0.31 \pm 0.14 \) |

Coulomb interaction at quark level? 

*PRD76,092006 (2007)  
**Z Phys C48, 23(1990)
Prospects for $e^+e^- \to \Lambda\Lambda, \Sigma\Sigma, \Xi\Xi$ ...

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

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

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

○ Imaginary part of FFs leads to polarization observables:

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

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

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

Complete determination of TL FFs possible!!

Also available from threshold:

$$ee \to \Lambda^0\Sigma^0, \Sigma^-\Sigma^+, \Sigma^0\Sigma^0, \Sigma^-\Sigma^+, \Xi^0\Xi^-, \Xi^+\Xi^-, \Omega^+\Omega^-, \Lambda^c_\Lambda^c$$

$$p\pi^0, \gamma\Lambda, \eta\pi^-, \Lambda\pi^0, \Lambda\pi, \Lambda K, \Lambda\pi,$$

64%, 52%, 100%, 100%, 100%, 100%, 68%, 1%
## Prospects for BES III

Other hyperon channels: $\Lambda\bar{\Sigma}^0$, $\Sigma^0\bar{\Sigma}^0$

<table>
<thead>
<tr>
<th>$E_{e^+e^-}$ (GeV)</th>
<th>$L$ (pb$^{-1}$)</th>
<th>$\epsilon_{\Lambda\bar{\Sigma}^0}$ (%)</th>
<th>$\sigma_{\Lambda\bar{\Sigma}^0}$ (pb)</th>
<th>$N_{\Lambda\bar{\Sigma}^0}$</th>
<th>$\epsilon_{\Sigma^0\bar{\Sigma}^0}$ (%)</th>
<th>$\sigma_{\Sigma^0\bar{\Sigma}^0}$ (pb)</th>
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</table>

- Luminosities from this proposal
- Acceptances from $J/\psi \rightarrow Y\bar{Y}$ (PRD 86 032008)
- Cross sections from:
  - BABAR (away from threshold)
  - Rinaldo Baldini (at threshold)

=> More than 10-fold increase of statistics.
**e^+e^- → Hyperons**

About 350 $\Lambda\bar{\Lambda}\gamma_{\text{ISR}}$ events with $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ selected by BaBar.

- Only one measurement before by DM2.
- Cross section roughly flat at threshold and possibly not vanishing even though no Coulomb correction for neutral baryons production.
- However, large error bars do not exclude $\sigma_{\text{threshold}} = 0$.

**Rise of FFs close to threshold** observed also in this case.
- Fit with $f = K/q^n$ gives $n = 9.2 \pm 0.3$.
  - pQCD asymptotic prediction ($q^4$) reached at 3GeV first.
- $F_\Lambda$ in agreement with DM2 and with $F_n$ by Fenice.
e+e- → Hyperons

- **Ratio of form factors** extracted from the analysis of the angular distribution of the lambda helicity angle

\[
\frac{|G_E^\Lambda|}{|G_M^\Lambda|} < 1.73^{+0.99}_{-0.57} \quad \text{and} \quad \frac{|G_E^\Lambda|}{|G_M^\Lambda|} < 0.71^{+0.66}_{-0.71}
\]

- Compatible with \(|G_E^\Lambda/G_M^\Lambda| = 1\), but with large uncertainties

- **Polarization** tested by fitting slope of angle between lambda polarization axis and proton momentum in \(\Lambda\) rest frame

\[
\frac{dN}{d\cos \theta_{p\zeta}} = A(1 + \alpha_L \zeta_f \cos \theta_{p\zeta})
\]

\[\implies -0.22 < \zeta_f < 0.28 \quad (90\% \text{ CL})\]

Under \(|G_E^\Lambda| = |G_M^\Lambda|\) assumption, tests a non-zero relative phase between \(G_E^\Lambda\) and \(G_M^\Lambda\):

\[-0.76 < \sin \phi < 0.98\]
**BESIII Data Samples**

**e^+e^- → Hyperons**

BaBar performed first measurement ever for these channels
Reconstruct Σ baryon in decay channels Σ → Λ γ and Λ → pπ : few tens of signal events

[B. Aubert et al., Phys. Rev. D 76, 092006 (2007)]

QCD predictions:

- **F_Λ/F_p = 0.24**
- **F_Σ/F_Λ = -1.18**
- **F_ΣΛ/F_Λ = -2.34**

- Effective |F| shows same rising behavior
- Data seem to agree with theory only for F_Σ/F_Λ (by accident?)
- F_Λ/F_p decrease with energy, similar to prediction close to 3 GeV

[Chernyak et al. Z. Phys. C 42, 569 (1989)]
New scan in 2 – 3.1 GeV

- 2014.12.30-2015.5.1;
- From high to low;
- Added 2.05 GeV;
- 20 energy points, total online luminosity 525 pb⁻¹;
- Allows for form factor measurements, threshold studies, ...

<table>
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<tr>
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<th>$E_{th}$ (GeV)</th>
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6-month plan, finished in ~4 months.