Baryon Electromagnetic Form Factors at BESIII

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- Introduction to electromagnetic form factors
- BESIII experiment
- Measurement of Baryon electromagnetic form factors at BESIII
- Summary

55th International Winter Meeting on Nuclear Physics
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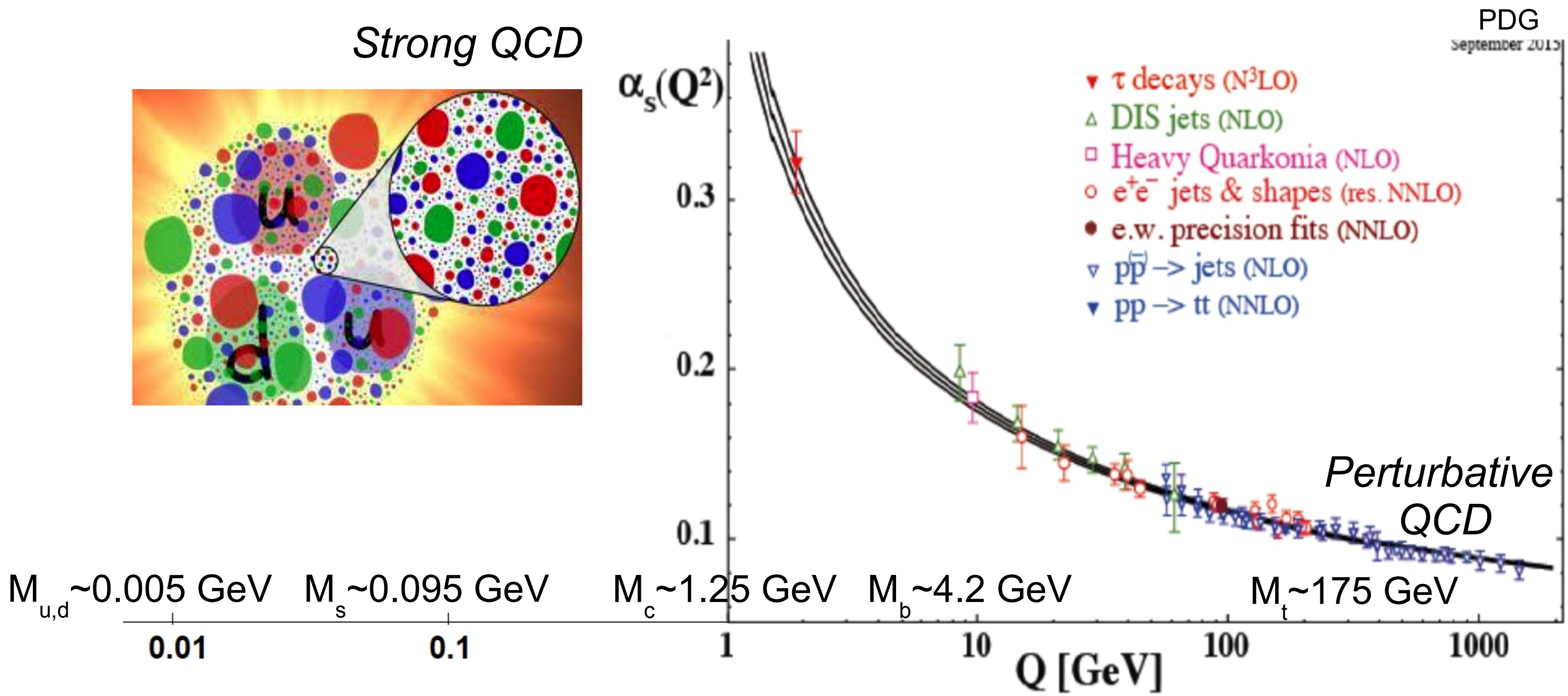
The structure of baryons

Baryons: simplest **non-perturvative systems** for which non-abelian nature of QCD is manifest



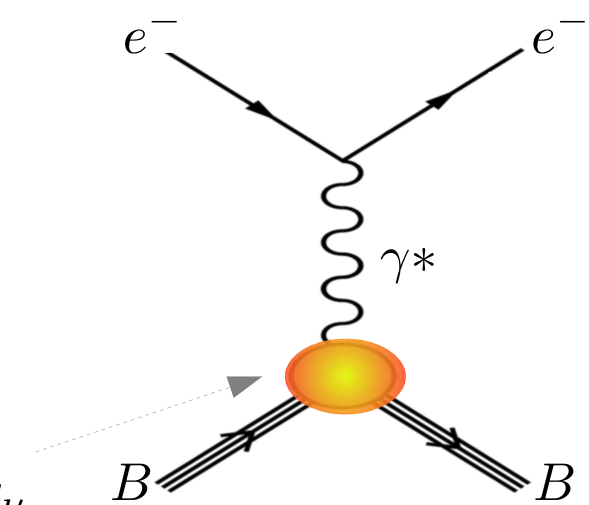
- Different quark masses **probe different regions of the strong interaction**
- Powerful **observables to understand baryon structure** (e.g. Form Factors, Distribution Amplitudes (GPD,TDA)) **obtained from electromagnetic processes**

Baryon electromagnetic form factors

All **hadronic structure** and **strong interactions** in EM FFs but subject to QED

Space-like: $q^2 = (p_{ie} - p_{fe})^2 < 0$

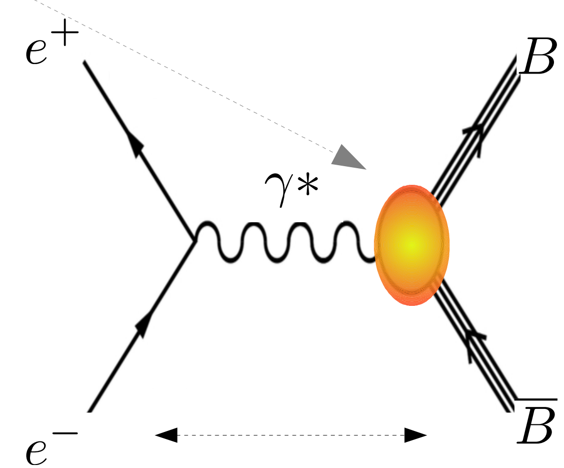
- Studied in $e^- B \to e^- B$ (elastic) scattering
- G_E and G_M real functions
- Rigurously studied for nucleons since 1960's
- Related to charge and magnetization distributions



$$\Gamma^\mu = \gamma^\mu \boldsymbol{F_1} + \frac{i\sigma^{\mu\nu} q_\nu}{2M} \boldsymbol{F_2}$$

Time-like: $q^2 \geq 4M_B^2$

- In $e^+e^- \leftrightarrow B\overline{B}$
- G_E and G_M complex functions
- Very few measurements



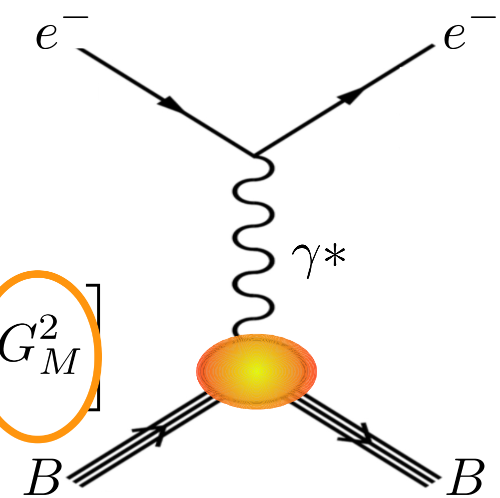
SL and TL FFs related through **dispersion relations**

Baryon electromagnetic form factors

Angular analysis to extract EM form factors

Space-like: $q^2 = (p_{ie} - p_{fe})^2 < 0$

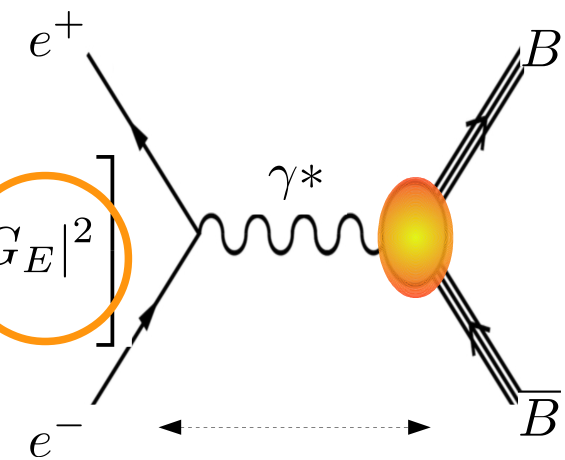
$$\left[\frac{d\sigma}{d\Omega_{\rm lab}}\right] = \frac{\alpha^2 E_{fe}\cos^2\frac{\theta_{fe}}{2}}{4E_{ie}^3\sin^4\frac{\theta_{fe}}{2}} \cdot \frac{1}{1-\frac{q^2}{4M_B^2}} \cdot \left[G_E^2 - \frac{q^2}{4M_B^2}\left(1+2\left(1-\frac{q^2}{4M_B^2}\right)\tan^2\frac{\theta_{fe}}{2}\right)G_M^2\right]$$



Rosenbluth separation, polarization observables

Time-like: $q^2 \geq 4M_B^2$

$$\left[\frac{d\sigma}{d\Omega_{\rm CM}}\right] = \frac{\alpha^2\beta C}{4q^2}\left[(1+\cos^2\theta_B)|G_M|^2 + \frac{1}{\frac{q^2}{4M_B^2}}\sin^2\theta_B|G_E|^2\right]$$

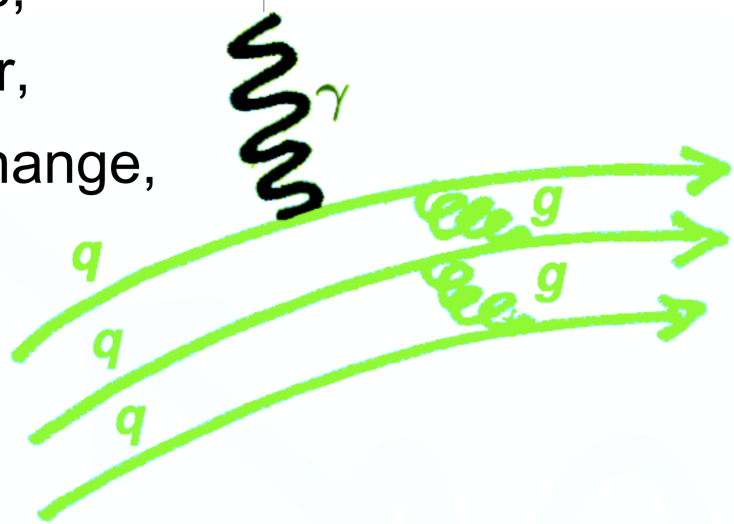


Total cross section does not allow separation of form factors → **effective form factor**

Baryon electromagnetic form factors

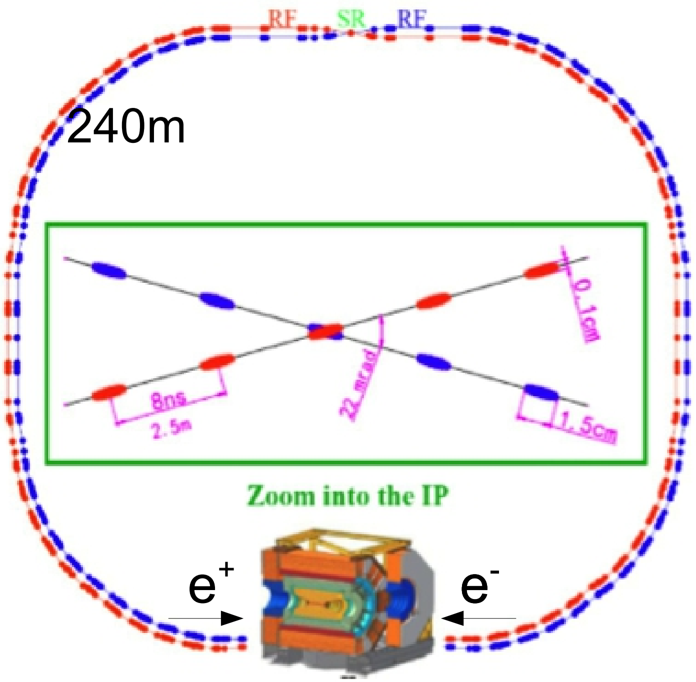
Playground for theory and experiments:

- From the **size of baryons** (low q^2)
  … to **QCD scaling** (at high q^2)
- Many **hot topics**: G_E/G_M, Charge Radius, Unphysical Region, Threshold Behaviour, Radiative Corrections, Two-Photon Exchange, Large Q^2 ...



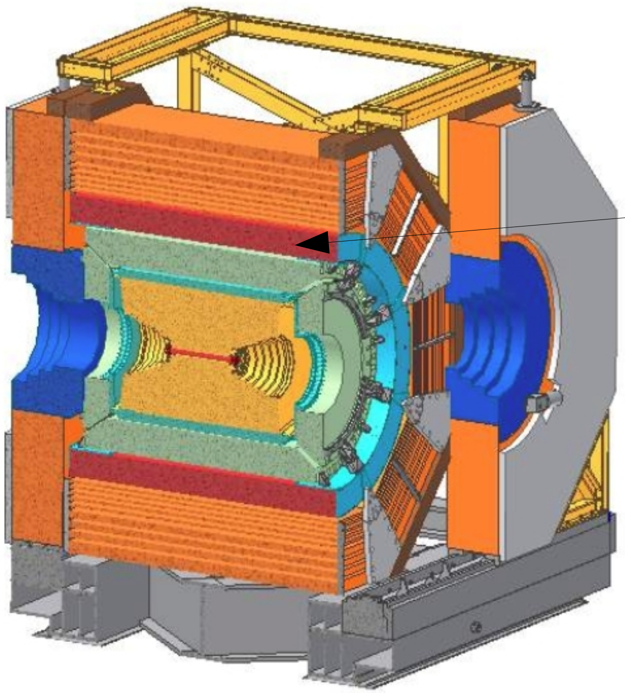
BESIII experiment at BEPCII

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

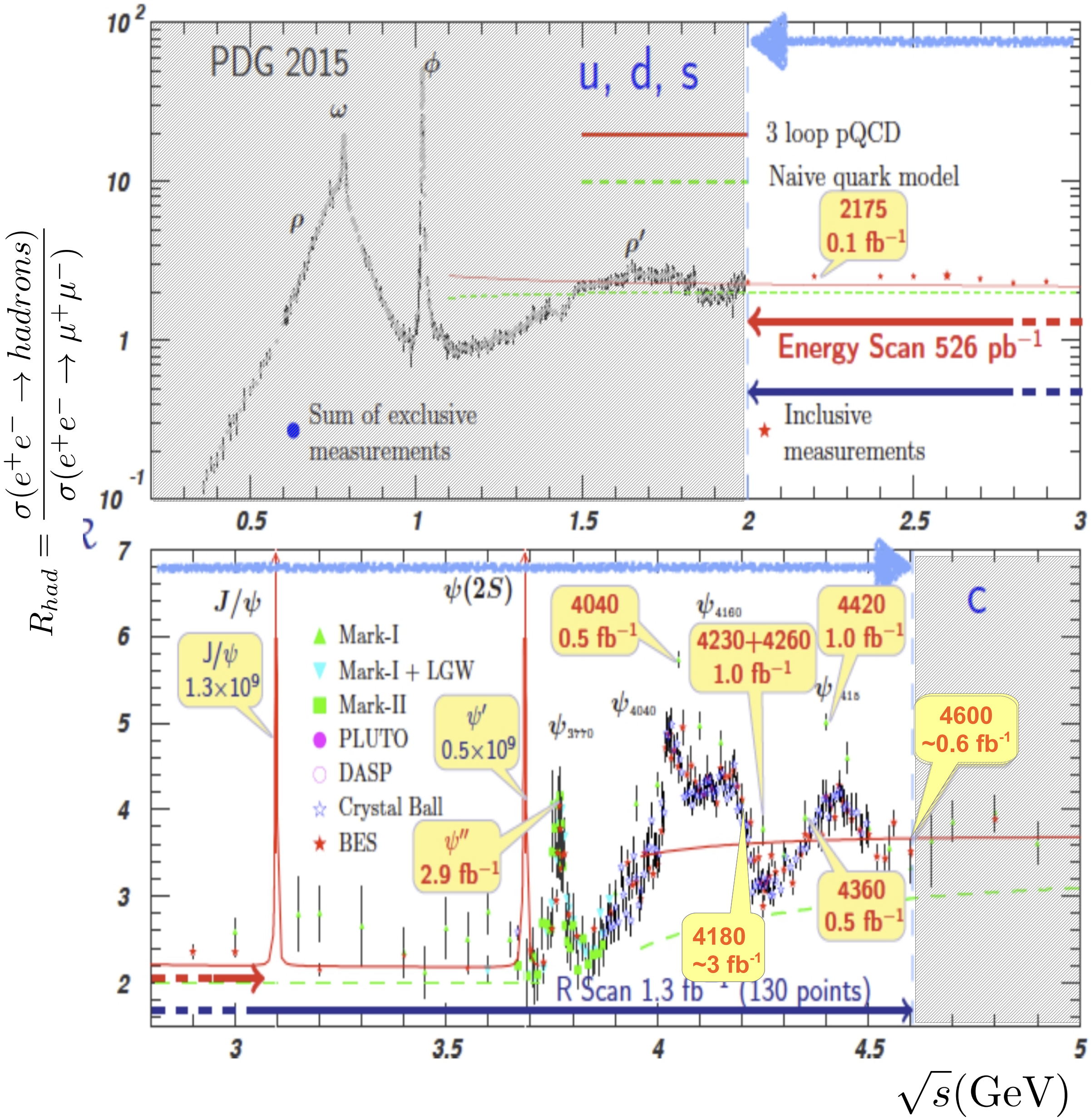
Multi-purpose detector: 93% of 4π



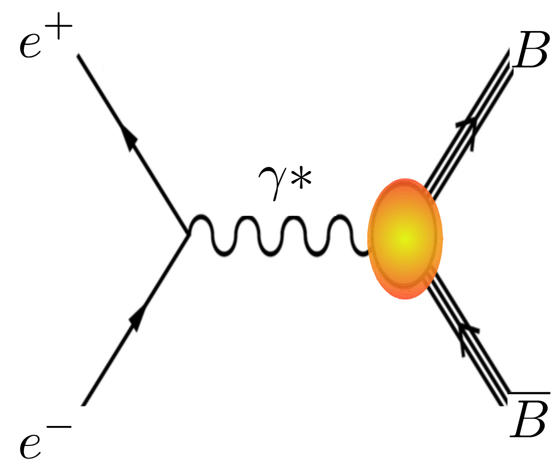
- **Main Drift Chamber**
  $\sigma(p)/p < 0.5$ % for 1 GeV tracks,
  $\sigma(dE/dx)/dE/dx < 6\%$, $\sigma(xy) = 130$ μm
- **Time of Flight** $\sigma(t) \sim 90$ ps
- **EMCalorimeter** $\sigma(E)/E < 2.5$ %,
  $\sigma(x) < 6$mm for 1 GeV e^-
- **Muon Counter** $\sigma(xy) < 2$ cm

BESIII data samples

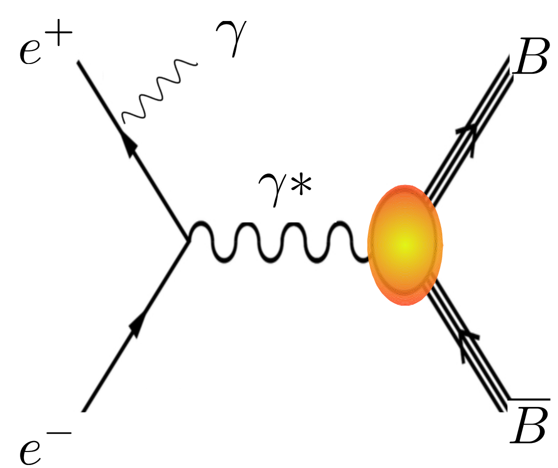
From 2009 until 2016:



From scan data:

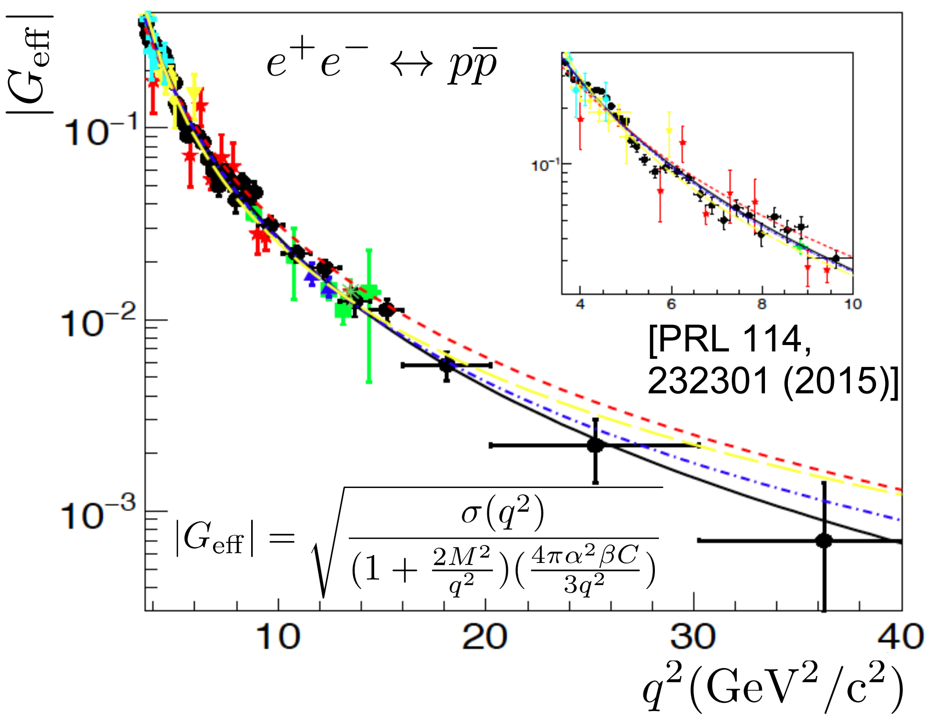


From data at the resonances:

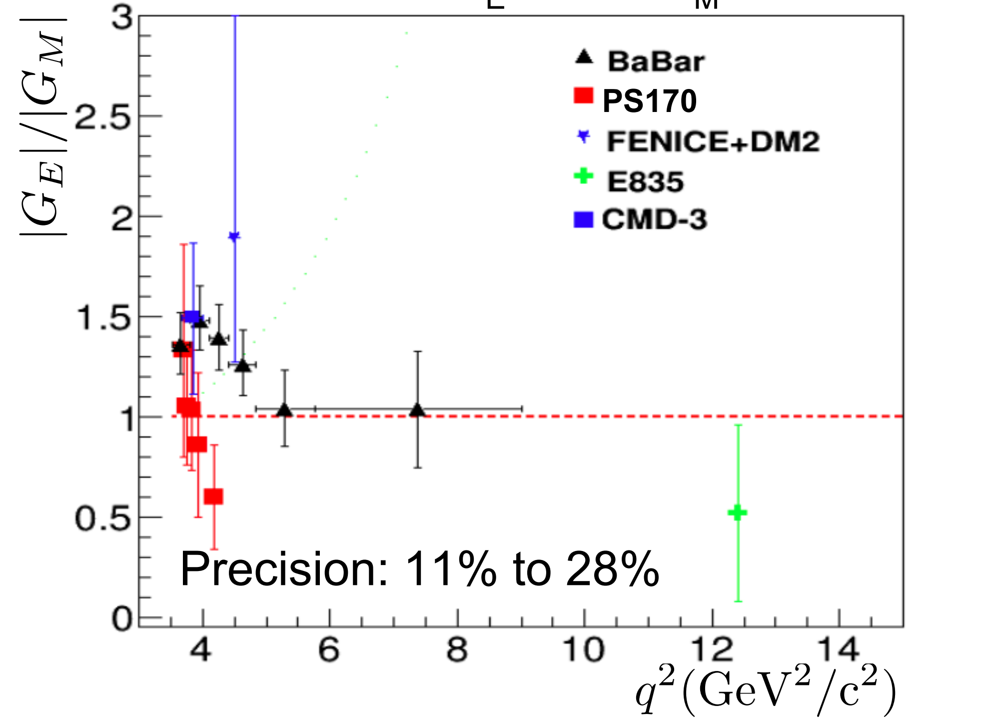


Time-like proton EM form factors

Effective form factor



Ratio of $|G_E|$ and $|G_M|$



- Steep behaviour of the **effective form factor** at threshold
- **Structures** appeared in BaBar data [PRD 87, 092005 (2013)]
  - Resonances [PRD 92, 034018 (2015)]
  - Rescattering processes between few coherent sources [PRL 114, 232301 (2015)]
- At high q^2 time-like FFs 2 times larger than space-like FFs
- Ratio of absolute vales of **form factors**: discrepancy between PS170 [NPB 411,3(1994)] and BaBar

$e^+e^- \to p\bar{p}$ at BESIII

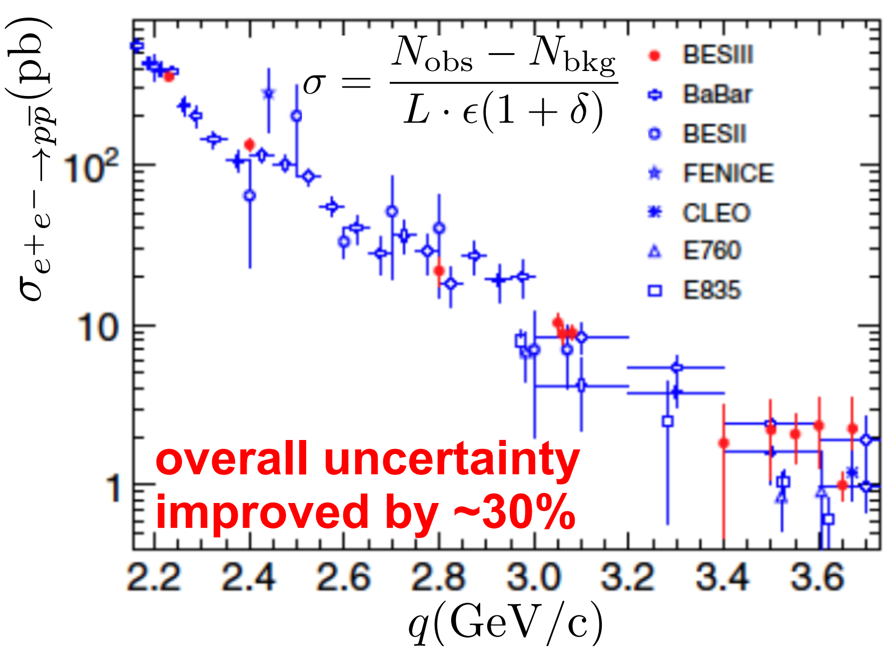
Phys. Rev. D91, 112004 (2015)

Based on **157 pb^{-1}** collected in 12 scan points with $\sqrt{s}$= **2.23 – 3.71 GeV** in 2011/2012

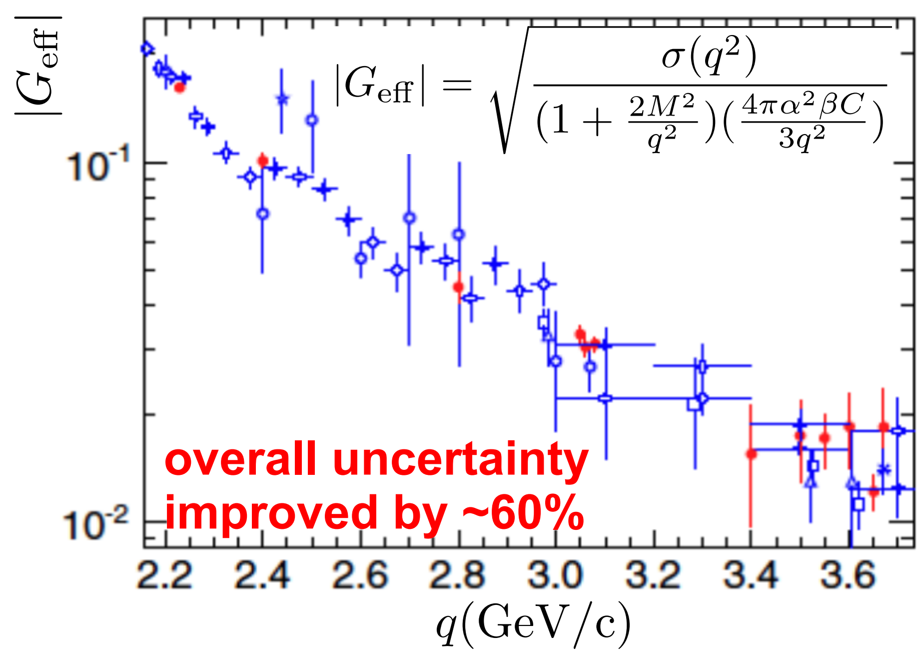
- p and $\bar{p}$ from vertex, in time, back to back, $E_{p,\bar{p}} = E_{CM}/2$
- Background negligible or subtracted
- Efficiencies around 60%
- Radiative corrections up to LO in ISR (ConExc)
- Normalization to $e^+e^- \to \gamma\gamma$ (Babayaga 3.5)

E_{CM} (GeV)	Ldt (pb^{-1})
2.23	2.6
2.40	3.4
2.80	3.8
3.05,3.06,3.08	60.7
3.40,3.50,3.54,3.56	23.3
3.60,3.65,3.67	63.0

Cross section



Effective form factor



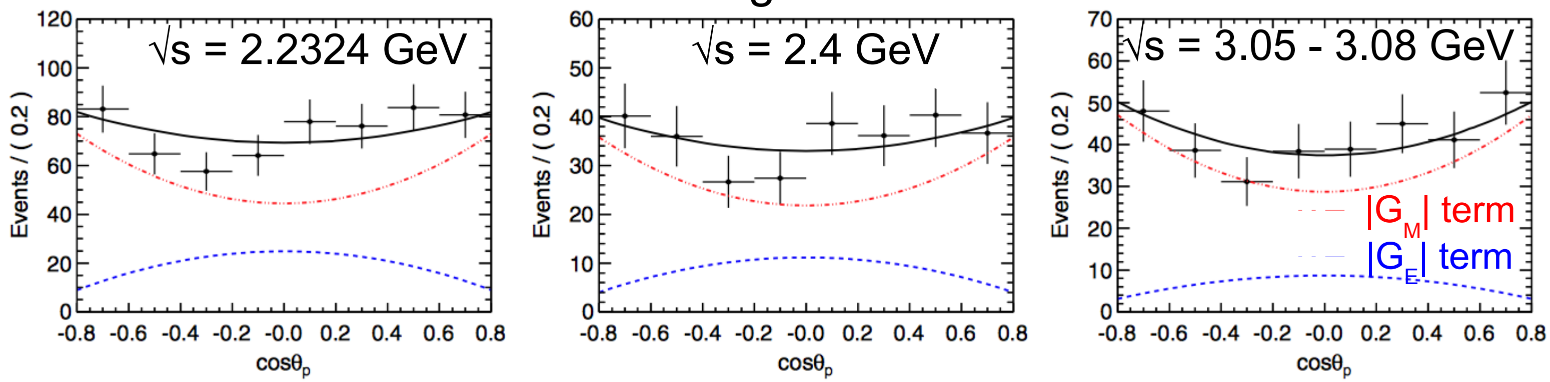
$e^+e^- \to p\bar{p}$ at BESIII

Phys. Rev. D91, 112004 (2015)

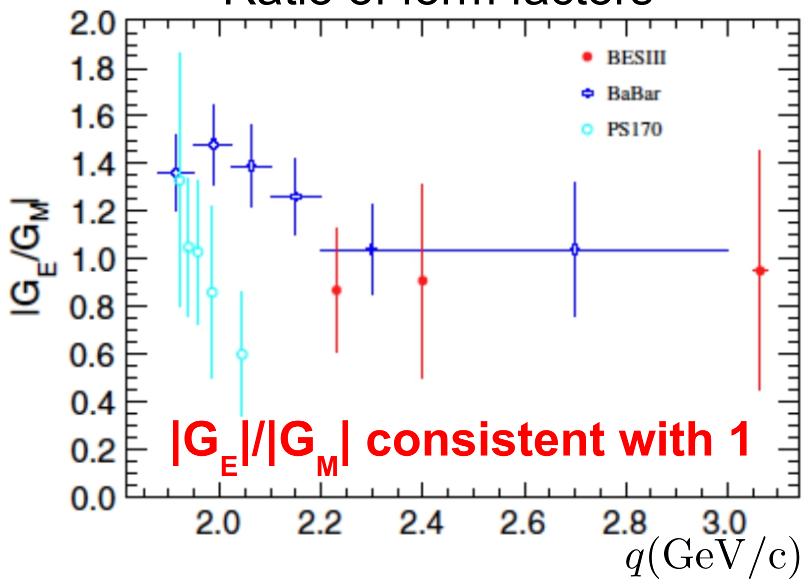
Extraction of electromagnetic form factors from proton angular distribution:

$$\frac{d\sigma}{\mathcal{L}\cdot d\cos\theta_p} = \frac{\pi\alpha^2\beta C}{2q^2}|G_M|^2[(1+\cos^2\theta) + \frac{|G_E|^2}{|G_M|^2}\cdot\frac{4M^2}{q^2}\sin^2\theta]$$

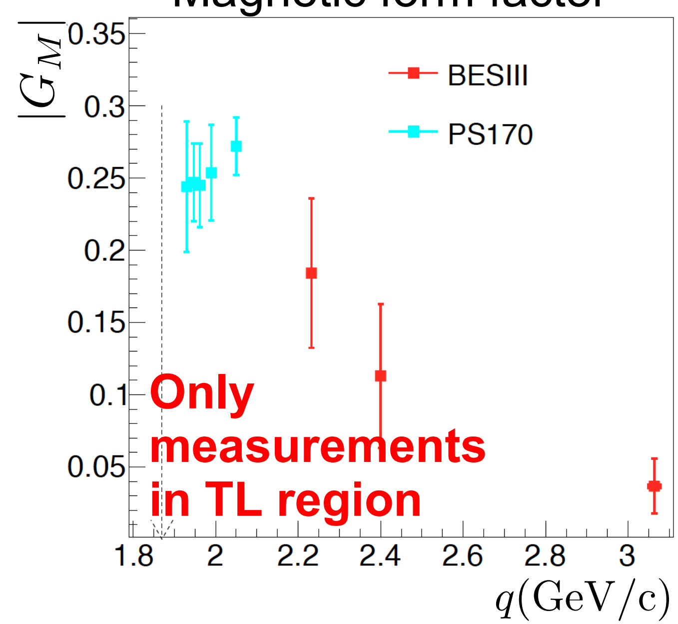
Proton angular distribution



Ratio of form factors



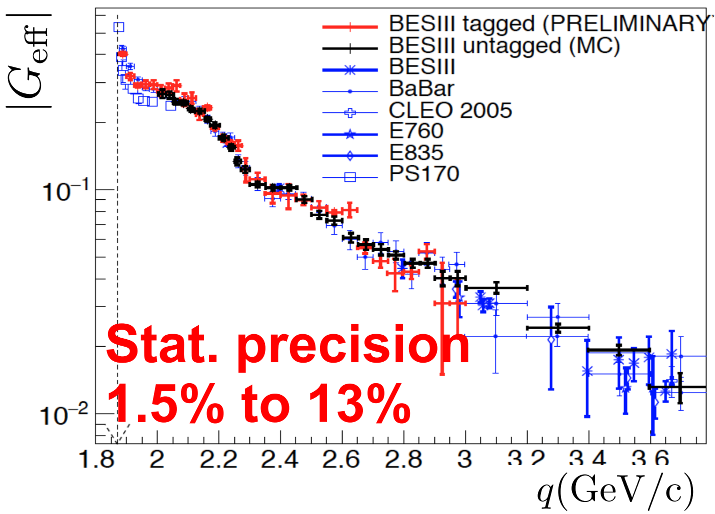
Magnetic form factor



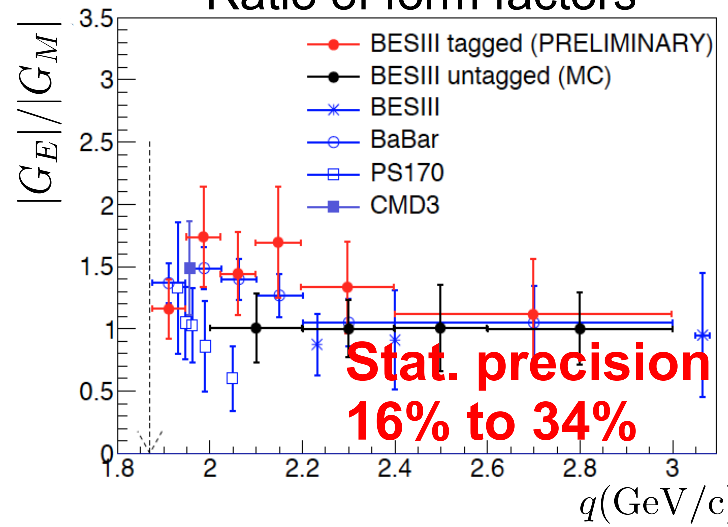
Prospects for $e^+e^- \to p\bar{p}$ at BESIII

From $e^+e^- \to p\bar{p}\gamma$ at the main charmonium resonances (**7.4 fb^{-1}**)

Effective form factor



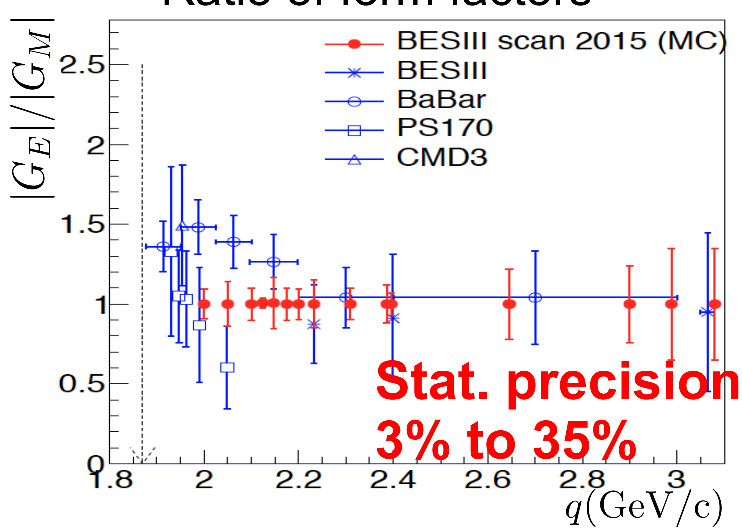
Ratio of form factors



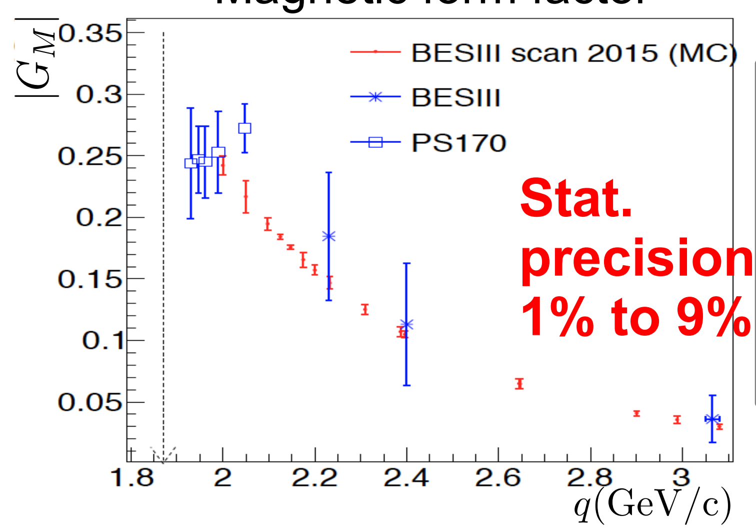
Wide continuous range from threshold to 3.8 GeV/c

From $e^+e^- \to p\bar{p}$ at 22 scan points between $\sqrt{s}$ = 2.0 – 3.08 GeV in 2015 (**630 pb^{-1}**)

Ratio of form factors



Magnetic form factor



Comparable accuracies in SL and TL regions for similar Q^2 values

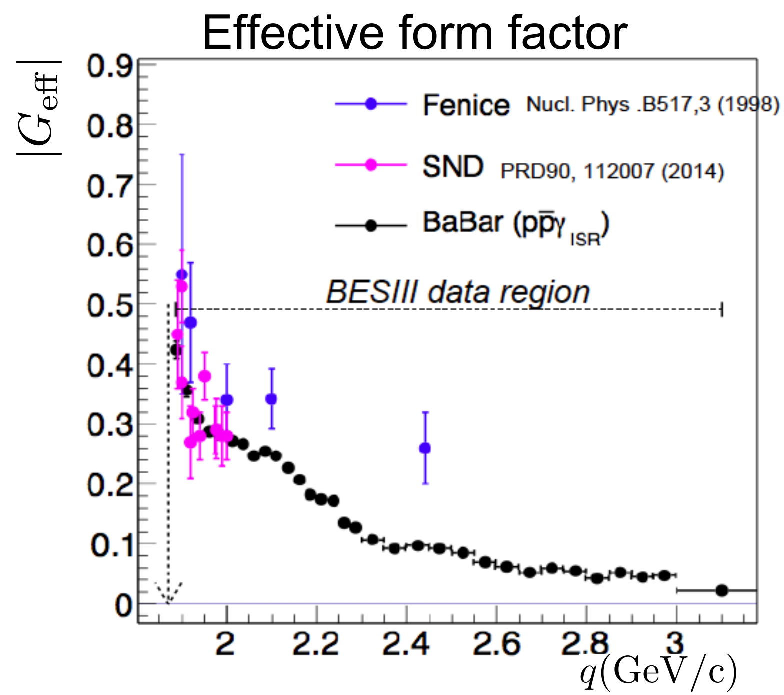
Prospects for $e^+e^- \to n\bar{n}(\gamma)$ at BESIII

Measurement of the total cross section and the effective FF in wide q^2-region

Possibility for a first time measurement of $|G_E|$ and $|G_M|$

Challenges:

- Large background contribution form neutral channels (? -final state) and beam associated processes
- Low trigger efficiencies for purely neutral channels
- Current analysis based only on EMC information → low signal efficiency (few %) Significant enhancement is expected from using TOF and MUC information



$n/\bar{n}$ interactction with BESIII

EMC calorimeter
CsI(Tl): $15X_0$,
→ 52% $n/\bar{n}$ interact in EMC

MUC: Iron + resistive plates
56 cm Fe thickness in barrel
→ ~96 % $n/\bar{n}$ interact in MUC

TOF: 2 plastic scintillator layers
Total width: 10 cm
$P_{\bar{n}}$ = 55%, P_n =13.5%

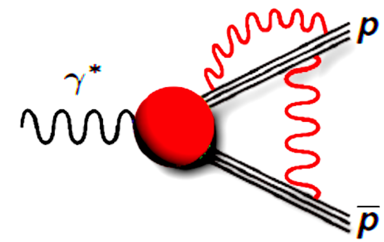
Baryon pair production: the threshold

Annihilation cross section (one-photon exchange)

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

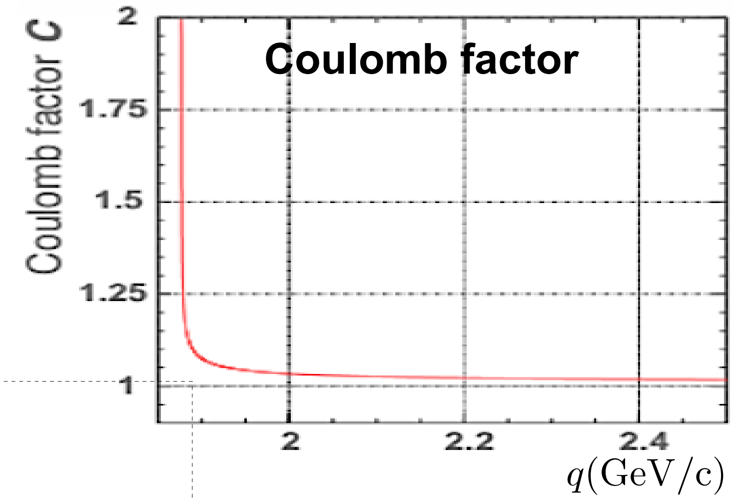
$p\bar{p}$ Coulomb interaction as FSI $C = \epsilon \times \mathcal{R}$

[Sommerfeld,Sakharov,Schwinger,Fadin,Khoze]



- Enhancement factor: $\epsilon = \pi\alpha/\beta$
- Step at threshold:

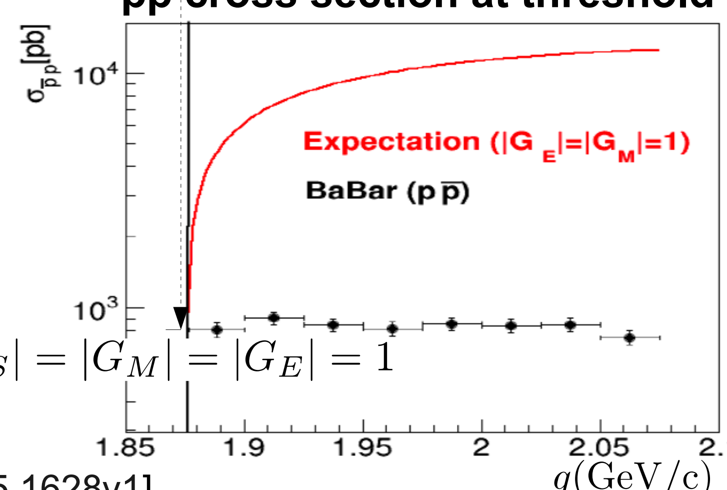
$$\sigma(4M_p^2) = \frac{\pi^2\alpha^3\beta}{2M_p^2\beta}|G_S(4M_p^2)|^2 = 0.85|G_S(4M_p^2)|^2\mathrm{nb}$$



- Resummation factor: $\mathcal{R} = 1/[1 - e^{-\pi\alpha/\beta}]$
- Few MeV above threshold:

$$C \simeq 1 \Longrightarrow \sigma(q^2) \propto \beta|G_S(q^2)|^2$$

$p\bar{p}$ cross section at threshold



$|G_S| = |G_M| = |G_E| = 1$

For a wide energy range (200 MeV) proton behaves like a point-like particle!!

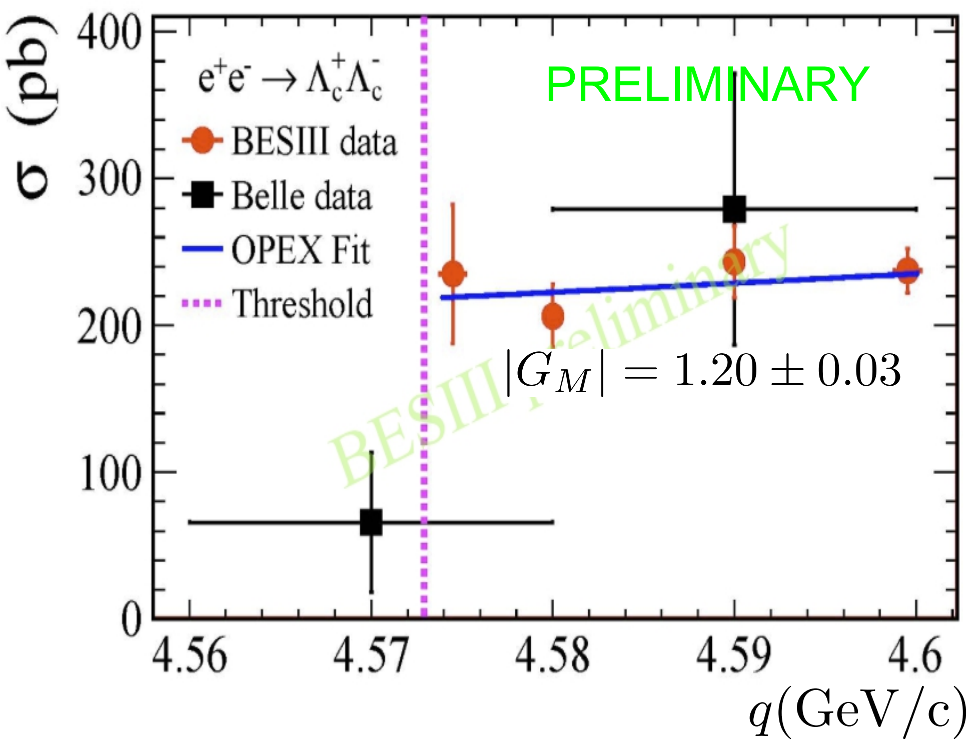
[Ferroli, R. B., Pacetti, S., & Tomasi-Gustafsson, E. Threshold phenomenology of nucleon form factors,ArxiV:1405.1628v1]

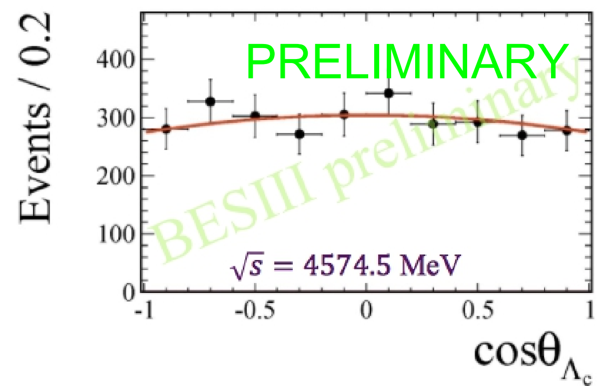
Baryon pair production at BESIII: $\Lambda_c^+\bar{\Lambda}_c^-$

Based on **631.3 pb^{-1}** collected in 4 scan points around Λ_c production threshold in 2014

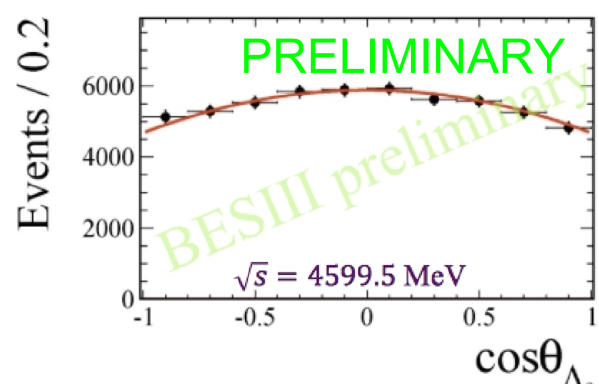
- 10 Λ_c decay modes independently reconstructed
- ~1.6 MeV away from threshold!
- Unprecedented statistical uncertainty (~2% at 4.6 GeV)
- **First measurement of $|G_E/G_M|$ for Λ_c** extracted at 2 energies: test of isotropy (analiticity of the FFs)

$\sqrt{s}$ MeV	$L_{int.}$ (pb^{-1})
4574.5	47.67
4580.0	8.545
4590.0	8.126
4599.5	566.9





$\lvert G_E/G_M\rvert$
$1.10 \pm 0.14 \pm 0.07$



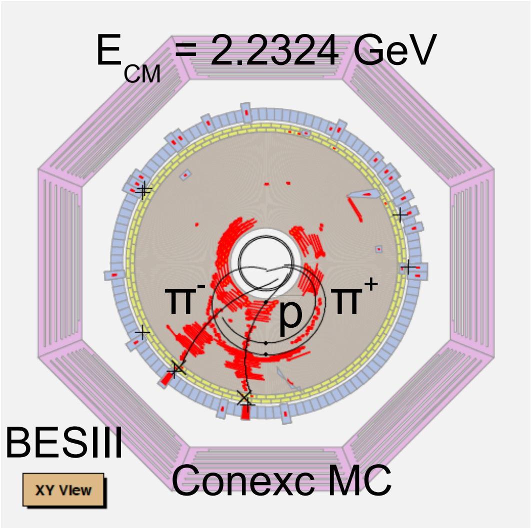
$\lvert G_E/G_M\rvert$
$1.23 \pm 0.06 \pm 0.03$

Baryon pair production at BESIII: $\Lambda\bar{\Lambda}$

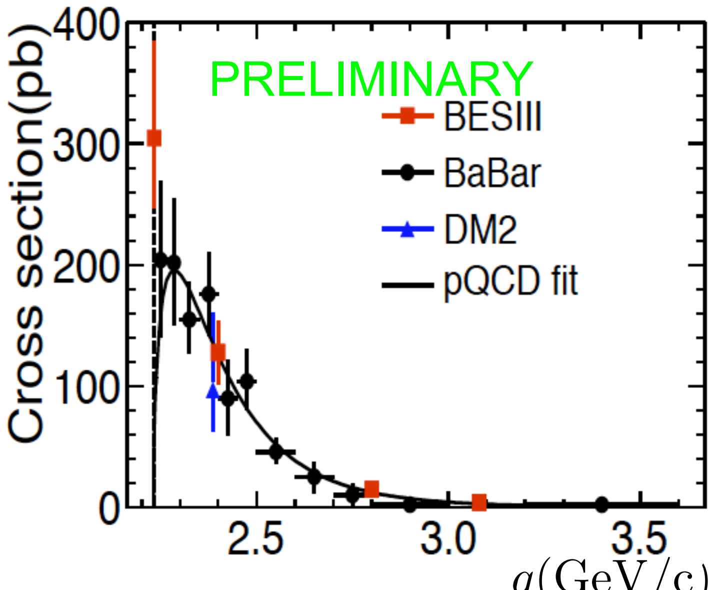
Based on **40.5 pb^{-1}** collected at √s= **2.2324, 2.4, 2.8, 3.08 GeV** in 2012 mini scan

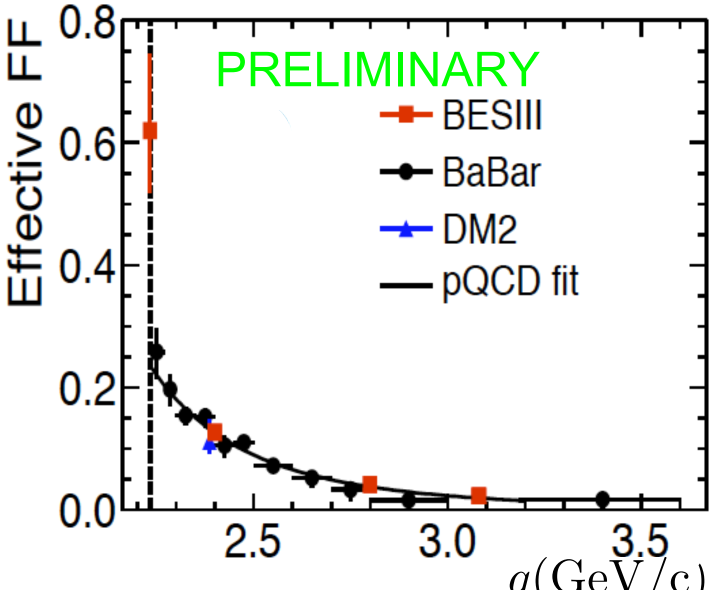
- Lowest energy only 1 MeV above theshold!
- Decay channels at 2.2324 GeV: $\Lambda \to p\pi^-$ & $\bar{\Lambda} \to \bar{p}\pi^+$, $\bar{\Lambda} \to \bar{n}\pi^0$ & Λ inclusive decay
- Decay channels at higher energies: $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$
- Annihilation cross section

$$\sigma_{\Lambda\bar{\Lambda}} = \frac{4\pi\alpha^2\beta \not{C}}{3q^2}\left[|G_M(q^2)|^2 + \frac{2M_\Lambda^2}{q^2}|G_E(q^2)|^2\right] \xrightarrow[\beta \to 0]{} \sigma_{\Lambda\bar{\Lambda}} \to 0$$



Non-vanishing threshold cross section observed!!





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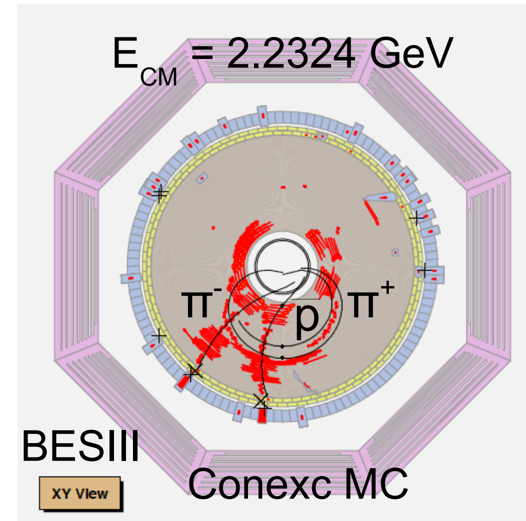
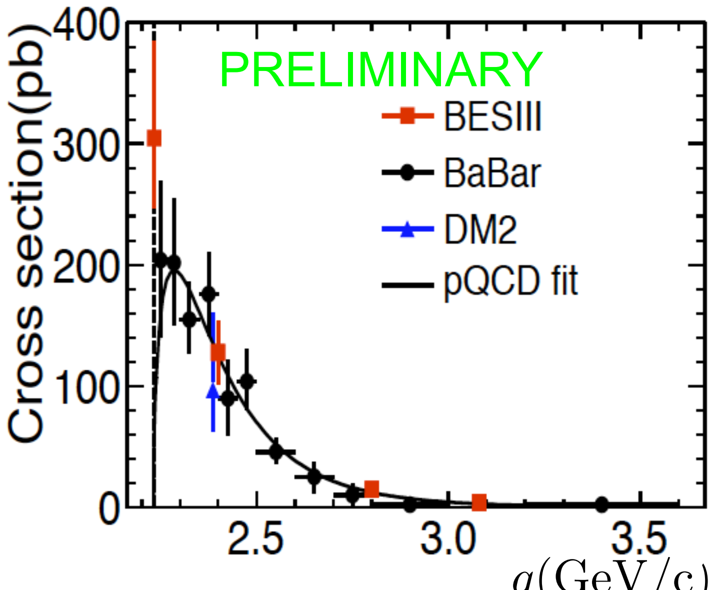
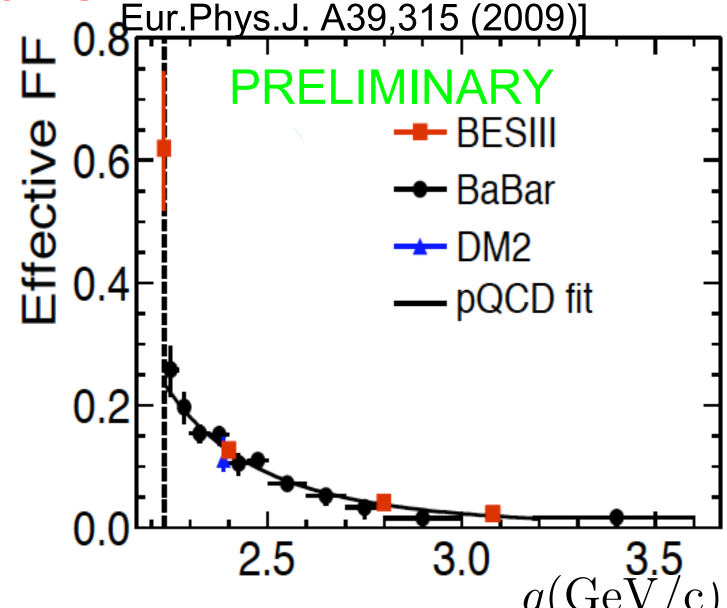


$$\sigma_{\Lambda\bar{\Lambda}} = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M(q^2)|^2 + \frac{2M_\Lambda^2}{q^2}|G_E(q^2)|^2\right] \xrightarrow[\beta \rightarrow 0]{} \sigma_{\Lambda\bar{\Lambda}} \rightarrow 0$$

Non-vanishing threshold cross section observed!!

→ more complicated physics scenario underlying: [arXiv:1608.02766v1,1405.1628v1 Eur.Phys.J. A39,315 (2009)]





Prospects for hyperons FFs at BESIII

What happens if we replace one of the light quarks in the nucleon with one or many heavier quark(s)?

Can we derive the properties of the hyperons from what we know about nucleons. i.e. **to which extent is SU(3) symmetry broken?**

Advantages of hyperons:

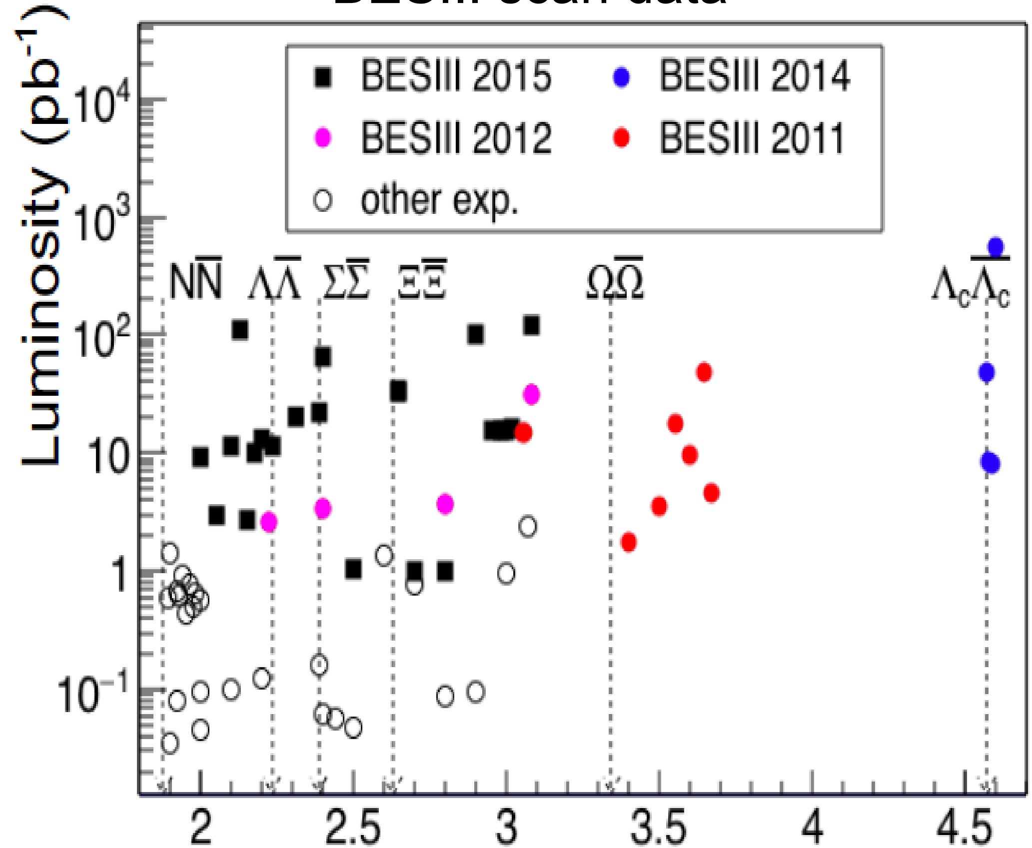
- Easier to trace the heavier quark
- Polarization accessible thanks to weak, parity violating decay

BESIII 2015 energy scan:

- Unprecedented statistics between 2.23-2.9 GeV
- At 5 energies large enough samples to extract $R^{\Lambda} = |G_E^{\Lambda}/G_M^{\Lambda}|$
- At 2.396 GeV complete spin decomposition possible: first determination of G_E^{Λ}-G_M^{Λ}-phase
- Also accessible:

$$e^+e^- \to \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0, \Sigma^+\bar{\Sigma}^-, \Sigma^-\bar{\Sigma}^+, \Xi^0\bar{\Xi}^0, \Xi^-\bar{\Xi}^+, \bar{\Omega}^+\Omega^-$$

BESIII scan data



Summary

- Electromagnetic FFs are fundamental, Lorentz-invariant properties of baryons that are rigurously defined, and provide a benchmark for theoretical models

- BESIII is unique in its capability to measure baryon form factors, from nucleons to Λ_c and use two complementary approaches: energy scan and initial state radiation technique:

  - Proton Form Factors have been measured using a test energy scan of 2012:
    - Effective form factors in good agreement with previous experiments and improving overall uncertainty by 30%
    - $|G_E|/|G_M|$ and $|G_M|$ extracted at three energy points with 25% to 50% uncertainty (dominated by statistics)
  - Very exciting results from ISR on protons expected very soon
  - Preliminary results on cross sections and FFs from Λ and Λ_c close to threshold

- The measurements of baryon FFs will be significantly improved and extended with the 2014 and 2015 high luminosity scan data: **full determination of Λ and Λ_c FFs possible, effective FFs accessible for neutrons, hyperons and multi-strange hyperons, neutron and Σ FFs accessible for the first time, and proton FFs with accuracies better than 10%**

Backup

Hyperons EM form factors

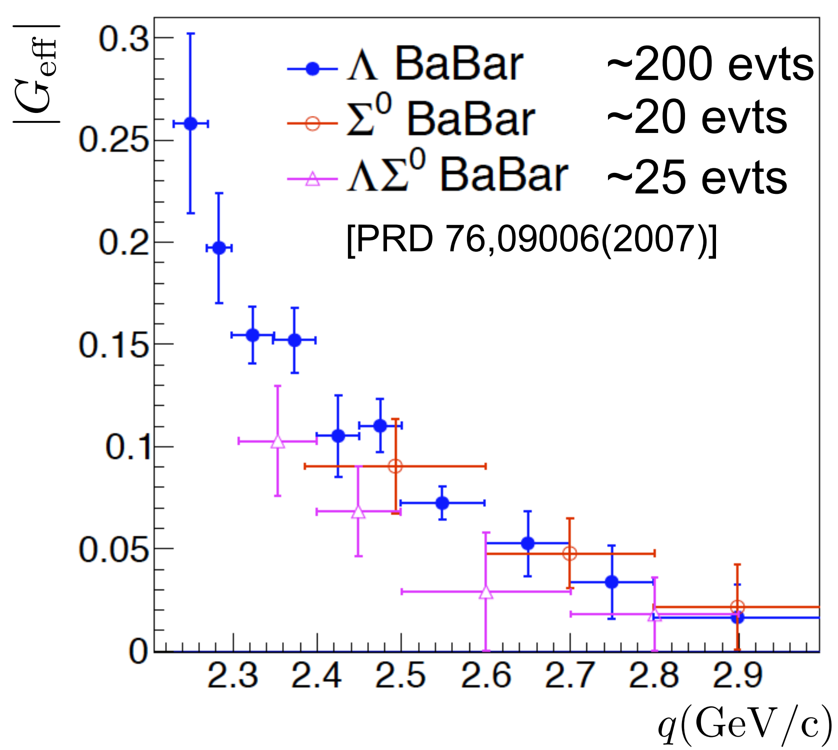
Hyperons unstable → cannot serve as targets: only TL EM FFs accessible

e+e- collisions are currently the best way to study hyperon structure

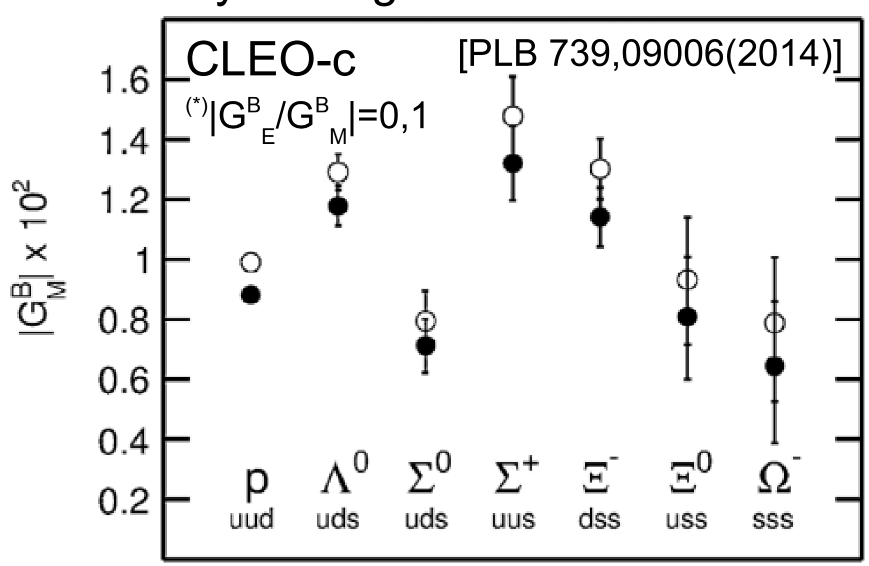
Through weak hyperon decays polarization observables accessible

Very little data published so far:

Lambda effective form factor



Baryon magnetic(*) FF at 3770 GeV



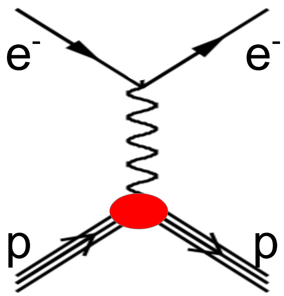
- Total error on $|G^\Lambda_E/G^\Lambda_M|$: 33-100%
- Relative phase: $-0.76 < \sin\varnothing^\Lambda < 0.98$

Cristina Morales

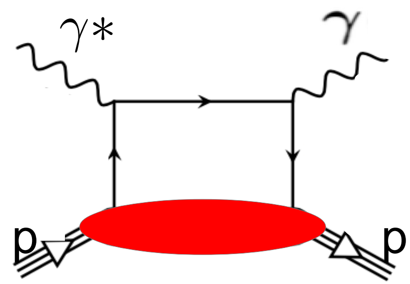
Structure of Hadrons

Electromagnetic probes allow to factorize hadronic interactions in terms of 'non-perturbative' objects: Form Factors, Distribution Amplitudes ...

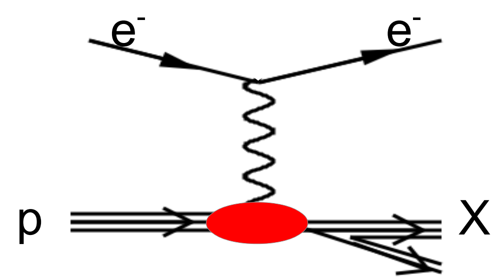
Scattering



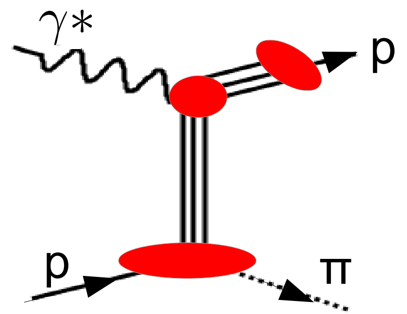
Elastic scattering



Deep Virtual Compton scattering

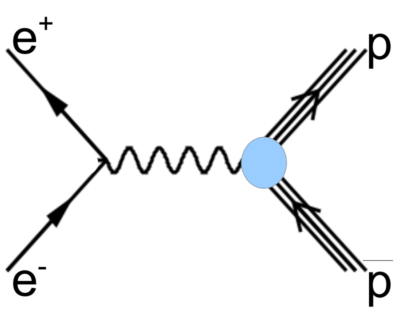


Deep Inelastic Scattering

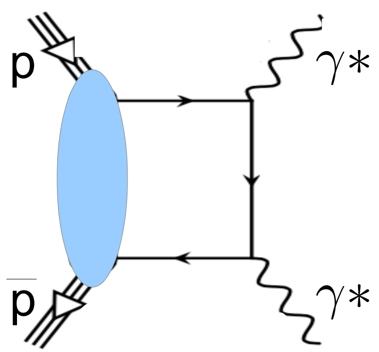


Electroproduction

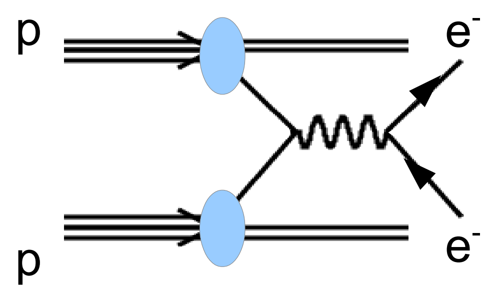
Annihilation



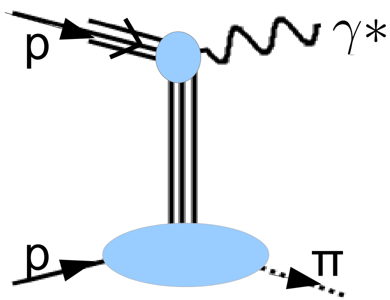
Annihilation into pair of proton/antiproton



Inverted wide angle Compton scattering



Drell-Yan



Annihilation into gamma star

Experiments: Now and Future

Space-like region

Mainz

- G_E^n at $-q^2 = 1.5$ GeV^2 (Pol. ^{3}He)
- G_E^p and G_M^p for $-q^2 \leq 2.0$ GeV^2

Jefferson Lab

- [Hall A] G_E^p/G_M^p up to 14 GeV^2
- [Hall A] G_M^n up to 18 GeV^2
- [Hall A] G_E^n/G_M^n up to 10.2 GeV^2
- [Hall B] G_M^n (^{2}H) up to 14 GeV^2
- [Hall C] G_E^n up to 7 GeV^2

Time-like region

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

$q^2 \leq (4.5\ \text{GeV})^2$

?

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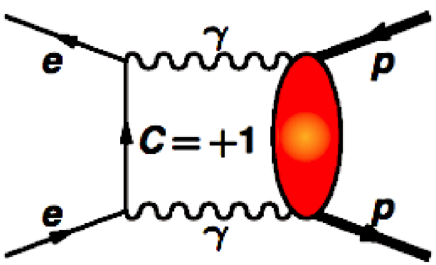
Two photon exchange

- Experimental access: **angular distribution of Nucleon in e^+e^--center-of-mass**

$\gamma\gamma$ exchange



$\gamma\gamma$ exchange interfere with the Born term

Asymmetry in angular distributions

[PLB659, 197]

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

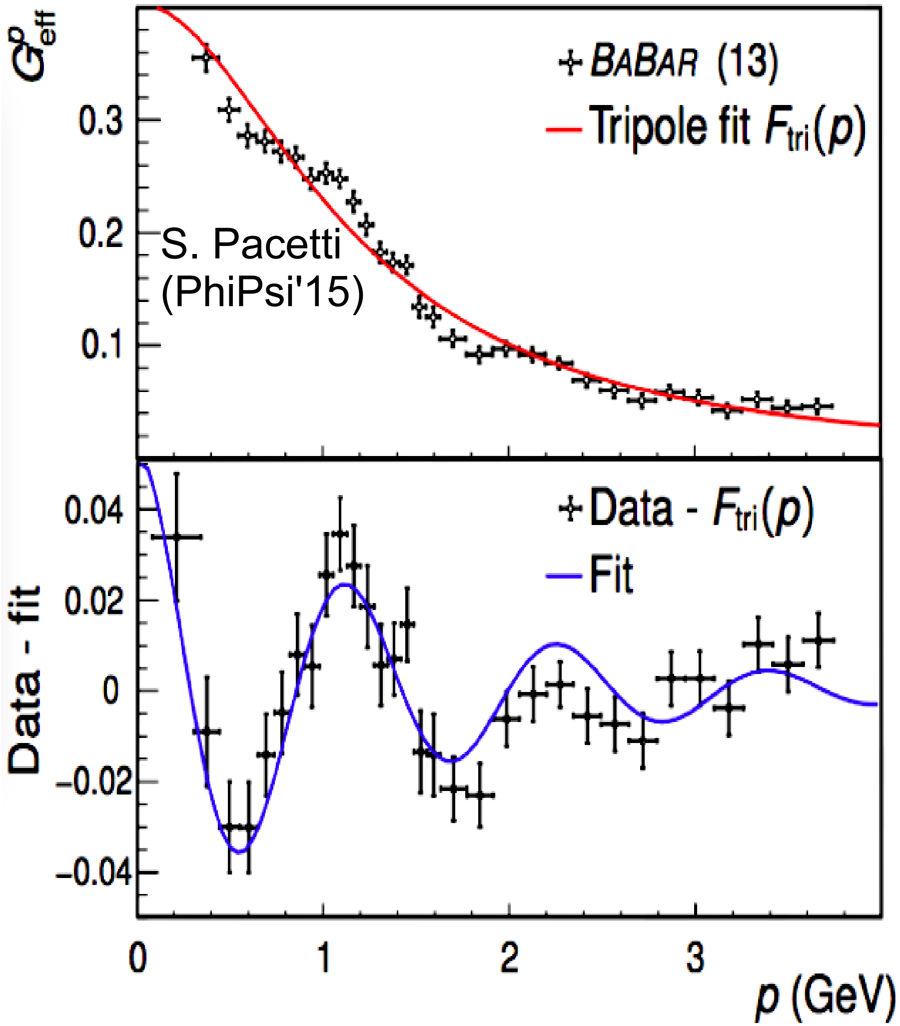
$$\frac{d\sigma^{1\gamma\otimes 2\gamma}}{d\Omega} = \cos\theta[c_0(M^2_{p\bar{p}}) + c_1(M^2_{p\bar{p}})\cos^2\theta + c_2(M^2_{p\bar{p}})\cos^4\theta + \ldots]$$

$$\mathcal{A}(\cos\theta, M_{p\bar{p}}) = \frac{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) - \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) + \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}$$

Also interference between ISR and FSR could cause an asymmetry!

Periodic interference near threshold

[Phys. Rev. Lett. 114, 232301]



$$F_{\text{oscl}}(p) = Ae^{-Bp}\cos(Cp + D)$$

A << 1 B damp. par.

C = r < 1 fm D thresh. shift

p = proton momentum in $\bar{p}$ rest frame

Periodical behavior suggests an interference due to **rescattering** of proton and antiproton at low kinetic energy and distance ~1fm

Proton and antiproton interact when they are almost phenomenological

Unitarity implies a large imaginary part of form factors

Prospects for $e^+e^- \to$ Hyperons

From 2015 scan full determination of lambda- FFs possible:

- Imaginary part of FFs leads to polarization observables:

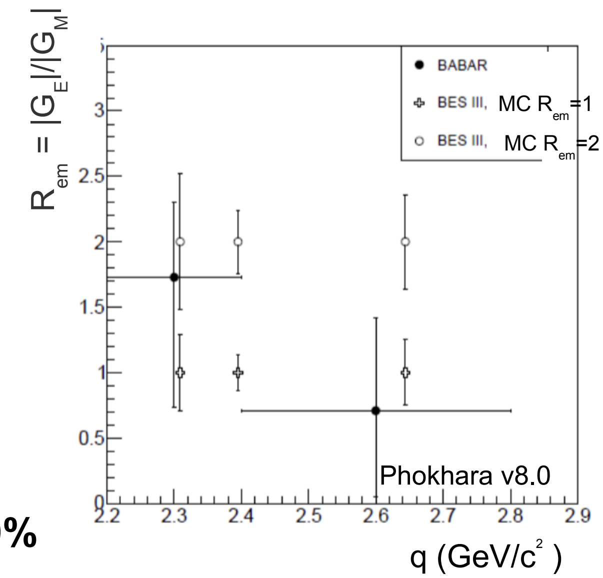
Parity violating decay: $\Lambda \to p\pi$

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

Θ_p : Angle between proton and polarization axis in Λ-CM

Θ_Λ: Λ polar angle in CM

Φ : 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%

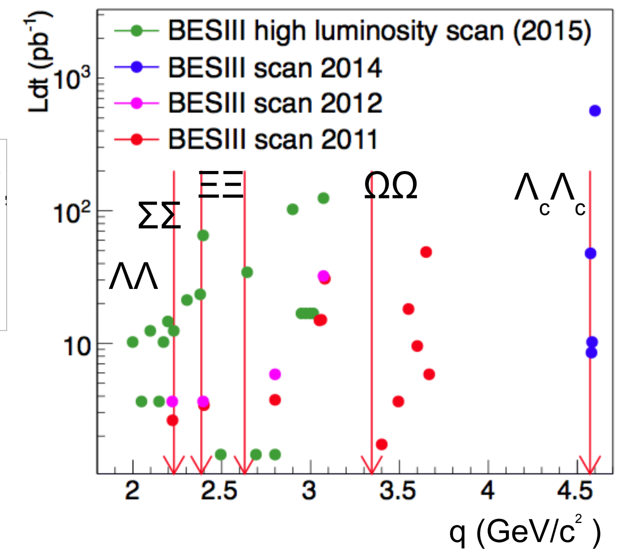
- Also available from threshold (2015, 2014, 2011 data):

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

measurements of effective FF and R_{em} , $|G_{E,M}|$ and P_n at single energy points possible

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

measurements of effective FF, R_{em} and $|G_{E,M}|$ at threshold possible



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