Baryon time-like form factors at BESIII

Monica Bertani
(on behalf of the BESIII Collaboration)
INFN, Laboratori Nazionali di Frascati

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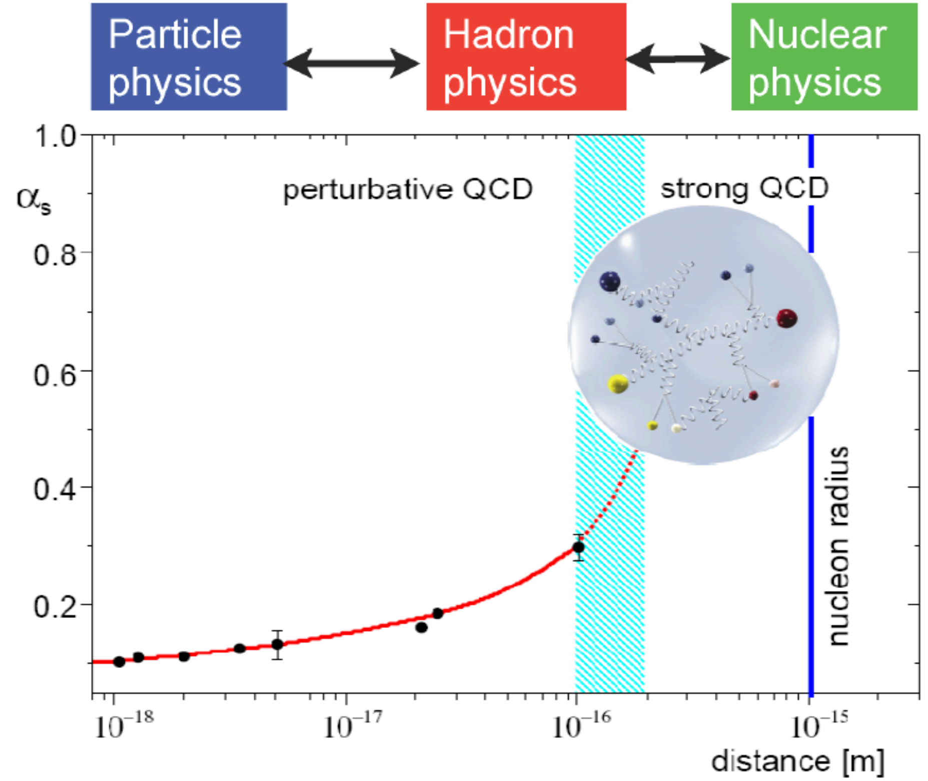
BARYON FORM FACTORS

- Fundamental properties of Baryons
  - Characterize the internal structure
  - Connected to charge and magnetization distributions
  - Playground for **theory** and **experiment:**
    - at low q^2 probe the size of the hadron
    - at high q^2 test QCD scaling

By a global analysis of scattering and annihilation experiments Form Factors can be extracted

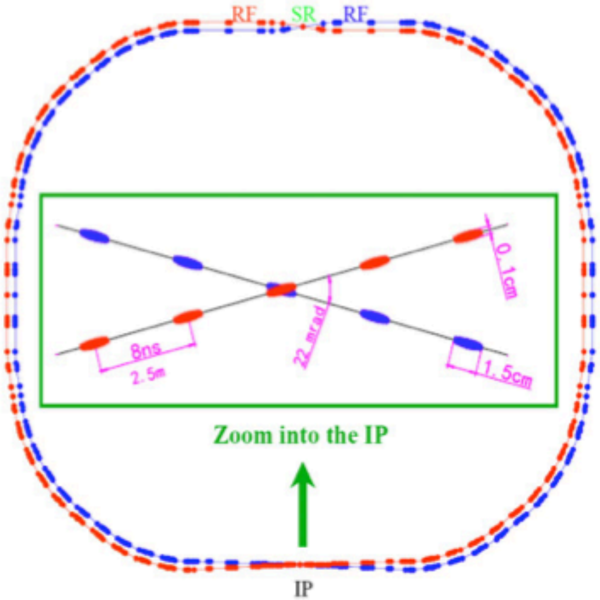


OUTLINE

- BEPCII and BESIII
- Electromagnetic form factors (FFs) formalism
- Measurement of the proton electromagnetic FFs with:
  - energy scan technique: $e^+e^- \rightarrow BB_{bar}$
  - Initial state radiation (ISR) technique: $e^+e^- \rightarrow BB_{bar}\gamma$
- Measurement of hyperon FFs: $e^+e^- \rightarrow \Lambda_c\Lambda_{c,bar}$, $\Lambda\Lambda_{bar}$
- Ongoing analysis on the measurement of baryon FFs at BESIII
- Summary

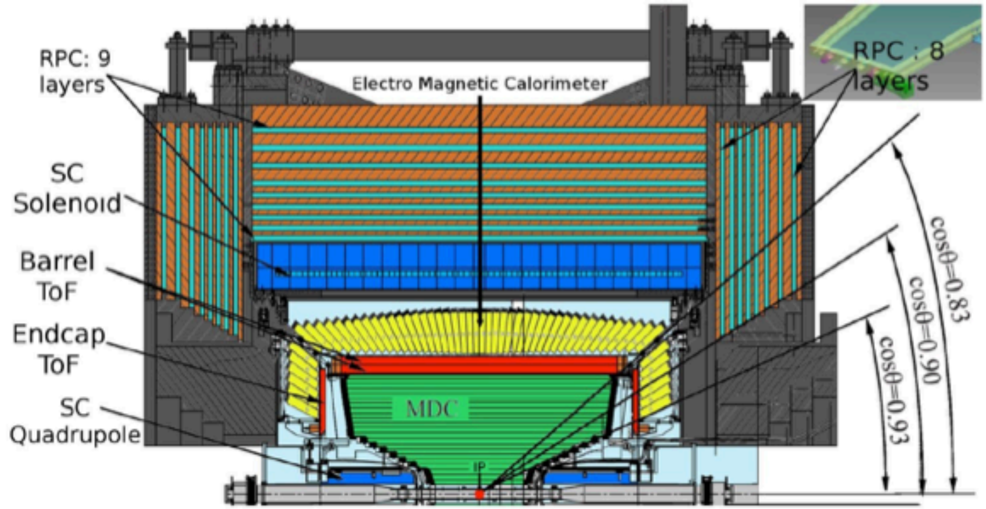
BEPCII and BESIII

Beijing Electron Positron Collider



- Symmetric e^+e^- collider
- Beam energy: 1.0 - 2.3 GeV
- Optimum energy: 1.89 GeV
- Design luminosity: 10^{33} cm^{-2} s^{-1}
- Crossing angle: 22 mrad

BESIII detector



Electromagnetic Calorimeter
$\sigma_E/\sqrt{E}(\%)$=2.5% (1 GeV),
(CsI) $\sigma_{z,\phi}$(cm)=0.5---0.7 cm/$\sqrt{E}$

Muon Counter
σ_{xy}<2 cm

1 Tesla
SC solenoid

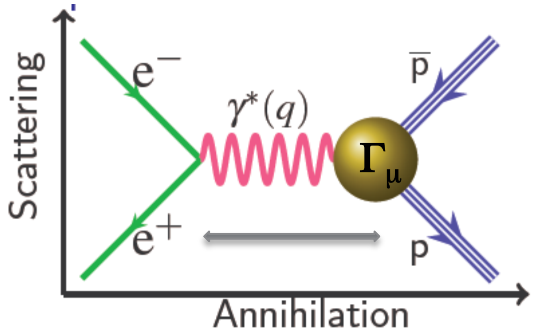
Time Of Flight
σ_T(barrel)=90 ps
σ_T(endcap)=110 ps

Main drif chamber
σ_{xy}=130μm, dE/dx≈6%
σ_p/p=0.5% at 1 GeV

c.m. energy range: 2 GeV- 4.6 GeV.

ELECTROMAGNETIC FORM FACTORS (FF)

- Spin ½ Baryons: two e.m. FFs



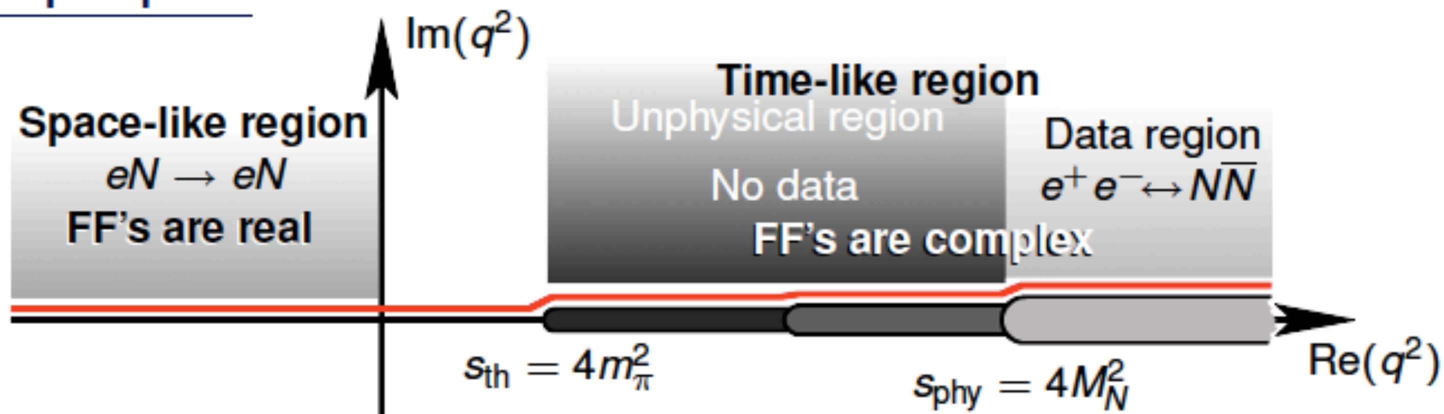
- The vertex Γ_μ contains the unknown structure, parametrized by F1 and F2:

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

- Sachs FFs:

$$\begin{cases} G_M(q^2) = F_1(q^2) + F_2(q^2) \\ G_E(q^2) = F_1(q^2) + \frac{q^2}{4M} F_2(q^2) \end{cases} \qquad \begin{cases} F_1(0) = Q, F_2(0) = k \\ G_M(0) = \mu, G_E(0) = Q \end{cases}$$

q^2-complex plane

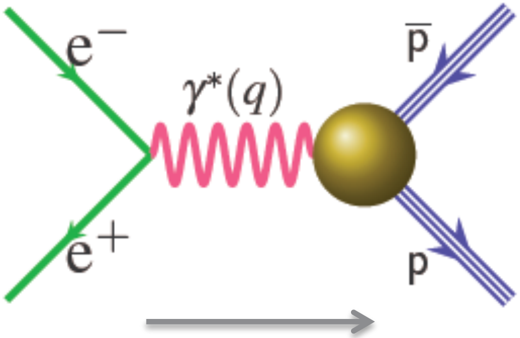


- Analyticity: $G_{E,M}(-\infty) = G_{E,M}(+\infty) \approx (q^2)^{-2}$ real FFs

$$G_E(4M^2) = G_M(4M^2)$$

EXPERIMENTAL ACCESS IN TIME-LIKE REGION

- Energy scan (direct annihilation): fixed q^2



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

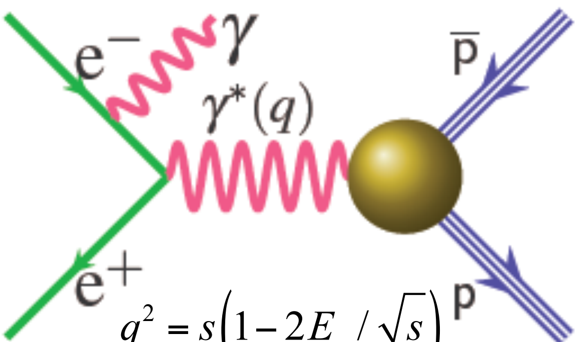
$$\sigma^{Born}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2}[|G_M(q^2)|^2 + \frac{2M^2}{q^2}|G_E(q^2)|^2]$$

$$C = \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(\pi\alpha/\beta)} \quad \text{charged B}$$

$$C = 1 \quad \text{neutral B}$$

$$k = \frac{g-2}{2}, g = \frac{\mu}{J}$$

- Initial State Radiation:



$$q^2 = s\left(1-2E_\gamma/\sqrt{s}\right)$$

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

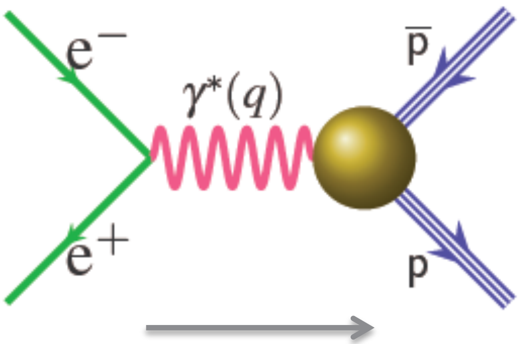
$$W^{LO}(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2}\right)$$

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

both techniques can be used at BESIII

EXPERIMENTAL ACCESS IN TIME-LIKE REGION

- Energy scan (direct annihilation): fixed q^2



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

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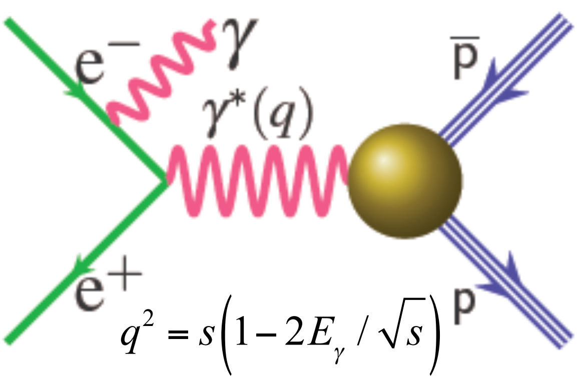
Effective FF: $|G| = \sqrt{\frac{\sigma^{Born}(q^2)}{(1+\frac{2M^2}{q^2})(\frac{4\pi\alpha^2\beta C}{3q^2})}}$

- Initial State Radiation:



$$\frac{d^2\sigma^{ISR}}{dx\,d\theta_\gamma} = -W(s,x,\theta_\gamma)\sigma^{Born}(q^2)$$

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

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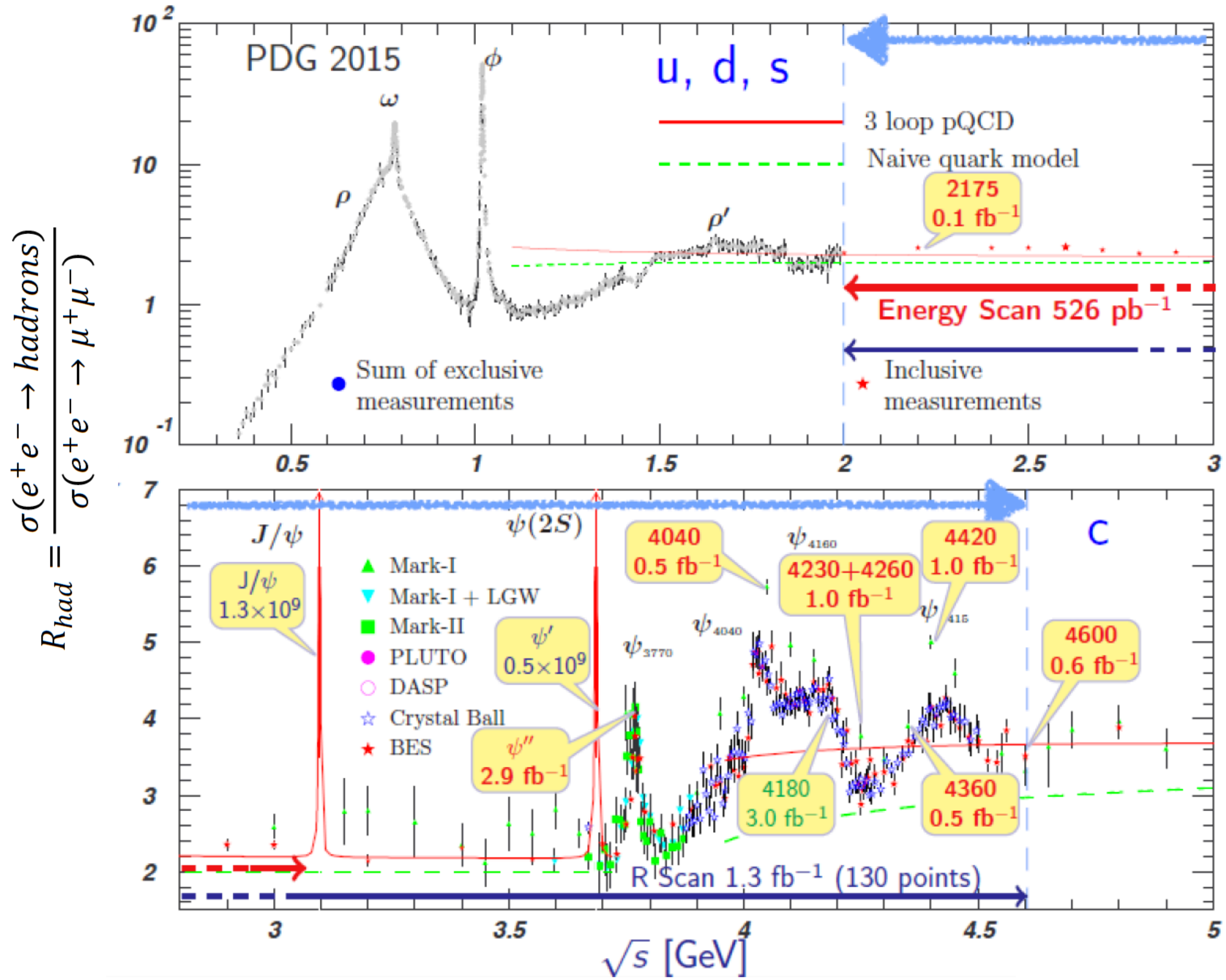
BESIII DATA SAMPLE



the world's largest dataset directly produced at e+e-

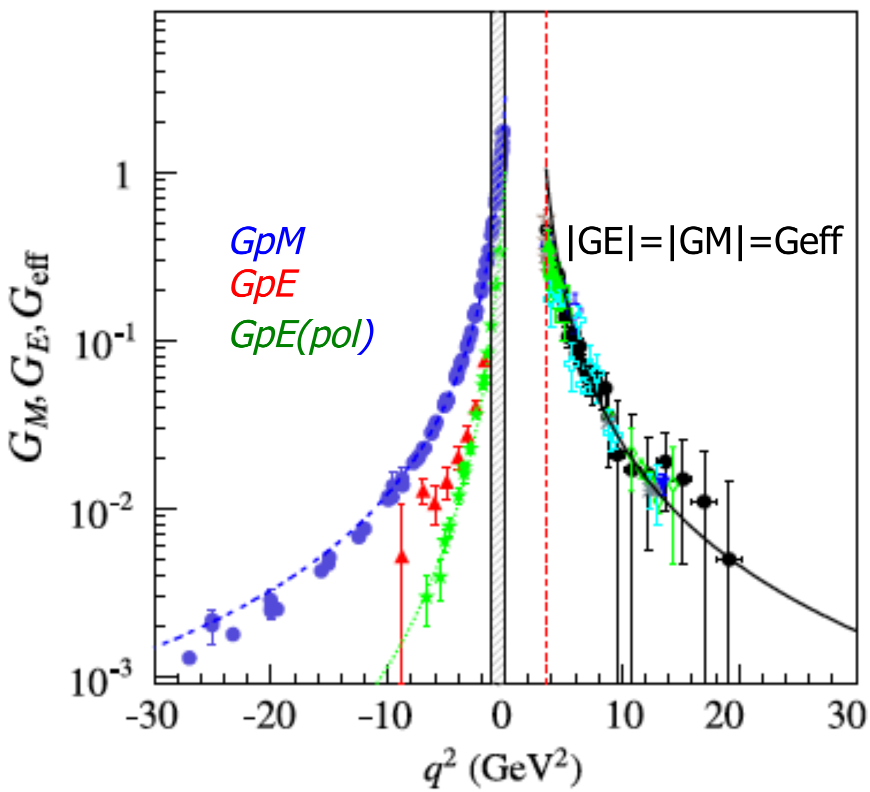
J/ψ , ψ(2S), ψ(3770), ψ(4180), Y(4260)

R-QCD studies, XYZ states

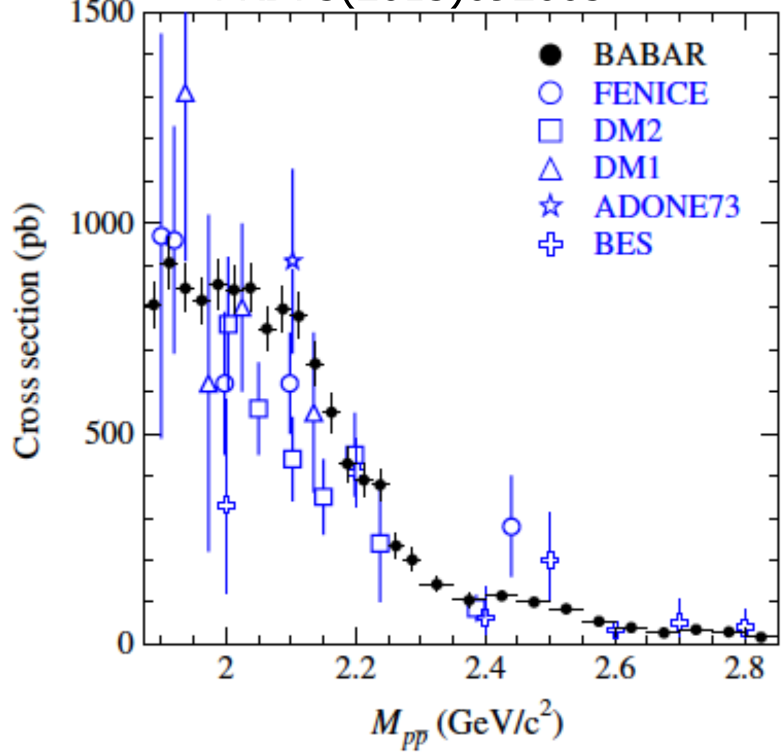
PROTON FORM FACTORS

PROTON SPACE-LIKE & TIME-LIKE FFs

S. Pacetti et al. / Physics Reports 550–551 (2015) 1–103



PRD73(2013)092005

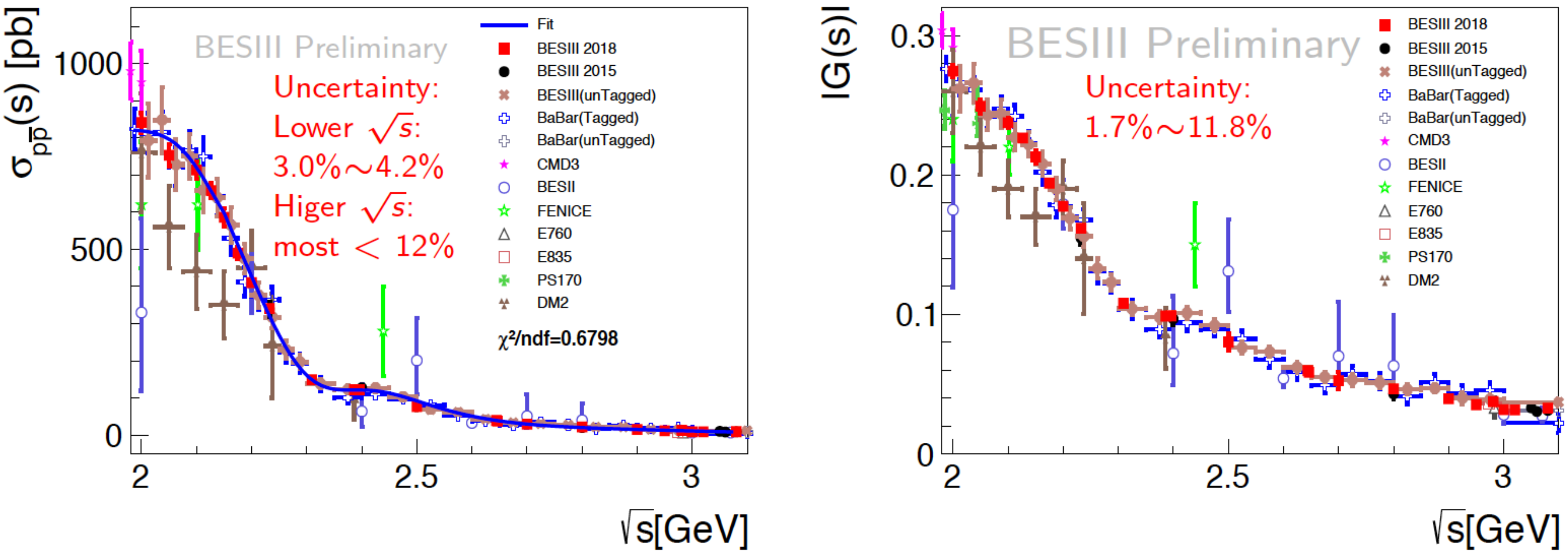


- Flat cross section near threshold followed by a step

$$\sigma_{p\bar{p}}(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\frac{\beta_p}{\beta_p}|G^p(4M_p^2)|^2 = 850\,|G^p(4M_p^2)|^2\ pb \Rightarrow \boxed{|G^p(4M_p^2)| = 1}$$

as point-like fermion pairs!
[EPJA39,315]

BESIII PRELIMINARY RESULTS



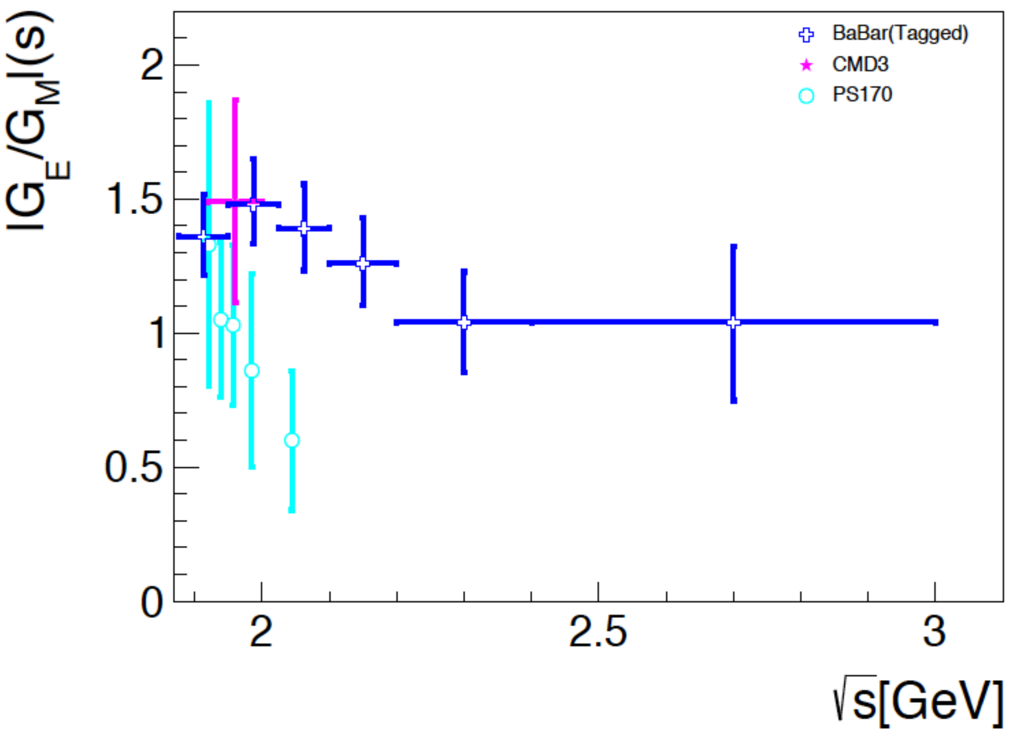
- Scan technique (black and red points):
  - 2012 data, 156.9 pb^{-1} [PRD 91, 112004 (2015)]
  - 2015 data, 688.5 pb^{-1} : preliminary results, improved precitions
- ISR technique (light brown points):
  - tagged (7.4 pb^{-1} above 3.773GeV), under reviewing
  - untagged (7.4 pb^{-1} above 3.773GeV): preliminary results

Results compatible with BABAR

G_E AND G_M RATIO

Extraction of the ratio R=|GE|/|GM| ratio from proton angular distribution

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



- Discrepancy between BaBar and PS170

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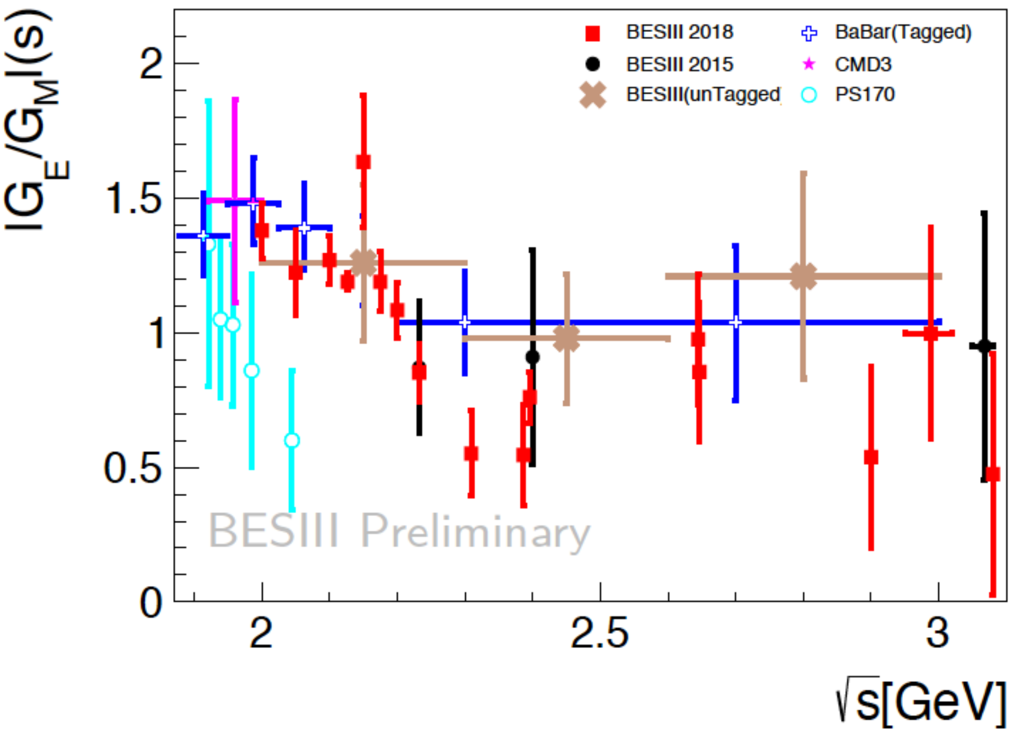
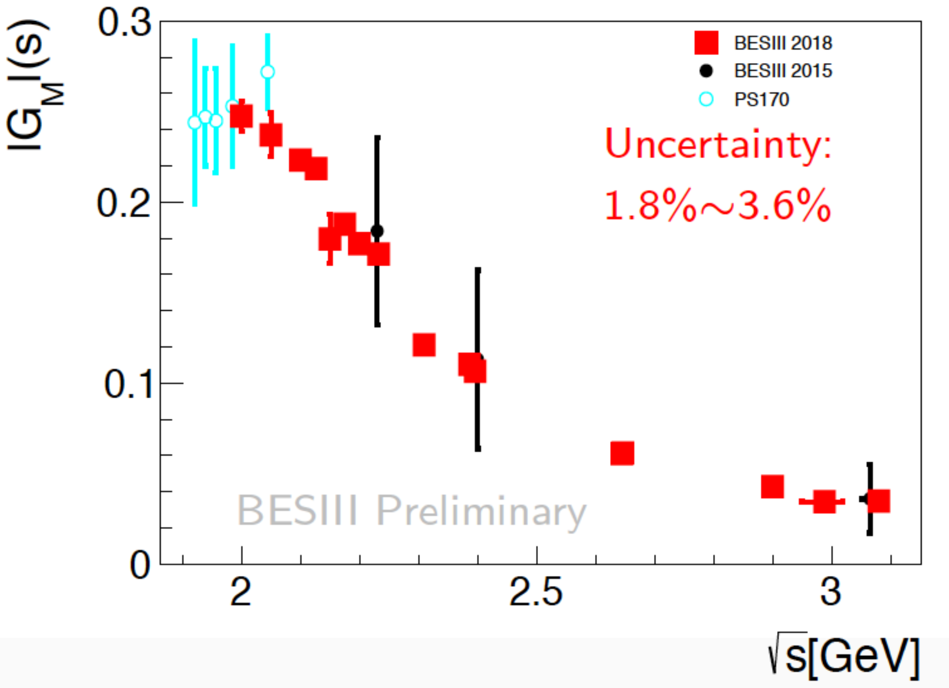


- Discrepancy between BaBar and PS170
- Tension with $R=|G_E|/G_M| = 1$ expectation

PRELIMINARY MEASUREMENT OF G_M

Extraction of the magnetic FF G_M:

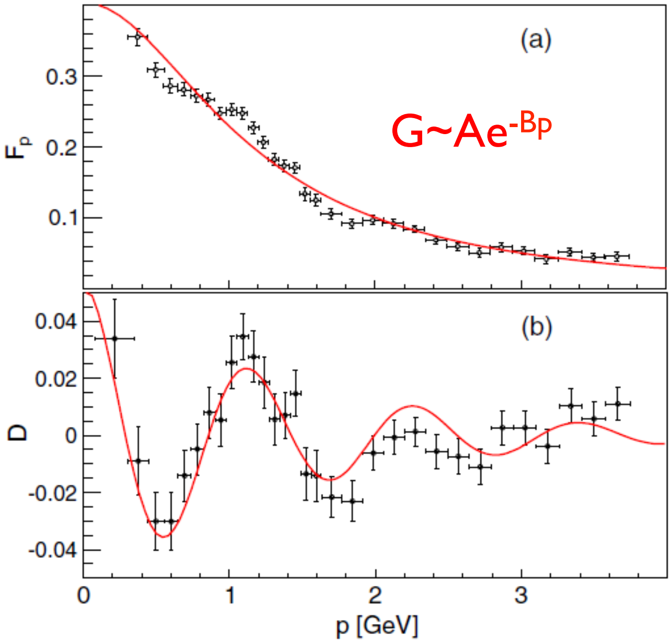
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}|G_M|^2[(1+\cos^2\theta) + \frac{|G_E|^2}{|G_M|^2}\cdot\frac{4M^2}{q^2}\sin^2\theta]$$

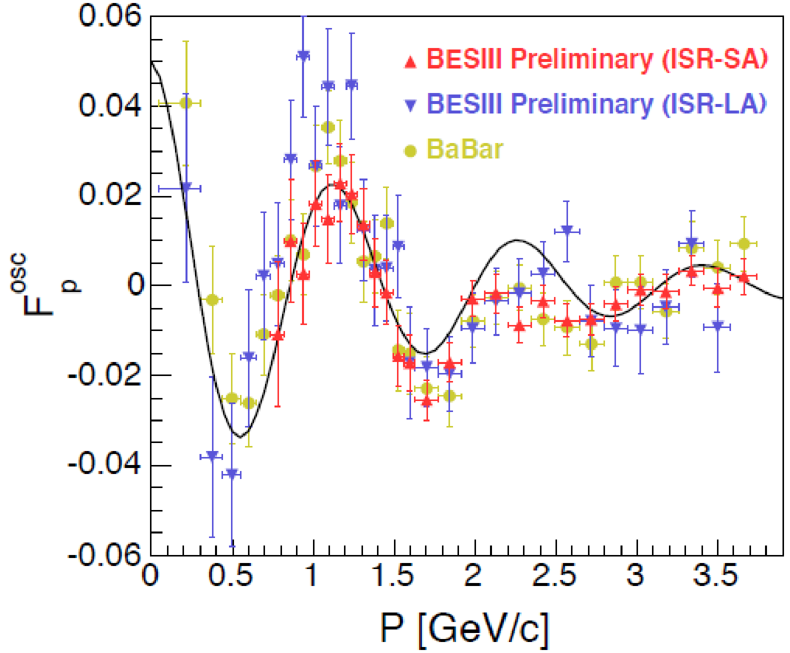


- few separate previous determinations of $|G_M|$
- great improvement with BESIII !

OSCILLATIONS IN PROTON FFs

[A. Bianconi, E. Tomasi-Gustafsson PRL114 (2015)232301, PRC93(2016)035201]





Periodic interference in F_p (e^+e^- -> pp_{bar}) first seen in BaBar data, confirmed in BESIII !

Oscillations due to re-scattering of p and pbar at ~1fm distance→large Imaginary part close to threshold

p=proton momentum in p rest frame

$D=F_{osc}$ =|Geff|-F0

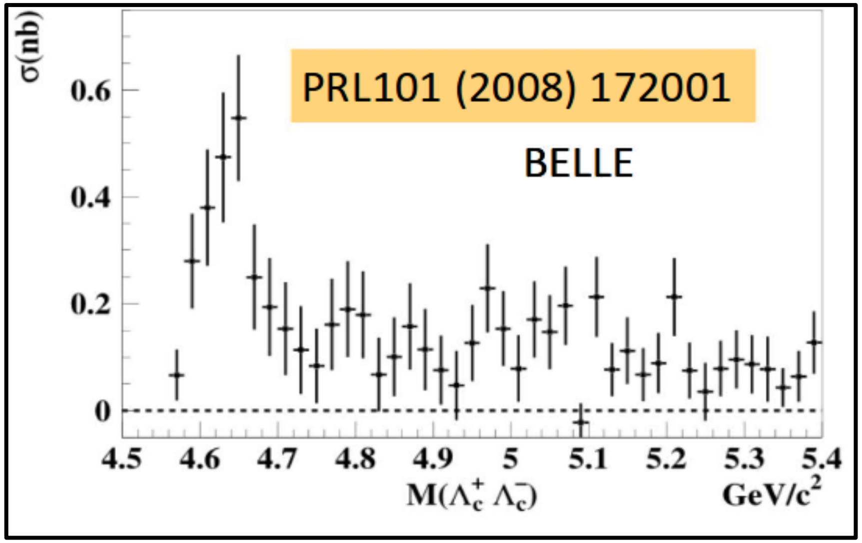
see Egle's talk !

$e^+e^- \rightarrow \Lambda_c\bar{\Lambda}_c$

MEASUREMENT OF $e^+e^- \to \Lambda_C\bar{\Lambda}_C$

Thanks to Λ_C weak decay $e^+e^- \to \Lambda_C\bar{\Lambda}_C$ can be detected with good efficiency even exactly at threshold

BELLE measurement has significant uncertainties:



- Y(4660) -> Λ_c Λ_{cbar} may be consistent with a hidden charm tetraquark (charmed baryonium) ?

[R. Faccini et al. arXiv:0911.2178(2017) , L. Maiani et al. Phys. Rev. D 72, 031502]

BESIII data set close to production threshold (+1.6MeV):

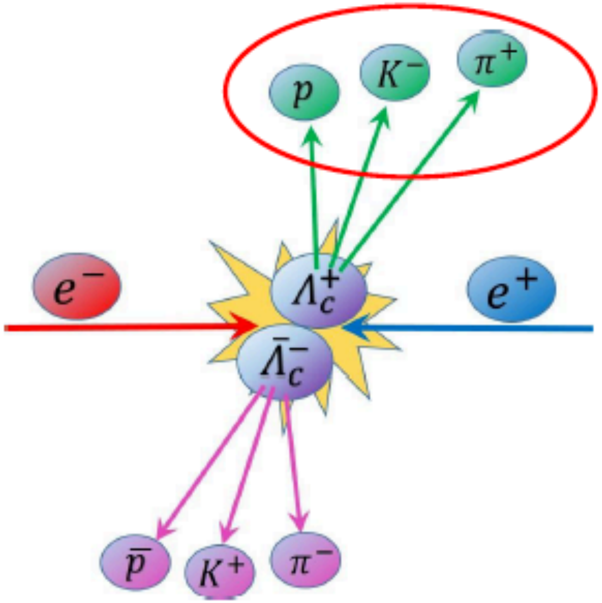
Energy (GeV)	Integrated lum. (pb^{-1})
4.5745	47.67
4.5800	8.54
4.5900	8.16
4.5995	566.93

[(PRL120 (2018) 132001]

BESIII MEASUREMENT OF $e^+e^- \rightarrow \Lambda_c\bar{\Lambda}_c$

Analysis method

Single Tag method:



- Only one of the baryon is reconstructed
- Energy difference:

$$\Delta E = E_{cand.} - E_{beam}$$

beam-constraint mass

$$M_{BC} = (E_{beam}^2 - p_{cand.}^2)^{1/2}$$

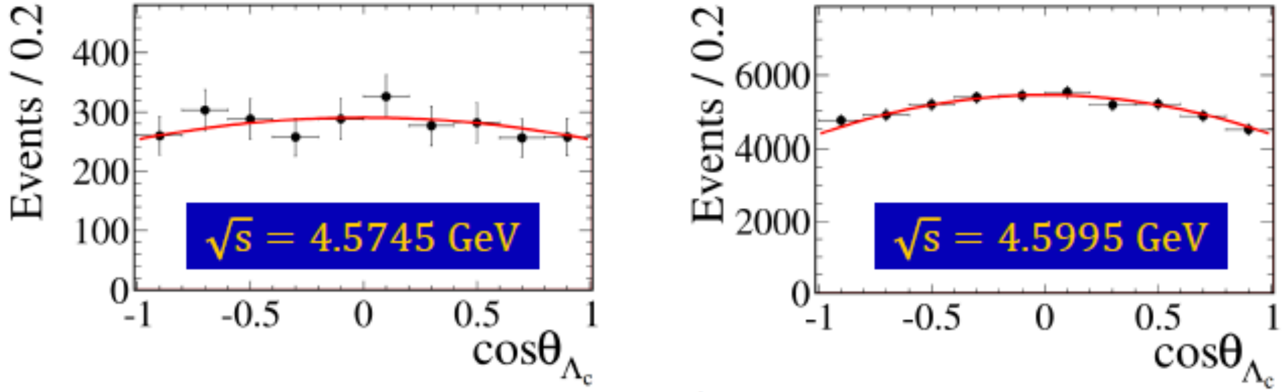
are used to extract the signals

- **10** Cabibbo-favored decay modes as well as corresponding charge-conjugate decay modes of Λ_c^+ are employed

[(PRL120 (2018) 132001]

BESIII MEASUREMENT OF $e^+e^- \rightarrow \Lambda_C\bar{\Lambda}_C$

Polar angle distribution



- Studied in center-of-mass system of $\Lambda_c^+\Lambda_c^-$
- Angle distribution is fitted by $1 + \alpha_{\Lambda_c} cos^2\theta$
- $|G_E/G_M|$ can be extracted from equation

$$|G_E/G_M|^2(1-\beta^2) = (1-\alpha_{\Lambda_c})/(1+\alpha_{\Lambda_c})$$

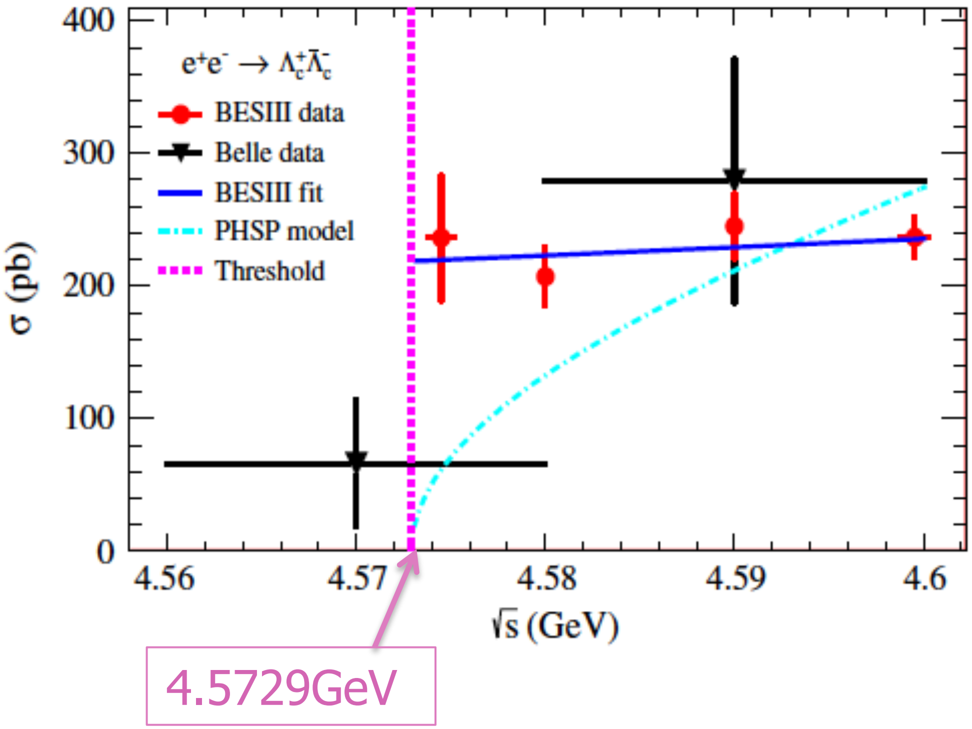
Only measured at two energy points due to the statistic limits

Energy (GeV)	$\lvert G_E/G_M \rvert$
4.5745	$1.14 \pm 0.14 \pm 0.07$
4.5995	$1.23 \pm 0.05 \pm 0.03$

[(PRL120 (2018) 132001]

$|G_E/G_M|$ measured for the first time by BESIII

CROSS SECTION OF $e^+e^- \to \Lambda_c\bar{\Lambda}_c$



- $\sigma(e^+ e^- \to \Lambda_c \bar{\Lambda}_c)$ behaviour similar to $\sigma(e^+ e^- \to p\bar{p})$:
  - Strong enhancement at threshold followed by a plateau
  - $\sigma(e^+ e^- \to \Lambda_c \bar{\Lambda}_c)$ close to the point-like value, once Coulomb factor is taken into account:

    $\sigma(e^+ e^- \to \Lambda_c \bar{\Lambda}_c)_{point} \approx \pi^2\alpha^3/(2M_B) \approx 145pb$
- Some tension between BELLE and BESIII at threshold, more data is needed at threshold and above 4.6 GeV

[(PRL120 (2018) 132001]

NEUTRAL BARYONS FORM FACTORS

NEUTRAL BARYONS ENERGY BEHAVIOUR AT THRESHOLD

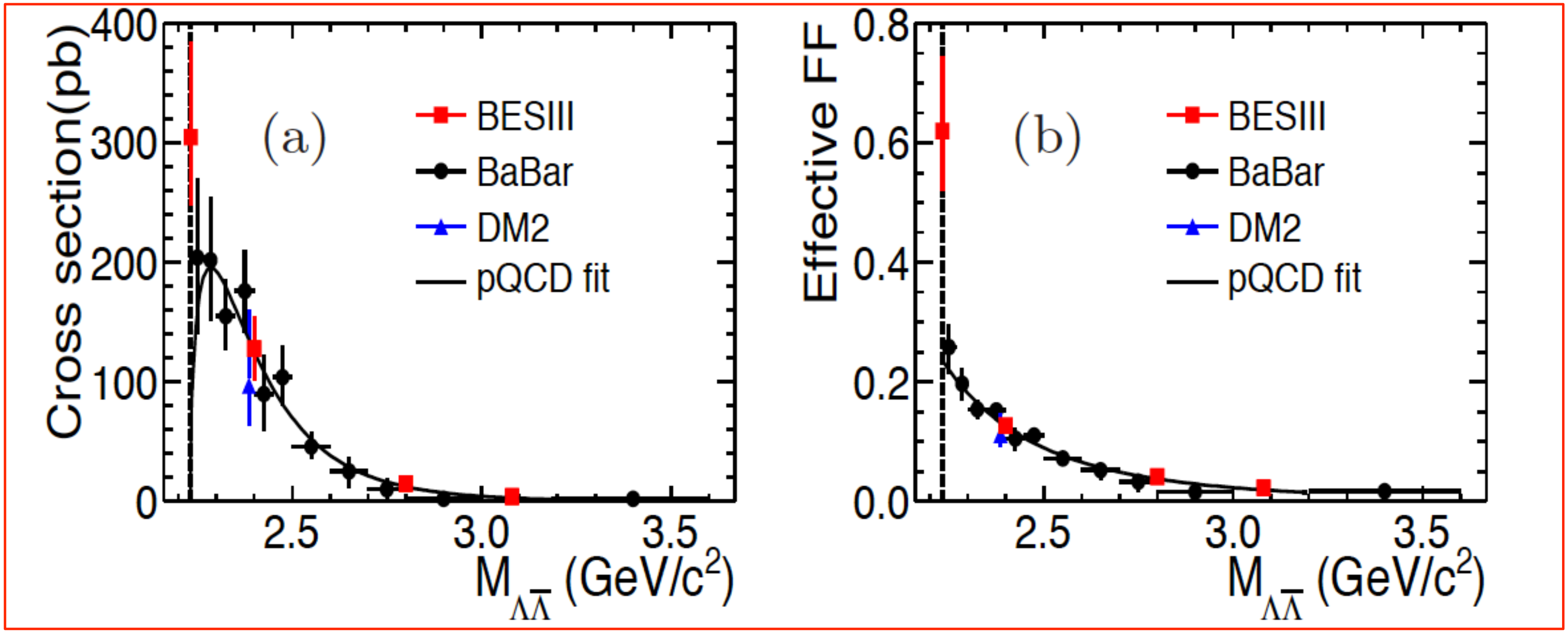
$$\sigma_{B^0\overline{B^0}}(q^2) = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q^2)|^2 + \frac{2M^2}{q^2}|G_E(q^2)|^2\right] \xrightarrow[q^2\to 4M^2]{} \frac{\pi\alpha^2\beta}{3q^2}|G|^2 \to 0$$

- NO Coulomb correction at hadronic level: C=1
  - σ -> 0 if β ->0
  - yet experimentally non zero σ are found

LAMBDA FORM FACTOR

- Only few measurements of σ ($e^+e^- \rightarrow \Lambda\bar{\Lambda}$) and Lambda Effective f.f.:
  - BaBar, DM2, very recently BESIII:

[(PRD92 (2015) 034018]



- Threshold enhancement: BESIII point only 1 MeV over threshold $M_{\Lambda\Lambda}$=2.2324 GeV: σ(e+e-→ΛΛbar)=(305+-45+66-36)pb , not zero !
- Away from threshold agreement between BESIII and BaBar points

LAMBDA FORM FACTOR

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

$\sqrt{s}$ (GeV)	Channel
2.2324	$\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$ $\bar{\Lambda} \to \bar{n}\pi^0$ combined
2.4000 2.8000 3.0800	$\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

- The Born cross section of $e^+e^- \to \Lambda\bar{\Lambda}$ is determined from:

$$\sigma^B = \frac{N_{obs}}{\mathcal{L}_{int} \cdot \varepsilon \cdot (1+\delta) \cdot \mathcal{B}}$$

The effective FF is defined by

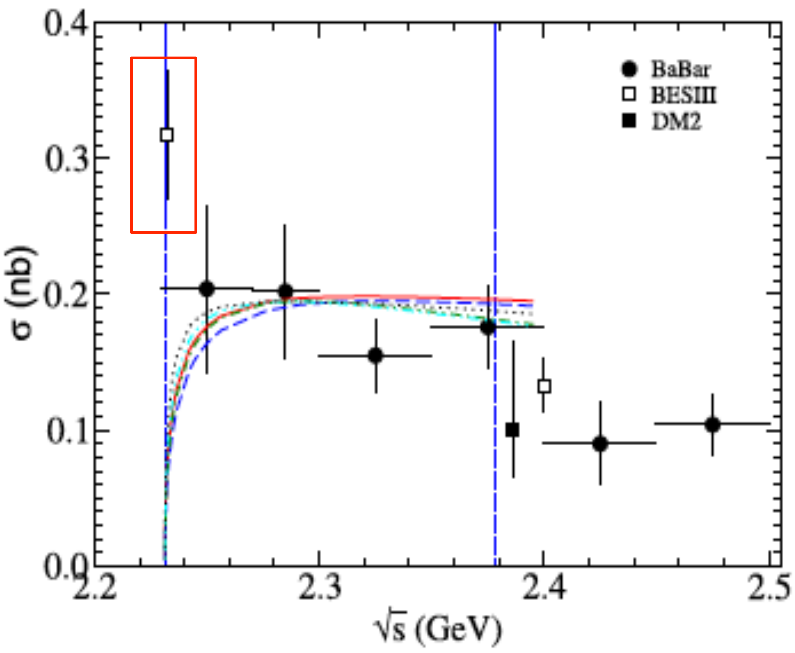
$$|G| = \sqrt{\frac{|G_M|^2 + 1/2\tau |G_E|^2}{1+1/2\tau}} = \sqrt{\frac{3s\sigma^B}{4\pi\alpha^2\beta} \cdot \frac{1}{1+1/2\tau}}$$

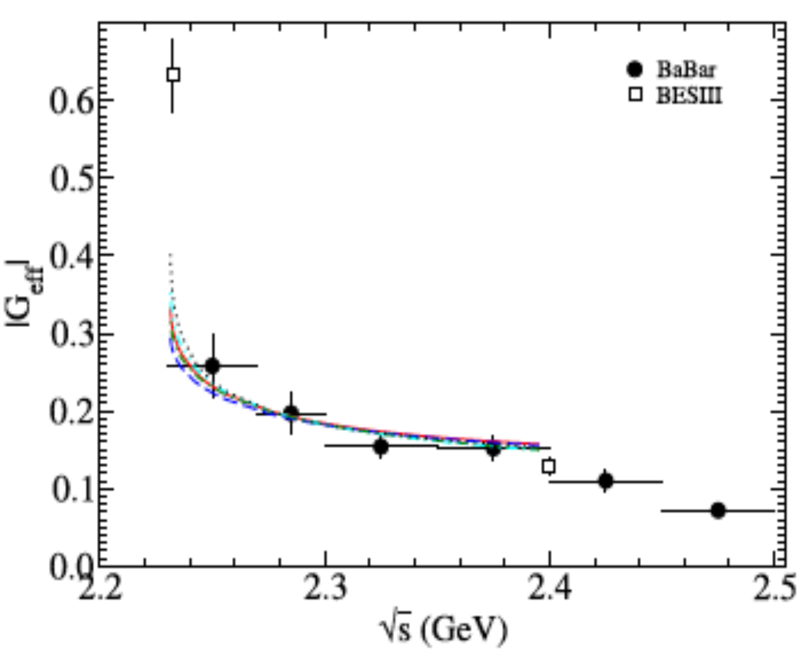
$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$N_{\rm obs}$	$\epsilon(1+\delta)$ (%)	σ^B (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)
2.2324_1	2.63	43 ± 7	12.9	$312 \pm 51^{+72}_{-45}$	
2.2324_2	2.63	22 ± 6	8.25	$288 \pm 96^{+64}_{-36}$	
2.2324_c				$305 \pm 45^{+66}_{-36}$	$61.9 \pm 4.6^{+18.1}_{-9.0}$
2.400	3.42	45 ± 7	25.3	$128 \pm 19 \pm 18$	$12.7 \pm 0.9 \pm 0.9$
2.800	3.75	8 ± 3	36.1	$14.8 \pm 5.2 \pm 1.9$	$4.10 \pm 0.72 \pm 0.26$
3.080	30.73	13 ± 4	24.5	$4.2 \pm 1.2 \pm 0.5$	$2.29 \pm 0.33 \pm 0.14$

LAMBDA FORM FACTOR

- Interactions in the final state of $\Lambda\bar{\Lambda}$ well reproduce BaBar data but not the first BESIII point near threshold.

J. Haidenbauer, U.-G. Meißner / Physics Letters B 761 (2016) 456–461





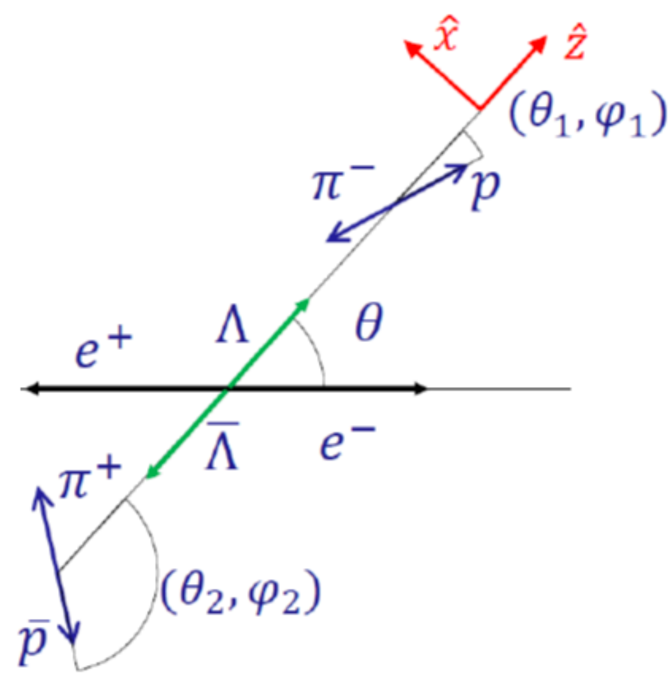
LAMBDA POLARIZATION OBSERVABLES

- With hyperons, polarization is experimentally observable by their weak Parity violating decay, polarization effects can be observed even if the initial e^+e^- state is unpolarized.
- Complex FFs and relative phase:
  - $G_M(q^2)=|G_M(q^2)|e^{i\Phi M}$, $G_E(q^2)=|G_E(q^2)|e^{i\Phi E}$
  - $\Delta\Phi = \Phi_E - \Phi_M$
- $\Delta\Phi$ can be obtained from angular distribution of daughter baryon from Λ weak decay
- 2015 scan data sample: E_{cm}=2.369, 66.9 pb^{-1}
- Multidimensional formalism developed * to extract G_E and G_M from the decay distribution

$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda \mathbf{P_y} \cdot \hat{\mathbf{q}},$$

$\alpha_{\Lambda:}$ asymmetry parameter,

$\hat{\mathbf{q}}$: unit vector along daughter baryon



*PLB 772 (2017) 16.

- Until now, no conclusive phase measurement exists !

RELATIVE PHASE MEASUREMENT

- Result:
  - $R = \mathbf{0.94 \pm 0.16 \pm 0.03}\ (\pm 0.02\ \alpha_\Lambda)$
  - $\Delta\Phi = \mathbf{42^o \pm 16^o \pm 8^o}\ (\pm 6^o\ \alpha_\Lambda)$

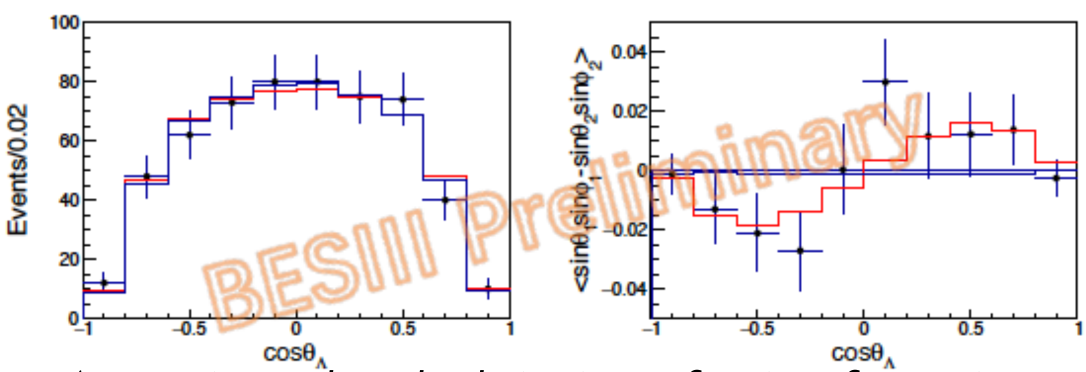
←**BES III PRELIMINARY**
@ E_{cm}=2.369

- Most **precise** result on *R*

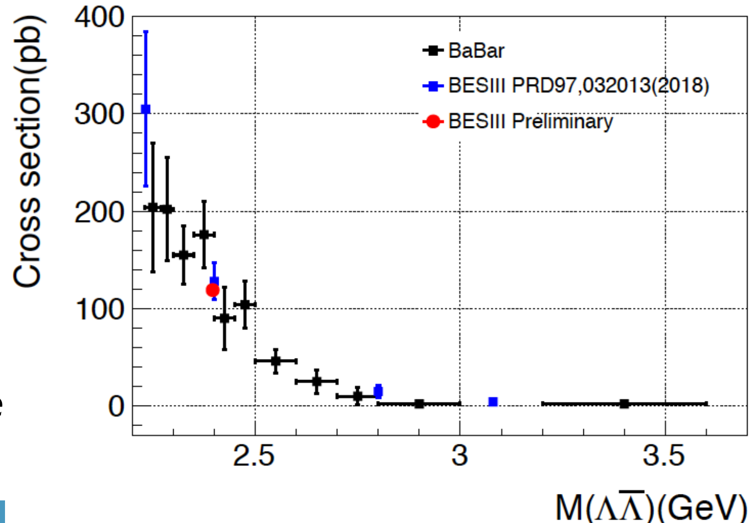
  (BaBar: $R = 1.73^{+0.99}_{-0.57}$ in $2.23 < q < 2.40$ GeV*)

- **First** conclusive result on $\Delta\Phi$

  (BaBar: $-0.76 < sin\Delta\Phi < 0.98$ in $2.23 < q < 2.80$ GeV*)



Λ scattering angle and polarization as function of scattering angle

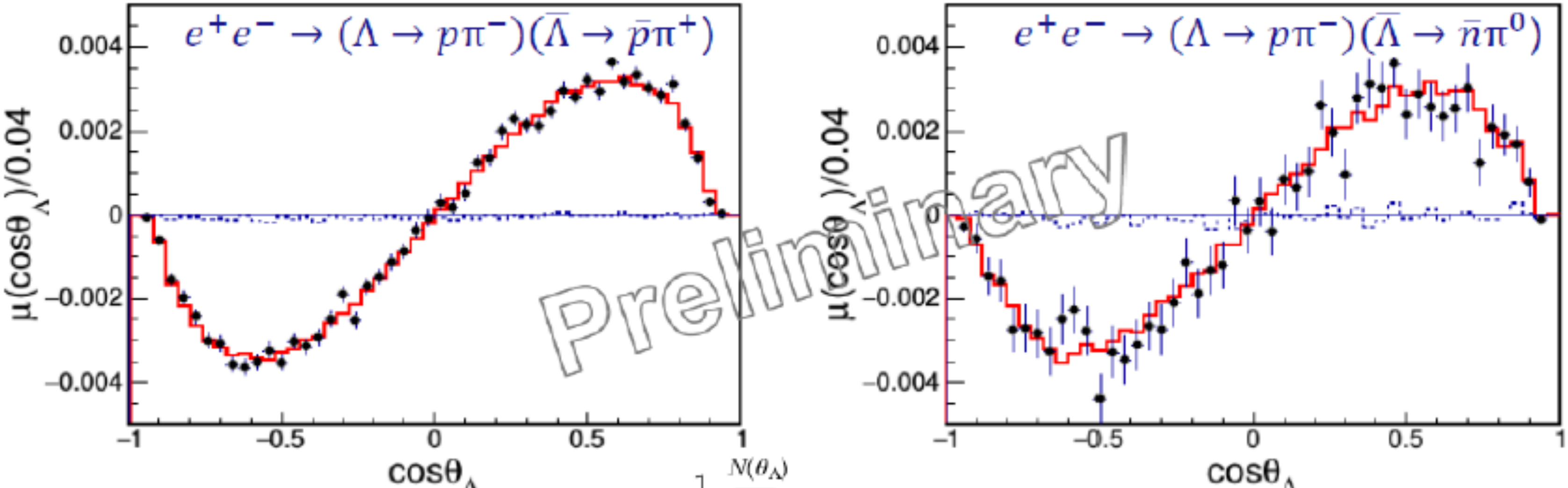


First time measurement of $\Delta\Phi$ for any baryon !

LAMBDA POLARIZATION MEASUREMENT
[arXiv:1808.08917v1]

- Using a large data of J/ψ collected by BESIII:
  - J/ψ → $\Lambda\bar{\Lambda}$
  - α_Λ=0.75 instead of 0.64 (PDG): 5σ deviations, affecting Δϕ results !
- Δϕ result at J/ψ is consistent and improves 2.369MeV finding:

ΔΦ=42.3°±0.6°±0.5°

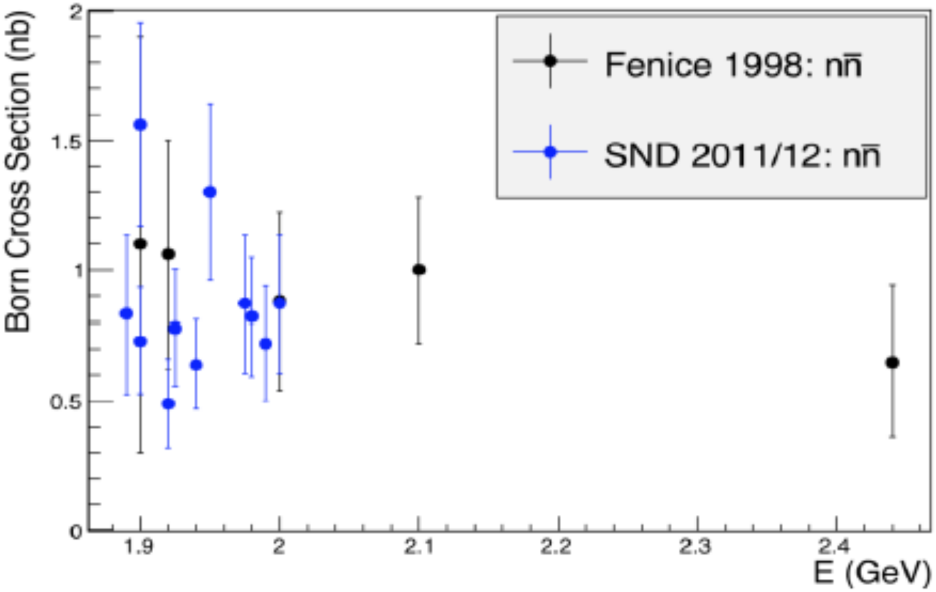


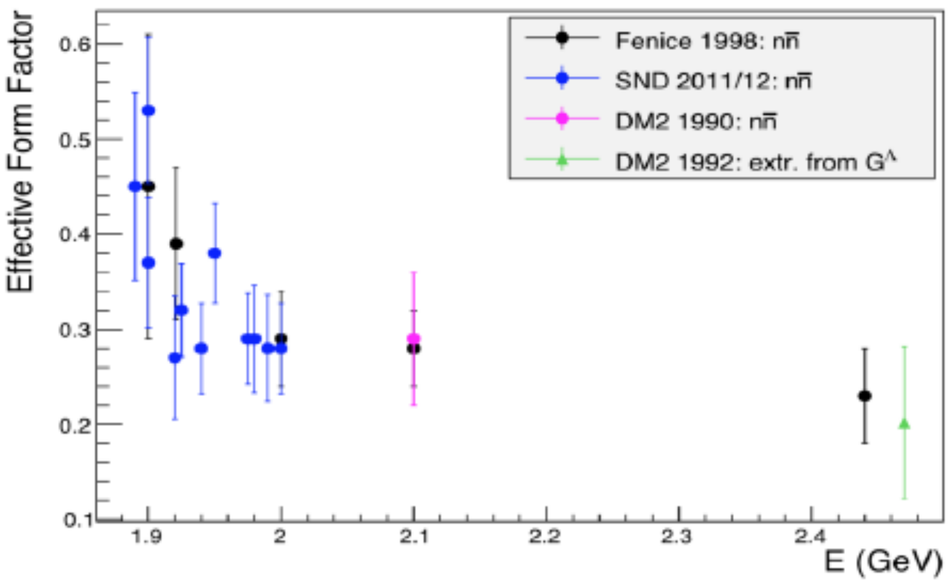
$$\mu(\cos\theta_\Lambda) = \frac{1}{N}\sum_i^{N(\theta_\Lambda)} (\sin\theta_1^i \sin\phi_1^i - \sin\theta_2^i \sin\phi_2^i)$$

First time measurement of ΔΦ for any baryon !

NEUTRON F.F.

- Only two direct measurements of σ (e+e- → $n\bar{n}$) and neutron Effective f.f.
- Large errors (30%)



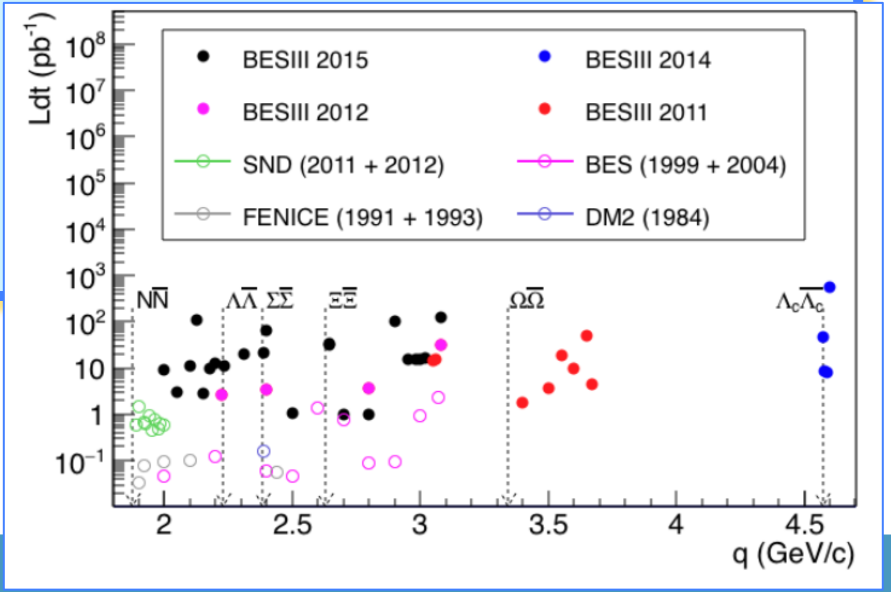


- No measurement of $R=|G_E/G_M|$ or $|G_E|$ and $|G_M|$
- q<2GeV σ (e+e- → nnbar) ≈σ (e+e- → ppbar)
- Non vanishing cross section at threshold ?
- |Gn| > |Gp| as q increases (pQCD: |Gp|≈: |Gn|)

BESIII has new, precise results, under internal review, stay tuned !

CONCLUSIONS AND PERSPECTIVES

- ✓ BESIII is an excellent laboratory for Baryon FFs measurement in the time-like region
- ✓ Present theory is missing something
- ✓ Proton FFs extracted with energy scan data and ISR analysis at resonances
- ✓ Λ, Λ_C FFs close to threshold, intriguing enhancement observed
- ✓ First measurement ever of the relative phase between Electric and Magnetic FFs
- ✓ More data on tape is being analyzed
- ✓ Neutron FFs results will soon be public
- ✓ Possibly higher energy data in the future



Thank you !