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Baryon form factors at BESIII

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16th Conference on Flavor Physics and CP Violation (FCPC 2018)

July 14th 2018, Indian Institute of Technology Hyderabad and University of Hyderabad, Hyderabad, India

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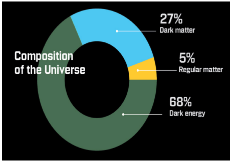
Preamble

- Baryon mass is the main component of the mass of the universe. It comes from the strong force, not from the Higgs mechanism. (K.Huang, Story of Gauge Fields, 2007, F. Wilczeck, A beautiful question, 2016).



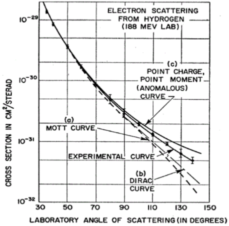
- Baryons, what they really are, is far from being understood.
- Many meson features come from QED to QCD, once $\alpha \to \alpha_s$. Baryon: no analogue in QED and unique QCD feature.
- For instance:
  - ✓ A fermion with mass, magnetic moment and other parameters close to proton and neutron ones can be obtained as a soliton of a π point-like boson field, by means of a non linear Lagrangian with one free parameter only (**Skyrme model**, Proc. Roy. Soc. **A 260**, (1961), 127)!
  - ✓ The baryon spin is not due to the spins of the valence quarks (**Proton Spin Crisis**, PLB **206**, 364, (1988))!
- Therefore it is meaningful to point out open questions, concerning baryon structure.

Nucleon Electromagnetic Form Factor

- Elastic scattering of electron and proton (Phys. Rev. **98**, 217 R. Hofstadter, Nobel Prize 1961).
  - ✓ Theoretically, differential cross section is:

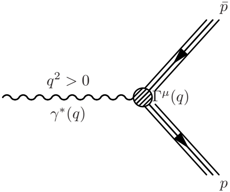
$$(\frac{d\sigma}{d\Omega})_{ep} = (\frac{d\sigma}{d\Omega})_{Mott}(1 + 2\tau tan^2\frac{\theta}{2})F(q^2)$$

  - ✓ The deviation represents the effect of a form factor (FF) for the proton.



- The nucleon electromagnetic vertex Γ_μ describing the hadron current:

$$\Gamma_\mu(p', p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p}F_2(q^2)$$



- Sachs FFs:

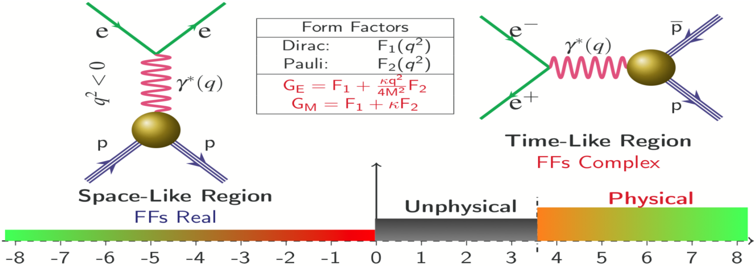
$$ElectronFF : G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$$
$$MagnetFF : G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$$

where $\tau = \frac{q^2}{4m^2}$, $\kappa = \frac{g-2}{2}$ and $g = \frac{\mu}{J}$

- In the Breit frame:
  Nucleon spin flip: G_M,
  non spin flip: G_E

Nucleon Electromagnetic Form Factor

- Measurement of baryon FF: Space-like (SL) and Time-like (TL).



- TL process includes energy scan and initial state radiation (ISR), both techniques can be used at BESIII.

	Energy scan	Initial state radiation
E_{beam}	discrete	fixed
$\mathcal{L}$	Low at each beam energy	High at one beam energy
σ	$\frac{d\sigma_{p\bar{p}}}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}[\lvert G_M\rvert^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}\lvert G_E\rvert^2\sin^2\theta]$	$\frac{d\sigma_{p\bar{p}\gamma}}{dq^2 d\theta_\gamma} = \frac{1}{s}W(s,x,\theta_\gamma)\sigma_{p\bar{p}}(q^2)$ $W(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2}\right)$ $\sim \frac{1}{400}$
q^2	Single at each beam energy	From threshold to s

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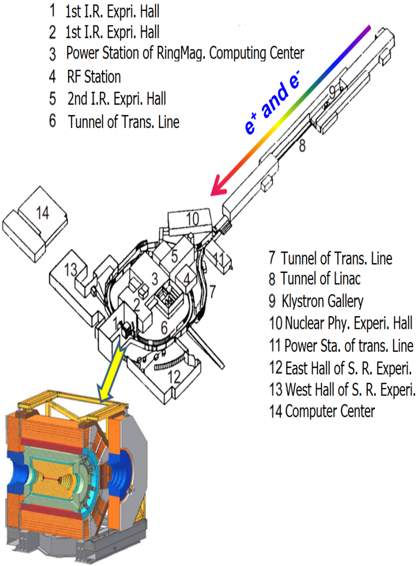
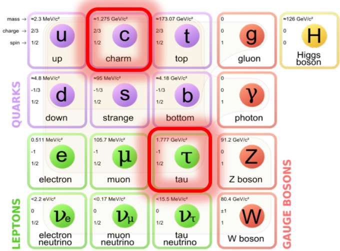
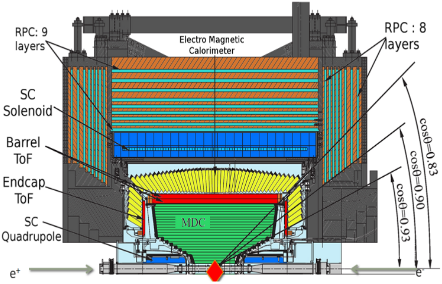
Beijing Electron Positron Collider II



- E_{beam}: 1.0∼2.3 GeV;
- Double storage ring: e^+ and e^-;
- No. of bunches: 93;
- Luminosity: 1.0×10^{33} cm^{-2}s^{-1} @3770MeV

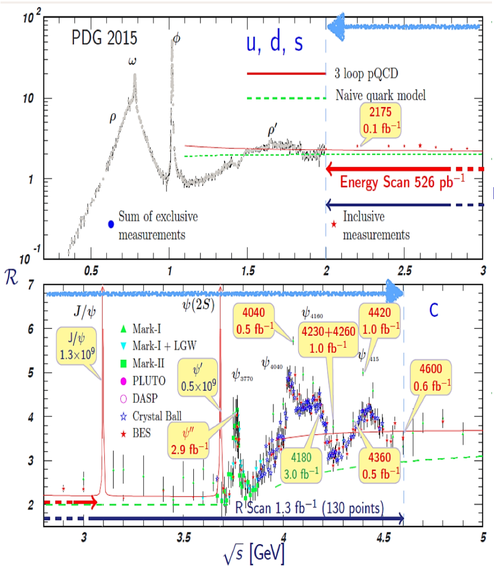


BEijing Spectrometer III



- Main Drift Chamber (MDC): (He/C_3H_8=60/40)
  - $\sigma_{xy}\approx130\mu$m, $dE/dx \sim$6%;
  - $\sigma_p/p\approx$0.5% at 1 GeV.
- Time Of Flight (TOF): (plastic scintillator)
  - σ_{time}(barrel)$\approx$80 ps,
  - σ_{time}(endcap)$\approx$65 ps.
- ElectroMagnetic Calorimeter (EMC): (CsI(Tl))
  - σ_E/E(barrel)$\approx$2.5% at 1 GeV,
  - σ_E/E(endcap)$\approx$5% at 1 GeV.
- Superconducting Magnet: B =1T.
- Muon Counter: Resistive Plate Chambers (RPC):
  - barrel: 9 layers;
  - endcap: 8 layers.
  - $\sigma_{spatial}$=2 cm.

Data set



- World largest data for
  - Charmonium spectroscopy
  - Charm physics
  - τ and R-QCD physics
  - Light hadrons
  - New physics research

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Measurement of proton form factor on BESIII

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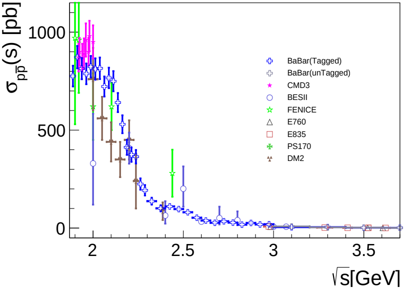

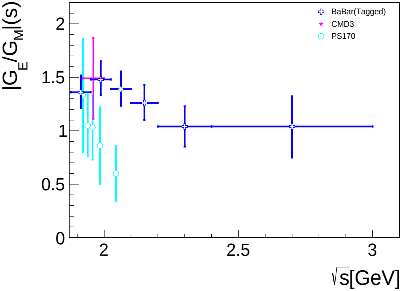

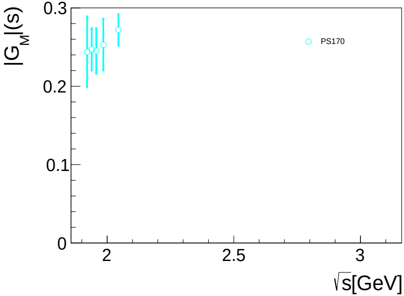

Measurement of proton form factor on BESIII

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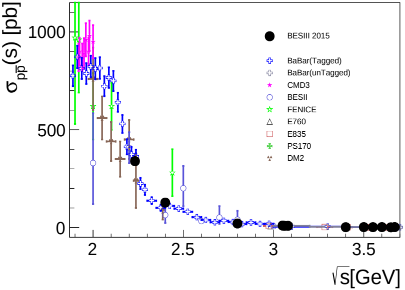
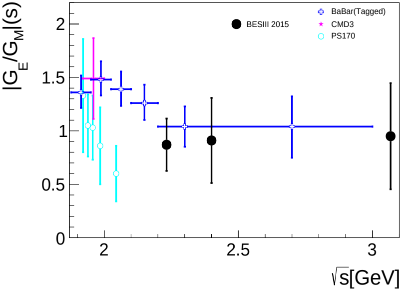
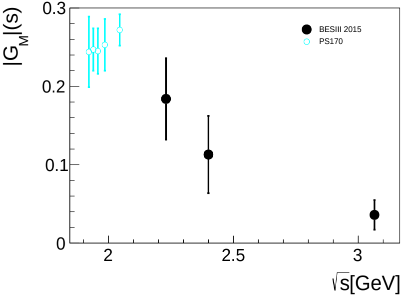
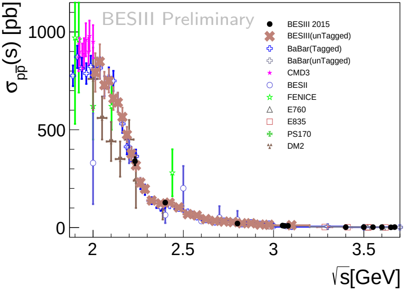


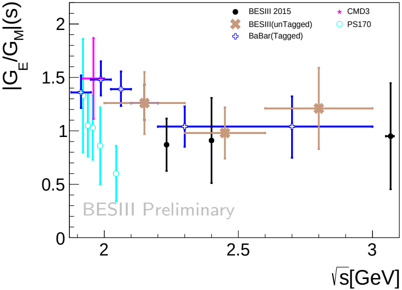


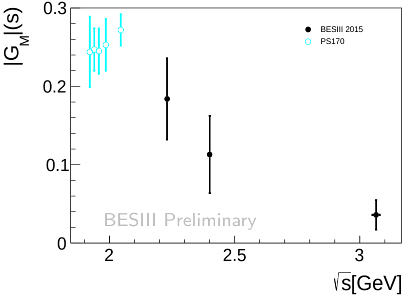


- Energy scan technique:
  - 2012 data, 156.9 pb^{-1}: PRD **91**, 112004 (2015).

Measurement of proton form factor on BESIII







- Energy scan technique:
  - 2012 data, 156.9 pb^{-1}: PRD **91**, 112004 (2015).
- ISR techniques:
  - Untagged (7.4 fb^{-1} above 3.773 GeV): preliminary results.

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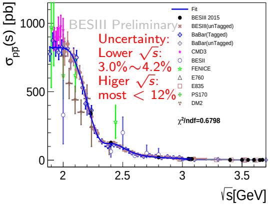
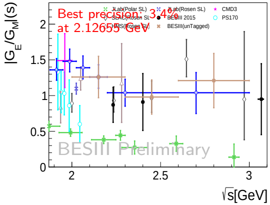
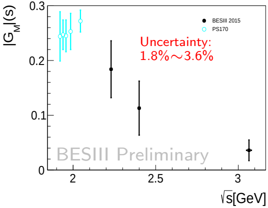






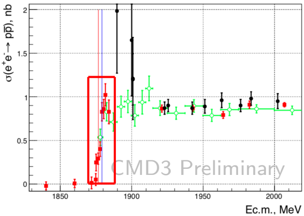
- Energy scan technique:
  - 2012 data, 156.9 pb^{-1}: PRD **91**, 112004 (2015).
  - 2015 R-scan data, 688.5 pb^{-1}: under reviewing.
- ISR techniques:
  - Tagged (7.4 fb^{-1} above 3.773 GeV): under reviewing.
  - Untagged (7.4 fb^{-1} above 3.773 GeV): preliminary results.
- Precision: Improved!

  In TL region, our results are unprecedented precision.

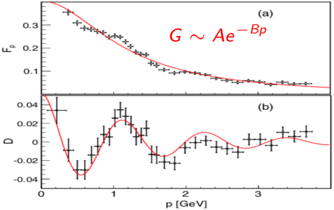
  Especially $|G_E/G_M|$ providing an uncertainty comparable to the SL region for the first time.

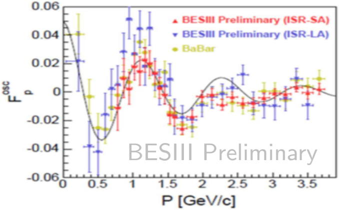
Some unexpected features are proved

- A step in the cross section is very likely due to Coulomb, since in the Coulomb factor there is a factor $1/\beta$ that cancels the factor beta in the cross section formula and produces a step.



- Andrea Bianconi and Egle Tomasi-Gustafsson PRL **114**, 232301 (2015) discovered the oscillations in effective FF (|G|) from BaBar PRD **87**, 092005 (2013) and PRD **88**, 072009 (2013), which was confirmed by BESIII.

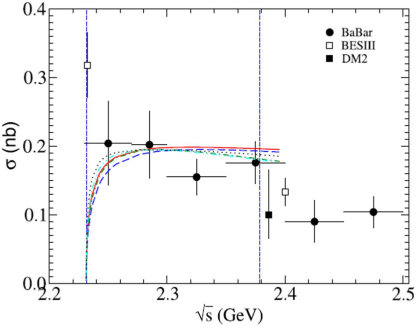




- Plateau above threshold, corresponding to |G| close to 1, like a point-like fermion, similar features is also shown $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$.

Measurement of Λ cross section on BESIII

- 2012 data, 2.63 pb^{-1}, PRD **97**, 032013 (2018).
- Neutral baryon: no Coulomb, but again a step at threshold!
- The observed threshold enhancement implies a more complicated underlying physics scenario.
- The Coulomb Enhancement Factor $C(s) = \frac{\pi\alpha}{\beta(s)} \frac{1}{1-e^{\frac{\pi\alpha}{\beta(s)}}}$, cancel the β for a charged $B\bar{B}$ pair, equals to 1 for a neutral $B\bar{B}$ pair.



- Recalling the baryon pair production cross section:

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

- Help to understand the mechanism of baryon production and test the theory hypotheses based on the threshold enhancement effect.

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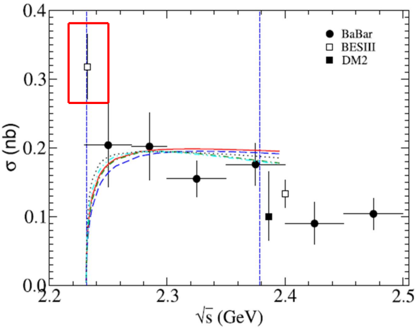

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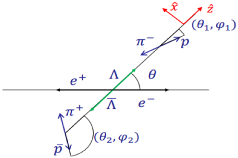
$$\sigma_{B\bar{B}}(s) = \frac{4\pi\alpha^2\beta(s)C(s)}{3s}[|G_M(s)|^2 + \frac{2m_p^2}{s}|G_E(s)|^2]$$

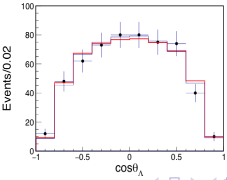
- Help to understand the mechanism of baryon production and test the theory hypotheses based on the threshold enhancement effect.

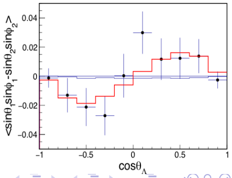
Measurement of Λ G_E/G_M phase on BESIII

- 2015 data, 66.9 pb^{-1}, preliminary result.
- Complex form of FFs:
  - $G_E = |G_E| e^{i\phi_E}$, $G_M = |G_M| e^{i\phi_M}$
  - Relative phase: $\Delta\phi = \phi_E - \phi_M$



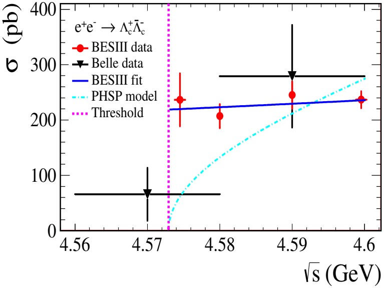
- A non-zero phase has polarization effect on the Baryons: $P_y \propto \sin\Delta\phi$
- With hyperon weak decay to $B + P$, the polarization of hyperon can be measurement, so does the relative phase between G_E and G_M!
- The angular distribution of daughter baryon from Hyperon weak decay:
  - $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda \mathbf{P_y} \cdot \hat{\mathbf{q}}$,
  - α_Λ: asymmetry parameter.
  - $\hat{\mathbf{q}}$: unit vector along the daughter baryon in hyperon rest frame.
- $|G_E/G_M| = 0.94 \pm 0.16 \pm 0.03 \pm 0.02(\alpha_\Lambda)$, $\Delta\phi = 42^\circ \pm 16^\circ \pm 8^\circ \pm 6^\circ(\alpha_\Lambda)$.





Measurement of Λ_c cross section on BESIII

- 2014 data, 631.3 pb^{-1}: PRL **120**, 132001 (2018).
- Ten modes of Λ_c^+ ($\bar{\Lambda}_c^-$) are reconstructed.
- Measurement of the σ_{Born} at 4 energy points below 4.6 GeV with unprecedented statistical accuracy (∼1.3% at 4.6 GeV).



- The σ_{Born} at near the threshold, indicates the complexity of production behavior of the Λ_c.
- At threshold, there is again a step in $\sigma_{\Lambda_c^+\bar{\Lambda}_c^-}$.
- Followed by a kind of a plateau.
- At threshold $\sigma_{\Lambda_c^+\bar{\Lambda}_c^-}$ is close to the point-like value, once the Coulomb Enhancement Factor is taken into account: $\sigma_{\Lambda_c^+\bar{\Lambda}_c^-(point-like)} \approx \frac{\pi^2\alpha^3}{2m_{\Lambda_c}} \approx 145$ pb.

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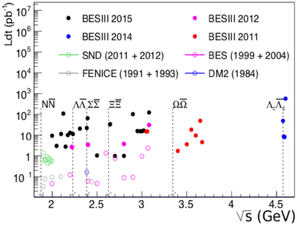
Summary: Discussion

- Electromagnetic FFs provide a quantitative description of hadron structure and are basic observables of QCD.
- BESIII is unique in its capability to measure baryon FFs, from nucleons to Λ_c and use two complementary approaches: energy scan and ISR technique:
  - Proton FFs have been measured using a test energy scan of 2012 and 2015, for 2012 data have published (PRD **91**, 112004 (2015)):
    - ✓ Precision improved:
    - ✓ 2015 R-scan data, 688.5 pb^{-1}: under reviewing.
    - ✓ In TL region, our results are unprecedented precision.
    - ✓ Especially $|G_E/G_M|$ providing an uncertainty comparable to the SL region for the first time.
  - Very exciting results from tagged ISR on protons expected very soon, preliminary results on untagged ISR techniques.
  - Published results on σ and FFs from Λ (PRD **97**, 032013 (2018)) and Λ_c (PRL **120**, 132001 (2018)) close to threshold.
    - ✓ Preliminary results on Λ Electromagnetic FFs relative phase.

Summary: Future

- Near future:
  - Present theory is missing something.
  - Proton: more data from CMD3 and BESIII.
  - Λ and ϕK^+K^-: more data around $\Lambda\bar{\Lambda}$ threshold.
  - Λ_c: more data at threshold and above by BESIII.



  - Neutron: more data from SND, CMD3. Publication by BESIII.
  - $Br(J/\psi \to \gamma n\bar{n})$: Publication by BESIII.
  - G_E/G_M phase: more data from BESIII.

Thanks all for hard work!

Thanks for your attention!