Studies of Baryon Form Factors at BESIII

Samer Ahmed::Isabella Garzia
on behalf of the BESIII Collaboration

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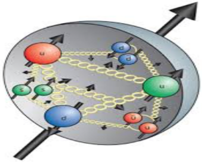
Outline

- **Introduction to the electromagnetic form factors**
- **Introduction to the BESIII experiment**
- **Measurements of the electromagnetic form factors of baryon**
  - **Proton form factors**
  - **Hyperon form factors**
  - **Charmed hyperon form factors**
- **Summary**

Electromagnetic Form Factors

- Baryons are non-point like particles and their structures and dynamics can be described :
  - Electromagnetic form factors
  - Parton Distribution Functions
  - Generalized Parton Distributions
  - ...

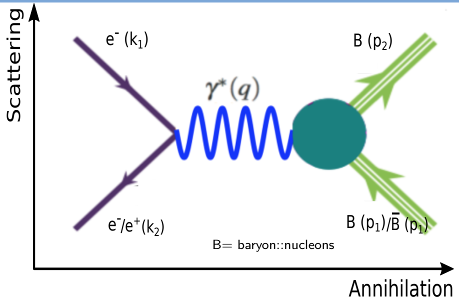


- By performing a global analysis on the data from scattering and annihilation experiments, one can determine these functions and well understand the structure of baryon.

Electromagnetic Form Factors:

- **Form Factors** characterize the internal structure and dynamics of baryons:
  - At low q2: they are related to the charge and magnetization distributions inside the baryons and hence probe the size of the baryons (nucleon).
    - In the limit of q2 goes to 0: determine the charge radius of the baryons.
  - At high q2: improve our understanding of QCD and testing its scaling.
- The electromagnetic structure of a particle of spin S is described by $2S + 1$ form factors.

Electromagnetic Form Factors



- Scattering amplitude in Born approximation:

$$\mathcal{M} = \frac{1}{q^2}\,[e\,\bar{u}(k_2)\gamma_\mu u(k_1)]\,\underbrace{\left[e\,\bar{U}(p_2)\Gamma^\mu(p_1,p_2)U(p_1)\right]}_{\text{Nucleon EM 4-current: } J_N^\mu}$$

- Baryonic current from Lorenz and gauge invarianc

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

Dirac FF: $F_1^B(q^2)$

Pauli FF: $F_2^B(q^2)$

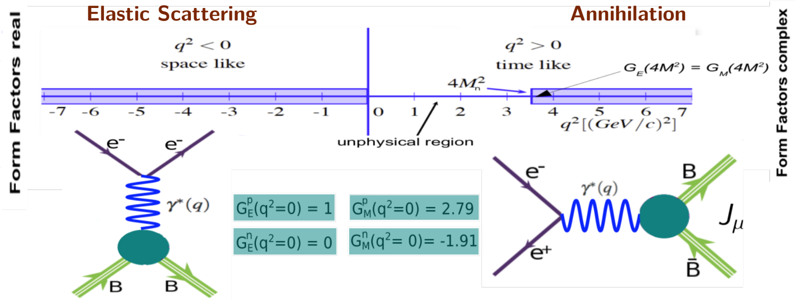
Sachs Form Factors:

- Combination of Pauli and Dirac FFs leads to the so called Sachs FFs:

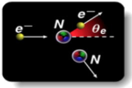
$$G_E = F_1(q^2) + (q^2/4M^2)F_2(q^2)$$

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

How experimentally the Form Factors are determined?



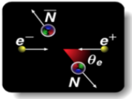
- The unphysical region can be accessed via $p\bar{p} \to e^+e^-\pi^0$.



Elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\omega_2\cos^2\frac{\theta_e}{2}}{4\omega_1^3\sin^4\frac{\theta_e}{2}}\left[G_E^2 - \tau\left(1+2(1-\tau)\tan^2\frac{\theta_e}{2}\right)G_M^2\right]\frac{1}{1-\tau}$$

$$\tau = \frac{q^2}{4M_N^2}$$



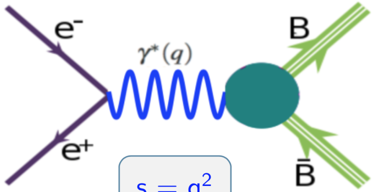
Annihilation

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

$$\beta = \sqrt{1-\frac{1}{\tau}}$$

Electromagnetic Form Factors in Time-Like Region

Direct Scan Method:



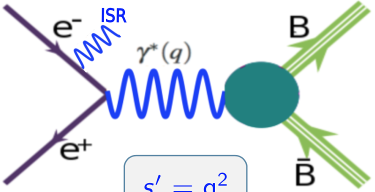
$s = q^2$

- Beam energy is discrete.
- Luminosity is relatively small.

$$\frac{d\sigma_{p\bar{p}}}{d(\cos\theta)} = \frac{\alpha^2 \beta C}{4q^2}[|G_M|^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}|G_E|^2\sin^2\theta]$$

- q^2 is single at each beam energy.

Initial State Radiation Method:



$s' = q^2$

$x \cong 2E_\gamma/\sqrt{s}$

- Beam energy is fixed.
- Luminosity is relatively high.

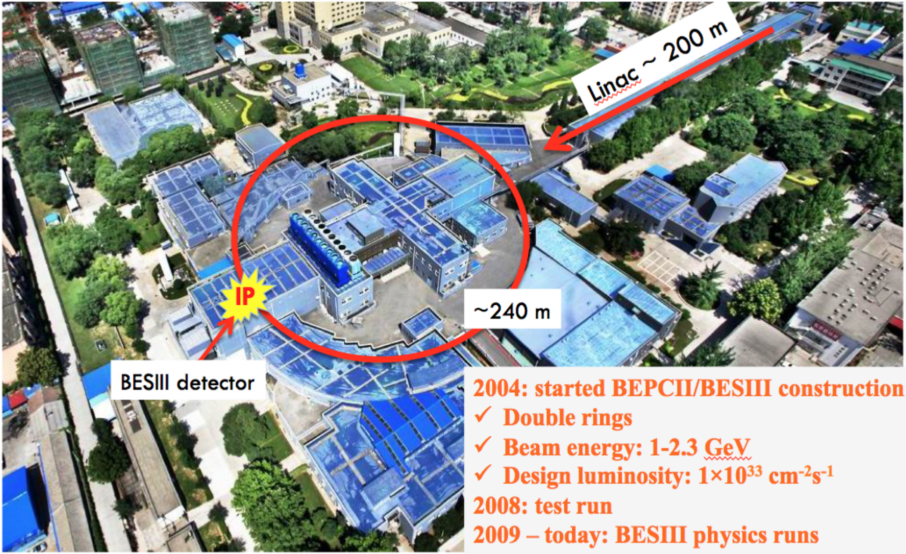
$$\frac{d^2\sigma_{p\bar{p}\gamma}}{dq^2 d\theta_\gamma} = \frac{1}{s} W(s, x, \theta_\gamma)\sigma_{p\bar{p}}(q^2)$$

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

- q^2 is continuous from threshold to s.

BEPCII & BESIII Detector

Beijing Electron Positron Collider II (BEPCII)



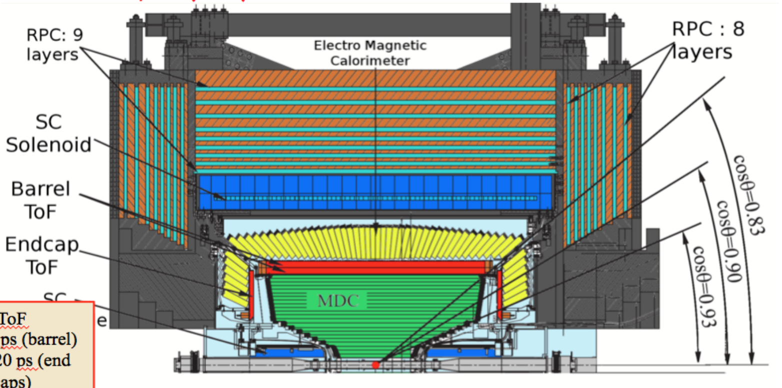
2004: started BEPCII/BESIII construction
- ✓ **Double rings**
- ✓ **Beam energy: 1-2.3 GeV**
- ✓ **Design luminosity: 1×10^{33} $cm^{-2}s^{-1}$**

2008: test run

2009 – today: BESIII physics runs

Beijing Electron Positron Collider II and BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)



ToF
$\sigma_t \sim 90$ ps (barrel)
$\sigma_t \sim 120$ ps (end caps)

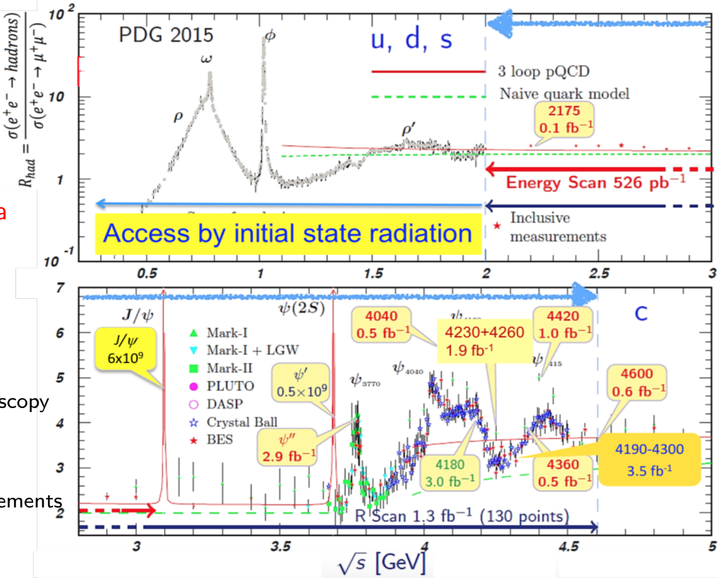
Drift Chamber
$\sigma_{r\phi} \sim 130$ μm (single wire)
$\sigma_{pt}/p_t \sim 0.5$ % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\ \text{mm})/E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi = 93\%$

BESIII Data Sets and Physics Program

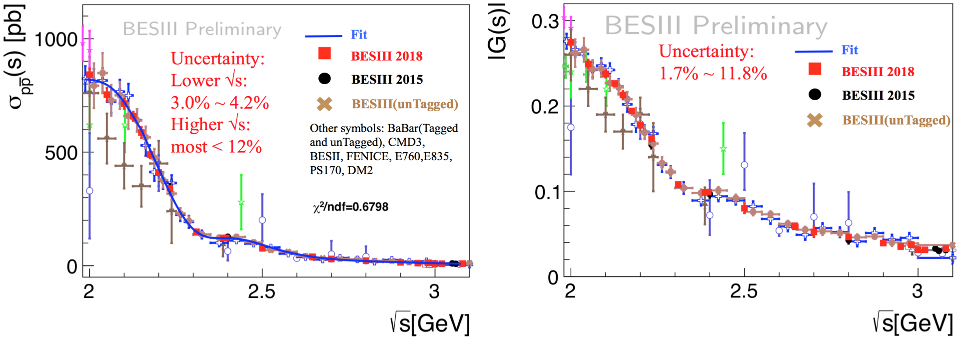
- World largest data samples for J/ψ, ψ' and ψ''



- Charm physics
- Charmonium spectroscopy
- Light hadrons
- New physics research
- Form factors measurements
- ....

Status of the Nucleon Form Factors at BESIII

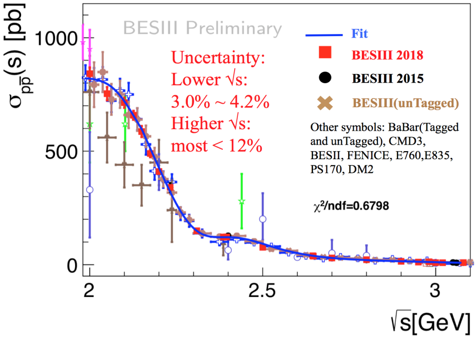
Measurements of proton form factors at BESIII

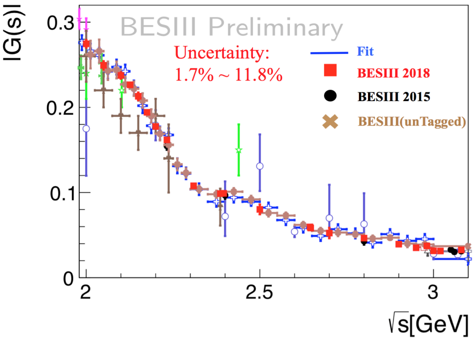


BESIII results on the $p\bar{p}$ cross section and effective form factors

- Direct scan method:
  - 2012 data, 156.7 pb^{-1}, PRD 91, 112004 (2015) ;
  - 2015 data, 668.5 pb^{-1}, arXiv:1905.09001 $\Longrightarrow$ most recent and precise results.
- Initial state radiation method:
  - Untagged analysis: data at [3.773 - 4.60 GeV], 7.4 pb^{-1}, Phys. Rev. D 99, 092002;
  - Tagged analysis: data at [3.773 - 4.60 GeV], 7.4 pb^{-1}, under review ;

Measurements of proton form factors at BESIII

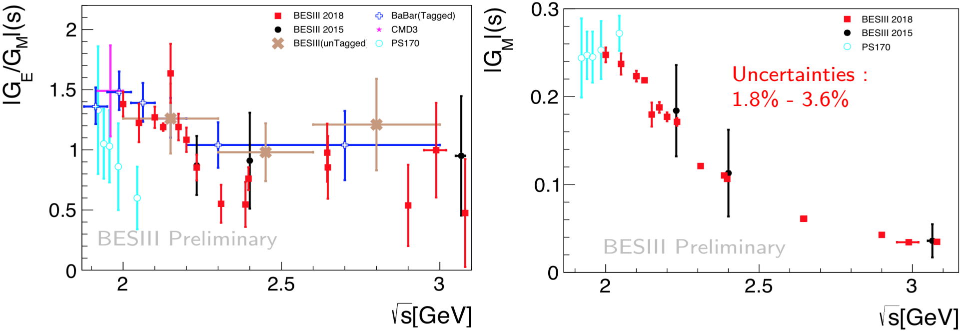




BESIII results on the $p\bar{p}$ cross section and effective form factors

- **BESIII results are consistent with the BaBar measurement.**
- **The precision of the BESIII results are significantly improved.**

Measurements of proton form factors at BESIII

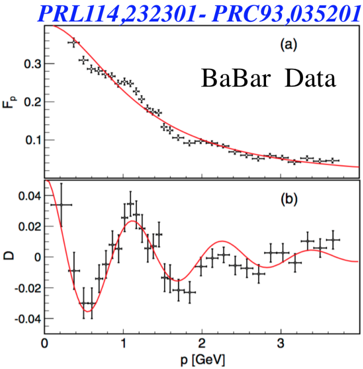


BESIII results for the electromagnetic form factors of proton

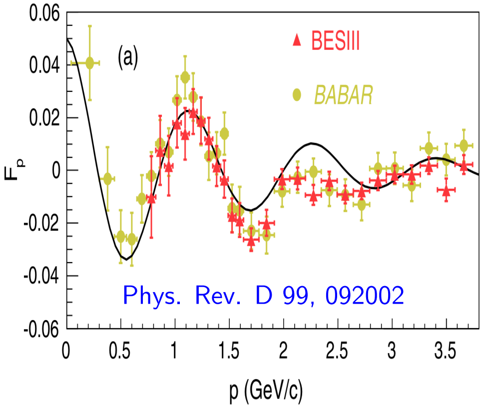
- Few results for the proton form factors exist but with big discrepancy (BaBar and PS170).
- BESIII results for the proton form factors have determined in a wide range of $\sqrt{s}$.
- BESIII results for the proton form factors ratio are consistent with BaBar results.
- **The recent results (BESIII 2018) greatly improve the precision of the proton form factors**.

Structure in the Effective Form Factor of Proton

- Oscillation in the effective form factor is observed by BaBar and then confirmed by BESIII.



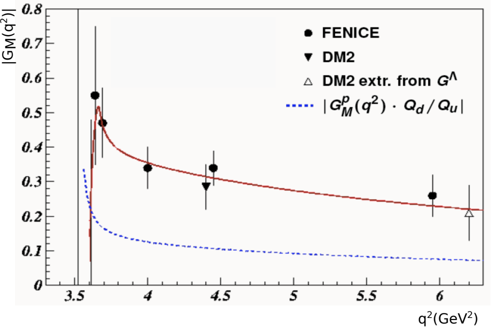
$$F_{\rm osc}(p) \equiv A\exp(-Bp)\cos(Cp+D)$$



▶ A physical explanation could be due to a possible interference effect involving rescattering processes at moderate kinetic energies of the outgoing hadrons (when the center-of-mass of the produced hadrons are separated by 1 fm

p is the three momentum of the proton in the frame of antiproton.

Measurements of Neutron Form Factors at BESIII



- Two measurements of neutron form factors:
- Feince experiment: Magnetic form factor of the neutron under the assumption $G_E = 0$. Nucl. Phys. B517, 3 (1998)
- DM2 experiment: Magnetic form factor of the neutron is determined from the magnetic form factor of Λ.

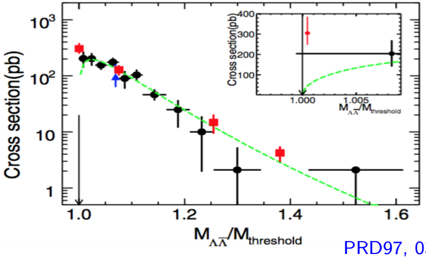
BESIII results for the electromagnetic form factors of neutron: ongoing analysis

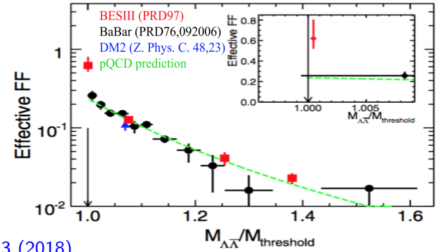
- The neutron form factors (R_{em}, G_M) have been determined in a wide range of q^2.
- The neutron form factors ratio has been determined for the first time.
- The precision of the neutron form factors are much better than those in previous results.
- **The results need to be firstly approved by the BESIII community**.

Status of the Hyperon Form Factors at BESIII

Measurements of Hyperon Form Factors at BESIII

- Data sets at 4 energy points [2.232 - 3.08] GeV with a luminosity of 40.5 pb^{-1} are used.
  - The lowest energy point is 1 MeV above the $\Lambda/\bar{\Lambda}$ mass threshold.
- Decay channels of $\Lambda\bar{\Lambda}$: $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$ and $\bar{\Lambda} \to \bar{n}\pi^0$ ($\Lambda \to$ inclusive decays).





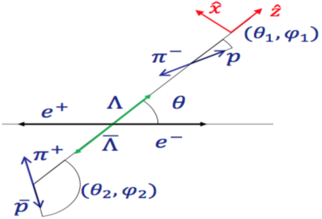
PRD97, 032013 (2018)

BESIII results for the cross section of the $e^+e^- \to \Lambda\bar{\Lambda}$ channel

- The Born cross section is measured at 4 energy points, **unexpected rise at threshold**.
- The results are in good agreement with BaBar and DM2 results.
- The results may help to understand the mechanism of baryon production.

Measurements of Hyperon Form Factors at BESIII

- Data set at $\sqrt{s}$= 2.396 GeV with a luminosity of 66.9 pb^{-1} is used.
- Multidimensional analysis is needed for a complete decomposition of G_E and G_M form factors.
- Form Factors has a complex form:
  - $G_E = |G_E|e^{i\phi_E}$ and $G_M = |G_M|e^{i\phi_M}$
  - Relative phase: $\Delta\phi = \phi_E - \phi_M$
- A non-zero relative phase has a polarization effect on the final state even if the initial state is unpolarized



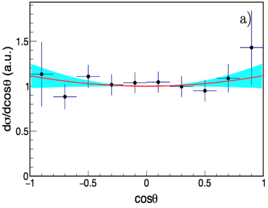
$$P_y = \frac{\sqrt{1-\eta^2}\cos\theta\sin\theta}{1+\eta\cos^2\theta}\sin(\Delta\Phi)$$

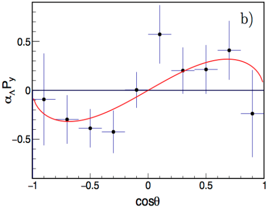
$\left|\frac{G_E}{G_M}\right|$ = **0.94±0.16±0.03**$_{\alpha_\Lambda}$

$\Delta\phi$ = **42°±16°±6°**$_{\alpha_\Lambda}$

- Determination of the polarization and the spin-correlation parameters allow to determine the relative phase

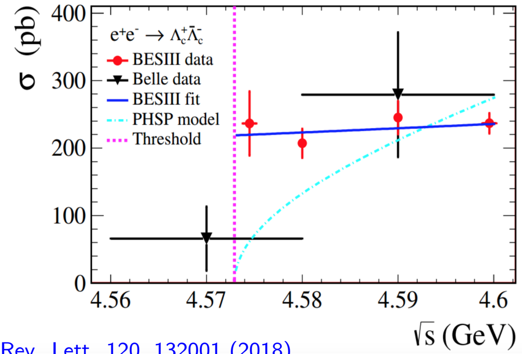
arXiv:1903.09421





Measurements of Charmed Hyperon Form Factors

- Four data sets at $\sqrt{s}$= [4.5 - 4.6] GeV.
- The total luminosity is 631.3 pb^{-1}.
- Ten Cabibbo-favored decay modes of Λ_c+ c.c are considered.

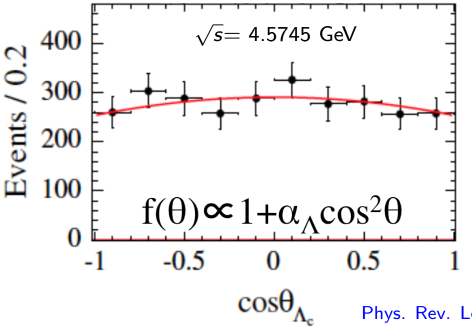


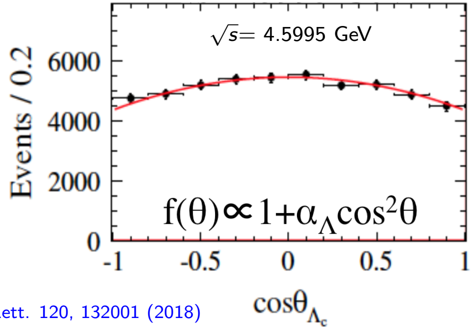
Phys. Rev. Lett. 120, 132001 (2018)

BESIII results for the cross section of $e^+e^- \to \Lambda_c\bar{\Lambda}_{\bar{c}}$ channel

- The Born cross section is measured at 4 energy points with unprecedented precision.
- The best precision is achieved at $\sqrt{s}$= 4.6 GeV to be ∼1.3%.

Measurements of Charmed Hyperon Form Factors





Phys. Rev. Lett. 120, 132001 (2018)

BESIII results for the electromagnetic form factors of Λ_c

- **The form factor ratio of Λ_c has been measured for the first time.**

$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

Summary

- Two complimentary methods are used for the measurements of baryon form factors:
  - Energy scan method
  - Initial state radiation method
- **The cross section of the $p\bar{p}$ channel has been measured in a wide range of q^2**
- **The form factors of proton (G_M and $|\frac{G_E}{G_M}|$) are measured with unprecedented precision**
  - Indication that $|\frac{G_E}{G_M}| \neq 1$ at threshold
- **An oscillation behaviour in the effective form factor of proton is obsessed**.
- **Results of neutron form factors (G_M and $|\frac{G_E}{G_M}|$) are coming soon**.
- **A non-vanishing cross section of $\Lambda\bar{\Lambda}$ and $\Lambda_c\bar{\Lambda}_{\bar{c}}$ at the threshold is observed.**
- **First measurements of the relative phase of the form factors G_E and G_M for Λ**.
- **First measurements of the form factors of Λ_c. More data will be collected in the next years**.

Thank you

Backup slides

arXiv:1903.09421v1: Λ FF

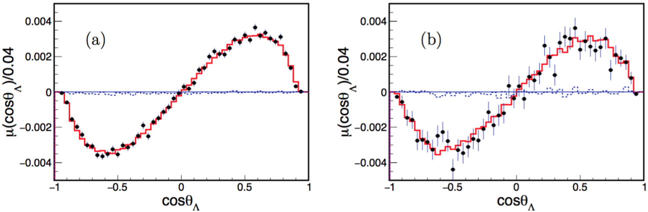
Decay distribution of $e^+e^- \to \Lambda\bar{\Lambda}$ ($\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$) derived in terms of the phase $\Delta\Phi$ and angular distribution parameter $\eta = \frac{\tau - R^2}{\tau - R^2}$, with $\tau = s/(4m_B^2)$

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi}) =& \mathcal{T}_0 + \eta \mathcal{T}_5 \\ & -\alpha_\Lambda^2 \left(\mathcal{T}_1 + \sqrt{1-\eta^2}\cos(\Delta\Phi)\mathcal{T}_2 + \eta\mathcal{T}_6\right) \\ & +\alpha_\Lambda \sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\mathcal{T}_3 - \mathcal{T}_4\right),\end{aligned}$$

$$\begin{aligned}\mathcal{T}_0(\boldsymbol{\xi}) =& 1, \\ \mathcal{T}_1(\boldsymbol{\xi}) =& \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2, \\ \mathcal{T}_2(\boldsymbol{\xi}) =& \sin\theta\cos\theta\left(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2\right), \\ \mathcal{T}_3(\boldsymbol{\xi}) =& \sin\theta\cos\theta\sin\theta_1\sin\phi_1, \\ \mathcal{T}_4(\boldsymbol{\xi}) =& \sin\theta\cos\theta\sin\theta_2\sin\phi_2, \\ \mathcal{T}_5(\boldsymbol{\xi}) =& \cos^2\theta, \\ \mathcal{T}_6(\boldsymbol{\xi}) =& \cos\theta_1\cos\theta_2 - \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2.\end{aligned}$$

arXiv:1808.08917 (published on Nature)

Polarization and Entanglement in $\Lambda\bar{\Lambda}$ pair production in e^+e^- annihilation at BESIII ($e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$)



$$\mu(\cos(\theta_\Lambda)) \sim \sqrt{1-\alpha_\phi^2}\,\alpha_- \sin\Delta\Phi \cos\theta_\Lambda \sin\theta_\Lambda$$

- Clear polarization, related to the moment $\mu(\cos(\theta_\Lambda))$
- 5σ deviation between α_- and α_-^{PDG}
- Most sensitive test of A_{CP} for the Λ baryon

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [25]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [27]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [27]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [27]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–