Baryon form factors at BESIII

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On behalf of BESIII collaboration

International Workshop on e^+e^- collisions from Phi to Psi

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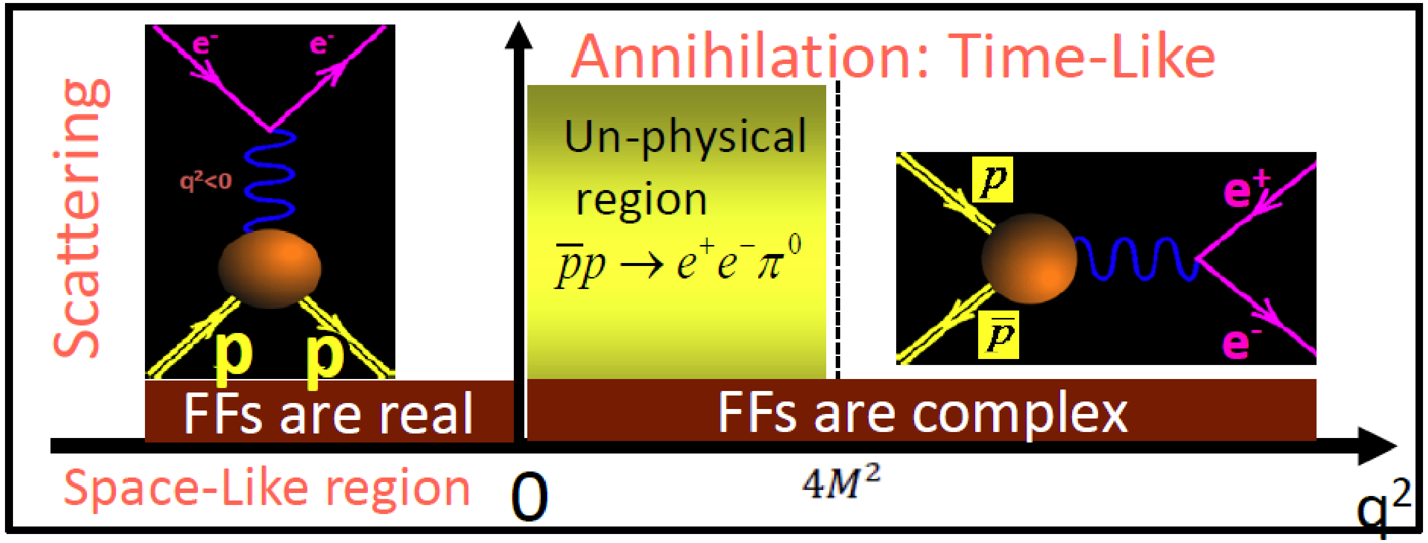
Outline

- Introduction (form factors and BESIII data)
- Time-like form factors of proton
  - ISR un-tag method with data at higher energies
  - Scan data
- Time-like form factors of Λ
- Time-like form factors of Λ_c
- Summary and outlook

Form factors of proton

- Understanding the inner structure of proton
-

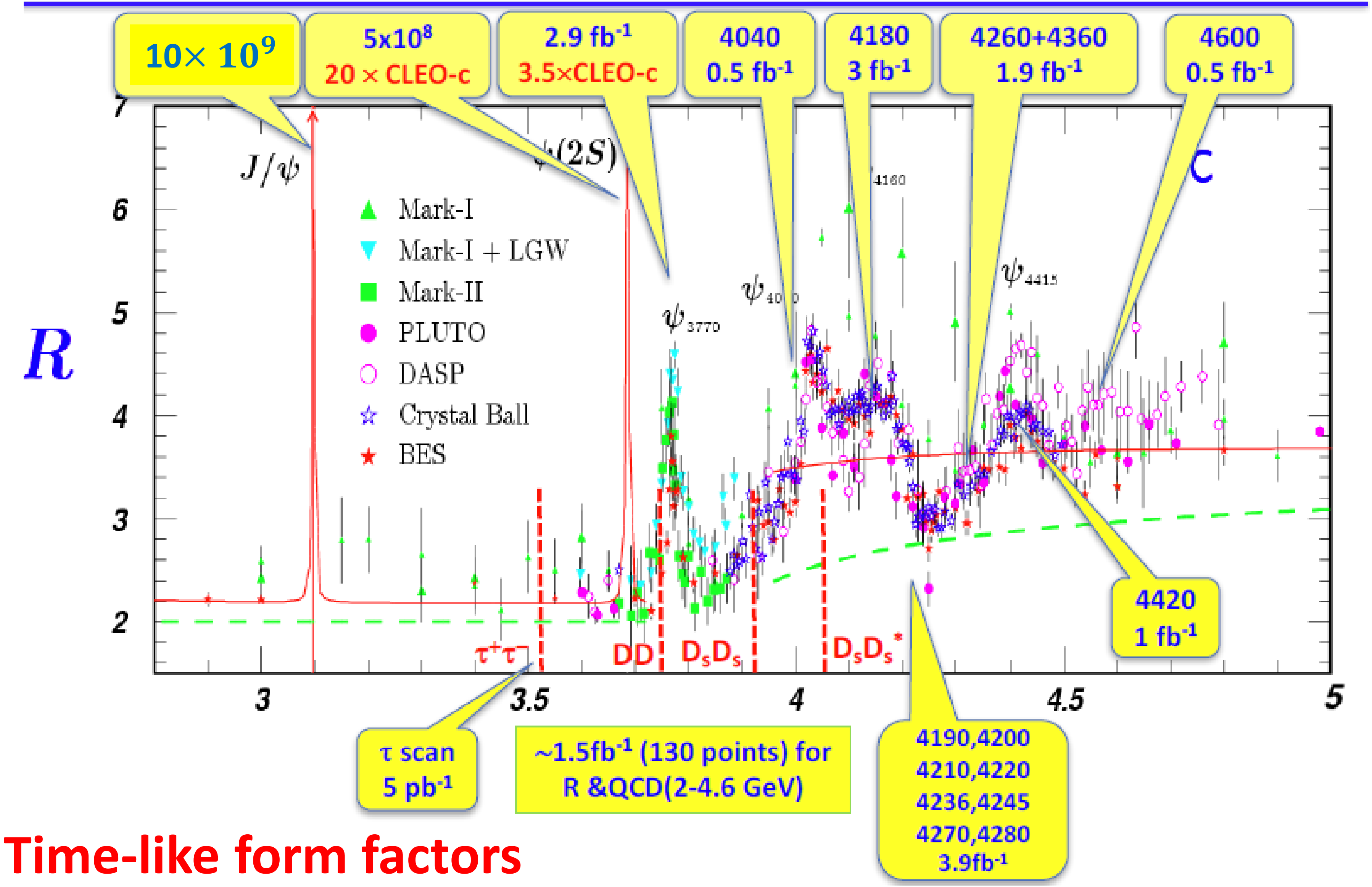


- Form factors represent the charge distribution in momentum space and are related to the cross sections directly
  - Probe the size of the nucleus
  - Test QCD scaling

Form factors for proton

- Space-like
  - Many measurements via scattering
  - At JLab, the ratio was measured precisely with an uncertainty of ~1%, based on which the proton electronic and magnetic radii could be extracted
- Time-like
  - Measurements via $p\bar{p}$ collision or $e^+e^- \to p\bar{p}$
  - $\sigma(e^+e^- \to p\bar{p})$ $\frac{d\sigma_{p\bar{p}}(s)}{d\Omega} = \frac{\alpha^2\beta C}{4s}[|G_M|^2(1+cos^2\theta_p) + \frac{4m_p^2}{s}|G_E|^2 sin^2\theta_p]$
  - Lacking accurate data on the angular distributions. Most experiments assume $|G_E| = |G_M| = |G_{eff}|$
  - Only two experiments measure $|G_E/G_M|$, with inconsistent results (Babar & PS170)

BESIII data: the largest e^+e^- collision samples in τ-charm region



Time-like form factors

Proton form factors at BESIII

Both scan and ISR can be used at BESIII

- High-energy data sets (3.773 ~ 4.6 GeV)
  - Untagged ISR technique
  - Tagged ISR technique
- Low-energy scan data sets (2.0 ~ 3.08 Gev)
  - Phys. Rev. D. 91, 112004 (2015), the first set
  - Full set; expected to supersede the previous results

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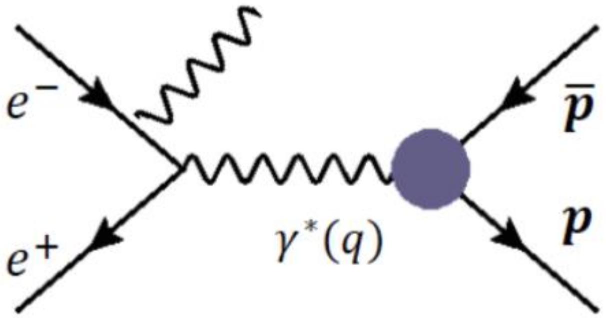
This talk

Untagged ISR technique

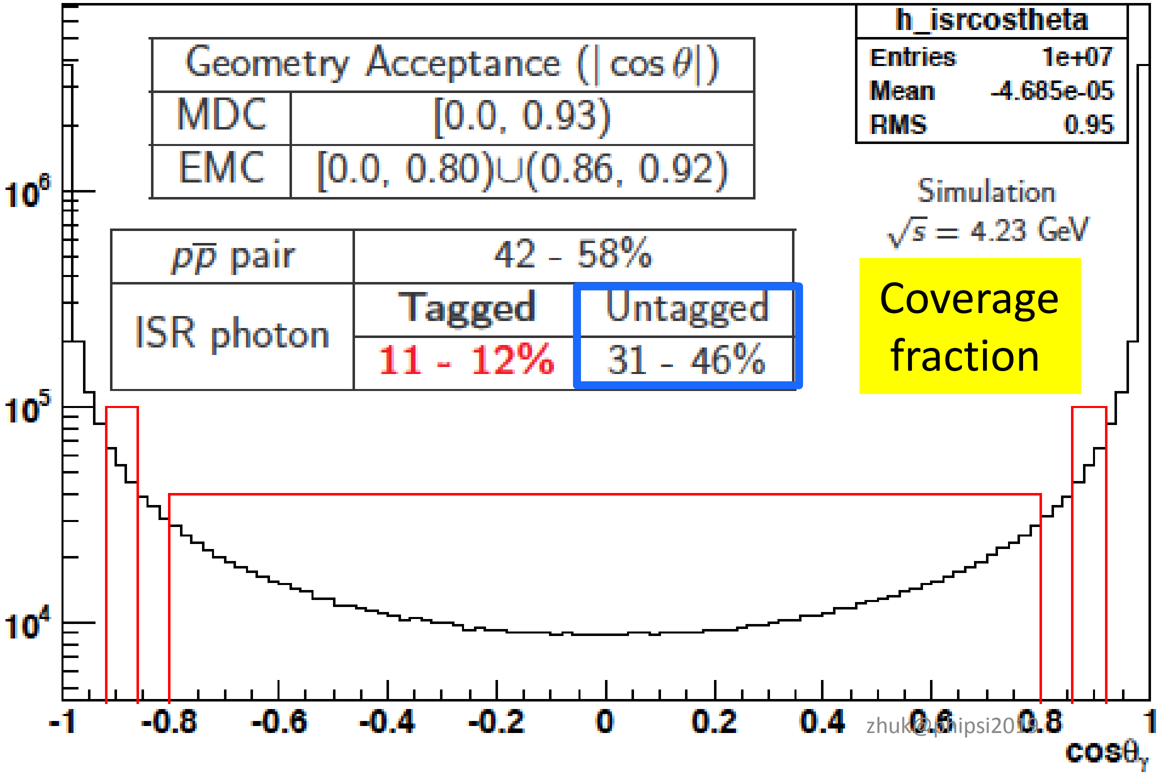
Proton form factors results at BESIII with un-tag ISR method

arXiv:1902.00665 [hep-ex]



E_{cm} [GeV]	L [pb^{-1}]
3.773	2931.8
4.008	481.96
4.226	1053.9
4.258	825.67
4.358	539.84
4.416	1041.3
4.600	585.4

Total: $7.4\ fb^{-1}$



- **ISR analysis**: continuous q^2 range
- **Untagged ISR analysis**: high statistic

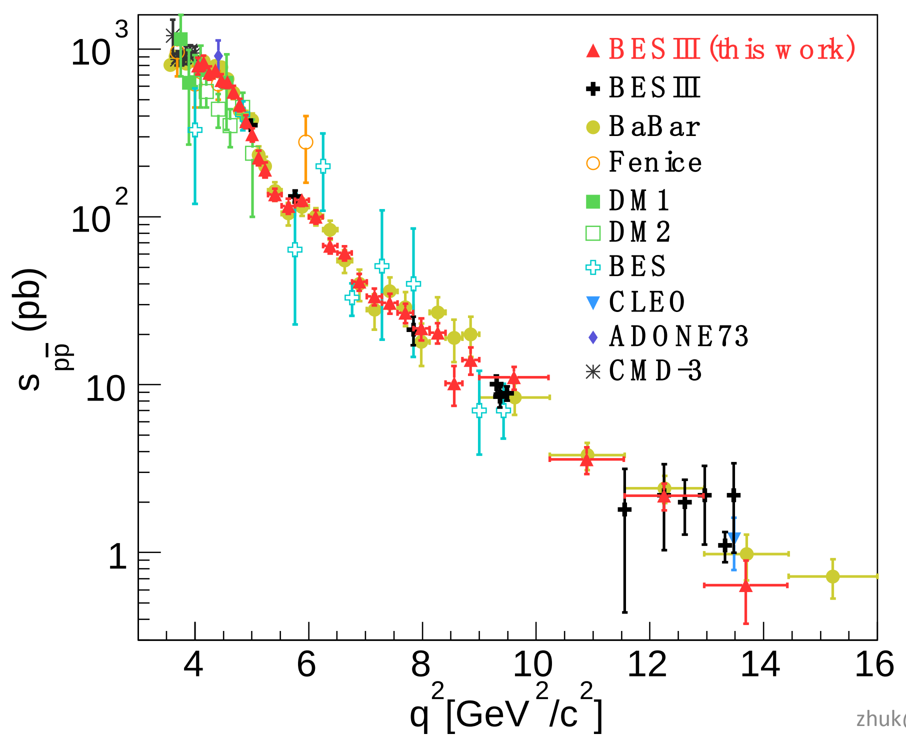
Total cross section and effective FFs in 30 intervals of the $M_{p\bar{p}}$ between 2.0 and 3.8 GeV

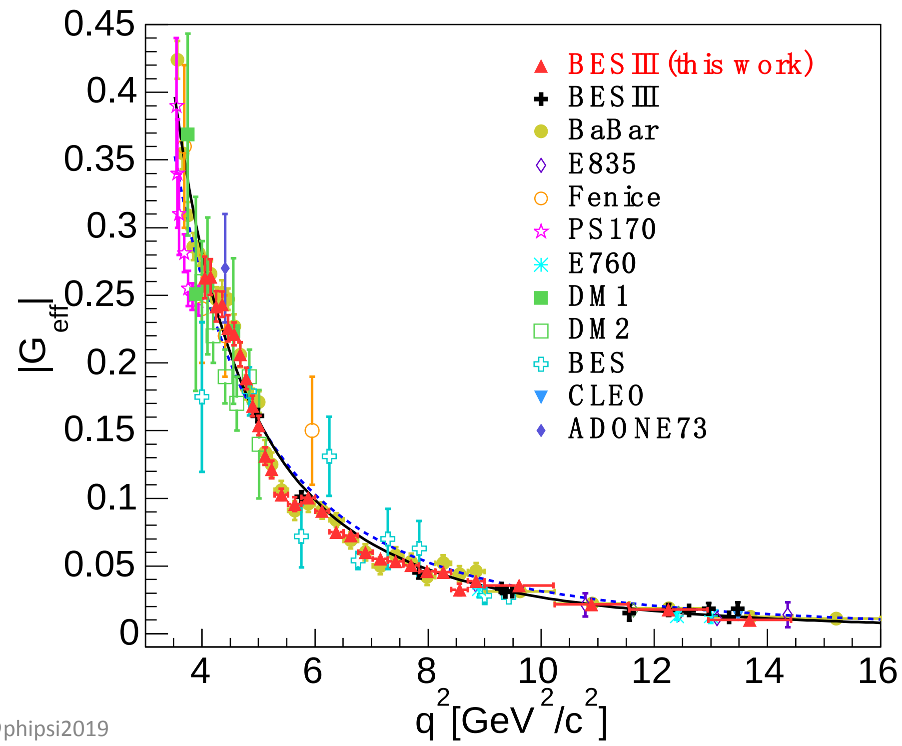
arXiv:1902.00665 [hep-ex]

The ISR and the Born cross sections are related by the radiator function W(s,x):

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

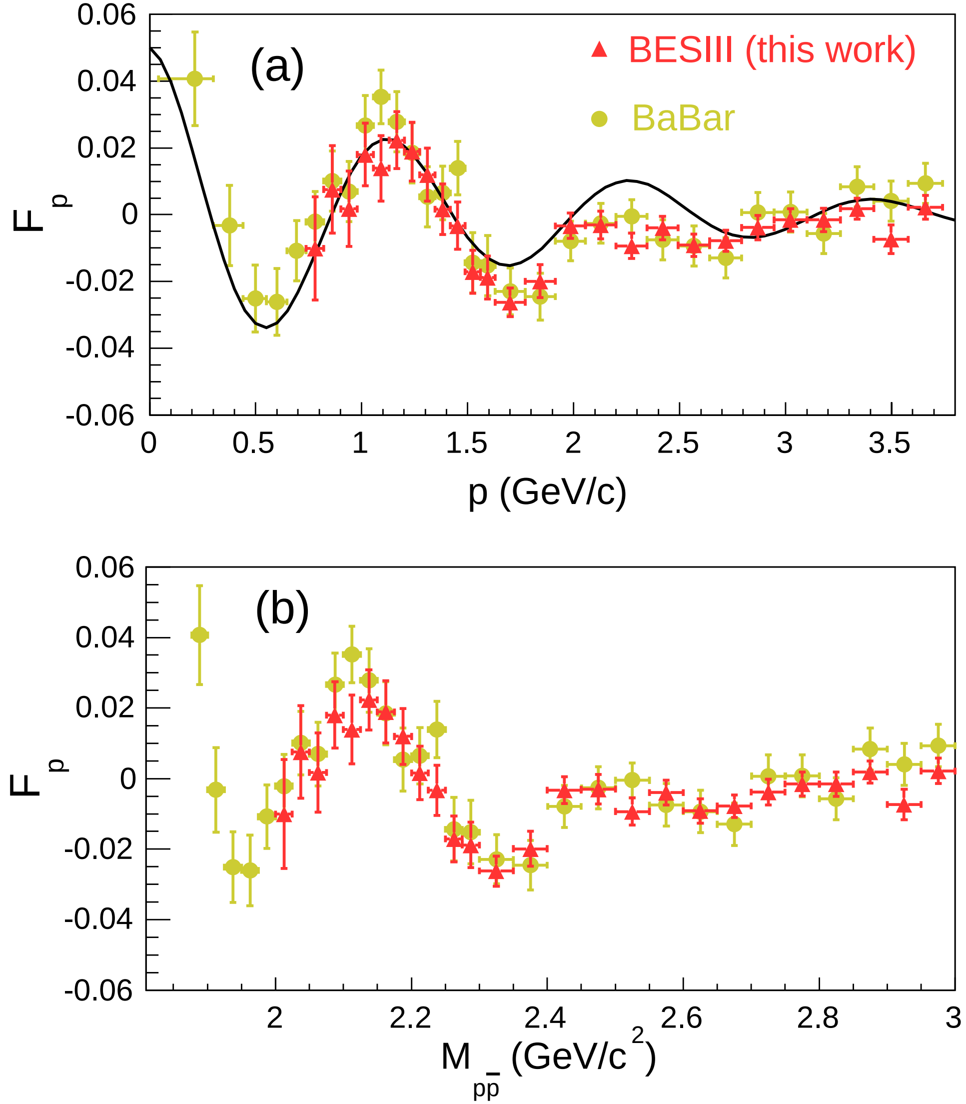
$$x = 1 - \frac{q^2}{s}, q^2 = M_{p\bar{p}}^2$$





Oscillations

arXiv:1902.00665 [hep-ex]



- The oscillations can be extracted as
  $F_p = |G_{eff}| - F^0$
  (F^0 : regular behavior over the long range)

Confirmed observation by Barbar
Phys. Rev. Lett. 114, 232301 (2015)
Phys. Rev. C 93, 035201 (2016)

Re-scattering effect?
Resonance contribution?

R= |GE|/|GM| in 3 intervals of $M_{p\bar{p}}$ between 2.0 and 3.0 GeV

$$\frac{d\sigma}{d\cos\theta_p} = A(H_M + \frac{R^2}{\tau} H_E)$$

$H_M(\cos\theta_p, M_{p\bar{p}})$ from MC ($G_{E=0}$)

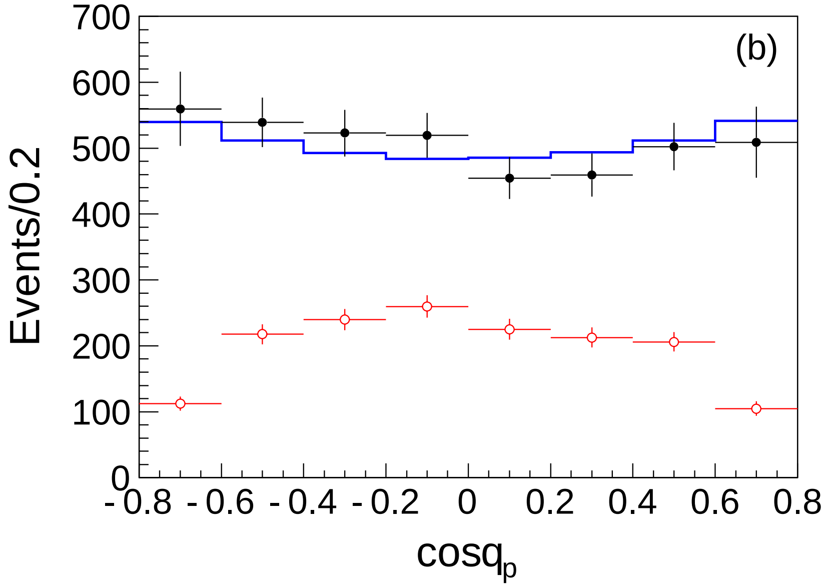
$H_E(\cos\theta_p, M_{p\bar{p}})$ from MC ($G_M = 0$)

Data of 7 samples are combined

After bkg. subtraction (red)

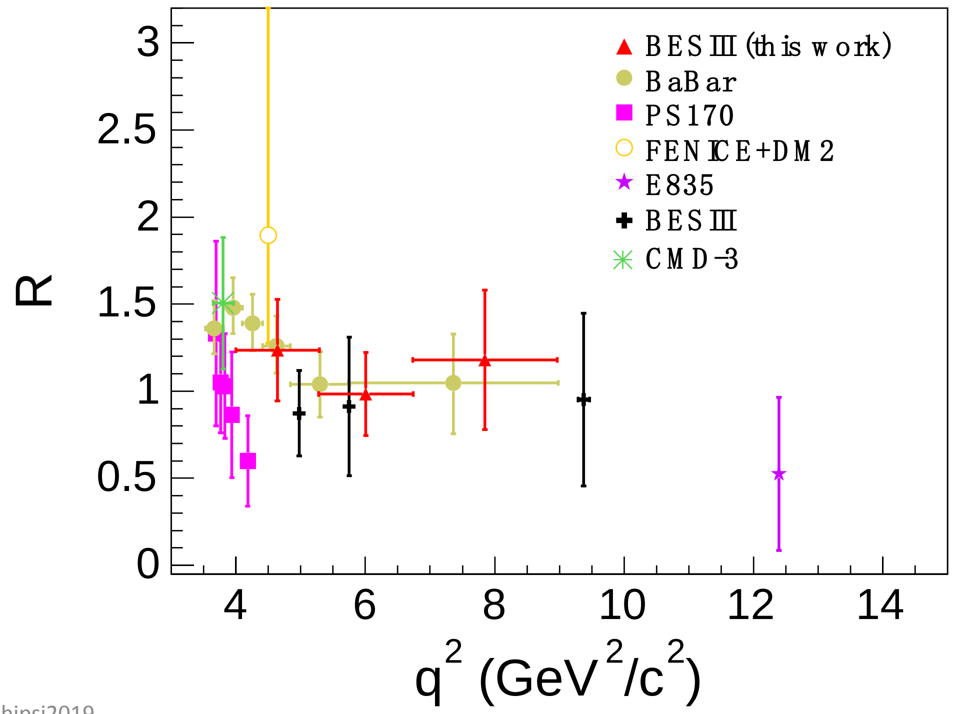
After efficiency correction (black)

Fit (blue)



arXiv:1902.00665 [hep-ex]

$M_{p\bar{p}}$ [GeV/c^2]	Fitting range ($\cos\theta_p$)	R
2.0 - 2.3	[-0.6,0.6]	1.24 ± 0.29
2.3 - 2.6	[-0.8,0.8]	0.98 ± 0.24
2.6 - 3.0	[-0.8,0.8]	1.18 ± 0.40



(Full) low-energy scan data sets

688.5 pb^{-1}*, 22 energies, 2.0 to 3.08 GeV*

Cross section of $e^+e^- \to p\bar{p}$ and effective FF

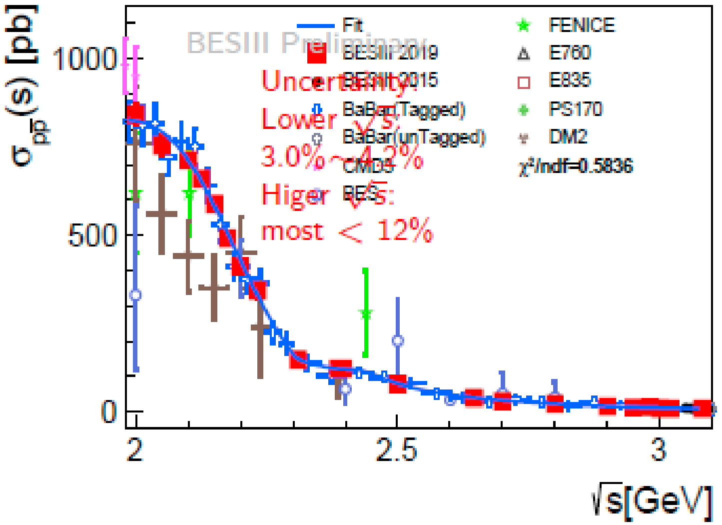
- **Strategy**:
  - In TL region:

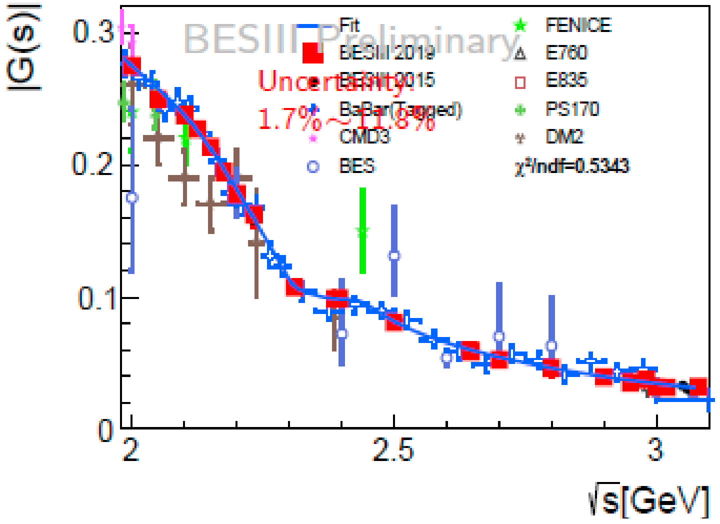
$$\frac{d\sigma_{p\bar{p}}(s)}{d\Omega} = \frac{\alpha^2\beta C}{4s}[|G_M|^2(1+cos^2\theta_p) + \frac{4m_p^2}{s}|G_E|^2 sin^2\theta_p]$$

  - Assume $|G| = |G_E| = |G_M|$, the effective FF is

$$|G| = \sqrt{\frac{\sigma_{p\bar{p}}}{\frac{4\pi\alpha^2\beta C}{3s}(1+\frac{2m_p^2}{s})}}$$

- **In time-like region, BESIII result is an unprecedented accuracy.**





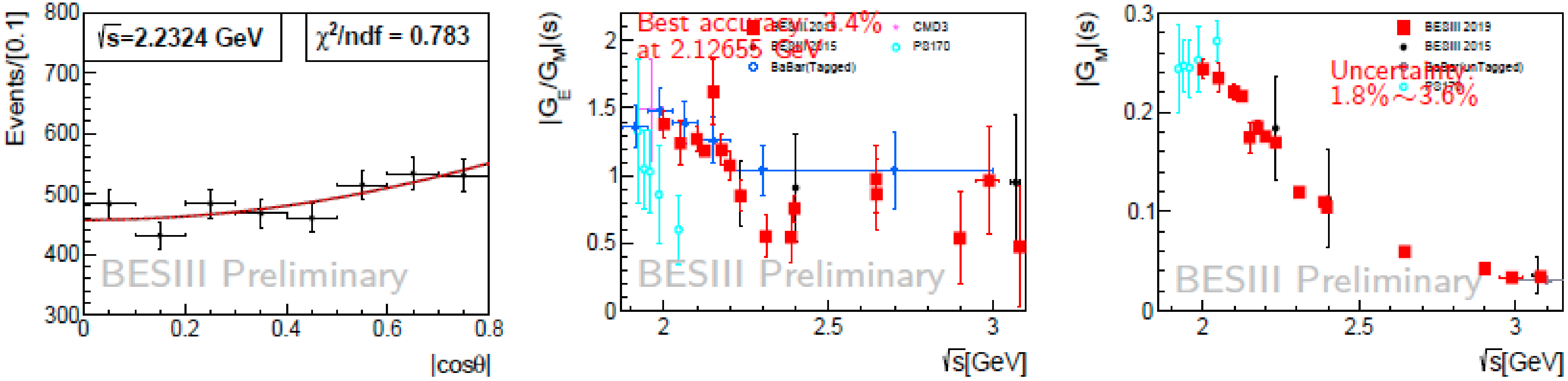
Oscillations has been confirmed, again

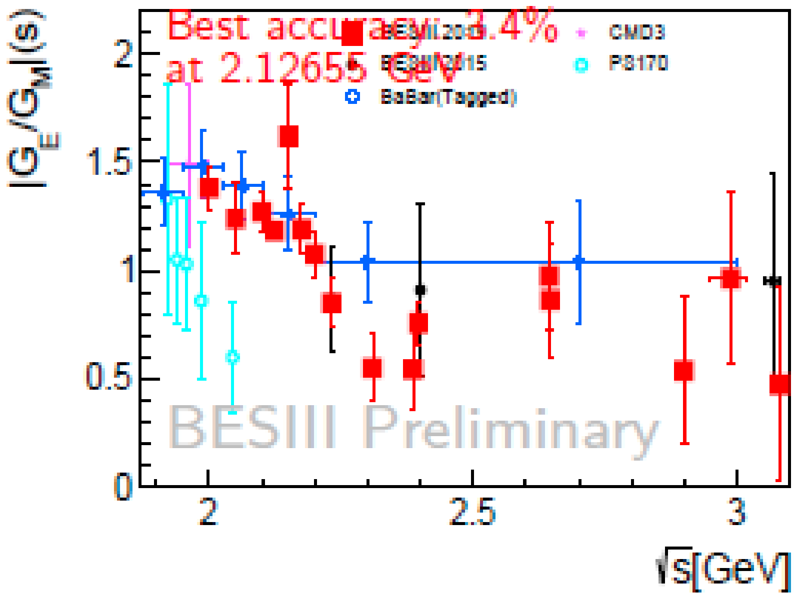
Measurement of $|G_E/G_M|$ and magnetic FF

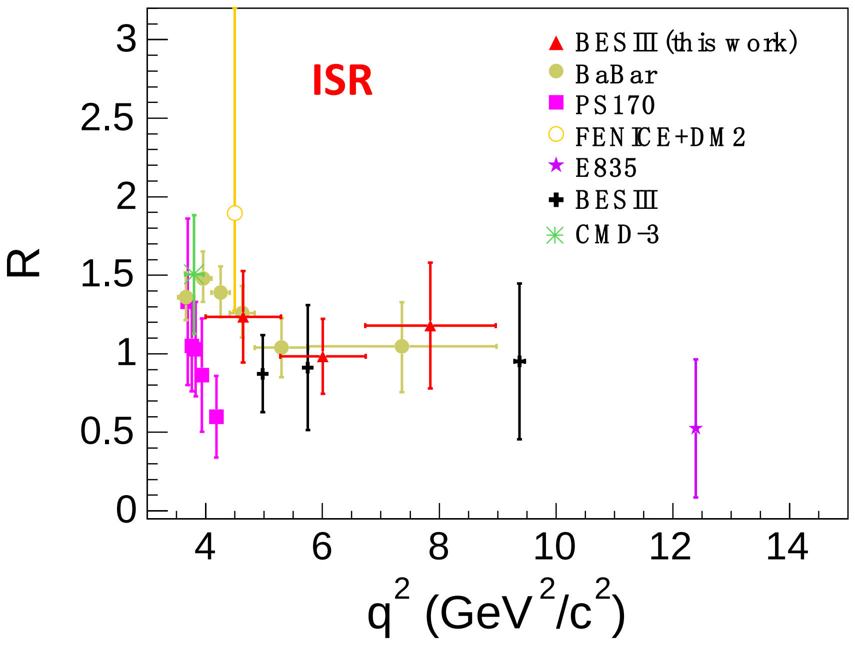
- **Strategy**:
  - Fit on the polar angular distribution of proton:

$$\frac{dN}{\epsilon(1+\delta)\times d\cos\theta_p}=\frac{\mathcal{L}\hbar c\pi\alpha^2\beta C}{2s}|G_M|^2[(1+\cos^2\theta_p)+\frac{4m_p^2}{s}|\frac{G_E}{G_M}|^2(1-\cos^2\theta_p)]$$

- Uncertainties include statistical and systematical.

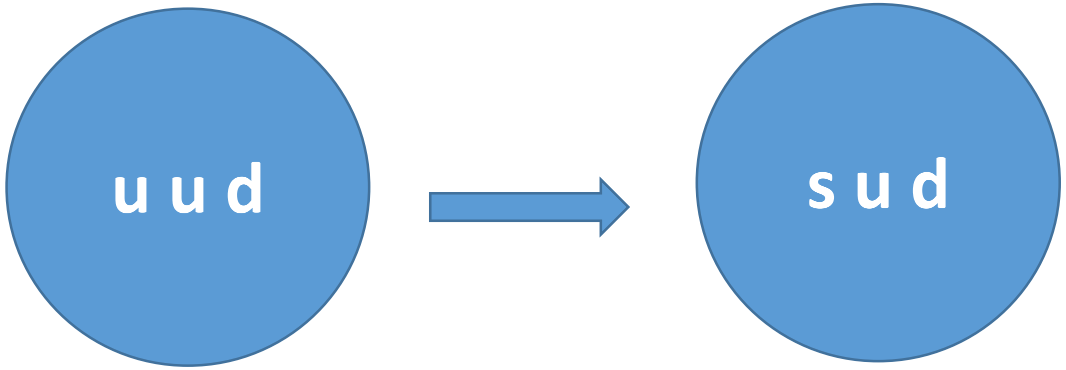






- $|G_E/G_M|$ providing an uncertainty comparable to the space-like region for the first time.
- BESIII measurement of $|G_E/G_M|$ strongly favors BaBar's compared to that of PS170.

Λ form factors



Hyperon structure

- Electromagnetic From Factors (EMFFs)
  - fundamental hadron structure observables
  - describe the deviation from the point-like case
  - related to the charge- and magnetization density

- EMFFs of nucleon can be studied in:
  - elastic scattering, $e^- N \to e^- N$, space-like
  - annihilation, $e^+e^- \to N\bar{N}$, $N\bar{N} \to e^+e^-$, time-like

- Hyperons are difficult to study in the space-like region
  - they are unstable – hyperon targets are unfeasible
  - the quality of hyperon beams is in general not sufficient

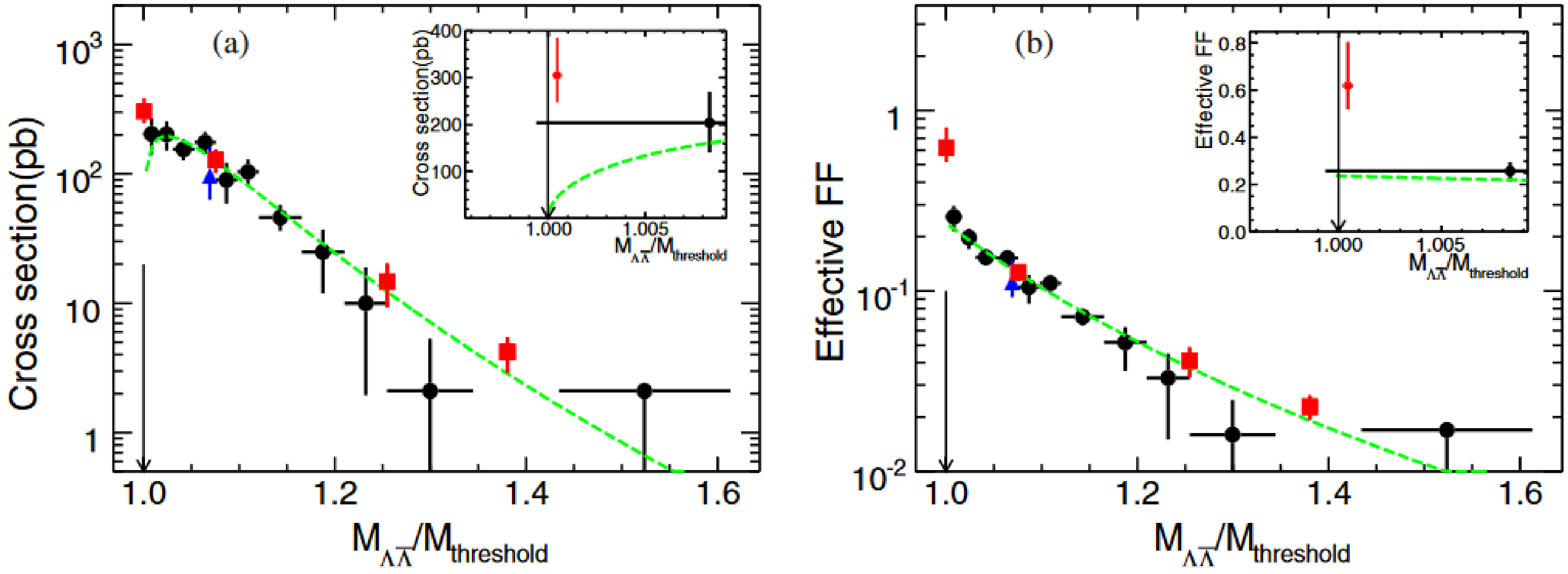
- e^+e^- annihilation offers the best opportunity to study hyperon structure

Previous BESIII measurements

PHYSICAL REVIEW D **97,** 032013 (2018)

Observation of a cross-section enhancement near mass threshold in $e^+e^- \to \Lambda\bar{\Lambda}$

$\sqrt{s} = 2.2324, 2.400, 2.800$ and 3.080 GeV



Results of the cross section and effective EMFFs

- The cross section $\sigma = \frac{N_{signal}}{L\epsilon(1+\delta)Br(\Lambda\to p\pi^-)Br(\bar{\Lambda}\to\bar{p}\pi^+)}$
  - ISR and vacuum polarization factor $1+\delta$ is from ConExc
  - ϵ is the detection efficiency, L is the luminosity
  - $\sigma = 119.0 \pm 5.3(stat.) \pm 7.3(sys.)$ pb[1]

$\sqrt{s} = 2.396$ **GeV**

- Effective form factors are related to σ, $|G(q^2)| = \sqrt{\frac{\sigma(q^2)}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta}{3q^2})}}$
  - $|G| = 0.123 \pm 0.003(stat.) \pm 0.004(sys.)$

$\alpha \approx \frac{1}{137}$ is the fine structure constant,
$\beta = \sqrt{1-\frac{1}{\tau}}$ is the velocity, $\tau = \frac{q^2}{4m_\Lambda^2}$.

Previous measurements

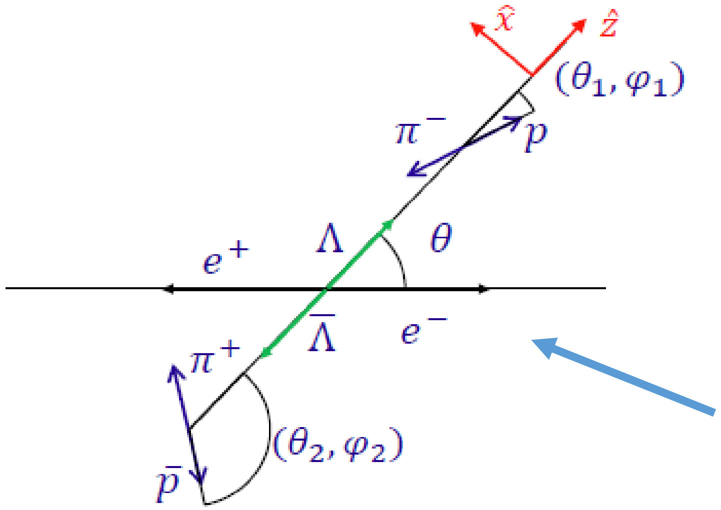
	σ(pb)	$\|G\|$	Reference
BESIII $\sqrt{s}$ =2.40GeV	128±19±18	0.127±0.009±0.009	Phys. Rev. D **97**, 032013 (2018)
BaBar $\sqrt{s}$ =2.35-2.40 GeV	176±34	0.152±0.016	Phys. Rev. D **76**, 092006 (2007)

[1] The systematic uncertainty is dominated by a conservative estimate of the contribution of $|\vec{p}|(\Lambda)$

Joint decay distribution

- Space-like region:
  - $e^- B \to e^- B$ scattering
  - $q^2 = (p_{ie} - p_{fe})^2 < 0$
  - G_E and G_M real numbers
- Time-like region:
  - $e^+e^- \leftrightarrow B\bar{B}$, $q^2 \geq 4M_B^2 > 0$
  - $G_E(q^2) = |G_E(q^2)|e^{i\Phi_E}$, $G_M(q^2) = |G_M(q^2)|e^{i\Phi_M}$
  - Relative phase: $\Delta\Phi = \Phi_E - \Phi_M$

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

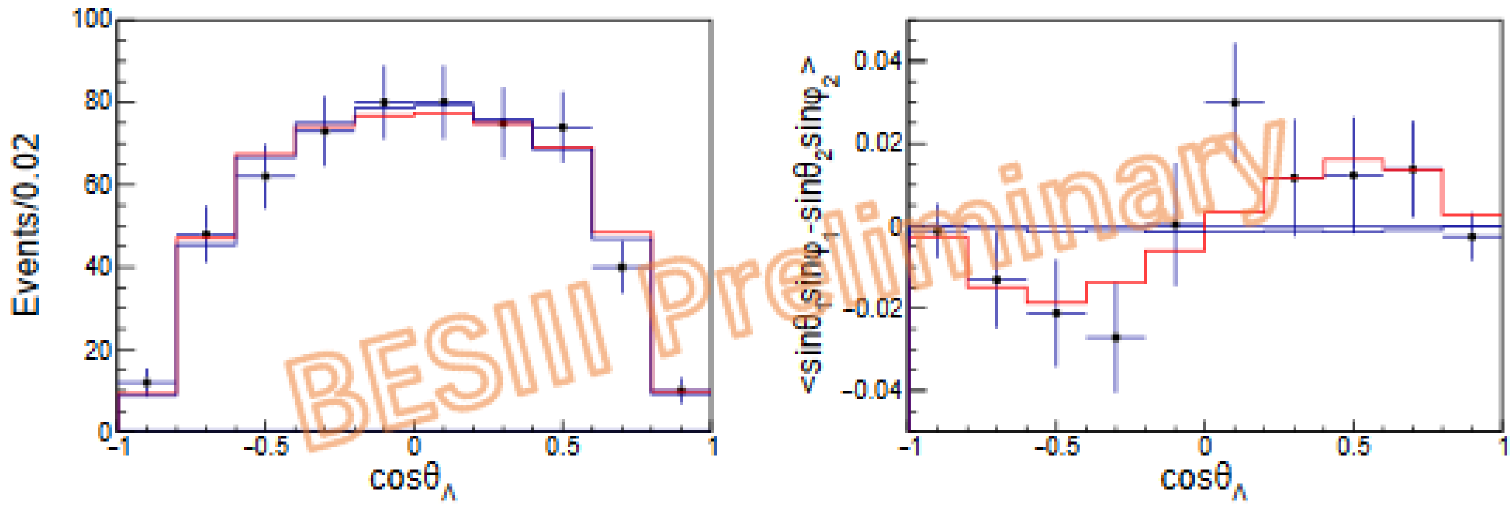


$$\begin{aligned}\mathcal{T}_0(\xi) =& 1, \\ \mathcal{T}_1(\xi) =& \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2, \\ \mathcal{T}_2(\xi) =& \sin\theta\cos\theta\left(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2\right),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

$|G_E/G_M|$ and relative phase

Fit by maximal likelihood

α_Λ is determined to be 0.75±0.01 by preliminary BESIII result

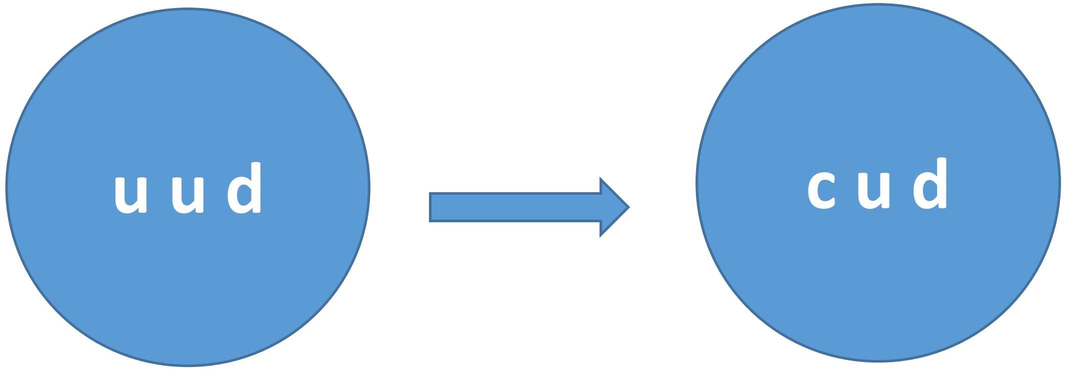


$R = 0.94 \pm 0.16(stat.) \pm 0.03(sys.) \pm 0.02(\alpha_\Lambda)$

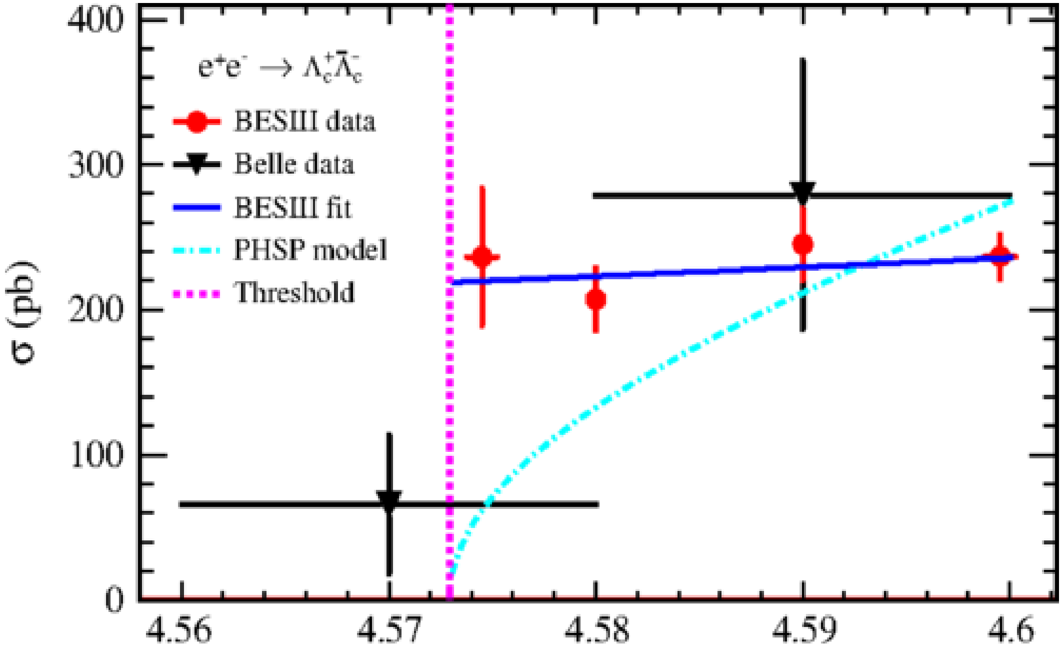
$\Delta\Phi = 42^o \pm 16^o(stat.) \pm 8^o(sys.) \pm 6^o(\alpha_\Lambda)$

The statistical significance of $\Delta\Phi$ is 4.3σ. **First measurement of $\Delta\phi$**

Λ_c form factors near threshold



$e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ near threshold Phys. Rev. Lett. 120, 132001 (2018)



√s=**4574.5**, 4580.0, 4590.0 and **4599.5** MeV

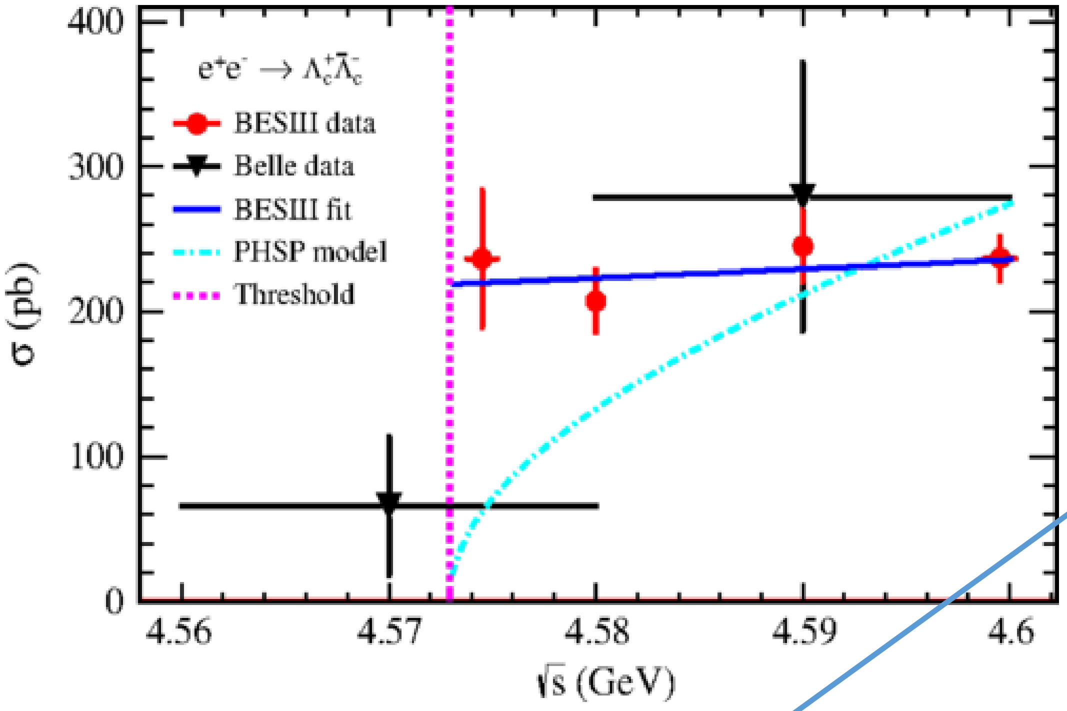
$|G_E/G_M|$:

$\mathbf{1.14 \pm 0.14 \pm 0.07}$

$\mathbf{1.23 \pm 0.05 \pm 0.03}$

- At thr there is indeed a step in $\sigma(e^+ e^- \to \Lambda_c \Lambda_{cbar})$,
- Followed by a kind of a plateau
- At thr $\sigma(e^+ e^- \to \Lambda_c \Lambda_{cbar})$ is close to the pointlike value, once the Coulomb enhancement factor is taken into account: $\sigma(e^+ e^- \to \Lambda_c \Lambda_{cbar})_{pointl} \approx \pi^2\alpha^3/(2M_B^2) \approx 145$ pb

$e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ near threshold **Phys. Rev. Lett. 120, 132001 (2018)**



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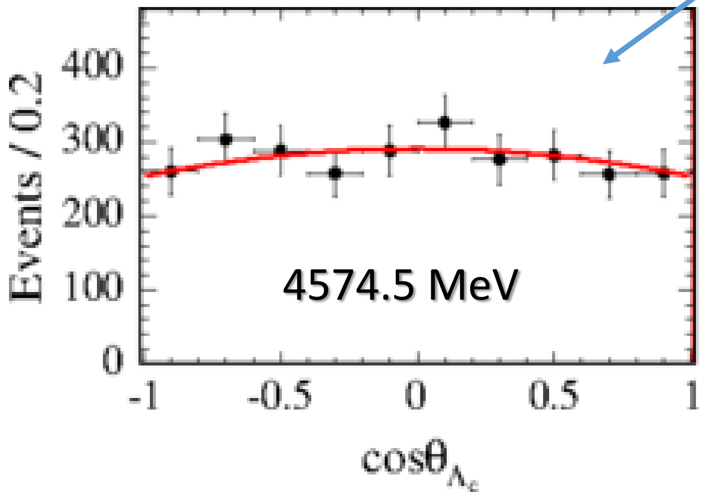
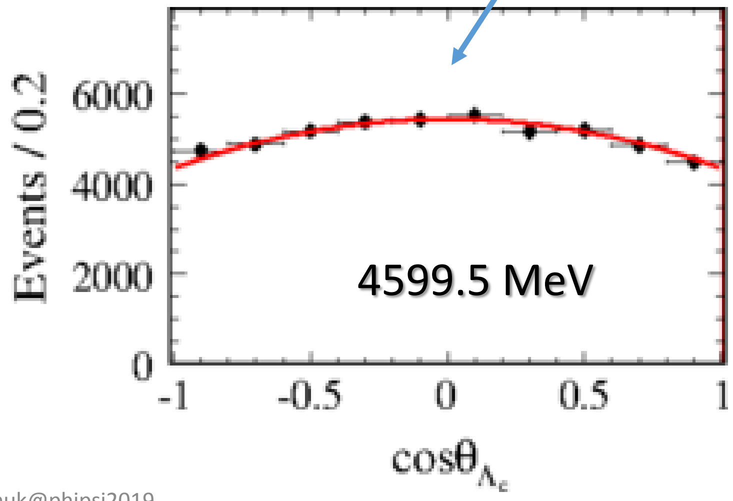
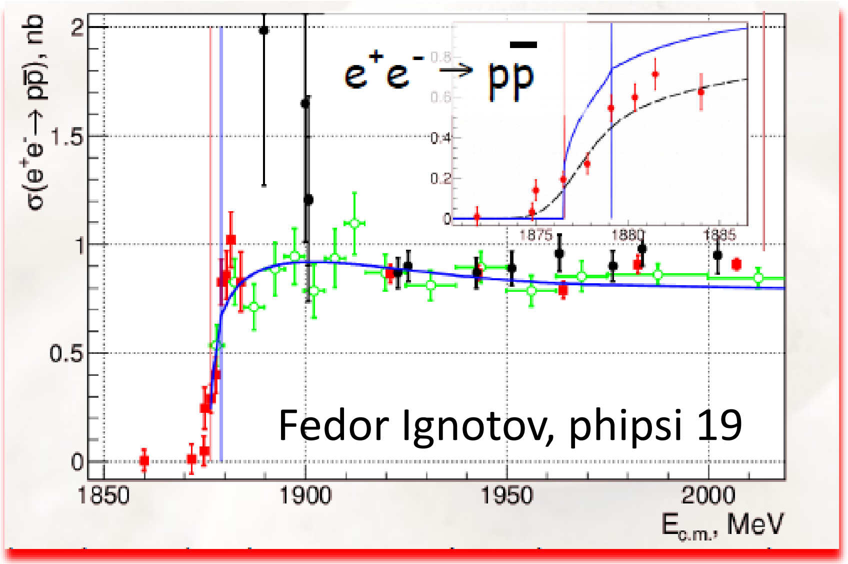


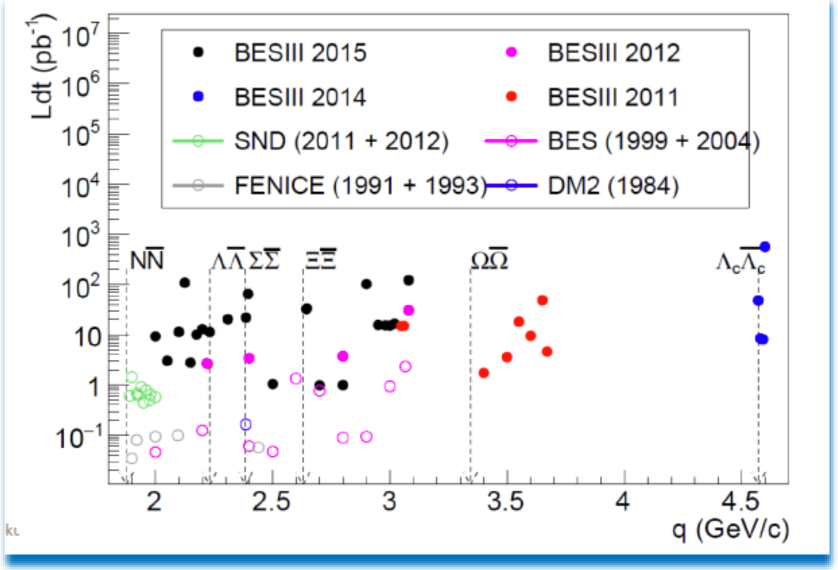


Summary and outlook (I)

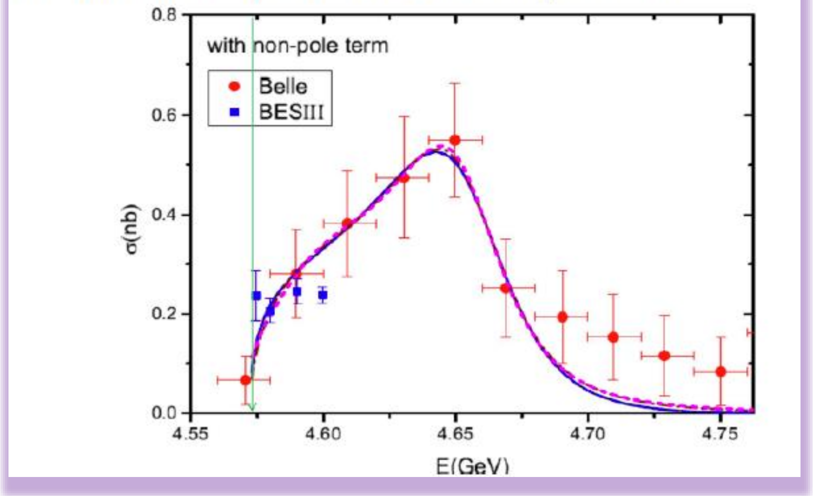
- Proton form factors have been measured at BESIII with ISR and scan technique
  - Result in significantly improved precision
  - Some novel/unexpected features observed/confirmed
- Λ form factors with relative phase between G_E and G_M first time
- Λ_c effective form factors and $|G_E/G_M|$ near threshold

Summary and outlook (II)





BESIII data up to 4.9 GeV expected.



- Will come
  - Proton form factors with varied technique (Ecm<2GeV)
  - Form factors of other baryons, such as neutron (will be released soon), Ω, Σ, Ξ, as well as polarizations
  - Λ_c form factors at higher energy

Thanks for your attention!

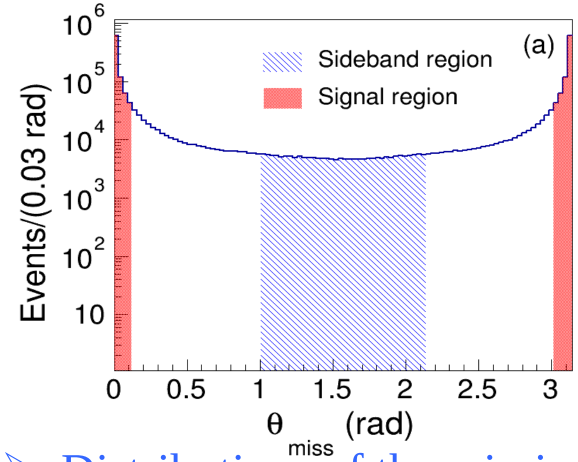
Backup

Background estimation based on Sideband method

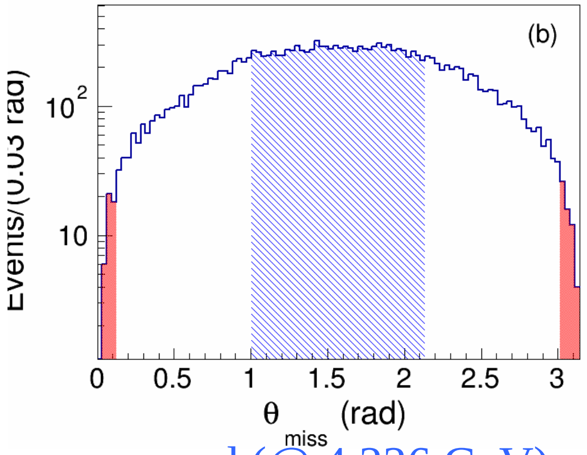
- Angular distributions of the missing momentum (@ 4.226 GeV):

Un-tag ISR

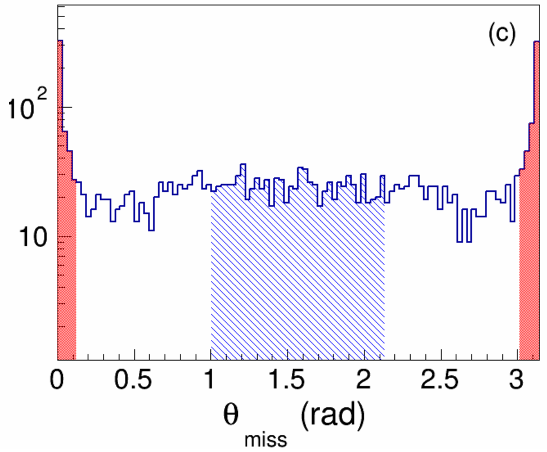
Signal MC $e^+e^- \to p\bar{p}g_{ISR}$



Bkg. MC $e^+e^- \to p\bar{p}p^0$

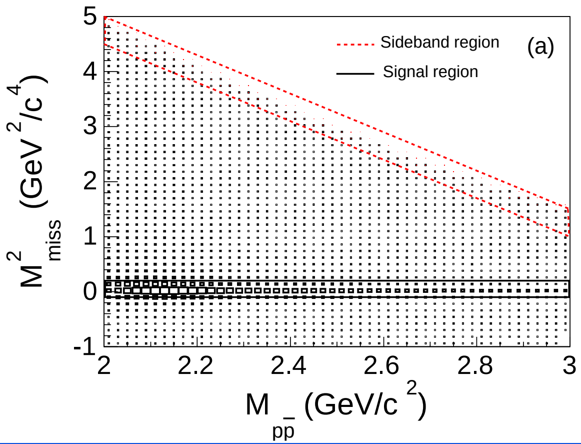


BESIII data

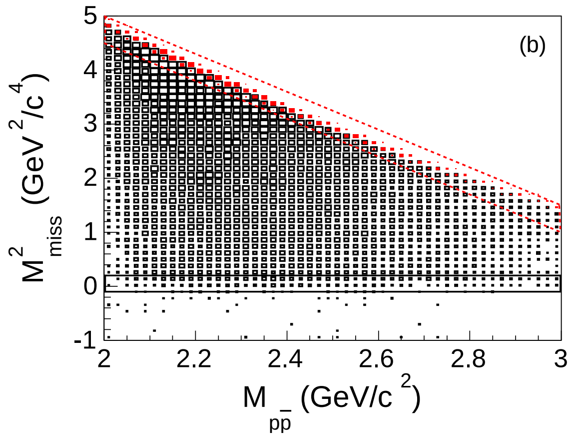


- Distributions of the missing mass squared (@ 4.226 GeV):

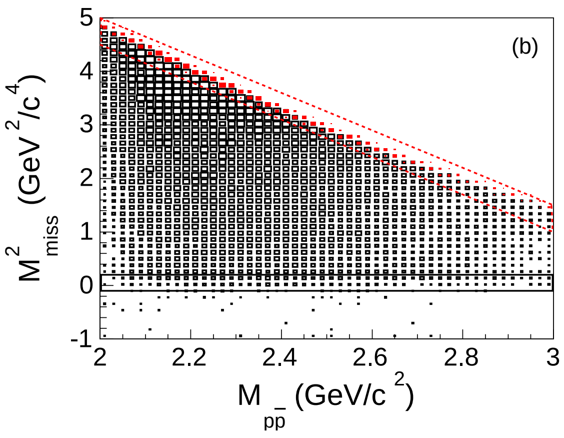
Signal MC $e^+e^- \to p\bar{p}g_{ISR}$



Bkg. MC from two-photon channel

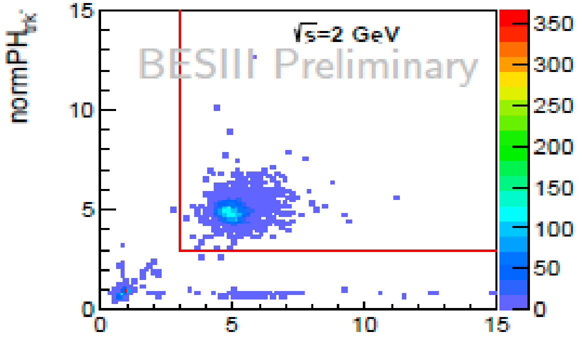


BESIII data

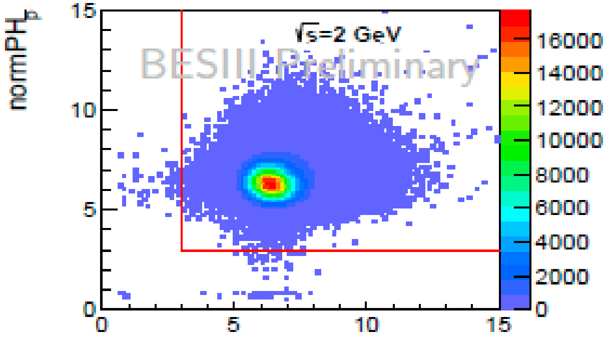


Scan data (selection I)

- Particle identification
  - At (2.0~2.15) GeV, use normalized pulse height,
  - At (2.175~3.08) GeV, use dE/dx and TOF.

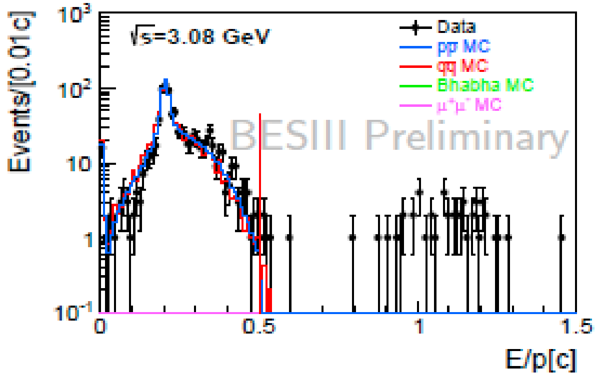


(a) Data

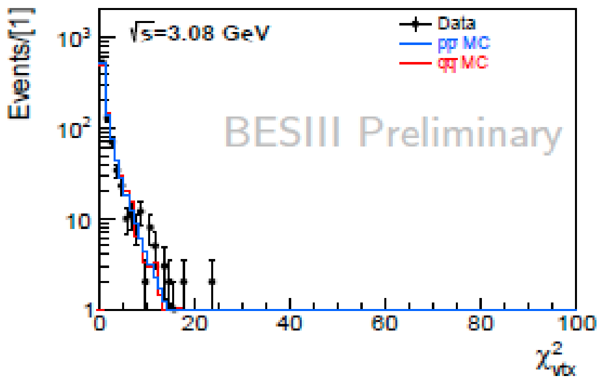


(b) MC

- Use E/p criteria.



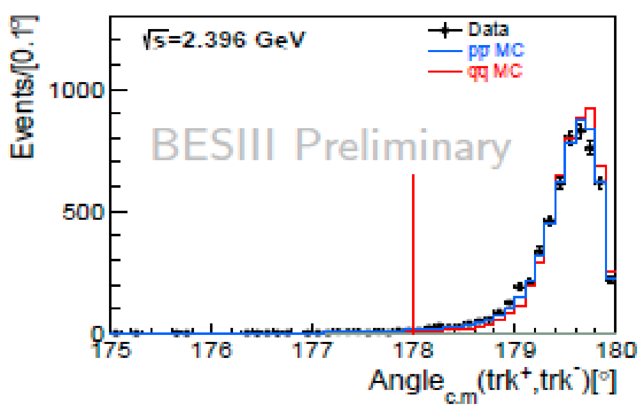
- Vertex fit.

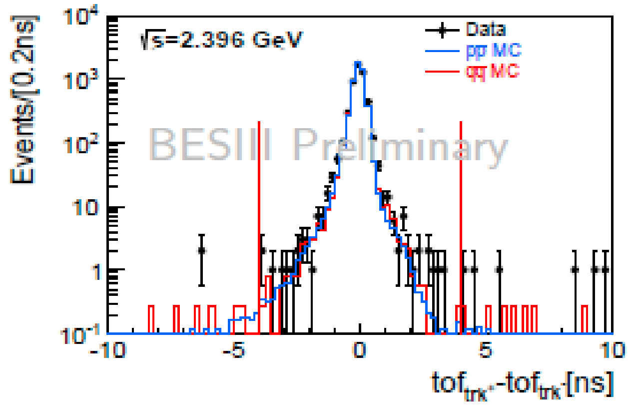


*The red line is $p\bar{p}$ signal events selected from the $q\bar{q}$ samples.

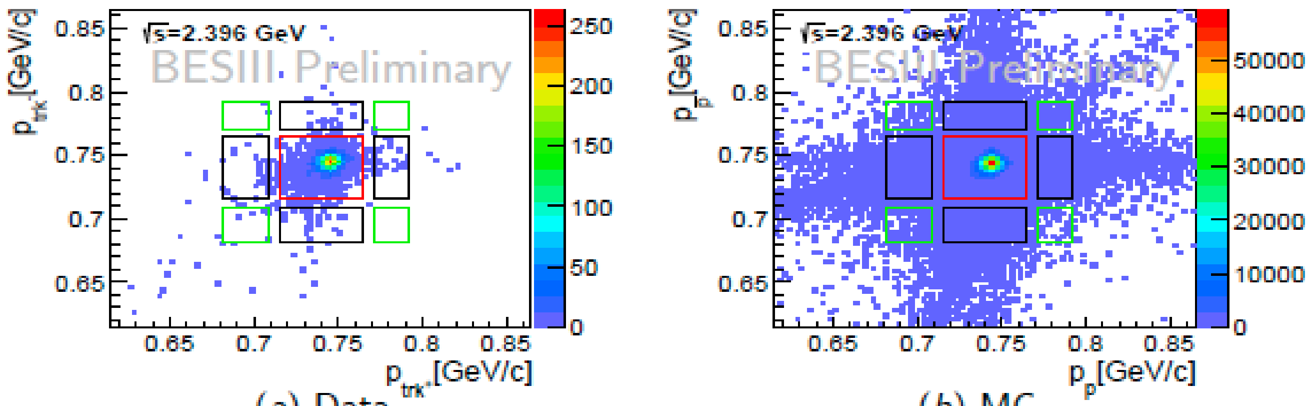
Scan data (selection II)

- Require angle between p and $\bar{p}$ in center-of-mass criteria.
- Require TOF information.





- Momentum window for p and $\bar{p}$:

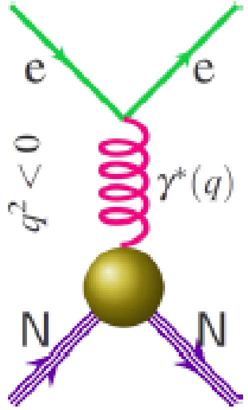


(a) Data (b) MC

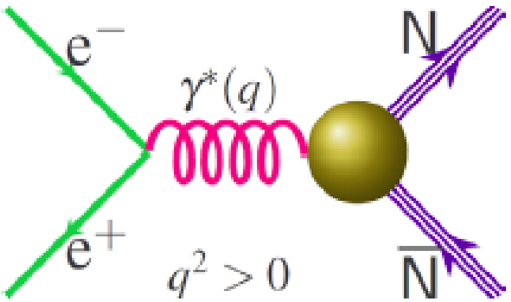
Electromagnetic Form Factors

$eN \longrightarrow eN$

Space-like:
FF real



$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, ...$



Time-like:
FF complex

Vector current, **two form factors** (F_1 and F_2)

$$\Gamma_\mu = e\bar{u}(p')[F_1(q^2)\gamma_\mu + \frac{\kappa}{2M_N}F_2(q^2)i\sigma_{\mu\nu}q^\nu]u(p)e^{iqx}$$

Dirac	**Pauli**
$F_1^p(q^2=0)=1$	$F_2^p(q^2)=1$
$F_1^n(q^2=0)=0$	$F_2^n(q^2)=1$

Sachs

$$G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

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

Baryon-pair production near threshold

➢ The Born cross section for $e^+e^- \to \gamma^* \to B\bar{B}$, can be expressed in terms of electromagnetic form factor G_E and G_M :

$$\sigma_{B\bar{B}}(m) = \frac{4\pi\alpha^2 C\beta}{3m^2}\left[|G_M(m)|^2 + \frac{1}{2\tau}|G_E(m)|^2\right]$$

$\alpha = \frac{1}{137}$ is fine structure constant, $\beta = \sqrt{1 - 4m_B^2/m^2}$ is the velocity, $\tau = m^2/4m_B^2$

➢ The Coulomb factor C= $\begin{cases} \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})} & \text{for a charged } B\bar{B} \text{ pair} \\ 1 & \text{for a neutral } B\bar{B} \text{ pair} \end{cases}$

➢ For the neutral pair production, the cross section should be 0 at threshold, and is expected to increase with the velocity near the threshold.