Fix the phase angles in proton electromagnetic form factors from charge asymmetry distribution in process $e^+e^- \to \gamma p\bar{p}$ at BESIII

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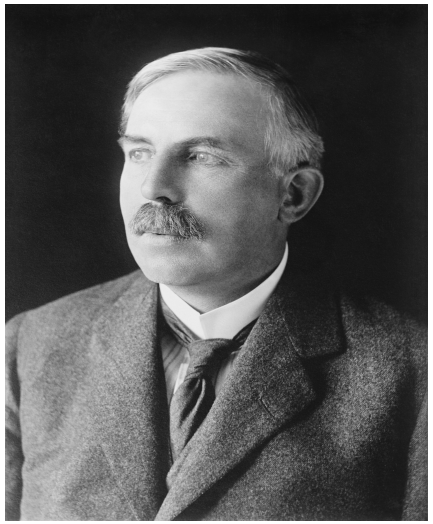
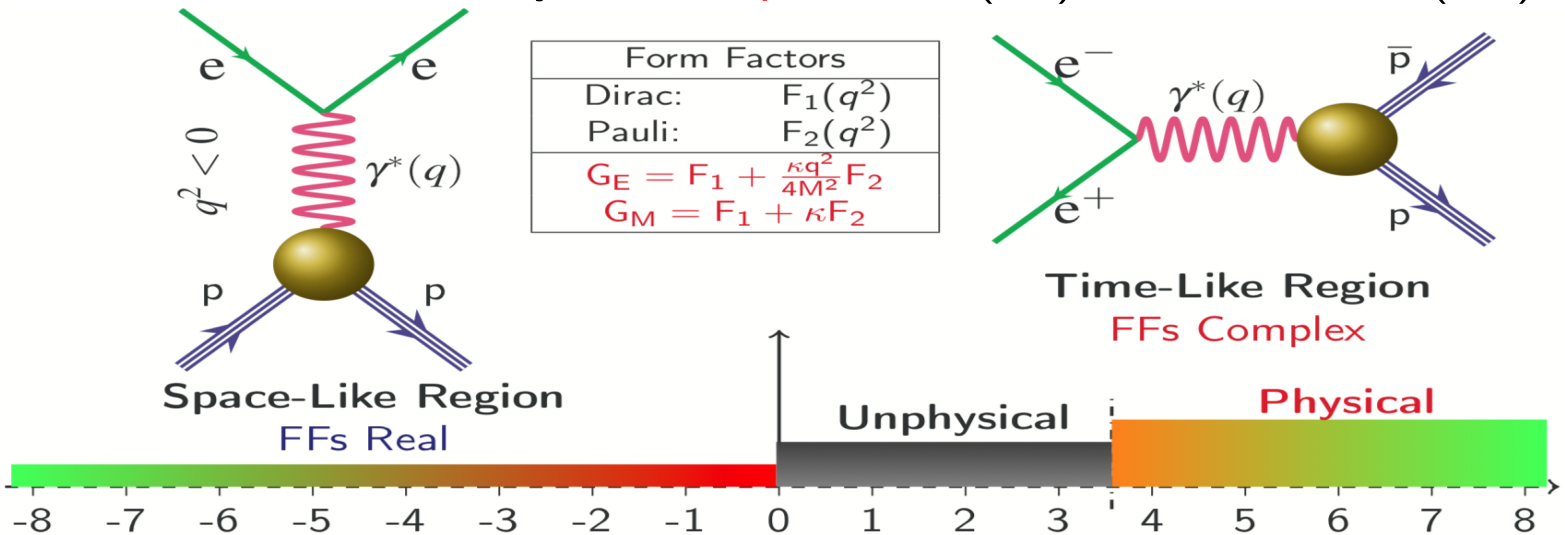
Outline



Baryon Form Factors

- Fundamental properties of the nucleon:
  - Connected to charge, magnetization distribution,
  - Crucial testing ground for models of the nucleon internal structure.
- Measurement of baryon FF: Space-like (SL) and Time-like (TL).



- The nucleon electromagnetic vertex Γ_μ describing the hadron current:

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

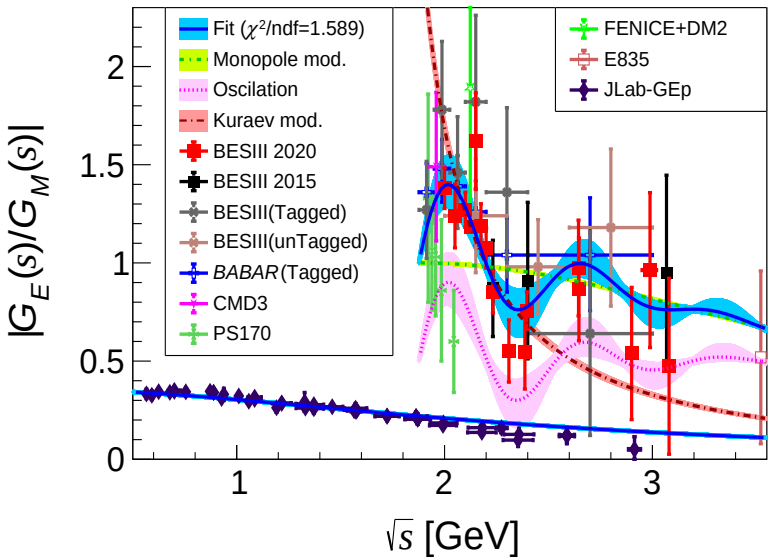
- Sachs FFs in TL:

$$\text{Electron FF: } G_E(q^2) = e^{-i\theta_2}[F_1(q^2) + \tau\kappa_p F_2(q^2)]$$

$$\text{Magnet FF: } G_M(q^2) = e^{-i(\theta_1+\theta_2)}[F_1(q^2) + \kappa_p F_2(q^2)]$$

Complex form of EMFFs: *holy grail* of time-like form factors of proton –Achim Denig

- History of TLFF measurements:
  - Numerous measurements historically, mostly assuming $|G_{\text{eff}}| = |G_E| = |G_M|$ due to limited statistics.



  - Separate measurements of $|G_E|$ and $|G_M|$ achieved only in the last 15 years (J. P. Lee *et al.* (*BABAR* collaboration), PRD **87**, 092005 (2013)).
  - First precise measurement of $|G_E|$ and $|G_M|$ in the range 2.00-3.08 GeV reported in 2020 (M. Ablikim *et al.* (BESIII Collaboration), PRL **124**, 042001 (2020), Lei Xia *et al.*, Symmetry **14**, 231 (2022)).
  - First observation of charge asymmetry (A_C) caused by two-photon exchange (TPE) in 2024 (M. Ablikim *et al.* (BESIII Collaboration), BAM-00575).
- Challenges in complex TLFF measurements:
  - Protons cannot decay, limiting the direct measurement approaches.
  - No polarization proton.
  - Measurements can only determine the module of $|G_E|$ and $|G_M|$.

The key process: high order of the process of $e^+e^- \to p\bar{p}$

- Strategy 1: TPE:

$$\begin{aligned}\frac{\mathrm{d}\sigma^{\mathrm{tot}}_{p\bar{p}}}{\mathrm{d}\cos\theta} &= \frac{\pi\alpha^2\beta C}{2q^2}\left\{|G_M|^2 + \frac{4m_p^2c^4}{q^2}|G_E|^2 + 2\left(\mathcal{R}(G_M\Delta G_M) + \frac{4m_p^2c^4}{q^2}\mathcal{R}(G_E\Delta G_E)\right)\right. \\ &\quad - \left[|G_M|^2 - \frac{4m_p^2c^4}{q^2}|G_E|^2 + 2\left(\mathcal{R}(G_M\Delta G_M) - \frac{4m_p^2c^4}{q^2}\mathcal{R}(G_E\Delta G_E)\right)\right]\cos^2\theta \\ &\quad - \frac{q}{2m_p^2c^4}\sqrt{q^2-4m_p^2c^4}\,\mathcal{R}\left((|G_M|^2 - \frac{4m_p^2c^4}{q^2}|G_E|^2)\Delta F_3^*\right)\cos\theta \\ &\quad \left. + \frac{q}{2m_p^2c^4}\sqrt{q^2-4m_p^2c^4}\,\mathcal{R}\left((|G_M|^2 - \frac{4m_p^2c^4}{q^2}|G_E|^2)\Delta F_3^*\right)\cos^3\theta\right\} \\ &= b_0(q^2) + b_1(q^2)\cos\theta + b_2(q^2)\cos^2\theta - b_1(q^2)\cos^3\theta,\end{aligned}$$

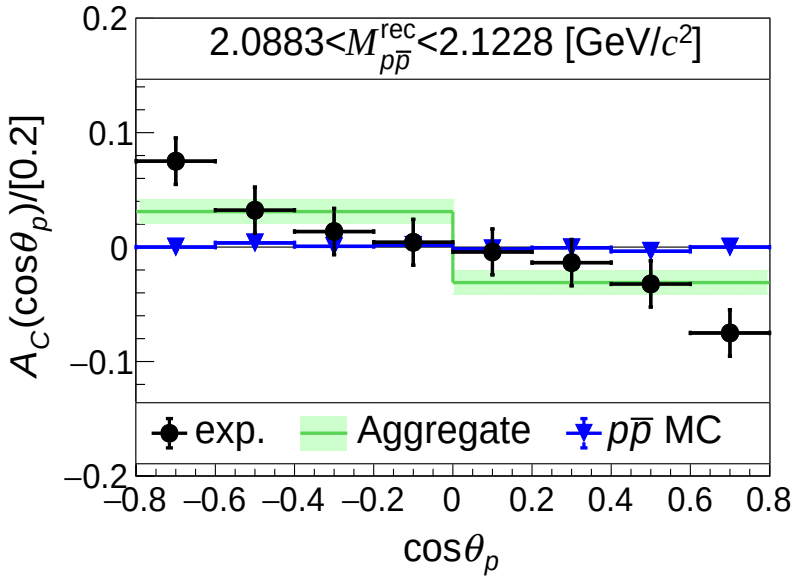
- Strategy 2: Radiation process: $e^+e^- \to \gamma p\bar{p}$:

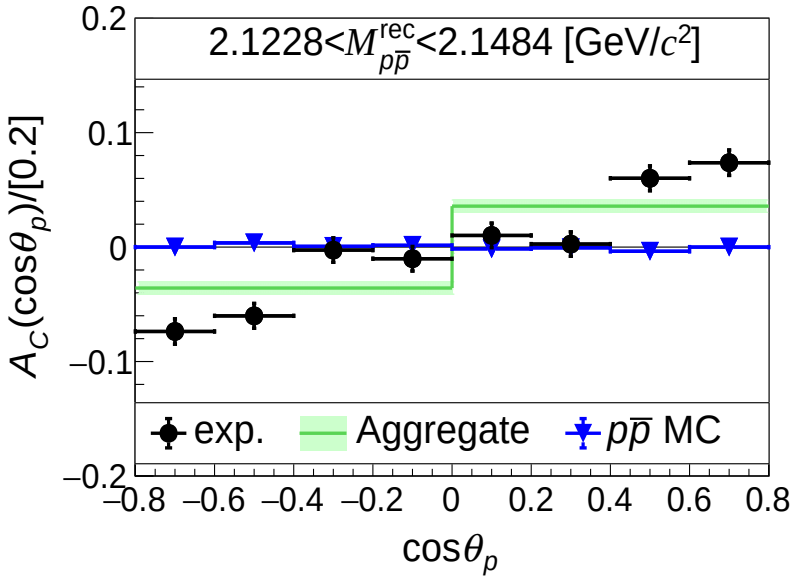
$$\mathrm{d}\sigma_{\gamma p\bar{p}} = \mathrm{d}\sigma^{\mathrm{ISR}}_{\gamma p\bar{p}} + \mathrm{d}\sigma^{\mathrm{FSR}}_{\gamma p\bar{p}} + \mathrm{d}\sigma^{\mathrm{IFI}}_{\gamma p\bar{p}},$$

  - $\mathrm{d}\sigma^{\mathrm{ISR}}_{\gamma p\bar{p}}$: no relation with phase angles, $\mathrm{d}\sigma^{\mathrm{FSR}}_{\gamma p\bar{p}}$: small.
  - $\mathrm{d}\sigma^{\mathrm{IFI}}_{\gamma p\bar{p}}$: the $p\bar{p}$ is produced with charge asymmetry (A_C): $C = -1$ (ISR), $C = +1$ (FSR).
  - $A_C \to$ Final states charge parity transformation:

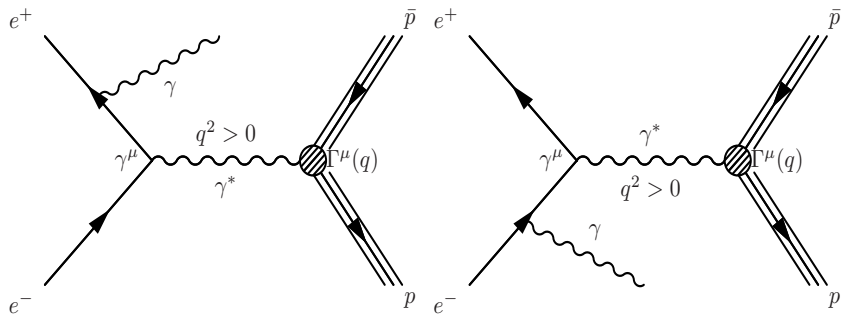
$$\mathrm{d}\sigma^{\mathrm{IFI}}_{\gamma p\bar{p}} = -\,\mathrm{d}\sigma^{c(FSR)}_{\gamma p\bar{p}}.$$

The key process: high order of the process of $e^+e^- \to p\bar{p}$

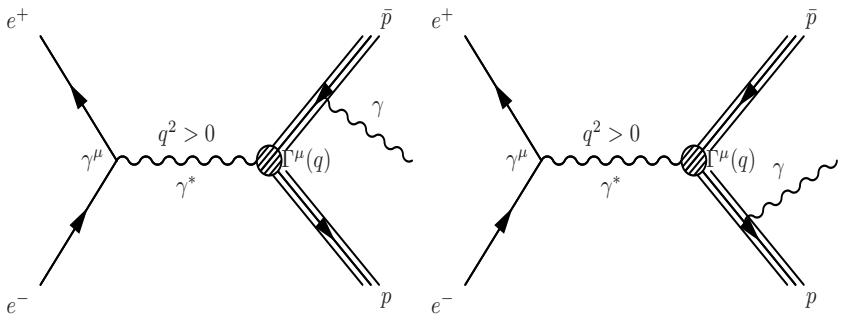




- Strategy 1: TPE: under planning.



(a): ISR

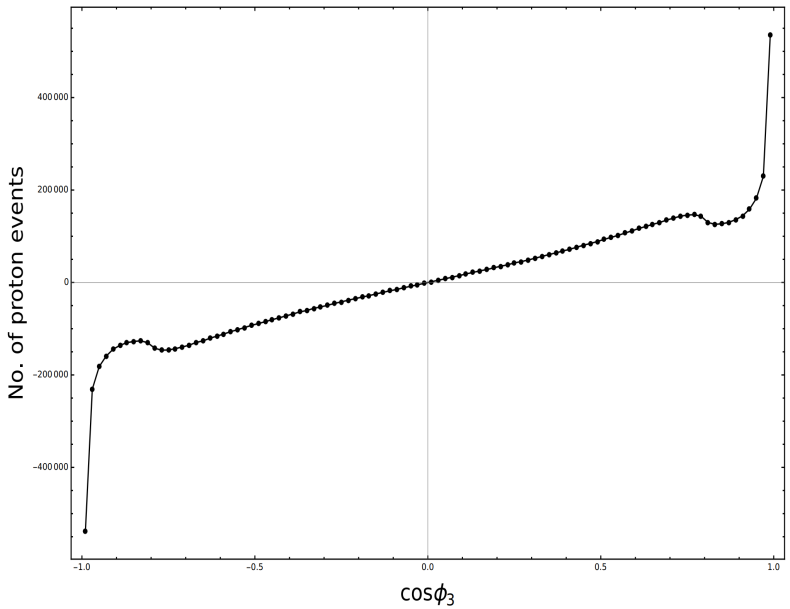


(b): FSR

- Strategy 2: Radiation process: $e^+e^- \to \gamma p\bar{p}$: This work.

The interference term

- A_C is a kind of forward-backward asymmetry (A_{FB}) and the cancellation is happened in the phase space.



$$\cos\phi_3 = \frac{(\mathbf{p}_e\times\mathbf{p}_\gamma)\cdot(\mathbf{p}_p\times\mathbf{p}_\gamma)}{|\mathbf{p}_e\times\mathbf{p}_\gamma||\mathbf{p}_p\times\mathbf{p}_\gamma|},$$

$$\cos\phi_3{}^C = \cos\phi_3.$$

- Do the final states charge parity transformation:

$$\cos\phi_3{}^{c(\mathrm{IFI})} = \frac{(\mathbf{p}_e\times\mathbf{p}_\gamma)\cdot[(-\mathbf{p}_p-\mathbf{p}_\gamma)\times\mathbf{p}_\gamma]}{|\mathbf{p}_e\times\mathbf{p}_\gamma||(-\mathbf{p}_p-\mathbf{p}_\gamma)\times\mathbf{p}_\gamma|},$$

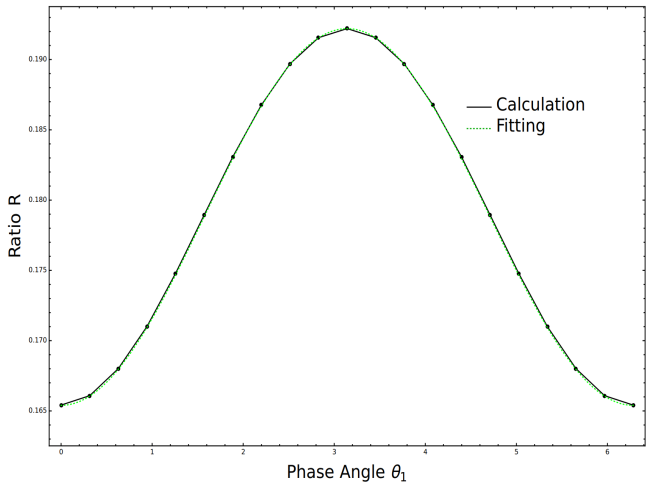
$$= -\cos\phi_3.$$

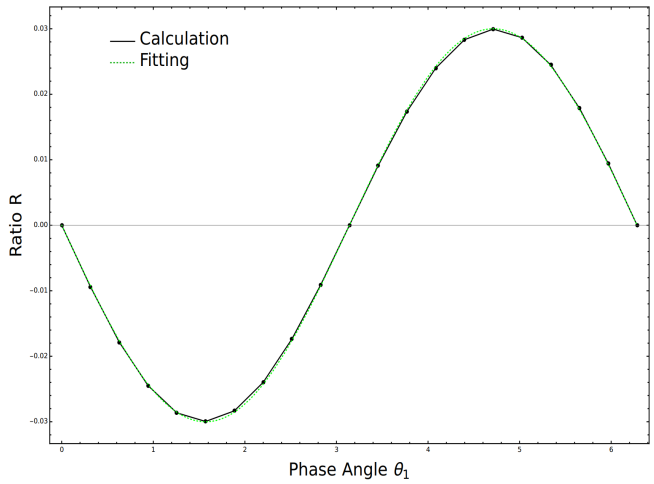
- From A_C: $\mathrm{d}\sigma^{\mathrm{IFI}}_{\gamma p\bar{p}} = -\,\mathrm{d}\sigma^{c(\mathrm{FSR})}_{\gamma p\bar{p}}$, we can obtain:

$$\mathrm{d}\sigma^{\mathrm{IFI}}_{\gamma p\bar{p}}(\cos\phi_3) = -\,\mathrm{d}\sigma^{\mathrm{IFI}}_{\gamma p\bar{p}}(-\cos\phi_3).$$

  - The C parity asymmetry or $A_{FB} \neq$ C parity violation.
  - To test C parity conservation:

$$\cos\beta = \frac{\mathbf{p}_e\cdot\mathbf{p}_\gamma}{|\mathbf{p}_e||\mathbf{p}_\gamma|}.$$





- Defining a value to reveal this asymmetry:

$$\sigma'^{\mathrm{IFI}}_{\gamma p\bar{p}} = \sigma^{\mathrm{IFI}}_{\gamma p\bar{p}}(\cos\phi_3 > 0) - \sigma^{\mathrm{IFI}}_{\gamma p\bar{p}}(\cos\phi_3 < 0).$$

Meanwhile, $\sigma^{\mathrm{ISR}}_{\gamma p\bar{p}}(\cos\phi_3 > 0) - \sigma^{\mathrm{ISR}}_{\gamma p\bar{p}}(\cos\phi_3 < 0) = 0$,
and $\sigma^{\mathrm{FSR}}_{\gamma p\bar{p}}(\cos\phi_3 > 0) - \sigma^{\mathrm{FSR}}_{\gamma p\bar{p}}(\cos\phi_3 < 0) = 0$.

- Now, one can define a ratio:

$$A_{FB} = \frac{\sigma_{\gamma p\bar{p}}(\cos\phi_3 > 0) - \sigma_{\gamma p\bar{p}}(\cos\phi_3 < 0)}{\sigma_{\gamma p\bar{p}}(\cos\phi_3 > 0) + \sigma_{\gamma p\bar{p}}(\cos\phi_3 < 0)}.$$

which represents the asymmetry.

Data sets

- Boss version: BOSS 6.6.5.p01, 6.6.4.p01, 7.0.3, 7.0.8.
- Data sets
  - 2012 and 2015 R-scan data (M. Ablikim *et al.*, CPC **41**, 063001 (2017)).
  - 2015 Y(2175) data (M. Ablikim *et al.*, CPC **41**, 113001 (2017)).
  - 2017-χ_{cJ} data (M. Ablikim *et al.*, PRL **129**, 122001 (2022)).
- The integrated luminosity of the analyzed data sets is quoted here.

$\sqrt{s}$ [GeV]	Run No.	Lumi [pb^{-1}]	$\sqrt{s}$ [GeV]	Run No.	Lumi [pb^{-1}]
2.0000	41729-41909	10.1 ± 0.1	2.9500	39619-39650	15.9 ± 0.1
2.0500	41911-41958	3.34 ± 0.03	2.9810	39651-39679	16.1 ± 0.1
2.1000	41588-41727	12.2 ± 0.1	3.0000	39680-39710	15.9 ± 0.1
2.1250	42004-43253	108 ± 1	3.0200	39711-39738	17.3 ± 0.1
2.1500	41533-41570	2.84 ± 0.02	3.0800	27147-27233, 28241-28266,	31.0 ± 0.2
2.1750	41416-41532	10.6 ± 0.1		39355-39618,	126 ± 1
2.2000	40989-41121	13.7 ± 0.1		54982-55053, 59016-59141	136 ± 1
2.2324	28624-28648,	2.65 ± 0.02	3.4900	47467-47493	$12.11 \pm 0.01 \pm 0.07$
	41122-41239	11.9 ± 0.1	3.5080	51657-51893	$181.79 \pm 0.04 \pm 1.04$
2.3094	41240-41411	21.1 ± 0.1	3.50967	51584-51656	$39.29 \pm 0.02 \pm 0.22$
2.3864	40806-40951	22.5 ± 0.2	3.51039	51894-52090	$183.64 \pm 0.04 \pm 1.05$
2.3960	40459-40769	66.9 ± 0.5	3.51458	52298-52332	$40.92 \pm 0.02 \pm 0.23$
2.6444	40128-40296	33.7 ± 0.2	3.7737	11414-13988, 14395-14604,	$2931.8 \pm 0.2 \pm 13.8$
2.6464	40300-40435	34.0 ± 0.3		20448-23454,	
2.9000	39775-40069	105 ± 1		70522-73929	

Event selections

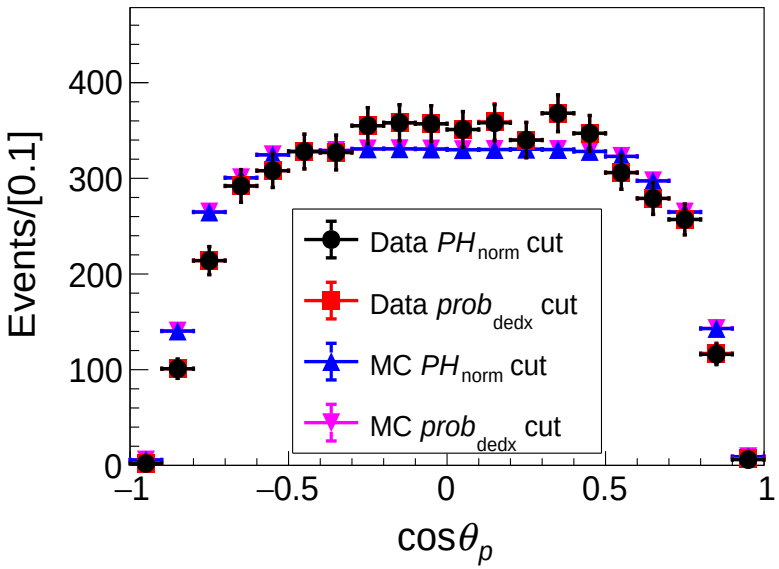
- Good charged tracks:

$$V_r < 1 \text{ cm}, \ |V_z| < 10 \text{ cm and } |\cos\theta| < 0.93.$$

- Charged tracks in a good event:

$$N_{\text{Good}} = 2, \ N_{\text{Charge}} = 0.$$

- Particle identification:



- $0.00 < p_{trk\pm} < 0.36$ GeV/c, use dE/dx, $Prob(p) + 0.00002 > Prob(e, \pi, K)$;
- $0.36 \leq p_{trk\pm} < 0.5$ GeV/c, use dE/dx, $Prob(p) + 0.00001 > Prob(e, \pi, K)$;
- $p_{trk\pm} > 0.5$ GeV/c, use dE/dx and TOF, $Prob(p) > Prob(e, \pi, K)$.

- To veto Bhabha, for positive track, require:

$$E_{trk^+}/p_{trk^+}c < 0.5.$$

If there is no valid EMC information, the event is kept for further selection, but discarded for $p_{trk^+} > 1.2$ GeV/c.

Event selections

- Good neutral tracks:

$$E_\gamma > 25 \text{ MeV (barrel)}, \ E_\gamma > 50 \text{ MeV (endcap)},$$
$$0 < t(50\ ns) < 14.$$

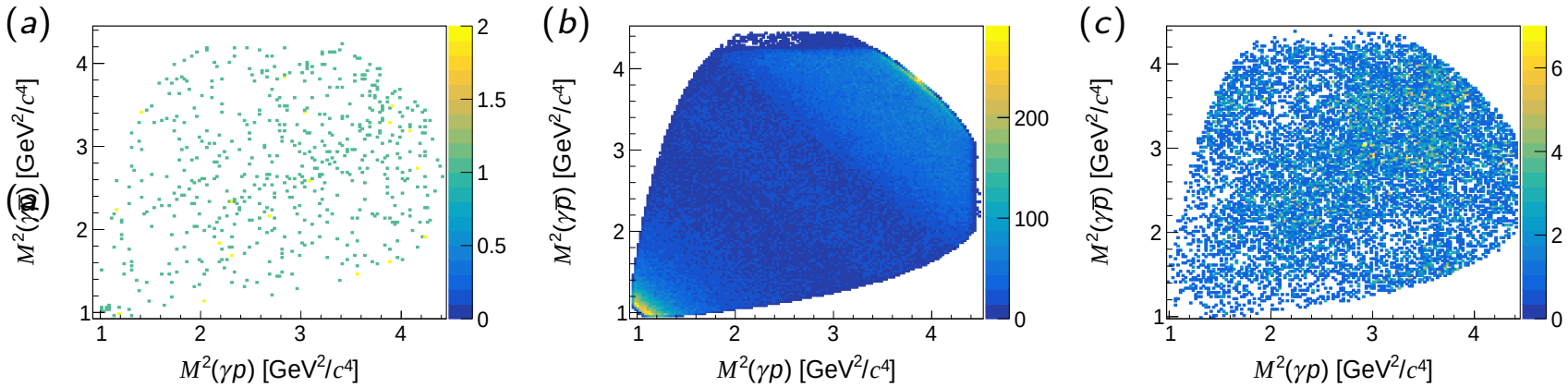
- Neutral tracks in a good event:

$$N_{\text{neutral}} \geq 1.$$

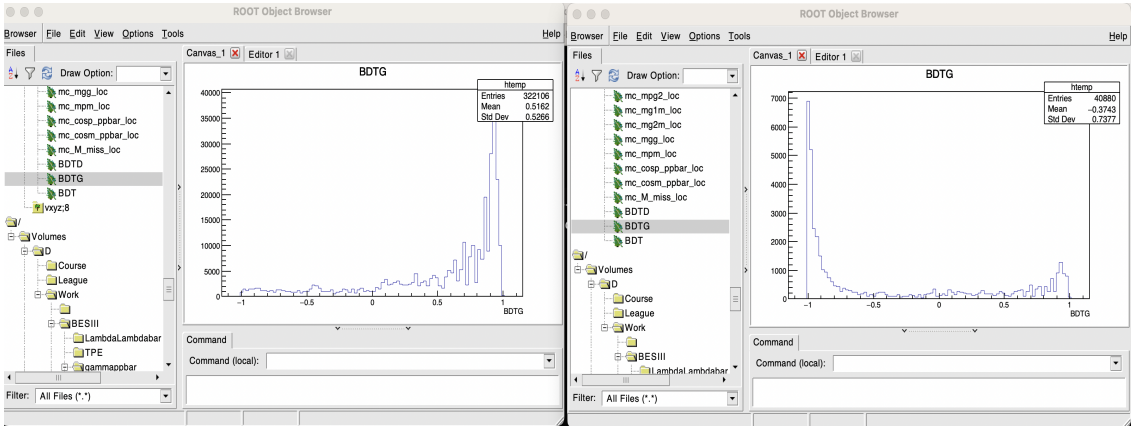
- Vertex fit for $trk^{\pm}$ to improve momentum resolution: $\chi^2_{\text{vtx}} < 100$.
- Four-constraint (4C) kinematic fit required, $\chi^2_{\text{4C}} < 200$.
- Five-constraint (5C) kinematic for $p\bar{p}\pi^0/\eta$, $\chi^2_{\text{5C}} > 25$.
- One-constraint (1C) kinematic for $\gamma J/\psi \to \gamma p\bar{p}$, $\chi^2_{\text{1C}} > 25$.
- To veto $p\bar{p}$ born events, require $\theta_{trk^+trk^-}$ in center-of- mass:
  $\theta_{trk^+trk^-} < 175^\circ$ at 2 GeV, $\theta_{trk^+trk^-} < 175.5^\circ$ at 2.05 GeV,
  $\theta_{trk^+trk^-} < 176^\circ$ at 2.1-2.2 GeV, $\theta_{trk^+trk^-} < 176.5^\circ$ at 2.2324 GeV,
  $\theta_{trk^+trk^-} < 177^\circ$ at 2.3094-2.3960 GeV,
  $\theta_{trk^+trk^-} < 177.5^\circ$ at 2.5-2.7 GeV, $\theta_{trk^+trk^-} < 178^\circ$ at 2.80-3.08 GeV,
  $\theta_{trk^+trk^-} < 178.5^\circ$ at 3.080-3.773 GeV.
  to archive $N_{p\bar{p}}/N_{\gamma p\bar{p}} < 2\%$.

Background Reduction

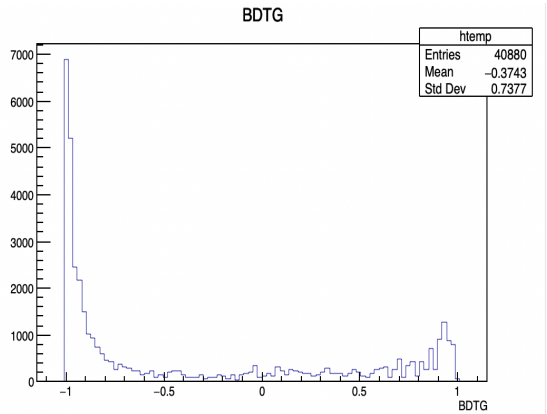
- Dalitz plots: (a) Data, (b) Sigbal MC, (c) $p\bar{p}\pi^0$ MC.



- TMVA: BDTG. (a) 2.1000 GeV, (b) 2.9000 GeV, (c) 3.0800 GeV.
- Combine of χ^2 of 5C $p\bar{\pi}^0$, χ^2 of 1C $\pi^0 \to \gamma\gamma$, angle of $p\bar{p}$, $\sqrt{s} - M_{p\bar{p}}c^2$.



(c)

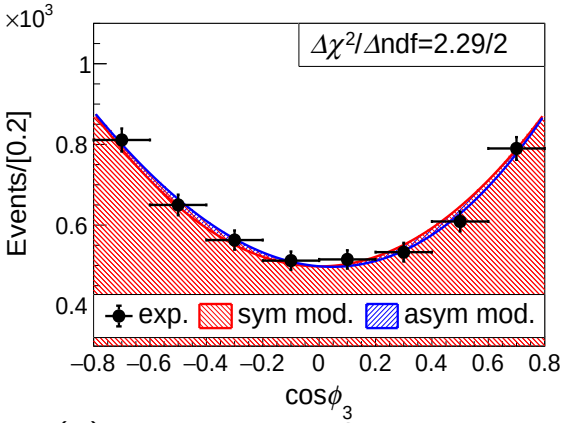


Background study

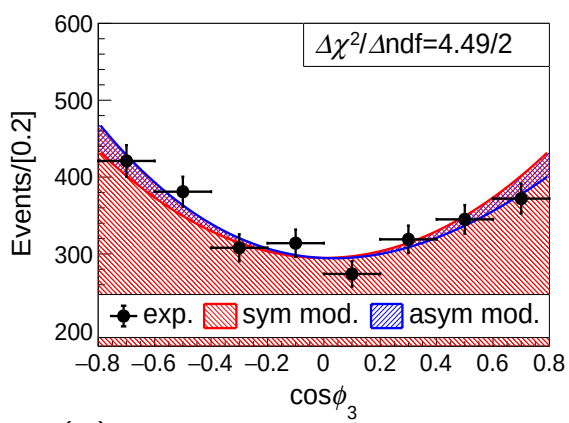
$\sqrt{s}$ [GeV]	Bhabha		Dimu		$p\bar{p}$ Born		$p\bar{p}\pi^0$		Other $q\bar{q}$	
	N_{gen}	N_{sur}	N_{gen}	N_{sur}	N_{gen}	N_{sur}	N_{gen}	N_{sur}	N_{gen}	N_{sur}
2.0000	18550000	0	250000	0	5000000	2	0	0	1740000	0
2.0500	5900000	0	100000	0	5000000	144	5000000	0	900000	0
2.1000	20300000	0	250000	0	5000000	342	5000000	87	1860000	0
2.1250	176850000	7	2200000	0	5000000	446	5000000	180	12300000	0
2.1500	4550000	0	100000	0	5000000	514	5000000	309	800000	0
2.1750	16600000	0	250000	0	5000000	546	5000000	545	1600000	0
2.2000	20800000	0	300000	0	5000000	696	5000000	701	1880000	0
2.2324	17550000	0	250000	0	5000000	1513	5000000	1479	1660000	0
2.3094	29100000	2	400000	0	5000000	3840	5000000	3069	2440000	0
2.3864	29250000	0	400000	0	5000000	3663	5000000	4440	2440000	0
2.3960	85900000	0	1050000	0	5000000	3598	5000000	4577	6200000	0
2.5000	1300000	0	50000	0	5000000	4193	5000000	4104	700000	0
2.6444	35500000	0	450000	0	5000000	3470	5000000	5457	2860000	0
2.6464	35900000	0	450000	0	5000000	3403	5000000	5392	2880000	0
2.7000	1050000	0	50000	0	5000000	3035	5000000	5518	700000	0
2.8000	950000	0	50000	0	5000000	9977	5000000	6845	700000	0
2.9000	92800000	0	1150000	0	5000000	10738	5000000	6876	6620000	0
2.9500	13550000	0	200000	0	5000000	11524	5000000	7108	1400000	0
2.9810	13400000	0	200000	0	5000000	10535	5000000	7183	1380000	0
3.0000	14250000	0	200000	0	5000000	10913	5000000	7389	1360000	0
3.0200	14050000	0	200000	0	5000000	10450	5000000	7440	1420000	0
3.0800	98350000	0	1250000	0	5000000	10773	5000000	6936	6680000	0

Asymmetry of the distribution of $\cos\phi_3$

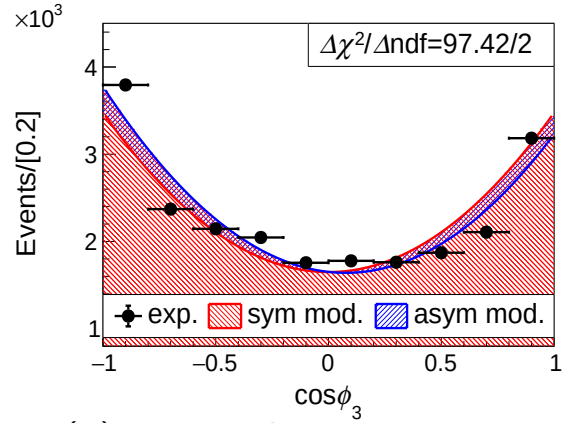
- We have confirmed the asymmetry in $\cos\phi_3$ distribution of the process $e^+e^- \to \gamma p\bar{p}$.



(a) 2.000-3.080 GeV, 1.0σ.



(b) 3.400-3.671 GeV, 1.6σ.



(c) 3.7737 GeV, 9.6σ.

- Fit of $\cos\phi_3$ in symmetric asymmetric model:
  - Symmetric model:

$$\frac{\mathrm{d}\sigma^{\mathrm{sym}}_{\gamma p\bar{p}}}{\mathrm{d}\cos\phi_3} = a_0(q^2) + a_2(q^2)\cos^2\phi_3.$$

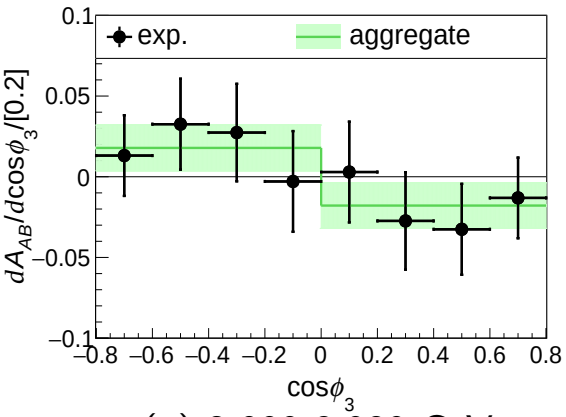
  - Asymmetric model:

$$\frac{\mathrm{d}\sigma^{\mathrm{asym}}_{\gamma p\bar{p}}}{\mathrm{d}\cos\phi_3} = a_0(q^2) + a_1(q^2)\cos\phi_3 + a_2(q^2)\cos^2\phi_3 + a_3(q^2)\cos^3\phi_3.$$

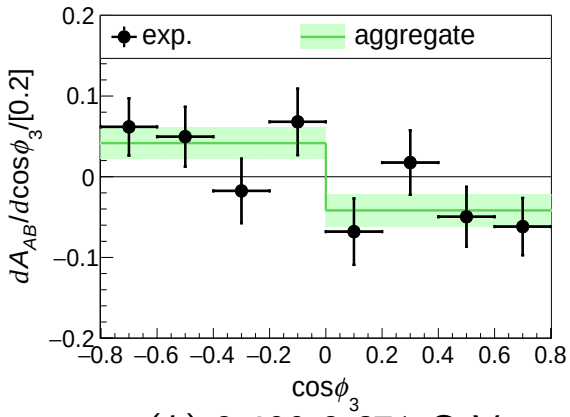
Forward-Backward asymmetry

- Forward-Backward asymmetry:

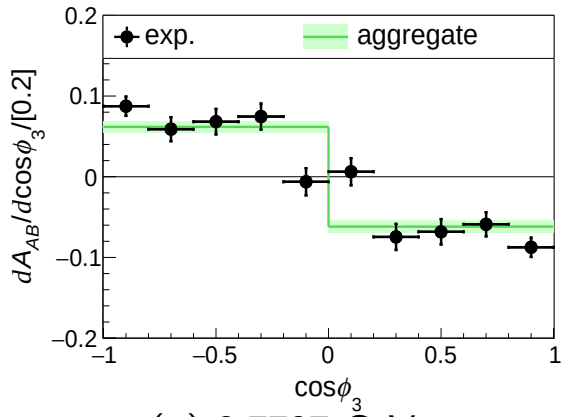
$$\frac{\mathrm{d}A_{FB}}{\mathrm{d}\cos\phi_3} = \frac{\mathrm{d}\sigma_{\gamma p\bar{p}}(\cos\phi_3) - \mathrm{d}\sigma_{\gamma p\bar{p}}(-\cos\phi_3)}{\mathrm{d}\sigma_{\gamma p\bar{p}}(\cos\phi_3) + \mathrm{d}\sigma_{\gamma p\bar{p}}(-\cos\phi_3)}.$$



(a) 2.000-3.080 GeV.



(b) 3.400-3.671 GeV.

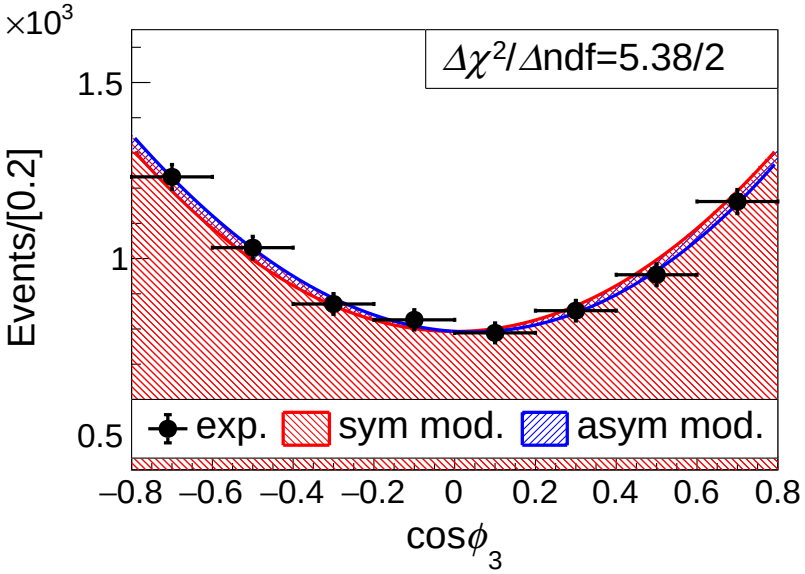


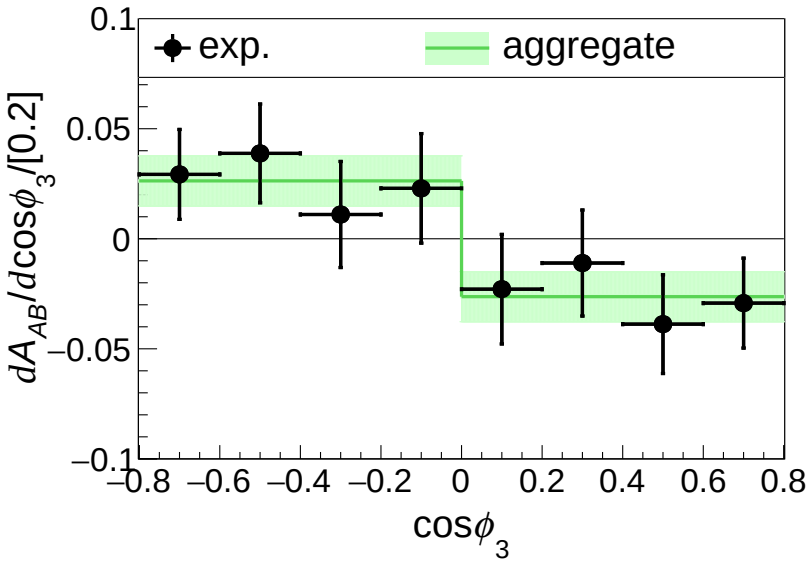
(c) 3.7737 GeV.

- Results:
  - 2.000-3.080 GeV: $A_{FB} = (-1.79 \pm 1.42)\%$;
  - 3.400-3.671 GeV: $A_{FB} = (-4.17 \pm 1.91)\%$;
  - 3.7737 GeV: $A_{FB} = (-6.18 \pm 0.66)\%$;
- Evidence of Forward-Backward asymmetry for the first time in $e^+e^- \to \gamma p\bar{p}$, with more than 3σ significance.

Forward-Backward asymmetry

- Combine energy points in the range of 2.000-3.671 GeV:

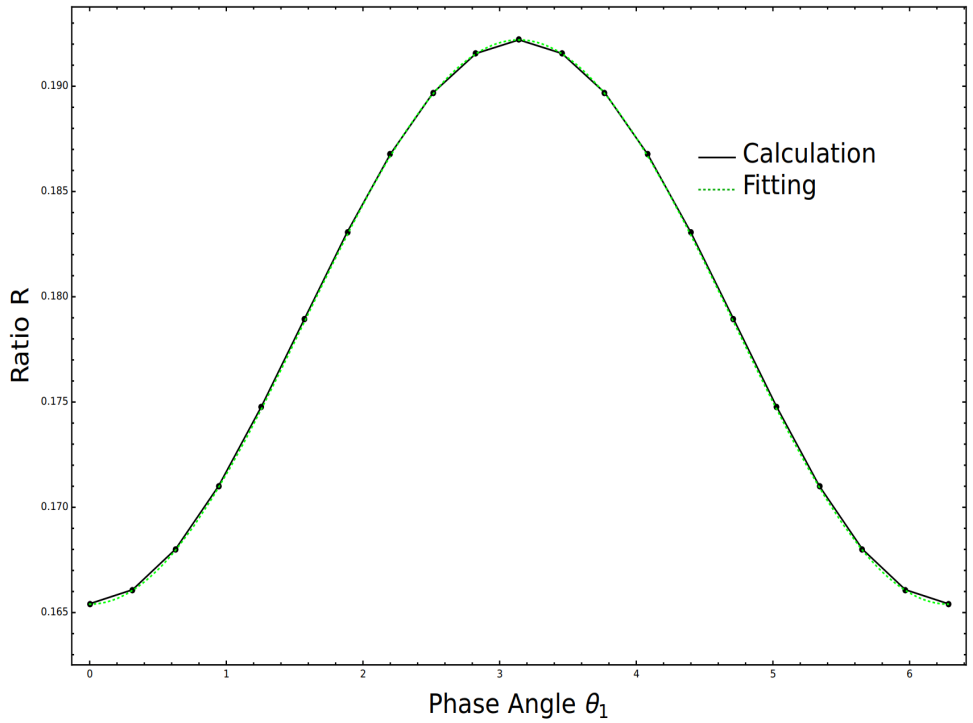




- Results:
  - 2.000-3.671 GeV: $A_{FB} = (-2.63 \pm 1.14)\%$;
  - Significance is 1.8σ.

Results of the Phase angle θ_1 of proton

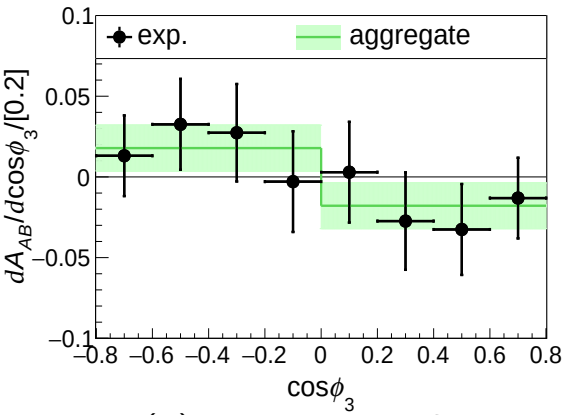
- Assump $\theta_2 = 90°$:



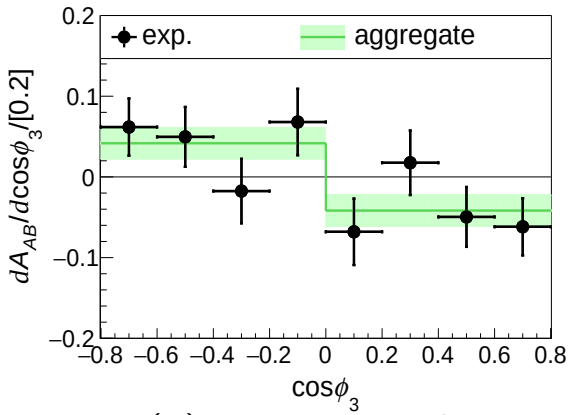
$\sqrt{s}$ [GeV]	A_{FB} [%]	θ_1 [°]	$\sqrt{s}$ [GeV]	A_{FB} [%]	θ_1 [°]
$2.000 - 3.080$	-1.79 ± 1.42	$143.4^{+29.5}_{-53.4}$	$2.000 - 3.671$	-2.63 ± 1.14	$118.4^{+31.8}_{-28.4}$
$3.400 - 3.671$	-4.17 ± 1.91	90.0 ± 41.0	3.7737	-3.74 ± 0.99	90.0 ± 23.4

Summary

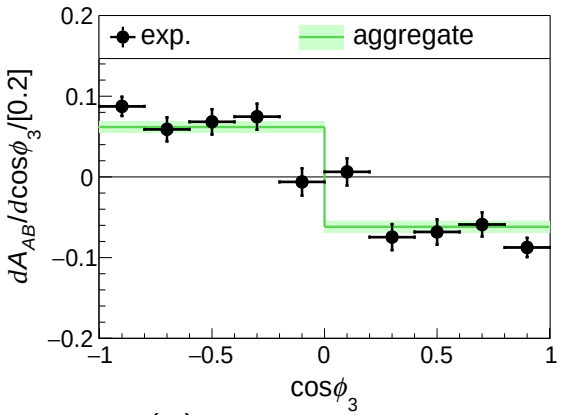
Summary



(a) 2.000-3.080 GeV.



(b) 3.400-3.671 GeV.



(c) 3.7737 GeV.

- Using data samples between 2.000 and 3.773 GeV collected with the BESIII detector, we studied the forward-backward asymmetry of $\cos\phi_3$ in $e^+e^- \to \gamma p\bar{p}$ reaction.
- Evidence of Forward-Backward asymmetry for the first time in $e^+e^- \to \gamma p\bar{p}$, with more than 3σ significance.
- A new window of insight into the phase angles of EMFF of proton.

$\sqrt{s}$ [GeV]	A_{FB} [%]	θ_1 [°]	$\sqrt{s}$ [GeV]	A_{FB} [%]	θ_1 [°]
$2.000 - 3.080$	-1.79 ± 1.42	$143.4^{+29.5}_{-53.4}$	$2.000 - 3.671$	-2.63 ± 1.14	$118.4^{+31.8}_{-28.4}$
$3.400 - 3.671$	-4.17 ± 1.91	90.0 ± 41.0	3.7737	-3.74 ± 0.99	90.0 ± 23.4

Thanks for your attention!