BEPC束流横向极化的测量

平荣刚

Institute of High Energy Physics, CAS

合作者：Zhe Duan[1], Aiqiang Guo[2], Daheng Ji[1], Yutie Liang[2], Dexu Lin[2], Jiashun Luo[1], Linghui Wu[1],Gao Zhi[1],Wang Zhi[1]

1. IHEP, CAS, 2. IMP, CAS

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Outline

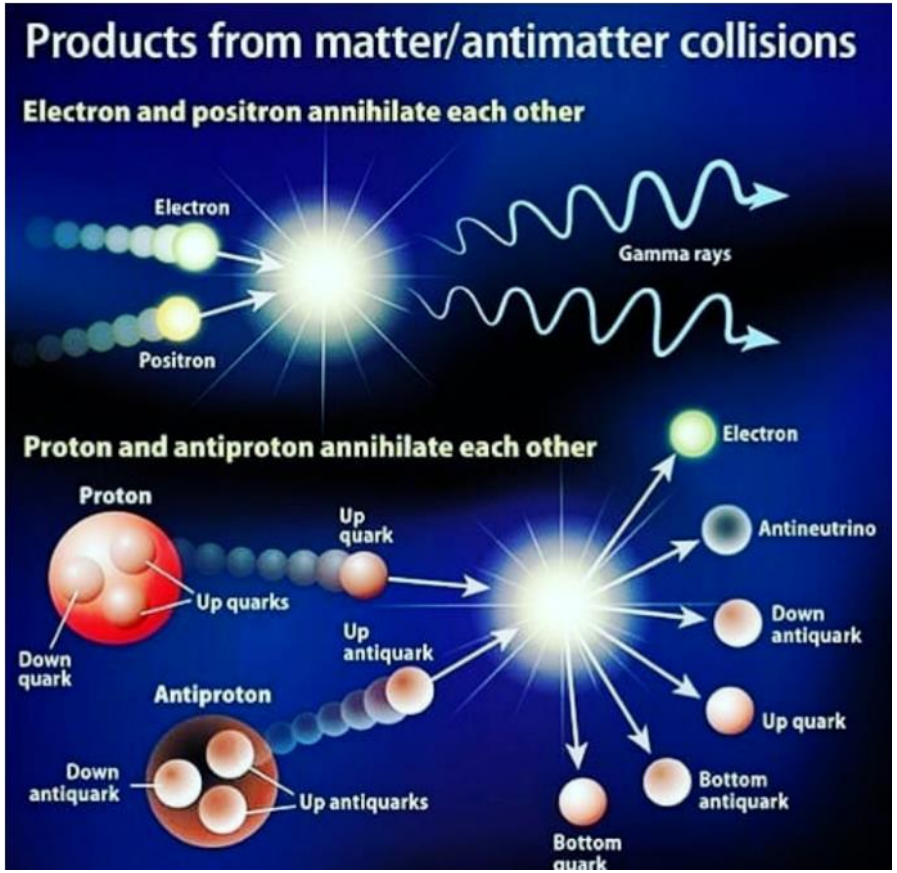
- Introduction
- Measurement with $e^+e^- \to \gamma\gamma, e^+e^-, \mu^+\mu^-$
- Effects on the baryon antibaryon pairs
- Effects on the $\psi' \to \eta J/\psi, \gamma\chi_{cJ}$
- Effects on the hyperon polarization measurements
- Summary and outlook

Introduction

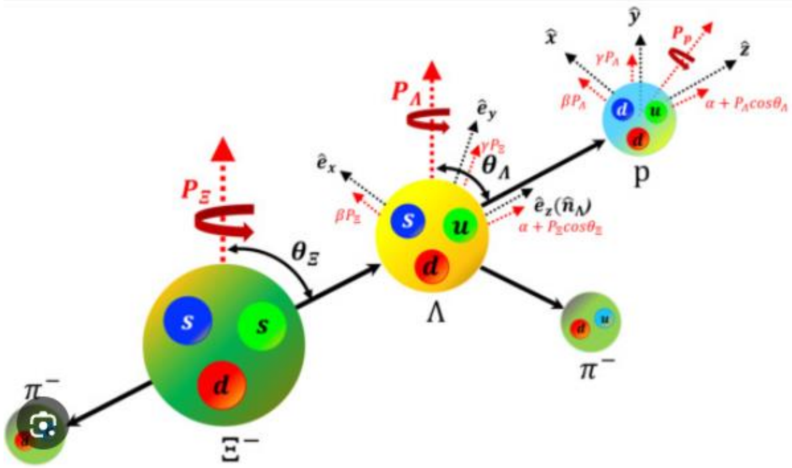
重子的不对称性

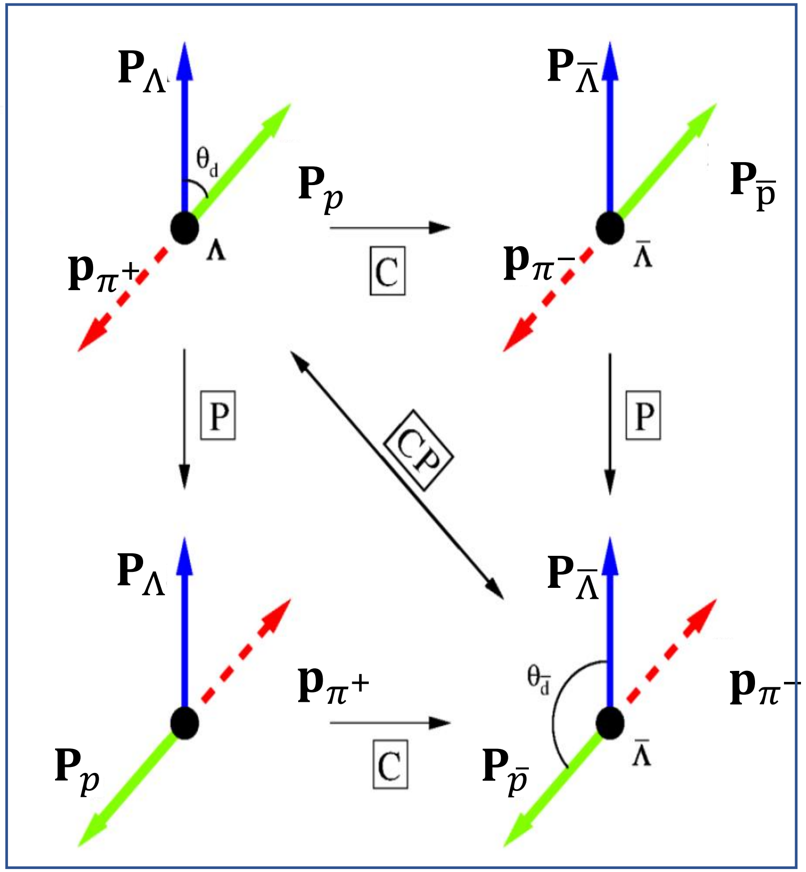
萨哈罗夫要件

- 重子数守恒的破坏。
- 电荷共轭对称与CP对称的破坏。
- 在热力学平衡之外的交互作用。



极化在BESIII探测超子-反超子对称性中的应用





$$\alpha = \frac{|B_+|^2 - |B_-|^2}{|B_+|^2 + |B_-|^2},$$

$$\bar\alpha = \frac{|\bar B_+|^2 - |\bar B_-|^2}{|\bar B_+|^2 + |\bar B_-|^2}$$

CP invariance :

$$\bar B_{-\lambda_p} = \eta_\Lambda \eta_p \eta_\pi (-1)^{s_\Lambda - s_p - s_\pi} B_{\lambda_p}$$

$$= -B_{\lambda_p}$$

$$\alpha = -\bar\alpha$$

$$\mathbf{P}_B = \frac{(\alpha + \mathbf{P}_Y \cdot \hat{\mathbf{n}})\hat{\mathbf{n}} + \beta(\mathbf{P}_Y \times \hat{\mathbf{n}}) + \gamma \hat{\mathbf{n}} \times (\mathbf{P}_Y \times \hat{\mathbf{n}})}{1 + \alpha \mathbf{P}_Y \cdot \hat{\mathbf{n}}}$$

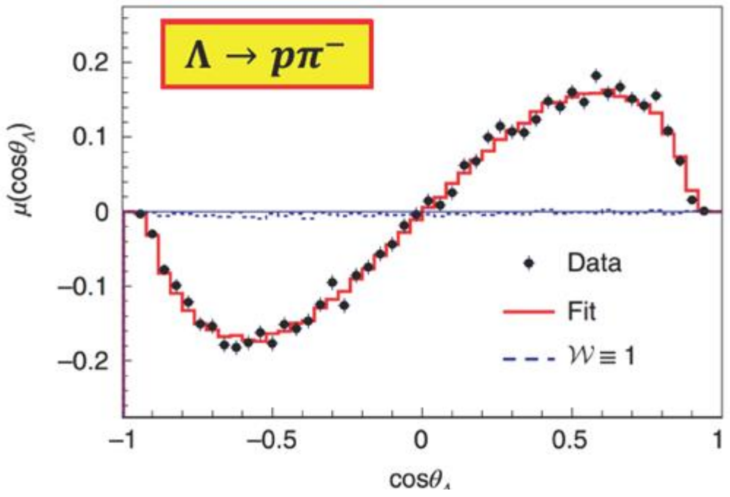
CP odd-variable:

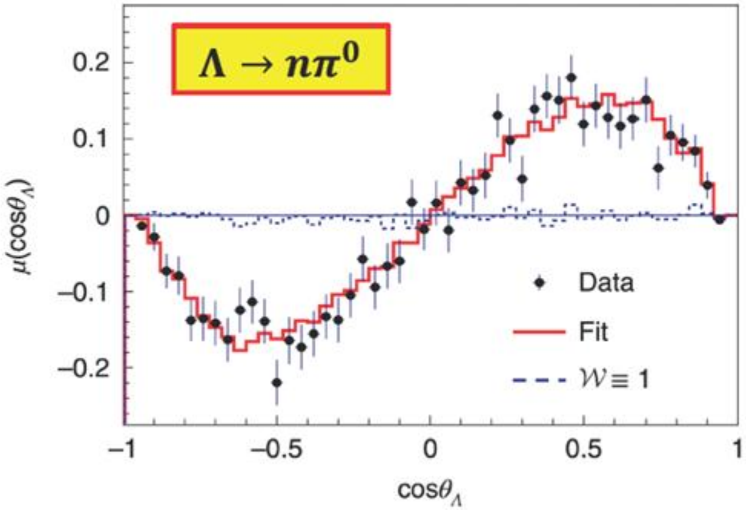
$$\Delta = \frac{\Gamma - \bar\Gamma}{\Gamma + \bar\Gamma}, A = \frac{\alpha + \bar\alpha}{\alpha - \bar\alpha}, B = \frac{\beta + \bar\beta}{\beta - \bar\beta}, B' = \frac{\beta + \bar\beta}{\alpha - \bar\alpha}$$

See talk by Wang XiongFei

超子-反超子对产生的特点

- 超子-反超的横向极化

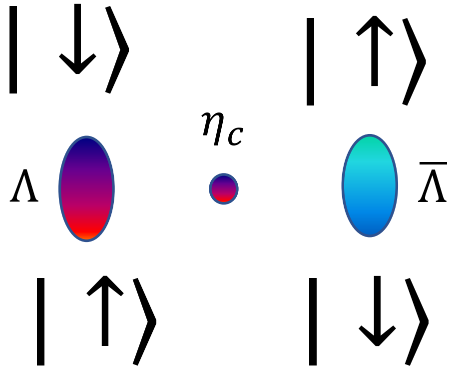




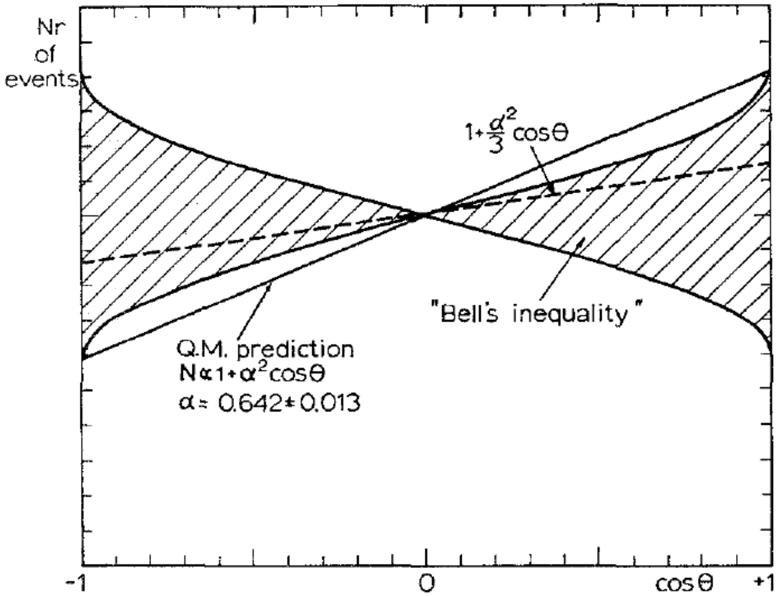
Nature Physics, 15, 631 (2019)

- 超子-反超形成纠缠态

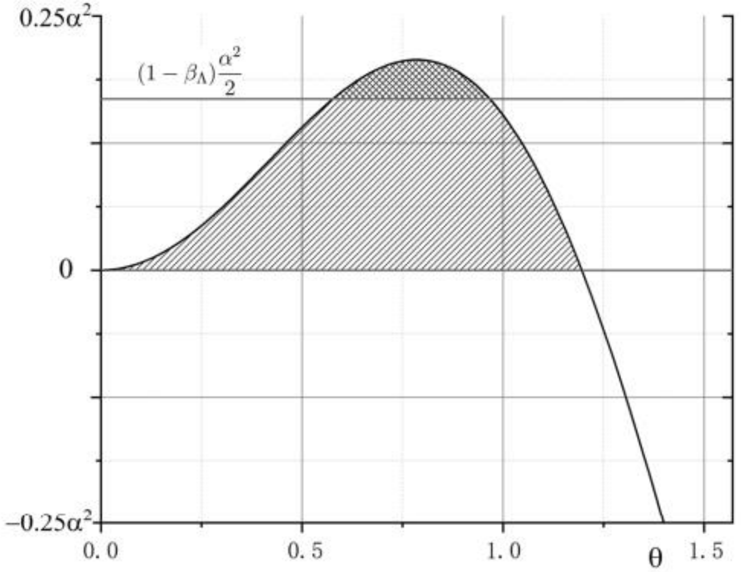
$$\eta_c \text{ spin: } |0\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)$$



Found. Phys., 11, 171

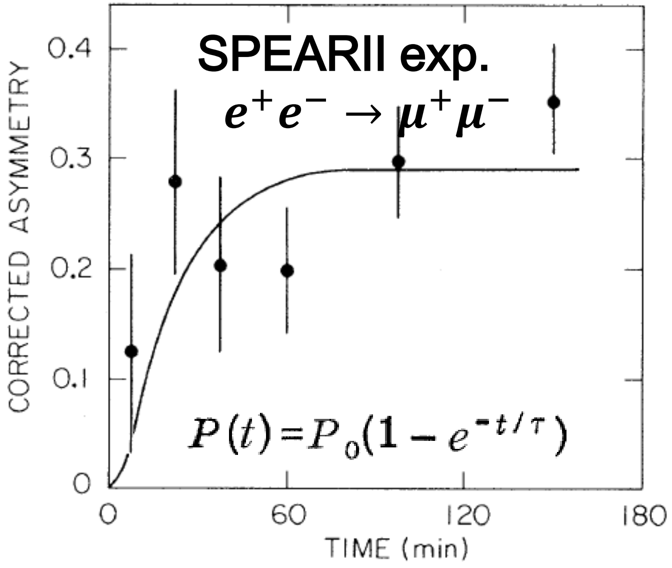


Phys. Rev., D101, 116004

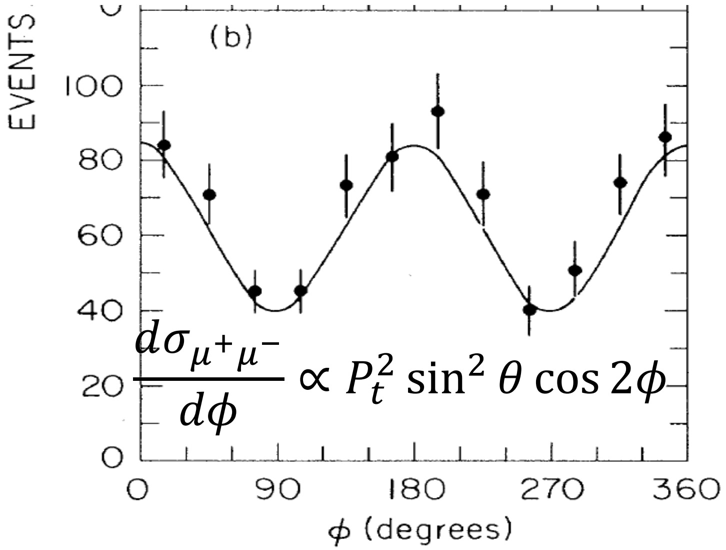


历史上的束流横向极化研究

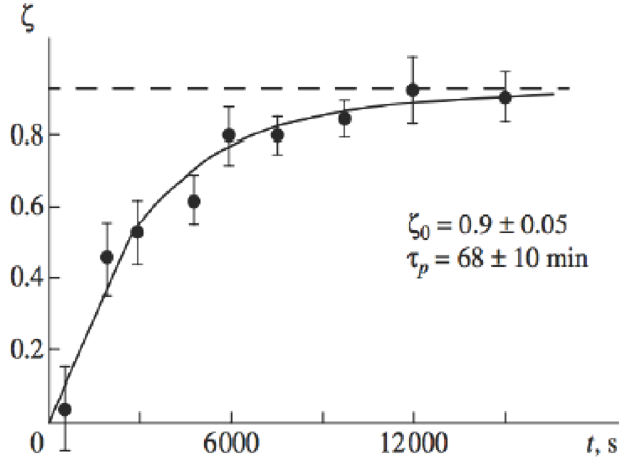
- A interest in motion of spinning electron arose in the 1920’s out of attempts to explain the anomalous effect.
- Theoretical discovery of radiative polarization was due to Sokolov and Ternov in 1963.
- Synchrotron radiation induces transverse polarization in the beam in storage rings, initially thought to be a free gift from nature, but it was later proven that nature is not so generous [Sov. Phys. Doklady, 10, 1145 (1965)].
- First experimental test of radiative polarization with the ACO storage ring at Orsay (1968) and in VEPP-2 (1970)
- Further experimental results approaching the theoretical limts of 92.4% achieved at Osay storage ring and VEPP-2m (1976)



Phys.Rev.Lett., 35, 1688(1975)



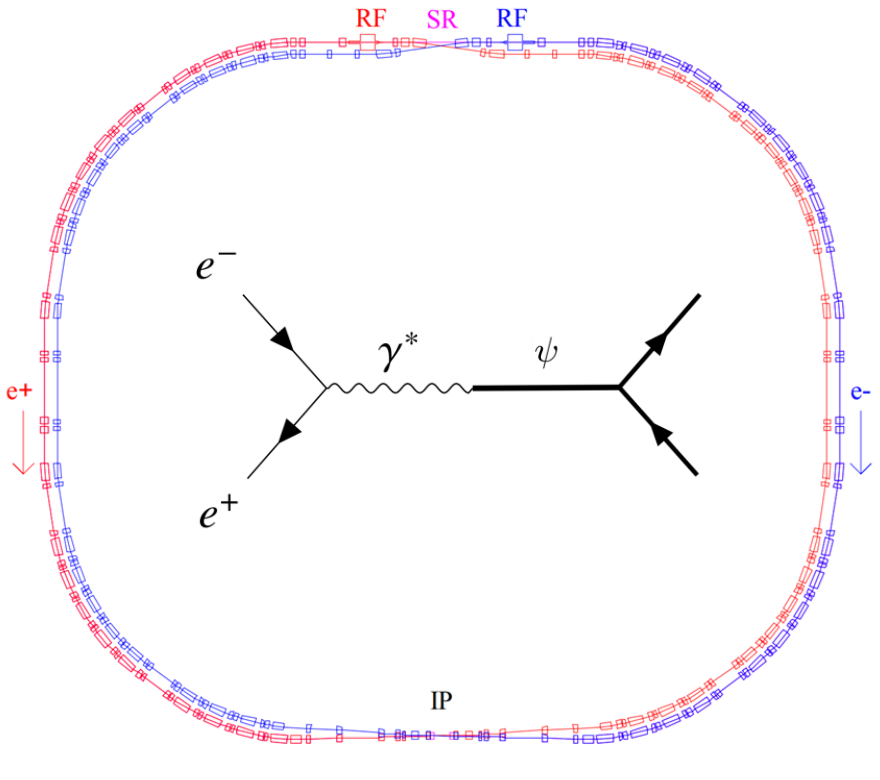
Phys.Rev.Lett., 35, 1688(1975)



Polarization buildup in VEPP-2M

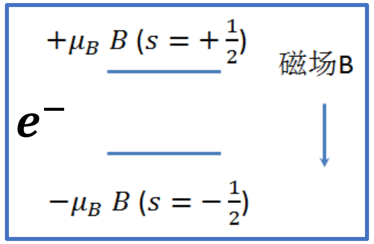
束流的横向极化建立

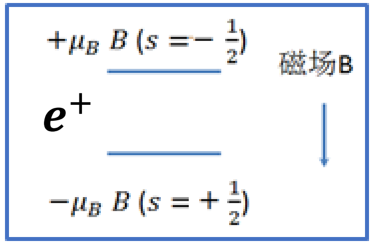
Naive picture



The BEPCII Complexity

$$\mathbf{U} = -\boldsymbol{\mu}_{\mathbf{s}} \cdot \boldsymbol{B} = -\mu_{sz} B$$

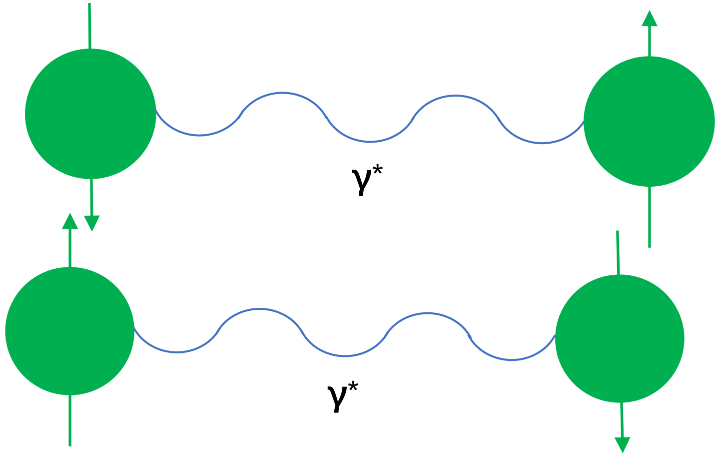




能级间隔： $\Delta E = 2\mu_B B = 4.4 \times 10^{-5}\ eV$

$$W_{\uparrow\downarrow} = \frac{5\sqrt{3}}{16}\ \frac{e^2\gamma^5\hbar}{m^2c^2\rho^3}\left(1 + \frac{8}{5\sqrt{3}}\right)$$

$$W_{\downarrow\uparrow} = \frac{5\sqrt{3}}{16}\ \frac{e^2\gamma^5\hbar}{m^2c^2\rho^3}\left(1 - \frac{8}{5\sqrt{3}}\right).$$



Bending magnetic， vertical downwards：

$$\boldsymbol{B = 0.76T}$$

Spin-flip transition: magnetic dipole

Spin-orbit interaction: semiclassical

束流的横向极化建立

The emission of synchrotron radiation could lead to transverse polarization of the beam in electron positron storage rings. (Sokolov Ternov effect, 1964)

For initially unpolarized electrons or positrons in storage ring, there is a gradual buildup of transverse polarization.

$$P(t) = P_0(1 - e^{-t/\tau_0})$$

where the maximum polarization is

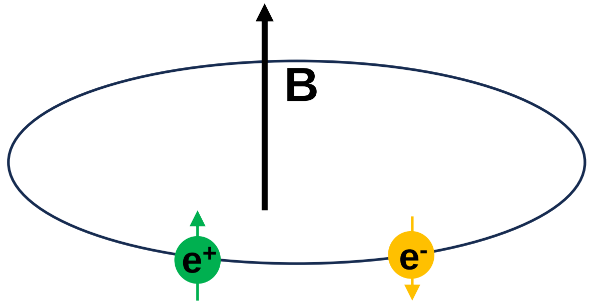
$$P_0 = \frac{8}{5\sqrt{3}} \approx 92.4\%$$

And the characteristic time is

$$\tau_0 = \left[\frac{5\sqrt{3}}{8}\frac{e^2\hbar\gamma^5}{m^2c^2\rho^3}\right]^{-1}$$

Self-polarization:

- **The electron spins antiparallel to the magnetic field.**
- **The positron spins become parallel to the field.**



Transverse polarized

BEPCII beam polarization

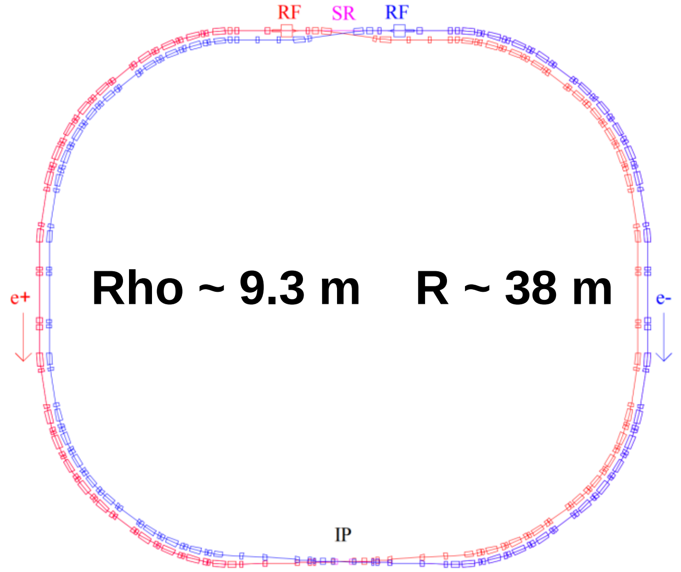
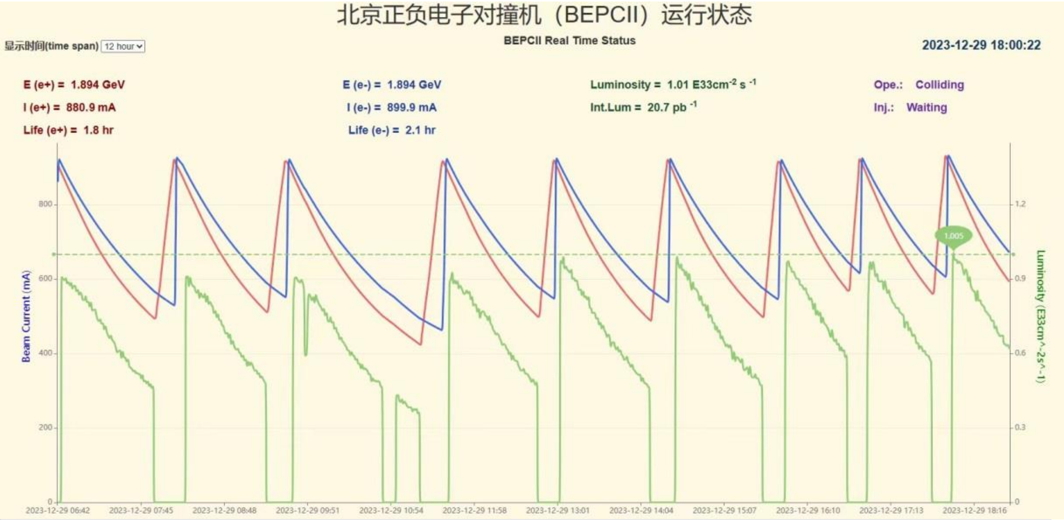
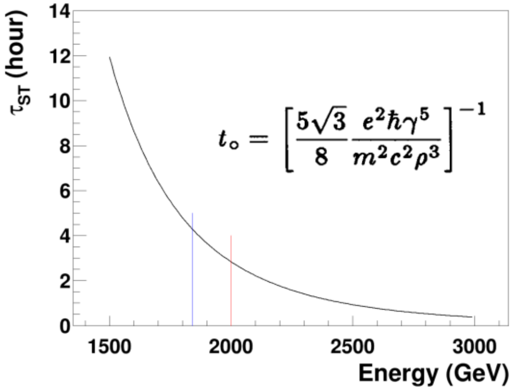
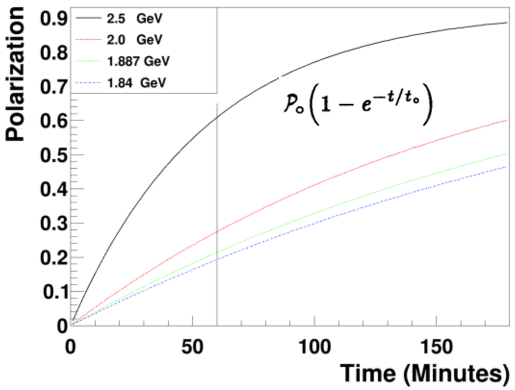


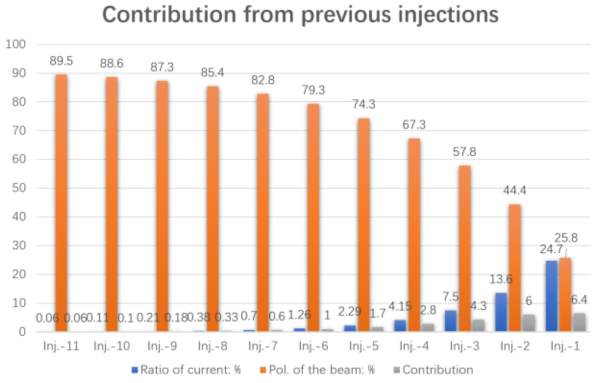
Figure 1: The BEPCII Complexity

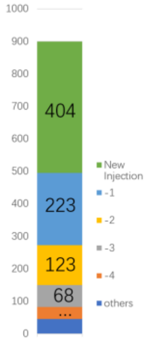






BEPCII beam polarization





Electron beam
Life time: 2.1 h
Data taking: 1 h
Injection: 0.25 h
P_1=> 23.6%

Positron beam
Life time: 1.8 h
Data taking: 1 h
Injection: 0.25 h
P_2=> 20.1%

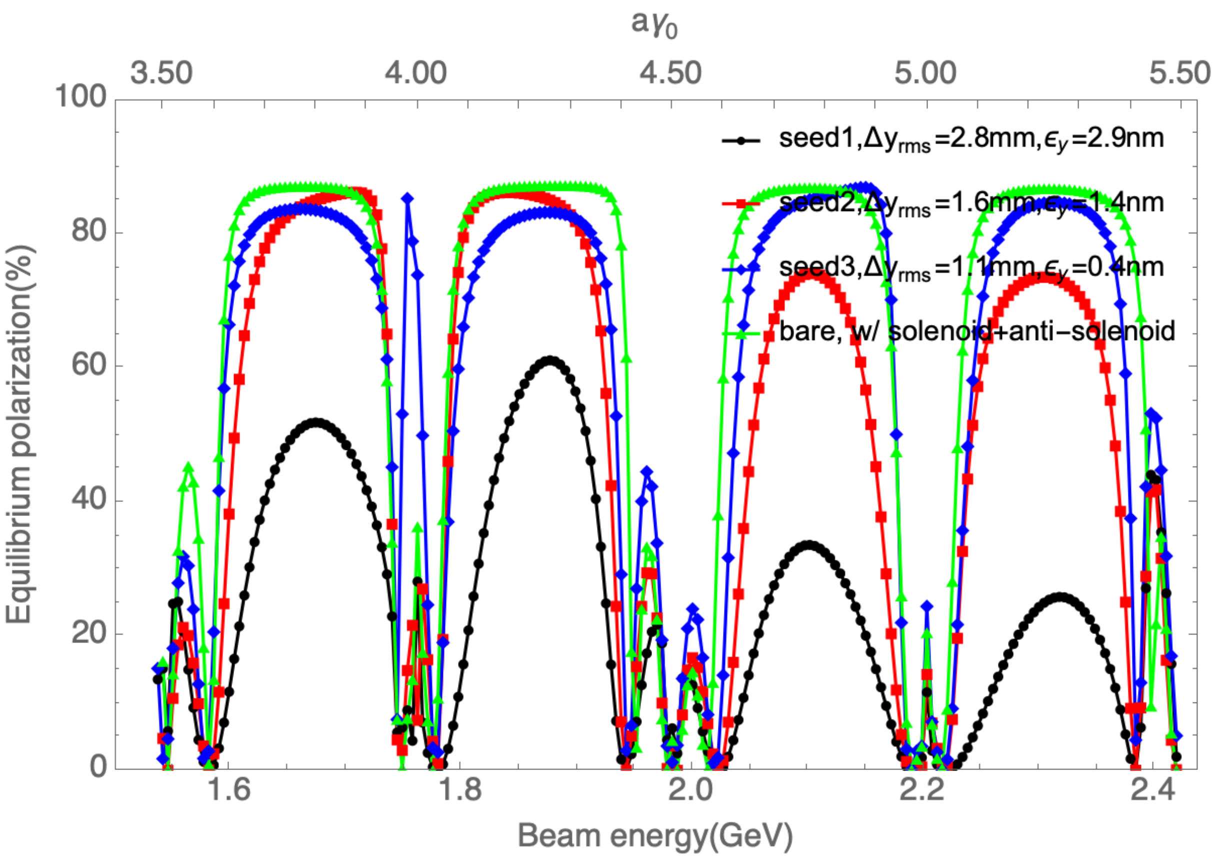
P*P = 0.05

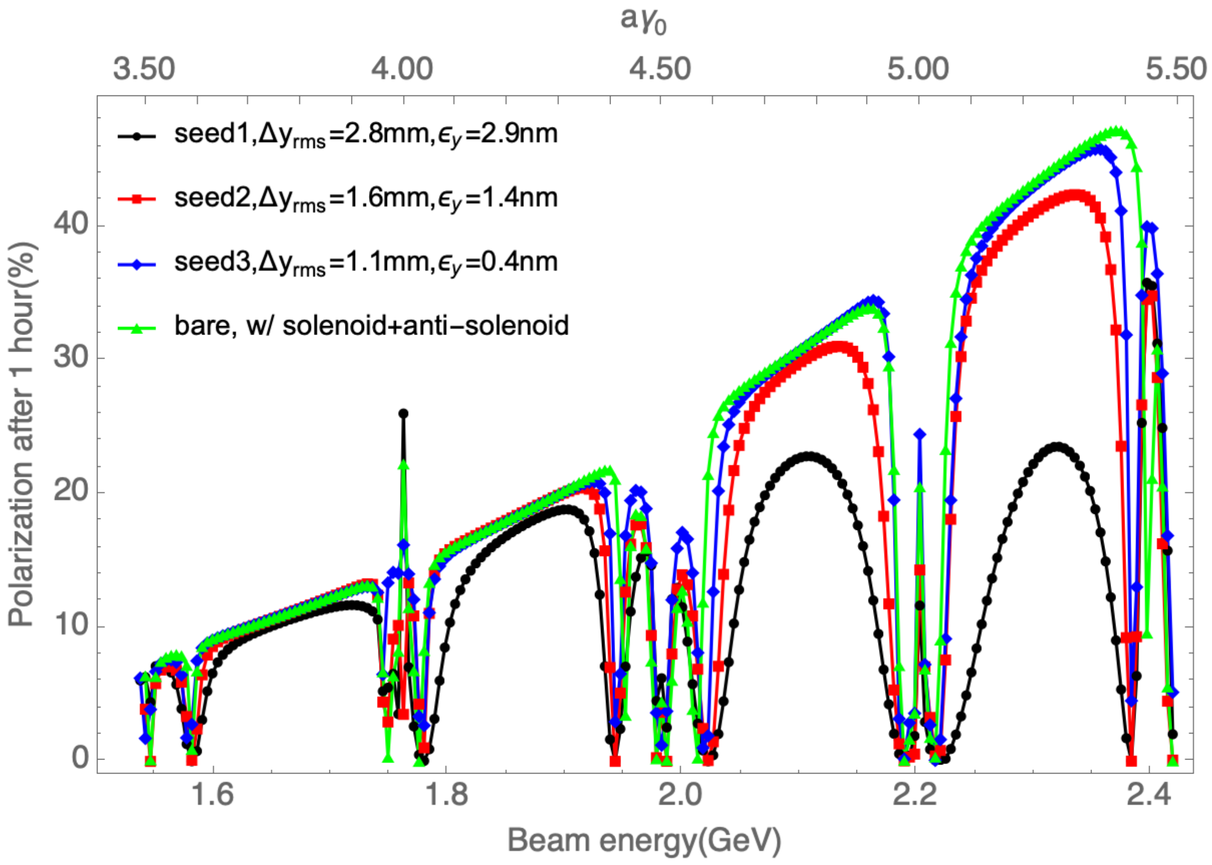
Previous injections contribute to the polarization!

Simulation from accelerator side

Slides from Zhe Duan

Assume an initial unpolarized beam stays in the ring for 1 hour, the final beam polarization level is $P(t) = P_{DK} (1 – exp(- t / \tau_{DK})$)

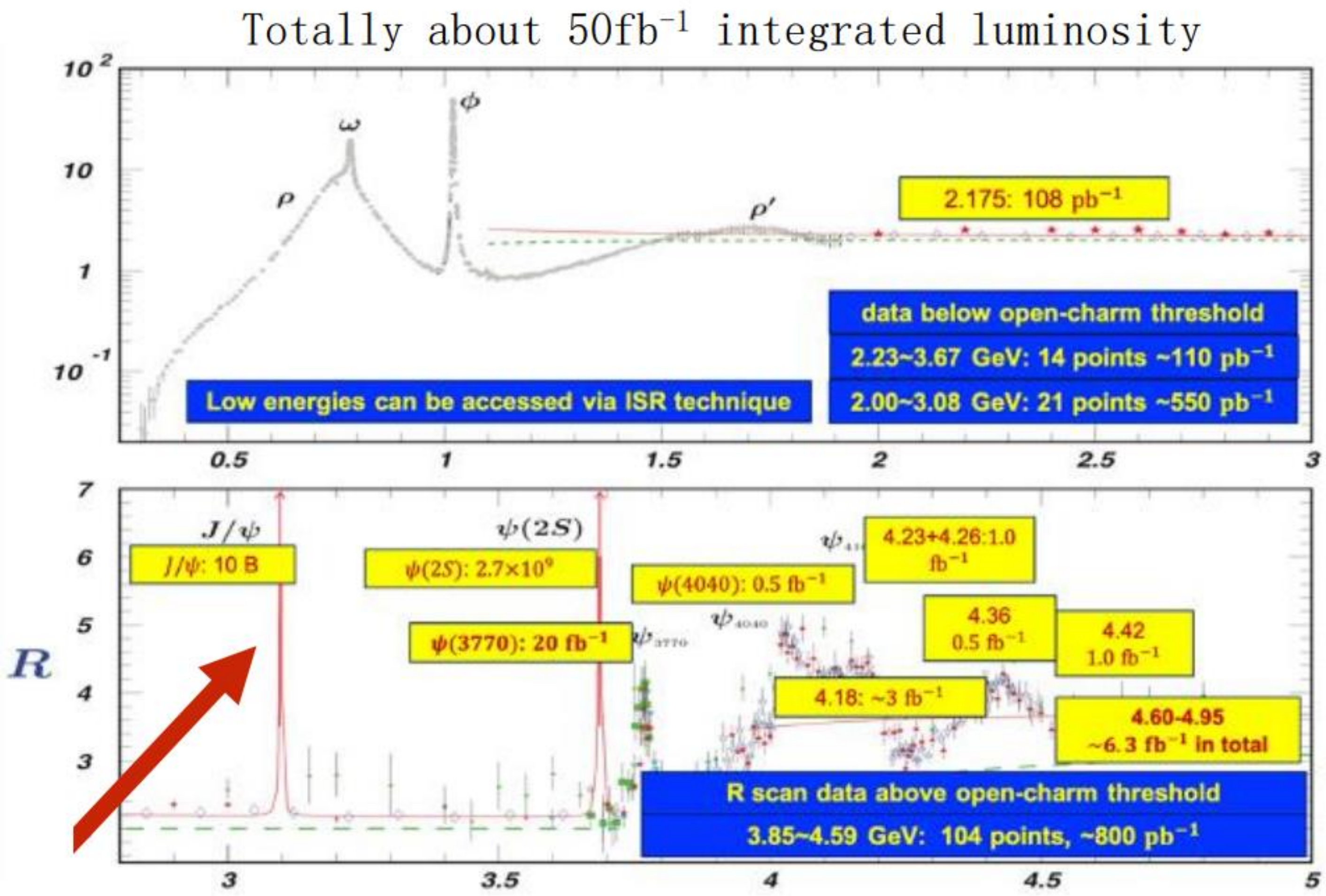




Measurement with $e^+e^- \to \gamma\gamma, e^+e^-, \mu^+\mu^-$

Charmonium data sets

- 10×10^9 J/ψ decays
- 2.7×10^9 $\psi(3686)$ decays
- $20\ \mathrm{fb}^{-1}$ $\psi(3770)$ decays
- Scan data between 2.0 and3.08 GeV, and above 3.74GeV
- Large datasets for XYZstudies: Scan with >500pb^{-1} per energy point space 10-20MeV apart



World largest J/ψ data sample : ~10 billion

束流横向极化下的QED过程的角分布

Erratum: transverse polarization should be replaced by $P^2 \rightarrow -P^2$

$e^+e^- \rightarrow e^+e^-$

The cross section for finite polarization (for $m_e \neq 0$) is

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{4s}\left\{\frac{4(1+\beta^2)^2}{\beta^4}\frac{1}{(1-\cos\theta)^2}+\frac{2}{\beta^2}\left[-8+\frac{1}{\gamma^4}\right]\frac{1}{1-\cos\theta}+4\left[2+\frac{1}{\gamma^2}\right]+(1+\beta^2\cos\theta)^2\right.$$
$$+P^2\frac{1}{\gamma^2}\left[\frac{2(2+\beta^2)}{\beta^2}\frac{1}{1-\cos\theta}-3+\left[\frac{1}{\beta}+\beta\cos\theta\right]^2\right]$$
$$\left.+P^2\left[-\frac{2}{\gamma^2\beta^2}\frac{1}{1-\cos\theta}+\frac{1}{\gamma^2}+\left[\frac{1}{\beta}+\beta\cos\theta\right]^2\right]\cos 2\phi\right\}.$$

The result for $P=0$ agrees with Bhabha.[134]

At high energies $s \gg m_e^2$, we have a very simple expression:

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{4s}\left[\frac{(3+\cos^2\theta)^2}{(1-\cos\theta)^2}+P^2(1+\cos\theta)^2\cos 2\phi\right]. \quad \text{(D4)}$$

Small oscillation from transverse polarization locates above the large platfrom.

$e^+e^- \rightarrow \mu^+\mu^-$

For instance, the cross section for $e^+e^- \rightarrow \mu^+\mu^-$ in the presence of transverse polarization to the lowest order in QED is[20]

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{4s}(1+\cos^2\theta-P^2\sin^2\theta\cos 2\phi), \quad (1.1)$$

where θ is the polar angle of μ^- with respect to the e^- direction, ϕ is the azimuthal angle[36] of μ^- relative to the polarization direction, and P is the magnitude of the polarization (we take the polarization of electrons and positrons equal and opposite). The extra term proportional to P has a $\cos 2\phi$ dependence. After integrating over the azimuthal angle, there remains no trace of polarization.

where $\gamma_\mu=\sqrt{s}/2m_\mu$ and $\gamma_e=\sqrt{s}/2m_e$.

The cross section for finite polarization is

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{4s}\frac{\beta_\mu}{\beta_e}\left[1+\cos^2\theta+\frac{1}{\gamma_\mu^2}\sin^2\theta\right.$$
$$+(1-P^2)\frac{1}{\gamma_e^2}\left[\sin^2\theta+\frac{1}{\gamma_\mu^2}\cos^2\theta\right]$$
$$\left.-P^2\beta_\mu^2\sin^2\theta\cos 2\phi\right], \quad \text{(C2)}$$

where $\beta_\mu^2=1-4m_\mu^2/s$ and $\beta_e^2=1-4m_e^2/s$. This result is consistent with Godine and Hankey.[22] The total cross section is

High sensitivity

$e^+e^- \rightarrow \gamma\gamma$

The lowest-order amplitude for the process $e^+e^- \rightarrow \gamma\gamma$ comes solely from the QED diagrams shown in Fig. 12.

The cross section is

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{s\beta}\frac{1}{(1-\beta^2\cos^2\theta)^2}\left[1-\beta^4\cos^4\theta+\frac{2\beta^2}{\gamma^2}\sin^2\theta\right.$$
$$-P^2\left[\beta^2\sin^4\theta\cos 2\phi\right.$$
$$\left.\left.+\frac{\beta^2}{\gamma^2}\sin^4\theta-\frac{1}{\gamma^4}\right]\right]. \quad \text{(E4)}$$

This is consistent with Page.[19]

We study several limiting cases. At high energies, we have

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{s}\left[\frac{1+\cos^2\theta}{\sin^2\theta}-P^2\cos 2\phi\right]. \quad \text{(E5)}$$

At threshold, the polarization effect is maximal

Similar to dimu

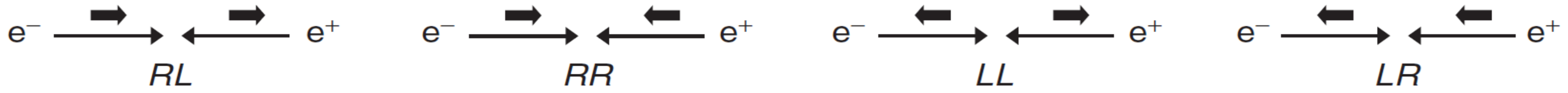
K. Hikasa, PRD33,3203(1986)

$e^+e^- \to \gamma^*/\psi$过程中ψ的自旋密度矩阵

- Forgotten Facts of Transversely Polarized electron/positron Beams

The four possible helicity combinations in the e^+e^- initial state

$$\rho_e^{\pm} = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$



- 1 = ½ - (-½)   0 = ½ - ½   0 = -½ - (-½)   -1 = -½ - ½

-

In facts	1	$m_e/\sqrt{s}$	$m_e/\sqrt{s}$	1

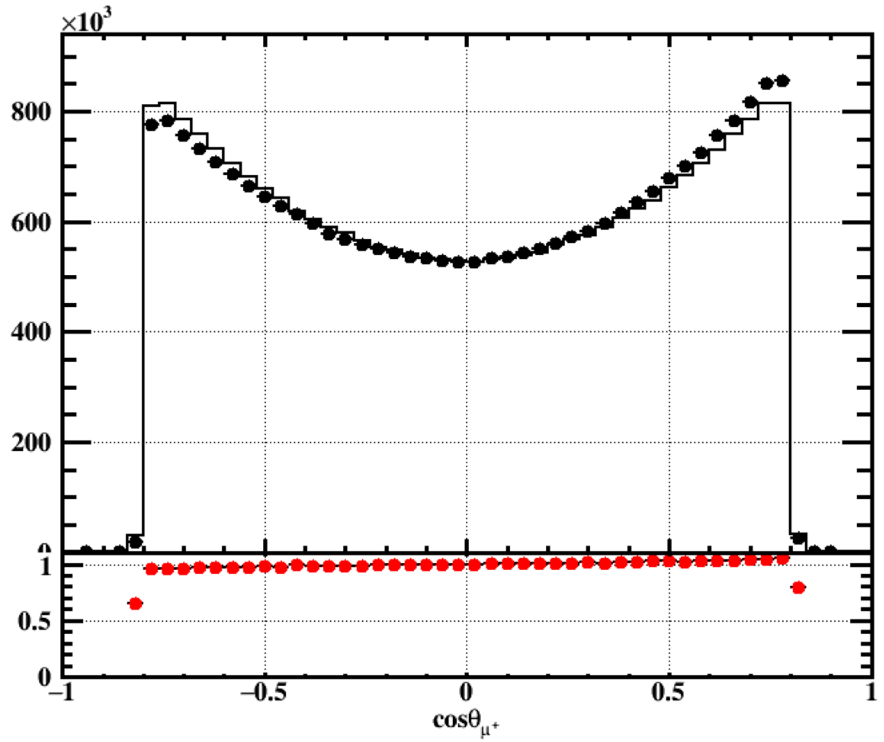
$$\rho^- = \frac{1}{2}\begin{pmatrix} 1+\mathcal{P}_z & \mathcal{P}_t \\ \mathcal{P}_t^* & 1-\mathcal{P}_z \end{pmatrix} \quad \text{for } e^-,$$

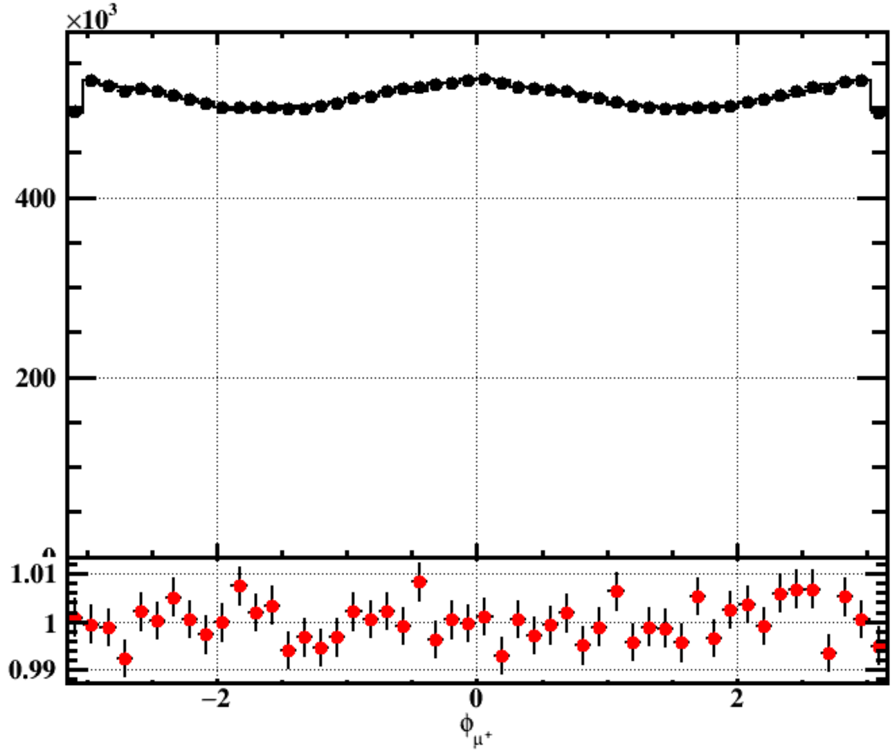
$$\rho^+ = \frac{1}{2}\begin{pmatrix} 1+\bar{\mathcal{P}}_z & \mathcal{P}_t \\ \mathcal{P}_t^* & 1-\bar{\mathcal{P}}_z \end{pmatrix} \quad \text{for } e^+,$$

$$\rho^{\gamma^*/\psi} = \frac{1}{2}\begin{pmatrix} (1+\bar{\mathcal{P}}_z)(1-\mathcal{P}_z) & 0 & P_T^2 \\ 0 & 0 & 0 \\ P_T^2 & 0 & (1-\bar{\mathcal{P}}_z)(1+\mathcal{P}_z) \end{pmatrix}.$$

- Xu Cao, Yu-tie Liang, Rong-Gang Ping, 2404.00298 [hep-ph]

First glimpse of angular distribution for $e^+e^- \rightarrow \mu^+\mu^-$

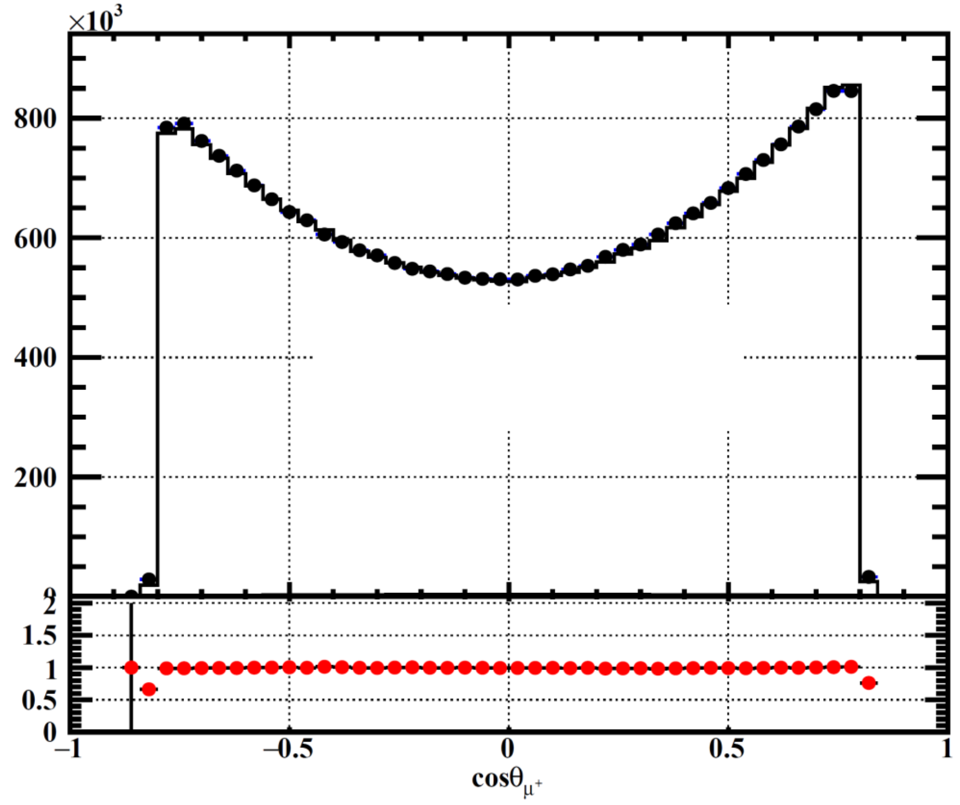


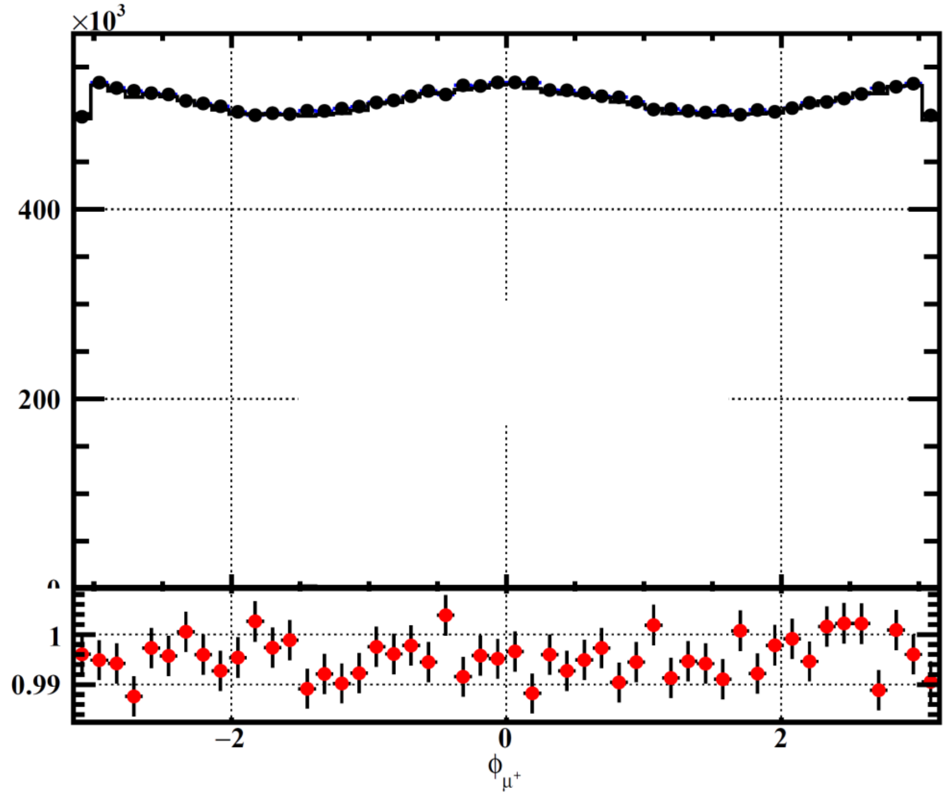


$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha \cos^2\theta + \alpha\, P_t^2 \sin^2\theta \cos 2\phi$$

1. Can not describe the asymmetry $\cos\theta$ distribution
2. Asymmetry distribution is up to cuts
3. $\alpha\, P_t^2$ term is with positive sign

First glimpse of angular distribution for $e^+e^- \to \mu^+\mu^-$





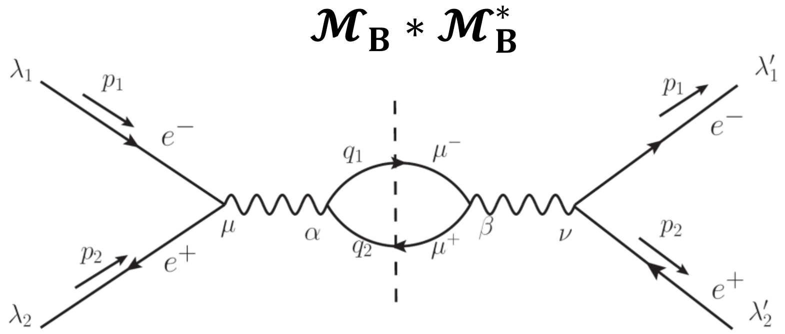
Empirical formula:

$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha \cos^2\theta + \beta \cos\theta + \alpha P_t^2 \sin^2\theta \cos 2\phi$$

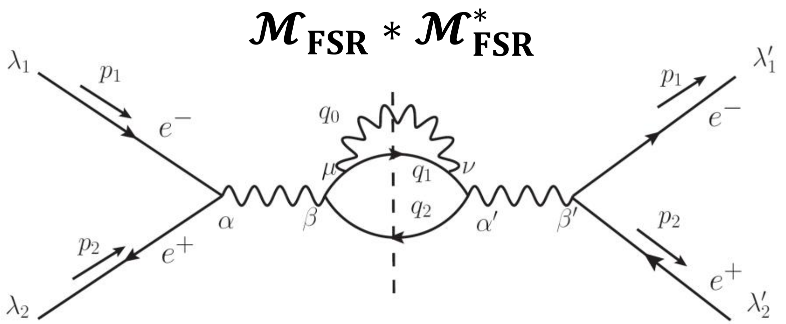
Further comments:

1. Is there additional asymmetry terms, e.g. $cos^3\theta,\ cos^5\theta$?
2. Is there asymmetry terms in ϕ distribution?

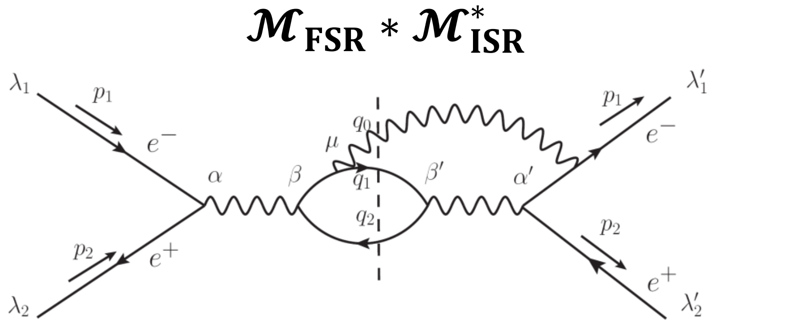
Effects of interference between the ISR and FSR processes



(a) Born process



(b) FSR process with additional photon



(c) Interference of FSR with ISR process

(a) $$\frac{d\sigma(e^+e^-\to\mu^+\mu^-)}{d\Omega(\mu^+)} = \frac{\alpha^2}{4s}\left(1+\cos^2\theta + P_t^2\sin^2\theta\cos 2\phi\right)$$

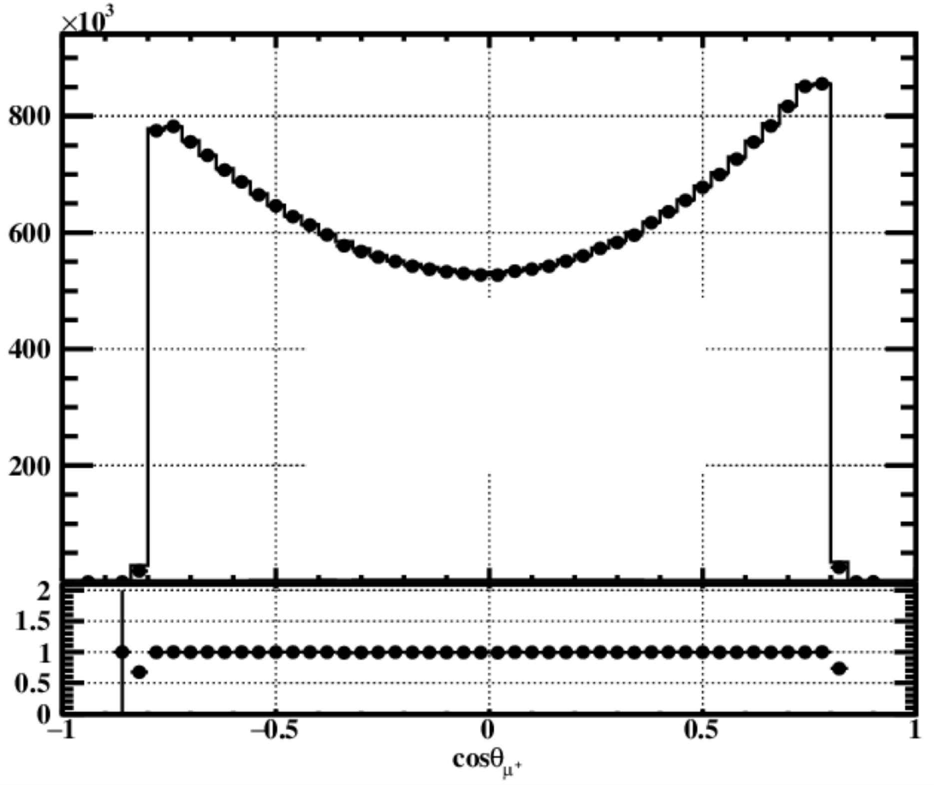
(b) $$\frac{d\sigma(e^+e^-\to\gamma_{FSR}\mu^+\mu^-)}{d\Omega(\mu^+)} \propto \frac{\alpha^4}{4s^2}\left(1+\cos^2\theta + P_t^2\sin^2\theta\cos 2\phi\right)$$

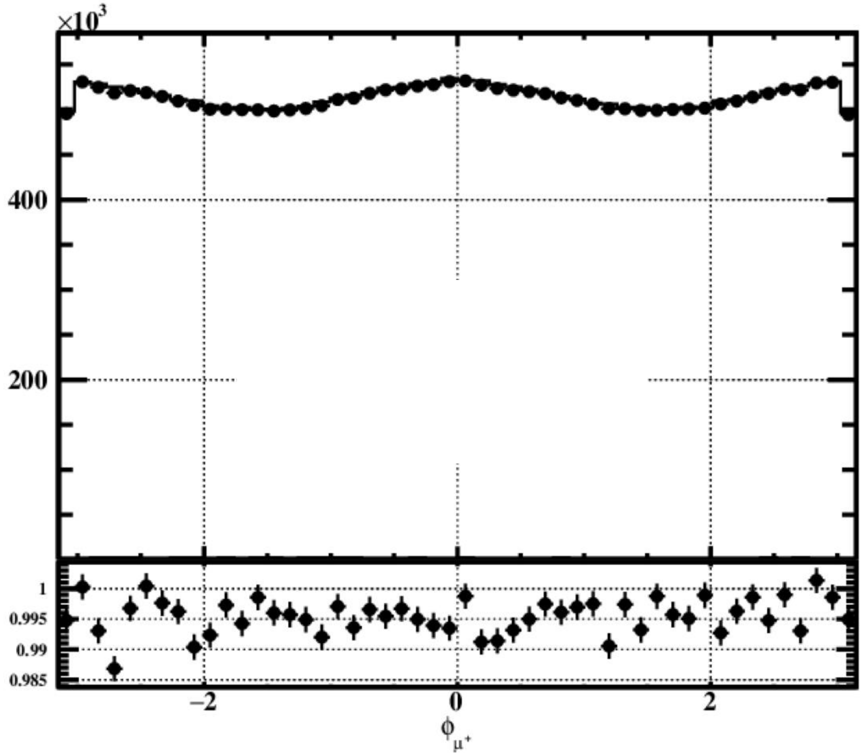
(c) $$\frac{d\sigma(e^+e^-\to\gamma_{FSR/\mathrm{ISR}}\mu^+\mu^-)}{d\Omega(\mu^+)} \propto \frac{\alpha^4}{4s^2}\left(1+\alpha\cos\theta+\beta\cos^2\theta+\gamma\cos^3\theta + P_t^2\sin^2\theta\cos 2\phi\,(1+\kappa\cos\theta)\right)$$

Put all things together, we suggest the formula to fit the data:

$$\frac{dN(e^+e^-\to(\gamma_{FSR/\mathrm{ISR}})\mu^+\mu^-)}{d\Omega(\mu^+)} \propto 1+\alpha\cos\theta+\beta\cos^2\theta+\gamma\cos^3\theta + P_t^2\sin^2\theta\cos 2\phi\,(1+\kappa\cos\theta)$$

Nominal fit to angular distribution of $e^+e^- \to \mu^+\mu^-$



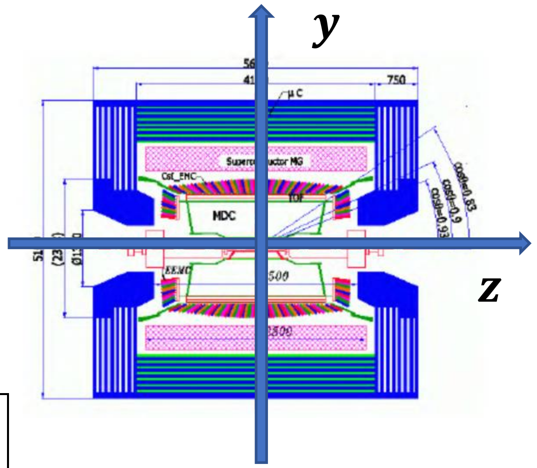


Nominal fit with formula :

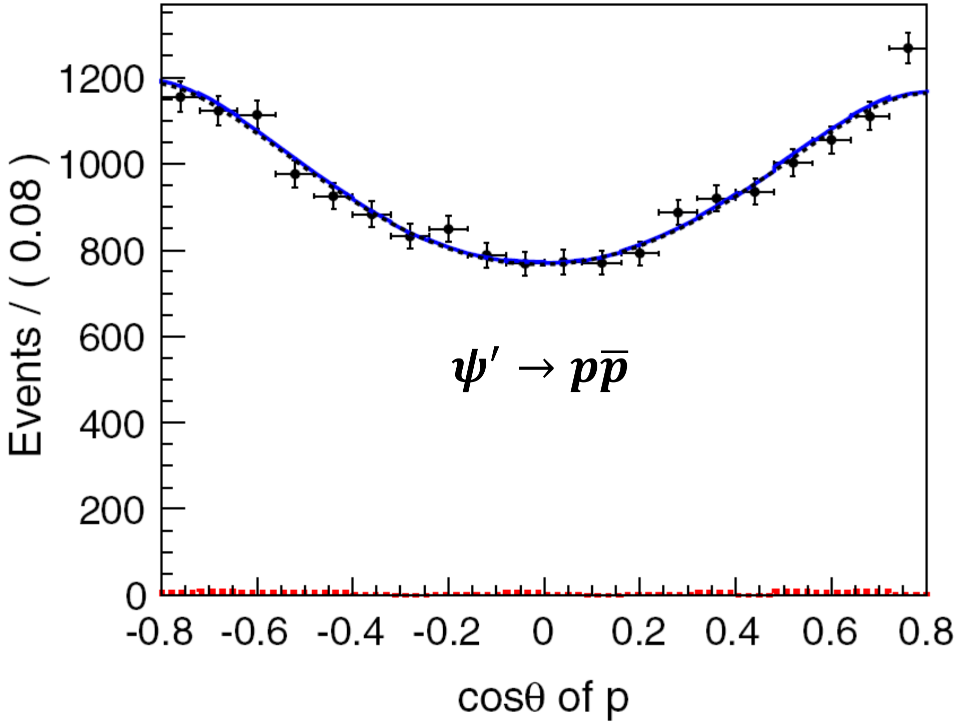
$$\frac{\mathrm{dN}\left(\mathrm{e}^+\mathrm{e}^-\to(\gamma_{FSR/\mathrm{ISR}})\mu^+\mu^-\right)}{d\Omega(\mu^+)} \propto 1+\alpha\cos\theta+\beta\cos^2\theta+\gamma\cos^3\theta+P_t^2\sin^2\theta\cos 2\phi\,(1+\kappa\cos\theta)$$

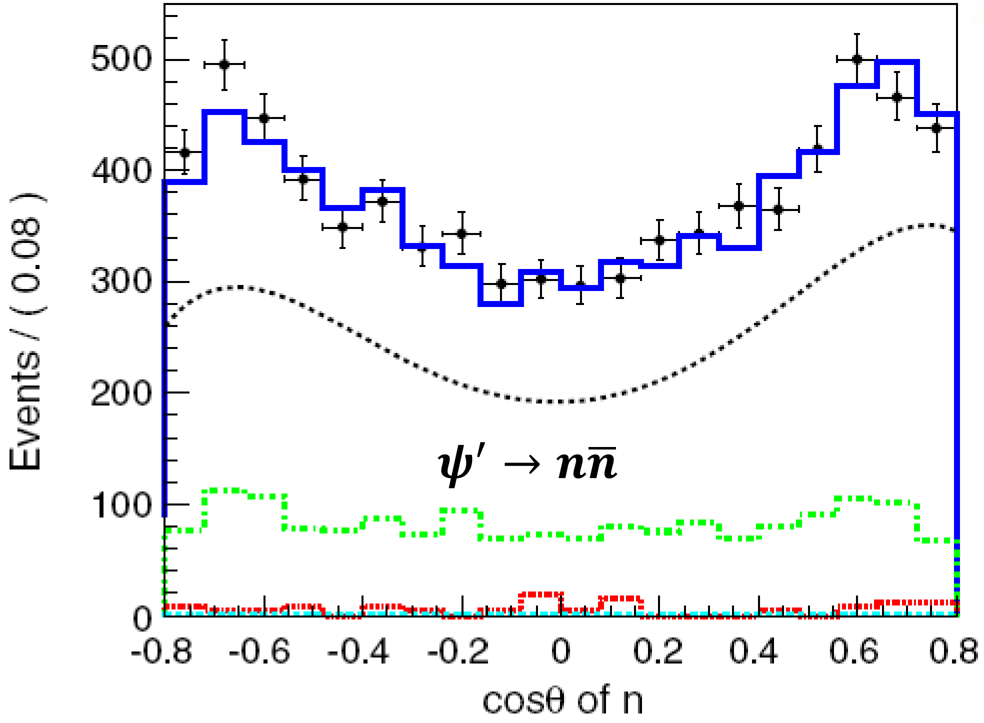
Effects on the baryon antibaryon pairs

- Angular distribution for $e^+e^- \to B\bar{B}$ with and without beam transverse polarization P_t



Without P_t	With P_t
$\frac{dN}{d\Omega} \propto 1 + \alpha \cos^2\theta$	$\frac{dN}{d\Omega} \propto 1 + \alpha \cos^2\theta + P_t^2 \sin^2\theta \cos 2\phi$





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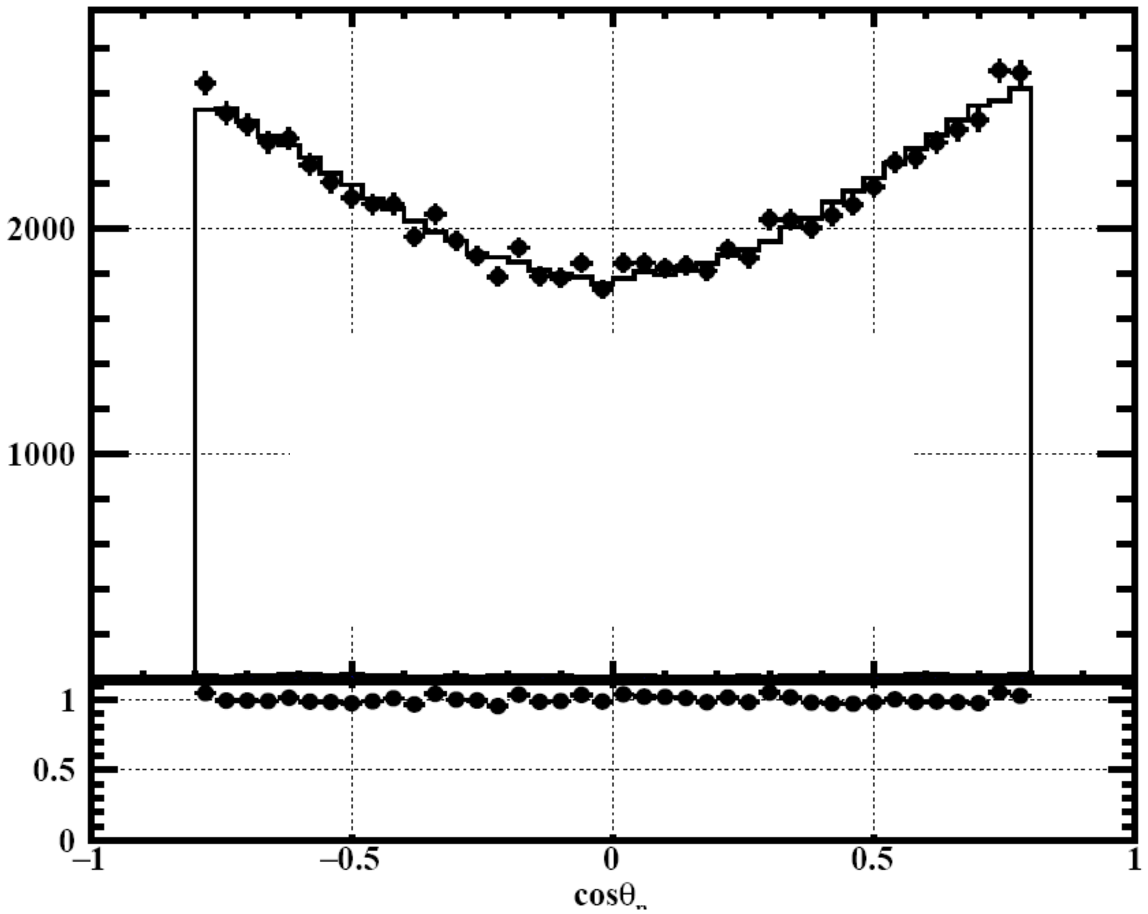
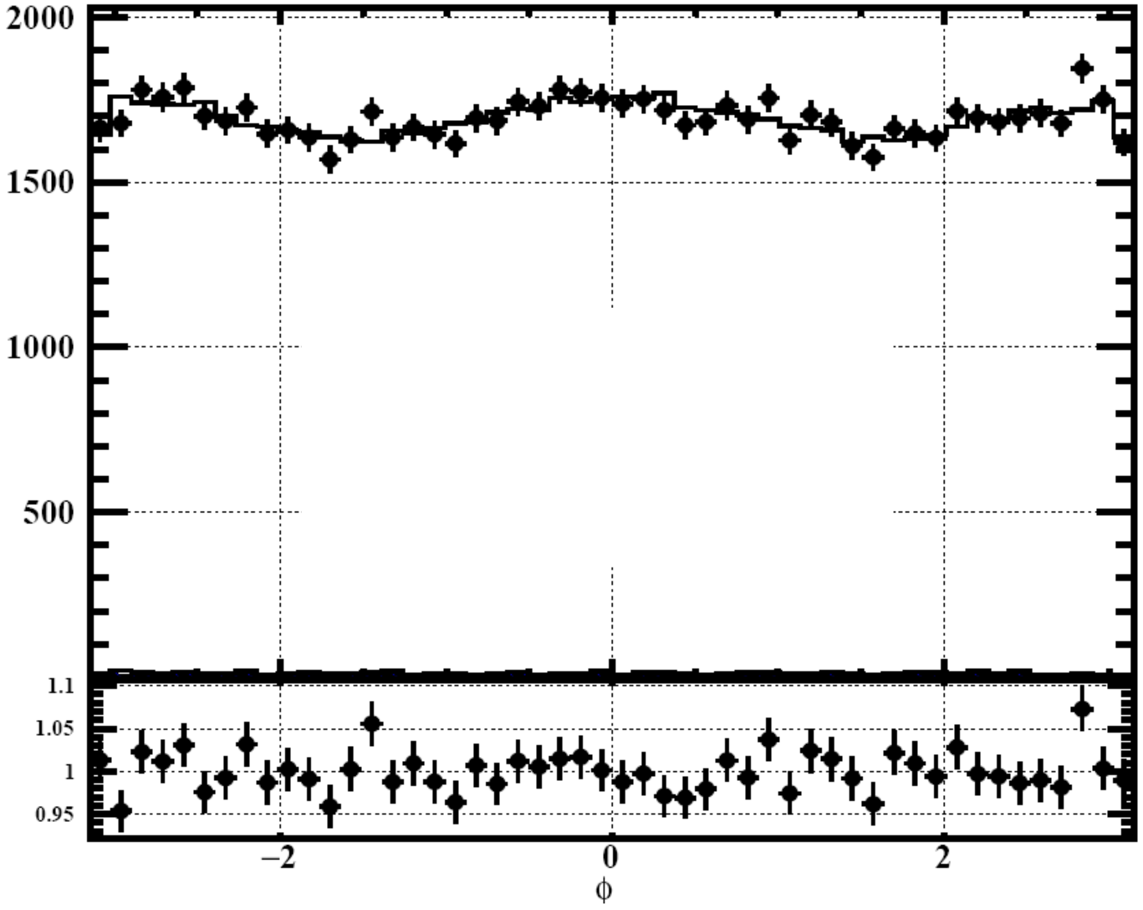
Effects on the baryon antibaryon pairs

$\psi' \to p\bar{p}$ with all ψ' data

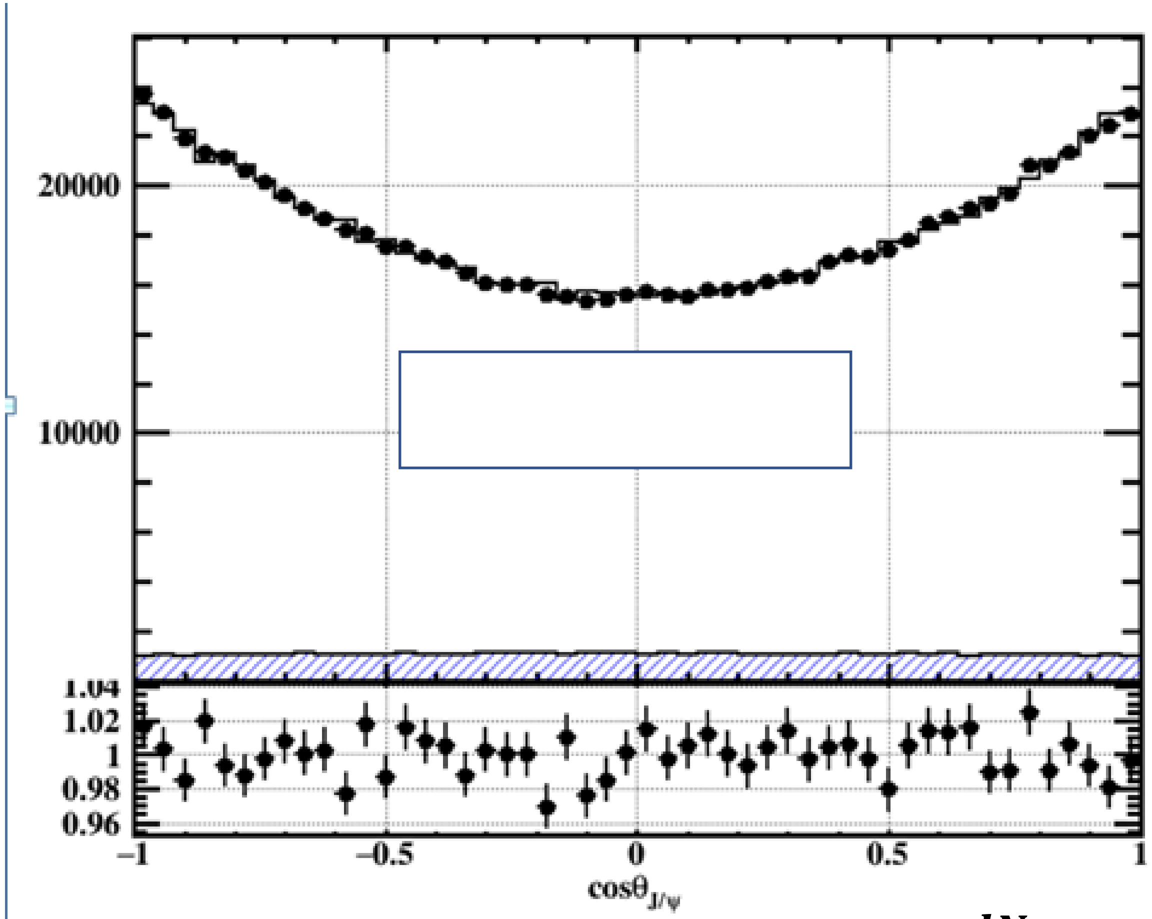


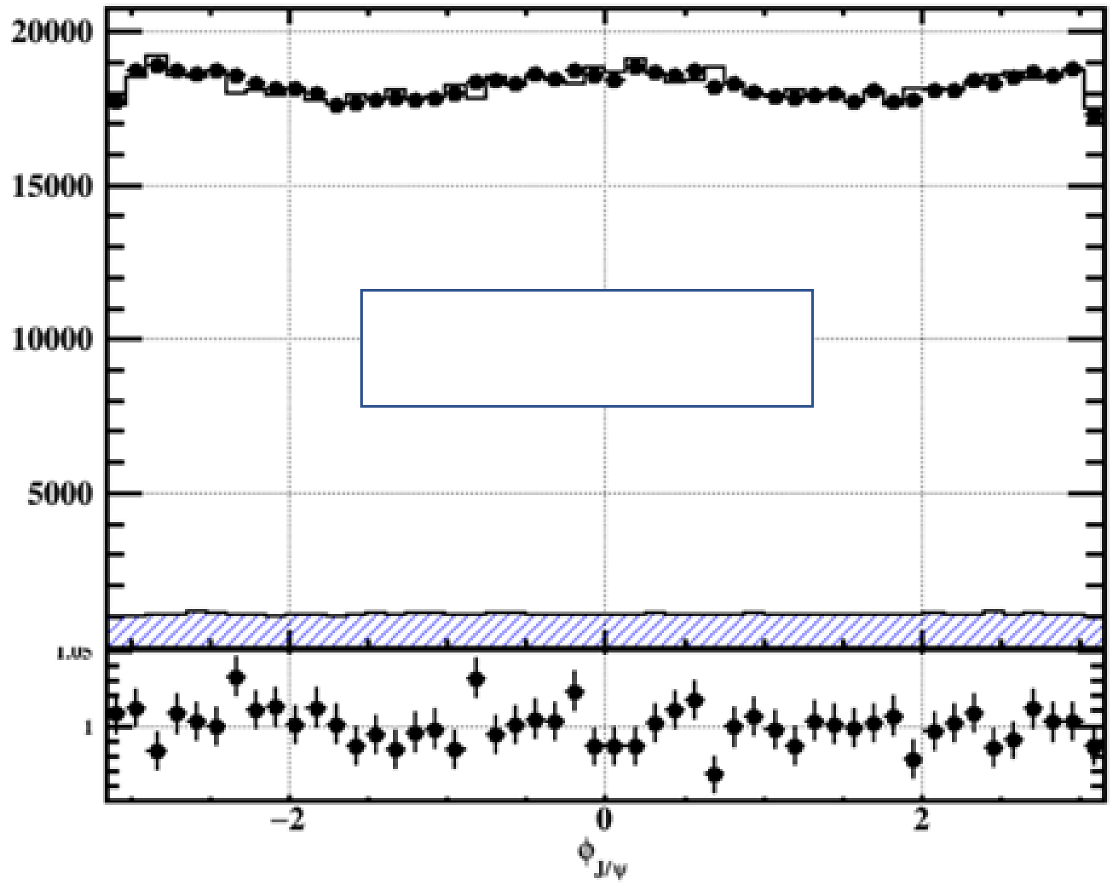


Fit with : $\frac{dN}{d\Omega} \propto 1 + \alpha\, cos^2\, \theta + P_t^2\, sin^2\, \theta\, cos\, 2\phi$

Effects on the $\psi(3686) \to \eta J/\psi, \gamma\chi_{c0}$

$\psi' \to \eta J/\psi$ with all ψ' data sets

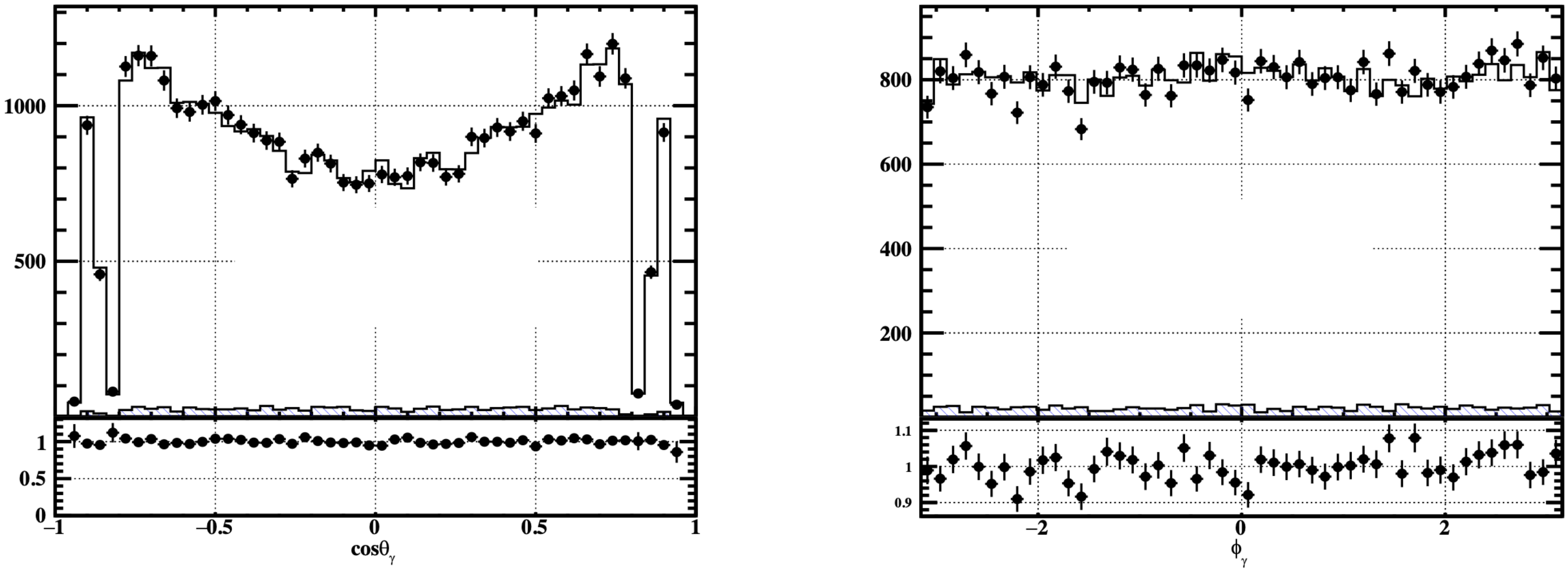




Fit with : $\frac{dN}{d\Omega} \propto 1 + \alpha\, cos^2\,\theta + P_t^2\, sin^2\,\theta\, cos\, 2\phi$

Effects on the $\psi(3686) \to \eta J/\psi, \gamma\chi_{c0}$

$\psi' \to \gamma\chi_{c0}$ with all ψ' data sets



Fit with : $\frac{dN}{d\Omega} \propto 1 + \alpha\, cos^2\,\theta + P_t^2\, sin^2\,\theta\, cos\, 2\phi$

Effects on the hyperon polarization measurements

- $e^+e^- \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

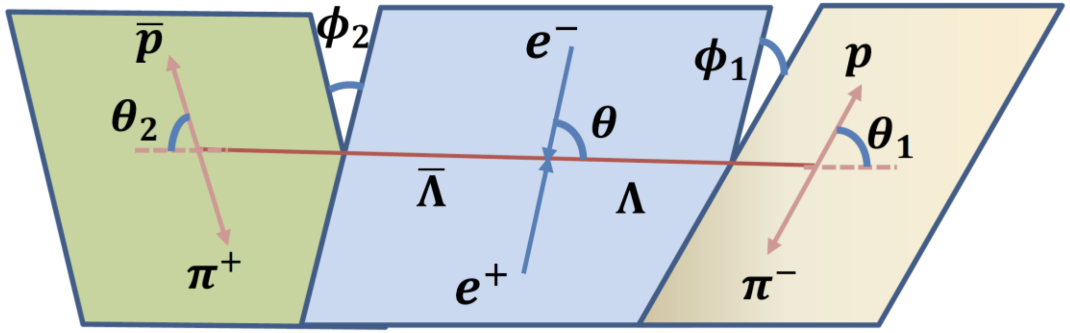
- Λ Transversely Polarized P_y^B, P_t **transfer to** P_x^B

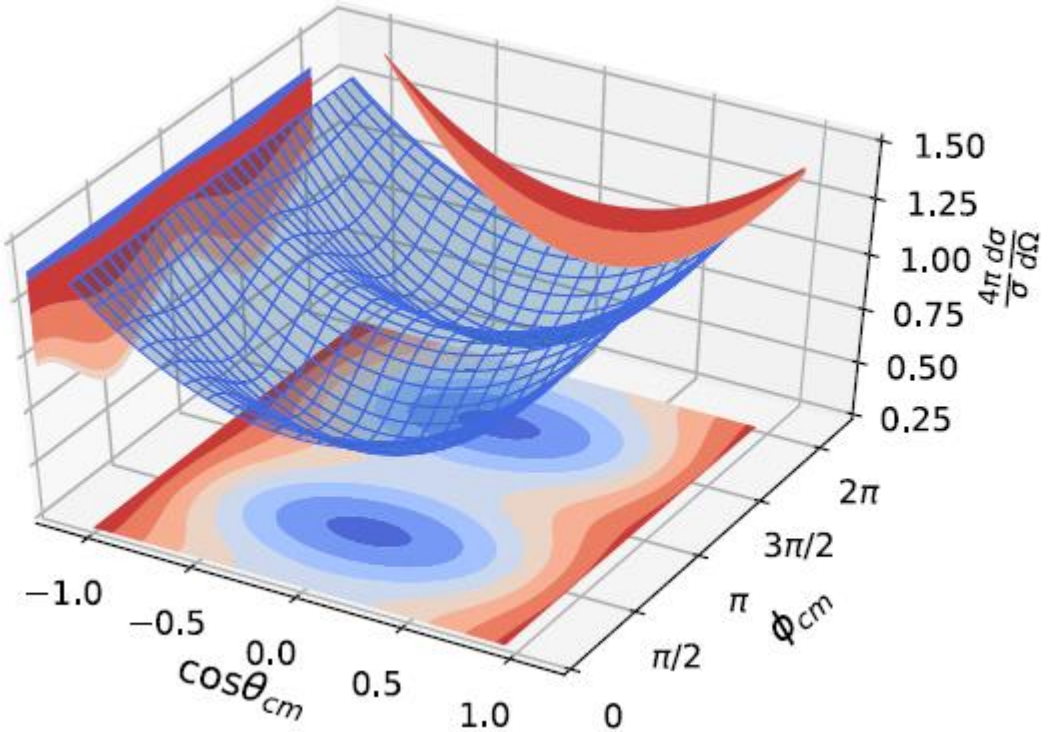
$$\frac{4\pi}{\sigma}\frac{d\sigma}{d\Omega_B} = \frac{3}{3+\alpha_\psi}(1+\alpha_\psi\cos^2\theta + \alpha_\psi P_T^2 \sin^2\theta\cos 2\phi)$$

$$P_y^B = \frac{\sqrt{1-\alpha_\psi^2}\sin\Delta\Phi\sin\theta\cos\theta(1-P_T^2\cos 2\phi)}{1+\alpha_\psi\cos^2\theta+\alpha_\psi P_T^2\sin^2\theta\cos 2\phi}$$

$$P_x^B = \frac{-P_T^2\sqrt{1-\alpha_\psi^2}\sin\Delta\Phi\sin\theta\sin 2\phi}{1+\alpha_\psi\cos^2\theta+\alpha_\psi P_T^2\sin^2\theta\cos 2\phi}$$

Integrating out the azimuthal angle is equal to $P_T = 0$





- **Xu Cao**, Yu-tie Liang, Rong-Gang Ping, 2404.00298 [hep-ph], to be published in PRD.

Effects on the hyperon polarization measurements

- **Probe CP violation via Transversely Polarized beams**

$$\mathcal{W}(\boldsymbol{\xi}) = \mathcal{F}_0 + \beta_\psi(\alpha_+\mathcal{F}_3 - \alpha_-\mathcal{F}_4) + \alpha_-\alpha_+(\mathcal{F}_1 + \gamma_\psi\mathcal{F}_2 + \alpha_\psi\mathcal{F}_5),$$

$$\mathcal{F}_0 = 1 + \alpha_\psi \cos^2\theta + \alpha_\psi P_T^2 \sin^2\theta \cos 2\phi,$$

$$\mathcal{F}_1 = (\sin^2\theta + P_T^2 \cos 2\phi \cos^2\theta) \sin\theta_1 \cos\phi_1 \sin\theta_2 \cos\phi_2 - (\cos^2\theta + P_T^2 \cos 2\phi \sin^2\theta) \cos\theta_1 \cos\theta_2 + P_T^2 \sin\theta_1 \sin\theta_2 (\sin 2\phi \cos\theta \sin(\phi_1 - \phi_2) + \cos 2\phi \sin\phi_1 \sin\phi_2),$$

$$\mathcal{F}_2 = (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta (\sin\theta_1 \cos\theta_2 \cos\phi_1 - \cos\theta_1 \sin\theta_2 \cos\phi_2) - P_T^2 \sin 2\phi \sin\theta (\sin\theta_1 \cos\theta_2 \sin\phi_1 + \cos\theta_1 \sin\theta_2 \sin\phi_2),$$

$$\mathcal{F}_3 = (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta \sin\theta_2 \sin\phi_2 - P_T^2 \sin 2\phi \sin\theta \sin\theta_2 \cos\phi_2,$$

$$\mathcal{F}_4 = (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta \sin\theta_1 \sin\phi_1 + P_T^2 \sin 2\phi \sin\theta \sin\theta_1 \cos\phi_1,$$

$$\mathcal{F}_5 = (\sin^2\theta + P_T^2 \cos 2\phi \cos^2\theta) \sin\theta_1 \sin\phi_1 \sin\theta_2 \sin\phi_2 - \cos\theta_1 \cos\theta_2 + P_T^2 \sin\theta_1 \sin\theta_2 [\sin 2\phi \cos\theta \sin(\phi_1 - \phi_2) + \cos 2\phi \cos\phi_1 \cos\phi_2],$$

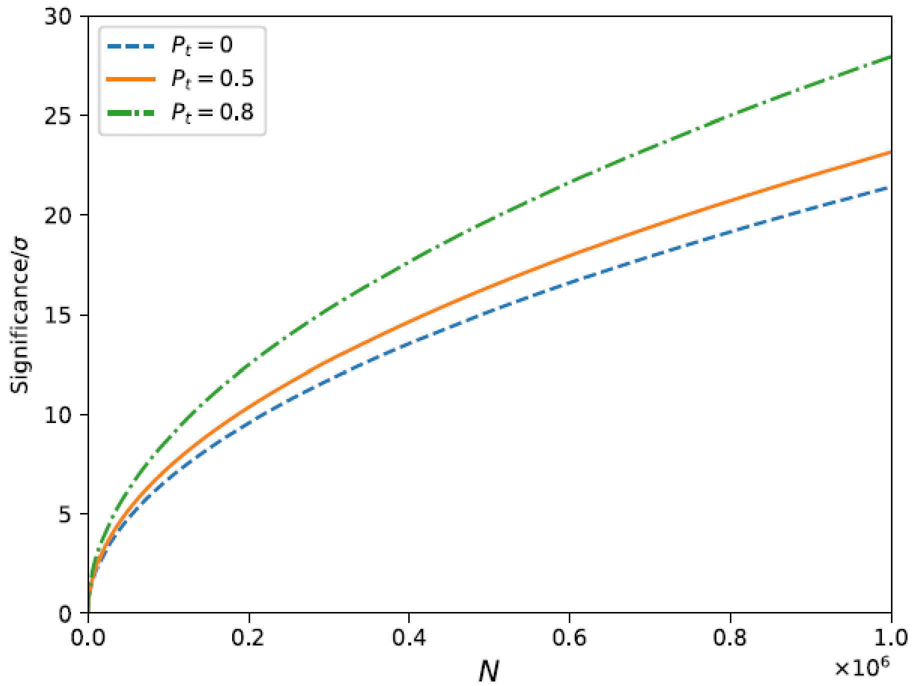


FIG. 7. Significance test for CP asymmetry in $\Lambda(\bar{\Lambda}) \to p\pi^-(\bar{p}\pi^+)$ decays as a function of the number of observed events N, using toy Monte Carlo events for $e^+e^- \to \psi(3686) \to \Lambda\bar{\Lambda}$ generated with parameters $\alpha_\psi = 0.69$, $\Delta\Phi = 23°$ [30], and $\alpha_- = 0.748$ and $\alpha_+ = -0.757$ [30,47] for different transverse polarizations $P_t = 0$, 0.5, and 0.8.

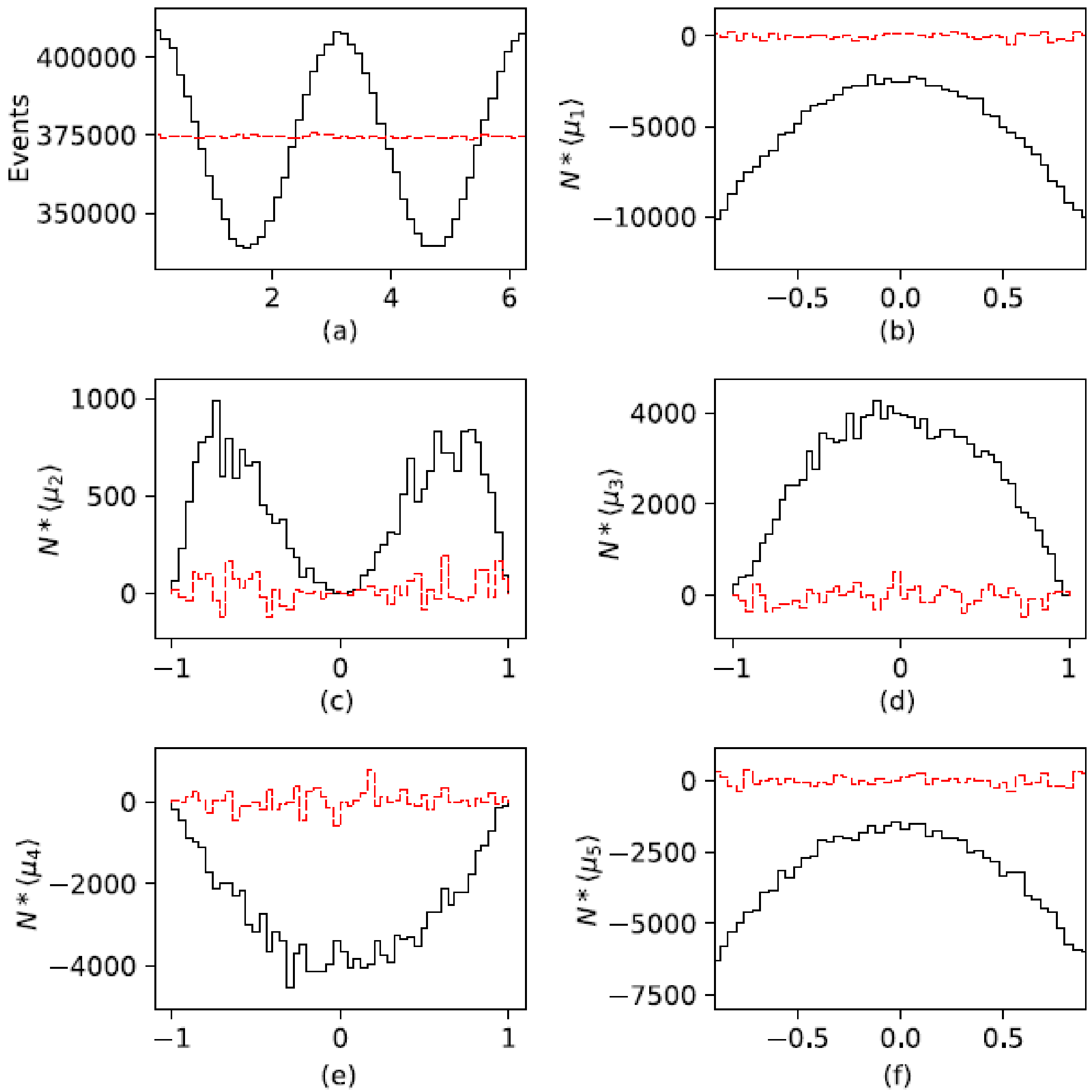
Ref.: Xu Cao, Yu-tie Liang, Rong-Gang Ping, 2404.00298 [hep-ph]

Effects on the hyperon polarization measurements

- Moments analysis

$$\mu_1 = \sin\theta_1 \sin\theta_2[\sin(2\phi)\cos\theta\sin(\phi_1-\phi_2) + \cos(2\phi)\sin\phi_1\sin\phi_2],$$
$$\mu_2 = \cos(2\phi)\sin\theta\cos\theta[\sin\theta_1\cos\theta_2\cos\phi_1 - \cos\theta_1\sin\theta_2\cos\phi_2],$$
$$\mu_3 = \sin(2\phi)\sin\theta\cos\phi_2,$$
$$\mu_4 = \sin(2\phi)\sin\theta\cos\phi_1,$$
$$\mu_5 = \sin\theta_1\sin\theta_2[\sin(2\phi)\cos\theta\sin(\phi_1-\phi_2) - \cos(2\phi)\cos\phi_1\cos\phi_2].$$

$$\frac{d\langle\mu_1\rangle}{d\cos\theta} = \frac{\alpha_-\alpha_+P_T^2[(3\alpha_\psi+2)\cos^2\theta+1]}{12(\alpha_\psi+3)},$$
$$\frac{d\langle\mu_2\rangle}{d\cos\theta} = -\frac{\alpha_-\alpha_+P_T^2\gamma_\psi\sin^2\theta\cos^2\theta}{6(\alpha_\psi+3)},$$
$$\frac{d\langle\mu_3\rangle}{d\cos\theta} = -\frac{3\alpha_+P_T^2\beta_\psi\sin^2\theta}{8(\alpha_\psi+3)},$$
$$\frac{d\langle\mu_4\rangle}{d\cos\theta} = -\frac{3\alpha_-P_T^2\beta_\psi\sin^2\theta}{8(\alpha_\psi+3)},$$
$$\frac{d\langle\mu_5\rangle}{d\cos\theta} = \frac{\alpha_-\alpha_+P_T^2[(2\alpha_\psi+1)\cos^2\theta+\alpha_\psi]}{12(\alpha_\psi+3)}.$$



Summary and outlook

- **Study focuses on measurements using $e^+ e^- \to \gamma\gamma, e^+ e^-$, and $\mu^+ \mu^-$ processes.**
- **Interference effects observed in baryon-antibaryon pairs** and ψ' **decay.**
- **Impact of interference on hyperon polarization measurements explored.**
- **Future research will delve deeper into polarization probe for enhanced particle physics understanding and potential advancements in high-energy physics.**

Thanks for your attention