正反重子对的产生、衰变和CP破坏
Production, Decay and CP violation of baryon-antibaryon pairs

曹　须

arXiv: 1808.06382, 2109.15132, 2304.04913, 2404.00298

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

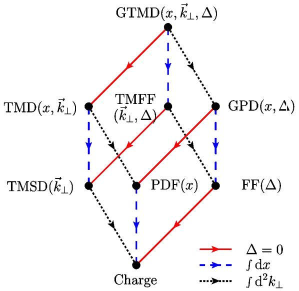
2025年7月11~15日
第八届强子谱和强子结构研讨会，广西师范大学

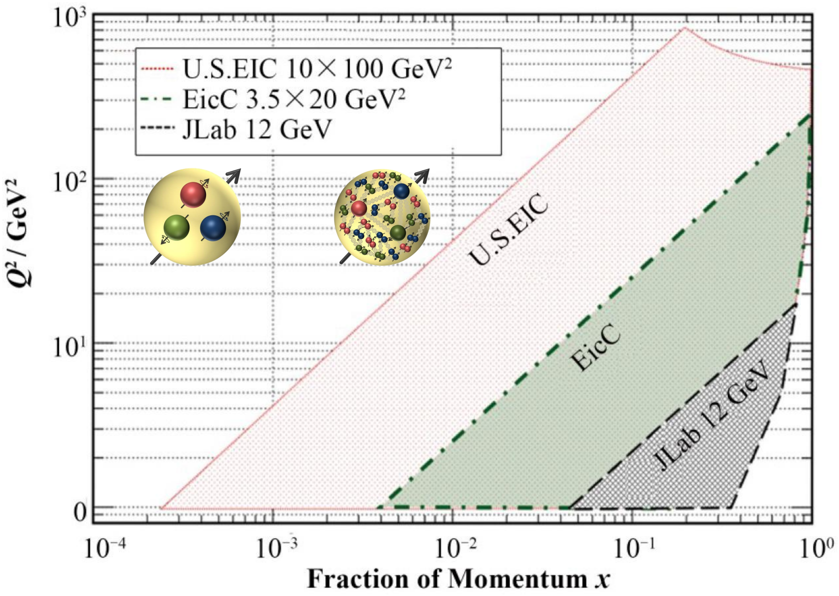
Introduction

- **TMD: Transverse Momentum Distributions (k ⊥ & longi. Momentum):**
- How is proton's spin correlated with the motion of the quarks/gluons?
- …… probed by the inclusive process

- **GPD: General Parton Distributions (trans. spatial position b⊥ & longi. Momentum):**
- How does proton's spin influence the spatial distribution of partons?
- …… probed by the exclusive process

- **From 1D to 3D picture of hadron & nuclei**
- **Origin of the Proton/Meson mass & spin**

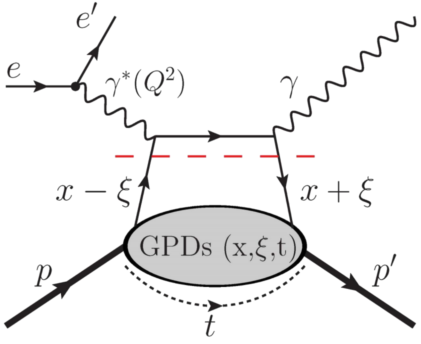


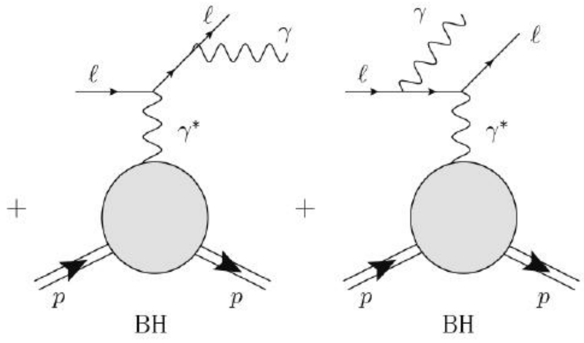


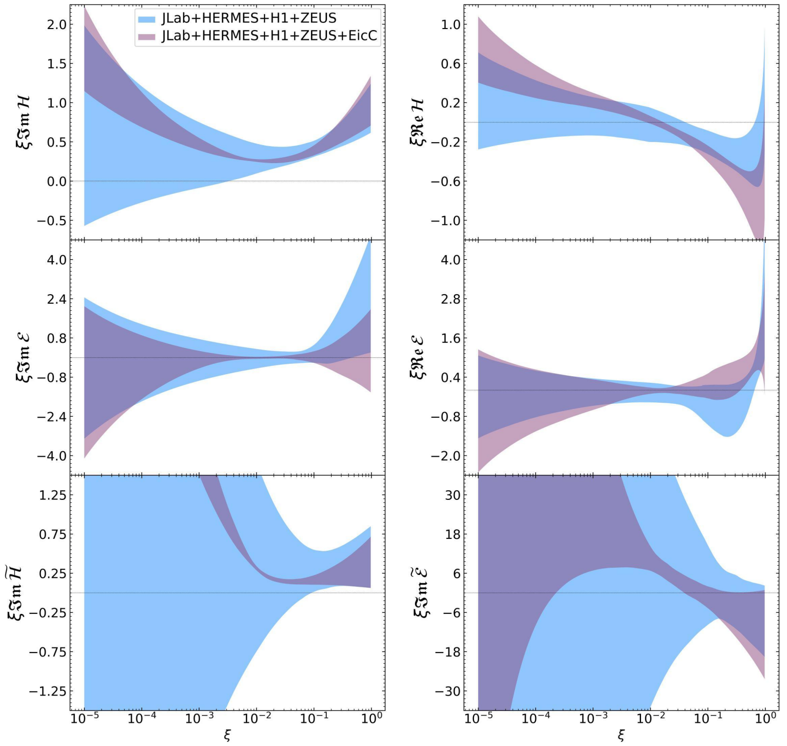
- **中国科学: 物理学力学天文学, 50: 112005 (2020)**
- **核技术, 43(2): 020001 (2020) ;Front. Phys. 16, 64701 (2021)**

Introduction

- **From 1D to 3D structure of proton & pion: GPD from DVCS**







Yuanyuan Huang, XC, Taifu Feng, K. Kumericki, Yu Lu, Neural network extraction of CFFs + LQCD data, to appear

Introduction

- R. Hofstadter, Rev. Mod. Phys. 1956，28：214
- 1961 Nobel Prize in Physics (together with Rudolf Mössbauer)
- "for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons"

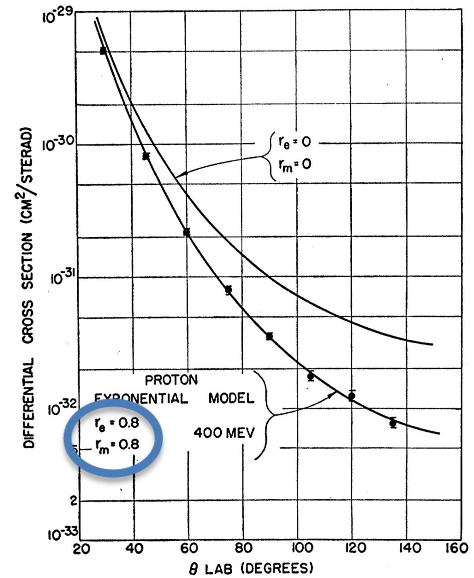
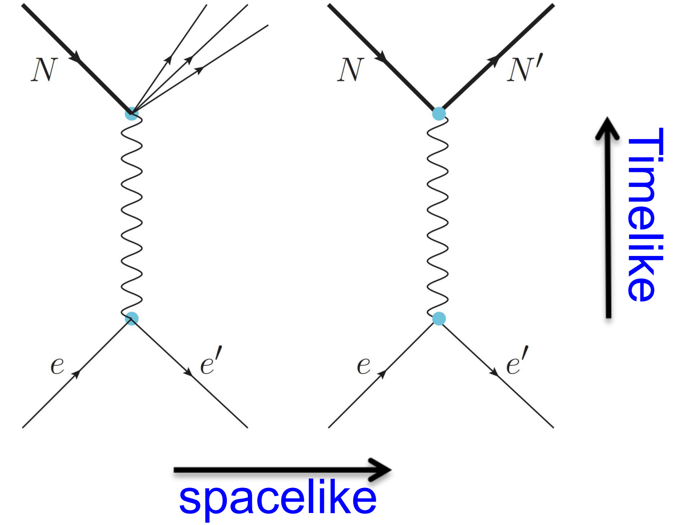


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii $=0.80\times10^{-13}$ cm.



$$r^2_{E/M} = -\frac{6}{G_{E/M}(0)}\frac{dG_{E/M}(Q^2)}{dQ^2}\Big|_{Q^2=0} = (0.84\ \text{fm})^2$$

Introduction

- Surprisingly, study of polarization effects in timelike region appears until 1996
  - A. Z. Dubnickova, S. Dubnicka, and M. P. Rekalo, Nuovo Cim. A 109, 241 (1996)
  - S. J. Brodsky, C. E. Carlson, J. R. Hiller, and D. S. Hwang, Phys. Rev. D 69, 054022 (2004)
  - E. Tomasi-Gustafsson, F. Lacroix, C. Duterte, and G. I. Gakh, Eur. Phys. J. A 24, 419 (2005)
  - H. Chen and R.-G. Ping, Phys. Rev. D 76, 036005 (2007)
  - G. Fäldt, A. Kupsc, Phys. Lett. B 772, 16 (2017)

finally leading to the most precise test of hyperon CP violation at BESIII: Nature 606, 64 (2022)

- …… polarization observables are totally different between:

	space-like (lab.)	time-like (c.m.)
Unpolarized	$\frac{d\sigma}{d\Omega}_e = \frac{d\sigma_M}{d\Omega_e}\left[2\tau G_M^2 \tan^2(\theta_e/2) + \frac{G_E^2+\tau G_M^2}{1+\tau}\right]$	$\frac{d\sigma}{d\Omega} = \frac{d\sigma_M}{d\Omega}\left[2\tau\|G_M\|^2\frac{\cot^2\theta}{1+\tau} + \frac{\|G_M\|^2+\tau\|G_E\|^2}{1+\tau}\right]$
Long. electron	$\frac{P_t}{P_\ell} = -2\cot(\theta_e/2)\frac{M_p}{\epsilon_1+\epsilon_2}\frac{G_E}{G_M}$	$\mathbf{P}_B = \frac{\gamma_\psi P_e \sin\theta\hat{\mathbf{x}}_1 - \beta_\psi \sin\theta\cos\theta\hat{\mathbf{y}}_1 - (1+\alpha_\psi)P_e\cos\theta\hat{\mathbf{z}}_1}{1+\alpha_\psi\cos^2\theta}$
Long. both beams	$A = -\frac{2\sqrt{\tau(1+\tau)}\tan(\theta_e/2)}{G_E^2+\frac{\tau}{\epsilon}G_M^2}\left[\sin\theta^*\cos\phi^* G_E G_M + \sqrt{\tau[1+(1+\tau)\tan^2(\theta_e/2)]}\cos\theta^* G_M^2\right].$	Nothing New

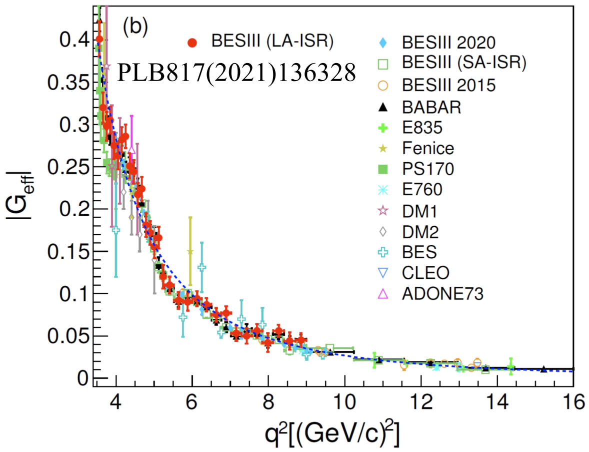
Introduction

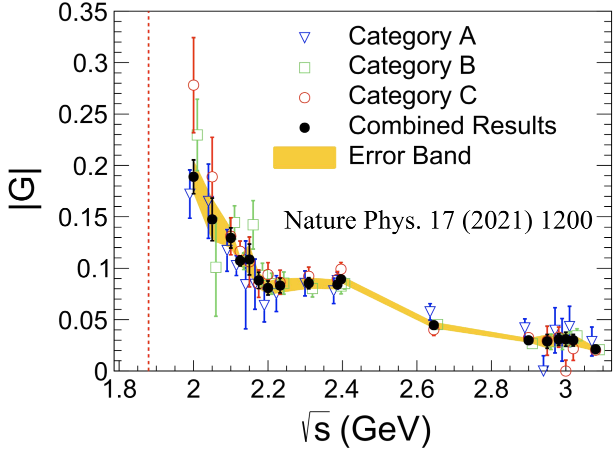
- Oscillation of Timelike Electro-Magnetic Form Factors

- Transversely Polarized beams at electron-positron colliders

Oscillation of Timelike EMFFs

- Surprisingly, periodic oscillation in timelike region appears

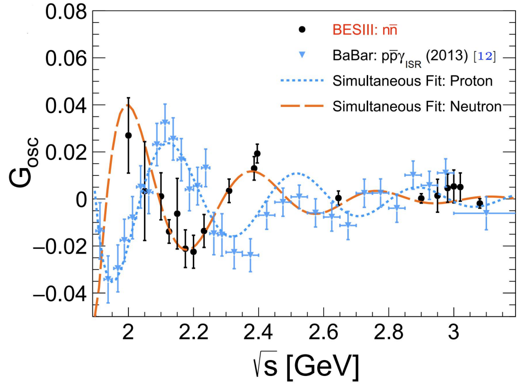




- A. Bianconi and E. Tomasi-Gustafsson, Phys. Rev. Lett. 114, 232301 (2015); Phys. Rev. C 93, 035201 (2016); Phys. Rev. C 103, 035203 (2021).

$$G_{\rm eff}\left(q^2\right)=\frac{A}{\left(1+q^2/m_a^2\right)\left[1-q^2/\left(0.71\,\mathrm{GeV}^2\right)\right]^2}$$

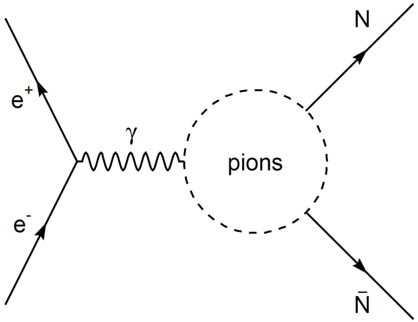
$$G_N^{\rm osc}=A_N\exp\left(-B_N p\right)\cos\left(C_N p+D_N\right)$$



- Dynamic origin?

Oscillation of Timelike EMFFs

- Smooth leading dipole component + unknown residual component



residual (rsd)

$$G_{p,n} = \frac{I^{D}_{p,n} + I^{\rm rsd}_{p,n}}{\sqrt{2}} = \frac{I^{D}_{1} \pm I^{D}_{0}}{\sqrt{2}} + \frac{I^{\rm rsd}_{1} \pm I^{\rm rsd}_{0}}{\sqrt{2}}$$

with $|I, I_3\rangle = |0, 0\rangle$ and $|1, 0\rangle$

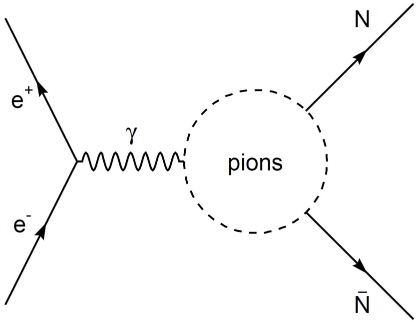
- Let's invoke the isospin symmetry—or more precisely, charge symmetry with isospin violation < 10 %
- Isospin amplitudes is complex as known:

$$I^{D}_{p,n} = I^{D}_{1} \pm I^{D}_{0} = \sqrt{2} G^{D}_{p,n} e^{i\phi^{D}_{p,n}},$$

$$I^{\rm rsd}_{p,n} = I^{\rm rsd}_{1} \pm I^{\rm rsd}_{0} = |I^{\rm rsd}_{p,n}| e^{i\phi^{\rm rsd}_{p,n}},$$

Oscillation of Timelike EMFFs

- Smooth leading dipole component + unknown residual component



residual (rsd)

$$G_{p,n} = \frac{I^D_{p,n} + I^{\text{rsd}}_{p,n}}{\sqrt{2}} =$$ with $|I, I_3\rangle = |0, 0\rangle$ and $|1, 0\rangle$

- Complex amplitudes is module squared in order to obtain the real form factors:

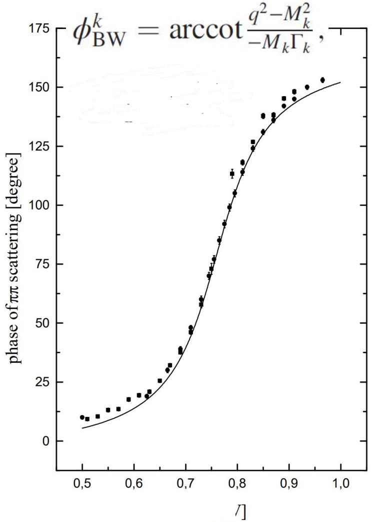
$$|G_N|^2 - (G^D_N)^2 = G^{\text{rsd}}_N (2G^D_N + G^{\text{rsd}}_N)$$
$$= \frac{1}{2}|I^{\text{rsd}}_N|^2 + \sqrt{2} G^D_N |I^{\text{rsd}}_N| \Re[e^{i(\phi^D_N - \phi^{\text{rsd}}_N)}].$$

- Complex amplitudes is module squared in order to obtain the real form factors:

$$|G_N|^2-(G_N^D)^2 = G_N^{\rm rsd}(2G_N^D+G_N^{\rm rsd})$$
$$=\frac{1}{2}|I_N^{\rm rsd}|^2+\sqrt{2}G_N^D|I_N^{\rm rsd}|\Re[e^{i(\phi_N^D-\phi_N^{\rm rsd})}].$$

- neglecting terms of order $|I_{p,n}^{\rm rsd}/I_{p,n}^D|\ll 1$, the leading-order solutions are

$$G_N^{\rm rsd}\simeq\frac{|I_N^{\rm rsd}|}{\sqrt{2}}\cos(\phi_N^D-\phi_N^{\rm rsd})+\frac{1}{4}\frac{|I_N^{\rm rsd}|^2}{G_N^D}\sin^2(\phi_N^D-\phi_N^{\rm rsd})$$

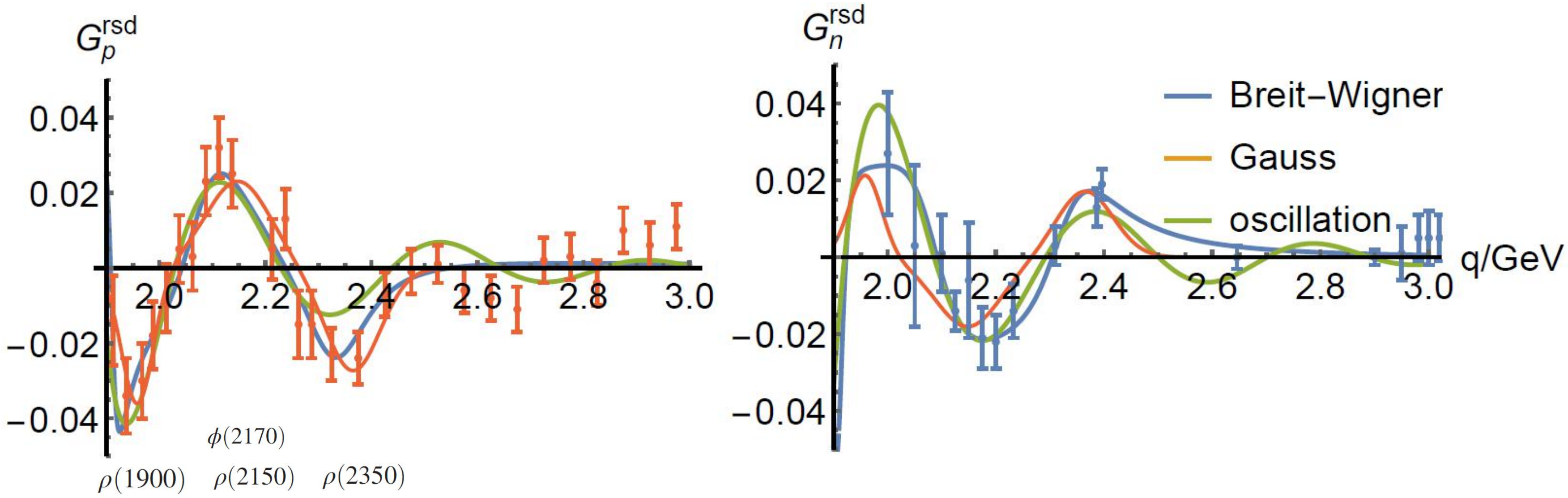


$\phi_N^{\rm rsd}$

- Proton and neutron should display sinusoidal modulations of a similar pattern
- For residual component, BESIII told us: $\frac{|I_1^{\rm rsd}+I_0^{\rm rsd}|}{|I_1^{\rm rsd}-I_0^{\rm rsd}|}=\frac{A_p}{A_n}=0.88\pm0.35,$
- Either $I_0^{\rm rsd}=0$ or $I_1^{\rm rsd}=0$ or —as an unlikely third option—a vanishing interference
- resulting into: $|\Delta\phi|=|D_n-D_p|=\arg\frac{I_1^D-I_0^D}{I_1^D+I_0^D}$ related to p/n sturcture difference

Oscillation of Timelike EMFFs

- Data of cross sections CAN't tell different dynamic origin!



- We know little about vector spectrum above NNbar threshold, see e.g.:

Li-Ming Wang, Si-Qiang Luo, Xiang Liu, Phys. Rev. D105, 034011 (2022); Cheng-Qun Pang et al., Phys. Rev. D101, 074022 (2020)

- Final State Interaction?

Zhao-Sai Jia et al. PhysRevD.111.054014; Qin-He Yang JHEP 08(2024)208; R-Q Qian, Z-W Liu, XC, X. Liu, PhysRevD.107.L091502

Oscillation of Timelike EMFFs

- Consequence: nucleon structure

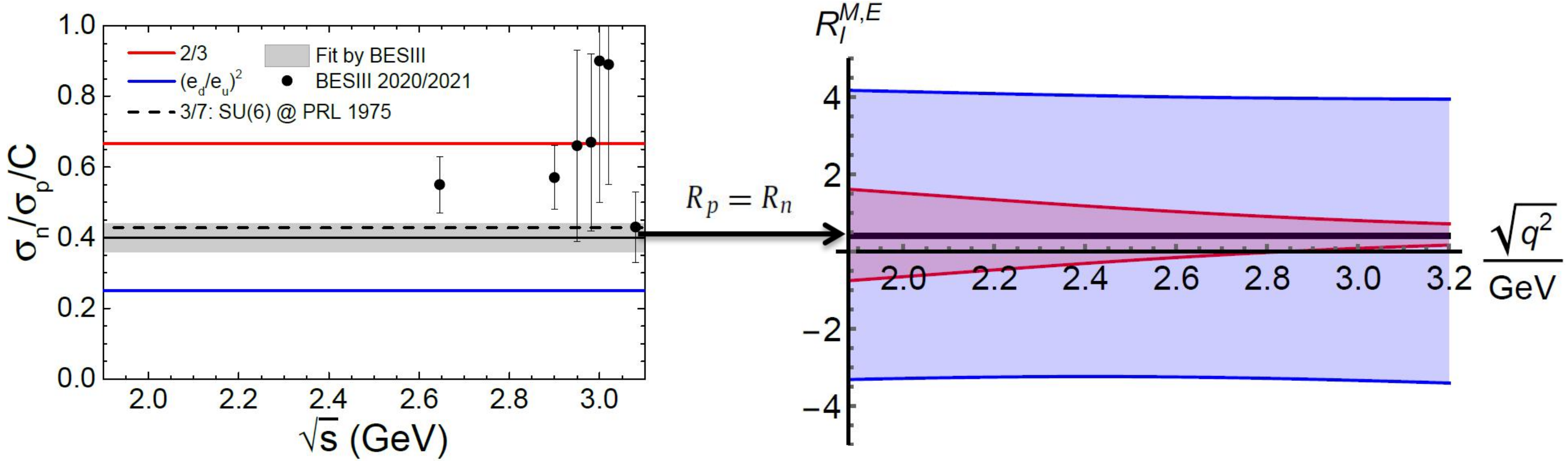
$$R_I^D = \frac{(G_p^D)^2-(G_n^D)^2}{(G_p^D)^2+(G_n^D)^2} = \frac{2\Re(I_0^D I_1^{D\dagger})}{|I_0^D|^2+|I_1^D|^2} = 0.43\pm 0.03$$

$$G_{E,M}^p = \frac{2}{3}G_{E,M}^u - \frac{1}{3}G_{E,M}^d = \frac{1}{2}\left(\frac{G_{E,M}^{u+d}}{3} + G_{E,M}^{u-d}\right),$$
$$G_{E,M}^n = \frac{2}{3}G_{E,M}^d - \frac{1}{3}G_{E,M}^u = \frac{1}{2}\left(\frac{G_{E,M}^{u+d}}{3} - G_{E,M}^{u-d}\right),$$

- Consequence: isospin separation

R_I^M {
$$\left|\frac{G_M^{u+d}}{3}\right|^2 + |G_M^{u-d}|^2 = 2(2\tau+1)\left(\frac{|G_p^D|^2}{2\tau+R_p^2} + \frac{|G_n^D|^2}{2\tau+R_n^2}\right)$$
$$\Re\left[\frac{G_M^{u+d}}{3}G_M^{u-d\dagger}\right] = (2\tau+1)\left(\frac{|G_p^D|^2}{2\tau+R_p^2} - \frac{|G_n^D|^2}{2\tau+R_n^2}\right)$$

R_I^E {
$$\left|\frac{G_E^{u+d}}{3}\right|^2 + |G_E^{u-d}|^2 = 2(2\tau+1)\left(\frac{R_p^2|G_p^D|^2}{2\tau+R_p^2} + \frac{R_n^2|G_n^D|^2}{2\tau+R_n^2}\right)$$
$$\Re\left[\frac{G_E^{u+d}}{3}G_E^{u-d\dagger}\right] = (2\tau+1)\left(\frac{R_p^2|G_p^D|^2}{2\tau+R_p^2} - \frac{R_n^2|G_n^D|^2}{2\tau+R_n^2}\right)$$



Oscillation of Timelike EMFFs

Applicable to the decay of Charmonium: isospin violation

$$R_I^{\text{eff}} = \frac{|G_p^D|^2 - |G_n^D|^2}{|G_p^D|^2 + |G_n^D|^2} = \frac{2\delta_I \cos\phi_I}{1+\delta_I^2}$$

$$R_I^M = \frac{|G_M^p|^2 - |G_M^n|^2}{|G_M^p|^2 + |G_M^n|^2} = \frac{2\delta_M \cos\phi_M}{1+\delta_M^2}$$

$$R_I^E = \frac{|G_E^p|^2 - |G_E^n|^2}{|G_E^p|^2 + |G_E^n|^2} = \frac{2\delta_E \cos\phi_E}{1+\delta_E^2}$$

Decay process	Branching ratio	α_B	R_I^{eff}	R_I^M	R_I^E
$J/\psi \to p\bar{p}$	$(2.120 \pm 0.029) \times 10^{-3}$	0.595±0.012±0.015 [85]	0.007±0.039	0.02±0.05	-0.11±0.26
$J/\psi \to n\bar{n}$	$(2.09 \pm 0.16) \times 10^{-3}$	0.50±0.04±0.21 [85]			
$J/\psi \to \Xi^0\bar{\Xi}^0$	$(1.17 \pm 0.04) \times 10^{-3}$	0.66±0.03±0.05 [86]	0.09±0.04	0.10±0.04	-0.01±0.10
$J/\psi \to \Xi^-\bar{\Xi}^+$	$(0.97 \pm 0.08) \times 10^{-3}$	0.586±0.012±0.010 [87] [a]			
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	$(1.172 \pm 0.032) \times 10^{-3}$	-0.449±0.020±0.008 [89]			
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	$(1.07 \pm 0.04) \times 10^{-3}$	-0.508±0.006±0.004 [90] [b]			
$J/\psi \to \Sigma^-\bar{\Sigma}^+$	—	—			
$J/\psi \to \Lambda\bar{\Lambda}$	$(1.89 \pm 0.09) \times 10^{-3}$	0.461±0.006±0.007 [92] [c]			
$J/\psi \to \Lambda\bar{\Sigma}^0 + \text{c.c.}$	$(2.83 \pm 0.23) \times 10^{-5}$	—			
$J/\psi \to \Sigma(1385)^0\bar{\Sigma}(1385)^0$	$(10.71 \pm 0.83) \times 10^{-4}$	-0.64±0.03±0.10 [86]			
$J/\psi \to \Sigma(1385)^+\bar{\Sigma}(1385)^-$	$(12.58 \pm 0.14) \times 10^{-4}$	-0.49±0.06±0.08 [88]	0.069±0.008	0.14±0.10	0.02±0.19
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$	$(10.96 \pm 0.12) \times 10^{-4}$	-0.58±0.05±0.09 [88]			
$\psi(2S) \to p\bar{p}$	$(2.94 \pm 0.08) \times 10^{-4}$	1.03±0.06±0.03 [93]	-0.020±0.028	0.02±0.04	-1.0±0.8
$\psi(2S) \to n\bar{n}$	$(3.06 \pm 0.15) \times 10^{-4}$	0.68±0.12±0.11 [93]			
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	$(2.3 \pm 0.4) \times 10^{-4}$	0.65±0.09±0.14 [86]	-0.11±0.08	-0.12±0.08	-0.04±0.28
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	$(2.87 \pm 0.11) \times 10^{-4}$	0.693±0.048±0.049 [94] [d]			
$\psi(2S) \to \Sigma^0\bar{\Sigma}^0$	$(2.35 \pm 0.09) \times 10^{-4}$	0.71±0.11±0.04 [89]			
$\psi(2S) \to \Sigma^+\bar{\Sigma}^-$	$(2.43 \pm 0.10) \times 10^{-4}$	0.682±0.03±0.011 [90] [e]	-0.074±0.026	-0.121±0.029	0.8±0.4
$\psi(2S) \to \Sigma^-\bar{\Sigma}^+$	$(2.82 \pm 0.09) \times 10^{-4}$	0.96±0.09±0.03 [95]			
$\psi(2S) \to \Lambda\bar{\Lambda}$	$(3.81 \pm 0.13) \times 10^{-4}$	0.82±0.08±0.02 [89]			
$\psi(2S) \to \Lambda\bar{\Sigma}^0 + \text{c.c.}$	$(1.6 \pm 0.7) \times 10^{-6}$	—			
$\psi(2S) \to \Sigma(1385)^0\bar{\Sigma}(1385)^0$	$(6.9 \pm 0.7) \times 10^{-5}$	0.59±0.25±0.25 [86]			
$\psi(2S) \to \Sigma(1385)^+\bar{\Sigma}(1385)^-$	$(8.5 \pm 0.7) \times 10^{-5}$	0.35±0.37±0.10 [88]	0.00±0.06	-0.06±0.11	0.3±0.7
$\psi(2S) \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$	$(8.5 \pm 0.8) \times 10^{-5}$	0.64±0.40±0.27 [88]			

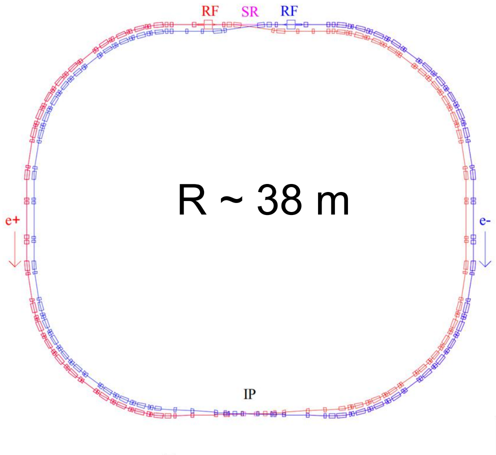
Transversely Polarized beams

- Known Fact of Lepton Beams at circular colliders: Sokolov-Ternov effect

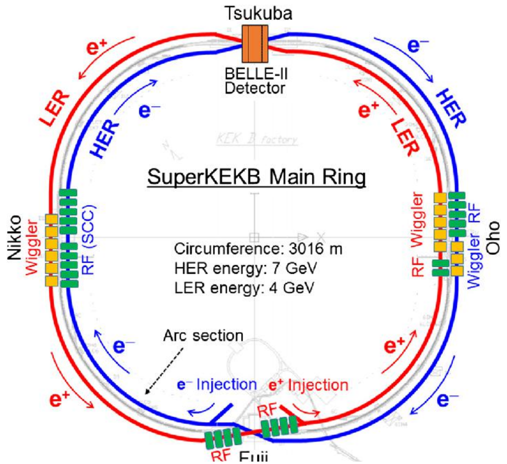
The self-polarization of relativistic electrons or positrons moving in a magnetic field at a storage ring occurs through the emission of spin-flip synchrotron radiation

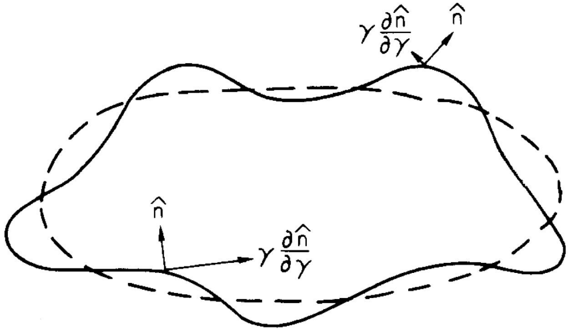
A. A. Sokolov and I. M. Ternov, Dokl. Akad. Nauk SSSR 153, 1052 (1963)

V. N. Baier and V. S. Fadin, Sov. Phys. Dokl. 10, 204 (1965); J. D. Jackson, Rev. Mod. Phys. 48, 417 (1976)



The BEPCII Complexity





Transversely Polarized beams

- Known Fact of Unpolarized Beams: measure the hyperon/anti-hyperon decay simultaneously

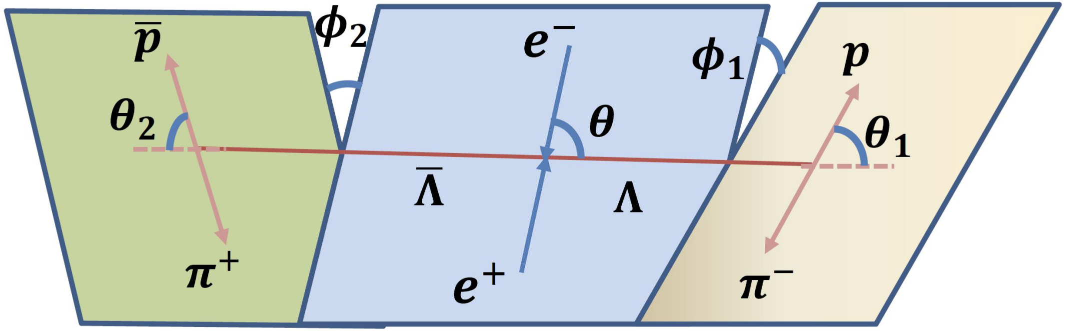
H. Chen, R.-G. Ping, Phys. Rev. D 76, 036005 (2007)

Göran Fäldt, Andrzej Kupsc, Phys.Lett.B 772, 16 (2017)

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

$$C_{xz}^B = \frac{\sqrt{1-\alpha_\psi^2}\,\cos\Delta\Phi \sin\theta\cos\theta}{1+\alpha_\psi\cos^2\theta}$$

$$\Delta\Phi = \arg\frac{G_E^B}{G_M^B}$$



$$\mathcal{W}(\xi) = \mathcal{F}_0(\xi) + \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)(\alpha_2\cdot\mathcal{F}_3 - \alpha_1\cdot\mathcal{F}_4)$$
$$+\alpha_1\alpha_2(\mathcal{F}_1 + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\cdot\mathcal{F}_2 + \alpha_\psi\cdot\mathcal{F}_5)$$

$$\mathcal{F}_0(\xi) = 1+\alpha_\psi\cos^2\theta,$$
$$\mathcal{F}_1(\xi) = \sin^2\theta\sin\theta_1\cos\varphi_1\sin\theta_2\cos\varphi_2 - \cos\theta^2\cos\theta_1\cos\theta_2,$$
$$\mathcal{F}_2(\xi) = \sin\theta\cos\theta(\sin\theta_1\cos\theta_2\cos\varphi_1 - \cos\theta_1\sin\theta_2\cos\varphi_2),$$
$$\mathcal{F}_3(\xi) = \sin\theta\cos\theta\sin\theta_2\sin\varphi_2,$$
$$\mathcal{F}_4(\xi) = \sin\theta\cos\theta\sin\theta_1\sin\varphi_1,$$
$$\mathcal{F}_5(\xi) = \sin^2\theta\sin\theta_1\sin\varphi_1\sin\theta_2\sin\varphi_2 - \cos\theta_1\cos\theta_2,$$

Hyperon decay as a polarimeter

to probe hyperon CP violation

Transversely Polarized beams

- Comparison of Transversely and Longitudinal Polarized Beams

$$(C_{\mu\nu}) = \frac{3}{3+\alpha_\psi} \cdot \begin{pmatrix} 1+\alpha_\psi\cos^2\theta & 0 & \beta_\psi\sin\theta\cos\theta & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi\sin\theta\cos\theta \\ -\beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & 0 \\ 0 & -\gamma_\psi\sin\theta\cos\theta & 0 & -\alpha_\psi-\cos^2\theta \end{pmatrix}$$

$$+ \frac{3P_T^2}{3+\alpha_\psi} \cdot \begin{pmatrix} \alpha_\psi\sin^2\theta\cos2\phi & -\beta_\psi\sin\theta\sin2\phi & -\beta_\psi\sin\theta\cos\theta\cos2\phi & 0 \\ -\beta_\psi\sin\theta\sin2\phi & (\alpha_\psi+\cos^2\theta)\cos2\phi & -(1+\alpha_\psi)\cos\theta\sin2\phi & -\gamma_\psi\sin\theta\cos\theta\cos2\phi \\ \beta_\psi\sin\theta\cos\theta\cos2\phi & (1+\alpha_\psi)\cos\theta\sin2\phi & (1+\alpha_\psi\cos\theta)\cos2\phi & -\gamma_\psi\sin\theta\sin2\phi \\ 0 & \gamma_\psi\sin\theta\cos\theta\cos2\phi & -\gamma_\psi\sin\theta\sin2\phi & -\sin^2\theta\cos2\phi \end{pmatrix}$$

$$+ \frac{3P_L}{3+\alpha_\psi} \cdot \begin{pmatrix} 0 & \gamma_\psi\sin\theta & 0 & (1+\alpha_\psi)\cos\theta \\ \gamma_\psi\sin\theta & 0 & 0 & 0 \\ 0 & 0 & 0 & -\beta_\psi\sin\theta \\ -(1+\alpha_\psi)\cos\theta & 0 & -\beta_\psi\sin\theta & 0 \end{pmatrix}$$

with the polarization vectors of leptons

$$\rho_e^\pm = \frac{1}{2}\begin{pmatrix} 1+\mathcal{P}_z & \mathcal{P}_t \\ \mathcal{P}_t^* & 1-\mathcal{P}_z \end{pmatrix}$$

and the spin densiry matrix

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

- **Xu Cao**, Yu-tie Liang, Rong-Gang Ping, 2404.00298 [hep-ph]
- N. Salone, P. Adlarson, V. Batozskaya, A. Kupsc, S. Leupold, and J. Tandean, Phys. Rev. D 105, 116022 (2022)

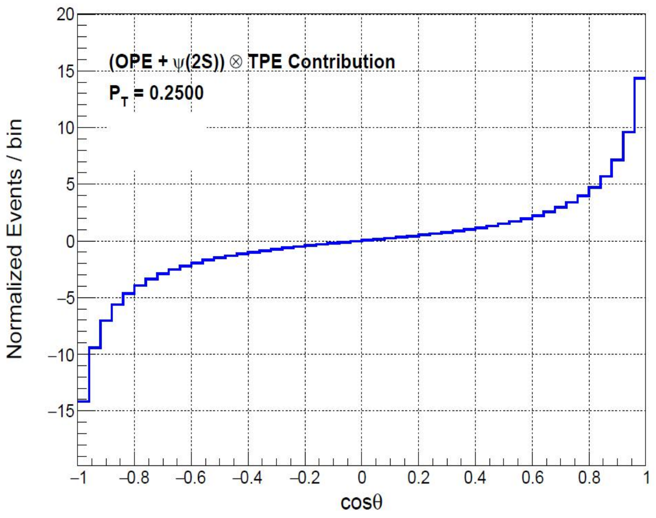
Transversely Polarized beams

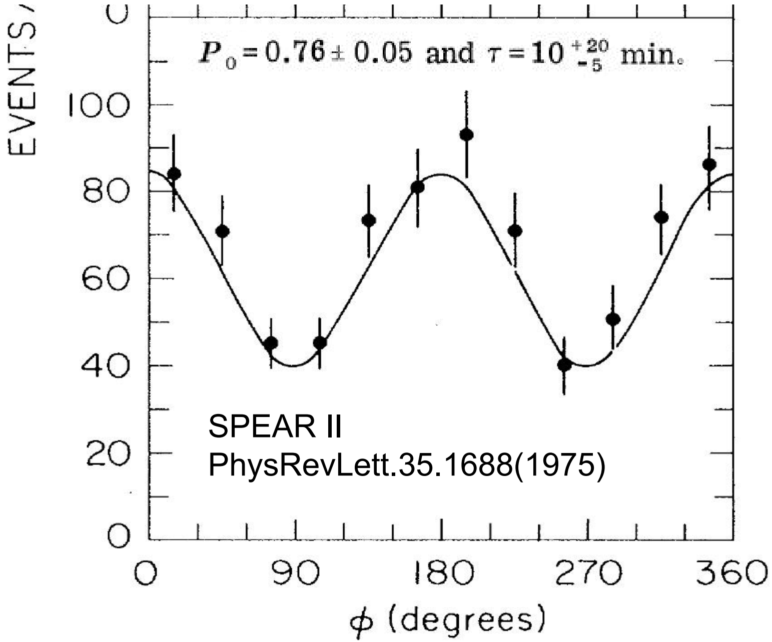
- Forgotten Facts of Transversely Polarized electron/positron Beams

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

$$- 2\beta\tau\cos\theta\sin^2\theta(1 - P_T^2\cos 2\phi)\Re\mathcal{A}_{2\gamma}$$

measured through $e^+e^- \to \mu^+\mu^-$ and e^+e^-





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

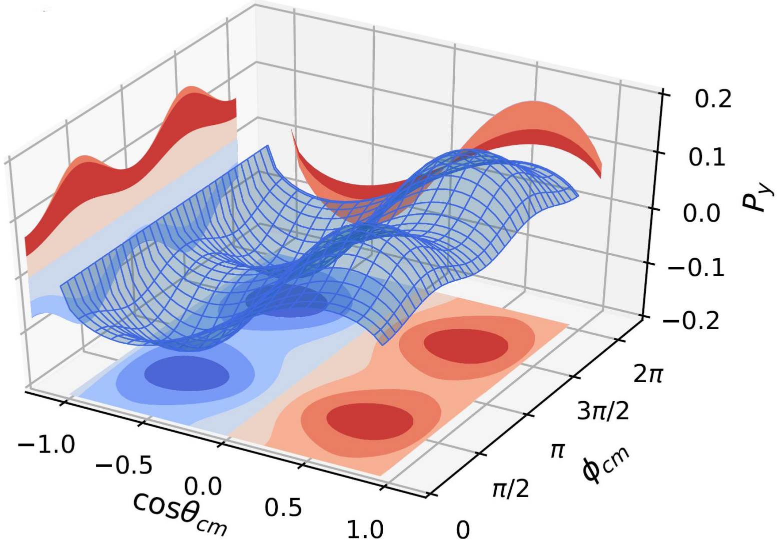
Transversely Polarized beams

- Forgotten Facts of Transversely Polarized electron/positron Beams

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

$$P_y^B = \frac{\sqrt{1-\alpha_\psi^2}\,\sin\Delta\Phi\sin\theta\cos\theta(1-P_T^2\cos2\phi)}{1+\alpha_\psi\cos^2\theta+\alpha_\psi P_T^2\sin^2\theta\cos2\phi}$$

$$P_x^B = \frac{-P_T^2\sqrt{1-\alpha_\psi^2}\,\sin\Delta\Phi\sin\theta\sin2\phi}{1+\alpha_\psi\cos^2\theta+\alpha_\psi P_T^2\sin^2\theta\cos2\phi}$$



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

Transversely Polarized beams

- Useful for improving the sensitivity of measurements $\sim \dfrac{1}{\sqrt{N_{events}}}$

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

$$+\alpha_- \cdot \mathcal{F}_6 + \alpha_+ \cdot \mathcal{F}_7 - \alpha_-\alpha_+ \cdot \mathcal{F}_8$$

$$\begin{aligned}
\mathcal{F}_0 =& 1 + \alpha_\psi \cos^2\theta + \alpha_\psi P_T^2 \sin^2\theta \cos 2\phi\,,\\
\mathcal{F}_1 =& (\sin^2\theta + P_T^2 \cos 2\phi \cos^2\theta) \sin\theta_1 \cos\phi_1 \sin\theta_2 \cos\phi_2\\
&- (\cos^2\theta + P_T^2 \cos 2\phi \sin^2\theta) \cos\theta_1 \cos\theta_2\\
&+ P_T^2 \sin\theta_1 \sin\theta_2 (\sin 2\phi \cos\theta \sin(\phi_1 - \phi_2) + \cos 2\phi \sin\phi_1 \sin\phi_2)\,,\\
\mathcal{F}_2 =& (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta (\sin\theta_1 \cos\theta_2 \cos\phi_1 - \cos\theta_1 \sin\theta_2 \cos\phi_2)\\
&- P_T^2 \sin 2\phi \sin\theta (\sin\theta_1 \cos\theta_2 \sin\phi_1 + \cos\theta_1 \sin\theta_2 \sin\phi_2)\,,\\
\mathcal{F}_3 =& (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta \sin\theta_2 \sin\phi_2 - P_T^2 \sin 2\phi \sin\theta \sin\theta_2 \cos\phi_2\,,\\
\mathcal{F}_4 =& (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta \sin\theta_1 \sin\phi_1 + P_T^2 \sin 2\phi \sin\theta \sin\theta_1 \cos\phi_1\,,\\
\mathcal{F}_5 =& (\sin^2\theta + P_T^2 \cos 2\phi \cos^2\theta) \sin\theta_1 \sin\phi_1 \sin\theta_2 \sin\phi_2 - \cos\theta_1 \cos\theta_2\\
&+ P_T^2 \sin\theta_1 \sin\theta_2 [\sin 2\phi \cos\theta \sin(\phi_1 - \phi_2) + \cos 2\phi \cos\phi_1 \cos\phi_2]\,,
\end{aligned}$$

$$\begin{aligned}
\mathcal{F}_6(\xi) &= P_e(\gamma_\psi \sin\theta \sin\theta_1 \cos\varphi_1 - (1+\alpha_\psi)\cos\theta\cos\theta_1),\\
\mathcal{F}_7(\xi) &= P_e(\gamma_\psi \sin\theta \sin\theta_2 \cos\varphi_2 + (1+\alpha_\psi)\cos\theta\cos\theta_2),\\
\mathcal{F}_8(\xi) &= P_e\beta_\psi \sin\theta(\cos\theta_1 \sin\theta_2 \sin\varphi_2 + \sin\theta_1 \sin\varphi_1 \cos\theta_2).
\end{aligned}$$

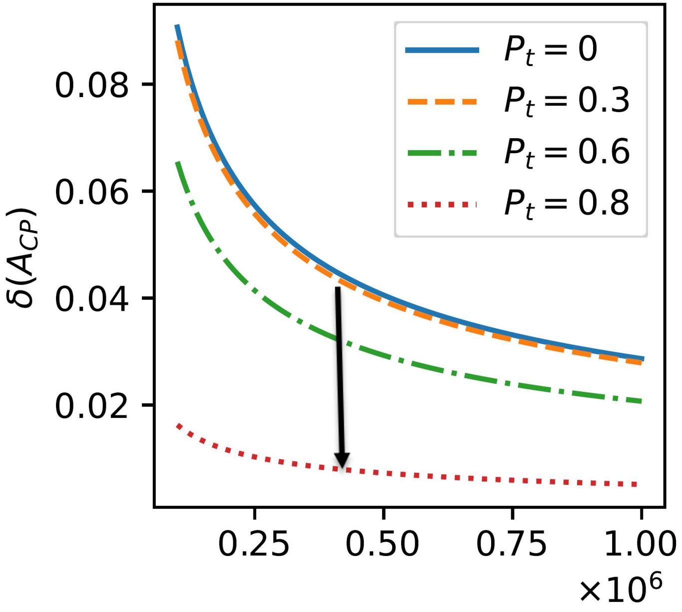
- **Xu Cao**, Yu-tie Liang, Rong-Gang Ping, 2404.00298 [hep-ph]
- N. Salone, P. Adlarson, V. Batozskaya, A. Kupsc, S. Leupold, and J. Tandean, Phys. Rev. D 105, 116022 (2022)

Transversely Polarized beams

- Useful for improving the sensitivity of measurements $\sim \dfrac{1}{\sqrt{N_{events}}}$

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

$$\begin{aligned}
\mathcal{F}_0 =& 1 + \alpha_\psi \cos^2\theta + \alpha_\psi P_T^2 \sin^2\theta \cos 2\phi\,,\\
\mathcal{F}_1 =& (\sin^2\theta + P_T^2 \cos 2\phi \cos^2\theta) \sin\theta_1 \cos\phi_1 \sin\theta_2 \cos\phi_2\\
& - (\cos^2\theta + P_T^2 \cos 2\phi \sin^2\theta) \cos\theta_1 \cos\theta_2\\
& + P_T^2 \sin\theta_1 \sin\theta_2 (\sin 2\phi \cos\theta \sin(\phi_1 - \phi_2) + \cos 2\phi \sin\phi_1 \sin\phi_2)\,,\\
\mathcal{F}_2 =& (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta (\sin\theta_1 \cos\theta_2 \cos\phi_1 - \cos\theta_1 \sin\theta_2 \cos\phi_2)\\
& - P_T^2 \sin 2\phi \sin\theta (\sin\theta_1 \cos\theta_2 \sin\phi_1 + \cos\theta_1 \sin\theta_2 \sin\phi_2)\,,\\
\mathcal{F}_3 =& (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta \sin\theta_2 \sin\phi_2 - P_T^2 \sin 2\phi \sin\theta \sin\theta_2 \cos\phi_2\,,\\
\mathcal{F}_4 =& (1 - P_T^2 \cos 2\phi) \sin\theta \cos\theta \sin\theta_1 \sin\phi_1 + P_T^2 \sin 2\phi \sin\theta \sin\theta_1 \cos\phi_1\,,\\
\mathcal{F}_5 =& (\sin^2\theta + P_T^2 \cos 2\phi \cos^2\theta) \sin\theta_1 \sin\phi_1 \sin\theta_2 \sin\phi_2 - \cos\theta_1 \cos\theta_2\\
& + P_T^2 \sin\theta_1 \sin\theta_2 [\sin 2\phi \cos\theta \sin(\phi_1 - \phi_2) + \cos 2\phi \cos\phi_1 \cos\phi_2]\,,
\end{aligned}$$



Observed events of $e^+e^- \to \gamma^*/\psi \to \Lambda(p\pi^-)\bar{\Lambda}(\bar{p}\pi^+)$

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

Summary and Perspective

- **Oscillations of baryon EMFFs:**
  - Robust conclusion driven by data:
  - oscillations of baryon EMFFs =
    the bulk dipole component +
    residual contribution from VM above threshold
  - … supported by isospin analysis
  - … extetened to understanding of charmonium decay

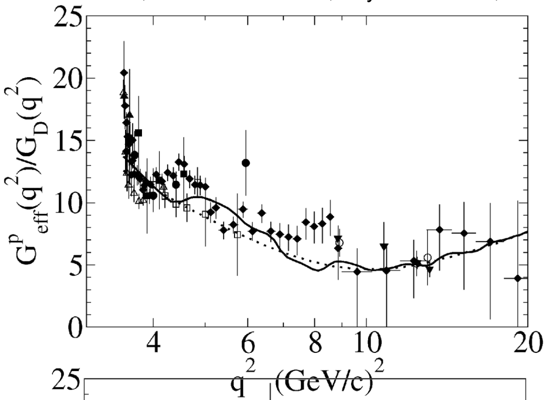
- **Transversely Polarization of lepton**
  - ... can be measured by muon (or e or photon) pairs production
  - … can used to enhance the sensitivity of the CP violation test
  - … is required to consider in the data analysis at circular collides
  - … technically easier to obtain in comparison of longitudinal polarization

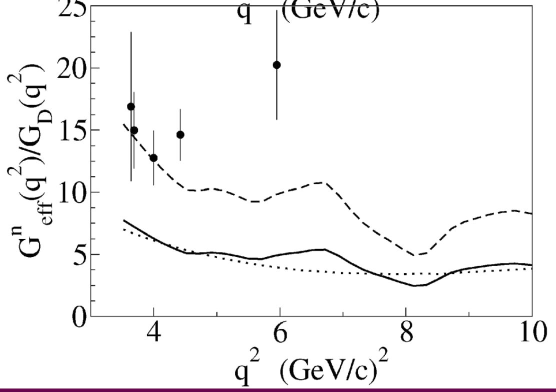
Thank You !

Oscillation of Timelike EMFFs

- Local structures: vector mesons

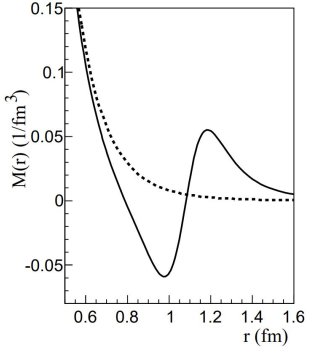
de Melo, T. Frederico, E. Pace, S. Pisano, G. Salme, Phys. Lett. B 671, 153 (2009),
see also: Y. H. Lin, H. Hammer, U. Meißner Phys. Rev. Lett. 128 (2022), 052002;
I. T. Lorenz, H.W. Hammer, and U. G. Meißner, Phys. Rev. D 92, 034018 (2015)





- Global structures: nucleon

A. Bianconi and E. Tomasi-Gustafsson, Phys. Rev. Lett. 114, 232301 (2015);
A. Bianconi and E. Tomasi-Gustafsson, Phys. Rev. C 93, 035201 (2016);
E. Tomasi-Gustafsson, A. Bianconi, S. Pacetti, Phys. Rev. C 103, 035203 (2021).
E. Tomasi-Gustafsson, S. Pacetti, Phys.Rev.C 106, 035203 (2022)



- Data always tells the truth:

Mag. of residual osc. is much smaller than that of the leading Dipole component
~ 0.2 for p, ~ 0.3 for n
The osc of proton&neutron are of (approximately) equal magnitude & period

$$\frac{A_p}{A_n} = 0.88 \pm 0.35$$

A phase difference between the osc of proton&neutron

$$|D_p - D_n| = 4.08 \pm 0.58\text{rad}$$

Oscillation of Timelike EMFFs

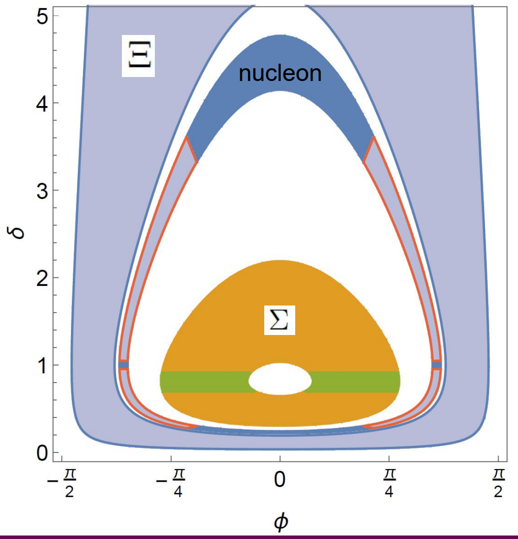
- Consequence: Hyperon

$$R_I^{\rm eff} = \frac{|G^D_{\Xi^-}|^2 - |G^D_{\Xi^0}|^2}{|G^D_{\Xi^-}|^2 + |G^D_{\Xi^0}|^2} = 0.22 \pm 0.15$$

$$R_I^{\rm eff} = \frac{|G_+|^2 - |G_-|^2}{|G_+|^2 + |G_-|^2} = \frac{2\sqrt{6}\delta_I \cos\phi_I}{3\delta_I^2 + 2} = 0.81 \pm 0.16$$

$$I_1 = I_0 \delta_I e^{i\phi_I}$$

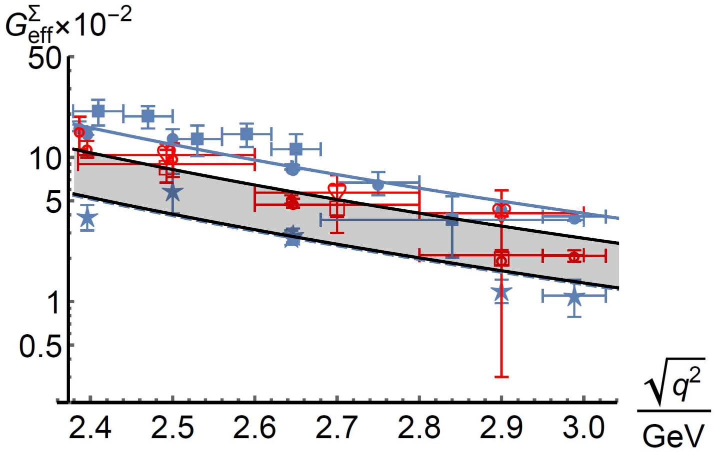
$$|\Delta\phi| = |D_n - D_p| = \arg\frac{I_1^D - I_0^D}{I_1^P + I_0^D}$$



- Consequence: Predict Σ isospin-triplet

$$G_+ = \frac{1}{\sqrt{2}}I_1 + \frac{1}{\sqrt{3}}I_0$$
$$G_- = \frac{1}{\sqrt{2}}I_1 - \frac{1}{\sqrt{3}}I_0$$
$$G_0 = \frac{1}{\sqrt{3}}I_0$$

$$||G_+| - |G_-|| \le 2|G_0| \le |G_+| + |G_-|$$



Oscillation of Timelike EMFFs

- Dispersion relations as an Inverse Problem: e.g. A.-S. Xiong, T. Wei, Fu-Sheng Yu, 2211.13753; R. Baldini et al., 0106006

$$F(q^2) = \frac{1}{\pi}\int_{q_t^2}^{\infty} \frac{\mathrm{Im}[F(t)]}{t-q^2}dt, \quad \forall q^2 \notin (q_t^2,\infty),\ t \le q_t^2 = 4m_\pi^2$$

- In the isospin/charge symmetry $G^{u/n} = G^{d/p}$ and $G^{d/n} = G^{u/p}$,4 complex variables (2 isospin × 2 electromagnetic form factors)

$$|\frac{G_M^{u+d}}{3}|^2 + |G_M^{u-d}|^2 = 2(2\tau+1)\left(\frac{|G_p^D|^2}{2\tau+R_p^2} + \frac{|G_n^D|^2}{2\tau+R_n^2}\right)$$

$$\Re[\frac{G_M^{u+d}}{3}G_M^{u-d\dagger}] = (2\tau+1)\left(\frac{|G_p^D|^2}{2\tau+R_p^2} - \frac{|G_n^D|^2}{2\tau+R_n^2}\right)$$

$$|\frac{G_E^{u+d}}{3}|^2 + |G_E^{u-d}|^2 = 2(2\tau+1)\left(\frac{R_p^2|G_p^D|^2}{2\tau+R_p^2} + \frac{R_n^2|G_n^D|^2}{2\tau+R_n^2}\right)$$

$$\Re[\frac{G_E^{u+d}}{3}G_E^{u-d\dagger}] = (2\tau+1)\left(\frac{R_p^2|G_p^D|^2}{2\tau+R_p^2} - \frac{R_n^2|G_n^D|^2}{2\tau+R_n^2}\right)$$

$$\Re\left[\frac{G_M^{u+d}}{3}G_E^{u+d*} + G_M^{u-d}G_E^{u-d*}\right] = -\frac{\sqrt{\tau_p}D_pP_x^p + \sqrt{\tau_n}D_nP_x^n}{\sin\theta}$$

$$\Re\left[\frac{G_M^{u+d}}{3}G_E^{u-d*} + G_M^{u-d}G_E^{u+d*}\right] = -\frac{\sqrt{\tau_p}D_pP_x^p - \sqrt{\tau_n}D_nP_x^n}{\sin\theta}$$

$$\Im\left[\frac{G_M^{u+d}}{3}G_E^{u+d*} + G_M^{u-d}G_E^{u-d*}\right] = \frac{\sqrt{\tau_p}D_pP_y^p + \sqrt{\tau_n}D_nP_y^n}{\sin\theta\cos\theta}$$

$$\Im\left[\frac{G_M^{u+d}}{3}G_E^{u-d*} + G_M^{u-d}G_E^{u+d*}\right] = \frac{\sqrt{\tau_p}D_pP_y^p - \sqrt{\tau_n}D_nP_y^n}{\sin\theta\cos\theta}$$

can be extracted from eight independent observables:

total and differential cross sections, two polarization observables for proton and neutron at each energy point

- Measurement of polarization is required: Polarimeter? Vortex beams (N. Korchagin, 2403.08949) ?

Hyperon decay and CP violation

- Hyperon decay as a polarimeter:

  T. D. Lee and C.-N. Yang, Phys. Rev. 108, 1645 (1957)

- The amplitude for a spin-1/2 hyperon decaying into a spin-1/2 baryon and a spin-0 meson:

$$M = G_F\, m_\pi^2 \cdot \overline{B}_f\, (A - B\gamma_5)\, B_i$$

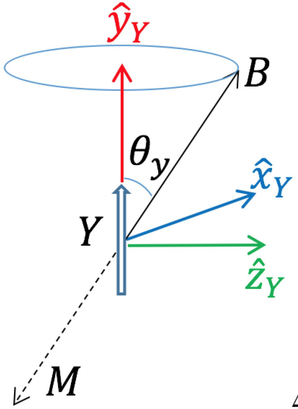
- Decay parameters:

$$\alpha = 2\,\mathrm{Re}(s^* p)/(|s|^2 + |p|^2)\,,$$
$$\beta = 2\,\mathrm{Im}(s^* p)/(|s|^2 + |p|^2)\,,$$
$$\gamma = (|s|^2 - |p|^2)/(|s|^2 + |p|^2)\,,$$

where $s = A$ and $p = |\mathbf{p}_f| B/(E_f + m_f)$

- Lee-Yang formula

$$\mathbf{P}_\Lambda = \frac{(\alpha_\Xi + \mathbf{P}_\Xi \cdot \hat{\mathbf{n}})\hat{\mathbf{n}} + \beta_\Xi \mathbf{P}_\Xi \times \hat{\mathbf{n}} + \gamma_\Xi \hat{\mathbf{n}} \times (\mathbf{P}_\Xi \times \hat{\mathbf{n}})}{1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{n}}}$$



- Strong and weak phase

  J. F. Donoghue and S. Pakvasa, Phys. Rev. Lett. 55, 162 (1985)

  J. F. Donoghue, X.-G. He, and S. Pakvasa, Phys. Rev. D 34, 833 (1986)

- The transition amplitudes L = S, P of hyperon can be decomposed as

$$L = \sum_j L_j \exp\{i(\xi_j^L + \delta_j^L)\}$$

while for the the antihyperon c.c. decay

$$\bar{S} = -\sum_j S_j \exp\{i(-\xi_j^S + \delta_{2I}^S)\}$$
$$\bar{P} = \sum_j P_j \exp\{i(-\xi_j^P + \delta_{2I}^P)\},$$

Leading to hyperon CT violation test

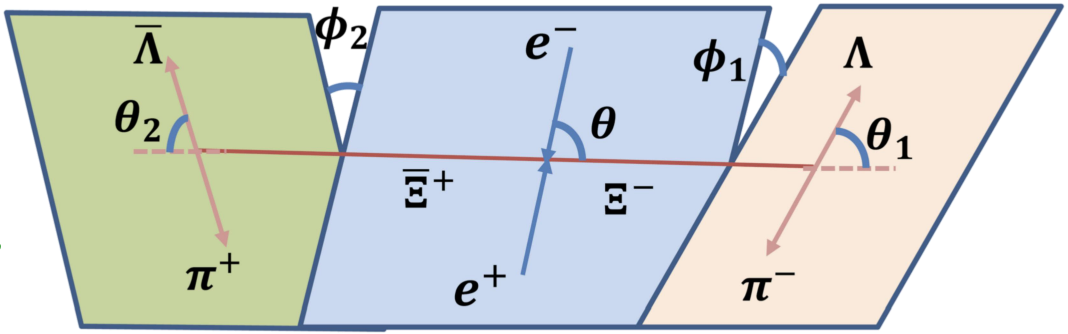
$$\Delta_{CP} = \frac{\Gamma_1 + \Gamma_2}{\Gamma_1 - \Gamma_2} \sim L^1 L^3 \sin(\delta_L^1 - \delta_L^3)\sin(\xi_L^1 - \xi_L^3)$$
$$A_{CP} = \frac{\alpha_1 + \alpha_2}{\alpha_1 - \alpha_2} = -\tan(\delta_P - \delta_S)\tan(\xi_P - \xi_S)$$
$$B_{CP} = \frac{\beta_1 + \beta_2}{\alpha_1 - \alpha_2} = -\tan(\xi_P - \xi_S)$$

Probe CP violation via Transversely Polarized beams

- Known Fact of Unpolarized Beams: measure the hyperon/anti-hyperon decay simultaneously

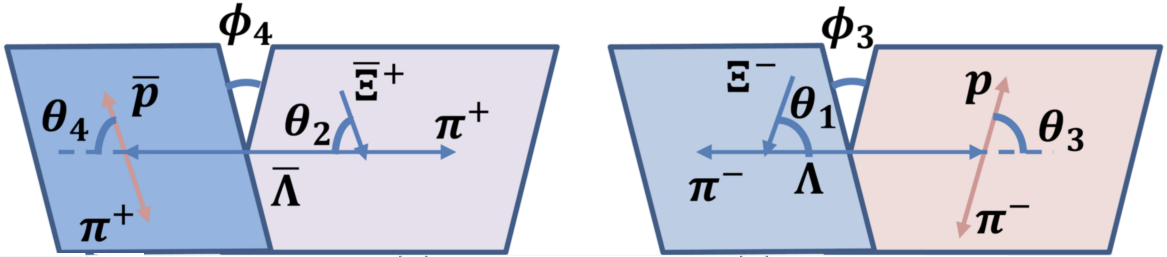
E. Perotti, G. Fäldt, A. Kupsc, *et al.*, Phys. Rev. D 99,056008 (2019)

P.-C. Hong, R.-G. Ping, T. Luo, X.-R. Zhou, H. Li, Chin. Phys. C 47, 093103 (2023)



Scattering angle only, no info. in azimuthal angle?

Cascade decay is much more complicated:



$$\mathcal{W}(\boldsymbol{\xi}) = \mathcal{F}'_0(\xi) + \mathcal{F}_{\Xi,\Delta\Phi}(\alpha_2 \cdot \mathcal{F}'_3 - \alpha_1 \cdot \mathcal{F}'_4) + \alpha_1\alpha_2\mathcal{F}'_{\Xi,\Delta\Phi}$$

$$B_{CP} = \frac{\beta_1+\beta_2}{\alpha_1-\alpha_2} = -\tan(\xi_P - \xi_S)$$

The SM prediction for $A_{\rm CP}^{[\Lambda p]}$ is $\sim(1\text{–}5)\times10^{-5}$, while for $B_{\rm CP}^{[\Xi-]}$, it amounts to $\mathcal{O}(10^{-4})$

	$\sigma(A_{\rm CP}^{[\Lambda p]})$	$\sigma(A_{\rm CP}^{[\Xi-]})$	$\sigma(B_{\rm CP}^{[\Xi-]})$	Comment
BESIII	1.0×10^{-2}	1.3×10^{-2}	3.5×10^{-2}	1.3×10^{9} J/ψ
BESIII	3.6×10^{-3}	4.8×10^{-3}	1.3×10^{-2}	1.0×10^{10} J/ψ (projection)
SCTF	2.0×10^{-4}	2.6×10^{-4}	6.8×10^{-4}	3.4×10^{12} J/ψ (projection)

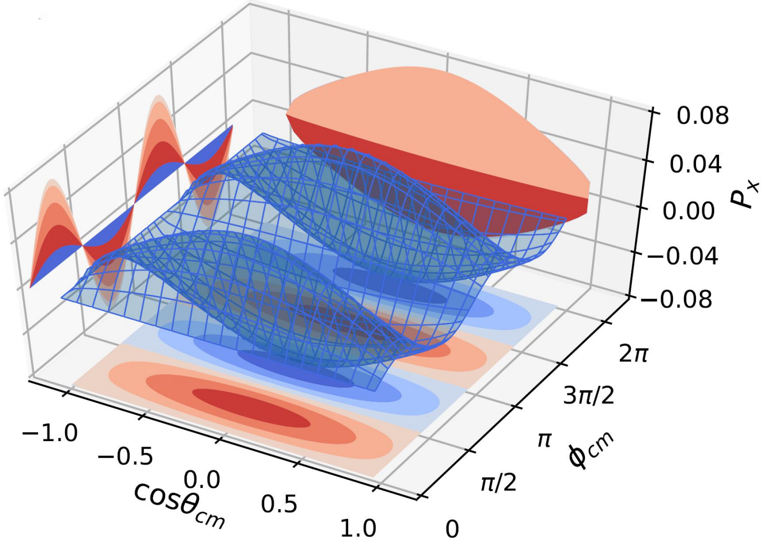
Probe CP violation via Transversely Polarized beams

- Forgotten Facts of Transversely Polarized electron/positron Beams

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

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

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



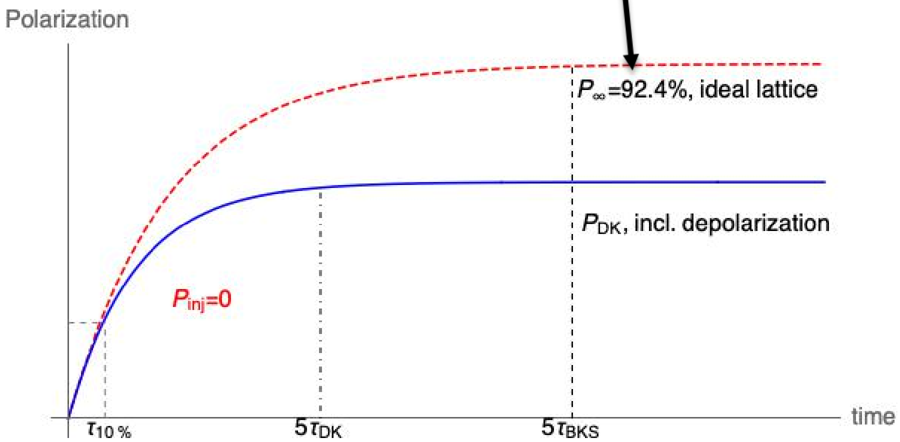
Integrating out the azimuthal angle is equal to $P_T = 0$

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

Probe CP violation via Transversely Polarized beams

- Zhe Duan@IHEP: thesis
- Sokolov-Ternov效应引起的束流极化建立时间在1.84 GeV 时约为 4.3 个小时，而在 2.0GeV 时约为 2.8 小时

$$P_0\left(1-e^{-t/t_0}\right) \qquad t_0 = \left[\frac{5\sqrt{3}}{8}\frac{e^2\hbar\gamma^5}{m^2c^2\rho^3}\right]^{-1}$$

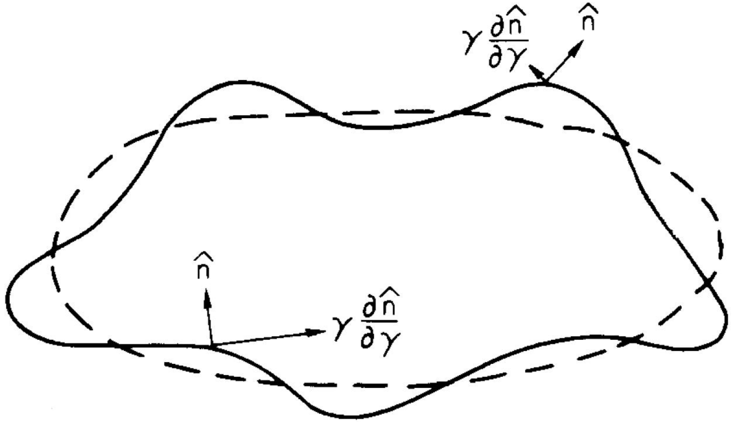


- Alexander W Chao(赵午)：
- SLAC-PUB-2781(1981)

  POLARIZATION OF A STORED ELECTRON BEAM

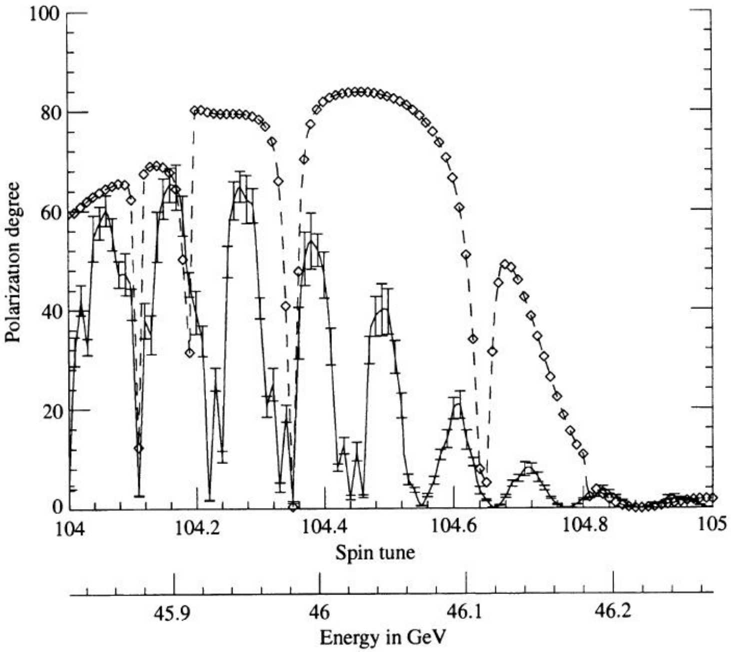
$$E_e = m_e\gamma c^2 = \frac{m_e c^2}{G_e}N \simeq 440.5 \cdot N \quad \text{MeV},$$

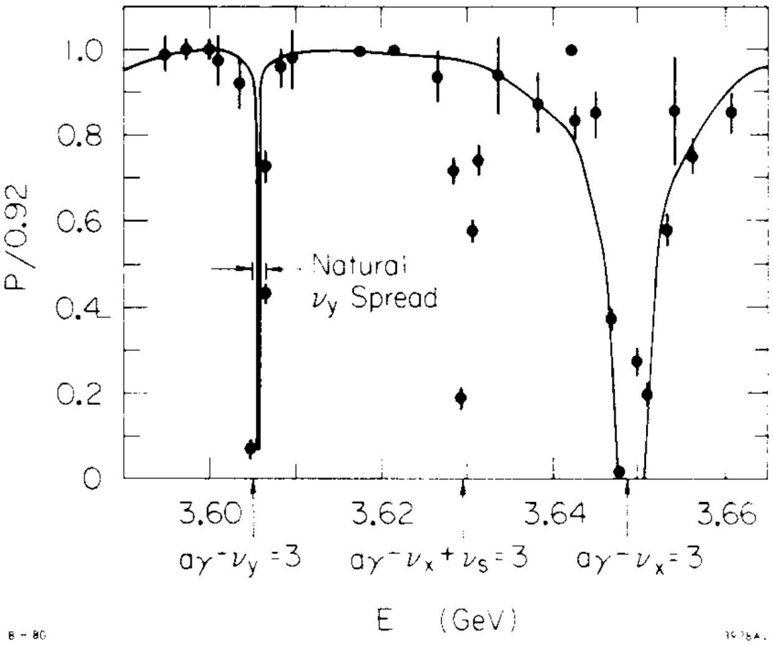
$$G_e \simeq 0.00116 \quad \text{the gyromagnetic anomaly}$$



Probe CP violation via Transversely Polarized beams

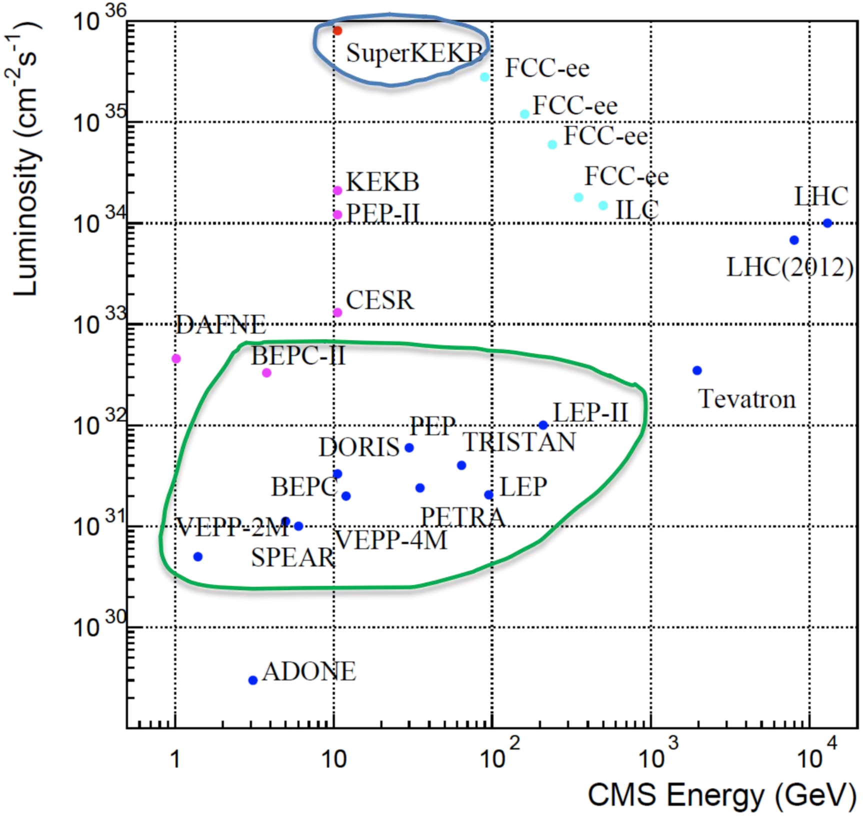
- Elliot Leader: Spin in particle physics
- LEP:
  The Large Electron-Positron Collider at CERN
- 赵午：SLAC-PUB-2781(1981)
- SPEAR:
  Stanford Positron Electron Asymmetric Ring





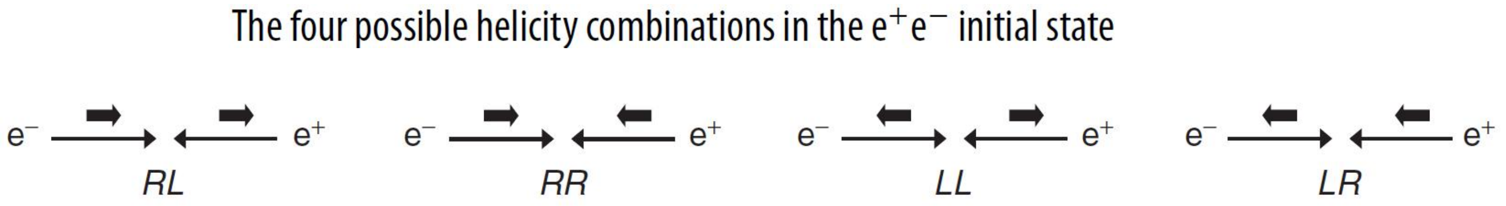
Probe CP violation via Transversely Polarized beams

- Transversely Polarization of Lepton Beams at BEPCII?



Probe CP violation via Transversely Polarized beams

- Forgotten Facts of Transversely Polarized electron/positron Beams



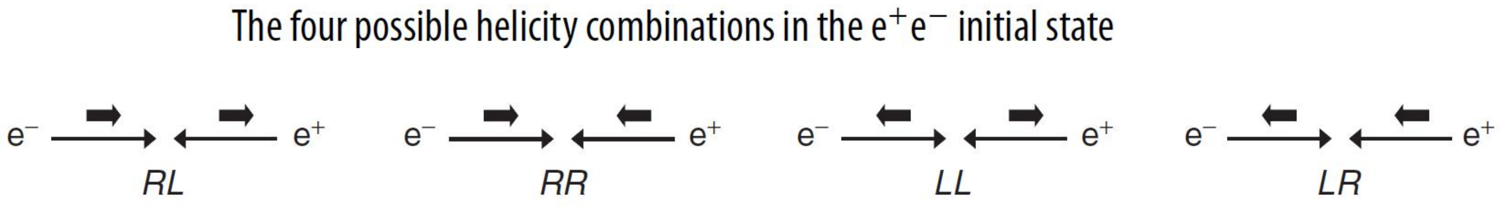
- $1 = \tfrac{1}{2} - (-\tfrac{1}{2})$ $\quad 0 = \tfrac{1}{2} - \tfrac{1}{2}$ $\quad 0 = -\tfrac{1}{2} - (-\tfrac{1}{2})$ $\quad -1 = -\tfrac{1}{2} - \tfrac{1}{2}$
- If.amp 1 1 1 1

$$\rho_e^{\pm} = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \rho^{\gamma^*/\psi}_{m,m'} = \sum_{\lambda_1,\lambda'_1\lambda_2,\lambda'_2} D^{1*}_{m,\lambda_1-\lambda_2} D^{1}_{m',\lambda'_1-\lambda'_2} \rho^{+}_{\lambda_1,\lambda'_1} \rho^{-}_{\lambda_2,\lambda'_2} = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **Xu Cao**, Yu-tie Liang, Rong-Gang Ping, to appear soon

Probe CP violation via Transversely Polarized beams

- Forgotten Facts of Transversely Polarized electron/positron Beams



- $1 = \tfrac{1}{2} - (-\tfrac{1}{2})$ $\quad 0 = \tfrac{1}{2} - \tfrac{1}{2}$ $\quad 0 = -\tfrac{1}{2} - (-\tfrac{1}{2})$ $\quad -1 = -\tfrac{1}{2} - \tfrac{1}{2}$
- In fact $\quad 1 \quad m_e/\sqrt{s} \quad m_e/\sqrt{s} \quad 1$

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

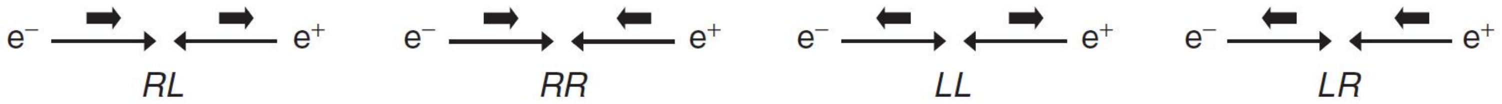
$$\rho^{\gamma^*/\psi}_{m,m'} = \sum_{\lambda_1,\lambda'_1\lambda_2,\lambda'_2} D^{1*}_{m,\lambda_1-\lambda_2} D^{1}_{m',\lambda'_1-\lambda'_2} \rho^{+}_{\lambda_1,\lambda'_1} \rho^{-}_{\lambda_2,\lambda'_2} \times \delta_{\lambda_1,-\lambda_2}\delta_{\lambda'_1,-\lambda'_2} = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Probe CP violation via Transversely Polarized beams

- Forgotten Facts of Transversely Polarized electron/positron Beams

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



- $1 = \frac{1}{2} - (-\frac{1}{2})$ $\quad 0 = \frac{1}{2} - \frac{1}{2}$ $\quad 0 = -\frac{1}{2} - (-\frac{1}{2})$ $\quad -1 = -\frac{1}{2} - \frac{1}{2}$
- In fact $\quad 1 \quad m_e/\sqrt{s} \quad m_e/\sqrt{s} \quad 1$

$$\rho_e^{\pm} = \frac{1}{2}\begin{pmatrix} 1 & \mathcal{P}_t \\ \mathcal{P}_t^* & 1 \end{pmatrix}$$

$$\rho^{\gamma^*/\psi}_{m,m'} = \sum_{\lambda_1,\lambda_1'\lambda_2,\lambda_2'} D^{1*}_{m,\lambda_1-\lambda_2} D^{1}_{m',\lambda_1'-\lambda_2'} \rho^{+}_{\lambda_1,\lambda_1'} \rho^{-}_{\lambda_2,\lambda_2'} \times \delta_{\lambda_1,-\lambda_2}\delta_{\lambda_1',-\lambda_2'} = \frac{1}{2}\begin{pmatrix} 1 & 0 & P_T^2 \\ 0 & 0 & 0 \\ P_T^2 & 0 & 1 \end{pmatrix}$$

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

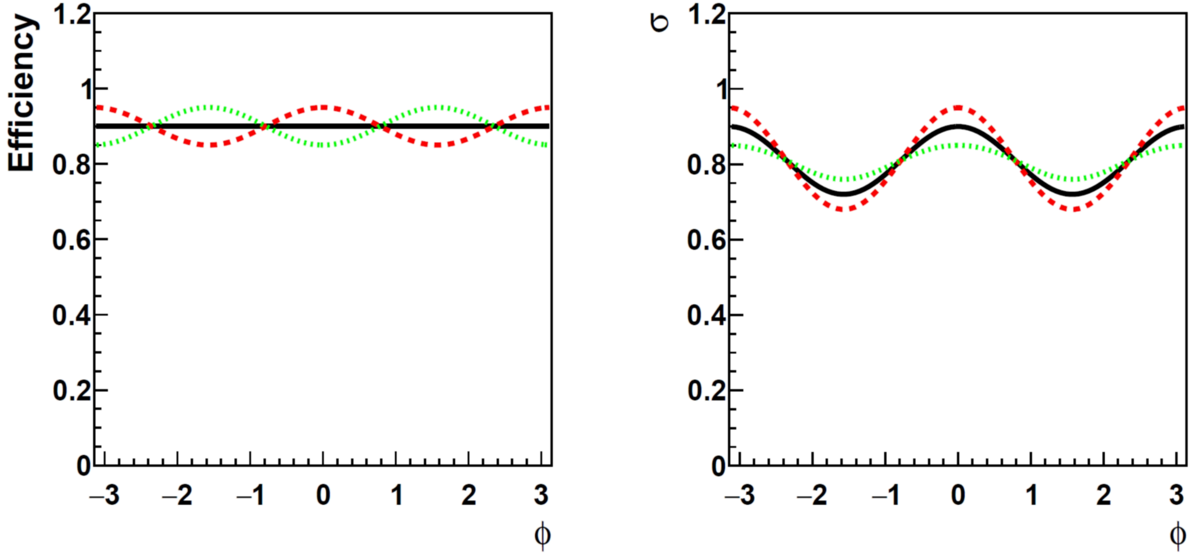
Probe CP violation via Transversely Polarized beams

- Requirement of estimation of systematic errors

Toy model:

efficiency curves over angle with 5% oscillation amplitude

a beam polarization of 30%, the measured cross sections will be 0.3% shift from the correct value.



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

Spares

➢ expansion

- Generally specking, the relation (7) is a series of Taylor expansion around a variable G_N^{osc}/G_N^D which is around 0.2 for proton and 0.3 for neutron. If we admit the pioneering decomposition in ref.[23]:

$$|G_{\rm eff}^N|^2 = (G_N^D + G_N^{osc})^2 = (G_N^D)^2 + 2G_N^D G_N^{osc} + (G_N^{osc})^2. \tag{1}$$

Note that the quantities as form factors in r.h.s. are all real. On the other hand, following our previous paper ref. [32], we have:

$$\begin{aligned} |G_{\rm eff}^N|^2 &= \left|\frac{1}{\sqrt{2}}I_N^D + \frac{1}{\sqrt{2}}I_N^{osc}\right|^2 \\ &= \left|\frac{1}{\sqrt{2}}I_N^D\right|^2 + \left|\frac{1}{\sqrt{2}}I_N^{osc}\right|^2 + 2\,\Re\left[\frac{1}{\sqrt{2}}I_N^D\frac{1}{\sqrt{2}}I_N^{osc\dagger}\right]. \end{aligned} \tag{2}$$

Note that the quantities as amplitudes in r.h.s. are all complex which is taken into account by using without loss of generality

$$I_N^D = \sqrt{2}G_N^D\, e^{i\phi_N^D(q^2)}, \quad I_N^{osc} = |I_N^{osc}|\, e^{i\phi_N^{osc}(q^2)}.$$

The irrelevant factor $\sqrt{2}$ is for the convenience of isospin decomposition, however, it does not need this *ad hoc* symmetry here. Now if comparing two decompositions and disregarding the $(G_N^{osc})^2 = |\frac{1}{\sqrt{2}}I_N^{osc}|^2$ term, the first term of relation (7) is retained. More generally it is a quadratic equation with a solution:

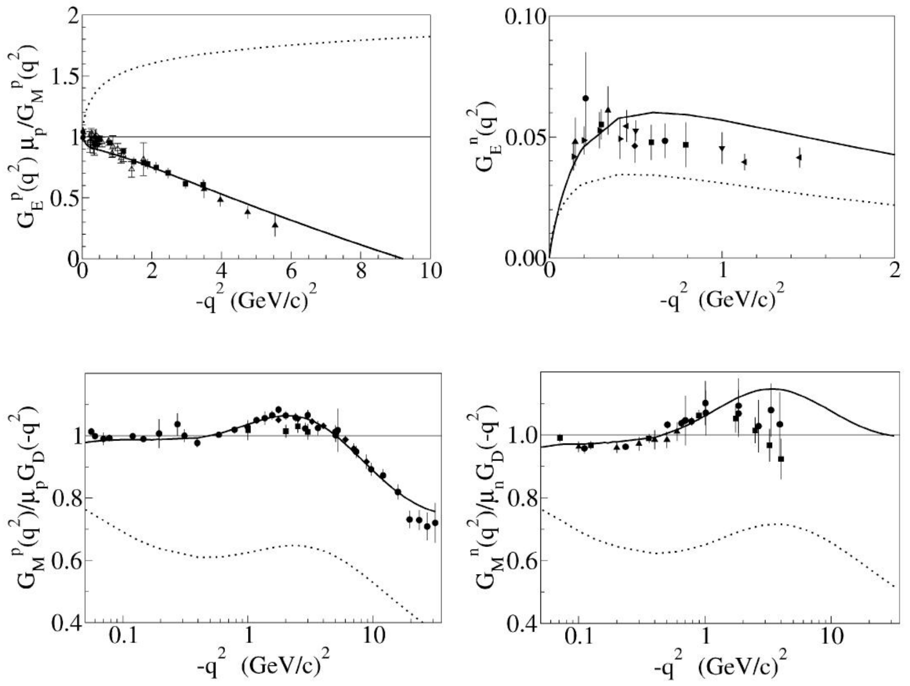
$$\begin{aligned} \frac{G_N^{osc}}{G_N^D} &= -1 + \sqrt{1 + \frac{\Re[I_N^D I_N^{osc\dagger}] + |\frac{1}{\sqrt{2}}I_N^{osc}|^2}{(G_N^D)^2}} \\ &\simeq \frac{|I_N^{osc}|}{\sqrt{2}G_N^D}\cos(\phi_N^D - \phi_N^{osc}) + \frac{1}{4}\frac{|I_N^{osc}|^2}{(G_N^D)^2}\sin^2(\phi_N^D - \phi_N^{osc}) + \mathcal{O}\left(\frac{|I_N^{osc}|^3}{(G_N^D)^3}\right). \end{aligned}$$

where another solution of $G_N^{osc} > G_N^D$ is ignored. Above is exactly the Eq. (7) in the paper. The Taylor series expansion allows to investigate the term of higher power. Since this expansion is irrelevant to the nature of periodic oscillations, we prefer to use residue (rsd) instead of oscillations (osc) in previous paper. The isospin decomposition of I_N^D and I_N^{osc} can be subsequently done. Considering the simplicity of this expansion, we show it only briefly in the paper.

Spares

➢ Spacelike Nucleon structure

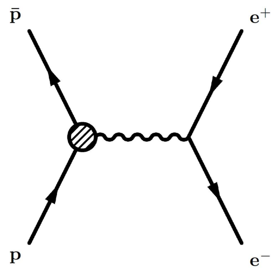
J.P.B.C. de Melo et al. / Physics Letters B 671 (2009) 153–157



- ➢A. Denig and G. Salme, Prog. Part. Nucl. Phys. 68, 113 (2013).
- ➢see also recent update: Y. H. Lin, H. Hammer, U. Meißner Phys. Rev. Lett. 128 (2022), 052002

Spares

Cross sections



Spacelike

$$\frac{d\sigma}{d\Omega_e} = \frac{\alpha^2}{-q^2}\left(\frac{\epsilon_2}{\epsilon_1}\right)^2\left[2\tau G_M^2 + \frac{\cot^2(\theta_e/2)}{1+\tau}\left(G_E^2+\tau G_M^2\right)\right] = \frac{d\sigma_M}{d\Omega_e}\left[2\tau G_M^2\tan^2(\theta_e/2) + \frac{G_E^2+\tau G_M^2}{1+\tau}\right]$$

$$\frac{d\sigma_M}{d\Omega_e} = \frac{\alpha^2}{-q^2}\left(\frac{\epsilon_2}{\epsilon_1}\right)^2\frac{\cos^2(\theta_e/2)}{\sin^2(\theta_e/2)} = \left(\frac{\alpha}{2\epsilon_1}\right)^2\frac{\cos^2(\theta_e/2)}{\sin^4(\theta_e/2)}\frac{1}{(1+2(\epsilon_1/M)\sin^2(\theta_e/2))},$$

$$\epsilon = \left[1+2(1+\tau)\tan^2(\theta_e/2)\right]^{-1}$$

Timelike

$$\frac{d\sigma}{d(\cos\theta)} = \sigma_0\left[1+\mathcal{A}\cos^2\theta\right]$$

$$\sigma_0 = \frac{\alpha^2}{4q^2}\sqrt{\frac{\tau}{\tau-1}}\left(|G_M|^2+\frac{1}{\tau}|G_E|^2\right)$$

$$\mathcal{A} = \frac{\tau|G_M|^2-|G_E|^2}{\tau|G_M|^2+|G_E|^2} = \frac{\tau-\mathcal{R}^2}{\tau+\mathcal{R}^2}, \qquad \mathcal{R} = \frac{|G_E|}{|G_M|}.$$

- S. Pacetti, R. Baldini Ferroli, and E. Tomasi-Gustafsson, Phys. Rep. 550–551, 1 (2015).

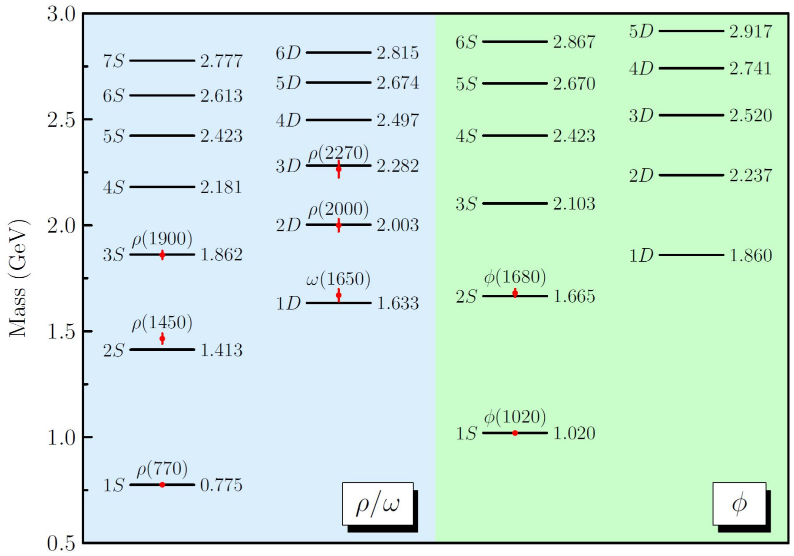
Spares

- However, we know little about vector spectrum:

V_s	M_V	Γ_V	a_1^V	a_2^V
ω	0.783	0	0.701	0.338
ϕ	1.019	0	−0.526	−0.997
s_1	1.031	0	0.422	−2.827
s_2	1.120	0	0.122	3.655
s_3	1.827	0	0.955	−1.122
r_{s1}	1.903	0.973	−2.653	−1.753
r_{s2}	1.914	0.541	−3.069	2.017
r_{s3}	1.879	0.895	4.953	0.501
V_v	M_V	Γ_V	a_1^V	a_2^V
v_1	1.050	0	0.782	−0.132
v_2	1.323	0	−4.873	−0.645
v_3	1.368	0	3.518	−0.987
v_4	1.462	0	2.243	−3.813
v_5	1.532	0	−1.422	3.668
r_{v1}	2.256	0.239	2.552	−1.217
r_{v2}	2.253	0.245	−1.947	0.551
r_{v3}	2.220	0.362	−0.985	1.061

TABLE II: Parameters for best fit to space- and timelike data. Masses (M_V) and width (Γ_V) are in GeV while the residua $a_{1,2}^V$ are given in GeV^2. The broad poles are denoted by the symbol r.

Li-Ming Wang, Si-Qiang Luo, Xiang Liu, Phys. Rev. D105, 034011 (2022)
Cheng-Qun Pang *et al.*, Phys. Rev. D101, 074022 (2020)



- see also recent update: Y. H. Lin, H. Hammer, U. Meißner, Phys. Rev. Lett. 128 (2022), 052002

Spares

➢ Isospin break of charmonium decay

Table 1
Amplitudes parameterization.

$\mathcal{B}\overline{\mathcal{B}}$	$\mathcal{A}_{\mathcal{B}\overline{\mathcal{B}}} = \mathcal{A}^{ggg}_{\mathcal{B}\overline{\mathcal{B}}} + \mathcal{A}^{gg\gamma}_{\mathcal{B}\overline{\mathcal{B}}} + \mathcal{A}^{\gamma}_{\mathcal{B}\overline{\mathcal{B}}}$
$\Sigma^0\overline{\Sigma}^0$	$(G_0 + 2D_m)e^{i\varphi} + D_e$
$\Lambda\overline{\Lambda}$	$(G_0 - 2D_m)e^{i\varphi} - D_e$
$\Lambda\overline{\Sigma}^0$ + c.c.	$\sqrt{3}\,D_e$
$p\overline{p}$	$(G_0 - D_m + F_m)(1 + R)e^{i\varphi} + D_e + F_e$
$n\overline{n}$	$(G_0 - D_m + F_m)e^{i\varphi} - 2\,D_e$
$\Sigma^+\overline{\Sigma}^-$	$(G_0 + 2D_m)(1 + R)e^{i\varphi} + D_e + F_e$
$\Sigma^-\overline{\Sigma}^+$	$(G_0 + 2D_m)(1 + R)e^{i\varphi} + D_e - F_e$
$\Xi^0\overline{\Xi}^0$	$(G_0 - D_m - F_m)e^{i\varphi} - 2\,D_e$
$\Xi^-\overline{\Xi}^+$	$(G_0 - D_m - F_m)(1 + R)e^{i\varphi} + D_e - F_e$

Table 3
Values of the parameters from the χ^2 minimization.

G_0	$(5.73511 \pm 0.0059) \times 10^{-3}$ GeV
D_e	$(4.52 \pm 0.19) \times 10^{-4}$ GeV
D_m	$(-3.74 \pm 0.34) \times 10^{-4}$ GeV
F_e	$(7.91 \pm 0.62) \times 10^{-4}$ GeV
F_m	$(2.42 \pm 0.12) \times 10^{-4}$ GeV
φ	$1.27 \pm 0.14 = (73 \pm 8)^\circ$
R	$(-9.7 \pm 2.1) \times 10^{-2}$

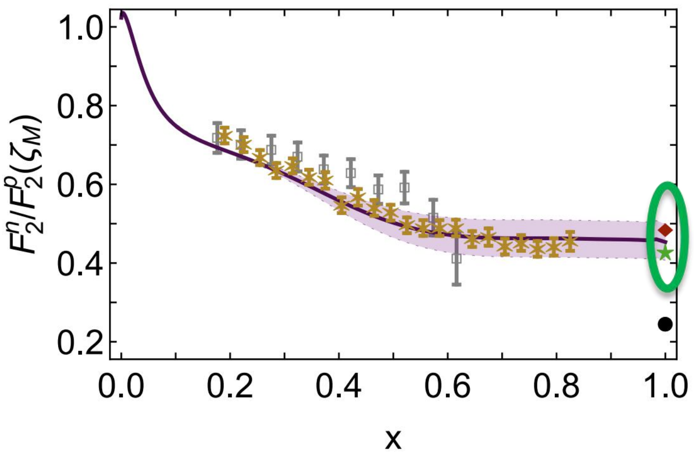
➢R. Baldini Ferroli et al. / Physics Letters B 799 (2019) 135041
➢See also X.H. Mo, J.Y. Zhang, Phys.Lett.B 826 (2022) 136927

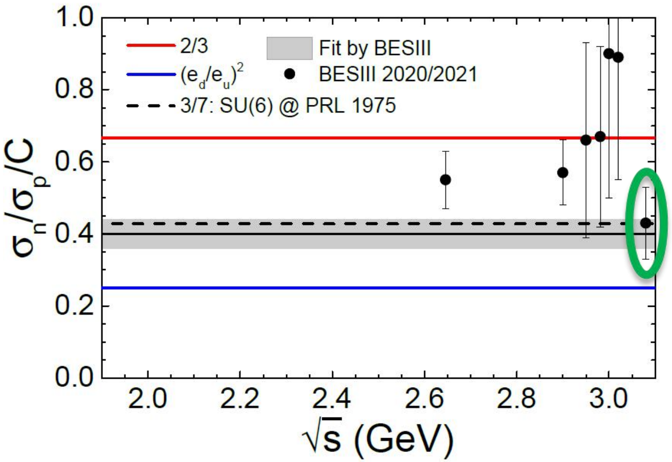
Isospin of amplitudes

- For timelike nucleon structure, BESIII told us:

$$R_N^D = \frac{\sigma_n^D}{\sigma_p^D/C} = |\frac{G_n^D}{G_p^D}|^2 = 0.40 \pm 0.03,$$

compatible with spacelike data of JLab MARATHON: Phys.Rev.Lett. 128 (2022) 132003
- see also JAM Collaboration: Phys.Rev.Lett. 127 (2021) 242001
- Zhu-Fang Cui, Fei Gao *et al*, Chin.Phys.Lett. 39 (2022) 041401

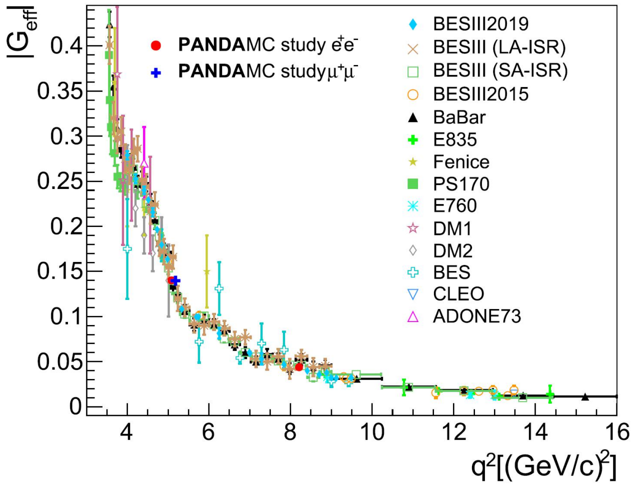


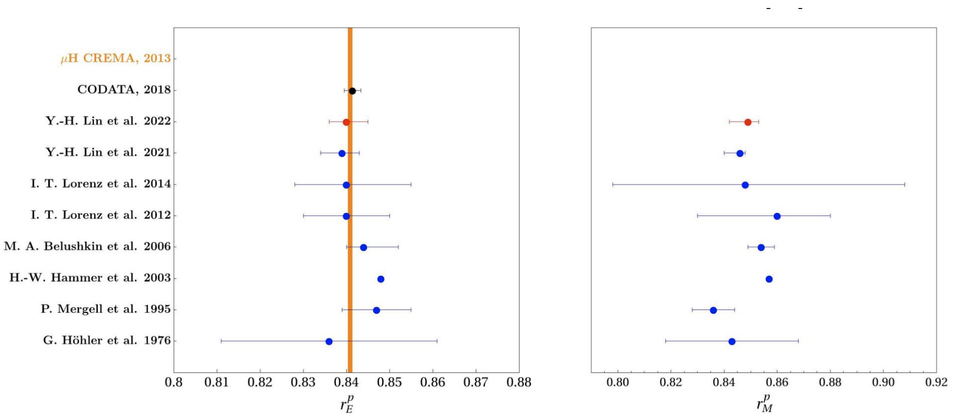


- Lei Chang, Fei Gao, Craig D. Roberts, Phys.Lett.B 829 (2022) 137078

Introduction

$$\sigma(e^+e^- \to \bar{p}p) = \beta^2 \sigma(\bar{p}p \to e^+e^-)$$



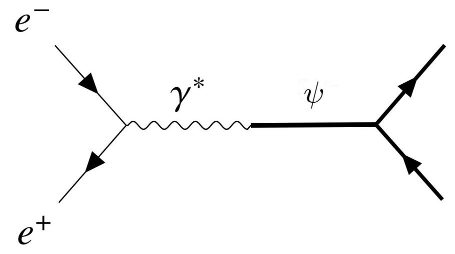


➢PANDA, EPJA57(2021)184

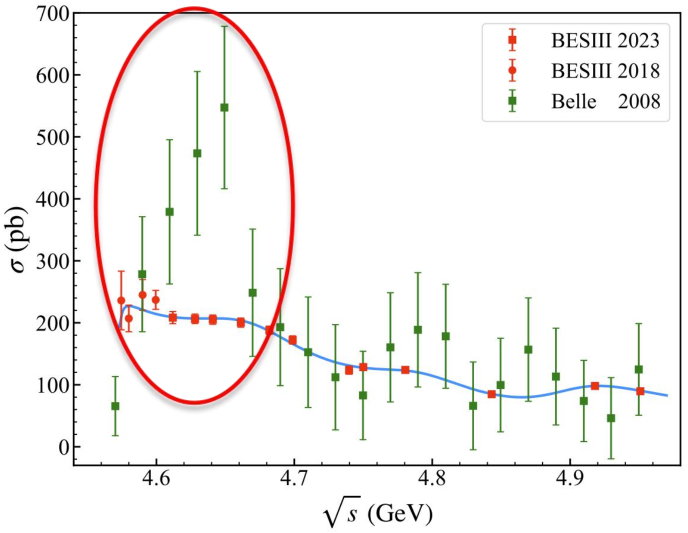
Ulf-G. Meißner, 2211.05419 [hep-ph]

粲偶素和强子分子态的产生

- **II: BEPCII上粲偶素产生：**$\Lambda_c\overline{\Lambda_c}$ **(粲重子)**



粲偶素 *VS.* 强子分子态



$$\frac{d\sigma_B}{d\Omega} = \frac{2\pi\alpha^2\beta}{4q^2}\left(1+\cos^2\theta + \frac{R^2}{\tau}\sin^2\theta\right)$$

$$R = |G_E(q^2)/G_M(q^2)|$$

State	Mass M_R (MeV)	Width Γ_R (MeV)
$\psi(4500)$	4500	125
$\psi(4660)$	4670	115
$\psi(4790)$	4790	100
$\psi(4900)$	4900	100

Known ψ' are ������! $B_{R_i} = \frac{M_{R_i}^2}{M_{R_i}^2 - s - iM_{R_i}\Gamma_{R_i}}$

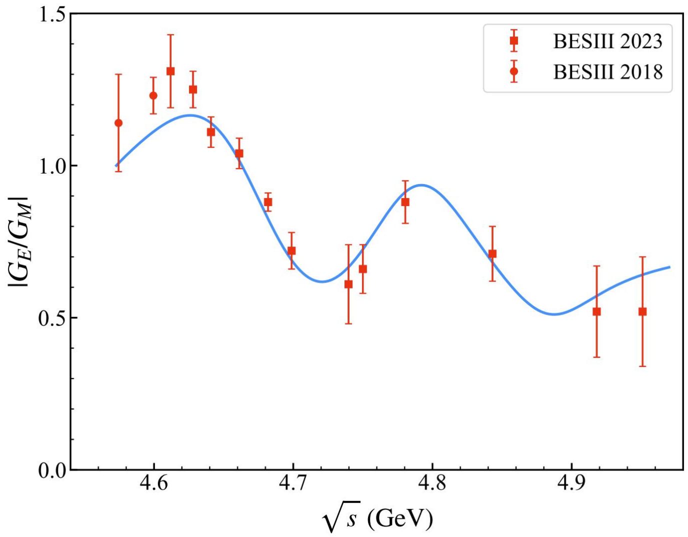
- Cheng Chen, Bing Yan, **Ju-Jun Xie**, Chin.Phys.Lett. 41 (2024) 2, 021302 • e-Print: 2312.16753 • Express Letter

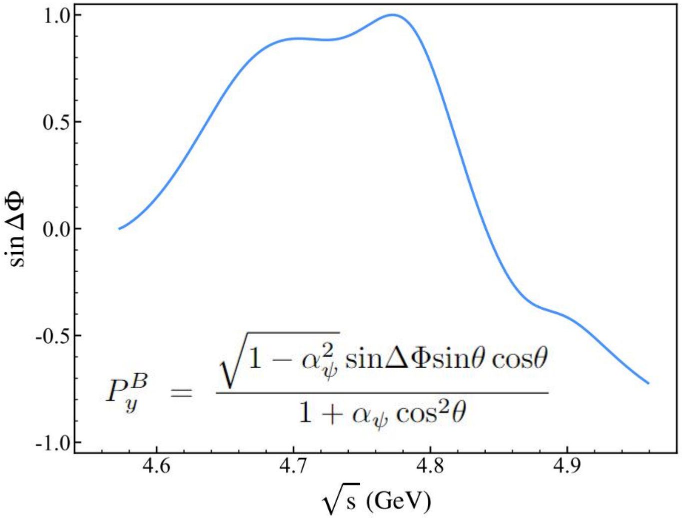
粲偶素和强子分子态的产生

- **II: BEPCII上粲偶素产生：** $\Lambda_c\overline{\Lambda_c}$ **(粲重子)**

粲偶素 *VS.* 强子分子态

$$P_y = \frac{\sin 2\theta}{\sqrt{\tau}D}\mathrm{Re}(G_M G_E^*)$$
$$P_x = -\frac{2\sin\theta}{\sqrt{\tau}D}\mathrm{Im}(G_M G_E^*)$$





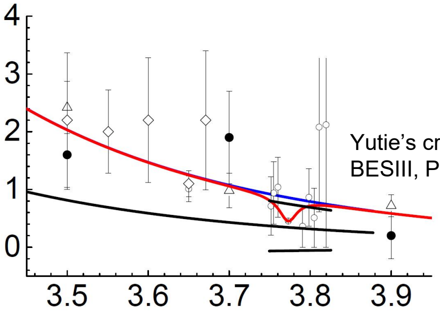
- Cheng Chen, Bing Yan, **Ju-Jun Xie**, Chin.Phys.Lett. 41 (2024) 2, 021302 • e-Print: 2312.16753 • Express Letter

Charmonium

- Trivial Facet I: Line shape of $\psi(3770)$ with higher harmonics

0.1 → 0.3

$$|I^{\rm rsd}_{p,n}/I^{D}_{p,n}| \ll 1$$

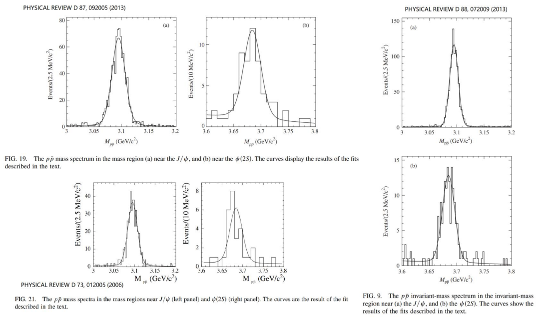


Yutie's crater
BESIII, Phys. Lett. B 735, 101(2014)

- Trivial Facet II: Deviation of J/ψ and $\psi(3686)$ from Breit-Wigner Peak

n: 2.09±0.16 3.06 ±0.15

p: 2.121±0.029 2.94 ±0.08



$$|G_N|^2-(G^D_N)^2 = G^{\rm rsd}_N(2G^D_N+G^{\rm rsd}_N)$$

1 0.01

$$= \frac{1}{2}|I^{\rm rsd}_N|^2+\sqrt{2}G^D_N|I^{\rm rsd}_N|\Re[e^{i(\phi^D_N-\phi^{\rm rsd}_N)}].$$

0.1=√0.01x1

See also Y. P. Guo and C. Z. Yuan, Phys. Rev. D 105, 114001

- Comparison of Transversely and Longitudinal Polarized Beams

$$
\begin{aligned}
\rho_1^{i,j}(\theta,\phi) &\equiv \sum_{k,k'=\pm1} \rho_{k,k'}^{\gamma^*/\psi} \mathcal{D}_{k,i}^{1*}(\phi,\theta,0)\, \mathcal{D}_{k',j}^{1}(\phi,\theta,0) \\
&= \sum_{k=\pm1} \left[\mathcal{D}_{k,i}^{1*}(\phi,\theta,0)\, \mathcal{D}_{k,j}^{1}(\phi,\theta,0)\right. \\
&+ P_T^2 \mathcal{D}_{k,i}^{1*}(\phi,\theta,0)\, \mathcal{D}_{-k,j}^{1}(\phi,\theta,0) \\
&+ \left. P_L k \mathcal{D}_{k,i}^{1*}(\phi,\theta,0)\, \mathcal{D}_{k,j}^{1}(\phi,\theta,0)\right]
\end{aligned}
$$

with the polarization vectors of leptons

$$
\rho_e^{\pm} = \frac{1}{2}\begin{pmatrix} 1+\mathcal{P}_z & \mathcal{P}_t \\ \mathcal{P}_t^* & 1-\mathcal{P}_z \end{pmatrix}
$$

and the spin densiry matrix

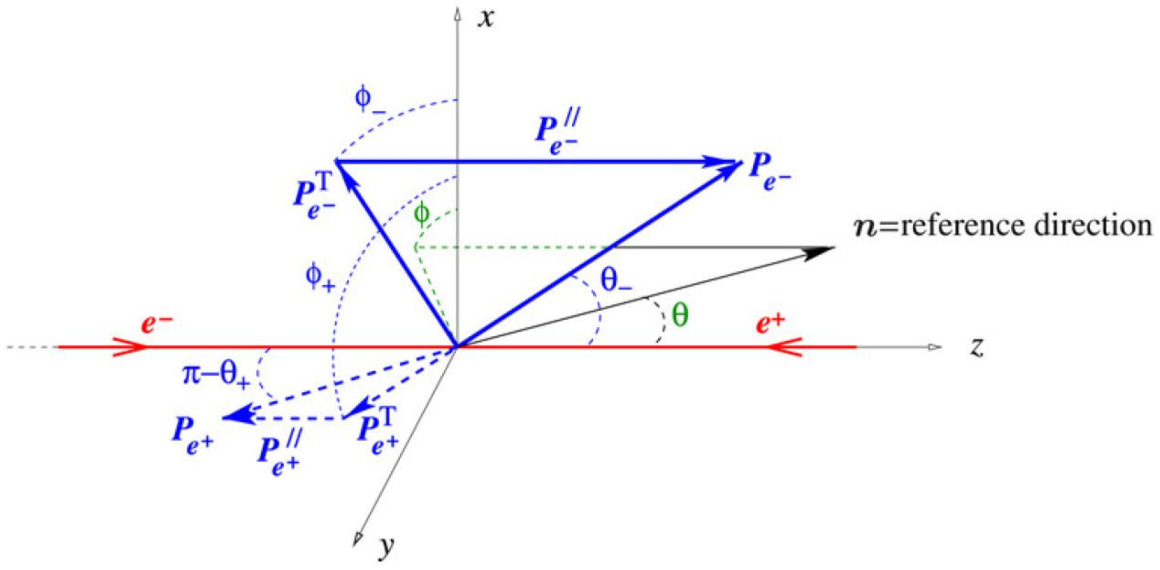
$$
\rho^{\gamma^*/\psi} = \frac{1}{2}\begin{pmatrix} 1+\mathcal{P}_z & 0 & P_T^2 \\ 0 & 0 & 0 \\ P_T^2 & 0 & 1-\mathcal{P}_z \end{pmatrix}
$$

$$
\begin{aligned}
\rho_1^{i,j}(\theta,\phi) &\equiv \sum_{k,k'=\pm1} \rho_{k,k'}^{\gamma^*/\psi} \mathcal{D}_{k,i}^{1*}(\phi,\theta,0)\, \mathcal{D}_{k',j}^{1}(\phi,\theta,0) \\
&= \sum_{k=\pm1} \left[\mathcal{D}_{k,i}^{1*}(\phi,\theta,0)\, \mathcal{D}_{k,j}^{1}(\phi,\theta,0)\right. \\
&+ P_T^2 \mathcal{D}_{k,i}^{1*}(\phi,\theta,0)\, \mathcal{D}_{-k,j}^{1}(\phi,\theta,0) \\
&+ \left. P_L k \mathcal{D}_{k,i}^{1*}(\phi,\theta,0)\, \mathcal{D}_{k,j}^{1}(\phi,\theta,0)\right]
\end{aligned}
$$

- **Xu Cao**, Yu-tie Liang, Rong-Gang Ping, 2404.00298 [hep-ph]
- N. Salone, P. Adlarson, V. Batozskaya, A. Kupsc, S. Leupold, and J. Tandean, Phys. Rev. D 105, 116022 (2022)

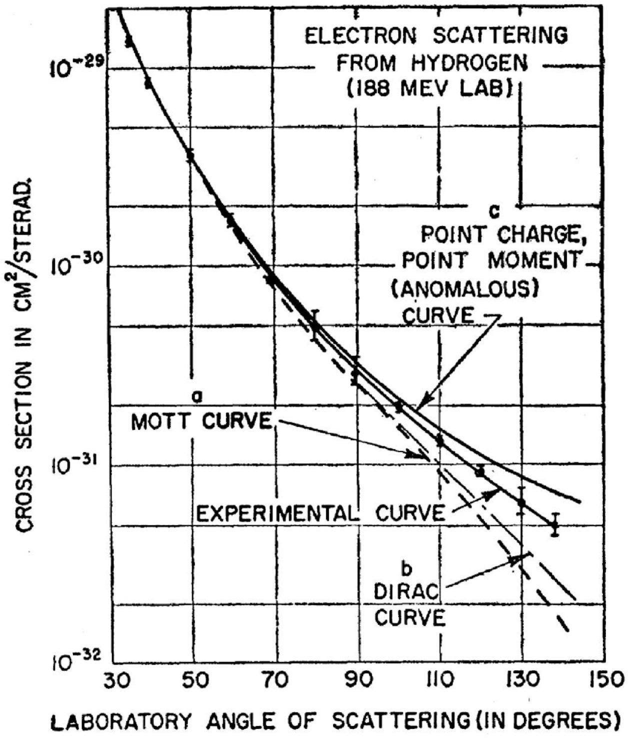
Spares

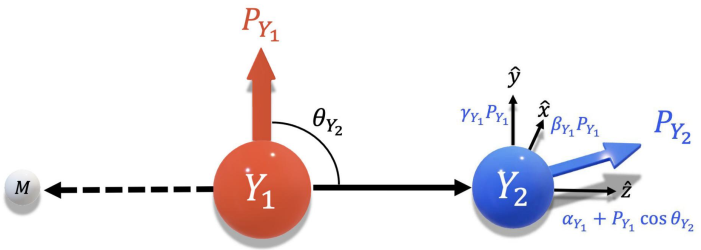
- Decomposition of the polarization vectors into a longitudinal components in the direction of the electron/positron momentum and transverse components with respect to a fixed coordinate system



- G. Moortgat-Pick et al. Physics Reports 460,2008,131

Spares


ELECTRON SCATTERING
FROM HYDROGEN
(188 MEV LAB)
c
POINT CHARGE,
POINT MOMENT
(ANOMALOUS)
CURVE
a
MOTT CURVE
EXPERIMENTAL CURVE
b
DIRAC
CURVE
CROSS SECTION IN CM²/STERAD.
10⁻²⁹
10⁻³⁰
10⁻³¹
10⁻³²
30 50 70 90 110 130 150
LABORATORY ANGLE OF SCATTERING (IN DEGREES)


P_{Y_1}
θ_{Y_2}
M
Y_1
Y_2
$\hat{y}$
$\hat{x}$
$\hat{z}$
$\gamma_{Y_1} P_{Y_1}$
$\beta_{Y_1} P_{Y_1}$
P_{Y_2}
$\alpha_{Y_1} + P_{Y_1} \cos\theta_{Y_2}$