正负电子对撞中超子极化的研究

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H-NS物理研讨会

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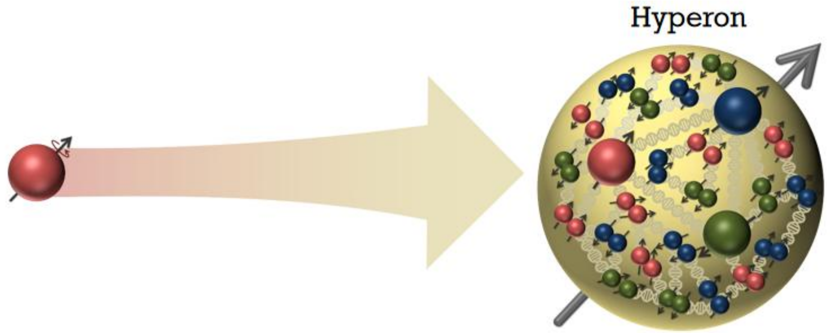
Outline

- Belle实验上 Λ 超子横极化的测量
  - 极化碎裂函数
- BESIII实验上量子纠缠超子对的产生和相关物理测量
  - 超子衰变常数、CPV
  - 电磁形状因子EMFF (Electromagnetic Form Factors)
  - 电偶极矩EDM (Electric Dipole Moment)
- 总结

Λ 超子的自发横极化

PRL36, 1113 (1976); PRL41, 607 (1978)

- 1976年在非极化束流的质子-反质子对撞中发现末态Λ显著的横极化现象（“Λ自发横极化之迷”）。
- 强子化过程中带来的横极化效应。
- 极化碎裂函数（Polarizing Fragmentation Function） $D_{1T}^{\perp}(z,p_{\perp}^2)$, 描述一个非极化的夸克碎裂到横极化的强子。
- 正负电子对撞实验可以为强子化过程的研究提供最干净的环境。
- OPAL实验（@LEP）曾测量Λ 的极化(1998)，大统计误差范围内没有看到Λ的横极化。

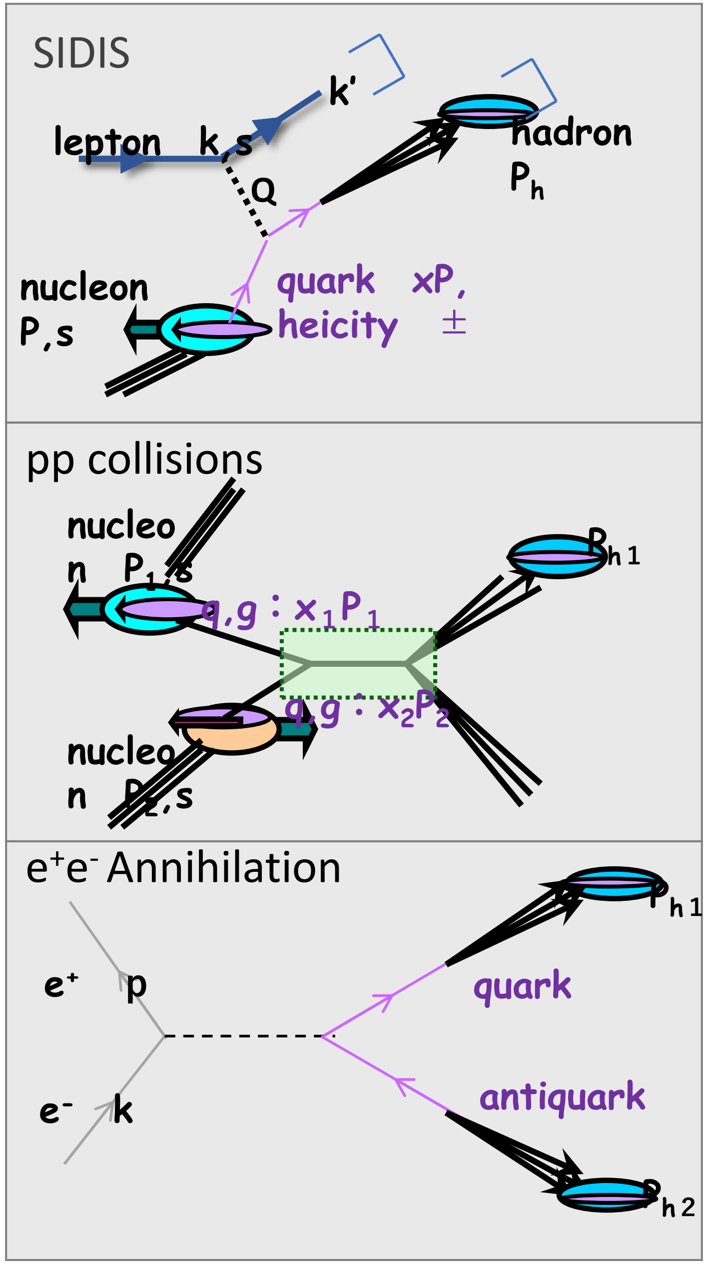


OPAL at LEP (e^+e^-)

Eur. Phys. J. C2, 49 (1998)

p_T (GeV/c)	P_T^{Λ} (%)
< 0.3	$-1.8 \pm 3.1 \pm 1.0$
$0.3 - 0.6$	$0.4 \pm 1.8 \pm 0.7$
$0.6 - 0.9$	$1.0 \pm 1.9 \pm 0.7$
$0.9 - 1.2$	$0.8 \pm 2.2 \pm 0.6$
$1.2 - 1.5$	$0.0 \pm 2.7 \pm 0.6$
> 1.5	$1.8 \pm 1.6 \pm 0.5$
> 0.3	$0.9 \pm 0.9 \pm 0.3$
> 0.6	$1.1 \pm 1.0 \pm 0.4$

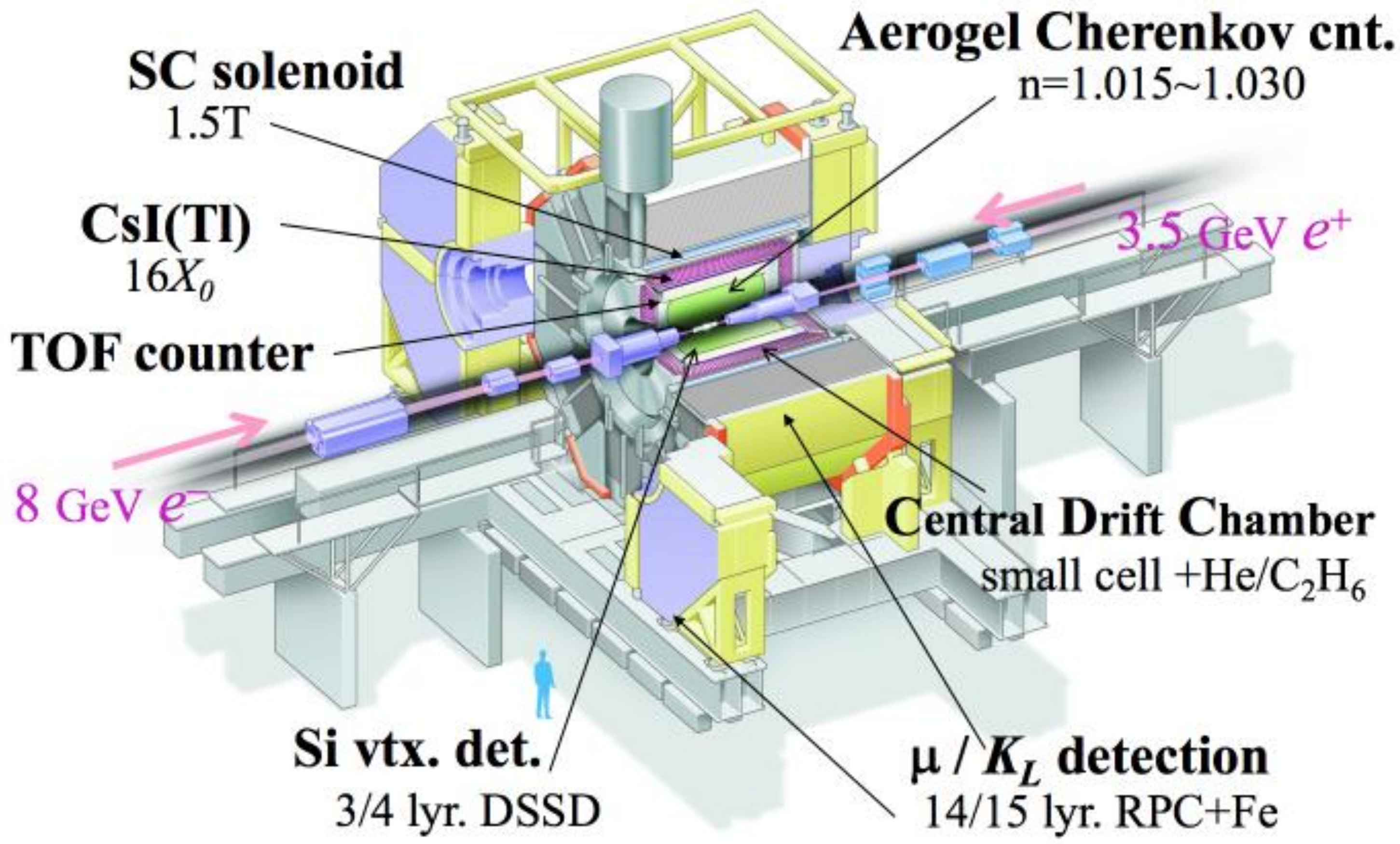
碎裂函数的测量



- 正负电子对撞，如B工厂
  - 初态不涉及分布函数，初始夸克动量已知，是提取碎裂函数最干净、直接的实验手段。
  - 大数据量，低本底，可做精确测量
  - 碎裂函数是深度非弹实验（SIDIS）测量分布函数的关键物理量输入。

KEKB@Tsukuba, Japan

Belle@KEKB

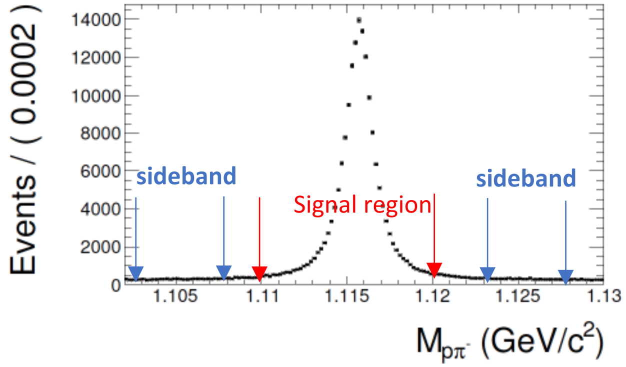


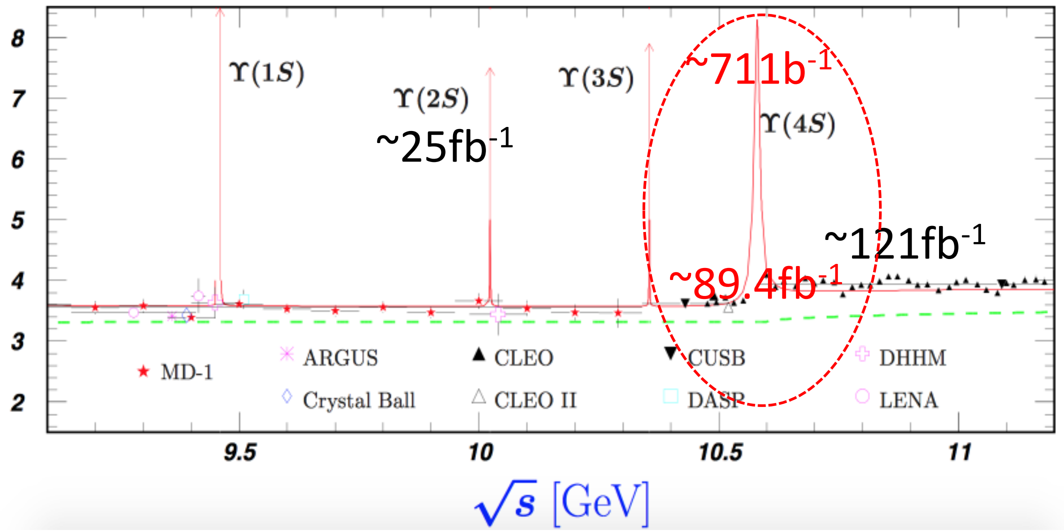
Nucl. Instrum. Meth. A479,117(2002)

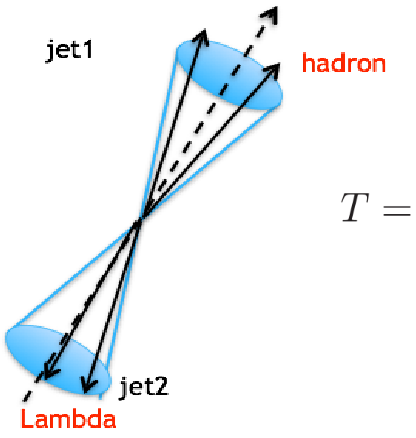
- 不对称对撞能量: e^+ (3.5 GeV) e^- (8 GeV)
- $\sqrt{s}$ = 10.58 GeV, e^+e^-→Υ(4S)→$B\bar{B}$
- $\sqrt{s}$ = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'
- 大覆盖角($17^\circ \leqslant \theta \leqslant 150^\circ$)，高径迹重建效率 (>95%), 粒子鉴别效率 (Kaon ~85%), 精确测量的理想环境。

Belle实验上Λ横极化的测量

- 数据: ~ 800 fb^{-1} at or near $\sqrt{s}$ ~10.58 GeV





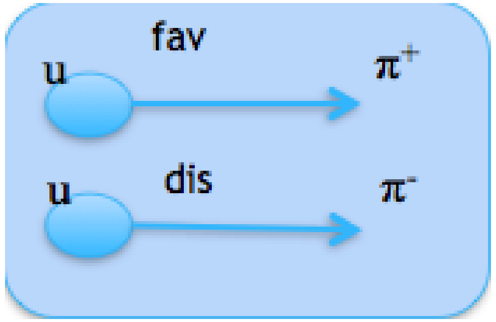


$$T = \mathrm{Max}\left[\frac{\sum_h |\mathbf{P}_h^{CMS} \cdot \hat{\mathbf{T}}|}{\sum_h |\mathbf{P}_h^{CMS}|}\right]$$

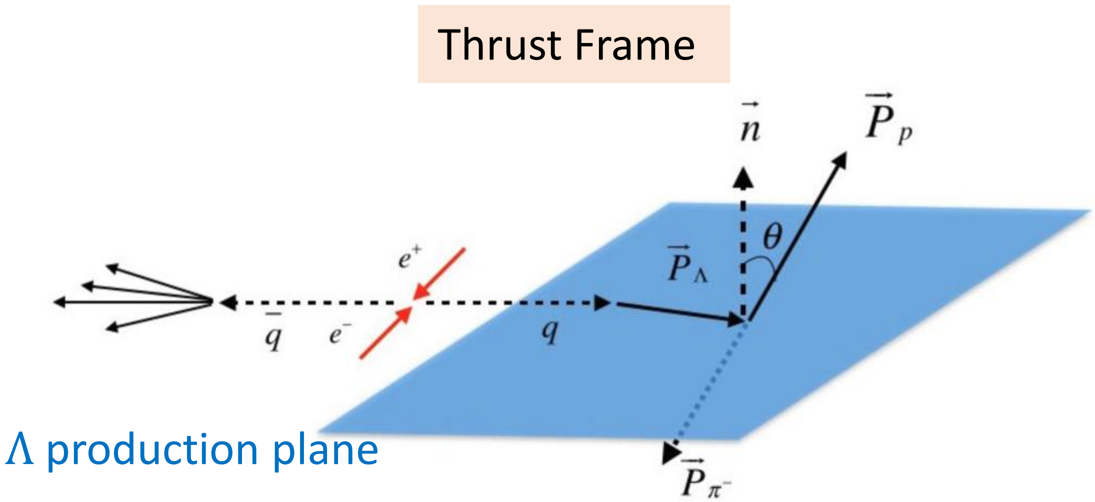
- 重建$\Lambda \to p\pi^-$($\bar{\Lambda} \to \bar{p}\,\pi^+$)，信号非常干净
- 重建冲度轴Thrust axis $\hat{T}$; T>0.8 挑选背对背的事例； *B*衰变的本底< 1%。
- Inclusive信号过程$e^+e^- \to q\bar{q} \to \Lambda + X$ 和$e^+e^- \to q\bar{q} \to \Lambda + K^-/\pi^- + X$ （K^-/π^- 在Λ 的对侧）
- $\hat{T}$ 是$q\bar{q}$方向的近似，但是有探测器分辨的影响。

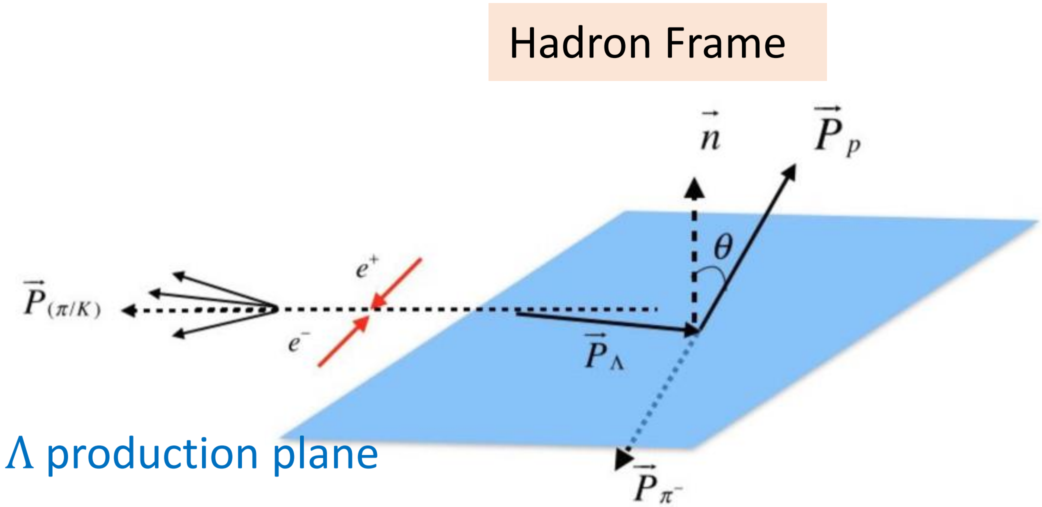
flavor tag

Λ(uds); π^+(u$\bar{d}$); K^+ (u$\bar{s}$)



Reference frames





- Λ 携带的能量分数 $z_\Lambda = 2E_\Lambda/\sqrt{s}$, Λ 相对于冲度轴（或强子轴）的横动量$p_t$。
- 通过观测$cos\theta$ 的分布来测量横极化度

$$\frac{1}{N}\frac{dN}{d\cos\theta} = 1 + \alpha P \cos\theta$$

- Λ , $\bar{\Lambda}$ decay parameter: α_+=0.642 ± 0.013; α_-=-0.71 ± 0.08（当时PDG的值）；假定CP守恒, α_-=-0.642 ± 0.013

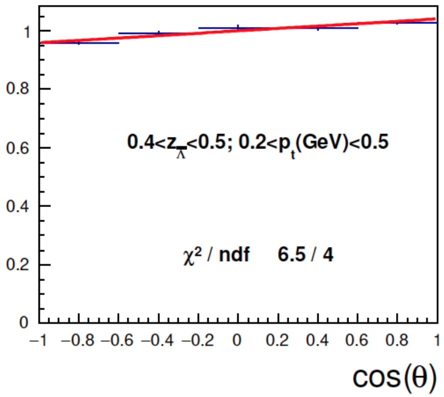
kinematic variables

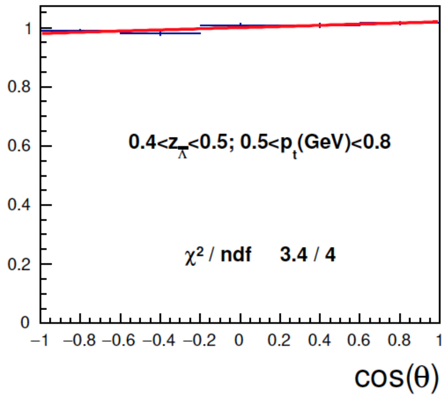
$\Lambda + X$	thrust frame	
variables	z_Λ , p_t	
$\Lambda + h + X$	thrust frame	hadron frame
variables	z_Λ, z_h, p_t	z_Λ, z_h, p_t

*BESIII(2026)： α_+=0.7519 ± 0.0036 ±0.0024 ; α_-=-0.7559 ± 0.0036 ± 0.0030

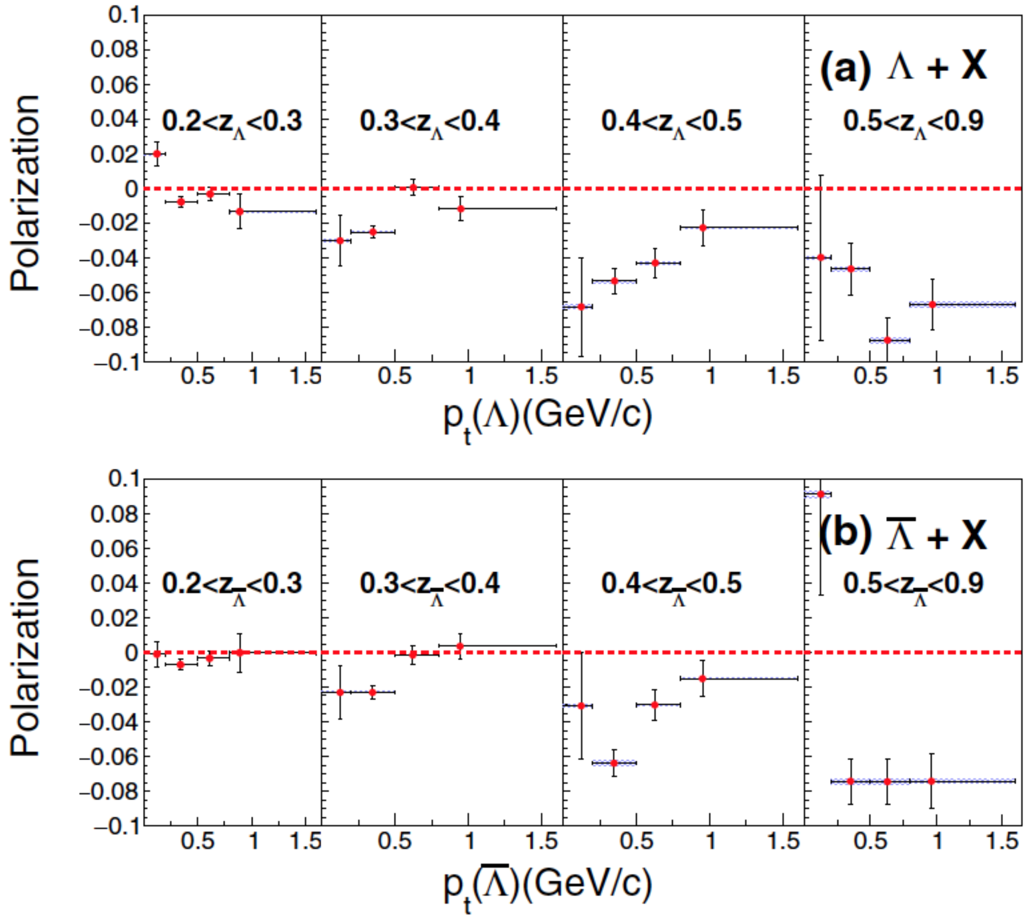
$e^+e^- \to \Lambda + X$ vs. (z,p_t)

(Belle collaboration)
Phys.Rev.Lett. 122, 042001 (2019)





Results in thrust frame

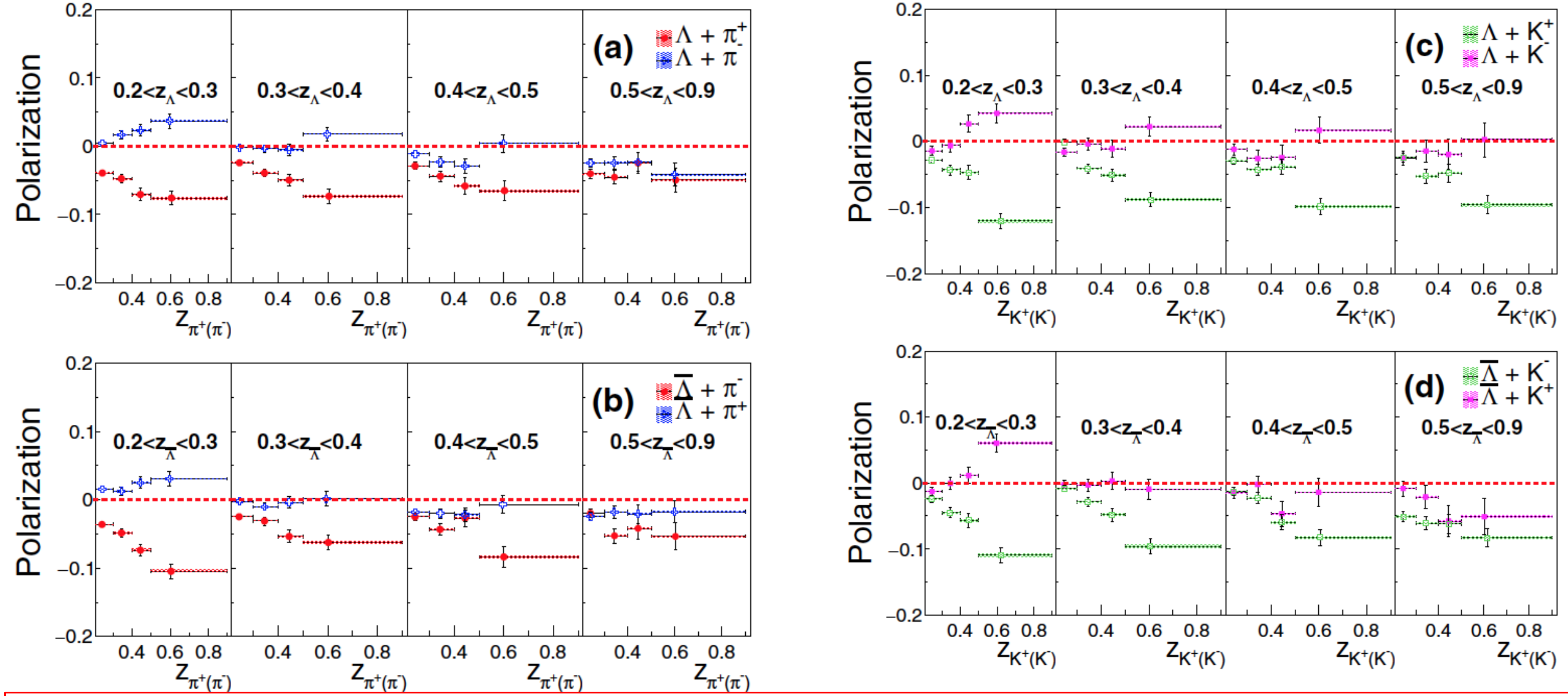


- 将z_Λ, p_t分成不同的区间，研究横极化随z和p_t的行为。
- z_Λ=[0.2,0.3,0.4,0.5,0.9]; p_t=[0.0,0.2,0.5,0.8,1.6] GeV。
- 探测器响应带来的影响由MC样本的效率矩阵估计。
- 实验结果观测到显著的横极化，随z_Λ和p_t规律变化。

$e^+e^- \to \Lambda + K^-/\pi^- + X$ vs. (z_Λ, z_h)

(Belle collaboration)
Phys.Rev.Lett. 122, 042001 (2019)

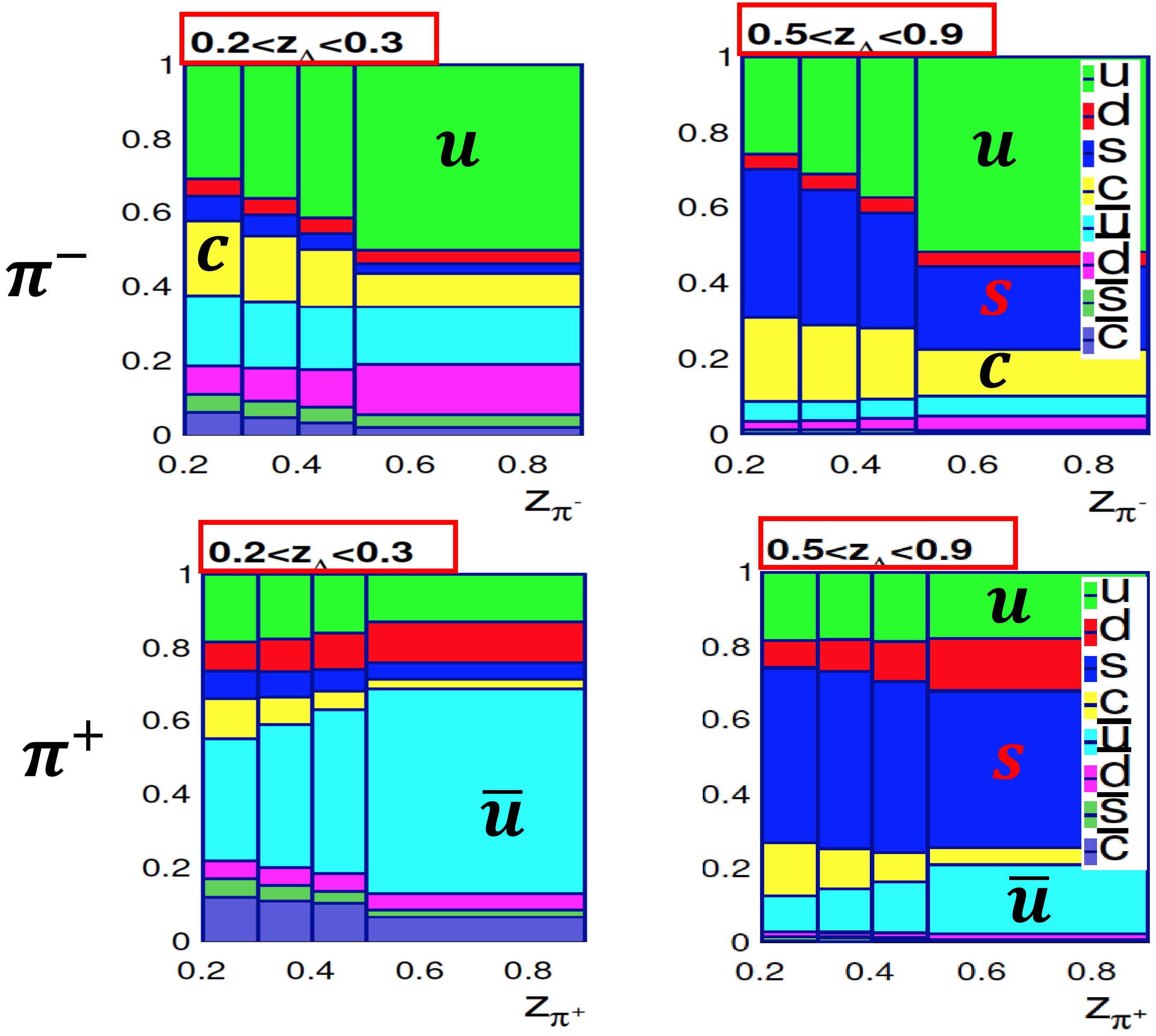
In the hadron frame



- 观测到显著的横极化；电荷共轭道的结果一致。
- 在低z_Λ, $\Lambda + h^+ + X$ 和 $\Lambda + h^- + X$ 过程中横极化符号相反。强子带来的“味道标记” 效应。
- 在较大的 z_Λ区间, $\Lambda + h^+ + X$ 和 $\Lambda + h^- + X$ 的表现趋于一致。

$K^{\pm}/\pi^{\pm}$的味道标记作用

$e^+e^- \to \Lambda + h^- + X$ MC研究



- MC simulation(Pythia6.2).
- 查看在Λ这一侧的夸克的味道.
- $\Lambda + \pi^- + X$过程中，$u \to \Lambda$(favor); $\bar{u} \to \pi^-$(favor)，在高z_Λ区间，有更多s夸克的贡献。
- $\Lambda + \pi^+ + X$过程中，在小z_Λ区间，$u \to \pi^+$(favor)。在高z_Λ区间，有更多s夸克的贡献。

Λ(uds); π^+(u$\bar{d}$); K^+ (u$\bar{s}$)

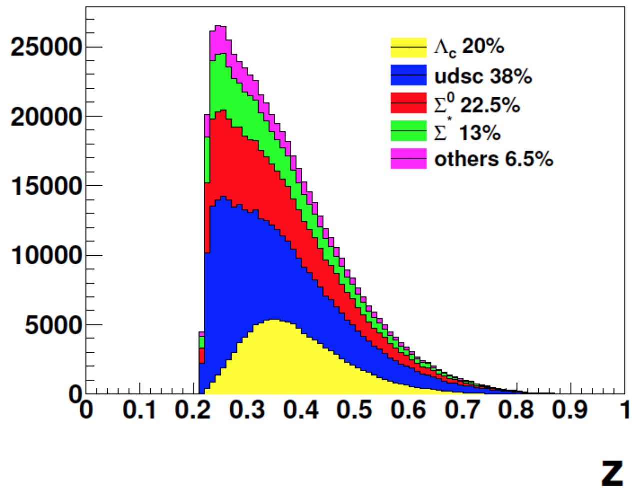
Λ 的来源

- Λ可能来直接来自uds夸克，也有些Λ来自Σ^0， Λ_c 等的衰变；重夸克c的行为可能和uds不同。
- 同时测量Σ^0-enhanced 和charm(D)-enhanced 数据样本中Λ的横极化
- 解出不同来源Λ的横极化值

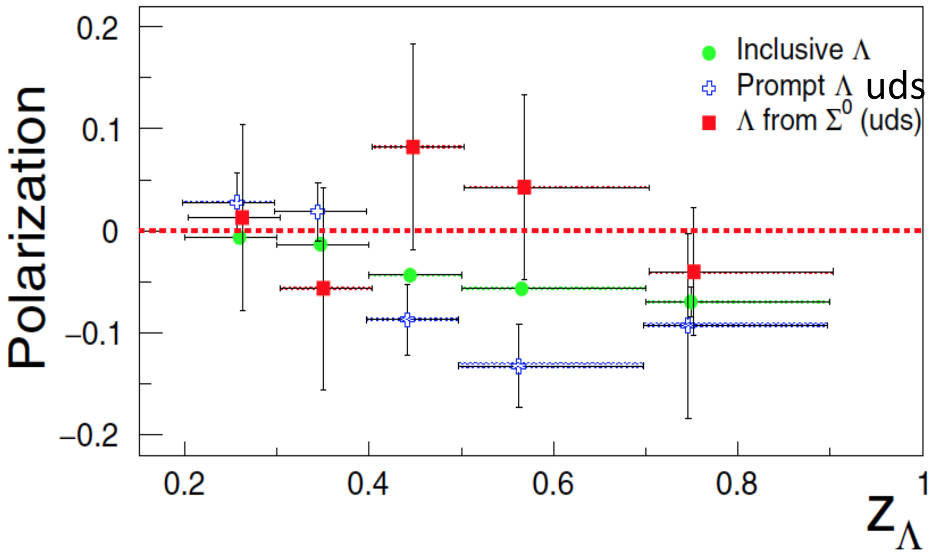
$$P^{\text{mea}} = \left(1 - \sum_i F_i\right) P^{\text{prompt}} + \sum_i F_i P_i,$$

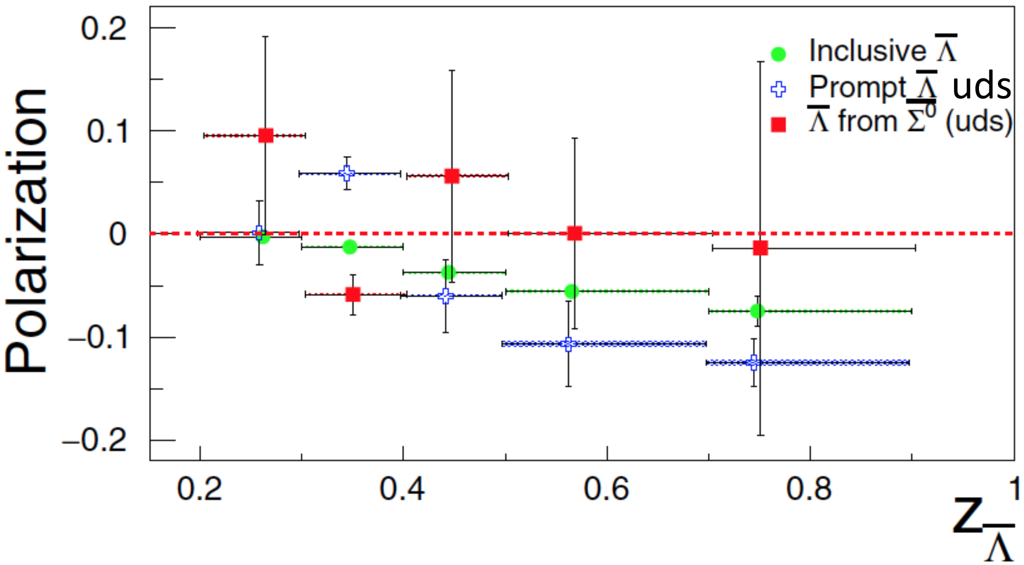
- 结果统计误差较大

MC



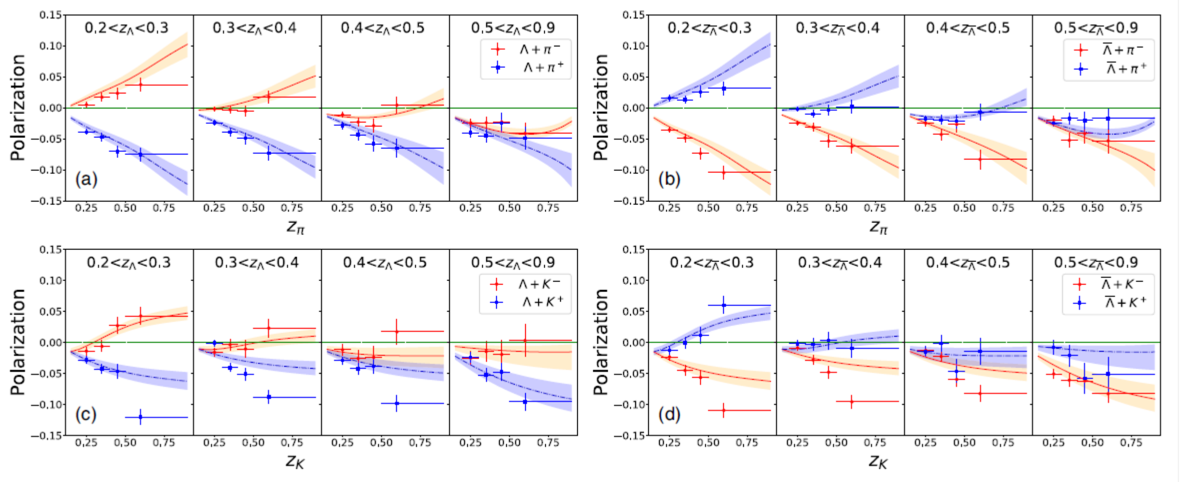
(Belle collaboration)
Phys.Rev.Lett. 122, 042001 (2019)



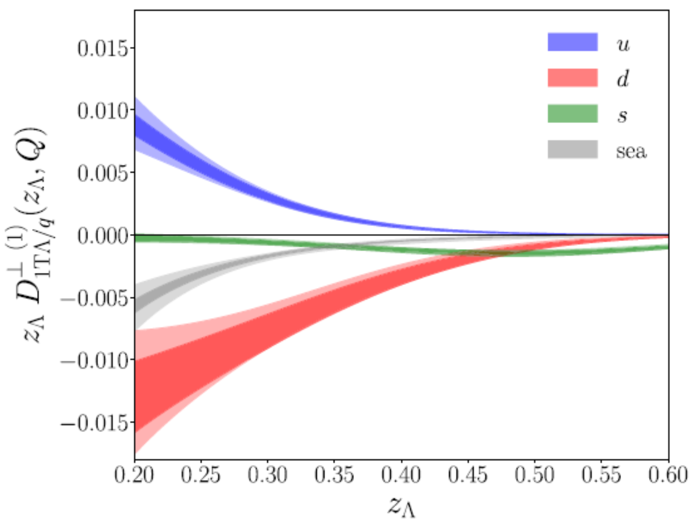


提取极化碎裂函数

D'Alesio, Murgia, Zaccheddu, PRD102,054001(2020)



Kang, Terry, Vossen, Xu, Zhang, PRD105,094033(2022)



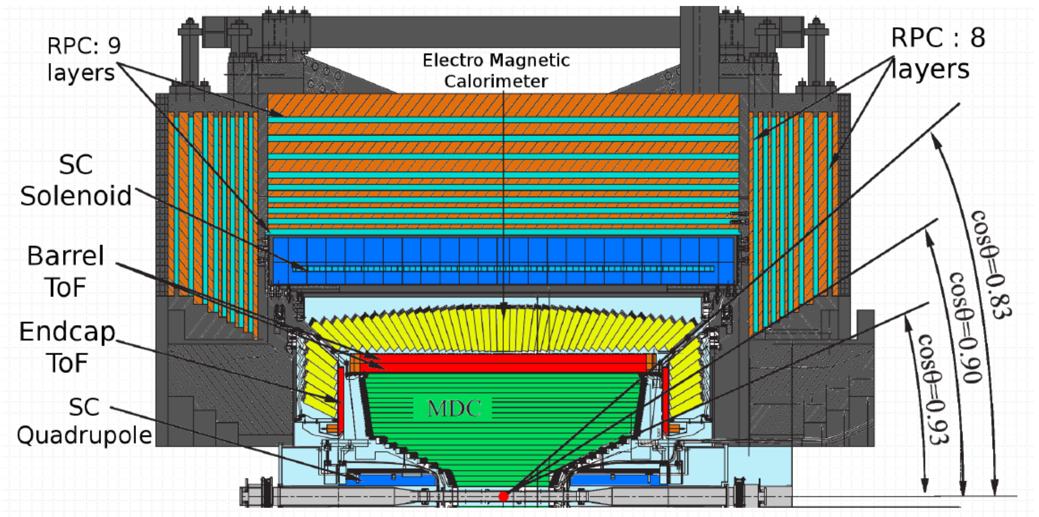
See also:
Callos, Kang, Terry, PRD102,096007(2022)
Chen, Liang, Song, Wei, PRD105,034027(2022)
Gamberg, Kang, Shao, Terry, Zhao, PLB 818 136371 (2021)
Chen, Liang, Pan, Song, Wei, PLB 816, 136217 (2021)

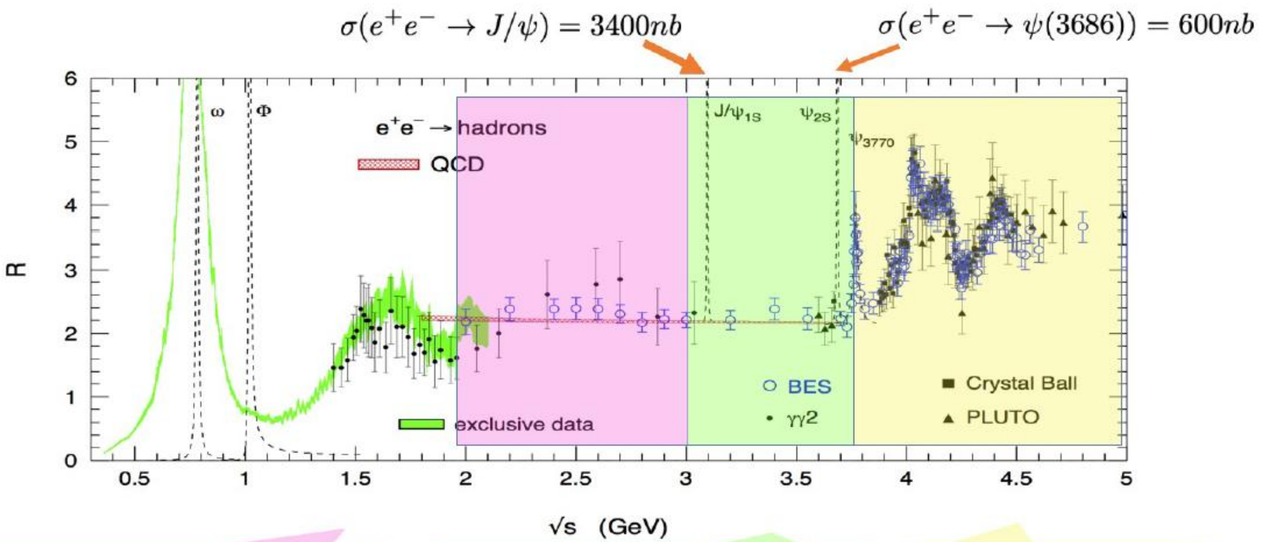
Light bands: uncertainties from the fit to Belle data
Dark bands: uncertainties from the fit to Belle data and EIC pseudo-data.

- 理论上第一次实现了提取Λ极化碎裂函数。PRD102,054001(2020)

BESIII实验上超子极化研究

BESIII @ BEPCII





- Hadron form factors
- R values and QCD
- Hadronization
- Fragmentation functions
- Nucleon structure

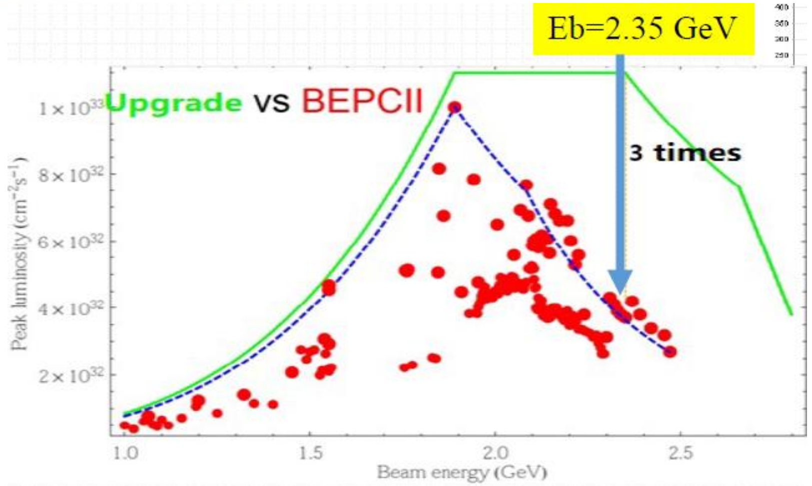
- Light hadron spectroscopy
- Hyperon physics
- Physics with τ lepton

- XYZ particles
- Charm mesons
- Charm baryons

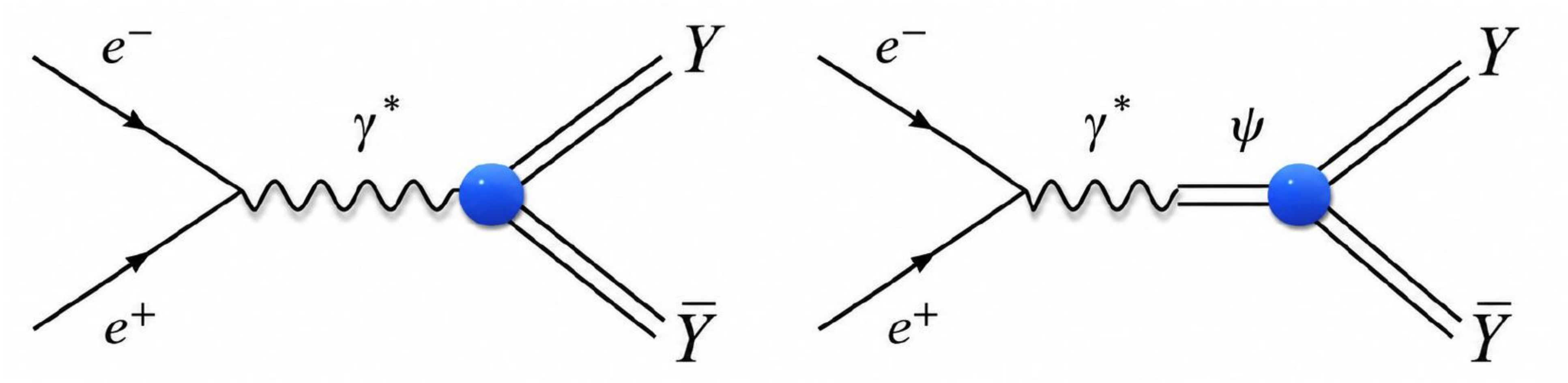
- 束流能量: 1 GeV - 2.8 GeV
- 瞬时亮度达到:

  $1.1 \times 10^{33} cm^{-2} s^{-1}$ （4.0 ~ 5.0 GeV）

  $(0.4 - 0.7) \times 10^{33} cm^{-2} s^{-1}$ （5.0 ~ 5.6 GeV）
- 10 billion J/ψ , 2.7 billion $\psi(3686)$, 10^7 超子对。

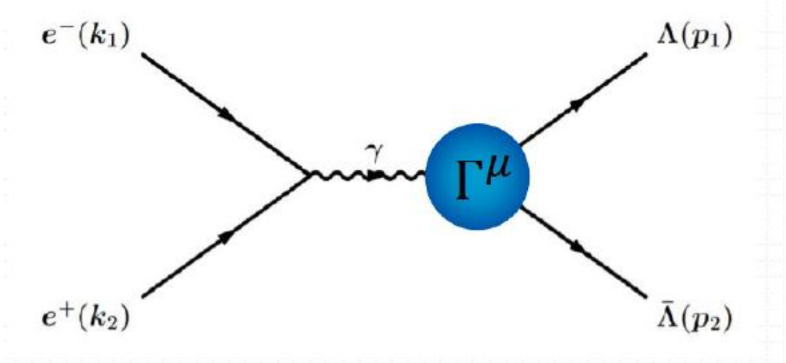


BESIII实验上超子的研究



- 遍举过程（exclusive)
- 核心优势：自旋纠缠（quantum-entangled）
- 可观测物理量：超子的decay parameters, CPV, 电磁形状因子(EMFF), 电偶极矩（EDM）

超子对的产生



$$\Gamma^\mu(p_1, p_2) = -ie\left[\gamma^\mu F_1(s) + i\frac{\sigma^{\mu\nu}}{2M_B}q_\nu F_2(s)\right]$$

Hadronic form factors：

$$G_M(s) = F_1(s) + F_2(s), \quad G_E(s) = F_1(s) + \tau F_2(s)$$

- In the case of a spin-1=2 hyperon pair, there are just two form factors. The angular distribution is described by two real numbers: the ratio and the relative phase:

$$\alpha_\psi = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2}$$

$$\Delta\Phi = \mathrm{Arg}\left(\frac{G_E}{G_E}\right)$$

- 形状因子G_M和G_F的相对相位$(\Delta\phi)$如果非零，会带来超子的横向极化。

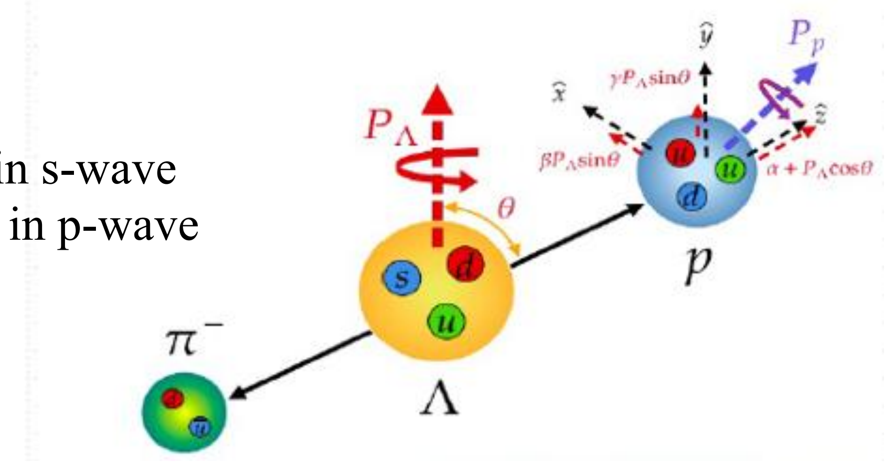
$$P_y(\cos\theta) = \frac{\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\cos\theta\sin\theta}{1+\alpha_\psi\cos^2\theta}$$

超子衰变和CPV 观测量

- Amplitude of hyperon decay

$$A = S + P\sigma\cdot\hat{n}$$

S (parity odd) final state in s-wave
P (parity even) final state in p-wave



strong phase

$$S = |S|e^{i(\delta_S+\xi_S)}$$
$$P = |P|e^{i(\delta_P+\xi_P)}$$

weak phase

$$\bar{S} = -|S|e^{i(\delta_S-\xi_S)}$$
$$\bar{P} = |P|e^{i(\delta_P-\xi_P)}$$

- Decay parameters Phys. Rev. 108, 1645 (1957)

$$\alpha_Y = \frac{2\,\mathrm{Re}\,(S^*P)}{|S|^2+|P|^2},\quad \beta_Y = \frac{2\,\mathrm{Im}\,(S^*P)}{|S|^2+|P|^2},\quad \gamma_Y = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

$$\alpha^2+\beta^2+\gamma^2 = 1$$
$$\beta = \sqrt{1-\alpha^2}\sin\phi$$
$$\gamma = \sqrt{1-\alpha^2}\cos\phi$$

CP conversation: $\alpha_Y = -\bar{\alpha}_Y, \beta_Y = -\bar{\beta}_Y, \phi_Y = -\bar{\phi}_Y$

CPV observables

$$\Delta = \frac{\Gamma-\bar{\Gamma}}{\Gamma+\bar{\Gamma}} \qquad -5.4\times10^{-7}$$

$$A = \frac{\Gamma\alpha+\bar{\Gamma}\bar{\alpha}}{\Gamma\alpha-\bar{\Gamma}\bar{\alpha}} \approx \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}}+\Delta \qquad -0.5\times10^{-4}$$

$$B = \frac{\Gamma\beta+\bar{\Gamma}\bar{\beta}}{\Gamma\beta-\bar{\Gamma}\bar{\beta}} \approx \frac{\beta+\bar{\beta}}{\beta-\bar{\beta}}+\Delta \qquad 3.0\times10^{-3}$$

$e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$

$$\mathcal{W}(\xi;\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+) = 1+\alpha_\psi\cos^2\theta_\Lambda$$

Unpolarized part

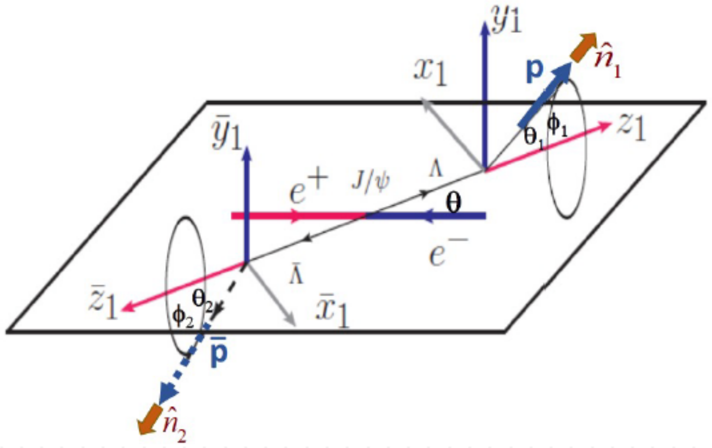
Spin correlated part

$$+\alpha_-\alpha_+\left[\sin^2\theta_\Lambda\left(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y}\right)+\left(\cos^2\theta_\Lambda+\alpha_\psi\right)n_{1,z}n_{2,z}\right]$$

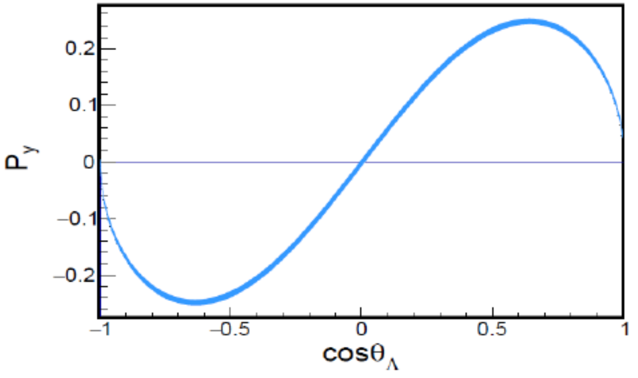
$$+\alpha_-\alpha_+\sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\left(n_{1,x}n_{2,z}+n_{1,z}n_{2,x}\right)$$

$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\,\sin\theta_\Lambda\cos\theta_\Lambda\left(\alpha_-n_{1,y}+\alpha_+n_{2,y}\right),$$

Spin Polarized part



Spin correlated term and polarization term can be used to determine α_- and α_+ simultaneously and precisely.



Λ

$$P_y(\cos\theta_\Lambda)=\frac{\sqrt{1-\alpha_\psi^2}\,\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}$$

Nuovo Cim. A 109, 241 (1996)
Phys. Rev.185 D 75, 074026 (2007)
Nucl. Phys. A190 771, 169 (2006)
Phys. Lett. B 772, 16(2017)

19

$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

[1] 1.3 billion: Nature Phys 15(2019)631
[2] 10 billion: Phys. Rev. Lett. 129 (2022) 13, 131801

3.2 M $\Lambda\bar{\Lambda}$ pairs were reconstructed.(0.1% bkg)

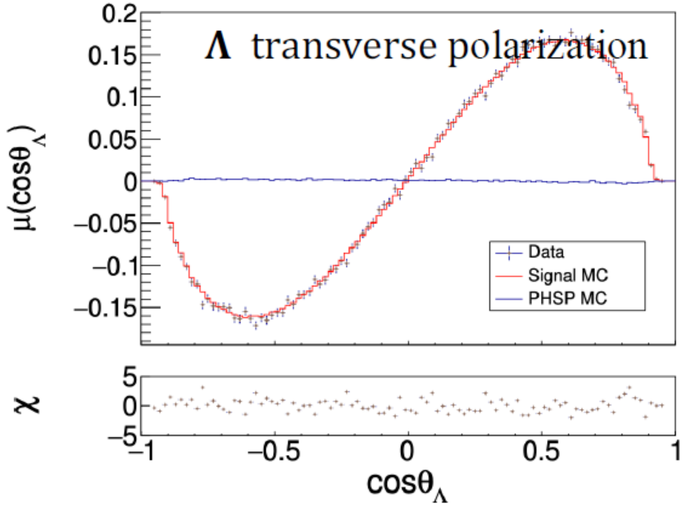
Most precise decay parameters:

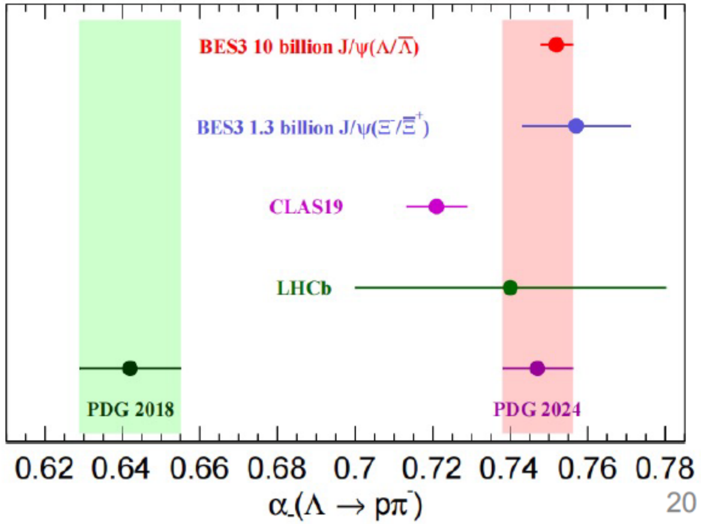
$$\Delta\Phi = 0.7521(42)(66)$$
$$\alpha_- = 0.7519(36)(24)$$
$$\alpha_+ = -0.7559(36)(30)$$
$$\alpha_{avg} = 0.7542(10)(24)$$

- Most precise measurement of Λ decay parameter
- Most precise A_{CP} measurement in hyperon decay:

$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = (-2.5 \pm 4.6 \pm 1.1)\times 10^{-3}$$

$$\mu(\cos\theta_\Lambda) \approx \frac{1+\alpha_{J/\psi}\cos^2\theta_\Lambda}{3+\alpha_{J/\psi}} P_y(\theta_\Lambda)$$





- 观测到明显的Λ横极化 ($\Delta\phi \neq 0$)
- 精确测量了Λ 和$\bar{\Lambda}$ decay parameters

$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+ ; \Xi^- \to \Lambda\pi^-$

Nature 606 (2022)64
PRL136(2026)201802

BESIII

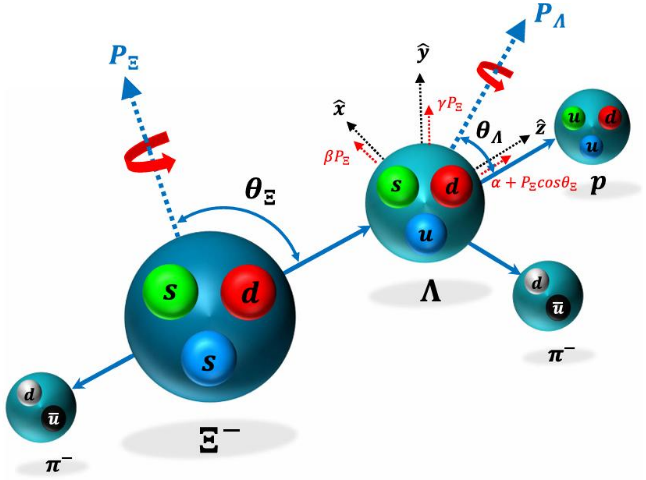
- Nine-dimensional phase space given by nine helicity angles

$$\boldsymbol{\xi} = (\theta, \theta_\Lambda, \varphi_\Lambda, \theta_{\bar{\Lambda}}, \varphi_{\bar{\Lambda}}, \theta_p, \varphi_p, \theta_{\bar{p}}, \varphi_{\bar{p}})$$

- Eight free global parameters determined by maximum log likelihood fit:

$$\boldsymbol{\omega} = (\alpha_\psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_{\bar{\Xi}}, \phi_{\bar{\Xi}}, \alpha_\Lambda, \alpha_{\bar{\Lambda}})$$

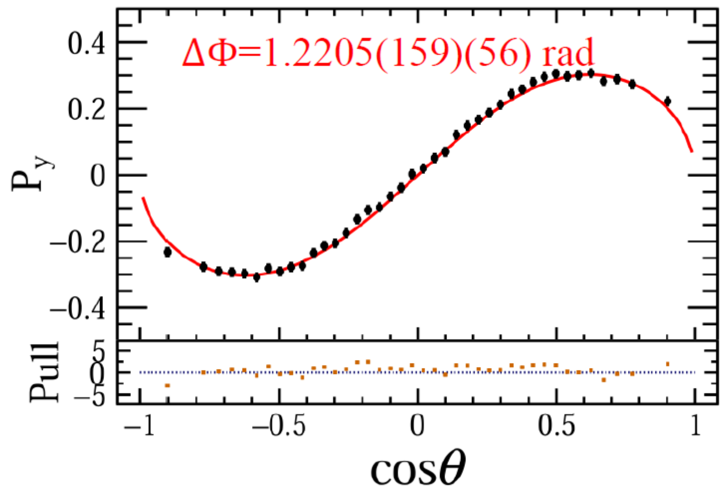
- The formalism exploits polarization, entanglement and sequential decays



Hyperon Production | Hyperon decays

$$W(\xi;\omega) = \sum_{\mu,\bar{\nu}} C_{\mu\bar{\nu}} \sum_{\mu'\bar{\nu}'} a^{\Xi}_{\mu,\mu'} a^{\bar{\Xi}}_{\bar{\nu},\bar{\nu}'} a^{\Lambda}_{\mu',0} a^{\bar{\Lambda}}_{\bar{\nu}',0}$$

Phys.Rev.D.99.056008

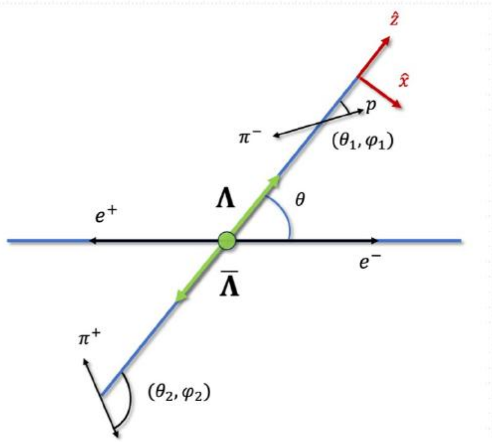


$\alpha_\Xi = -0.3813(26)(5)$
$\bar{\alpha}_\Xi = 0.3873(26)(6)$
$\Phi_\Xi = -0.0008(72)(10)$ rad
$\bar{\Phi}_\Xi = 0.0020(72)(6)$ rad
$\alpha_\Lambda = 0.7434(39)(15)$
$\bar{\alpha}_\Lambda = -0.7478(38)(15)$

The weak CP and strong phases are extracted :

$(\xi_P - \xi_S) = (-0.2 \pm 1.2 \pm 0.1)\times 10^{-2}$ rad
$(\delta_P - \delta_S) = (0.3 \pm 1.2 \pm 0.2)\times 10^{-2}$ rad

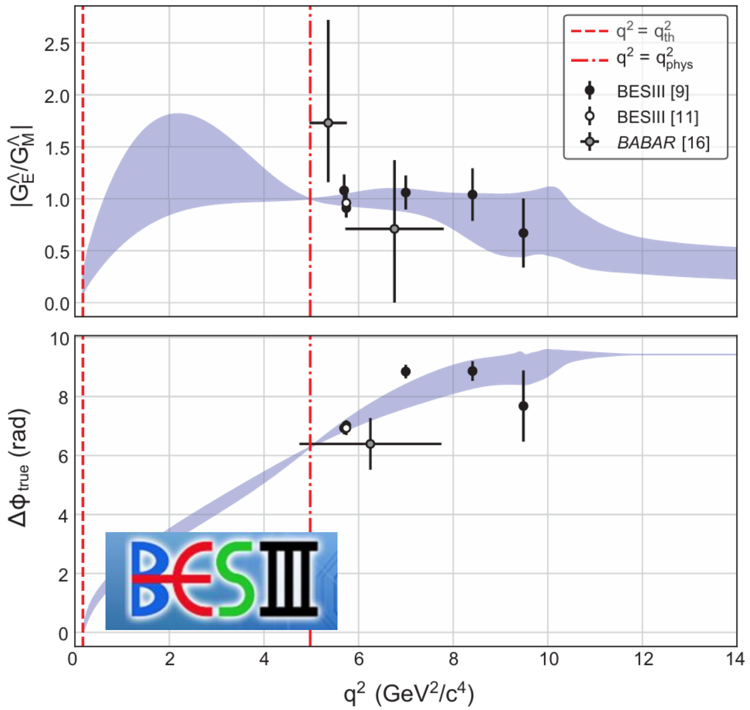
$e^+e^- \to \Lambda\bar{\Lambda}$ 测量电磁形状因子



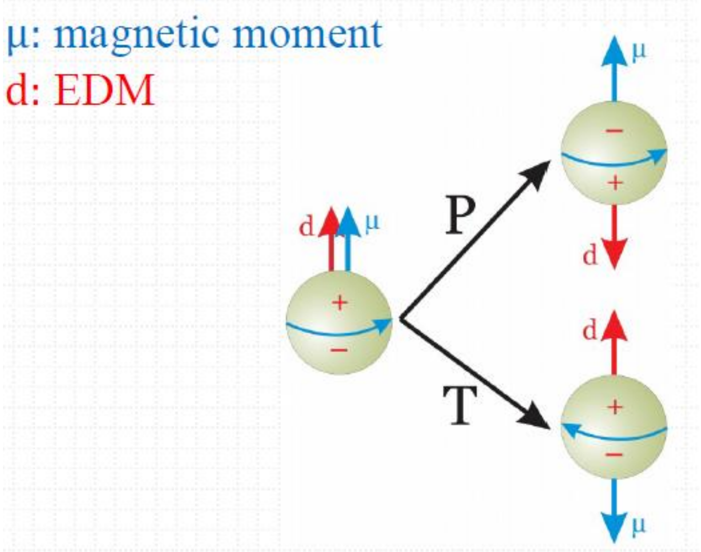
- The production mechanism is expected to be dominated by one-photon exchange.(2.0 - 3.08GeV)
- Electromagnetic form factors (EMFF): quantify hadron structure in terms of analytic functions of q^2 carried by the photon.
- Measurement of Λ EMFF (G_{eff},$R = \frac{G_E}{G_M}$,$\Delta\phi$) in the time-like region ($q^2 > 0$).

Phys.Rev.Lett. 135 (2025) 191902

- 在不同的能量点R几乎保持不变。
- 相对相位$\Delta\phi$从 37° 到 148°, 变化超过 90°。
- zero-crossings（零点）与Dyson-Schwinger方程对核子的预测一致。
- Λ charge rms radius: $\bar{r}_E^{\Lambda} = -0.076 \pm 0.043$ fm → ds 更靠近Λ的中心。

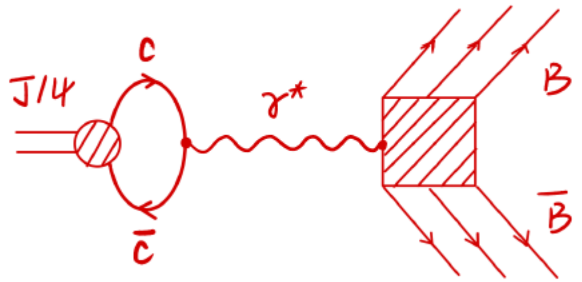


电偶极矩 Electric Dipole Moment



A non-zero intrinsic EDM would violate both parity (P) and time-reversal (T) symmetries. When CPT symmetry is conserved, T violation is equivalent to CP violation.

X.G.He, J.P. Ma, B. McKellar, Phys.RevD47(1993)1744
X.G.He, J.P. Ma, Phys.Lett.B 839 (2023) 137834



H_T is included in this term

$$H_T(q^2) = \frac{2e}{3m_{J\psi}^2} g_V d_B(q^2)$$

Assuming $d_B(q^2) \equiv d_B(0)$

$d_B(q^2)$: electric dipole form factor
$d_B(0)$: electric dipole moment
Physics Letters B 551 (2003) 16–26

$J/\psi \to \Lambda\bar{\Lambda}$ @BESIII
可以用来测量EDM.
引入形状因子H_T:
CP violation term mediated by virtual photon exchange between J/ψ and the $\Lambda\bar{\Lambda}$ pair.

- 非零的EDM会使粒子在电磁场中产生一个力矩，导致粒子的自旋进动。
- 超子：寿命短，较难直接测量，Fermilab曾测量 Λ粒子的EDM（1981年）

Λ EDM的测量

- $J/\psi \to \Lambda\bar{\Lambda}$ full angular analysis
- EDM会在超子内部等效电场中产生一个力矩，导致超子自旋产生额外的横向进动
- 寻找Λ 和$\bar{\Lambda}$ 之间极微小的不对称性，提取EDM
- 比之前Fermilab的结果提高了3个量级

arXiv:2506.19180

$$Re(d_\Lambda) = (-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}\ e\ \text{cm},$$

$$Im(d_\Lambda) = (2.9 \pm 2.6 \pm 0.6) \times 10^{-19}\ e\ \text{cm}.$$

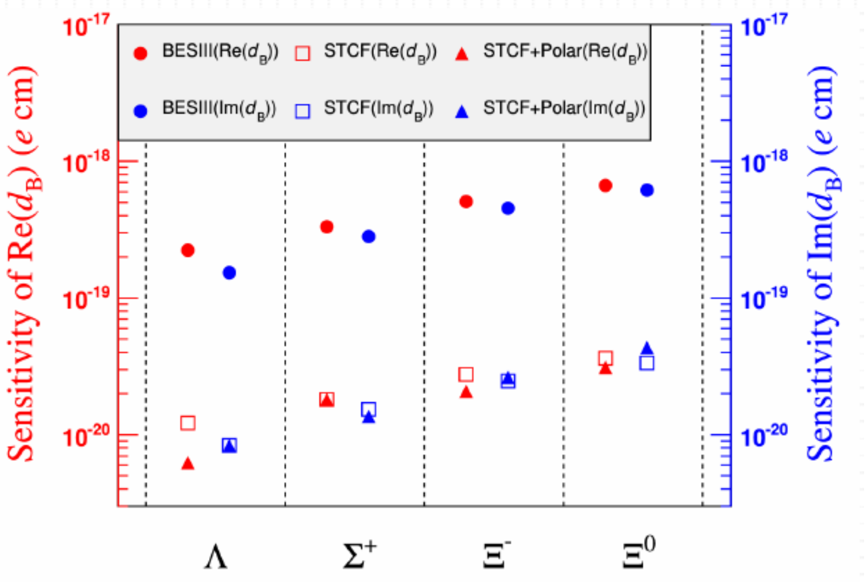
$$-8.6 \times 10^{-19} < Re(d_\Lambda) < 3.3 \times 10^{-19}\ e\ \text{cm},$$

$$-2.5 \times 10^{-19} < Im(d_\Lambda) < 7.2 \times 10^{-19}\ e\ \text{cm},$$

$$|d_\Lambda| < 6.5 \times 10^{-19}\ e\ \text{cm}.$$

SM: $\sim 10^{-26}$ e cm

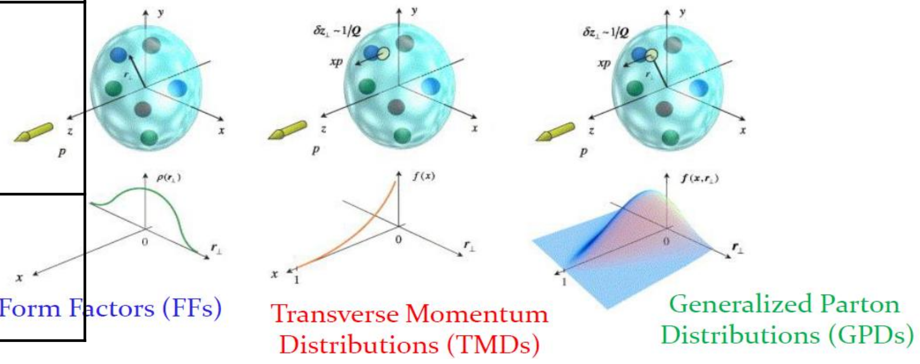
BESIII: milestone for hyperon EDM measurement
Λ 10^{-19}e cm (FermiLab 10^{-16} e cm)
first achievement for Σ^+,Ξ^- and Ξ^0 at level of 10^{-19}e cm
a litmus test for new physics



(a) Sensitivity for $Re(d_B)$ and $Im(d_B)$

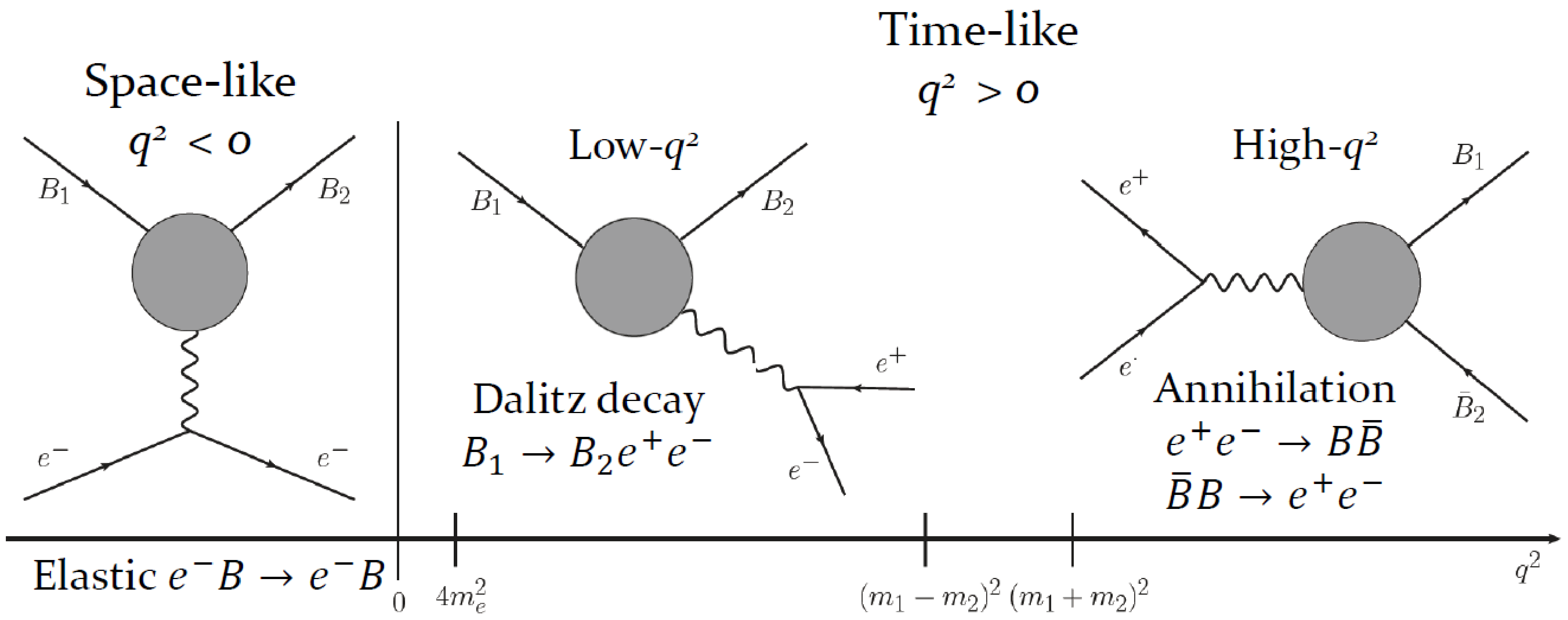
总结

	Belle	BESIII
物理过程	单举过程 $e^+e^- \to \mathrm{q}\bar{\mathrm{q}} \to \Lambda + X$；$e^+e^- \to q\bar{q} \to \Lambda + \mathrm{K}^-/\pi^- + X$	遍举过程 $e^+e^- \to J/\psi \to Y\bar{Y}$；$e^+e^- \to \gamma^* \to Y\bar{Y}$
超子横极化来源	碎裂过程	形状因子的相位差
物理量	极化碎裂函数	超子衰变常数，CPV，电磁形状因子，EDM
优势/特点	continuum过程，干净地提取碎裂函数；“味道标记”	超子对的量子纠缠
物理结果	首次观测到e^+e^-中Λ超子的横极化现象； 首次提取极化碎裂函数。	观测到显著的超子横极化； 超子衰变常数精确测量； EDM测量
未来	Belle II 数据量超过了Belle	BESIII 升级，更高亮度； STCF



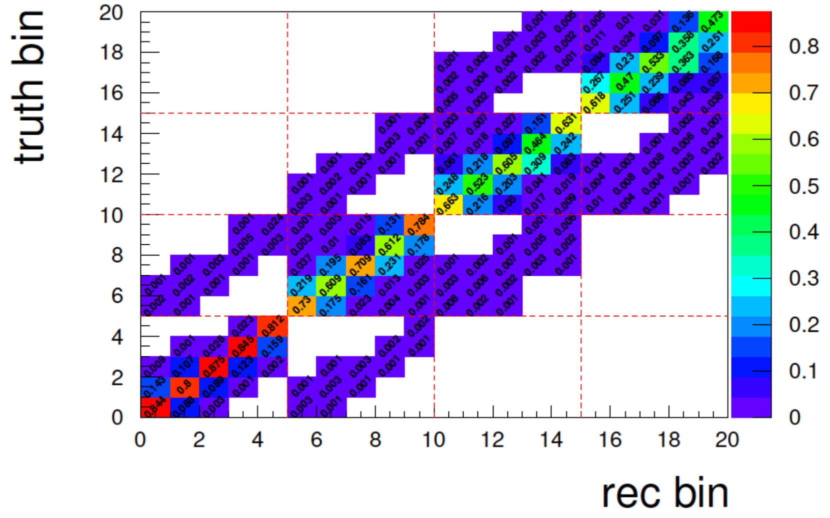
Extra

Electromagnetic Form Factors

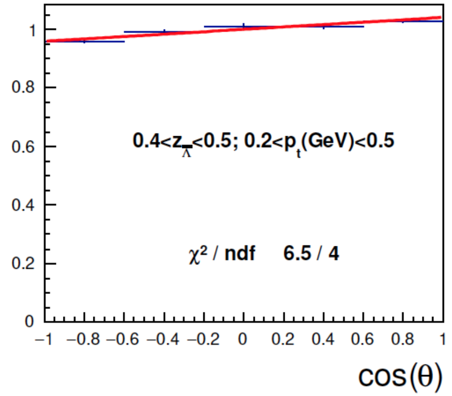


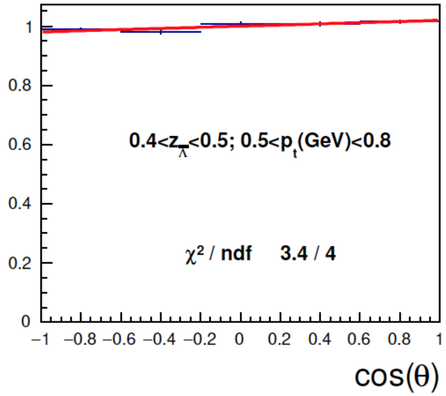
Cross-feed Unfolding

- The bin-to-bin migrations estimated in MC.



- The svd-unfolded and normalized distributions in two specific $[z_\Lambda , p_t]$ bins.

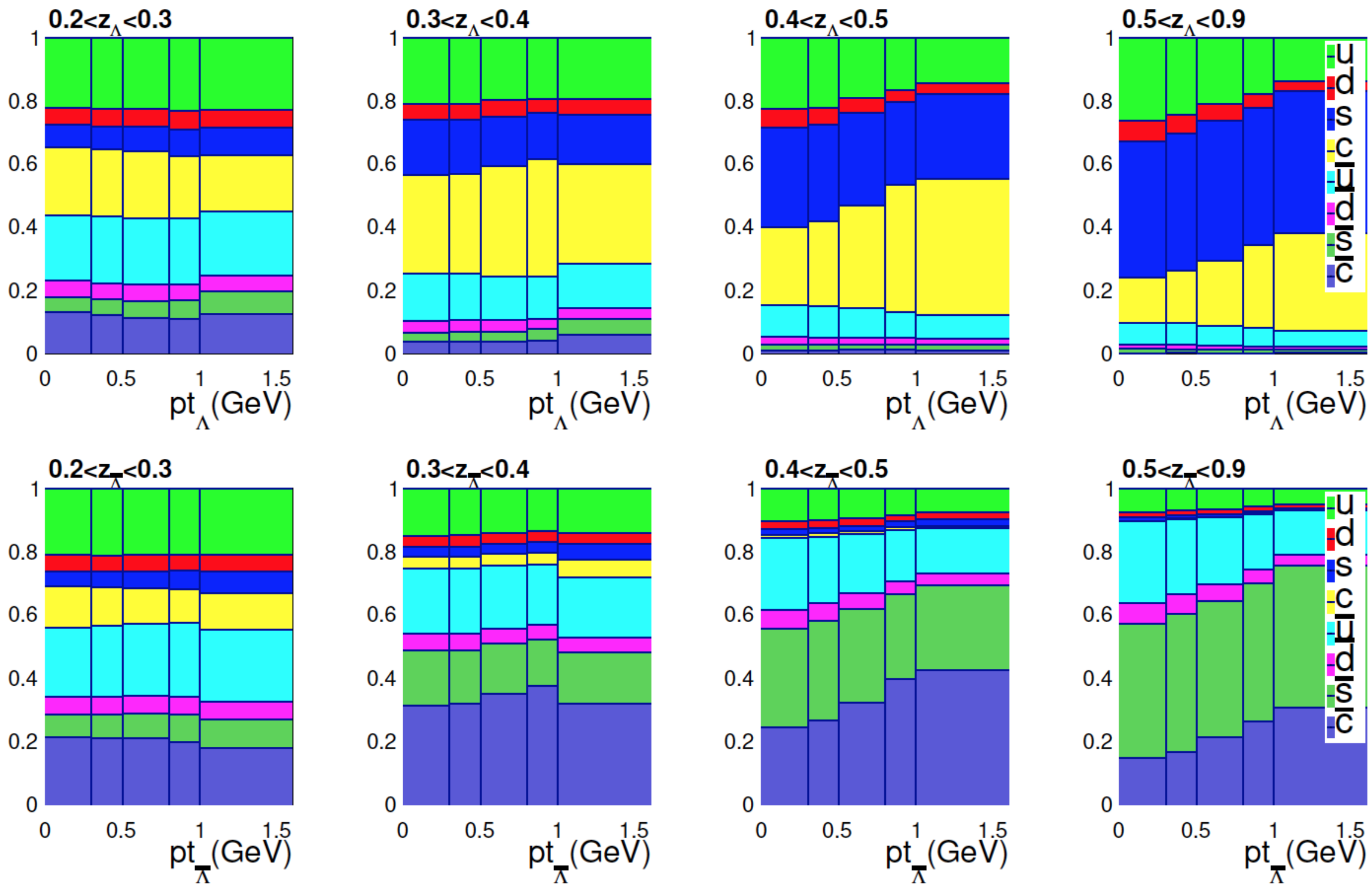




- In the thrust frame, the bin migration is dominated by the smearing in p_t, caused by the **resolution of the thrust axis**.
- 2% - 35 % events are falsely reconstructed in the adjacent p_t bin.
- Singular value decomposition(svd) unfolding is used to correct the z_Λ, p_t, and cos θ smearing and detector efficiencies simultaneously.
- In the hadron frame, the resolution of the axis of the tagged light hadron is much better than thrust axis, and not significant migration is seen. The svd unfolding is not applied for the hadron frame.

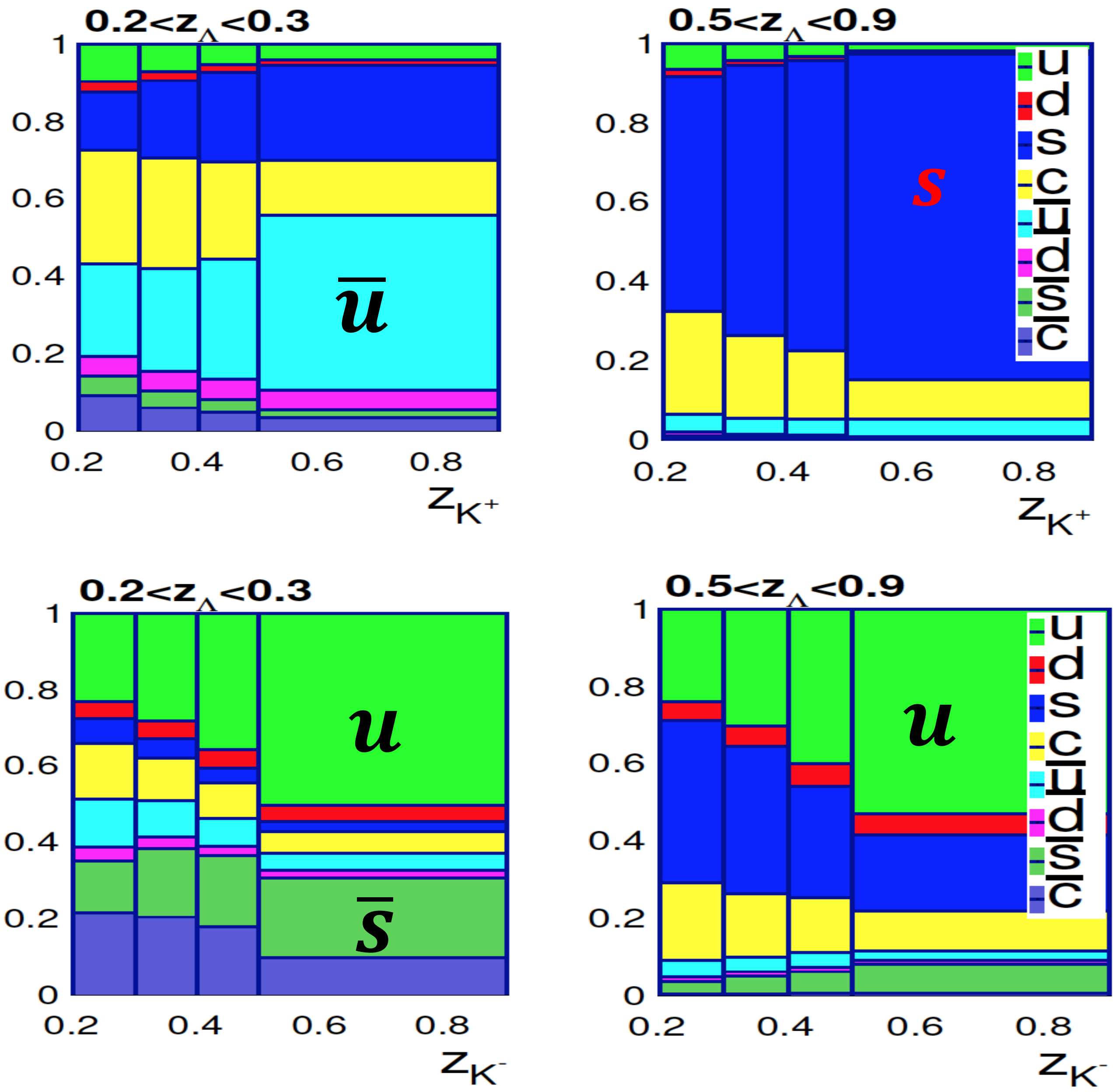
SVD unfolding: Nucl. Instrum. Methods A 372, 469

Quark flavor in $e^+e^- \rightarrow \Lambda(\bar{\Lambda}) + X$



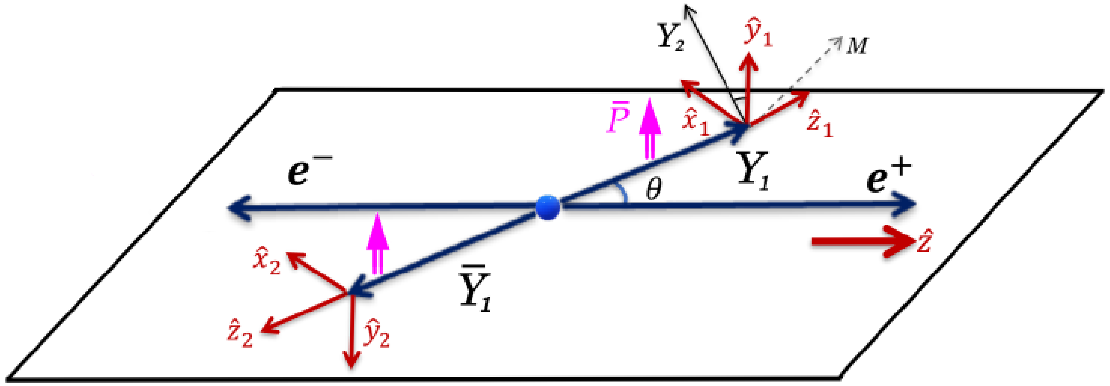
- Look at the flavor of the quark fragmenting to $\Lambda(\bar{\Lambda})$, based on MC simulation (Pythia6.2).

Quark flavor tagged by Kaon



- In $\Lambda + K^+(u\,\bar{s}) + X$, at low z_Λ, there is anti-u quark contribution. At high z_Λ, s quark dominates and the Λ polarization is negative.
- In $\Lambda + K^-(\,\bar{u}s) + X$, at low z_Λ, u/$\bar{s}$ dominate and at high z_Λ, s/u dominate.
- MC indicates that the tag of the quark flavors is more efficient at low z_Λ and high z_h. It might explain why at low z_Λ and high z_h, polarization in $\Lambda + h^+$ and $\Lambda + h^-$ have opposite sign.
- Note that charm contribution is not excluded out here.

quantum-entangled baryon pair production



- Spin $\frac{1}{2}+\frac{\bar{1}}{2}$ baryon-antibaryon density matrix:

$$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\sigma_\mu^{Y_1}\otimes\sigma_{\bar{\nu}}^{\bar{Y}_1}$$

Y_1 transverse polarization

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

$\bar{Y}_1$ transverse polarization

$$\beta_\psi = \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi), \quad \gamma_\psi = \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)$$

- Unpolarised e^+e^- beams $\Longrightarrow$ transverse polarisation (if $\Delta\Phi\neq 0$):

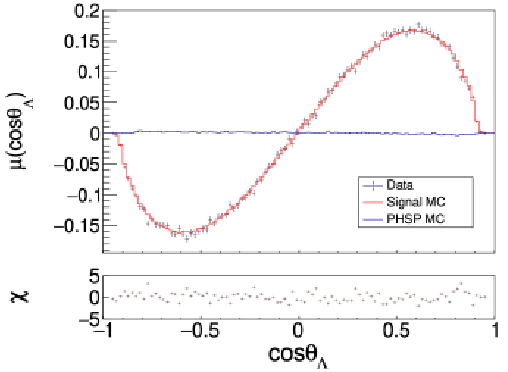
$$P_y(\cos\theta) = \frac{\sqrt{1-\alpha_\psi{}^2}\cos\theta\sin\theta}{1+\alpha_\psi\cos^2\theta}\sin(\Delta\Phi)$$

Hyperon polarization

$$\mu(\cos\theta_\Lambda) \approx \frac{1+\alpha_{J/\psi}\cos^2\theta_\Lambda}{3+\alpha_{J/\psi}} P_y(\theta_\Lambda)$$

$J/\psi \to \Lambda\bar{\Lambda}$

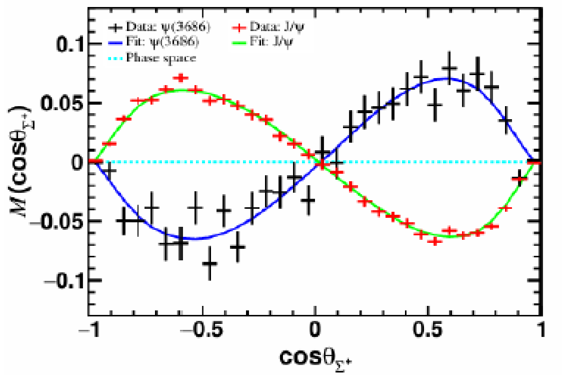
PRL129, 131801(2022)



$\Delta\Phi = (0.7521 \pm 0.0042 \pm 0.0066)$ rad

$\psi \to \Sigma^+\bar{\Sigma}^-$

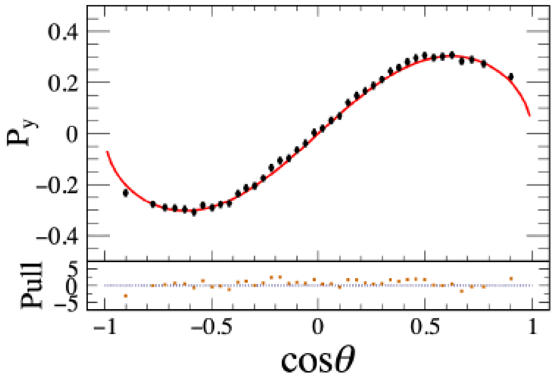
PRL135, 141804 (2025)



$\Delta\Phi(J/\psi) = (-0.2744 \pm 0.0033 \pm 0.0010)$rad
$\Delta\Phi(\psi(2S)) = (0.427 \pm 0.022 \pm 0.003)$rad

$J/\psi \to \Xi^-\bar{\Xi}^+$

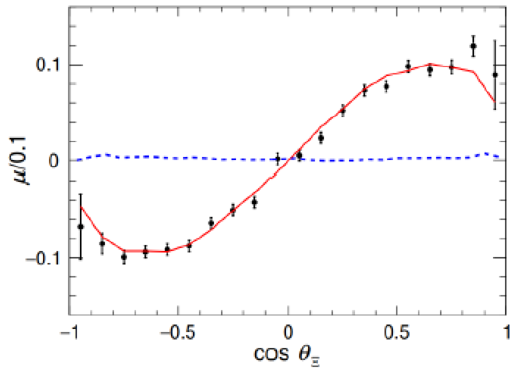
Phys. Rev. Lett. 136, 201802 (2026)



$\Delta\Phi = (1.2205 \pm 0.0159 \pm 0.0056)$ rad

$J/\psi \to \Xi^0\bar{\Xi}^0$

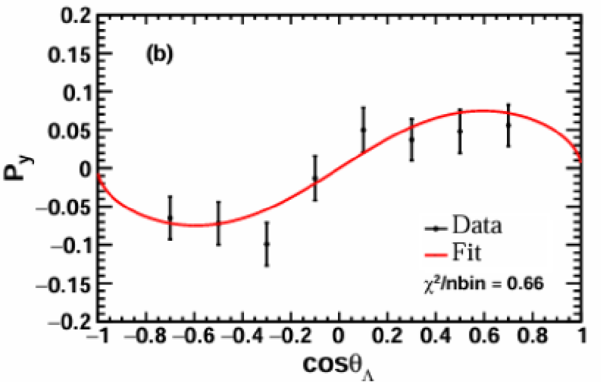
Phys. Rev. D 108, L031106 (2023)



$\Delta\Phi = (1.168 \pm 0.019 \pm 0.018)$ rad

$\psi(3686) \to \Lambda\bar{\Lambda}$

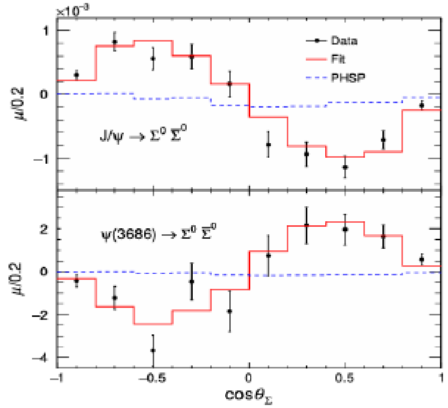
arXiv:2509.15276



$\Delta\Phi = (0.366 \pm 0.064 \pm 0.013)$ rad

$\psi \to \Sigma^0\bar{\Sigma}^0$

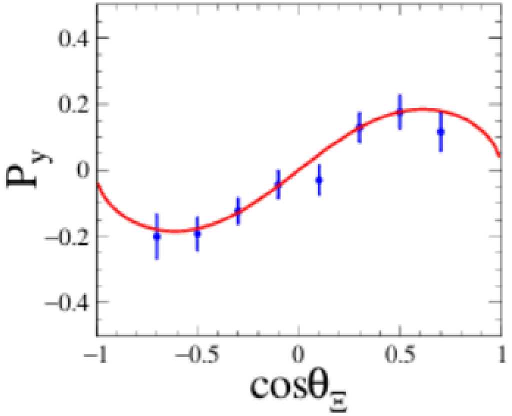
Phys. Rev. Lett. 133 (2024) 10, 101902



$\Delta\Phi(J/\psi) = (-0.0828 \pm 0.0068 \pm 0.0033)$rad
$\Delta\Phi(\psi(2S)) = (0.512 \pm 0.085 \pm 0.034)$rad

$\psi(2S) \to \Xi^-\bar{\Xi}^+$

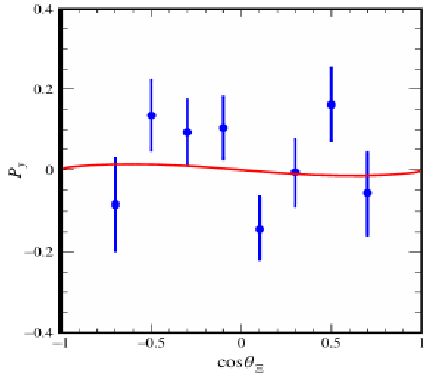
Phys. Rev. D 106, L091101 (2022)



$\Delta\Phi = (0.667 \pm 0.111 \pm 0.058)$ rad

$\psi(3686) \to \Xi^0\bar{\Xi}^0$

Phys. Rev. D 108, L011101 (2023)



$\Delta\Phi = (-0.050 \pm 0.150 \pm 0.020)$ rad