Light hyperon physics at BESIII

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Introduction

- More than 50 years of the knowledge about CP violation (CPV)
  - Confirmed only in meson decays

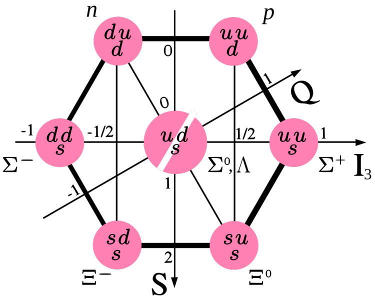
- SM CPV is not sufficient to explain observed matter-antimatter asymmetry
- Baryogenesis requires C and CP violation in the processes

  [PismaZh.Eksp.Teor.Fiz.5(1967)32]

- Systematical mapping with different hadronic systems and complementary methods are needed for understanding CPV in flavour sector

Ground-state strange baryons

- Spin-$\frac{1}{2}$ baryon octet
- Weak $\Delta S = 1$ transitions



$+\ \Omega^-(sss)$ spin-$\frac{3}{2}$

Hyperon	Mass [GeV/c^2]	Decay ($\mathcal{B}$)
$\Lambda(uds)$	1.116	$p\pi^-(63.9\%)$ $n\pi^0(35.8\%)$
$\Sigma^-(dds)$	1.197	$n\pi^-(99.8\%)$
$\Sigma^+(uus)$	1.189	$p\pi^0(51.6\%)$ $n\pi^+(48.3\%)$
$\Xi^0(uss)$	1.315	$\Lambda\pi^0(99.5\%)$
$\Xi^-(dss)$	1.321	$\Lambda\pi^-(99.8\%)$
$\Omega(sss)$	1.672	$\Lambda K^-(67.8\%)$ $\Xi^0\pi^-(23.6\%)$ $\Xi^-\pi^0(8.6\%)$

Decay amplitudes in hyperon decays

- P- and S-wave amplitudes:
  $\Lambda \to p\pi^-$, $\Xi^- \to \Lambda\pi^-$, $\Sigma \to N\pi$

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

- $|\Delta I| = 1/2$
- Contribution of $|\Delta I| = 3/2$ is $\sim 10\%$

weak CP-odd phases

$$S = |S|exp(\xi_S)exp(i\delta_S)$$
$$P = |P|exp(\xi_P)exp(i\delta_P)$$

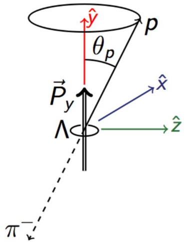
strong phases

- Two measurable parameters

$$\alpha = \frac{2\mathrm{Re}(S{*}P)}{|S|^2+|P|^2} \qquad \beta = \frac{2\mathrm{Im}(S{*}P)}{|S|^2+|P|^2} = \sqrt{1-\alpha^2}\sin\phi$$

Measurement of hyperon decay parameters

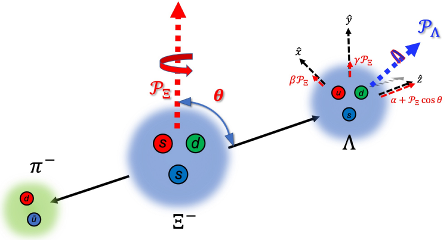
- Polarisation of hyperons experimentally accessible in weak parity violating decays



- Example:
  angular distribution of $\Lambda \to p\pi^-$

$$I(\cos\theta_p) \propto 1 + \alpha_\Lambda P_\Lambda \cos\theta_p$$

- Angle ϕ accessible when daughter baryon polarisation measured
- Example: $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$



CP tests in hyperon decays

- If CP conserved: $\bar{\alpha} = -\alpha$, $\bar{\beta} = -\beta$, $\bar{\phi} = -\phi$
- Possible CP tests:

weak P-S phase difference

$$A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -\sin\phi\tan(\xi_P - \xi_S)\frac{\sqrt{1-\alpha^2}}{\alpha}$$

$$\Phi_{CP} = \frac{\phi+\bar{\phi}}{2} = \cos\phi\tan(\xi_P - \xi_S)\frac{\alpha}{\sqrt{1-\alpha^2}}$$

- `HyperCP` measurement [PRL93(2004)262001]:

$$A^{\Lambda}_{CP} + A^{\Xi}_{CP} = (0.0 \pm 5.1_{\text{stat}} \pm 4.4_{\text{syst}}) \cdot 10^{-4}$$

- SM predictions [PRD67(2003)056001]

$$-3\cdot 10^{-5} \leq A_{\Lambda} \leq 4\cdot 10^{-5}$$
$$-2\cdot 10^{-5} \leq A_{\Xi} \leq 1\cdot 10^{-5}$$

Decay mode	$\xi_P - \xi_S$ ($\eta\lambda^5 A^2$)
$\Lambda \to p\pi^-$	0.2 ± 1.6
$\Xi^- \to \Lambda\pi^-$	-1.4 ± 1.2

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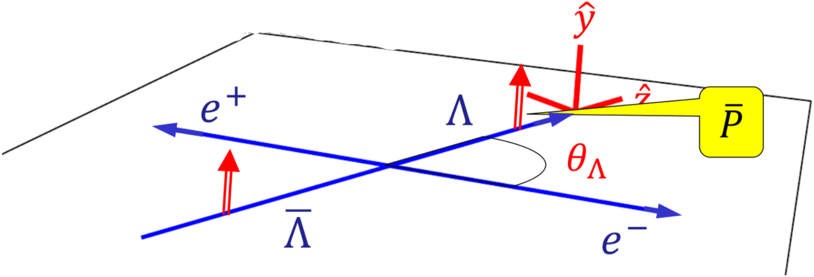
$$(\xi_P - \xi_S)_{BSM} = \frac{C'_B}{B_G}\left(\frac{\epsilon'}{\epsilon}\right)_{BSM} + \frac{C_B}{\kappa}\epsilon_{BSM}$$

- BSM predictions [PRD69(2004)076008]

$0.5 < B_G < 2$ and $0.2 < |\kappa| < 1$

Decay	C_B	C'_B
$\Lambda \to p\pi^-$	1.1 ± 2.2	0.4 ± 0.8
$\Xi^- \to \Lambda\pi^-$	-0.5 ± 1.0	0.4 ± 0.7

Baryon polarisation in e^+e^- collisions



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

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

- Angular distribution:

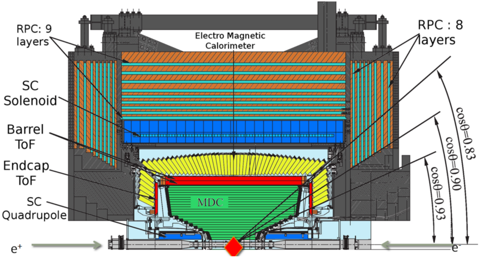
$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi\cos^2\theta_\Lambda \text{ with } \alpha_\psi \in [-1, 1]$$

BESIII @ BEPCII

[Nucl.Instrum.Meth.A598(2009)7]

- Beijing Electron-Positron Collider (BEPCII)
  - e^+e^- collider with 2.0 GeV$< E_{\text{CMS}} <$ 4.95 GeV
  - $\mathcal{L}_{\text{peak}} = 10^{33}\text{cm}^{-2}\text{s}^{-1}$
  - Data taking since 2009

- Beijing Spectrometer (BESIII)
  - Optimized for flavour physics
  - Covers 93% of the 4π solid angle
  - 1.0 T super-condacting solenoid
  - Momentum resolution:
    $\sigma(p)/p = 0.5\%$ at 1 GeV/c
  - Time resolution:
    68 (65) ps in the barrel (end cap)



Decay	$\mathcal{B}(\cdot 10^{-4})$	$\epsilon(\%)$	N_{obs}	Reference
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	42.37 ± 0.14	$441 \cdot 10^3$	[PRD95(2017)052003]
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	$11.64 \pm 0.04 \pm 0.23$	17.83 ± 0.06	$111 \cdot 10^3$	
$J/\psi \to \Xi^-\bar{\Xi}^+$	$10.40 \pm 0.06 \pm 0.74$	18.40 ± 0.04	$43 \cdot 10^3$	[PRD93(2016)072003]
$\psi(2S) \to \Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	42.83 ± 0.34	$31 \cdot 10^3$	[PRD95(2017)052003]
$\psi(2S) \to \Sigma^0\bar{\Sigma}^0$	$2.44 \pm 0.03 \pm 0.11$	14.79 ± 0.12	$6.6 \cdot 10^3$	
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	$2.78 \pm 0.05 \pm 0.14$	18.04 ± 0.04	$5.3 \cdot 10^3$	[PRD93(2016)072003]

Formalism $e^+e^- \to J/\psi(\psi(2S)) \to B_1\bar{B}_1,\ B_1 \to B_2 M$ + c.c.

- Two spin-$\frac{1}{2}$ particle state:

$$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}} \sigma_\mu^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_1}$$

Transverse polarisation

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

Spin correlations

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

- Decay can be presented via decay matrices:

$$\sigma_\mu^{B_1} \to \sum_{\mu'=0}^{3} a_{\mu\mu'}^{B_1}\sigma_{\mu'}^{B_2}$$

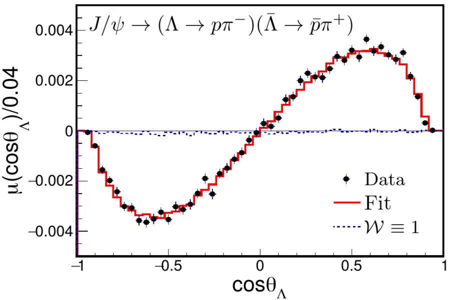
- Full angular distribution:

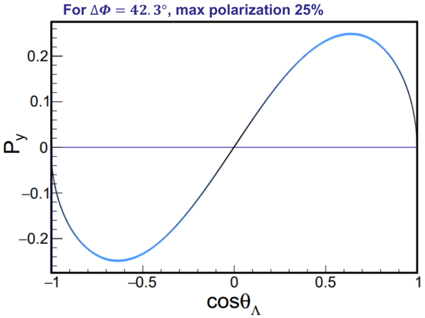
$$\mathcal{W}(\xi,\omega) = \mathrm{Tr}\rho_{B_2\bar{B}_2} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} a_{\mu 0}^{B_1} a_{\bar{\nu}0}^{\bar{B}_1}$$

$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda},\ \Lambda \to p\pi^- + \text{c.c.}$ (1)

[Nature Phys.15(2019)631]

- Data sample of $1.31 \cdot 10^9$ J/ψ events
- Exclusive analysis: $N_{\text{sig}} = 421 \cdot 10^3$ with $N_{\text{bkg}} = 399$





Parameters	This work	Previous results	
α_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027	[BESIII]
$\Delta\Phi$ (rad)	$\mathbf{0.740 \pm 0.010 \pm 0.008}$	–	
α_Λ	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013	[PDG]
$\bar{\alpha}_\Lambda$	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08	[PDG]

$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda},\ \Lambda \to p\pi^- + \text{c.c.}\ (2)$

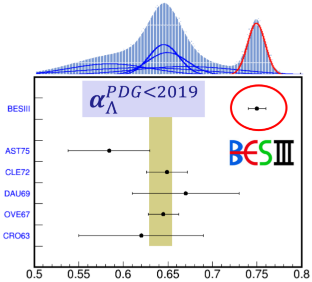
[Nature Phys.15(2019)631]

$$A_{CP}^{\Lambda} = \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda} = -0.006 \pm 0.012_{\text{stat}} \pm 0.007_{\text{syst}}$$

- PS185: $A_{CP}^{\Lambda} = 0.013 \pm 0.021_{\text{tot}}$ [PRC54(1996)1877]

$$\langle \alpha_\Lambda \rangle = \frac{\alpha_\Lambda - \bar{\alpha}_\Lambda}{2} = 0.754 \pm 0.003_{\text{stat}} \pm 0.002_{\text{syst}}$$

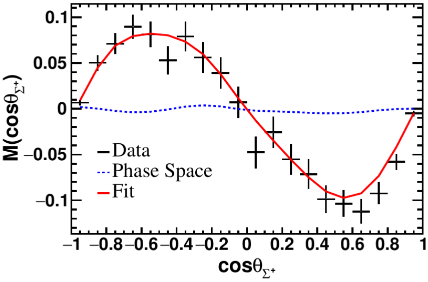
- CLAS: $\alpha_\Lambda = 0.721 \pm 0.006_{\text{stat}} \pm 0.005_{\text{syst}}$ [PRL123(2019)182301]

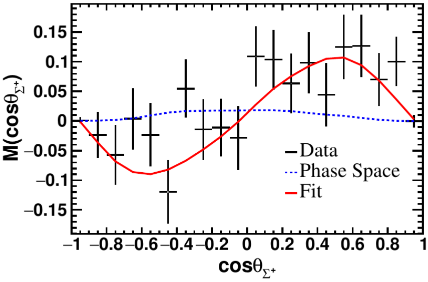


$e^+e^- \to J/\psi, \psi' \to \Sigma^+\bar{\Sigma}^-$, $\Sigma^+ \to p\pi^0$+c.c.

[PRL125(2020)052004]

Plots acceptance uncorrected





- Data sample of $1.31 \cdot 10^9$ J/ψ events
- $87 \cdot 10^3$ events with 5% bkg

$$\alpha_{J/\psi} = -0.507 \pm 0.006_{\text{stat}} \pm 0.002_{\text{syst}}$$
$$\Delta\Phi(J/\psi) = (-15.4 \pm 0.7_{\text{stat}} \pm 0.3_{\text{syst}})^\circ$$

- Data sample of $0.5 \cdot 10^9$ ψ' events
- $5 \cdot 10^3$ events with 1% bkg

$$\alpha_{\psi} = 0.676 \pm 0.030_{\text{stat}} \pm 0.006_{\text{syst}}$$
$$\Delta\Phi(\psi) = (21.5 \pm 0.4_{\text{stat}} \pm 0.5_{\text{syst}})^\circ$$

$$\langle\alpha_\Sigma\rangle = -0.994 \pm 0.004_{\text{stat}} \pm 0.002_{\text{syst}}$$
$$A_{CP}^{\Sigma} = -0.004 \pm 0.037_{\text{stat}} \pm 0.010_{\text{syst}}$$

- SM predictions [PRD67(2003)056001]

$$A_{CP}^{\Sigma^+} \sim 3.6 \cdot 10^{-6}$$

Formalism sequential weak decays

[PRD99(2019)056008] [PRD100(2019)114005]

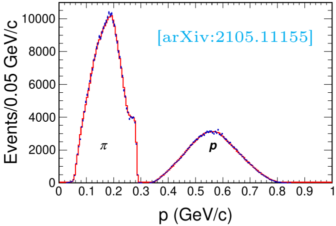
- Decays $B_1 \to B_2(\to B_3 + M_2) + M_1$
  - $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$+c.c.
- Formalism exploits polarisation, entanglement and sequential decays

$$\mathcal{W}(\boldsymbol{\xi},\boldsymbol{\omega}) = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} \sum_{\mu',\bar{\nu}'=0}^{3} a^{B_1}_{\mu\mu'} a^{\bar{B}_1}_{\bar{\nu}\bar{\nu}'} a^{B_2}_{\mu'0} a^{\bar{B}_2}_{\bar{\nu}'0}$$

- 9-dimensional phase space given by 9 helicity angles
- 8 free parameters determined by unbinned MLL method

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

not measured before



- $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$, $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$+c.c.
- Data sample of $1.3 \cdot 10^9 J/\psi$ events
- $73.2 \cdot 10^3$ events with $N_{\text{bkg}} = 199$

$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$, $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$+c.c. (1)

[arXiv:2105.11155]

- First measurement of the polarisation
- First direct determination of all $\Xi^-\bar{\Xi}^+$ decay parameters
- Independent measurement of Λ decay parameters
    - Excellent agreement with previous BESIII results

Parameter	This work	Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	[1]
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–	
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010	[2]
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad	[2]
$\overline{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–	
$\overline{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	[3]
$\overline{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	[3]
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–	
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad	[4]
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–	
A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	[3]
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

[1] [PRD93(2016)072003] [2] [PTEP2020(2020)083C01] [3] [Nature Phys.15(2019)631] [4] [PRL93(2004)011802]

$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+,\ \Xi^- \to \Lambda(\to p\pi^-)\pi^-$+c.c. (2)

[arXiv:2105.11155]

- First measurement of weak phase difference
  - Consistent with SM prediction

$(\xi_P - \xi_S)_{\rm SM} = (1.8 \pm 1.5) \cdot 10^{-4}$ rad
[PRD67(2003)056001]

- Three independent CP tests

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$A_{\rm CP}^{\Xi}$	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{\rm CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–	
$A_{\rm CP}^{\Lambda}$	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	[3]
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

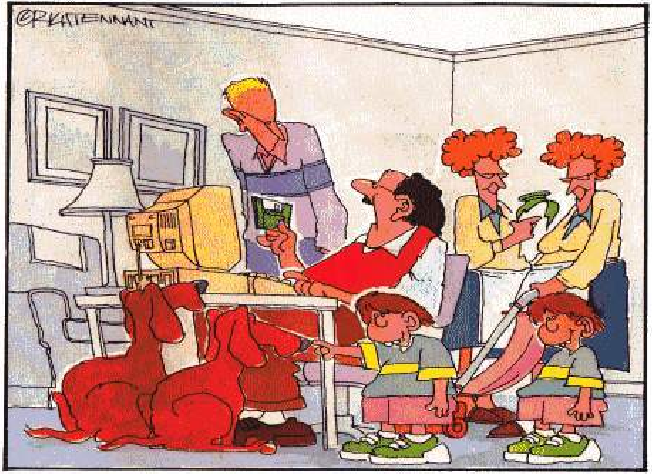
[1] [PRD93(2016)072003] [2] [PTEP2020(2020)083C01] [3] [Nature Phys.15(2019)631] [4] [PRL93(2004)011802]

Summary and Outlook

- BESIII has performed
  - Measurements of polarisation and spin correlations in
    - $J/\psi(\psi') \to \Lambda\bar{\Lambda}, \to \Sigma\bar{\Sigma}$
    - $J/\psi \to \Xi\bar{\Xi}$, $\psi(3686) \to \Omega\bar{\Omega}$
  - Determination of hyperon and anti-hyperon decay parameters
  - CP tests comparing hyperon and anti-hyperon
    - Separation of strong and weak decay phases $\Longrightarrow$ more sensitive CP tests
- Future prospects
  - Recently collected 10^{10} J/ψ and $3 \cdot 10^{9}$ ψ' events
    - Many interesting results are expected
  - Good prospects for future Super Charm-Tau Factories [Phys.-Usp.61(2018)405] [IPAC2018Preceedings]
    - Planning produce more than 10^{12} J/ψ events
    - Polarized electron beam
    - Statistical precision will be comparable to the SM predictions

Thank you for your attention!

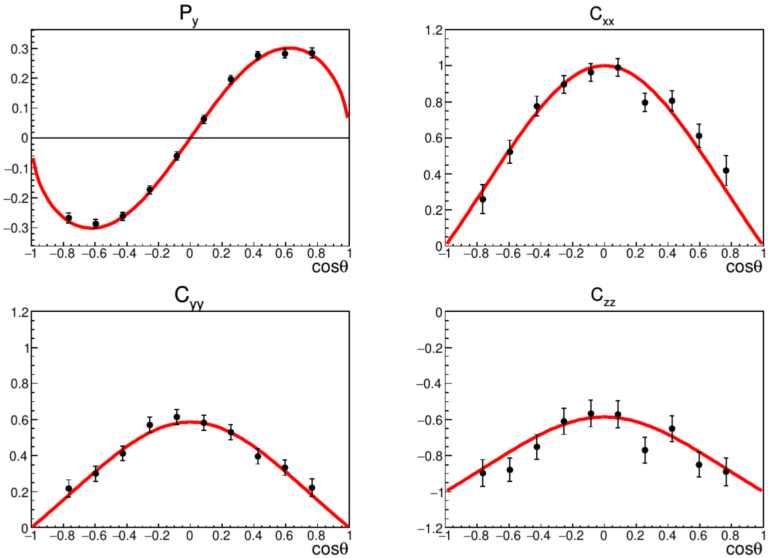
Backups



" I ALWAYS BACK UP EVERYTHING."

Polarisation and spin correlations $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$

[arXiv:2105.11155]



Acceptance corrected