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Prospects for hyperon decay studies at future facilities

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NCBJ
ŚWIERK

$e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$ Nature Phys. 15 (2019) 631
arXiv:2204.11058

BESIII $J/\psi \rightarrow \Xi\bar{\Xi}$ Nature 606 (2022) 64–69

Methods:

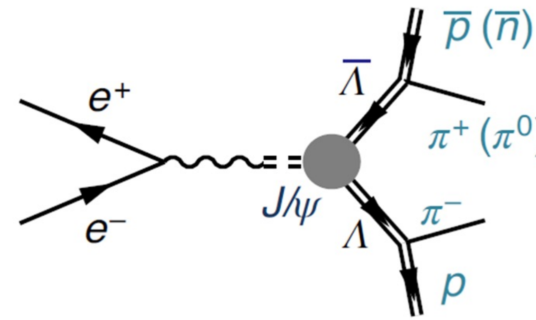
Phys.Rev.D 100 (2019) 114005
Phys.Lett.B 772 (2017) 16
Phys.Rev.D 99 (2019) 056008
arXiv:2203.03035

nature physics
LETTERS
https://doi.org/10.1038/s41567-019-0494-8

Polarization and entanglement in baryon-antibaryon pair production in electron-positron annihilation

The BESIII Collaboration*

Nature Phys. 15 (2019) 631



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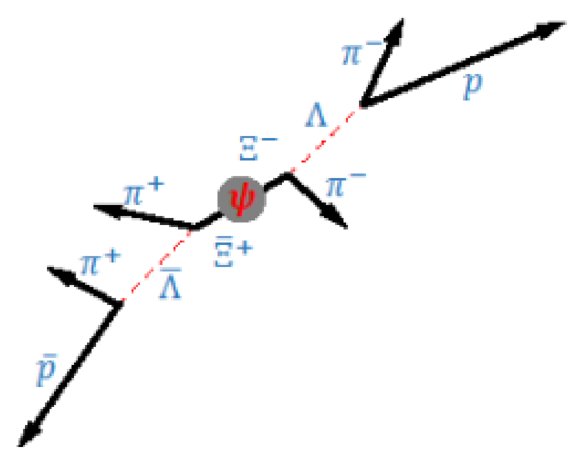
Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

Nature **606**, 64–69 (2022) | Cite this article



2022 Snowmass Summer Study APS

New Physics Searches at Kaon and Hyperon Factories

arXiv: 2201.07805

Study of CP violation in hyperon decays at super charm-tau factories with a polarized electron beam

arXiv: 2203.03035

The REDTOP experiment: Rare η/η' Decays To Probe New Physics

arXiv: 2203.07651

Content

1. BSM searches: Rare decays vs asymmetries
2. CPV kaons vs hyperons
3. Hyperon-antihyperon system at e^+e^- colliders
4. Experiments at (super)tau-charm factories: CPV sensitivity, polarized electron beam,…

Two strategies for new physics searches

(CP) asymmetries vs rare decays]

$$\Gamma_{BSM} = |M_{BSM}|^2$$

$$\eta, \eta' \to \pi^+\pi^-, \pi^0\pi^0$$

$$BF_{SM} \sim 10^{-27}$$

$$\mathrm{A} = \frac{1}{2}|M_{SM} + M_{BSM}|^2 - \frac{1}{2}|M_{SM} - M_{BSM}|^2 = 2\,\mathrm{Re}(M_{SM}M_{BSM}^*)$$

$$K_L \to \pi^+\pi^-, \pi^0\pi^0$$

$$\Lambda \to p\pi^-$$

$$|M_{SM}|^2 = 1$$

ΔI=1/2 law (violation)

lifetime=12 ns

ΔI=1/2 law: $K^+ \rightarrow \pi^+\pi^0$ (ΔI=3/2 transition) : $\Gamma(K^+ \rightarrow \pi^+\pi^0) = |T_{3/2}|^2 \approx Bf\,(K^+ \rightarrow \pi^+\pi^0)/\tau_{K+}$

$K_S \rightarrow \pi^+\pi^-$ (ΔI=1/2 transition) : $\Gamma(K_S \rightarrow \pi^+\pi^-) = |T_{1/2}|^2 \approx Bf\,(K_S \rightarrow \pi^+\pi^-)/\tau_{KS}$

lifetime=0.21 ns

$$\frac{|T_{3/2}|}{|T_{1/2}|} \approx \frac{\sqrt{Bf(K^+ \rightarrow \pi^+\pi^0)\tau_{KS}}}{\sqrt{Bf(K_S \rightarrow \pi^+\pi^-)\tau_{K+}}} = \sqrt{\frac{0.21\times 0.1\text{ns}}{0.69\times 12\text{ns}}} \simeq \frac{1}{22}$$

Slide from Steve Olsen

$A_{2\Delta I,I}$

$$\mathcal{A}(K^0 \rightarrow \pi^+\pi^-) = \sqrt{\frac{1}{3}}A_{3,2}\exp(i\xi_{3,2} + i\delta_2) + \sqrt{\frac{2}{3}}A_{1,0}\exp(i\xi_{1,0} + i\delta_0)$$

$$\mathcal{A}(K^0 \rightarrow \pi^0\pi^0) = \sqrt{\frac{2}{3}}A_{3,2}\exp(i\xi_{3,2} + i\delta_2) - \sqrt{\frac{2}{3}}A_{1,0}\exp(i\xi_{1,0} + i\delta_0)$$

Kaon direct CPV

$$\frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)} := \epsilon + \epsilon' \quad \text{and} \quad \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)} := \epsilon - 2\epsilon'$$

$$\epsilon' \simeq -\frac{i}{\sqrt{2}} \exp\left(i\delta_2 - i\delta_0\right) \frac{A_{3,2}}{A_{1,0}} (\xi_{1,0} - \xi_{3,2})$$

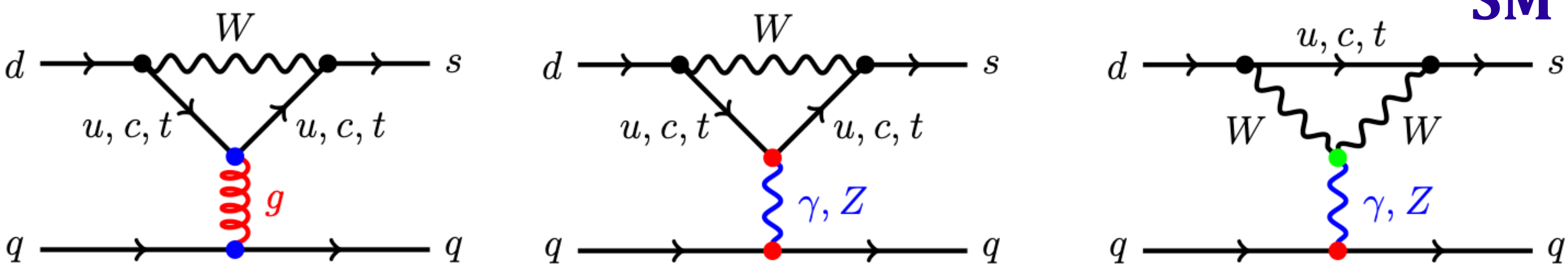
ϵ' in SM and BSM

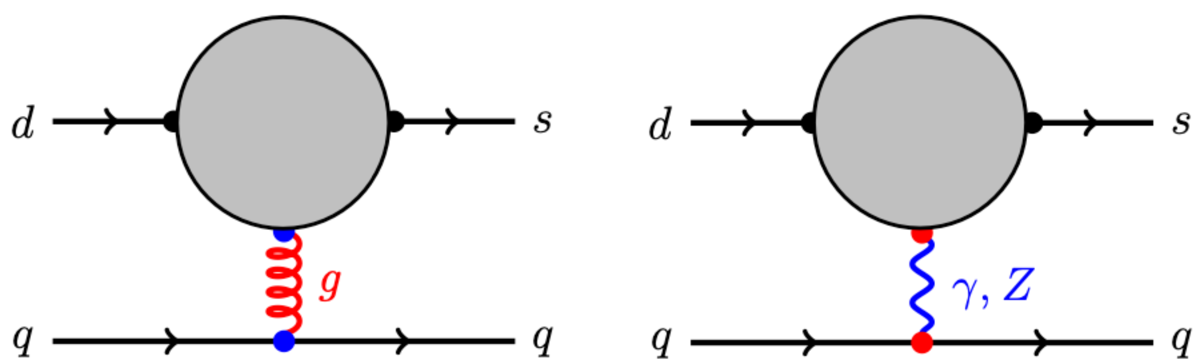
$$\mathrm{Re}(\epsilon'/\epsilon) = (16.6 \pm 2.3) \cdot 10^{-4}$$ Experiment

$$\mathrm{Re}(\epsilon'/\epsilon) = (21.7 \pm 8.2) \times 10^{-4}$$ Lattice QCD

$$\mathrm{Re}(\epsilon'/\epsilon) = (14 \pm 5) \times 10^{-4}$$ EFT

SM





BSM

Strategies for new physics searches

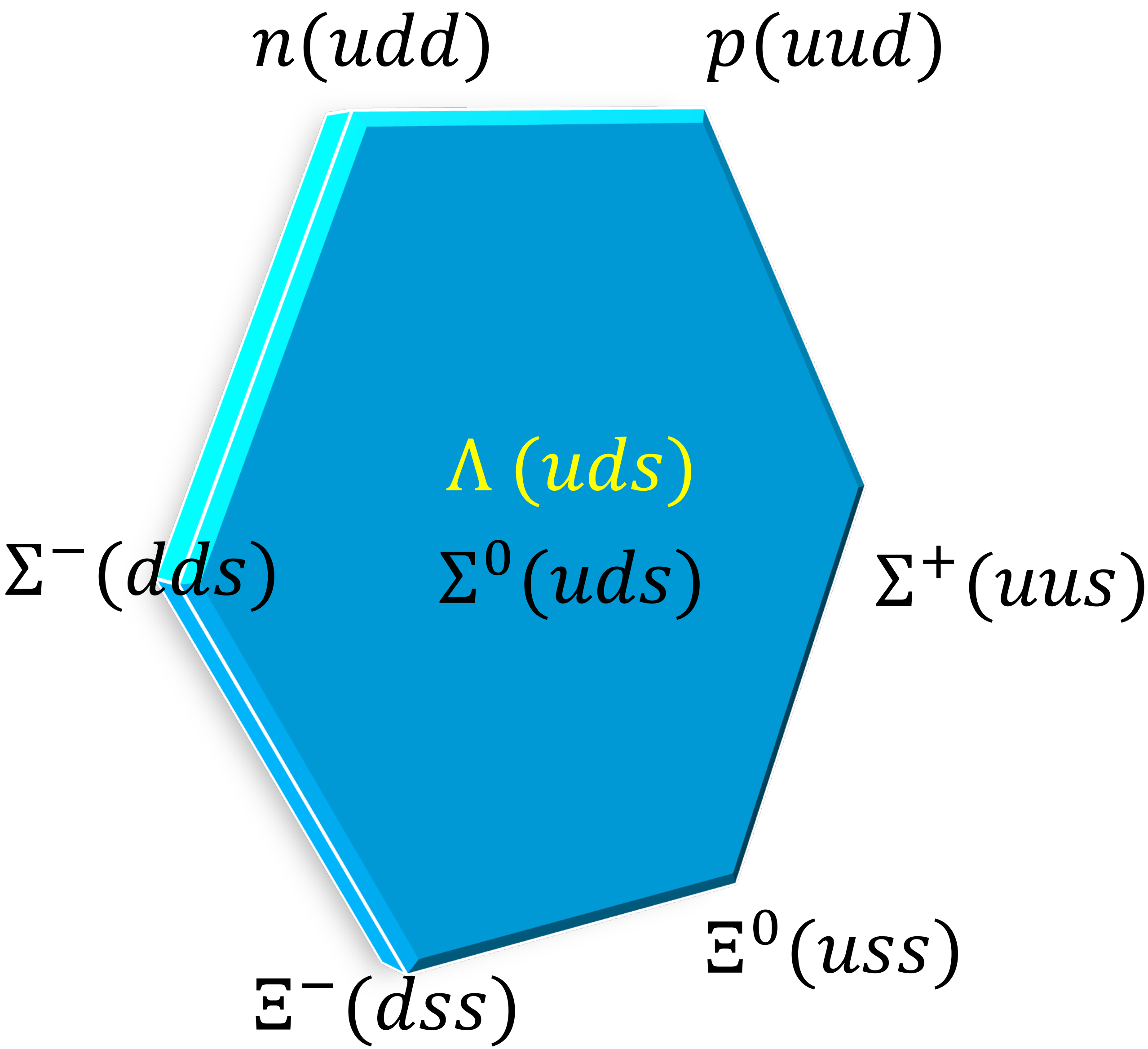
(CP) asymmetries [vs   Rare decays]

$$\sigma(A) \approx \frac{\mathcal{O}(1)}{\sqrt{N}} \equiv \frac{\boldsymbol{\sigma_C}}{\sqrt{N}}$$

$\sigma(A) \sim 10^{-4}$ requires $N \sim 10^{8}$

Goal: minimize $\boldsymbol{\sigma_C}$
eg 4 ↘ 1 reduction implies 16×less data needed

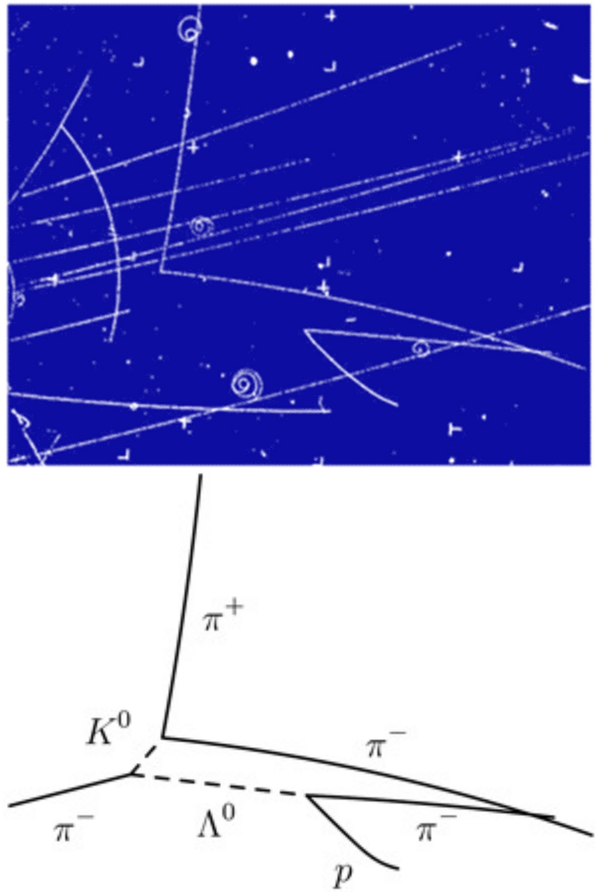
Spin ½ baryon octet:



Λ hyperon:

$$M_\Lambda = 1.115\ \text{GeV}/c^2$$

$$c\tau = 7.9\ \text{cm}$$



Decay amplitudes in hyperon decays

$K \to \pi\pi$ interference $|\Delta I| = 1/2$ and $3/2$

Hyperons:

$\Lambda \to p\pi^-$

$\Xi^- \to \Lambda\pi^-$

P and S amplitudes

$$\mathcal{A}(\Xi^- \to \Lambda\pi^-) = S + P\boldsymbol{\sigma}\cdot\hat{\mathbf{n}}$$

weak CP-odd phases

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

strong phases

$|\Delta I| = 1/2$

For $\Lambda \to p\pi^-$ $|\Delta I| = 3/2$ contribution ~5%

Measurable: BF and two decay parameters

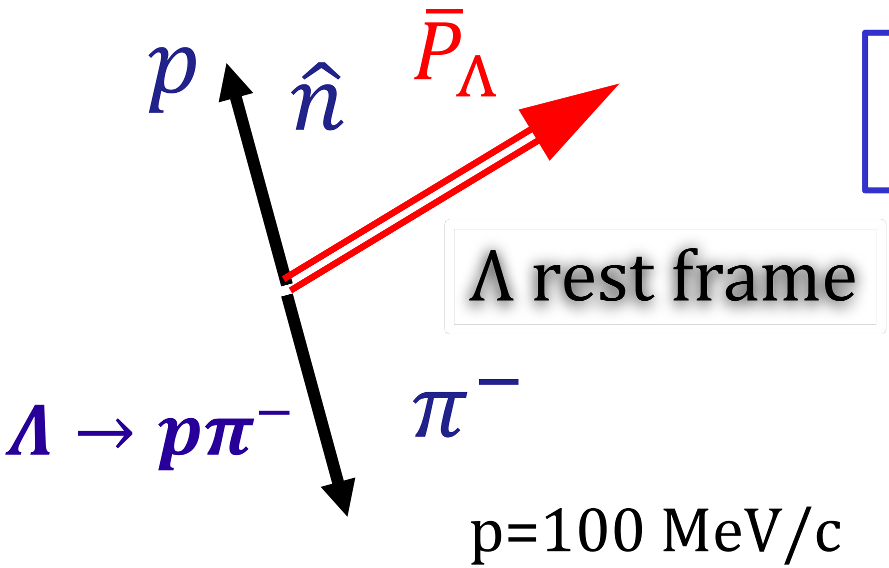
$$\alpha = \frac{2\,\mathrm{Re}(S^*P)}{|S|^2+|P|^2}$$

$$\beta = \frac{2\mathrm{Im}(S^*P)}{|P|^2+|S|^2}$$

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

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

Measuring hyperon decay parameter α



$$\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \hat{n}\,\bar{P}_\Lambda)$$

α_Λ= 0.750(10)

α_Ξ=-0.392(8)

$\alpha_{\Sigma^+ p} = -0.994(4)$

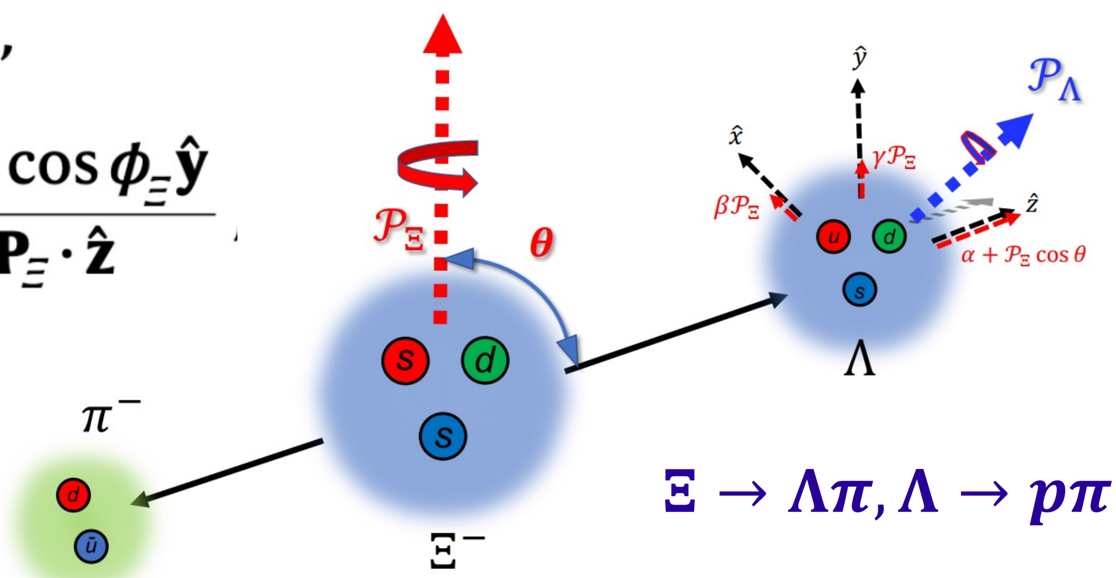
$\alpha_{\Sigma^+ n} = -0.068(13)$

Measuring hyperon decay parameter ϕ

$$\mathbf{P}_\Lambda \cdot \hat{\mathbf{z}} = \frac{\alpha_\Xi + \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}}{1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}},$$

$$\mathbf{P}_\Lambda \times \hat{\mathbf{z}} = \mathcal{P}_\Xi \sqrt{1-\alpha_\Xi^2}\, \frac{\sin\phi_\Xi \hat{\mathbf{x}} + \cos\phi_\Xi \hat{\mathbf{y}}}{1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}}$$

$$\mathbf{P}_\Xi = 0 \;\Rightarrow\; \mathbf{P}_\Lambda = \alpha\, \hat{\mathbf{z}}$$



$\Xi \to \Lambda\pi, \Lambda \to p\pi$

ϕ_Λ=-0.113(61)

ϕ_Ξ=-0.042(16)

Ξ rest frame

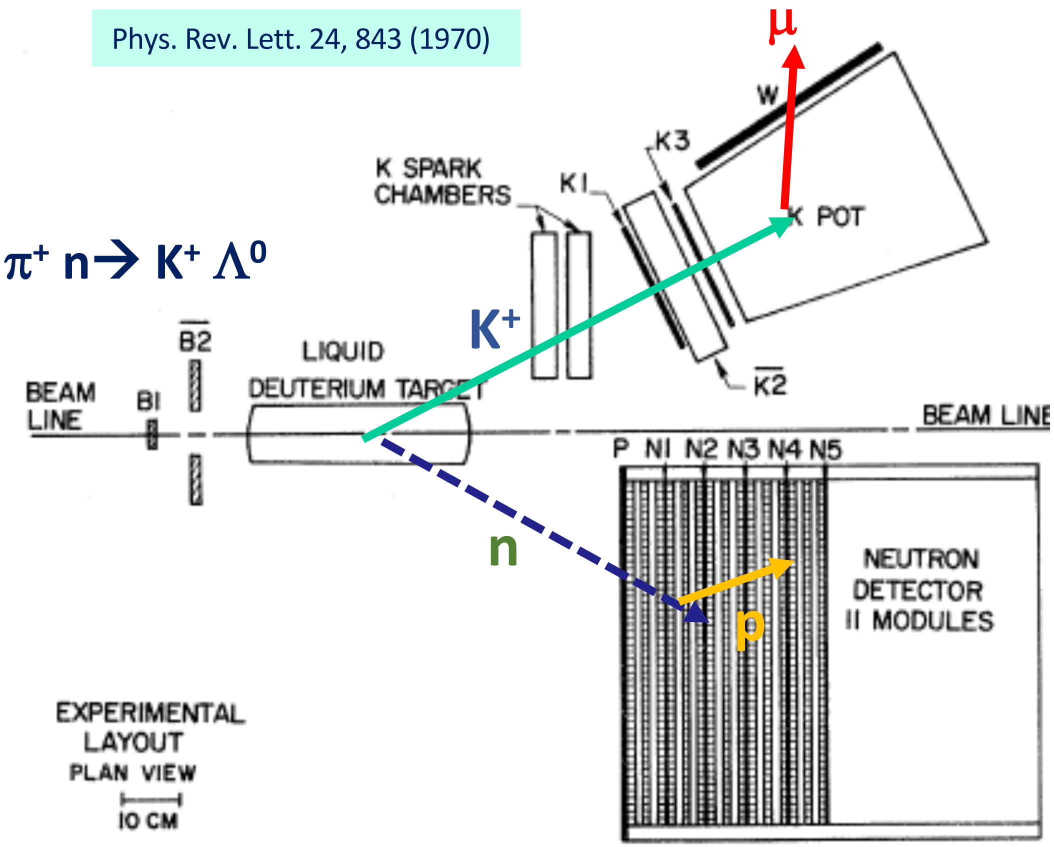
Accesible if daughter baryon polarization measured eg in decay sequence: $\Xi \to \Lambda\pi, \Lambda \to p\pi$

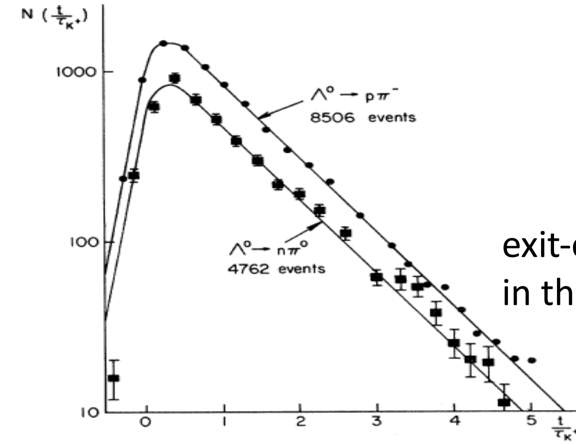
Lee, Yang PhysRev.108(1957)1645

Olsen et al., α_0 parameter in $\Lambda \rightarrow n\pi^0$

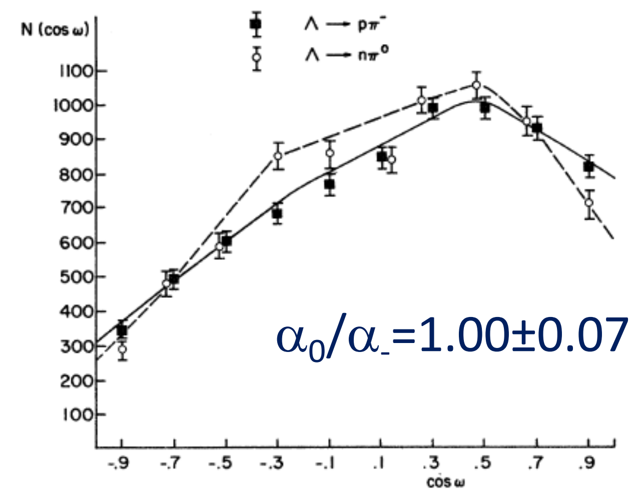
Phys. Rev. Lett. 24, 843 (1970)

$\pi^+ n \rightarrow K^+ \Lambda^0$

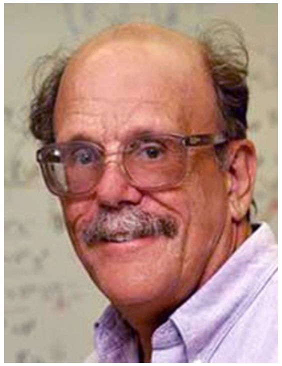




exit-entry time in the H_2O tank



$\alpha_0/\alpha_- = 1.00 \pm 0.07$

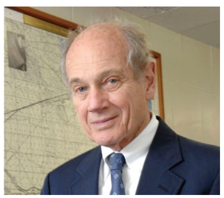


(Steve PhD thesis)

Slide from Steve Olsen

Measuring α, β, γ in the 20th century

James Cronin
1931-2016



Oliver Overseth
1928-2008

PHYSICAL REVIEW VOLUME 129, NUMBER 4 15 FEBRUARY 1963

Measurement of the Decay Parameters of the Λ^0 Particle*

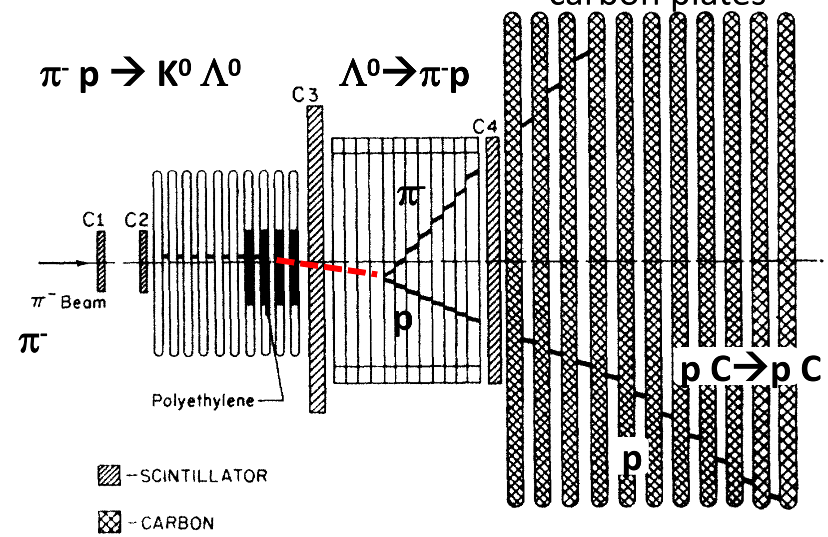
JAMES W. CRONIN AND OLIVER E. OVERSETH†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 26 September 1962)

The decay parameters of $\Lambda^0 \to \pi^- + p$ have been measured by observing the polarization of the decay protons by scattering in a carbon-plate spark chamber. The experimental procedure is discussed in some detail. A total of 1156 decays with useful proton scatters was obtained. The results are expressed in terms of polarization parameters, α, β, and γ given below:

$$\alpha = 2\,\mathrm{Re}\,sp^*/(|s|^2+|p|^2) = +0.62\pm0.07,$$
$$\beta = 2\,\mathrm{Im}\,sp^*/(|s|^2+|p|^2) = +0.18\pm0.24,$$
$$\gamma = |s|^2-|p|^2/(|s|^2+|p|^2) = +0.78\pm0.06,$$

where s and p are the s- and p-wave decay amplitudes in an effective Hamiltonian $s+p\boldsymbol{\sigma}\cdot\mathbf{p}/|\mathbf{p}|$, where $\mathbf{p}$ is the momentum of the decay proton in the center-of-mass system of the Λ^0, and $\boldsymbol{\sigma}$ is the Pauli spin operator. The helicity of the decay proton is positive. The ratio $|p|/|s|$ is $0.36_{-0.06}^{+0.05}$ which supports the conclusion that the $K\Lambda N$ parity is odd. The result $\beta = 0.18\pm0.24$ is consistent with the value $\beta = 0.08$ expected on the basis of time-reversal invariance.

$$P_p = \frac{(\alpha + P_\Lambda \cos\theta)\hat{z}' + \beta P_\Lambda \hat{x}' + \gamma P_\Lambda \hat{y}'}{1 + \alpha P_\Lambda \cos\theta}$$



no H_2 target, no magnet;
use kinematics and proton's
range in carbon to infer E_p

Slide from Steve Olsen

Polarization of daughter baryons:

Density matrix for a spin ½ particle in the rest frame:

$$\rho_{1/2} = \frac{1}{2}\sum_{\mu=0}^{3} I_\mu \sigma_\mu = \frac{1}{2} I_0 \begin{pmatrix} 1+P_z & P_x - iP_y \\ P_x + iP_y & 1-P_z \end{pmatrix}$$

$$\sigma_0 = \mathbf{1}_2, \sigma_1 = \sigma_x, \sigma_2 = \sigma_y, \sigma_3 = \sigma_z$$

Decay matrices

$$\sigma_\mu \to \sum_{\nu=0}^{3} a_{\mu,\nu}\sigma_\nu^d$$

Transformation of base matrices:

$$\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^- \quad e.g.\ \Lambda \to p + \pi^-$$

4×4 decay matrix: $a_{\mu,\nu}$

$$\begin{pmatrix} 1 & 0 & 0 & \alpha_D \\ \alpha_D \sin\theta\cos\varphi & \gamma_D\cos\theta\cos\varphi - \beta_D\sin\varphi & -\beta_D\cos\theta\cos\varphi - \gamma_D\sin\varphi & \sin\theta\cos\varphi \\ \alpha_D\sin\theta\sin\varphi & \beta_D\cos\varphi + \gamma_D\cos\theta\sin\varphi & \gamma_D\cos\varphi - \beta_D\cos\theta\sin\varphi & \sin\theta\sin\varphi \\ \alpha_D\cos\theta & -\gamma_D\sin\theta & \beta_D\sin\theta & \cos\theta \end{pmatrix}$$

E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

Testing CP violation in hyperon decays

$$\Delta_{\mathrm{CP}} := \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$

?

Compare the two decay parameters for c.c. decay modes:

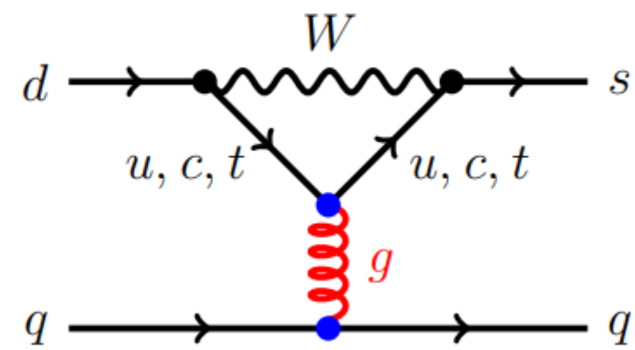
$$A_{CP} := \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \text{ and } B_{CP} := \frac{\beta + \overline{\beta}}{\alpha - \bar{\alpha}}$$

$$\Phi_{\Xi} = \frac{\phi_{\Xi} + \overline{\phi}_{\Xi}}{2} = \frac{\alpha_{\Xi}}{\sqrt{1-\alpha_{\Xi}^2}} \cos\phi_{\Xi}\, B_{CP}^{\Xi}$$

Hyperon CPV in SM and BSM

$$A_{\rm CP} = -\frac{\sqrt{1-\alpha^2}}{\alpha}\sin\phi\tan(\xi_P-\xi_S)$$
$$= -\tan(\delta_P-\delta_S)\tan(\xi_P-\xi_S)$$
$$B_{\rm CP} = \tan(\xi_P-\xi_S)\ ,$$
$$\Phi_{\rm CP} = \frac{\alpha}{\sqrt{1-\alpha^2}}\cos\phi\tan(\xi_P-\xi_S)$$

weak *P-S* phase diff.

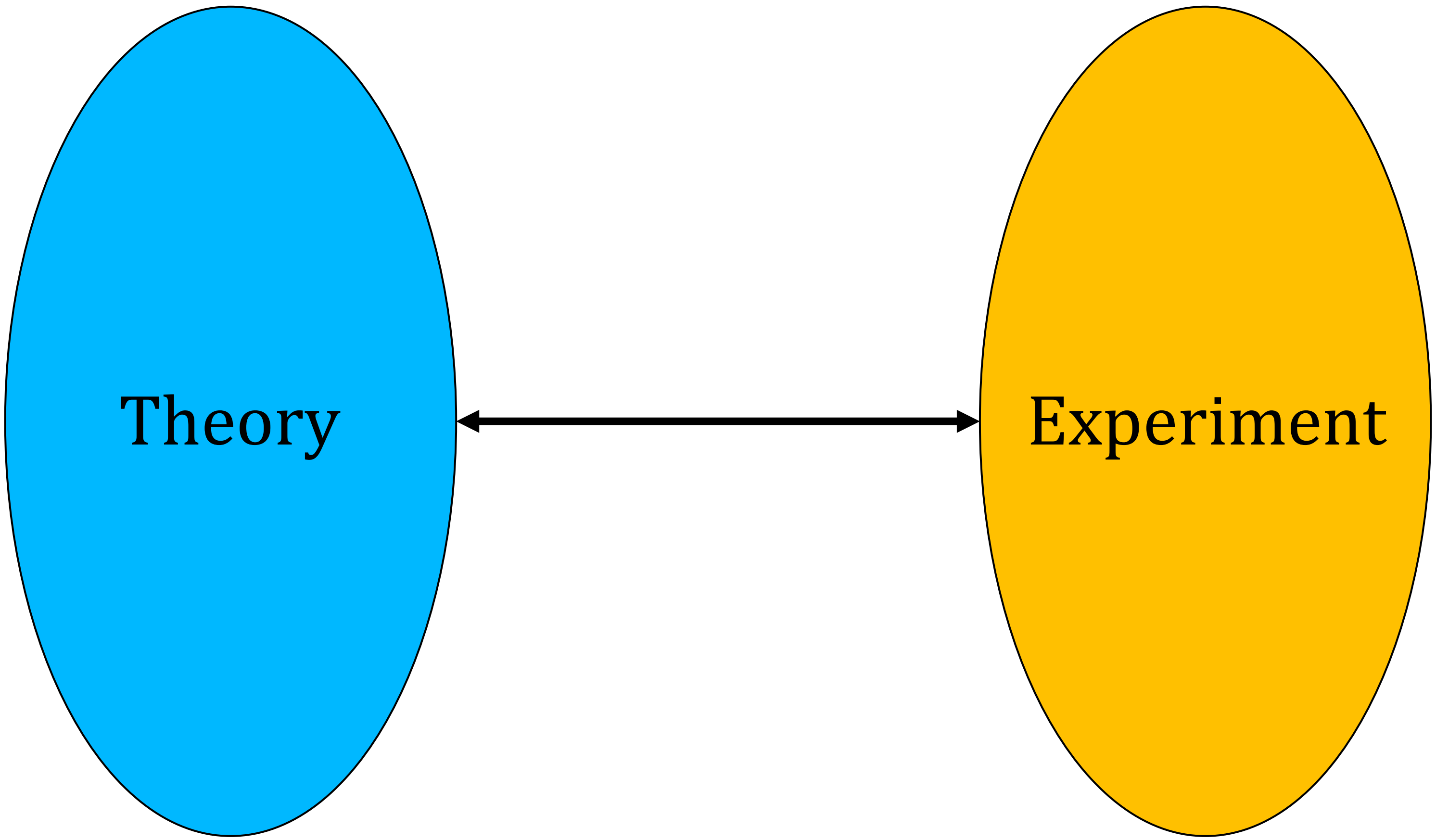


	$\xi_P-\xi_S$ $(\eta\lambda^5 A^2)$	$[10^{-4}$ rad$]$	C_B	C'_B
	SM		BSM	
$\Lambda\to p\pi^-$	-0.1 ± 1.5	-0.2 ± 2.2	0.9 ± 1.8	0.4 ± 0.9
$\Xi^-\to\Lambda\pi^-$	-1.5 ± 1.2	-2.1 ± 1.7	-0.5 ± 1.0	0.4 ± 0.7

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

Kaon bounds for CPV in hyperon decays assuming chromomagnetic penguin

Connection between theory and experiment



Content

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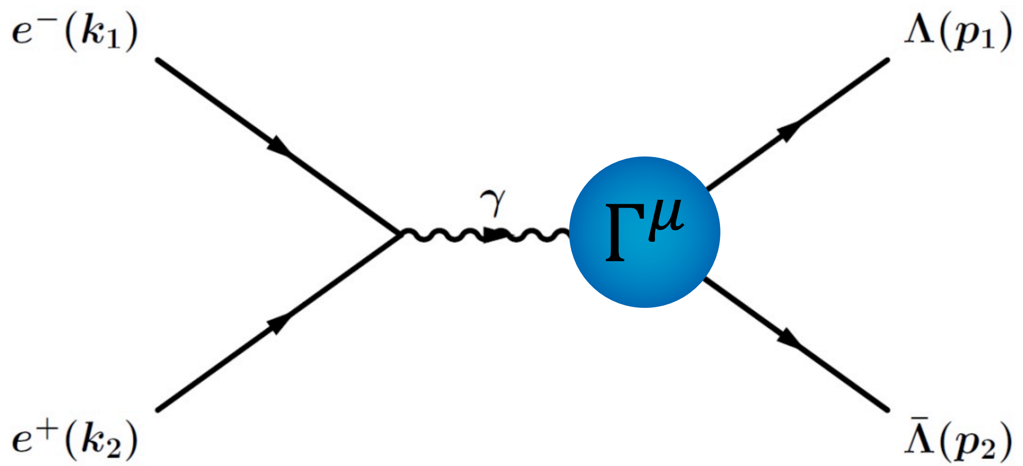
4. Experiments at (super)tau-charm factories: CPV sensitivity, polarized electron beam,…

$e^+e^- \rightarrow \gamma^* \rightarrow B\overline{B}$ (spin 1/2)



$$s = (p_1 + p_2)^2$$
$$q = p_1 - p_2$$

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

F_1 (Dirac) and F_2 (Pauli) Form Factors

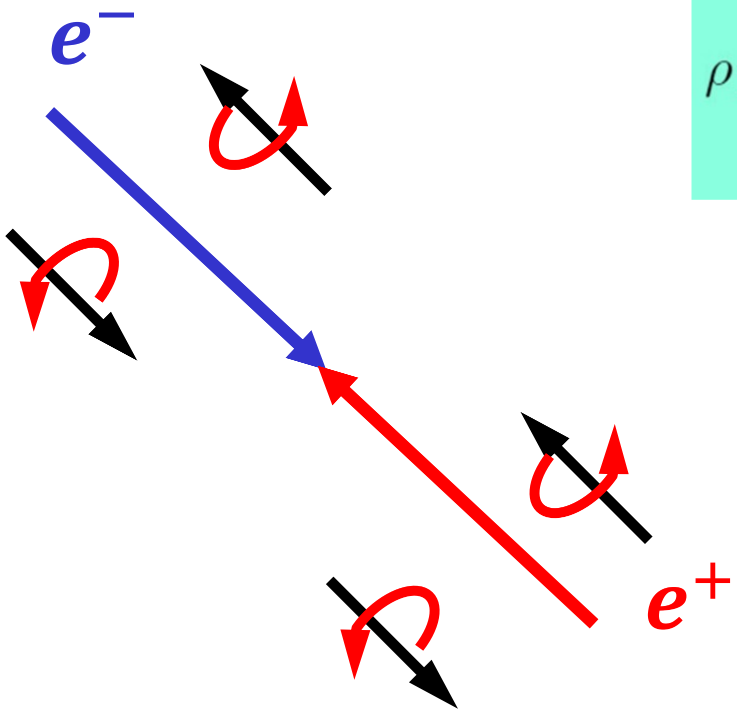
Sachs Form Factors (FFs) ⇔ helicity amplitudes:

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

$$\tau = \frac{s}{4M_B^2}$$

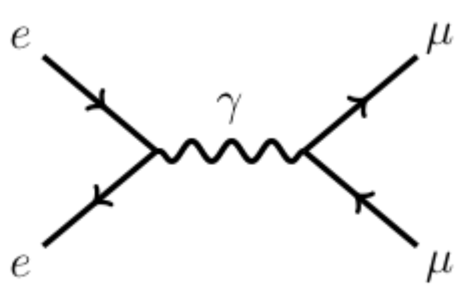
$$e^+e^- \to \mu^+\mu^-$$

At high energies annihilating e+e- have opposite helicities.



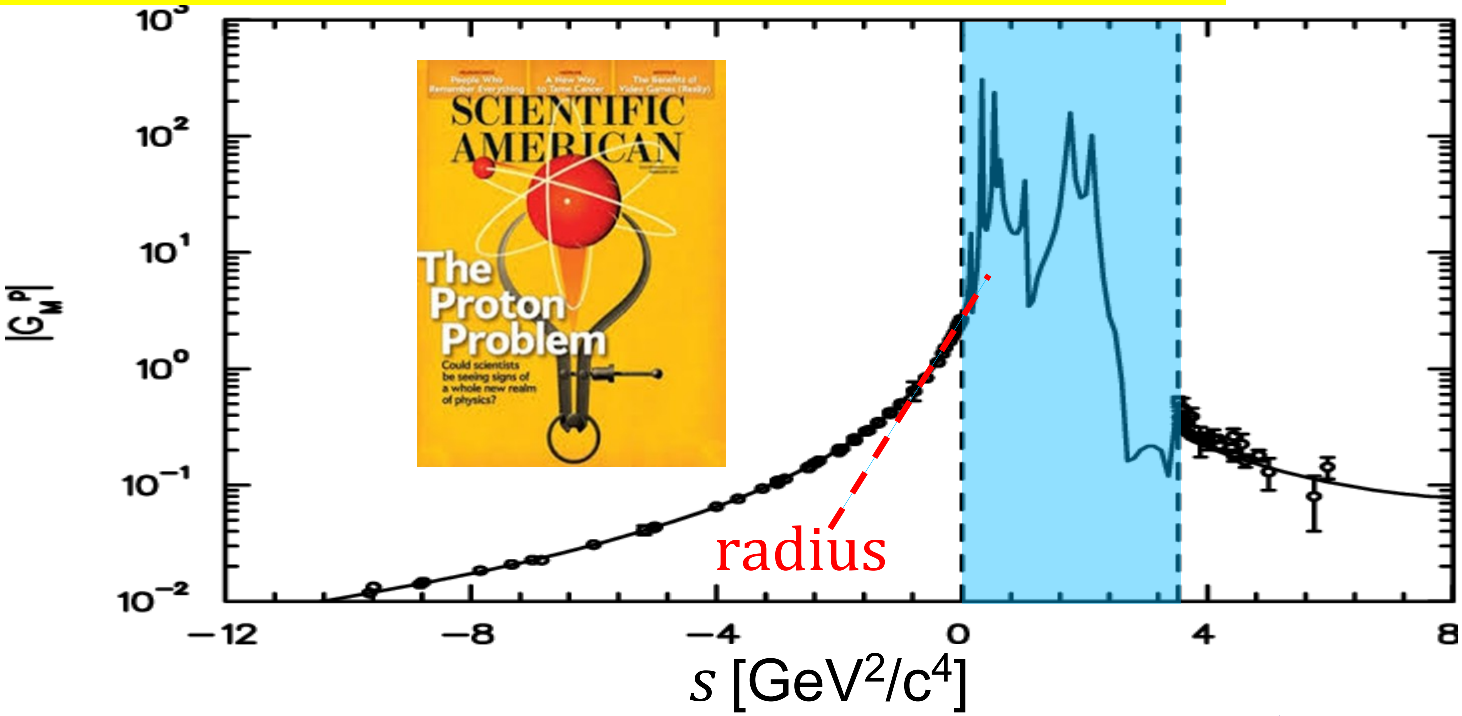
$$\rho_1(\theta) = \begin{pmatrix} \frac{1+\cos^2\theta}{2} & -\frac{\cos\theta\sin\theta}{\sqrt{2}} & \frac{\sin^2\theta}{2} \\ -\frac{\cos\theta\sin\theta}{\sqrt{2}} & \sin^2\theta & \frac{\cos\theta\sin\theta}{\sqrt{2}} \\ \frac{\sin^2\theta}{2} & \frac{\cos\theta\sin\theta}{\sqrt{2}} & \frac{1+\cos^2\theta}{2} \end{pmatrix}$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1 + \cos^2\theta)$$



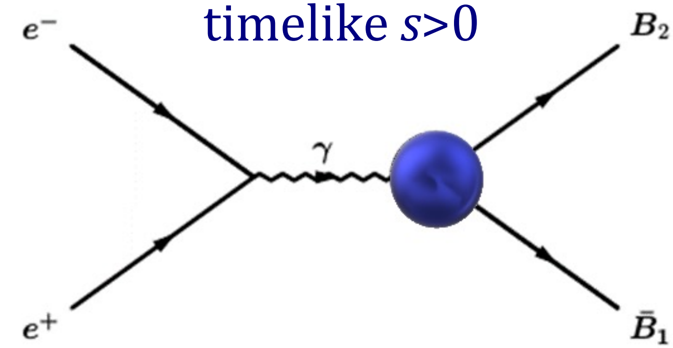
$$F_1(0) = 1, \quad F_2(0) = a_\mu$$

Baryon Electromagnetic Form Factors



timelike $s>0$

spacelike $s<0$



$\boldsymbol{\gamma^* \rightarrow B_1\bar{B}_2}$

$\boldsymbol{B_1 \rightarrow B_2 e+e-}$

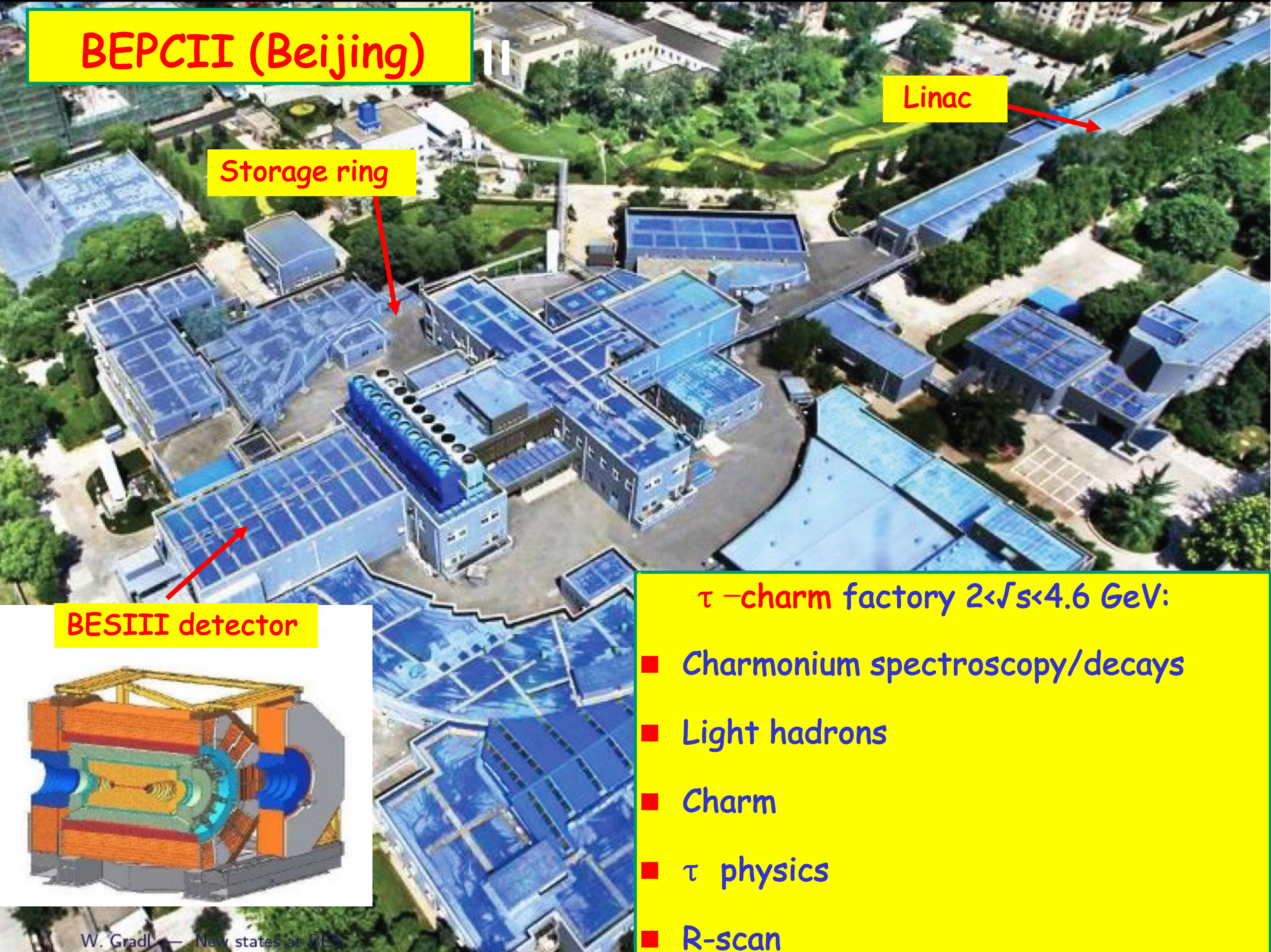
$\boldsymbol{p\bar{p} \rightarrow e+e-}$

$\boldsymbol{p\bar{p} \rightarrow \pi^0 e+e-}$

elastic: $B_2=B_1$

($B_2 \neq B_1$ transition)

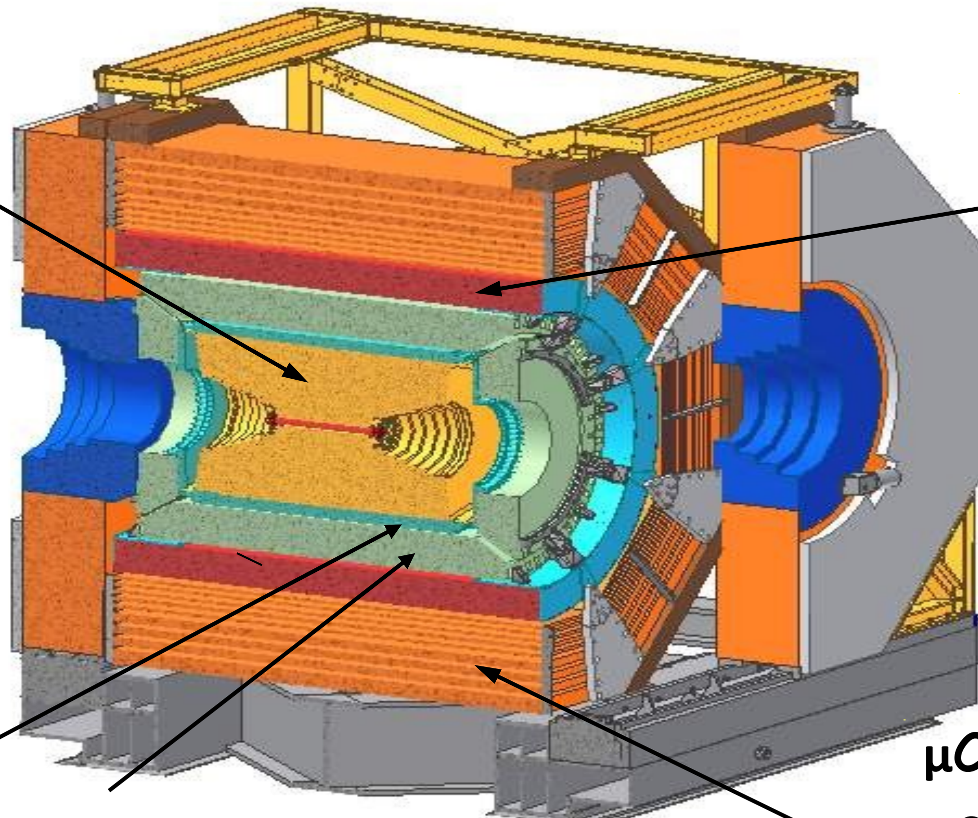
BEPCII (Beijing)



τ –charm factory $2 < \sqrt{s} < 4.6$ GeV:

- Charmonium spectroscopy/decays
- Light hadrons
- Charm
- τ physics
- R-scan

BESIII Detector



Drift Chamber (MDC)

$\sigma P/P$ = 0.5%(1GeV)

$\sigma(dE/dx)$ = 6%

Superconducting magnet (1.0 Tesla)

Time Of Flight (TOF)

$\sigma(t)$: 90 ps Barrel

110 ps endcap

EMC: $\sigma E/\sqrt{E}$ = 2.5 % (1 GeV)

(CsI) $\sigma_{z\varphi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

μCounter

8- 9 layers RPC

$\delta R\Phi$=1.4 – 1.7 cm

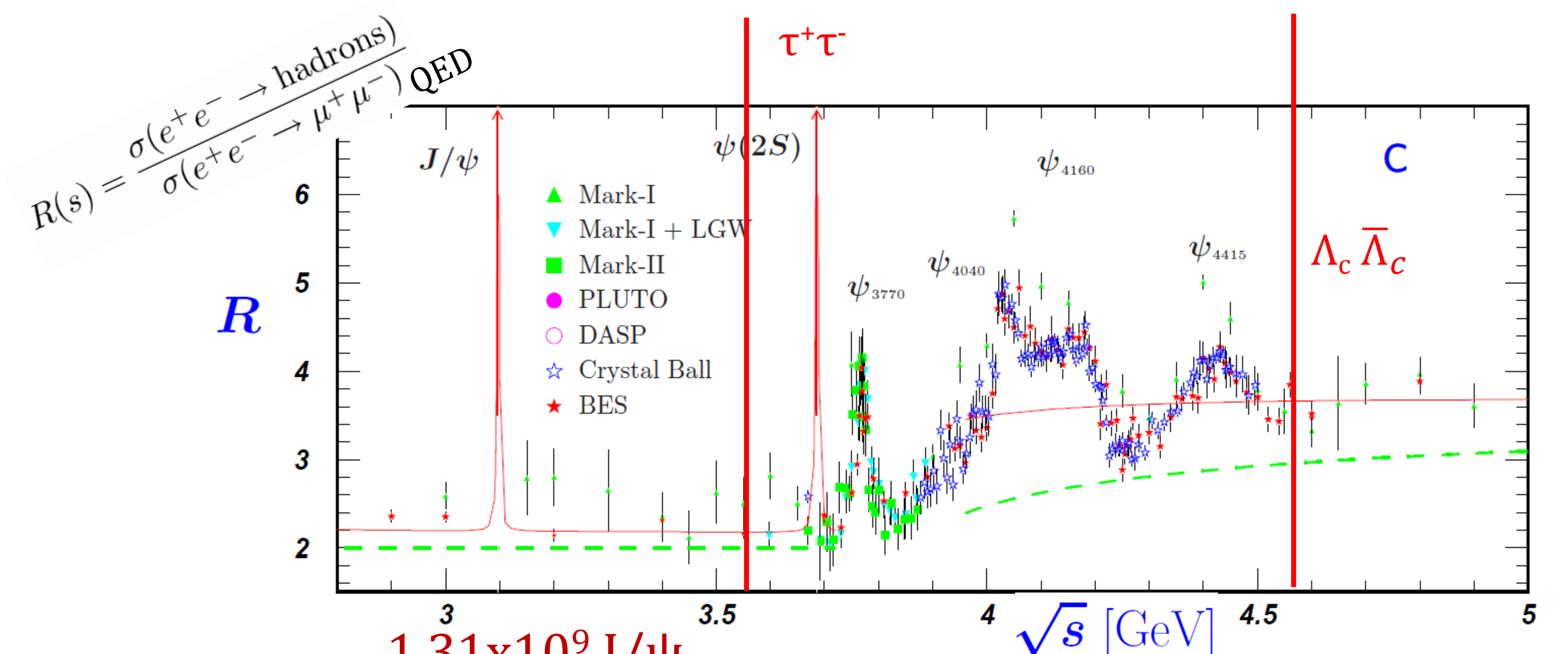
Hyperon-$\overline{\text{hyperon}}$ pair production at BESIII

$2.0\ \text{GeV} \leq \sqrt{s} \leq 4.6\ \text{GeV}$

Thresholds:

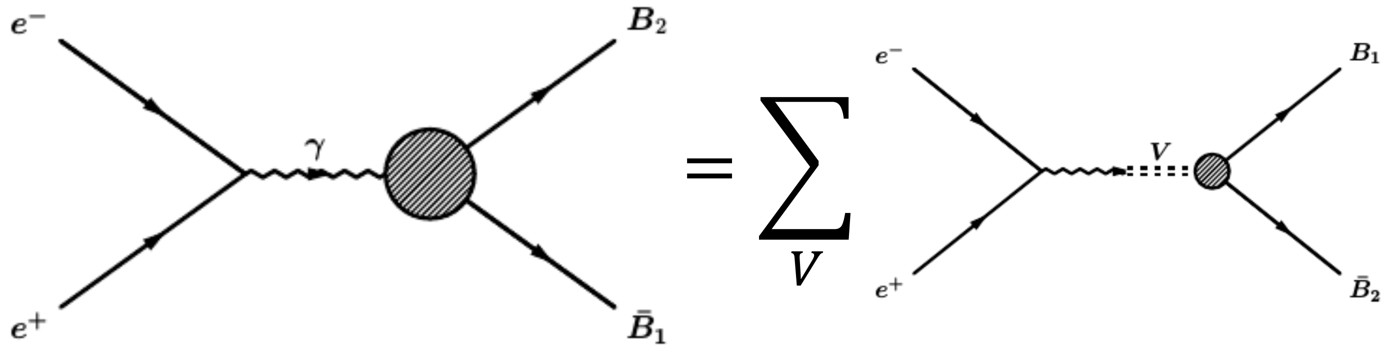
$\Lambda\overline{\Lambda}$:	2.231 GeV	$\Sigma^{+}\overline{\Sigma}^{-}$	2.379 GeV
$\Sigma^{0}\overline{\Sigma}^{0}$	2.385 GeV	$\Sigma^{-}\overline{\Sigma}^{+}$	2.395 GeV
$\Xi^{0}\overline{\Xi}^{0}$	2.630 GeV	$\Xi^{-}\overline{\Xi}^{+}$	2.643 GeV
$\Lambda\overline{\Sigma}^{0}$	2.308 GeV		

($\Omega\overline{\Omega}$ 3.345 GeV)



$1.31\text{x}10^{9}\ J/\psi$

Baryon FFs (continuum):



Baryons B_1 and $\bar{B}_2$ (spin 1/2, ...)

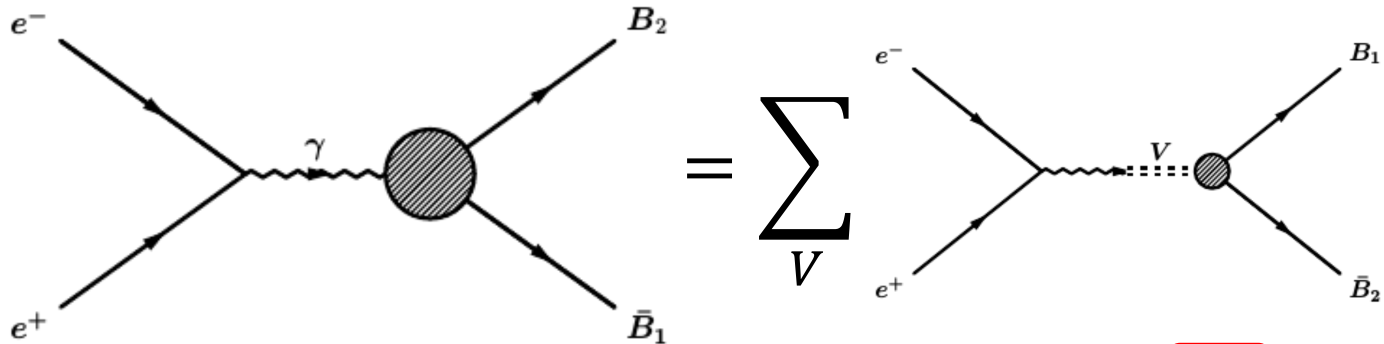
$V = \gamma, \rho, \omega, \varphi, \ldots, J/\psi, \psi(2S), \ldots$

Cabibbo, Gatto PR124 (1961)1577

Time like spin ½ baryon FFs:

Dubnickova, Dubnicka, Rekalo
Nuovo Cim. A109 (1996) 241
Gakh, Tomasi-Gustafsson Nucl.Phys. A771 (2006) 169
Czyz, Grzelinska, Kuhn PRD75 (2007) 074026
Fäldt EPJ A51 (2015) 74; EPJ A52 (2016)141

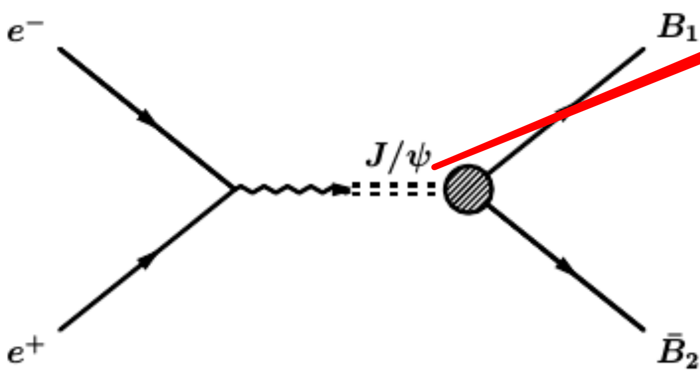
Baryon FFs (continuum):



Baryons B_1 and $\bar{B}_2$
(spin 1/2, ...)

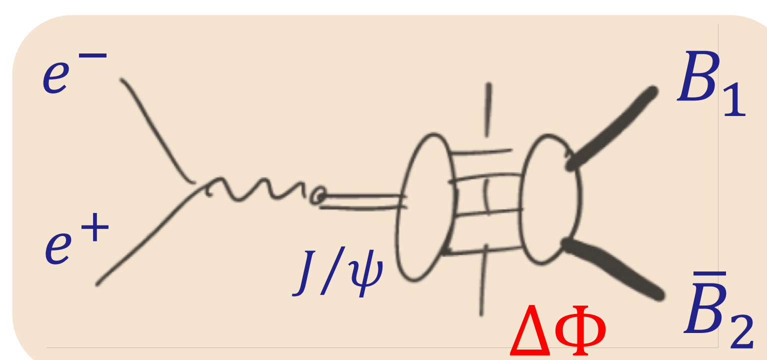
$V = \gamma, \rho, \omega, \varphi, \ldots, J/\psi, \psi(2S), \ldots$

vs J/ψ decay:



Both processes described by two complex FFs: relative phase $\Delta\Phi$

Cabibbo, Gatto PR124 (1961)1577



Time like spin ½ baryon FFs:
Dubnickova, Dubnicka, Rekalo
Nuovo Cim. A109 (1996) 241
Gakh, Tomasi-Gustafsson Nucl.Phys. A771 (2006) 169
Czyz, Grzelinska, Kuhn PRD75 (2007) 074026
Fäldt EPJ A51 (2015) 74; EPJ A52 (2016)141

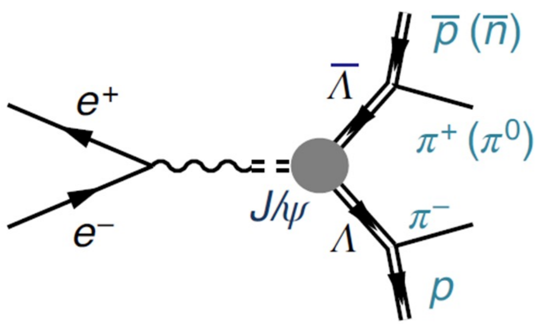
Charmonia decays:
Fäldt, Kupsc PLB772 (2017) 16

$e^+e^- \to J/\psi, \psi(2S) \to B\bar{B}$

#events at BESIII (estimate)

BESIII 10^{10} J/ψ

decay mode	$\mathcal{B}$(units 10^{-4})	α_ψ	eff ST	
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	0.469 ± 0.026	40%	3200×10^3
$\psi(2S) \to \Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	0.824 ± 0.074	40%	650×10^3
$J/\psi \to \Xi^0\bar{\Xi}^0$	11.65 ± 0.04	0.66 ± 0.03	14%	670×10^3
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	2.73 ± 0.03	0.65 ± 0.09	14%	160×10^3
$J/\psi \to \Xi^-\bar{\Xi}^+$	10.40 ± 0.06	0.58 ± 0.04	19%	810×10^3
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	2.78 ± 0.05	0.91 ± 0.13	19%	210×10^3



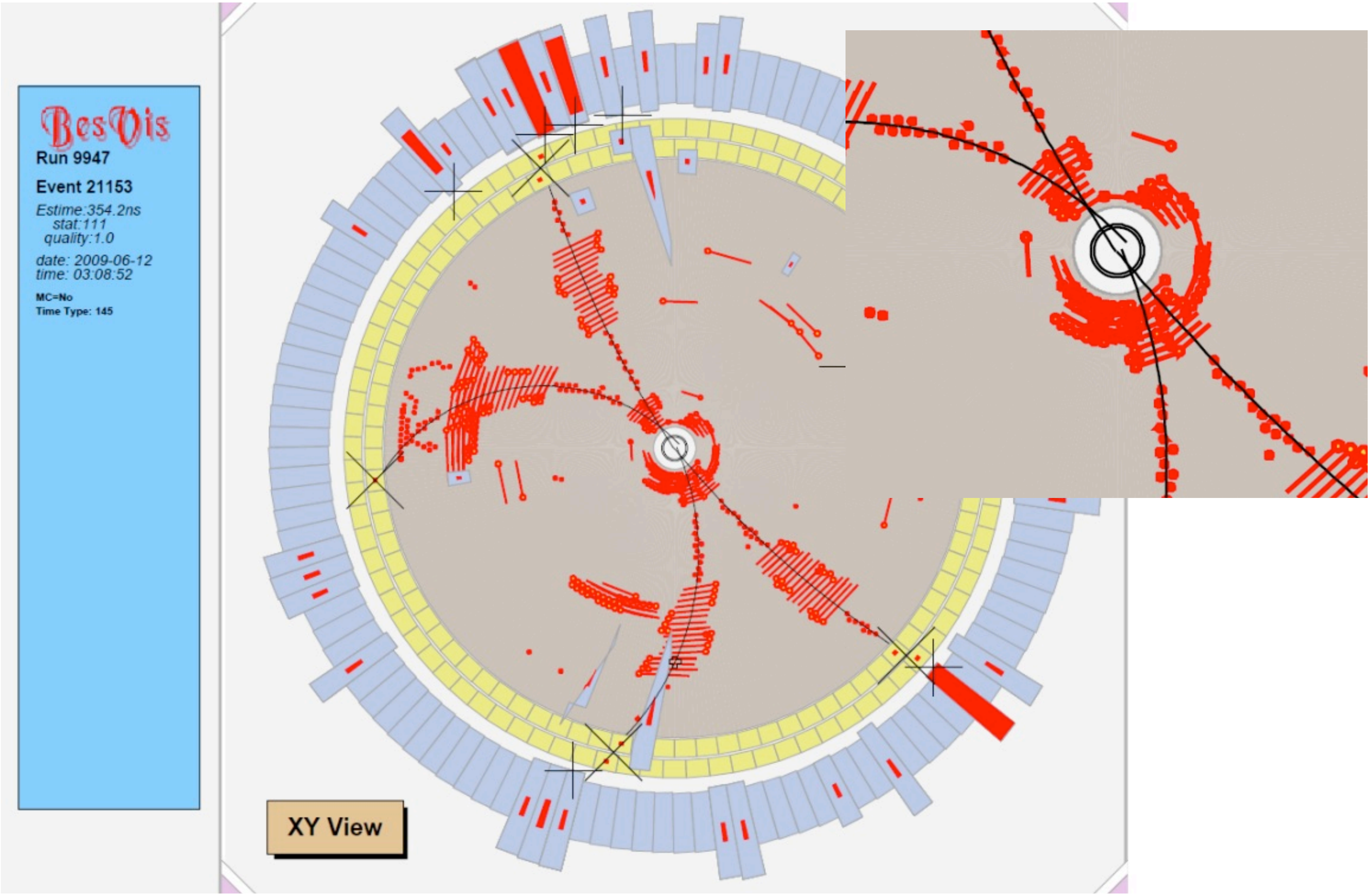
PRD 93, 072003 (2016)
PLB770,217 (2017)
PRD 95, 052003 (2017)

BESIII proposal:3.2x10^9 ψ(2S)

$\mathcal{B}(\psi(2S) \to \Omega^-\bar{\Omega}^+) = 5.2(5)\times10^{-5}$

$$e^+e^- \to J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$$

an event in BESIII detector



$e^+e^- \rightarrow \gamma^* \rightarrow B\bar{B}$

For spin ½ $B\bar{B}$ production two complex FFs: $G_M(s)$, $G_E(s)$

⇨ process described by three parameters at fixed $\sqrt{s}$:

- ❑ cross section (σ)
- ❑ FFs ratio R or angular distribution parameter α_ψ
- ❑ relative phase between FFs (ΔΦ)

$$R = \left| \frac{G_E}{G_M} \right| \quad \left(\alpha_\psi = \frac{\tau - R^2}{\tau + R^2} \right) \qquad G_E = R G_M e^{i\Delta\Phi}$$

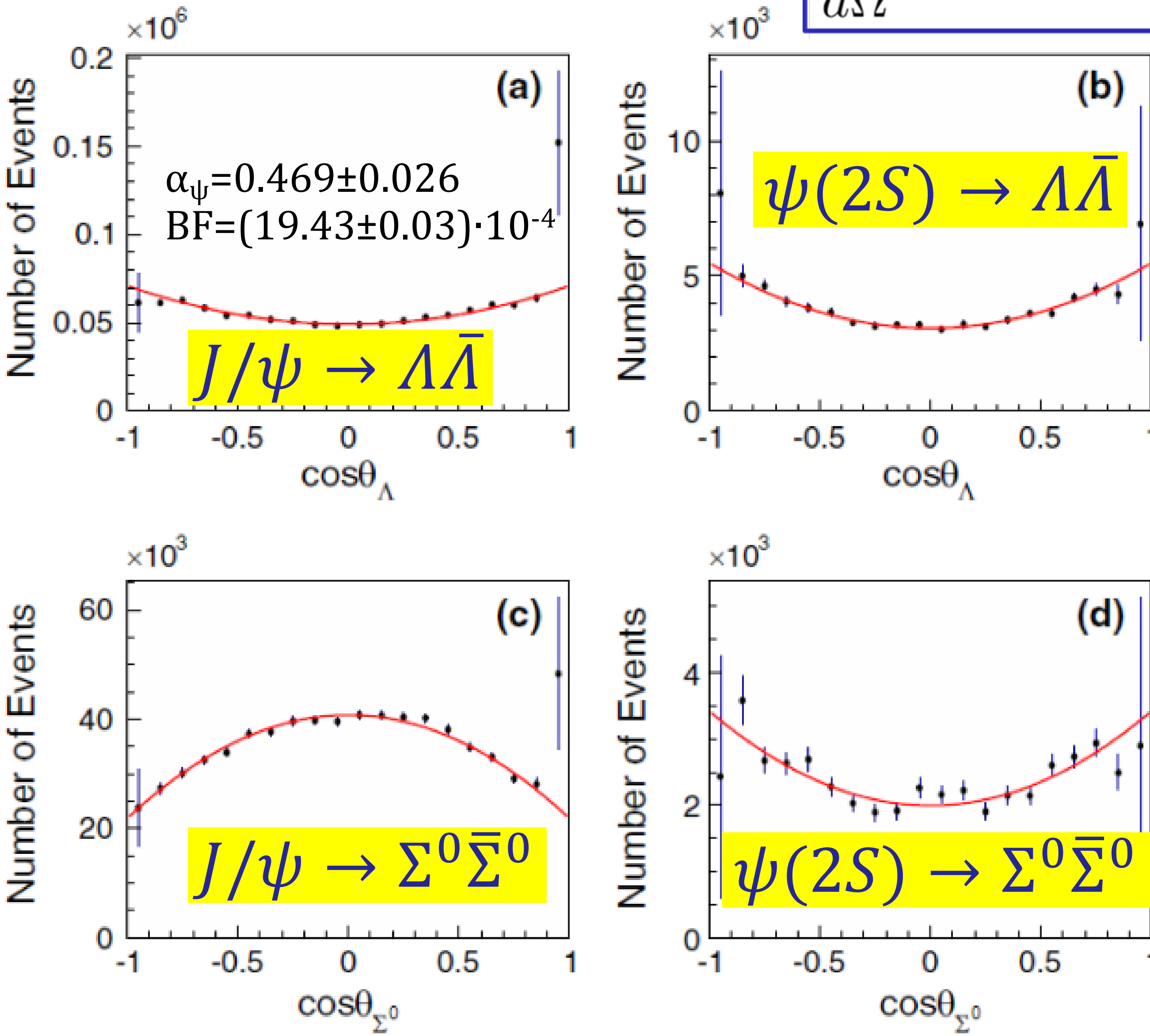
$$\tau = \frac{s}{4M_B^2}$$

Phase ***ΔΦ*** expected/predicted for continuum
but neglected/not expected for the decays

$J/\psi, \psi(2S) \to B\bar{B}$

Angular distribution:

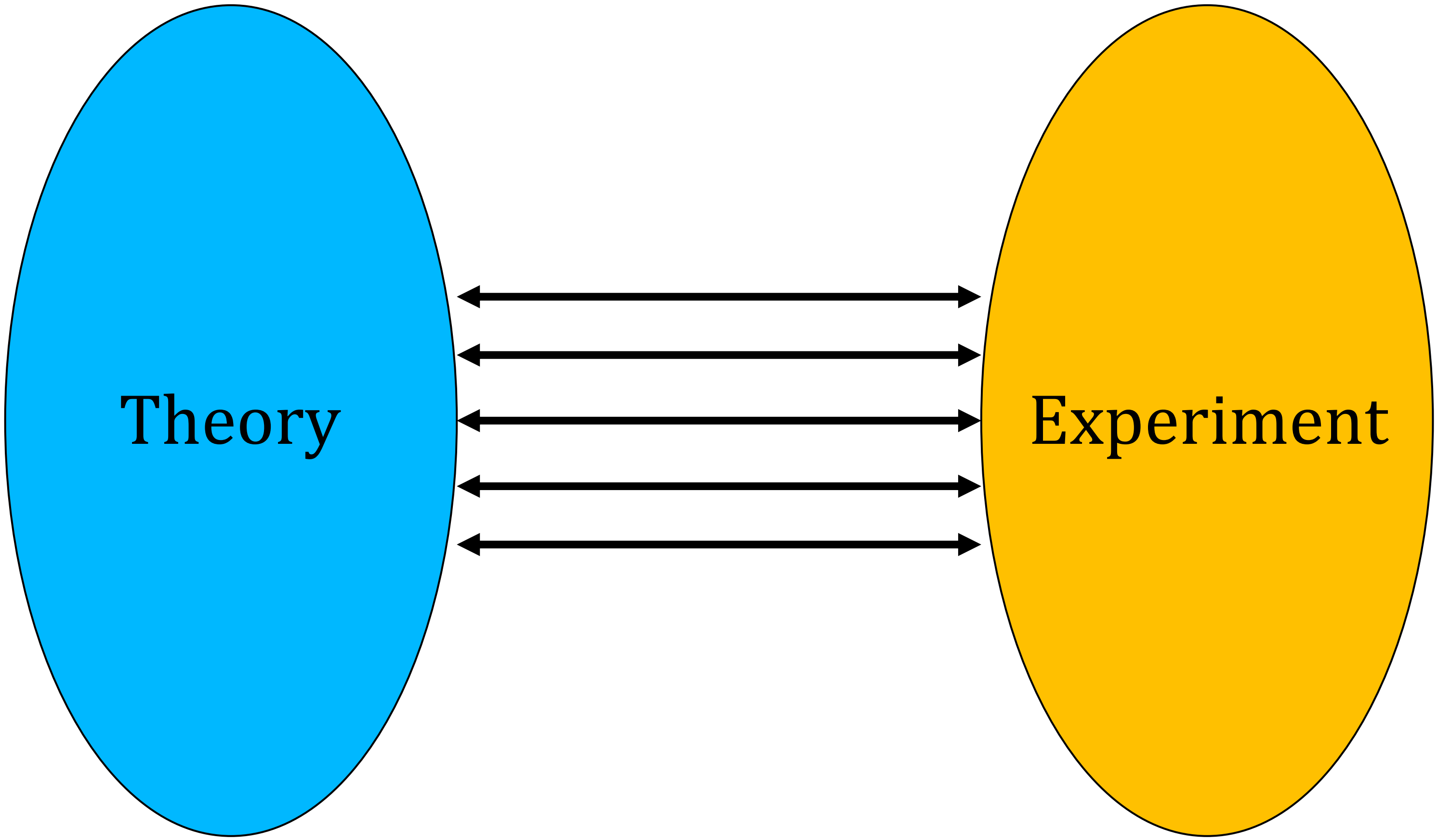
$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta \qquad -1 \le \alpha_\psi \le 1$$



α_ψ measurements at BESIII

BESIII,PRD 95, 052003 (2017)

Connection between theory and experiment



Multidimensional link, exclusive angular distributions

Baryon-antibaryon spin density matrix

$$e^+e^- \to B_1\bar{B}_2$$

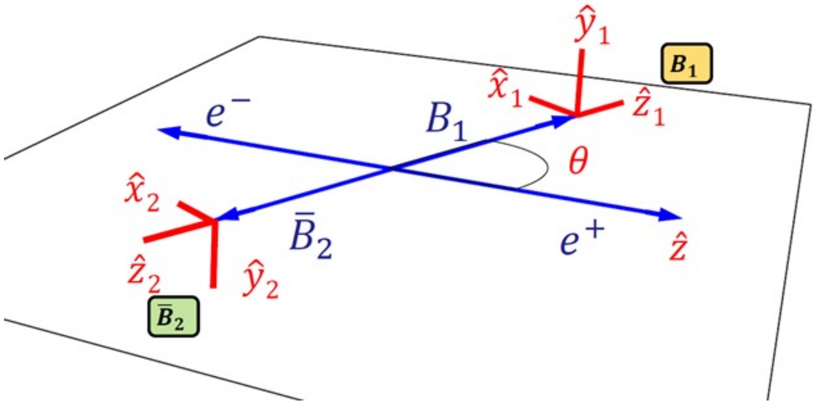
General two spin ½ particle state: $$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_\mu^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_2}$$

$(\sigma_0 = \mathbf{1}_2, \sigma_1 = \sigma_x, \sigma_2 = \sigma_y, \sigma_3 = \sigma_z)$

P_y

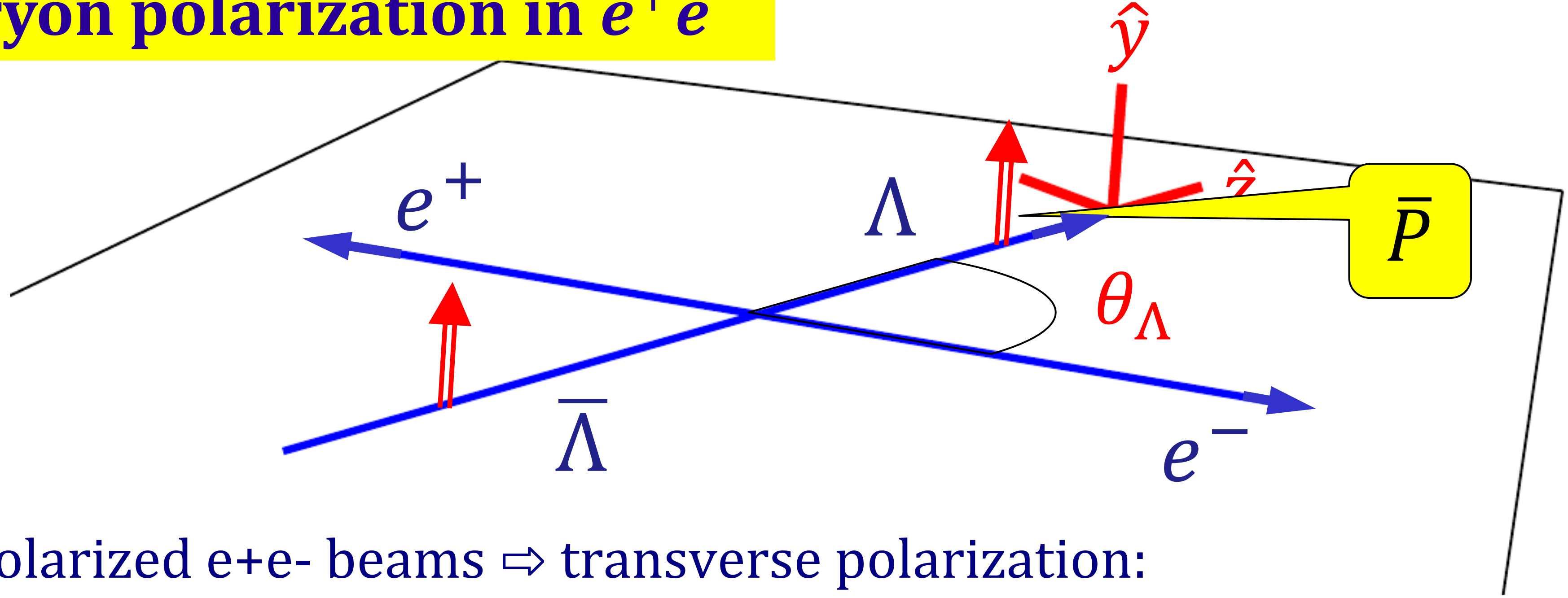
$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi\cos^2\theta & 0 & \beta_\psi\sin\theta\cos\theta & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi\sin\theta\cos\theta \\ -\beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & 0 \\ 0 & -\gamma_\psi\sin\theta\cos\theta & 0 & -\alpha_\psi-\cos^2\theta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

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



E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

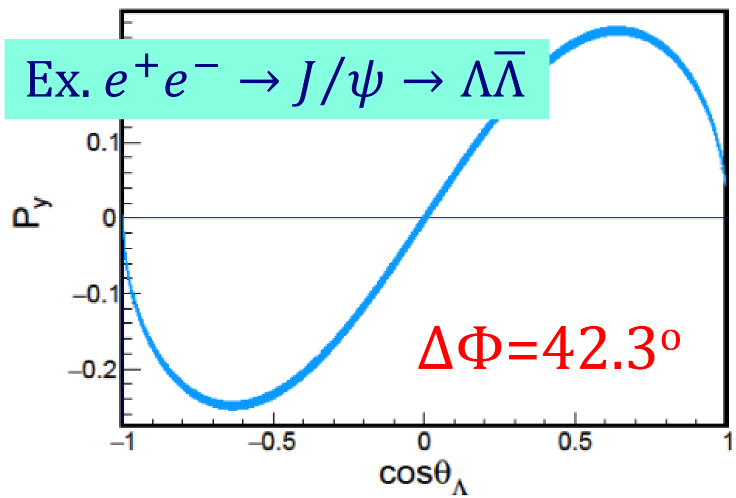
Baryon polarization in e^+e^-



Unpolarized e+e- beams ⇨ transverse polarization:

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

$\Delta\Phi \neq 0$



$\alpha_\psi = 0.469$

DT - joint angular distribution (modular form)

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

General two spin ½ particle state: $$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_\mu^{\Lambda} \otimes \sigma_{\bar{\nu}}^{\bar{\Lambda}}$$

$(\sigma_0 = \mathbf{1}_2, \sigma_1 = \sigma_x, \sigma_2 = \sigma_y, \sigma_3 = \sigma_z)$

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

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

Apply decay matrices:

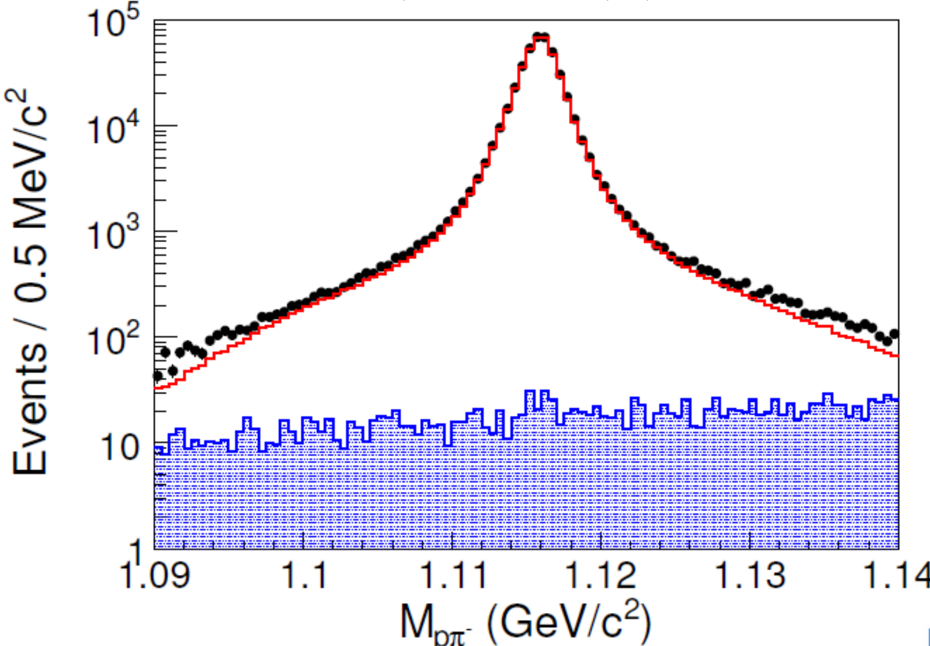
$$\sigma_\mu^{\Lambda} \to \sum_{\mu'=0}^{3} a_{\mu,\mu'}^{\Lambda}\, \sigma_{\mu'}^{p}$$

The angular distribution:

$$W = Tr\rho_{p,\bar{p}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} a_{\mu,0}^{\Lambda} a_{\bar{\nu},0}^{\bar{\Lambda}}$$

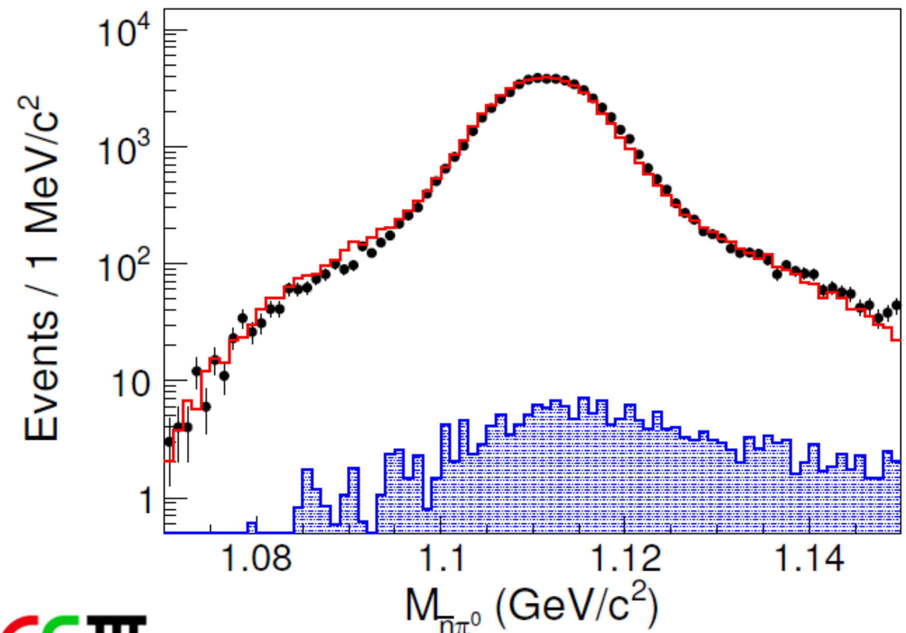
E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

$e^+e^- \rightarrow (\Lambda \rightarrow p\pi^-)(\bar{\Lambda} \rightarrow \bar{p}\pi^+)$



420593 events

$e^+e^- \rightarrow (\Lambda \rightarrow p\pi^-)(\bar{\Lambda} \rightarrow \bar{n}\pi^0)$

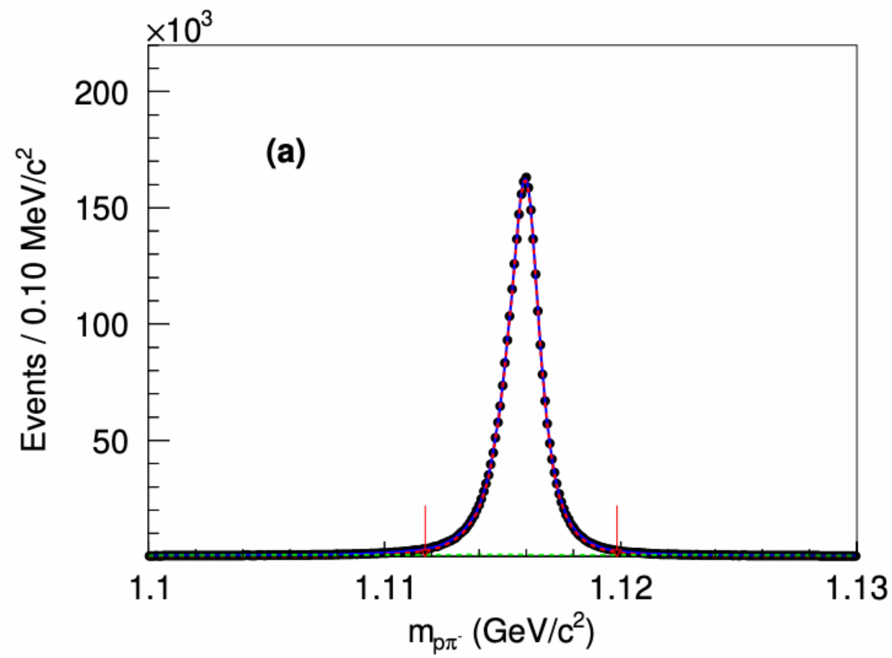


47009 events

66 background

Nature Phys. 15 (2019) 631

(1.31×10^9 J/ψ)

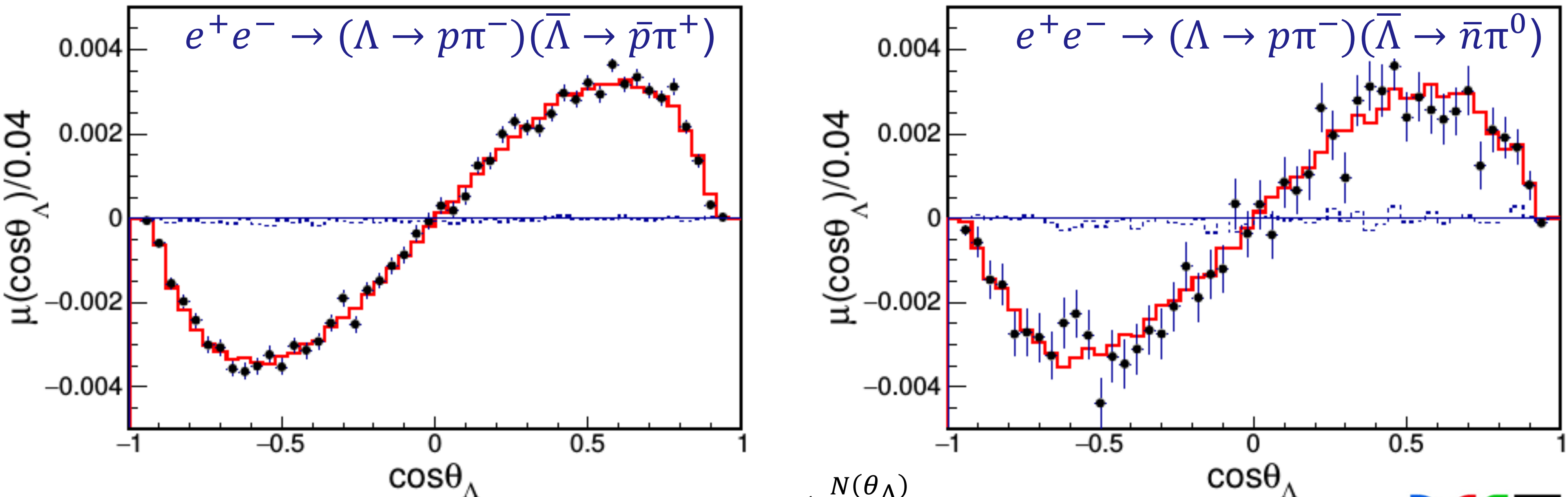


arXiv:2204.11058

(10^{10} J/ψ)

Fit results

$\Delta\Phi = 42.3^o \pm 0.6^o \pm 0.5^o$

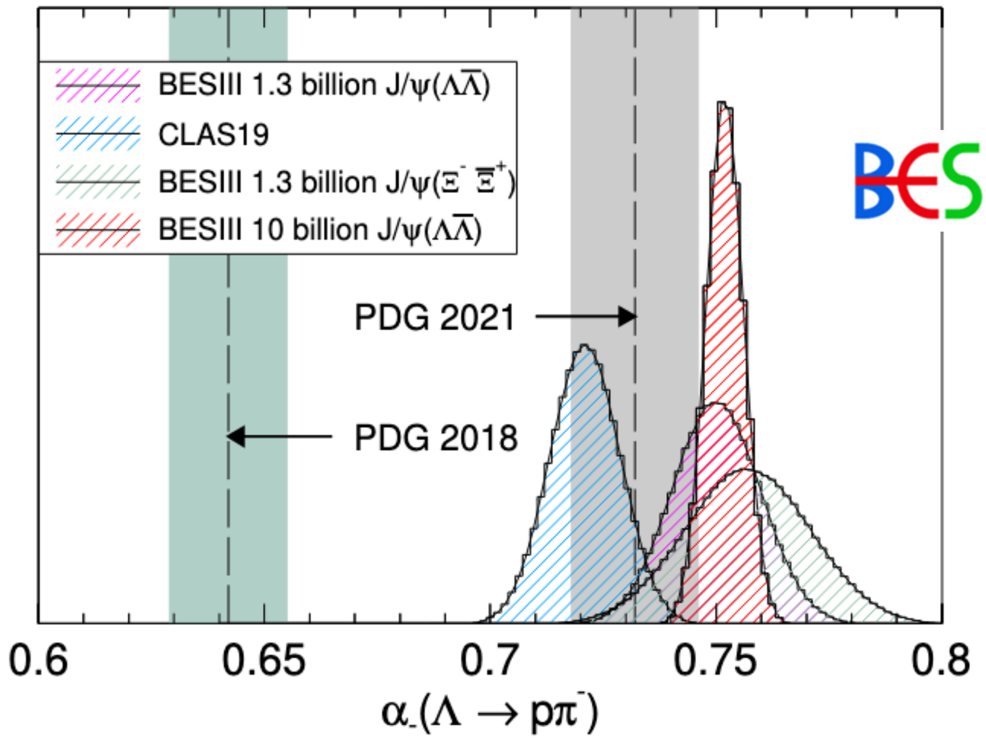


moment: $$\mu(\cos\theta_\Lambda) = \frac{1}{N}\sum_{i=1}^{N(\theta_\Lambda)}\left(n_{1,y}^{(i)} - n_{2,y}^{(i)}\right)$$

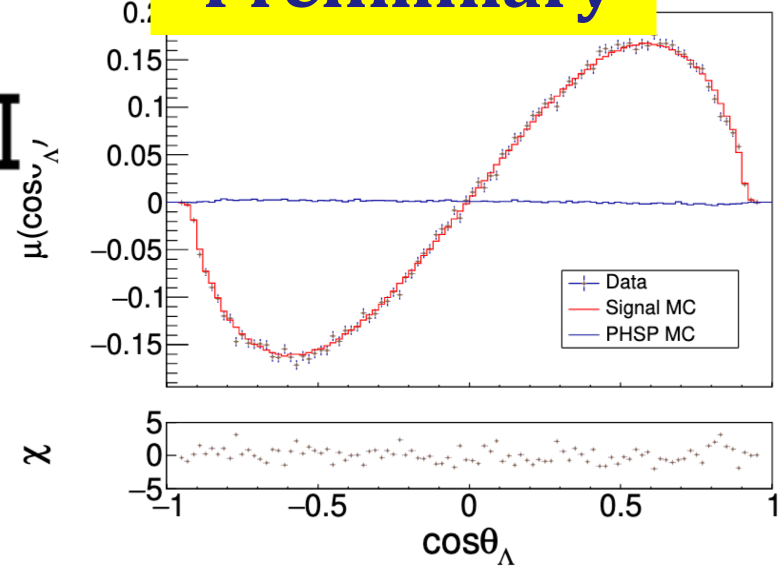
(uncorrected for acceptance)

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_-	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013	PDG
α_+	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08	PDG
$\bar{\alpha}_0$	$\mathbf{-0.692 \pm 0.016 \pm 0.006}$	–	

Nature Phys. 15 (2019) 631



Preliminary



arXiv:2204.11058

$$A_\Lambda = -0.0025 \pm 0.0046 \pm 0.0011$$

$$A_{CP}^{\Lambda} = 0.12\,(\xi_P^\Lambda - \xi_S^\Lambda)$$

BESIII
10^{10} J/ψ

CP test:

$$\mathrm{A}_\Lambda = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

A_Λ = -0.006 ± 0.012 ± 0.007

A_Λ = 0.013 ± 0.021
PS185 PRC54(96)1877

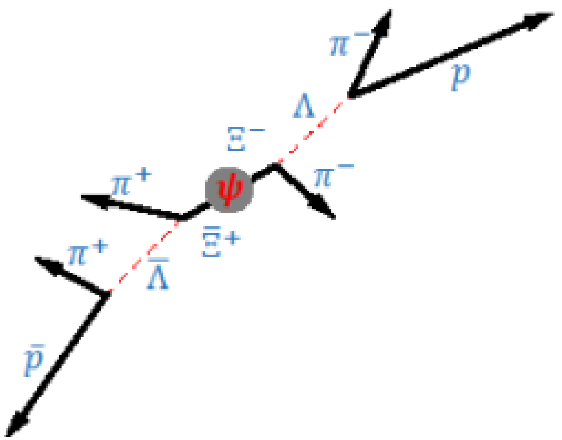
$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$

$d\Gamma \propto W(\boldsymbol{\xi};\boldsymbol{\omega})$ $\quad \boldsymbol{\xi}$ **9 kinematical variables 9D PhSp**

Parameters: 2 production + 6 for decay chains

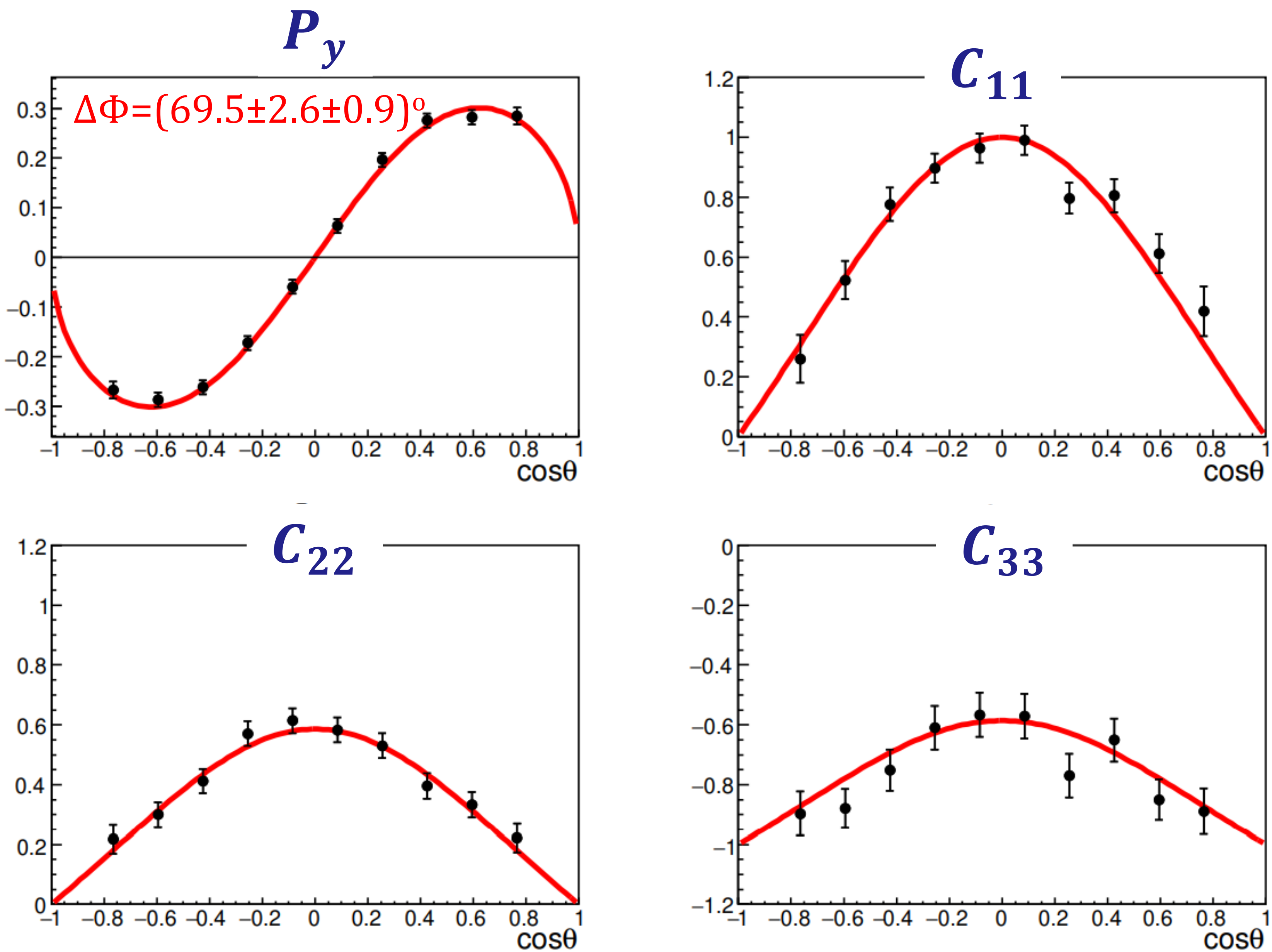
$$\boldsymbol{\omega} = (\alpha_\psi, \Delta\Phi, \overbrace{\alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \bar{\alpha}_\Lambda})$$

$$W = \sum_{\mu,\bar{\nu}} C_{\mu\bar{\nu}} \sum_{\mu',\bar{\nu}'} a^{\Xi}_{\mu,\mu'} a^{\bar{\Xi}}_{\bar{\nu},\bar{\nu}'} a^{\Lambda}_{\mu',0} a^{\bar{\Lambda}}_{\bar{\nu}',0}$$



E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008
P.Adlarson, AK PRD100 (2019) 114005

Polarization and C_{ii} for $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$



Nature 606 (2022) 64–69

BESIII

	This work	Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	39
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–	
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010	22
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad	22
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–	
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	4
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	4
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ 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	3
$A_{\rm CP}^{\Xi}$	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{\rm CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–	
$A_{\rm CP}^{\Lambda}$	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

fit

First measurement for any baryon!

3 CP tests

$$A_{CP}^{\Xi} = ??\ (\xi_P^{\Xi} - \xi_S^{\Xi})$$

$$\Phi_{CP}^{\Xi} = 0.40\ (\xi_P^{\Xi} - \xi_S^{\Xi})$$

Nature 606 (2022) 64–69

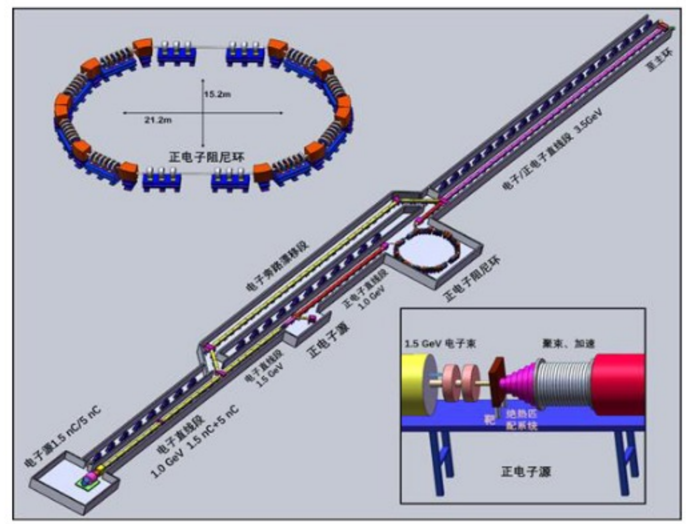
Content

1. BSM search: Rare decays vs asymmetries
2. CPV kaons vs hyperons
3. Hyperon-antihyperon system at e^+e^- colliders
4. Experiments at (super)tau-charm factories: CPV sensitivity, polarized electron beam,…

Super Tau-Charm Facility (STCF) in China

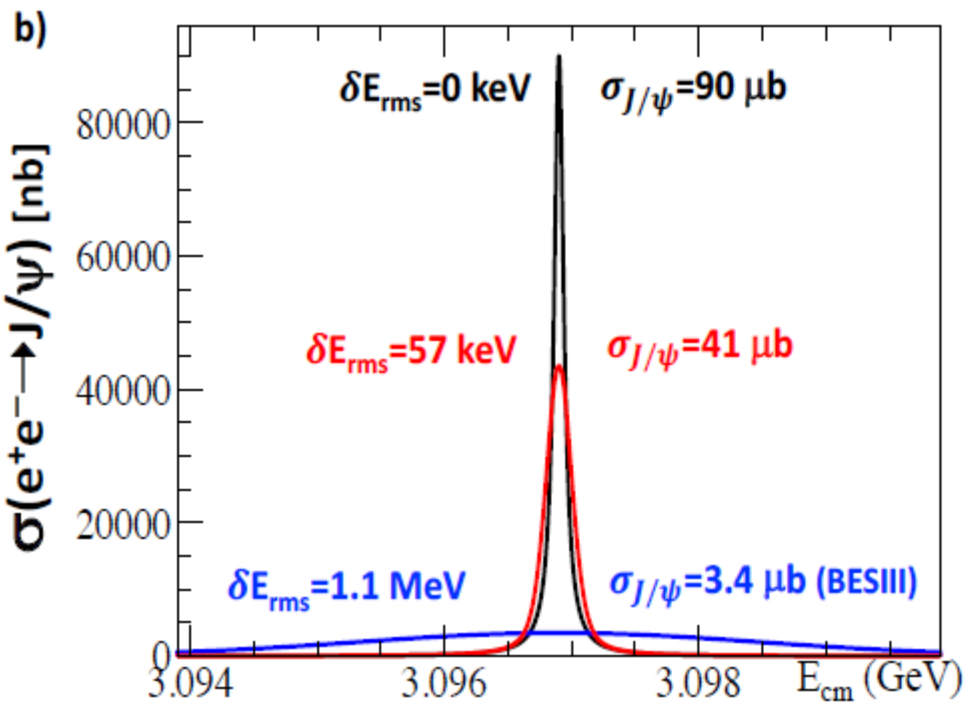
- Peaking luminosity >0.5×10^{35} $cm^{-2}s^{-1}$ at 4 GeV
- Energy range E_{cm} = 2-7 GeV
- Potential to increase luminosity and realize beam polarization
- A nature extension and a viable option for China accelerator project in the post BEPCII/BESIII era

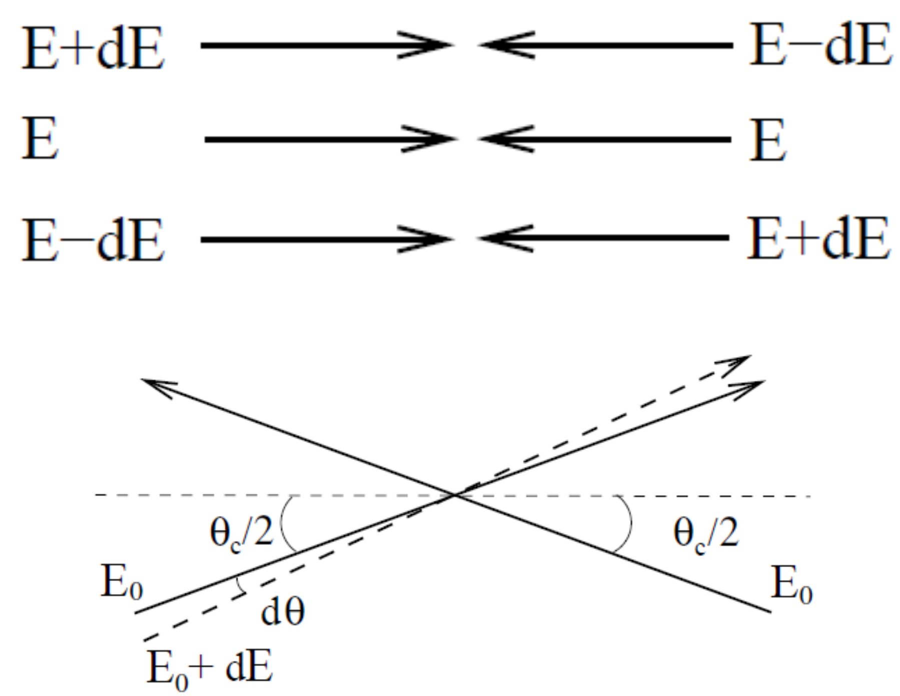
Xiaorong Zhou
CHARM2020



	$\sigma(A_{CP}^{[\Lambda p]})$	$\sigma(A_{CP}^{[\Xi-]})$	$\sigma(B_{CP}^{[\Xi-]})$	Comment
BESIII	1.0×10^{-2} [a]	1.3×10^{-2}	3.5×10^{-2}	1.3×10^{9} J/ψ [28, 29]
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)

Monochromator





V.Telenov arXiv:2008.13668

Polarized e^- beam

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

+ 80% longitudinal e^- polarization

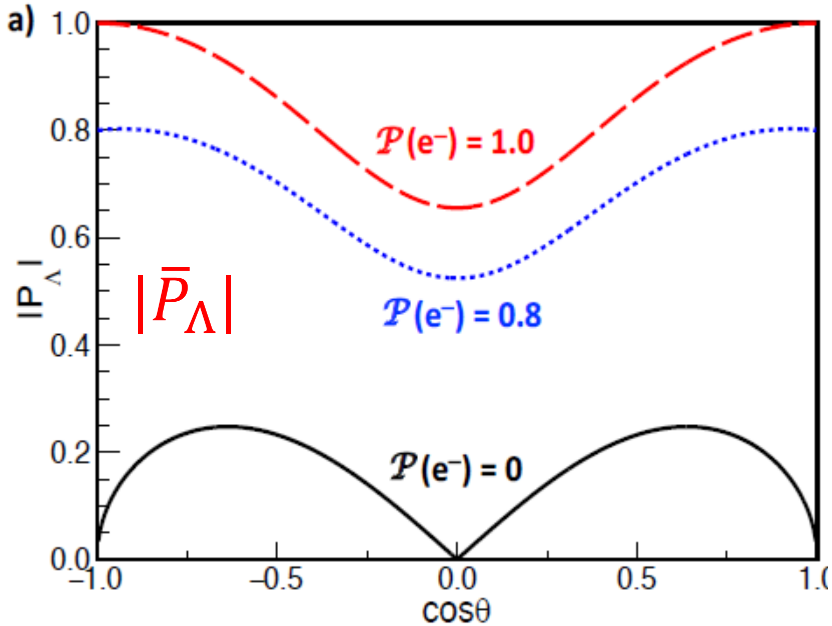
Bondar et al. JHEP 03 (2020) 076

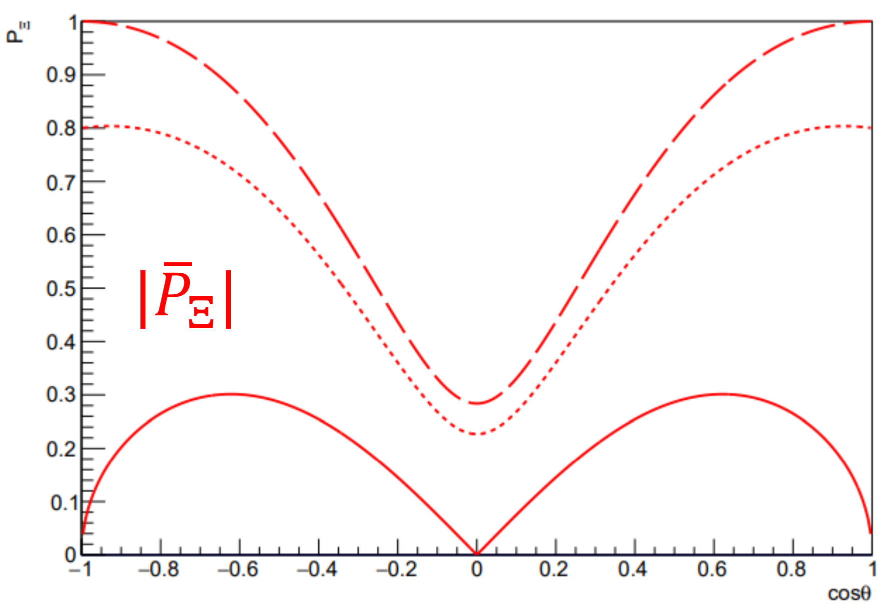
arXiv:2203.03035

$\langle \mathbb{P}^2_{\Xi} \rangle$ $\quad \bar{P}_{\Lambda,\Xi}$

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

$\langle \mathbb{S}^2_{\Xi} \rangle$





Optimizing future measurements

$$\mathcal{P}^{\Xi\overline{\Xi}}(\boldsymbol{\xi}_{\Xi\overline{\Xi}};\boldsymbol{\omega}_{\Xi}) = \frac{1}{(4\pi)^5}\sum_{\mu,\nu=0}^{3} C_{\mu\nu}\left(\sum_{\mu'=0}^{3} a^{\Xi}_{\mu\mu'}a^{\Lambda}_{\mu'0}\right)\left(\sum_{\nu'=0}^{3} a^{\overline{\Xi}}_{\nu\nu'}a^{\overline{\Lambda}}_{\nu'0}\right)$$

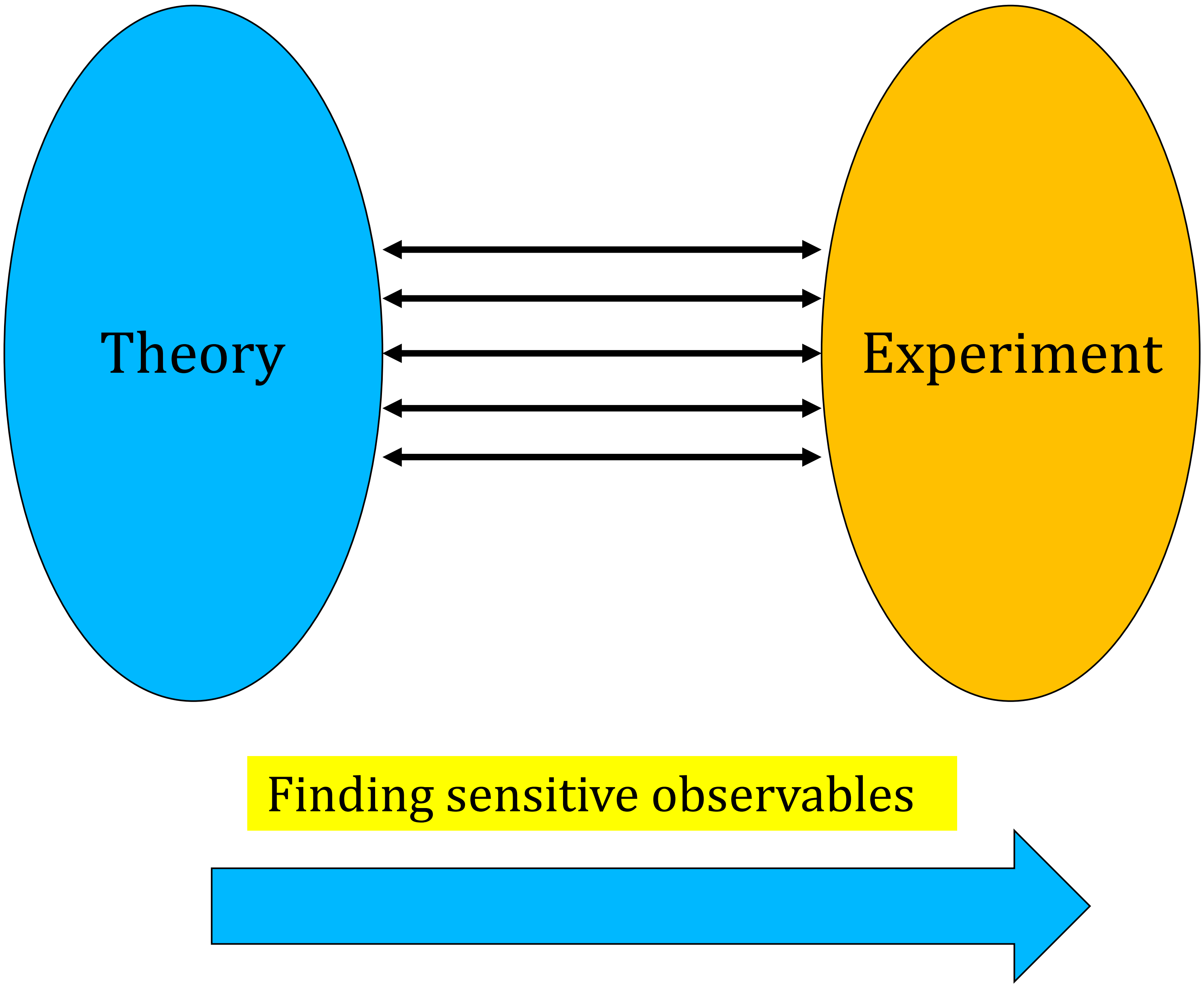
$$\mathcal{P}^{D\overline{D}}(\boldsymbol{\xi};\boldsymbol{\omega}) = \frac{1}{(4\pi)^3}\sum_{\mu,\nu=0}^{3} C_{\mu\nu}(\Omega_B;\alpha_\psi,\Delta\Phi,P_e)a^{D}_{\mu0}(\Omega_b;\alpha_D)a^{\overline{D}}_{\nu0}(\Omega_{\bar{b}};\overline{\alpha}_D)$$

maximum likelihood method:

$$\mathcal{L}(\boldsymbol{\omega}) = \prod_{i=1}^{N}\mathcal{P}(\boldsymbol{\xi}_i,\boldsymbol{\omega}) \equiv \prod_{i=1}^{N}\frac{\mathcal{W}(\boldsymbol{\xi}_i,\boldsymbol{\omega})}{\int\mathcal{W}(\boldsymbol{\xi},\boldsymbol{\omega})d\boldsymbol{\xi}}$$

$$V^{-1}_{kl} = E\left(-\frac{\partial^2\ln\mathcal{L}}{\partial\omega_k\partial\omega_l}\right)$$

Connection between theory and experiment



Asymptotic maximum likelihood method

$$V_{kl}^{-1} = E\left(-\frac{\partial^2 \ln \mathcal{L}}{\partial\omega_k \partial\omega_l}\right) = N \int \frac{1}{\mathcal{P}} \frac{\partial \mathcal{P}}{\partial\omega_k} \frac{\partial \mathcal{P}}{\partial\omega_l} d\boldsymbol{\xi}$$

V_{kl} – covariance matrix

$$\mathcal{L}(\boldsymbol{\omega}) = \prod_{i=1}^{N} \mathcal{P}(\boldsymbol{\xi}_i, \boldsymbol{\omega}) \equiv \prod_{i=1}^{N} \frac{\mathcal{W}(\boldsymbol{\xi}_i, \boldsymbol{\omega})}{\int \mathcal{W}(\boldsymbol{\xi}, \boldsymbol{\omega}) d\boldsymbol{\xi}},$$

Tool to determine:

- Best possible (ultimate) sensitivity and correlations for parameters
- Structure of complicated angular distribution:
  e.g. V_{kl}^{-1} singular – parameters cannot be determined separately

Validation of the method

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

Error correlation matrix

	$\bar{\alpha}_\Lambda$	α_ψ	$\Delta\Phi$
α_Λ	0.87	−0.05	−0.07
$\bar{\alpha}_\Lambda$		0.05	0.07
α_ψ			0.28

$$\sigma(\alpha_\Lambda) = \frac{7}{\sqrt{N}} \quad (0.011)$$

$$\sigma(A_\Lambda) = \frac{9}{\sqrt{N}} \quad (0.014)$$

Consistent with BESIII Nature Phys. 15,631(2019)

Analytic approximations for uncertainties

$$\text{Information} \equiv (\text{covariance matrix})^{-1}$$

$$\mathcal{I}(\omega_k, \omega_l) := N \int \frac{1}{\mathcal{P}} \frac{\partial \mathcal{P}}{\partial \omega_k} \frac{\partial \mathcal{P}}{\partial \omega_l} \mathrm{d}\boldsymbol{\xi}$$

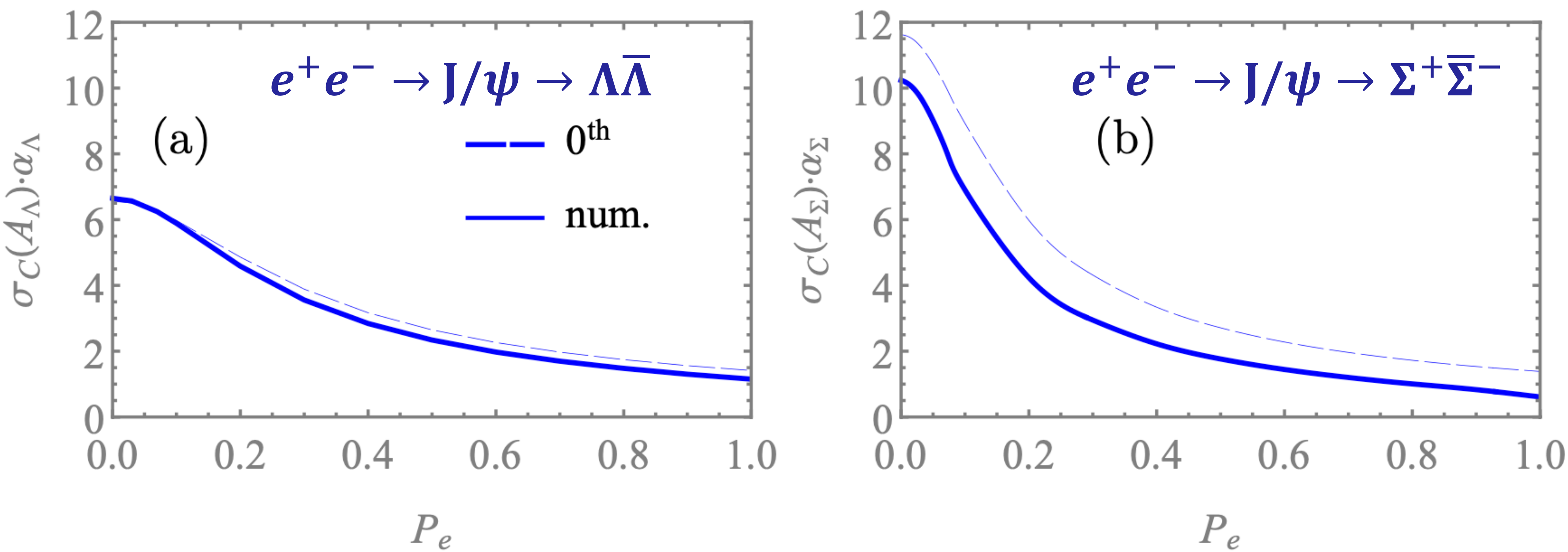
$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}, \Sigma^+\bar{\Sigma}^-$$

$$\frac{1}{\mathrm{Var}(A_{\mathrm{CP}})} = \mathcal{I}(A_{\mathrm{CP}}) := N \int \frac{1}{\mathcal{P}^{D\bar{D}}} \left(\frac{\partial \mathcal{P}^{D\bar{D}}}{\partial A_{\mathrm{CP}}} \right)^2 \mathrm{d}\boldsymbol{\xi}$$

$$\frac{1}{\mathcal{P}} = \frac{\mathcal{V}}{C_{00}} \frac{1}{1+\mathcal{G}} = \frac{\mathcal{V}}{C_{00}} \sum_{i=0}^{\infty} (-\mathcal{G})^i$$

$$\mathcal{I}_0(\omega_k, \omega_l) := N \int \frac{\mathcal{V}}{C_{00}} \frac{\partial \mathcal{P}}{\partial \omega_k} \frac{\partial \mathcal{P}}{\partial \omega_l} \mathrm{d}\boldsymbol{\xi},$$

Analytic approximations



$$\sigma(A_{\rm CP})\sqrt{N} = \sigma_C(A_{\rm CP}) \approx \sqrt{\frac{3}{2}}\frac{1}{\alpha_D\sqrt{\langle \mathbf{P}_B^2\rangle}}$$

$$\alpha_{\Sigma^+p} = -0.994(4)$$

$$\alpha_{\Sigma^+n} = -0.068(13)$$

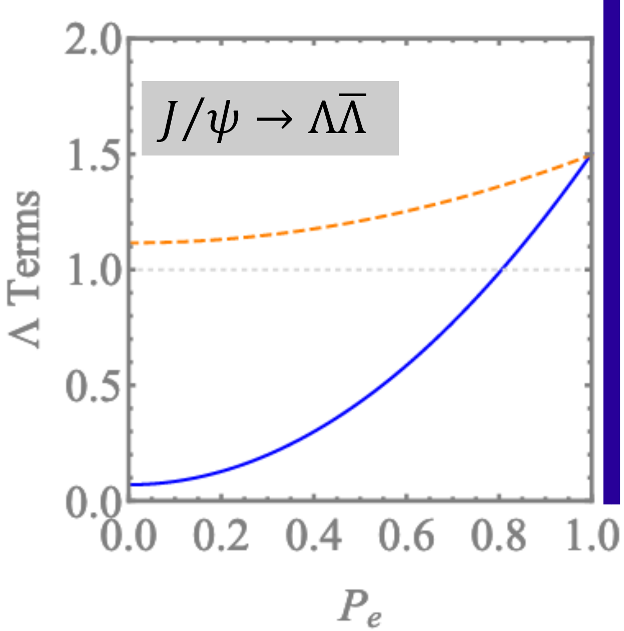
$$I(\Phi_\Xi) = N\frac{2}{27}(1-\alpha_\Xi^2)\alpha_\Lambda^2[3.08\langle\mathbb{P}_\Xi^2\rangle + 1.30\langle\mathbb{S}_\Xi^2\rangle]$$

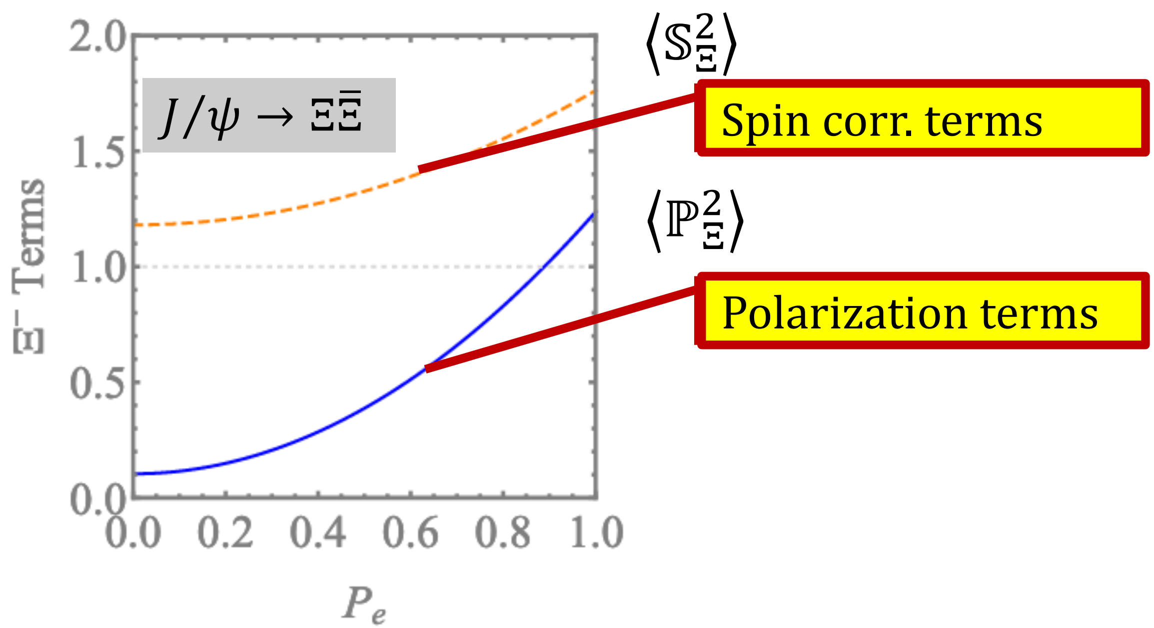
$$I(A_\Xi) = N\frac{2}{3}\alpha_\Xi^2\alpha_\Lambda^2(1 + 1.05\langle\mathbb{P}_\Xi^2\rangle + 0.38\langle\mathbb{S}_\Xi^2\rangle)$$

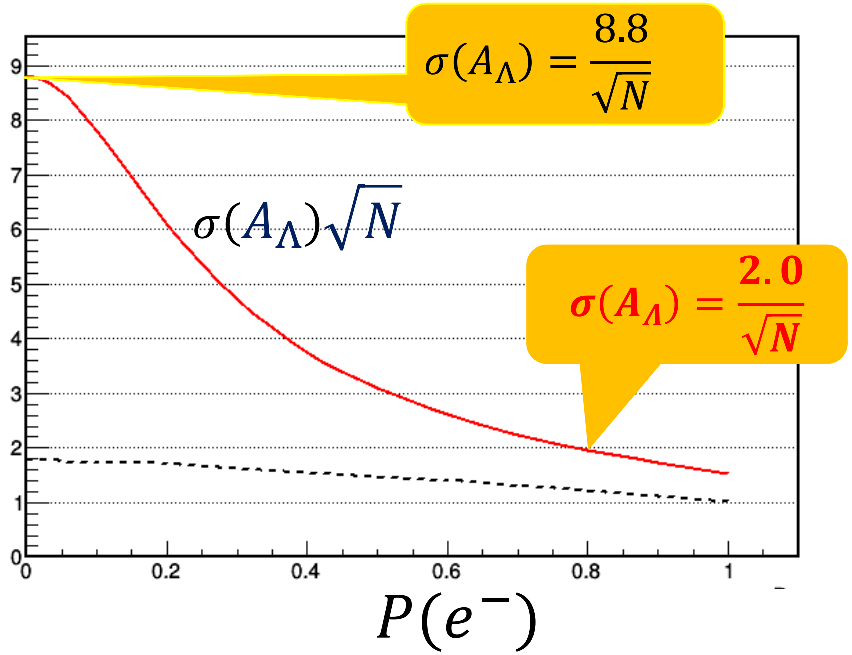
$$I(A_\Lambda) = N\frac{2}{3}\alpha_\Xi^2\alpha_\Lambda^2(1 + 3.28\langle\mathbb{P}_\Xi^2\rangle + 0.30\langle\mathbb{S}_\Xi^2\rangle)$$

$$I(A_\Xi, A_\Lambda) = N\frac{2}{3}\alpha_\Xi^2\alpha_\Lambda^2(1 - \frac{1}{3}\langle\mathbb{P}_\Xi^2\rangle - \frac{1}{3}\langle\mathbb{S}_\Xi^2\rangle)$$

$$I(A_\Lambda) = N\frac{1}{3}\alpha_\Lambda^2\langle\mathbb{P}_\Xi^2\rangle$$

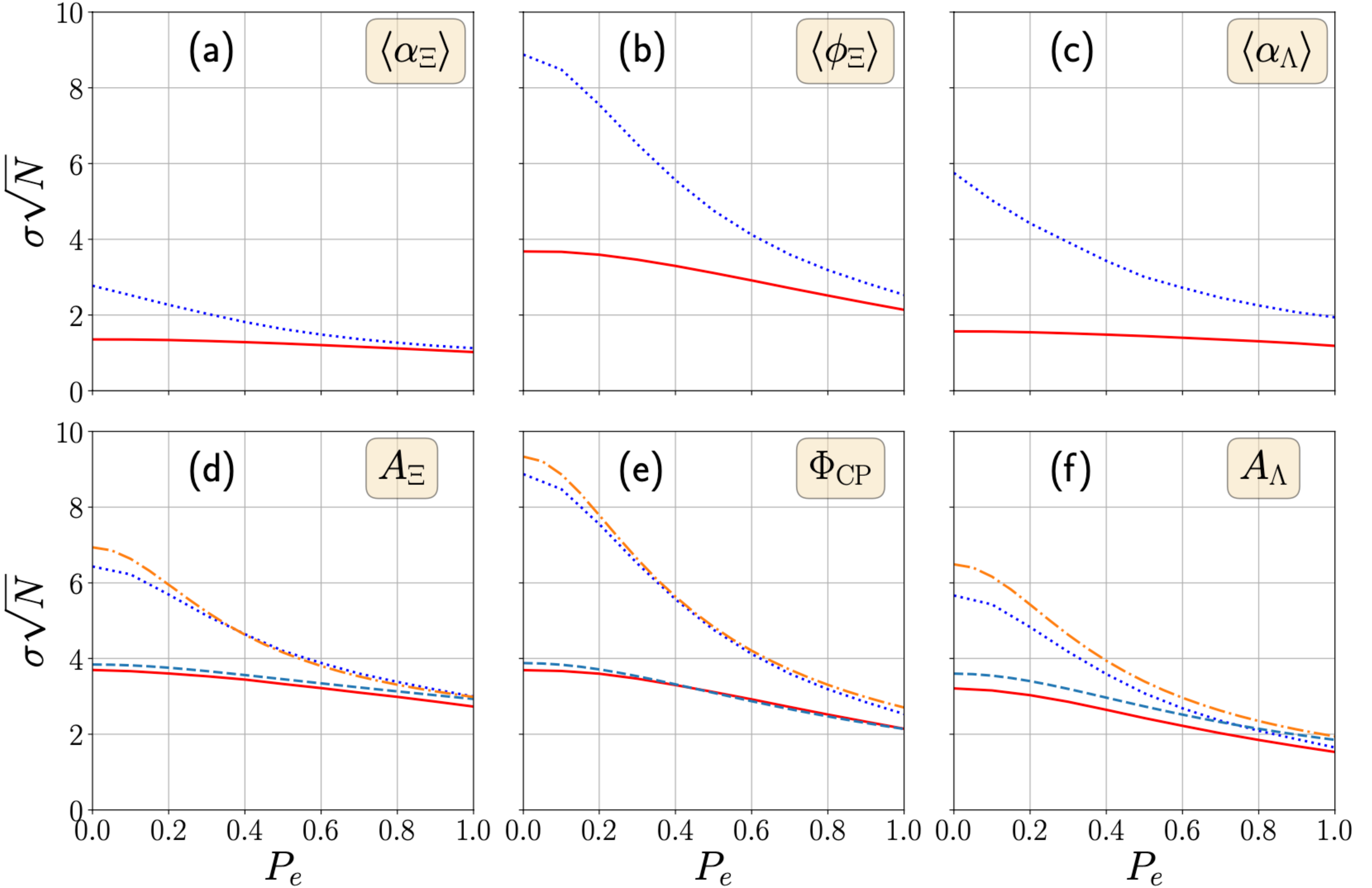






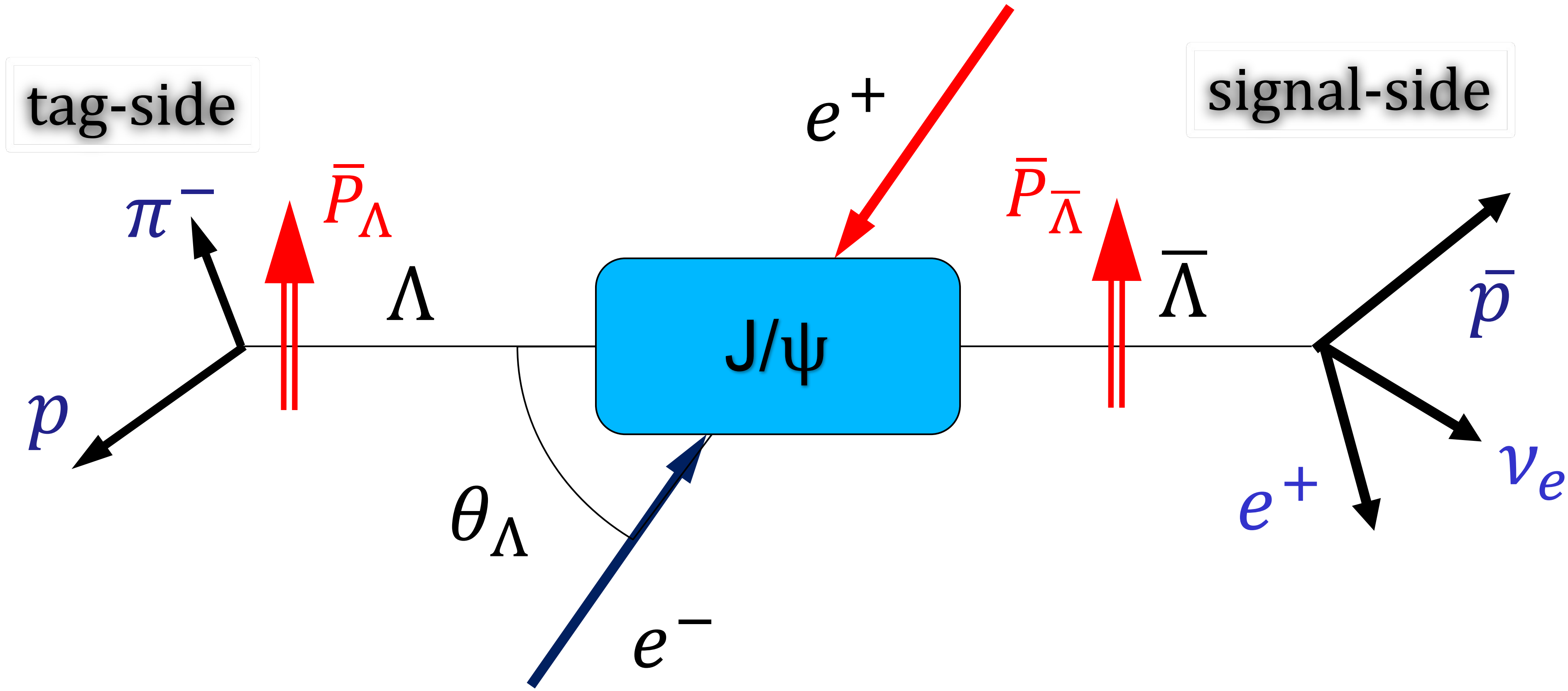
Electron beam polarization 80%

Equiv. to ×16 more $J/\psi \to \Lambda\bar{\Lambda}$ data for A_Λ



(a)
$\langle\alpha_\Xi\rangle$
(b)
$\langle\phi_\Xi\rangle$
(c)
$\langle\alpha_\Lambda\rangle$
(d)
A_Ξ
(e)
Φ_{CP}
(f)
A_Λ
$\sigma\sqrt{N}$
P_e
0
2
4
6
8
10
0.0
0.2
0.4
0.6
0.8
1.0

Double tag: polarization + spin correlations ...



Rare hyperon decays at BESIII and STCF run at $J/\psi, \psi'$:

$10^6 \div 10^9$ $B\bar{B}$ data samples: rare decays,

decay parameters

Conclusions:

- J/ψ and ψ' decays into hyperon-antihyperon: unique spin entangled system for CP tests and for determination of (anti-)hyperon decay parameters
- Polarization observed for J/ψ,(ψ') $\rightarrow \Lambda\bar{\Lambda}, \Sigma^+\bar{\Sigma}^-, \Xi^-\bar{\Xi}^+, \Omega^-\bar{\Omega}^+$

$J/\psi \rightarrow \Lambda\bar{\Lambda}$ $(\xi_P^\Lambda - \xi_S^\Lambda) = (-2.0 \pm 3.8) \times 10^{-2}$

BESIII 10^{10} J/ψ

$A_{CP}^\Lambda = 0.12\ (\xi_P^\Lambda - \xi_S^\Lambda)$

$J/\psi \rightarrow \Xi\bar{\Xi}$

Polarization vs spin correlations

three independent CP tests

measurement of ϕ_Ξ

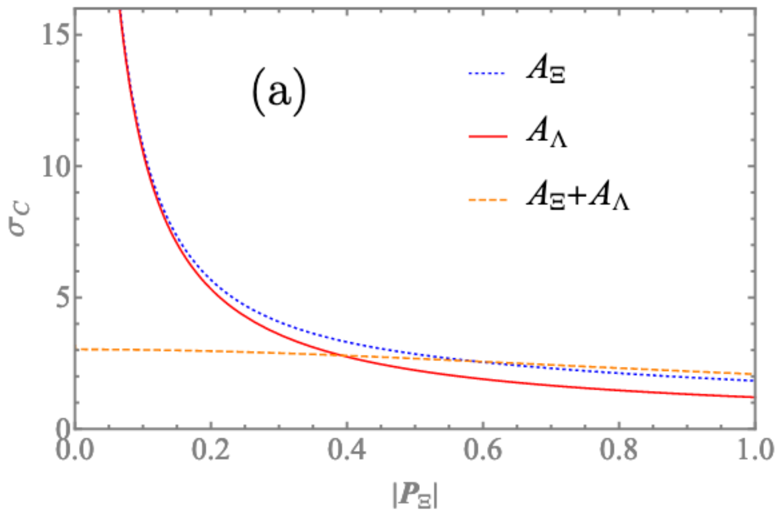
direct measurement of weak phase: $(\xi_P^\Xi - \xi_S^\Xi) = (1.2 \pm 3.5) \times 10^{-2}$

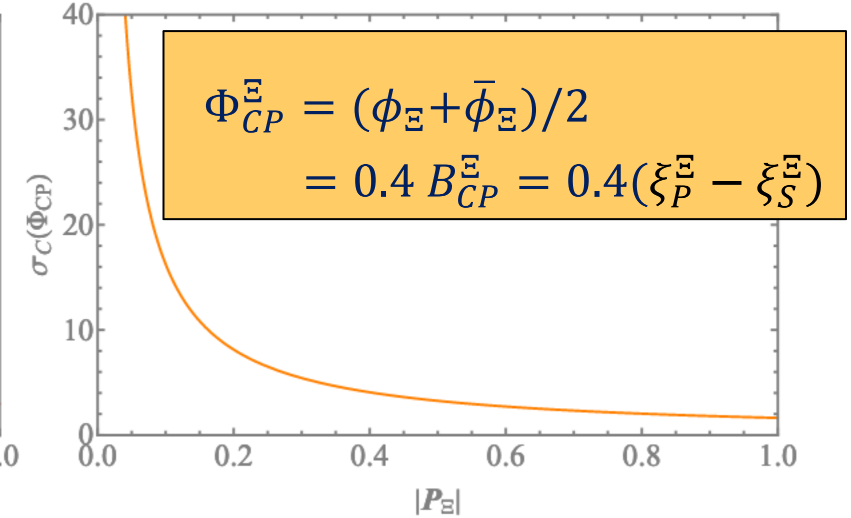
BESIII 1.3×10^9 J/ψ

Experiments:

BESIII	super tau-charm factory
	PANDA
HyperCP	LHCb

$\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$+c.c



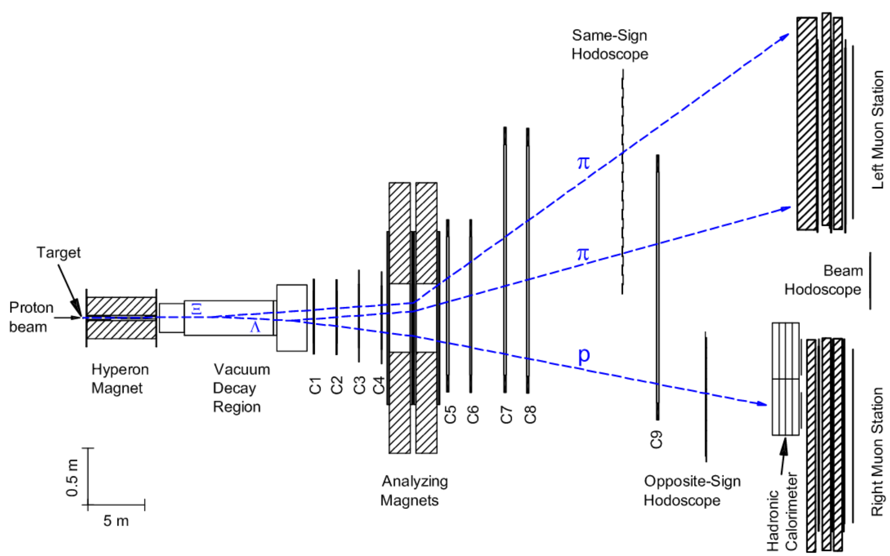


$$\Phi_{CP}^{\Xi} = (\phi_\Xi + \bar{\phi}_\Xi)/2$$
$$= 0.4\, B_{CP}^{\Xi} = 0.4(\xi_P^{\Xi} - \xi_S^{\Xi})$$

$$A_\Xi + A_\Lambda = (0.0 \pm 5.1 \pm 4.4)\times 10^{-4}$$

HyperCP PRL 93 (2004) 262001

1.2×10^{8} Ξ^- **4.1×10^{7}** $\bar{\Xi}^+$

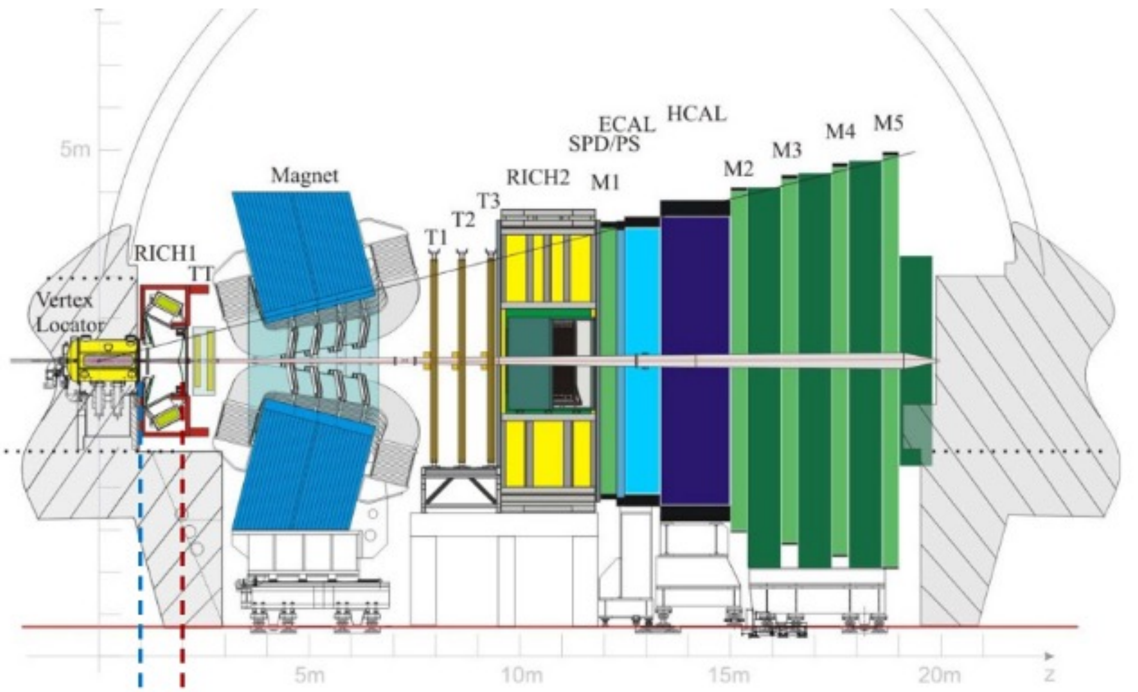


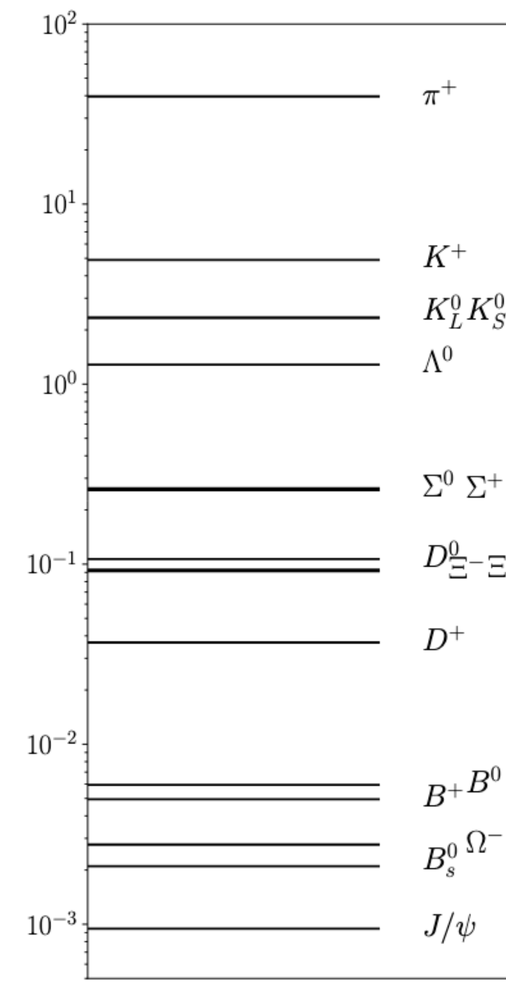
Ξ^- **Polarization (** 3.7%)

HyperCP → LHCb?

$\Xi^{-} \rightarrow \Lambda\pi^{-} \rightarrow p\pi^{-}\pi^{-}$+c.c

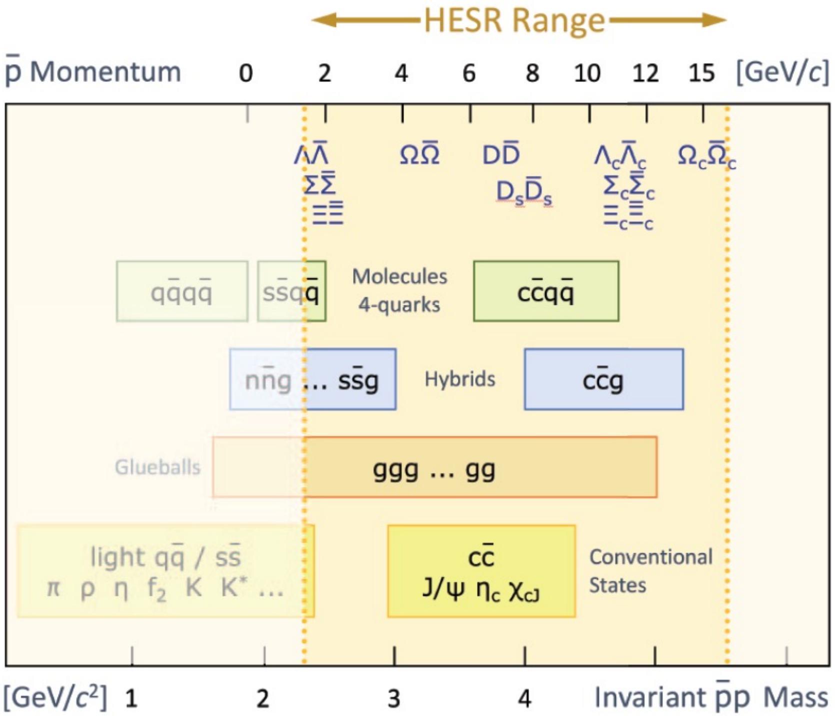
LHCb



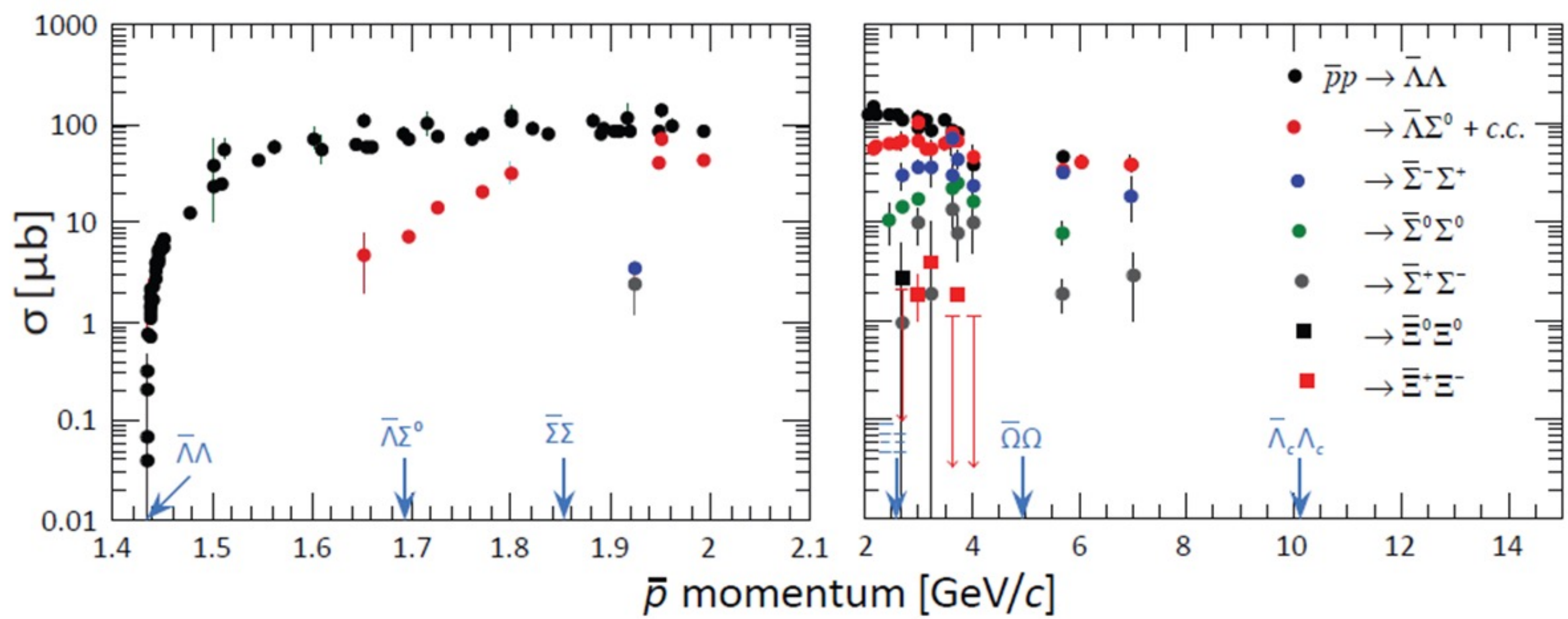


#particles per pp interaction
(√s = 13 TeV at LHCb

JHEP05(2019)048



Reaction	σ (μb)	Efficiency (%)	Rate (with 10^{31} cm^{-1}s^{-1})
$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	30 s^{-1}
$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$	~40	30	30 s^{-1}
$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~2	20	2 s^{-1}
$\bar{p}p \rightarrow \bar{\Omega}\Omega$	~0.002	30	~4 h^{-1}
$\bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c$	~0.1	35	~2 day^{-1}



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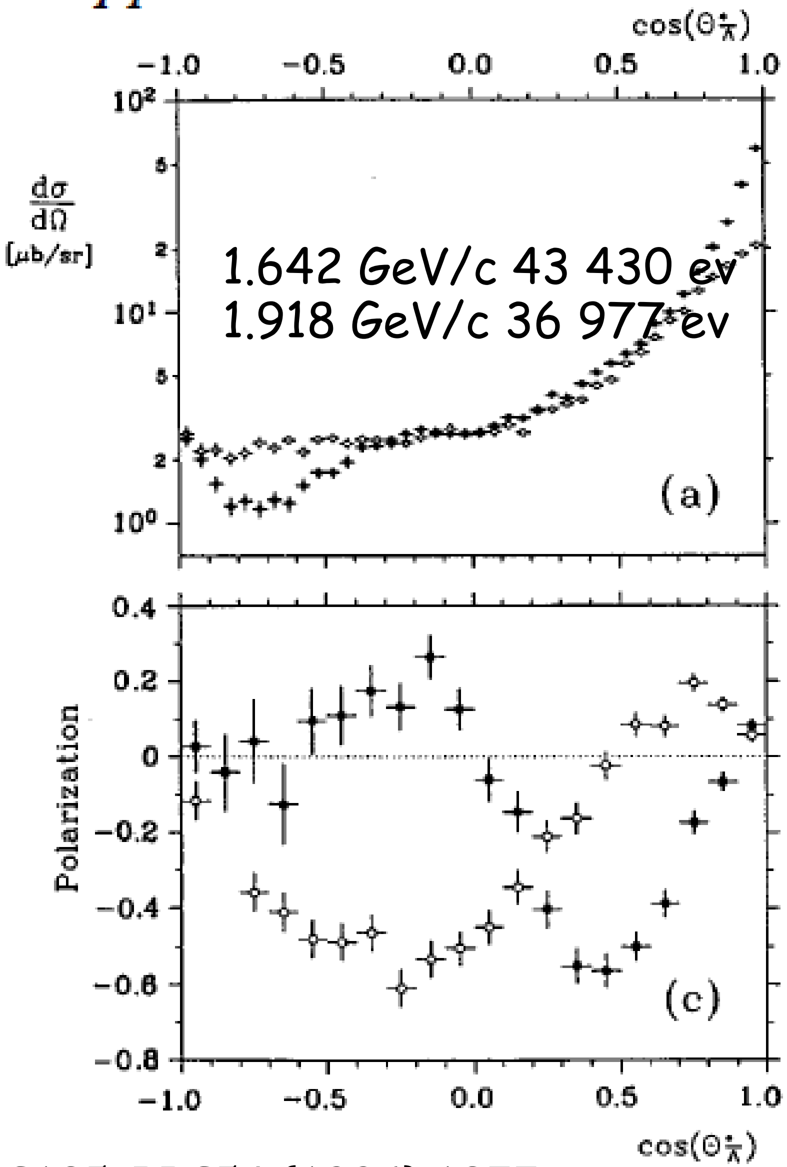
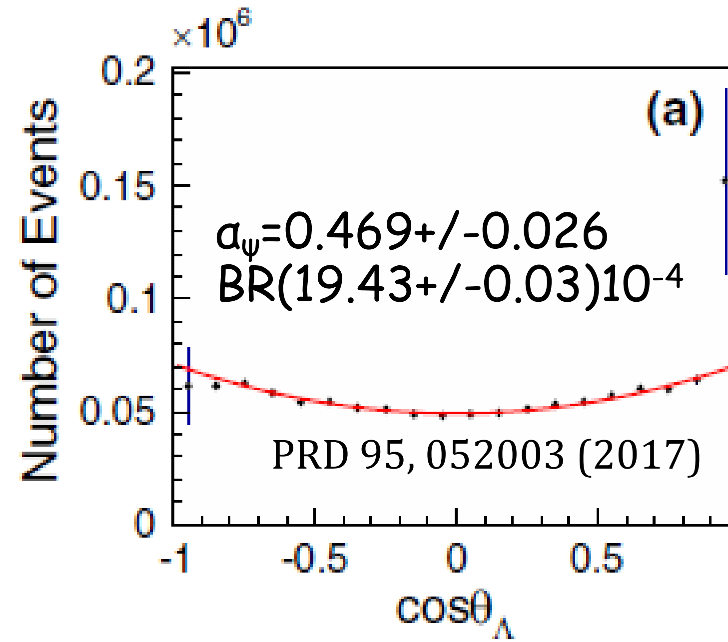
$\overline{p}p \rightarrow \overline{\Lambda}\Lambda$

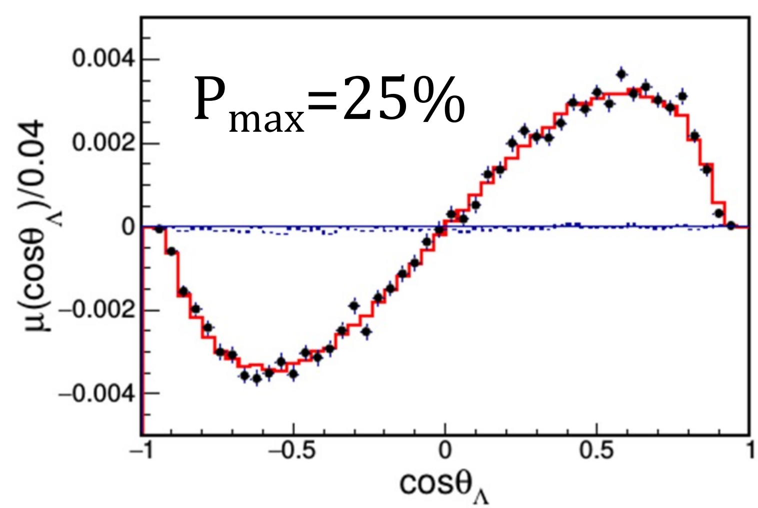


PS185, PRC54 (1996) 1877

5 parameters at each θ_Λ
Can't determine Λ decay param.

$e^+e^- \rightarrow \gamma^* \rightarrow J/\psi \rightarrow \Lambda\overline{\Lambda}$





2 global parameters
extract Λ decay par. α