Novel aspects of baryon-antibaryon production in e^+e^- annihilation

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

G.Fäldt, AK PLB772 (2017) 16

Observation of Λ transverse polarization

⇨ Determination of Λ decay parameter and CP test

arXiv:1808.08917

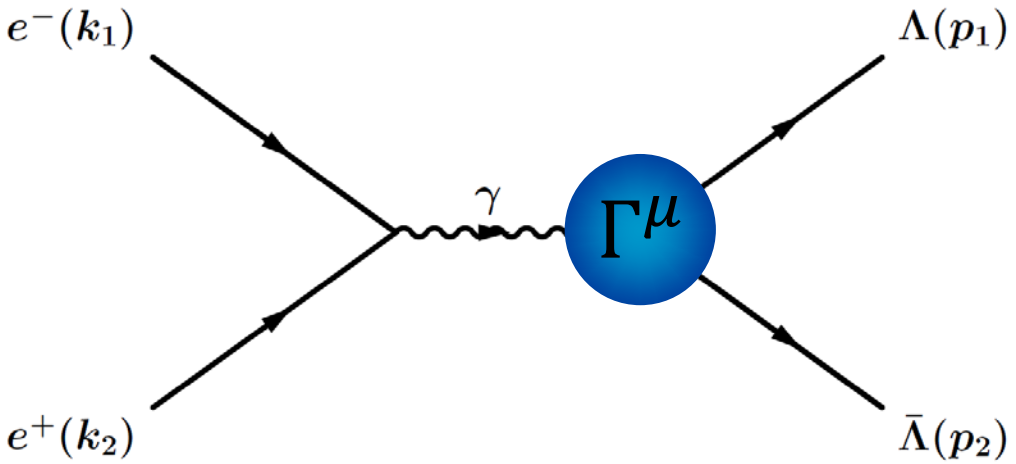
Outlook -> general formalism:

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

- decay parameters
- CP tests
- polarization tagging

E.Perotti,G.Fäldt,AK,S.Leupold,JJ.Song arXiv:1809.04038 -> PRD

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



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

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

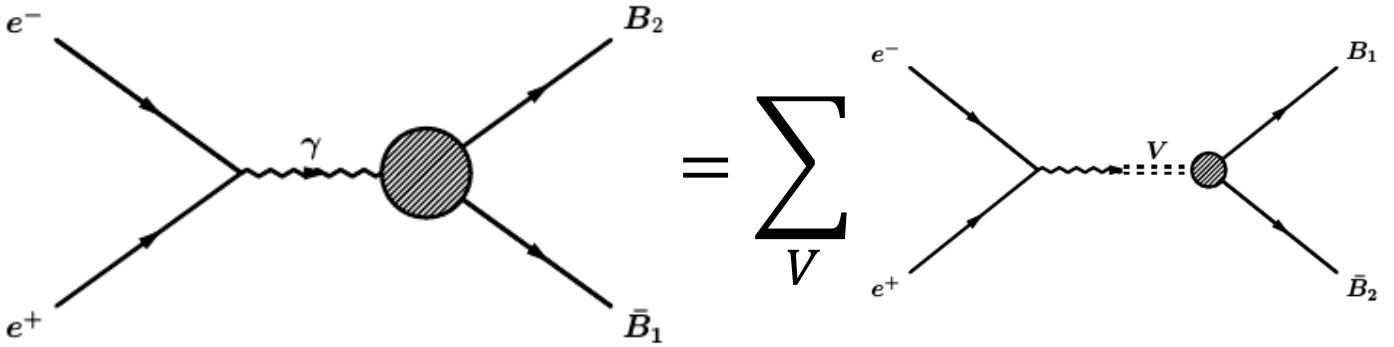
F_1 (Dirac) and F_2 (Pauli) Form Factors (complex)

Sachs Form Factors (FFs) ⇔ helicity amplitudes:

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

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

Baryon FFs (continuum):



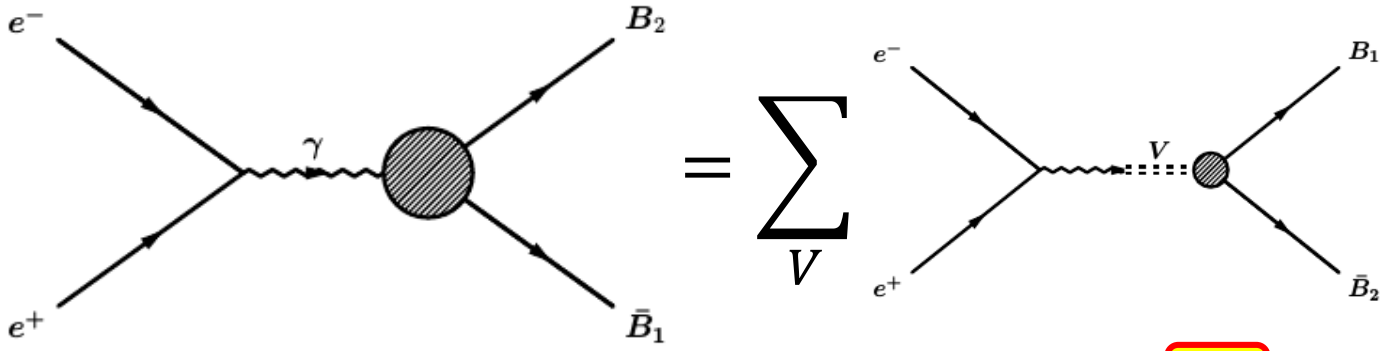
Baryons B_1 and $\bar{B}_2$ (spin 1/2, ...)

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

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

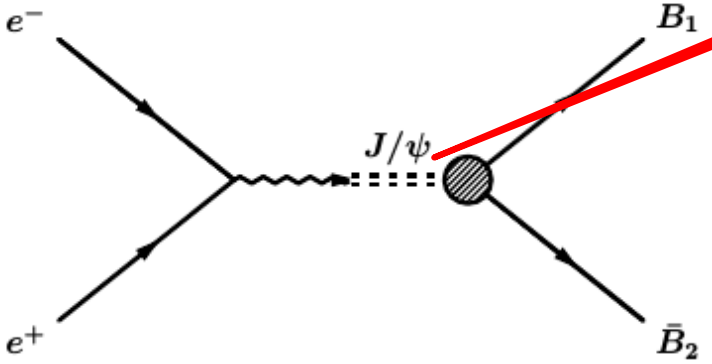
Baryon FFs (continuum):



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

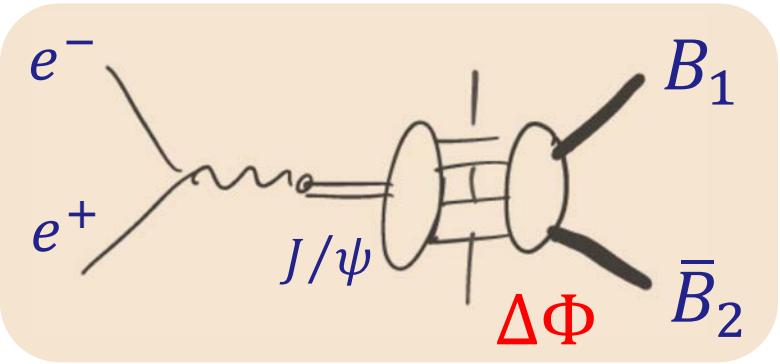
$V = \gamma, \rho, \omega, \varphi, \ldots, J/\psi, \psi(2S), \ldots$

vs J/ψ decay:



Both processes described by two complex FFs: relative phase ΔΦ

Cabibbo, Gatto PR124 (1961)1577



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Charmonia decays:
Fäldt, Kupsc PLB772 (2017) 16

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

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)

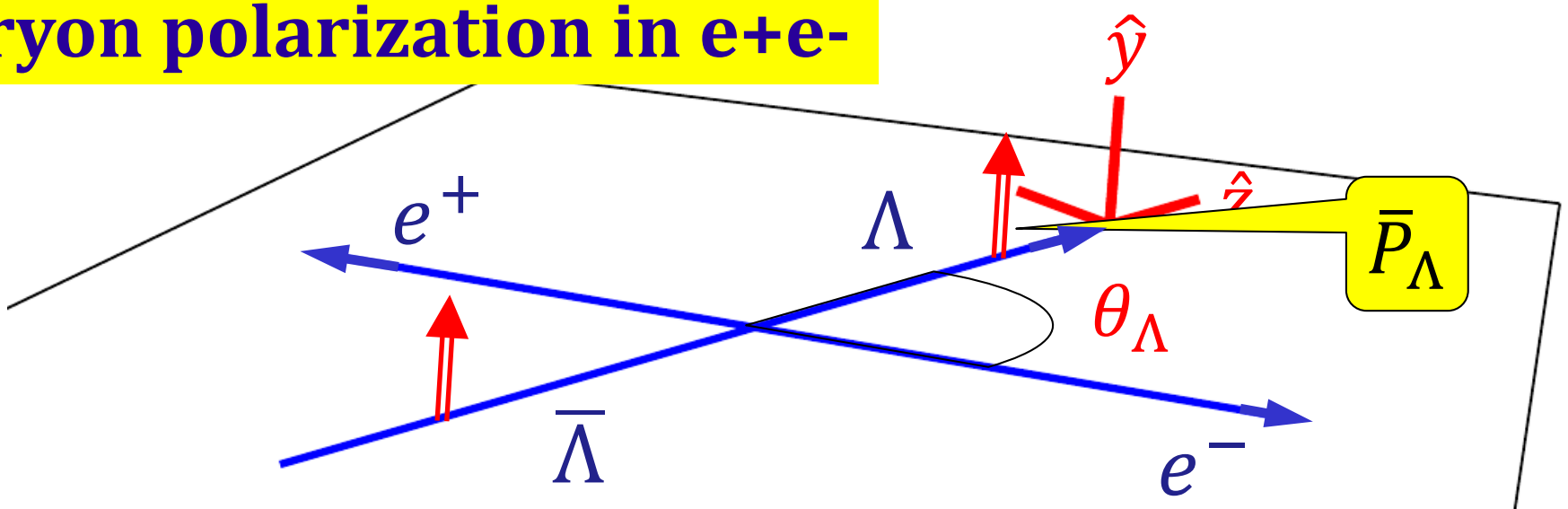
$$R = \left|\frac{G_E}{G_M}\right| \quad \left(\alpha_\psi = \frac{\tau - R^2}{\tau + R^2}\right) \qquad G_E = R G_M e^{i\Delta\Phi}$$

Angular distribution:

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

Phase $\Delta\Phi$ expected/predicted for continuum but neglected/not expected for the decays

Baryon polarization in e+e-



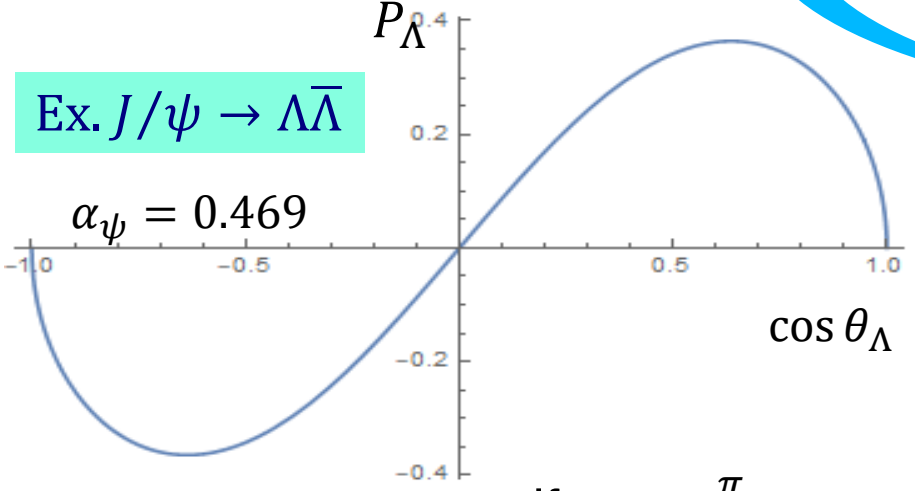
Unpolarized e+e- beams ⇨ transverse polarization:

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

$\Delta\Phi \neq 0$

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

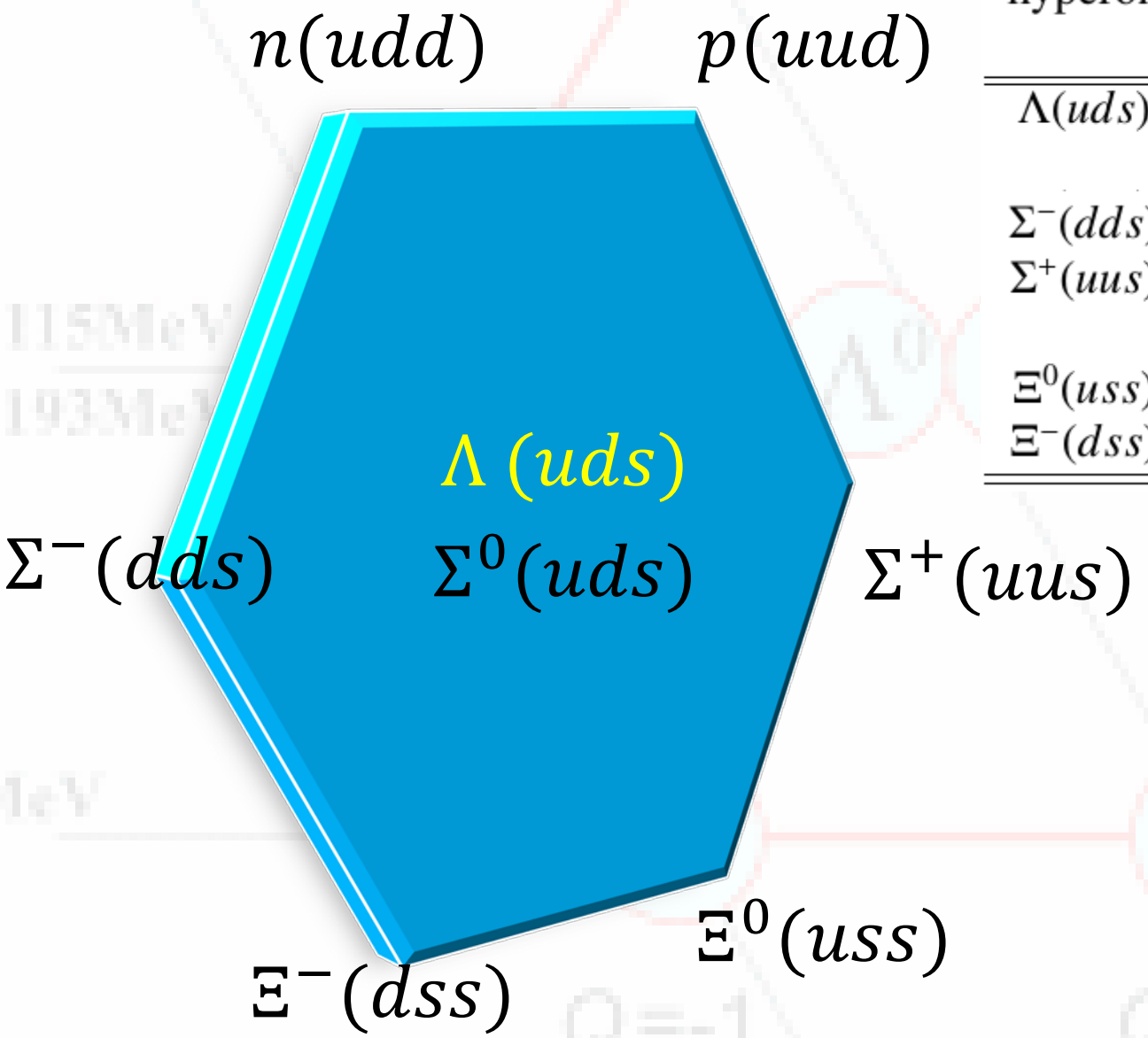
$\alpha_\psi = 0.469$



Max P_Λ= 36.4%

if $\Delta\Phi = \frac{\pi}{2}$

Spin ½ baryon octet



hyperon	Mass [GeV/c^2]	$c\tau$ [cm]	decay (BF)
$\Lambda(uds)$	1.116	7.9	$p\pi^-$ (63.9%)
			$n\pi^0$ (35.8%)
$\Sigma^-(dds)$	1.197	4.4	$n\pi^-$ (99.8%)
$\Sigma^+(uus)$	1.189	2.4	$p\pi^0$ (51.6%)
			$n\pi^+$ (48.3%)
$\Xi^0(uss)$	1.315	8.7	$\Lambda\pi^0$ (99.5%)
$\Xi^-(dss)$	1.321	5.1	$\Lambda\pi^-$ (99.8%)

Weak hadronic two body decays

$Y \to B\pi$: $^1/_2 \to {}^1/_2 + 0$

s wave parity violating
p wave parity conserving

$$\alpha_Y = \frac{2\mathrm{Re}(s^* p)}{|s|^2 + |p|^2}, \quad \beta_Y = \frac{2\mathrm{Im}(s^* p)}{|s|^2 + |p|^2} = \sqrt{1 - \alpha_Y^2}\sin\phi_Y$$

$$\gamma_Y = \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2} = \sqrt{1 - \alpha_Y^2}\cos\phi_Y$$

α_-

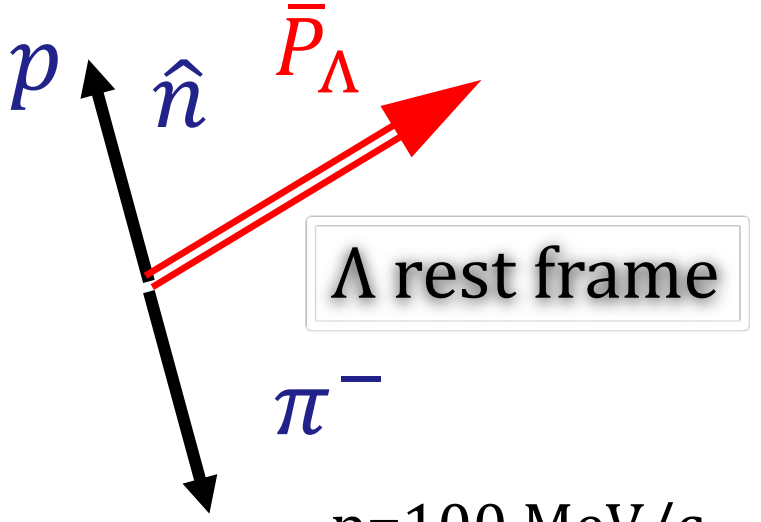
hyperon	decay (BF)	α	ϕ
$\Lambda(uds)$	$p\pi^-$ (63.9%)	**0.642 ± 0.013**	−6.5° ± 3.5°
α_0	$n\pi^0$ (35.8%)		
$\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$	$\bar{p}\pi^+$ (63.9%)	**−0.71 ± 0.08**	–
$\Sigma^-(dds)$	$n\pi^-$ (99.8%)	−0.068 ± 0.008	10° ± 15°
$\Sigma^+(uus)$	$p\pi^0$ (51.6%)	−0.980 ± 0.017	36° ± 34°
	$n\pi^+$ (48.3%)	−0.068 ± 0.013	167 ± 20°
$\Xi^0(uss)$	$\Lambda\pi^0$ (99.5%)	−0.406 ± 0.085	21° ± 12°
$\Xi^-(dss)$	$\Lambda\pi^-$ (99.8%)	−0.458 ± 0.012	−2.1° ± 0.8°

α_+

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

Polarization of Λ is determined using this decay in all experiments. Relies on:

$\alpha_- = 0.642 \pm 0.013$



Value in PDG unchanged since 1978: average based on 1963-75 experiments

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

CP odd asymmetries

Compare partial decay widths

$$\frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

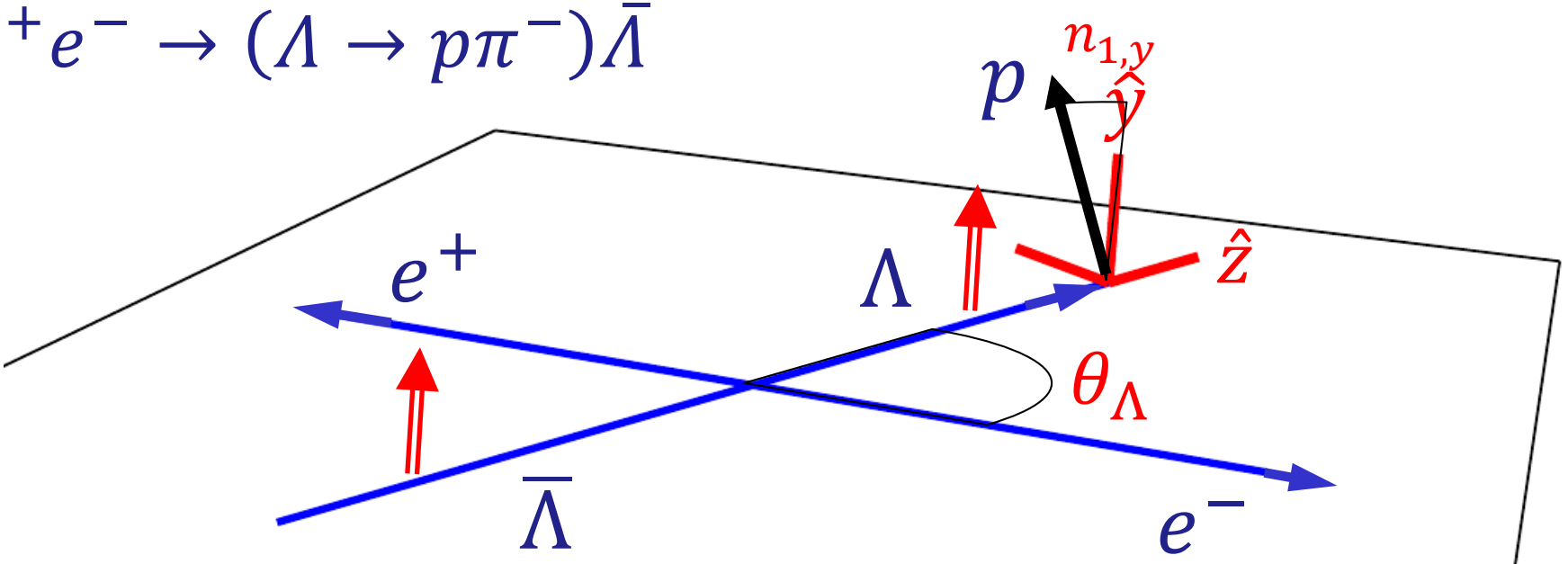
For sequential decays: ϕ (β) is accessible

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

$$B_{CP} = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}$$

Inclusive angular distribution

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



$$\frac{d\Gamma}{d\cos\theta_\Lambda d\Omega_1} \propto (1 + \boldsymbol{\alpha_\psi}\cos^2\theta_\Lambda)\{1 + \boldsymbol{\alpha_-} P_y n_{1,y}\}$$

$\Lambda \to p\pi^-$: $\hat{\mathbf{n}}_1 \to \Omega_1 = (\cos\theta_1, \phi_1)$: α_-

⇒Determine product: $\boldsymbol{\alpha_-} \cdot \sin(\boldsymbol{\Delta\Phi})$

Exclusive joint angular distribution

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

$\Lambda \to p\pi^-$: $\hat{\mathbf{n}}_1 \to (\cos\theta_1, \phi_1)$: α_- $\quad$ $\bar{\Lambda} \to \bar{p}\pi^+$: $\hat{\mathbf{n}}_2 \to (\cos\theta_2, \phi_2)$: α_+

$\xi : (\cos\theta_\Lambda, \hat{\mathbf{n}}_1, \hat{\mathbf{n}}_2)$ 5D PhSp

$$d\Gamma \propto W(\xi; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+) =$$

$$1 + \alpha_\psi \cos^2\theta_\Lambda \quad \text{Cross section}$$

$$+\alpha_-\alpha_+ \{\sin^2\theta_\Lambda (n_{1,x}n_{2,x} - \alpha_\psi n_{1,y}n_{2,y}) + (\cos^2\theta_\Lambda + \alpha_\psi) n_{1,z}n_{2,z}\} \quad \text{Spin correlations}$$

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

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

$\Delta\Phi \neq 0$ $\Rightarrow$ independent determination of α_- and α_+

Fäldt, Kupsc PLB772 (2017) 16

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

decay mode	events			$\mathcal{B}$(units 10^{-4})
$J/\psi \to \Lambda\bar{\Lambda}$	440675	±	670	19.43 ± 0.03 ± 0.33
$\psi(2S) \to \Lambda\bar{\Lambda}$	31119	±	187	3.97 ± 0.02 ± 0.12
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	111026	±	335	11.64 ± 0.04 ± 0.23
$\psi(2S) \to \Sigma^0\bar{\Sigma}^0$	6612	±	82	2.44 ± 0.03 ± 0.11
$J/\psi \to \Xi^0\bar{\Xi}^0$	134846	±	437	11.65 ± 0.04
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	10839	±	123	2.73 ± 0.03
$J/\psi \to \Xi^-\bar{\Xi}^+$	42811	±	231	10.40 ± 0.06
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	5337	±	83	2.78 ± 0.05

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

PRD 95, 052003 (2017)

BESIII

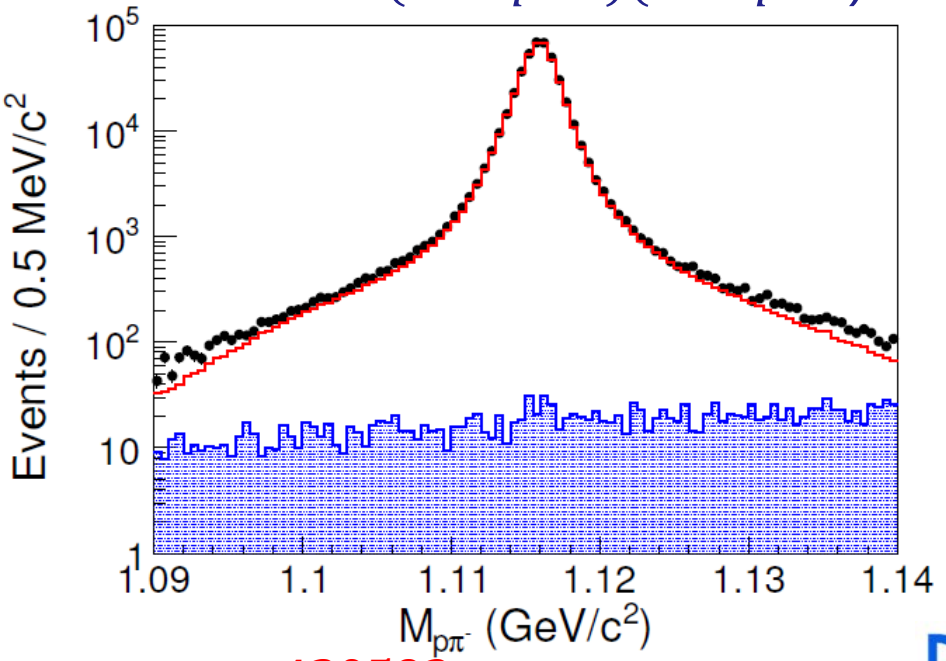
1.31×10^9 J/ψ

and $(4.48) \times 10^8$ ψ(2S)

0.223×10^9 J/ψ

Now (Feb 2019): 10^{10} J/ψ

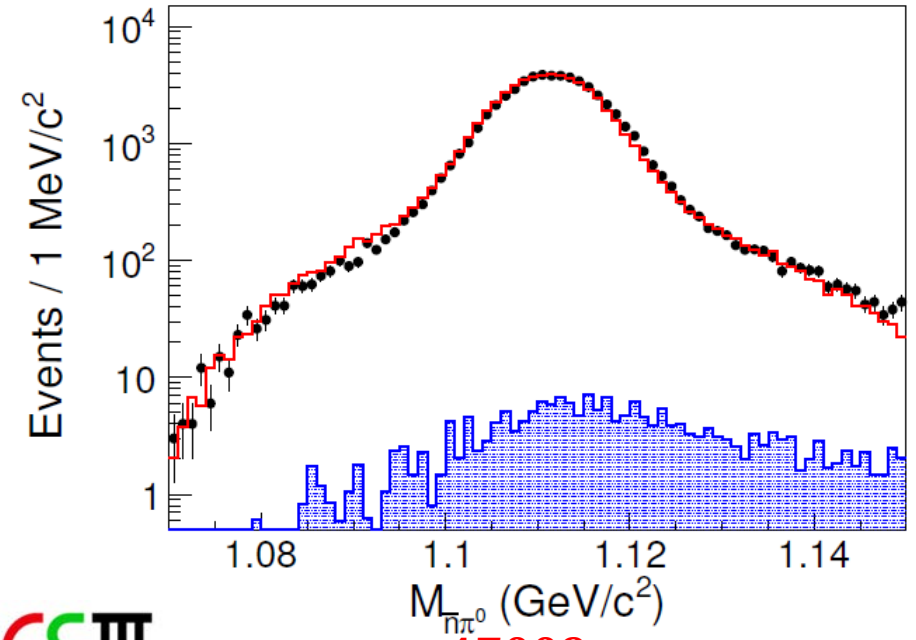
$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$



420593 events

399 background

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



47009 events

66 background

Global unbinned maximum log likelihood fit to the two data sets with the likelihood function constructed from probability function:

$$\mathcal{C}(\alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)\mathcal{W}(\boldsymbol{\xi}_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$$

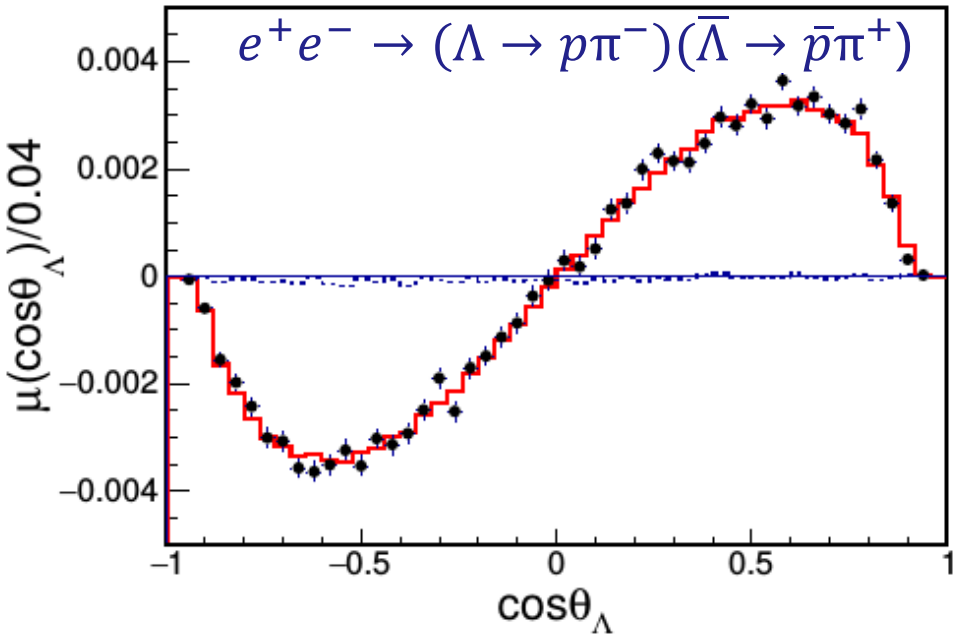
Where $\mathcal{C}(\alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$ is the normalization factor obtained from $\mathcal{W}(\boldsymbol{\xi}_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$ weighted sum for flat phase space model MC events after detector reconstruction.

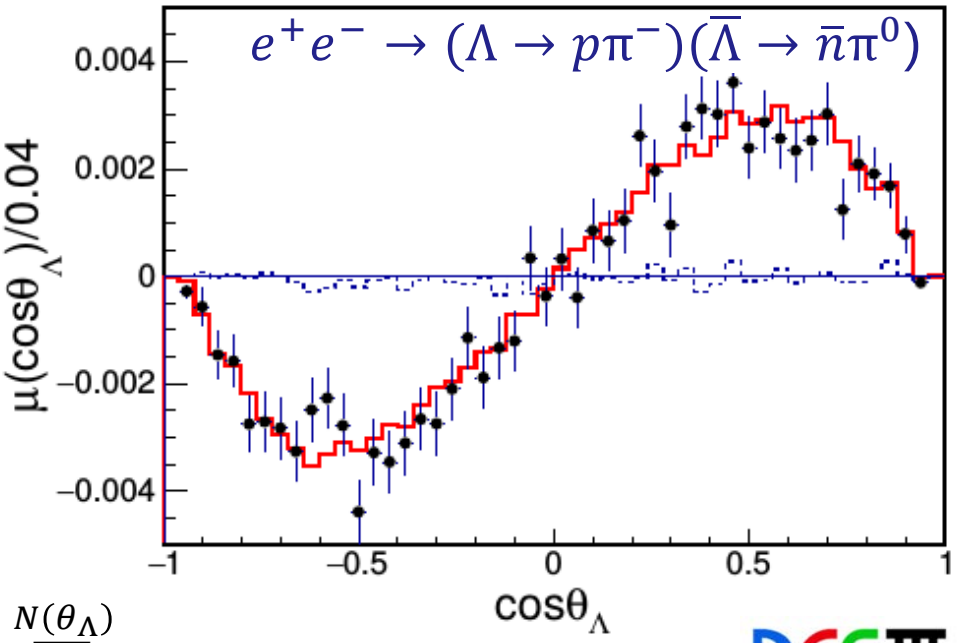
$(1.31\text{x}10^9\ \text{J}/\psi)$

arXiv:1808.08917

Fit results

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





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

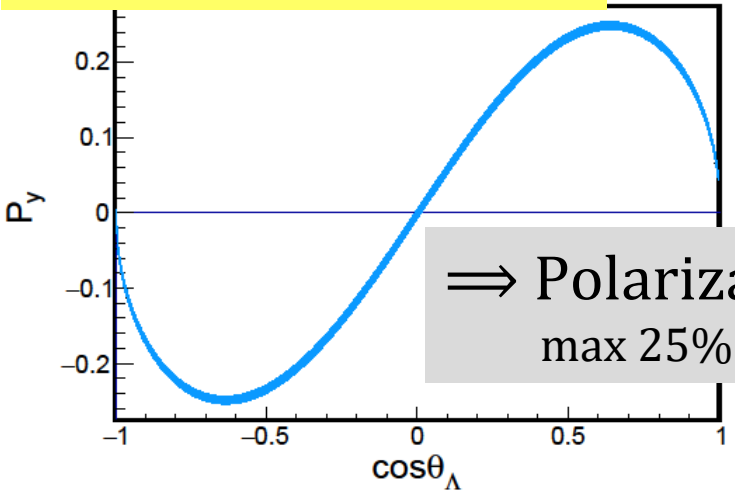
(uncorrected for acceptance)

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
$\bar{\alpha}_0$	$\mathbf{-0.692 \pm 0.016 \pm 0.006}$	–

arXiv:1808.08917

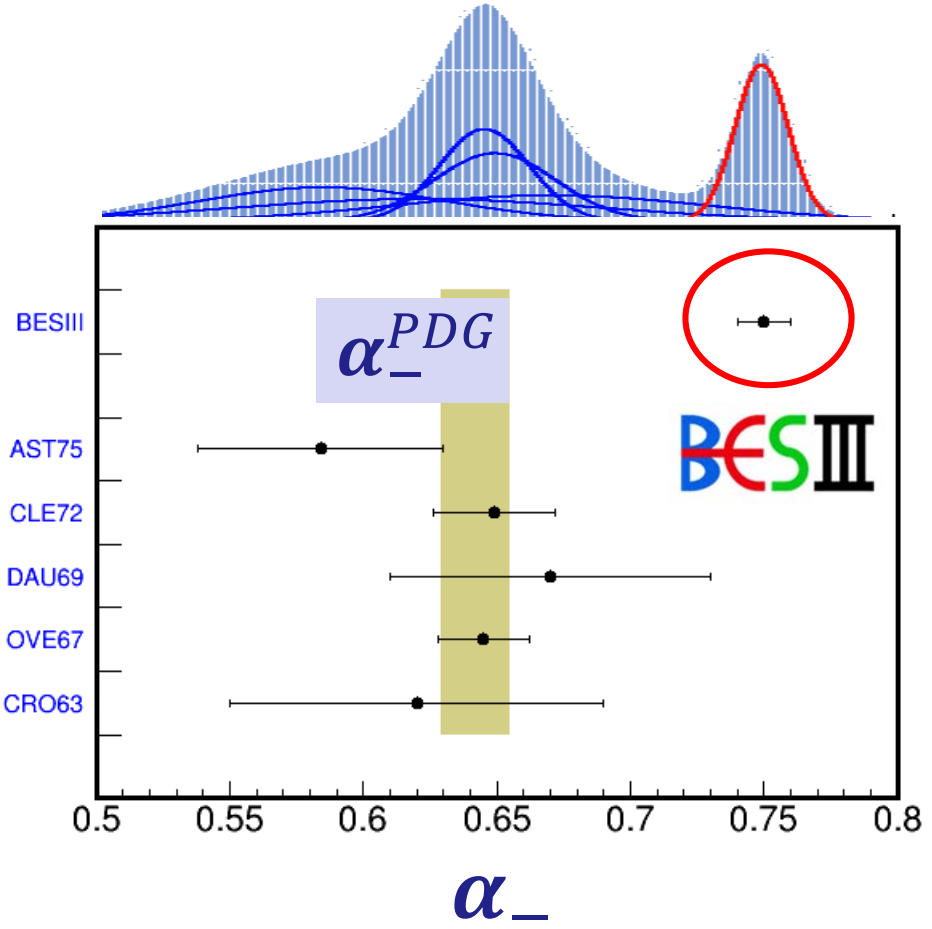
Implications of the $J/\psi \to \Lambda\bar{\Lambda}$ analysis

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



$\Longrightarrow$ Polarization:
max 25%

$\Lambda \to p\pi^-$: $\alpha_- = 0.750 \pm 0.009 \pm 0.004$



⇨ New value for e.g.
$\alpha(\Omega \to \Lambda K)$, $\alpha(\Xi \to \Lambda\pi)$,
$\alpha(\Lambda_c \to \Lambda K)$

⇨ Calls for reinterpretation of **all** Λ polarization measurements

17(3)% larger than α_-^{PDG}

arXiv:1808.08917

Can one observe strange baryon CPV?

CP test: $A_\Lambda = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$

$A_\Lambda = -0.006 \pm 0.012 \pm 0.007$

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

Previous result (using αP product):

$A_\Lambda = 0.013 \pm 0.021$

PS185 PRC54(96)1877

	Events	Error A_Λ	
BESIII(2018)	**$4.2 \cdot 10^5$**	**$1.2 \cdot 10^{-2}$**	**$1.31\ 10^9$ J/ψ**
BESIII	$3 \cdot 10^6$	$5 \cdot 10^{-3}$	10^{10} J/ψ $L=0.47 \cdot 10^{33}$ $\Delta\sqrt{s} = 0.9$ MeV
SCTF	$6 \cdot 10^8$	$3 \cdot 10^{-4}$	$L=10^{35}$ cm^{-2}s^{-1} $2 \cdot 10^{12}$ J/ψ
SCTF+ΔE?	$3 \cdot 10^9$	$1.4 \cdot 10^{-4}$	10^{12} J/ψ

a guess

CKM $A_\Lambda \sim (1\text{-}5) \cdot 10^{-5}$

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

$d\Gamma \propto W(\xi;\pi)$ ξ 9 kinematical variables 9D PhSp

Parameters: 2 production + 6 decay chains

$$\pi = (\alpha_\psi, \Delta\Phi, \alpha(\Xi^-), \phi(\Xi^-), \alpha_-, \alpha(\bar{\Xi}^+), \phi(\bar{\Xi}^+), \alpha_+)$$

Variables and parameters factorize:

$$W(\xi;\pi) = \sum_{k=1}^{M} f_k(\pi) T_k(\xi)$$

	$\Xi^-\bar{\Xi}^+$	$\Lambda\bar{\Lambda}$
$\Delta\Phi \neq 0$	$\Rightarrow M = 72$	(7)
$\Delta\Phi = 0$	$\Rightarrow M = 56$	(5)

$\Delta\Phi \neq 0$ is not neccesary!

but $\Delta\Phi \neq 0$ increases sensitivity...

E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song, arXiv:1809.04038 -> PRD

Can one observe strange baryon CPV?

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

$A_{\Xi\Lambda} = (0.0 \pm 5.1 \pm 4.4) \times 10^{-4}$ 1.2×10^8 Ξ^- 4.1×10^7 $\bar{\Xi}^+$

$$\frac{[\alpha(\Xi^-)\alpha_-(\Lambda) - \alpha(\bar{\Xi}^+)\alpha_+(\bar{\Lambda})]}{[\alpha(\Xi^-)\alpha_-(\Lambda) + \alpha(\bar{\Xi}^+)\alpha_+(\bar{\Lambda})]}$$

present best limit...

HyperCP PRL 93 (2004) 262001

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

$$\{1 + \alpha(\Xi^-)\alpha_-(\Lambda)\cos\theta_p\}\{1 + \alpha(\bar{\Xi}^+)\alpha_+(\bar{\Lambda})\cos\theta_{\bar{p}}\}$$

...just (random) 4 terms out of 72 ...

$4.3\text{x}10^4$ BESIII PRD93,072003 ($0.223\text{x}10^9$ J/ψ) ⇨ $2\text{x}10^6$ (BESIII10^{10} J/ψ)

STCF (200 ×): $4 \times 10^8 \Rightarrow$ Error $A_{\Xi\Lambda} \sim 1.6 \times 10^{-4}$

primitive guess

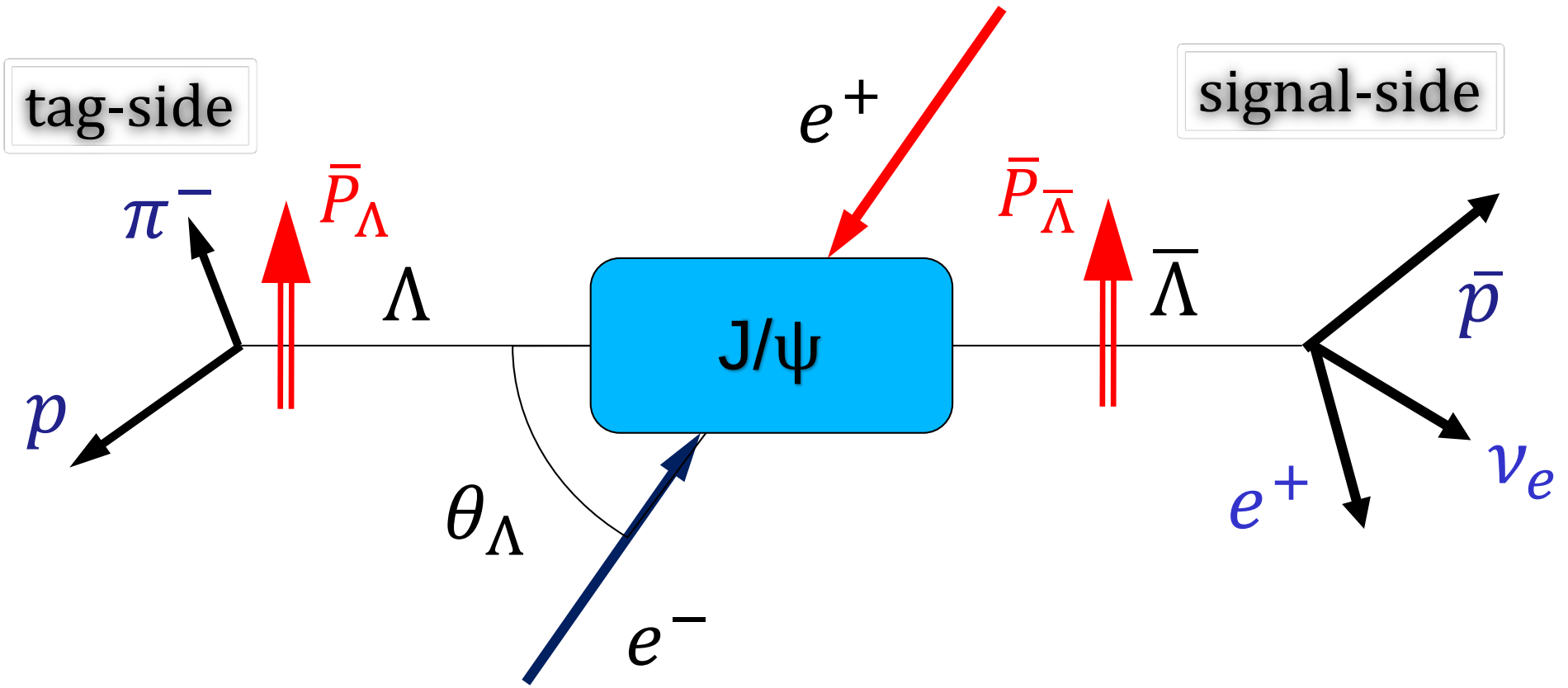
$-3 \times 10^{-5} \le A_\Lambda \le 4 \times 10^{-5}$
$-2 \times 10^{-5} \le A_\Xi \le 1 \times 10^{-5}$
$-5 \times 10^{-5} \le A_{\Xi\Lambda} \le 5 \times 10^{-5}$

CKM

Tandean,Valencia PRD67 (2003) 056001

	s/p amplitude ratio	
	Λ	Ξ
PDG	0.368(11)	0.243(13)
BESIII	0.455(10)	0.204(10)

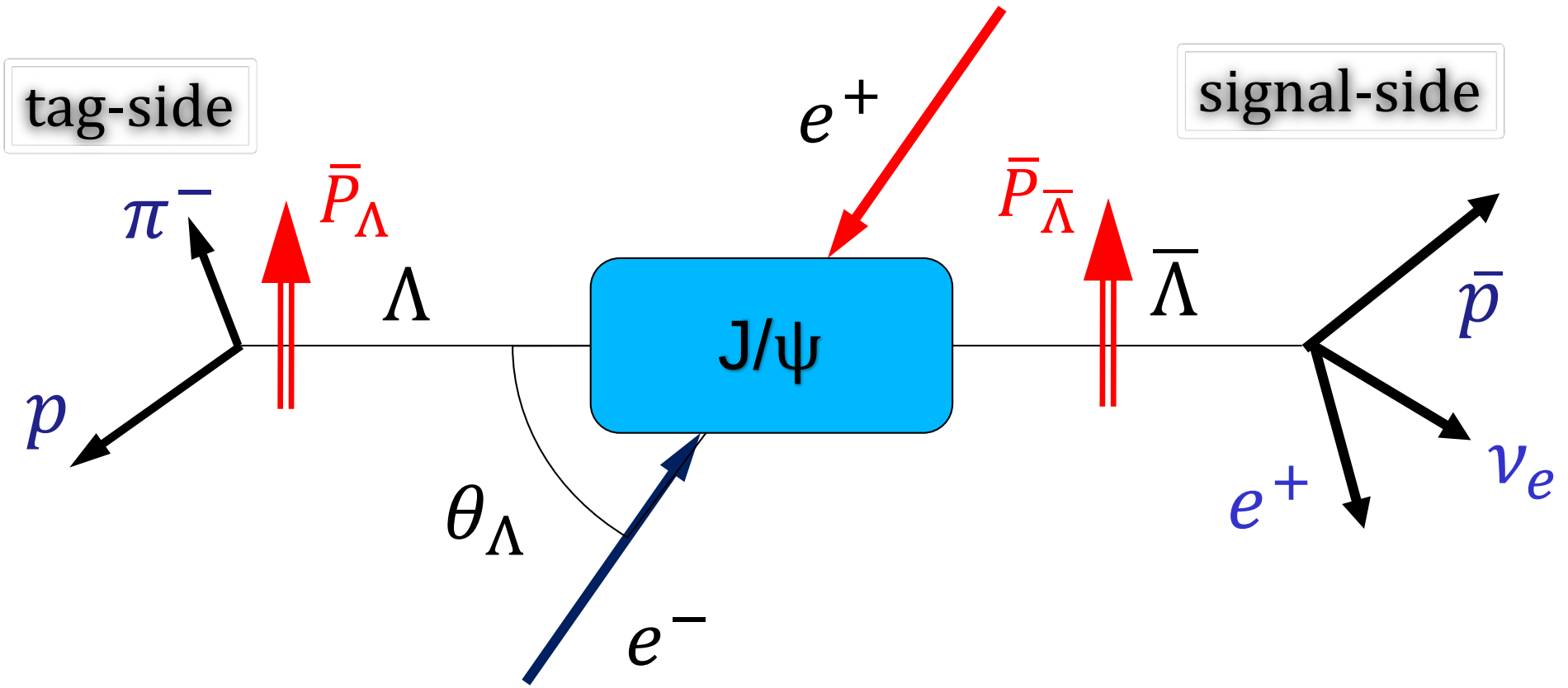
Double tag: polarization + spin correlations ...



"Byproduct" of BESIII and STCF run at $J/\psi, \psi'$:

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

Double tag: polarization + spin correlations ...

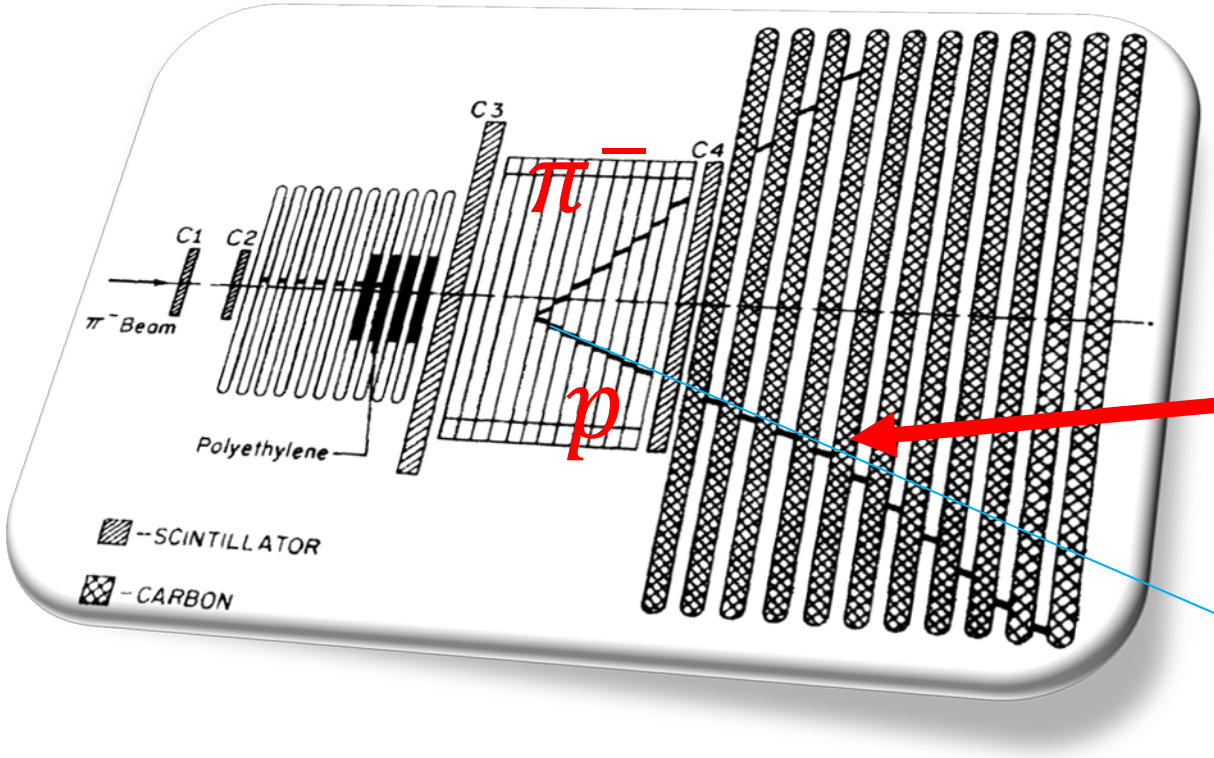


"Byproduct" of BESIII and STCF run at $J/\psi, \psi'$:

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

Thank you!

$\Lambda \rightarrow p\pi^-$



Secondary scattering of polarized proton

Principle of previous α_- measurements

Cronin, Overseth Phys. Rev. 129, 1795 (1963)

Overseth, Roth Phys. Rev. Lett. 19, 391 (1967)