Precision hyperon physics at BESIII

Hai-Bo Li (IHEP, CAS)

11th Workshop on Hadron Physics in China and Opportunities Worldwide

Nankai University, Tianjin, Aug. 22-28, 2019

Roadmap of CP violation in flavored hadrons

1980

2008

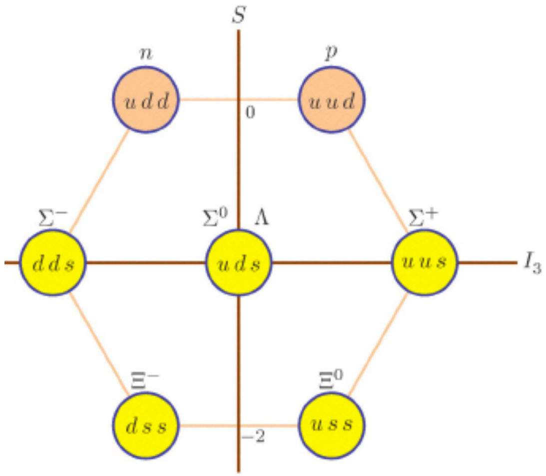
- In 1964, the first CPV was discovered in Kaon ;
- In 2001, CPV in B was established by two B-factories;
- In 2019, CPV discovered in D meson: 10^{-4}, 10^{8} reconstructed D mesons (LHCb)
- All are consistent with CKM theory in the Standard model
- But no evidence was found in baryon system?

Baryon asymmetry of the Universe means that there must be non-SM CPV source.

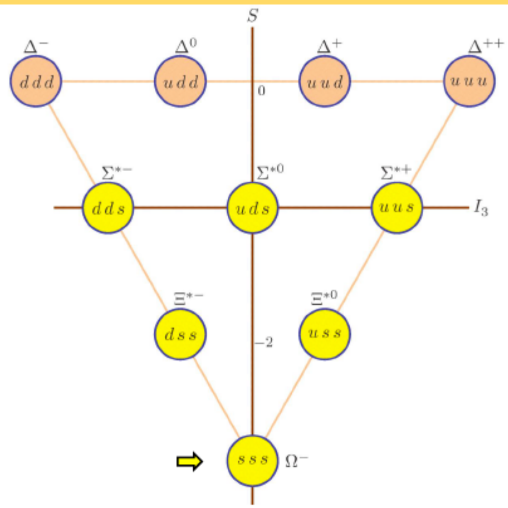
CPV in hyperon decays and New physics

CPV in SM is small :			# events	Experiments
B meson :	$O(1)$	discovered (2001)	10^3	***B factory***
K meson :	$O(10^{-3})$	discovered (1964)	10^6	***Fix targets***
D meson :	$O(10^{-4})$	evidence(2019)	10^8	LHCb
Hyperon :	$O(10^{-5})$	no evidence	$O(10^8)$	***Fix targets***
				→ BESIII ?

Flavor-SU(3) Octet of spin ½



Flavor-SU(3) Decuplet of spin 3/2



Why Hyperon physics at BESIII?

10 billion J/psi events collected

- Large BRs in J/ψ decays
- Quantum correlated pair productions
- Background free

[Hai-Bo Li, arXiv:1612.01775](https://arxiv.org/abs/1612.01775)
[A. Adlarson, A. Kupsc, arXiv:1908.03102](https://arxiv.org/abs/1908.03102)

Decay mode	$\mathcal{B}(\times 10^{-3})$	N_B $(\times 10^6)$	Detection Efficiency	Number of reconstructed
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5	40%	3200 X 10^3
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9	25%	600 X 10^3
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4	24%	640 X 10^3
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.1 ± 0.5		
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.10 ± 0.12	11.0 ± 1.2		
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.20 ± 0.24	12.0 ± 2.4	14%	670 X 10^3
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0	19%	810 X 10^3
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.2 ± 1.4		
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.59 ± 0.15	5.9 ± 1.5		
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.05 ± 0.01	0.15 ± 0.03		

Advantage at e^+e^- machine

Known initial 4-momentum

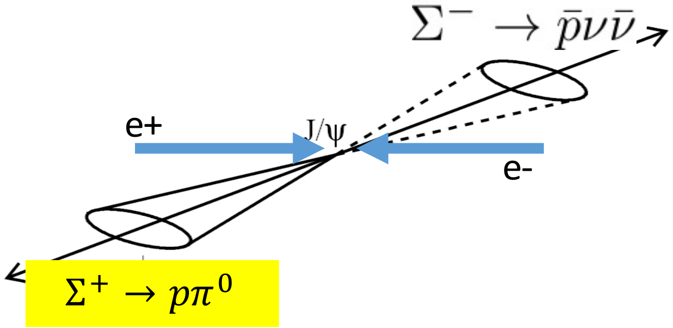
Strongly boosted

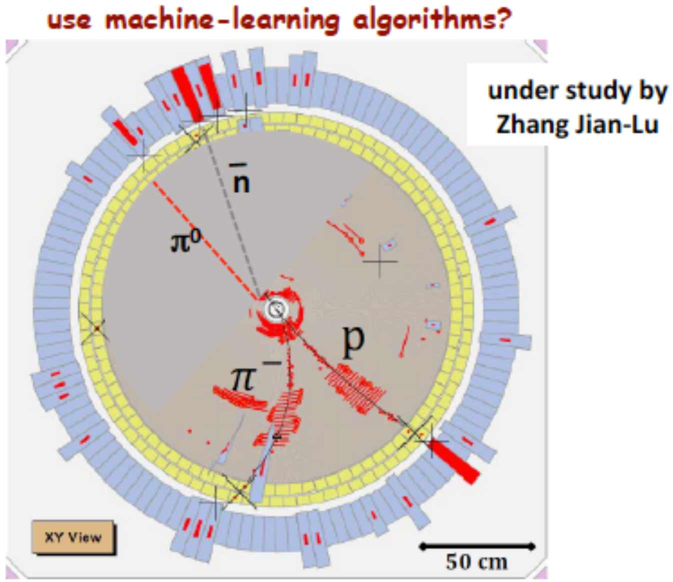
Substantial polarization

Decay with neutron & π^0

Decay with invisibles

Single tag

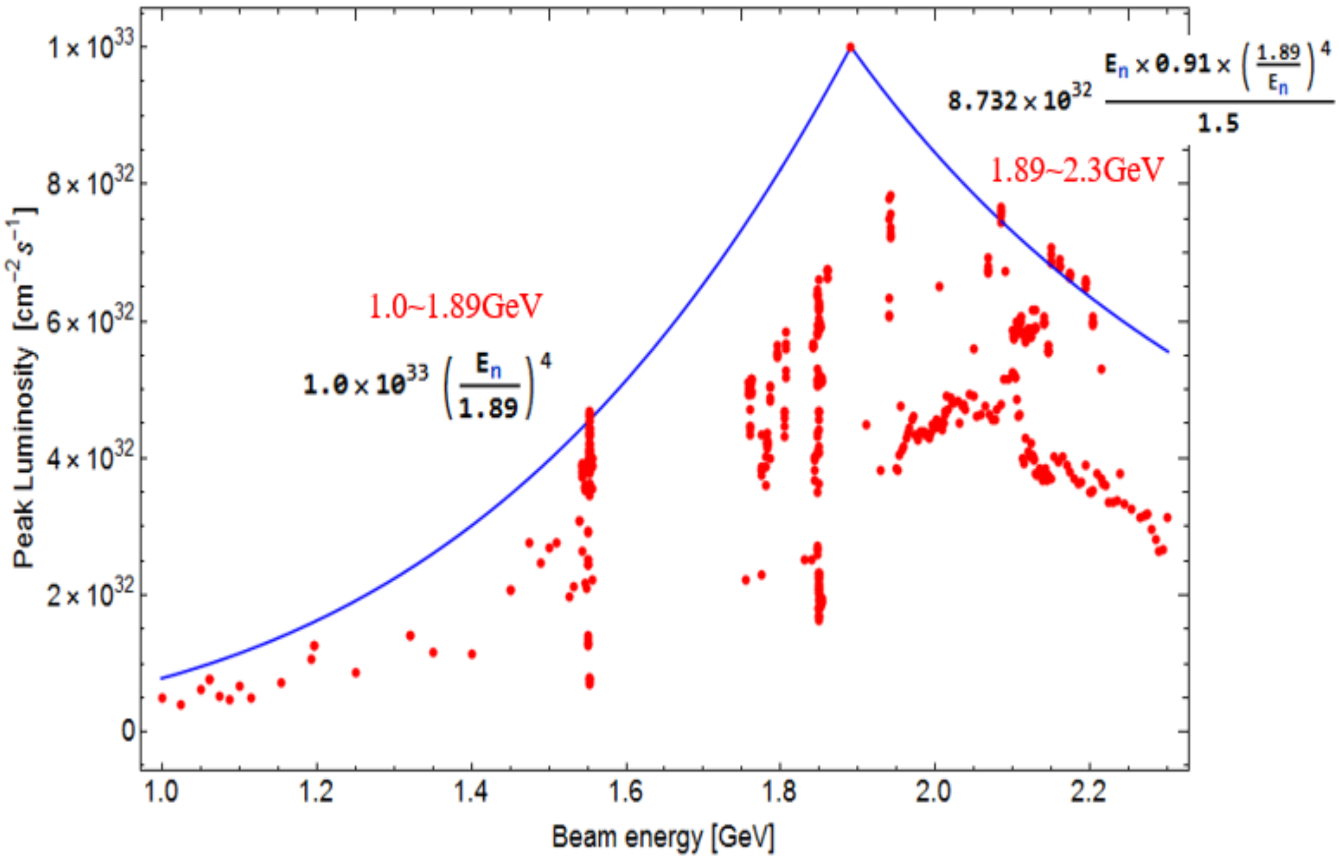




Both hyperons can be reconstructed, and the systematic uncertainties are under control.

BEPCII luminosity optimized for ψ(3770) running

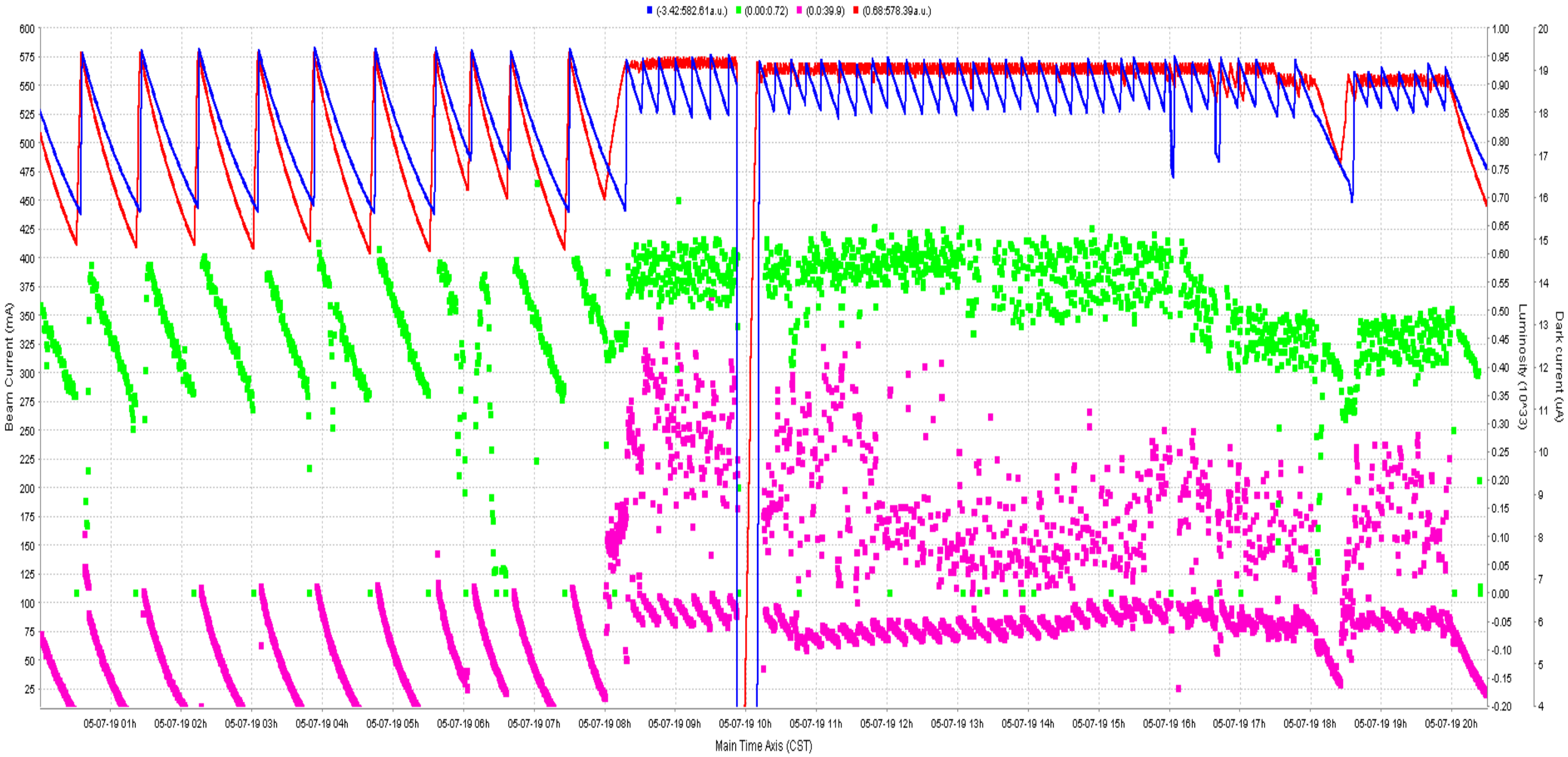
A factor of 2 gain for lattice optimized at J/ψ running



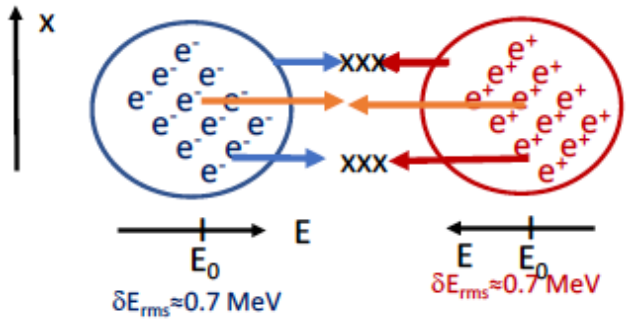
Gain on integrated luminosity from “Topup” injection

12 injections every 12 hours

20% gain on the integrated luminosity

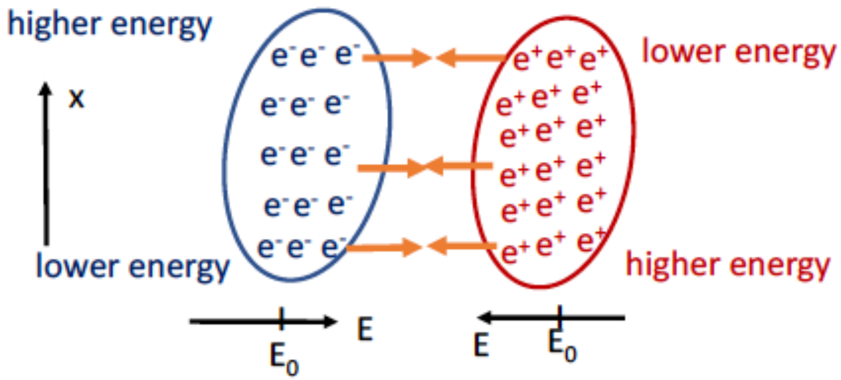


Monochromatic collision: factor of 10 from reduction of e⁺e⁻ CM spread

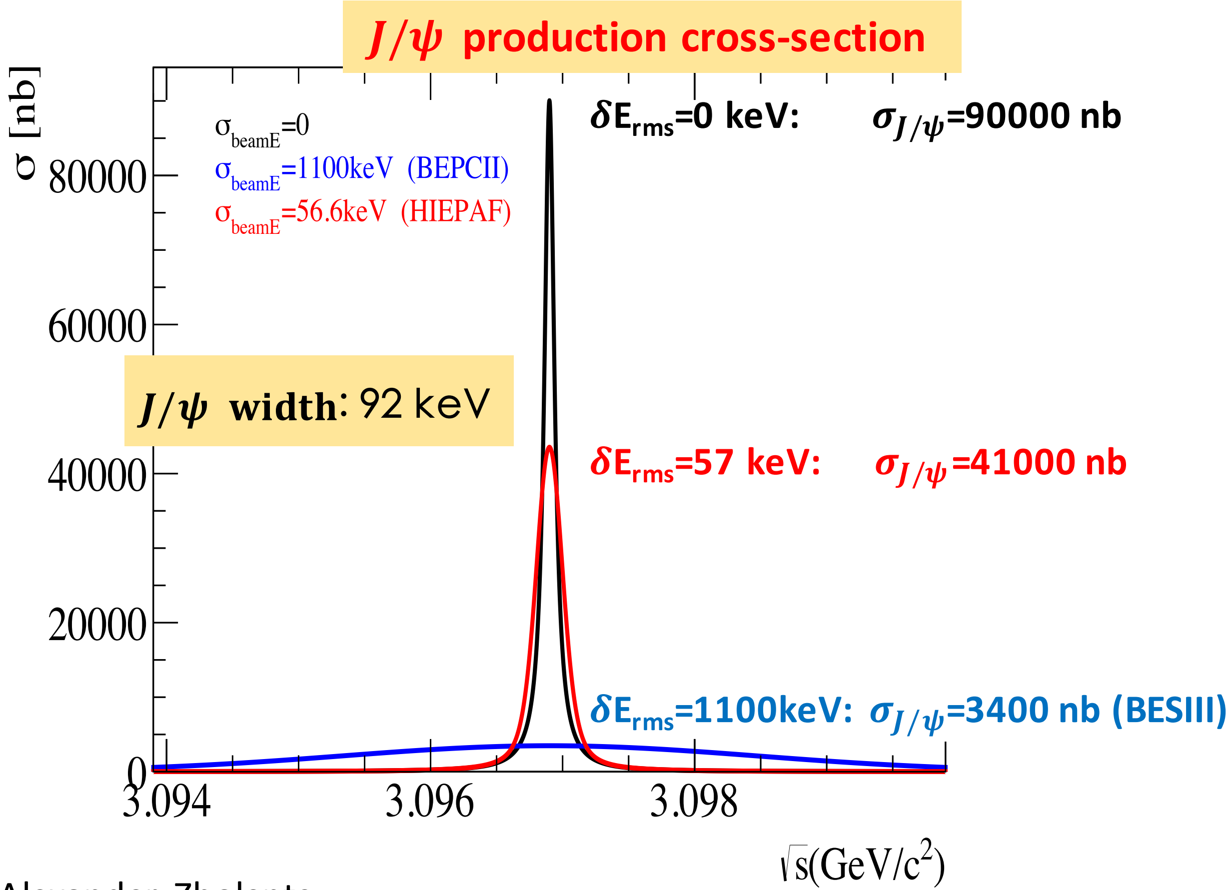


only e^+e^- pairs with E_{cm}=3096 ± 0.14 MeV
can produce a J/ψ, ~1/30th of the total

introduce dispersion



more e^+e^- pairs with E_{cm}=3096 ± 0.14 MeV



Alexander Zholents
CERN SL/92-27/AP

Future J/ψ factory

BESIII collected 10 billion J/ψ

Current technology "Topup" $\times 2$ +
"improved technology "monochromatic collision" $\times 10$ +
Someday with new facility (J/ψ factory) $\times 100$

10^{13} J/ψ per year at a super J/ψ factory

10 Billions of hyperon pairs produced

Billion of hyperon pairs reconstructed

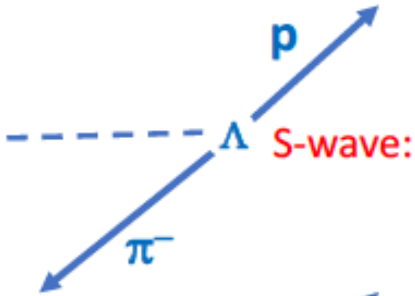
CPV: $10^{-4} - 10^{-5}$

Challenge the SM

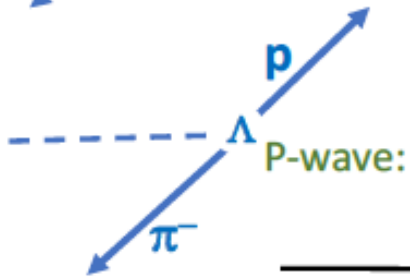
Example CPV in $\Lambda \to p\pi^-$ ($\bar{\Lambda} \to \bar{p}\pi^+$)

-- assume CPV is in P-wave --

From S. L. Olsen



S-wave: $S\,e^{i\delta^S}$

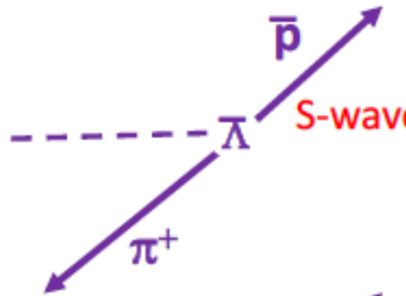


P-wave: $P\,e^{i\delta^P + i\phi_{CP}}$

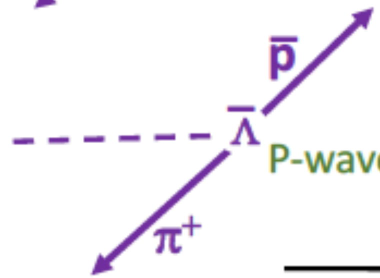
$$e^{-i\delta^S}\left(S + P\,e^{i(\delta^P - \delta^S) + i\phi_{CP}}\right)$$

or $(\Delta_s = \delta^P - \delta^S)$

$$e^{-i\delta^S}\left(S + P\,e^{i\Delta_s + i\phi_{CP}}\right)$$



S-wave: $S\,e^{i\delta^S}$



P-wave: $P\,e^{i\delta^P - i\phi_{CP}}$

$$e^{-i\delta^S}\left(S + P\,e^{i\Delta_s - i\phi_{CP}}\right)$$

α, β *and* γ parameters for hyperon decays

1957

Chen Ning Yang

Tsung-Dao Lee

Phys. Rev. 108 1645 (1957)

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. LEE* AND C. N. YANG

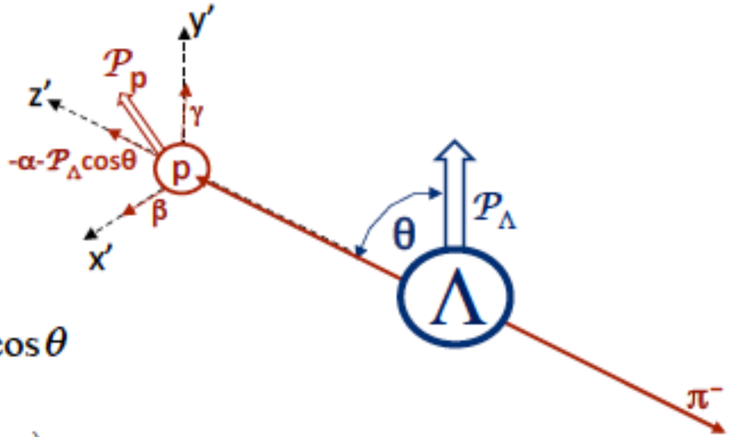
Institute for Advanced Study, Princeton, New Jersey

(Received October 22, 1957)

$\Lambda \to p\pi^-, \quad \Sigma^+ \to p\pi^0$

$$\bar{S} = -\sum_i S_i e^{i(\delta_i^S - \phi_i^S)},$$

$$\bar{P} = \sum_i P_i e^{i(\delta_i^P - \phi_i^P)}.$$



$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$$

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

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

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

$$\gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

CP asymmetry $A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \quad B = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}.$

CPV observables

Sandip PAKVASA

hep-ph/991023v1
hep-ph/0002210

From S. L. Olsen

decay rate difference

$$\Delta\Gamma = \frac{\Gamma_{\bar{p}\pi^+} - \Gamma_{p\pi^-}}{\Gamma} \approx \sqrt{2}\left(T_{3/2} \big/ T_{1/2} \right) \sin\Delta_S \sin\phi_{CP}$$

← $T_{3/2(1/2)}$: Ispin=3/2 (1/2) ampl & $\Delta_s = \delta_{3/2} - \delta_{1/2}$

decay asymmetry difference

$$\alpha_{\mp} = \pm\frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2} = \pm\frac{2|S||P|\cos(\Delta_S \pm \phi_{CP})}{|S|^2 + |P|^2}$$

$$\Delta\alpha = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = \frac{\sin\Delta_S \sin\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\Delta_S \tan\phi_{CP}$$

← for $\Lambda \to p\pi$, need measurement of $\Delta_s = \delta_S - \delta_P$

final-state polarization difference

$$\beta_{\mp} = \pm\frac{2\mathrm{Im}(S^* P)}{|S|^2 + |P|^2} = \pm\frac{2|S||P|\sin(\Delta_S \pm \phi_{CP})}{|S|^2 + |P|^2}$$

$$\Delta\beta = \frac{\beta_- + \beta_+}{\alpha_- - \alpha_+} = \frac{\cos\Delta_S \sin\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\phi_{CP}$$

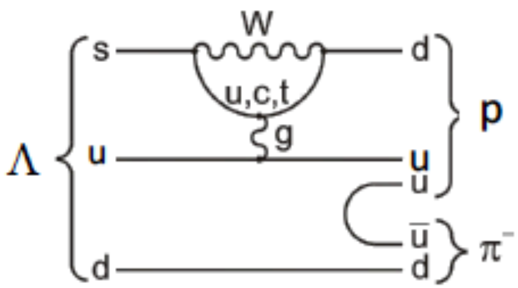
$$\frac{\beta_- - \beta_+}{\alpha_- - \alpha_+} = \frac{\sin\Delta_S \cos\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\Delta_S$$

← strong phase cancels out
← measures the strong phase

} only practical in BESIII for $\Xi \to \Lambda\pi$ or $\Omega^- \to \Lambda K$

Constraints from Kaon decays

He & Valencia PRD 52, 5257

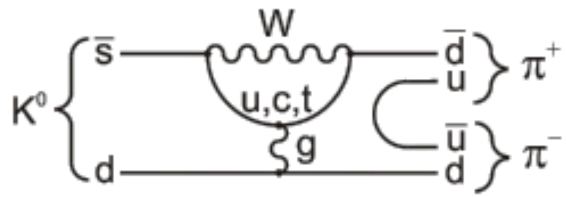


S- and P-waves
(parity violating
& conserving)

$\Lambda \rightarrow p\pi^-$	A_{NP}	
S-wave	$<6\times10^{-5}$	parity violating
P-wave	$<3\times10^{-4}$	parity conserving

$A_{SM} \sim 10^{-5}$

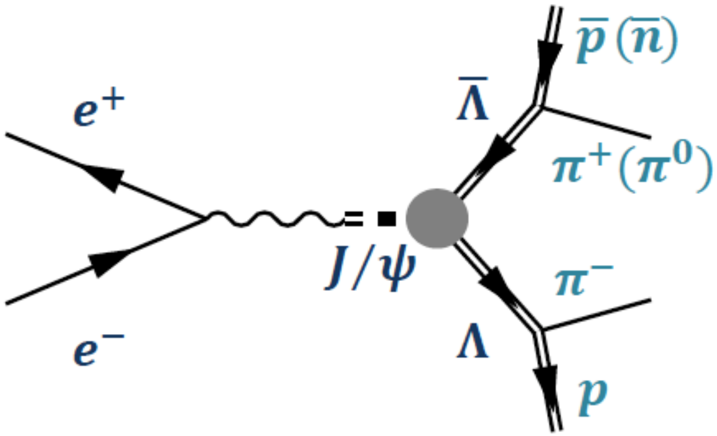
$Re(\varepsilon'/\varepsilon)=(1.6+0.3)\times10^{-3}$



S-wave only
(parity violating)

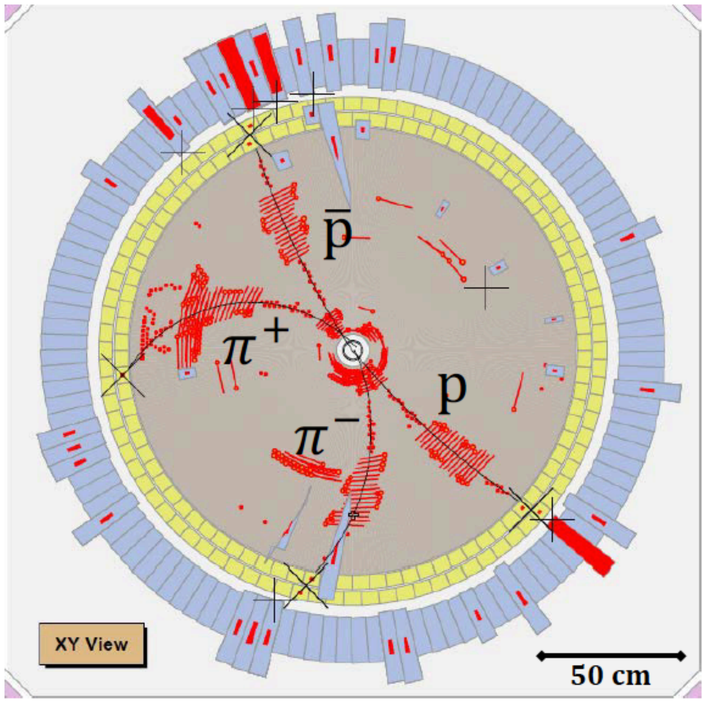
CPV measurement in Kaon system strongly constrains NP in S-waves, but no P-waves. Thus, searches of CPV in hyperon are complementary to those with Kaons.

Entangled hyperon pairs



Kang, Li, Lu, Phys.Rev. D81 (2010) 051901

$$|\Lambda\bar{\Lambda}\rangle^{C=-1} = \chi_1 \frac{1}{\sqrt{2}}[|\Lambda\rangle|\bar{\Lambda}\rangle - |\bar{\Lambda}\rangle|\Lambda\rangle],$$



To determine parameters:

$$\alpha(\Lambda \to p\pi^-) = \alpha_-$$

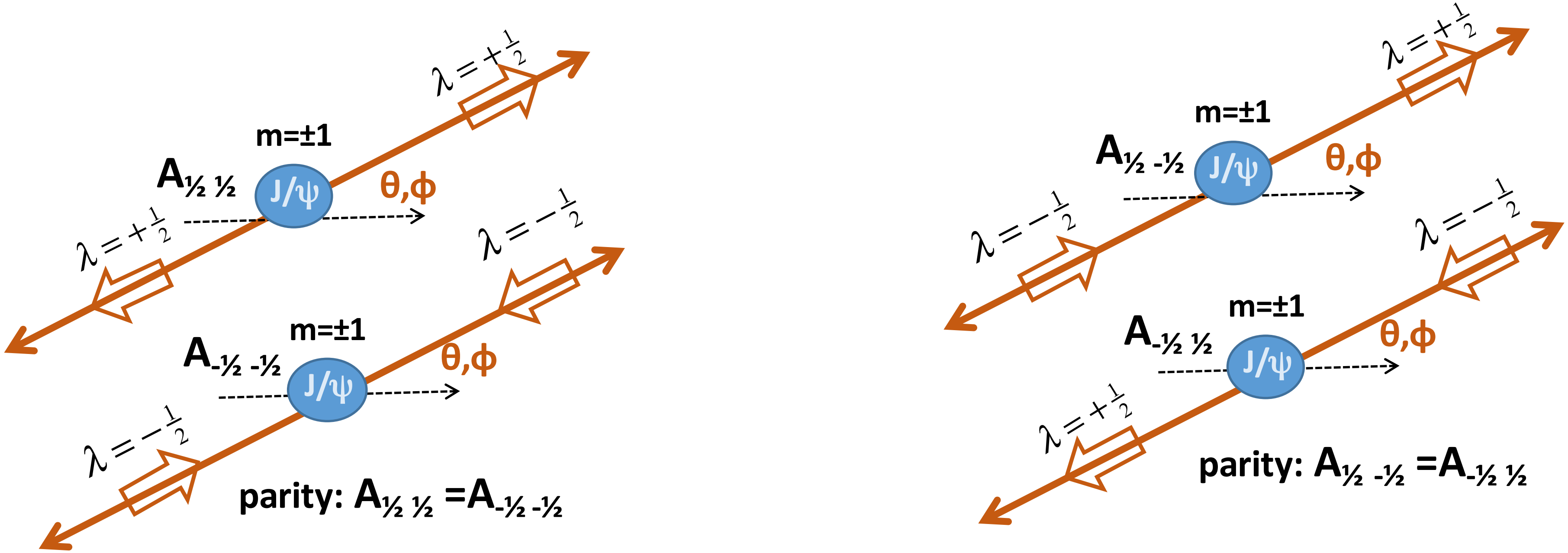
$$\alpha(\bar{\Lambda} \to \bar{p}\pi^+) = \alpha_+$$

$$\alpha(\bar{\Lambda} \to \bar{n}\pi^0) = \bar{\alpha}_0$$

$$\alpha(\Lambda \to n\pi^0) = \alpha_0$$

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

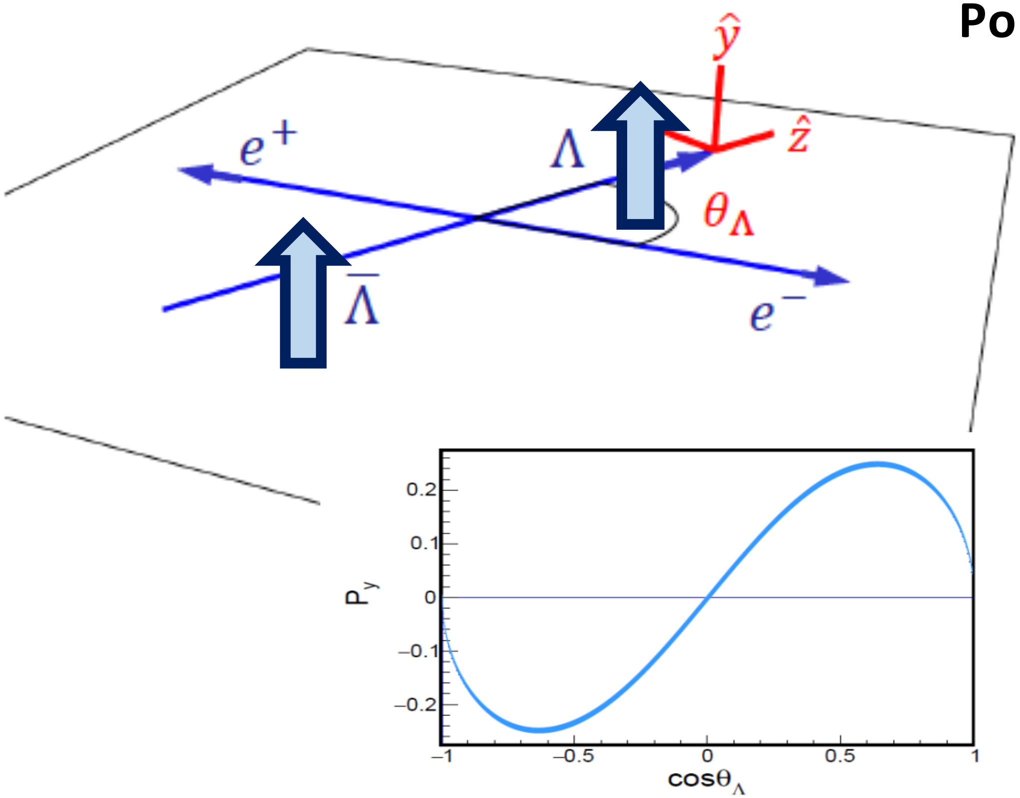
Production: 2 independent helicity amplitudes: $A_{½\,½}$, $A_{½\,-½}$



Δ= complex phase between $A_{½\,½}$ and $A_{½\,-½}$

$$\frac{d|\mathcal{M}|^2}{d\cos\theta} \propto (1+\alpha_{J/\psi}\cos^2\theta), \quad \text{with} \quad \alpha_{J/\psi} = \frac{|A_{1/2,-1/2}|^2 - 2|A_{1/2,1/2}|^2}{|A_{1/2,-1/2}|^2 + 2|A_{1/2,1/2}|^2}$$

if $\Delta \neq 0$, Λ and $\bar{\Lambda}$ are transversely polarized



Polarization is:

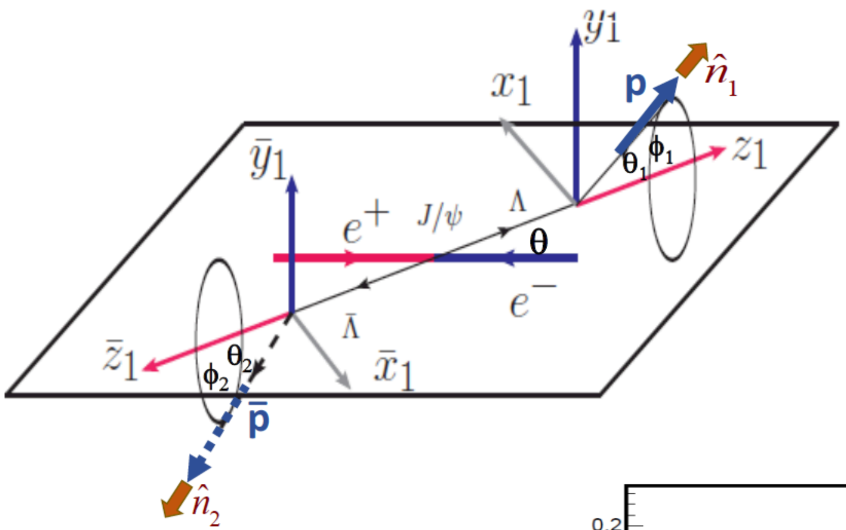
perpendicular to the production plane

θ_Λ-dependent

Same direction for Λ and $\bar{\Lambda}$

Correlated 5-dim. angular distribution

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



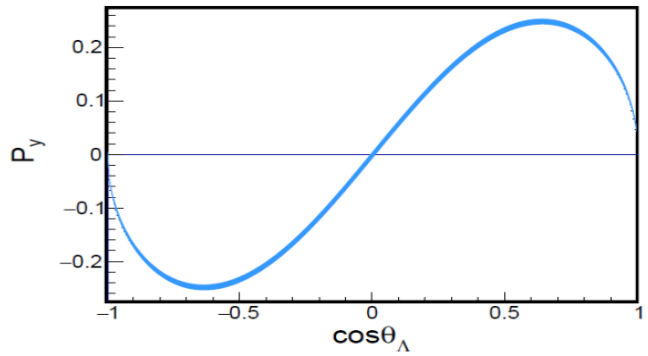
$$+\alpha_-\alpha_+\left[\sin^2\theta_\Lambda\left(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y}\right)+\left(\cos^2\theta_\Lambda+\alpha_\psi\right)n_{1,z}n_{2,z}\right]$$

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

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

polarization-term

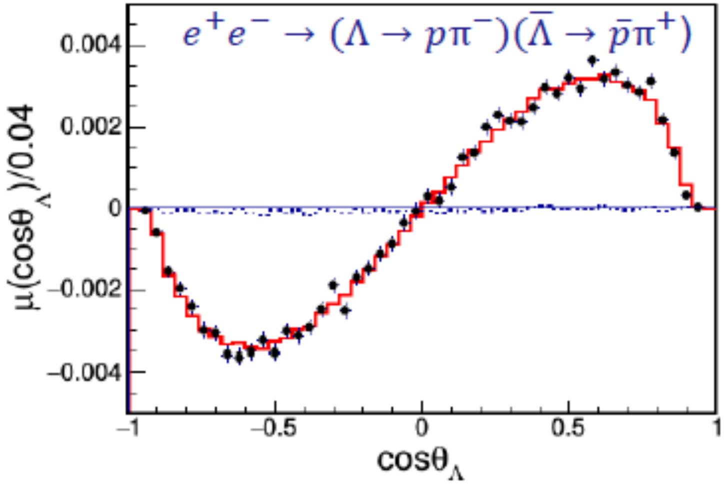
independent α_- and α_+ dependence

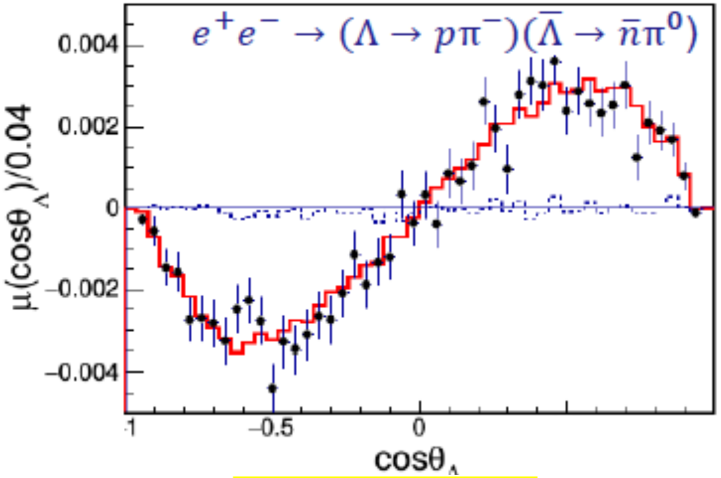


$$P_y(\cos\theta_\Lambda)=\frac{\sqrt{1-\alpha_\psi^2}\,\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}$$

Fit results

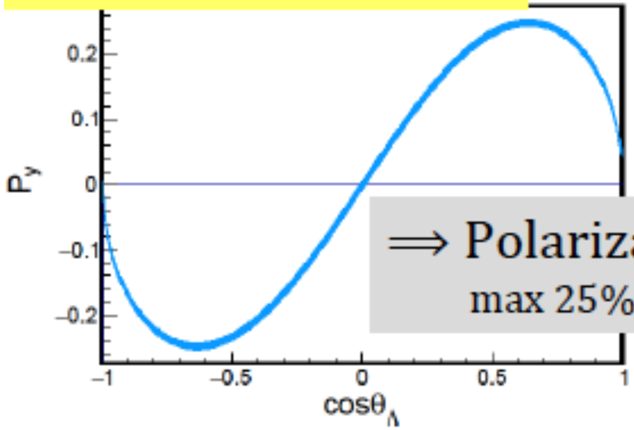
ΔΦ=42.3°±0.6°±0.5°



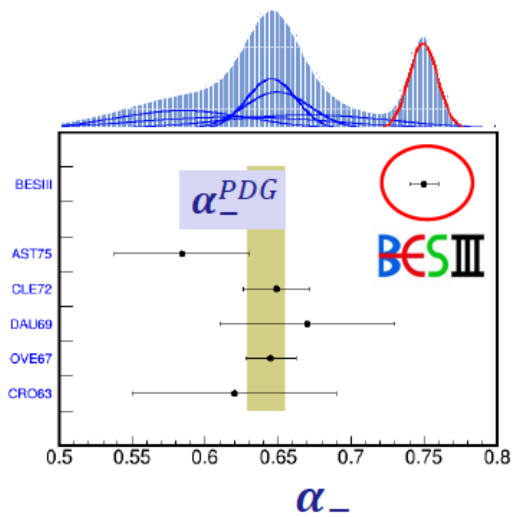


$\Lambda \to p\pi^-$: α_=0.750±0.009±0.004

ΔΦ=42.3°±0.6°±0.5°



⟹ Polarization: max 25%



BESIII results with 1.3 billion J/ψ

Nature Physics May 2019
arXiv:1808.08917

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [14]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [16]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [16]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [16]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

I have comments on these 3 items:

← 1) 3x precision improvement -same data sample-

← 2) ~7σ upward shift from all previous measurements

← 3) ~3σ difference from 1. Is this reasonable?

$\alpha_+/\bar{\alpha}_0 \neq 1$: $\Delta I=1/2$ law violation

From S.L. Olsen

lifetime=12 ns

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

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

lifetime=0.21 ns

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

$$\langle \bar{\Lambda} | \bar{p}\pi^+ \rangle = T_{1/2}\left(1 + \tfrac{1}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)\right) \Rightarrow \alpha_+ = \alpha_{\Delta I=1/2}\left(1 + \tfrac{1}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)\right)$$

$$\langle \bar{\Lambda} | \bar{n}\pi^0 \rangle = T_{1/2}\left(1 - \sqrt{2}\left(T_{3/2}/T_{1/2}\right)\right) \Rightarrow \bar{\alpha}_0 = \alpha_{\Delta I=1/2}\left(1 - \sqrt{2}\left(T_{3/2}/T_{1/2}\right)\right)$$

$$\frac{\alpha_+}{\bar{\alpha}_0} = \frac{1 + \frac{1}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)}{1 - \sqrt{2}\left(T_{3/2}/T_{1/2}\right)} \approx 1 + \left(\tfrac{1}{\sqrt{2}} + \sqrt{2}\right)\left(T_{3/2}/T_{1/2}\right) = 1 + \tfrac{3}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)$$

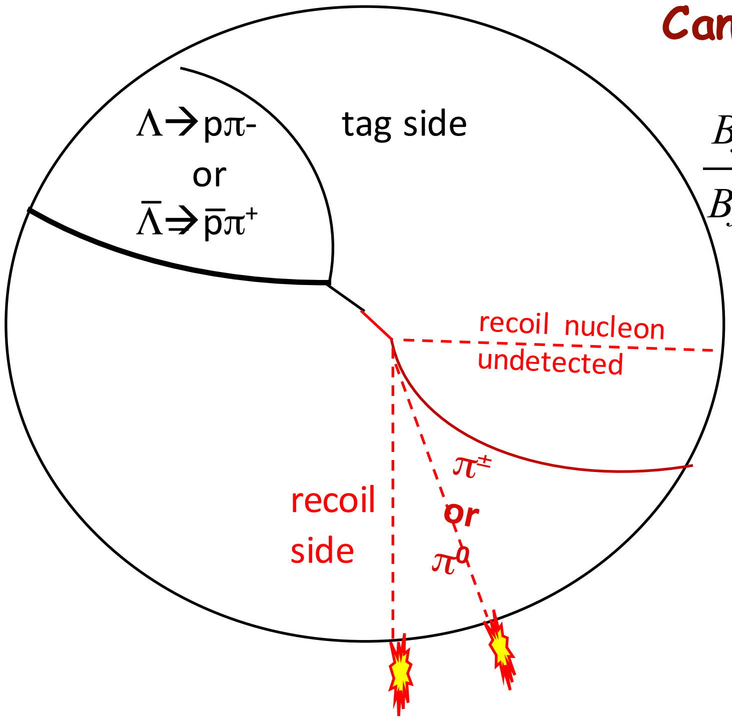
$$\frac{\alpha_+}{\bar{\alpha}_0} - 1 = 0.087 \pm 0.030 = \tfrac{3}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right) \quad \Rightarrow \left(T_{3/2}/T_{1/2}\right) = 0.041 \pm 0.014$$

good agreement

$T_{3/2} \neq 0$: decay rate asymmetry in BESIII?

From S.L. Olsen

use *partial* reconstruction of $J/\psi \rightarrow \Lambda\bar{\Lambda}$?



Can BESIII measure this with low systematic errors?

$$\frac{Bf(\Lambda \rightarrow n\pi^0)}{Bf(\Lambda \rightarrow p\pi^-)} - \frac{Bf(\bar{\Lambda} \rightarrow \bar{n}\pi^0)}{Bf(\bar{\Lambda} \rightarrow \bar{p}\pi^+)} = \frac{N(\bar{\Lambda}_{tag} + \pi^0)}{N(\bar{\Lambda}_{tag} + \pi^-)} - \frac{N(\Lambda_{tag} + \pi^0)}{N(\Lambda_{tag} + \pi^+)}$$

Detect a $\Lambda \rightarrow p\pi^-$ or $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ accompanied by a $\pi^\pm$ or π^0
Infer presence of the recoil nucleon by missing mass

the 10^{10} J/ψ data sample has >1M events in each category ➔ statistical precision $\approx 10^{-3}$

α_- FOR $\Lambda \to p\pi^-$

INSPIRE search

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.750 \pm 0.009 \pm 0.004$	420k	ABLIKIM	2018AG	BES3	J/ψ to $\Lambda\overline{\Lambda}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.584 ± 0.046	8500	ASTBURY	1975	SPEC	
0.649 ± 0.023	10325	CLELAND	1972	OSPK	
0.67 ± 0.06	3520	DAUBER	1969	HBC	From Ξ decay
0.645 ± 0.017	10130	OVERSETH	1967	OSPK	Λ from $\pi^- p$
0.62 ± 0.07	1156	CRONIN	1963	CNTR	Λ from $\pi^- p$

References:

ABLIKIM	2018AG	arXiv:1808.08917	
ASTBURY	1975	NP B99 30	Measurement of the Differential Cross Section and the Spin Correlation Parameters P, A, and R in the Backward Peak of $\pi^- p \to K^0\Lambda$ at 5 GeV/c
CLELAND	1972	NP B40 221	A Measurement of the β-Parameter in the Charged Nonleptonic Decay of the Λ^0 Hyperon
DAUBER	1969	PR 179 1262	Production and Decay of Cascade Hyperons
OVERSETH	1967	PRL 19 391	Time Reversal Invariance in Λ Decay

α_+ FOR $\overline{\Lambda} \to \overline{p}\pi^+$

INSPIRE search

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.758 \pm 0.010 \pm 0.007$	420k	ABLIKIM	2018AG	BES3	J/ψ to $\Lambda\overline{\Lambda}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-0.755 \pm 0.083 \pm 0.063$	$\approx$ 8.7k	ABLIKIM	2010	BES	$J/\psi \to \Lambda\overline{\Lambda}$
-0.63 ± 0.13	770	TIXIER	1988	DM2	$J/\psi \to \Lambda\overline{\Lambda}$

References:

ABLIKIM	2018AG	arXiv:1808.08917	
ABLIKIM	2010	PR D81 012003	Measurement of the Asymmetry Parameter for the Decay $\overline{\Lambda} \to \overline{p}\pi^+$
TIXIER	1988	PL B212 523	Looking at CP Invariance and Quantum Mechanics in $J/\psi \to \Lambda\overline{\Lambda}$ Decay

PDG2019 updates

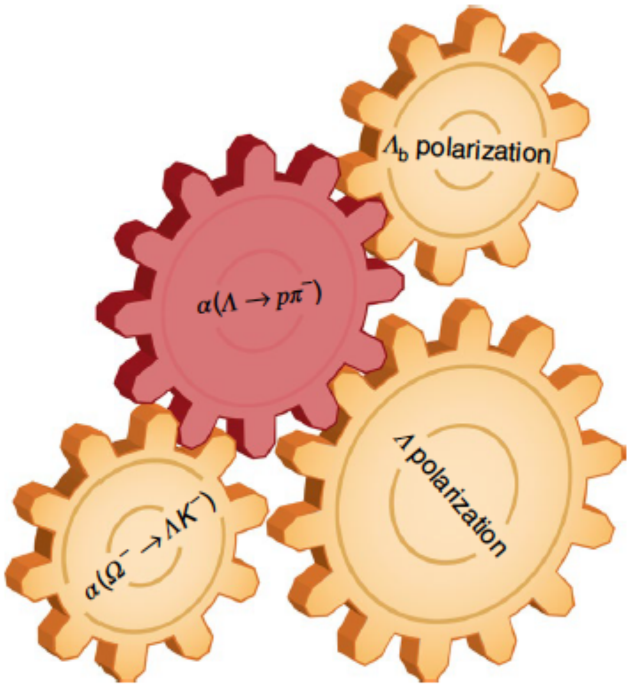
news & views

PARTICLE PHYSICS

Anomalous asymmetry

A measurement based on quantum entanglement of the parameter describing the asymmetry of the Λ hyperon decay is inconsistent with the current world average. This shows that relying on previous measurements can be hazardous.

Ulrik Egede



New input for many other measurements：

1) polarization

2) Asymmetry of the Λ_b and Λ_c

3) CPV in Λ_b and Λ_c decays

4) Decays of other charmed and beauty baryons

CP violation with 10 billion J/ψ, and future facilities

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

From A. Kupas

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

Previous result:

$A_\Lambda = 0.013 \pm 0.021$ PS185 PRC54(96)1877

BESIII

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

	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 $L=0.47 \cdot 10^{33}$ $\Delta E = 0.9$ MeV
SuperTauCharm	$6 \cdot 10^8$	$3 \cdot 10^{-4}$	$L=10^{35}$ cm^{-2}s^{-1} $2 \cdot 10^{12}$ J/ψ $\Delta E = 0.9$ MeV
SuperTauCharm + reduced ΔE	$3 \cdot 10^9$	$1.4 \cdot 10^{-4}$	$L=10^{35}$ cm^{-2}s^{-1} 10^{13} J/ψ $\Delta E < 0.9$ MeV??

a guess

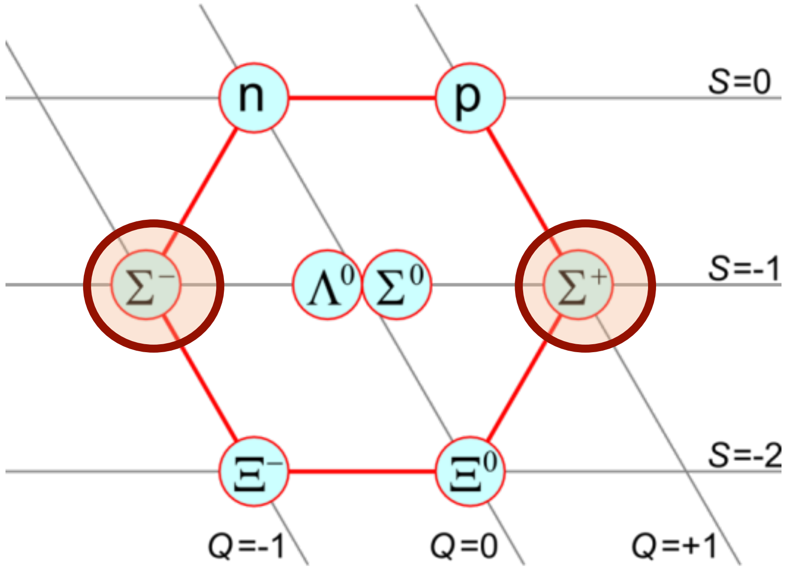
$-3 \times 10^{-5} \leq A_\Lambda \leq 4 \times 10^{-5}$
$-2 \times 10^{-5} \leq A_\Xi \leq 1 \times 10^{-5}$
$-5 \times 10^{-5} \leq A_{\Xi\Lambda} \leq 5 \times 10^{-5}$

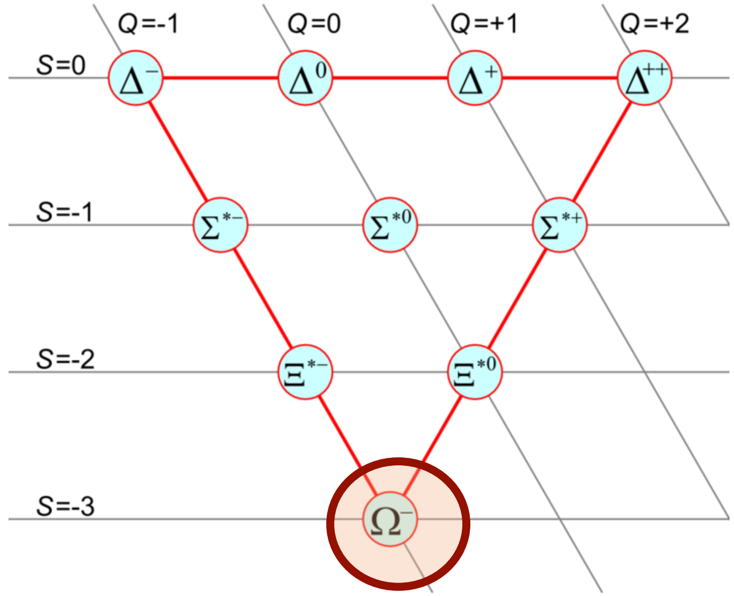
CKM

Tandean,Valencia PRD67, 056001

$$\sigma(A_\Lambda) = \frac{\sqrt{1+\varrho}}{\sqrt{2}\alpha_\Lambda}\sigma(\alpha_\Lambda)$$

How about other weakly decaying hyperons?





$\Sigma^+ \to p\pi^0$

$\to n\pi^+$

$\Sigma^- \to n\pi^-$

final state baryon polarization measurements impractical with BESIII

$\Omega^- \to \Lambda K^-$

$\to \Xi^0\pi^-$

$\to \Xi^-\pi^0$

need $\psi' \to \Omega^-\overline{\Omega}^+$ data rates are low

CPV observables in $\Xi^- \rightarrow \Lambda\pi$ decay

decay rate difference

$$\frac{\Gamma_{\bar{\Lambda}\pi^+} - \Gamma_{\Lambda\pi^-}}{\Gamma} \equiv 0$$

← $\Lambda\pi$ final states are purely Ispin=1, only $\Delta I=1/2$ transitions allowed, no $\Delta I=3/2$ transition possible

decay asymmetry difference

$$\alpha_{\mp} = \pm \frac{2\,\mathrm{Re}(S^* P)}{|S|^2 + |P|^2} = \pm \frac{2|S||P|\cos\left(\Delta_S \pm \phi_{CP}\right)}{|S|^2 + |P|^2}$$

$$\frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = \frac{\sin\Delta_S \sin\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\Delta_S \tan\phi_{CP}$$

← in this case, the strong phase ($\Delta_s = \delta_S - \delta_P$) is measureable (see below)

final-state polarization difference

$$\beta_{\mp} = \pm \frac{2\,\mathrm{Im}(S^* P)}{|S|^2 + |P|^2} = \pm \frac{2|S||P|\sin\left(\Delta_S \pm \phi_{CP}\right)}{|S|^2 + |P|^2}$$

$$\frac{\beta_- + \beta_+}{\alpha_- - \alpha_+} = \frac{\cos\Delta_S \sin\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\phi_{CP}$$

← Strong phase cancels out

$$\frac{\beta_- - \beta_+}{\alpha_- - \alpha_+} = \frac{\sin\Delta_S \cos\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\Delta_S$$

← measures the strong phase

} big advantage for Ξ over Λ

From S.L. Olsen

Σ^+?

α_0 FOR $\Sigma^+ \to p\pi^0$

VALUE	EVTS	DOCUMENT ID	
$-0.980^{+0.017}_{-0.015}$ OUR FIT			
$-0.980^{+0.017}_{-0.013}$ OUR AVERAGE			
$-0.945^{+0.055}_{-0.042}$	1259	[15] LIPMAN	73
-0.940 ± 0.045	16k	BELLAMY	72
$-0.98\ ^{+0.05}_{-0.02}$	1335	[16] HARRIS	70
-0.999 ± 0.022	32k	BANGERTER	69

Fred Harris
PhD Thesis

Σ^+ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$p\pi^0$	(51.57 ± 0.30) %
Γ_2	$n\pi^+$	(48.31 ± 0.30) %

$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\bar{\nu})$

Test of $\Delta S = \Delta Q$ rule.

VALUE	EVTS	DOCU
<0.043 OUR LIMIT	Our 90% CL limit,	

50 year-old measurements,

probably wrong for the same reason the Λ measurements were wrong

$\alpha_0 \approx 1$ ➔ S-wave ≈ P-wave

interference is maximum

well suited for $\alpha_0 + \bar{\alpha}_0 / \alpha_0 - \bar{\alpha}_0$

No measurements of $\bar{\alpha}_0$ or $\bar{\alpha}_-$ for $\bar{\Sigma}^-$

$\Gamma(p\pi^0) \approx \Gamma(n\pi^+)$ to ~10% 🡐 $T_{3/2} \approx 5\%\ T_{1/2}$

$\Delta\Gamma$ will be suppressed

PDG 2018 $\Delta S = \Delta Q$ limit is not severe,

BESIII can probably improve on this by a large factor

Σ^-?

From S.L. Olsen

α_- FOR $\Sigma^- \to n\pi^-$

VALUE	*EVTS*	*DOCUMENT ID*	
−0.068±0.008 OUR AVERAGE			
−0.062±0.024	28k	HANSL	78
−0.067±0.011	60k	BOGERT	70
−0.071±0.012	51k	BANGERTER	69

Σ^- DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$n\pi^-$	(99.848±0.005) %

40~50 year-old measurements,

probably wrong for the same reason the Λ measurements were wrong

$\alpha\_ \approx 0$ ➔ 1 partial wave dominates

interference is small not well suited for $\alpha_- + \alpha_+ / \alpha_- - \alpha_+$ measurements

no measurements of $\bar{\alpha}_+$ for $\bar{\Sigma}^+$

single dominant decay mode

no suitable for $\Delta\Gamma$ measurements

Ω^-?

α FOR $\Omega^- \to \Lambda K^-$

Some early results have been omitted.

VALUE	EVTS	DOCUMENT ID	
0.0180±0.0024 OUR AVERAGE			
+0.0207±0.0051±0.0081	960k	[7] CHEN	05
+0.0178±0.0019±0.0016	4.5M	[7] LU	05A

α FOR $\Omega^- \to \Xi^0 \pi^-$

VALUE	EVTS	DOCUMENT ID	
+0.09±0.14	1630	BOURQUIN	84

α FOR $\Omega^- \to \Xi^- \pi^0$

VALUE	EVTS	DOCUMENT ID	
+0.05±0.21	614	BOURQUIN	84

Ω^- DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	ΛK^-	(67.8±0.7) %
Γ_2	$\Xi^0 \pi^-$	(23.6±0.7) %
Γ_3	$\Xi^- \pi^0$	(8.6±0.4) %

$\alpha \approx 0$ ➔ 1 partial wave dominates all modes

interference is small, not well suited for $\alpha + \bar{\alpha}/\alpha - \bar{\alpha}$ measurements

$\Gamma(\Xi^0\pi^-) \approx 3x\ \Gamma(\Xi^-\pi^0)$ ⇐ $T_{3/2} \approx T_{1/2}$

$\Delta\Gamma$ will be enhanced

Hyperon decays

Rare and forbidden decays

Front. Phys. 12(5), 121301 (2017)
DOI 10.1007/s11467-017-0691-9

PERSPECTIVE

Prospects for rare and forbidden hyperon decays at BESIII

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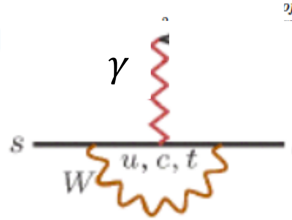
ademy of Sciences, Beijing 100049, China
uthor. E-mail: †lihb@ihep.ac.cn

7, 2017; accepted May 8, 2017

Electron Spectrometer III (BESIII) is proposed t
pairs, which provide a pristine experimental envir
. About 10^6–10^8 hyperons, i.e., Λ, Σ, Ξ, and Ω,
h the proposed data samples at BESIII. Based o
branching fractions of the hyperon decays is in th
ie", rare

SM



$B_i \to B_f\gamma$	$\mathcal{B}$ ($\times10^{-3}$)	α_γ
$\Lambda \to n\gamma$	1.75 ± 0.15	–
$\Sigma^+ \to p\gamma$	1.23 ± 0.05	-0.76 ± 0.08
$\Sigma^0 \to n\gamma$	–	–
$\Xi^0 \to \Lambda\gamma$	1.17 ± 0.07	-0.70 ± 0.07
$\Xi^0 \to \Sigma^0\gamma$	3.33 ± 0.10	-0.69 ± 0.06
$\Xi^- \to \Sigma^-\gamma$	0.127 ± 0.023	1.0 ± 1.3
$\Omega^- \to \Xi^-\gamma$	< 0.46 (90% C.L.)	–

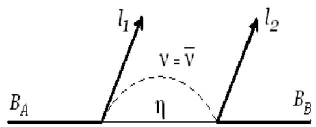
FCNC: radiative decays

Decay mode	Current data $\mathcal{B}(\times10^{-6})$	Sensitivity $\mathcal{B}$(90%C.L.) ($\times10^{-6}$)	Type
$\Lambda \to ne^+e^-$	-	< 0.8	
$\Sigma^+ \to pe^+e^-$	< 7	< 0.4	
$\Xi^0 \to \Lambda e^+e^-$	7.6 ± 0.6	< 1.2	
$\Xi^0 \to \Sigma^0 e^+e^-$	-	< 1.3	
$\Xi^- \to \Sigma^- e^+e^-$	-	< 1.0	
$\Omega^- \to \Xi^- e^+e^-$	-	< 26.0	Type A
$\Sigma^+ \to p\mu^+\mu^-$	$(0.09^{+0.09}_{-0.08})$	< 0.4	
$\Omega^- \to \Xi^-\mu^+\mu^-$	-	< 30.0	
$\Lambda \to n\nu\bar{\nu}$	-	< 0.3	
$\Sigma^+ \to p\nu\bar{\nu}$	-	< 0.4	
$\Xi^0 \to \Lambda\nu\bar{\nu}$	-	< 0.8	
$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	-	< 0.9	Type B
$\Xi^- \to \Sigma^-\nu\bar{\nu}$	-	-*	
$\Omega^- \to \Xi^-\nu\bar{\nu}$	-	< 26.0	
$\Sigma^- \to \Sigma^+e^-e^-$	-	< 1.0	
$\Sigma^- \to pe^-e^-$	-	< 0.6	
$\Xi^- \to pe^-e^-$	-	< 0.4	
$\Xi^- \to \Sigma^+e^-e^-$	-	< 0.7	
$\Omega^- \to \Sigma^+e^-e^-$	-	< 15.0	
$\Sigma^- \to p\mu^-\mu^-$	-	< 1.1	
$\Xi^- \to p\mu^-\mu^-$	< 0.04	< 0.5	Type C
$\Omega^- \to \Sigma^+\mu^-\mu^-$	-	< 17.0	
$\Sigma^- \to pe^-\mu^-$	-	< 0.8	
$\Xi^- \to pe^-\mu^-$	-	< 0.5	
$\Xi^- \to \Sigma^+e^-\mu^-$	-	< 0.8	
$\Omega^- \to \Sigma^+e^-\mu^-$	-	< 17.0	

EM penguin

Weak penguin

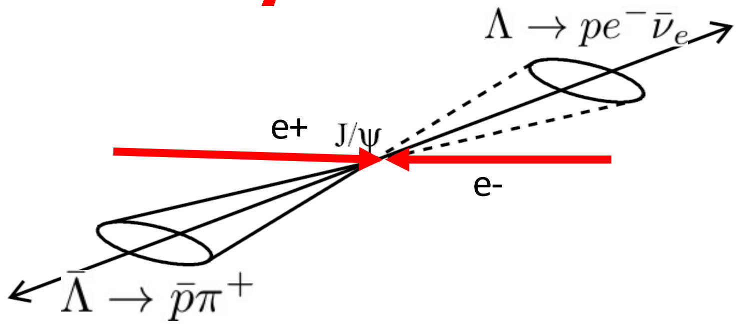
Neutrinoless double beta decays



Most of them never studied.

Semileptonic decays

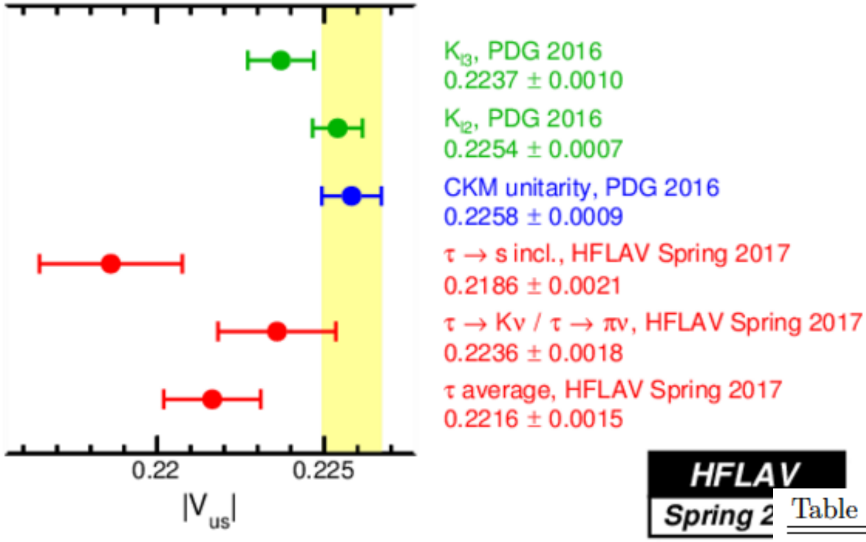
Fully reconstruct one of the hyperons, then the momentum of the other hyperon will be known, which provides hyperon beam, so we can look for invisible final states:
– neutrino ; other invisible particles

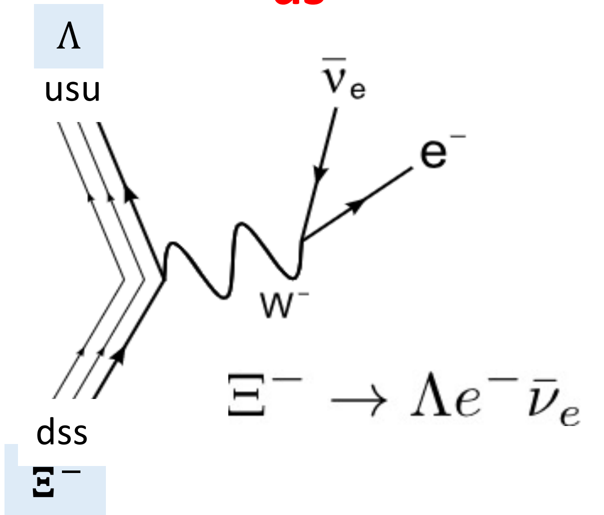


Decay mode	$\mathcal{B}\ (\times 10^{-4})$	$\lvert\Delta S\rvert$	$g_1(0)/f_1(0)$
$\Lambda \to pe^-\bar{\nu}_e$	8.32 ± 0.14	1	0.718 ± 0.015
$\Sigma^+ \to \Lambda e^+\nu_e$	0.20 ± 0.05	0	–
$\Sigma^- \to ne^-\bar{\nu}_e$	10.17 ± 0.34	1	-0.340 ± 0.017
$\Sigma^- \to \Lambda e^-\bar{\nu}_e$	0.573 ± 0.027	0	–
$\Sigma^- \to \Sigma^0 e^-\bar{\nu}_e$	–	0	–
$\Xi^0 \to \Sigma^+ e^-\bar{\nu}_e$	2.52 ± 0.08	1	1.210 ± 0.050
$\Xi^- \to \Lambda e^-\bar{\nu}_e$	5.63 ± 0.31	1	0.250 ± 0.050
$\Xi^- \to \Sigma^0 e^-\bar{\nu}_e$	0.87 ± 0.17	1	–
$\Xi^- \to \Xi^0 e^-\bar{\nu}_e$	< 23 (90% C.L.)	0	–
$\Omega^- \to \Xi^0 e^-\bar{\nu}_e$	56 ± 28	1	–

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

Semileptonic decays: V_{us}





V_{us} measurements are inconsistent:

K semileptonic and leptonic decays

tau decays

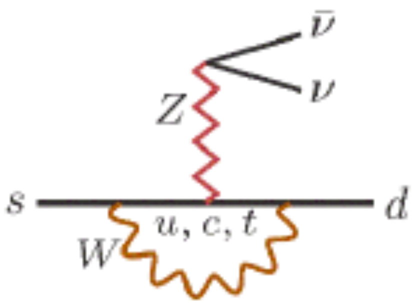
N. Cabibbo, E. Swallon, R. Winston
Ann.Rev.Nucl.Part.Sci. 53:39-75,2003

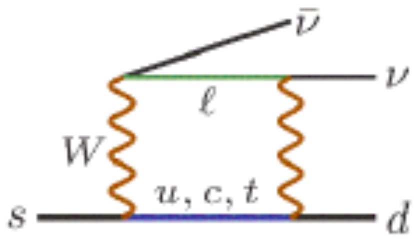
Table 5: Results from V_{us} analysis using measured g_1/f_1 values

Decay Process	Rate (μsec^{-1})	g_1/f_1	V_{us}
$\Lambda \to p e^- \overline{\nu}$	3.161(58)	0.718(15)	0.2224 ± 0.0034
$\Sigma^- \to n e^- \overline{\nu}$	6.88(24)	−0.340(17)	0.2282 ± 0.0049
$\Xi^- \to \Lambda e^- \overline{\nu}$	3.44(19)	0.25(5)	0.2367 ± 0.0099
$\Xi^0 \to \Sigma^+ e^- \overline{\nu}$	0.876(71)	1.32(+.22/ − .18)	0.209 ± 0.027
Combined	—	—	0.2250 ± 0.0027

Search for rare decay and New physics

SM





JT, arXiv:1901.10447 [JHEP 04 (2019) 104]
G Li, JY Su, JT, arXiv:1905.08759

SM predictions:

$\Lambda \to n\nu\bar{\nu}$	$\Sigma^+ \to p\nu\bar{\nu}$	$\Xi^0 \to \Lambda\nu\bar{\nu}$	$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	$\Xi^- \to \Sigma^-\nu\bar{\nu}$	$\Omega^- \to \Xi^-\nu\bar{\nu}$
7.1×10^{-13}	4.3×10^{-13}	6.3×10^{-13}	1.0×10^{-13}	1.3×10^{-13}	4.9×10^{-12}

$\mathcal{B}(\Lambda \to n f\bar{f}) < 6.6 \times 10^{-6}$, $\mathcal{B}(\Sigma^+ \to p f\bar{f}) < 1.7 \times 10^{-6}$

$\mathcal{B}(\Xi^0 \to \Lambda f\bar{f}) < 9.4 \times 10^{-7}$, $\mathcal{B}(\Xi^0 \to \Sigma^0 f\bar{f}) < 1.3 \times 10^{-6}$

$\mathcal{B}(\Omega^- \to \Xi^- f\bar{f}) < 7.5 \times 10^{-5}$

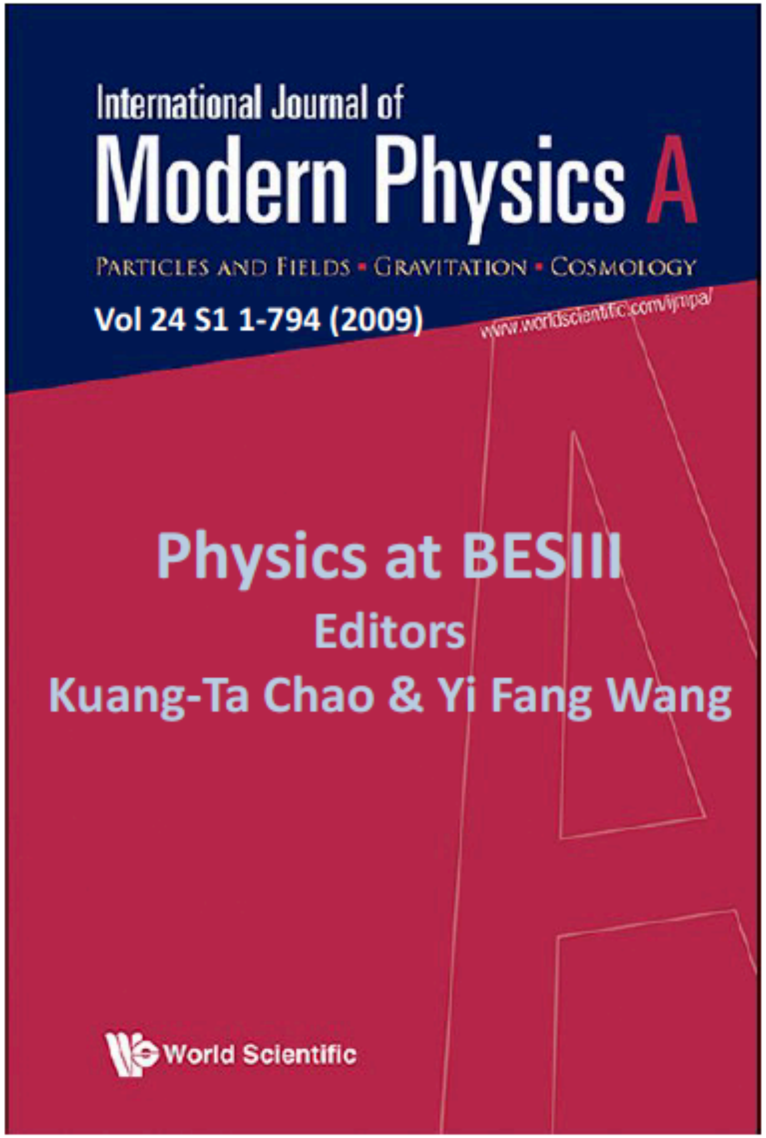
Sensitivities from BESIII 10 billion J/ ψ

$\Lambda \to n\nu\bar{\nu}$	$\Sigma^+ \to p\nu\bar{\nu}$	$\Xi^0 \to \Lambda\nu\bar{\nu}$	$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	$\Omega^- \to \Xi^-\nu\bar{\nu}$
3×10^{-7}	4×10^{-7}	8×10^{-7}	9×10^{-7}	2.6×10^{-5}

BESIII is uniquely well suited for a variety of studies of properties of the stable baryon, which is largely unanticipated in our original planning.

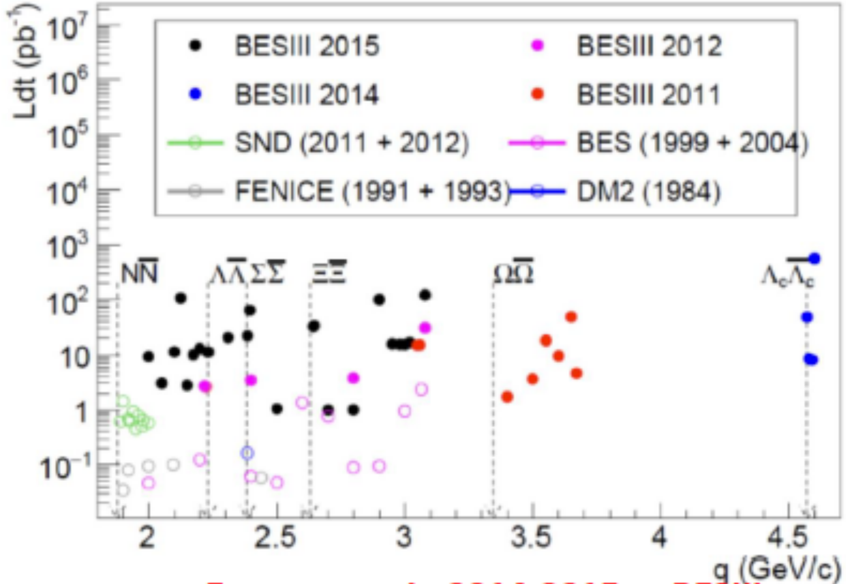
BESIII Physics Book:

Total length: 794 pages
hyperons mentioned ~5 times
(mostly in context of Λ^*,Σ^*, & Ξ^* searches)

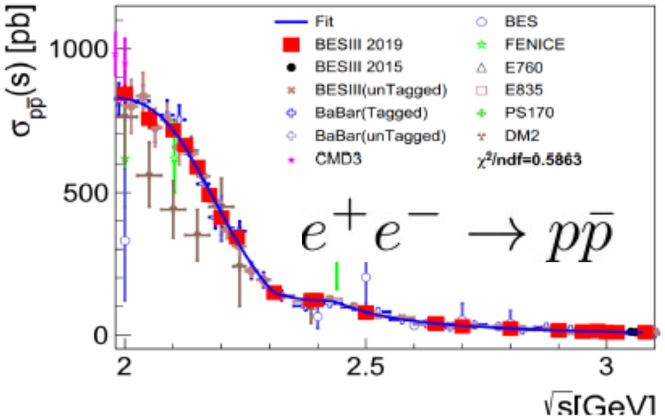


Advantage: data near to the thresholds

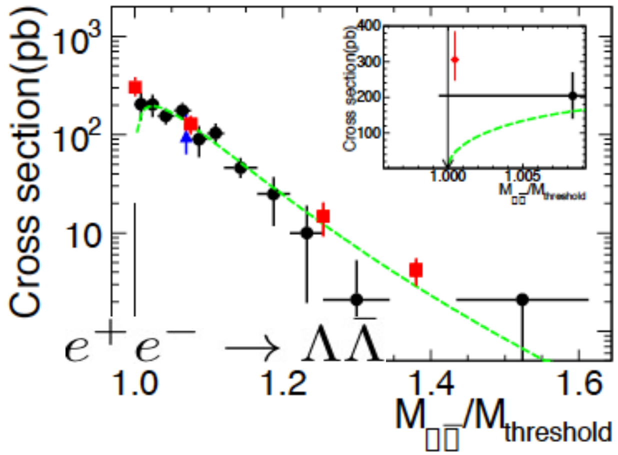
- **Baryon pair productions near thresholds: precision branching fractions, unique access to the relative phase, test of QCD**
- **Hyperon and charmed baryon Spin polarization in QC**
- **Form-factors in the time-like production**
- **CP violation with quantum-correlated pair productions of hyperons and charmed baryon**

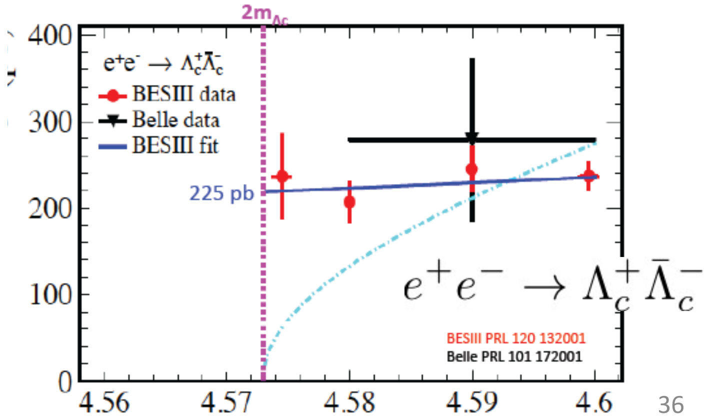


Energy scan in 2014-2015 at BESIII



Best precision on σ: 3% (systematic dominant)





summary

Hyperon polarization in J/ψ (ψ') decays → new way to study CPV

- → complementary to CPV studies with Kaons
- → BESIII as already rewritten the PDG book for Λ decays
- → about to do the same for Ξ /Σ^+ decays
- → good opportunities for $\Delta\alpha$ measurements with Σ^+
- → Σ^- and Ω CPV measurements are probably hopeless

Can partial reconstruction techniques be exploited

- → extracting π^0 from antineutron debris is essential for $\Delta\alpha_0$ & $\Delta\Gamma$ measurements

BESIII analyses *must* advance to 21st century techniques

- → multi-dim fit to $\Lambda\bar{\Lambda}$ gives 3x better (!) precision than cut/count + 1-dim fit
- → machine learning algorithms need to be developed & exploited

Hyperon physics at BESIII: next new frontier for CPV studies!

Special thanks to S. L. Olsen, and A. Kupsc for sharing slides

Thank you!

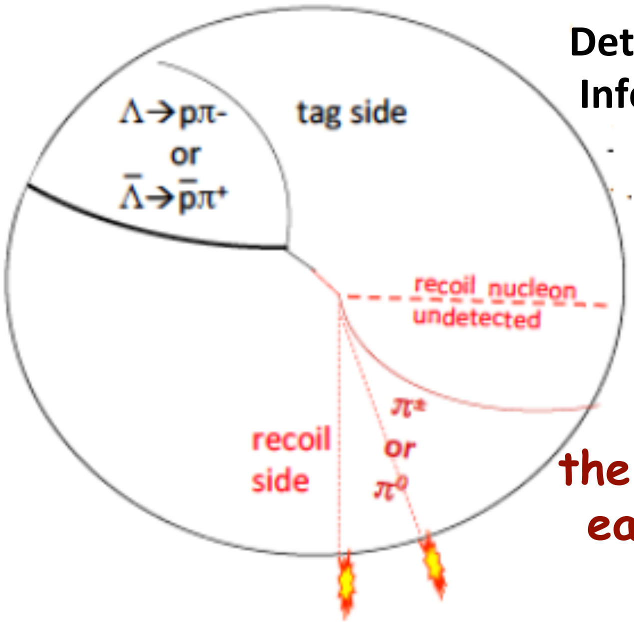
附件

$T_{3/2} \neq 0$: decay rate asymmetry in BESIII?

use *partial* reconstruction of J/ψ→ΛΛ?

Can BESIII measure this with low systematic errors?

$$\frac{Bf\left(\Lambda \to n\pi^0\right)}{Bf\left(\Lambda \to p\pi^-\right)} - \frac{Bf\left(\bar{\Lambda} \to \bar{n}\pi^0\right)}{Bf\left(\bar{\Lambda} \to \bar{p}\pi^+\right)} = \frac{N\left(\bar{\Lambda}_{\text{tag}} + \pi^0\right)}{N\left(\bar{\Lambda}_{\text{tag}} + \pi^-\right)} - \frac{N\left(\Lambda_{\text{tag}} + \pi^0\right)}{N\left(\Lambda_{\text{tag}} + \pi^+\right)}$$



Detect a Λ→pπ⁻ or Λ→pπ⁺ accompanied by a π± or π0
Infer presence of the recoil nucleon by missing mass

the 10^{10} J/ψ data sample has >1M events in each category → statistical precision ≈10^{-3}

Decay rate asymmetry in BESIII

using partially reconstructed $J/\psi \rightarrow \Lambda\Lambda$ events --

this $\Delta_s = \delta_{3/2} - \delta_{1/2}$

$$\frac{Bf(\Lambda \rightarrow n\pi^0)}{Bf(\Lambda \rightarrow p\pi^-)} - \frac{Bf(\bar{\Lambda} \rightarrow \bar{n}\pi^0)}{Bf(\bar{\Lambda} \rightarrow \bar{p}\pi^+)} = \frac{\Gamma_{n\pi^0}}{\Gamma_{p\pi^-}} - \frac{\Gamma_{\bar{n}\pi^0}}{\Gamma_{\bar{p}\pi^+}} = \frac{\Gamma_{n\pi^0}\Gamma_{\bar{p}\pi^+} - \Gamma_{\bar{n}\pi^0}\Gamma_{p\pi^-}}{\Gamma_{p\pi^-}\Gamma_{\bar{p}\pi^+}} \approx 2\left(1+\sqrt{2}\right)\left(\frac{T_{3/2}}{T_{1/2}}\right)\sin\Delta_s \sin\phi_{CP}$$

sensitivity is nominally reduced by a factor of ~5

here I used:

$$\Gamma_{p\pi^-} \approx \left|T_{1/2}\right|^2 + \sqrt{2}\left|T_{1/2}\right|\left|T_{3/2}\right|\cos(\Delta_s + \phi_{CP})$$

$$\Gamma_{n\pi^0} \approx \tfrac{1}{2}\left|T_{1/2}\right|^2 - \left|T_{1/2}\right|\left|T_{3/2}\right|\cos(\Delta_s + \phi_{CP})$$

$$\Gamma_{\bar{p}\pi^-} \approx \left|T_{1/2}\right|^2 + \sqrt{2}\left|T_{1/2}\right|\left|T_{3/2}\right|\cos(\Delta_s - \phi_{CP})$$

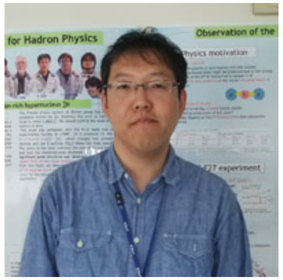
$$\Gamma_{\bar{n}\pi^0} \approx \tfrac{1}{2}\left|T_{1/2}\right|^2 - \left|T_{1/2}\right|\left|T_{3/2}\right|\cos(\Delta_s + \phi_{CP})$$

same data would be useful for an $\alpha_0+\alpha_0/\alpha_0-\alpha_0$ measurement

2) Why the big change in α?

Why different?

from: Kiyoshi Tanida
JAEA Japan



- Multiple scattering:
  - E.g., at 95 MeV with 3 cm scatterer (target), θ_0 becomes as large as 1.5 degree.
    → 5 degree multiple scattering occurs with a probability of 1 % order and dominates over single scattering
  - Actual scatterer thickness is even larger
  - Of course, analyzing power for multiple Coulomb scattering is almost 0
    → Can explain the difference
- Note: effective A_N depends on target thickness
  - This is why target thickness is explicit in the new data.
  - We have to be careful!!

轻子数和重子数破坏的寻找

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PERSPECTIVE

Prospects for rare and forbidden hyperon decays at BESIII

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The study of hyperon decays at the Beijing Electron Spectrometer III (BES
tigate the events of J/ψ decay into hyperon pairs, which provide a pristine e
at the Beijing Electron–Positron Collider II. About 10^6–10^8 hyperons, i.e.,
produced in the J/ψ and $\psi(2S)$ decays with the proposed data samples at
samples, the measurement sensitivity of the branching fractions of the hyper
of 10^{-5}–10^{-8}. In addition, with the known center-of-mass energy and "tag
and decays with invisible final states can be probed.

Keywords BESIII, J/ψ decay, hyperon, rare decay, FCNC, lepton flavor v

BESIII的敏感度

Decay mode	Current data $\mathcal{B}$ ($\times 10^{-6}$) (90% C.L.)	Sensitivity $\mathcal{B}$ ($\times 10^{-6}$)	ΔL	ΔB
$\Lambda \to M^+ l^-$	< 0.4–3.0 [68]	< 0.1	$+1$	-1
$\Lambda \to M^- l^+$	< 0.4–3.0 [68]	< 0.1	-1	-1
$\Lambda \to K_S \nu$	< 20 [68]	< 0.6	$+1$	-1
$\Sigma^+ \to K_S l^+$	–	< 0.2	-1	-1
$\Sigma^- \to K_S l^-$	–	< 1.0	$+1$	-1
$\Xi^- \to K_S l^-$	–	< 0.2	$+1$	-1
$\Xi^0 \to M^+ l^-$	–	< 0.1	$+1$	-1
$\Xi^0 \to M^- l^+$	–	< 0.1	-1	-1
$\Xi^0 \to K_S \nu$	–	< 2.0	$+1$	-1

对未来J/ψ工厂的影响

目前BEPCII的亮度，每年可以积累100亿J/ψ样本： 10^{10}

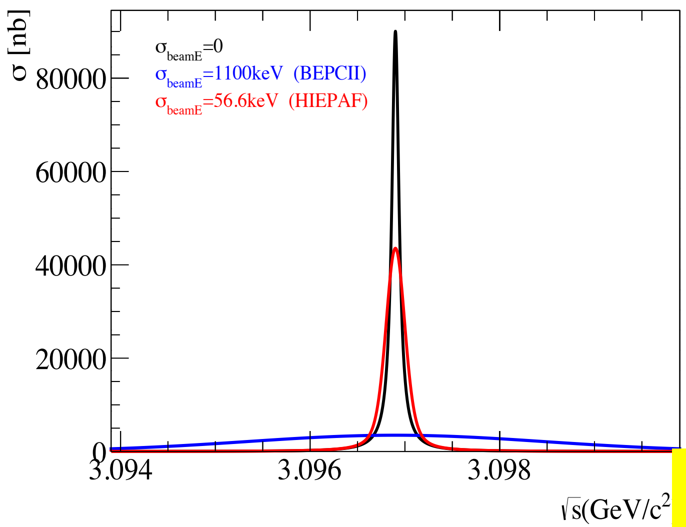
J/ψ 的物理宽度 92 keV

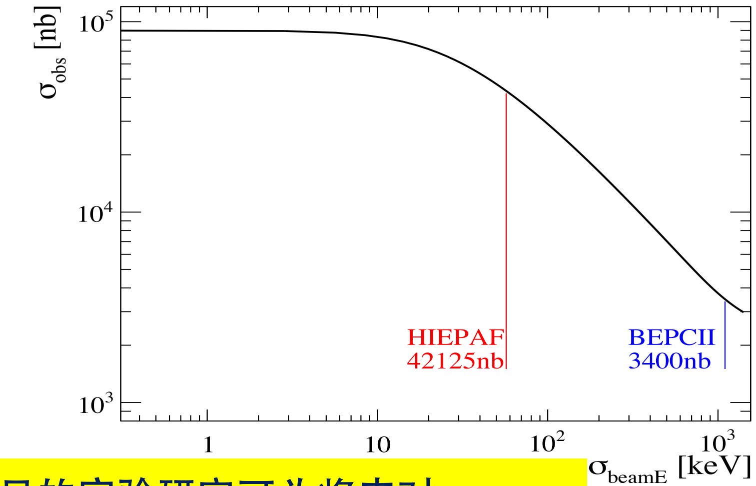
BEPCII上，质心能量的不确定性：1.2 MeV → J/ψ的有效观测截面：3400 nb；

升级后的BEPCII， 利用单色对撞模式，把质心能散降低到100 keV

→ J/ψ 的有效观测截面：41000 nb 这是激动人心的事情！

同样数据获取时间， 在超级J/ψ 工厂上将比BEPCII提高1000倍。





本项目的实验研究可为将来对撞机的设计提供极其有价值的参考，从而可以每年获取$10^{13}J/\psi$

单色对撞模式

单色模式概念，垂直位置的质心能量

上	高能量电子	E+ ε →← E - ε	低能量正电子
中	理想能量电子	E →← E	理想能量正电子
下	低能量电子	E - ε →← E + ε	高能量正电子

对撞质心能量：

$$E_{CM} = 2E_{e^-}E_{e^+} + 2m_e^2c^4 + 2\sqrt{E_{e^-}^2 - m_e^2c^4}\sqrt{E_{e^+}^2 - m_e^2c^4}cos(\theta)$$

头对头对撞时 $\boldsymbol{\theta = 0}$，$\boldsymbol{cos(\theta) = 1}$，$E_{e^-} = E(1+\epsilon_{e^-})$，$E_{e^+} = E(1+\epsilon_{e^+})$，

ϵ_{e^-}，ϵ_{e^+} 为两束流能量偏差的相对值，假设：$E_{e^-} \sim E_{e^+} \sim E$

$$E_{CM} = 2E\sqrt{1+\epsilon_{e^-}}\sqrt{1+\epsilon_{e^+}} \sim 2E\sqrt{1+\epsilon_{e^-}+\epsilon_{e^+}}$$

如果 $\epsilon_{e^-} = -\epsilon_{e^+}$ 束流质心能量散度为零.

单色对撞模式

实际情况下，对撞点处束流有一个分布（不是质点），不同粒子的位置（垂直方向）

$$y^*=\sigma_y^*+\sigma_\varepsilon\times D_y^*$$ （*：表示对撞点）

这里σ_y^*：垂直尺寸的分布（$=\sqrt{\beta_y^*\varepsilon_y}$），$\beta_y^*$为对撞点振幅函数，$\varepsilon_y$为垂直方向发射度。

σ_ε：能散的分布，D_y^*：垂直色散函数

束流的分布会使质心系能散增加，但束流尺寸越小，质心系能散也会越小。

这对J/ψ很窄的共振峰通道的事例率提高意义很大

事例率提高因子是

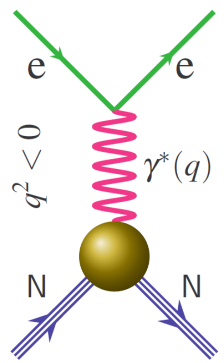
$$\lambda=\sqrt{1+\frac{D_y^{*2}\sigma_\varepsilon^2}{\beta_y^*\varepsilon_y}}$$

λ通常可以设计到大于10

Nucleon Form Factor

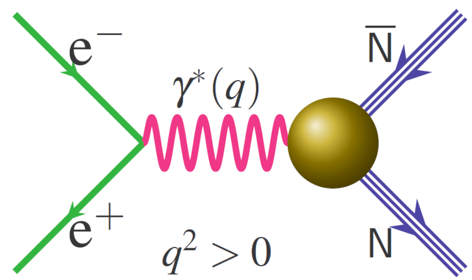
- **Fundamental properties of the nucleon**
  - **Connected to charge, magnetization distribution**
  - **Crucial testing ground for models of the nucleon internal structure**
- **Can be measured from space-like processes (eN) (precision 1%) or time-like process (e^+e^- annihilation) (precision 10%-30%)**

eN → eN



Space-like:
FF real

$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}$



Time-like:
FF complex

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

-- formulae & definitions --

Sachs form factors

$G_E = F_1 + \frac{q^2}{4M^2}F_2$

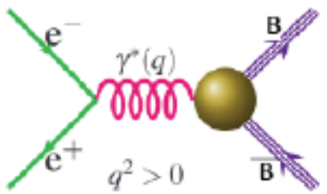
$G_M = F_1 + F_2$

$G_E(0) = Q_N$

$G_M(0) = \mu_N$

Born cross section:

$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \ldots$



time-like "Sachs" form-factors

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta\, C}{4m^2_{B\bar{B}}}\left[\left(1+\cos^2\theta\right)\left|G_M(m_{B\bar{B}})\right|^2 + \frac{1}{\tau}\sin^2\theta\left|G_E(m_{B\bar{B}})\right|^2\right]$$

$$\tau = \frac{m^2_{B\bar{B}}}{4M^2_B} \qquad \beta = \sqrt{1-\frac{1}{\tau}}$$

Coulomb enhancement factor

$$C_{\text{charged}} = \frac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)} \xrightarrow{(\beta\to 0)} \pi\alpha/\beta$$

$$C_{\text{neutral}} = 1$$

in point-like approx

integrated cross section:

$$\sigma_{B\bar{B}}(m_{B\bar{B}}) = \frac{4\pi\alpha^2\beta C}{3m_B^2}\left[\left|G_M(m_{B\bar{B}})\right|^2 + \frac{1}{2\tau}\left|G_E(m_{B\bar{B}})\right|^2\right] = \frac{4\pi\alpha^2\beta C}{3m_B^2}\left|G_{eff}(m_{B\bar{B}})\right|^2\left(1+1/2\tau\right)$$

"effective" form factor

effective form factor:

$$\left|G_{eff}\right|^2 = \frac{\left|G_M\right|^2 + \frac{1}{2\tau}\left|G_E\right|^2}{1+\frac{1}{2\tau}}\sigma_{B\bar{B}}(m_{B\bar{B}}) \Rightarrow \left|G_{eff}\right| = \left(\frac{3m^2_{B\bar{B}}}{\pi\alpha^2\beta C\left(1+\frac{1}{2\tau}\right)}\right)^{\frac{1}{2}}\sqrt{\sigma_{B\bar{B}}}$$

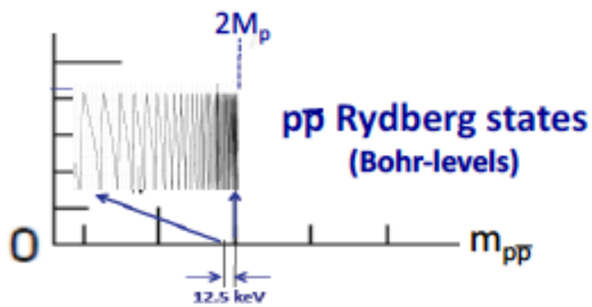
analyticity:

$$G_M(4M_B^2) = G_E(4M_B^2) \Rightarrow G_{eff}(4M_B^2) = G_M(4M_B^2)$$

$e^+e^- \to p\bar{p}$ at threshold

Integrated cross section:

$$\sigma_{p\bar{p}}(m_{p\bar{p}}) = \frac{4\pi\alpha^2 \beta C}{3m_p^2}\left|G_{eff}(m_{p\bar{p}})\right|^2 (1+1/2\tau)$$



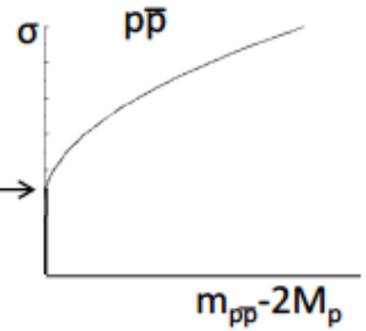
$$\text{for } p\bar{p}: C = \frac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)} \to \frac{\pi\alpha}{\beta}$$

Sommerfeld resummation factor

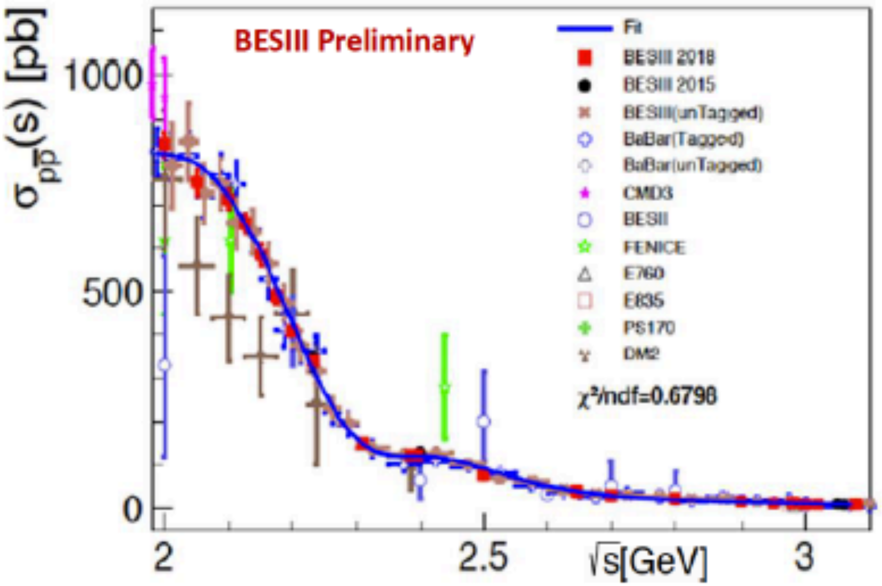
in point-like approx:

$$\sigma_0 = \frac{\pi^2\alpha^3}{2M_p^2}\left|G_{eff}(2M_p)\right|^2$$

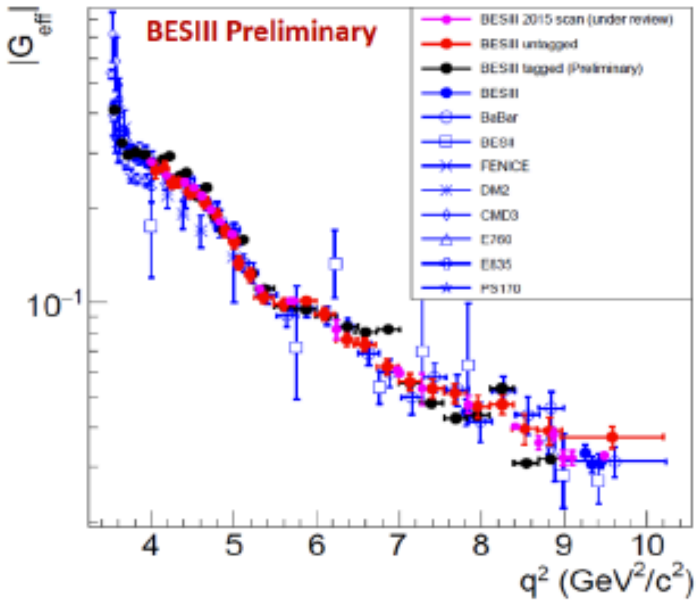
$$\approx 0.85\text{nb}\left|G_{eff}(2M_p)\right|^2 \longrightarrow$$



$G_{eff}(q^2)$



BESIII Preliminary
$\sigma_{p\bar{p}}(s)$ [pb]
√s[GeV]
Fit
BESIII 2018
BESIII 2015
BESIII(unTagged)
BaBar(Tagged)
BaBar(unTagged)
CMD3
BESII
FENICE
E760
E835
PS170
DM2
χ²/ndf=0.6798



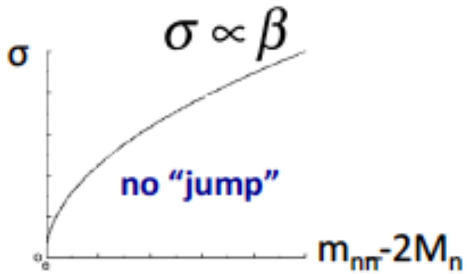
BESIII Preliminary
$|G_{eff}|$
q^2 (GeV²/c²)
BESIII 2015 scan (under review)
BESIII untagged
BESIII tagged (Preliminary)
BESII
BaBar
BES
FENICE
DM2
CMD3
E760
E835
PS170

$e^+e^- \rightarrow n\bar{n}$ (or $\Lambda\bar{\Lambda}$) at threshold

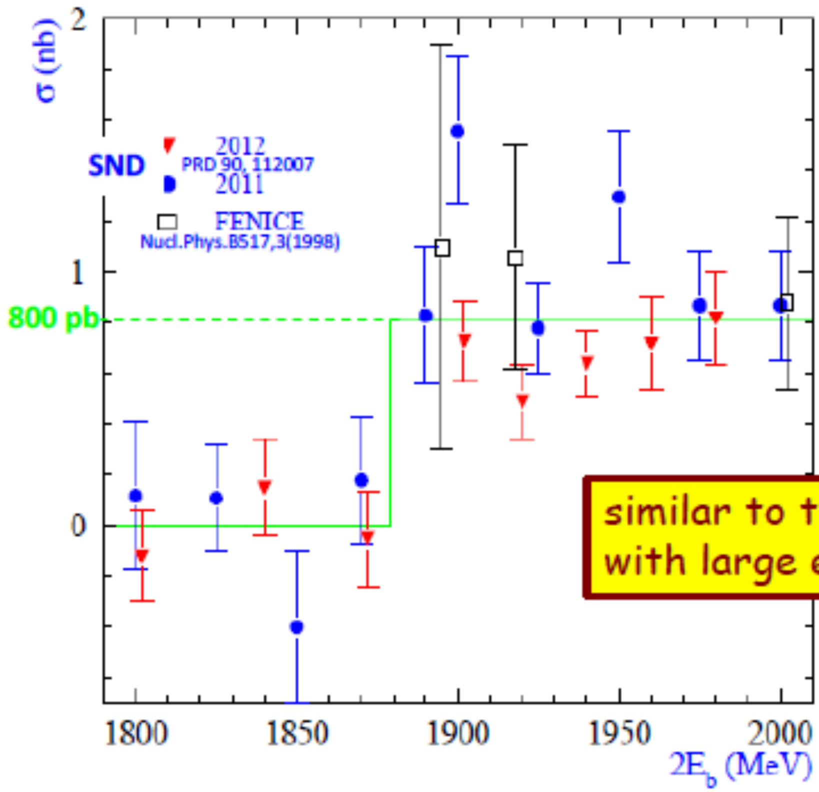
Integrated cross section: $$\sigma_{n\bar{n}}(m_{n\bar{n}}) = \frac{4\pi\alpha^2\beta C}{3m_n^2}\left|G_{eff}(m_{n\bar{n}})\right|^2(1+1/2\tau)$$

no Rydberg states
(Bohr-levels)

for $n\bar{n}$ ($\Lambda\bar{\Lambda}$): $C = 1$
in point-like approx:



indications of $\sigma(e^+e^- \rightarrow n\bar{n})$ jump at $E_{cm}=2m_n$



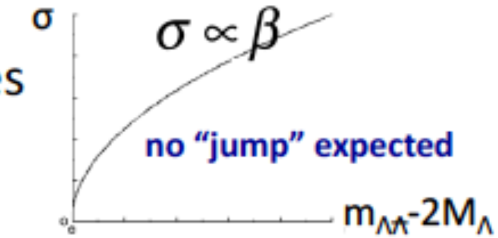
similar to the $p\bar{p}$ with large errors

BESIII results will be reported soon

$e^+e^- \rightarrow \Lambda\bar{\Lambda}$

Electrically neutral → no Rydberg states

- no Coulomb enhancement



in point-like approx:

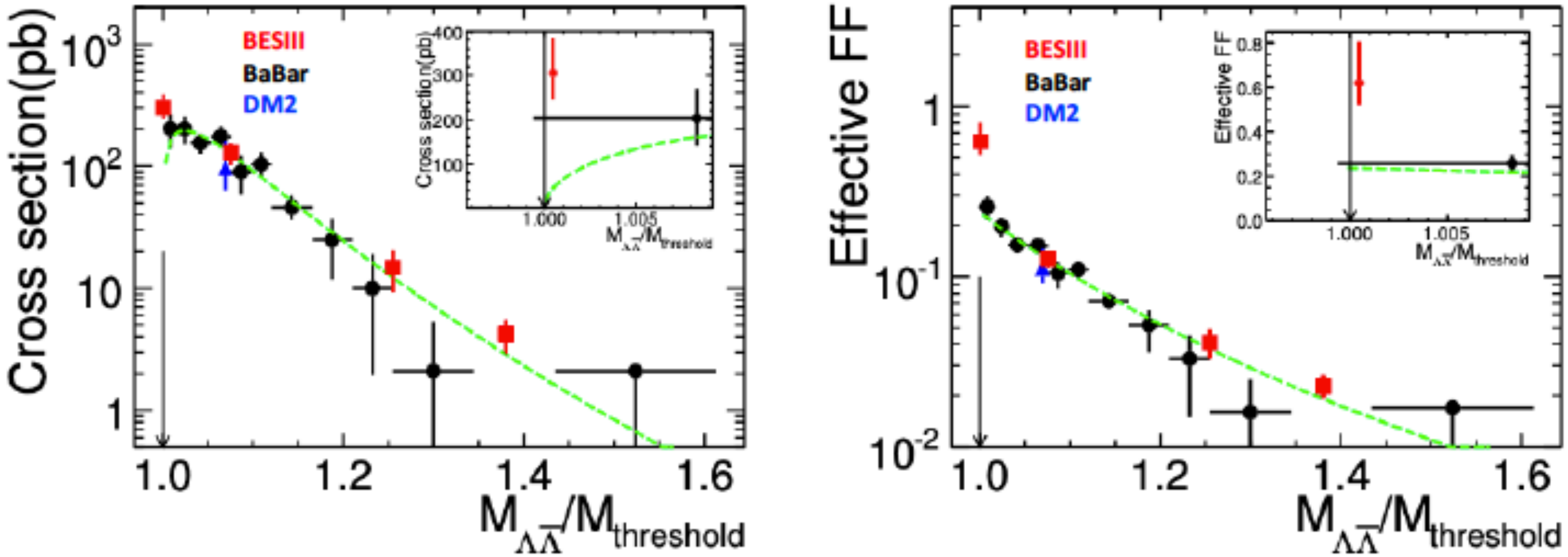
Isospin singlet, π-exchange not allowed

- Λ-$\bar{\Lambda}$ molecule is unlikely

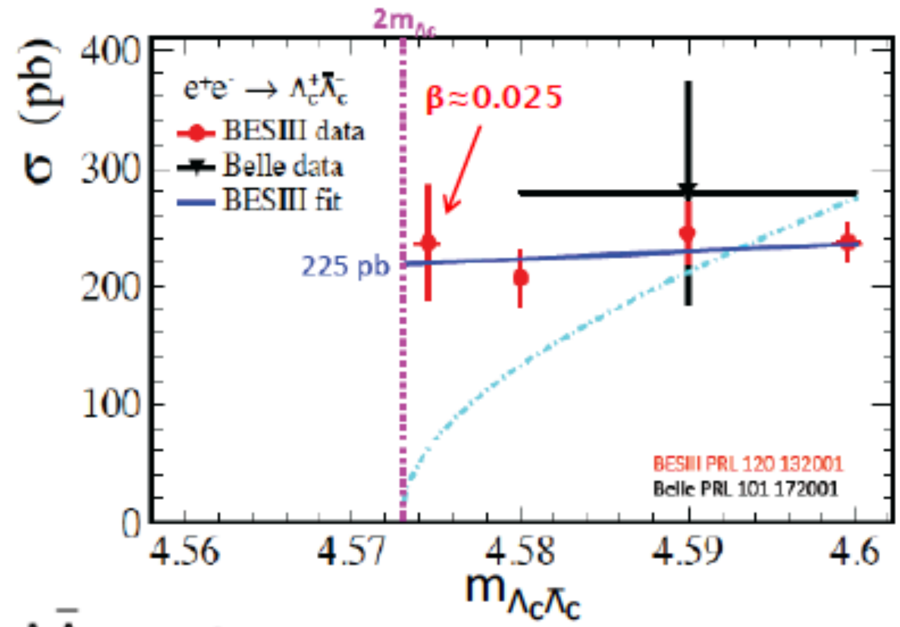
$\sigma(e^+e^- \rightarrow \Lambda\bar{\Lambda})$ & G_{eff} at threshold

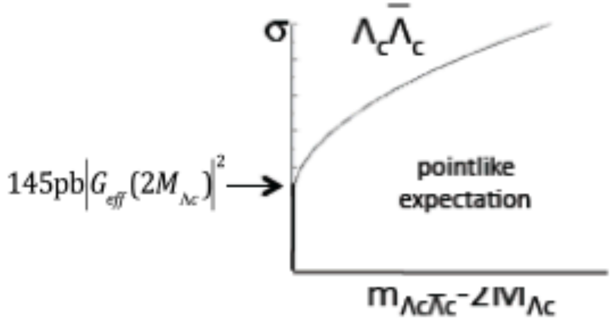
$$\sigma_{\Lambda\bar{\Lambda}}(m_{\Lambda\bar{\Lambda}}) = \frac{4\pi\alpha^2\beta}{3m_\Lambda^2}\left|G_{eff}(m_{\Lambda\bar{\Lambda}})\right|^2(1+1/2\tau)$$

no sign of $\sigma \propto \beta$ threshold behaviour



$\sigma(e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-)$ @~threshold





≈225 pb "jump" at threshold

≈consistent with δσ ≈ 145 pb
$|G_{eff}|$=1 pointlike jump

but ≈flat after that (like pp)