Hyperon decays: the next frontier for CPV studies (?)

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FLASY2019: 8th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology

Shanghai Jiao-Tong University, July 22, 2019

hyperon CP violation and new physics

Why CPV? -- QCD conserves CP. QCD processes, in & of themselves, don't produce CPV asymmetries

-- **Baryon Asymmetry of the Universe** means there **must be non-SM CPV** processes

Why hyperons? -- SM CPV processes are expected to be small

b-sector: SM CPV effects are $\mathcal{O}(1)$
c-sector: " " " $\mathcal{O}(10^{-3})$
s-sector: $\mathcal{O}(10^{-5})$

-- Current limits are not severe: $\mathcal{O}(10^{-2})$

3 orders of magnitude of NP reach

Why BESIII? -- $Bf(J/\psi \rightarrow B\bar{B}) \approx 10^{-3}$ → 10^{10} J/ψ: $\mathcal{O}(5\text{x}10^{6})$ $\Lambda\bar{\Lambda}$ & $\mathcal{O}(10^{6})$ $\Xi\bar{\Xi}$ pairs fully reconstructed

-- Polarized, quantum correlated, nearly zero background

-- Large acceptance; good control of systematics.

-- ~$10^{2\sim3}$ x larger data samples possible at a dedicated $e^+e^- \rightarrow J/\psi$ factory

Roadmap of CPV

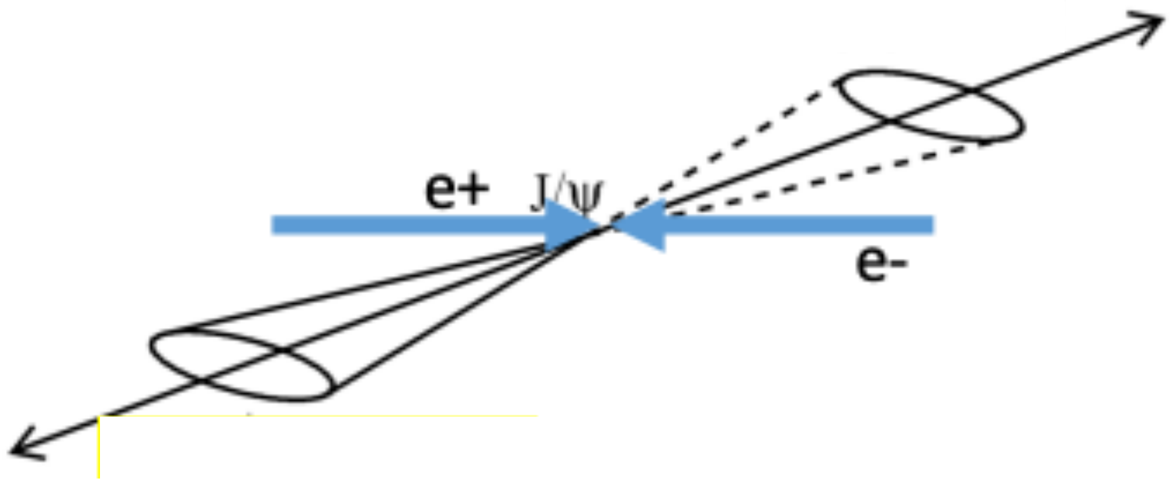
- In 1964, the first CPV was discovered in Kaon;
- In 2001, CPV in B was established by two B-factories;
- In 2019, CPV was discovered in D meson: 10^{-4}, 10^{8} reconstructed D mesons.
- All are consistent with CKM theory in the Standard model
- But no evidence was found in baryon system?

Why $e^+e^- \rightarrow J/\psi \rightarrow$ hyperon-hyperon ?

high signal rates
- quantum correlated
- well defined 4-momentum
- substantial polarization

conveniently boosted
- decays with neutrals/invisibles

well controlled systematics



BESIII Λ results with a 1.3B J/ψ event sample

(now BESIII has 10B J/ψ events)

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]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

← 1) substantial polarization

$\mathcal{P}_\Lambda = \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda$: $\langle\mathcal{P}_\Lambda\rangle \approx 0.13$

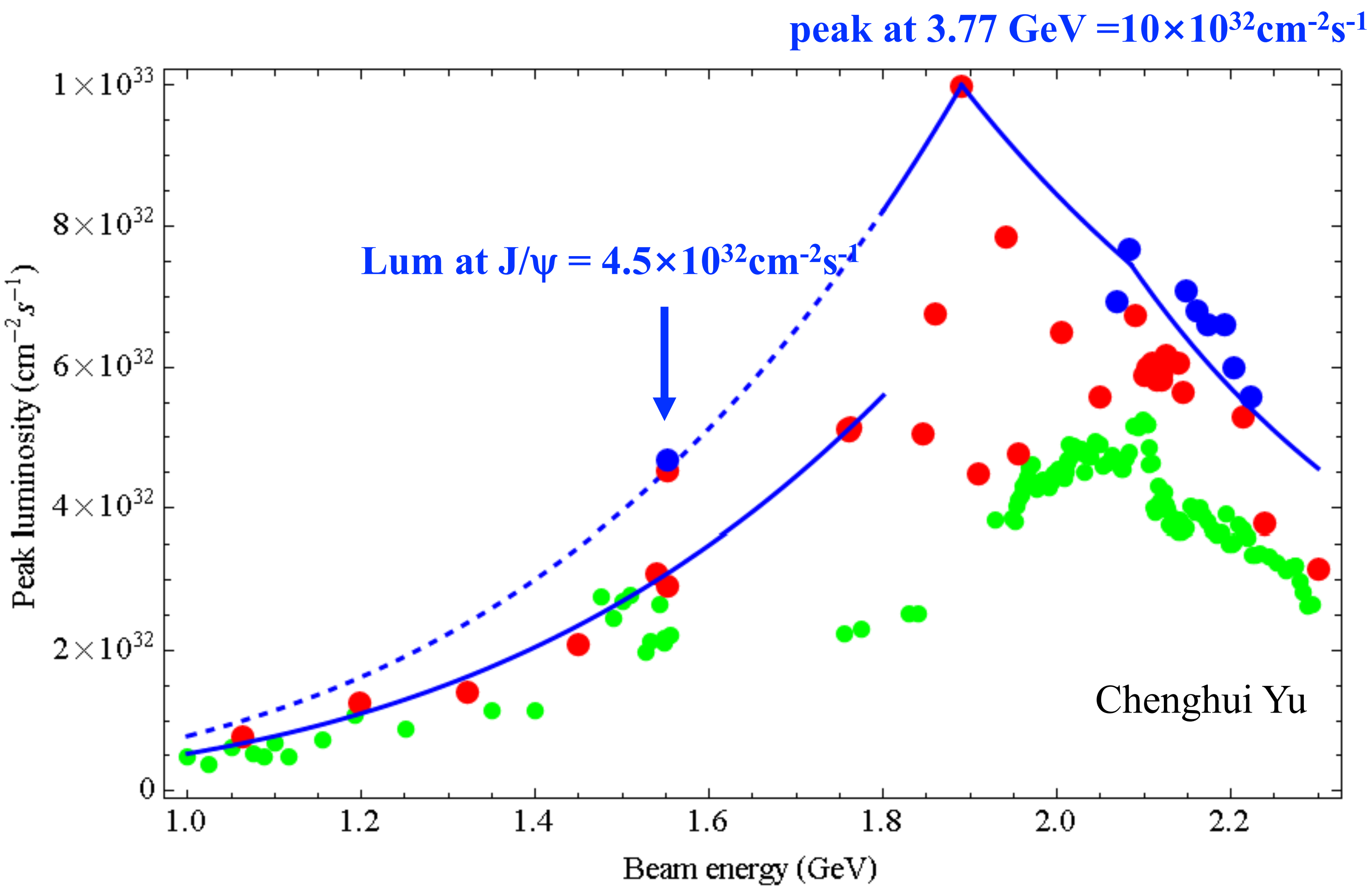
← 2) ~7σ upward shift from all previous measurements

← 3) best measurement to date

-with 8x more data on disc-

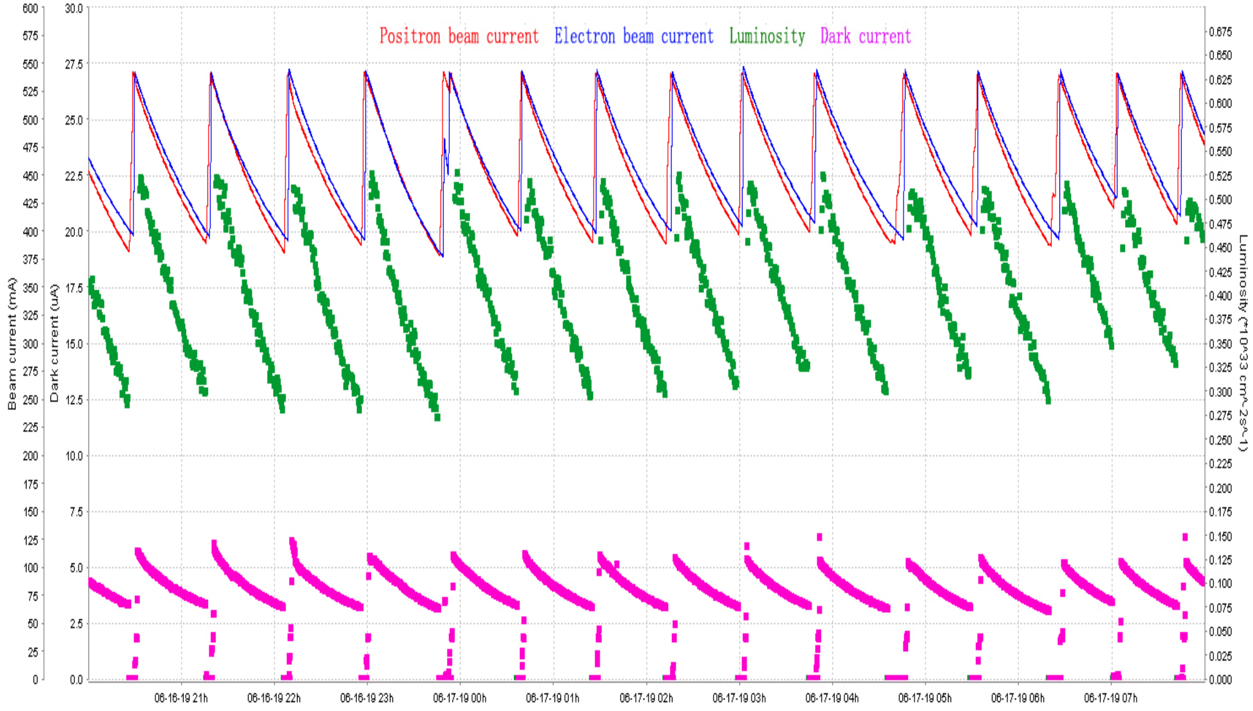
BEPCII luminosity optimized for ψ(3770) running

factor of ~2 gain for lattice optimized for J/ψ running

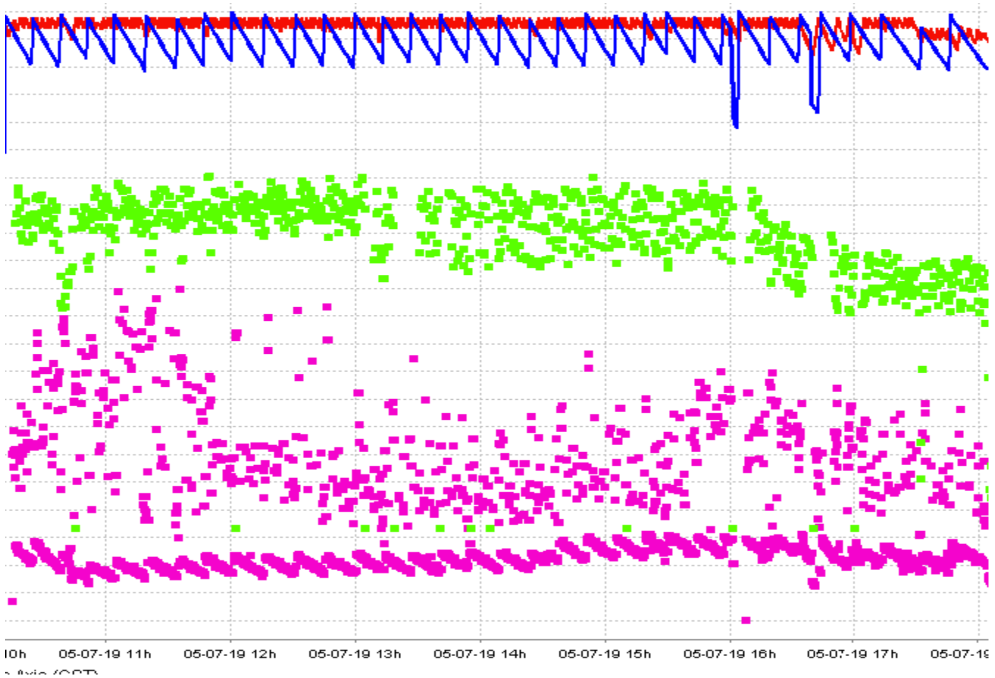


another factor of ~2 from “topup” running

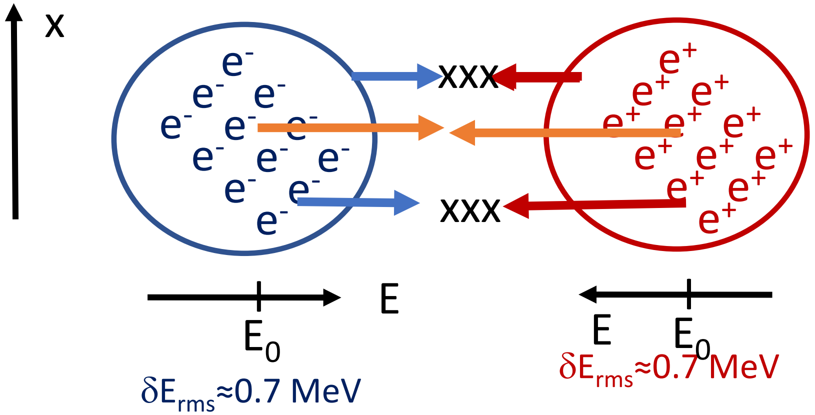
2019 running



future running?

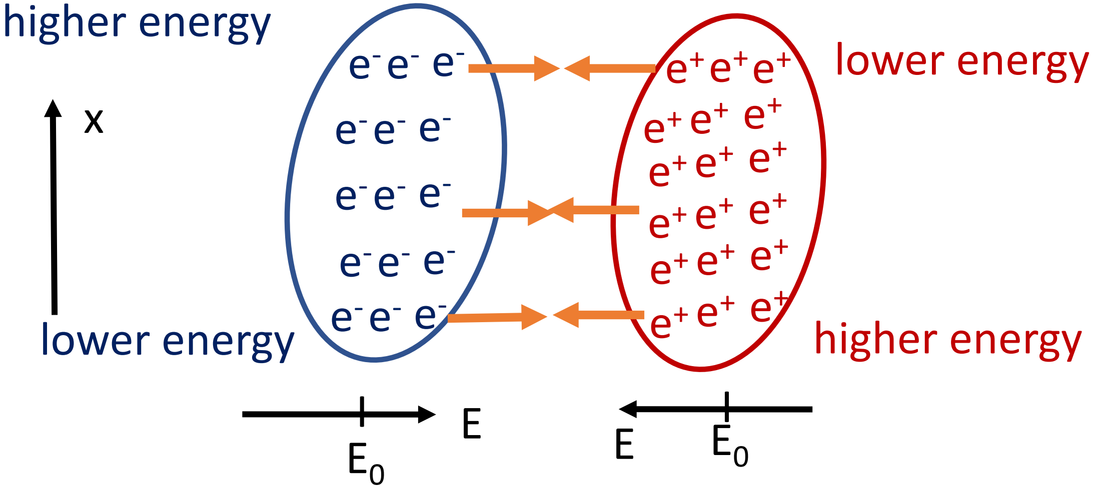


factor of 10 from reduction in e^+e^- CM energy spread (?)

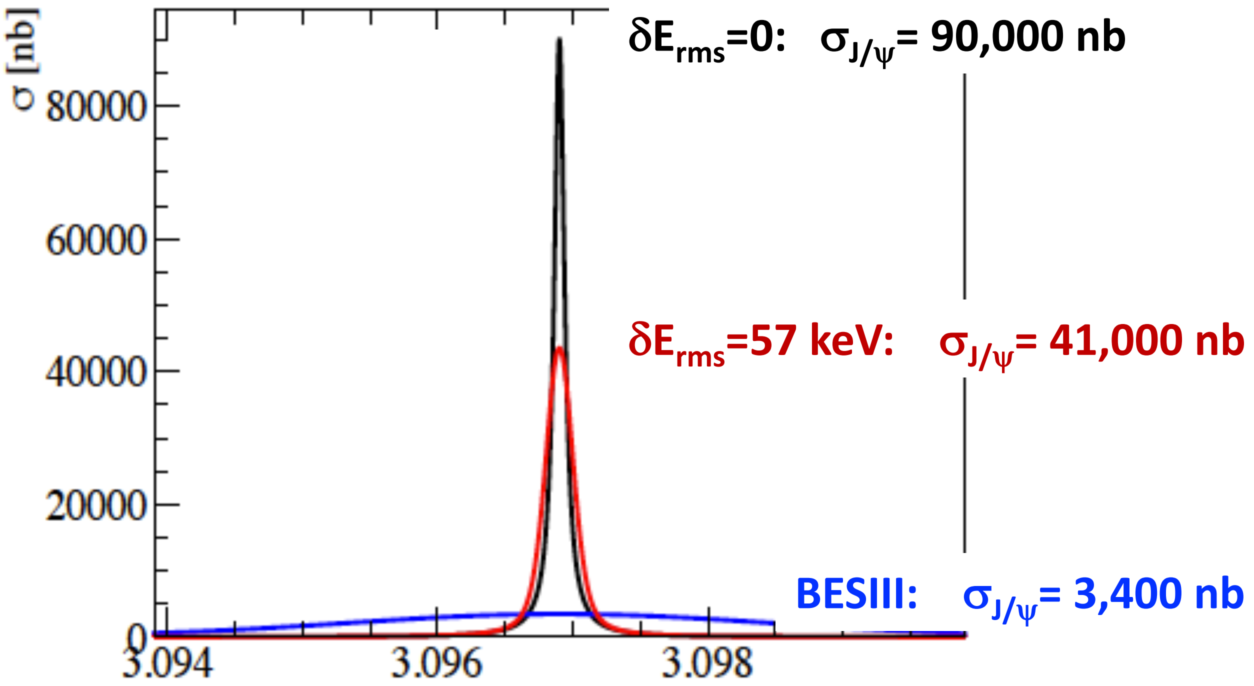


only e^+e^- pairs with E_{cm}=3096 ± 0.14 MeV
can produce a J/ψ, ~1/30th of the total

introduce dispersion

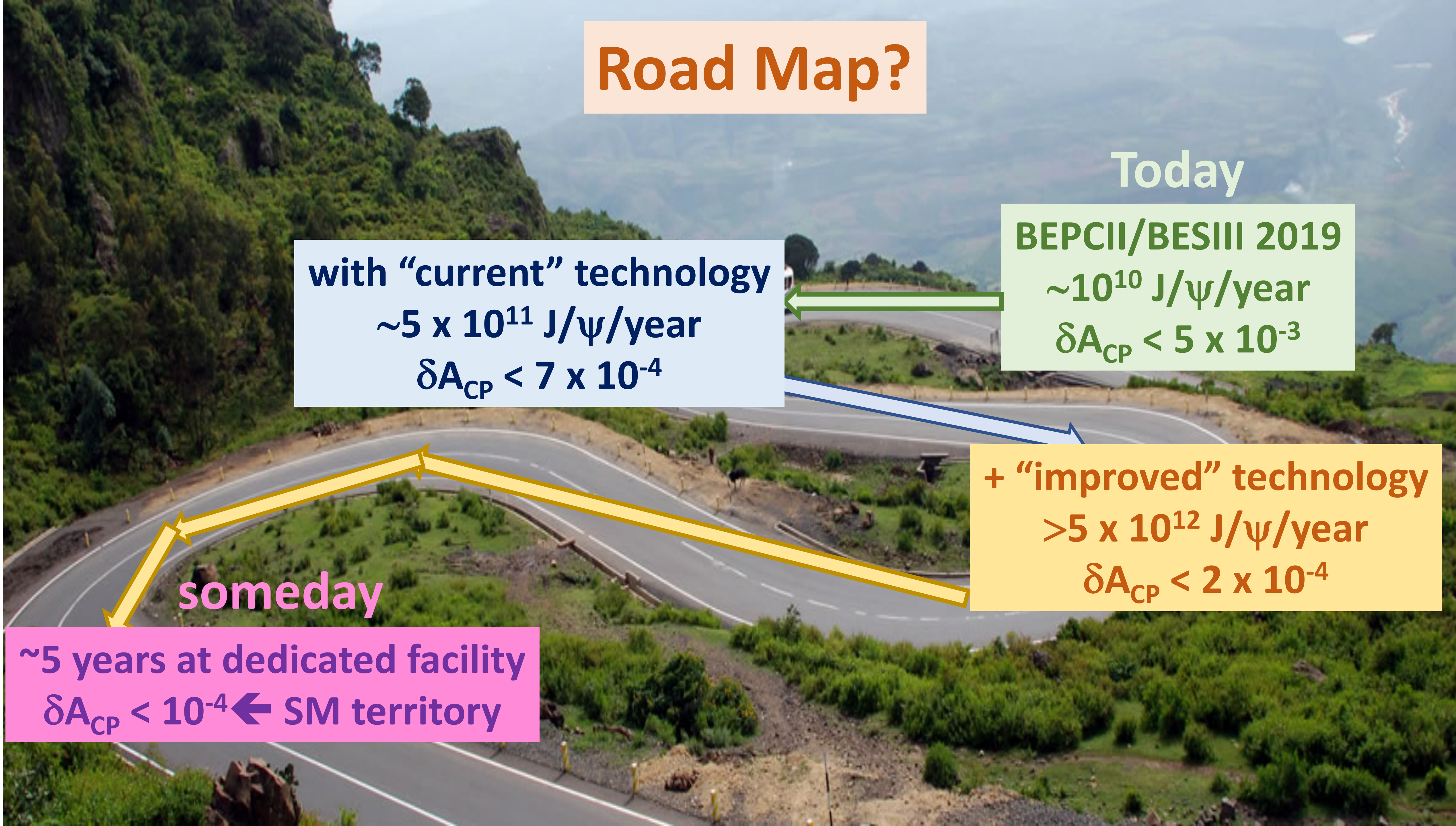


more e^+e^- pairs with E_{cm}=3096 ± 0.14 MeV



Alexander Zholents*
CERN SL/92-27 (AP)

Road Map?



Today

BEPCII/BESIII 2019
~10^{10} J/ψ/year
$\delta A_{CP} < 5 \times 10^{-3}$

with "current" technology
~5×10^{11} J/ψ/year
$\delta A_{CP} < 7 \times 10^{-4}$

+ "improved" technology
>5×10^{12} J/ψ/year
$\delta A_{CP} < 2 \times 10^{-4}$

someday

~5 years at dedicated facility
$\delta A_{CP} < 10^{-4}$ ← SM territory

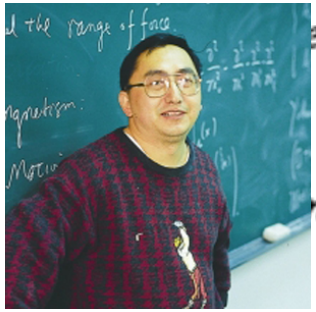
CPV with hyperons

Classic paper

Phys. Rev. D34, 833 (1986)

Hyperon decays and *CP* nonconservation

John F. Donoghue



ent of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

Xiao-Gang He and Sandip Pakvasa

nent of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 9

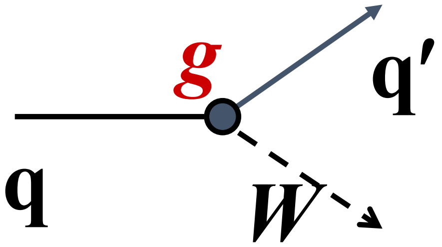
(Received 7 March 1986)

We study all modes of hyperon nonleptonic decay and consider the *CP*-odd observables which result. Explicit calculations are provided in the Kobayashi-Maskawa, Weinberg-Higgs, and left-right-symmetric models of *CP* nonconservation.

primer on CP

P: multiply by $\gamma_0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$

C: multiply by $i\gamma_2\gamma_0 = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$ ***& take charge conjugate***



some basic process

primer on CP

P: multiply by $\gamma_0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$

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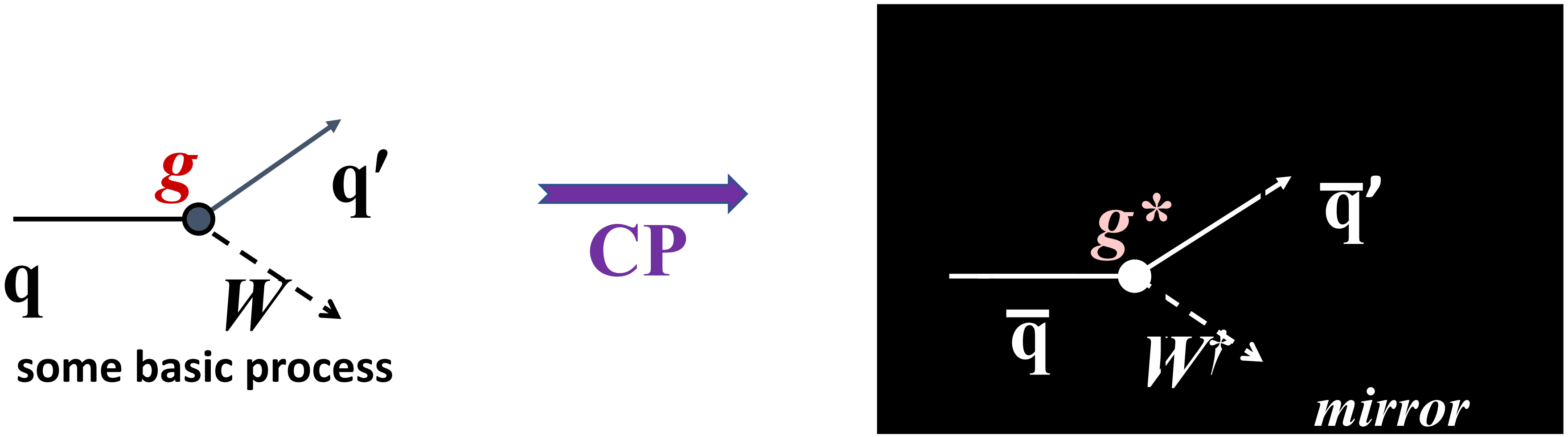
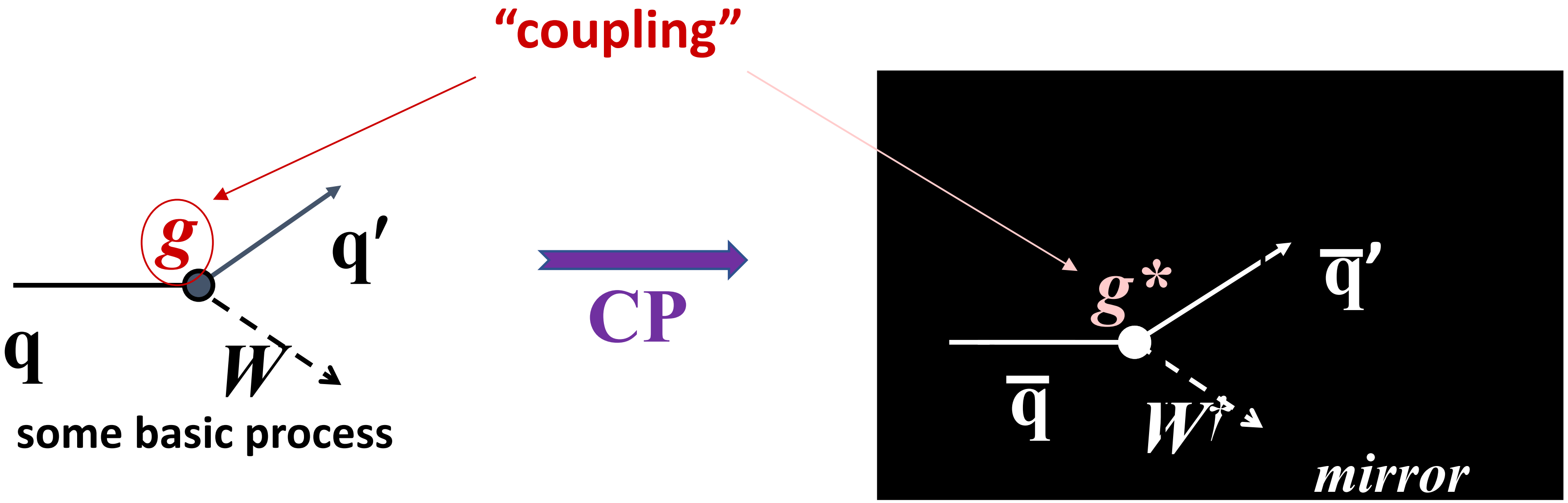


primer on CP

P: multiply by $\gamma_0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$ ***C***: multiply by $i\gamma_2\gamma_0 = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$ ***& take charge conjugate***



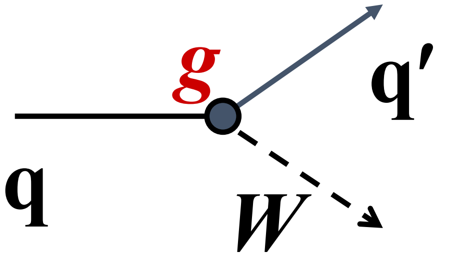
CP Violation: coupling has a complex phase

two kinds of phases in QFT

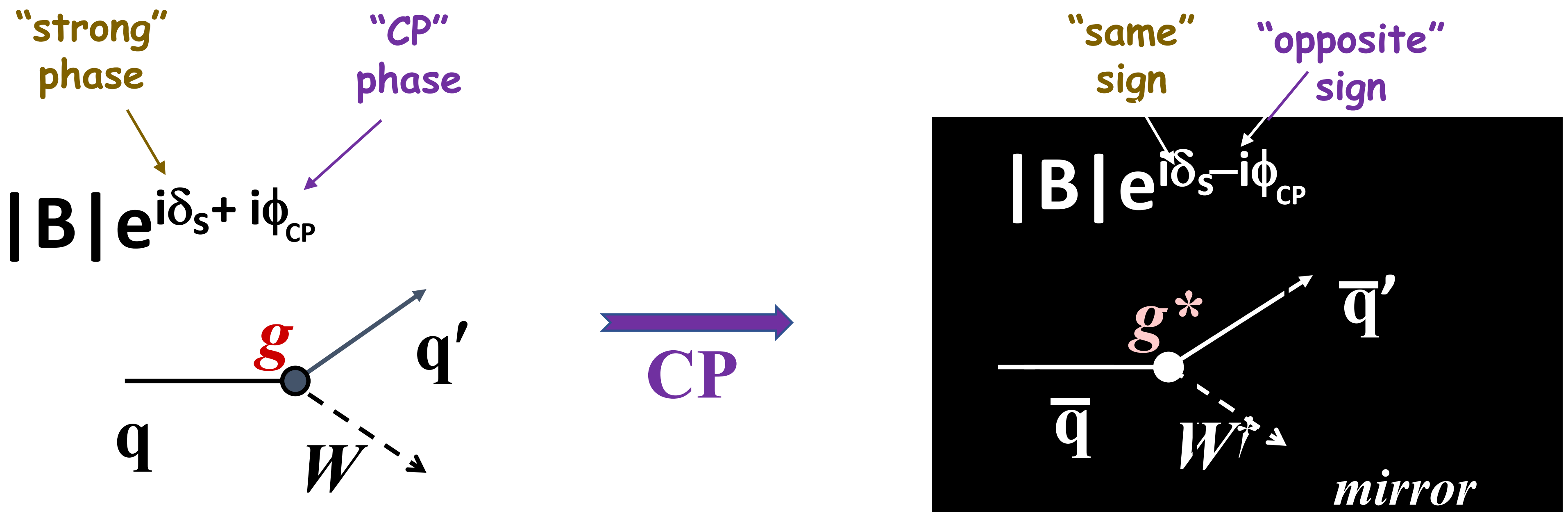
"strong" phase

"CP" phase

$$|B|e^{i\delta_s + i\phi_{CP}}$$



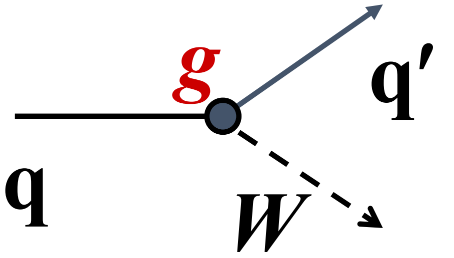
two kinds of phases in QFT



two kinds of phases in QFT

"strong" phase — "CP" phase

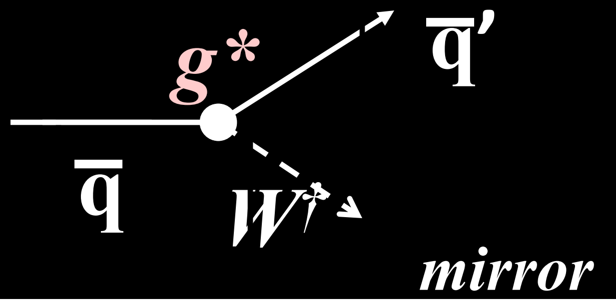
$$|B|\,e^{i\delta_s + i\phi_{CP}}$$



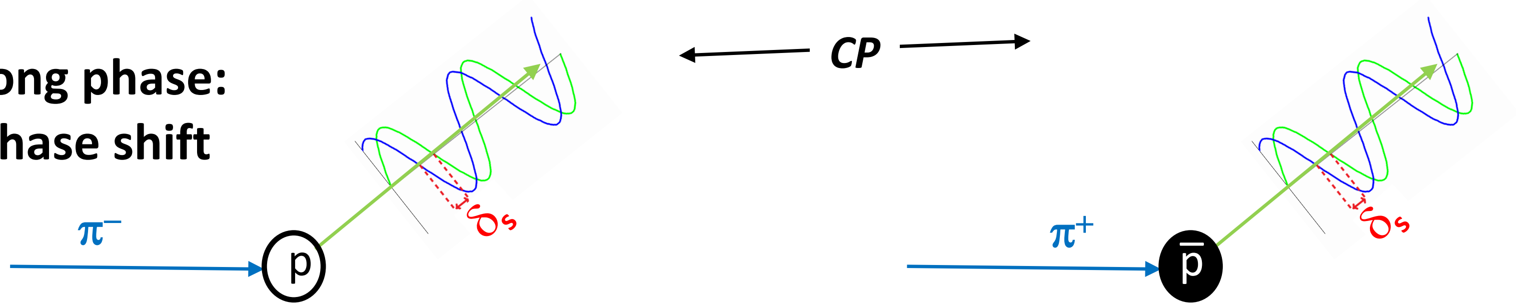
CP →

"same" sign — "opposite" sign

$$|B|\,e^{i\delta_s - i\phi_{CP}}$$



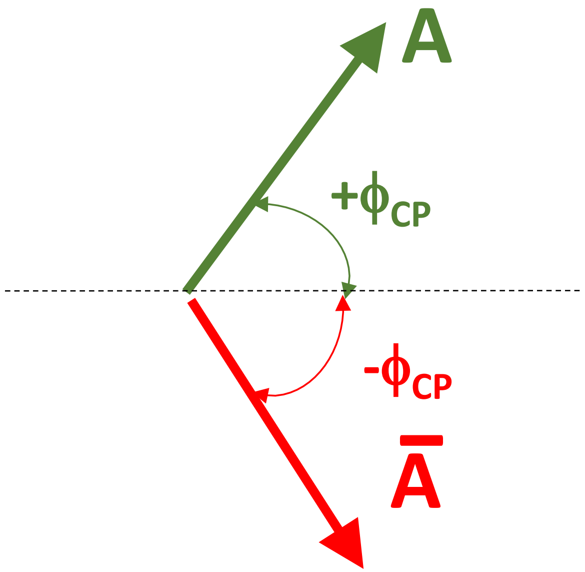
example of a strong phase:
$\pi^{-}p$ scattering phase shift



particle-antiparticle phase shifts are the same

QM phase measurements require interference

$A = |A| e^{+i\phi_{CP}} \xrightarrow{CP} \bar{A} = |A| e^{-i\phi_{CP}}$ $\Longleftarrow$ (CPT requires that $|A| = |\bar{A}|$)



$|A|^2 = |A|^2 \Longrightarrow$ no CPV asymmetry

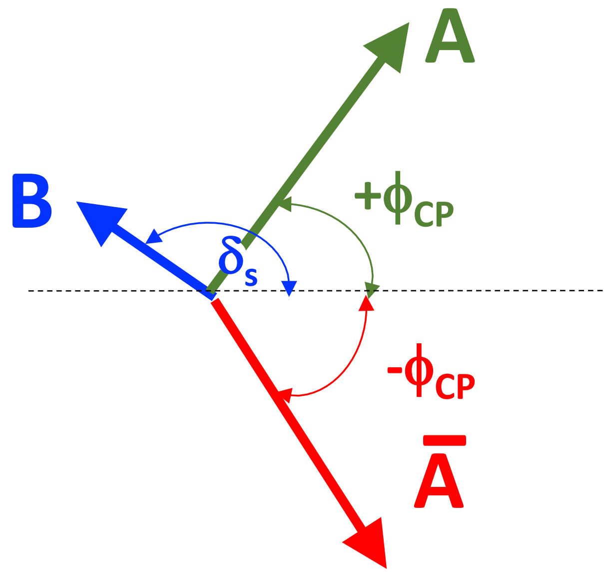
QM phase measurements require interference

$A=|A|e^{+i\phi_{CP}} \xrightarrow{CP} \bar{A}=|A|e^{-i\phi_{CP}}$ $\Longleftarrow$ (CPT requires that $|A| = |\bar{A}|$)

include $B=|B|e^{+i\delta_s}$

B: non-CPV process to the same final state

δ_s; **B** and $A+\bar{A}$ strong phase difference



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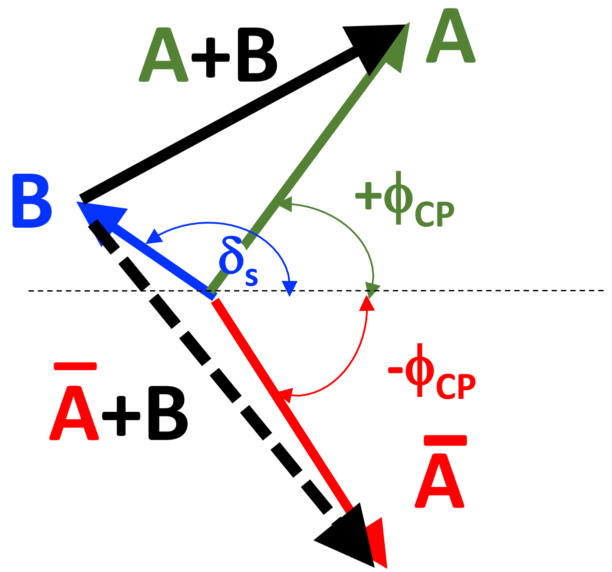
include $B = |B| e^{+i\delta_s}$

B: non-CPV process to the same final state
δ_s; **B** and $A + \bar{A}$ strong phase difference

$$|A+B| - |\bar{A}+B| = 4|A||B| \sin\delta_s \sin\phi_{CP}$$



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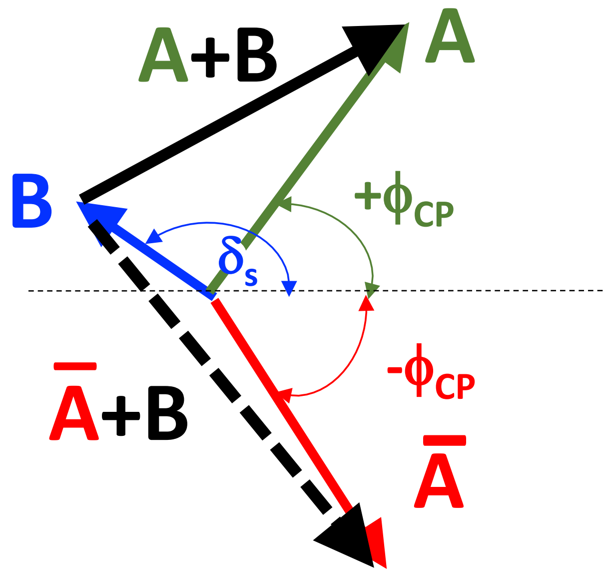
$$|A+B| - |\bar{A}+B| = 4|A||B| \sin\delta_s \sin\phi_{CP}$$



measureable CPV asymmetry requires:

1) non-zero ϕ_{CP}
2) interfering amplitude
3) non-zero δ_s

QM phase measurements require interference

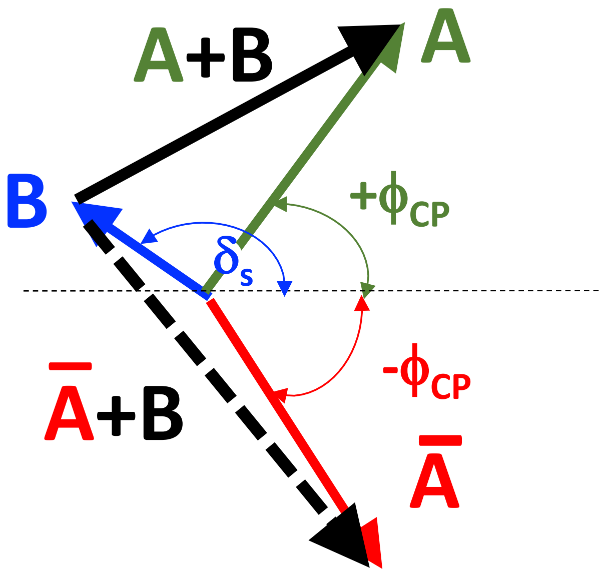
$A=|A|e^{+i\phi_{CP}} \xrightarrow{CP} \bar{A}=|A|e^{-i\phi_{CP}} \Longleftarrow$ (CPT requires that $|A| = |\bar{A}|$)

include $B=|B|e^{+i\delta_s}$

B: non-CPV process to the same final state

δ_s; **B** and $A+\bar{A}$ strong phase difference

$$|A+B|-|\bar{A}+B|=4|A||B|\sin\delta_s\sin\phi_{CP}$$



measureable CPV asymmetry requires:

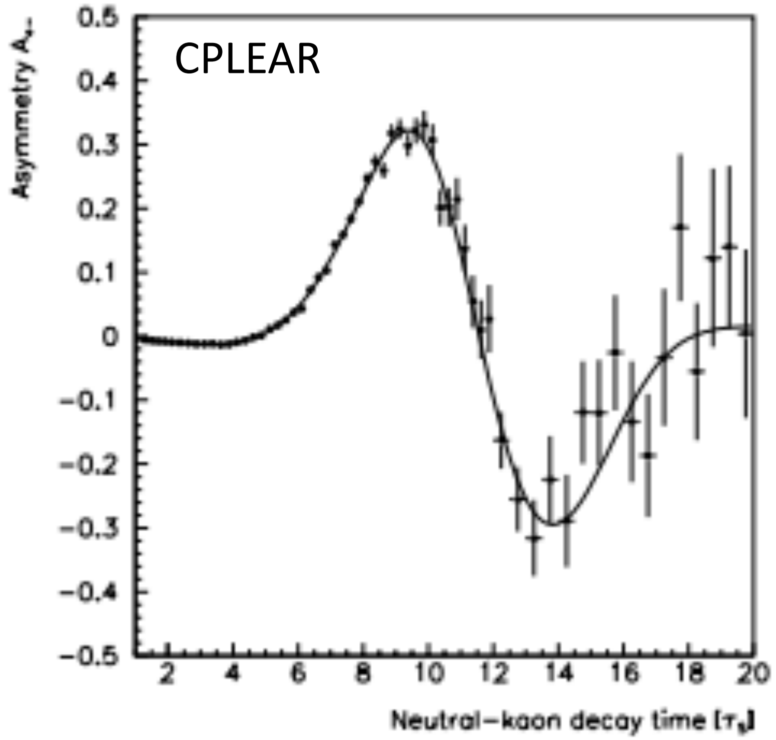
1) **non-zero ϕ_{CP}**
2) **interfering amplitude**
3) **non-zero δ_s**

non-zero ϕ_{CP} is not enough!!

It doesn't have to a S.I. scattering phase shift

$$A_{+-}(\tau) = \frac{N_{\bar{K}^0}(\tau) - N_{K^0}(\tau)}{N_{\bar{K}^0}(\tau) + N_{K^0}(\tau)}$$

$$= -2\frac{|\eta_{+-}|e^{\frac{1}{2}(\tau/\tau_S - \tau/\tau_L)}\cos(\Delta m\tau - \phi_{+-})}{1 + |\eta_{+-}|^2 e^{(\tau/\tau_S - \tau/\tau_L)}}.$$

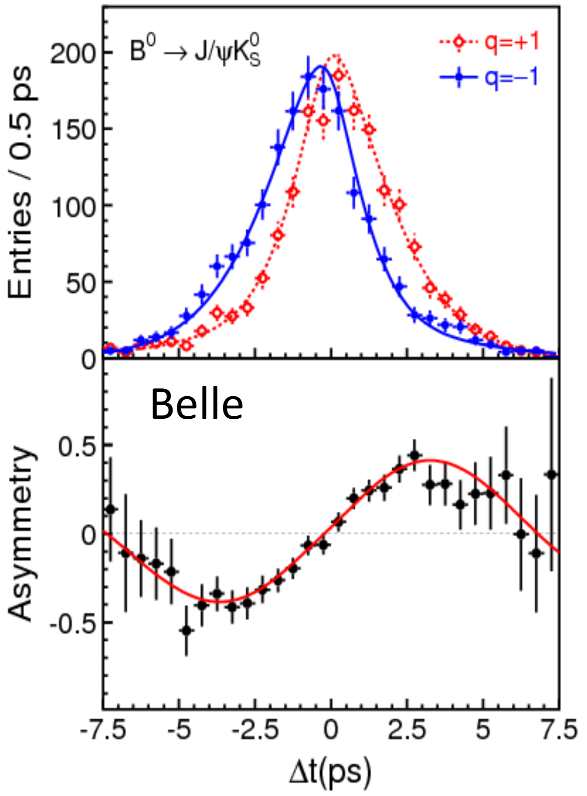


Phys. Lett. B458, 545 (1999)

In these experiments the "strong" phase is exp(iΔmτ) from mixing

$$A_{+-}(\tau) = \frac{N_{\bar{B}^0}(\tau) - N_{B^0}(\tau)}{N_{\bar{B}^0}(\tau) + N_{B^0}(\tau)}$$

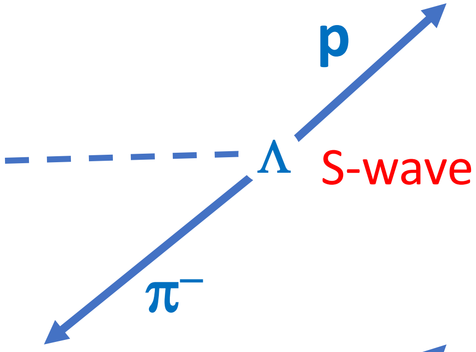
$$= \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B}(1 - \xi_f q(1-2w)\sin 2\phi_1 \sin \Delta m\Delta t)$$



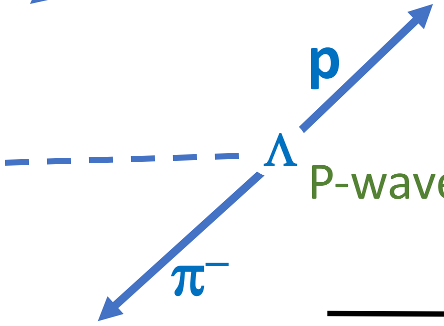
Phys. Rev. Lett. 108, 171802 (2012)

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

-- assume CPV is in P-wave --



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

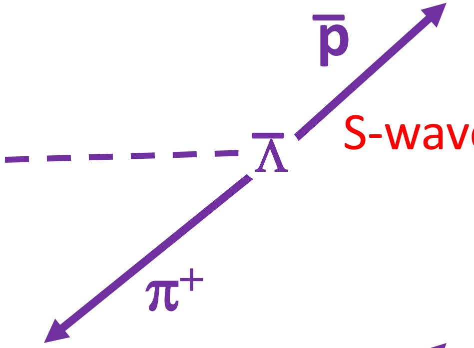


P-wave: $P\, e^{i\delta^P + i\phi_{CP}}$

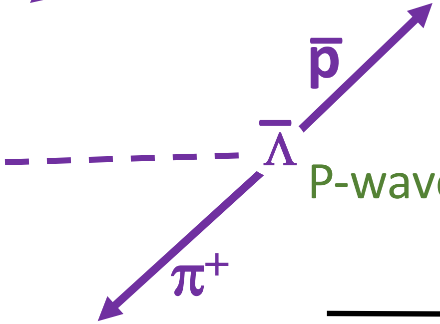
$$e^{-i\delta^S}\left(S + P\, e^{i(\delta^P - \delta^S) + i\phi_{CP}} \right)$$

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 & γ parameters for hyperon decay

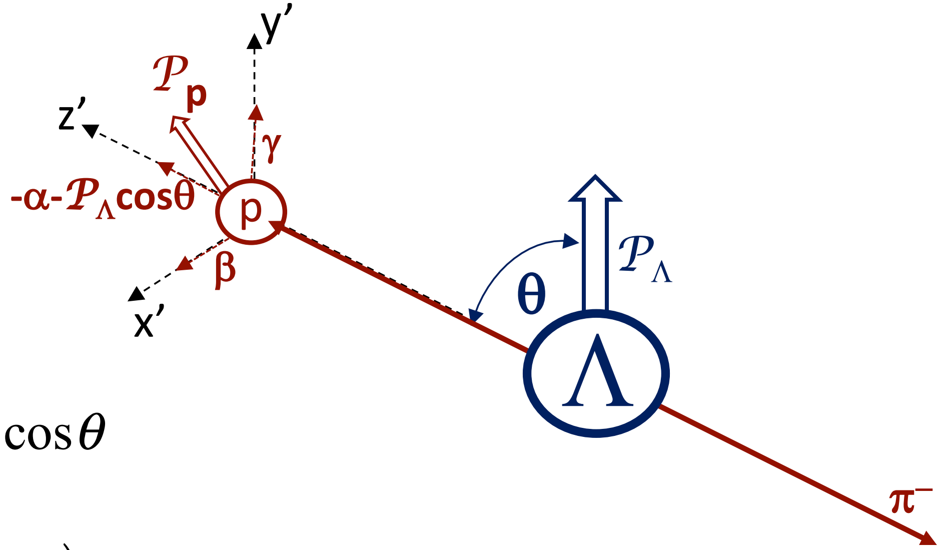
Phys. Rev. 108 1645 (1957)

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)



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

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

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

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

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

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

CPV observables in Λ decay:

hep-ph/991023v1
hep-ph/0002210

decay rate difference

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

← $T_{3/2(1/2)}$: 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 Λ→pπ, need measurement of $\Delta_s = \delta_S - \delta_P$

final-state polarization difference

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

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

← strong phase cancels out

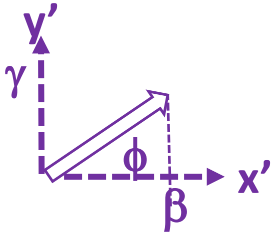
$$\frac{\beta_- - \beta_+}{\alpha_- - \alpha_+} = \frac{\sin\Delta_S \cos\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\Delta_S$$

← measures the strong phase

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

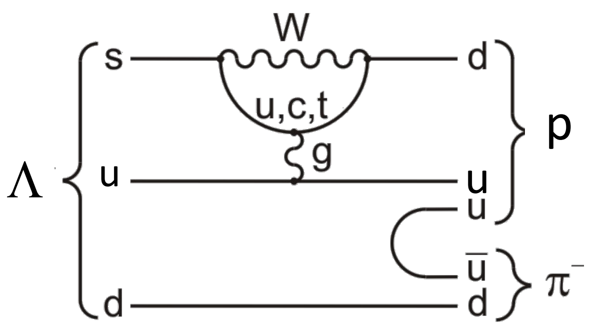
≈β/α

β/γ (= tanϕ) is commonly used



Constraints from Kaon decays

He & Valencia PRD 52, 5257

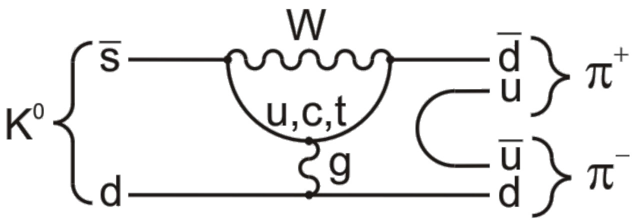


S- and P-waves
(parity violating
& conserving)

$\Lambda \rightarrow p\pi^-$	A_{NP}	
S-wave	$<6\text{x}10^{-5}$	parity violating
P-wave	$<3\text{x}10^{-4}$	parity conserving

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

$Re(\varepsilon'/\varepsilon)=(1.6+0.3)\text{x}10^{-3}$



S-wave only
(parity violating)

ε'/ε strongly constrains NP in S-waves, but *not* P-waves. Thus, hyperon NP searches are *complementary* to those with Kaons.

Measurements

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)

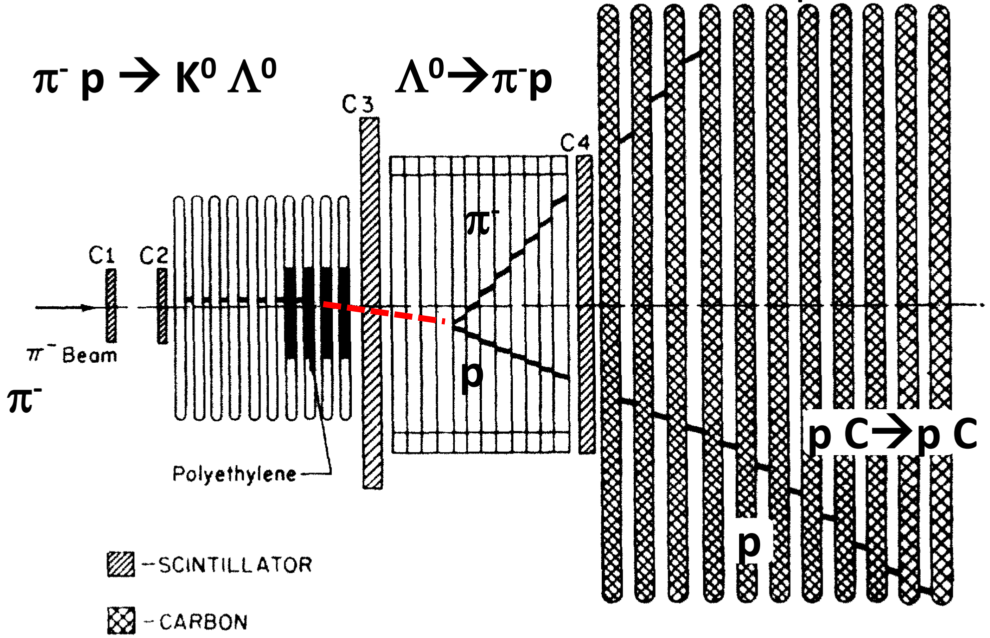
The decay parameters of $\Lambda^0 \to \pi^- + p$ have been measured by observing the polarization of the decay protons by scattering in a carbon-plate spark chamber. The experimental procedure is discussed in some detail. A total of 1156 decays with useful proton scatters was obtained. The results are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

$$\alpha = 2\,\mathrm{Re}\,sp^*/(|s|^2+|p|^2) = +0.62 \pm 0.07,$$
$$\beta = 2\,\mathrm{Im}\,sp^*/(|s|^2+|p|^2) = +0.18 \pm 0.24,$$
$$\gamma = |s|^2 - |p|^2/(|s|^2+|p|^2) = +0.78 \pm 0.06,$$

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 $\beta = 0.18 \pm 0.24$ is consistent with the value $\beta = 0.08$ expected on the basis of time-reversal invariance.

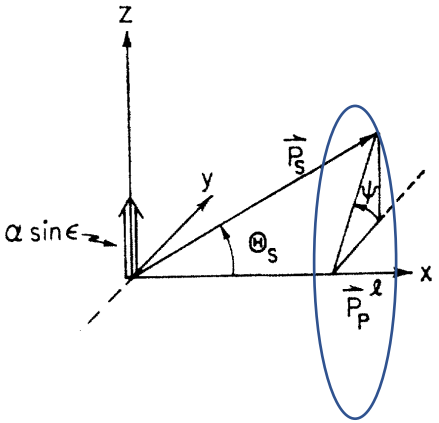
$$P_p = \frac{(\alpha + P_\Lambda \cos\theta)\hat{z}' + \beta P_\Lambda \hat{x}' + \gamma P_\Lambda \hat{y}'}{1 + \alpha P_\Lambda \cos\theta}$$

1.25 cm-thick carbon plates



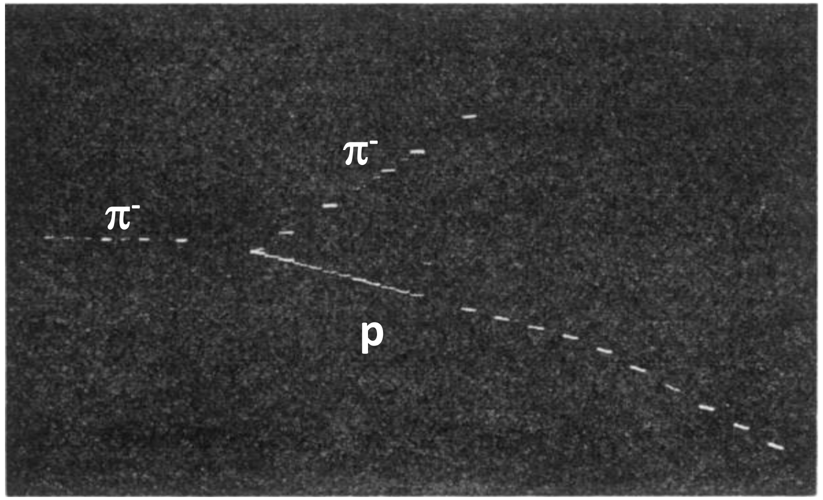
no H_2 target, no magnet; use kinematics and proton's range in carbon to infer E_p

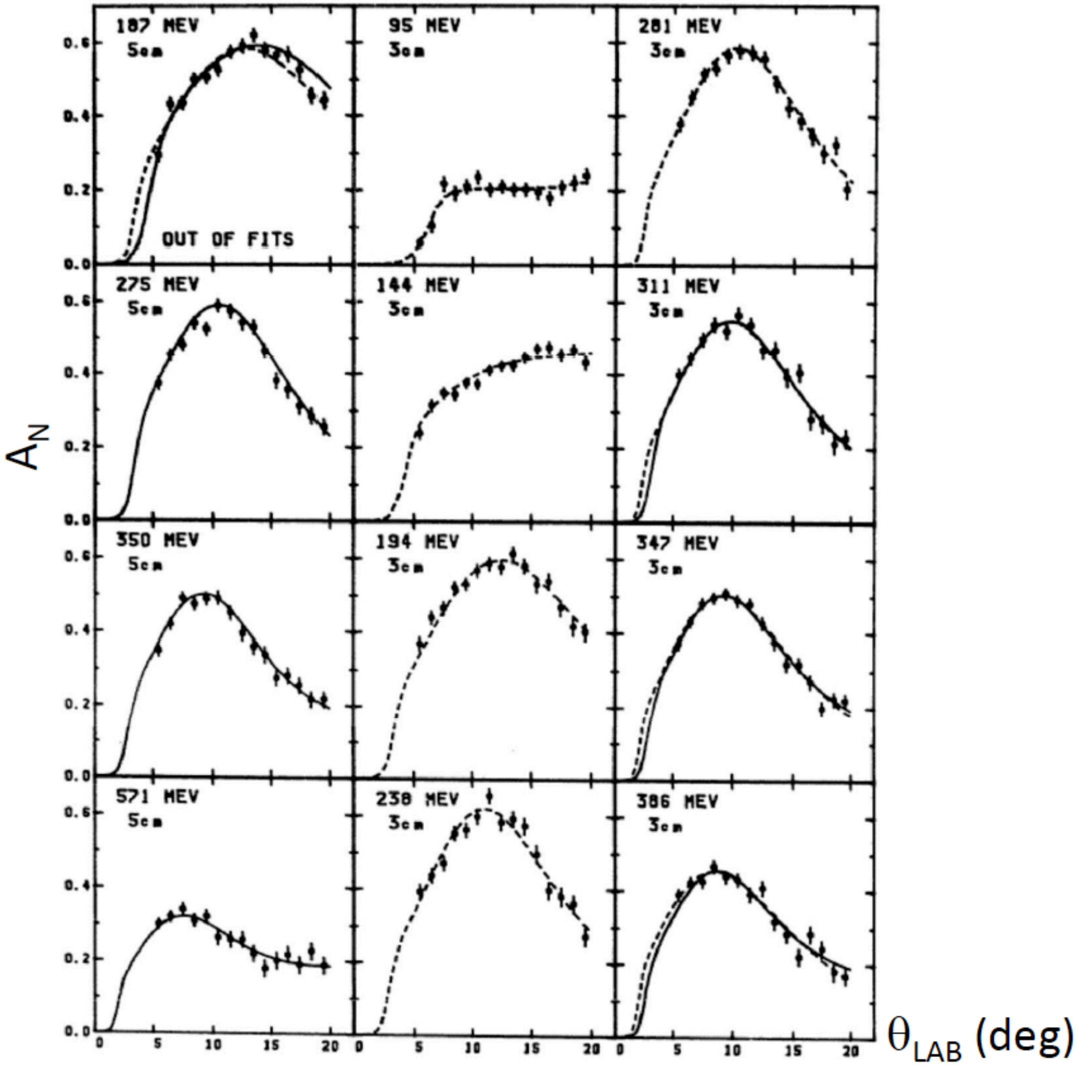
Use p C elastic scattering to measure p spin



$$P = \langle S_i \rangle \frac{N_L - N_R}{N_L + N_R}$$

$$\langle S_i \rangle$$



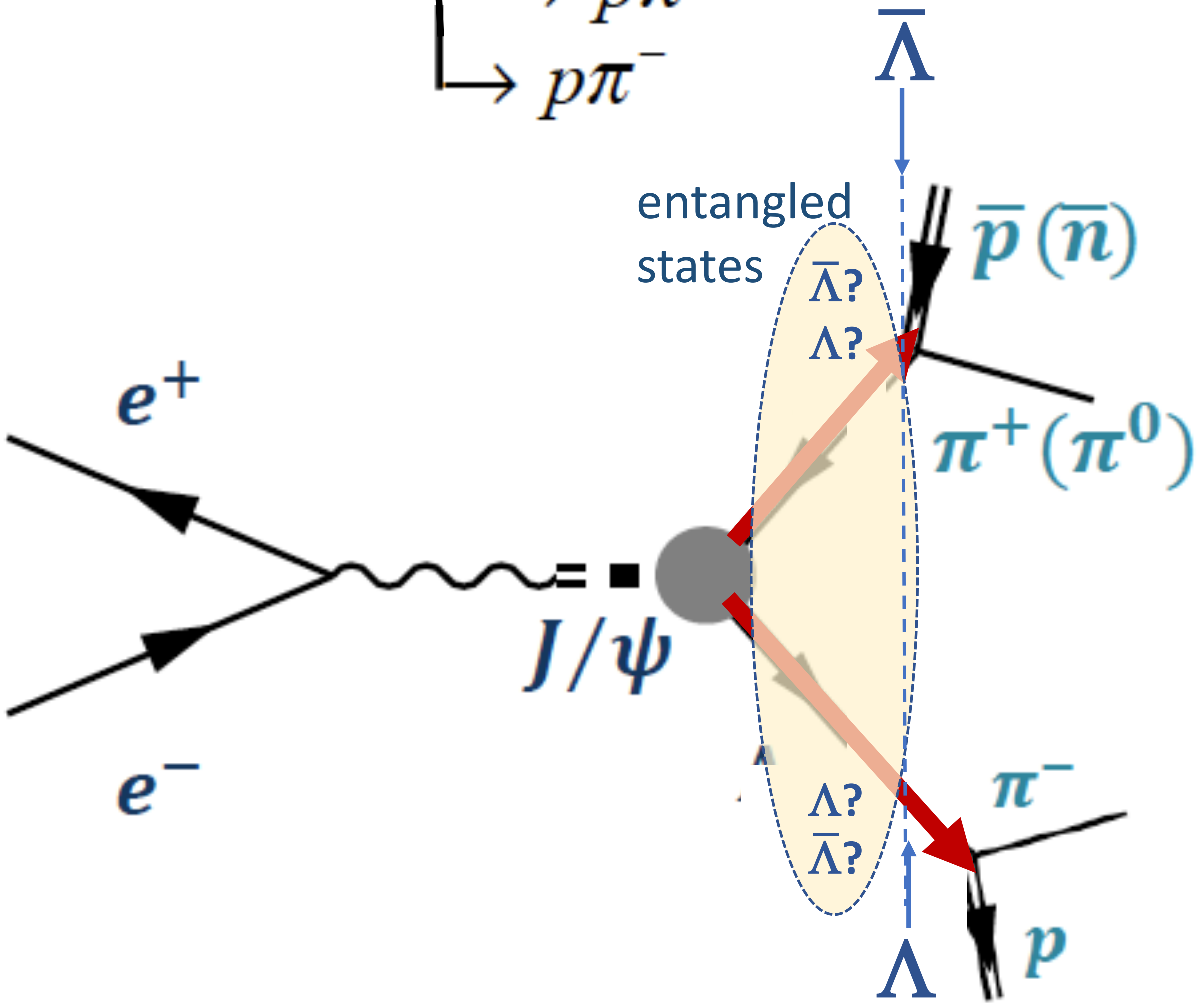


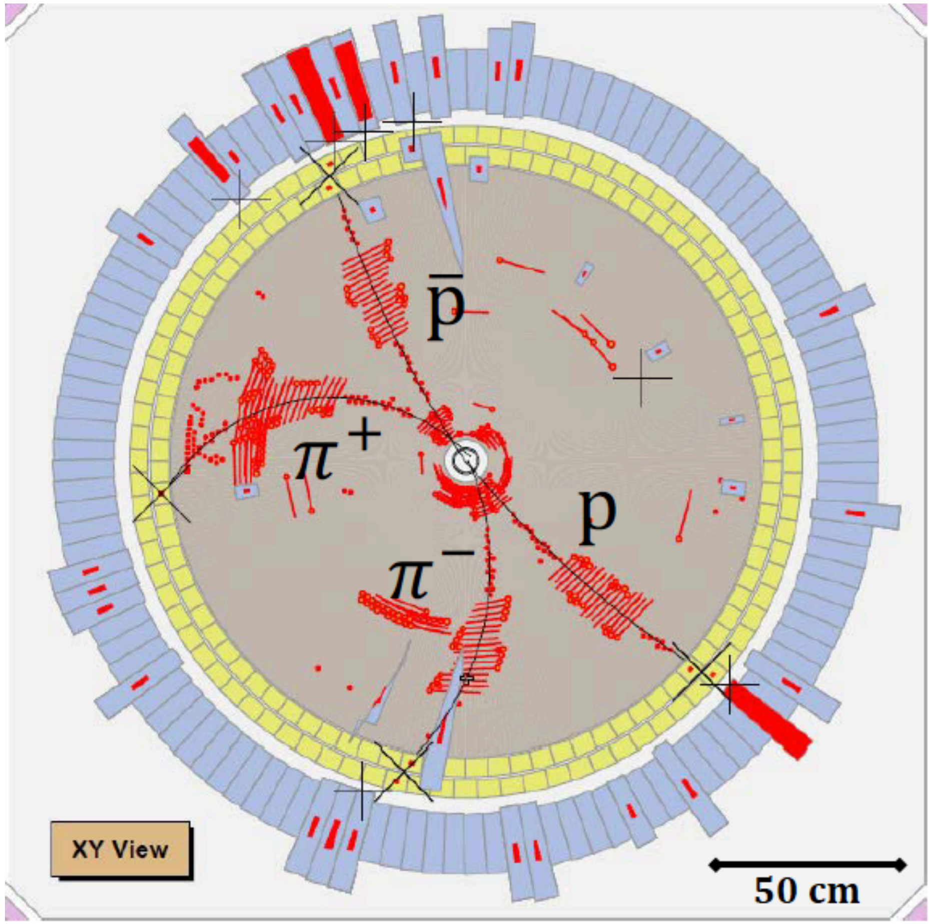
Measuring these in the 21st century

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

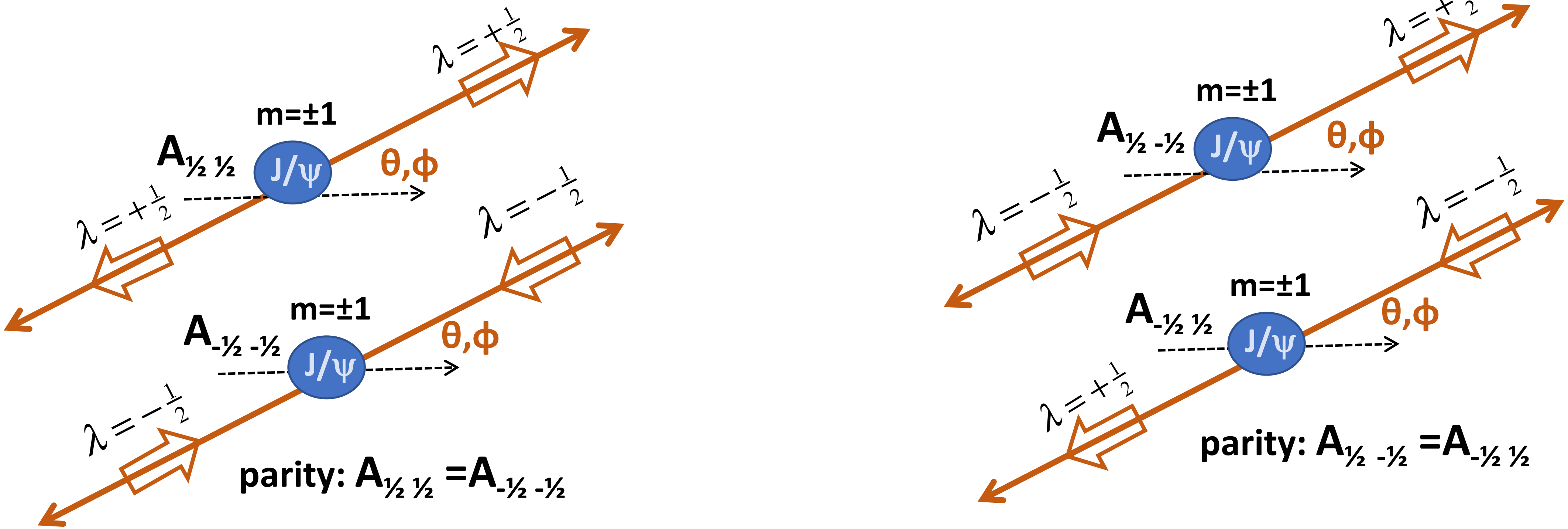
$\bar{\Lambda} \to \bar{p}\pi^+$

$\Lambda \to p\pi^-$





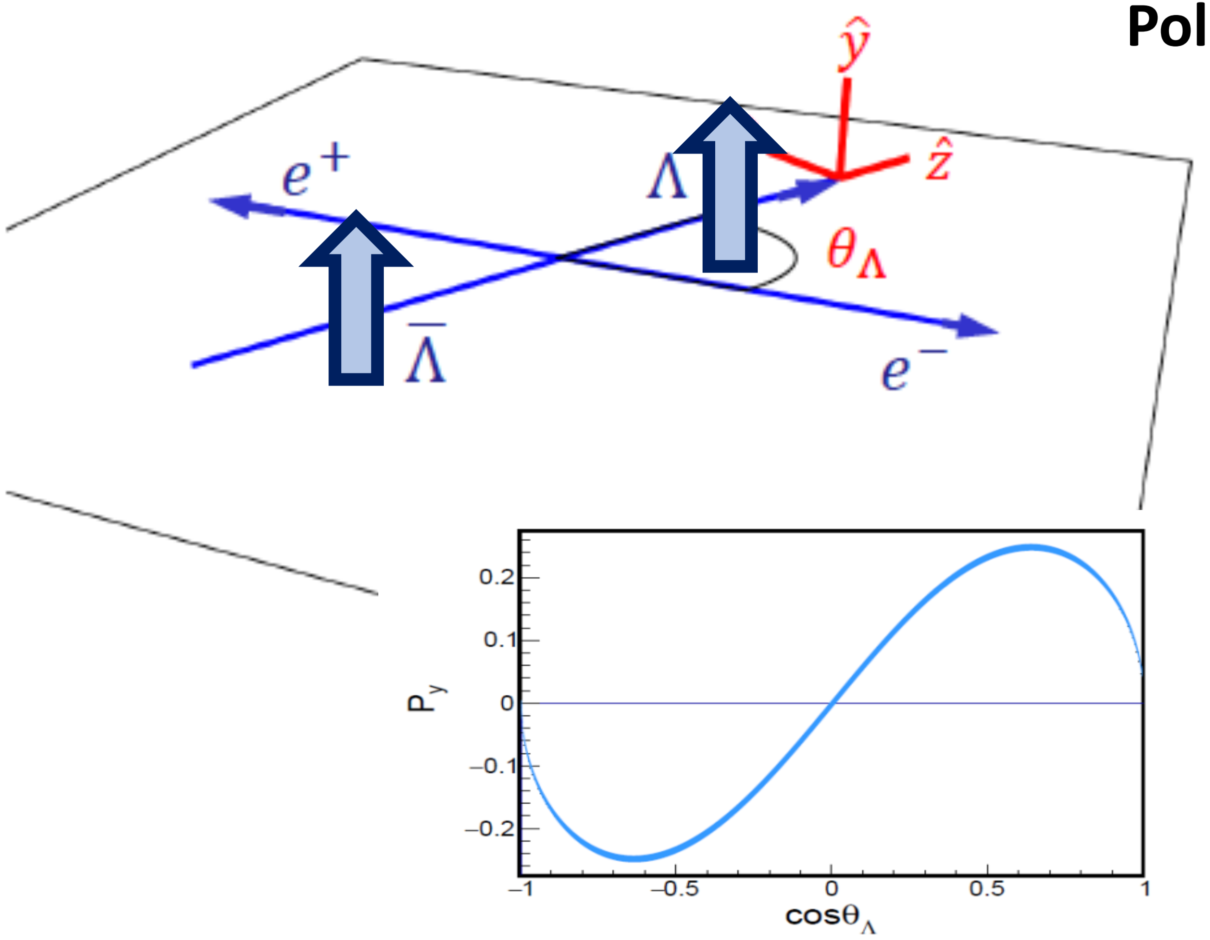
Production: 2 independent helicity amplitudes: $A_{½\,½}$, $A_{½\,-½}$



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

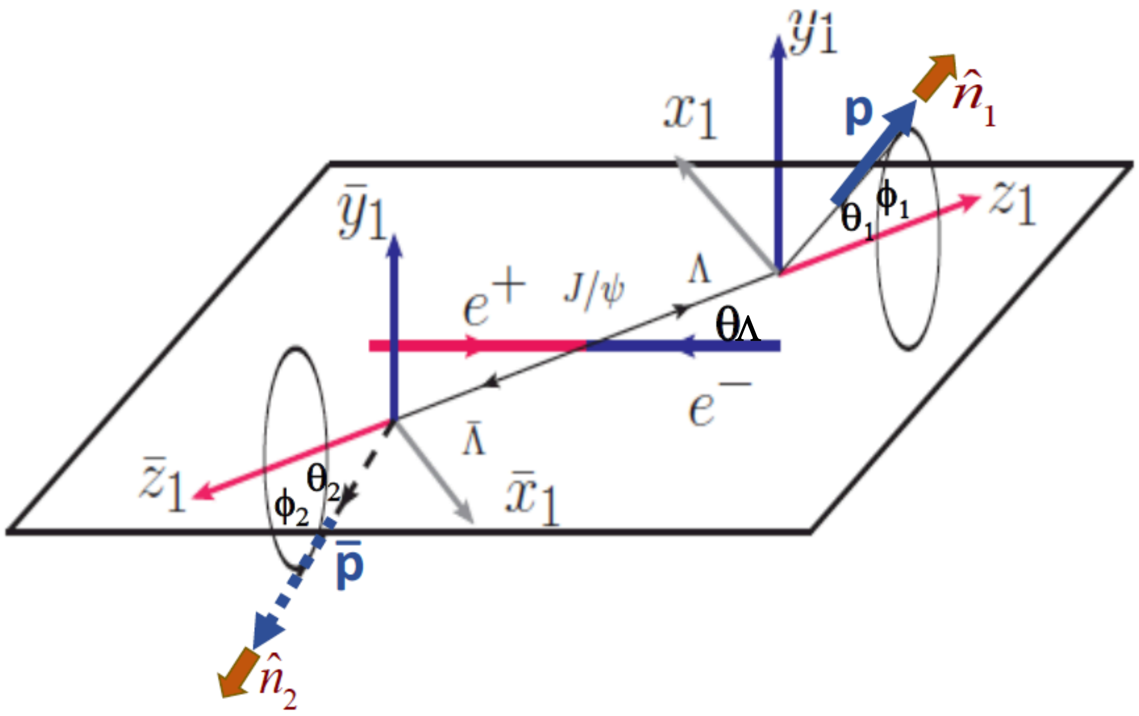
same direction for Λ and $\bar{\Lambda}$

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



BESIII results

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) 4x precision improvement -same data sample-

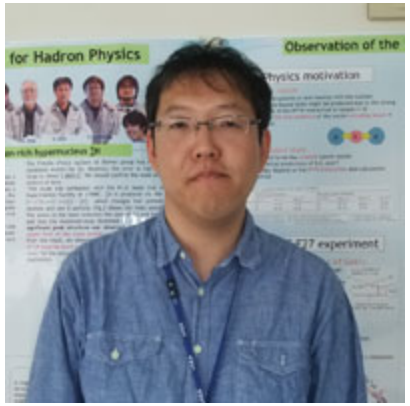
← 2) ~7σ upward shift from all previous measurements

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

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!!

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

lifetime=12 ns

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

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

lifetime=0.21 ns

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

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

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

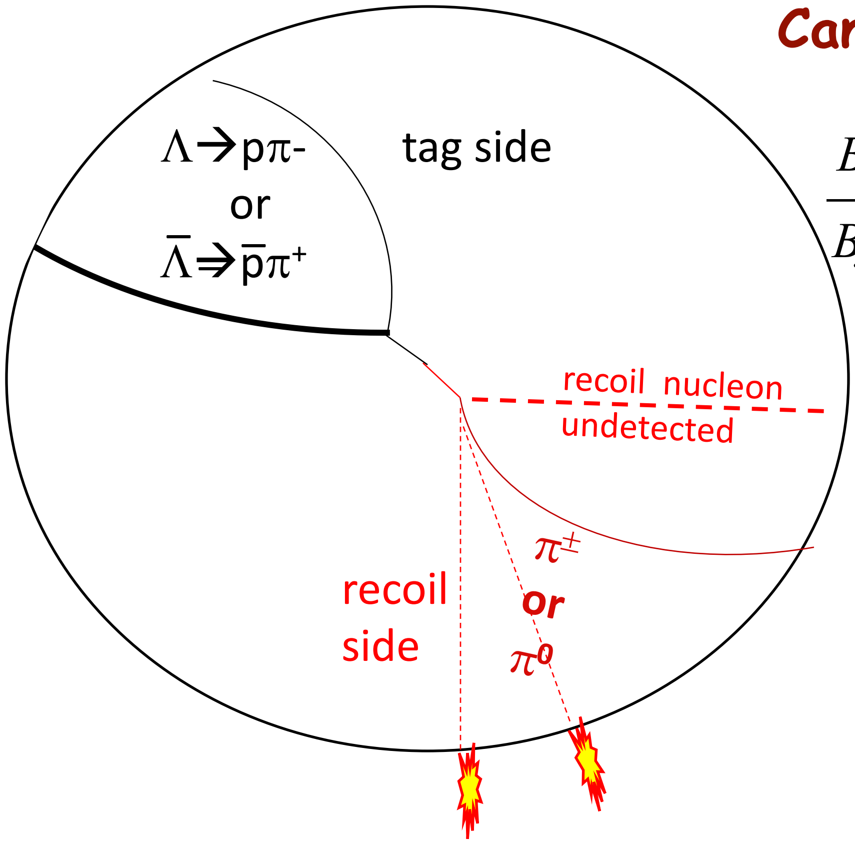
$$\frac{\alpha_+}{\bar{\alpha}_0} = \frac{1 + \frac{1}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)}{1 - \sqrt{2}\left(T_{3/2}/T_{1/2}\right)} \approx 1 + \left(\tfrac{1}{\sqrt{2}} + \sqrt{2}\right)\left(T_{3/2}/T_{1/2}\right) = 1 + \tfrac{3}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)$$

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

good agreement

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

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



Can BESIII measure this with low systematic errors?

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

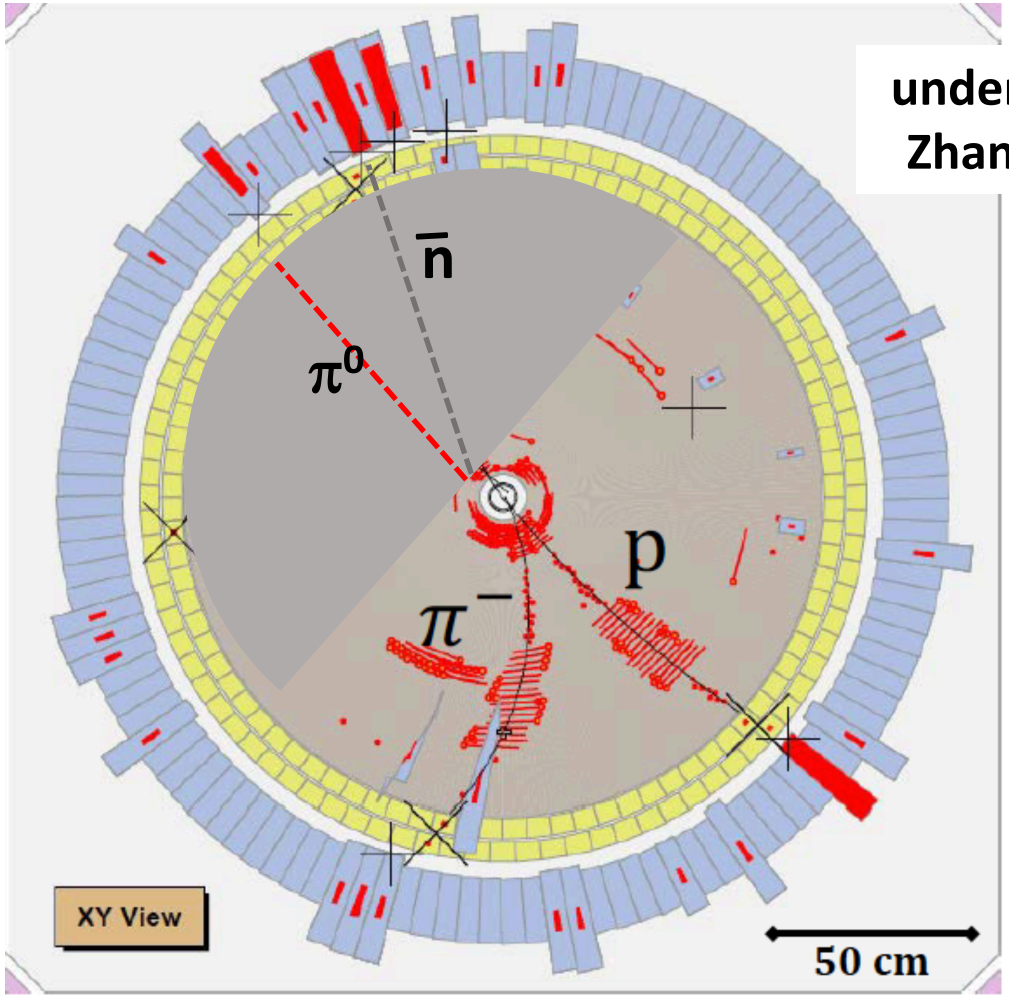
Detect a $\Lambda \rightarrow p\pi^-$ or $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ accompanied by a $\pi^\pm$ or π^0
Infer presence of the recoil nucleon by missing mass

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

π^0 must be distinguished from $\bar{n}$ annihilation debris

-- not so easy --

use machine-learning algorithms?



under study by
Zhang Jian-Lu

Decay rate asymmetry in BESIII

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

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

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

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 $\alpha_0+\bar{\alpha}_0/\alpha_0-\bar{\alpha}_0$ measurement

CPV with Ξ→Λπ decays

Ξ ← Greek letter "Xi"

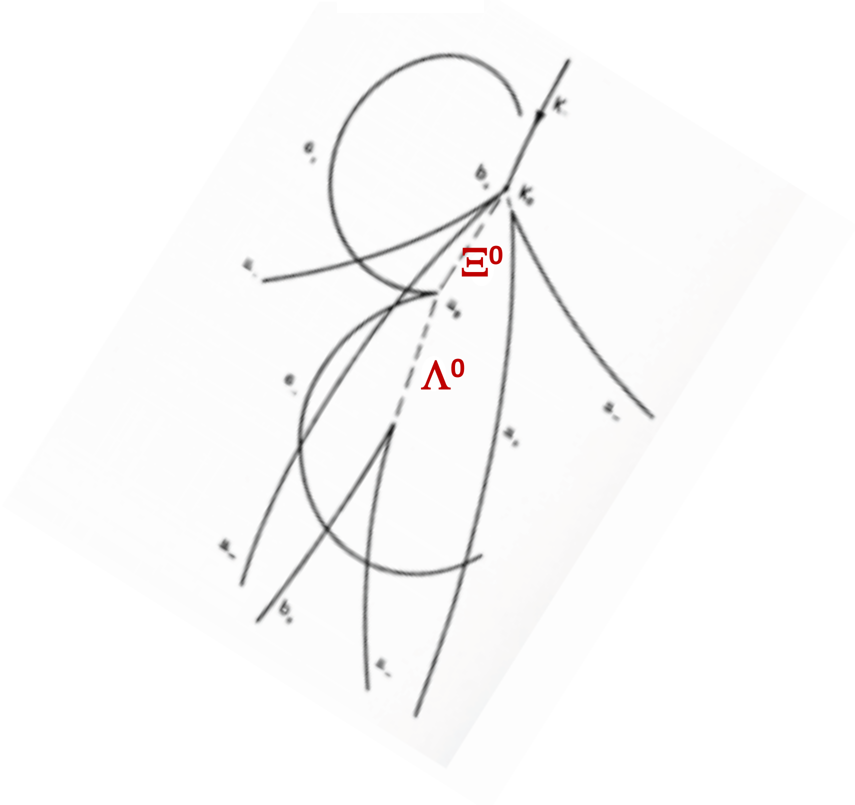
sounds like "psi" (ψ)

"cascade" ←English word for multi-tier waterfall

$K^- p \rightarrow K^0 \Xi^0 \pi^+ \pi^-$

$K^0 \rightarrow \pi^+\pi^-$, $\Xi^0 \rightarrow \pi^0 \Lambda^0$

$\pi^0 \rightarrow \gamma\, e^+ e^-$, $\Lambda^0 \rightarrow \pi^- p$



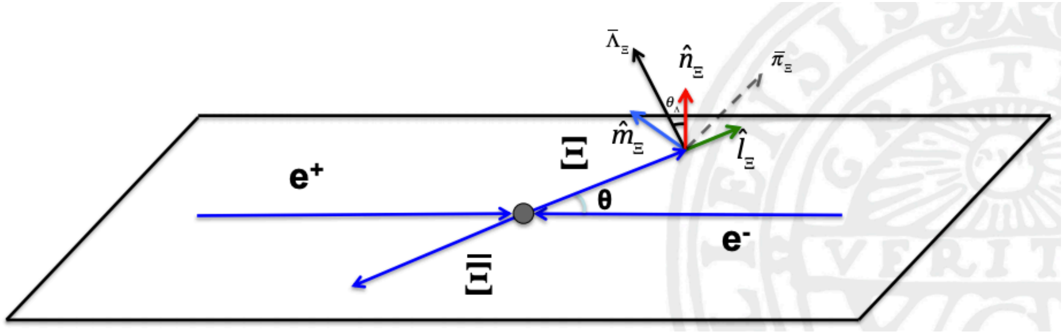
CPV with $J/\psi \to \Xi^-(\to\Lambda\pi^-)\ \bar{\Xi}^+(\to\bar{\Lambda}\pi^+)$: plusses and minuses

Minuses:

complicated topology: 9-dimensions

$\theta_\Xi, \theta_\Lambda, \varphi_\Lambda, \theta_{\bar{\Lambda}}, \varphi_{\bar{\Lambda}}, \theta_p, \varphi_p, \theta_{\bar{p}}, \varphi_{\bar{p}}$

72 terms, 8 parameters to determine



Low rate compared to $\Lambda\bar{\Lambda}$

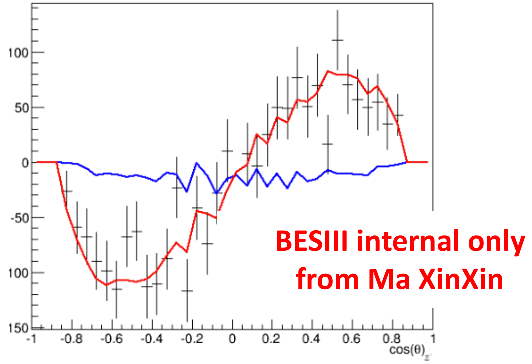
1.3B J/ψ: 420K $\Lambda(p\pi^-)\bar{\Lambda}(\bar{p}\pi^+)$ evts

61K $\Xi(\Lambda\pi^-)\ \bar{\Xi}(\bar{\Lambda}\pi^-)$

$p\pi^-$ $\bar{p}\pi^+$ evts

Pluses:

$\Lambda(\bar{\Lambda})$ polarizations are measureable via their parity-violating $p\pi^-$ ($p\pi^+$) decays; β_- and β_0 parameters can be determined.



Preliminary results indicate that the Ξs are even more polarized than the Λs.

CPV observables in Ξ^- decay

decay rate difference

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

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

decay asymmetry difference

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

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

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

final-state polarization difference

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

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

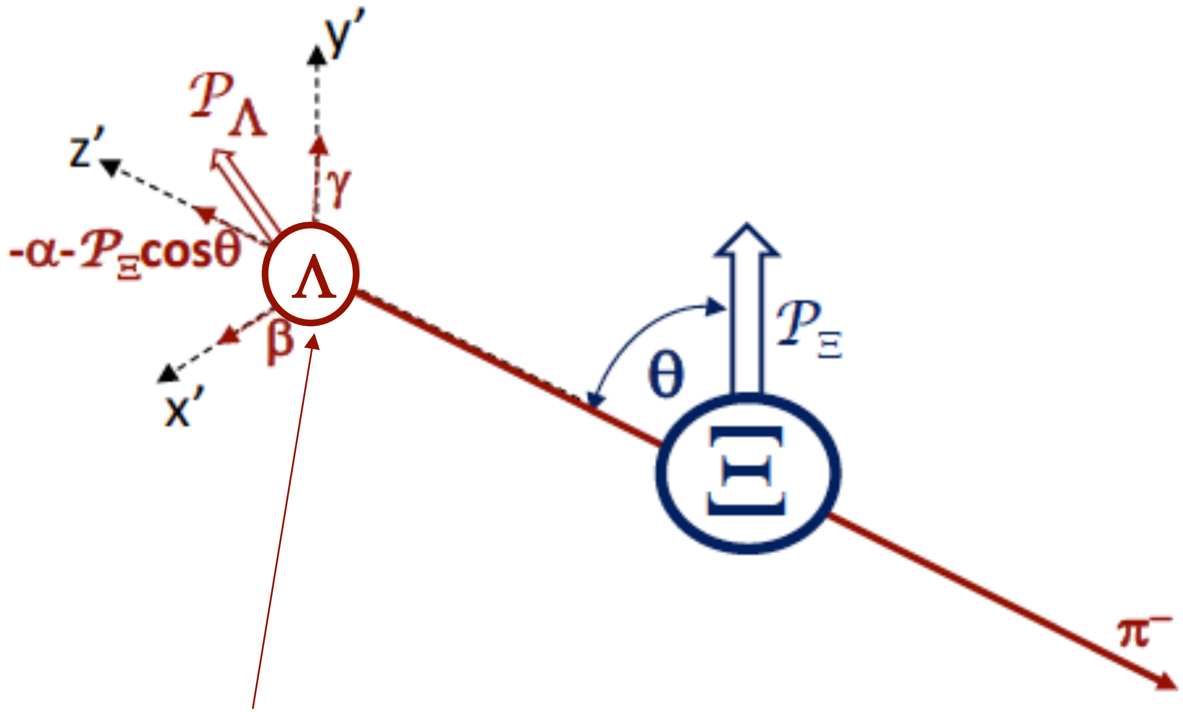
← Strong phase cancels out

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

← measures the strong phase

} big advantage for Ξ over Λ

Bonus from Ξ CPV studies



these Λs are 100% polarized and, event-by-event, the $\mathcal{P}_\Lambda$ direction is well known.

experimental sensitivity for $A_{CP}(\Lambda)$:

$$\delta(A_{CP}^{\Lambda}) \propto \sqrt{N_{evts}}$$

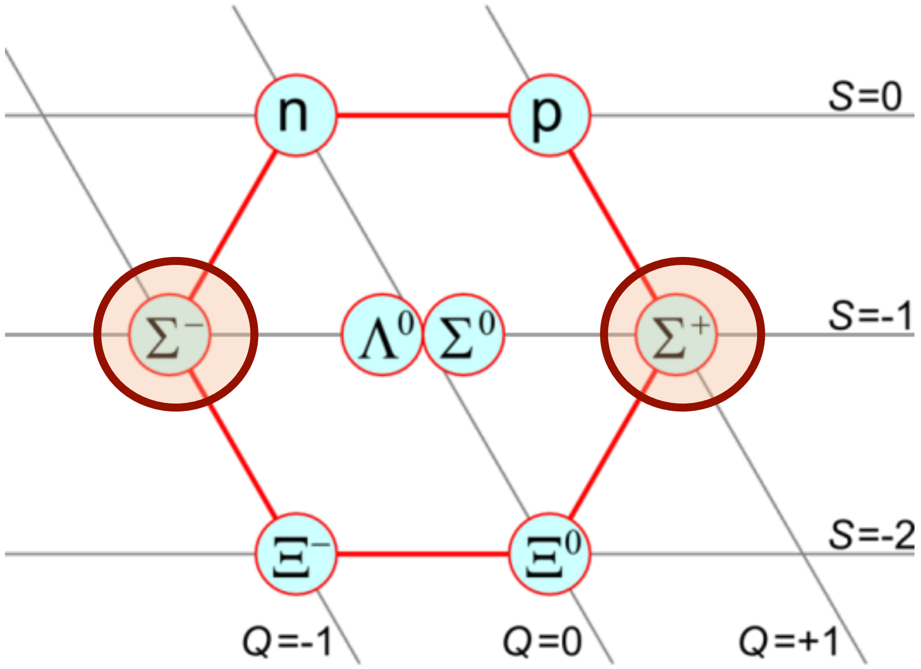
$$\delta(A_{CP}^{\Lambda}) \propto |P_\Lambda|$$

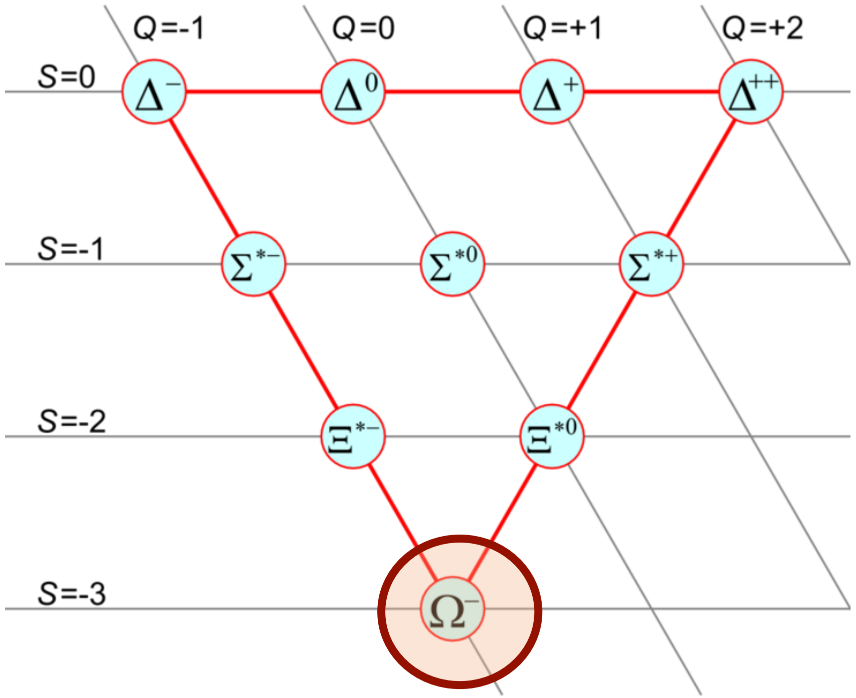
for $J/\psi \to \Lambda\bar{\Lambda}$: $\langle\mathcal{P}_\Lambda\rangle \approx 0.13$

for $J/\psi \to \Xi(\to\pi\Lambda)\,\bar{\Xi}(\to\pi\bar{\Lambda})$: $\langle\mathcal{P}_\Lambda\rangle = 1$

although $N_{evt}(J/\psi \to \Xi\bar{\Xi}) < N_{evt}(J/\psi \to \Lambda\bar{\Lambda})$,
A_{CP}^{Λ} sensitivities for the 2 modes are similar

How about other weakly decaying hyperons?





$\Sigma^+ \rightarrow p\pi^0$
$\rightarrow n\pi^+$

$\Sigma^- \rightarrow n\pi^-$

final state baryon polarization measurements impractical with BESIII

$\Omega^- \rightarrow \Lambda K^-$
$\rightarrow \Xi^0\pi^-$
$\rightarrow \Xi^-\pi^0$

need $\psi' \rightarrow \Omega^-\Omega^+$ data rates are low

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

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) %

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

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 α_-

$\Gamma(p\pi^0) \approx \Gamma(n\pi^+)$ 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^-?

α_- FOR $\Sigma^- \rightarrow n\pi^-$

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

$\alpha_0 \approx 0$ ➔ 1 partial wave dominates

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

no measurements of α_+

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) %

$\Gamma(\Xi^0\pi^-)$ =(2.74 + 0.15) x $\Gamma(\Xi^-\pi^0)$

$\Delta I=1/2$ rule expectation: ≈ 2 : ← $T_{3/2} \approx 0.15\ T_{1/2}$

$\Delta\Gamma$ will be enhanced (compared to Λs)

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

interference is small, not well suited

for $\alpha + \bar{\alpha}/\alpha - \bar{\alpha}$ measurements

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

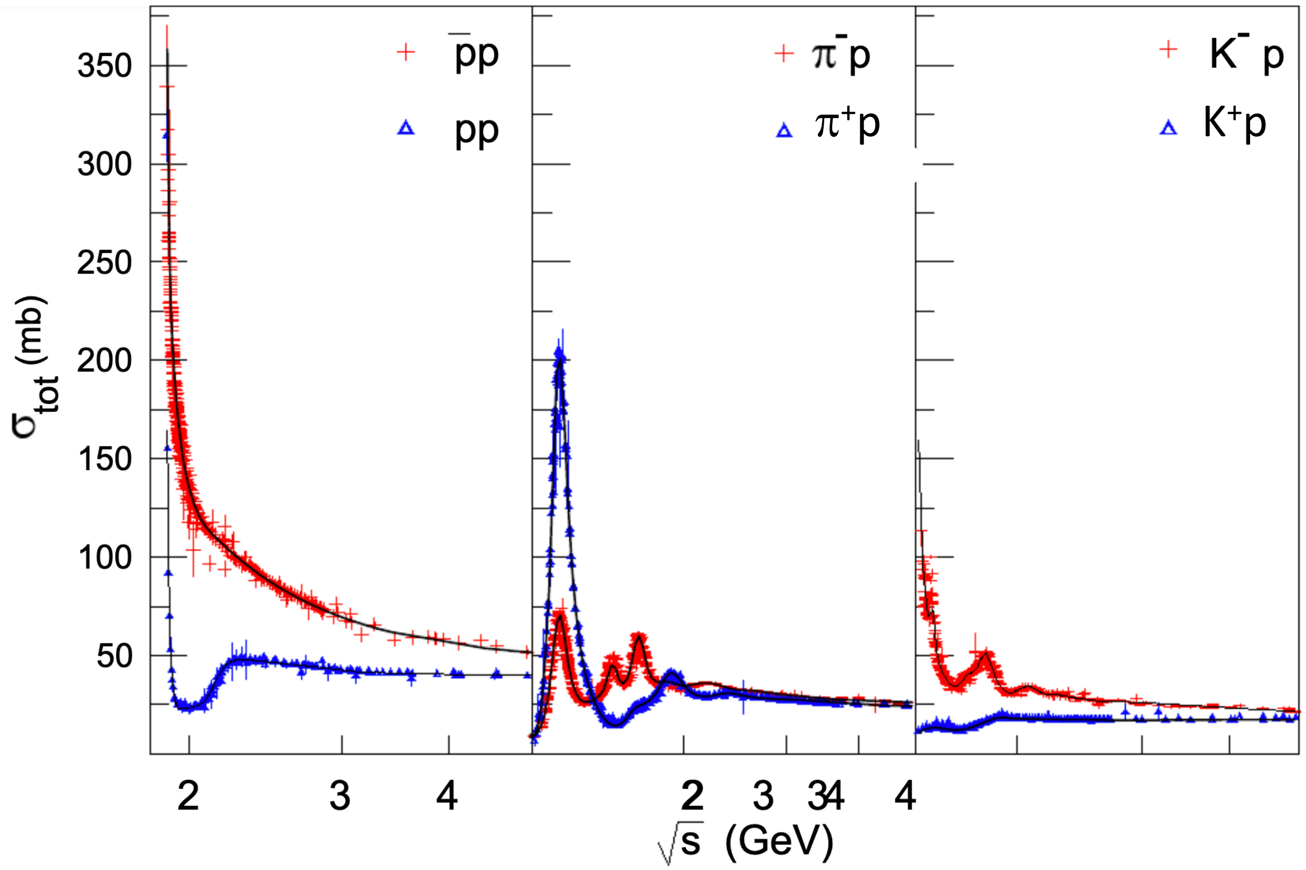
$$\frac{Bf(\Omega^- \to \Xi^-\pi^0)}{Bf(\Omega^- \to \Xi^0\pi^-)} - \frac{Bf(\bar{\Omega}^+ \to \bar{\Xi}^+\pi^0)}{Bf(\bar{\Omega}^+ \to \bar{\Xi}^0\pi^=)} = 2\left(1+\sqrt{2}\right)\left(T_{3/2}/T_{1/2}\right)\sin\Delta_s \sin\phi_{CP}$$

sensitivity is reduced but only by a factor of ~0.7

BESIII should check all these measurements

Implications for a J/ψ factory for CPV measurements

Minimize inner detector material

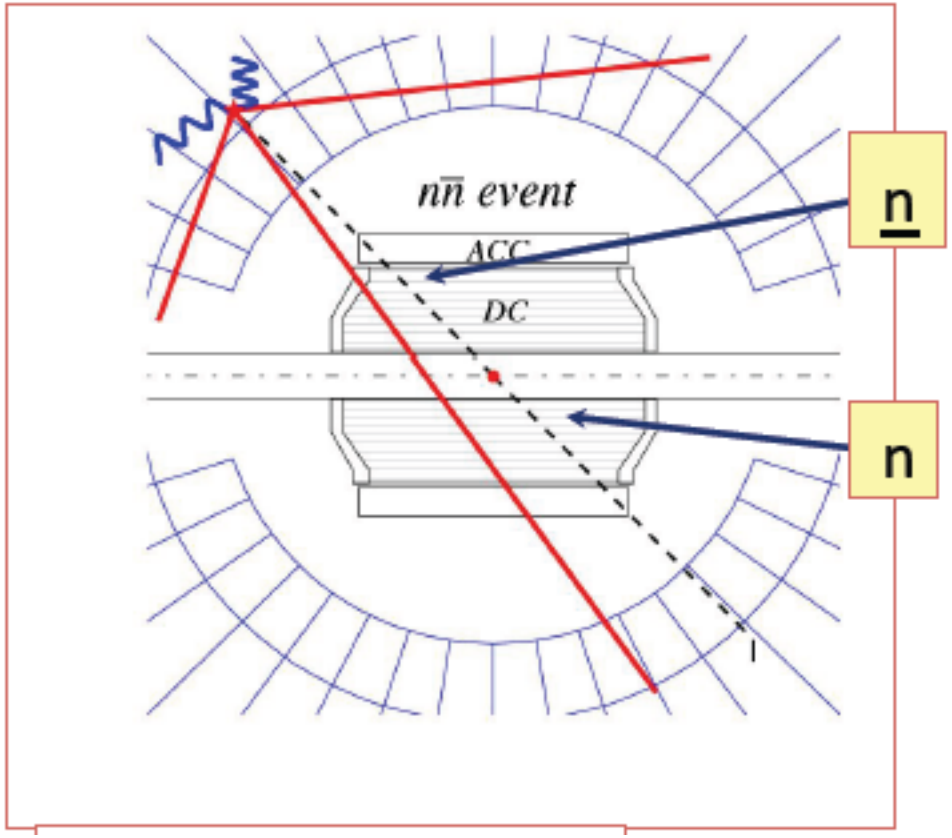


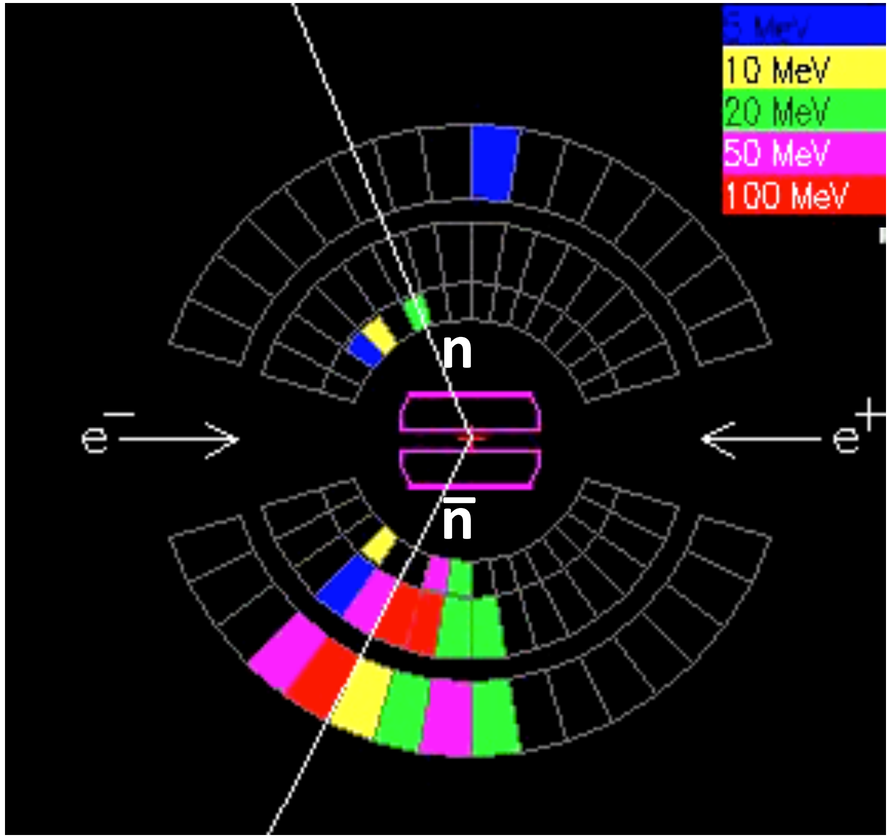
huge differences between particle & antiparticle nuclear interaction lengths.

gms/cm^2 is the relevant measure not radiation length

no vertex detectors!
no GEMs!

SND: $e^+e^- \rightarrow n\bar{n}$ at threshold

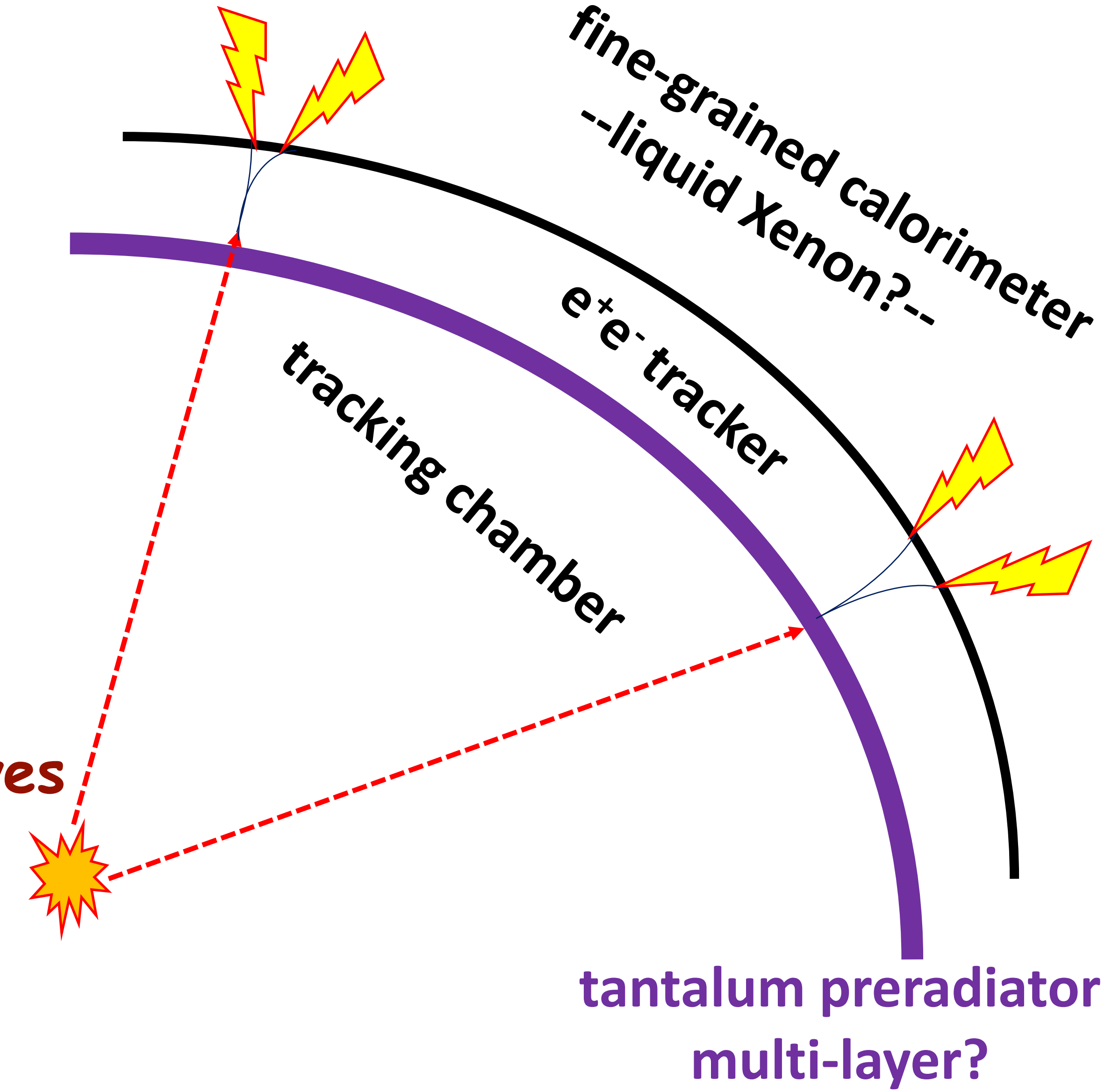




$\Lambda \rightarrow n\pi^0$ & $\bar{\Lambda} \rightarrow \bar{n}\pi^0$ backgrounds are totally different

γ-ray microscope?

need very high-Z
“pre-radiator”



trick is to develop a highly granular system that preserves γ-ray energy resolution

summary and some random questions

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 decays
- → good opportunities for $\Delta\alpha$ measurements with Σ^+
- → Σ^- and Ω^- CPV measurements are probably hopeless

Can partial reconstruction techniques be exploited with BESIII data

- → extracting π^0 from $\bar{n}$ debris is essential for $\Delta\alpha_0$ & $\Delta\Gamma$ measurements
- → Ω^- → $\Xi\pi$ measurements are severely rate limited

Questions:

- → can BESIII measure πN scattering phases at $E_{cm}=m_\Lambda$ & m_Σ precisely?
- → how does the material of the inner detector and the B-field?

thank you