中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

BESIII

Hyperon polarization and decay properties from J/ψ and ψ' at BESIII

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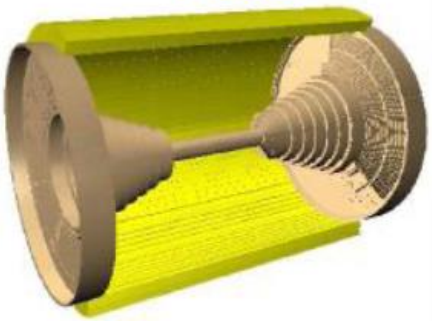
On behalf of BESIII Collaboration

QWG2021, virtual meeting, March 15-19 , 2021

BESIII Detector

MDC

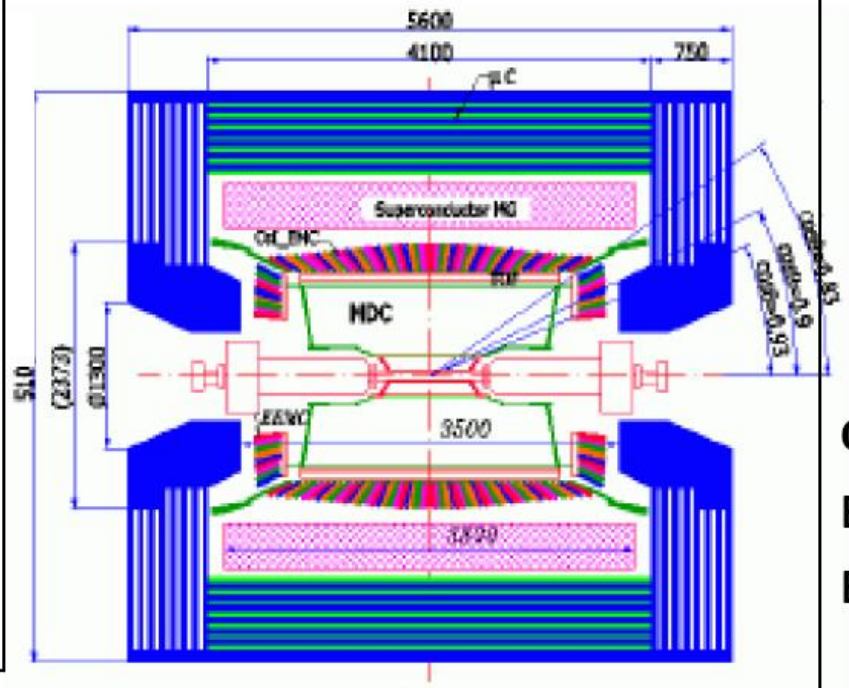


R inner: 63mm ;

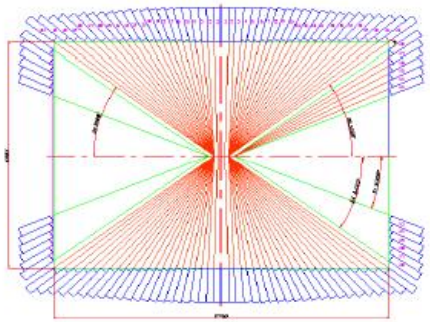
R outer: 810mm

Length: 2582 mm

Layers: 43



CsI(Tl) EMC



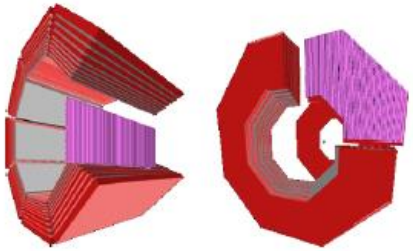
Crystals: 28 cm(15 X_0)

Barrel: $|\cos\theta|<0.83$

Endcap:

$0.85 < |\cos\theta| < 0.93$

RPC MUC



BMUC: 9 layers – 72 modules

EMUC: 8 layers – 64 modules

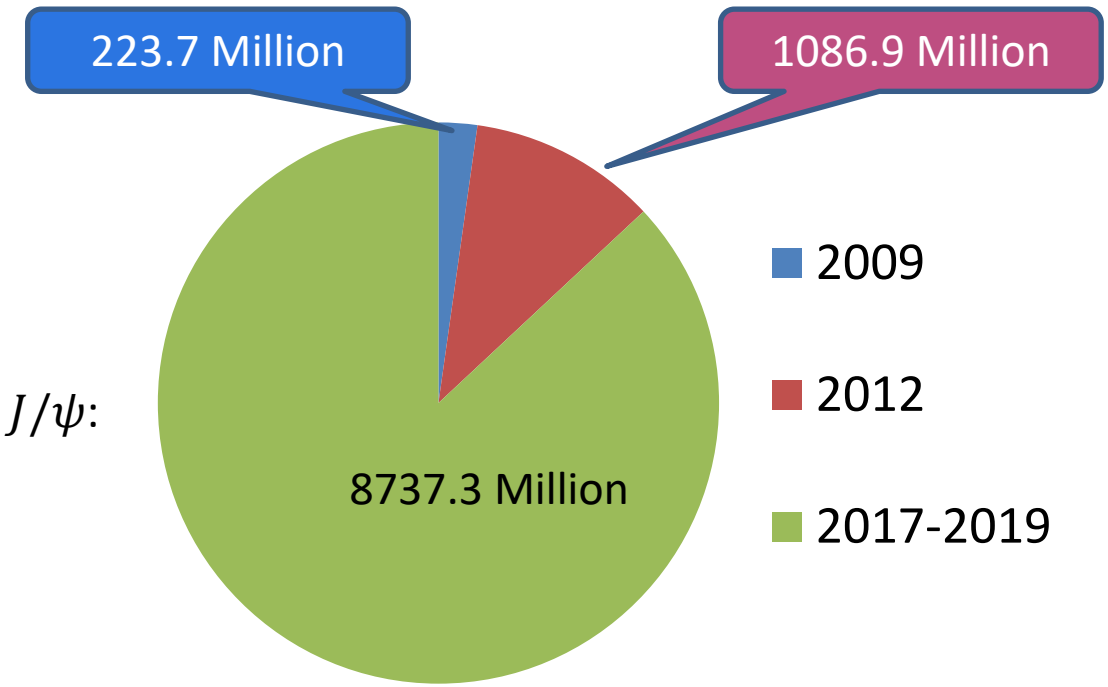
TOF

BTOF: two layers

ETOF: 48 scintillators for each

MRPC --- new ETOF

BESIII $J/\psi, \psi'$ data sets



The analysis based on 2009+2012 J/ψ data:

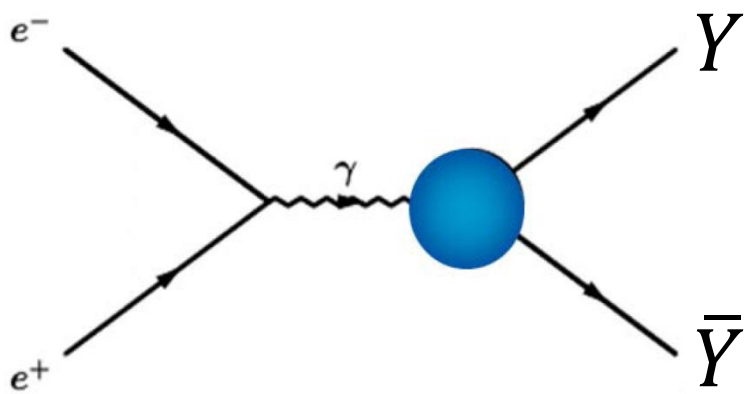
$\sim$1.31 billion decays

J/ψ : Total 10.047 billion J/ψ decays

ψ': 448 million decays

Hyperon pair production at BESIII

- $e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}, \Lambda_c^+\bar{\Lambda}_c^-,$ @ $\sqrt{s} = 2.0 \sim 4.6$ GeV, or update for $\Lambda_c^+\bar{\Sigma}_c^-$, $\Sigma_c\bar{\Sigma}_c$



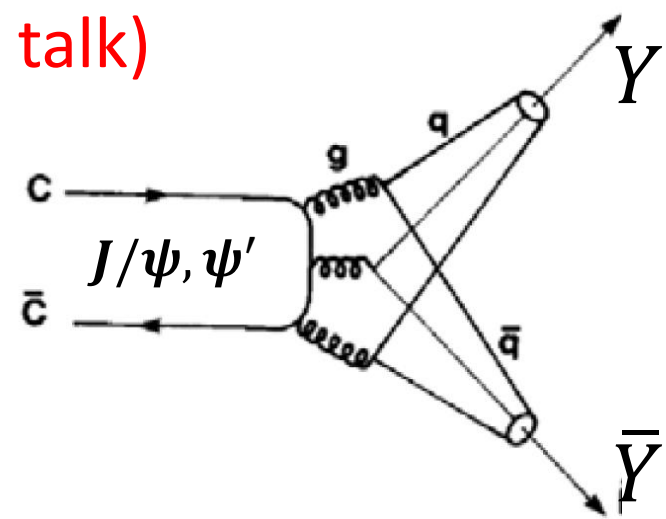
- Threshold enhancement
- Form factor
- EPR test ....

- $J/\psi, \psi' \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}$ (in this talk)

e.g. 10 billion J/ψ decays:

Selected events

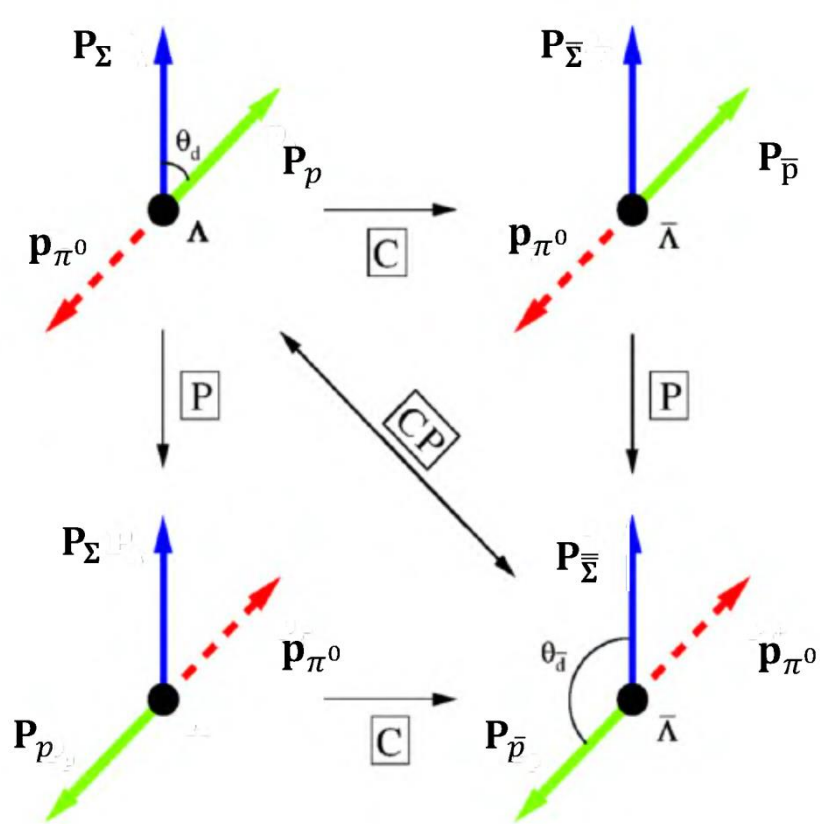
3.4×10^6	$\Lambda\bar{\Lambda}$
1.0×10^6	$\Xi^0\bar{\Xi}^0$
0.8×10^6	$\Sigma^0\bar{\Sigma}^0$
0.3×10^6	$\Xi^-\bar{\Xi}^+$



Parity violation in $\Sigma^+ \to p\pi^0$ and test CP

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}\left(1 + \alpha_\Sigma \vec{P} \cdot \hat{q}\right) = \frac{1}{4\pi}\left(1 + \alpha_\Sigma P_\Sigma cos\theta_p\right)$$

α_Σ: Σ decay parameter, P_Σ: Σ polariation



$$\alpha_\Sigma = \frac{|B_+|^2 - |B_-|^2}{|B_+|^2 + |B_-|^2}, \alpha_{\bar{\Sigma}} = \frac{|\bar{B}_+|^2 - |\bar{B}_-|^2}{|\bar{B}_+|^2 + |\bar{B}_-|^2}$$

Helicity amplitude under CP invariance:

$$\bar{B}_{-\lambda_p} = \eta_\Sigma \eta_p \eta_\pi (-1)^{s_\Sigma - s_p - s_\pi} B_{\lambda_p} = -B_{\lambda_p}$$

So: $\alpha_\Sigma = -\alpha_{\bar{\Sigma}}$

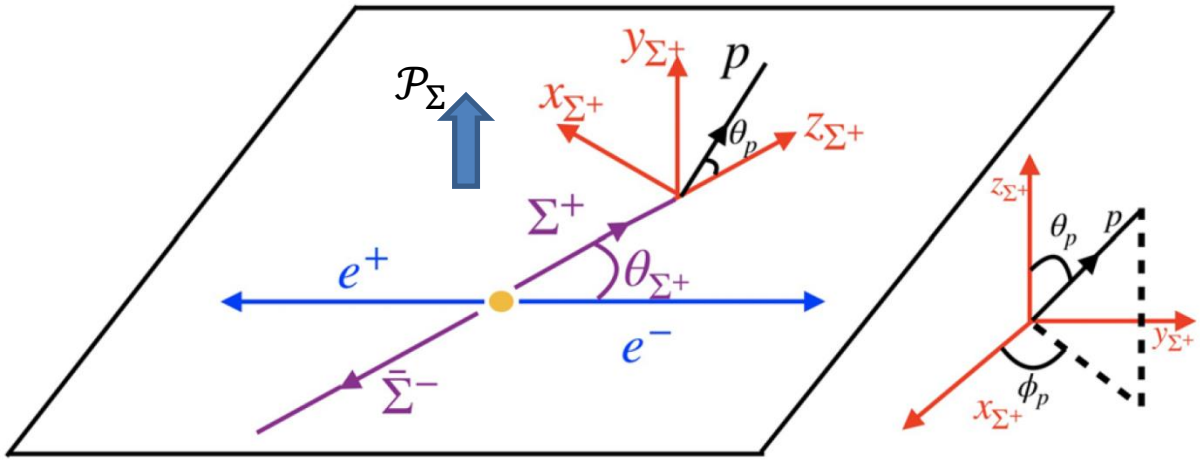
CP-odd observable:

$$A_\Sigma = \frac{\alpha_\Sigma + \alpha_{\bar{\Sigma}}}{\alpha_\Sigma - \alpha_{\bar{\Sigma}}}$$

SM prediction: $A_\Sigma \sim 3.6 \times 10^{-6}$

PRD67, 056001 (2003)

Σ^+ and $\bar{\Sigma}^-$ polarization in J/ψ and ψ' decays



- Unpolarized e^-, e^+ beams
- No longitudinal Σ polarization
- Transverse Σ polarization

$$\mathcal{W}(\xi) = \mathcal{F}_0(\xi) + \alpha\mathcal{F}_5(\xi)$$

unpolarized cross section

$$+\alpha_1\alpha_2\left(\mathcal{F}_1(\xi) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \alpha\mathcal{F}_6(\xi)\right)$$

spin correlation

$$+\sqrt{1-\alpha^2}\sin(\Delta\Phi)\left(\alpha_1\mathcal{F}_3(\xi) + \alpha_2\mathcal{F}_4(\xi)\right),$$

transverse polarization

$$\mathcal{F}_0(\xi) = 1$$

$$\mathcal{F}_1(\xi) = \sin^2\theta\sin\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 + \cos^2\theta\cos\theta_1\cos\theta_2$$

$$\mathcal{F}_2(\xi) = \sin\theta\cos\theta\left(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2\right)$$

$$\mathcal{F}_3(\xi) = \sin\theta\cos\theta\sin\theta_1\sin\phi_1$$

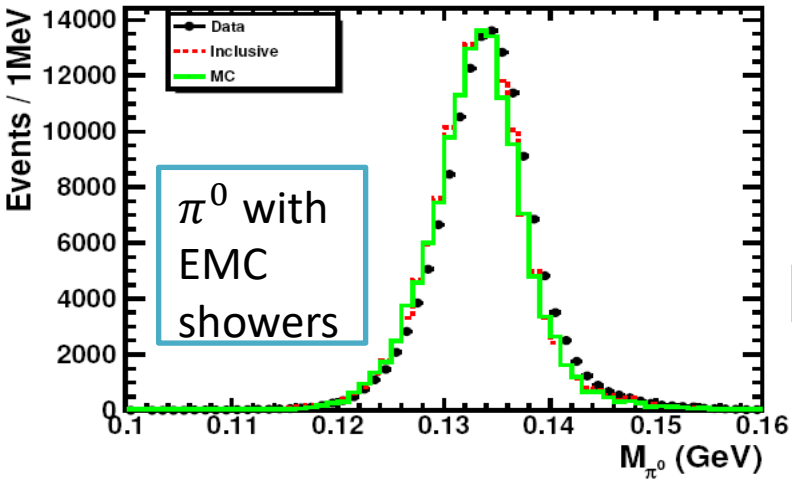
$$\mathcal{F}_4(\xi) = \sin\theta\cos\theta\sin\theta_2\sin\phi_2$$

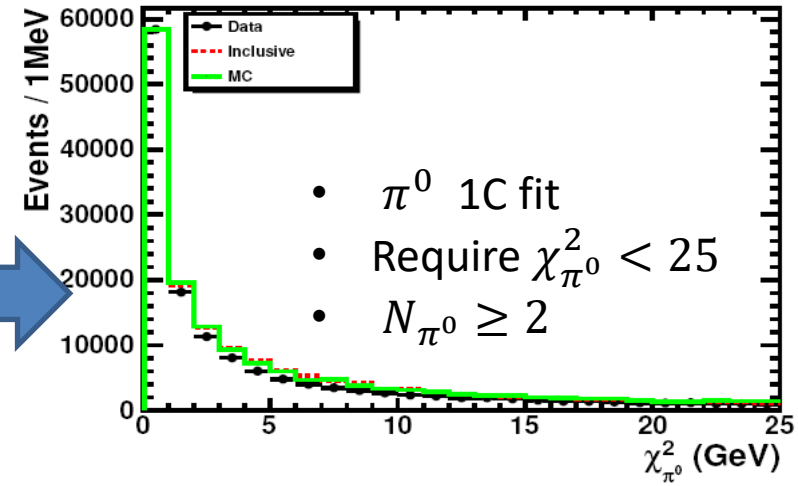
$$\mathcal{F}_5(\xi) = \cos^2\theta \qquad \mathcal{F}_6(\xi) = \cos\theta_1\cos\theta_2 - \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2.$$

Φ: phase angle difference
α_1, α_2: decay parameters for $\Sigma, \bar{\Sigma}$, respectively.

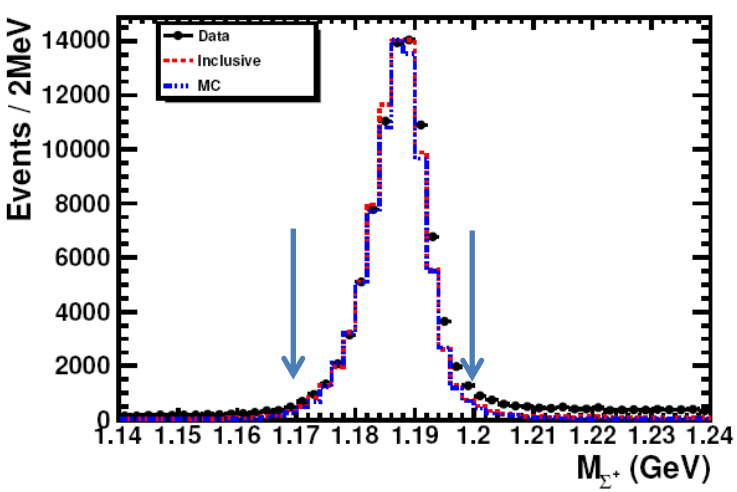
Σ^+ and $\bar{\Sigma}^-$ polarization in J/ψ and ψ' decays (cont.)

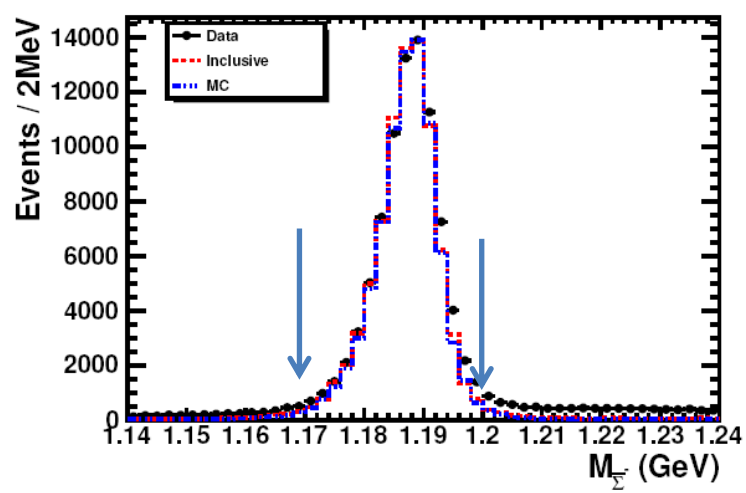
- $J/\psi \to \Sigma^+\bar{\Sigma}^-,\ \Sigma^+ \to p\pi^0,\ \bar{\Sigma} \to \bar{p}\pi^0$





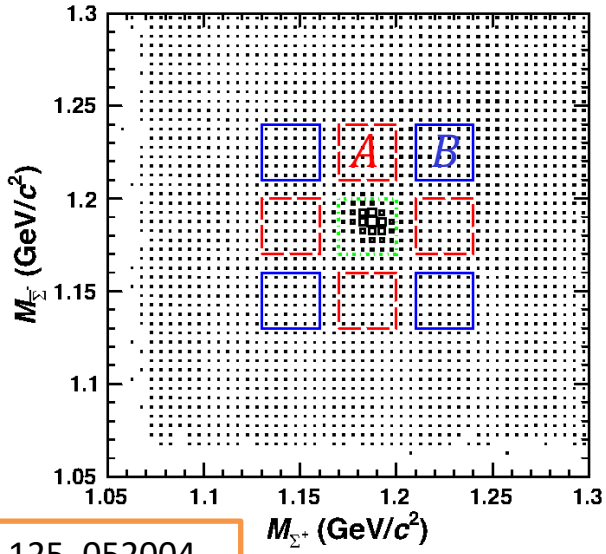
- Σ reconstruction: minimize $\sqrt{\left(M_{p\pi^0} - m_{\Sigma^+}\right)^2 + \left(M_{\bar{p}\pi^0} - m_{\bar{\Sigma}^-}\right)^2}$



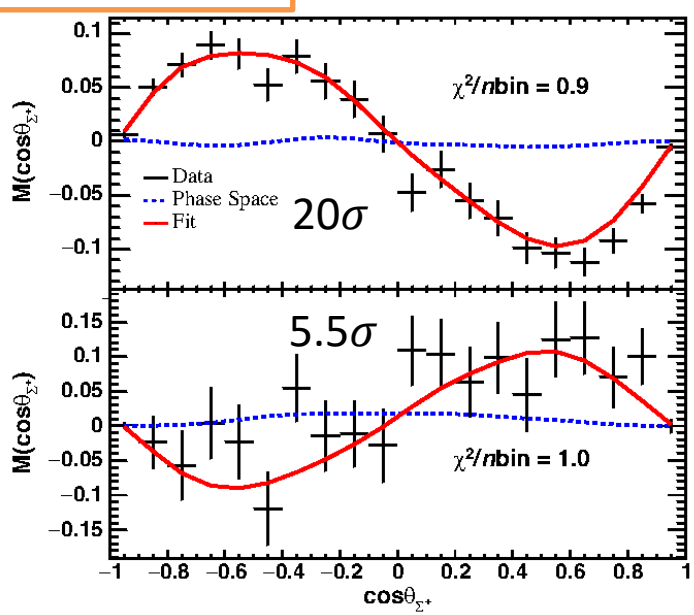


Σ^+ and $\bar{\Sigma}^-$ polarization in J/ψ and ψ' decays (cont.)

- **Background events estimated with inclusive MC decays and sideband**



Phys.Rev.Lett. 125, 052004



- $N_{bg} = 0.5N_A - 0.25N_B$
  background level: 5%(1%) for J/ψ (ψ')
- Number of candidates
  J/ψ: 87,815 ; ψ': 5,327
- Simultaneous fit to J/ψ and ψ' events
  $S = -\ln\mathcal{L}_{\text{data}} + \ln\mathcal{L}_{\text{bg}}$

Parameter	Measured value
$\alpha_{J/\psi}$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.270 \pm 0.012 \pm 0.009$
$\alpha_{\psi'}$	$0.682 \pm 0.03 \pm 0.011$
$\Delta\Phi_{\psi'}$	$0.379 \pm 0.07 \pm 0.014$
α_0	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.990 \pm 0.037 \pm 0.011$

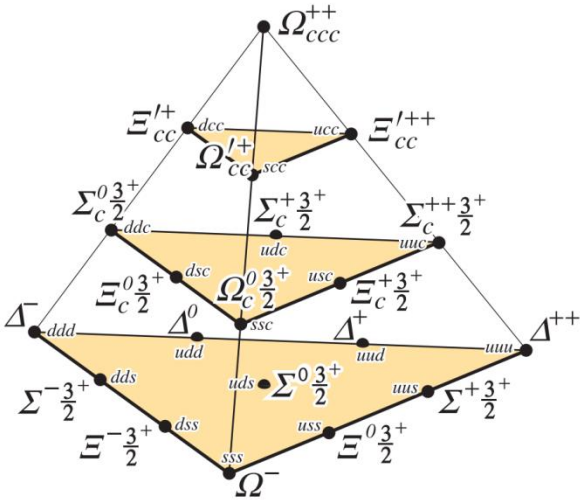
$$A_{CP,\Sigma} = \frac{\alpha_0 + \overline{\alpha_0}}{\alpha_0 - \overline{\alpha_0}} = -0.004 \pm 0.037 \pm 0.002$$

$$\frac{1}{2}(\alpha_0 - \overline{\alpha_0}) = -0.994 \pm 0.004 \pm 0.002$$

Ω^- spin and its polarization alignment in $\psi(2S) \to \Omega^-\bar{\Omega}^+$

- **Spin assignment in quark model**

  Ω^- as sss bound state in SU(3) decuplet, $J = 3/2$



- **Experimental determination of spin**
  - fixed target experiment (1978)

$$K^- p \to \Omega^- + \text{anything},$$
$$\hookrightarrow \Lambda^0 K^-$$
$$\hookrightarrow p\pi^- .$$

Rule out $J = \frac{1}{2}$,

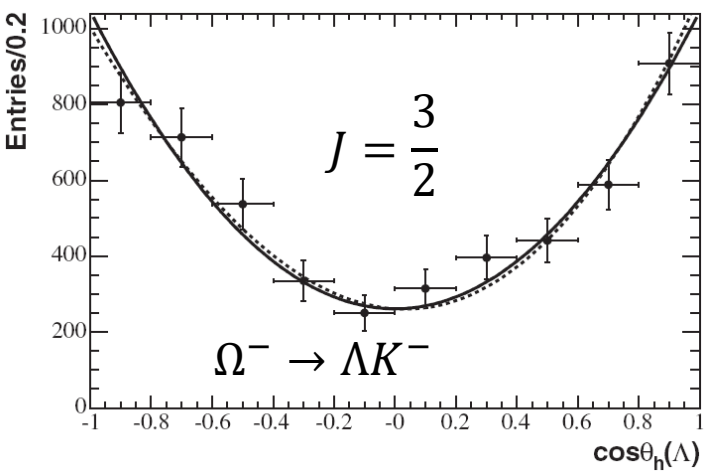
consistent with $J = \frac{3}{2}$

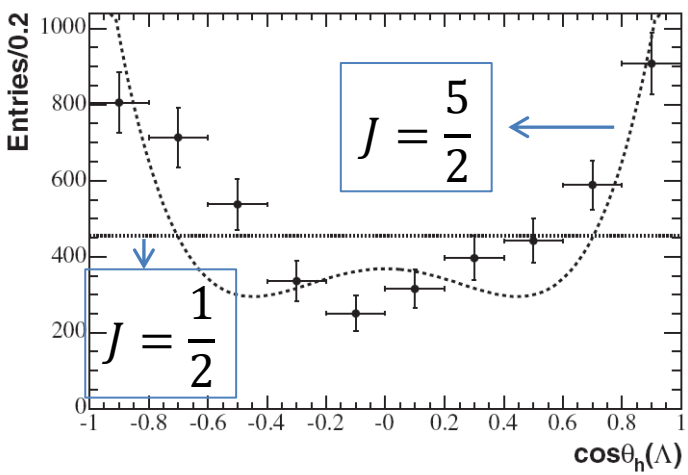
  - *BABAR* experiment (2006)

Assume $J = 1/2$ for Ω_c^0 and Ξ_c^0

i. $\Xi_c^0 \to \Omega^- K^+$, ii. $\Omega_c^0 \to \Omega^- \pi^+$

with $\Omega^- \to \Lambda K^-$, $\Lambda \to p\pi^-$



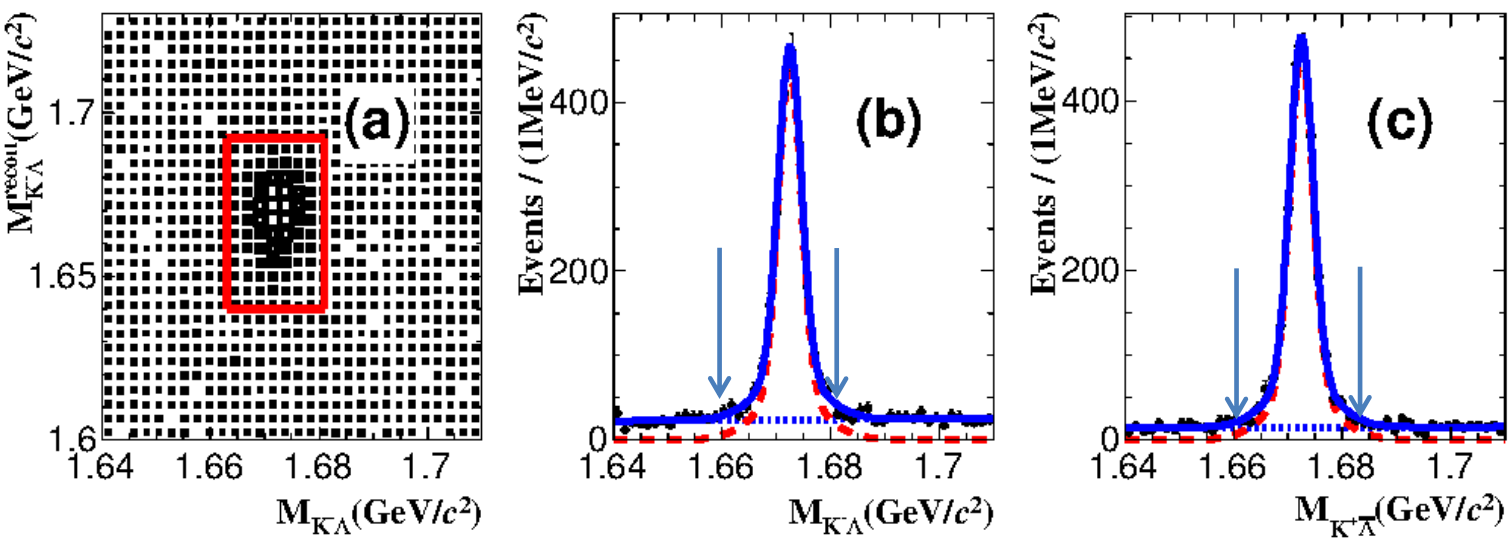


Ω^- spin and its polarization alignment in $\psi(2S) \to \Omega^-\bar{\Omega}^+$ (cont.)

- **BESIII: $e^+e^- \to \psi(2S) \to \Omega^-\bar{\Omega}^+$**
  - Polarization well known, very clean data events
  - Ω^- or $\bar{\Omega}^+$ single tag analysis

    $\Omega^- \to \Lambda K^-, \Lambda \to p\pi^-$; $\bar{\Omega}^+ \to \bar{\Lambda}K^+, \bar{\Lambda} \to \bar{p}\pi^+$

    - 3 charged tracks selected from MDC, and p, K^- or $\bar{p}, K^+$ PID required
    - Λ or $\bar{\Lambda}$ reconstructed with second vertex fit
    - undetected Ω^- or $\bar{\Omega}^+$ inferred from the recoil mass of the tagged side



$K^-\Lambda$ tag

$K^+\bar{\Lambda}$ tag

BESIII, Phys.Rev.Lett. 126.092002

Ω^- spin and its polarization alignment in $\psi(2S) \to \Omega^-\bar{\Omega}^+$ (cont.)

- **Spin observable: real multipole parameters r_M^L**

$$\rho_J(\Omega^-) = \frac{r_0^0}{2J+1}\left(I + 2J\sum_{L=1}^{2J}\sum_{M=-L}^{L} r_M^L\, Q_M^L\right)$$

Q_M^L: Hermitian basis matrix, constructed with spherical tensor operators T_M^L

- **Test two spin hypotheses:**

$e^+e^- \to \psi(2S) \to \Omega^-\bar{\Omega}^+\,(\theta_\Omega)$, $\bar{\Omega}^+$ undetected

$\downarrow$

$\rho_J(\Omega) = r_\mu\, Q_\mu$ $\quad$ $\Lambda\, K^-(\theta_\Lambda, \phi_\Lambda)$ $\quad$ Polarimeter: $Q_\mu \to \sum b_{\mu\nu}\sigma_\nu$

$\downarrow$

$\mathrm{p}\,\pi^-\,(\theta_p, \phi_p)$ $\quad$ Polarimeter: $\sigma_\nu \to \sum a_{\nu\rho}\sigma_\rho$

Joint angular distribution:

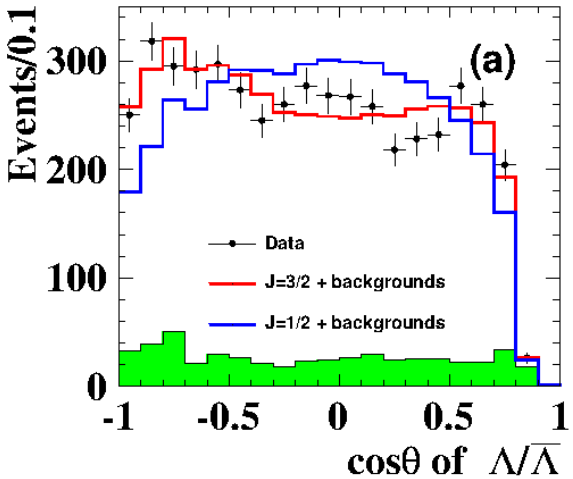
$$J = \tfrac{3}{2}:\ \mathcal{W}(\theta_\Omega, \theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) = \textstyle\sum_{\mu=0}^{15}\sum_{\nu=0}^{3} r_\mu(\theta_\Omega) b_{\mu\nu}(\theta_\Lambda, \phi_\Lambda) a_{\nu 0}(\theta_p, \phi_p)$$

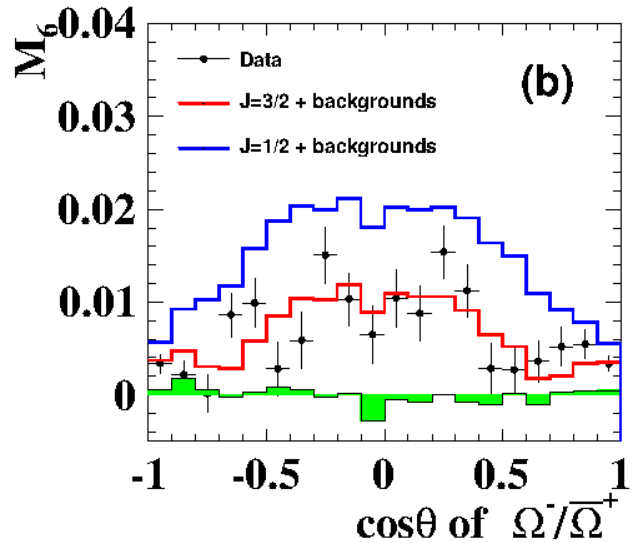
$$J = \frac{1}{2}: \mathcal{W}(\theta_\Omega, \theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) = \sum_{\mu=0}^{3}\sum_{\nu=0}^{3} r_\mu(\theta_\Omega) b_{\mu\nu}(\theta_\Lambda, \phi_\Lambda) a_{\nu 0}(\theta_p, \phi_p)$$

Ω^- spin and its polarization alignment in $\psi(2S) \to \Omega^-\bar{\Omega}^+$ (cont.)

- Likelihood test

Data favor $J = 3/2$ hypothesis.

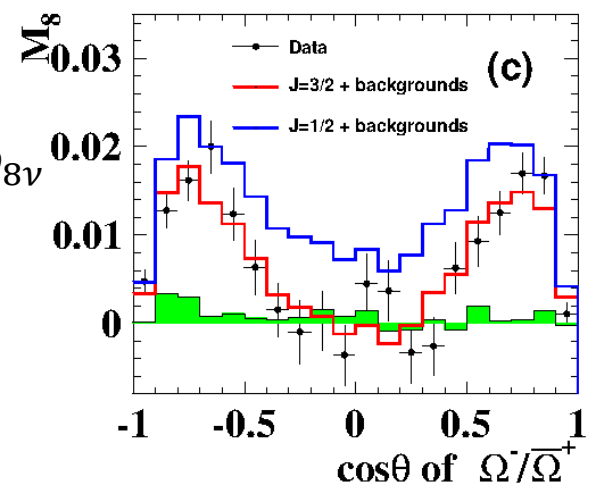




$M_6 \to b_{6\nu}$

Fix: $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.75,\ \alpha_{\Omega^-} = -\alpha_{\bar{\Omega}^+} = 0.0154$

$M_8 \to b_{8\nu}$



Two solutions under $J = 3/2$ hypothesis

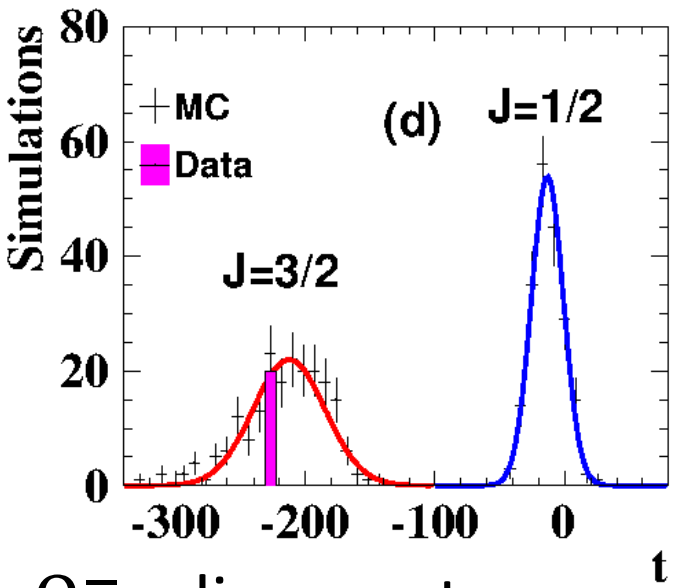
parameter	solution I	solution II
h_1	0.30±0.11±0.04	0.31±0.10±0.04
ϕ_1	0.69±0.41±0.13	2.38±0.37±0.13
h_3	0.26±0.05±0.02	0.27±0.05±0.01
ϕ_3	2.60±0.16±0.08	2.57±0.16±0.04
h_4	0.51±0.03±0.01	0.51±0.03±0.01
ϕ_4	0.34±0.80±0.31	1.37±0.68±0.16
ϕ_Ω	4.29±0.45±0.23	4.15±0.44±0.16

BESIII, Phys.Rev.Lett. 126.092002

Ω^- spin and its polarization alignment in $\psi(2S) \to \Omega^-\bar{\Omega}^+$ (cont.)

- TOY MC test

BESIII, Phys.Rev.Lett. 126.092002

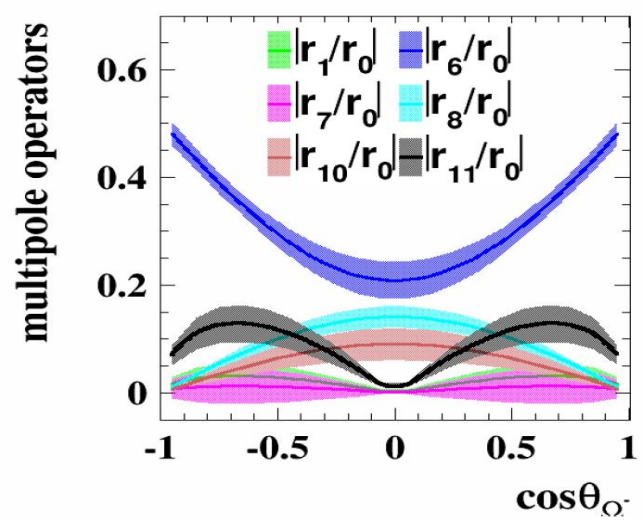


- ✓ MC events generated with fitted parameters
- ✓ same selection criteria applied
- ✓ ensembles of MC events with same data size
- ✓ t distribution:

$$t = 2(\mathcal{L}^{J=1/2} - \mathcal{L}^{J=3/2})$$

- ✓ Significance $J = \frac{3}{2}$ over $J = \frac{1}{2}$ with $> 14\sigma$

- Ω^- alignment



- ✓ r_i basis
  $r_1: Q^1_{-1}, r_6: Q^2_0,$
  $r_7: Q^2_1, r_8: Q^2_2, r_{10}: Q^3_{-2}, r_{11}: Q^2_{-1}$
- ✓ alignment symmetry under polar angle θ_Ω
- ✓ alignment dominated by Q^2_0
- ✓ $\Omega^- \to \Lambda K^-$ favors D wave

$$\frac{|A_D|^2}{|A_P|^2} = \begin{cases} 2.4 \pm 2.0 \text{ (solution I)} \\ 3.3 \pm 2.9 \text{ (solution II)} \end{cases}$$

Where does the TP come from?

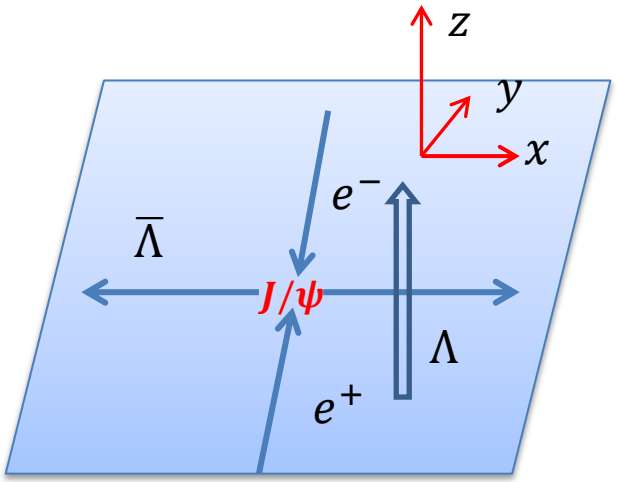
- From the e^+/e^- beam ?
  - ✘ No, BEPC beams unpolarized
- From the e^+/e^- natural polarization when circulating in the BEPCII storage ring ?
  - ✘ Sokolov-Ternov effects: 4.3 hs @ψ' peak, but beam lifetime ~ 2.0 hs
- From the J/ψ spin transfer ?
  - ✓ Yes, it does from the J/ψ tensor polarization

J/ψ polarization: $\mathcal{P}_z = 0$, $T_{zz} = \frac{1}{\sqrt{6}}$

Σ transverse polarization:

$$\mathcal{P}_y = \sqrt{6}\frac{T_{zz}\sin\theta\cos\theta\sin\Delta\sqrt{1-\alpha_\psi^2}}{1+\alpha_\psi\left[\frac{1}{3}+\frac{1}{\sqrt{6}}T_{zz}(1+3\cos 2\theta)\right]}$$

$\mathcal{P}_y$ manifest if $\sin\Delta \neq 0$

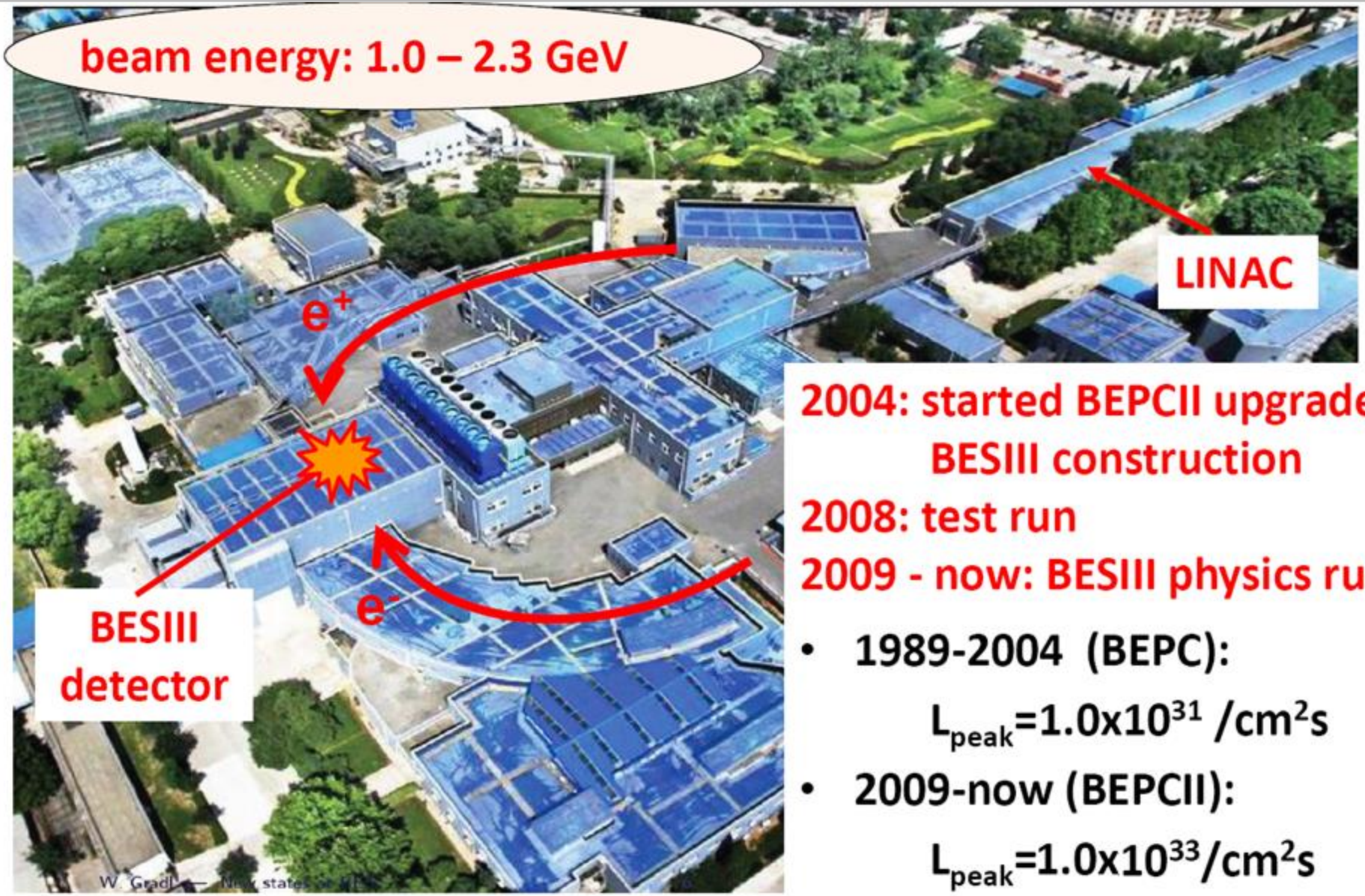


Summary

- Significant observation of $\Sigma^+ / \bar{\Sigma}^-$ transverse polarization in J/ψ and ψ' decays.
- Ω^- spin determined to be $3/2$ and its polarization alignment measured.
- BESIII 10 billion J/ψ data provides us chances to access hyperon physics.
- Extension study to charmed hyperon are ongoing.
- Polarized beam in the future super-tau charm facility (STCF) help to improve the precision.

Thanks for your attention!

Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade, BESIII construction

2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC): $L_{peak}=1.0\times10^{31}\ /cm^2s$
- 2009-now (BEPCII): $L_{peak}=1.0\times10^{33}/cm^2s$

On 29. Feb., 2021, Beam Energy upgrade, run at $\sqrt{s}$=4.916 GeV