Paradigm changing studies of spin entangled hyperons and antihyperons at BESIII

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(On behalf of the BESIII collaboration)

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Outline

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- Introduction
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- Summary

Beijing Electron-Positron Collider II (BEPCII)

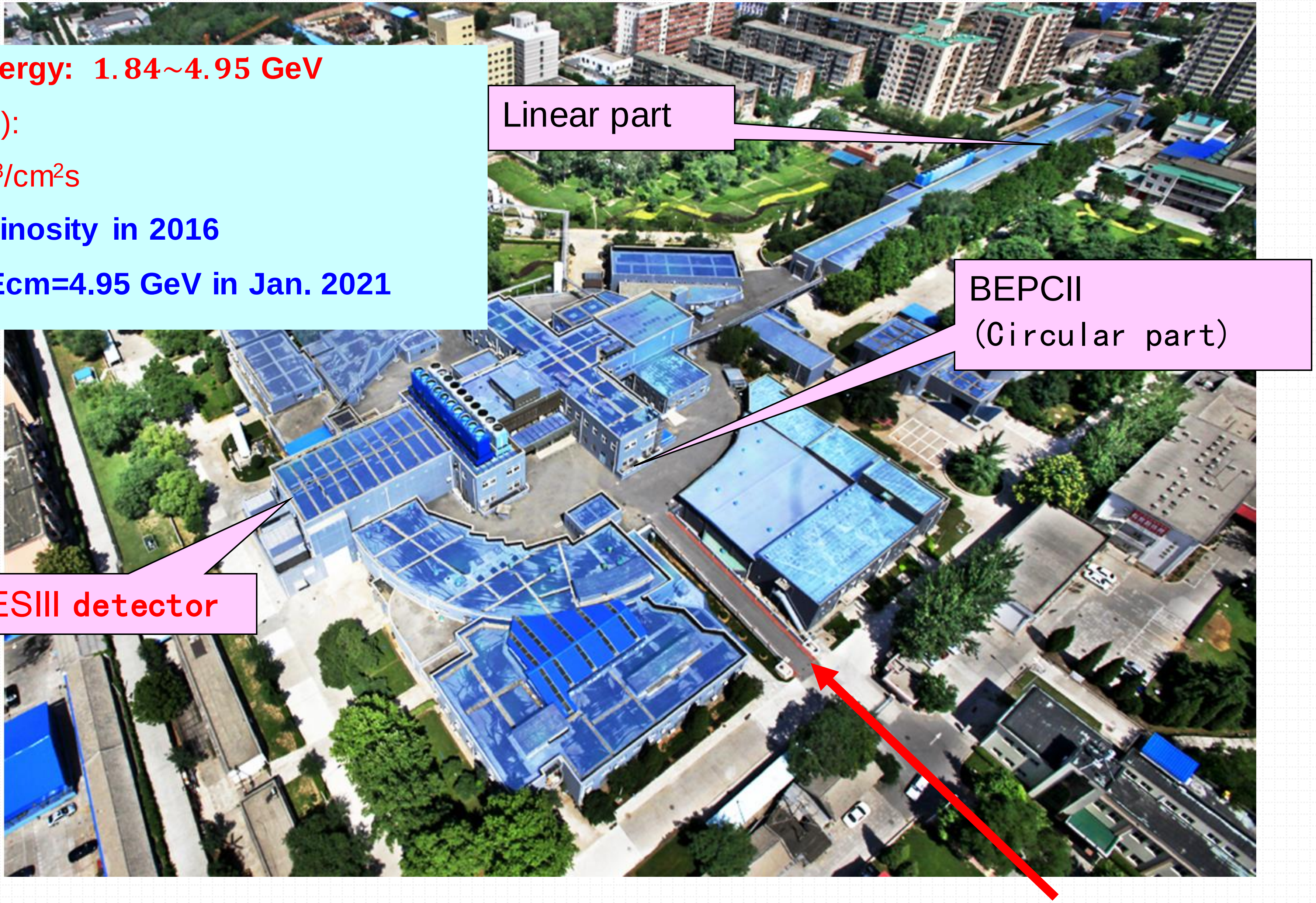
Center of mass energy: 1.84~4.95 GeV

2008- **Now** (BEPCII):

L_{peak}=1.1x10^{33}/cm^{2}s

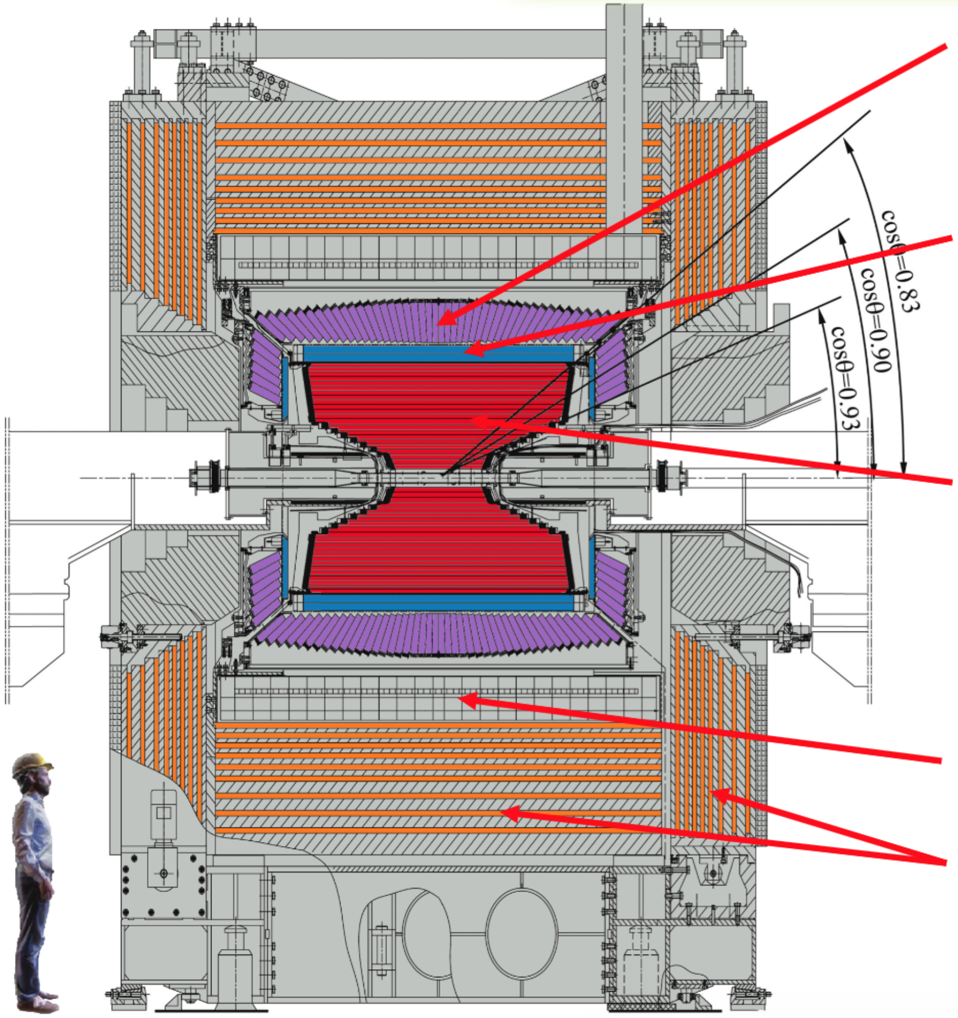
Reached peak luminosity in 2016

Reached highest Ecm=4.95 GeV in Jan. 2021



BESIII detector

The detector is designed for neutral and charged particle with excellent resolution, PID, and large coverage.



EMC: CsI crystals
$\Delta E/E = 2.5\%$ @ 1 GeV - Barrel
$\Delta E/E = 5.0\%$ @ 1 GeV - Endcaps

TOF:
σ_T = 80 ps Barrel
σ_T = 110 (60) ps Endcap

MDC: small cell & He gas
σ_{xy}= 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%

Magnet: 1T Super conducting

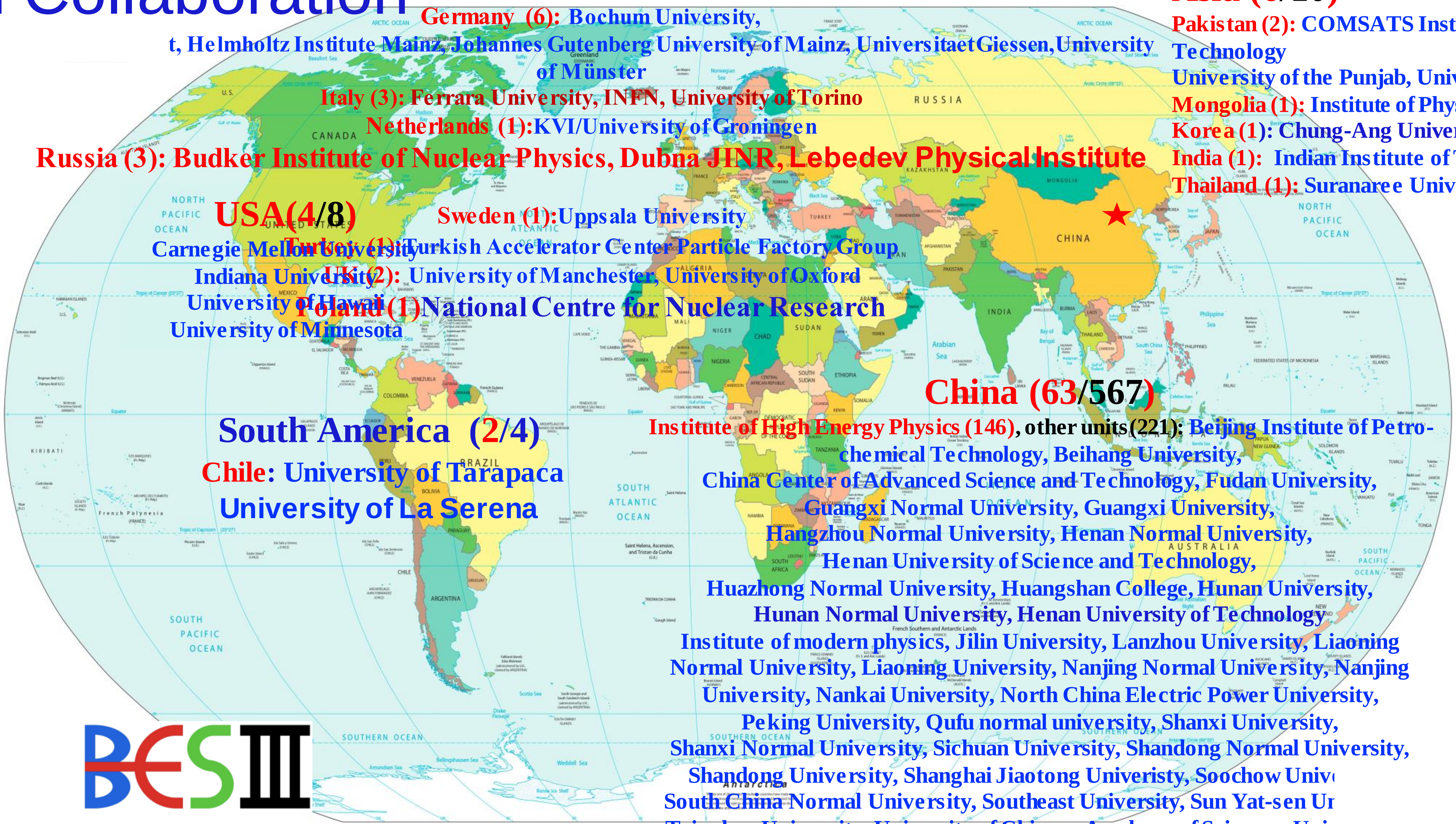
Muon ID: 9 layer RPC

Trigger: Tracks & Showers

Total weight 730 ton, ~40,000 readout channels, Data rate: 5kHz, 50Mb/s

Has been in full operation since 2008, all subdetectors are in very good status!

BESIII Collaboration



Europe (19/130)

Germany (6): Bochum University,
t, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, UniversitaetGiessen,University of Münster
Italy (3): Ferrara University, INFN, University of Torino
Netherlands (1):KVI/University of Groningen
Russia (3): Budker Institute of Nuclear Physics, Dubna JINR, Lebedev Physical Institute
Sweden (1):Uppsala University
Turkey (1):Turkish Accelerator Center Particle Factory Group
UK (2): University of Manchester, University of Oxford
Poland (1)National Centre for Nuclear Research

USA(4/8)

Carnegie Mellon University
Indiana University
University of Hawaii
University of Minnesota

Asia (6/10)

Pakistan (2): COMSATS Institute of Information Technology
University of the Punjab, University of Lahore
Mongolia (1): Institute of Physics and Technology
Korea (1): Chung-Ang University
India (1): Indian Institute of Technology madras
Thailand (1): Suranaree University of Technology

South America (2/4)

Chile: University of Tarapaca
University of La Serena

China (63/567)

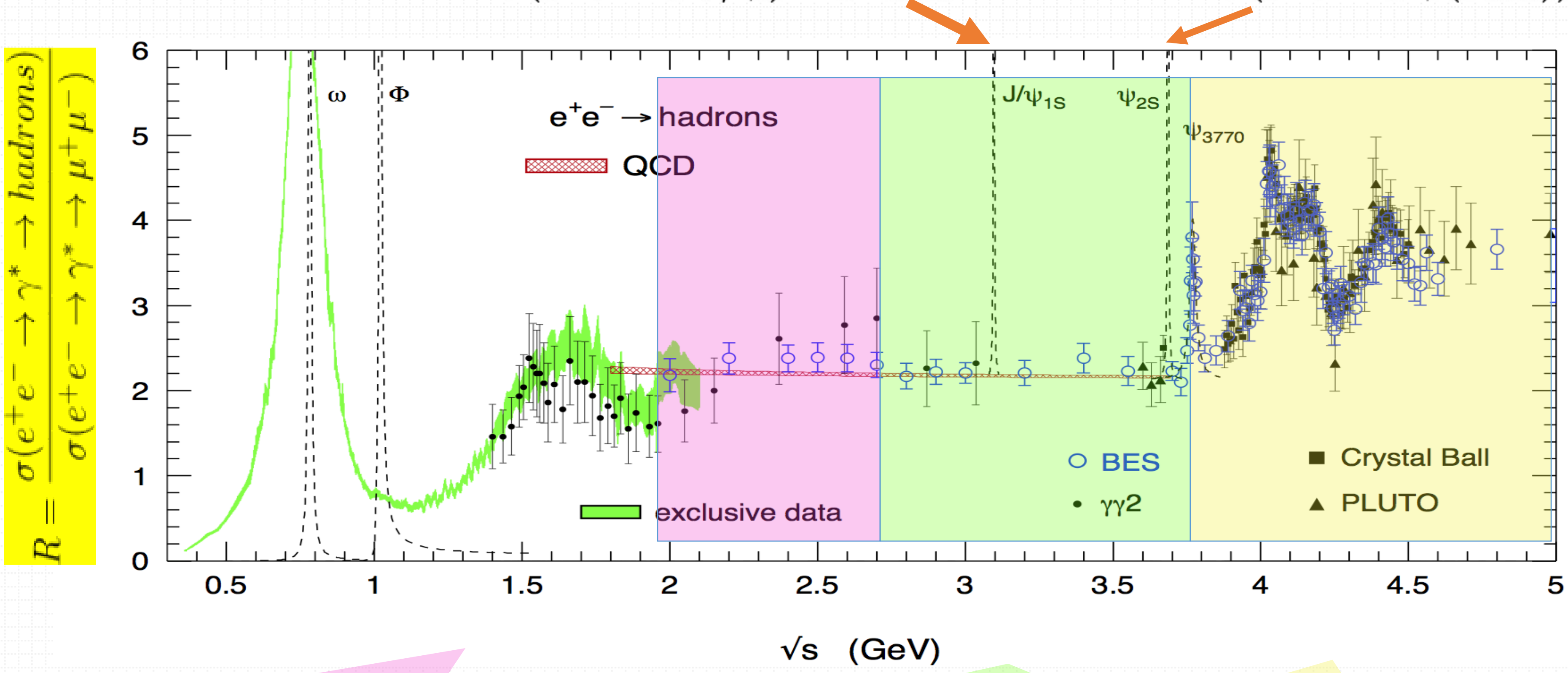
Institute of High Energy Physics (146), other units(221): Beijing Institute of Petro-chemical Technology, Beihang University, China Center of Advanced Science and Technology, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Hunan Normal University, Henan University of Technology Institute of modern physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu normal university, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shanghai Jiaotong Univeristy, Soochow Univ
South China Normal University, Southeast University, Sun Yat-sen Ur
Tsinghua University, University of Chinese Academy of Sciences, Univ
Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Zhejiang University, Zhengzhou University,YunNan University , China University of Geosciences

~700 members
From 96 institutions in 15 countries

Rich Physics at τ-charm Energy Region

$\sigma(e^+e^- \to J/\psi) = 3400nb$

$\sigma(e^+e^- \to \psi(3686)) = 600nb$

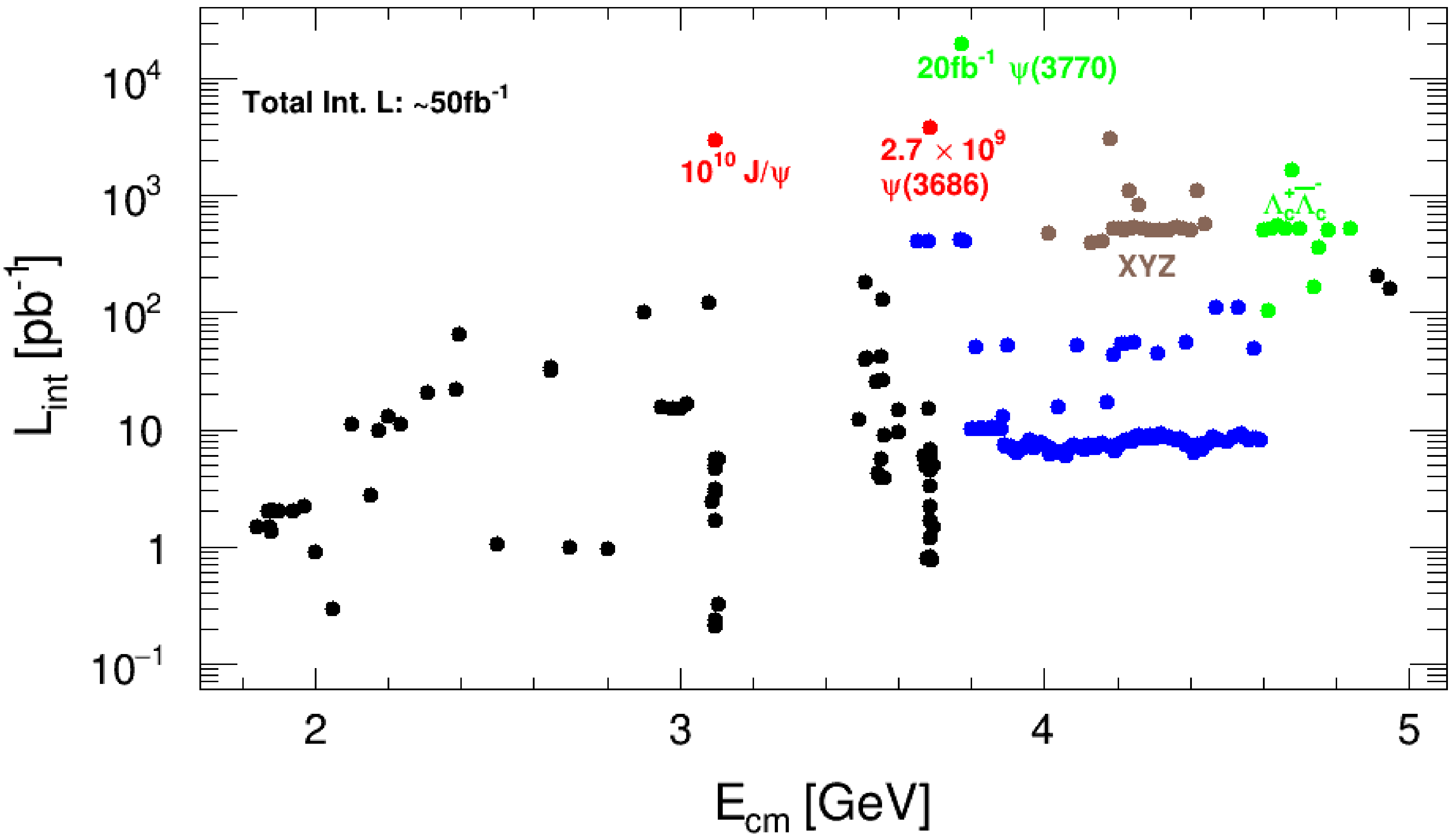


- Hadron form factors
- R values and QCD

- Light hadron spectroscopy
- Gluonic and exotic states
- Physics with τ lepton

- XYZ particles
- Charm mesons
- Charm baryons

BESIII data sets



BEPCII upgrades in 2024

BEPCII upgrade (installation: 2024. 7- 2024. 12)

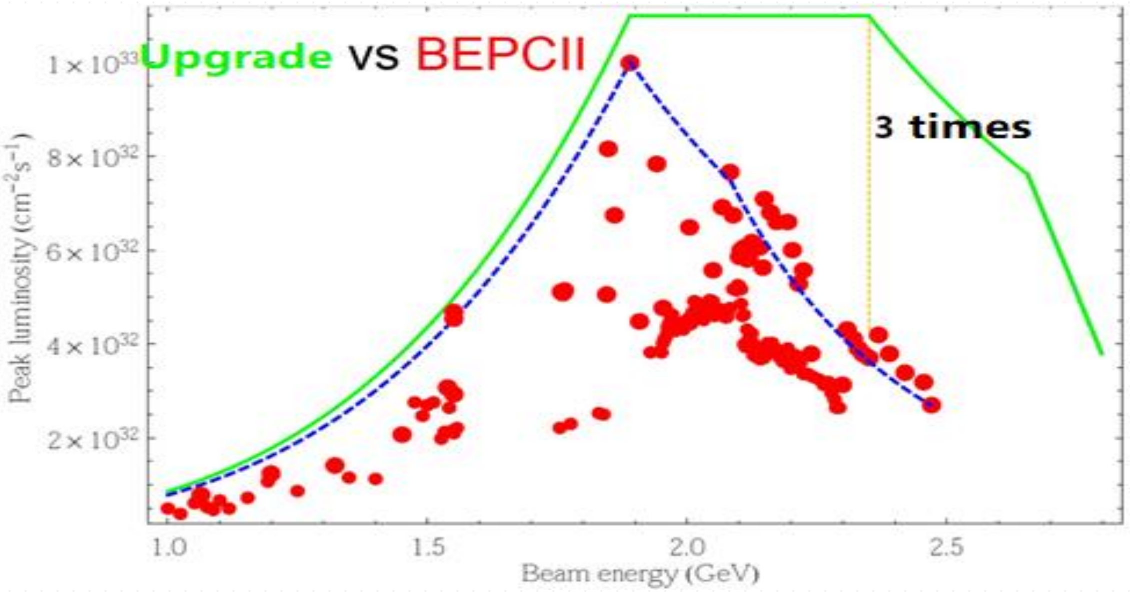
Highest beam energy: 2.8 GeV

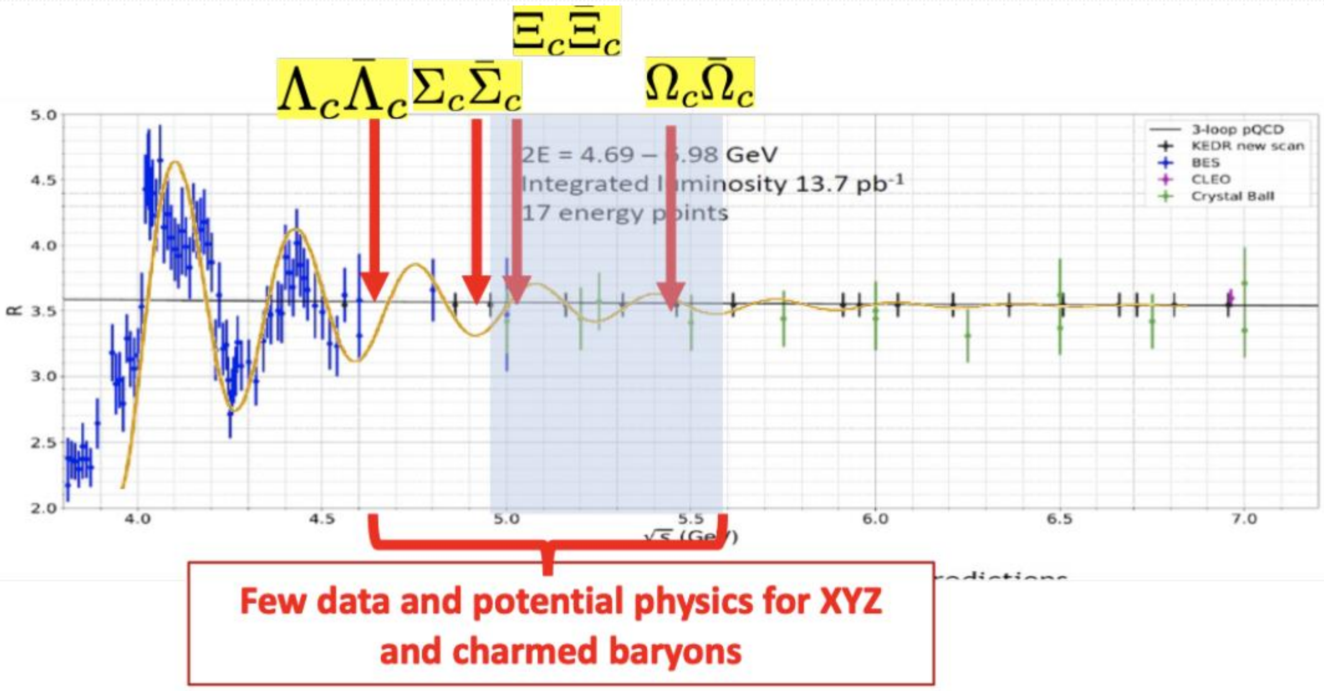
Luminosity: 1.2×10^{33} $cm^{-2}s^{-1}$ (4.0 ~ 5.0 GeV)

(0.4-0.7) $\times 10^{33}$ $cm^{-2}s^{-1}$ (5.0 ~ 5.6 GeV)

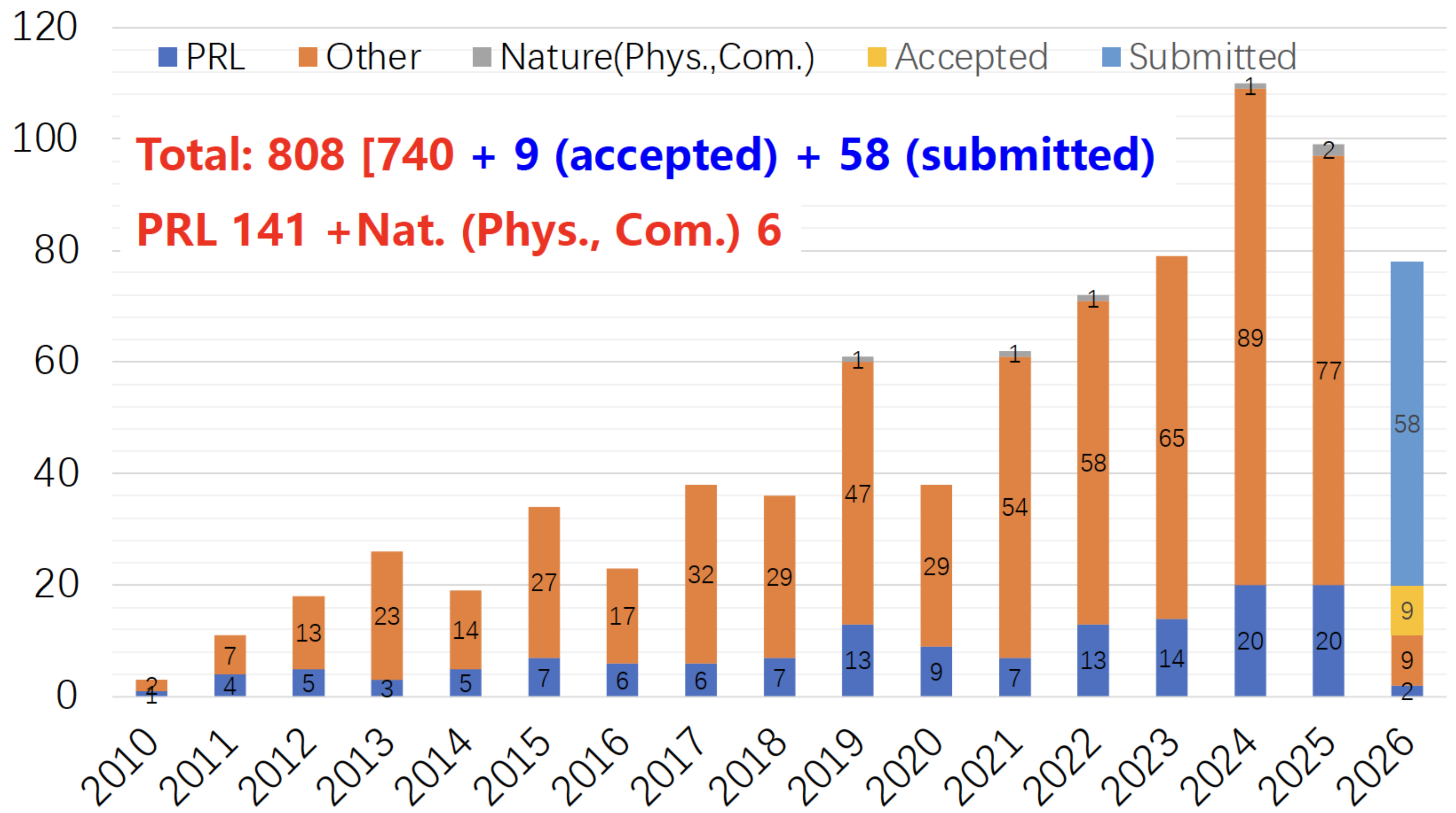
BESIII will collect about **60 fb^{-1}** between 4.0 – 5.6 GeV, and to study potential physics:

- ✓ Cover energy up to 5.6 GeV
- ✓ Deeper studies of the XYZ states
- ✓ Study the ground-state charmed baryons
- ✓ Provide information on charm-quark fragmentation function





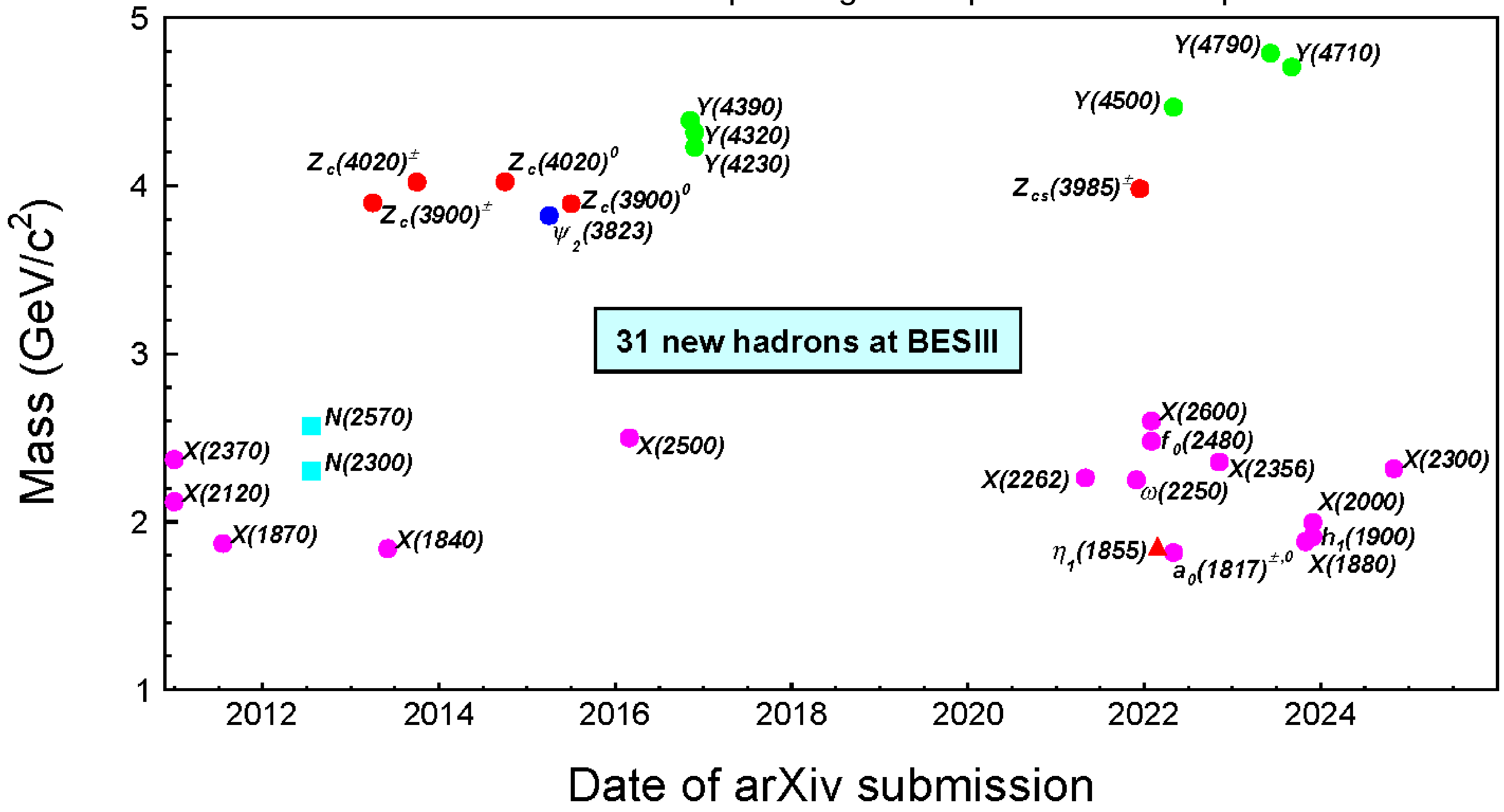
BESIII Overall Publications Status



https://hnbes3.ihep.ac.cn/publication-status.php

New hadrons discovered at BESIII

https://english.ihep.cas.cn/bes/re/pu/NewParticles/



BESIII advantage: unique data near to the thresholds

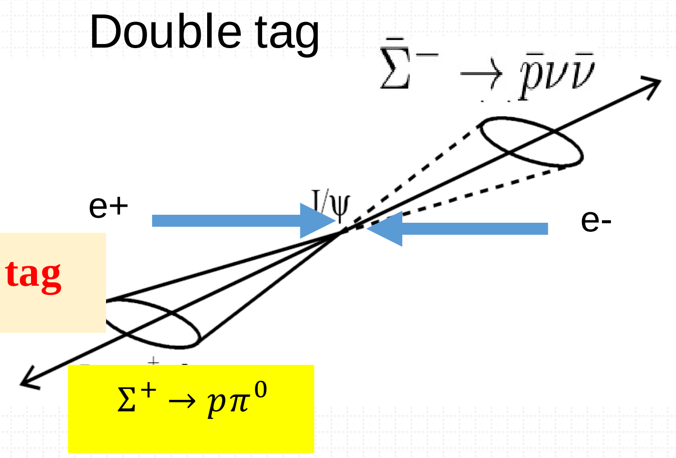
Known initial 4-momentum

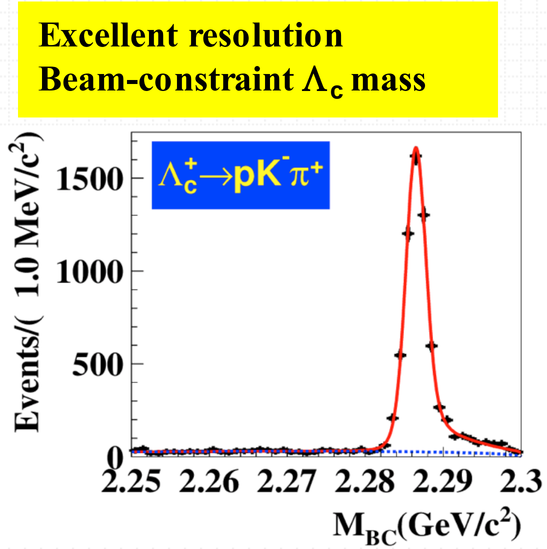
Known beam energy: pair productio

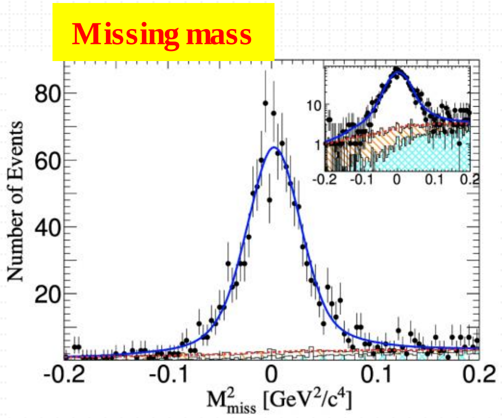
Decay with neutron & π^0

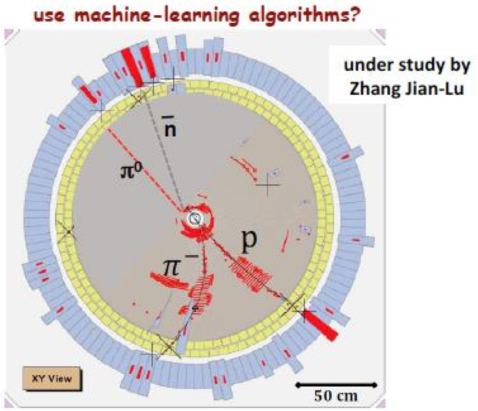
Decay with invisibles: neutrinos

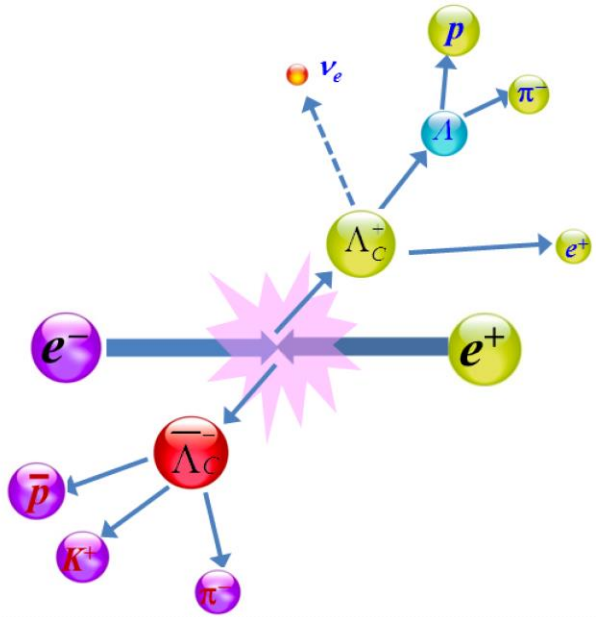
Missing mass or missing energy

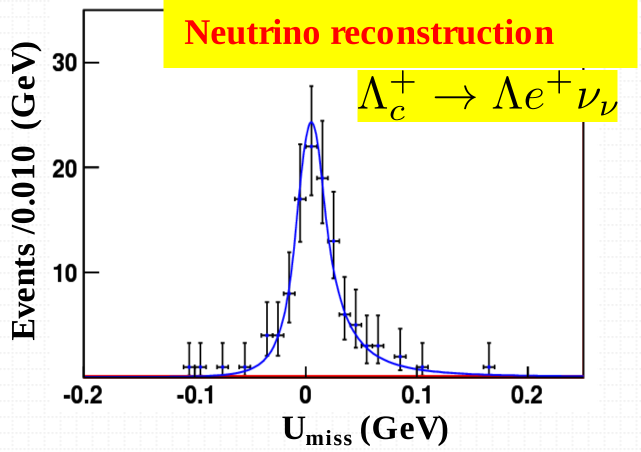




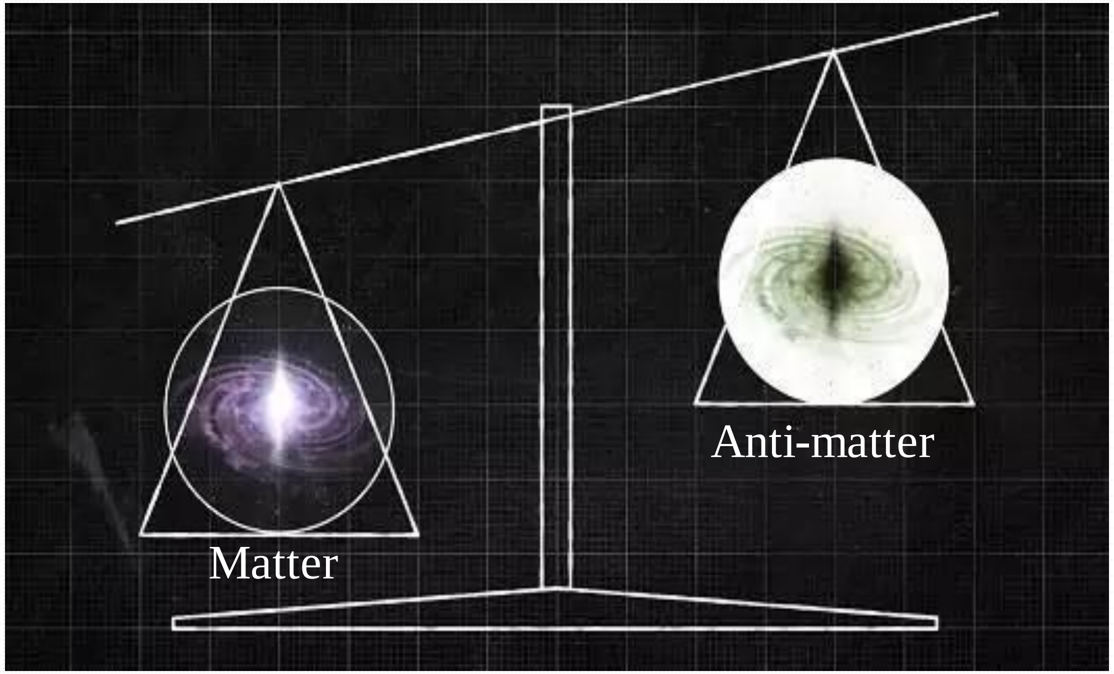








Mystery of matter-antimatter asymmetry



- According to the Big Bang theory:
  - Matter and anti-matter have the same amount
- The observed universe is matter dominant:

$$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$$

- The standard model predicted value：

$$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}$$

- Why has the anti-matter disappeared？
- Sakharov's three conditions：
  - Baryon number violation
  - C and CP violation
  - Thermal non-equilibrium

Pisma Zh. Eksp. Teor. Fiz., 1967, 5: 32-35

Roadmap of CP violation in flavored hadrons

- **All of them are consistent with CKM theory in the Standard Model, but too small to explain the matter-dominant world.**
- **Before 21 Mar 2025, there is no observation of CPV in the baryon system.**

5.2σ CPV in Λ_b decay: $\Lambda_b \rightarrow p\pi^+\pi^-K^-$

K meson CPV	B meson CPV	D meson CPV	Λ_b baryon	Hyperon/charmed baryon?
1964	2001	2019	2025	

James Watson Cronin

Val Logsdon Fitch

[1] Phys. Rev. 104 (1956) 254-258
[2] Phys. Rev. 105 (1957) 1413-1414
[3] Phys. Rev. Lett., 1964, 13: 138-140
[4] Phys. Rev. Lett., 2001, 87: 091801
[5] Phys. Rev. Lett., 2001, 87: 091802
[6] Phys. Rev. Lett., **122**, 211803 (2019)
[7] Nature **643** (2025) 8074, 1223-1228

Search for CP violation in hyperon decays

1) a CP-violating phase:

Ordinary phases in QM

matter — **antimatter**

δ — δ (same sign)

CP violating phases

matter — **antimatter**

ξ — −ξ (opposite sign)

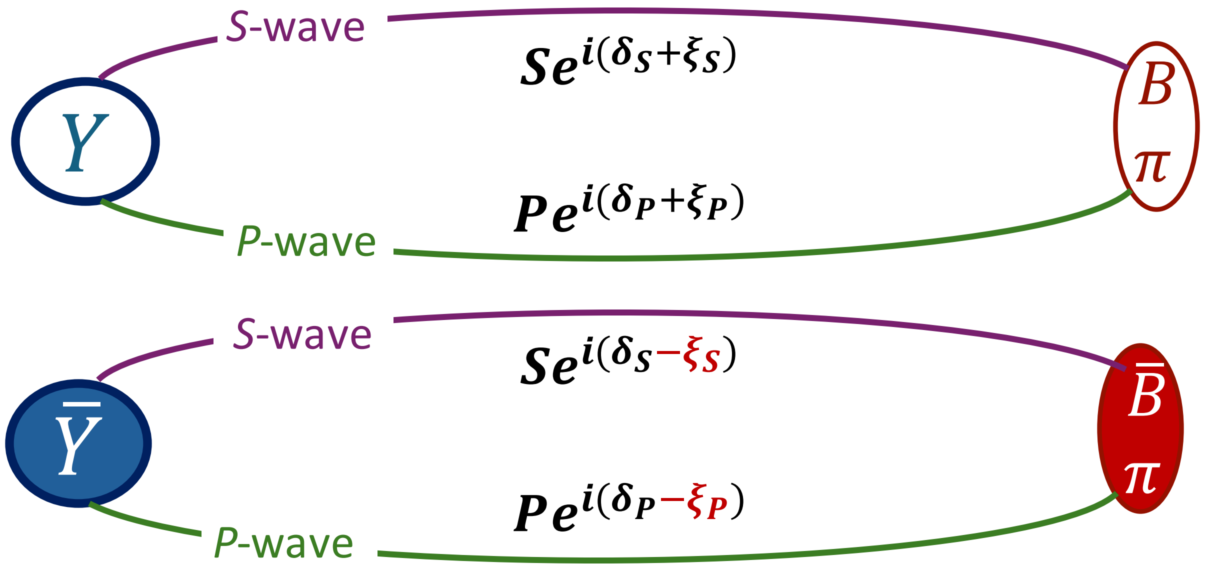
If only have one path:

$$\left|Ae^{i(\delta+\xi)}\right|^2 = A^2$$

The CPV phase vanishes in the probability density.

2) two or more interfering paths to the same final state

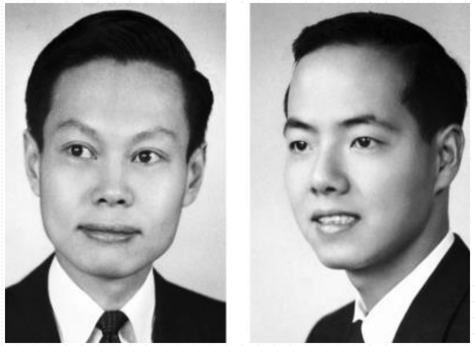
Spin-1/2 hyperon



Spin-1/2 baryon

Suitable for CPV searches!

Non-leptonic hyperon decays



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)

Phys. Rev. 108, 1645 (1957)

The amplitude of spin-1/2 hyperon B_i decay to a spin-1/2 baryon B_f and a π can be completely described by three decay parameters:

$$\alpha_Y = \frac{2\,\mathrm{Re}\,(S^* P)}{|S|^2 + |P|^2}, \quad \beta_Y = \frac{2\,\mathrm{Im}\,(S^* P)}{|S|^2 + |P|^2}, \quad \gamma_Y = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

$$\alpha_Y^2 + \beta_Y^2 + \gamma_Y^2 = 1$$

$$\beta_Y = (1 - \alpha_Y^2)^{\frac{1}{2}} sin\phi_Y\,, \;\; \gamma_Y = (1 - \alpha_Y^2)^{\frac{1}{2}} cos\phi_Y$$

CP convervation: $\alpha_Y = -\bar{\alpha}_Y, \beta_Y = -\bar{\beta}_Y, \phi_Y = -\bar{\phi}_Y$

CP observables in hyperon decay

John F. Donoghue

Xiao-Gang He

Sandip Pakvasa

PHYSICAL REVIEW D VOLUME 34, NUMBER 3 1 AUGUST 1986

Hyperon decays and *CP* nonconservation

John F. Donoghue
Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

Xiao-Gang He and Sandip Pakvasa
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

(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.

PRD 34,833 1986

SM Prediction of Λ decay

strong phase | CPV phase

Not sensitive to CPV

Decay width difference $\Delta_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \approx \sqrt{2}\frac{T_{\frac{3}{2}}}{T_{\frac{1}{2}}}\sin(\delta_P - \delta_S)\sin(\xi_P - \xi_S)$ — -5.4×10^{-7}

Easiest to measure

Decay parameter difference $A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \approx -\tan(\delta_P - \delta_S)\,tan(\xi_P - \xi_S)$ — -0.5×10^{-4}

Polarization of decayed baryon needs to be measured

Decay parameter difference $B_{CP} = \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}} \approx tan(\xi_P - \xi_S)$ — 3.0×10^{-3}

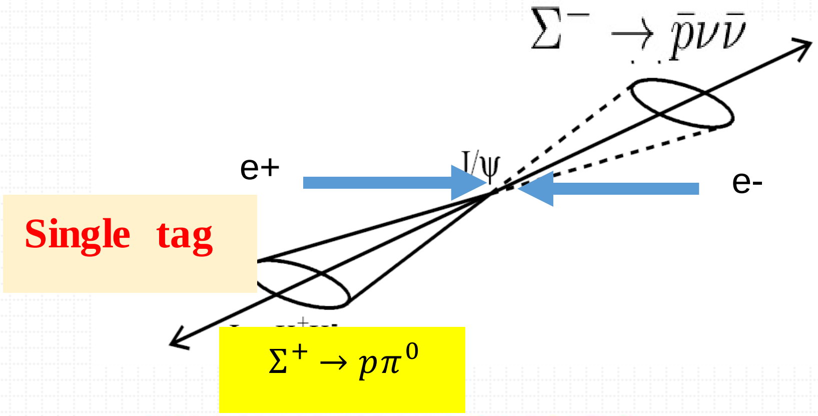
Ξ^-, Ξ^0, Ω^- cascade decay

BESIII: A hyperon factory

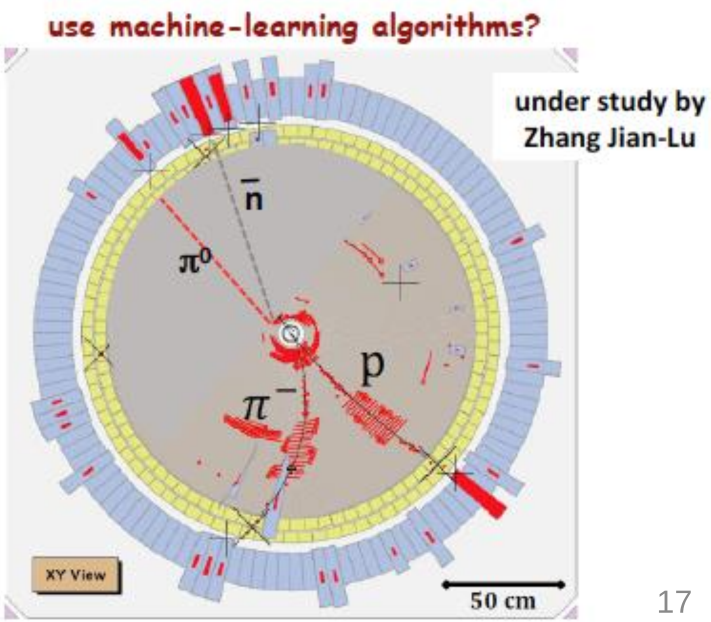
10 billion J/ψ and 2.7 billion $\psi(2S)$events collected

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

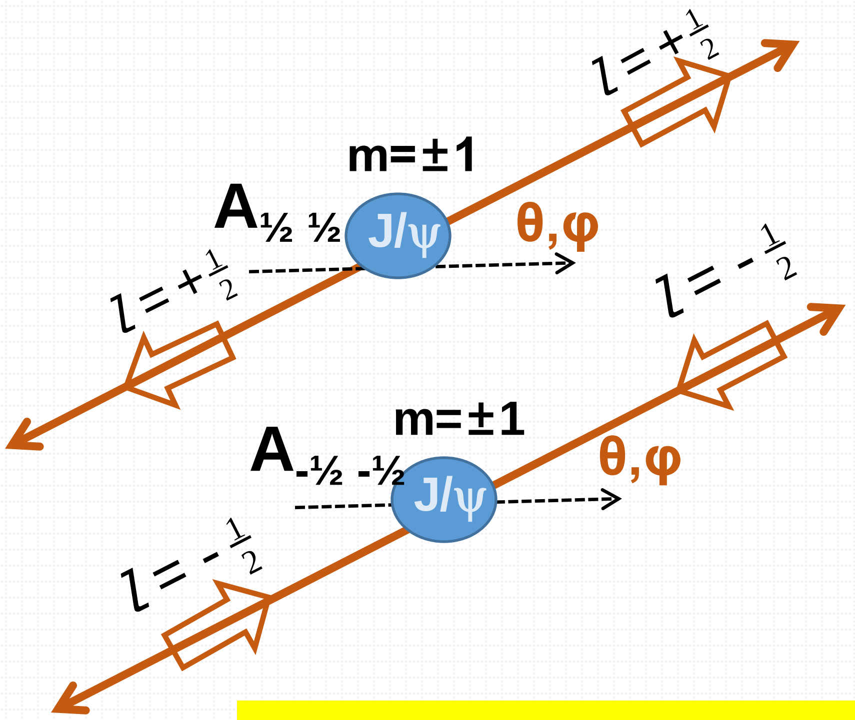
Hai-Bo Li, arXiv:1612.01775
A. Adlarson, A. Kupsc, arXiv:1908.03102

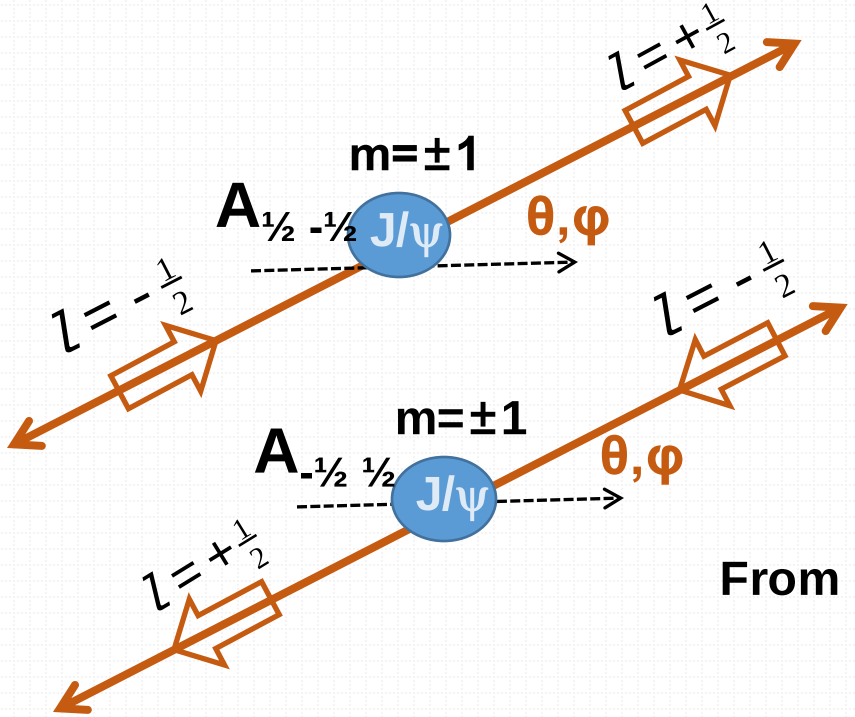


Decay mode	$\mathcal{B}(\times 10^{-3})$	N_B $(\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.1 ± 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
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	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



Entangled and Polarized hyperon pairs produced in e^+e^- collisions





From Steve Olsen

Parity conservation : $A_{½\ ½} = A_{-½\ -½}$

Parity conservation : $A_{½\ -½} = A_{-½\ ½}$

ΔΦ= 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 $\Delta\Phi \neq 0$, Λ and $\bar{\Lambda}$ are transversely polarized

Correlated 5-dim. angular distribution in differential cross-section of this process: $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

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

Unpolarized part

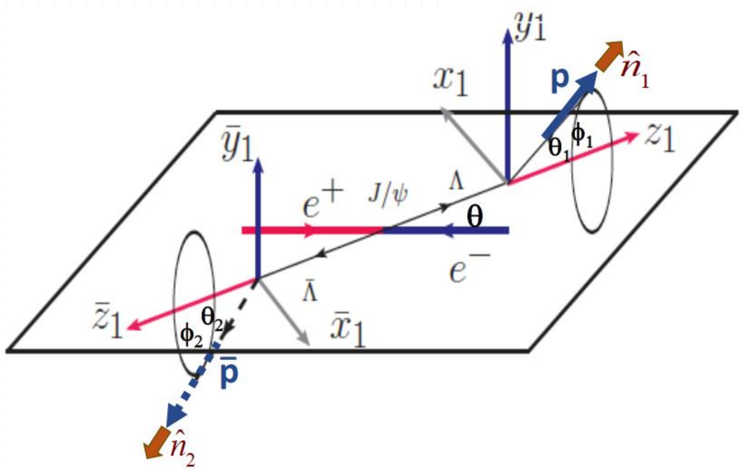
Spin correlated part

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

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

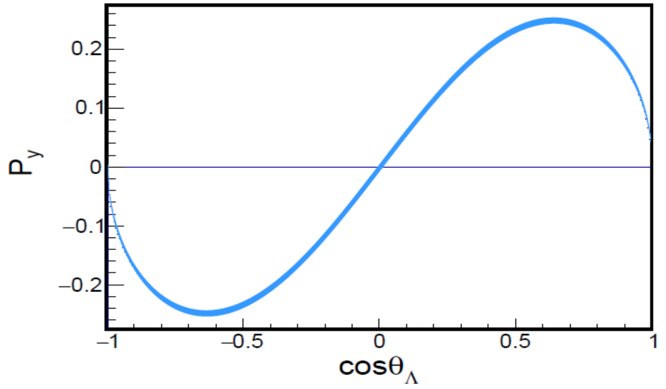
$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\,\sin\theta_\Lambda\cos\theta_\Lambda\left(\alpha_-n_{1,y}+\alpha_+n_{2,y}\right),$$

Spin Polarized part



Spin correlated term and polarization term can be used to determine α_- and α_+ precisely

Λ



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

Nuovo Cim. A 109, 241 (1996)
Phys. Rev.185 D 75, 074026 (2007)
Nucl. Phys. A190 771, 169 (2006)
Phys. Lett. B 772, 16(2017)

Search for CPV in $\Lambda \to p\pi^-$ decay

Two BESIII papers have been published:

[1] 1.3 billion: Nature Phys 15(2019)631

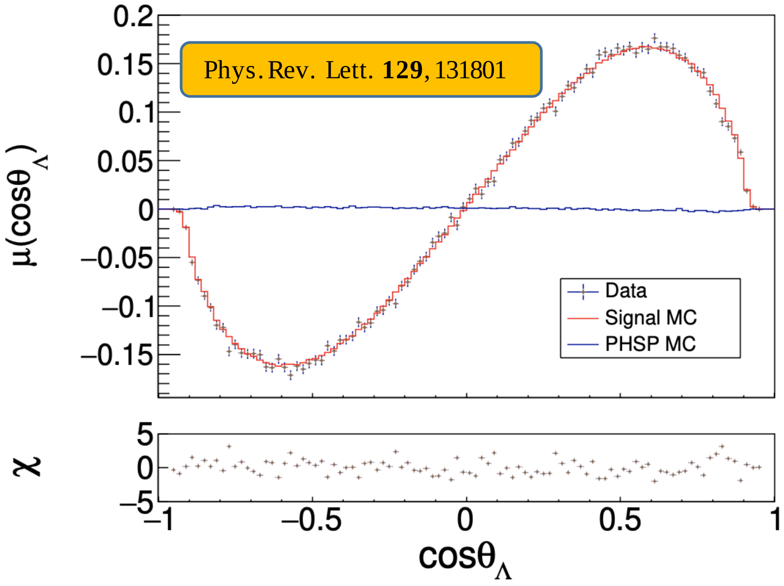
[2] 10 billion: Phys. Rev. Lett. 129 (2022) 13, 131801

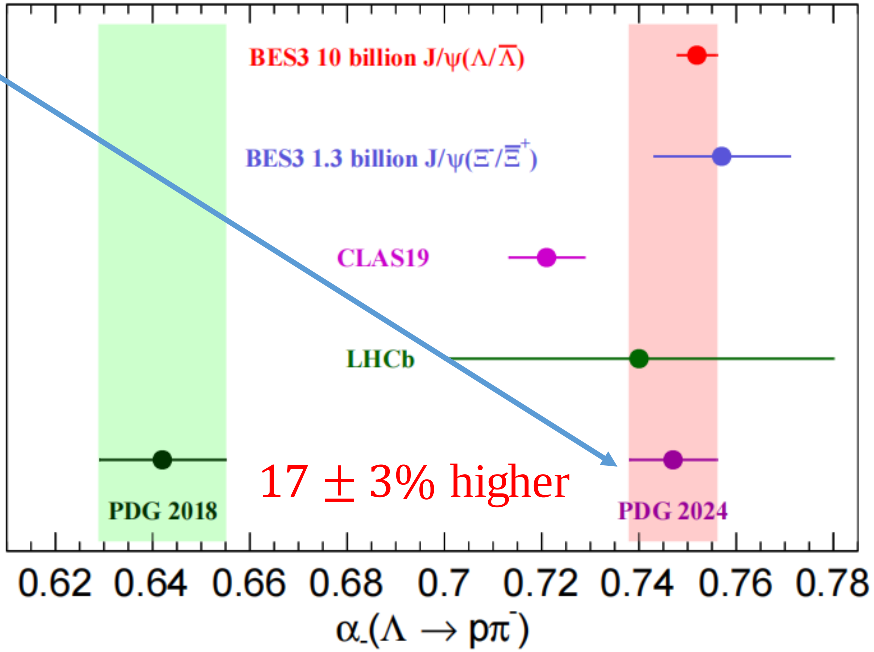
Par.	BESIII 10 billion [2]	BESIII 1.3 billion [1]
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0031$	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0066$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.7519 \pm 0.0036 \pm 0.0024$	$0.750 \pm 0.009 \pm 0.004$
α_+	$-0.7559 \pm 0.0036 \pm 0.0030$	$-0.758 \pm 0.010 \pm 0.007$
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0012$	$0.006 \pm 0.012 \pm 0.007$
α_{avg}	$0.7542 \pm 0.0010 \pm 0.0024$	-

3.2 M $\Lambda\bar{\Lambda}$ pairs were reconstructed.

- Most precise measurement of Λ decay parameter
- Most precise A_{CP} measurement in hyperon decay:

$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = -0.0025 \pm 0.0046 \pm 0.0011$$





Search for CPV in $\Lambda \to n\pi^0$ decay

[1] arXiv:2510.24333

[2] Phys.Rev.Lett. 132 (2024) 10, 101801

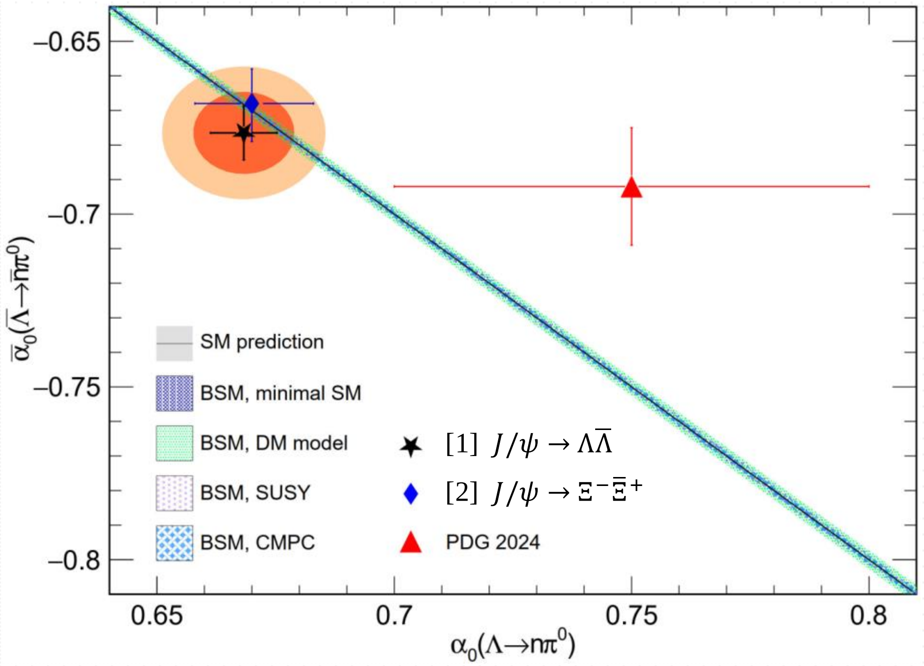
Two channels used to study $\Lambda \to n\pi^0$:

[1] $J/\psi \to \Lambda\bar{\Lambda} \to \boldsymbol{n\pi^0}\bar{p}\pi^+ + c.c$

[2] $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(\to \boldsymbol{n\pi^0})\pi^-\bar{\Lambda}(\to \bar{p}\pi^+)\pi^+ + c.c$

Parameter	[1] $J/\psi \to \Lambda\bar{\Lambda}$	[2] $J/\psi \to \Xi^-\bar{\Xi}^+$
α_-	$0.756 \pm 0.008 \pm 0.003$	$0.764 \pm 0.008^{+0.005}_{-0.006}$
α_+	$-0.764 \pm 0.008 \pm 0.001$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$
α_0	$0.668 \pm 0.007 \pm 0.002$	$0.670 \pm 0.009^{+0.009}_{-0.008}$
$\bar{\alpha}_0$	$-0.677 \pm 0.007 \pm 0.003$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$
A_{CP}^-	$-0.005 \pm 0.007 \pm 0.002$	$-0.007 \pm 0.008^{+0.002}_{-0.003}$
A_{CP}^0	$-0.006 \pm 0.007 \pm 0.002$	$0.001 \pm 0.009^{+0.005}_{-0.007}$
α_0/α_-	$0.884 \pm 0.013 \pm 0.006$	$0.877 \pm 0.015^{+0.014}_{-0.010}$
$\bar{\alpha}_0/\alpha_+$	$0.885 \pm 0.013 \pm 0.004$	$0.863 \pm 0.014^{+0.012}_{-0.008}$

$\Delta I = 1/2$ rule: $\frac{\alpha_0}{\alpha_-} = 1$



The most precise results of Λ neutral decay

43% and 27% improvement in $J/\psi \to \Lambda\bar{\Lambda}$ compared with $J/\psi \to \Xi^-\bar{\Xi}^+$

Most precise CP test in Λ neutral decay

SM prediction: $A_{CP} \sim 10^{-5}$ (PRD 67, 056001(2003))

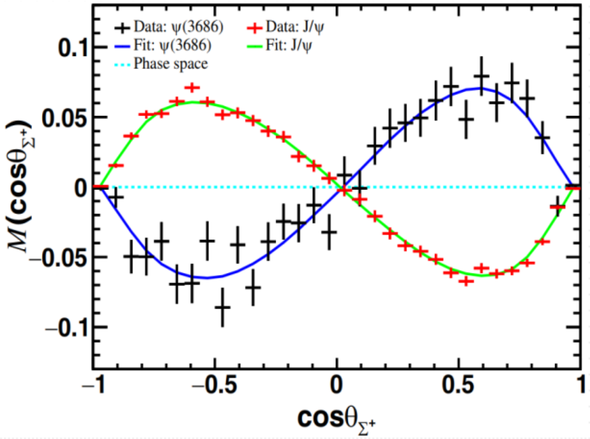
Deviate from unity more than 5σ, indicates the $\Delta I = 3/2$ contributions in Λ decay

Search for CPV in Σ^+ decay

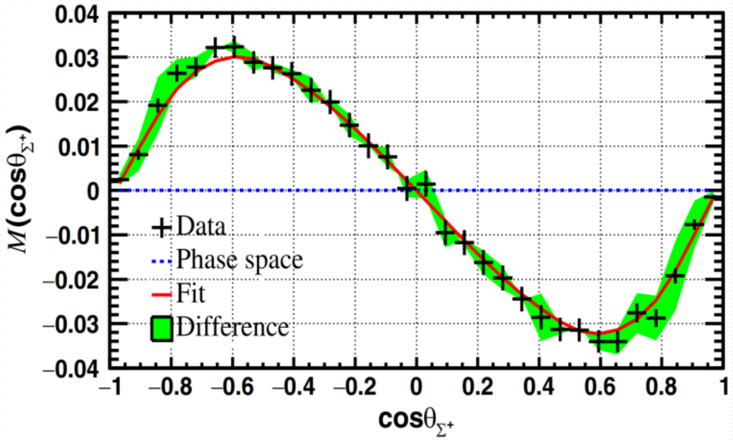
[1] Phys.Rev.Lett. 135 (2025) 14, 141804

[2] Phys.Rev.Lett. 131 (2023) 19, 191802

[1] $J/\psi[\psi(3686)] \to \Sigma^+\bar{\Sigma}^- \to p\pi^0\bar{p}\pi^0$ [2] $J/\psi \to \Sigma^+(\to n\pi^+)\bar{\Sigma}^-(\to \bar{p}\pi^0) + c.c.$



10B J/ψ and 2.7B $\psi(3686)$



10B J/ψ

Polarization of Σ^+

Opposite direction of the Σ^+ polarization in J/ψ and $\psi(3686)$

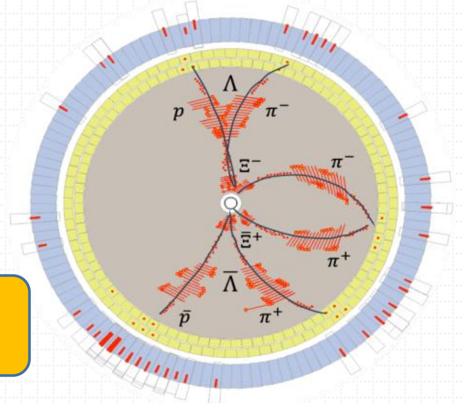
Parameter	[1] $\Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0$	[2] $\Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{n}\pi^- + c.c.$
$\alpha_{J/\psi}$	$-0.5047 \pm 0.0018 \pm 0.0010$	$-0.5156 \pm 0.0030 \pm 0.0061$
$\Delta\Phi_{J/\psi}$	$-0.2744 \pm 0.0033 \pm 0.0010$	$-0.2772 \pm 0.0044 \pm 0.0041$
$\alpha_{\psi(3686)}$	$0.7133 \pm 0.0094 \pm 0.0065$	–
$\Delta\Phi_{\psi(3686)}$	$0.427 \pm 0.022 \pm 0.003$	–
$\alpha_0(\Sigma^+ \to p\pi^0)$	$-0.975 \pm 0.011 \pm 0.002$	–
$\bar{\alpha}_0(\bar{\Sigma}^- \to \bar{p}\pi^0)$	$0.999 \pm 0.011 \pm 0.004$	–
$\alpha_+(\Sigma^+ \to n\pi^+)$	–	$0.0481 \pm 0.0031 \pm 0.0019$
$\alpha_-(\bar{\Sigma}^- \to \bar{n}\pi^-)$	–	$-0.0565 \pm 0.0047 \pm 0.0022$

The most precise CP test in Σ sector:

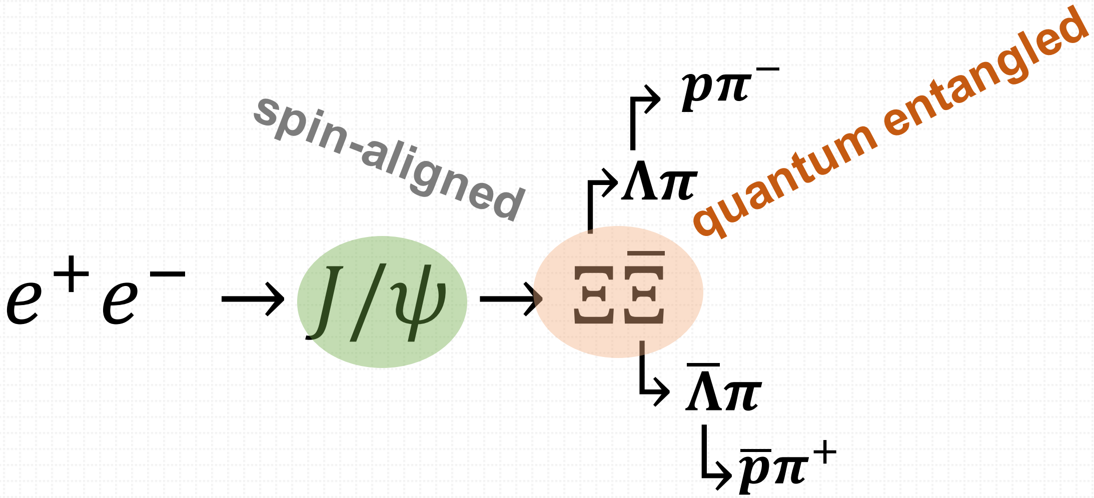
$$A_{CP}(\Sigma^+ \to p\pi^0) = \frac{\alpha_0 + \bar{\alpha}_0}{\alpha_0 - \bar{\alpha}_0} = -0.0118 \pm 0.0083 \pm 0.0028$$

$$A_{CP}(\Sigma^+ \to n\pi^+) = \frac{\alpha_+ + \bar{\alpha}_-}{\alpha_+ - \bar{\alpha}_-} = -0.080 \pm 0.052 \pm 0.028$$

Search for CPV in Ξ decay



Phys. Rev. D 99, 056008 (2019)
Phys. Lett. B 772, 16 (2017)



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

Hyperon Production | Hyperon decays

$$W(\boldsymbol{\xi}; \boldsymbol{\omega}) = \sum_{\mu,\bar{\nu}} C_{\mu\bar{\nu}} \sum_{\mu'\bar{\nu}'} a^{\Xi}_{\mu,\mu'} a^{\bar{\Xi}}_{\bar{\nu},\bar{\nu}'} a^{\Lambda}_{\mu',0} a^{\bar{\Lambda}}_{\bar{\nu}',0}$$

$$\boldsymbol{\xi} = (\theta_\Xi, \theta_\Lambda, \phi_\Lambda, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}})$$

Through the sequential decays of Ξ, the B_{CP} (CPV phase) can be directly measured!

Big branching fraction!

The *perfect* reaction for hyperon CPV searches!

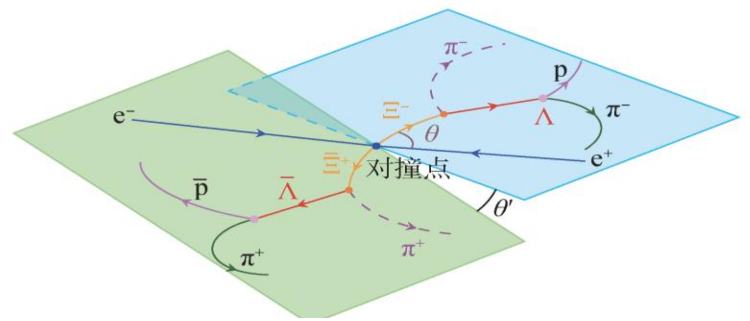
Search for CP violation in spin-correlated $\Xi^- - \bar{\Xi}^+$ pairs

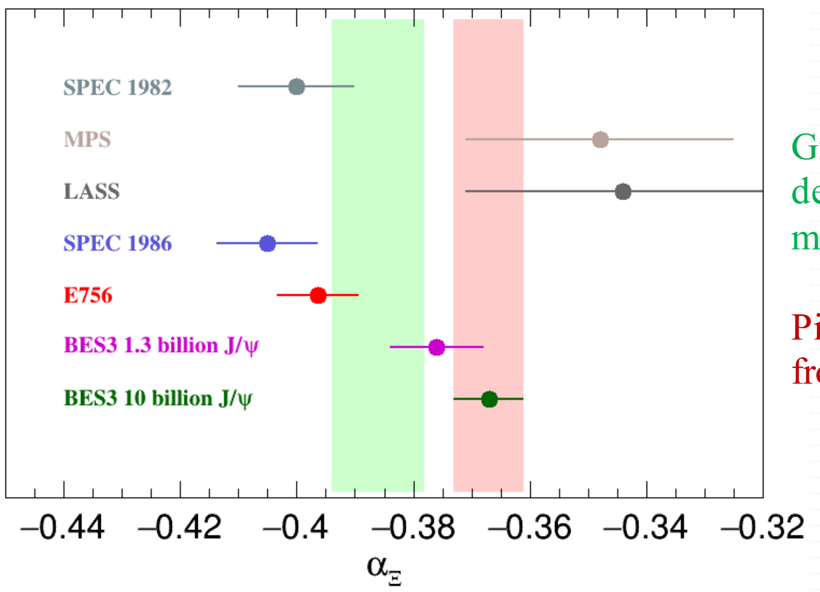
BESIII Nature 606 (2022) 64-69

1.3 billion J/ψ $\quad e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+ \quad \Xi^- \to \Lambda\pi$

73 K $\Xi^- - \bar{\Xi}^+$ pairs with 99% purity

Parameter	This work	Previous result
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–
A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad	





Green band: the PDG α_Ξ value derived from the $\alpha_\Xi\alpha_\Lambda$ measurements

Pink band: the PDG α_Ξ value from direct measurements

By analyzing the spin-correlated $\Xi^- - \bar{\Xi}^+$ pairs, the α_Ξ can be independently measured, all other experiments can only measure the product of α_Ξ and α_Λ ($\alpha_\Xi\alpha_\Lambda$).

Search for CP violation in quantum-entangled $\Xi^0 - \bar{\Xi}^0$ pairs

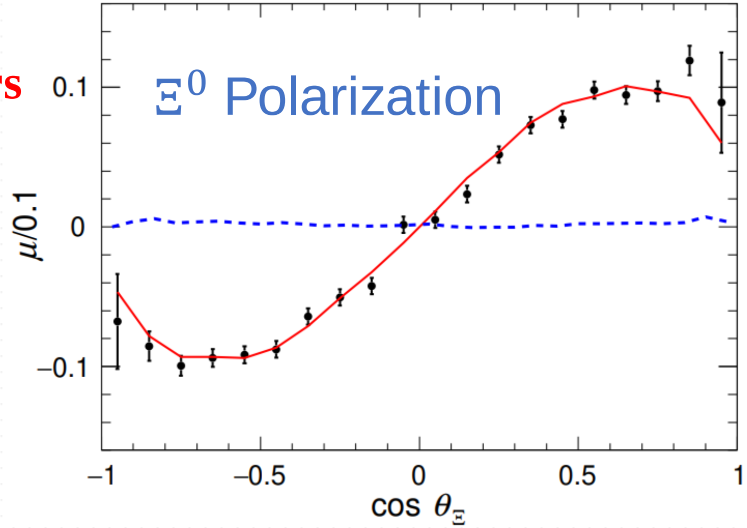
10 billion **J/ψ**

$e^+e^- \to J/\psi \to \Xi^0\bar{\Xi}^0$ $\Xi^0 \to \Lambda\pi^0$

Parameter	This work	Previous result
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$	0.66 ± 0.06 [34]
$\Delta\Phi$(rad)	$1.168 \pm 0.019 \pm 0.018$	-
α_Ξ	$-0.3750 \pm 0.0034 \pm 0.0016$	-0.358 ± 0.044 [18]
$\bar{\alpha}_\Xi$	$0.3790 \pm 0.0034 \pm 0.0021$	0.363 ± 0.043 [18]
ϕ_Ξ(rad)	$0.0051 \pm 0.0096 \pm 0.0018$	0.03 ± 0.12 [18]
$\bar{\phi}_\Xi$(rad)	$-0.0053 \pm 0.0097 \pm 0.0019$	-0.19 ± 0.13 [18]
α_Λ	$0.7551 \pm 0.0052 \pm 0.0023$	0.7519 ± 0.0043 [13]
$\bar{\alpha}_\Lambda$	$-0.7448 \pm 0.0052 \pm 0.0017$	-0.7559 ± 0.0047 [13]
$\xi_P - \xi_S$(rad)	$(0.0 \pm 1.7 \pm 0.2) \times 10^{-2}$	-
$\delta_P - \delta_S$(rad)	$(-1.3 \pm 1.7 \pm 0.4) \times 10^{-2}$	-
A^Ξ_{CP}	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$	$(-0.7 \pm 8.5) \times 10^{-2}$ [18]
$\Delta\phi^\Xi_{CP}$(rad)	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$	$(-7.9 \pm 8.3) \times 10^{-2}$ [18]
A^Λ_{CP}	$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$	$(-2.5 \pm 4.8) \times 10^{-3}$ [13]
$\langle\alpha_\Xi\rangle$	$-0.3770 \pm 0.0024 \pm 0.0014$	-
$\langle\phi_\Xi\rangle$(rad)	$0.0052 \pm 0.0069 \pm 0.0016$	-
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$	0.7542 ± 0.0026 [13]

Phys. Rev. D 108, L031106 (2023) Editors' suggestion

320 K $\Xi^0 - \bar{\Xi}^0$ pairs with 98% purity



The precision of the asymmetry parameter: 10^{-3}

Measurement of the weak (CPV) phase difference in Ξ^0 decays, most precise results in weakly baryon decays: $|\xi_P-\xi_S|<1.4^o$ (@ 90% C.L.)

Three CP tests

The precision of $\langle\alpha_\Lambda\rangle$ obtained from 320K Ξ^0 is comparable to that obtained from the measurement of 3.2 million Λ decays!

Search for CPV in Ξ⁻ decay

New Measurement of $\Xi^- \to \Lambda\pi^-$ Decay Parameters

M. Huang,[10] R. A. Burnstein,[5] A. Chakravorty,[5] Y. C. Chen,[1] W. S. Choong,[2,7] K. Clark,[9] E. C. Dukes,[10] C. Durandet,[10] J. Felix,[4] G. Gidal,[7] H. R. Gustafson,[8] T. Holmstrom,[10] C. James,[3] C. M. Jenkins,[9] T. Jones,[7] D. M. Kaplan,[5] L. M. Lederman,[5] N. Leros,[6] M. J. Longo,[8] Fred Lopez,[8] L. Lu,[10] W. Luebke,[5] K. B. Luk,[2,7] K. S. Nelson,[10] H. K. Park,[8] J. P. Perroud,[6] D. Rajaram,[5,8] H. A. Rubin,[5] J. Volk,[3] C. White,[5] S. White,[5] and P. Zyla[7]

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(Received 13 February 2004; published 30 June 2004)

Based on a sample of 144×10^6 polarized $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ decays collected by the HyperCP experiment (E871) at Fermilab, we report a new measurement of the Ξ^- decay-parameter angle $\phi_\Xi = (-2.39 \pm 0.64 \pm 0.64)°$ from which we deduce the decay parameters $\beta_\Xi = -0.037 \pm 0.011 \pm 0.010$ and $\gamma_\Xi = 0.888 \pm 0.0004 \pm 0.006$. Assuming that the *CP*-violating phase difference between *s* and *p* waves is negligible, the strong phase-shift difference, $\delta_p - \delta_s$, for $\Lambda\pi$ scattering is determined to be $(4.6 \pm 1.4 \pm 1.2)°$.

HyperCP: Phys. Rev. Lett. 93 (2004) 011802

144 M Ξ^-: $\phi_\Xi = -0.032 \pm 0.011 \pm 0.011$ rad

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

events. The final-state particles are measured in the main drift chamber, where a superconducting solenoid provides a magnetic field allowing momentum determination with an accuracy of 0.5% at 1.0 GeV/*c*. The Λ ($\bar\Lambda$) candidates are identified by combining $p\pi^-$ ($\bar p\pi^+$) pairs and the Ξ^- ($\bar\Xi^+$) candidates by subsequently combining $\Lambda\pi^-$ ($\bar\Lambda\pi^+$) pairs. Because it was found that the long-lived Ξ^- and $\bar\Xi^+$ can only be reconstructed with sufficient quality if they fulfil $|\cos\theta| < 0.84$, only Ξ^- and $\bar\Xi^+$ reconstructed within this range were considered. After applying all selection criteria, 73,244 $\Xi^-\bar\Xi^+$ event candidates remain in the sample. The number of background events in the signal is estimated to be 199 ± 17. More details of the analysis are given in Methods.

BESIII: Nature 606 (2022) 64-69

73K $\Xi^-\bar\Xi^+$ pairs : $\langle\phi_\Xi\rangle = 0.016 \pm 0.014 \pm 0.007$ rad

With 73 K reconstructed $\Xi^-\bar\Xi^+$ pairs from 1.3 billion J/ψ events at BESIII, we achieved a precision for ϕ parameter comparable to that in the HyperCP experiment in which 144 million Ξ^- are reconstructed.

The spin correlation between the Ξ^- and $\bar\Xi^+$ significantly improved the precision of the decay parameter measurements; the single-event sensitivity of BESIII is 1000 times that of HyperCP.

Search for Strong CPV in $\Sigma^0 \to \Lambda\gamma$ decay

The CPV sources in SM:

- Weak interaction, CKM (observed, but too small)
- Strong interaction, θ-term (Not yet observed)

10 B J/ψ and 2.7 B $\psi(3686)$

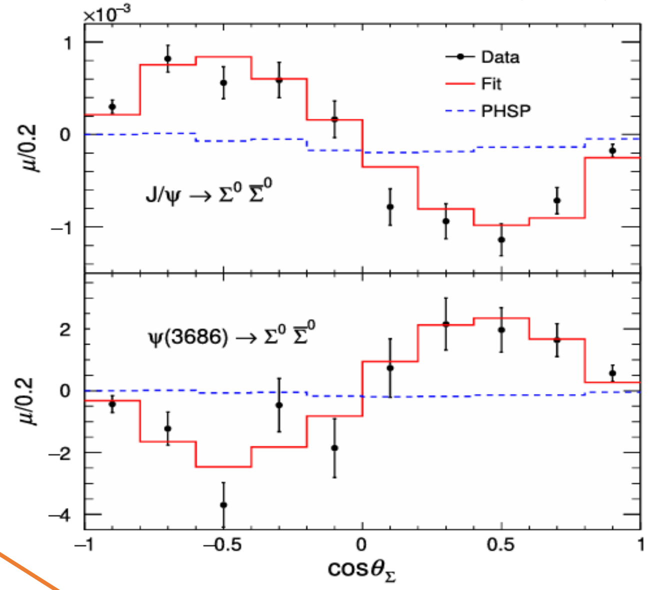
$e^+e^- \to J/\psi, \psi(3686) \to \Sigma^0(\to \Lambda\gamma)\bar{\Sigma}^0(\to \bar{\Lambda}\gamma), \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

Parameter	Phys. Rev. Lett. 133 (2024) 10, 101902
$\alpha_{J/\psi}$	$-0.4133 \pm 0.0035 \pm 0.0077$
$\Delta\Phi_{J/\psi}$ (rad)	$-0.0828 \pm 0.0068 \pm 0.0033$
$\alpha_{\psi(3686)}$	$0.814 \pm 0.028 \pm 0.028$
$\Delta\Phi_{\psi(3686)}$ (rad)	$0.512 \pm 0.085 \pm 0.034$
α_{Σ^0}	$-0.0017 \pm 0.0021 \pm 0.0018$
$\bar{\alpha}_{\Sigma^0}$	$0.0021 \pm 0.0020 \pm 0.0022$
α_{Λ}	$0.730 \pm 0.051 \pm 0.011$
$\bar{\alpha}_{\Lambda}$	$-0.776 \pm 0.054 \pm 0.010$
A_{CP}^{Σ}	$(0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$
A_{CP}^{Λ}	$(-3.0 \pm 6.9 \pm 1.5) \times 10^{-2}$

Phys. Lett. B **788**, 535 (2019)

The Transition EDM of $\Sigma^0 \to \Lambda\gamma$ —SU(3) symmetry→ Neutron EDM

$$\frac{d_{\Sigma\Lambda}}{d_n} = \frac{d_{\Sigma\Lambda}^{\text{tree}} + d_{\Sigma\Lambda}^{\text{loop}}}{d_n^{\text{tree}} + d_n^{\text{loop}}} \approx -0.88$$



Polarizations of Σ^0

Similar behavior is observed in Σ^+, but not in Λ or Ξ!

Opposite directions of the Σ^0 polarization

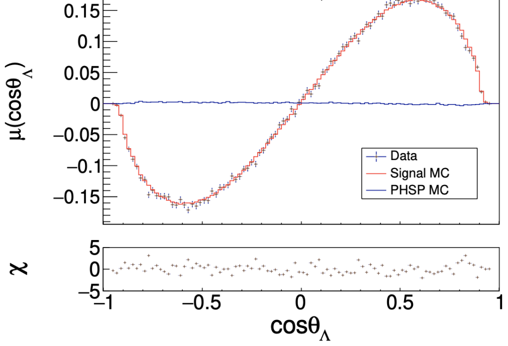
The first attempt to measure the P-violating decay parameter of $\Sigma^0 \to \Lambda\gamma$.

The first strong-CP test in hyperon decays.

Spin polarizations of different hyperons

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

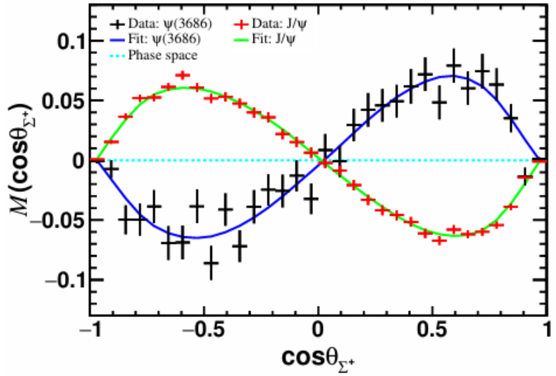
PRL129, 131801(2022)



$\Delta\Phi = (0.7521 \pm 0.0042 \pm 0.0066)$ rad

$\psi \to \Sigma^+\bar{\Sigma}^-$

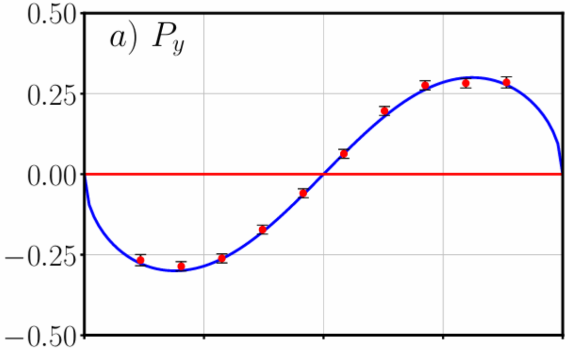
Phys. Rev. Lett. 135 (2025) 14, 141804



$\Delta\Phi(J/\psi) = (-0.2744 \pm 0.0033 \pm 0.0010)$rad
$\Delta\Phi(\psi(2S)) = (0.427 \pm 0.022 \pm 0.003)$rad

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

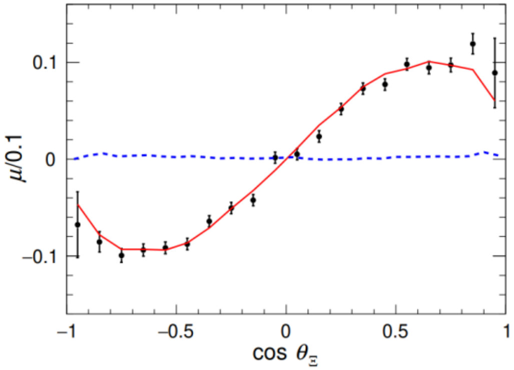
Nature 606, 64 (2022)



$\Delta\Phi = (1.213 \pm 0.046 \pm 0.016)$ rad

$J/\psi \to \Xi^0\bar{\Xi}^0$

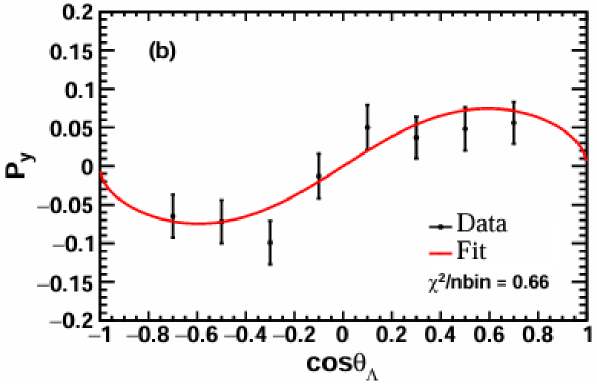
Phys. Rev. D 108, L031106 (2023)



$\Delta\Phi = (1.168 \pm 0.019 \pm 0.018)$ rad

$\psi(3686) \to \Lambda\bar{\Lambda}$

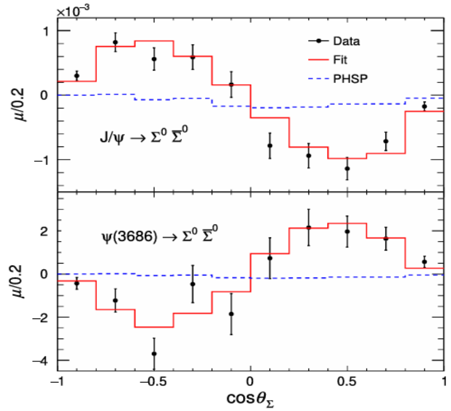
arXiv:2509.15276



$\Delta\Phi = (0.366 \pm 0.064 \pm 0.013)$ rad

$\psi \to \Sigma^0\bar{\Sigma}^0$

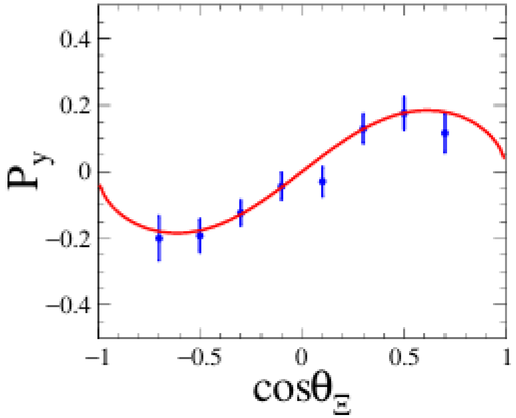
Phys. Rev. Lett. 133 (2024) 10, 101902



$\Delta\Phi(J/\psi) = (-0.0828 \pm 0.0068 \pm 0.0033)$rad
$\Delta\Phi(\psi(2S)) = (0.512 \pm 0.085 \pm 0.034)$rad

$\psi(2S) \to \Xi^-\bar{\Xi}^+$

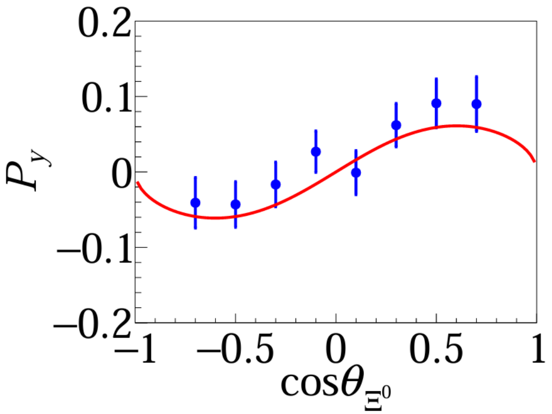
Phys. Rev. D 106, L091101 (2022)



$\Delta\Phi = (0.667 \pm 0.111 \pm 0.058)$ rad

$\psi(3686) \to \Xi^0\bar{\Xi}^0$

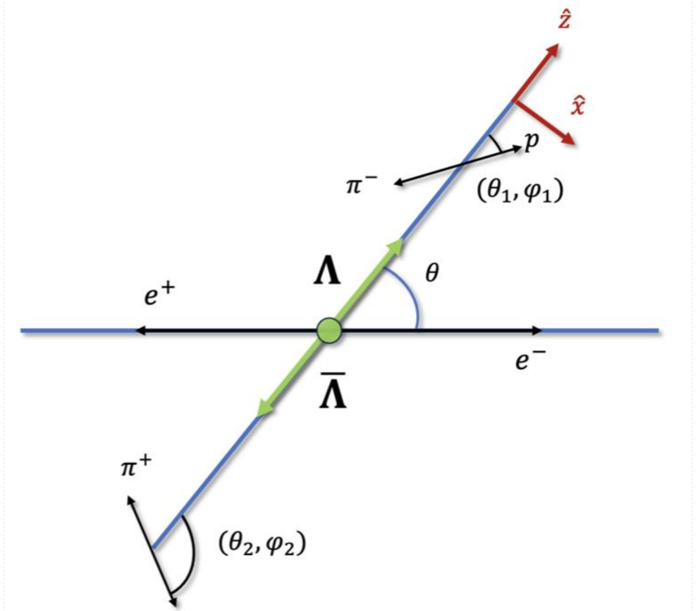
arXiv:2510.19571

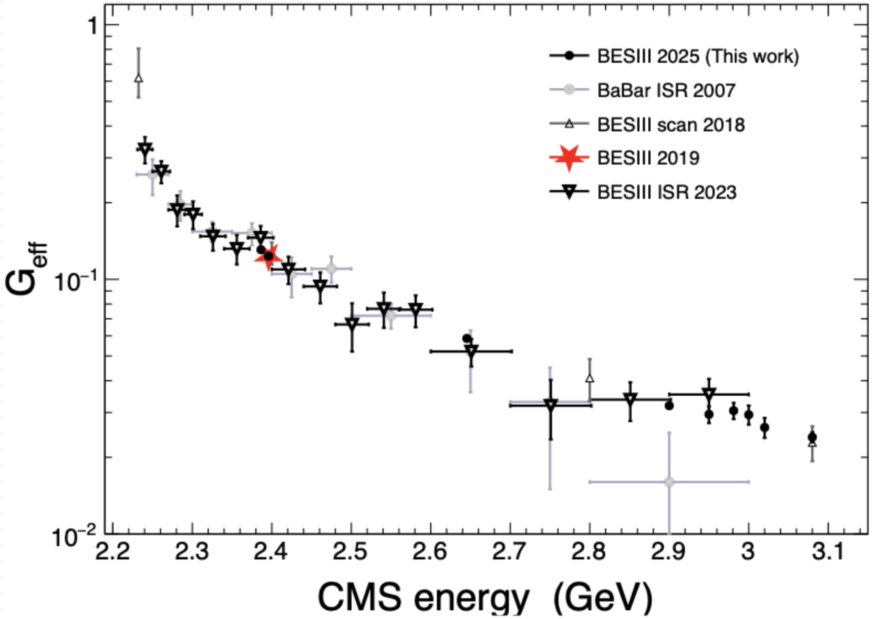


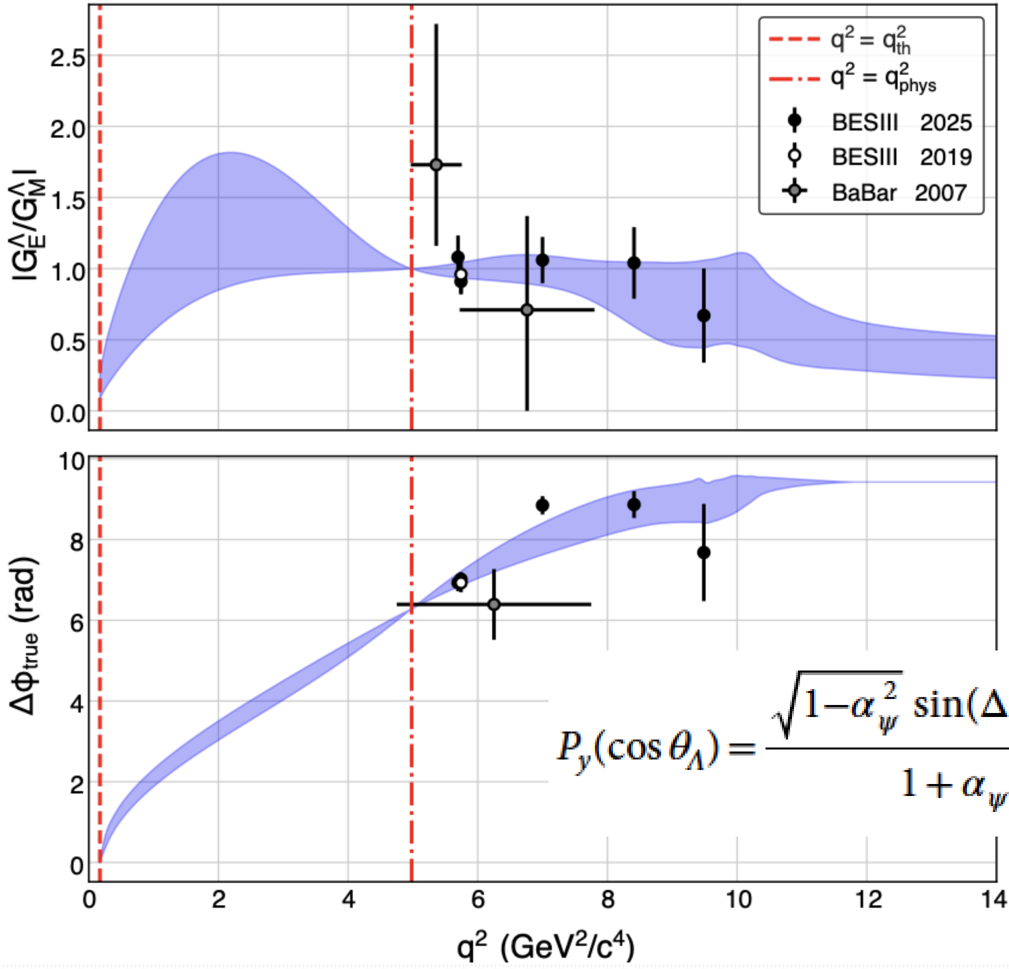
$\Delta\Phi = (0.257 \pm 0.061 \pm 0.009)$ rad

Energy-dependent polarization in $e^+e^- \to \Lambda\bar{\Lambda}$

BESIII: *Phys.Rev.Lett.* 135 (2025) 191902



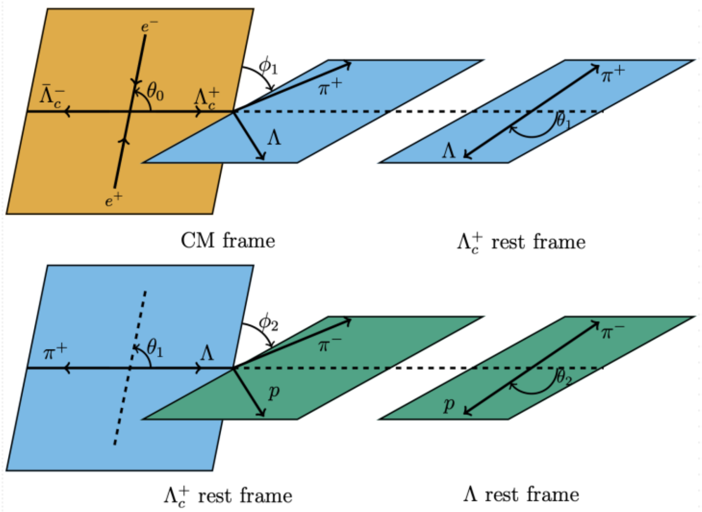


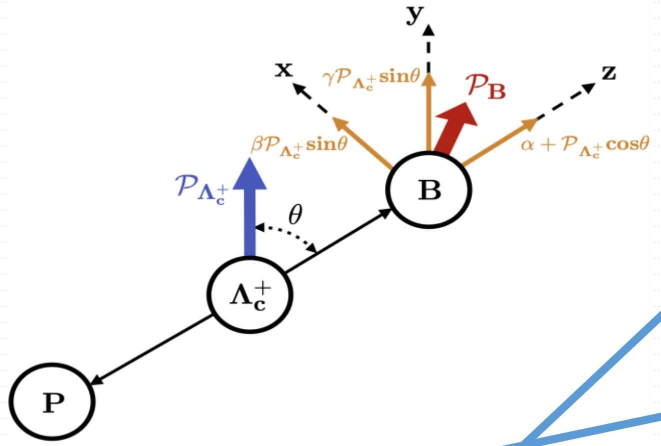


$$P_y(\cos\theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi^2}\,\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}$$

The modulus of the ratio between the electric and magnetic form factor, remains fairly constant across the considered energy range, the relative phase changes by more than 90^o between 2.40 and 2.65 GeV.

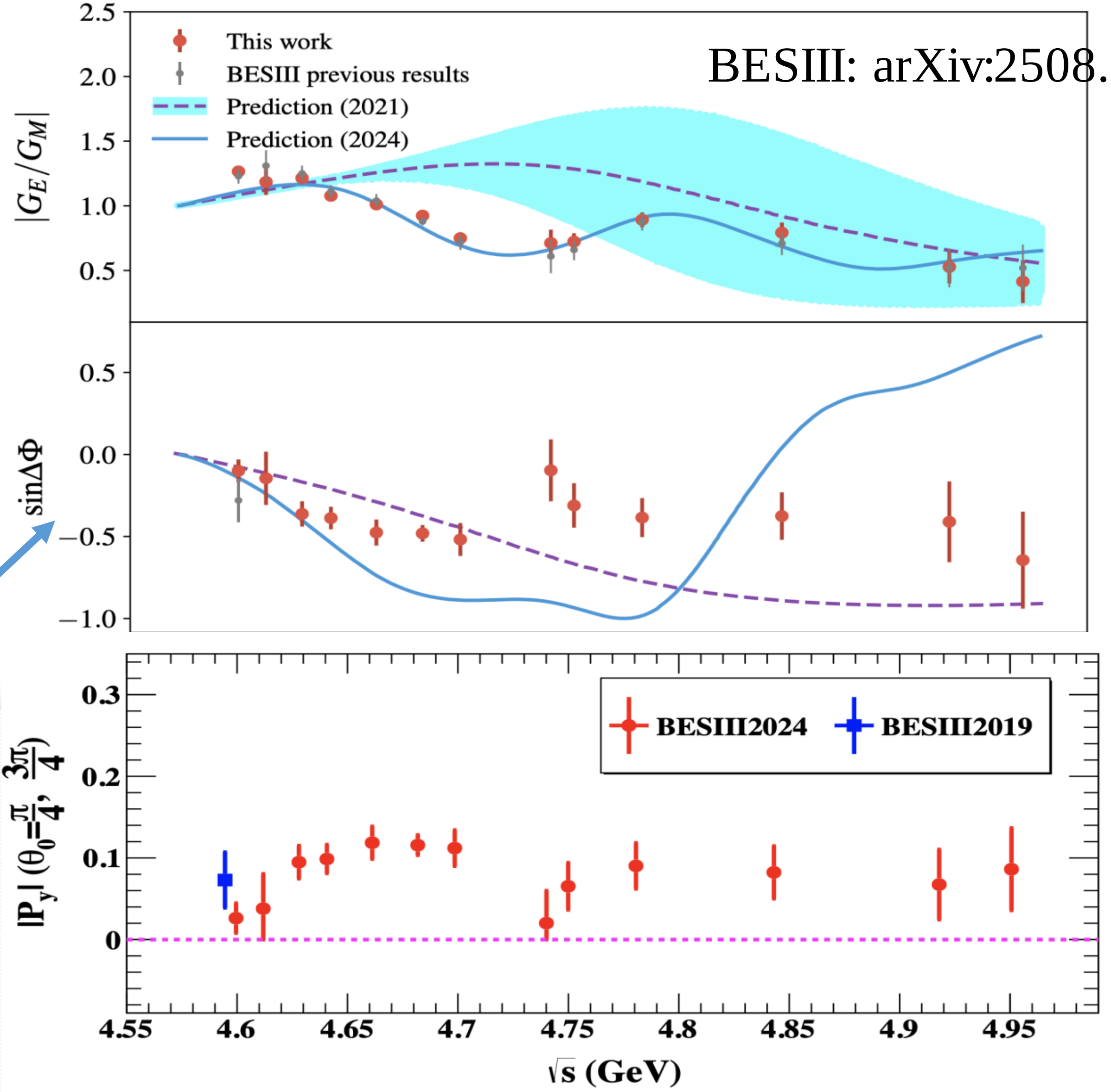
Energy-dependent polarization in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$





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

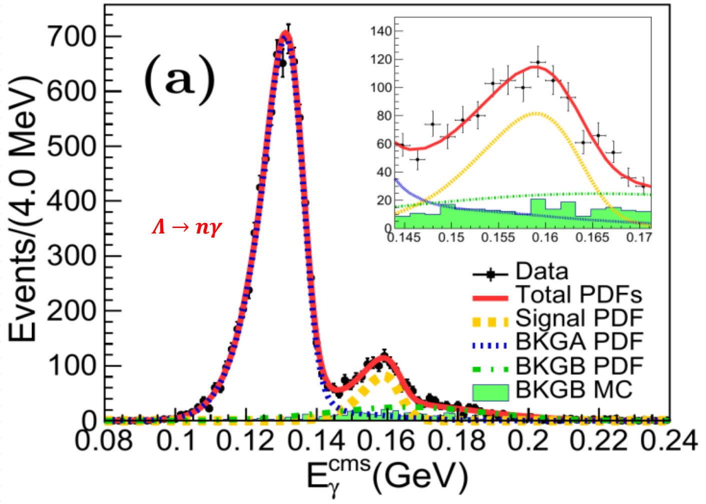
BESIII: arXiv:2508.11400

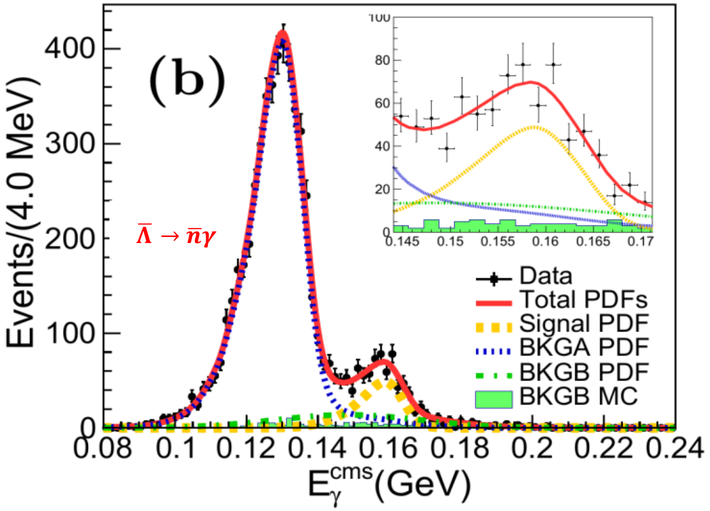


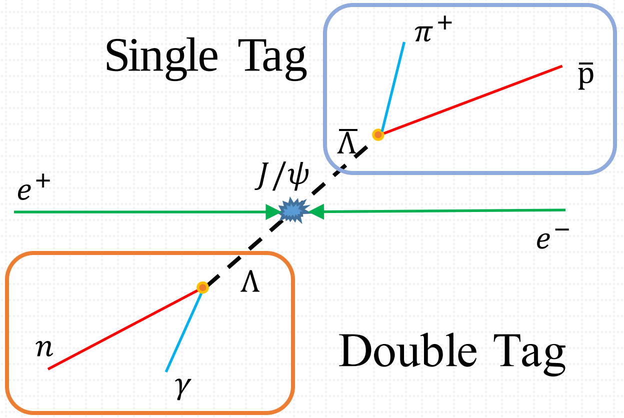
What's the production dynamics of charmed baryon?

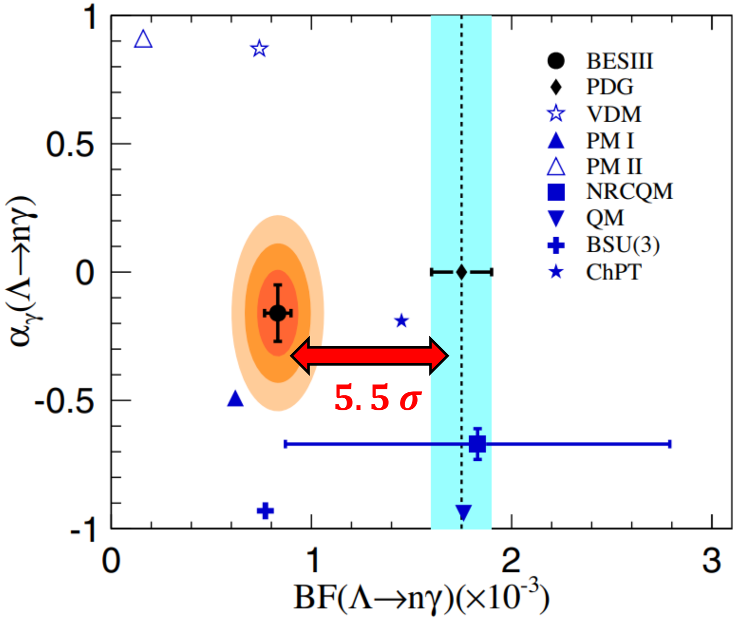
Radiative decay: $\Lambda \to n\gamma$ in $J/\psi \to \Lambda\bar{\Lambda}$

Phys. Rev. Lett. 129, 212002 (2022)







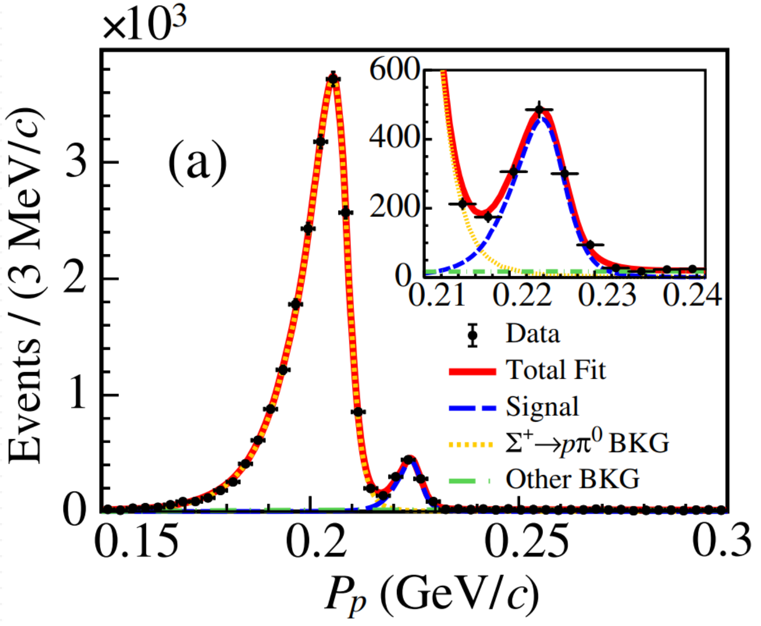


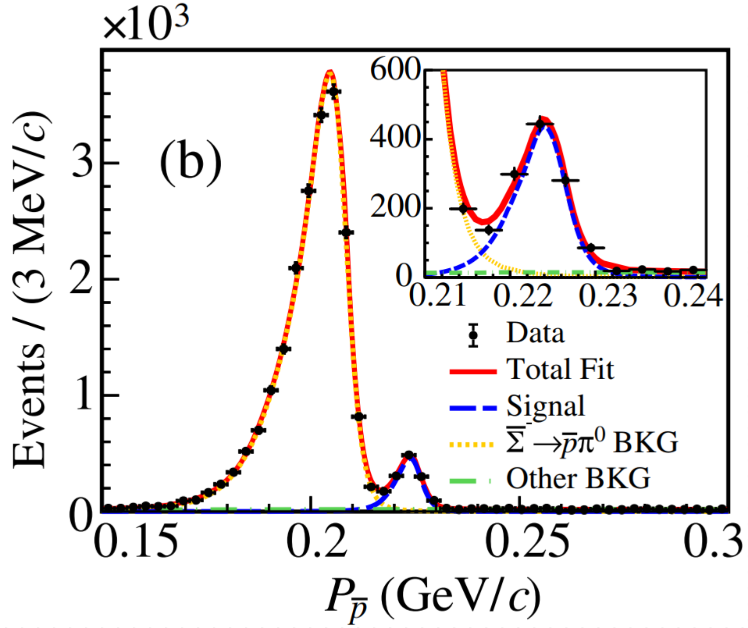
Variables	$\Lambda \to \gamma n (\times 10^{-3})$	$\bar{\Lambda} \to \gamma \bar{n} (\times 10^{-3})$	Combined$(\times 10^{-3})$
BF	$0.834 \pm 0.046 \pm 0.064$	$0.876 \pm 0.071 \pm 0.082$	$0.832 \pm 0.038 \pm 0.054$
α_γ	$-0.13 \pm 0.13 \pm 0.02$	$0.21 \pm 0.15 \pm 0.06$	$-0.16 \pm 0.10 \pm 0.05$
Δ_{CP}	$-0.025 \pm 0.049 \pm 0.060$		
A_{CP}	$-0.25 \pm 0.61 \pm 0.15$		

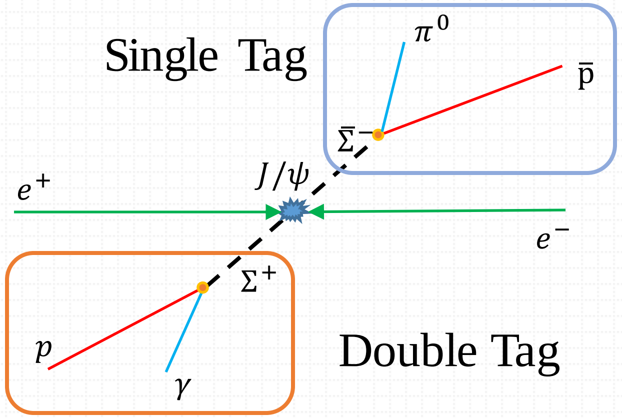
BF of $\Lambda \to n\gamma$, with improved precision, smaller than PDG value by 5.5σ

Radiative decay: $\Sigma^+ \to p\gamma$ in $J/\psi \to \Sigma^+\bar{\Sigma}^-$

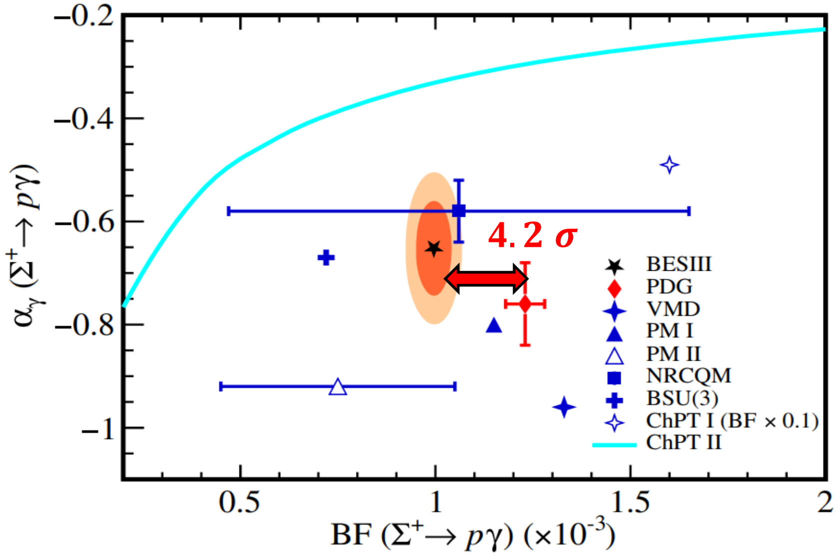
Phys. Rev. Lett. 130, 211901(2023)







The decay rate deviates from previous value by 4.2σ



The most precise branching fraction and decay parameter of $\Sigma^+ \to p\gamma$:

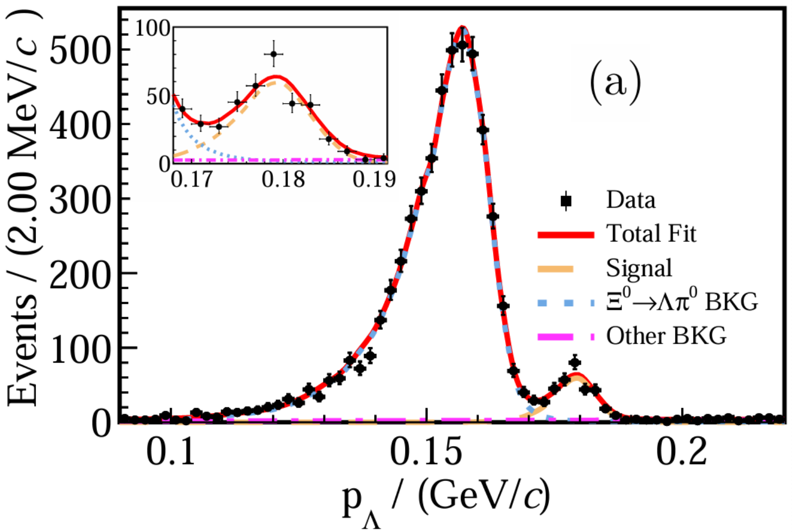
- $\mathcal{B}(\Sigma^+ \to p\gamma) = (0.996 \pm 0.021 \pm 0.018) \times 10^{-3}$
- $\alpha_\gamma = -0.652 \pm 0.056 \pm 0.020$

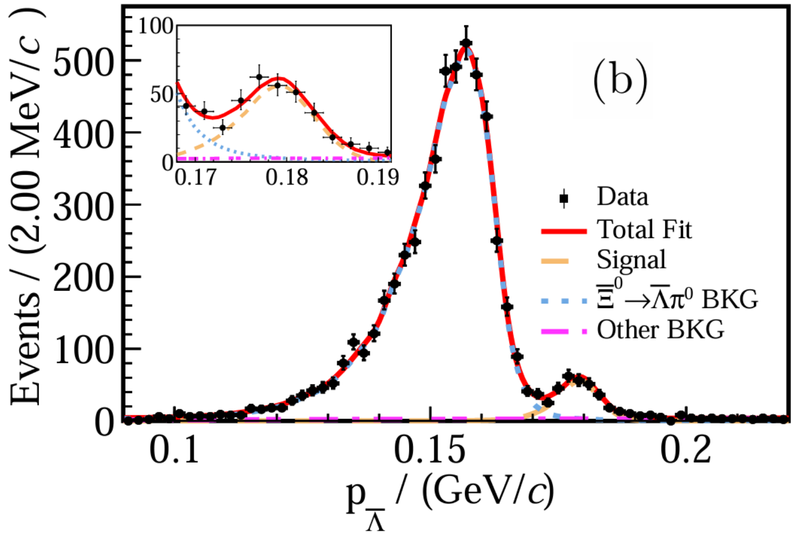
The CP asymmetry is calculated to be:

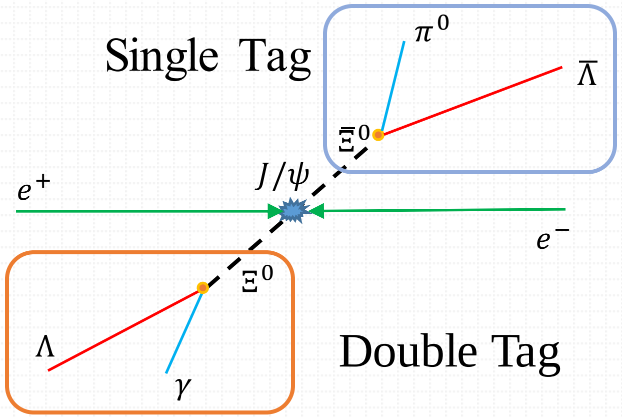
- $A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+) = 0.095 \pm 0.087 \pm 0.018$
- $\Delta_{CP} = (\mathcal{B}_+ - \mathcal{B}_-)/(\mathcal{B}_+ + \mathcal{B}_-) = 0.006 \pm 0.011 \pm 0.004$

Radiative decay: $\Xi^0 \to \Lambda\gamma$ in $J/\psi \to \Xi^0\bar{\Xi}^0$

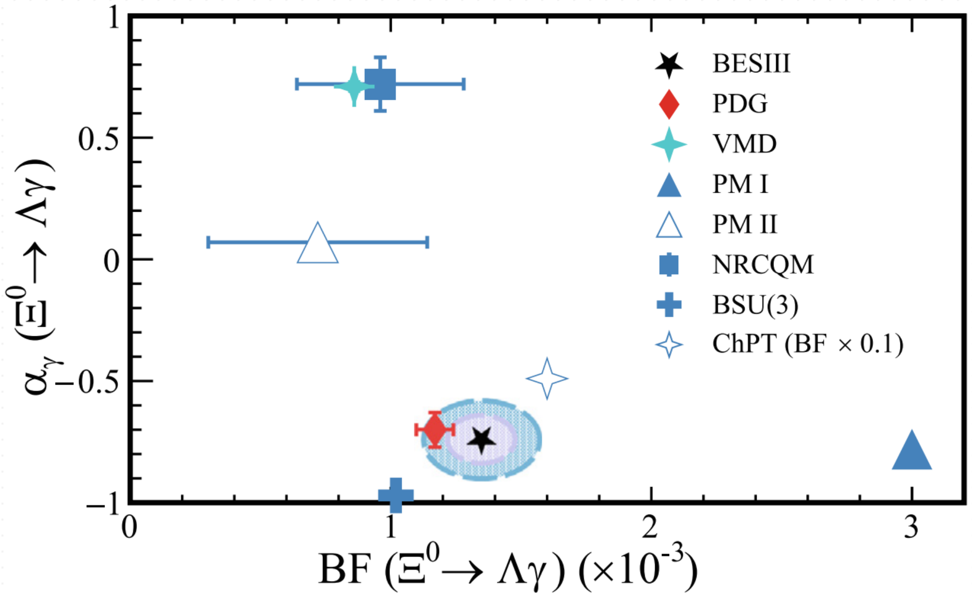
Sci. Bull. 70 (2025) 454-459







$$\mathcal{B}(\Xi^0 \to \Lambda\gamma) = \frac{N_{DT}}{N_{ST}} \times \frac{\epsilon_{ST}}{\epsilon_{DT}} \times \frac{1}{\mathcal{B}(\Lambda \to p\pi^-)}$$

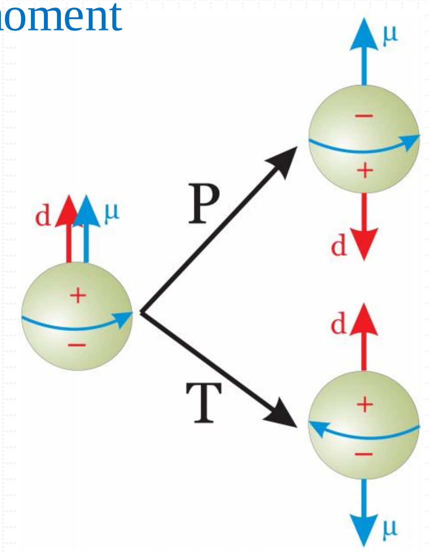


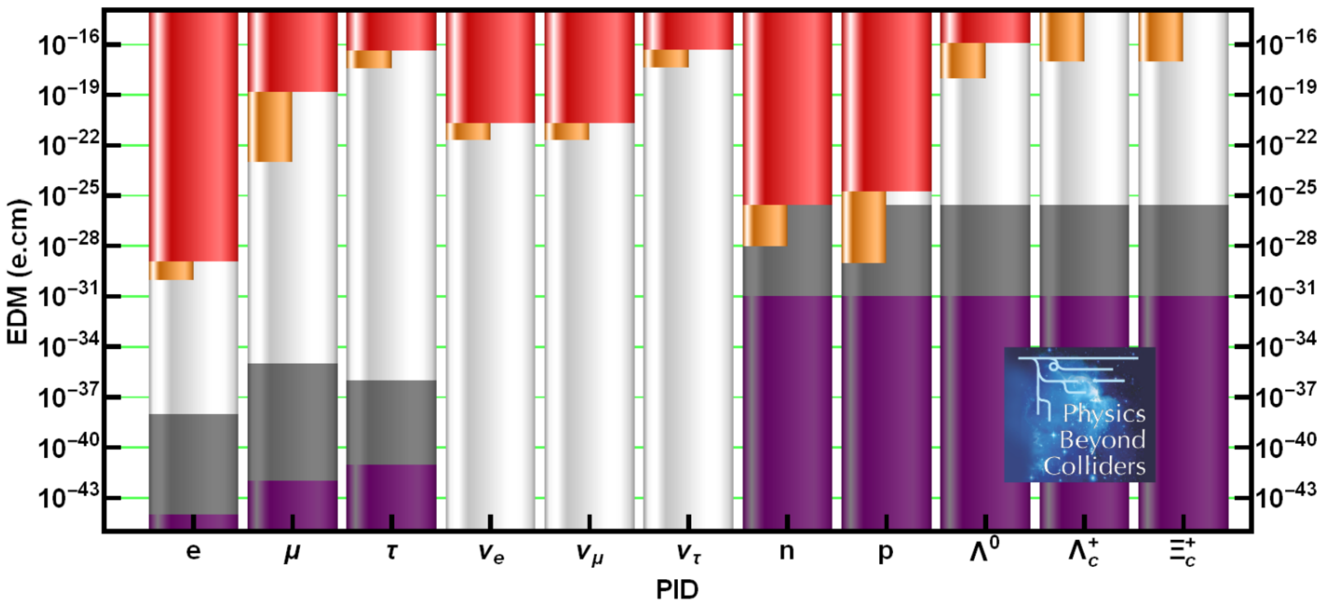
Channels	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
Individual BF(10^{-3})	$1.348 \pm 0.090 \pm 0.054$	$1.326 \pm 0.098 \pm 0.066$
Combined BF(10^{-3})	$1.347 \pm 0.066 \pm 0.054$	
Individual $\alpha_\gamma(\bar{\alpha}_\gamma)$	$-0.652 \pm 0.092 \pm 0.016$	$0.830 \pm 0.080 \pm 0.044$
Combined α_γ	$-0.741 \pm 0.062 \pm 0.019$	

First CP test in $\Xi^0 \to \Lambda\gamma$: $A_{CP} = -0.120 \pm 0.084 \pm 0.029$

Search for hyperon electric dipole moments at BESIII

μ: magnetic moment
d: EDM





■ SM (CKM) ■ SM (θ) ■ $<$ d (Current data) ■ $<$ d (Expectations)

J. Phys. G 47 (2020) 1, 010501

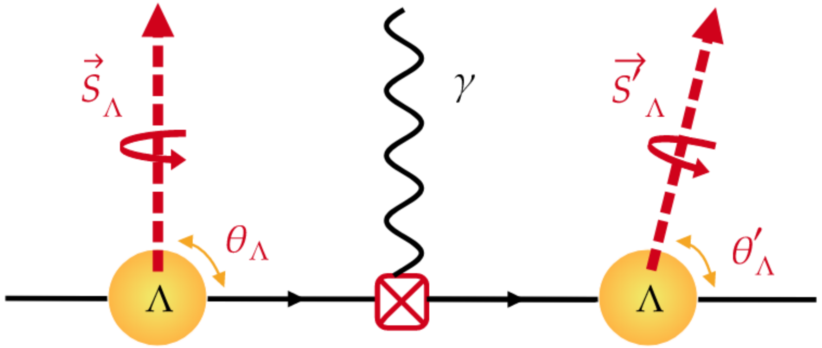
A non-zero intrinsic EDM would violate both parity (P) and time-reversal (T) symmetries.

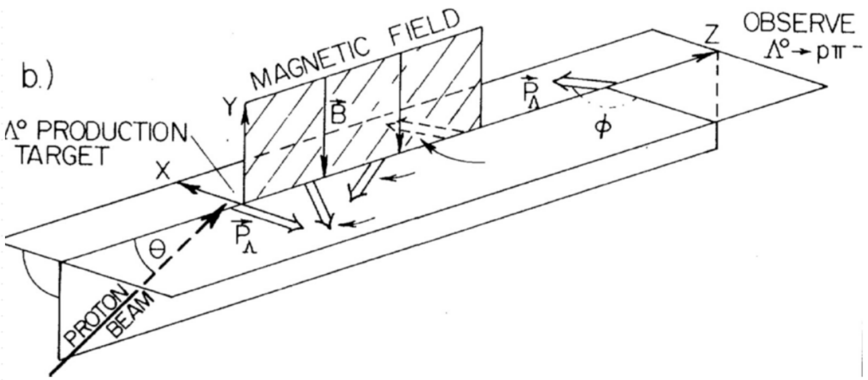
➢ When CPT symmetry is conserved, T violation is equivalent to CP violation.

Traditional approach and its Limitations

$H = -\mu \cdot B - d \cdot E$

- Method: Measure EDM via spin precession induced by an external EM field
  - $\vec{S}_\Lambda$ and $\vec{S}'_\Lambda$: Spin directions of the Λ before and after precession
  - θ_Λ and θ'_Λ: Angles between spin and momentum
- Applications: Successfully applied to electrons, neutrons, protons, etc.
- Challenges:
  - Short lifetime: $\sim 10^{-10} s$, limiting precession time
  - Low polarization: Difficult to produce highly polarized hyperon beams
- Current Status: Only the EDM of the Λ hyperon has been explored. The most stringent upper limit, 1.5×10^{-16} e·cm, comes from a 1981 Fermilab experiment, with significant room for improvement.





Phys. Rev. D23 (1981) 814

$d_\Lambda < 1.5 \times 10^{-16} e$ cm @ 95% C.L.

Phys. Rev. Lett. 41 (1978) 1348

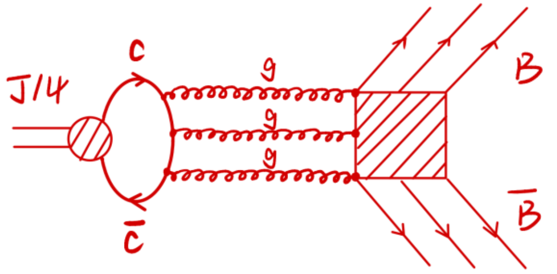
$\mu_\Lambda = (-0.613 \pm 0.004)\mu_N$

Searching for hyperon EDM at BESIII

X.G. He, J.P. Ma, Phys. Lett. B 839(2023)137834
X.G. He, J.P. Ma, B. McKellar, Phys. Rev. D 47 (1993) R1744-R1746

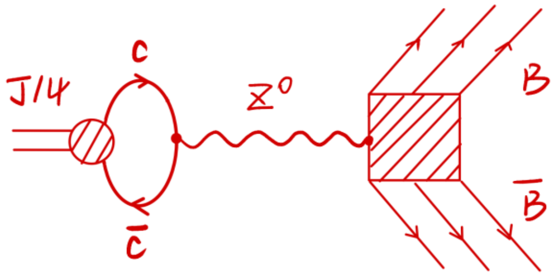
Detailed dynamics in J/ψ decay to hyperon pair, have been studied:

$$\mathcal{A} = \epsilon_\mu(\lambda)\bar{u}(\lambda_1)\left(F_V\gamma^\mu + \frac{i}{2M_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T \right)\nu(\lambda_2)$$



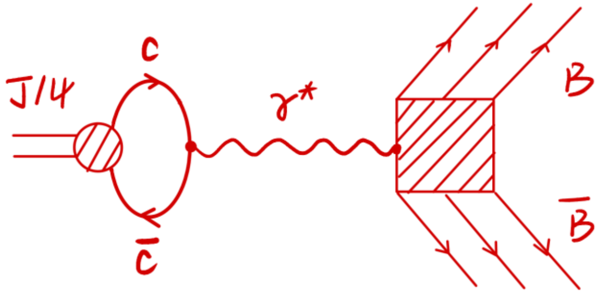
Dominant contribution
arXiv:hep-ph/0412158

Psionic form factor
F_V and H_σ
can also be represented as G_1 and G_2



P violation term

Complex form factor, $F_A \neq 0$ indicate P violation



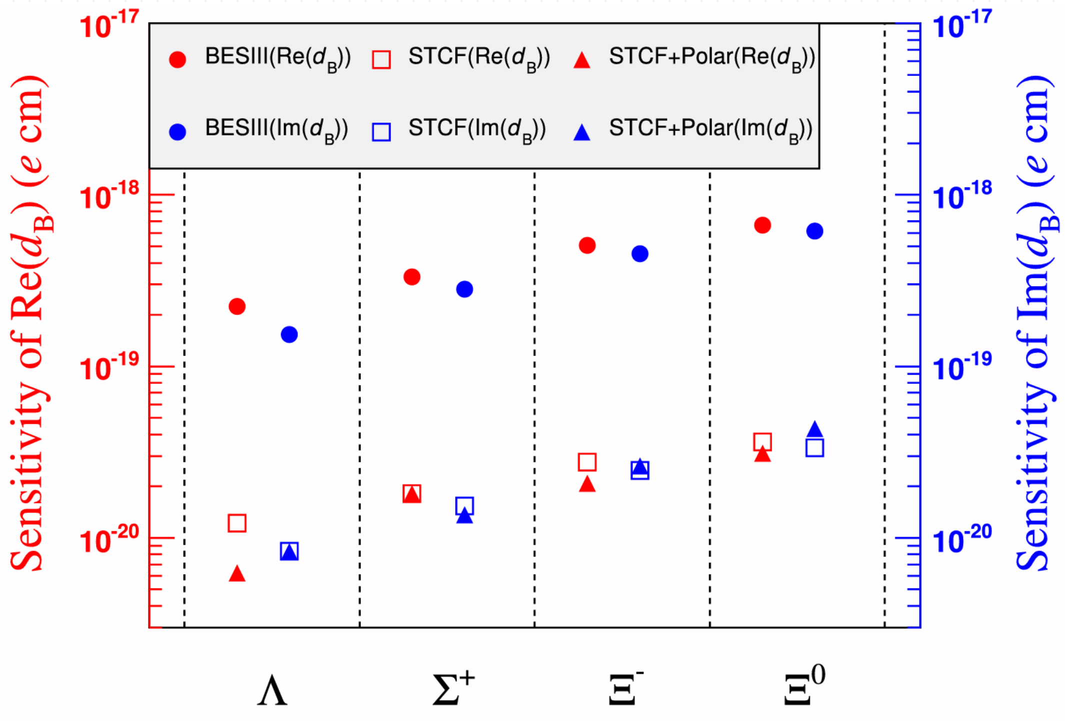
H_T is included in this term

$$H_T(q^2) = \frac{2e}{3m_{J/\psi}^2} g_V d_B(q^2)$$

Assuming $d_B(q^2) \equiv d_B(0)$

$d_B(q^2)$: electric dipole form factor
$d_B(0)$: electric dipole moment
Physics Letters B 551 (2003) 16–26

Sensitivities of hyperon EDM at BESIII



(a) Sensitivity for $Re(d_B)$ and $Im(d_B)$

J. Fu, H.B. Li, J. Wang, F. Yu, and J. Zhang, PhysRevD.108.L091301

SM: $\sim 10^{-26}$ e cm

BESIII: milestone for hyperon EDM measurement
Λ $10^{-19}$$e$ cm (FermiLab 10^{-16} e cm)
first achievement for Σ^+,Ξ^- and Ξ^0 at level of $10^{-19}$$e$ cm
a litmus test for new physics

STCF: improved by more than one order of magnitude

World's most precise Λ EDM measurement

- EDM extracted via **full angular analysis** of entangled decays:

$$\mathrm{Re}(d_\Lambda) = (-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}\, e \cdot \mathrm{cm}$$
$$\mathrm{Im}(d_\Lambda) = (2.9 \pm 2.6 \pm 0.6) \times 10^{-19}\, e \cdot \mathrm{cm}$$

which corresponds to an upper bound of:

$$|d_\Lambda| < 6.5 \times 10^{-19}\ e \cdot cm \quad (95\%\ CL)$$

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

BESIII: arXiv:2506.19180

- Improves sensitivity by more than **2 orders of magnitude** over previous best.

Prior direct Λ EDM limit (Fermilab, 1981): $|d_\Lambda| < 1.5 \times 10^{-16} e \cdot cm$.

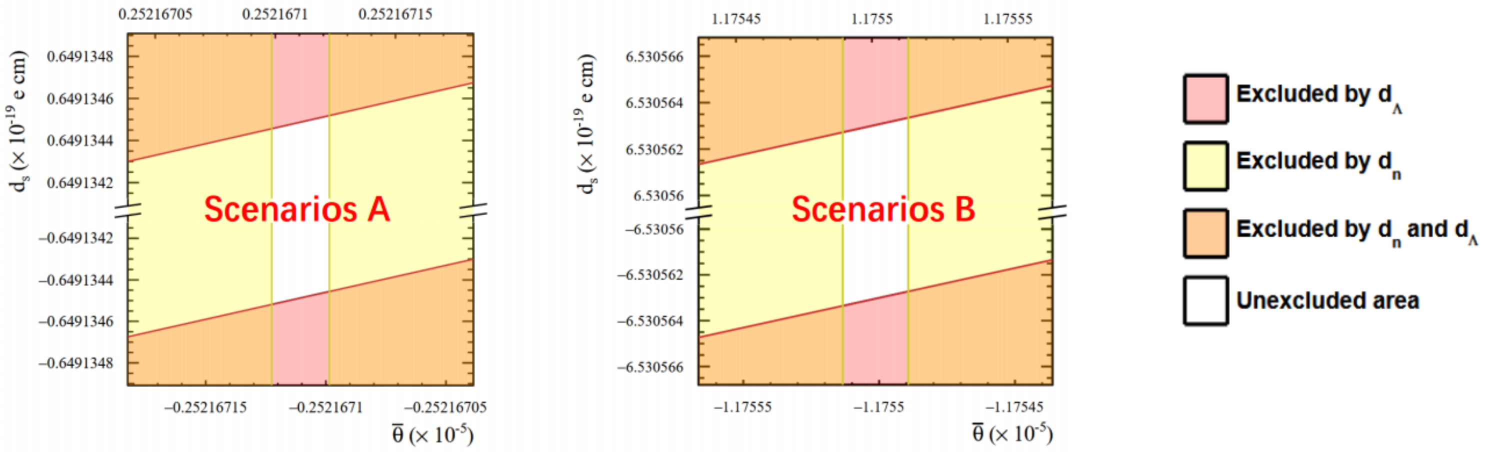
- The Λ EDM is sensitive to the **QCD vacuum angle ($\bar{\theta}$)** and the **strange quark EDM (d_s).**
- **Effective EDM relation** from theory:

$$d_\Lambda = (-2.6 \pm 0.4) \times 10^{-16} \bar{\theta}\, e\, \mathrm{cm} + d_s$$
$$d_n = -(1.5 \pm 0.7) \times 10^{-16} \bar{\theta}\, e\, \mathrm{cm} - (0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.0016) d_s$$

- Combining Λ and neutron EDM constraints allows tighter exclusion of BSM scenarios.

A. With SU(3) flavor symmetry: $d_u = d_d = d_s$

B. Without SU(3) symmetry: $d_s \gg d_u, d_d$



Complementarity of Λ hyperon and neutron EDMs

K. C. Chen, X. G. He, J. P. Ma, X. B. Tong, Phys. Rev. Lett. 136 (2026) 5, 051902

$\tilde{d}$: chromo-electric dipole moments

$$d_\Lambda = \boxed{5.29 \times 10^{-4} d_s} + 4.61 \times 10^{-5}(d_u + d_d) + \boxed{6.21 \times 10^{-5} e\tilde{d}_s} + 1.98 \times 10^{-5} e\tilde{d}_d - 2.14 \times 10^{-5} e\tilde{d}_u$$

$$d_n = -(0.20 \pm 0.01)d_u + (0.78 \pm 0.03)d_d + \boxed{(0.0027 \pm 0.0016)d_s} - (0.55 \pm 0.28)e\tilde{d}_u - (1.1 \pm 0.55)e\tilde{d}_d$$

The QCD theta-term is neglected

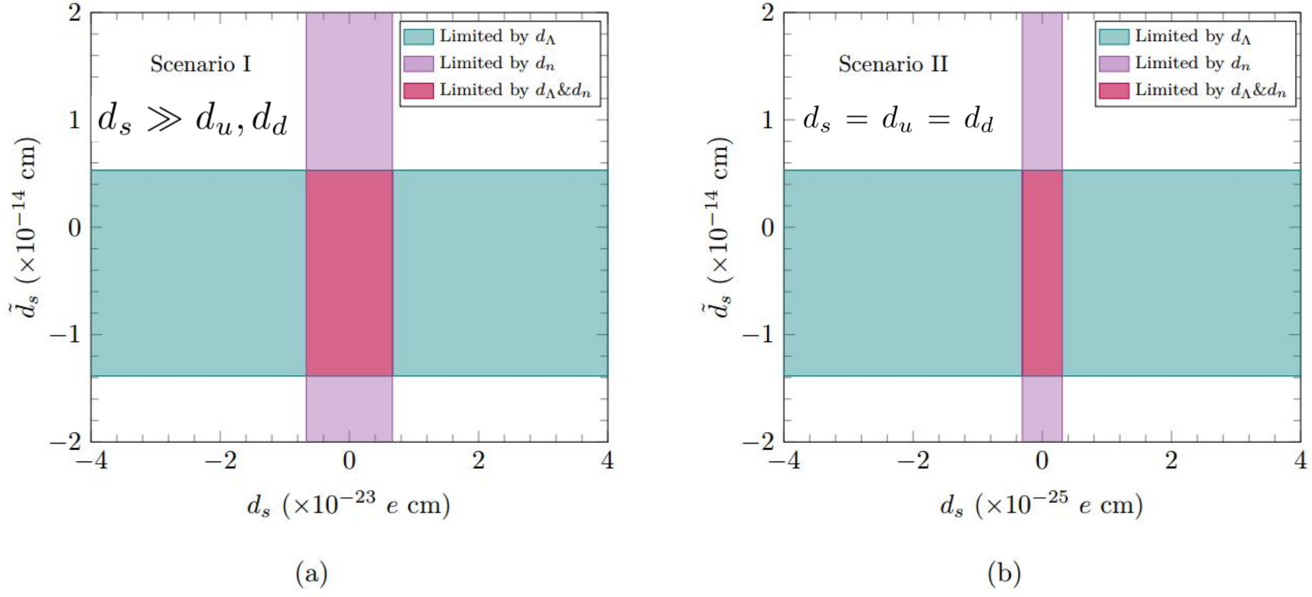


Figure 2: Constraints on the s-quark EDM d_s and CEDM $\tilde{d}_s$ from the measurements on the Λ and n EDMs.

Limitations of the Neutron EDM:

- Sensitive mainly to the EDMs of up and down quarks.
- Insensitive to the chromo-EDM of the strange quark ($\tilde{d}_s$)

Unique Advantage of the Λ Hyperon EDM:

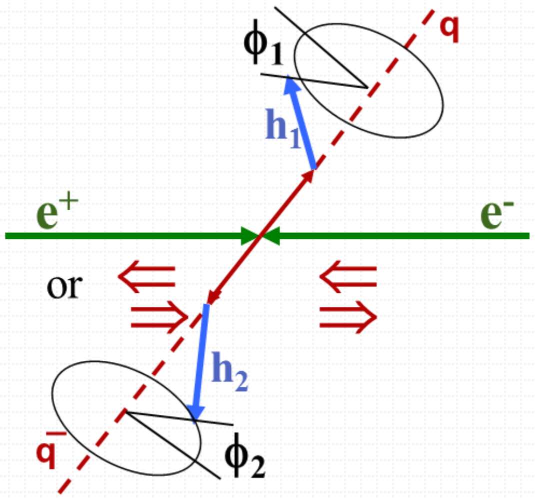
- Particularly sensitive to the strange quark chromo-EDM

Complementary Information:

- Λ EDM provides information on the strange quark chromo-EDM that cannot be accessed via the neutron EDM

Spin correlated quark-anti-quark in e^+e^- Annihilation

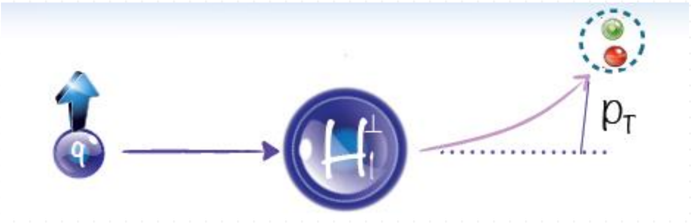
- In e^+e^- annihilation, $e^+e^- \rightarrow \gamma^*$ (spin-1) $\rightarrow$ spin-1/2 q and $\bar{q}$
  - In a given event, the spin directions are unknown, but they must be parallel
  - Exploit this correlation by using hadrons in opposite jets (hemisphere)



Using 62 pb^{-1} @ 3.65 GeV continuum region below open-charm threshold

Collins Fragmentation Function (FF)

The measurement of the Collins FF provides an important test in understanding strong interaction dynamics and thus is of fundamental interest in understanding QCD



J. C. Collins, Nucl.Phys. B396, 161 (1993)

$$D_{hq^\uparrow}(z, P_{h\perp}) = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2)\frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{zM_h},$$

D_1: the unpolarized FF

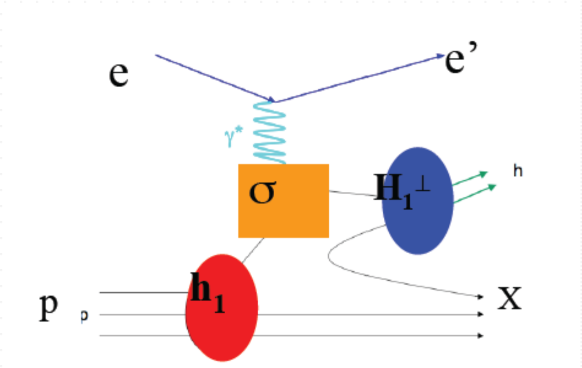
H_1: Collins FF

→ describes the fragmentation of a transversely polarized quark into a spinless hadron *h*.

→ depends on $z = 2E_h/\sqrt{s}$ $\mathbf{P}_{h\perp}$

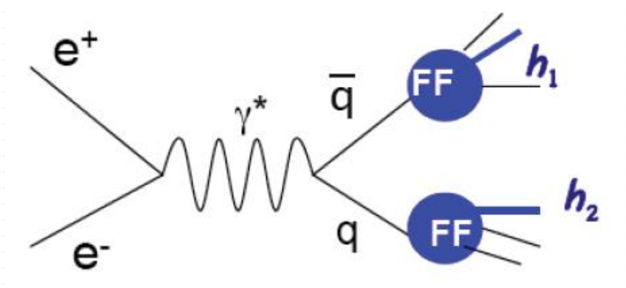
→leads to an azimuthal modulation of hadrons around the quark momentum.

SIDIS Transversity ⊗ Collins FF



e^+e^- collision

Collins FF ⊗ Collins FF

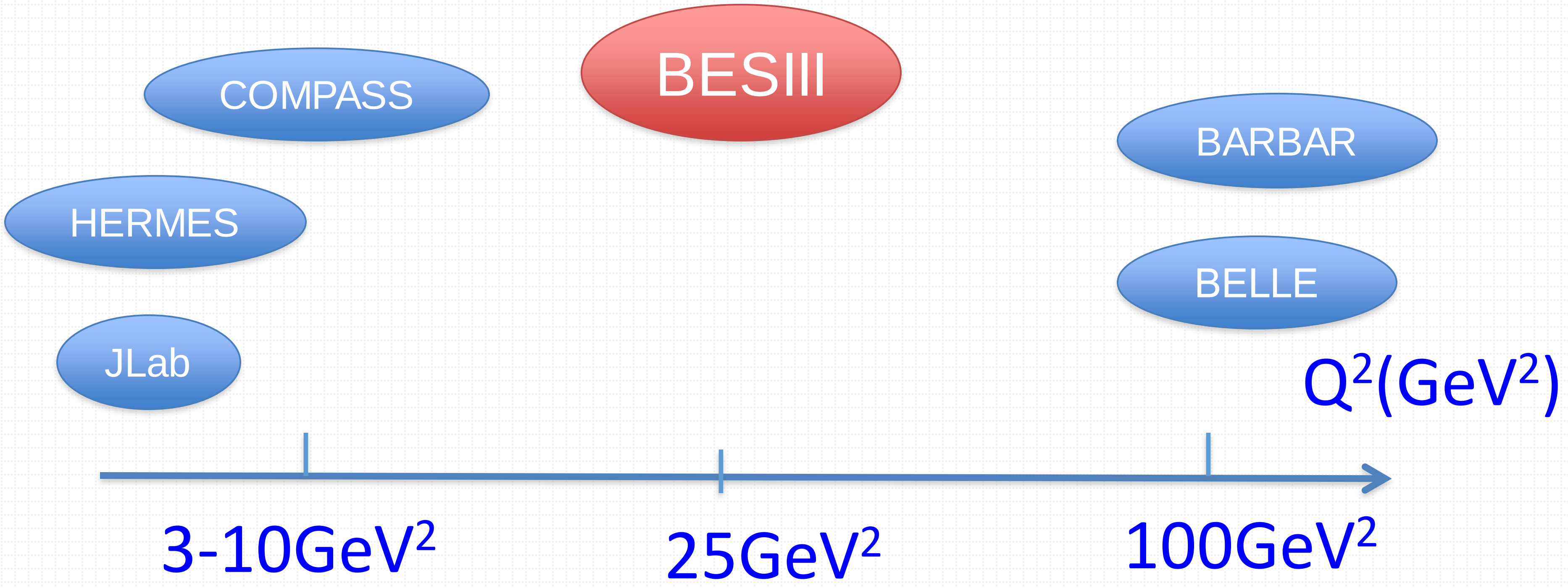


Importance : Q^2 evolution of spin dependent fragmentation function

From Feng Yuan 2013 @IHEP, Beijing

PRD 88. 034016; arXiv:1505.05589

- Reliable determination of the Collins functions, and extraction of the nucleon tensor charge
- Study the QCD evolution effects with global analysis
  - SIDIS + $\boldsymbol{e^+e^-}$: to extract the nucleon transverse spin distribution

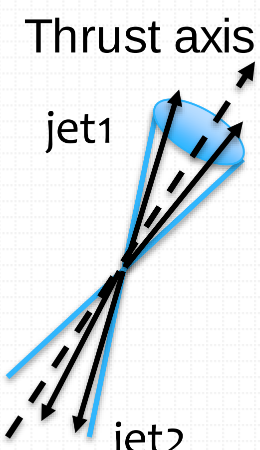


Reference frame @ BESIII

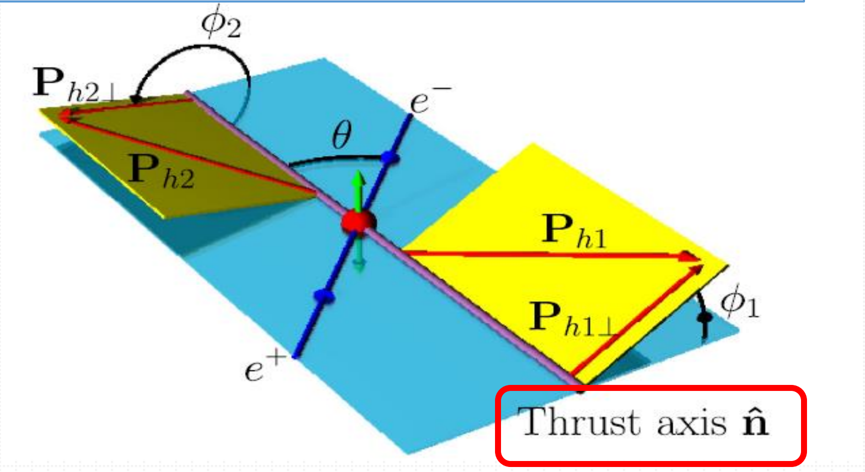
PRD 78, 032011

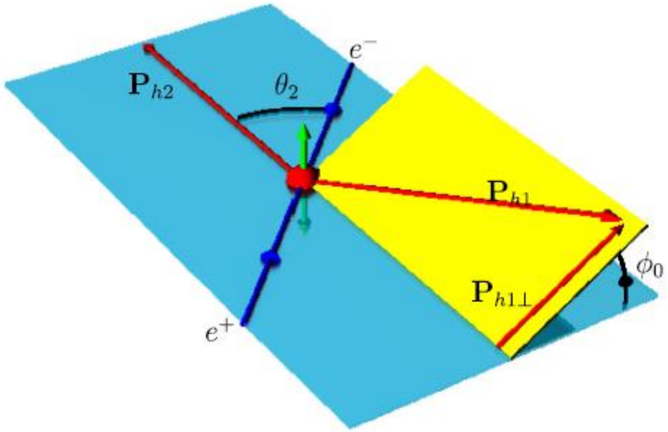
The Thrust frame: Method12

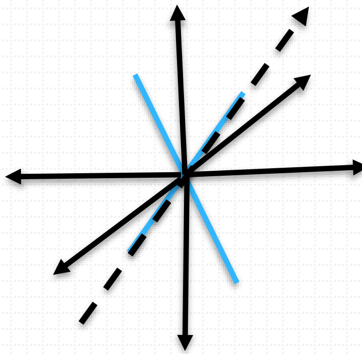
The second hadron frame: Method0



Belle/ BABAR







At low energy: no jet like BESIII

The thrust frame

$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d\phi_1d\phi_2} = \sum_{q,\bar q}\frac{3\alpha^2}{Q^2}\frac{e_q^2}{4}z_1^2z_2^2\{(1+\cos^2\theta)D_1^{q,[0]}(z_1)\bar{D}_1^{q,[0]}(z_2) + \sin^2\theta\cos(\phi_1+\phi_2)H_1^{\perp,[1],q}(z_1)\bar{H}_1^{\perp,[1],q}(z_2)\},$$

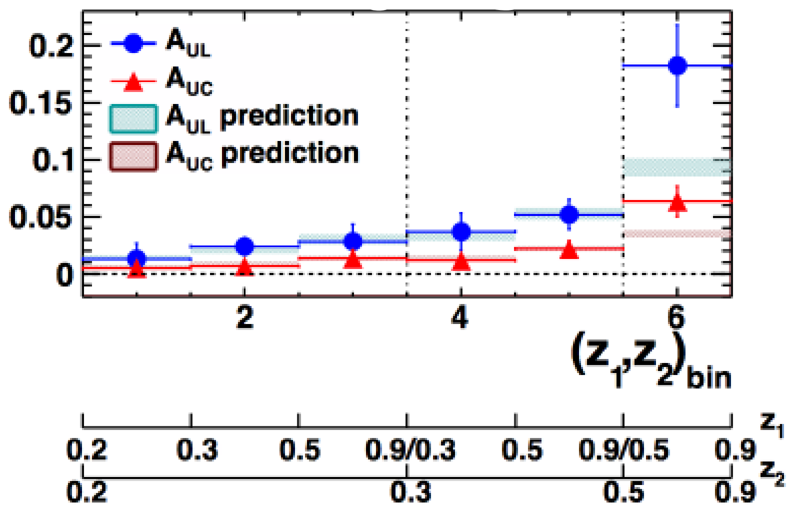
The second hadron frame

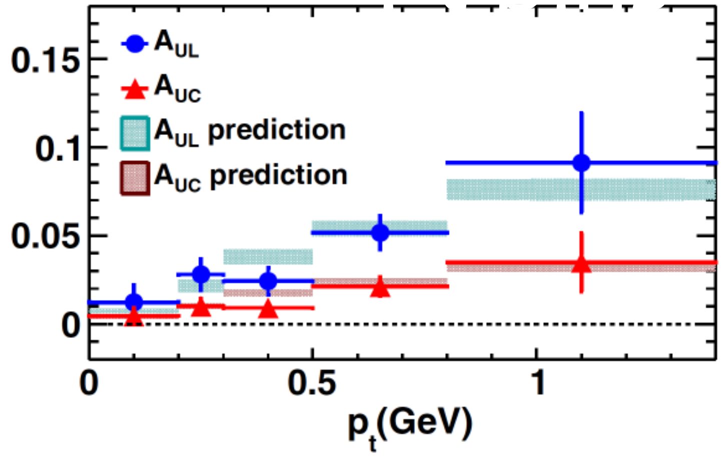
$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d^2\mathbf{q}_T} = \frac{3\alpha^2}{Q^2}z_1^2z_2^2\Big\{A(y)\mathcal{F}[D_1\bar{D}_2] + B(y)\times\cos(2\phi_0)\mathcal{F}\Big[(2\hat{\mathbf{h}}\cdot\mathbf{k}_T\hat{\mathbf{h}}\cdot\mathbf{p}_T - \mathbf{k}_T\cdot\mathbf{p}_T)\frac{H_1^\perp\bar{H}_2^\perp}{M_1M_2}\Big]\Big\},$$

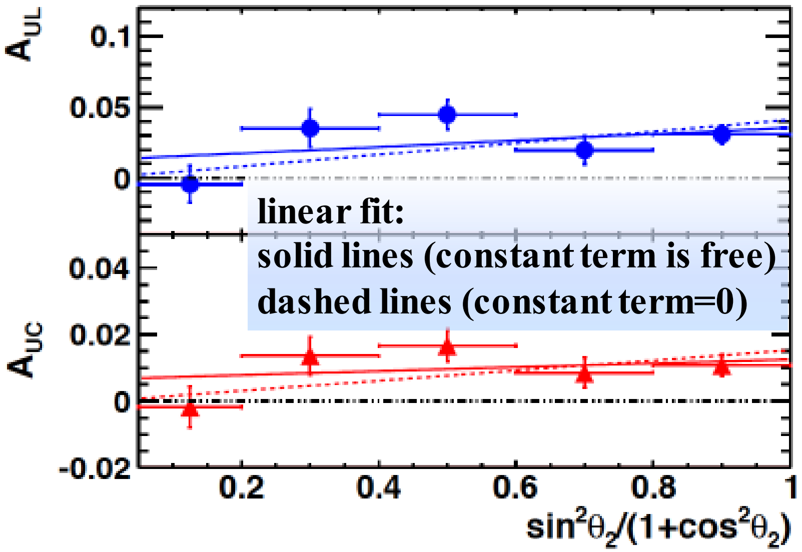
- **Only the second method could be performed at BESIII**

Results of Collins asymmetry

BESIII : PRL 116, 042001 (2016)



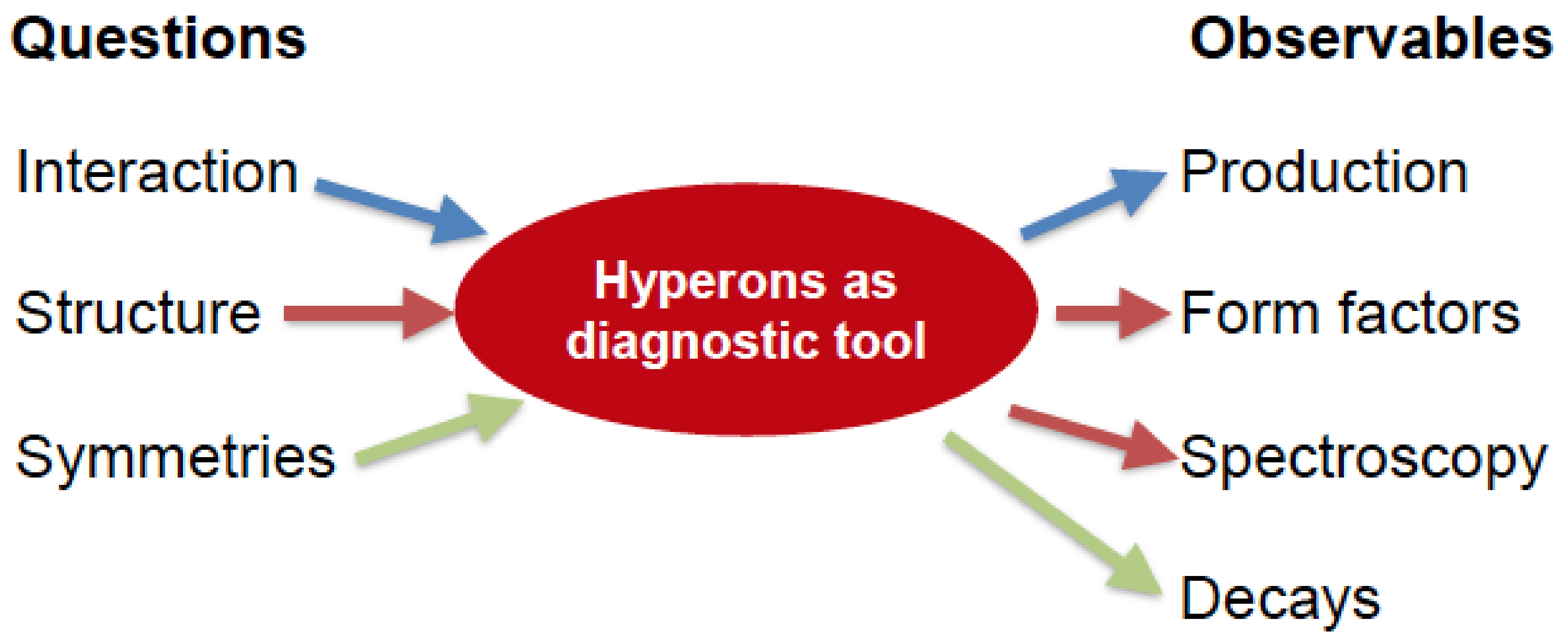




- ➢ Clear nonzero Collins asymmetries, increase with higher fraction energy, pt
- ➢ The expected behavior of the Collins asymmetries as a function of $\sin^2\theta_2/(1+\cos^2\theta_2)$ is linear and vanish at $\theta_2=0$
- ➢ comparable with predictions from authors of PRD 93, 014009, who provided the predictions using BESIII kinematics (z,pt)

Summary

BESIII provides huge amount quantum-correlated hyperon pairs!



BESIII has pioneered an innovative paradigm by utilizing spin-entangled hyperon-antihyperon pairs.

Backup

Test of $\Delta I = 1/2$ rule in hyperon decays

- In the weak interaction, the isospin is not a conserved quantity, however, there is an experimentally well-established empirical rule -- $\Delta I = 1/2$ rule.

- The $\Delta I = 1/2$ rule allows only those decay transitions in which the change in the total isospin is 1/2.

- Originally, this rule is found in the kaon decays $K \to \pi\pi$, which give the ratio between the $\Delta I = 3/2$ amplitude and the $\Delta I = 1/2$ amplitude: $\frac{Re(A2)}{Re(A0)} = 0.0445 \pm 0.0001 \approx 1/22.47$. In hyperon decays, there are no observations of the existence of the $\Delta I = 3/2$ component before the BESIII measurements.

V. Cirigliano, G. Ecker, H. Neufeld, A. Pich, and J. Portoles, Rev. Mod. Phys. 84, 399 (2012).

Dynamics of the Standard Model, section XII–6

DOI: 10.1017/9781009291033

$$W(\theta) = 1 + \alpha \mathbf{P}_B \cdot \hat{\mathbf{p}}_{B'}, \qquad \alpha = \frac{2\mathrm{Re}\,(A^* \bar{B})}{|A|^2 + |\bar{B}|^2}, \tag{6.4}$$

and the polarization $\langle \mathbf{P}_{B'} \rangle$ of the final-state baryon,

$$\langle \mathbf{P}_{B'} \rangle = \frac{(\alpha + \mathbf{P}_B \cdot \hat{\mathbf{p}}_{B'})\, \hat{\mathbf{p}}_{B'} + \beta\,(\mathbf{P}_B \times \hat{\mathbf{p}}_{B'}) + \gamma\,[\hat{\mathbf{p}}_{B'} \times (\mathbf{P}_B \times \hat{\mathbf{p}}_{B'})]}{W(\theta)},$$

$$\beta = \frac{2\mathrm{Im}(A^* \bar{B})}{|A|^2 + |\bar{B}|^2}, \qquad \gamma = \frac{|A|^2 - |\bar{B}|^2}{|A|^2 + |\bar{B}|^2} = \pm\sqrt{1 - \alpha^2 - \beta^2}, \tag{6.5}$$

where $\mathbf{P}_B$ is the polarization of B and $\hat{\mathbf{p}}_{B'}$ is a unit vector in the direction of motion of B'. Experimental studies of these distributions lead to the amplitudes listed in Table XII–5.

The nonleptonic amplitudes may be decomposed into isospin components in a notation where superscripts refer to $\Delta I = 1/2,\ 3/2$,

$$\begin{aligned}
A_{\Lambda\to p\pi^-} &= \sqrt{2}\,A_\Lambda^{(1)} - A_\Lambda^{(3)}, & A_{\Sigma^-\to n\pi^-} &= A_\Sigma^{(1)} + A_\Sigma^{(3)},\\
A_{\Lambda\to n\pi^0} &= -A_\Lambda^{(1)} - \sqrt{2}\,A_\Lambda^{(3)}, & A_{\Sigma^+\to n\pi^+} &= \frac{1}{3}A_\Sigma^{(1)} - \frac{2}{3}A_\Sigma^{(3)} + X_\Sigma,\\
A_{\Xi^0\to \Lambda\pi^0} &= -A_\Xi^{(1)} - \sqrt{2}\,A_\Xi^{(3)}, & \sqrt{2}\,A_{\Sigma^+\to p\pi^0} &= -\frac{2}{3}A_\Sigma^{(1)} + \frac{4}{3}A_\Sigma^{(3)} + X_\Sigma,\\
A_{\Xi^-\to \Lambda\pi^-} &= \sqrt{2}\,A_\Xi^{(1)} - A_\Xi^{(3)}, & &
\end{aligned} \tag{6.6}$$

and X_Σ is of mixed symmetry. Similar relations hold for the B amplitudes. From

A stands for S-wave amplitude
B stands for P-wave amplitude

If only $\Delta I = 1/2$ component exists:

$$A_{\Lambda\to p\pi^-} = -\sqrt{2}A_{\Lambda\to n\pi^0},$$
$$B_{\Lambda\to p\pi^-} = -\sqrt{2}B_{\Lambda\to n\pi^0},$$

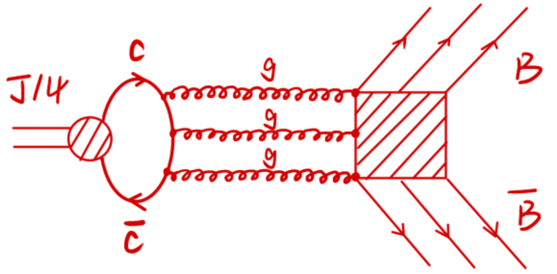
then $\alpha_{\Lambda\to p\pi^-} = \alpha_{\Lambda\to n\pi^0}$

Searching for hyperon EDM at BESIII

Phys.Lett.B 839(2023)137834

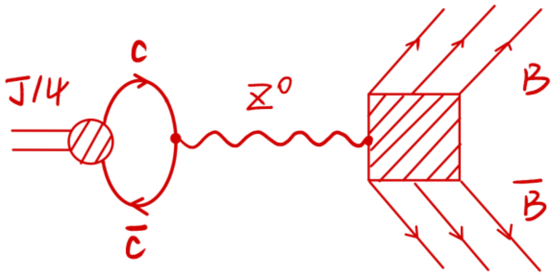
Detailed dynamics in J/ψ decay to hyperon pair, have been studied:

$$\mathcal{A} = \epsilon_\mu(\lambda)\bar{u}(\lambda_1)\left(F_V\gamma^\mu + \frac{i}{2M_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T\right)v(\lambda_2)$$



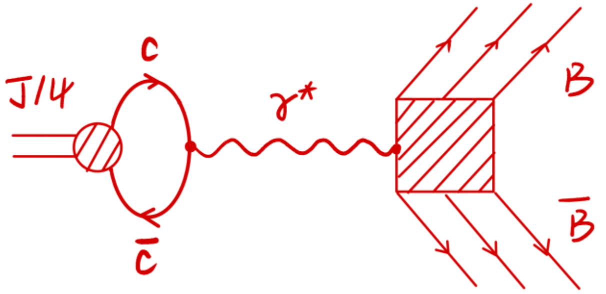
Dominant contribution
arXiv:hep-ph/0412158

Psionic form factor
F_V and H_σ
can also be represented as G_1 and G_2



P violation term

Complex form factor, $F_A \neq 0$ indicate P violation



H_T is included in this term

$$H_T(q^2) = \frac{2e}{3m_{J\psi}^2} g_V d_B(q^2)$$

Assuming $d_B(q^2) \equiv d_B(0)$

$d_B(q^2)$: electric dipole form factor
$d_B(0)$: electric dipole moment
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