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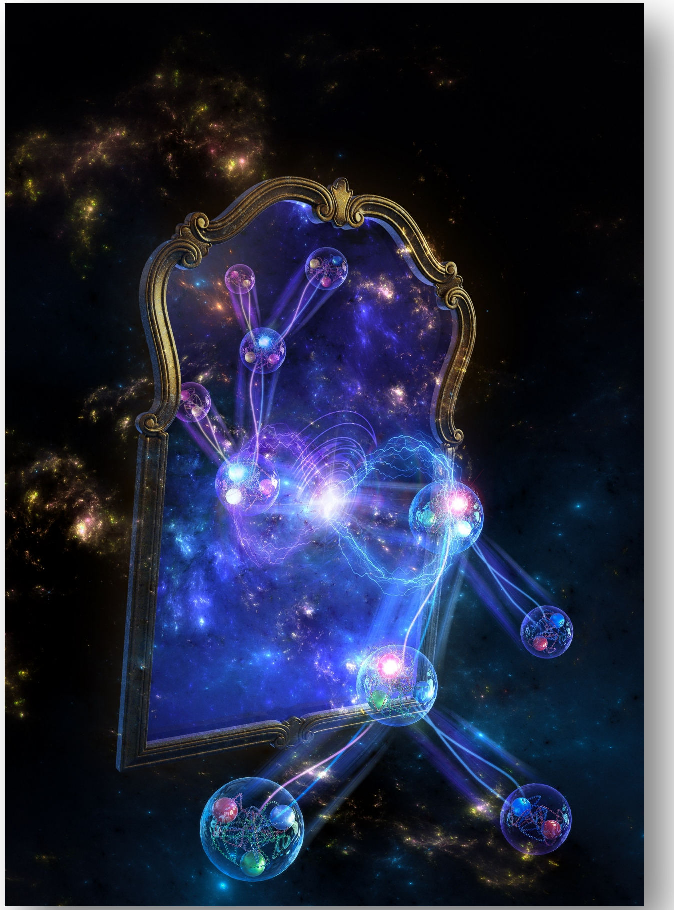

CP symmetry tests of baryon weak decays with LHCb and BESIII

Patrik Adlarson

Department of Physics and Astronomy

Oct 21, 2024

On behalf of the LHCb and BESIII collaborations

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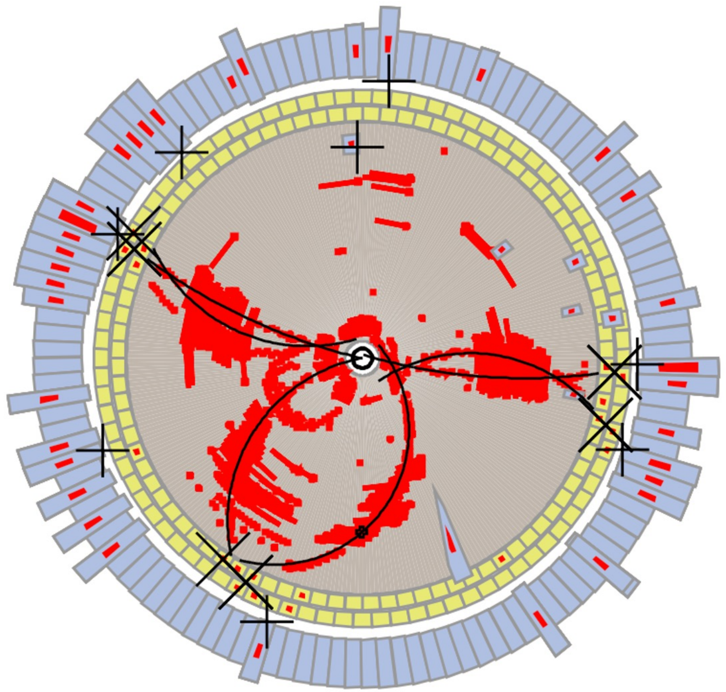
Outline

- Introduction
- The Experiments
- Strange and Charm CP tests
- Summary and Outlook



Display of simulated
$\Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$

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Matter - Antimatter Asymmetry and Baryogenesis

No quantitative understanding of what happened to the missing anti-symmetry

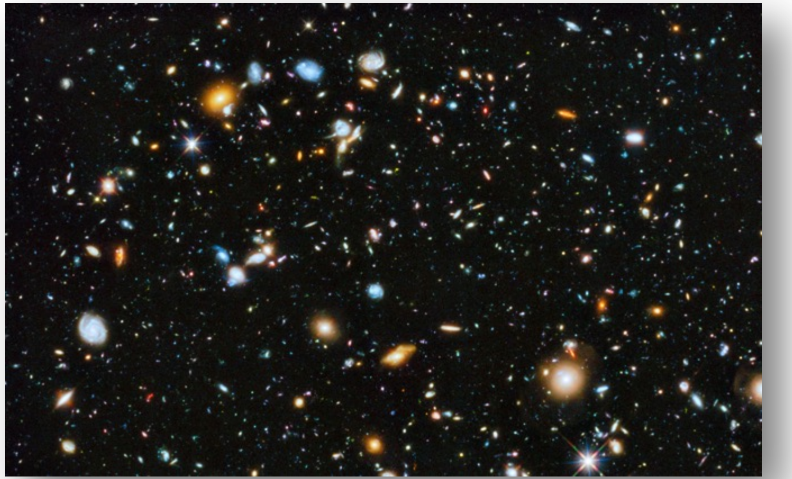
The dynamical mechanism, *baryogenesis*, not understood

Sakharov's three criteria *

1) Baryon number violation

2) Charge, C, and combined with Parity, *P*, violating processes

3) Departure from thermal equilibrium



CP violation is subtle effect requiring precision studies of many particle physics processes using complementary methods

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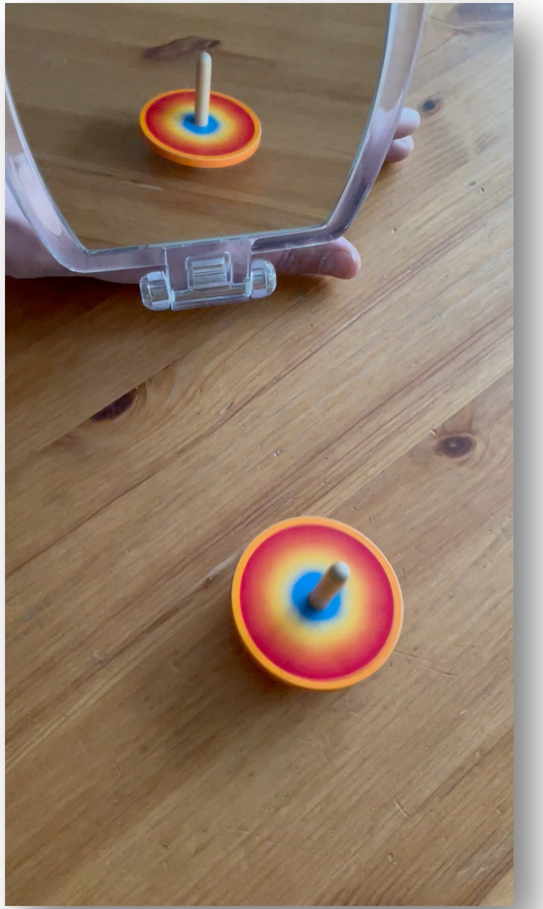
**A. D. Sakharov, J. Exp. Theor. Phys. Lett. 5, 24*

Spinning baryons

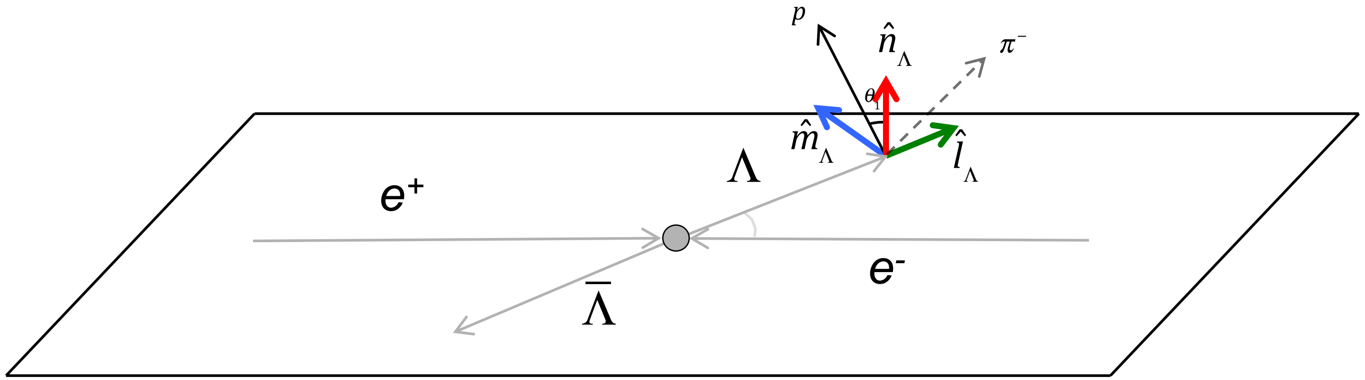


CPV only confirmed in meson systems. No CP violation detected for *baryons*

Additional degree of freedom for baryons compared to mesons : spin

Studying baryons provides a complementary path to understanding CP symmetry

spare slide for example



Schematic of strange – anti-strange baryon pair at BESIII

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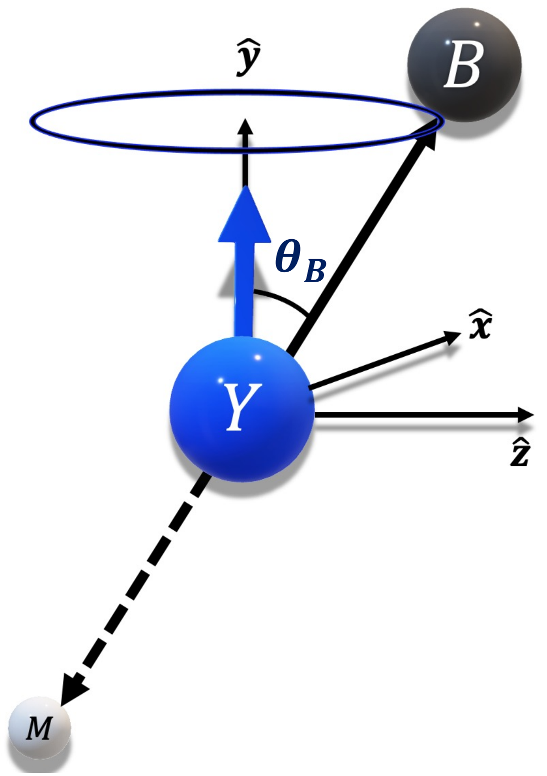
Asymmetry parameters and Polarization



Polarization of hyperons experimentally accessible in weak parity violating decays

They are *self analysing*: daughter particles are emitted according to polarization of mother hyperon

Example: Angular distribution of $\Lambda \to p\pi^-$

$$\boxed{I(\cos\theta_B) \propto 1 + \alpha\, P_Y \cos\theta_B}$$

Asymmetry parameter
CP-observable

Polarization

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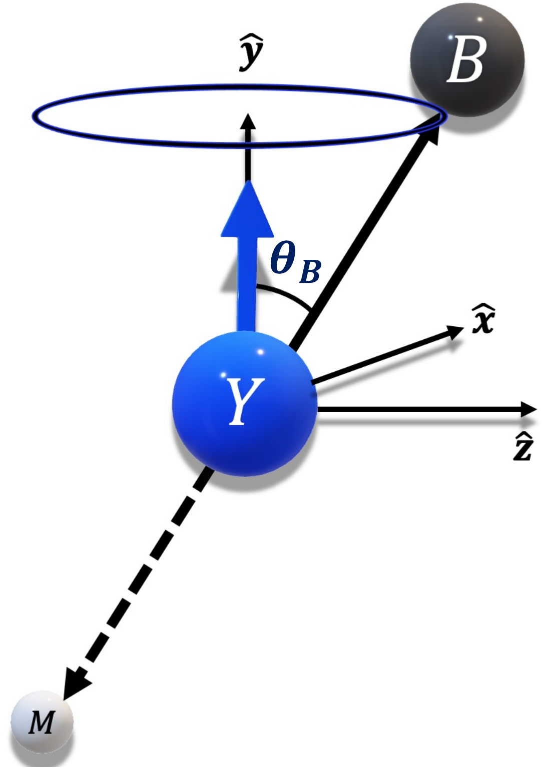
Asymmetry parameters and Polarization



$-1 \leq \alpha \leq 1$

weak CP-odd phases

$$S = |S| exp(\xi_S) exp(i\delta_S)$$
$$P = |P| exp(\xi_P) exp(i\delta_P)$$

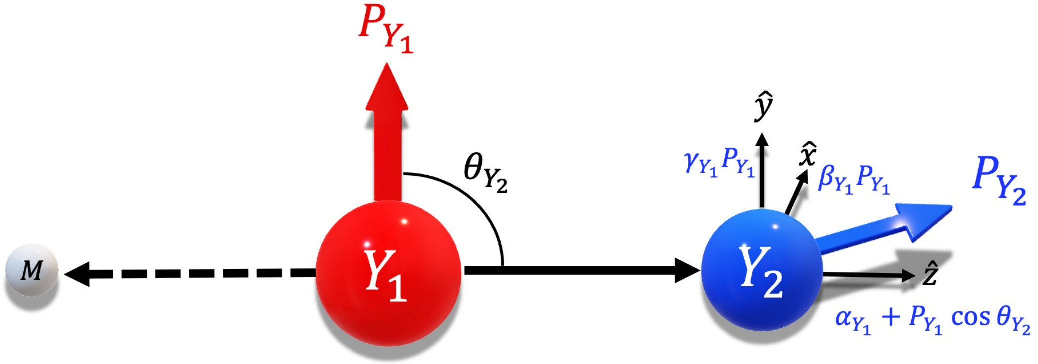
strong phases

δ strong baryon pion phase shift at cm energy of Y mass

ξ weak CP-odd phase for ΔI = 1/2

Asymmetry parameters give relationship of
S (parity violating) and *P* (parity conserving) amplitudes

$$\alpha = \frac{2\mathrm{Re}(S*P)}{|S|^2+|P|^2} \qquad \beta = \frac{2\mathrm{Im}(S*P)}{|S|^2+|P|^2} = \sqrt{1-\alpha^2}\sin\phi$$



$-\pi \leq \phi \leq \pi$

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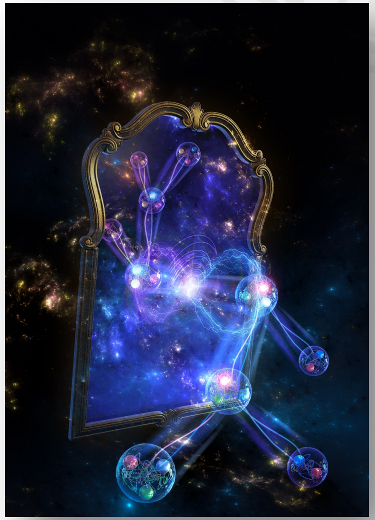
CP and weak phase difference

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

$$A_{CP}^{\Xi} = \frac{\alpha_\Xi + \bar{\alpha}_\Xi}{\alpha_\Xi - \bar{\alpha}_\Xi} \approx -\sin\langle\phi_\Xi\rangle \frac{\sqrt{1-\alpha_\Xi^2}}{\alpha_\Xi} \tan(\xi_P - \xi_S)_\Xi \ *$$

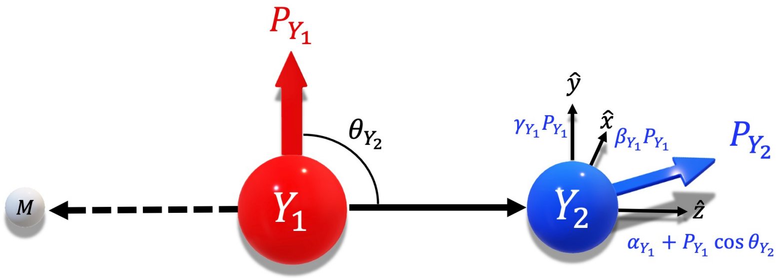
$$\Delta\phi_{CP} = \frac{\phi_\Xi + \bar{\phi}_\Xi}{2} \approx \cos\langle\phi_\Xi\rangle \frac{\alpha_\Xi}{\sqrt{1-\alpha_\Xi^2}} \tan(\xi_P - \xi_S)_\Xi \ *$$



strong contribution $\phi_\Xi \approx 0$ weak phase diff - potentially CPV

$\Delta\phi_{CP}$ more sensitive to CP-violating effects cf A_{CP}^{Ξ}*

* Phys. Rev Lett 55 162 (1985)



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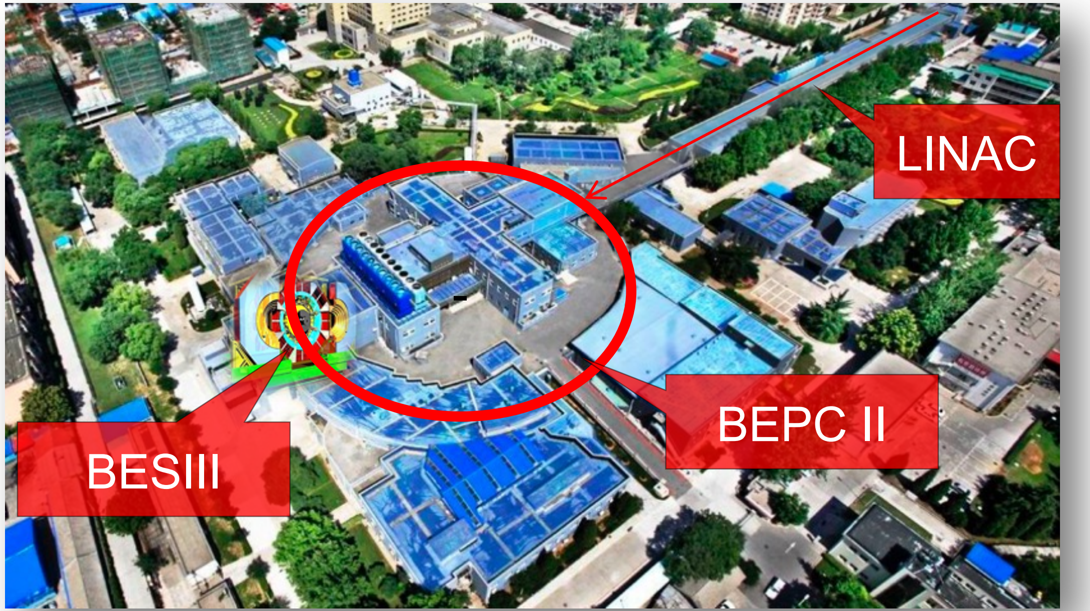
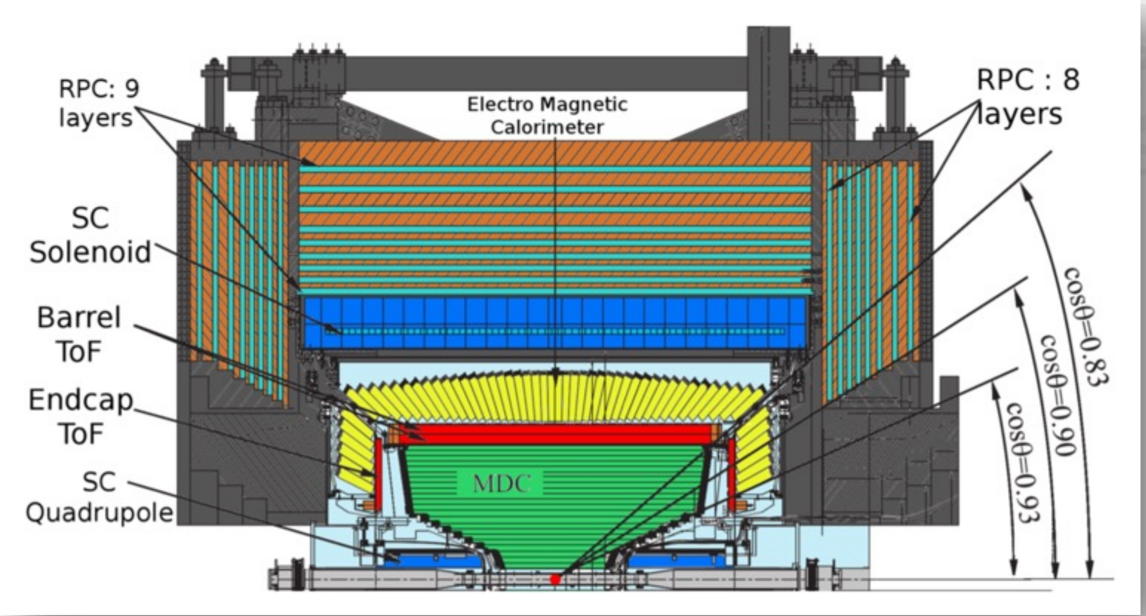
BEPC II and BESIII



Aerial view of BEPC II and BESIII

- e^+e^- collider in CMS range 2.0 – 4.95 GeV
- Data taking since 2009, peak luminosity 10^{33} $cm^{-2}s^{-1}$



- Multipurpose detector, near 4π coverage
- Symmetric particle – anti-particle conditions, entangled state
- Low hadronic background
- World's largest charmonia data samples

10B J/ψ, 3B ψ(2S)

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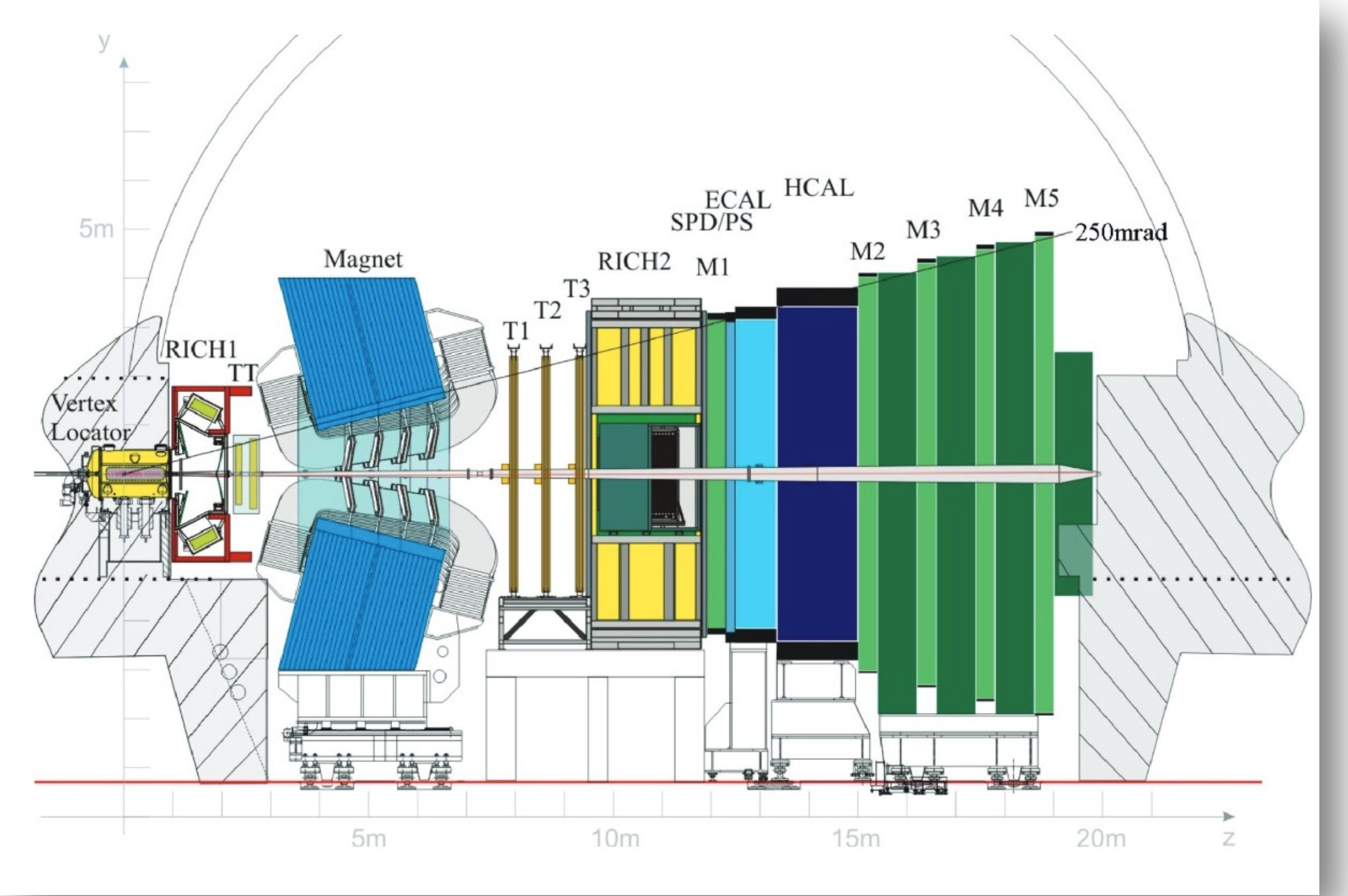
LHCb Run 1 + 2

LHCb detector setup



General purpose detector forward geometry

SMOG, MoEDAL, CodexB

One of four experiments in LHC ring

At high energies production of the b and anti-b highly correlated

Pseudorapidity range $2 < \eta < 5$

Run 1 and Run 2 integrated luminosity 9 fb^{-1}

2011-2018 (Run1: 3fb^{-1} + Run2: 6fb^{-1}) (2011-12, 2016-2018)

VELO and Hadron PID are excellent, neutrals possible, but challenging

VELO resolution σ_{IP} (15 + 29/pT) μm

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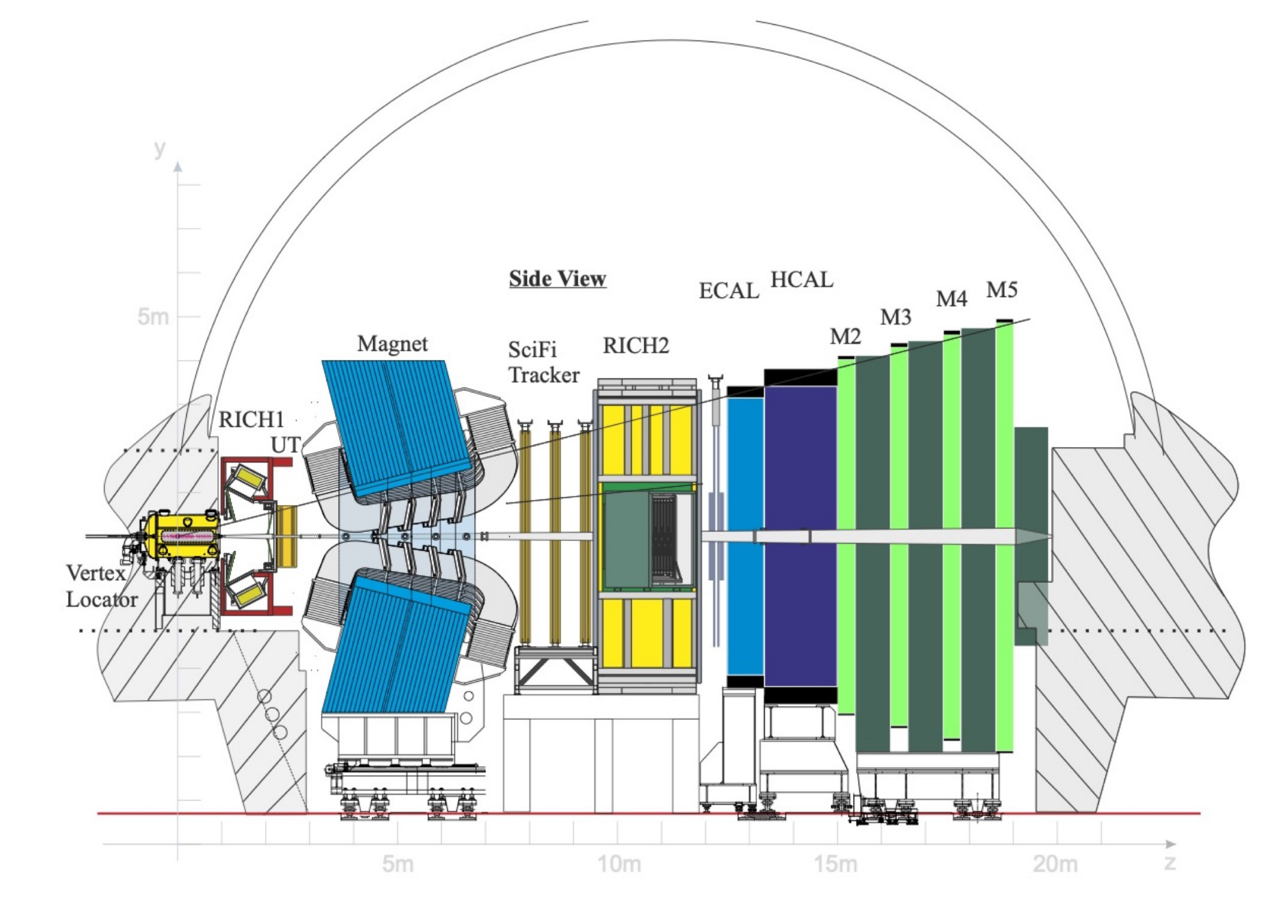
LHCb Run 3

LHCb Run 3 (Upgrade 1)



Theseus's Paradox applied to particle physics experiment – LHCb Upgrade I

New tracking detectors

VELO strip → pixels; 5 → 3.5 mm to beam

Software based triggers

Increase of instantaneous luminosity by factor 5

End of Run 3 (4) goal 23 (50)fb^{-1}

2010-2018 (Run1: 3fb^{-1} + Run2: 6fb^{-1})

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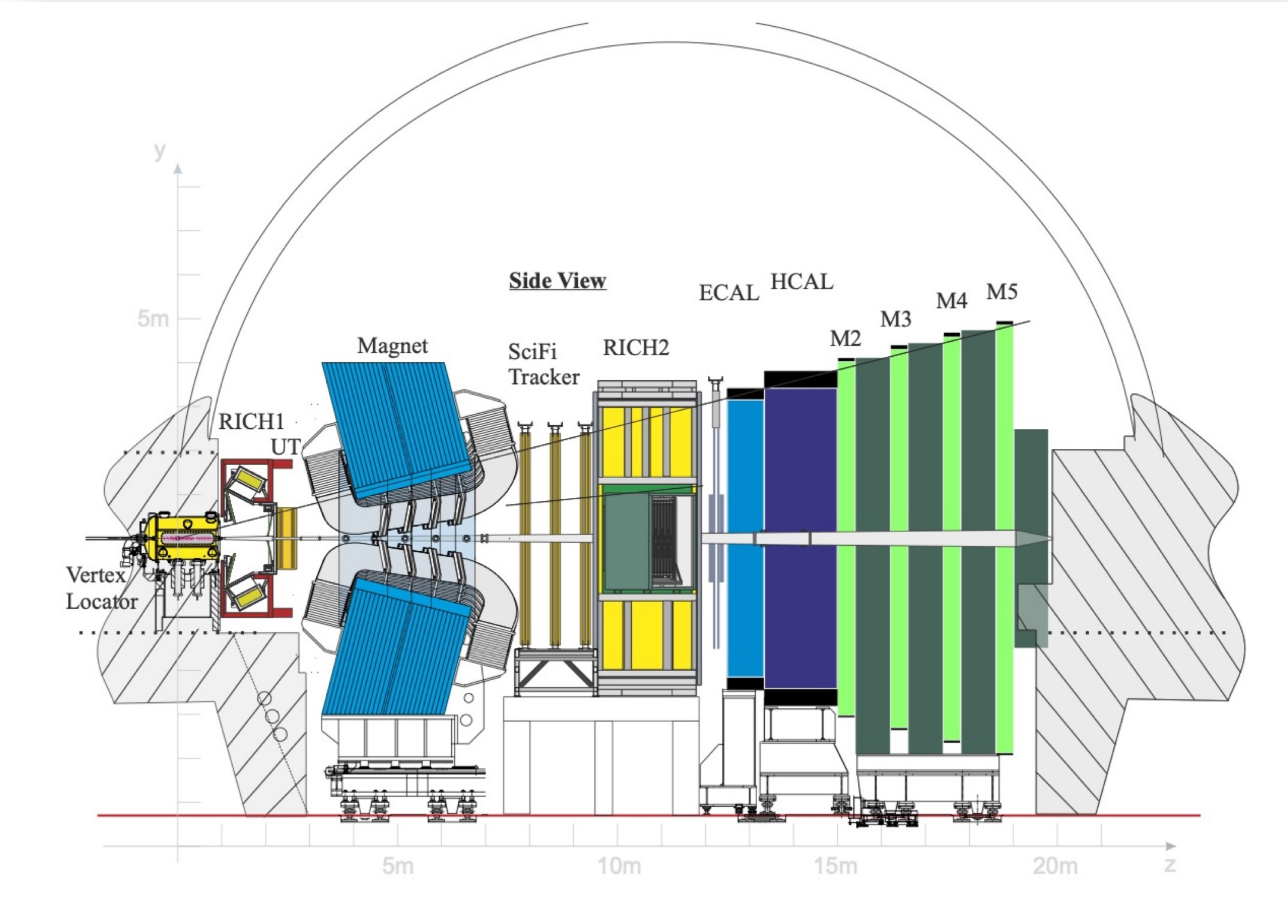
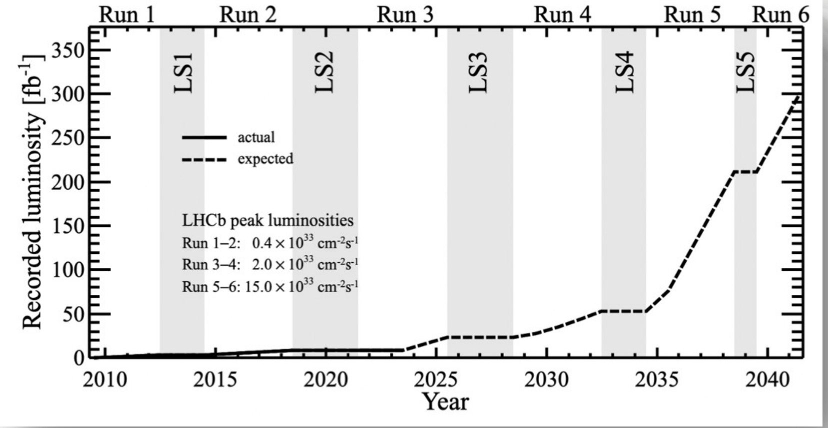
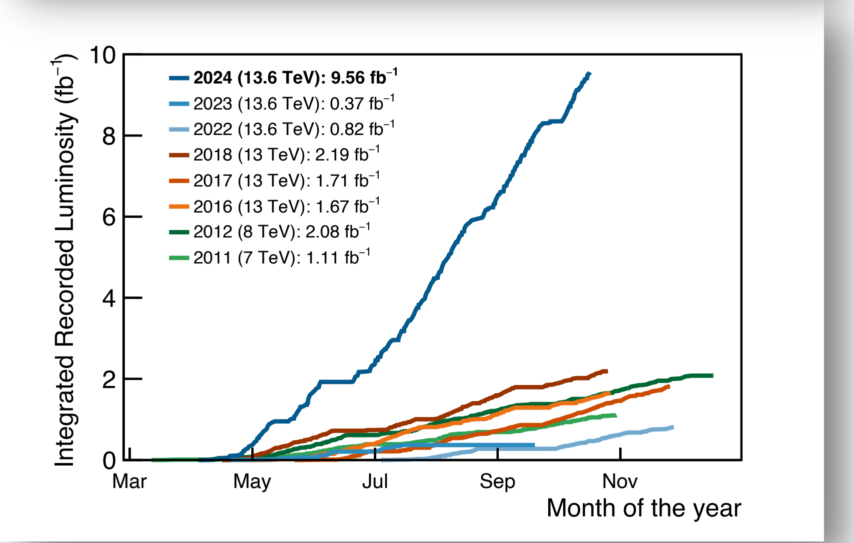
LHCb Run 3

LHCb Run 3 (Upgrade 1)







Status

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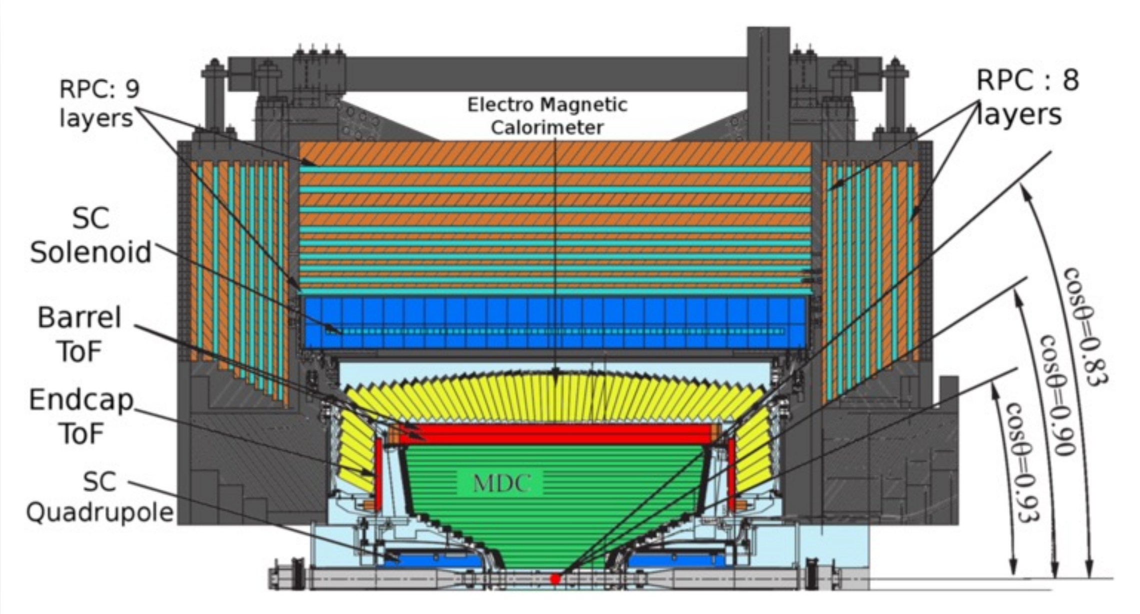
BESIII results



BESIII

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

Table 1 | Summary of results

Parameter	This work	Previous result	Reference	
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08	Ref. [49]	*
$\Delta\Phi$	1.213±0.046±0.016 rad	–		
α_Ξ	−0.376±0.007±0.003	−0.401±0.010	Ref. [26]	**
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad	Ref. [26]	**
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	–		
$\bar{\phi}_\Xi$	−0.021±0.019±0.007 rad	–		
α_Λ	0.757±0.011±0.008	0.750±0.009±0.004	Ref. [4]	***
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007	Ref. [4]	***
$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–		
$\delta_P-\delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad	Ref. [3]	****
A^Ξ_{CP}	$(6\pm13\pm6)\times10^{-3}$	–		
$\Delta\phi^\Xi_{CP}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–		
A^Λ_{CP}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$	Ref. [4]	***
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad			

The $J/\psi\to\Xi^-\bar{\Xi}^+$ angular distribution parameter α_ψ, the hadronic form factor phase $\Delta\Phi$, the decay parameters for $\Xi^-\to\Lambda\pi^-$ (α_Ξ,ϕ_Ξ), $\bar{\Xi}^+\to\bar{\Lambda}\pi^+$ $(\bar{\alpha}_\Xi,\bar{\phi}_\Xi)$ $\Lambda\to p\pi^-$ (α_Λ) and $\bar{\Lambda}\to\bar{p}\pi^+$ $(\bar{\alpha}_\Lambda)$; the CP asymmetries A^Ξ_{CP}, $\Delta\phi^\Xi_{CP}$ and A^Λ_{CP}, and the average $\langle\phi_\Xi\rangle$. The first and second uncertainties are statistical and systematic, respectively.

Nature 606 64-69 (2022)

First extraction of weak phase diff for *any* weakly decaying baryon

$$(\xi_p-\xi_s) = (1.2\ \pm 3.4 \pm 0.8)\times10^{-2}\ \mathrm{rad}$$

Consistent with SM expectation

$$(\xi_p-\xi_s)_{SM} = (1.8\ \pm 1.5)\times10^{-4}\ \mathrm{rad}$$

New method for direct weak phase extraction!

Two CP-tests in single measurement

* PRD 93, 072003 (2018)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

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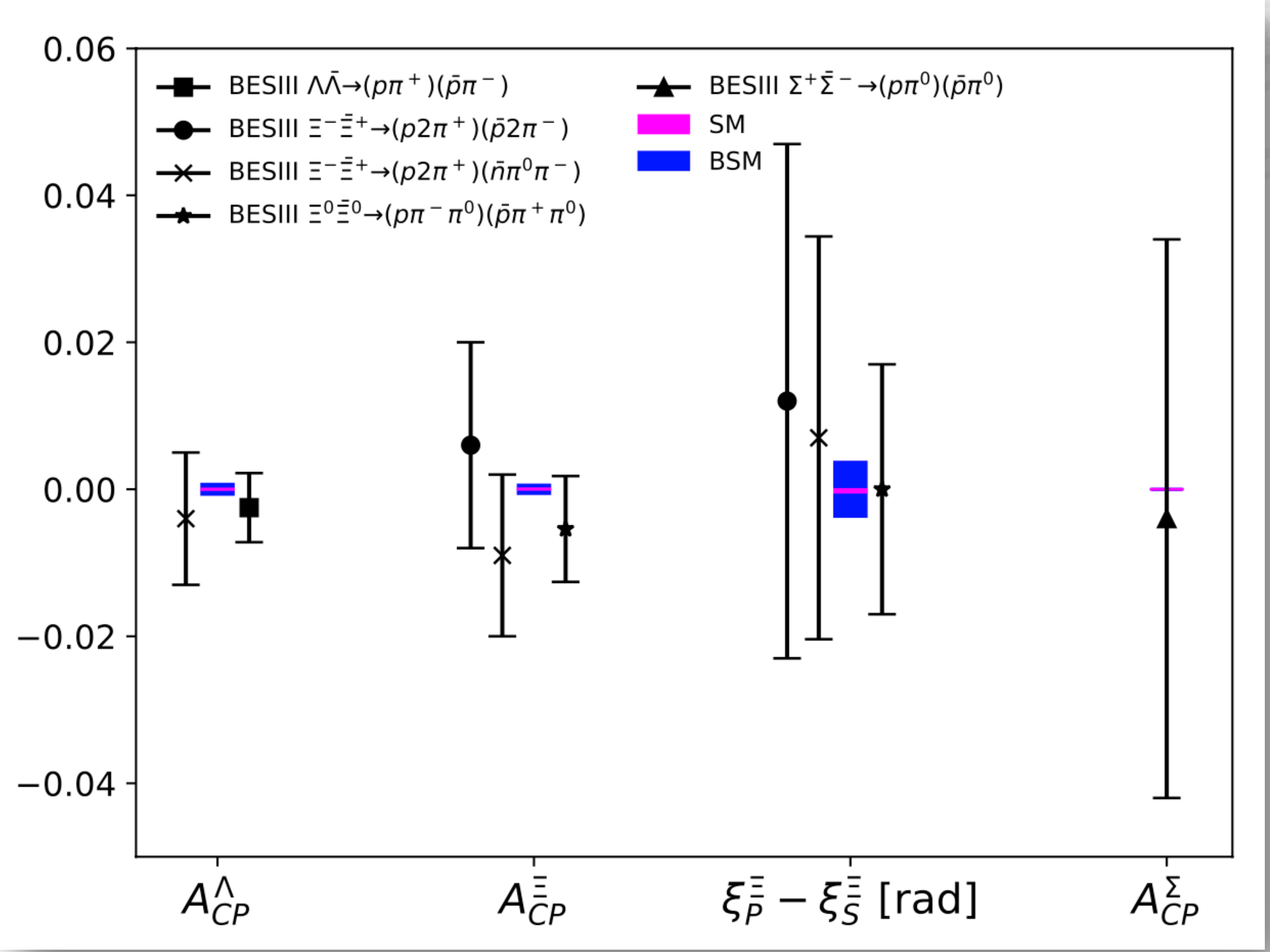
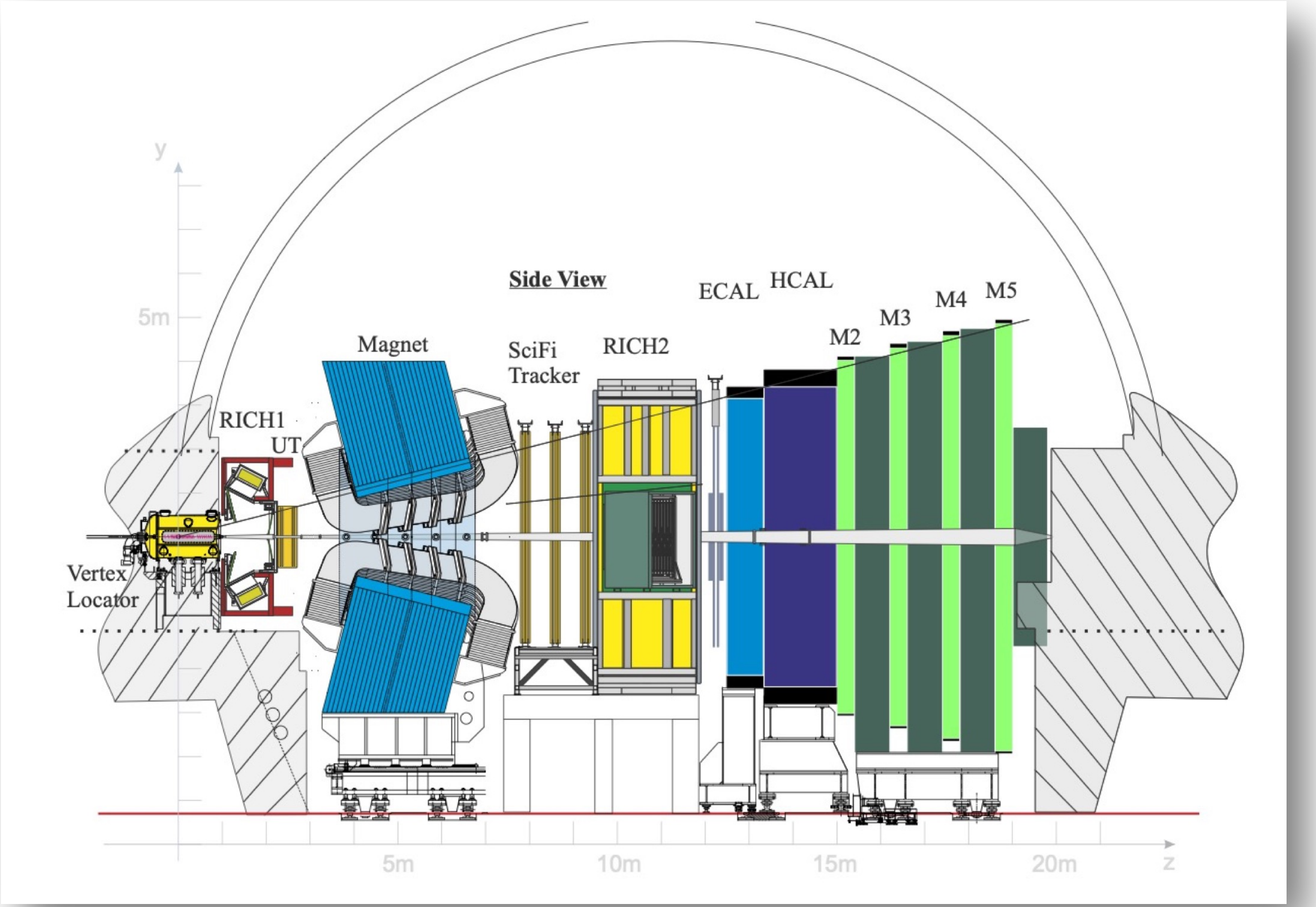
$\Xi^0\bar{\Xi}^0 \to \Lambda(p\pi^-)\pi^0\bar{\Lambda}(\bar{p}\pi^+)\pi^0$ and more…

- $\Xi^0\bar{\Xi}^0$ production and decay parameters
- with 3.3x10^5 events (previous determination 330 events) [PRD108(2023)L031106]
- Weak phase difference $\Xi^0 \to \Lambda\pi^0$
- Also results from $\Sigma^+ \to p\pi^0$ (see plot)
- Uncertainties improved by future BESIII measurements
  and next generation *e+e-* colliders , STCF

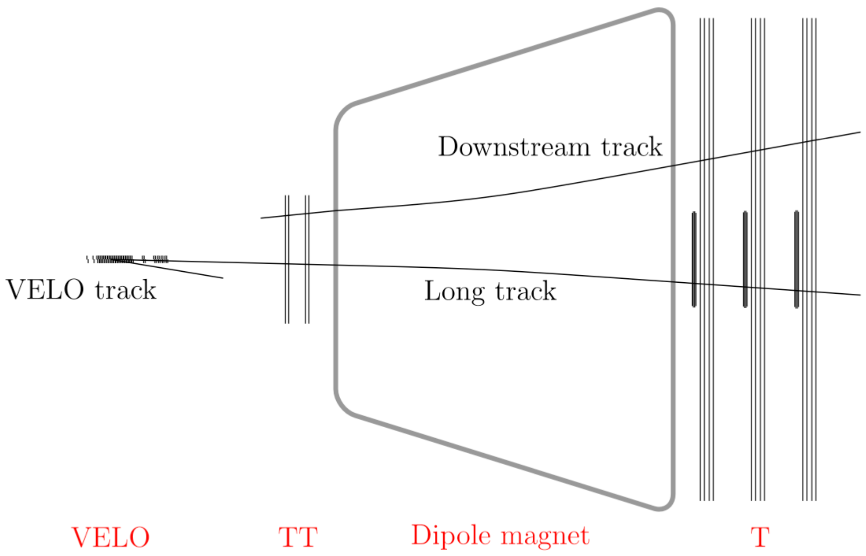


Credit Varvara Batozskaya

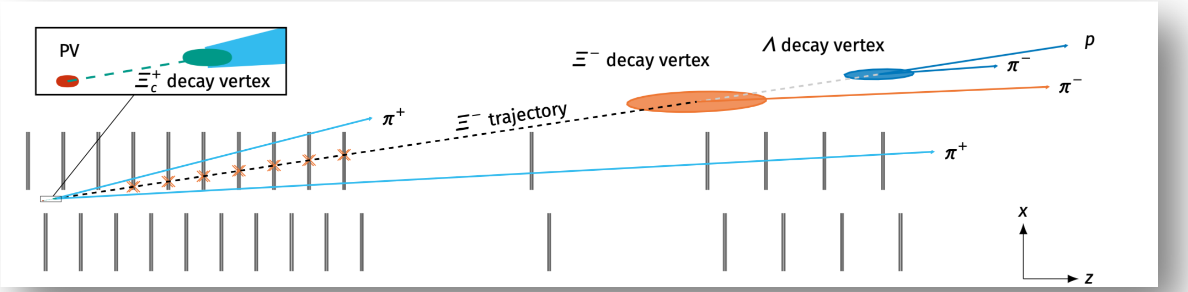
LHCb results



LHCb Long-lived particles

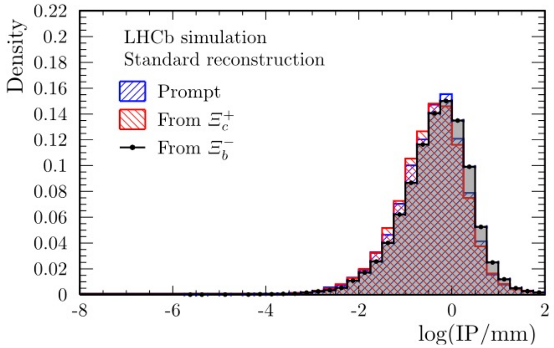


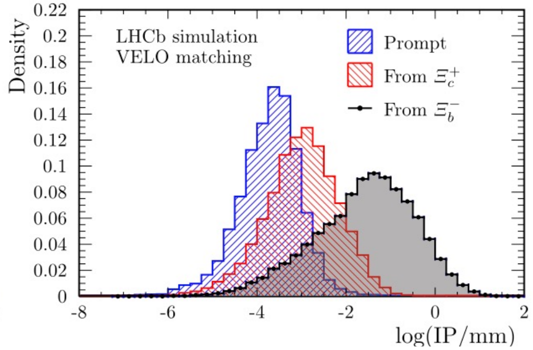
L = long D = downstream



EPJC 84 (2024) 761

- "Direct detection" of Ξ and potential for charged LLP
- Most analyses utilize long tracks (L), with info from VELO
- Poor spatial resolution for Ξ^- reconstructed from DDD
- New algorithm implemented, hits from Ξ^- as it passes VELO
- From IP possible to infer if mother particle is charm or beauty
- Increases yields of polarized Ξ for CP tests
  70% of Ξ from charm decay downstream



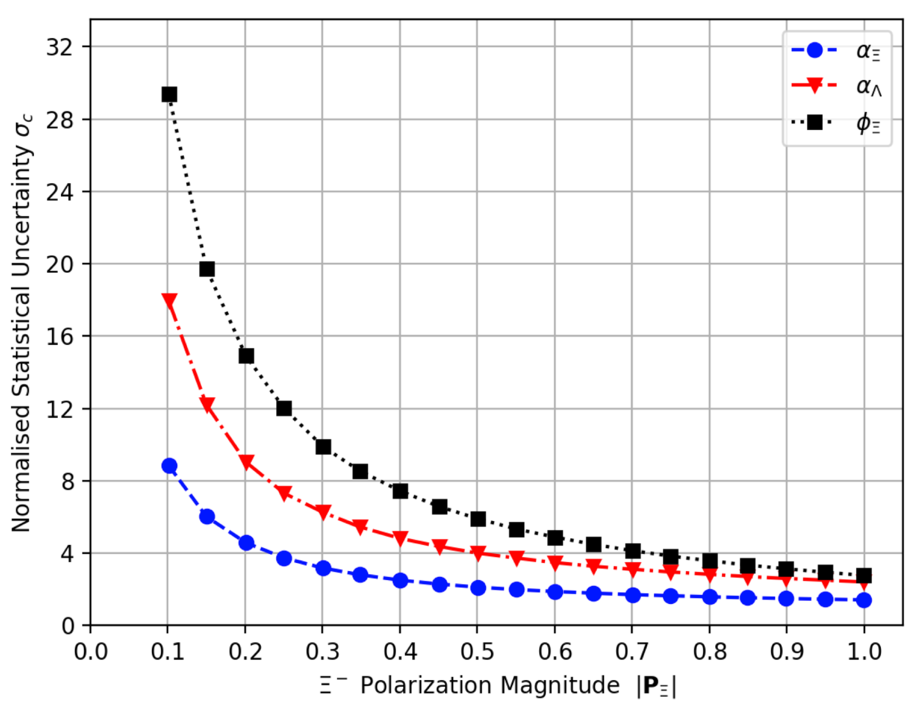


Prospect for strange CP tests LHCb

- LHCb has collected large Ξ^- samples
- Best sensitivity to CP is obtained from $\boldsymbol{\phi}$ (and $\bar{\boldsymbol{\phi}}$) but requires polarized Ξ^- .
- Charm baryons weak decays polarize Ξ^- and improves sensitivity
- A combination of large Run 3 yields and maximal use of LHCb detector can further set limits (or discover) CPV in strange baryon decays

$$\mathbf{P}_\Lambda \cdot \hat{\mathbf{z}} = \frac{\alpha_\Xi + \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}}{1+\alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}},$$

$$\mathbf{P}_\Lambda \times \hat{\mathbf{z}} = \mathbf{P}_\Xi \sqrt{1-\alpha_\Xi^2}\, \frac{\sin\ \phi_\Xi \hat{\mathbf{x}} + \cos\ \phi_\Xi \hat{\mathbf{y}}}{1+\alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}}$$



B.Sc. Thesis Roman Sultanov

$$\sigma_c = \sigma\sqrt{N}$$

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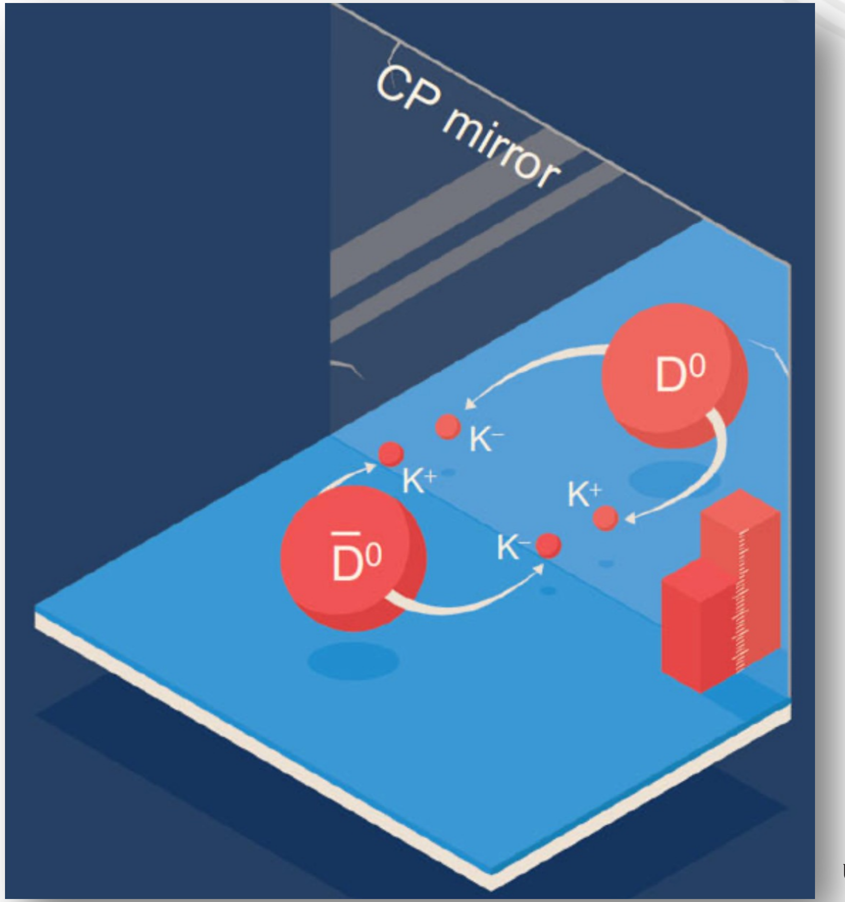
Charm CPV

- LHCb discovered charm CPV in 2019

$$\Delta a_{CP} \equiv a_{CP}^{dir}(D^0 \to K^+K^-) - a_{CP}^{dir}(D^0 \to \pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$$

PRL 108 (2012) 111602

- The Standard Model contribution tiny~10^{-4}
- A good place to search for BSM physics
- Most promising Cabibbo – suppressed channels: interference between tree and penguin amplitudes
- Charm baryons complementary to D-meson studies



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Charm baryon CP tests

Baryon charm cousin decay, Λ_c^+ consistent with CP symmetry

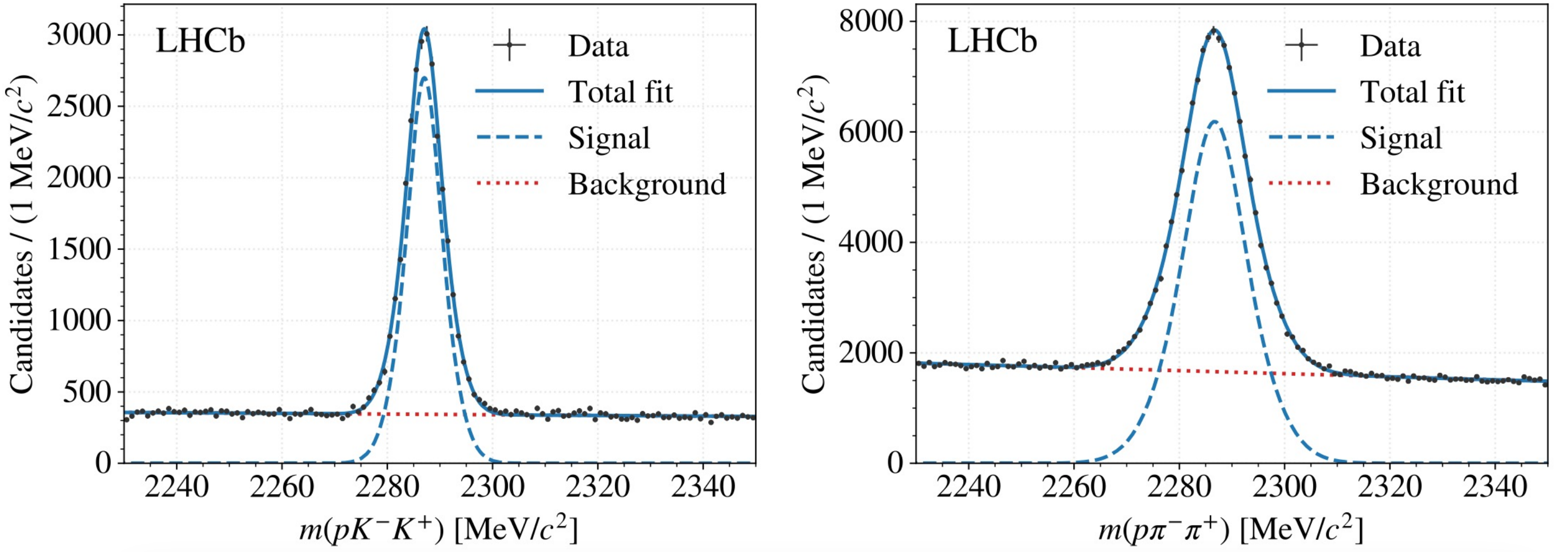
$$\Delta A_{CP}^{wgt} = A_{CP}(pK^-K^+) - A_{CP}^{wgt}(p\pi^-\pi^+) \approx A_{raw}(pK^-K^+) - A_{raw}^{wgt}(p\pi^-\pi^+)$$

Run 1 data

$\Lambda_c^+ \rightarrow p\, K^+K^-$ (25 k)

$\Lambda_c^+ \rightarrow p\, \pi^+\pi^-$ (187 k)

JHEP03 (2018) 182



$$\Delta A_{CP}^{wgt} = (0.30 \pm 0.91 \pm 0.61)\%$$

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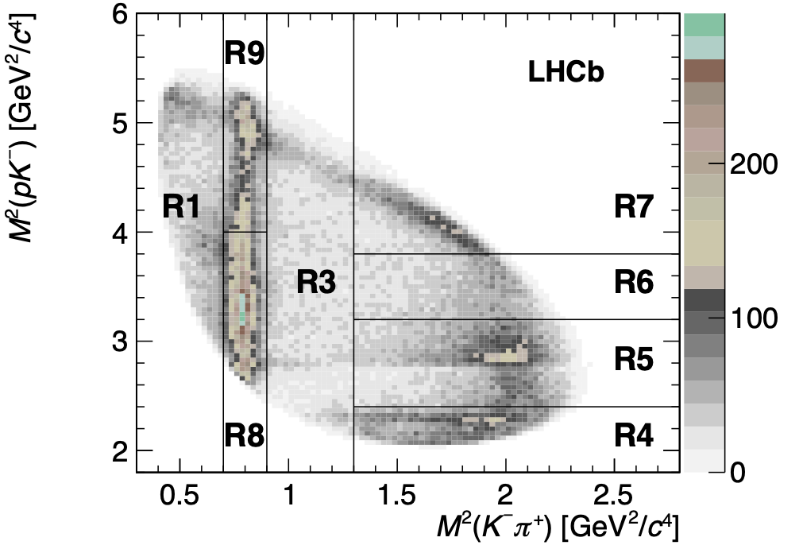
Model independent CP tests $\Xi_c^+ \to p\, K^- \pi^+$

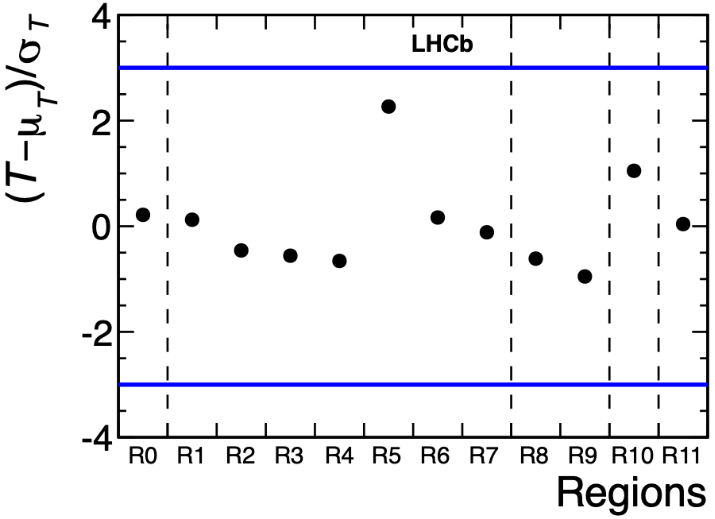
Eur Phys J C80 (2020) 986

- $\Xi_c^+ \to p\, K^- \pi^+$ is CS. Λ_c^+ control mode (CF)
- Two model independent CP tests
- Consistent with CP conservation
- One region show slight asymmetry

R5 : Λ resonances

- To be continued with Run 2 data





200 k events

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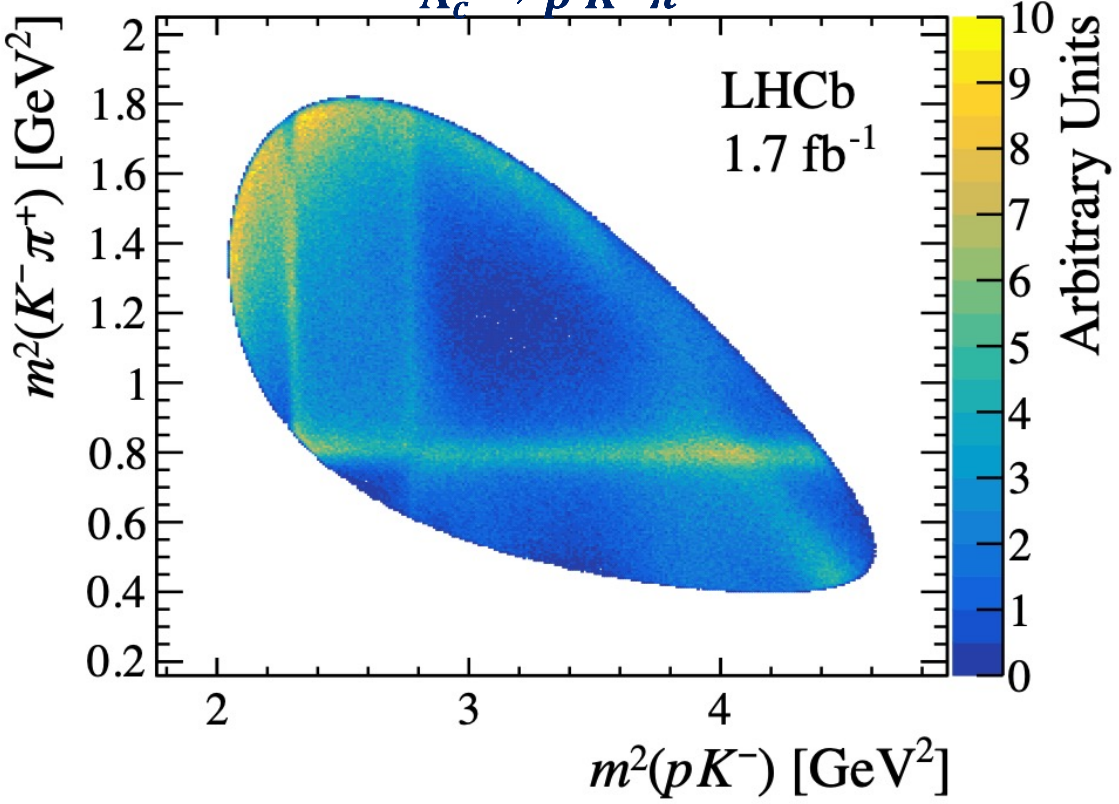
LHCb model dependent $\Lambda_c^+ \to p\, K^- \pi^+$

Phys. Rev. D108 (2023) 012023

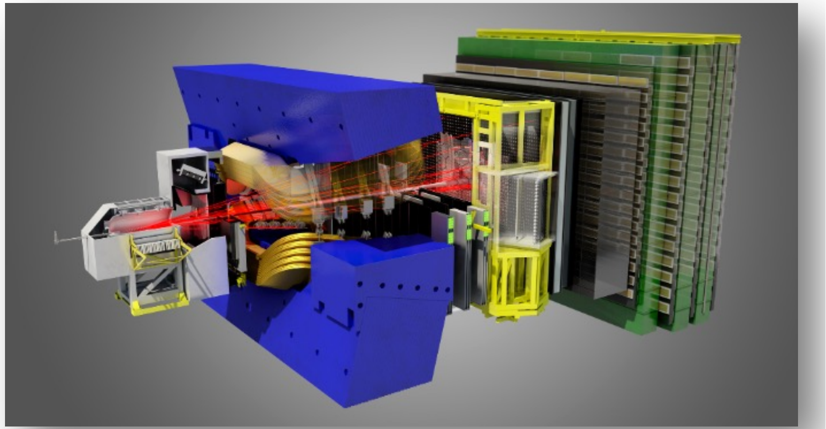
- Charmed three body decays have rich resonant structure
- $\Lambda_c^+ \to p\, K^- \pi^+$ has many states which interfer with each other
- Even more information available from Λ_c^+ which comes from a beauty mother $\Lambda_b^0 \to \Lambda_c^+ l^- \bar{\nu}$
- Amplitude analysis is a pre-requisite for CP test
- Roman Sultanov M. Sc. Thesis (UU) explores this topic further

$\Lambda_c^+ \to p\, K^- \pi^+$



Summary & Outlook

- BESIII and LHCb are both capable of performing CP precision test
- First measurement of weak phase difference for any baryon decay BESIII
- LHCb is ramping up its integrated luminosity in Run 3
- Many exciting results are expected from LHCb in the future



Thank you for your attention!

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Strangeness $\Delta S = 1$ mesons

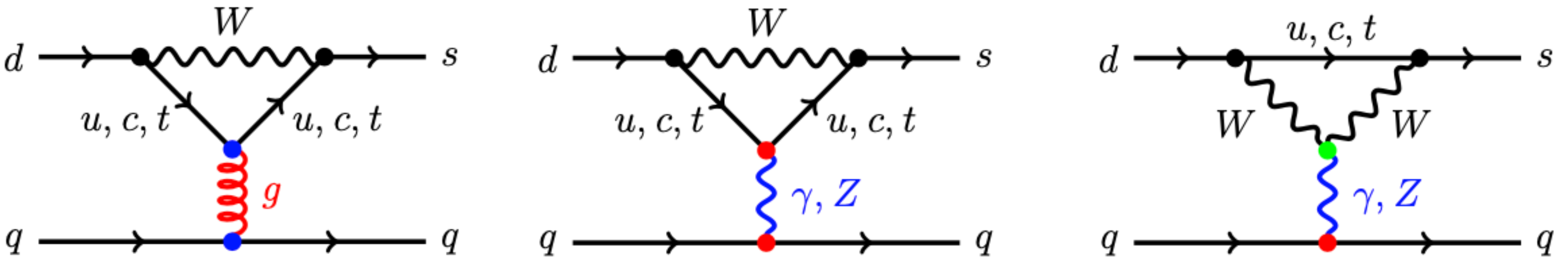
In strange sector most precise probe is $\boldsymbol{\Delta S = 1}$ direct CPV (ε') relative to indirect CPV (ε) in $K_{S,L} \to \pi\pi$ decays

CPV mechanism in SM requires penguin diagrams involving all three quark families

$$(\varepsilon'/\varepsilon)_{EXP} = (16.6 \pm 2.3)\times 10^{-4} \ *$$

$$(\varepsilon'/\varepsilon)_{SM} = (17.4 \pm 6.1)\times 10^{-4} \ + (\varepsilon'/\varepsilon)_{BSM} = (-4 \ - \ +10)\times 10^{-4} \ **$$

SM calculation involves partial cancellation of QCD and EW penguins which posed challenge until recently



QCD (left) and EW penguin diagrams (middle, right)***

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* Phys. Lett. B544 (2002) 97–112; 0909.2555 [hep-ex]
** *Eur. Phys. J. C* 80 (2020) 8, 705
*** arXiv: 2203.03035

Strangeness $\Delta S = 1$ SM + BSM

$$A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -\sin\phi\tan(\xi_P - \xi_S)\frac{\sqrt{1-\alpha^2}}{\alpha}$$
$$\Phi_{CP} = \frac{\phi+\bar{\phi}}{2} = \cos\phi\tan(\xi_P - \xi_S)\frac{\alpha}{\sqrt{1-\alpha^2}}$$

$-3 \times 10^{-5} \leq A_{\Lambda\,\mathrm{SM}} \leq 4 \times 10^{-5}$ *
$0.5 \times 10^{-5} \leq A_{\Xi\,\mathrm{SM}} \leq 6 \times 10^{-5}$ *

SM

Decay mode	$\xi_P - \xi_S$ [10^{-4}rad] ***
$\Lambda \to p\pi^-$	-0.2 ± 2.2
$\Xi^- \to \Lambda\pi^-$	-2.1 ± 1.7

Chromomagnetic BSM penguin operators

$Y \to B\pi$

$$(\xi_P - \xi_S)_{\mathrm{BSM}} = \frac{C'_B}{B_G}\left(\frac{\epsilon'}{\epsilon}\right)_{\mathrm{BSM}} + \frac{C_B}{\kappa}\epsilon_{\mathrm{BSM}}$$

BSM

$|A_\Lambda + A_\Xi| \lesssim 11 \cdot 10^{-4}$

Decay	$\lvert\xi_P - \xi_S\rvert$ ***
$\Lambda \to p\pi^-$	$\lesssim 5.3 \cdot 10^{-3}$
$\Xi^- \to \Lambda\pi^-$	$\lesssim 3.7 \cdot 10^{-3}$

* *Phys. Rev. D 67, 056001 (2003)*
** *Phys. Rev. D 69, 076008 (2004)*
*** PRD105 (2022) 116022

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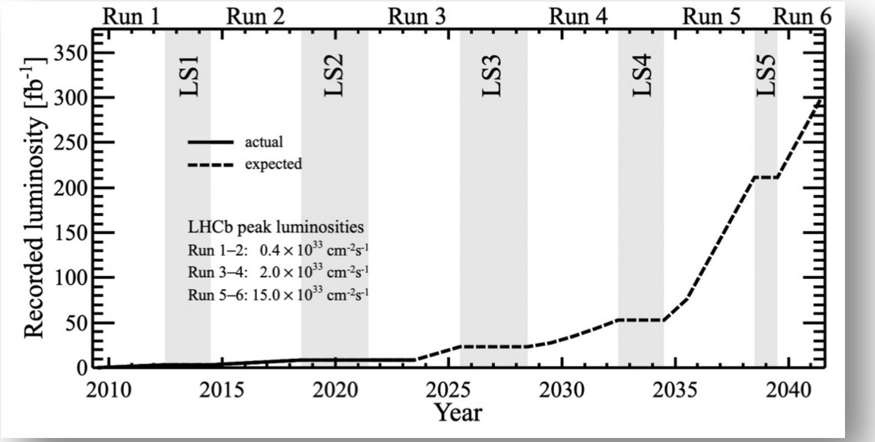
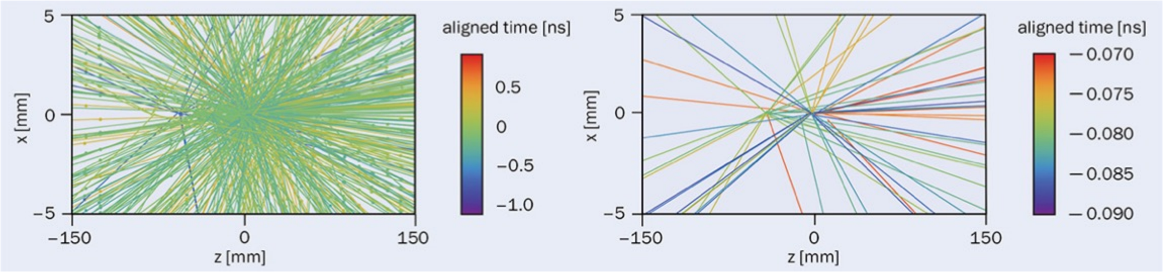
LHCb Upgrade II





Theseus's Paradox again! applied to particle physics experiment – LHCb Upgrade II

New tracking detectors

VELO strip → pixels; 5 → 3.5 mm to beam

Software based triggers

Increase of instantaneous luminosity by factor 50 cf Run 1 and 2

End of Run 4 goal 50fb^{-1}
2010-2018 (Run1: 3fb^{-1} + Run2: 6fb^{-1})

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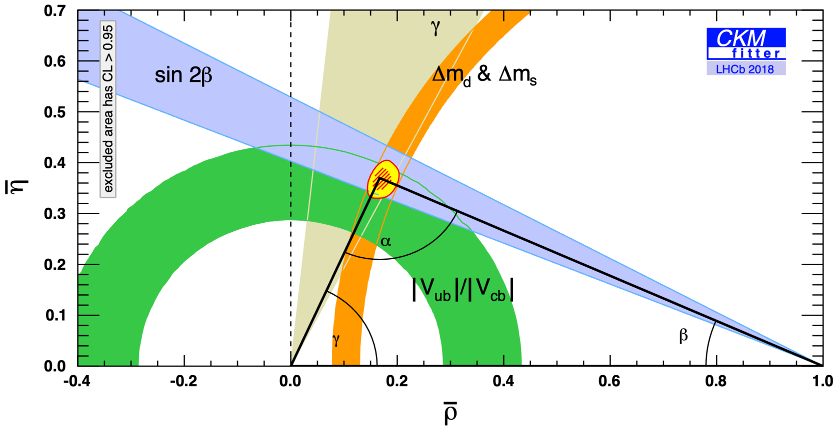
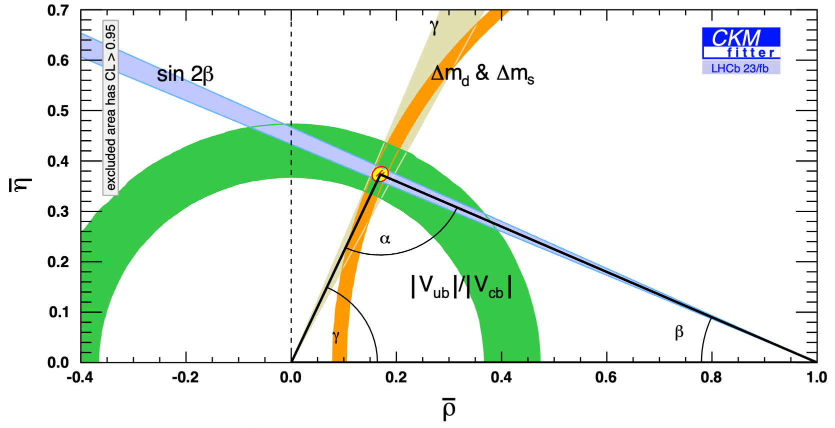
LHCb Upgrade II effect on CKM

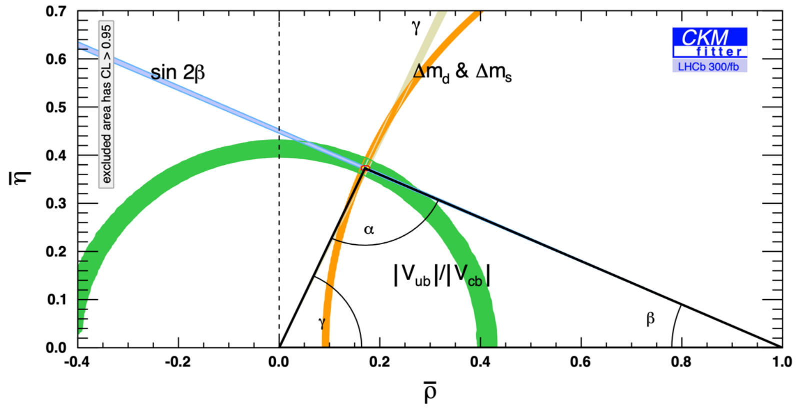
As of 2018



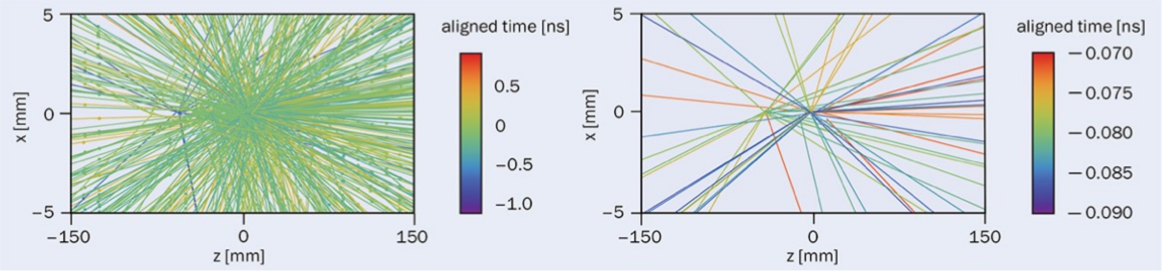
(end of Run 3) 23 fb^{-1}



(end of Run 4) 300 fb^{-1}



Precisions with LHCb data and LQCD input alone



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BESIII ❤ Hyperons

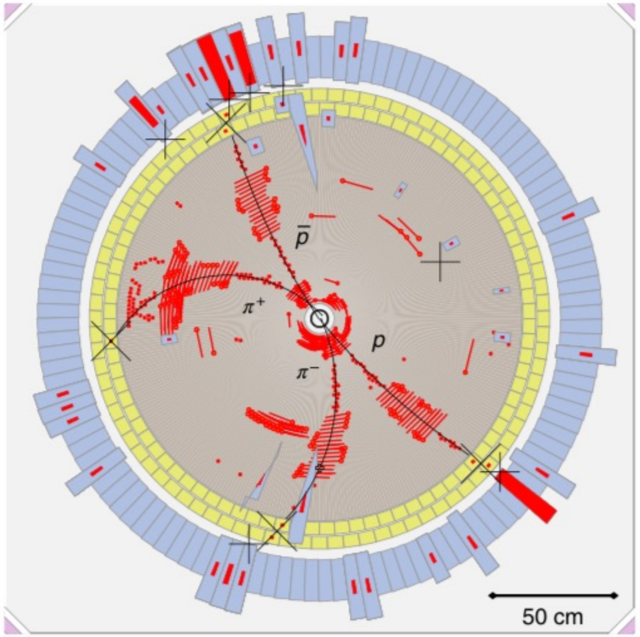

Fig. 2 | An example $J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ event in the BESIII detector. Cross-section of the detector in the plane perpendicular to the colliding electron-positron beams and a schematic representation of the information collected for the event. The mean decay length of the neutral $\Lambda(\bar{\Lambda})$ is 5 cm. The curved tracks of the charged particles from the subsequent $\Lambda(\bar{\Lambda})$ decays are registered in the drift chamber, indicated by the brown region of the display. The momenta of (anti-)baryons are greater than 750 MeV c^{-1} and pions are less than 300 MeV c^{-1}.

BESIII, Nature Physics 15 (2019) 631

Charged track coverage |cosθ| < 0.93

Mom. res of charged tracks 0.5% at 1 GeV/c

Neutrals |cosθ| < 0.8 and 0.86 < |cosθ| < 0.92

Energy resolution 2.5% (5%) at 1 GeV for barrell (end cap)

ToF can be used together with dE/dx MDC for PID

But for fully charged modes e.g. Λ and Ξ momentum requirements enough to separate protons from pions

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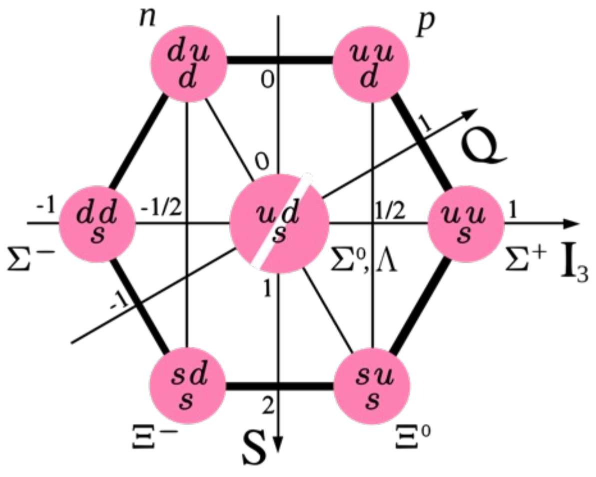
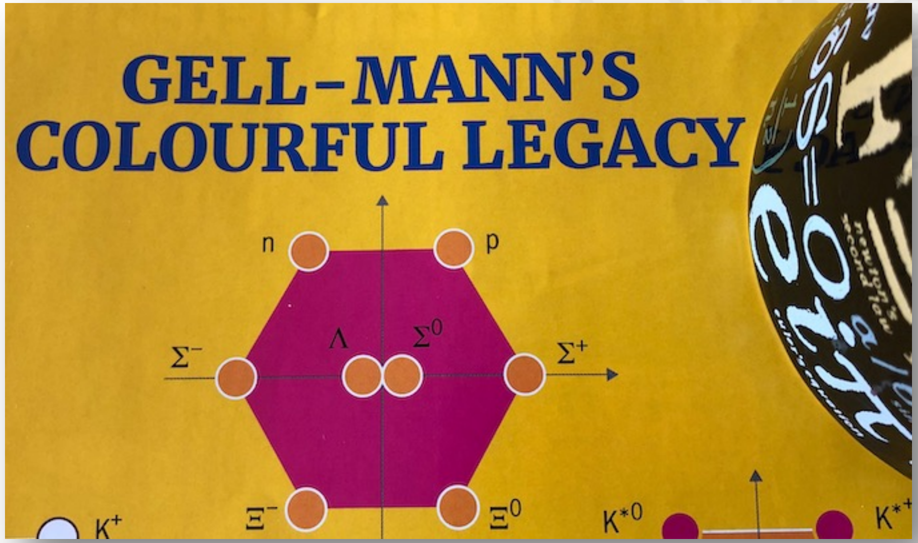
Non-leptonic two body decays



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

From CERN Courier cover July-August 2019



Thresholds:

$\Lambda\bar{\Lambda}$ **2.231 GeV**

$\Sigma^+\bar{\Sigma}^-$ **2.379 GeV** $\Sigma^0\bar{\Sigma}^0$ **2.385 GeV** $\Sigma^-\bar{\Sigma}^+$ **2.395 GeV**

$\Xi^0\bar{\Xi}^0$ **2.630 GeV** $\Xi^-\bar{\Xi}^+$ **2.643 GeV**

Full baryon octet kinematically accessible at J/ψ resonance

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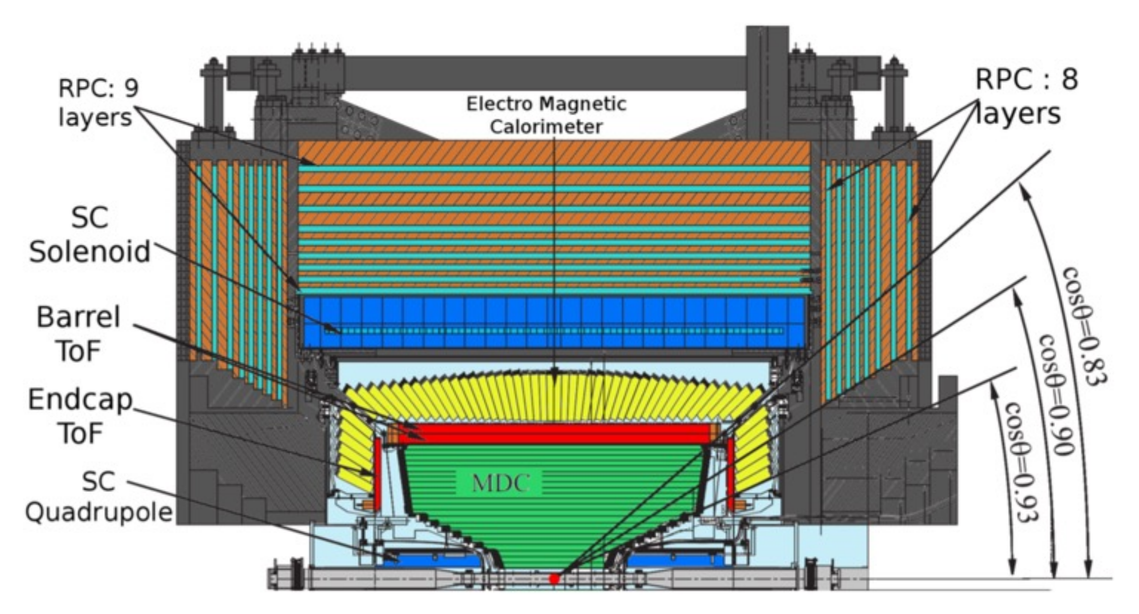
BEPC II and BESIII



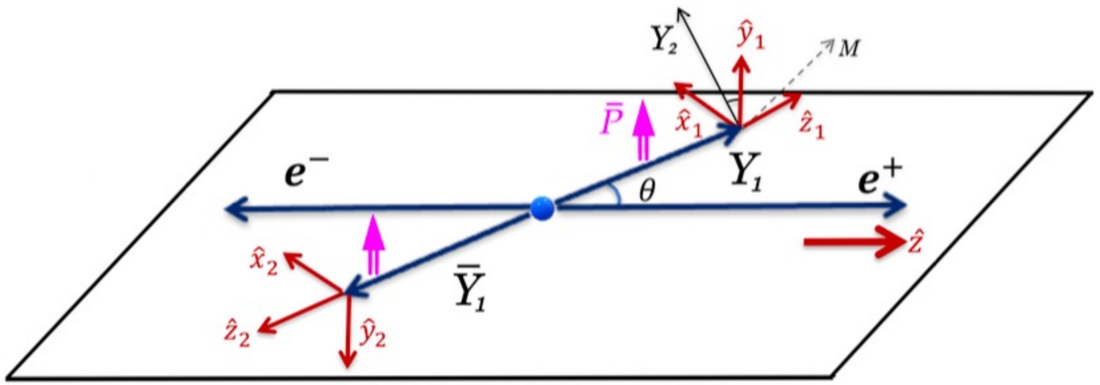
- Multipurpose detector, excellent resolution, near 4π coverage
- Symmetric particle – anti-particle conditions, produced in entangled state
- Low hadronic background
- World's largest charmonia data samples

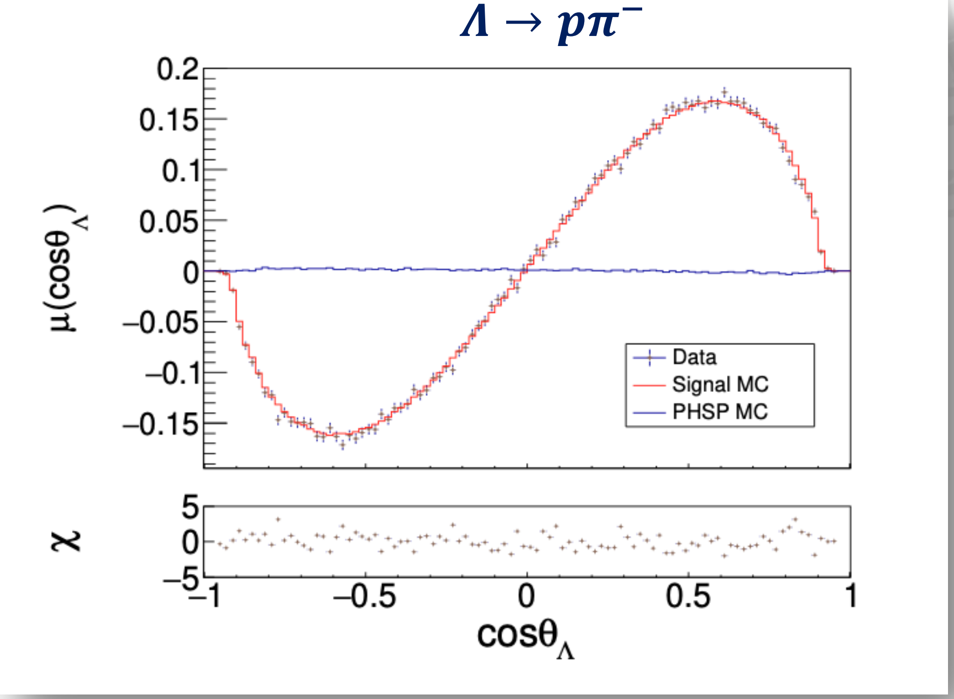
Resonance	Pair	$\mathcal{B}(\cdot 10^{-4})$	$\epsilon(\%)$	$N_{obs}(10^3)$	Reference
J/ψ	$\Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	42.37 ± 0.14	441	[PRD95(2017)052003]
	$\Sigma^0\bar{\Sigma}^0$	$11.64 \pm 0.04 \pm 0.23$	17.83 ± 0.06	111	
	$\Xi^-\bar{\Xi}^+$	$10.40 \pm 0.06 \pm 0.74$	18.40 ± 0.04	43	[PRD93(2016)072003]
$\psi(2S)$	$\Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	42.83 ± 0.34	31	[PRD95(2017)052003]
	$\Sigma^0\bar{\Sigma}^0$	$2.44 \pm 0.03 \pm 0.11$	14.79 ± 0.12	6.6	
	$\Xi^-\bar{\Xi}^+$	$2.78 \pm 0.05 \pm 0.14$	18.04 ± 0.04	5.3	[PRD93(2016)072003]
	$\Omega^-\bar{\Omega}^+$	$0.59 \pm 0.01 \pm 0.03$	$17.1/18.9$	4.1	[PRL126(2021)092002]

BESIII

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

$$\mu(\cos\theta_\Lambda) = \frac{\alpha_\Lambda - \bar{\alpha}_\Lambda}{2} \frac{1+\alpha_\psi \cos^2\theta_\Lambda}{3+\alpha_\psi} P_y(\cos\theta_\Lambda)$$





[PRL129(2022)131801]

3.23M $\bar{\Lambda}\Lambda$

Par.	This work	Previous results [8]
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$
α_+	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0011$	$0.006 \pm 0.012 \pm 0.007$
α_{avg}	$0.7542 \pm 0.0010 \pm 0.0020$	-

Polarization necessary for disentangling α and $\bar{\alpha}$

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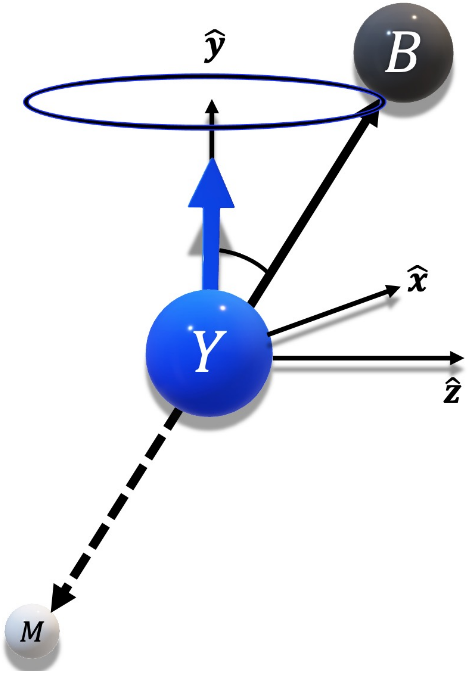
$J/\psi \to \Lambda\bar{\Lambda} \to p\pi^- \bar{p}\pi^+$

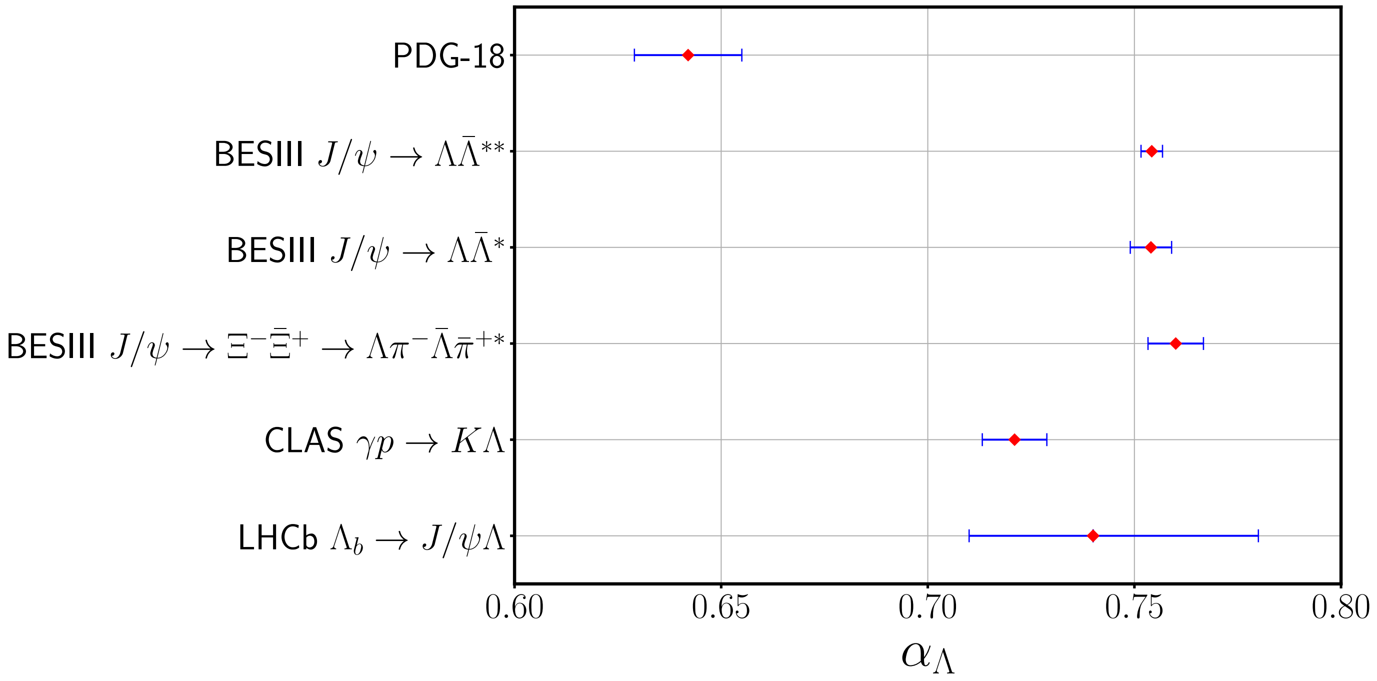


Most precise $A_{CP,\Lambda}$

$$A_{CP}^{\Lambda} = \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda} = -0.0025 \pm 0.0046_{\text{stat}} \pm 0.0011_{\text{syst}}$$

Based on 3.23M $\bar{\Lambda}\Lambda$

$\Lambda \to p\pi^-$



$$\langle\alpha(\Lambda \to p\pi^-)\rangle_\Lambda = 0.754(1)(2)$$
$$\langle\alpha(\Lambda \to p\pi^-)\rangle_\Xi = 0.760(6)(3)$$

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BESIII

Formalism sequential weak decays

- The formalism polarisation, entanglement and sequential decays * **

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu'\nu'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\overline{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu'0} a^{\overline{\Lambda}}_{\nu'0}$$

- Nine-dimensional phase space given by nine helicity angles

- Eight free parameters determined by maximum log likelihood method:

α_ψ , $\boldsymbol{\Delta\Phi}$, $\boldsymbol{\alpha_\Xi}$, $\boldsymbol{\overline{\alpha}_\Xi}$, ϕ_Ξ, $\boldsymbol{\overline{\phi}_\Xi}$, α_Λ, $\overline{\alpha}_\Lambda$

not measured before

* Phys. Rev. D 99, 056008 (2019)
** Phys. Rev. D 100, 114005 (2019)

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BESIII

$\Xi^-\bar{\Xi}^+ \rightarrow \Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{p}\pi^+)\pi^+$

Table 1 | Summary of results

Parameter	This work	Previous result	Reference	
α_ψ	$0.586\pm0.012\pm0.010$	$0.58\pm0.04\pm0.08$	Ref. [49]	*
$\Delta\Phi$	$1.213\pm0.046\pm0.016$ rad	–		
α_Ξ	$-0.376\pm0.007\pm0.003$	-0.401 ± 0.010	Ref. [26]	**
ϕ_Ξ	$0.011\pm0.019\pm0.009$ rad	-0.037 ± 0.014 rad	Ref. [26]	**
$\bar{\alpha}_\Xi$	$0.371\pm0.007\pm0.002$	–		
$\bar{\phi}_\Xi$	$-0.021\pm0.019\pm0.007$ rad	–		
α_Λ	$0.757\pm0.011\pm0.008$	$0.750\pm0.009\pm0.004$	Ref. [4]	***
$\bar{\alpha}_\Lambda$	$-0.763\pm0.011\pm0.007$	$-0.758\pm0.010\pm0.007$	Ref. [4]	***
$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–		
$\delta_P-\delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad	Ref. [3]	****
A^Ξ_{CP}	$(6\pm13\pm6)\times10^{-3}$	–		
$\Delta\phi^\Xi_{CP}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–		
A^Λ_{CP}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$	Ref. [4]	***
$\langle\phi_\Xi\rangle$	$0.016\pm0.014\pm0.007$ rad			

The $J/\psi\rightarrow\Xi^-\bar{\Xi}^+$ angular distribution parameter α_ψ, the hadronic form factor phase $\Delta\Phi$, the decay parameters for $\Xi^-\rightarrow\Lambda\pi^-$ (α_Ξ,ϕ_Ξ), $\bar{\Xi}^+\rightarrow\bar{\Lambda}\pi^+$ $(\bar{\alpha}_\Xi,\bar{\phi}_\Xi)$ $\Lambda\rightarrow p\pi^-$ (α_Λ) and $\bar{\Lambda}\rightarrow\bar{p}\pi^+$ $(\bar{\alpha}_\Lambda)$; the CP asymmetries A^Ξ_{CP}, $\Delta\phi^\Xi_{CP}$ and A^Λ_{CP}, and the average $\langle\phi_\Xi\rangle$. The first and second uncertainties are statistical and systematic, respectively.

First measurement of polarization

First direct determination of all $\Xi^-\bar{\Xi}^+$ decay parameters

Previous experiments determined product $\boldsymbol{\alpha_\Xi\,\alpha_\Lambda}$

Independent measurement of Λ decay parameters. Excellent agreement with previous BESIII results. Similar precision despite 6x smaller data sample

* PRD 93, 072003 (2018)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

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BESIII

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

Table 1 | Summary of results

Parameter	This work	Previous result	Reference	
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$\Delta\Phi$	1.213±0.046±0.016 rad	–		
α_Ξ	−0.376±0.007±0.003	−0.401±0.010	Ref. 26	**
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad	Ref. 26	**
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	–		
$\bar{\phi}_\Xi$	−0.021±0.019±0.007 rad	–		
α_Λ	0.757±0.011±0.008	0.750±0.009±0.004	Ref. 4	***
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007	Ref. 4	***
$\xi_P-\xi_S$	(1.2±3.4±0.8)×10^{-2} rad	–		
$\delta_P-\delta_S$	(−4.0±3.3±1.7)×10^{-2} rad	(10.2±3.9)×10^{-2} rad	Ref. 3	****
A_{CP}^{Ξ}	(6±13±6)×10^{-3}	–		
$\Delta\phi_{CP}^{\Xi}$	(−5±14±3)×10^{-3} rad	–		
A_{CP}^{Λ}	(−4±12±9)×10^{-3}	(−6±12±7)×10^{-3}	Ref. 4	***
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad			

The $J/\psi\to\Xi^-\bar{\Xi}^+$ angular distribution parameter α_ψ, the hadronic form factor phase $\Delta\Phi$, the decay parameters for $\Xi^-\to\Lambda\pi^-$ (α_Ξ, ϕ_Ξ), $\bar{\Xi}^+\to\bar{\Lambda}\pi^+$ ($\bar{\alpha}_\Xi$, $\bar{\phi}_\Xi$) $\Lambda\to p\pi^-$ (α_Λ) and $\bar{\Lambda}\to\bar{p}\pi^+$ ($\bar{\alpha}_\Lambda$); the CP asymmetries A_{CP}^{Ξ}, $\Delta\phi_{CP}^{\Xi}$ and A_{CP}^{Λ}, and the average $\langle\phi_\Xi\rangle$. The first and second uncertainties are statistical and systematic, respectively.

Nature 606 64-69 (2022)

We obtain the same precision for ϕ as HyperCP with ***three orders of magnitude*** smaller data sample!

$$\phi_{\Xi,\mathrm{HyperCP}} = -0.042 \pm 0.011 \pm 0.011$$

$$\langle\phi_\Xi\rangle = 0.016 \pm 0.014 \pm 0.007$$

Strong phase measurement compatible with SM (1.9±4.9)x10^{-2} but in tension with HyperCP 2.6σ

PRD 67 056001 (2004)

* PRD 93, 072003 (2018)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

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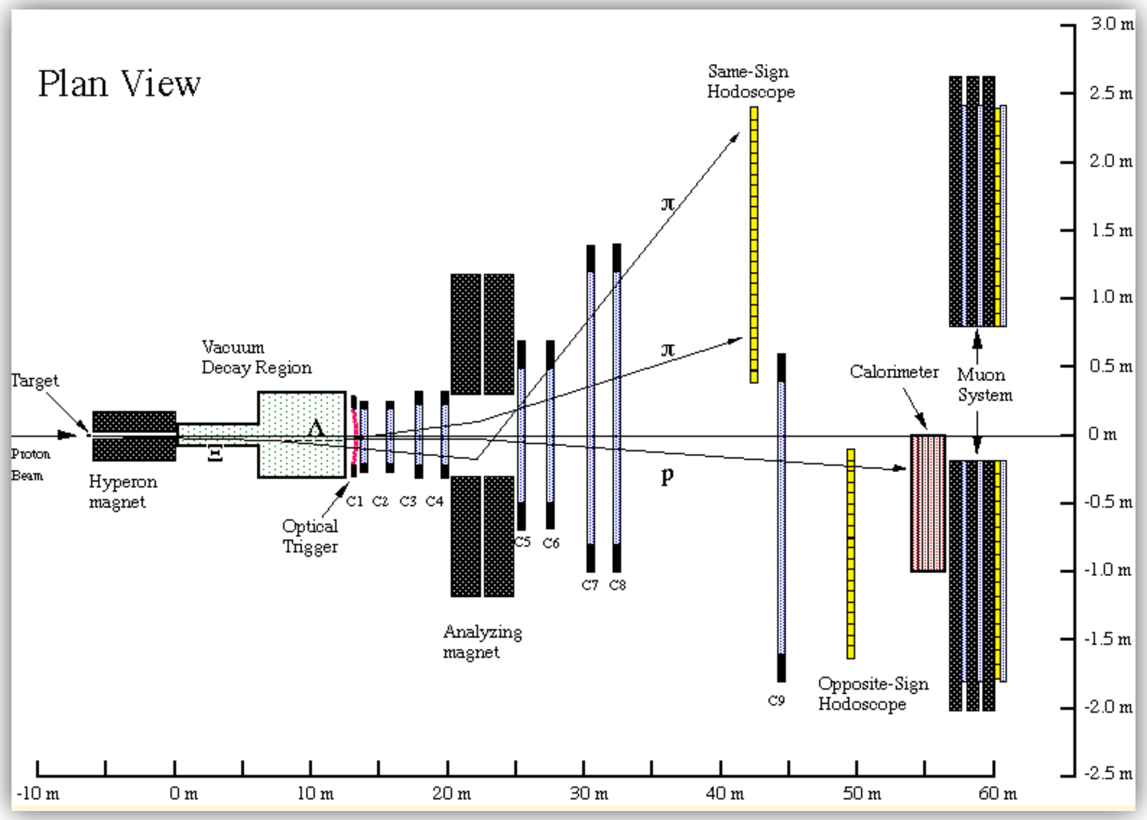
HyperCP



HyperCP (**E871**) Fermilab

800 GeV/c proton on fixed target Cu

Best A_{CP} limits obtained so far 117M Ξ and 41M $\bar{\Xi}$

$$A_{CP\ \Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda + \bar{\alpha}_\Xi\bar{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda - \bar{\alpha}_\Xi\bar{\alpha}_\Lambda} = (0.0 \pm 5.1 \pm 4.7)\times10^{-4}\ *$$

$$|A_{SM\ \Xi\Lambda}| \leq 5\times10^{-5}\ **$$

144M polarized Ξ (~5%) $\phi_{\Xi,\mathrm{HyperCP}} = -0.042 \pm 0.011 \pm 0.011$

862M Ξ & 230M $\bar{\Xi}$ $A_{CP\ \Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda+\bar{\alpha}_\Xi\bar{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda-\bar{\alpha}_\Xi\bar{\alpha}_\Lambda} = (-6.0 \pm 2.1 \pm 2.0)\times10^{-4}$ ***

*PRL 93, 262001 (2004)
** PRD 67, 056001 (2003)
*** NPB, Proc Suppl 187, 208 (2009)

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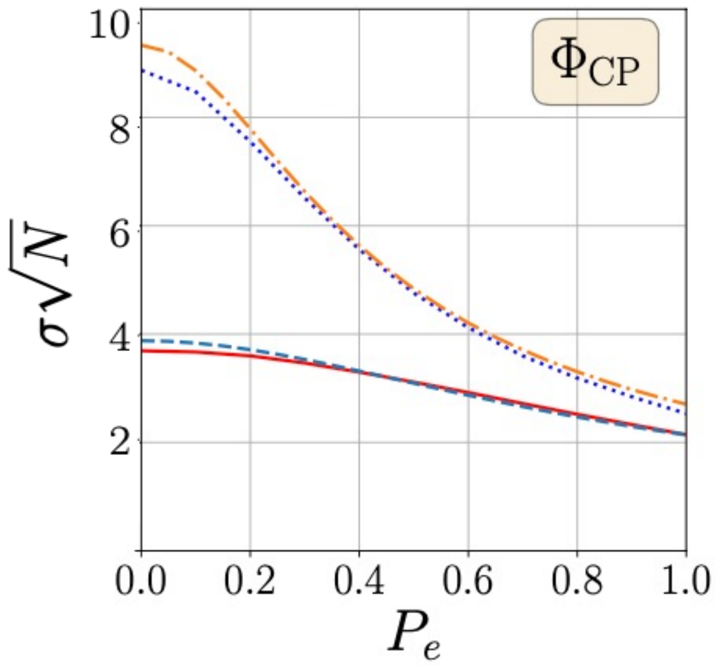
SτCF: sequential weak decay

Using polarized electron beam can greatly enhance sensitivity!

$$\mathcal{I}_0(\Phi_{\rm CP}) = \frac{2N}{27}\left(1-\alpha_\Xi^2\right)\alpha_\Lambda^2\left[\left(3+\alpha_\Xi^2\alpha_\Lambda^2\right)\langle\mathbb{P}_\Xi^2\rangle + \frac{2}{3}\left(\alpha_\Xi^2\left(3-2\alpha_\Lambda^2\right)+3\alpha_\Lambda^2\right)\langle\mathbb{S}_{\Xi\bar{\Xi}}^2\rangle\right]$$

Spin correlation contributions

$$\sigma(\Phi_{\rm CP}) = 1/\sqrt{\mathcal{I}(\Phi_{\rm CP})}$$



Dotted: ST
Solid: DT

Analytic approximation: dashed dotted dashed

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