Search for Rare decay at BESIII

Luyan Tao

University of South China

NPG Workshop 2024

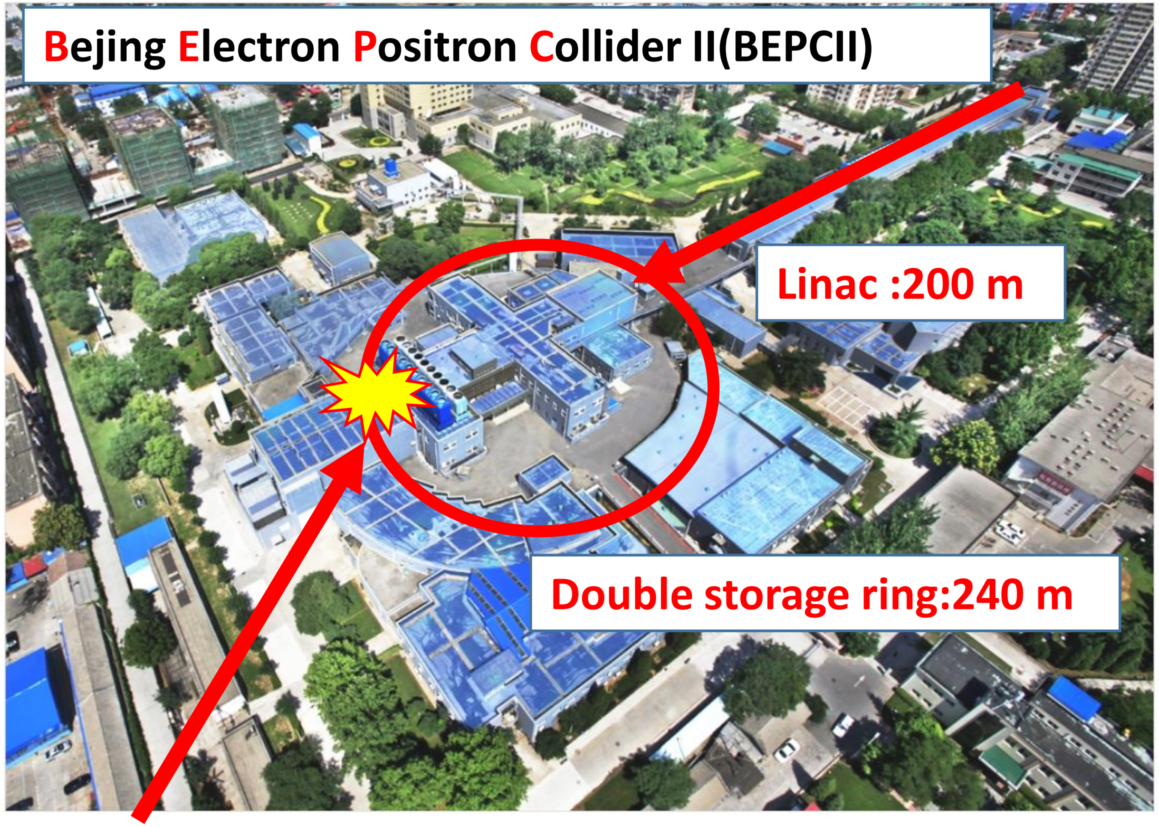
26-30 Aug 2024

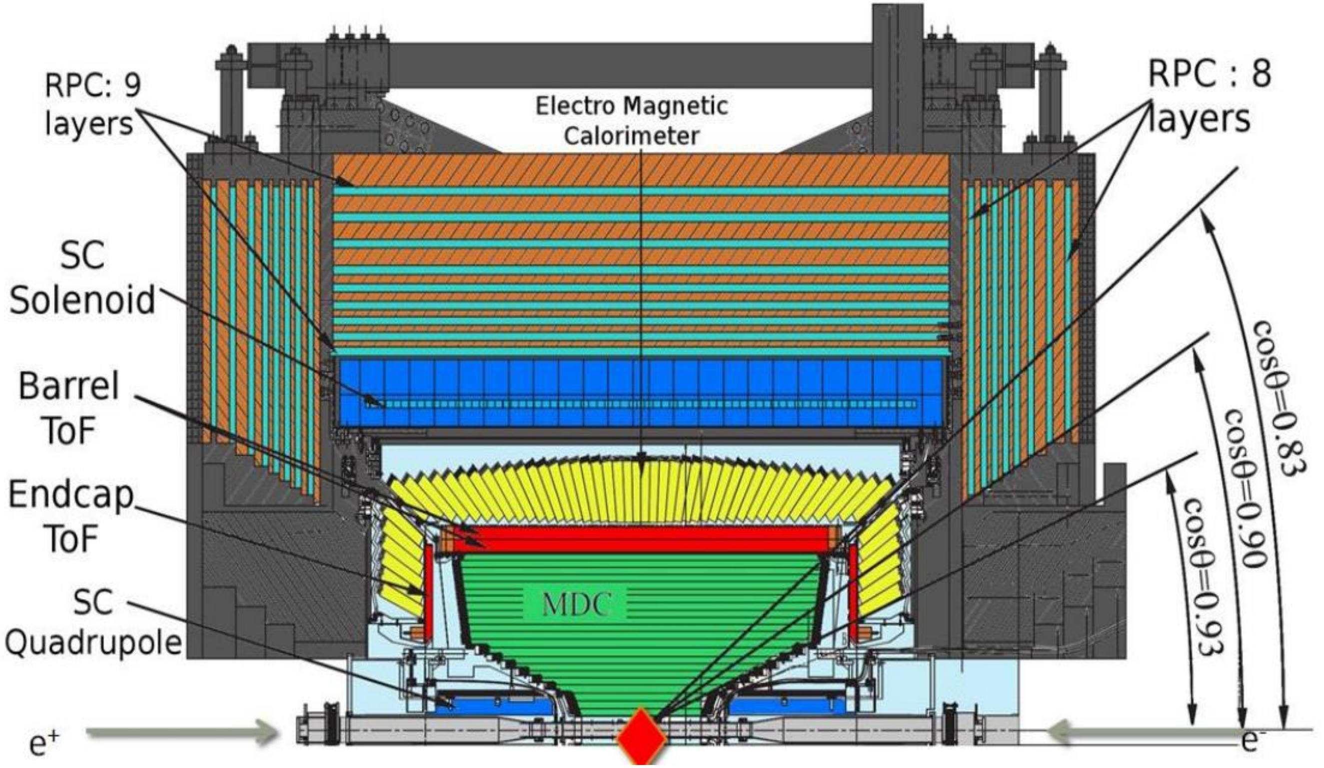
Outline

- BEPCII and BESIII experiment
- Data samples at BESIII
- New Physics and benefit of BESIII
- Rare decays results at BESIII
  - $\Omega^- \to \Sigma^0\pi^-, nK^-$ JHEP 05 141 (2024)
  - $\Xi^0 \to \Sigma e\nu$ Phys. Rev. D 107, 012002 (2023)
  - $\psi(2S) \to \Lambda_c^+\bar{\Sigma}^- + \mathrm{c.c.}$ Chinese Phys. C 47 013002 (2023)
  - $\psi(2S) \to e^+e^-\eta_c$ Phys. Rev. D 106, 112002 (2022)
- Summary

BEPCII and BESIII experiment

- Bird View of BEPCII/BESIII





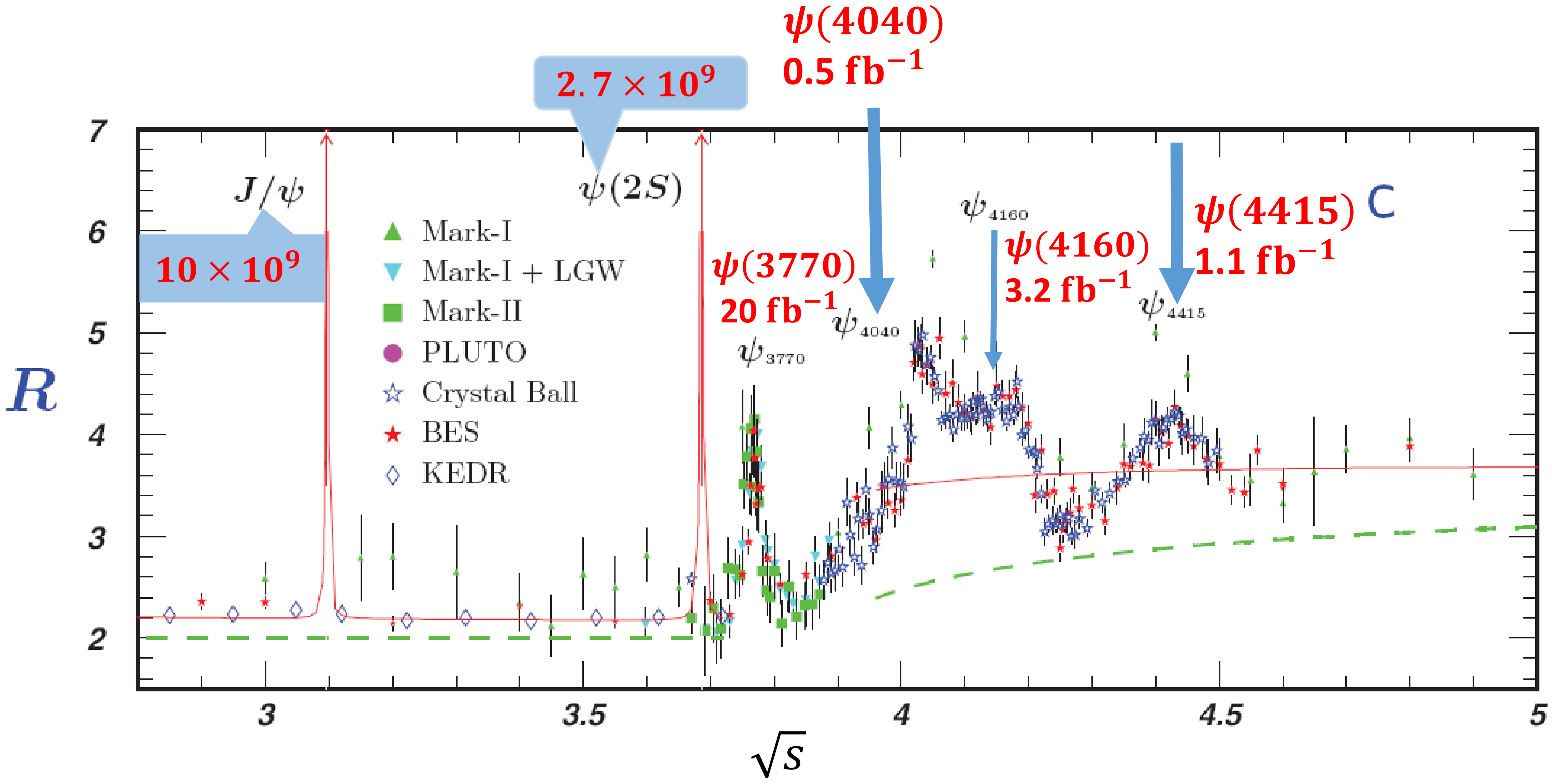
BESIII detector

- CMS energy: 2 - 4.95 GeV
- Luminosity: $1 \times 10^{33}\ cm^{-2}s^{-1}$
- 2008:Test run
- 2009-now:$\tau - charm$ physics runs

- MDC: σ_p/p=0.5%@1 GeV, $\sigma_{dE/dx}$=6%;
- TOF: $\sigma_T = 68(110)$ ps for barrel(endcap); endcap TOF upgraded in 2015→ 60 ps;
- EMC: σ_E/E = 2.5% (5%) ps for barrel(endcap)

Data samples at BESIII

- Collected the world largest J/ψ, $\psi(2S)$ and $\psi(3770)$ data samples;
- BESIII has collected 20 fb^{-1} $\psi(3770)$, large D meson sample from $\psi \to D\bar{D}$.



New Physics and benefit of BESIII

- Standard Model (SM) is incredibly successful, it is well tested by many experiments.
- But it cannot explain:
  - Existence & mechanism of dark matter and dark energy;
  - Baryon asymmetry of the universe
  - Neutrino masses and oscillations, hierarchy

……

Benefit

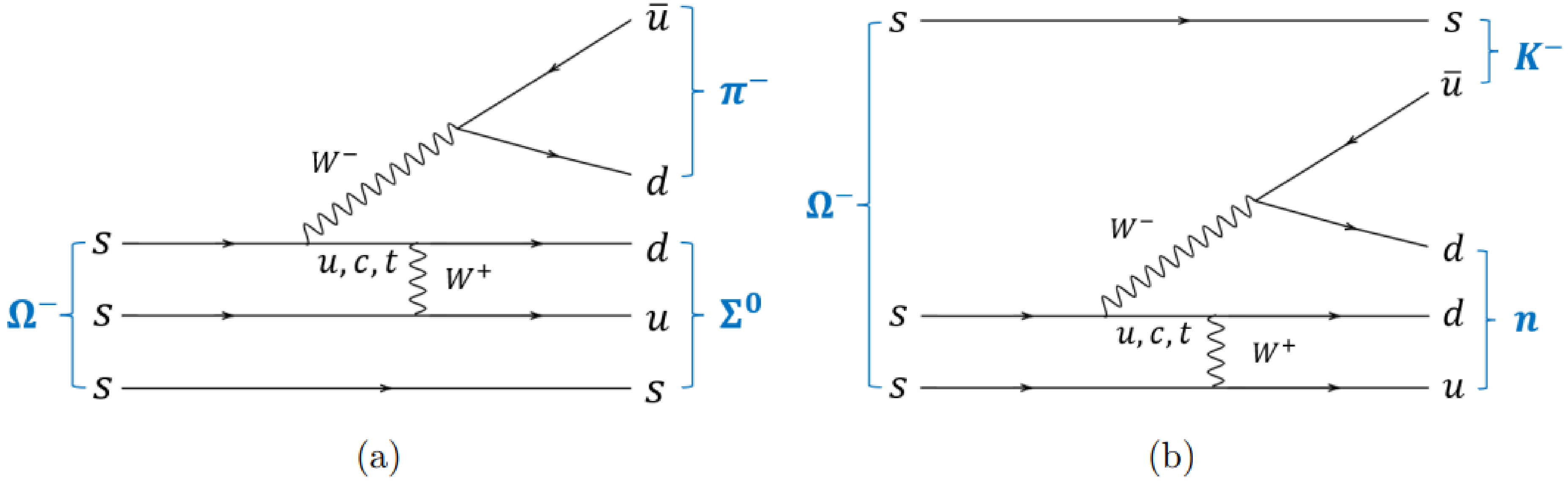
- **Huge data samples;**
- **Kinematic constraints:** deliver high purity for final states with invisible energy and photons;
- **Double-tag method**: allows almost background free studies, quantum coherence, high trigger efficiency, and easy detection of neutral particles
- **Semi-blind /full-blind strategy**: to avoid voluntary bias from analyst.

Search for $\Delta S = 2$ nonleptonic hyperon decays $\Omega^- \to \Sigma^0 \pi^-$ and nK^-

Motivation

JHEP 05 141 (2024)

- In the Standard Model (SM), nonleptonic hyperon decays involving a change in strangeness by two units (ΔS = 2) are highly suppressed. The branching fractions (BFs) of these decays in the SM are at the level of $10^{-17}\sim10^{-12}$[Phys. Rev. D 108 (2023) 055012].
- The ΔS = 2 nonleptonic hyperon decays may serve as probes of new physics, where the BFs could be enhanced to the level of $10^{-10}\sim10^{-7}$[Phys. Rev. D 108 (2023) 055012] when beyond the SM effects are considered.

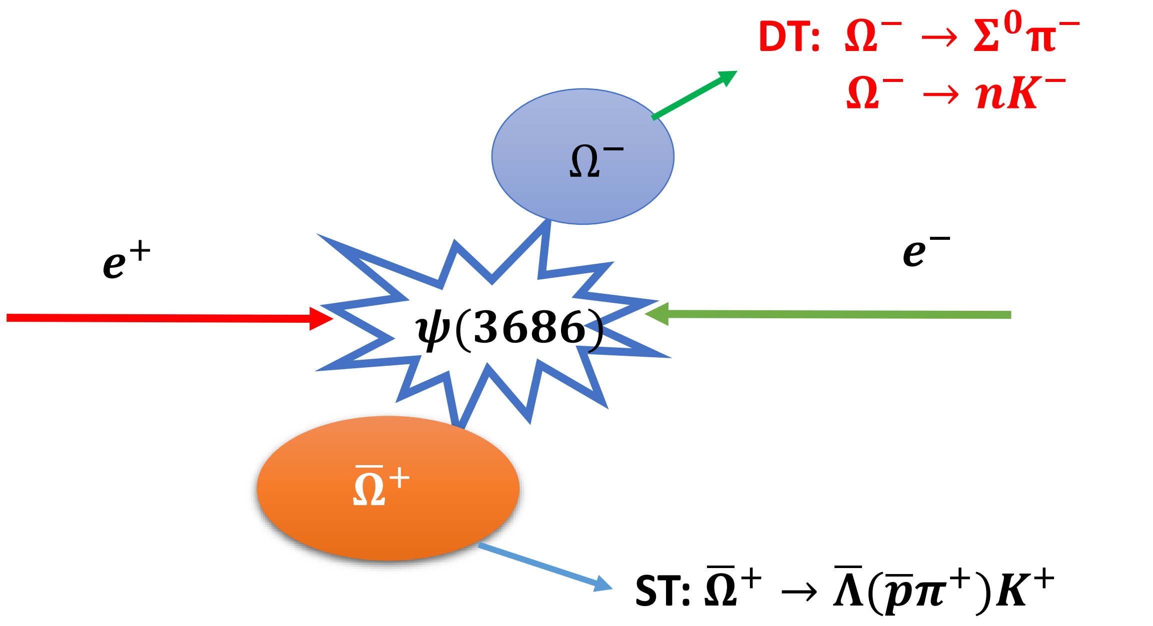


Feynman diagrams contributing to the ΔS = 2 nonleptonic hyperon decays (a)$\Omega^- \rightarrow \Sigma^0\pi^-$ and (b)$\Omega \rightarrow nK^-$ in the SM.

Analysis strategy and ST yields

JHEP 05 141 (2024)

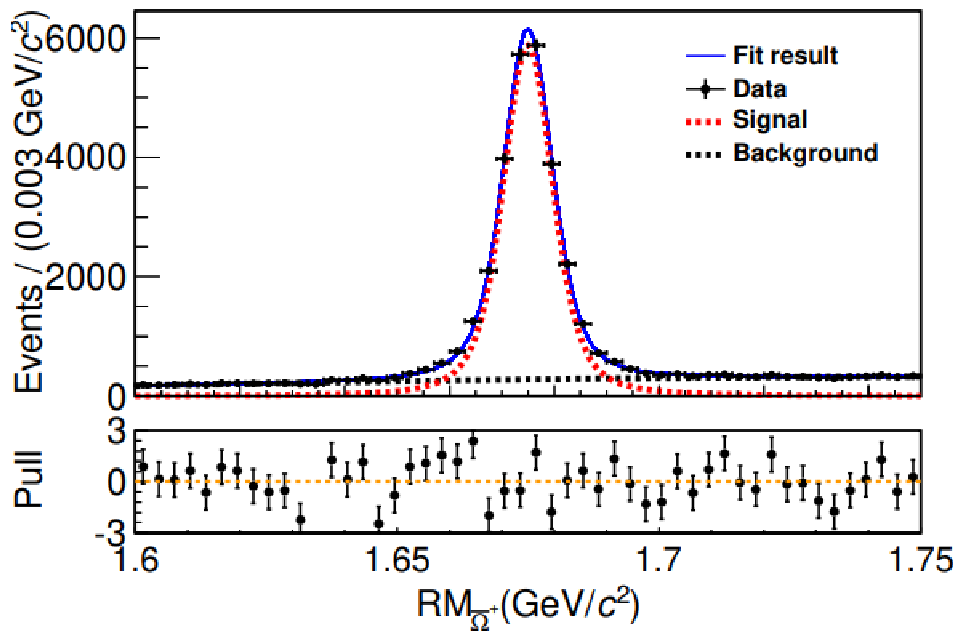
- **Data sample:**
  - Data: 2.712 billion $\psi(3686)$
  - Inclusive MC: 2.747 billion $\psi(3686)$
  - Signal MC: 1.27 million events
- **Double-tag method**
  - Single Tag(ST) model: $\bar{\Omega}^+ \to \bar{\Lambda} K^+$
  - Double Tag(DT) model: $\Omega^- \to \Sigma^0\pi^-$, $\Omega^- \to nK^-$



- **ST yields:** By fitting to the recoiling mass of $\bar{\Omega}^+$ from data to obtain the ST yields

$$\mathrm{RM}_{\bar{\Omega}^+} = \sqrt{(E_{CM} - E_{\bar{\Omega}^+})^2 - (\hat{p}_{\bar{\Omega}^+})^2}$$

- Signal shape: MC shape convolved Gaussian function
- Background shape: 2nd order Chebychev polynomial
- Signal region: $\mathrm{RM}_{\bar{\Omega}^+} \in (1.625, 1.695)\ \mathrm{GeV}/c^2$
- ST $\bar{\Omega}^+$ signal yields: (25819 ± 188), $\epsilon_{ST} = 21.11\%$



DT selection and DT yields

JHEP 05 141 (2024)

☐ DT selection:

- Candidates for DT from the surviving tracks in the system recoiling against the ST $\bar{\Omega}^{+}$ hyperons;
- Only reconstruct π^{-}/K^{-}
- PID:

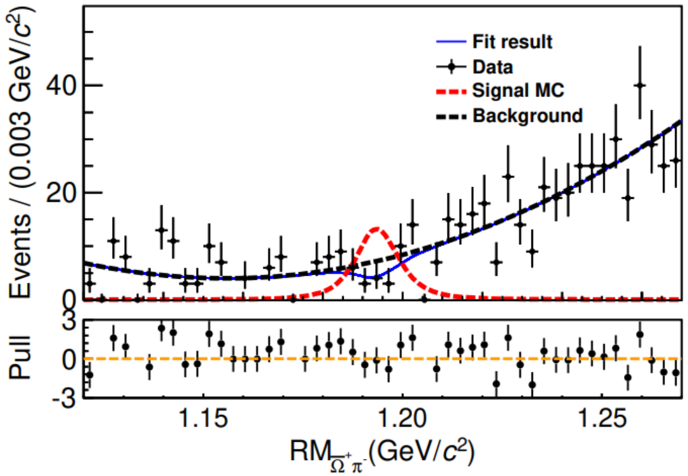
  π^{-}: $CL_{\pi} > CL_{K}\ \&\& CL_{\pi} > 0$

  K^{-}: $CL_{K} > CL_{\pi}\ \&\& CL_{K} > 0$
- $\Omega^{-} \to \Sigma^{0}\pi^{-}$: If there is more than one π^{-} candidate, the one with the highest momentum is retained.
- $\Omega^{-} \to nK^{-}$: No extra charged tracks.
- DT yields: By using the recoiling mass distribution of $\bar{\Omega}^{+}h(RM_{\bar{\Omega}^{+}h})$ to extract the DT yield, where h $=\pi$ or K

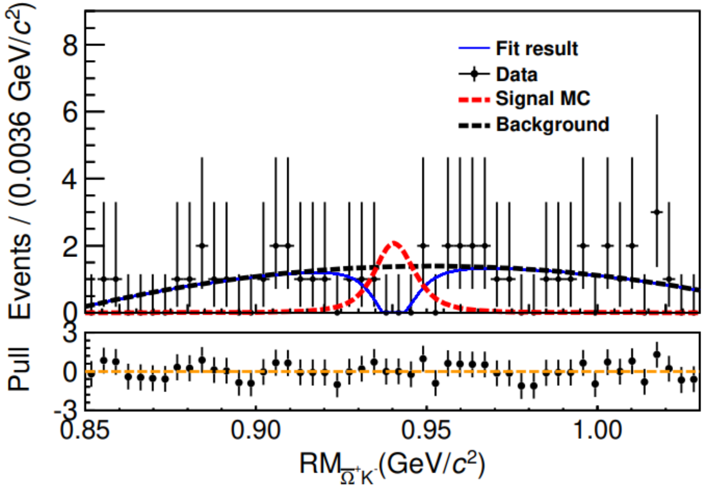
$$\mathrm{RM}_{\bar{\Omega}^{+}h} = \sqrt{(E_{CM} - E_{\bar{\Omega}^{+}h})^{2} - (\hat{p}_{\bar{\Omega}^{+}h})^{2}}$$

☐ DT yields:

- Signal shape: MC shape convolved Gaussian function
- Background shape: 2nd order Chebychev polynomial



$N^{DT} = -15.4^{+10.0}_{-9.1}$



$N^{DT} = -8.3^{+10.0}_{-3.71}$

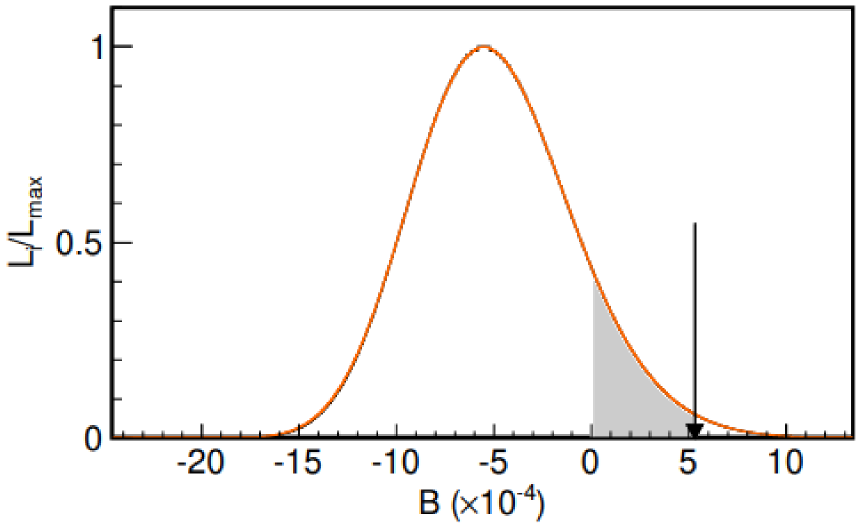
Results

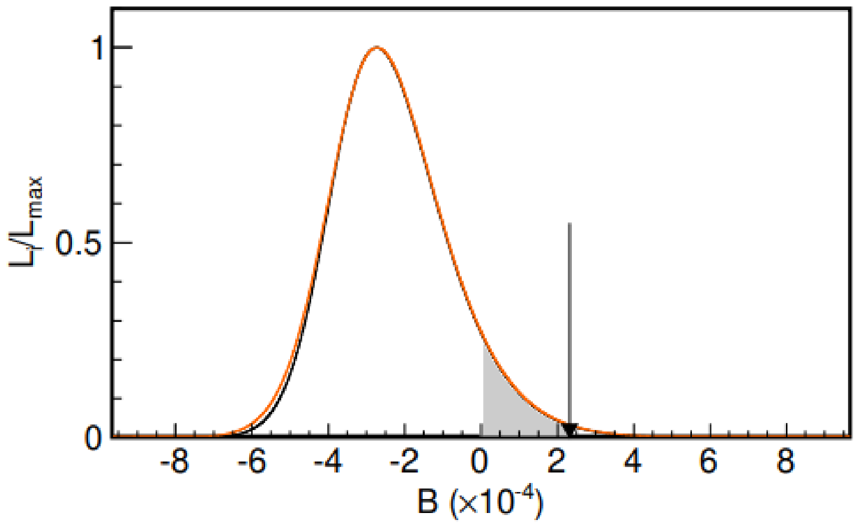
JHEP 05 141 (2024)

- The upper limit on the observed number of events(N_{sig}^{up}) with the Beyasian method at the 90% C.L. as

$$\frac{\int_0^{N_{sig}^{up}} \mathcal{L} dN_{sig}}{\int_0^{\infty} \mathcal{L} dN_{sig}}$$

$$\mathcal{B}^{U.L.} < \frac{N_{DT}/\epsilon_{DT}}{N_{ST}/\epsilon_{ST}}$$





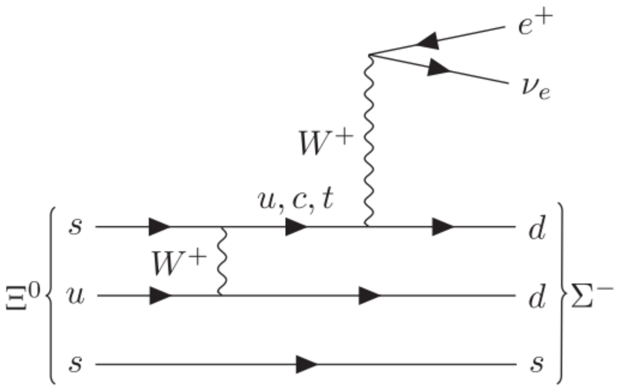
Decay mode	$N_{\rm ST}$	$\epsilon_{\rm ST}$ (%)	$N_{\rm DT}^{\rm U.L.}$	$\epsilon_{\rm DT}$ (%)	$\mathcal{B}^{\rm U.L.}$ ($\times 10^{-4}$)
$\Omega^- \to \Sigma^0\pi^-$	25819 ± 188	21.11	12	18.29	5.4
$\Omega^- \to nK^-$			5	16.92	2.4

Search for hyperon $\Delta S = \Delta Q$ violating decay $\Xi^0 \to \Sigma^- e^+ \nu_e$

Motivation(I)

Phys. Rev. D 107, 012002 (2023)

- Hyperon semileptonic decays play an important role in understanding the interplay between weak and strong interactions, where the former determines quark flavor transitions and the latter determines hadronic structures[Phys. Rev. D 35, 934 (1987)];
- The $\boldsymbol{\Delta S} = \boldsymbol{\Delta Q}$ rule: change in strangeness (ΔS) should have the same sign as charge (ΔQ)
  - First proposed in 1958[Phys. Rev. 109, 193 (1958)] to explain the absence of certain hyperon decays;
  - Became one of the basic assumptions in Cabibbo's weak interaction theory propose exact SU(3) symmetry for weak hadronic currents. Therefore, any violation of this rule, which is allowed by the Standard Model in second-order weak interaction as the Feynman diagram shown below, would demonstrate the existence of weak currents belonging to higher multiples.



Phys. Rev. Lett. 10, 531 (1963);
Annu. Rev. Nucl. Part. Sci. 53, 39 (2003).;
F. James, J. Phys. (Paris), Colloq. 32, C3 (1971)

Motivation(II)

Phys. Rev. D 107, 012002 (2023)

- **On experimental side**:
  - No $\Delta S = \Delta Q$ violating decay has been observed yet;
  - Much attention drawn to neutral kaon decays $K_S^0 \to \pi^{\pm} e^{\mp} \nu$ for they also relates to CP & CPT invariance as input variables, results last updated in 2018 by KLOE-2[JHEP 09 (2018) 021];
  - Searches in hyperons stopped in 1970s alone with most typical hyperon semi-leptonic decays;
  - Current upper limit of $\mathcal{B}(\Xi^0 \to \Sigma^- l^+ \nu_l)$ is 0.9×10^{-3}, last updated 1974 by fixed target experiment based on 2975 Ξ^0 events, and is a relative BF result [Phys. Rev. D 10 (1974) 3545].

- BESIII has collected 10 billion J/ψ events, could produce $\sim 10^6$ hyperon pairs via $J/\psi \to B\bar{B}$
  - Capable to search for many rare and forbidden hyperon decays;
  - Recent BESIII results with hyperon semileptonic decays comprise the studies of the decays $\Lambda \to p\mu^- \bar{\nu}_\mu$ [Phys. Rev. Lett. 127, 121802 (2021)] and $\Xi^- \to \Xi^0 e^- \bar{\nu}_e$[Phys. Rev. D 104, 072007 (2021)]

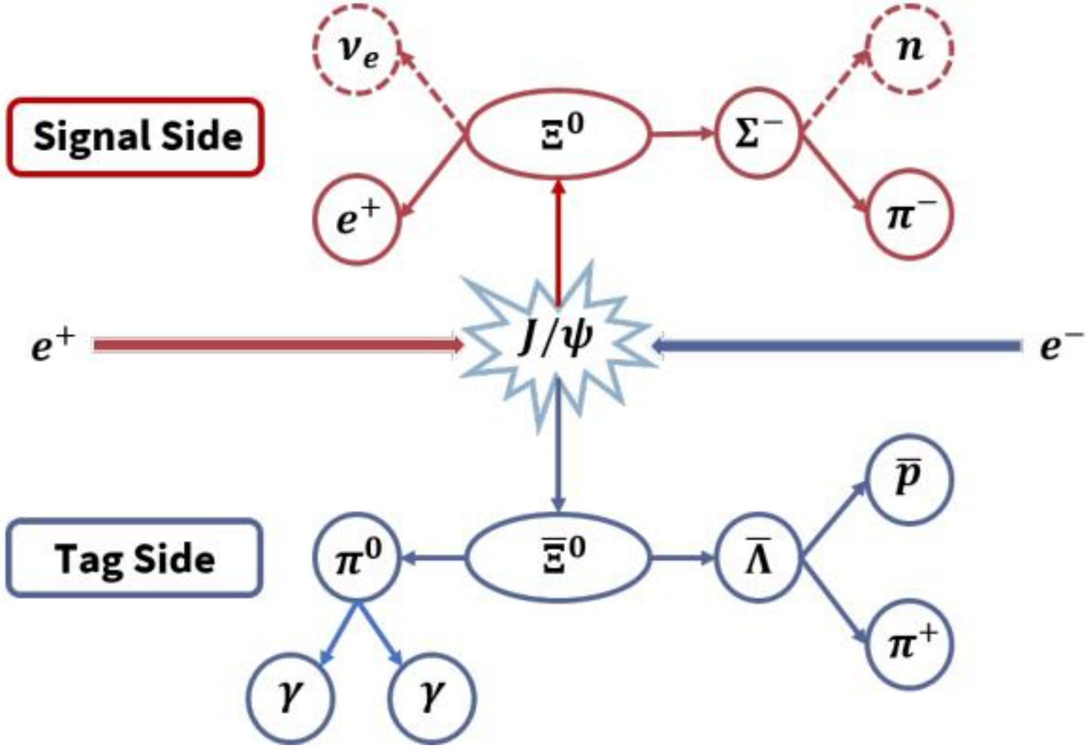
- Measure the absolute BF of this process at a collider experiment for the first time, and with higher precision.

Analysis method and data sets

Phys. Rev. D 107, 012002 (2023)

☐ Double tag method

$$\mathcal{B}_{sig} = \frac{N_{sig}^{obs}/\epsilon_{sig}}{N_{tag}^{obs}/\epsilon_{tag}}$$



☐ Data sets

Year	Total $N_{J/\psi}$ (10^6)	Semi-blind ratio (%)	Semi-blind $N_{J/\psi}$ (10^6)
2009	224.04	~ 30	67.21
2012	1088.5	~ 10	108.9
2018	4581.8	~ 10	458.2
2009	4190.5	~ 10	419.1
Total	10087.8	~ 10	1053.2

- Data: NPG semi-blind J/ψ data sample

  ~30 % of 2009 data, ~10% of 2012&2018&2019 data
- Inclusive MC:

  Official inclusive MC corresponding to the full (10 billion) J/ψ data
- Signal MC: 1×10^6 in total

  $J/\psi \to \Xi^0\bar{\Xi}^0$ J2BB1

  $\Xi^0 \to \bar{\Lambda}\pi^0$ HypWK/PHSP

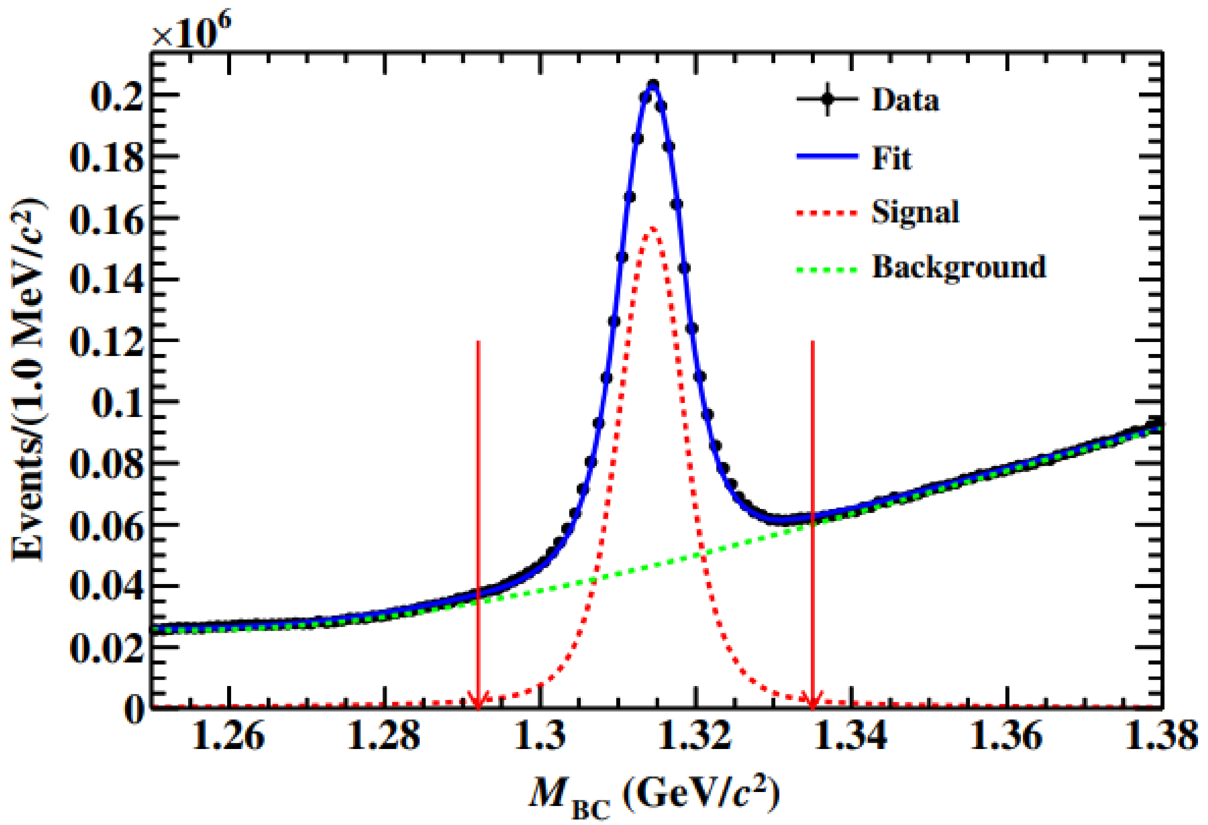
  $\Xi^0 \to \Sigma^- e^+ \nu_e$ PHOTOS PHSP

ST yields and efficiency

Phys. Rev. D 107, 012002 (2023)

- The yields of ST $\bar{\Xi}^0$ hyperons is obtained from a binned maximum-likelihood fit to the distribution of beam-constrained mass defined as：

$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2/c^4 - |\vec{p}_{\bar{\Lambda}\pi^0}|^2/c^2}$$



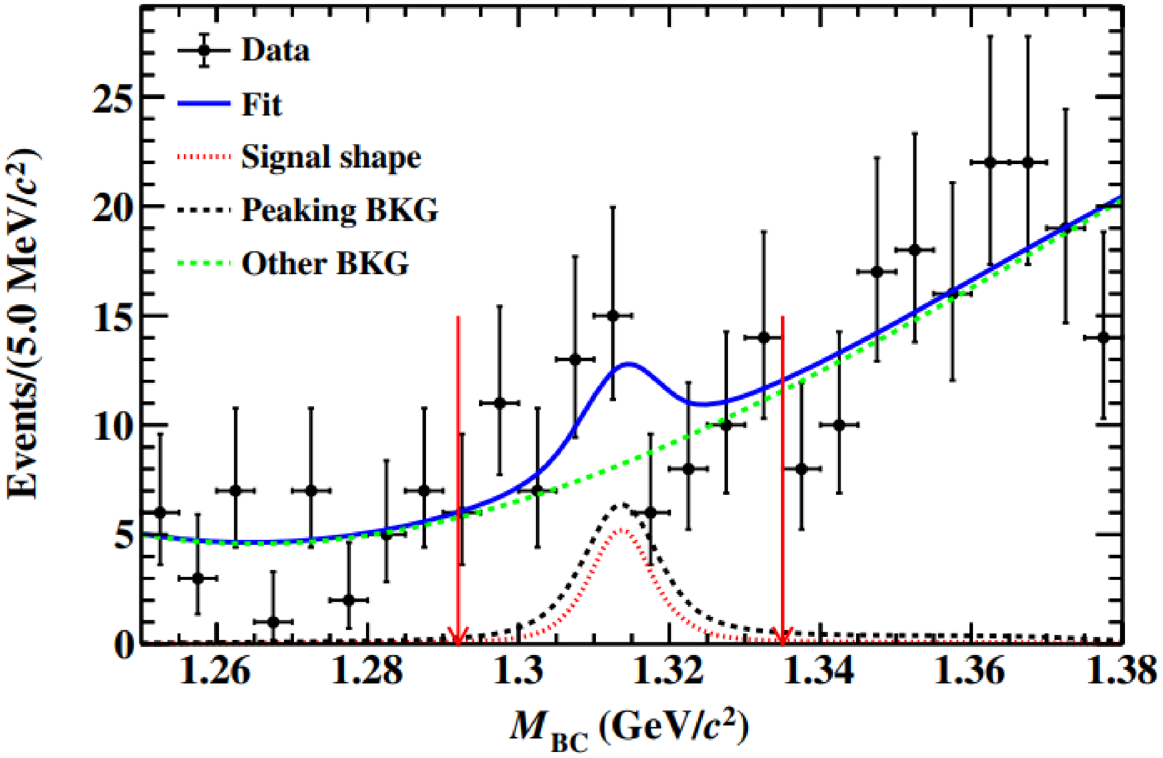
- The ST yield: $(1,855,681 \pm 1{,}865)$ in the signal region (1.292, 1.335) GeV/c^2;
- $\epsilon_{tag} = (12.23 \pm 0.01)\%$
- The signal shape is modeled by the MC simulated shape convolved with a Gaussian function;
- The background shape is described by a second-order Chebychev polynomial.

DT selection and DT yields —($\Xi^0 \to \Sigma^- e^+ \nu_e$)

Phys. Rev. D 107, 012002 (2023)

- **Σ^- candidate is reconstructed via the $\Sigma^- \to n\pi^-$ decay;**
- Treat both the neutron and neutrino as missing particles;
- No extra charge track in the signal side;

- The DT signal yield is measured from the fit to the M_{BC} distribution of ST side because no similar observables could be constructed at the DT side.



➢ $N_{\mathrm{DT}} = (-4.9 \pm 8.6)$ in the signal region of (1.292,1.335) GeV/c^2;

➢ $\epsilon_{DT} = (5.68 \pm 0.04) \times 10^{-3}$

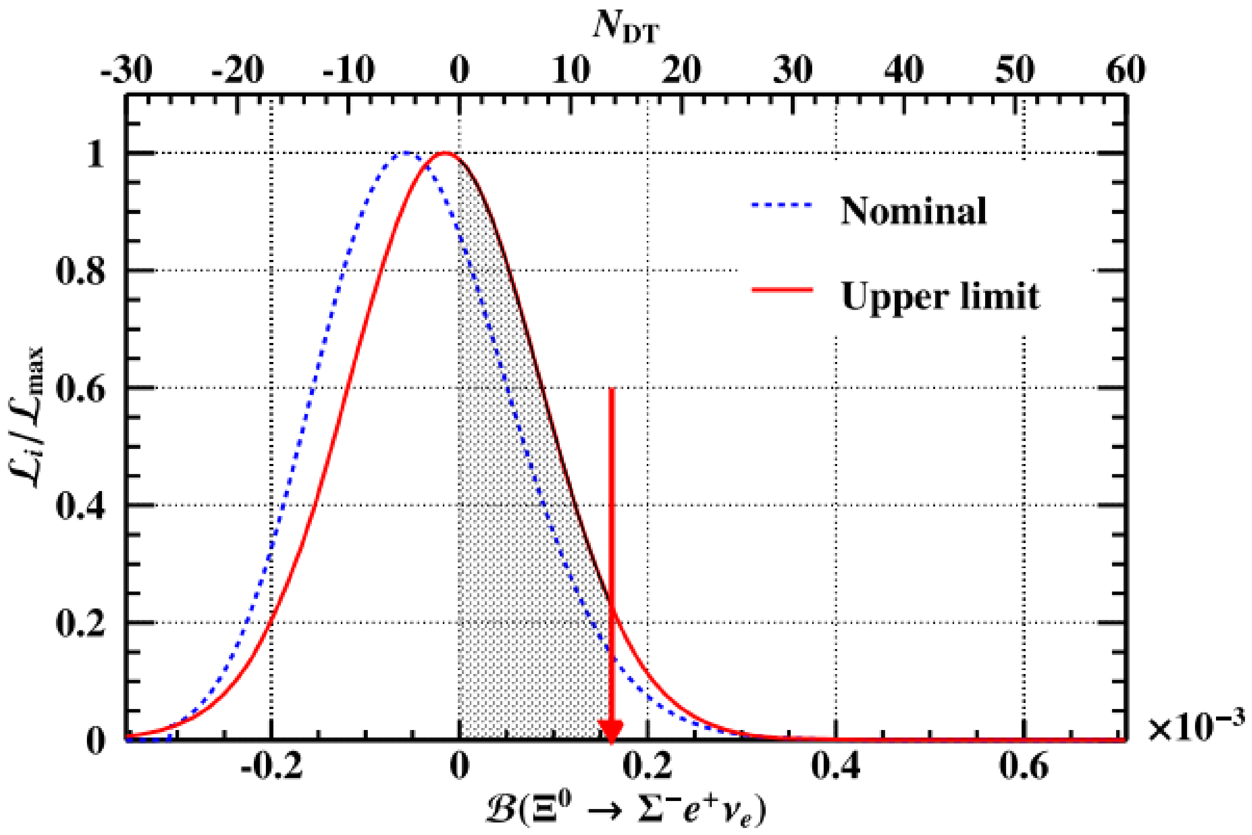
Result

Phys. Rev. D 107, 012002 (2023)

- No significant signal observed in data, the upper limit on the branching fraction $\mathcal{B}(\Xi^0 \to \Sigma^- e^+ \nu_e)$ is set using Bayesian method.

The formula for considering the systematic uncertainty into the likelihood distribution

$$\mathcal{L}'(n) \propto \int_0^1 \left(n \frac{\epsilon}{\epsilon_0}\right) e^{-\frac{(\epsilon-\epsilon_0)^2}{2\epsilon_\epsilon^2}} d\epsilon$$



- $\mathcal{B}(\Xi^0 \to \Sigma^- e^+ \nu_e) < 1.6\times 10^{-4}$ @90% C.L.

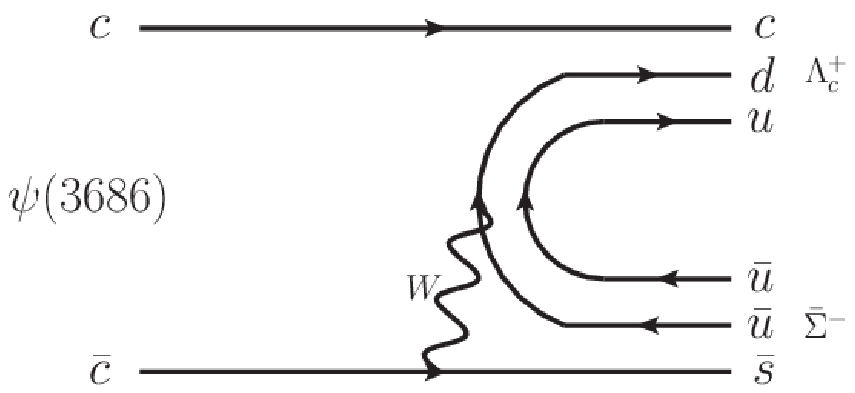
Search for the rare decay $\psi(3686) \to \Lambda_c^+ \overline{\Sigma}^- + c.c.$

Motivation

Chinese Phys. C 47 013002 (2023)

- A thorough study of the production and decay processes of baryons will provide a clearer insight into the structure of hadrons, the underlying physics , the mechanism and the fundamental interactions, and such processes may be more sensitive to new physics beyond the SM.
- Searches for purely baryonic weak $\psi(3686)$ decays involving a charmed baryon Λ_c^+ in the final state have never previously been performed.
- SM : $\mathcal{B}(\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.) \sim 10^{-10}$ [1]   [1] Chin.Phys.Lett. 28 071301

  BSM: $\mathcal{B}(\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.) \sim 10^{-5} - 10^{-6}$.



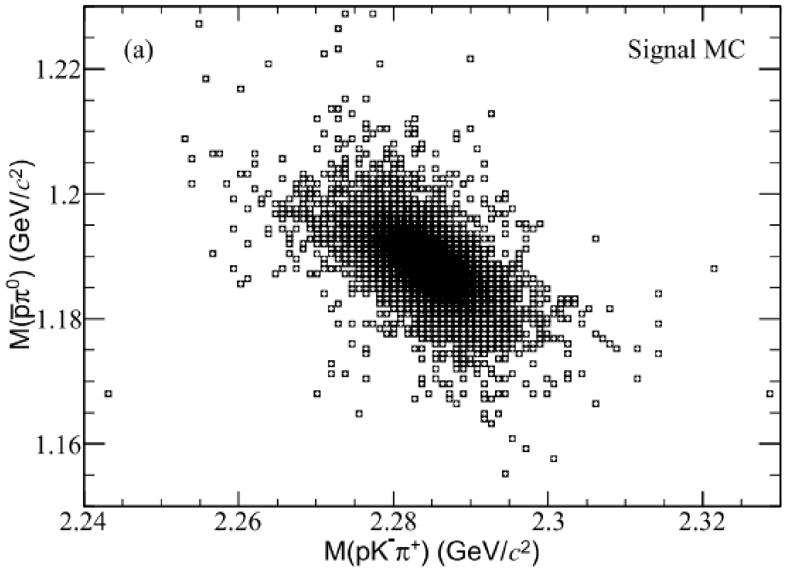
Feynman diagram for $\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^-$ in the SM.

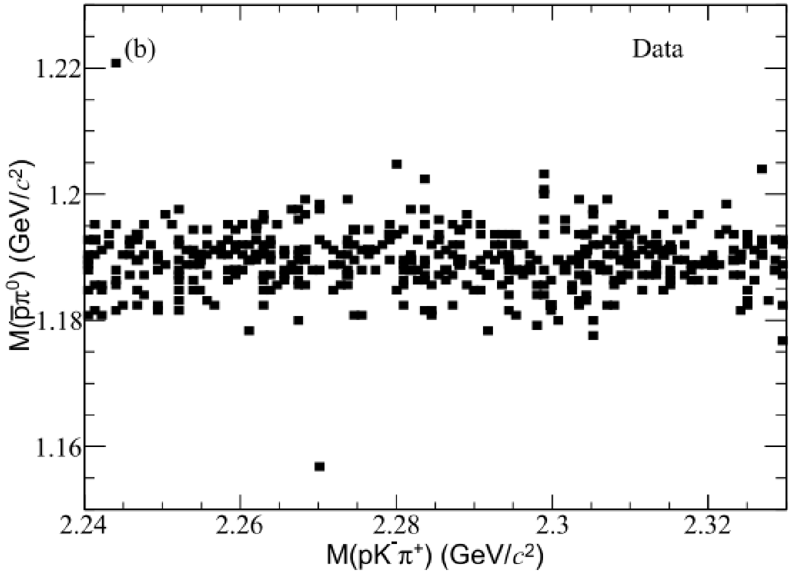
Background analysis

Chinese Phys. C 47 013002 (2023)

- Two main background sources
  - $\psi(3686) \to K^*(892)^- p\bar{\Lambda}$ $(K^*(892)^- \to \pi^0 K^-,\ \bar{\Lambda} \to \pi^+\bar{p})$
    - ✓ Suppressed by requiring the invariant mass $\pi^+ p (M(\pi^+\bar{p})) \notin [1.090, 1.130]\ \mathrm{GeV}/c^2$
  - $\psi(3686) \to \bar{K}^{*0}(892) p\bar{\Sigma}^-$ $(\bar{K}^{*0}(892) \to \pi^+ K^-,\ \bar{\Sigma}^- \to \bar{p}\pi^0)$
    - ✓ Suppressed by requiring the invariant mass $K^-\pi^+ (M(K^-\pi^+)) \notin [0.756, 1.036]\ \mathrm{GeV}/c^2$

Distribution of $M(\bar{p}\pi^0)$ versus $M(pK^-\pi^+)$ for the accepted candidate events in the signal MC sample and data.



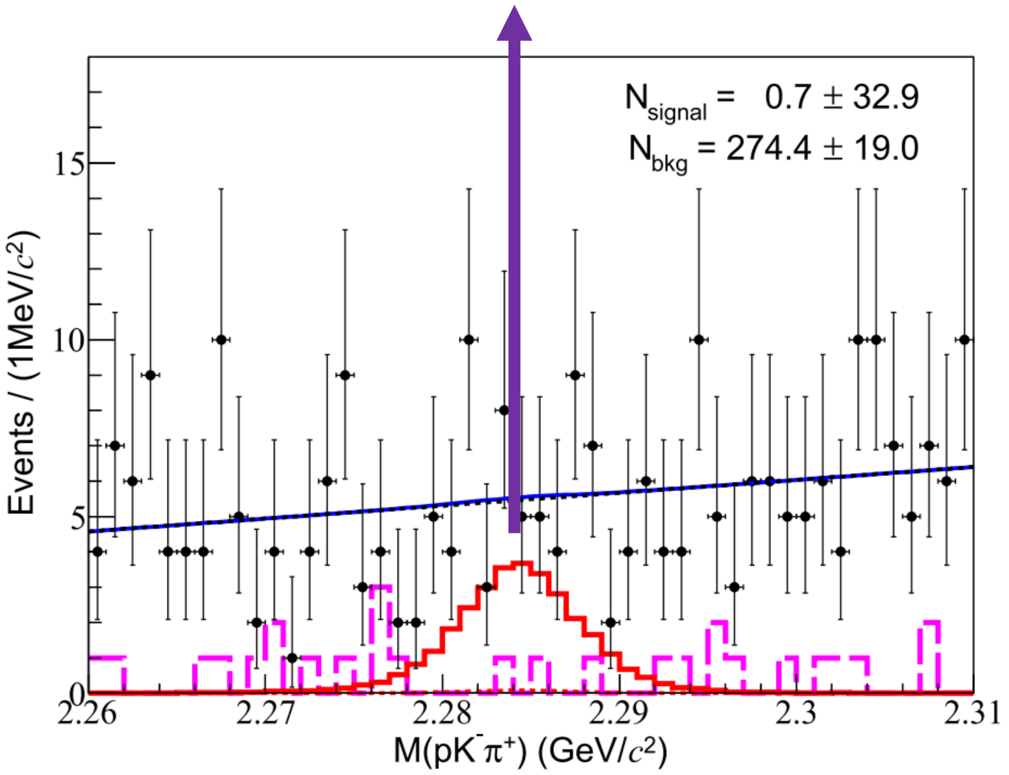


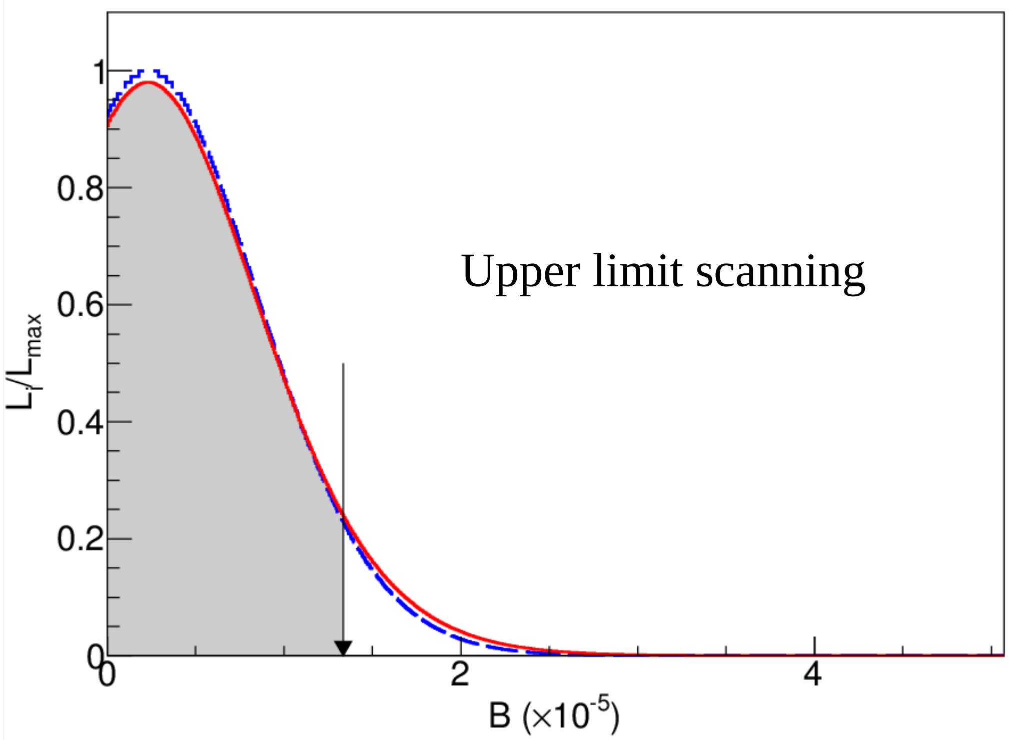
Result

Chinese Phys. C 47 013002 (2023)

➢ Fit in $M(pK^-\pi^+)$ to extract the signal yields

If a signal exists, the Λ_c^+ peak will be observed.





➢ Signal shape: MC shape convolved Gaussian function

➢ Background shape: 1st order Chebychev polynomial

➢ No significant signal is observed;

➢ $\mathcal{B}(\psi(3686)\to\Lambda_c^+\bar{\Sigma}^- + c.c.) < 1.4\times 10^{-5}$ @90% C.L.

➢ First time to search for the purely baryonic rare $\psi(3686)$ decay

Observation of the hindered electromagnetic Dalitz decay $\psi(3686) \to e^+e^-\eta_c$

Motivation(I)

Phys. Rev. D 106, 112002 (2022)

- In experiment, the electromagnetic(EM) Dalitz decays of light unflavoured vector mesons(ρ^0, ω, φ) have been widely observed. But only few decays of charmonium vector mesons ($J/\psi, \psi(3686)$) to light unflavoured pseudo-scalar mesons are studies in theory and observed by experiments.
- The EM Dalitz decay, $\psi(3686) \to e^+e^-\eta_c$, provides an ideal opportunity to probe the structure of $\psi(3686)$ and to investigate the interaction between $\psi(3686)$ and virtual photon.
- The hindered M1 transition, $\psi(3686) \to \gamma\eta_c$, **is a significant process to understand the spin interaction between charmonium states. In experiment, the ratio**

$$R = \frac{\Gamma(\psi(3686) \to e^+e^-\eta_c)}{\Gamma(\psi(3686) \to \gamma\eta_c)}$$

can be used to test theoretical models, where many uncertainties can be cancelled out.

Motivation(II)

Phys. Rev. D 106, 112002 (2022)

- In general, the q^2-dependent($q^2 = M(e^+e^-)$) differential decay width of $\psi(3686) \to e^+e^-\eta_c$ can be normalized to the width of the corresponding radiative decay $\psi(3686) \to \gamma\eta_c$;

$$\frac{d\Gamma(\psi(3686) \to e^+e^-\eta_c)}{d\Gamma(\psi(3686) \to \gamma\eta_c)} = \left|F_{\psi(3686)\eta_c}(q^2)\right|^2 \times QED(q^2)$$

- In the Vector Dominance Model (VDM), the transition form factor between $\psi(3686)$ and η_c can be parameterized in the single pole approximation,

$$F_{\psi(3686)\eta_c(q^2)} = \frac{1}{1-q^2/\Lambda^2}$$

- This study can be also provide an important opportunity to measure the absolute branching fraction of η_c decays.

Data sets and analysis Method

Phys. Rev. D 106, 112002 (2022)

- **Data**
  - $(448.1 \pm 2.9) \times 10^6\ \psi(3686)$ events taken at $\sqrt{s} = 3.686$ GeV
  - 2.93 fb^{-1} data taken at $\sqrt{s} = 3.773$ GeV – study the continuum process $e^+e^- \to e^+e^-\eta_c$
  - Inclusive MC: 506 M inclusive MC at $\sqrt{s} = 3.686$ GeV—study the potential background events
  - Exclusive MC: Detection efficiency , Peaking background

- Partial reconstruction (in order to observe more signal events):
  - Only reconstruct the lepton pair(e^+e^-): save all combinations of e^+e^- in an event;
  - In the recoil mass of e^+e^-[RM(e^+e^-)], look for the η_c signal.

- Branching fraction of $\psi(3686) \to e^+e^-\eta_c(\mathcal{B}_{sig})$ is calculated by

$$\mathcal{B}_{sig} = \frac{N_{sig}^{obs}}{N_{\psi(3686)} \cdot \epsilon_{sig}}$$

Result

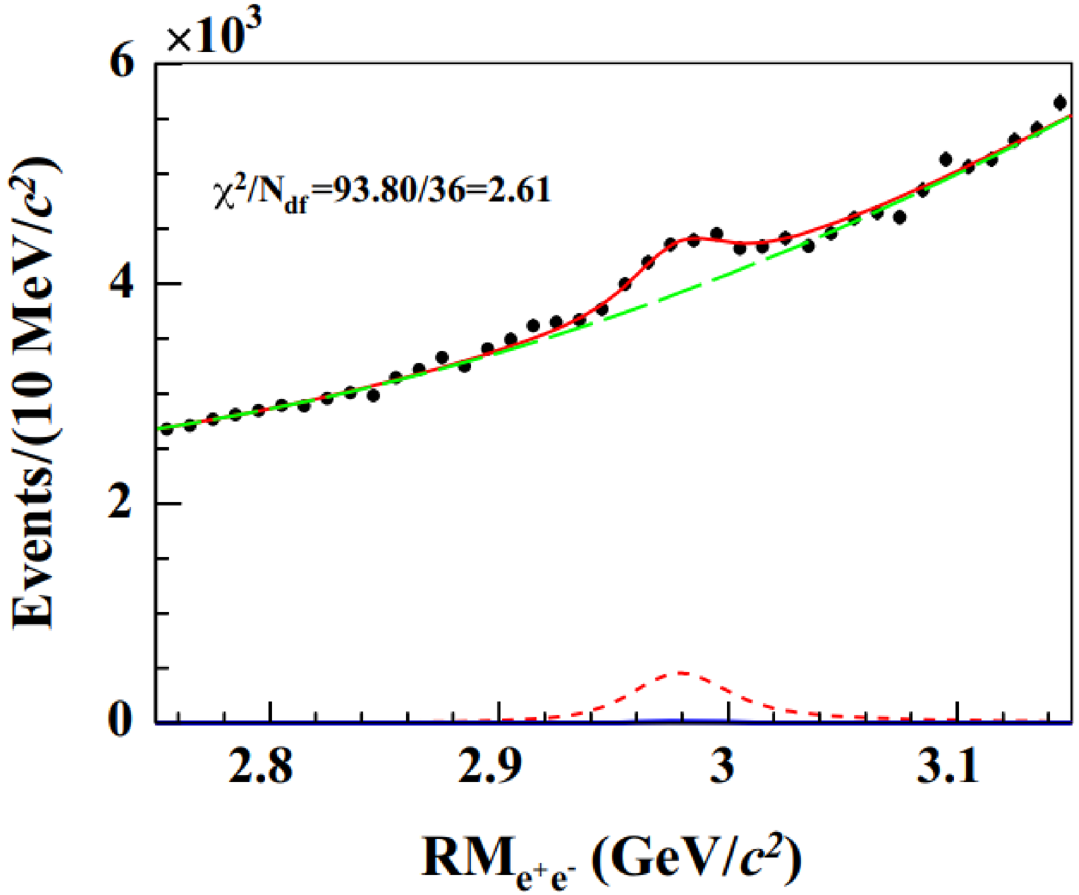
- **Signal shape:** Signal MC shape convolved with a Gaussian function;
- **Non-peaking background**: a second-order Chebyshev polynomial function.
- **Peaking background: fixed size of 76.**
  - $\gamma^*\gamma^* \to \eta_c$
  - $\psi(3686) \to \gamma\eta_c$

✓ An observation of the hindered electromagnetic Dalitz decay $\psi(3686) \to e^+e^-\eta_c$ with a significance of 7.9σ

$$N_{\rm sig}^{\rm obs} = 3078 \pm 329$$

$$\epsilon_{sig} = 18.22\%$$

An unbinned maximum likelihood fit



$$\mathcal{B}(\psi(3686) \to e^+e^-\eta_c)$$

$$= (3.77 \pm 0.40_{stat} \pm 0.18_{syst}) \times 10^{-5}$$

Summary

- The rare decays are important to probe New Physics beyond the Standard Model;
- With $10.1 \times 10^9\ J/\psi$ events @3.097 GeV, 2.7 billion events and $(448.1 \pm 2.9) \times 10^6\ \psi(3686)$ and @ 3.686 GeV, BESIII has performed studies on rare decay and the upper limit of branching fractions (@90% C.L) are obtained. An observation of the hindered electromagnetic Dalitz decay $\psi(3686) \to e^+e^-\eta_c$ with a significance of 7.9σ.

  - $\mathcal{B}(\Omega^- \to \Sigma^0\pi^-) < 5.4 \times 10^{-4}$

    $\mathcal{B}(\Omega^- \to \Sigma^0\pi^-, nK^-) < 2.4 \times 10^{-4}$ JHEP 05 141 (2024)
  - $\mathcal{B}(\Xi^0 \to \Sigma e \nu) < 1.6 \times 10^{-4}$ Phys. Rev. D 107, 012002 (2023)
  - $\mathcal{B}(\psi(2S) \to \Lambda_c^+\bar{\Sigma}^- + c.c.) < 1.4 \times 10^{-5}$ Chinese Phys. C 47 013002 (2023)
  - $\mathcal{B}(\psi(2S) \to e^+e^-\eta_c) = (3.77 \pm 0.40_{stat} \pm 0.18_{syst}) \times 10^{-5}$ Phys. Rev. D 106, 112002 (2022)

Thank you for your attention!