BESIII新物理实验结果

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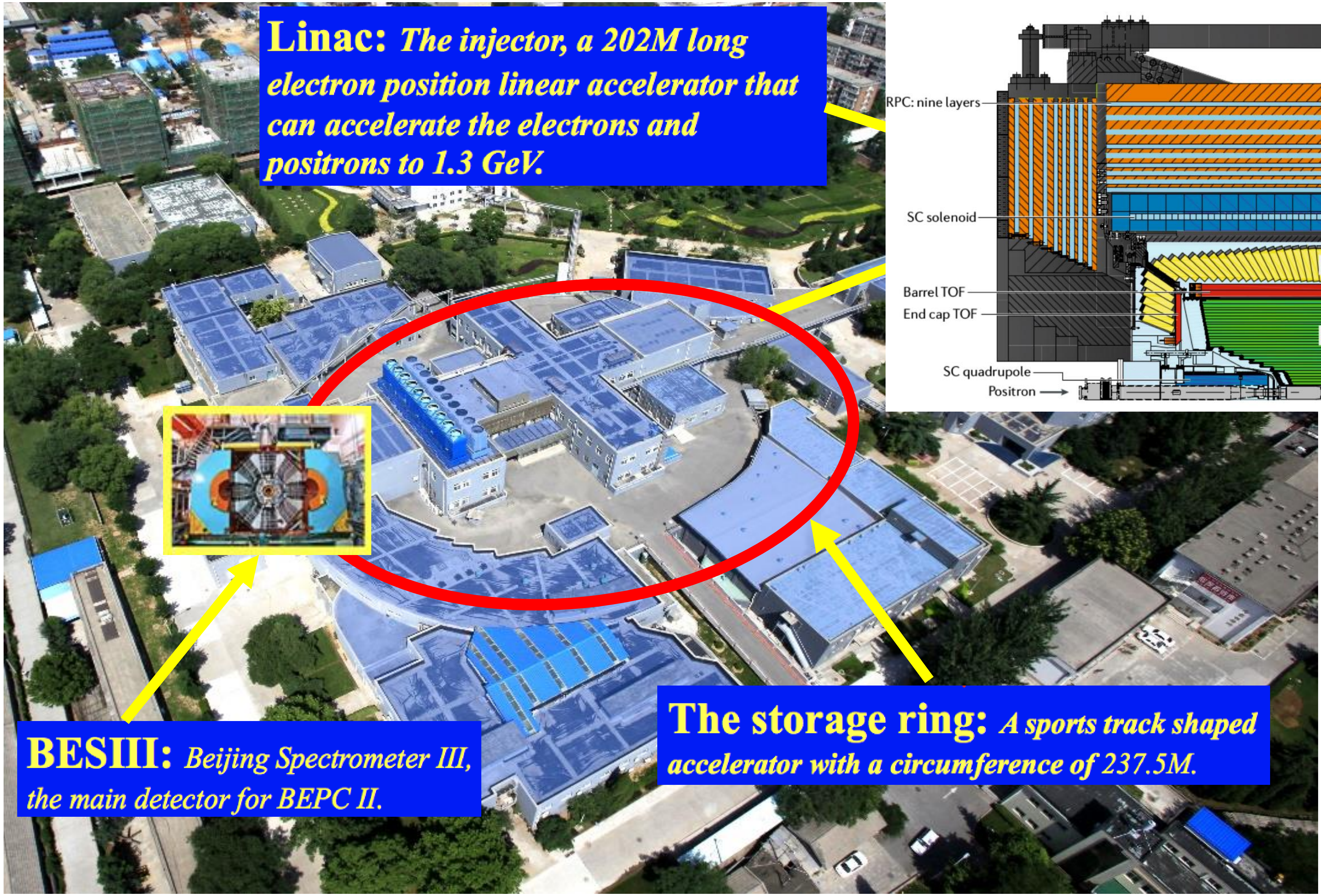
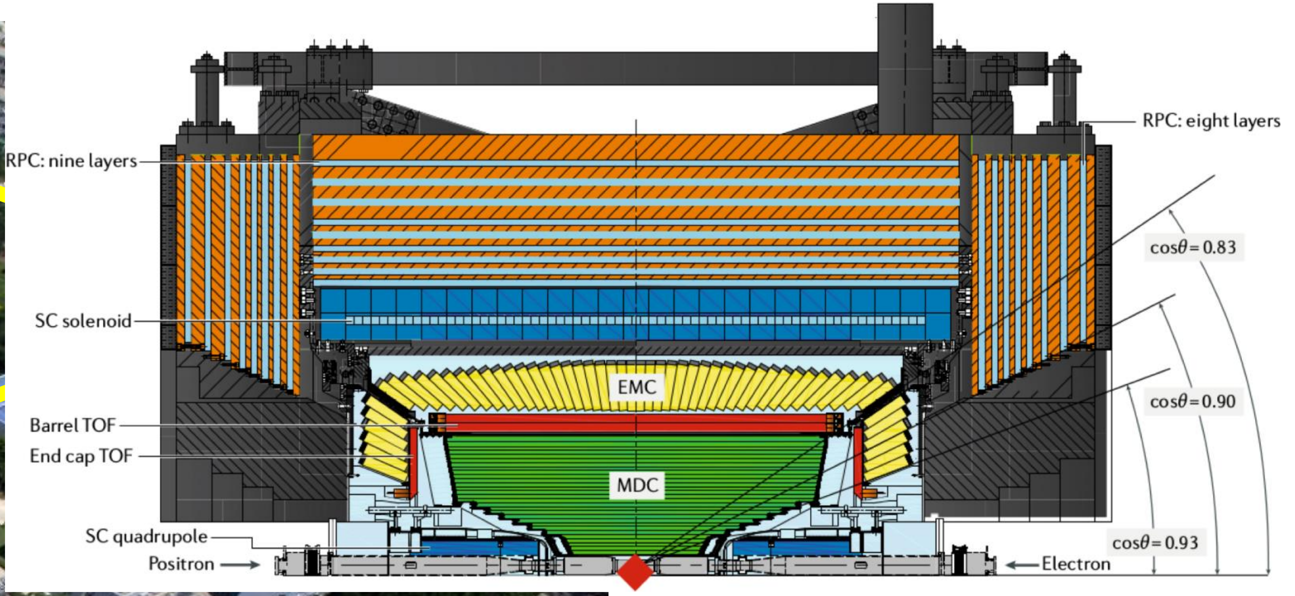
BESIII实验物理研讨会

2026.02.06-08

Outline

01 Introduction





Electromagnetic Calorimeter

- CsI(Tl): $\frac{\sigma_E}{E} = 2.5\%(5\%)$ for barrel(endcap)

Time-of-Flight System

- $\sigma_T = 68(60)$ps for barrel(endcap)

Muon Chamber

Superconducting Solenoid $(1T)$

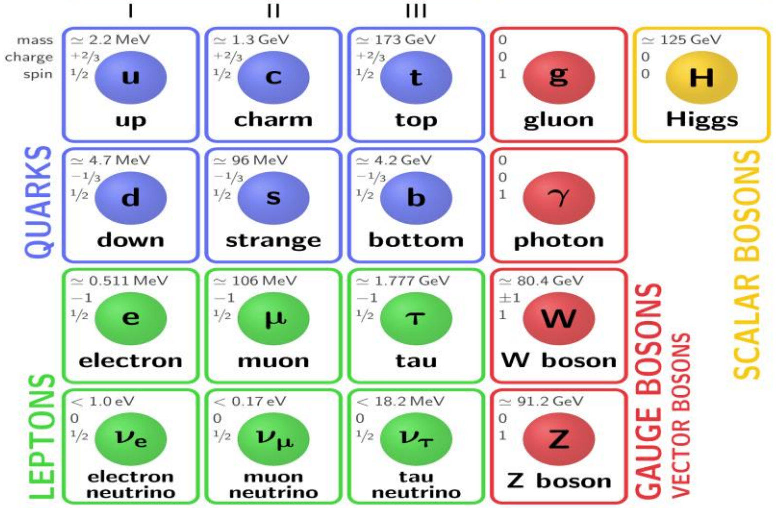
Main Drift Chamber

- $\frac{\sigma_p}{p} = 0.5\%$ @ $1\ \mathrm{GeV}/c$
- $\sigma_{dE/dx} = 6\%$

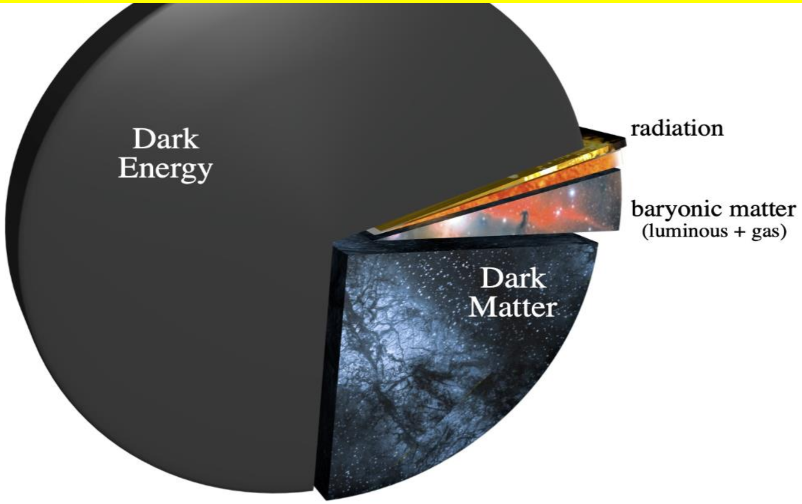
01 Introduction

- **The existence of new physics is inevitable**
  - ✓ Although SM is successful
  - ✓ Yet SM can't explain many experimental results
- **Why low energy region**
  - ✓ Non-Collider Exp.: many, no observation
  - ✓ High Energy Collider Exp.: many, no observation
  - ✓ Low Energy Collider Exp.: few, complementary
- **Our Advantages**
  - ✓ High lum, large data, good detector, clean environment
  - ✓ Complete kinematic constraint: MM^2, U_{miss}, M_{recoil}, M_{BC}, DT method
  - ✓ Richness of various control samples
  - ✓ Common usage of miscellaneous tools

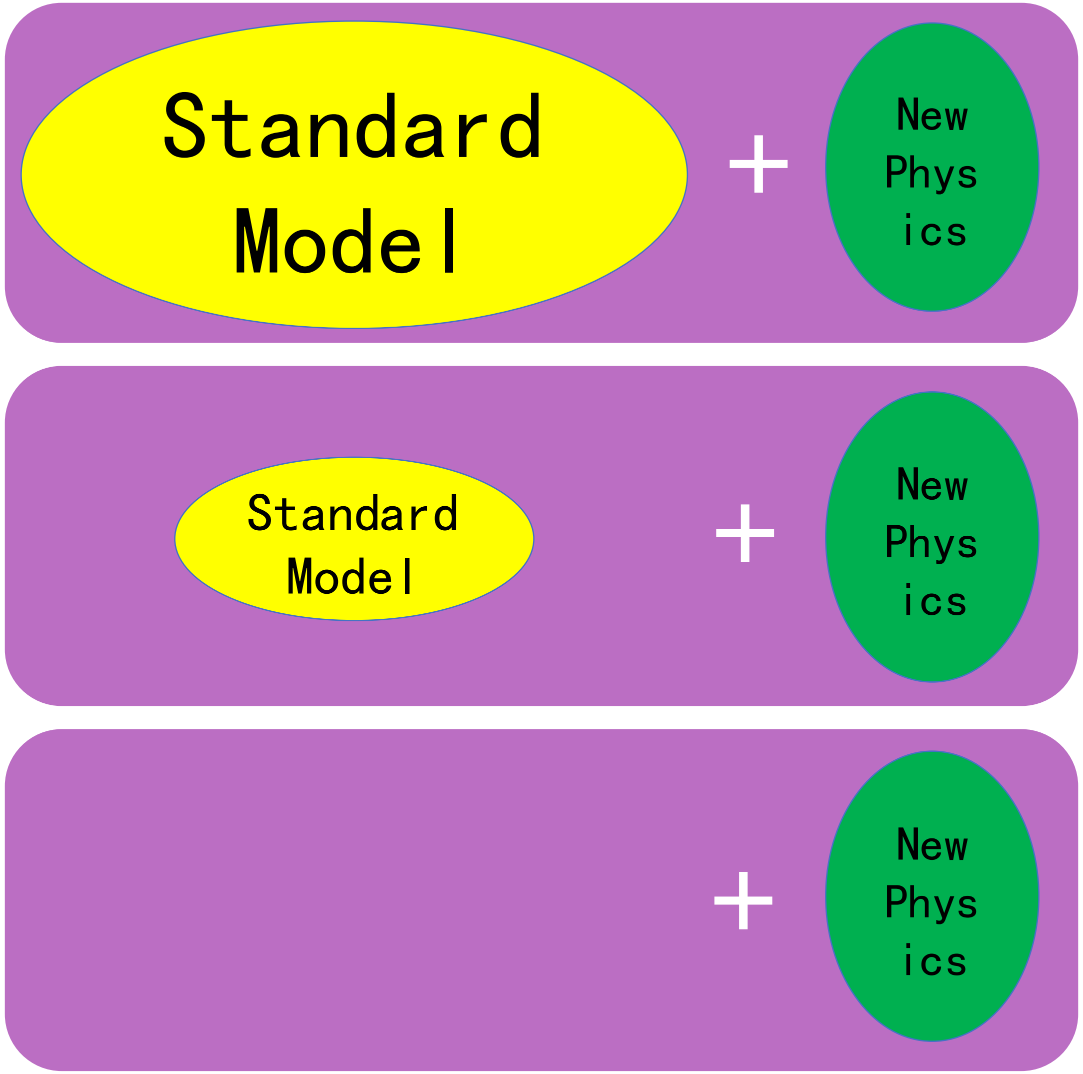
Seems already known a lot



Actually knows little(<5%)



01 Introduction



Based on vast data samples and the secondary particle samples ($\eta, \eta', \omega, \phi, K_S^0, \Lambda$, etc.) at BESIII, rare or forbidden processes are studied with high precision, thereby testing various BSM theories.

SM process: "dominant"

SM process: "highly suppressed"

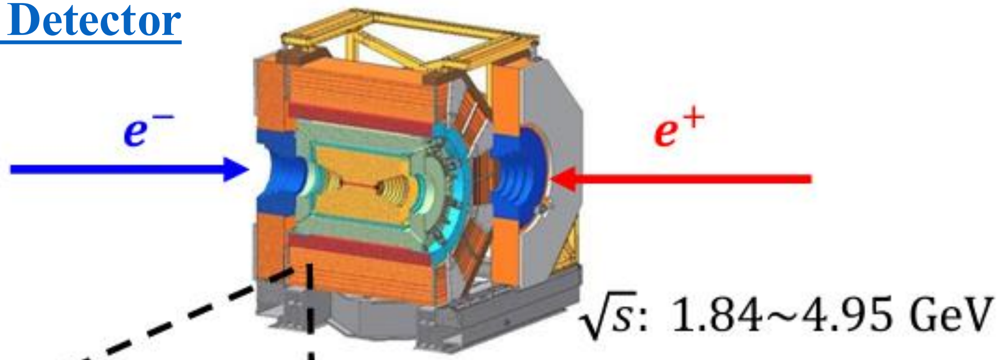
SM process: "forbidden"

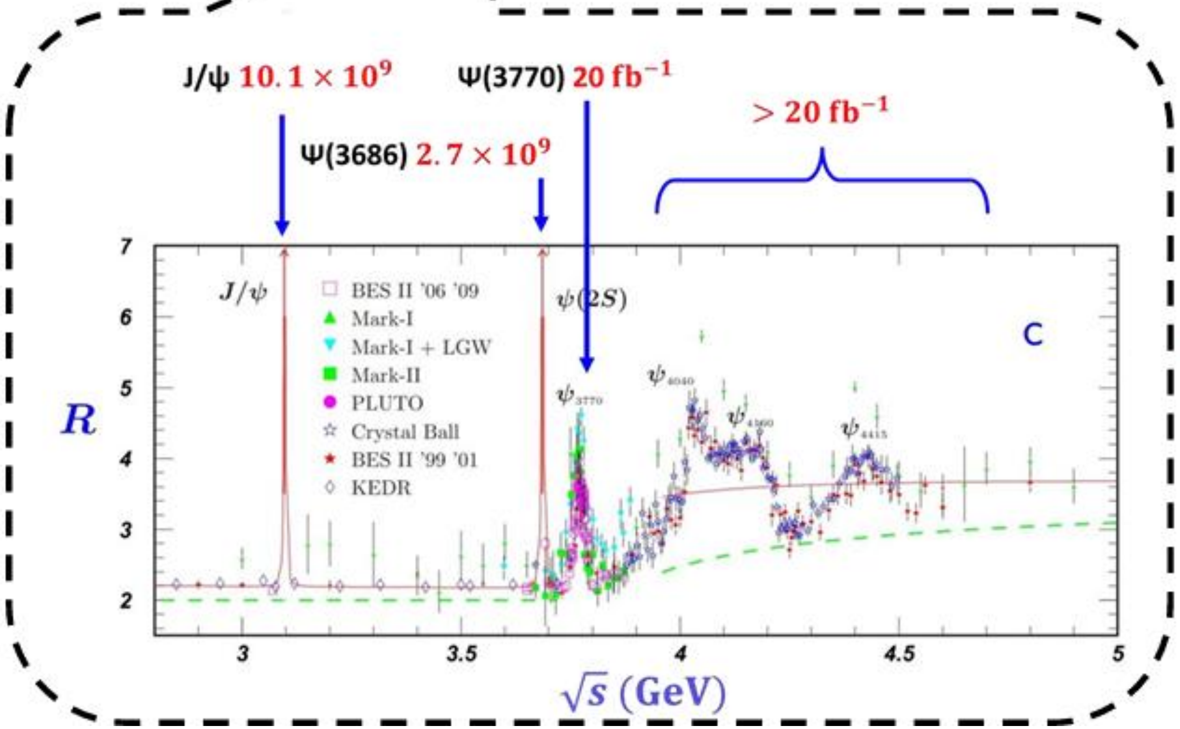
NP would be very small

$\Longrightarrow$ sensitive to rare/forbidden processes

01 Introduction

BESIII Detector





- 10.1×10^9 J/ψ events
  - Hyperon: Λ, $\bar{\Lambda}$, $\Sigma^{0,+}$, $\bar{\Sigma}^{0,-}$, $\Xi^{0,-}$, $\bar{\Xi}^{0,+}$ ~10^7
  - Light meson: η, η', ϕ, ω, K_S^0 ~10^7
- 20 fb^{-1} $\psi(3770)$
  - D^0, $\bar{D}^0$, D^+, D^- ~10^7
- ......

Rich Physics with clean environment

Chin. Phys. C **44**, 040001 (2020)

Outline

02 Searching for BSM particles

BSM particles Searching

Axion-like particle (ALP) via $J/\psi \to \gamma a$

a) With $\psi(2S)$ data
PLB **838**, 137698 (2023)

b) With J/ψ data
PRD **110**, L031101 (2024)

Light CP-odd Higgs boson via $J/\psi \to \gamma A^0$

Visible (di-muon) decay
PRD **105**, 012008 (2022)
PRD **93**, 052005 (2016)
PRD **85**, 092012 (2012)

invisible decay
PRD **101**, 112005 (2020)

Dark baryon

a) $\Xi^- \to \pi^- \chi$
PLB 872, 140099 (2026)

Dark photon

Massive

a) Via $J/\psi \to U\eta(')$
PRD **99**, 012013 (2019)
PRD **99**, 012006 (2019)
PRD **102**, 052005 (2020)

b) Via ISR process
PLB **774**, 252 (2017) (visible)
PLB **839**, 137785 (2023) (invisible)

Massless

a) $\Lambda_c^+ \to p\gamma'$
PRD **106**, 072008 (2022)

b) $D^0 \to \omega/\gamma\gamma'$
PRD **111**, L011103 (2025)

c) $\Sigma^+ \to p + \text{invisible}$
PLB **852**, 138614 (2024)

Fully invisible decays

Invisible decays of Λ baryon
PRD **105**, L071102 (2022)

Invisible decays of ω/ϕ mesons
PRD **98**, 032001 (2018)

Invisible decays of η/η' mesons
PRD **87**, 012009 (2013)

invisible muon philic scalar or vector meson
PRD **109**, L031102 (2024)

Invisible K_S^0 decays
JHEP **05**, 092 (2025)

$J/\psi \to \phi + \text{invisible}$
PRL 135, 151804 (2025)

02 Searching for BSM particles: Axion Like Particle

An Axion-like particle (ALP), a

PRD 110, L031101 (2024)

- is a pseudo-scalar particle
- introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QCD

  Phys. Rev. Lett. **40**, 223 (1978); Phys. Rev. Lett. **40**, 279 (1978)   Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977)

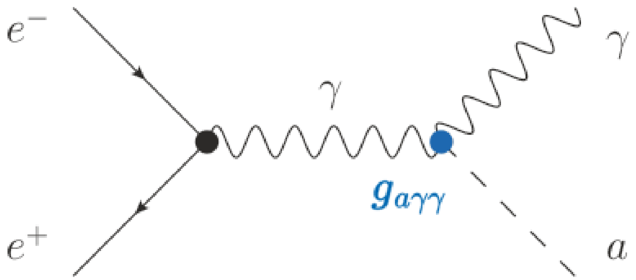
- Predicted by many models beyond the SM and proposed to be a cold DM candidate.

  Phys. Lett. B 753, 482 (2016)

- ALP production at e^+e^- colliders

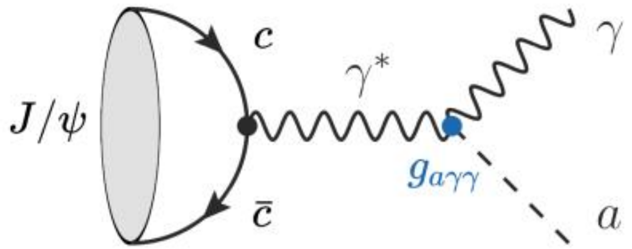
  - **ALP-Strahlung process**

    Phys. Rev. D **52**, 1755 (1995)



$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha.(\hbar.c)^2}{24}\left(1-\frac{m_a^2}{m_{J/\psi}^2}\right)^3$$

  - **Radiative decay process**



JHEP **06**, 091 385 (2019)

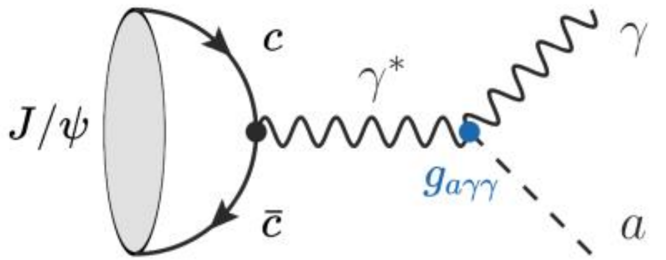
$$\mathcal{B}(J/\psi \to \gamma a) = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1-\frac{m_a^2}{m_{J/\psi}^2}\right)^3 \mathcal{B}(J/\psi \to e^+e^-)$$

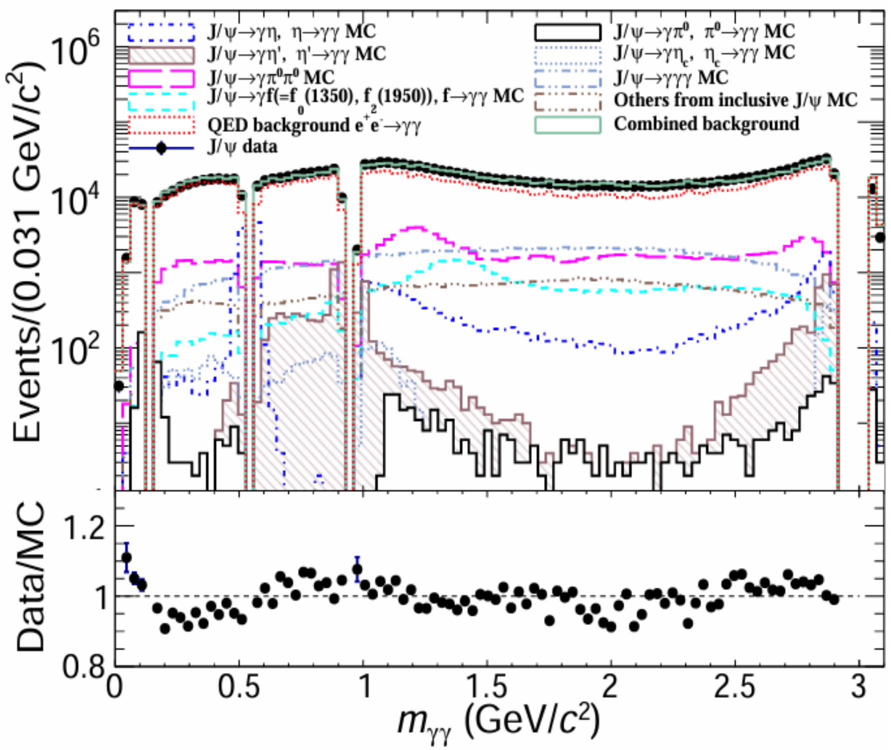
02 Searching for BSM particles: Axion Like Particle

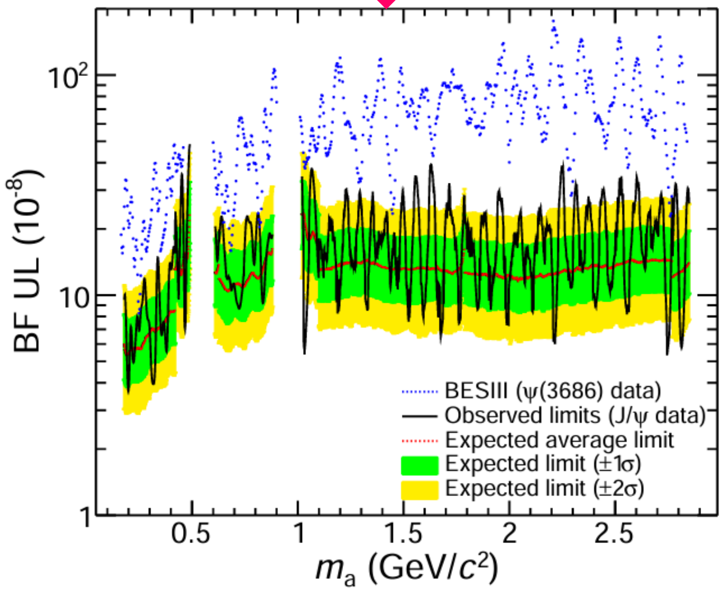
PRD 110, L031101 (2024)

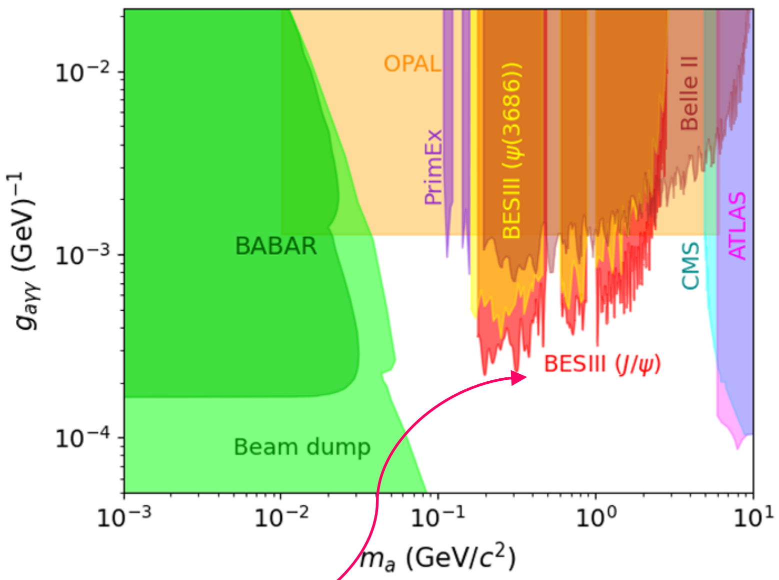
- 10^{10} J/ψ events
- Extract signal from $M_{\gamma\gamma}$ distribution
- Maximum signal significance: $< 3\sigma$

- UL on the BF of $\mathcal{B}(J/\psi \to \gamma a) \times \mathcal{B}(a \to \gamma\gamma)$
  $(3.6\sim53.1) \times 10^{-8}$ @ 90% C.L.





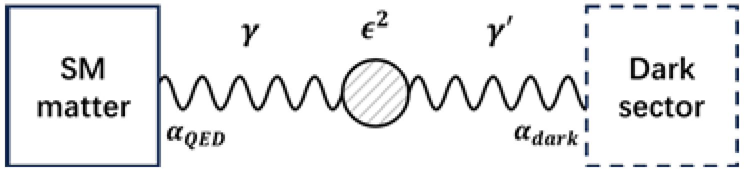




- **New stringent constraints on ALP-photon coupling for $0.18 \le m_a \le 2.85$ GeV**

02 Searching for BSM particles: Dark Photon

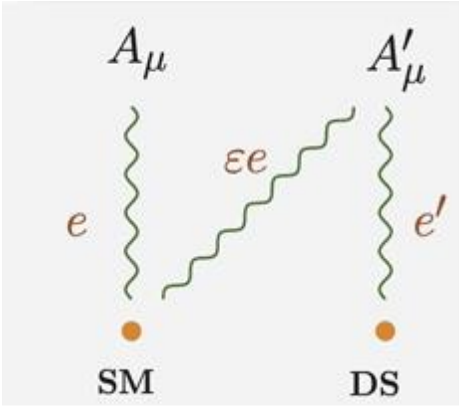
Simplest extension of the SM $\Longrightarrow$ An extra Abelian gauge group, $\boldsymbol{U(1)_D}$ $\Longrightarrow$ dark photon



B. Batell, et al, PRD **79**, 115008 (2009);
R. Essig, et al, PRD **80**, 015003 (2009)

Massive dark photon

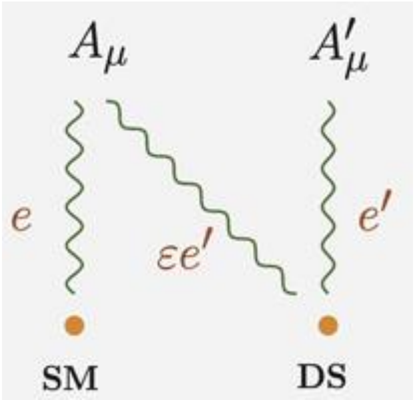
arises when the symmetry of the additional Abelian gauge group is spontaneously broken



- Massive dark photon
- Coupling with SM fermion
- Strong constraint

Massless dark photon

Symmetry remains unbroken



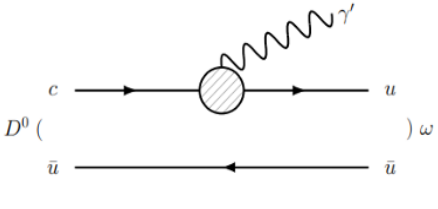
- Massless dark photon
- No direct coupling with SM fermion
- Less constraint
- Also, important role in dark sector

A dimension-six operator has been proposed to provide a connection between SM fermions and the massless dark photon

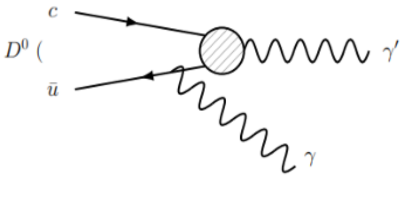
$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda_{\rm NP}^2}(C_{jk}^U \bar{q}_j \sigma^{\mu\nu} u_k \tilde{H} + C_{jk}^D \bar{q}_j \sigma^{\mu\nu} d_k H + C_{jk}^L \bar{l}_j \sigma^{\mu\nu} e_k H + {\rm H.c.}) F'_{\mu\nu}$$

- Naturally allow the FCNC coupling
- Less background and higher sensitivity

PRL **94**, 151802 (2005)



(a) $D^0 \to \omega\gamma'$



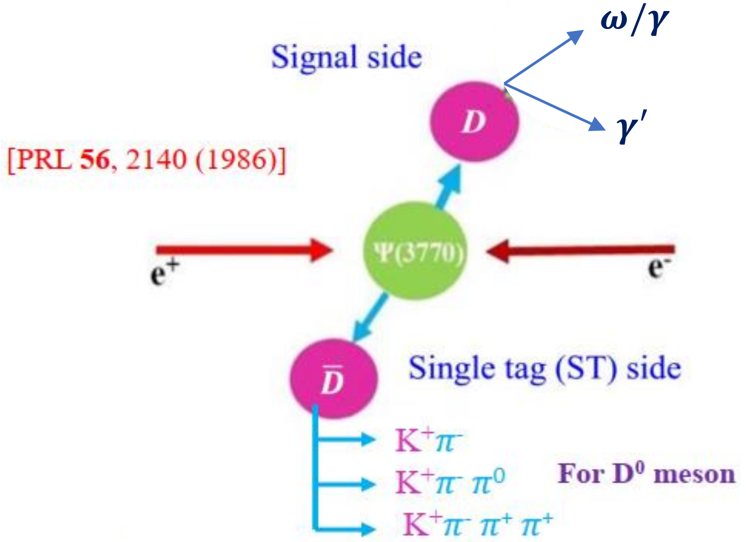
(b) $D^0 \to \gamma\gamma'$

02 Searching for BSM particles: Dark Photon

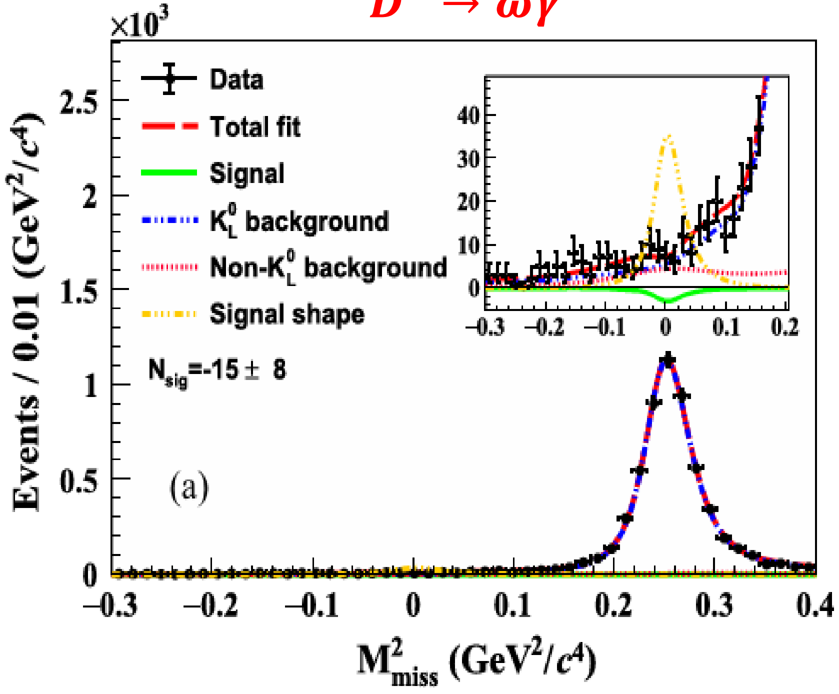
PRD 111, L011103 (2025)

- ✓ Search is based on 7.9 fb^{-1} $\psi(3770)$ data using a double tag (DT) technique
- ✓ The signals of the massless dark photon are extracted from a fit on the distribution of missing mass square

$$M^2_{\rm miss} = |p_{\rm c.m.s.} - p_{\bar{D}^0} - p_{\omega(\gamma)}|^2/c^4$$

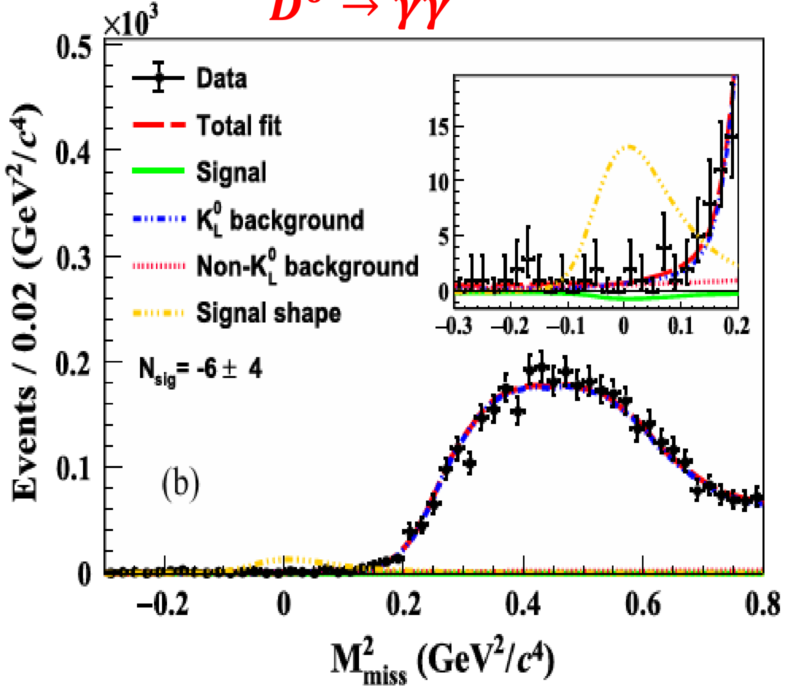


$D^0 \to \omega\gamma'$

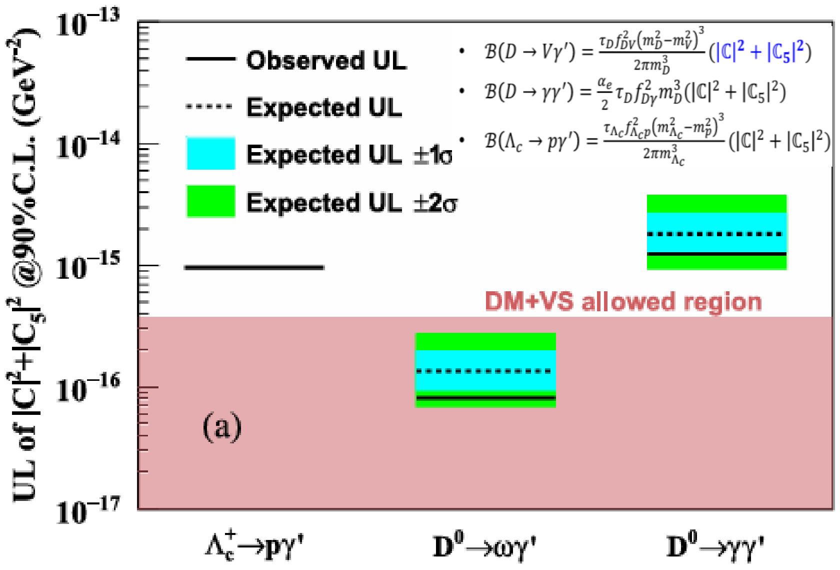


$\mathrm{B}(D^0 \to \omega\gamma') < 1.1 \times 10^{-5}$

$D^0 \to \gamma\gamma'$



$\mathrm{B}(D^0 \to \gamma\gamma') < 2.0 \times 10^{-6}$



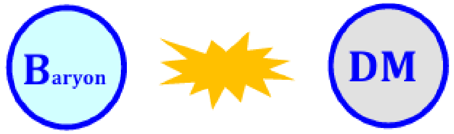
02 Searching for BSM particles: Dark Baryon

PLB 872, 140099 (2026)

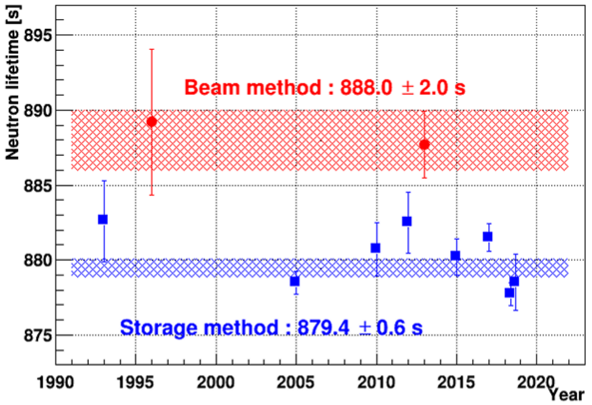
❖ **Coincidence issue:**

Similarity between DM and baryon densities: $\rho_{DM} \approx 5.4\rho_{baryon}$

Potential connection between their origins
DM may have non-zero baryon number



❖ **Neutron lifetime puzzle**



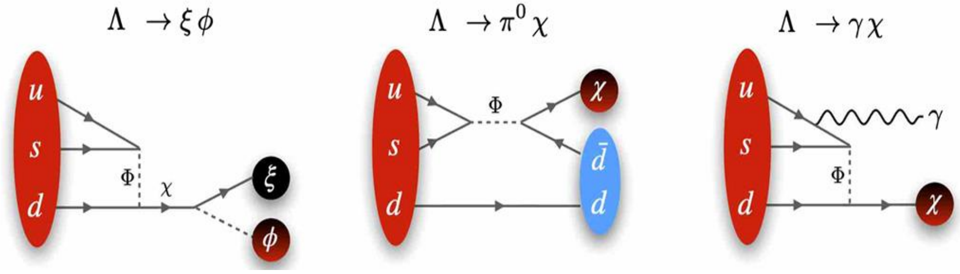
$$\tau_n^{\text{beam}} = \frac{\tau_n^{\text{bottle}}}{\text{Br}(n \to p + \text{ anything })}$$

$$\mathcal{B}(n \to \text{dark}) \sim 1\%$$

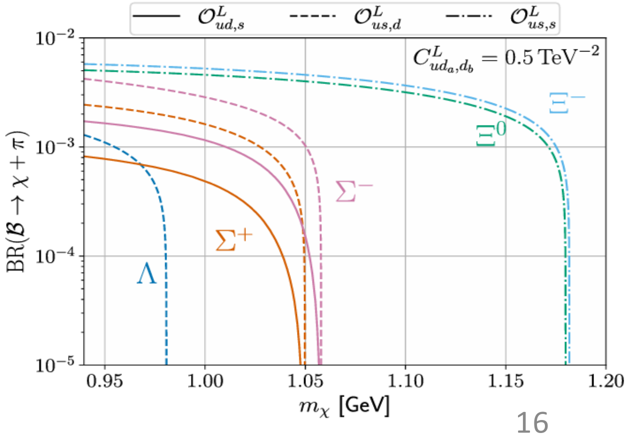
- **Motivates the existence of dark baryon**

❖ **B-Mesogenesis mechanism:** Can explain the symmetry between visible mater and antimatter and origin of DM.

❖ **Hyperon dark decays**



PRD **105**, 115005 (2022)

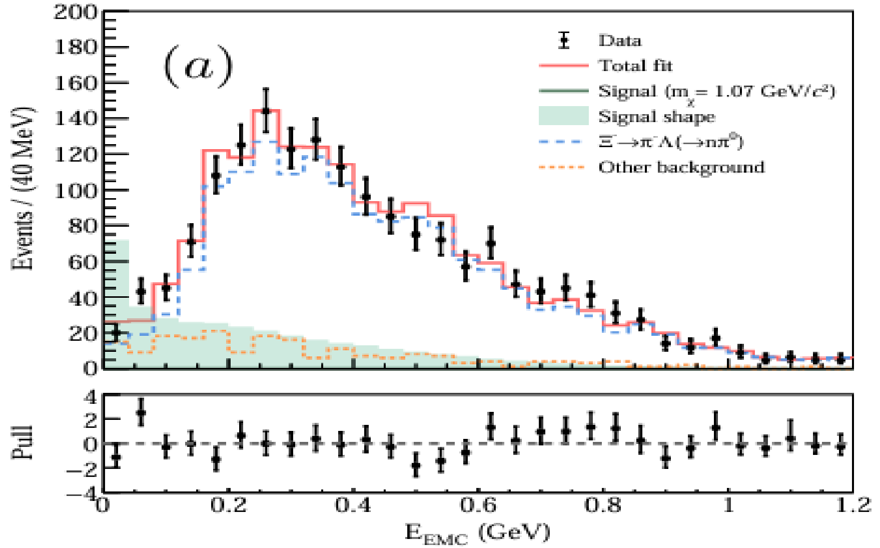


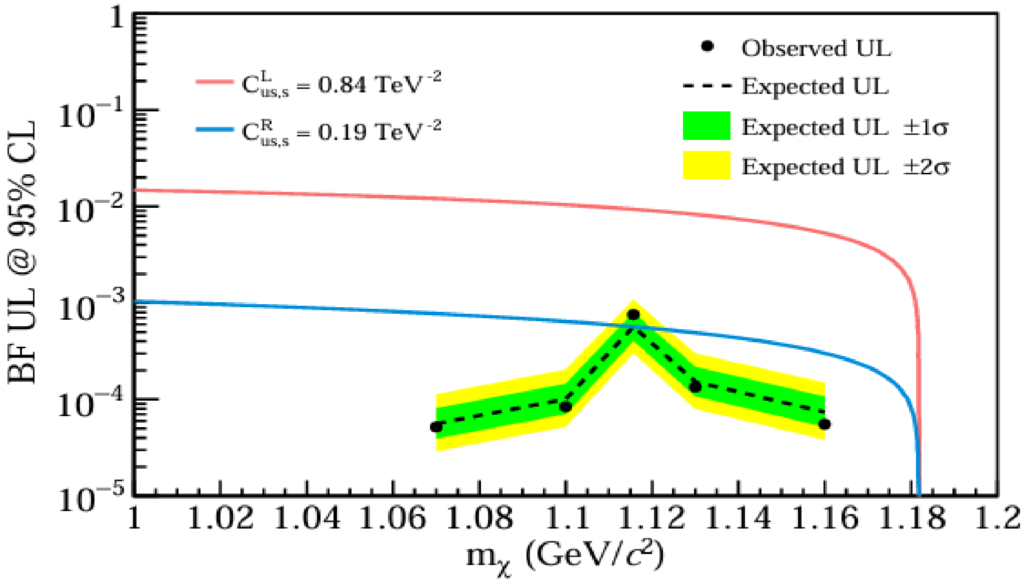
02 Searching for BSM particles: Dark Baryon

PLB 872, 140099 (2026)

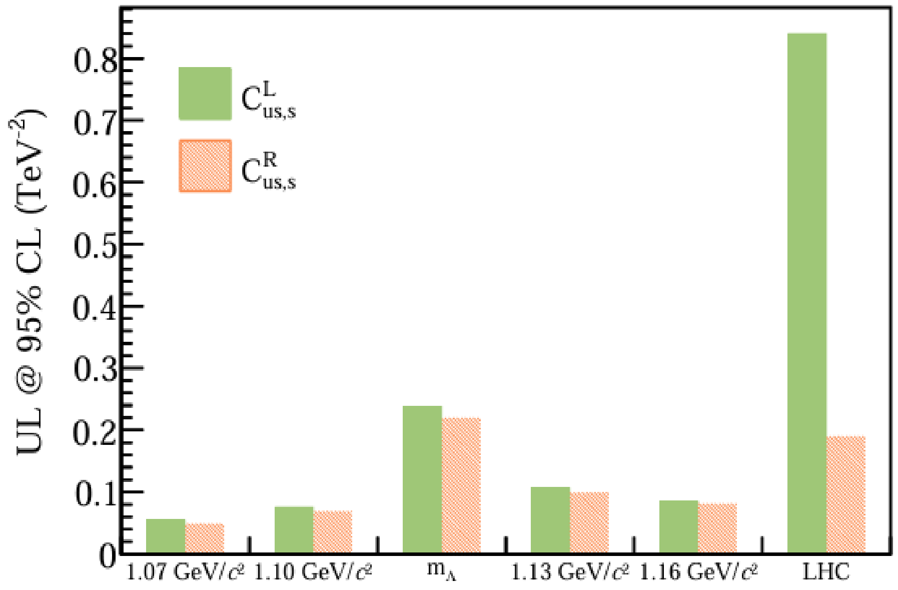
Analysis strategy:

- $J/\psi \to \bar{\Xi}^{+}\Xi^{-}$ from 10 billion J/ψ events
- Double tag method: $\bar{\Xi}^{+} \to \bar{\Lambda}\pi^{+}$, $\bar{\Lambda} \to \bar{p}\pi^{+}$, $\Xi^{-} \to \pi^{-} + \chi$
- χ is the dark baryon with an invisible signature with masses of 1.07, 1.10, m_{Λ}, 1.13, 1.13 GeV/c^2
- The invisible signal should have EMC energy deposit peaking at zero
- No evidence of significant signal events





Corresponding Wilson coefficients C^L_{uss} and C^R_{uss} are more stringent than the previous limits from the LHC searches for the colored mediators



90% C.L. UL on B($\Xi^- \to \pi^- + \chi$) varies from $(4.5 - 76) \times 10^{-5}$

02 Searching for BSM particles: Muonphilic Dark Particles

- ✓ A new type of massive vector meson X_1 or scalar boson X_0 may appear in SM extension of the anomaly free gauged U(1) or $U(1)_{L_\mu - L_\tau}$ model.

- ✓ They only couple to the second or third generations of leptons $(\mu, \nu_\mu, \tau, \nu_\tau)$ with the coupling strength $g'_{0,1}$.

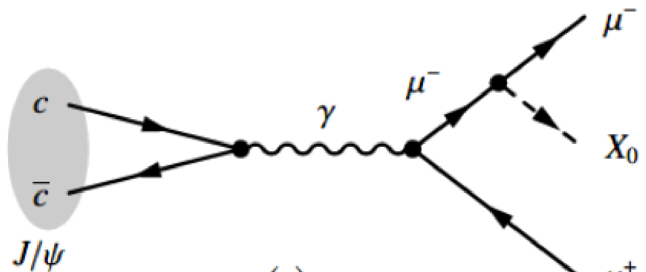
- ✓ The $X_{0,1}$ can contribute to the muon anomalous magnetic moment and explain the $(g\text{-}2)_\mu$ anomaly.

$$\Delta a_\mu^{scalar} = \frac{g_0^2}{8\pi^2}\int_0^1 dx \frac{m_\mu^2(1-x)(1-x^2)}{m_\mu^2(1-x)^2 + m_{Z'}^2 x}$$

$$\Delta a_\mu^{vector} = \frac{g_1^2}{8\pi^2}\int_0^1 dx \frac{2m_\mu^2 x(1-x)^2}{m_\mu^2(1-x)^2 + m_{Z'}^2 x}$$

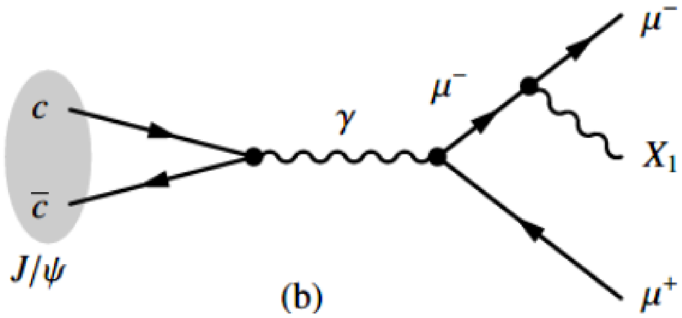
- ✓ Can be accessible via $J/\psi \to \mu^+\mu^- X_{0,1}$

arXiv:1610.06587 (2016)



(a)

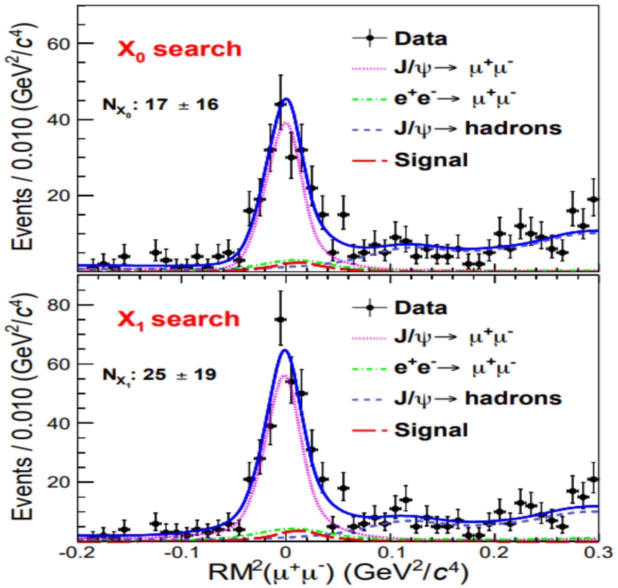
JHEP 10 (2020) 207

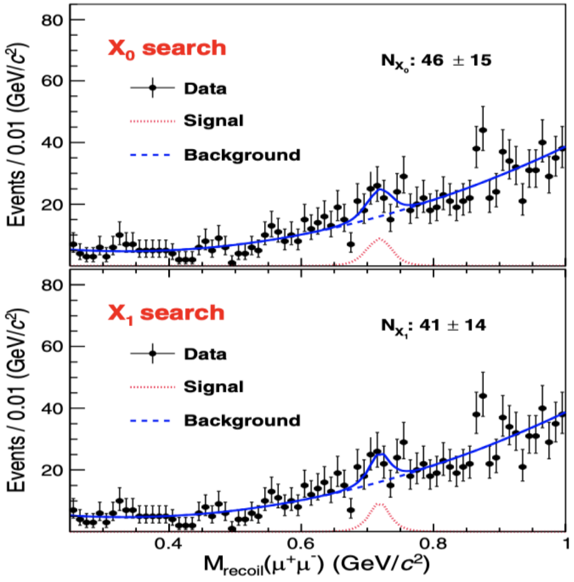


(b)

02 Searching for BSM particles: Muonphilic Dark Particles

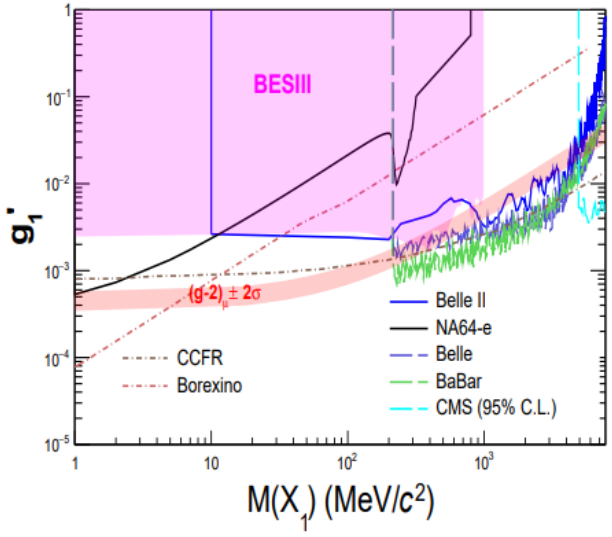
PRD 109, L031102 (2024)



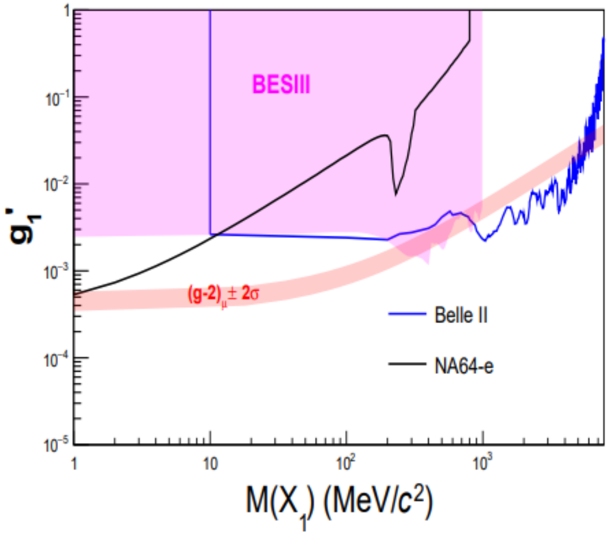


- ✓ $J/\psi \to \mu^+\mu^-$ from ~9 billion J/ψ events
- ✓ $M^2_{recoil}(\mu^+\mu^-) = (p_{J/\psi} - p_{\mu^+} - p_{\mu^-})^2$
- ✓ Signal yield is extracted by performing a series of ML fits.
- Red long-dashed curves are the $X_{0,1}$ signals.
- Green dashed and magenta dotted curves are the peaking backgrounds from $J/\psi \to \mu^+\mu^-$; $e^+e^- \to \mu^+\mu^-$ processes.
- Dots with error bars are data, and blue dashed curves are the backgrounds from $J/\psi \to$ hadrons

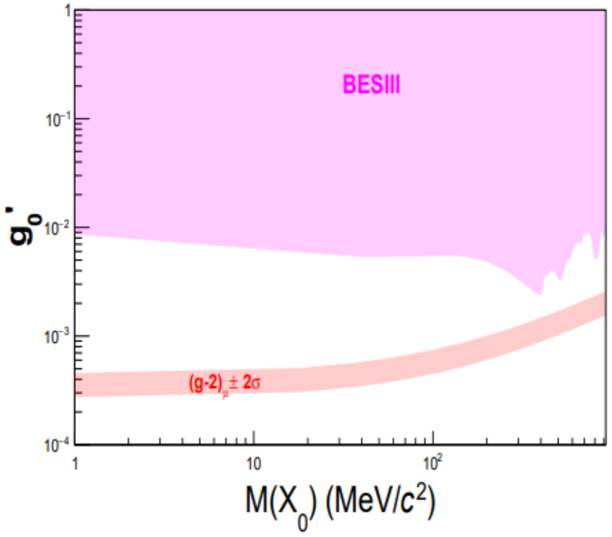
“vanilla” $L_\mu - L_\tau$ model



“invisible” $L_\mu - L_\tau$ model



“scalar” $U(1)$ model



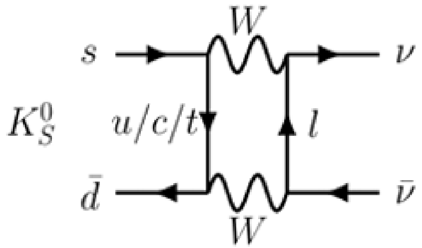
X_0 is long-lived with displaced decay or predominately decays to invisible particles

02 Searching for BSM particles: Invisible Decay

JHEP 05, 092 (2025)

Invisible

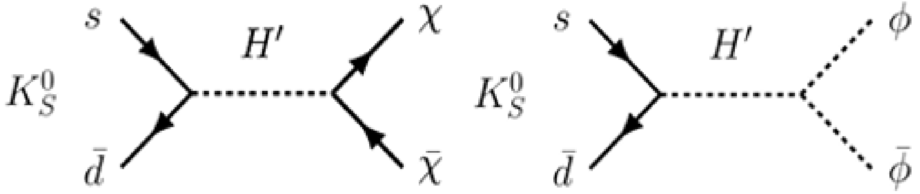
- ✓ **SM decays**



Very rare (BF < 10^{-16})
FCNC and Helicity suppression

Phys. Rev. D **91**, 015004 (2015)

- ✓ **Decay to DM particles**



Two Higgs doublet model

BF~$\mathcal{O}(10^{-6})$

Natural Sci. Rev. **1**, 5 (2024)

- ✓ **Ordinary matter particle oscillation** $K_S^0 \dashrightarrow K_S^{0\prime}$

Mirror matter model arXiv: 2006.10746

BF~$\mathcal{O}(10^{-6})$

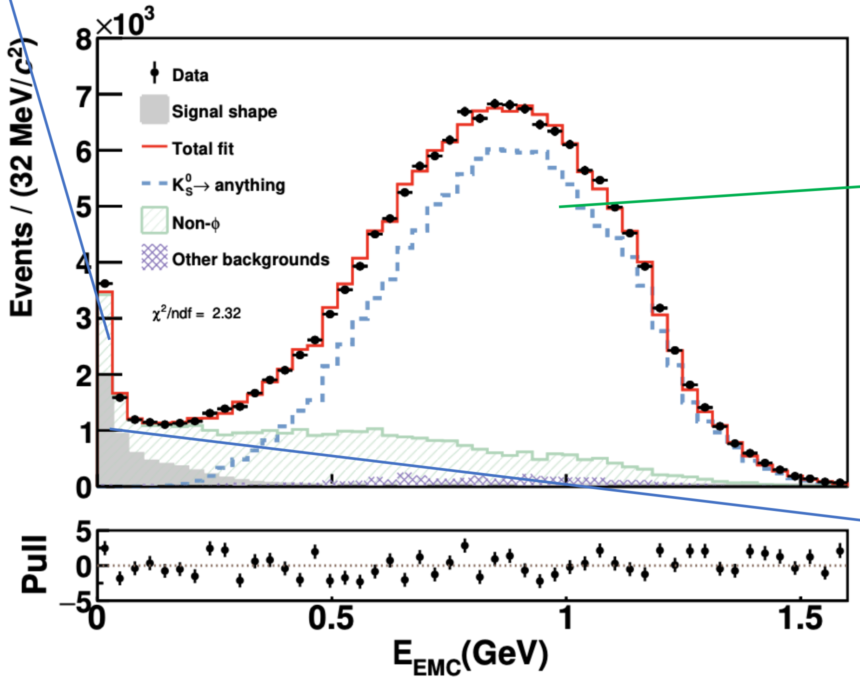
02 Searching for BSM particles: Invisible Decay

- Search is based on 10 billion J/ψ events collected by the BESIII detector via $J/\psi \to \phi K_S^0 K_S^0$ decay.
- $J/\psi \to \phi K_S^0 K_L^0$ is forbidden by C-parity conservation.
- K_S^0 →invisible decay rate can be calculated as,

JHEP 05, 092 (2025)

$$\mathcal{B}(K_S^0 \to \text{invisible}) = \frac{N_{\text{signal}}}{N_{\text{non}-\pi^+\pi^-}\,(\varepsilon_{\text{signal}}/\varepsilon_{\text{non}-\pi^+\pi^-})}(1-\mathcal{B}(K_S^0 \to \pi^+\pi^-))$$

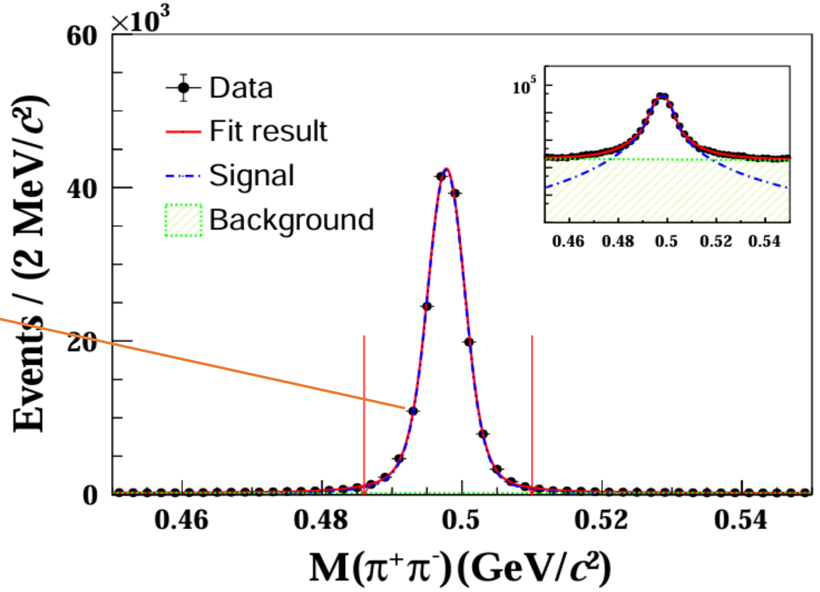
Peaking background from non-ϕ processes, $J/\psi \to K^+K^-K_SK_L$, Shape from ϕ sideband



Other background modeled with MC simulation, such as $K_S \to \pi^0\pi^0$, validated by control sample $J/\psi \to \phi K_S(\pi^0\pi^0)K_S(\pi^+\pi^-)$

Backgrounds from four-pion and non-phi backgrounds are subtracted

No obvious signal (56 ± 201, peaks at zero) production for K_S^0 →invisible is found

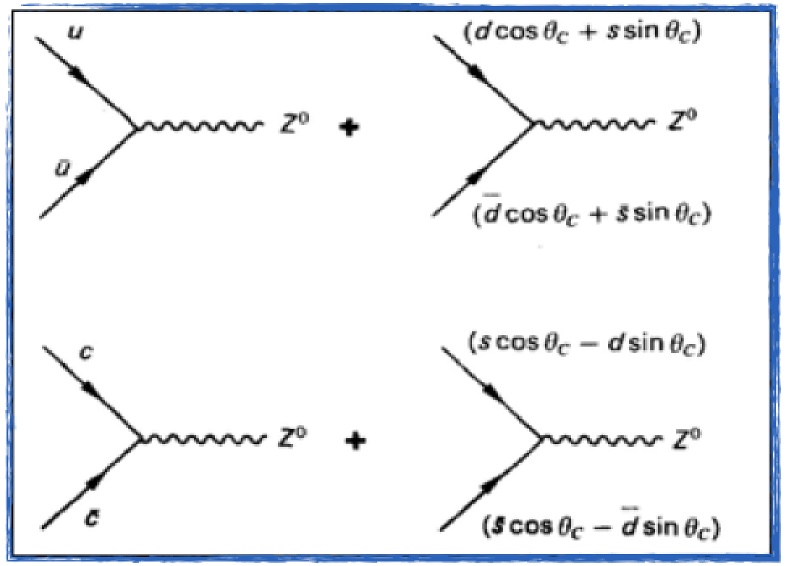


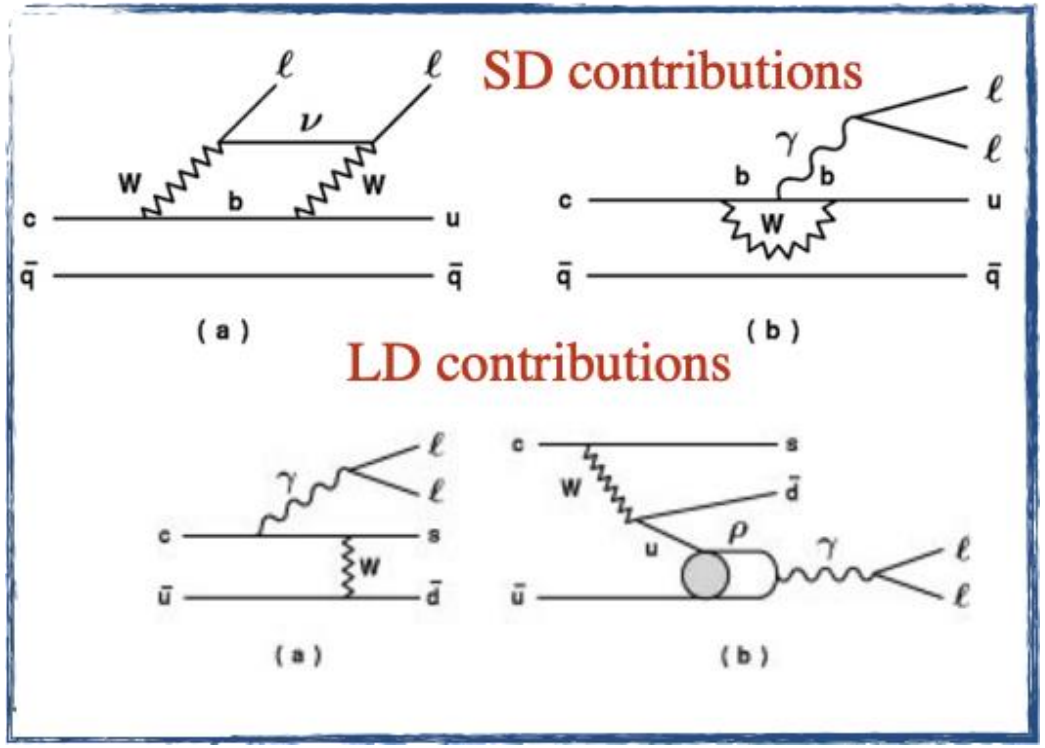
$B(K_S^0 \to \text{invisible}) < 8.4 \times 10^{-4}$ at the 90% CL (**First direct measurement**).

Outline

03 Investigation of rare decays: Flavor Changing Neutral Current

- In SM, FCNC is strongly suppressed by GIM mechanism and can happen only through loop diagram, leading to a very small BF (10^{-9}) theoretically.
- The suppression in charm decays is much stronger than those in B and K system due to stronger diagram cancellation than the down-type quarks.
- However, it can reach 10^{-6} under LD contribution.
- Strongly suppressed in SM → Sensitive to New Physics .





03 Investigation of rare decays: Flavor Changing Neutral Current

Decay Mode	$B_{90\%}^{UP}$ $(\times 10^{-6})$	Experiment	Published
$D_S^+ \to \phi\pi^+, \phi \to e^+e^-$	$11.7^{+2.3}_{-2.1} \pm 0.3$	BESIII [PRL133, 121801]	2024
$D_S^+ \to \phi\rho^+, \phi \to e^+e^-$	$24.4^{+6.7}_{-6.2} \pm 1.6$		
$D_S^+ \to \pi^+\pi^0e^+e^-$	70		
$D_S^+ \to K^+\pi^0e^+e^-$	71		
$D_S^+ \to K_S^0\pi^+e^+e^-$	81		
$D^0 \to \pi^0\nu\bar{\nu}$	210 (2.93/fb)	BESIII [PRD105, L071102]	2022
$\psi(3686) \to \Lambda_c^+\bar{p}e^+e^- + c.c.$	1.7	BESIII [PRD97, 091102]	2018
$D^+ \to \pi^+\pi^0e^+e^-$	14	BESIII [PRD97, 072015]	2018
$D^+ \to K^+\pi^0e^+e^-$	15		
$D^+ \to K_S^0\pi^+e^+e^-$	26		
$D^+ \to K_S^0K^+e^+e^-$	11		
$D^0 \to \pi^+\pi^-e^+e^-$	7		
$D^0 \to K^+K^-e^+e^-$	11		
$D^0 \to K_S^0e^+e^-$	12		
$D^0 \to \pi^0/\eta/\omega e^+e^-$	4/3/6		

03 Investigation of rare decays: Flavor Changing Neutral Current

PRL133, 121801 (2024)

- Data: 7.33 fb^{-1} data taken @4.128-4.226 GeV
- The LD contributions dominate the decays of $D_s^+ \to h(h')e^+e^-$ **(10^{-6})**
- The SD effects can be accessed through measurements in the dilepton mass regions away from intermediate $(\eta, \rho, \omega, \phi)$ mesons
- $D_s^+ \to Ve^+e^-$ (V is a light vector meson) receive considerable contributions from virtual photons: **10^{-5}**
- Distinguishes LD dominated modes from SD sensitive modes .

LD processes:

✓ $D_s^+ \to \pi^+\phi, \phi \to e^+e^-$

✓ $D_s^+ \to \rho^+\phi, \phi \to e^+e^-$

SD processes:

$D_s^+ \to \pi^+\pi^0e^+e^-$

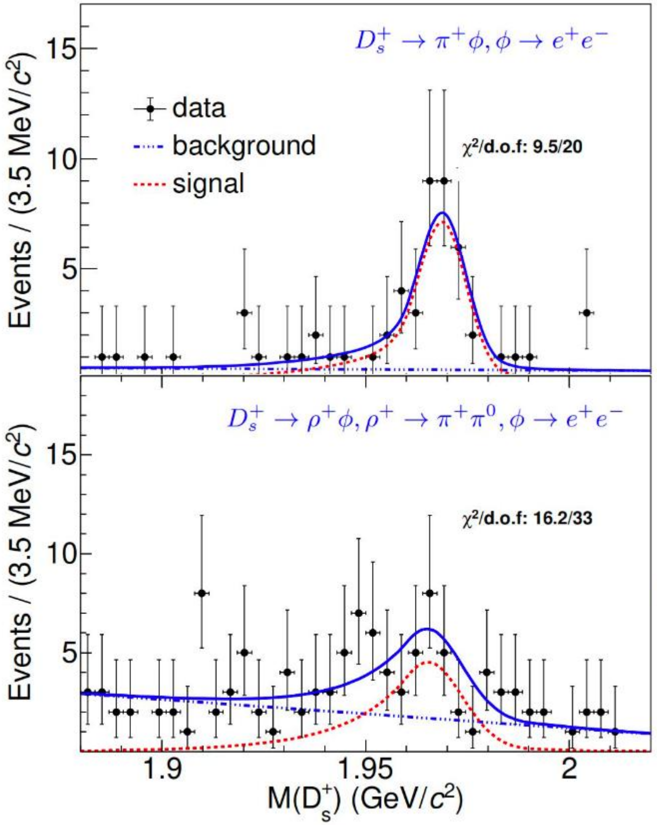
$D_s^+ \to K^+\pi^0e^+e^-$

$D_s^+ \to K_S^0\pi^+e^+e^-$

First systematic search for $D_s^+ \to h(h')e^+e^-$ decays.

Provides new experimental input for FCNC studies in the charm sector, LU tests, and $D_s^+ \to V\gamma$ research.

03 Investigation of rare decays: Flavor Changing Neutral Current



Fit to $M_{D_s^+}$ distribution

The e^+e^- invariant mass to be consistent with a $\phi(1020)$, $\phi(1020) \in (0.98, 1.04)$ GeV/c^2

PRL133, 121801 (2024)

Decay	N_{sig}	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$
$D_s^+ \to \pi^+\pi^0 e^+e^-$	...	7.4	< 7.0
$D_s^+ \to K^+\pi^0 e^+e^-$	...	5.3	< 7.1
$D_s^+ \to K_S^0\pi^+ e^+e^-$	...	6.7	< 8.1

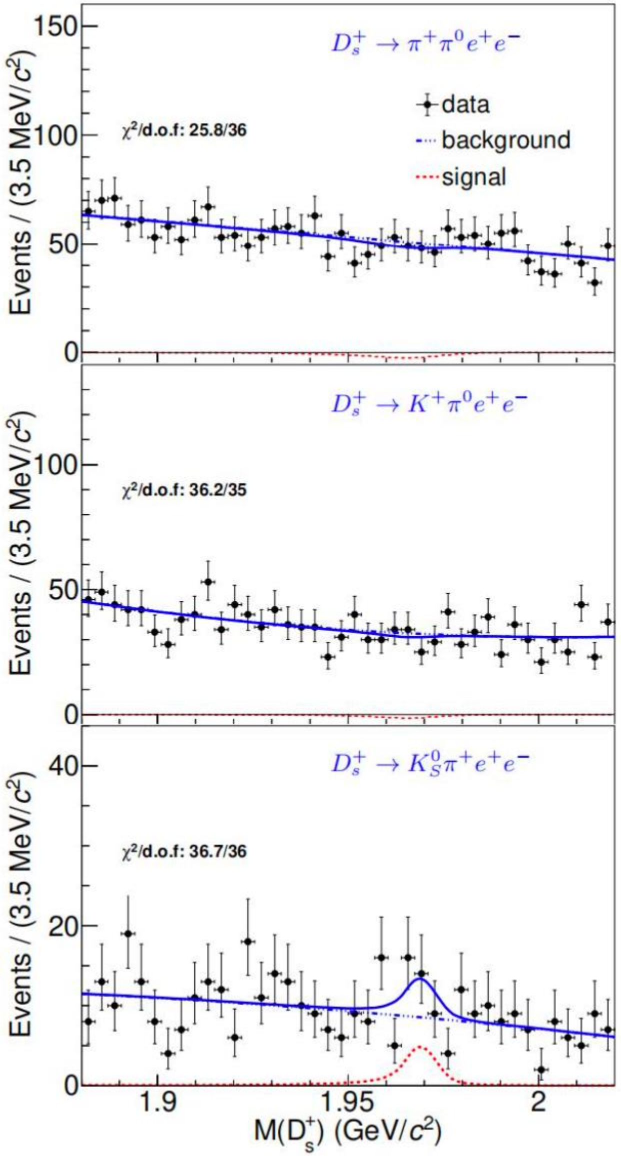
LD decays:

$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$ is observed with a statistical significance of 7.8σ

$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$ is found for the first time with a statistical significance of 4.4σ

Four body decays:

No obvious signal is observed and the ULs of BFs are about ~ 10^{-5} at 90% C.L.



03 Investigation of rare decays: Charmonium Weak Decays

- Charmonium weak decays are **allowed in SM**, but highly suppressed to 10^{-10} by strong and EM decays.
- The inclusive J/ψ weak decay is predicted to be at the order of $\mathbf{10^{-8}}$ **or below in SM** [Z. Phys. C 62 271 (1994)].
- Some **new physics models** can enhance the BF of J/ψ weak decay to 10^{-5}.
- Searching for the J/ψ weak decays can provide an experimental test of the SM.
- Searching for NP: top-color model, the minimal supersymmetric, and the two-Higgs doublet model.

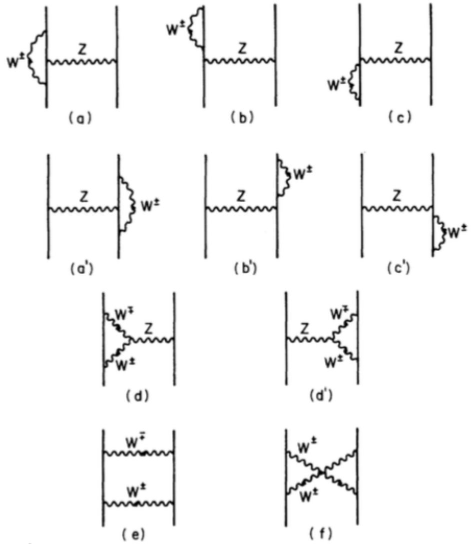
Top-color model

[Phys. Letter. B 16 (1982)]

- $0\nu\beta\beta$ decay Mediated by the photino λ_γ is negligible for reasonable photino masses
- Predict the existence of a light mass (~100 keV) scalar boson very weakly coupled to matter.

Minimal supersymmetric

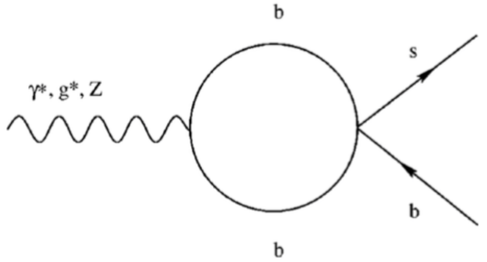
[PRD 15, 1958 (1977)]



Produce strangeness-nonconserving (charm-nonconserving) Fermi interactions of order αG_F

Two-Higgs doublet model

[PRD 60, 014011 (1999)]



- Effective $\bar{s}b\gamma^*(g^*, Z)$ vertices generated by L_{new}
- L_{new}: Four-quark operators with two scalar currents:

03 Investigation of rare decays: Charmonium Weak Decays

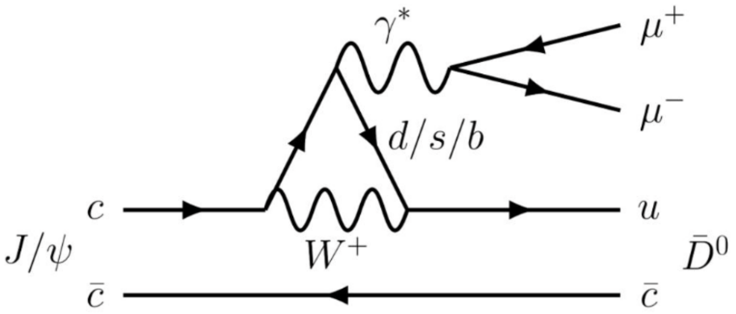
Decay Mode	$B^{UP}_{90\%}$ $(\times 10^{-7})$	Experiment	Published
$J/\psi \to D^0 K^{*0} + c.c.$	1.9	BESIII [arXiv:2511.16083]	2026
$J/\psi \to D_s^- e^+ \nu_e + c.c.$	1.0	BESIII [arXiv:2510.25100]	2026
$J/\psi \to D^0 \mu^+ \mu^- + c.c.$	1.1	BESIII [JHEP04, 61]	2025
$J/\psi \to D_s^- \rho^+ + c.c.$	8.0	BESIII [JHEP12, 77]	2025
$J/\psi \to D_s^- \pi^+ + c.c.$	4.1		
$J/\psi \to D^- \mu^+ \nu_\mu + c.c.$	*5.6*	BESIII [JHEP01, 126]	2024
$J/\psi \to \gamma D^0$	0.91	BESIII [PRD110, 112012]	2024
$J/\psi \to D^0 \pi^0 + c.c.$	4.7	BESIII [PRD110, 032020]	2024
$J/\psi \to D^0 \eta + c.c.$	6.8		
$J/\psi \to D^0 \rho^0 + c.c.$	5.2		
$J/\psi \to D^- \pi^+ + c.c.$	7.0		
$J/\psi \to D^- \rho^+ + c.c.$	6.0		
$\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.$	140	BESIII [CPC47, 013002]	2023
$J/\psi \to D^- e^+ \nu_e + c.c.$	*0.71*	BESIII [JHEP06, 157]	2021
$J/\psi \to D^0 e^+ e^- + c.c.$	0.85	BESIII [PRD96, 111101]	2017
$\psi(3686) \to D^0 e^+ e^- + c.c.$	1.4		
$J/\psi \to D_s^{*-} e^+ \nu_e + c.c.$	18	BESIII [PRD90, 112014]	2014

03 Investigation of rare decays: Charmonium Weak Decays

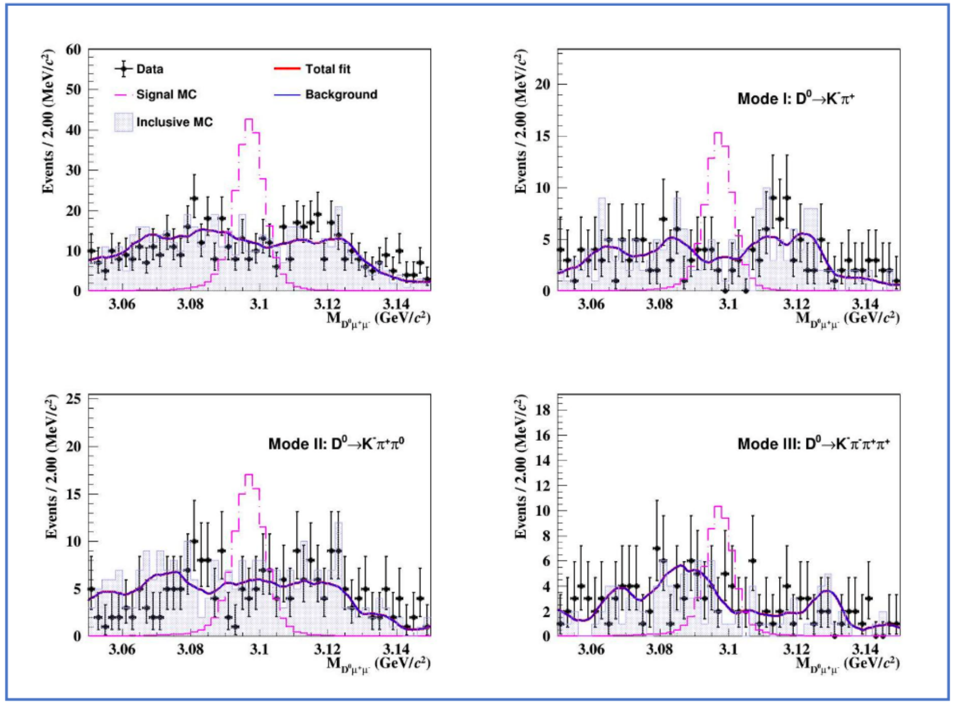
JHEP 04, 061 (2025)

- Data: 10 billion J/ψ events taken @3.097 GeV
- The FCNC decay $J/\psi \to D^0\ell^+\ell^-$ to have a BFs on the order of $\sim 10^{-13}$ in the SM.
- FCNC processes have been probed in the charmonium:

Experiment	Decay mode	$N_{J/\psi}$ or $N_{\psi(3686)}$	UL	Year
BESIII	$J/\psi \to D^0 e^+ e^-$	1310.6×10^6	8.5×10^{-8}	2017
BESIII	$\psi(3686) \to D^0 e^+ e^-$	447.9×10^6	1.4×10^{-7}	2017
BESIII	$J/\psi \to \gamma D^0$	10087×10^6	9.1×10^{-8}	2024



Fit results for J/ψ mass with different decay mode.

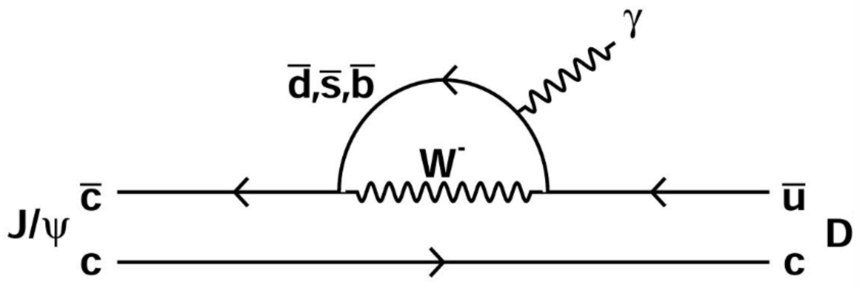


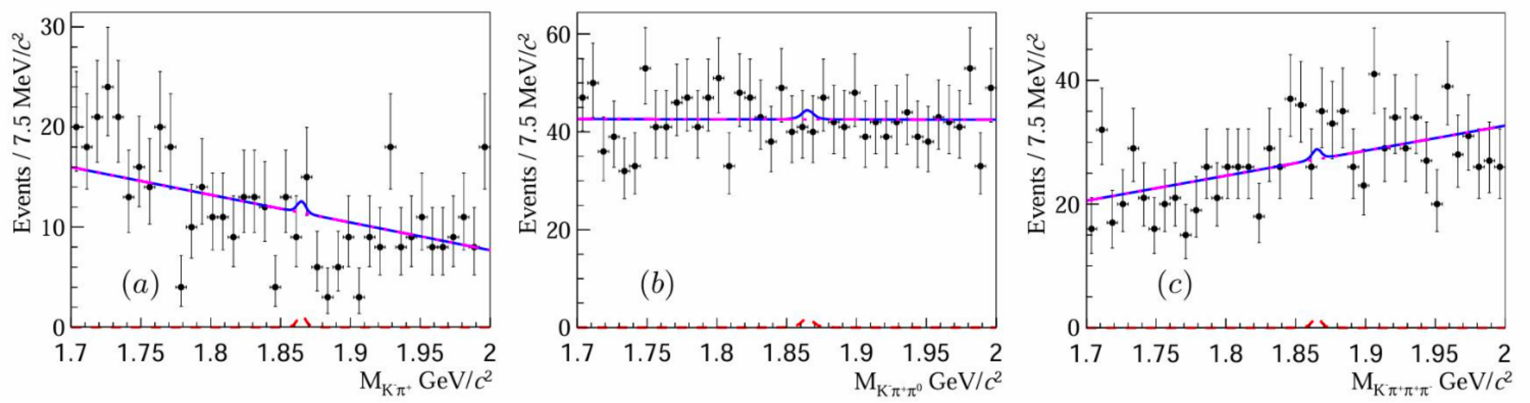
The first search for a charmonium FCNC process involving muons in the final state.
No signal events are found: 1.1×10^{-7} @90%C.L.

03 Investigation of rare decays: Charmonium Weak Decays

PRD 111, 112012 (2024)

- Data: 10 billion J/ψ events taken @3.097 GeV
- D0 is reconstructed through its three prominent exclusive hadronic decay modes:
  - $D^0 \to K^+\pi^-$ (Mode I)
  - $D^0 \to K^-\pi^+\pi^0$ (Mode II)
  - $D^0 \to K^-\pi^+\pi^+\pi^-$ (ModeIII)
- As the data are consistent with the background-only hypothesis, a Bayesian approach is employed to set the 90% C.L. upper limit on the branching fraction of $J/\psi \to \gamma D^0$.



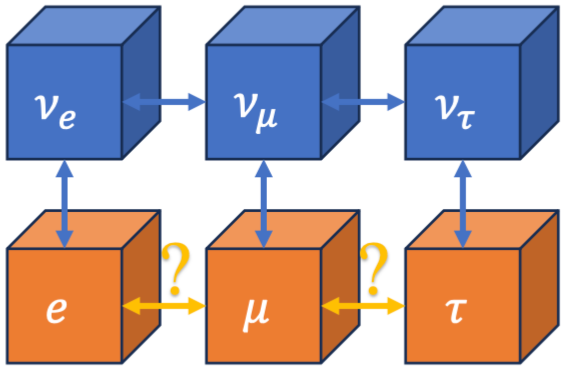


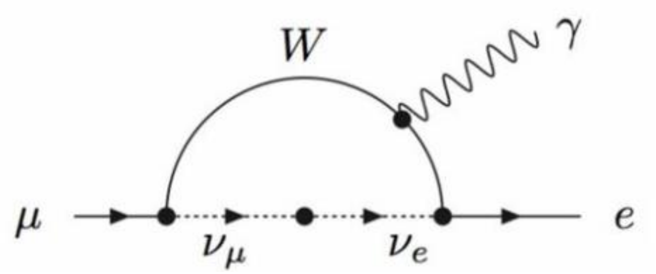
No signal events are found: 9.1×10^{-8} @90%C.L. with the systematic uncertainties

Outline

04 Precision test of conservation laws： Changed Lepton Flavor Violation

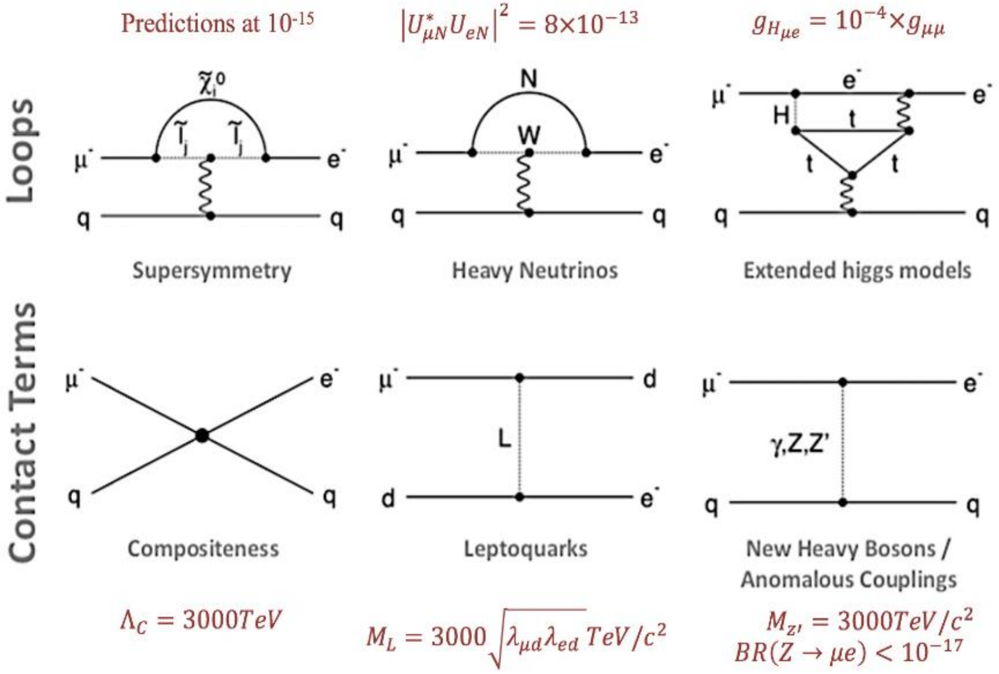
- ✓ Neutrino flavor violation is observed





$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

- ✓ In the Standard Model (SM) of particle physics, the LFV process is forbidden. However, flavor non-conserving mixing among generations has been observed in neutrino oscillations.
- ✓ The smallness of neutrino masses leads to a very large suppression of the predicted branching fractions. So, any significant sign of a CLFV signal could indicate physics beyond the SM.



04 Precision test of conservation laws： Changed Lepton Flavor Violation

- ✓ Many New Physics models enhance CLFV effects up to a detectable level
  - SUSY particles
  - Top-quark condensation
  - ……
- ✓ Effective Field Theory (EFT)
  - Upper limit of Wilson coefficients
  - Energy scale of new physics

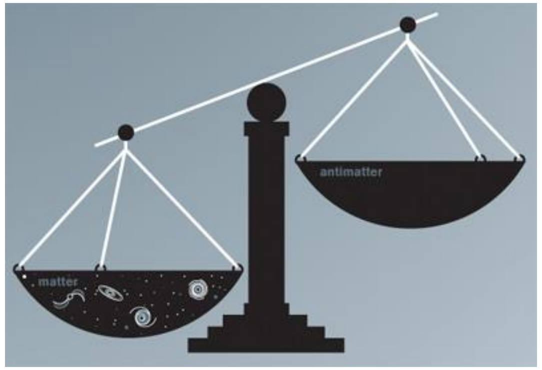
Phys. Rev. D 62, 073007 (2000)
Rev. Mod. Phys. 71, 513 (1999)
Phys. Rev. D 106, 115039 (2022)
Phys. Rev. D 94, 074023 (2016)

- ✓ New physics models predicts $B(J/\psi \to e\mu)$ to $10^{-16} \sim 10^{-9}$, $B(J/\psi \to e\tau(\mu\tau))$ to $10^{-10} \sim 10^{-8}$
  - model-independent prediction [1, 2]
  - rotating mass matrix [3]
  - unparticle physics [4]
  - effective Lagrangian [5]
  - MSSM with gauged baryon and lepton number [6]

[1] X. M. Zhang et al, Phys. Rev. D 63, 016003 (2000).
[2] T. Gutche et al, Phys. Rev. D 83, 115015 (2011).
[3] J. Bordes and H. M. Chan, Phys. Rev. D 63, 016006 (2000).
[4] K. S. Sun et al, Mod. Phys. Lett. A 27, 1250172 (2012).
[5] D. E. Hazard and A. A. Petrov, Phys. Rev. D 94, 074023 (2016).
[6] X. X. Dong et al, Phys. Rev. D 97, 056027 (2018).

Decay Mode	$B^{UP}_{90\%}$ $(\times 10^{-8})$	Experiment	Published
$\psi(3686) \to e\mu$	1.4	BESIII [arXiv: 2507.10331]	2025
$J/\psi \to e\mu$	0.45 (8.998 B)	BESIII [SCPMA66, 221011]	2023
	16 (0.225 B)	BESIII [PRD87, 112007]	2013
$J\psi \to e\tau(\tau \to \pi\pi^0\nu_\tau)$	7.5	BESIII [PRD103, 112007]	2021

04 Precision test of conservation laws： Baryon Number Violation

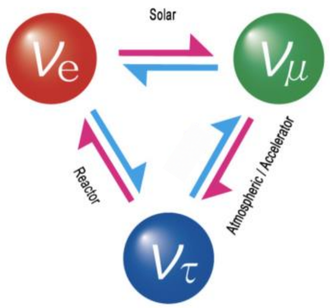


- Asymmetry of matter and anti-matter: big problem in the universe evolution.
- BNV: even a small amount would have major consequences on the universe and its evolution, as many theories have suggested.
- For example, in the Grand Unified Theory, proton can decay into several modes through leptoquarks, such as $p \rightarrow e^{+}\pi^{0}$. Such mechanism simultaneously breaks BN and LN while conserving $\Delta(B-L)$.
- Searches for physics BSM with collider experiments are complementary to searches with specifically designed precision detection experiments.
- The two independent ways of searching for new physics are fruitfully supporting each other.

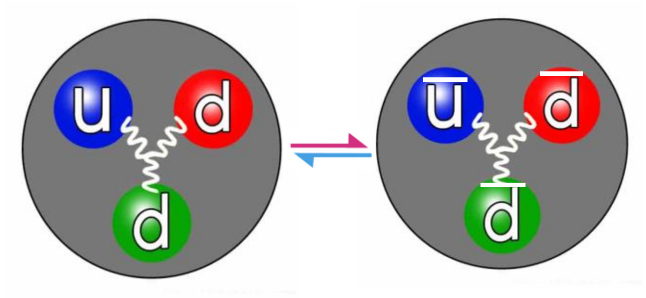
04 Precision test of conservation laws： Baryon Number Violation

Decay Mode	$B^{UP}_{90\%}$ $(\times 10^{-8})$	Experiment	Year
$\Lambda-\bar{\Lambda}$ *oscillation in* $J/\psi \to \Lambda\bar{\Lambda}$	$140\ (2.1\times 10^{-18}\ \mathrm{GeV})$	BESIII [PRD111, 052014]	2025
$\Lambda-\bar{\Lambda}$ *oscillation in* $J/\psi \to pK^-\bar{\Lambda}$	$440\ (3.8\times 10^{-18}\ \mathrm{GeV})$	BESIII [PRL131, 121801]	2023
$J/\psi \to pe^- + c.c.$	3.1	BESIII [PRD111, 112010]	2025
$\Xi^0 \to K^+e^-$	190	BESIII [PRD108, 012006]	2023
$\Xi^0 \to K^-e^+$	360		
$D^+ \to \bar{n}e^+$ / $D^- \to ne^-$	1430	BESIII [PRD106, 112009]	2022
$D^+ \to ne^+$ / $D^- \to \bar{n}e^-$	2910		
$D^0 \to \bar{p}e^+$	120	BESIII [PRD105, 032006]	2022
$D^0 \to pe^-$	220		
$D^+ \to \Lambda e^+$	110	BESIII [PRD101, 031102(R)]	2020
$D^+ \to \Sigma^0 e^+$	170		
$D^+ \to \bar{\Lambda}e^+$	65		
$D^+ \to \bar{\Sigma}^0 e^+$	130		
$J/\psi \to \Lambda_c^+ e^- + c.c.$	6.9	BESIII [PRD99, 072006]	2019

04 Precision test of conservation laws： Baryon Number Violation



- The discoveries of neutrino oscillations have made $N-\bar{N}$ oscillation to be quite plausible theoretically[PRL96, 061801(2006)], if small neutrino masses are to be understood as a consequence of the seesaw mechanism, which indicates the existence of $\Delta(B-L)=2$ interactions.



- Since 1980[PRL44,1316], there have been many experiments searching for BNV through $n-\bar{n}$ oscillation[PDG2019] with upper limit results, while few results from other baryons.

- 2007, K.-B. Luk pointed out that $\Lambda-\bar{\Lambda}$ oscillation may also exist.
- 2010, X.-W. Kang and H.-B. Li[PRD81,051901] give a prospect of searching for $\Lambda-\bar{\Lambda}$ oscillation at the BESIII experiment.
- 2017, the LHCb experiment presented a constraint on $\Xi_b^0-\bar{\Xi}_b^0$ oscillation.
- The theoretical advantage for using $\Lambda-\bar{\Lambda}$ is it has a second generation quark, which can give further information compared with the result of proton decay which only have the first generation quark.
- A six-fermion operator, which could arise in models with leptoquarks or R-parity violating supersymmetric extensions of the SM, could allow BNV while being consistent with the experimental limit on the proton lifetime[PLB721, 82(2013)].

04 Precision test of conservation laws： Baryon Number Violation

- Starting with a beam of free $\bar{\Lambda}$, the probability of generating a Λ after time t can be described by $P(\Lambda, t) = \sin^2(\delta m_{\Lambda\bar{\Lambda}} \cdot t)$, where $\delta m_{\Lambda\bar{\Lambda}}$ is the oscillation parameter and t is the decay time.

- Since there is no vertex detector at the BESIII, we can only measure the time integrated result

$$P(\bar{\Lambda} \to \Lambda) = \frac{\int_0^\infty \sin^2(\delta m_{\Lambda\bar{\Lambda}} \cdot t) \cdot e^{-t/\tau_\Lambda} \cdot dt}{\int_0^\infty e^{-t/\tau_\Lambda} \cdot dt}$$

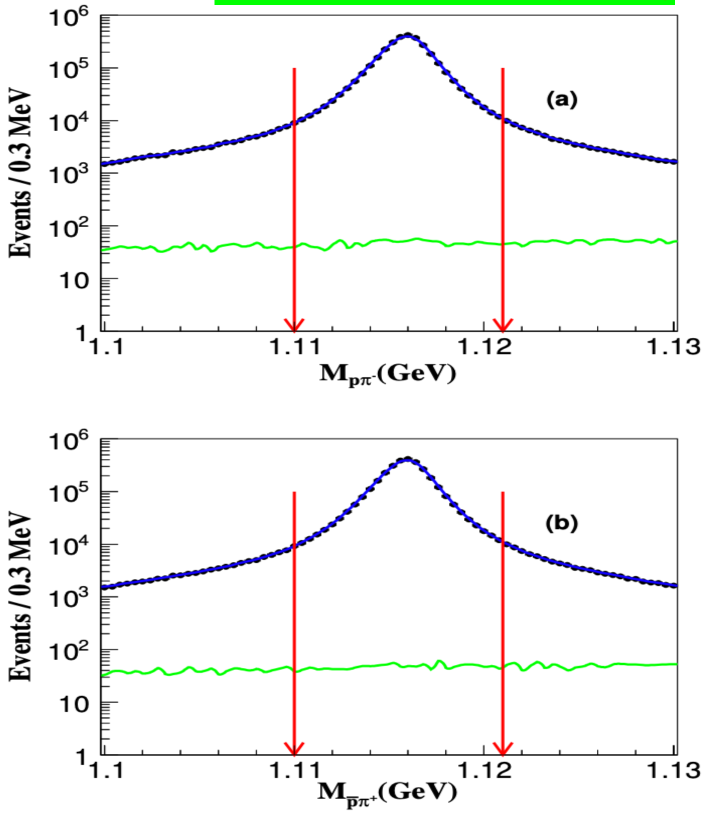
$$\left(J/\psi \to \Lambda\bar{\Lambda} \xrightarrow{oscillate} \Lambda\Lambda\right)$$

PRD111, 052014 (2025)

- Therefore, the oscillation parameter can be deduced as $(\delta m_{\Lambda\bar{\Lambda}})^2 = P(\Lambda)/[2 \cdot (\tau_\Lambda/\hbar)^2]$
- Upper limit based on 10 B J/ψ: $P(\Lambda) = \frac{B(J/\psi \to \Lambda\Lambda + c.c.)}{B(J/\psi \to \Lambda\bar{\Lambda})} < 1.4 \times 10^{-6}$
- Oscillation parameter (90% CL)

$$\delta m_{\Lambda\bar{\Lambda}} < 2.1 \times 10^{-18} \text{ GeV}$$
$$\tau_{OSC} > 3.1 \times 10^{-7} \text{ s}$$

- Charmonium decays at BESIII offer a unique, low background platform for BNV in baryon-pair decays, providing novel pathways in addition to proton decay and n-nbar oscillations.



04 Precision test of conservation laws： Lepton Number Violation

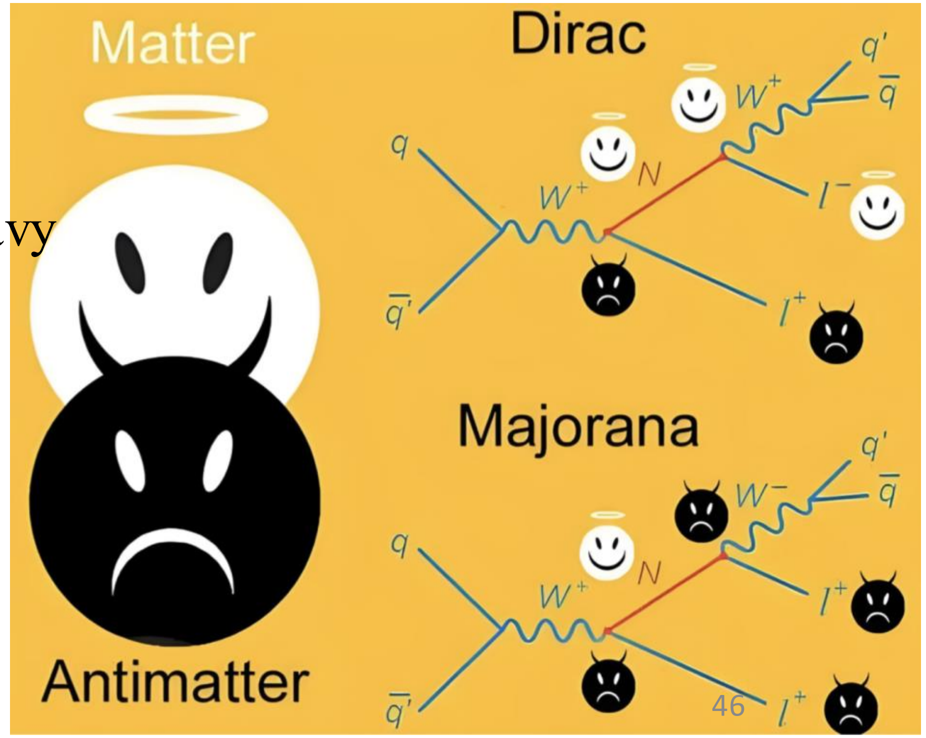
- ✓ Experimentally, neutrino oscillations strongly indicate neutrinos have mass
- ✓ Theoretically, “see-saw” mechanism can explain the neutrino mass
  - The small mass of the observed neutrino arises from heavy Majorana neutrino
  - Whether neutrino is Dirac or Majorana particle is an open question
- ✓ Majorana neutrino can be manifested through the LNV decays by $\Delta L = 2$
  - Most promising way: neutrinoless double beta ($0\nu\beta\beta$) decay

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{l=e}^{\tau} V_{lN}^* \overline{N^c} \gamma^\mu P_L l + h.c.$$ CPC39,013101 (2015)

  - V_{lN}: Mixing matrix between the charged lepton l nuetrino ν_l and heavy Majorana neutrino

$$|V_{eN}|^2 < 3\times10^{-3},\ |V_{\mu N}|^2 < 3\times10^{-3},\ |V_{\tau N}|^2 < 6\times10^{-3}$$

- ✓ Search for $\Delta L = 2$ process in hadron decays



04 Precision test of conservation laws： Lepton Number Violation

Decay Mode	$B^{UP}_{90\%}$ ($\times 10^{-7}$)	Latest Experiment	Published
$\Xi^- \to \Sigma^+ e^- e^-$	200	BESIII [arXiv:2511.15394]	2026
$J/\psi \to K^+ K^+ e^- e^- + c.c.$	0.021	BESIII [CPC50, 013107]	2026
$\eta \to \pi^+ \pi^+ e^- e^- + c.c.$	46	BESIII [PRD112, 112021]	2025
$\omega \to \pi^+ \pi^+ e^- e^- + c.c.$	28	BESIII [CPC49, 103002]	2025
$\phi \to \pi^+ \pi^+ e^- e^- + c.c.$	97	BESIII [CPC49, 043001]	2025
$D_s^+ \to \phi \pi^- e^+ e^+$	690	BESIII [JHEP01, 109]	2025
$D_s^+ \to \phi K^- e^+ e^+$	990		
$D_s^+ \to K_S^0 \pi^- e^+ e^+$	130		
$D_s^+ \to K_S^0 K^- e^+ e^+$	290		
$D_s^+ \to \pi^0 \pi^- e^+ e^+$	290		
$D_s^+ \to \pi^0 K^- e^+ e^+$	340		
$\Sigma^- \to p e^- e^-$	6700	BESIII [PRD103, 052011]	2021
$D^0 \to K^- \pi^- e^+ e^+$	280	BESIII [PRD99, 112002]	2019
$D^+ \to K_S^0 \pi^- e^+ e^+$	330		
$D^+ \to K^- \pi^0 e^+ e^+$	850		

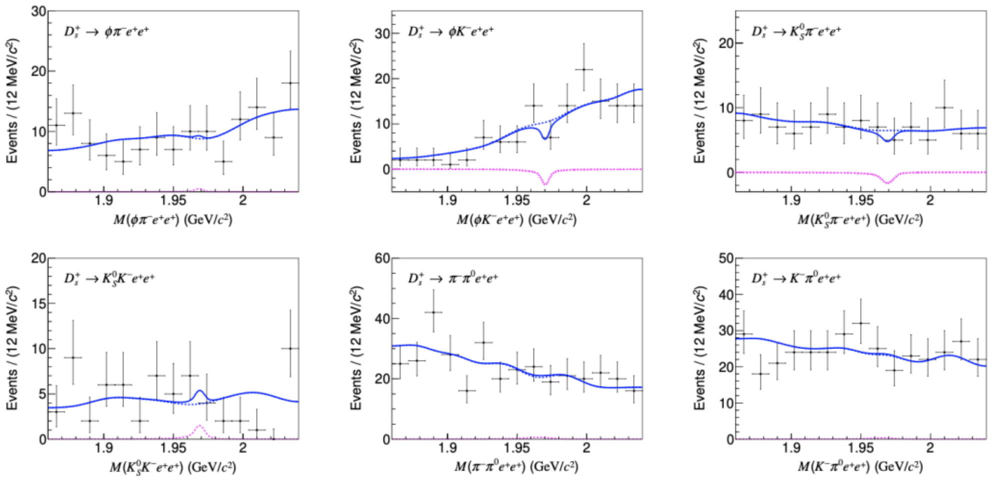
04 Precision test of conservation laws： Lepton Number Violation

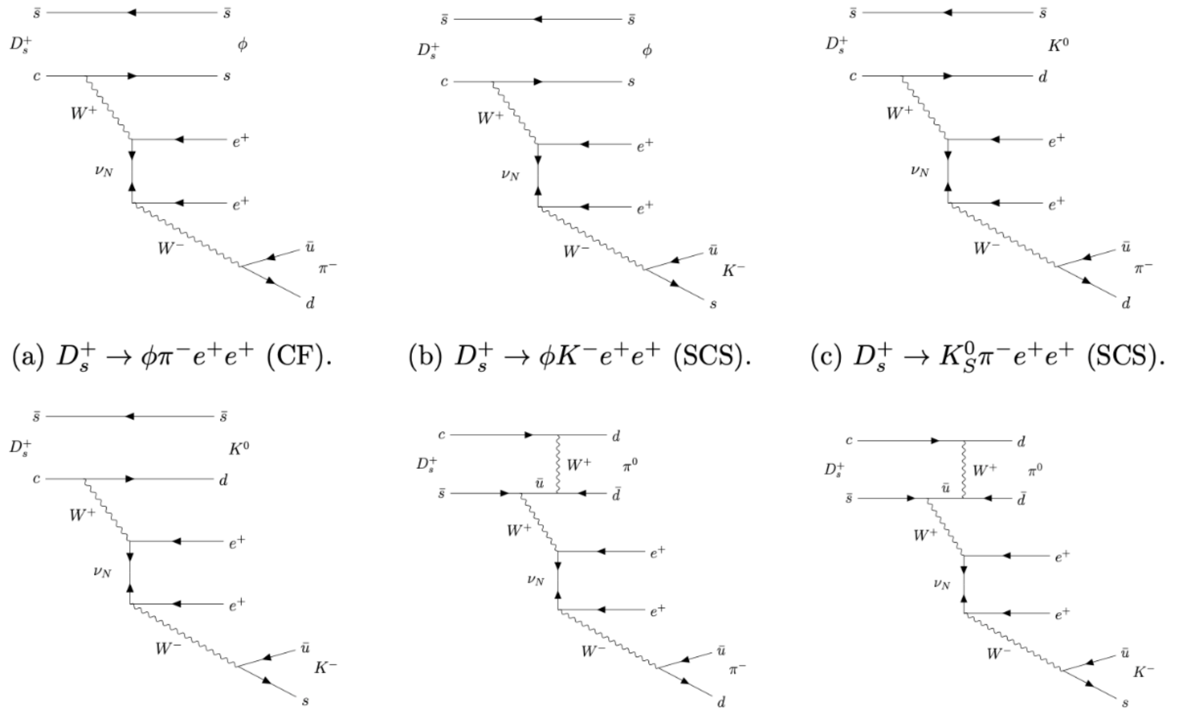
JHEP01, 109 (2025)

- ➔ $h^- : K^-/\pi^-,\ h^0 : \pi^0/K^0_S/\phi \Rightarrow$ 6 signal channels in total
  - ❖ CF: $D_s^+ \to \phi\pi^- e^+ e^+$; SCS: $D_s^+ \to \phi K^- e^+ e^+$, $D_s^+ \to K^0_S \pi^- e^+ e^+$; DCS: $D_s^+ \to K^0_S K^- e^+ e^+$, $D_s^+ \to \pi^- \pi^0 e^+ e^+$, $D_s^+ \to K^- \pi^0 e^+ e^+$;
- ➔ Data: 7.33 fb^{-1} data taken between 4.128 to 4.226 GeV
- ➔ $e^+e^- \to D_s^{*\pm} D_s^{\mp}$, single tag method

$$\mathcal{B}(D_s^+ \to h^- h^0 e^+ e^+) = \frac{N_{\rm sig}}{2 \cdot N_{D_s^{*\pm} D_s^{\mp}} \cdot \epsilon \cdot \mathcal{B}_{\rm inter}}$$

- ➔ First measurement of four-body $\Delta L = 2\ D_s^+$ decay
- ➔ Some model predictions up to $\mathcal{O}(10^{-6})$





(a) $D_s^+ \to \phi\pi^- e^+ e^+$ (CF). (b) $D_s^+ \to \phi K^- e^+ e^+$ (SCS). (c) $D_s^+ \to K^0_S\pi^- e^+ e^+$ (SCS).
(d) $D_s^+ \to K^0_S K^- e^+ e^+$ (DCS). (e) $D_s^+ \to \pi^-\pi^0 e^+ e^+$ (W-exc.). (f) $D_s^+ \to K^-\pi^0 e^+ e^+$ (W-exc.).

Feynman diagrams

04 Precision test of conservation laws： Lepton Number Violation

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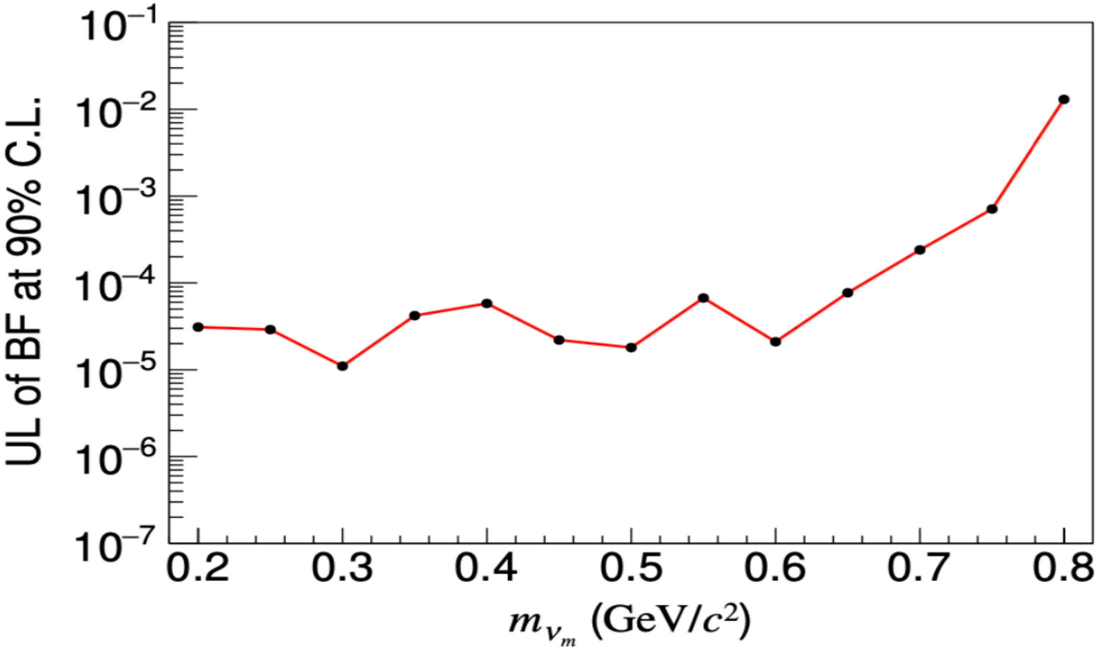
- No obvious signal is observed
- Upper limits of BFs of $D_s^+ \to h^- h^0 e^+ e^+$ decays at the 90% C.L.
- Searching for Majorana (ν_m) in the decay of $D_s^+ \to \phi e^+ \nu_m (\to \pi^- e^+)$
  - Different assumptions of m_{ν_m} ranging from 0.20 to 0.80 GeV
- Require the invariant mass of any $\pi^- e^+$ combination (two combinations per event) to be within the range of $[m_{\nu_m} - 5\sigma, m_{\nu_m} + 4\sigma]$



Decay channel	ϵ (%)	$\mathcal{B}_{\rm UL}$ ($\mathcal{B}_{\rm UL}^{\rm expected}$)
$D_s^+ \to \phi \pi^- e^+ e^+$	3.0 ± 0.1	$6.9\ (3.5) \times 10^{-5}$
$D_s^+ \to \phi K^- e^+ e^+$	1.8 ± 0.1	$9.9\ (10.8) \times 10^{-5}$
$D_s^+ \to K_S^0 \pi^- e^+ e^+$	6.4 ± 0.1	$1.3\ (2.4) \times 10^{-5}$
$D_s^+ \to K_S^0 K^- e^+ e^+$	4.0 ± 0.1	$2.9\ (2.3) \times 10^{-5}$
$D_s^+ \to \pi^- \pi^0 e^+ e^+$	6.4 ± 0.1	$2.9\ (2.7) \times 10^{-5}$
$D_s^+ \to K^- \pi^0 e^+ e^+$	5.1 ± 0.1	$3.4\ (3.9) \times 10^{-5}$

04 Precision test of conservation laws： CP Violation

Sensitive probe of several symmetries in SM

- Forbidden by Bose-Einstein statistics
- CP violating, but could proceed via K° oscillation: 10^{-9} [1][2]
  - $Br(J/\psi \to K_S^0 K_S^0) = (1.94 \pm 0.2)\times 10^{-9}$
  - $Br(\psi(3686) \to K_S K_S) = (0.56 \pm 0.08)\times 10^{-9}$
- CPT invariance test through KsKs over KsKL
  - Could be violated in quantum gravity models with $\omega \sim 10^{-3}$[3][4][5]
- Fobiden by QM, but allowed by EPR locality[6*]
  - $Br(J/\psi \to K_S^0 K_S^0) = (5.5 \pm 0.1)\times 10^{-6}, Br(\psi(3686) \to K_S^0 K_S^0) = (2.1 \pm 0.3)\times 10^{-6}$

[1] Phys. Rev. Lett. 96, 192001 (2006)
[2] Chin. Phys. C 33, 85 (2009)
[3] Phys. Rev. Lett. 92, 131601 (2004).
[4] Nucl. Phys. B744, 180 (2006).
[5] Phys. Rev. D 74, 045014 (2006).
[6] Int. J. Mod. Phys. A 36, 2150178 (2021).
potential CP violation and kaon regeneration considered

Previous experimental results

Decay channels	$J/\psi \to K_S^0 K_S^0$		$\psi(3686) \to K_S^0 K_S^0$	
Experiments	Event number J/ψ	Upper Limit	Event number $\psi(3686)$	Upper Limit
MARKIII	2.7×10^{6}	$<5.2\times 10^{-6}$（90%C.L.)	–	–
BESII	5.8×10^{7}	$< 1.0\times 10^{-6}$（95%C.L.)	1.4×10^{7}	$< 4.6\times 10^{-6}$（95%C.L.)
BESIII(2017)	1.3×10^{9}	$< 1.4\times 10^{-8}$（90%C.L.)		

04 Precision test of conservation laws： CP Violation

- The signal region

$$\sqrt{\left(P^a_{K^0_S}-P_0\right)^2+\left(P^b_{K^0_S}-P_0\right)^2}<5\sigma$$

- Blind analysis:
  - Study cut criteria with MC sample.
  - Estimate the upper limit with 10% semi-blind data.
  - Unblindt after approval from BESIII review committee.

Sample	Round	$N_{tot}(\times10^6)$	semi-blind ratio(%)	semi-blind $N_{tot}(\times10^6)$
J/ψ	2009	224.0	~ 30	67.2
	2012	1088.5	~ 10	108.9
	2018	4581.8	~ 10	458.2
	2019	4190.0	~ 10	419.0
	Total	10087	~ 10	1053.3
$\psi(2S)$	2009	107.0	~ 30	32.1
	2012	341.1	~ 10	34.1
	2021	2260	~ 10	226.0
	Total	2708.1	~ 10	292.2

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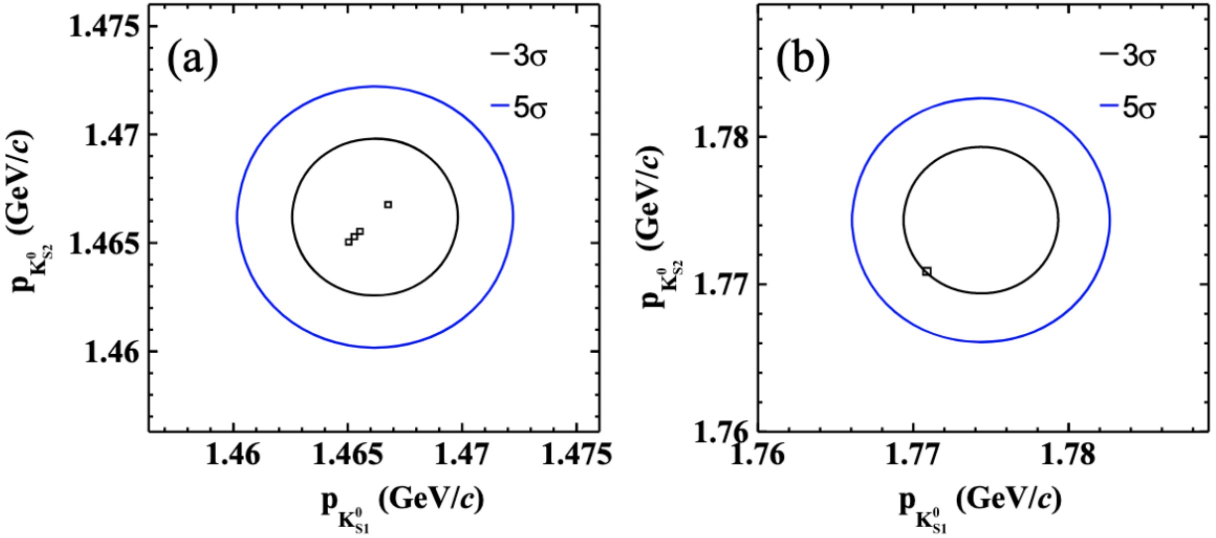
$$Br\left(J/\psi\to K^0_S K^0_S\right)<4.7\times10^{-9}@90\%\ C.L.$$
$$Br\left(\psi(3686)\to K^0_S K^0_S\right)<1.1\times10^{-8}@90\%\ C.L.$$



- Improve previous best limits by a factor of three for J/ψ and ~400 for ψ(3686)
- excluded the EPR locality expectations
- reach the level of the CP violation expectations
- Constraining CPT violation parameter |ω|: <(4.91+- 0.14)×10^{-3} and (1.44+- 0.04)×10^{-2}

Outline

05 Summary

- Rare/forbidden decays provide a unique lab to look for NP.
- Rare charm/charmonium decays is a unique window on NP, which are complementary to those of strange and beauty hadrons.
- Present limits are still above SM predictions, no NP effects have been found yet.
- Better limits and new results are expected from BESIII, Belle II, LHCb, and Super Tau-Charm Factories.
- PS, several most recent achievements are not included in this talk.

BSM searches

谢谢！