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HENAN NORMAL UNIVERSITY

BESIII

Searching for New Physics in Rare Decays at BESIII

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2024年8月13日–18日, 青岛

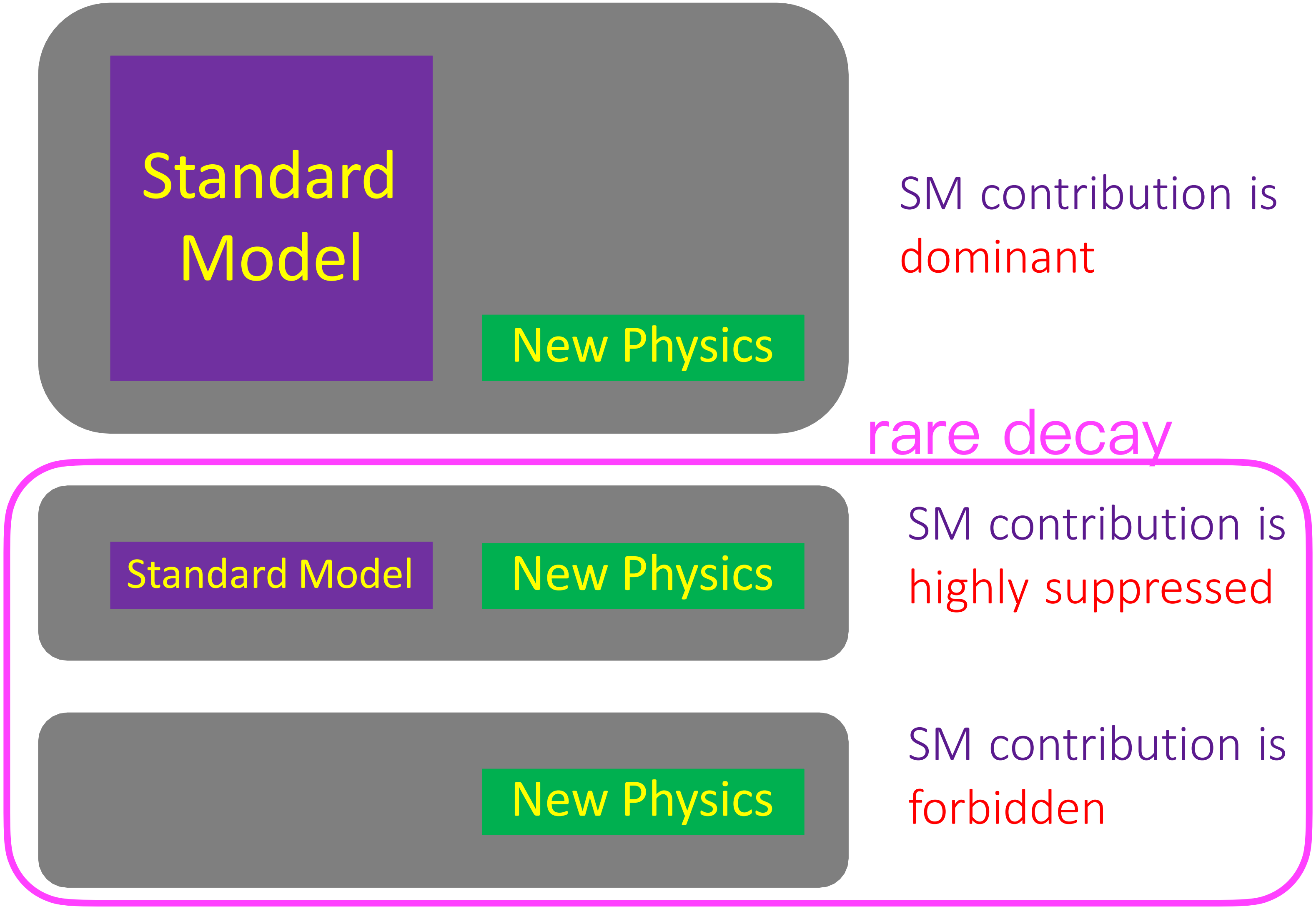
Outline

- Introduction
- Results from BESIII
- Summary and Outlook

Introduction: Why NP?

- SM achieved great success, including the discovery of Higgs particle. However, It is regard as an low energy effective theory which can not explain:
  - experimentally:
    - small mass of neutrino raising in neutrino oscillation
    - dark matter
    - dark energy
    - CKM based CPV is not enough to produce matter/anti-matter asymmetry in universe
  - theoretically:
    - mass hierarchy
    - why only three generation of fermion
    - neutrino is Dirac or Majorana
    - ...
- Pursue theory of everything
  - ...

Why rare decay?



High order, FCNC, Weak decay in charmonium
…

BNV/LNV, cLFV
…

Resent results of rare decay at BESIII

Decay Mode	$B^{UP}_{90\%}$ ($\times 10^{-8}$)	Publication	Type
$J/\psi \to \mu^+\mu^-\mu^+\mu^-$	160	PRD109, 052006 (2024)	rare QED
$\Xi^0 \to \Sigma^- e^+ \nu_e$	16000	PRD107, 012002 (2023)	SU(3)f breaking
$\Omega^- \to \Sigma^0 \pi^-$	54000	JHEP05, 141 (2024)	$\Delta S = 2$
$\Omega^- \to n K^-$	24000		
$D_S^+ \to \pi^+\pi^0 e^+ e^-$	7000	arXiv:2404.05973 accepted by PRL	FCNC
$D_S^+ \to K^+\pi^0 e^+ e^-$	7100		
$D_S^+ \to K_S^0 \pi^+ e^+ e^-$	8100		
$\psi(3696) \to \Lambda_c^+ \bar{\Sigma}^-$+c.c	1400	CPC47,013002 (2023)	Weak decay
$J/\psi \to D^- \mu^+ \nu_\mu$	56	JHEP01, (2024) 126	Weak decay
$J/\psi \to \bar{D}^0 \pi^0$	47	arXiv:2310.07277 accept by PRD	Weak decay
$J/\psi \to \bar{D}^0 \eta$	68		
$J/\psi \to \bar{D}^0 \rho^0$	52		
$J/\psi \to D^- \pi^+$	7		
$J/\psi \to D^- \rho^+$	60		

Resent results of BNV&LNV at BESIII

Decay Mode	$B^{UP}_{90\%}$ $(\times 10^{-8})$	Publication	Type
$\Lambda \to \bar{\Lambda}$	440	PRL131, 121801 (2023)	BNV
$\Xi^0 \to K^- e^+$	360	PRD108, 012006 (2023)	BNV
$\Xi^0 \to K^+ e^-$	190		
$D^0 \to \bar{p} e^+$	120	PRD105, 032006 (2022)	BNV
$D^0 \to p e^-$	220		
$D^+ \to \bar{n} e^+$+c.c	1430	PRD106, 112009 (2022)	BNV
$D^- \to p e^-$+c.c	2920		
$\phi \to \pi^+\pi^+e^-e^-$	370	arXiv:2308.05490 submitted	LNV
$J/\psi \to e\mu$	0.45	Sci.China Phys.Mech.Astron. 66, 221011 (2023)	cLFV

highly suppressed: Search for $J/\psi \to l_a^+ l_a^- l_b^+ l_b^-$

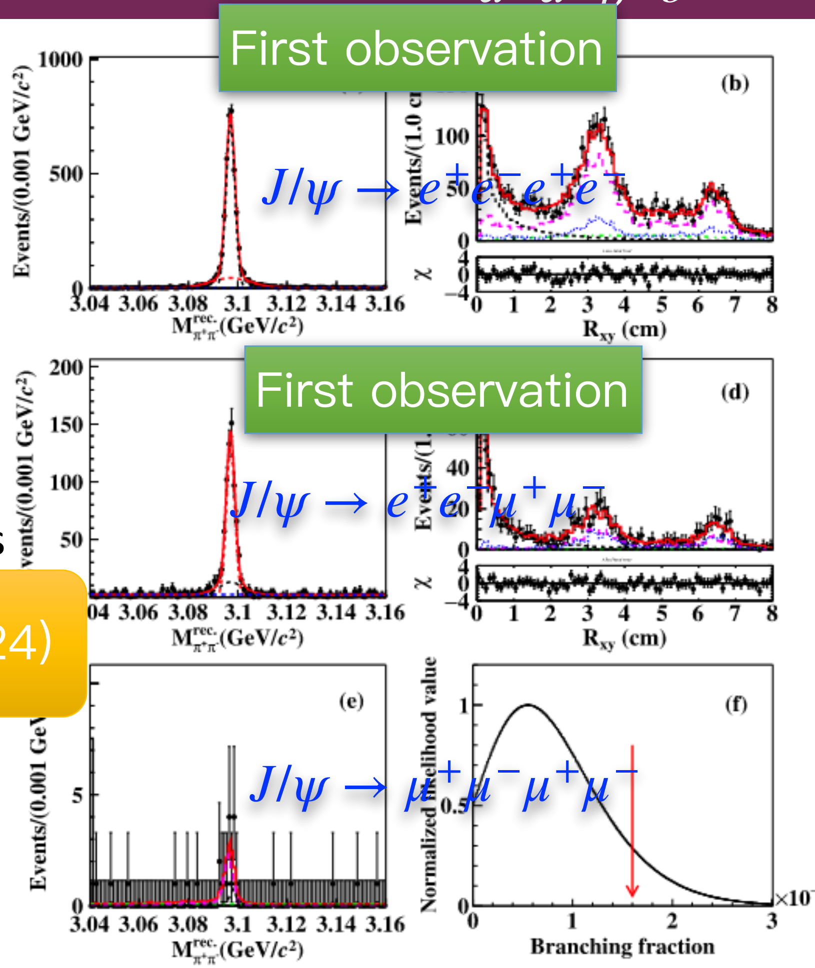
- Pure leptonic processes are ideal for testing accurate QED predictions due to their simplicity and lack of nonperturbative effects.
- Test CP, further LFU if the sub $a \neq b$
- Data: 0.45 billion $\psi(3686)$ events through $\psi(3686) \to \pi^+\pi^- J/\psi$
- Signal extracted through vertex of e^+e^- tracks in first two modes
- LFU

PRD 109, 052006 (2024)

$B_{eeee}/B_{ee\mu\mu} = 1.55 \pm 0.13 \pm 0.14$ 1σ of NRQCD

$B_{\mu\mu\mu\mu}/B_{eeee} < 0.033$

$B_{\mu\mu\mu\mu}/B_{ee\mu\mu} < 0.050$



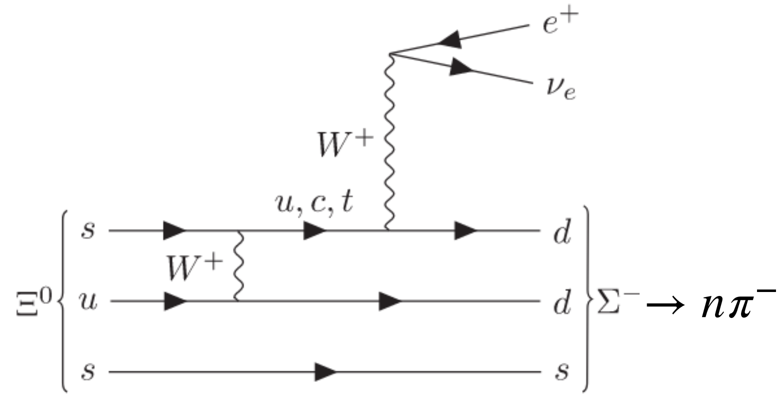
			This work				Theory [2]
Decay mode	N_{sig}	$\epsilon(\%)$	$N(C_T > 0)$	$N(C_T < 0)$	$\mathcal{B}(\times 10^{-5})$	$\mathcal{A}_T$	$\mathcal{B}(\times 10^{-5})$
$J/\psi \to e^+e^-e^+e^-$	700 ± 39	8.22 ± 0.02	355 ± 27	363 ± 28	$5.48 \pm 0.31 \pm 0.45$	$-0.012 \pm 0.054 \pm 0.010$	5.288 ± 0.028
$J/\psi \to e^+e^-\mu^+\mu^-$	354 ± 22	6.46 ± 0.04	193 ± 15	170 ± 15	$3.53 \pm 0.22 \pm 0.13$	$0.062 \pm 0.059 \pm 0.006$	3.763 ± 0.020
$J/\psi \to \mu^+\mu^-\mu^+\mu^-$	3.4 ± 4.1	3.96 ± 0.03	...	...	<0.16	...	0.0974 ± 0.0005

theo.: PRD104,094023

NP in Hyperon: Search for $\Delta S = \Delta Q$ violation

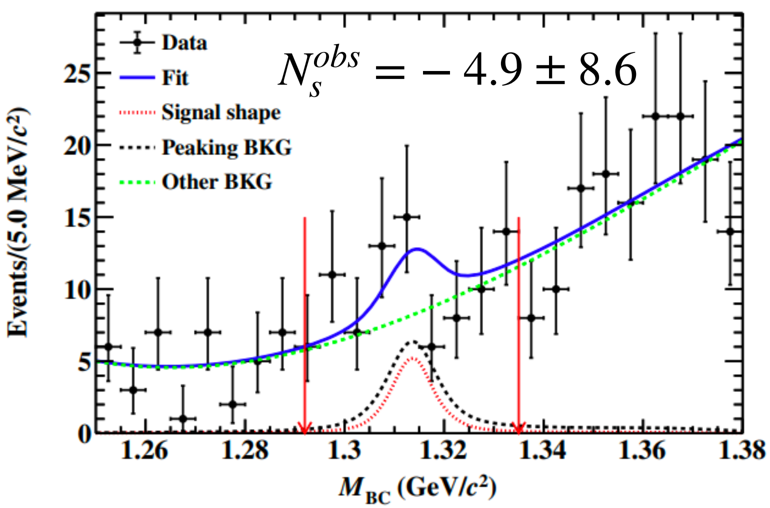
- BF of $\Delta S \neq \Delta Q$ process highly suppressed in SM, or related to breaking effect of SU(3)$_f$, CP and CPT invariance
- Data: 10 billion @J/ψ energy point through $J/\psi \to \Xi^0(\to \text{Signal})\bar{\Xi}^0(\to \bar{\Lambda}\pi^+)$, provide 10^6 hyperon pairs, double tag method
- Upper limit at 90% C.L.

$$B(\Xi^0 \to \Sigma^- e^+ \nu_e) < 1.6 \times 10^{-4}$$

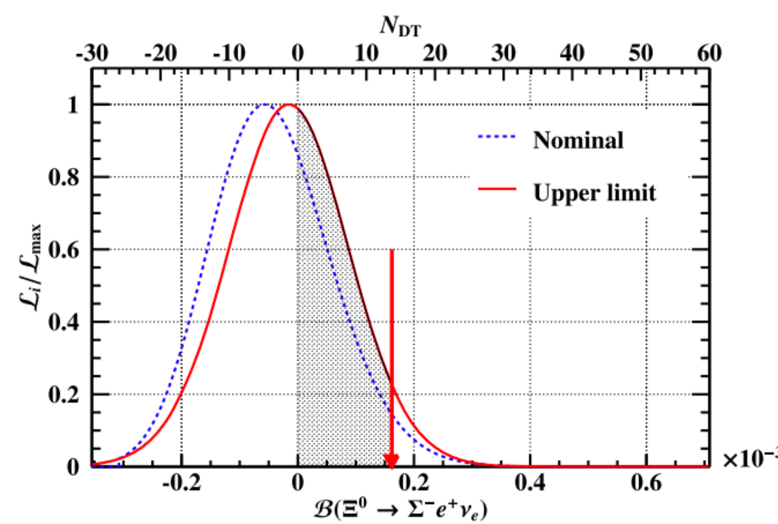


Second order weak interaction in SM

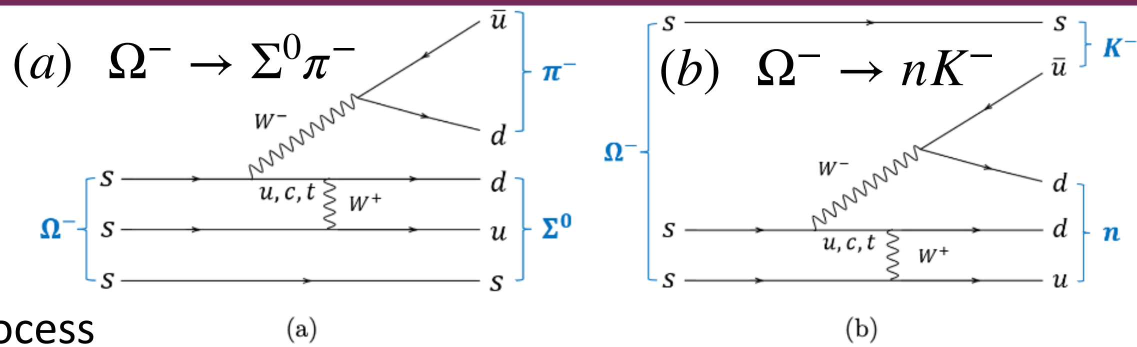
PRD 107, 012002(2023)



black dashed: peaking background(fixed Num.)



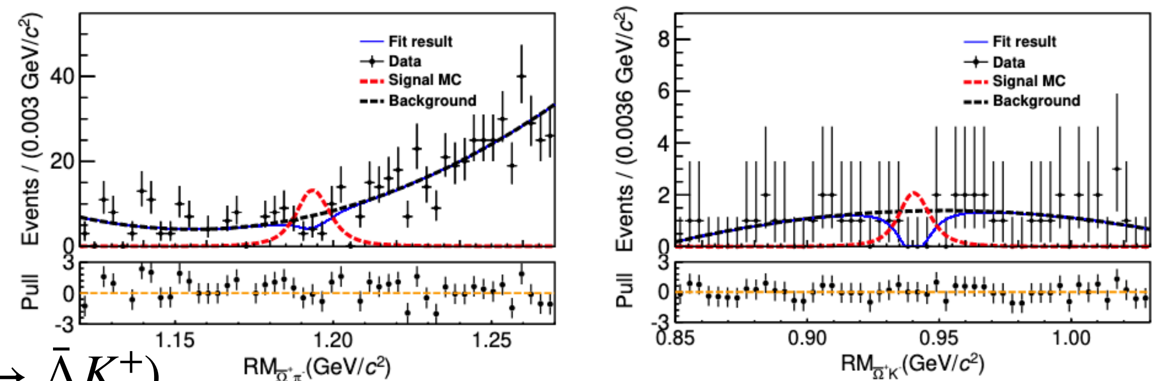
NP in Hyperon: Search for $\Delta S = 2$ process

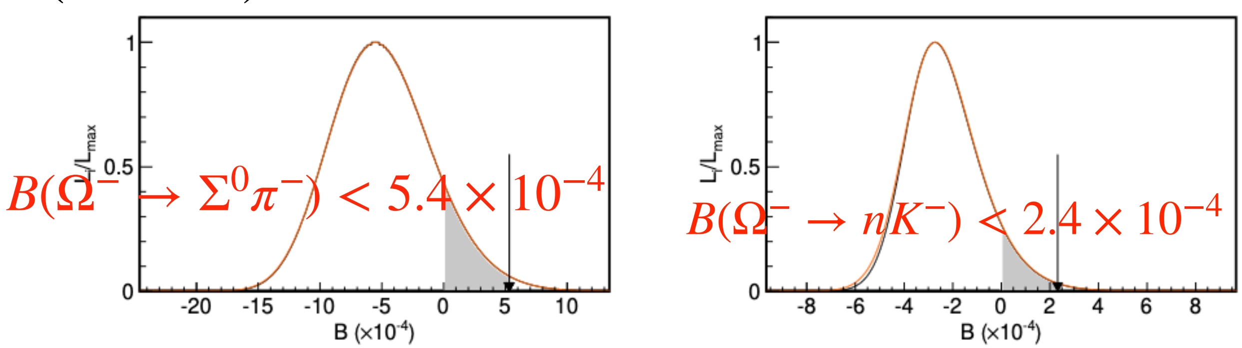


Second order weak interaction in SM

- BF of $\Delta S = 2$ process highly suppressed in SM
- May enhance to 10^{-7} with some NPs[X.G. He,PRD108,055012]
- Data: 2.7 billion $@\psi(3686)$ energy point $\psi(3686) \to \Omega^-(\to \text{Signal})\bar{\Omega}^+(\to \bar{\Lambda}K^+)$
- $\sim 10^4\ \Omega$ pairs
- Look in recoil mass (RM)

JHEP 05, 141 (2024)





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

FCNC: Search for $D_s \to h^+(h^0)e^+e^-$

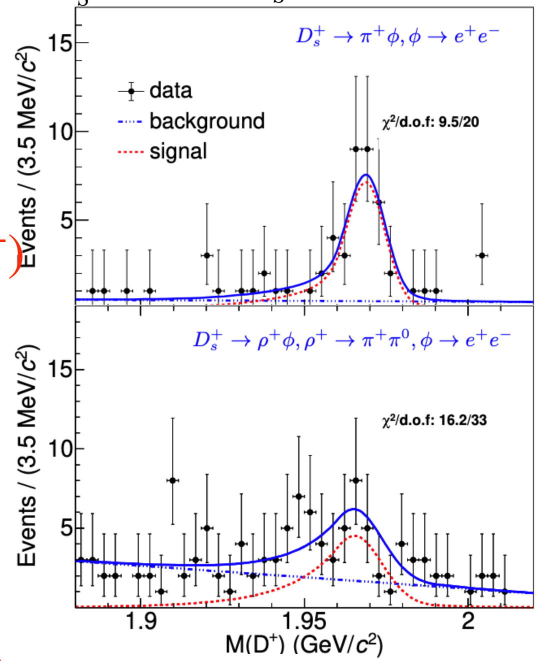
- Data: 7.33 fb^{-1} @4.128~4.226 energy point
- Single tag analysis

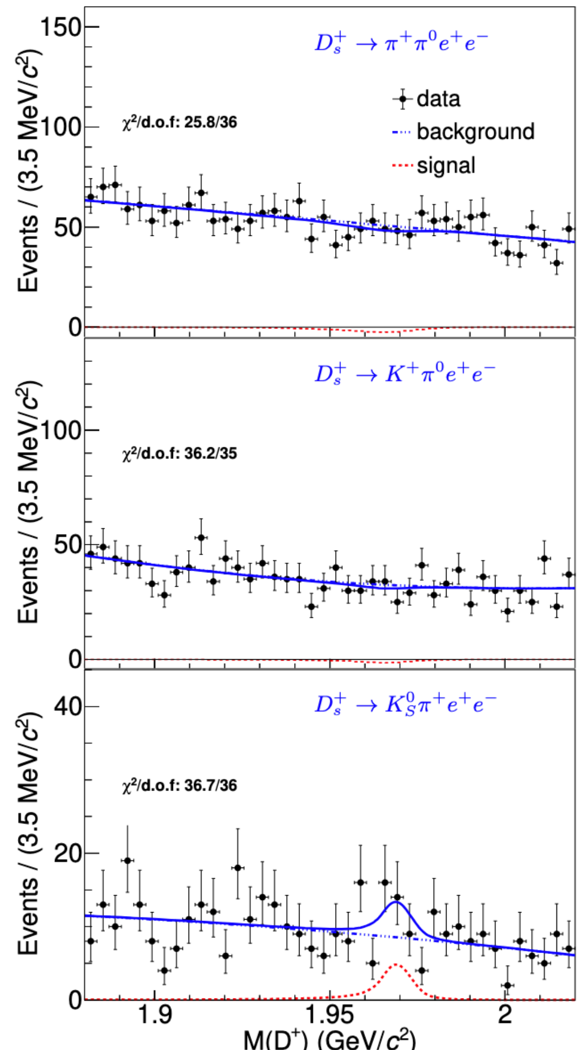
$$M_{\mathrm{rec}} = \sqrt{\left(E_{\mathrm{cm}} - \sqrt{|\vec{P}_{D_S^+}|^2 + m^2_{D_S^+}}\right)^2 - |\vec{P}_{D_S^+}|^2}$$

$$\Delta M = M(D_S^+\gamma) - M(D_S^+)$$

- First observation of long-distance interaction in $D_S^+ \to \rho^+\phi(\to e^+e^-)$
- First upper limits
- Enlighten $c \to u^+ l^+ l^-$ and $D_s \to V\gamma$

arXiv:2404.05973
accept by PRL

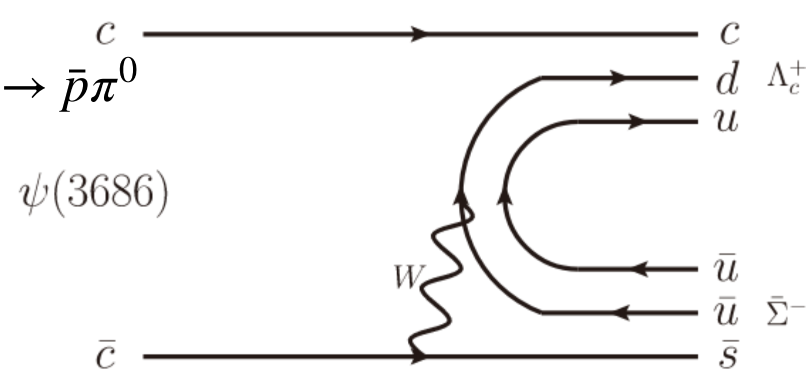


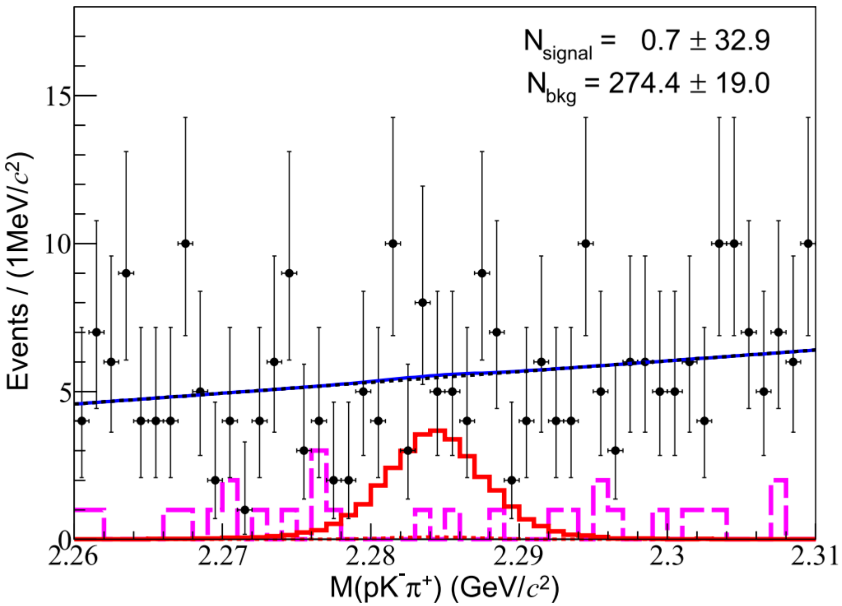


Decay	N_{sig}	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$
$D_s^+ \to \pi^+\pi^0e^+e^-$	...	7.4	< 7.0
$D_s^+ \to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

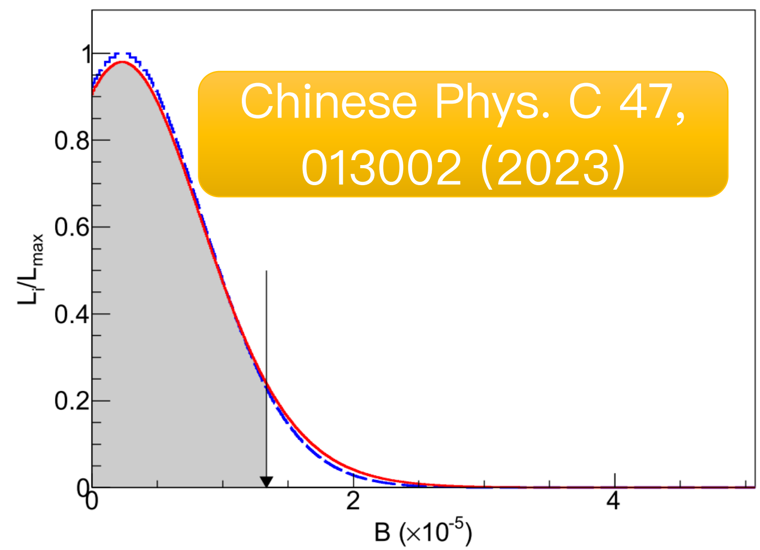
Weak decay: Search for $\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + \text{c.c}$

- 0.45 billion $\psi(3686)$ events @3.69GeV
- $\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + \text{c.c}$, with $\Lambda_c^+ \to p K^- \pi^+$, $\bar{\Sigma}^- \to \bar{p}\pi^0$
- Look signal in mass of $M(pK^-\pi^+)$





(color online) Fit to the $M(pK^-\pi^+)$ distribution for the candidate events from $\psi(3686) \to \Lambda_c^+\bar{\Sigma}^-$. Points with error bars are data. The red (black) dashed line is the signal (background), and the blue solid curve is the total fit. The pink dashed line is the inclusive MC sample. The red solid curve is the signal shape enlarged by a factor of 100.



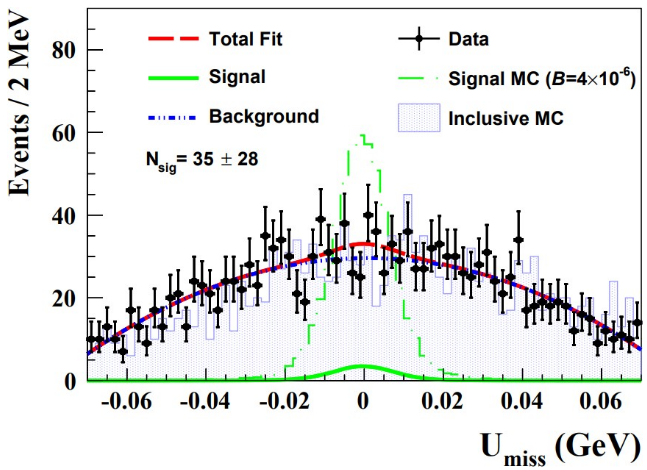
Chinese Phys. C 47, 013002 (2023)

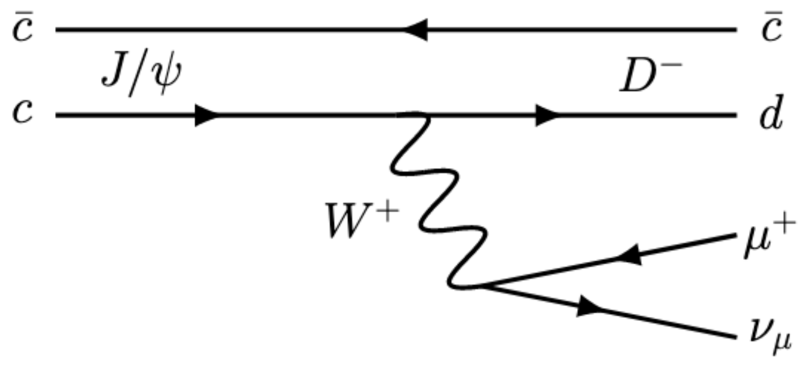
$B(\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + \text{c.c}) < 1.4 \times 10^{-5}$

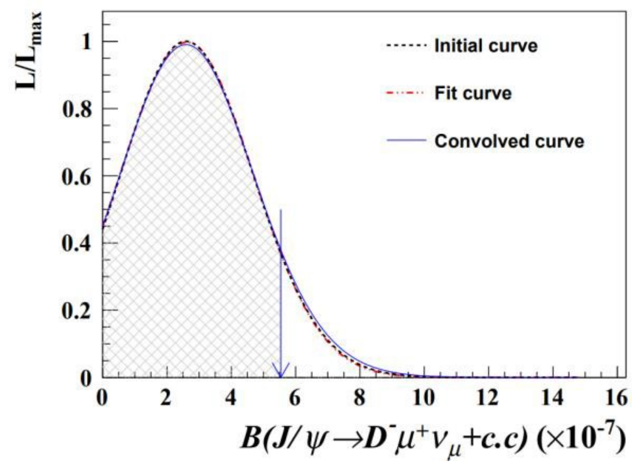
@ 90% C.L.

Weak decay: Search for $J/\psi \to D^- \mu^+ \nu_\mu + c.c$

- 10 billion J/ψ events @3.09GeV
- Using $J/\psi \to D^- \mu^+ \nu_\mu$, $D^- \to K^+ K^- \pi^-$
- Signal extracted by
  $U_{\text{miss}} = E_{\text{miss}} - |P_{\text{miss}}|$



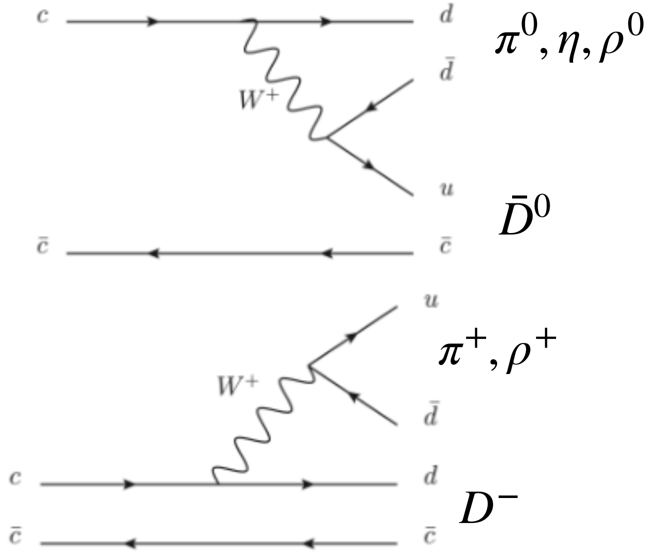




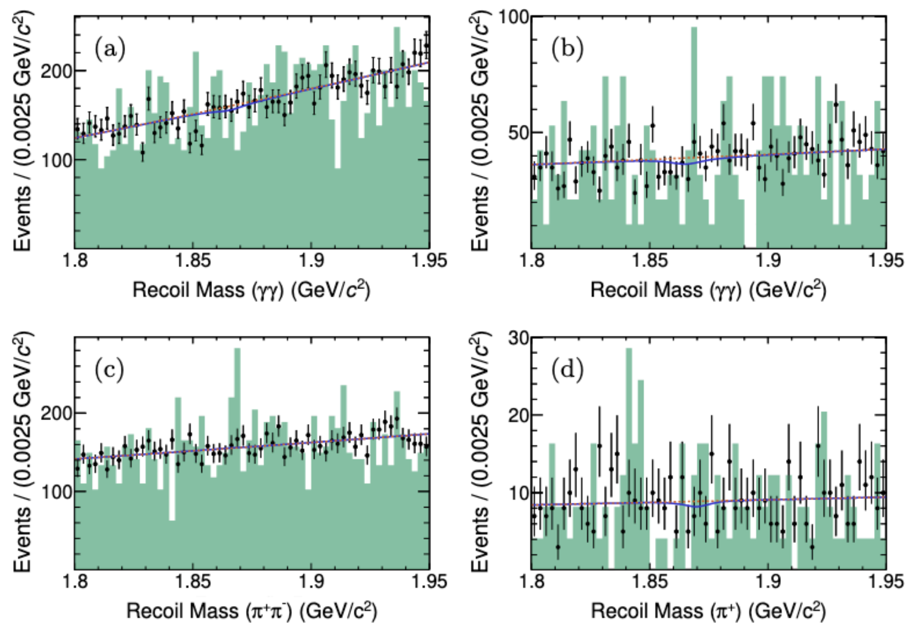
- Upper limit at 90% CL
  $\mathcal{B}(J/\psi \to D^- \mu^+ \nu_\mu + c.c.) < 5.6 \times 10^{-7}$
- Predict to be at order of 10^{-8} or lower in SM
- The first search of a charmonium weak decay with a muon in the final state.

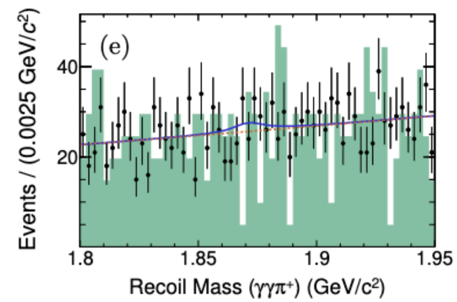
JHEP 01, 126(2024)

Weak decay: Search for $J/\psi \to D^{0,-}h^{0,+}$



- 10 billion J/ψ events @3.09GeV
- Reconstruction through $\bar{D}^0 \to K^+e^-\bar{\nu}_e$ or $D^- \to K^0_S e^-\bar{\nu}_e$
- Signal extracted by recoiling mass of $h^{0,+}$
- Upper limit on branching rate at 90% C.L.

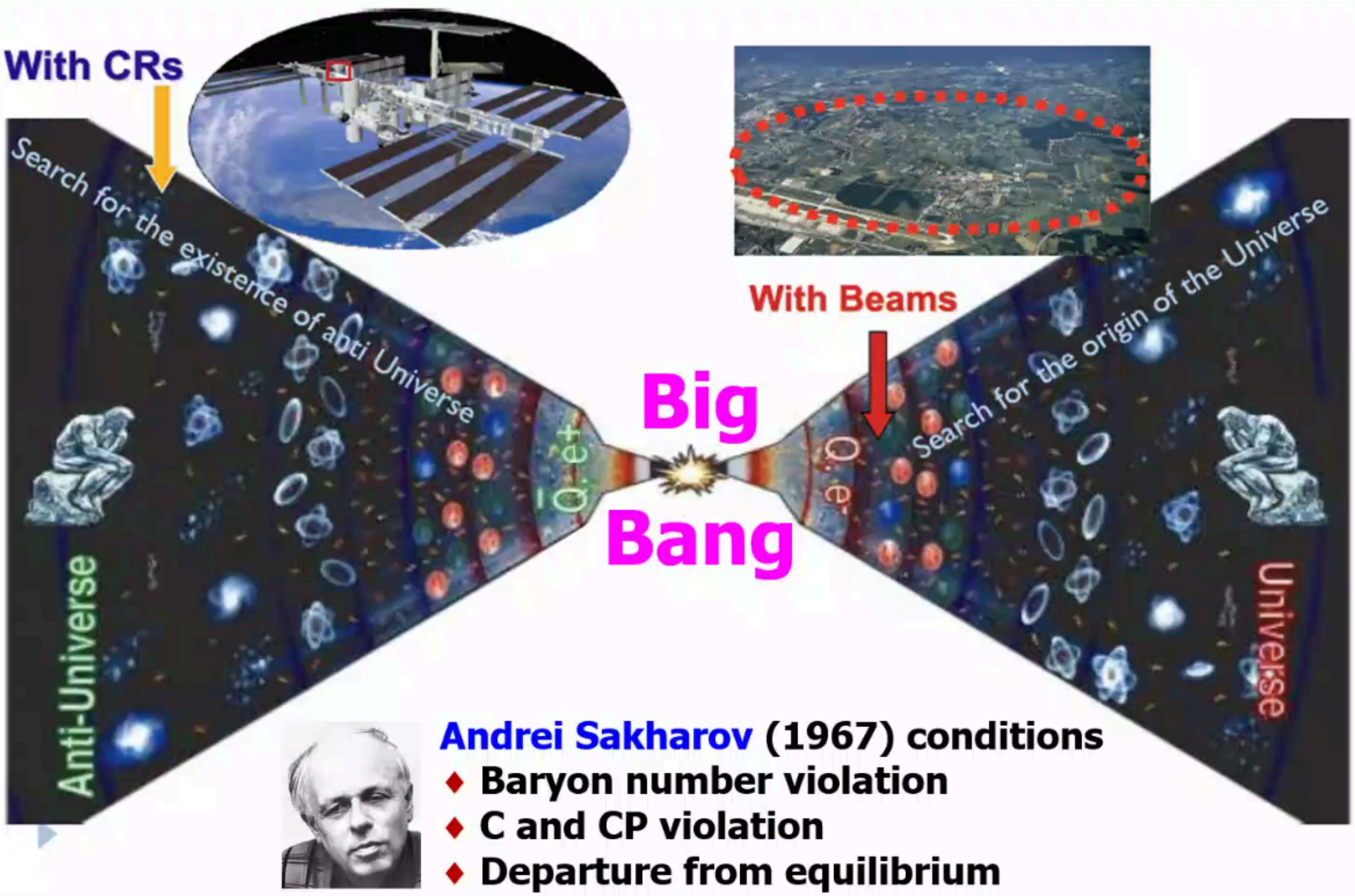




Mode	N_{sig}	N_{sig}^{UL}	$\mathcal{B}$ (90% C.L.) this work	$\mathcal{B}$ (90% C.L.) previous
$J/\psi \to \bar{D}^0\pi^0$	-49.5 ± 69.3	< 68.8	$< 4.7 \times 10^{-7}$	...
$J/\psi \to \bar{D}^0\eta$	-28.9 ± 34.5	< 32.9	$< 6.8 \times 10^{-7}$	...
$J/\psi \to \bar{D}^0\rho^0$	2.0 ± 37.1	< 59.9	$< 5.2 \times 10^{-7}$	...
$J/\psi \to D^-\pi^+$	-4.3 ± 10.3	< 14.4	$< 7.0 \times 10^{-8}$	$< 7.5 \times 10^{-5}$ [3]
$J/\psi \to D^-\rho^+$	18.6 ± 26.2	< 51.4	$< 6.0 \times 10^{-7}$	...

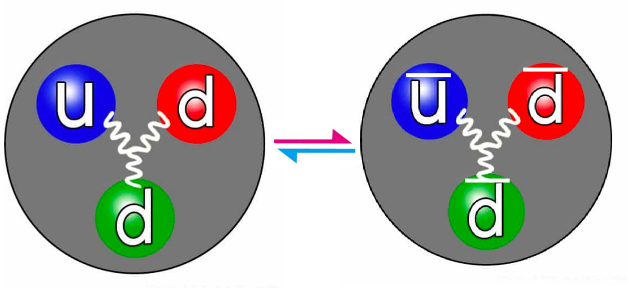
arXiv:2310.07277
accept by PRD

Why BNV?



The asymmetry of matter and antimatter in the universe is one of the major frontier issues urgently to be solved in particle physics, astrophysics and cosmology.

Search for $\Lambda - \bar{\Lambda}$ oscillation



- 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 present 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 searches with the result of proton decay which only have the first generation quark.

Search for $\Lambda - \bar{\Lambda}$ oscillation

- Result based on 1.31 billion J/ψ events
- An oscillation event (c.c. implied)

$$J/\psi \to pK^-\bar{\Lambda} \xrightarrow{\text{oscillating}} pK^-\Lambda$$

- Time integrated oscillation rate

$$\mathscr{P}(\Lambda) = \frac{\mathscr{B}(J/\psi \to pK^-\Lambda)}{\mathscr{B}(J/\psi \to pK^-\bar{\Lambda})} = \frac{N^{\rm obs}_{WS}/\epsilon_{WS}}{N^{\rm obs}_{RS}/\epsilon_{RS}}$$

- Bkg free, sys. uncertainty very low (1%)
- Upper limit on oscillation rate at 90% CL

$$\mathscr{P}(\Lambda) < \frac{N^{\rm obs}_{\rm RS}/\epsilon_{\rm WS}}{N^{\rm obs}_{\rm RS}/\epsilon_{\rm RS}} = 4.4 \times 10^{-6}.$$

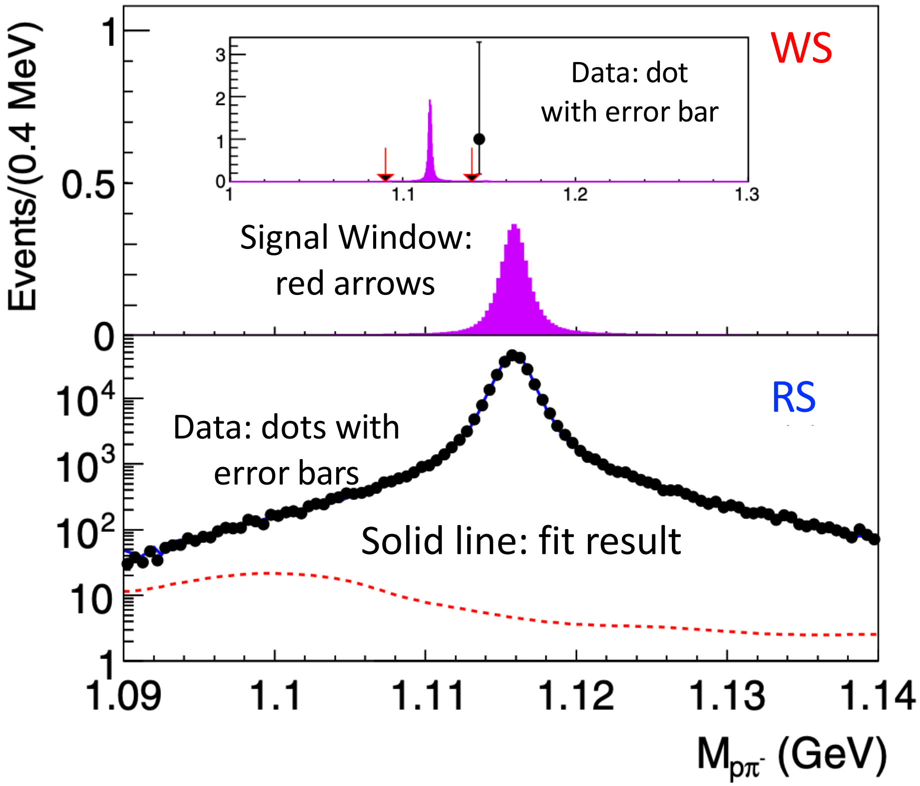
- Oscillation parameter (90% CL)

$$\delta m_{\Lambda\bar{\Lambda}} = \frac{\mathscr{P}(\Lambda)}{2\tau_{\Lambda}^2} < 3.8 \times 10^{-18}\ \text{GeV}$$

Wrong Sign Channel (Same Charge)

$J/\psi \to pK^-\Lambda \to pK^-(p\pi^-)$

PRL 131, 121801 (2023)

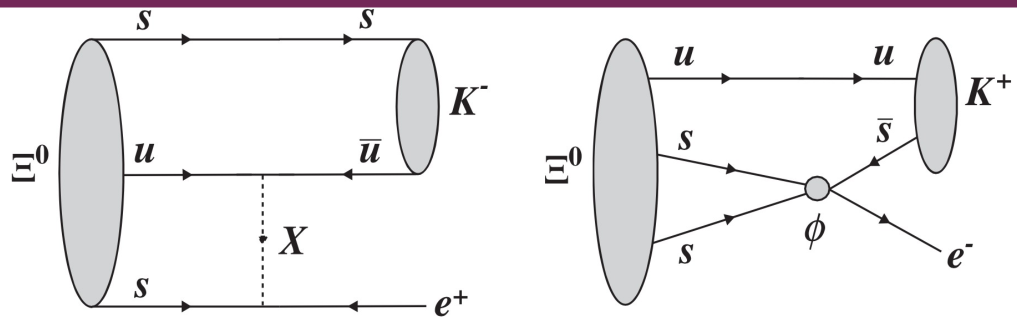


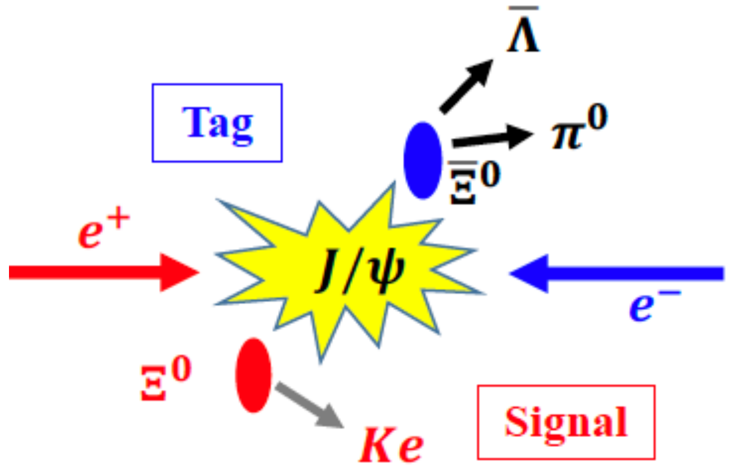
Right Sign Channel (Opposite Charge)

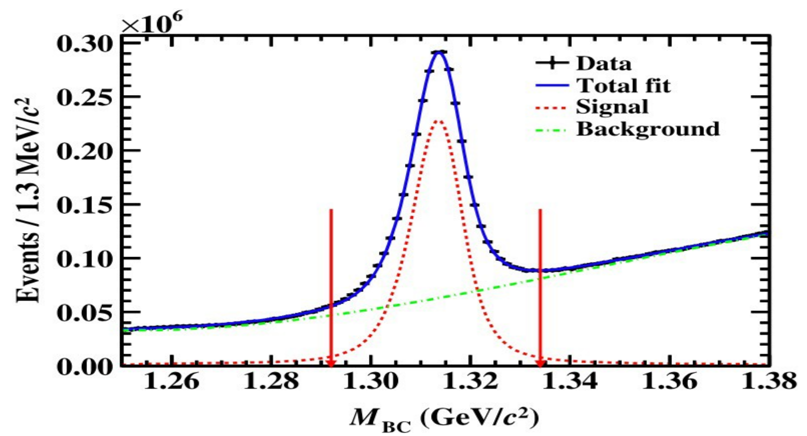
$J/\psi \to pK^-\bar{\Lambda} \to pK^-(\bar{p}\pi^+)$

BNV/LNV: Search for $\Xi^0 \to Ke$

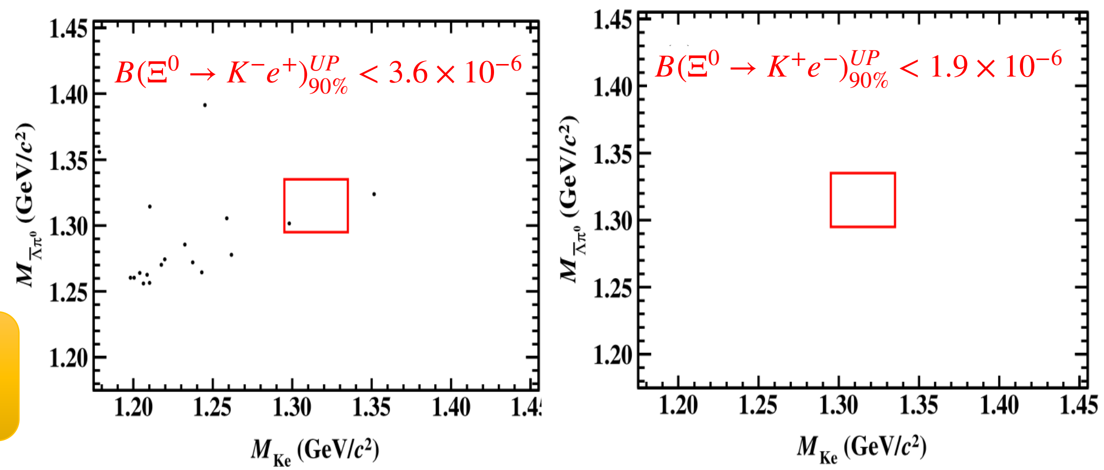
- 10 billion J/ψ events
- First search of BNV in Ξ decay
- Double tag method







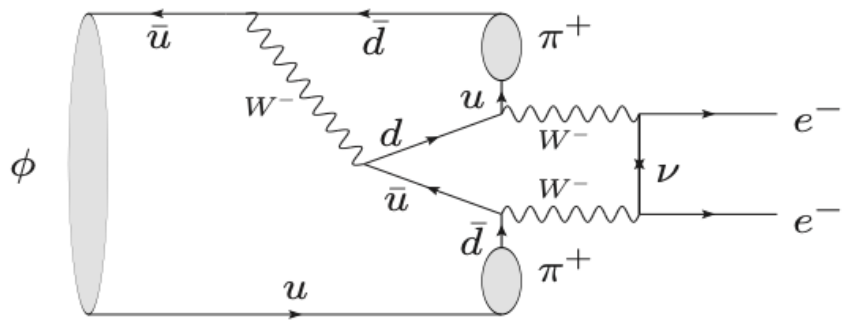
- Background free analysis
- Low systematic uncertainty (3.4%)
- No obvious signal observed



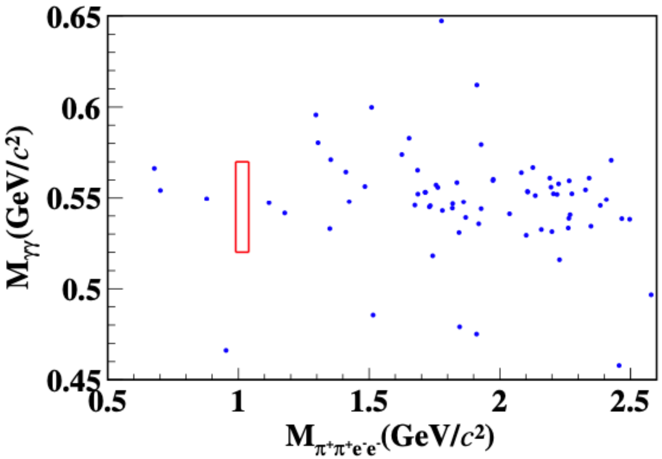
PRD 108, 012006 (2023)

LNV: Search for $\phi \to \pi^+\pi^+e^-e^-$

- 10 billion J/ψ events through $J/\psi \to \phi\eta$
- First search of LNV in ϕ



arXiv:2308.05490
submitted

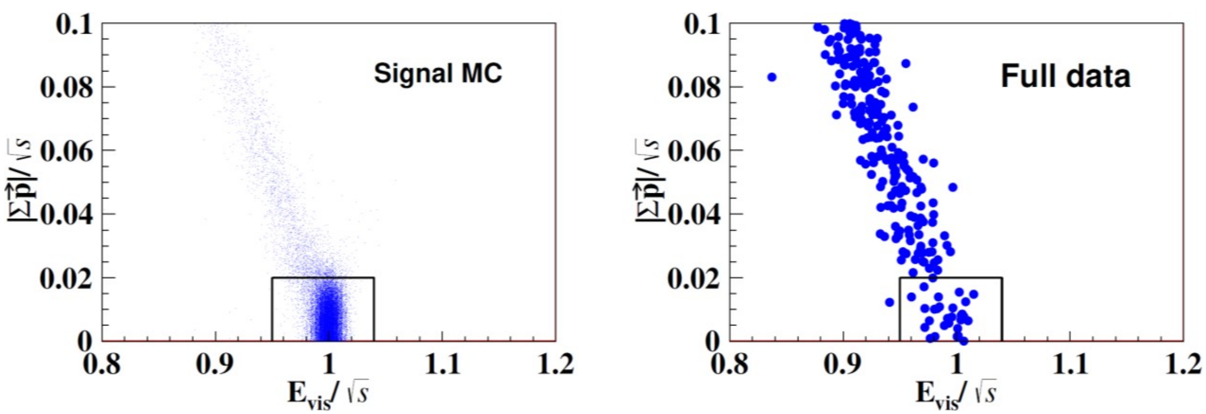


- Background free analysis
- Upper limit at 90% C.L.

$$\mathcal{B}(\phi \to \pi^+\pi^+e^-e^-) < 3.7 \times 10^{-6}$$

cLFV: Search for $J/\psi \to e\mu$

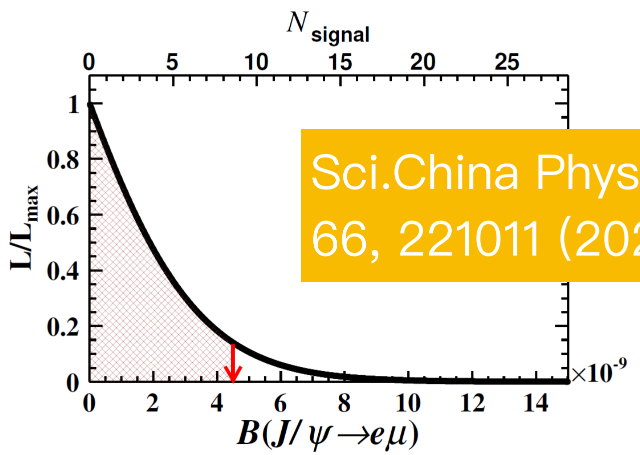
- 8.998×10^9 J/ψ events (without 2012 data)
- Searching for two back-to-back e μ
- Expected 24.8(J/ψ)+12.0(continuum) bkg events
- Observe 29 candidate events



- Upper limit at 90% C.L.

$$\mathcal{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9}$$

- Improve the previous best limit by a factor of **30**
- The most precise cLFV search in heavy quarkonium



Sci.China Phys.Mech.Astron. 66, 221011 (2023)

Summary

- Searching rare decay from experiment plays key role to reveal NP beyond SM.
- Present constraints are still above SM predictions, no evidence of NP have been found yet.
- In the future, more data on BESIII will collected, new results and more strict constraints can be expected.

Thank you!

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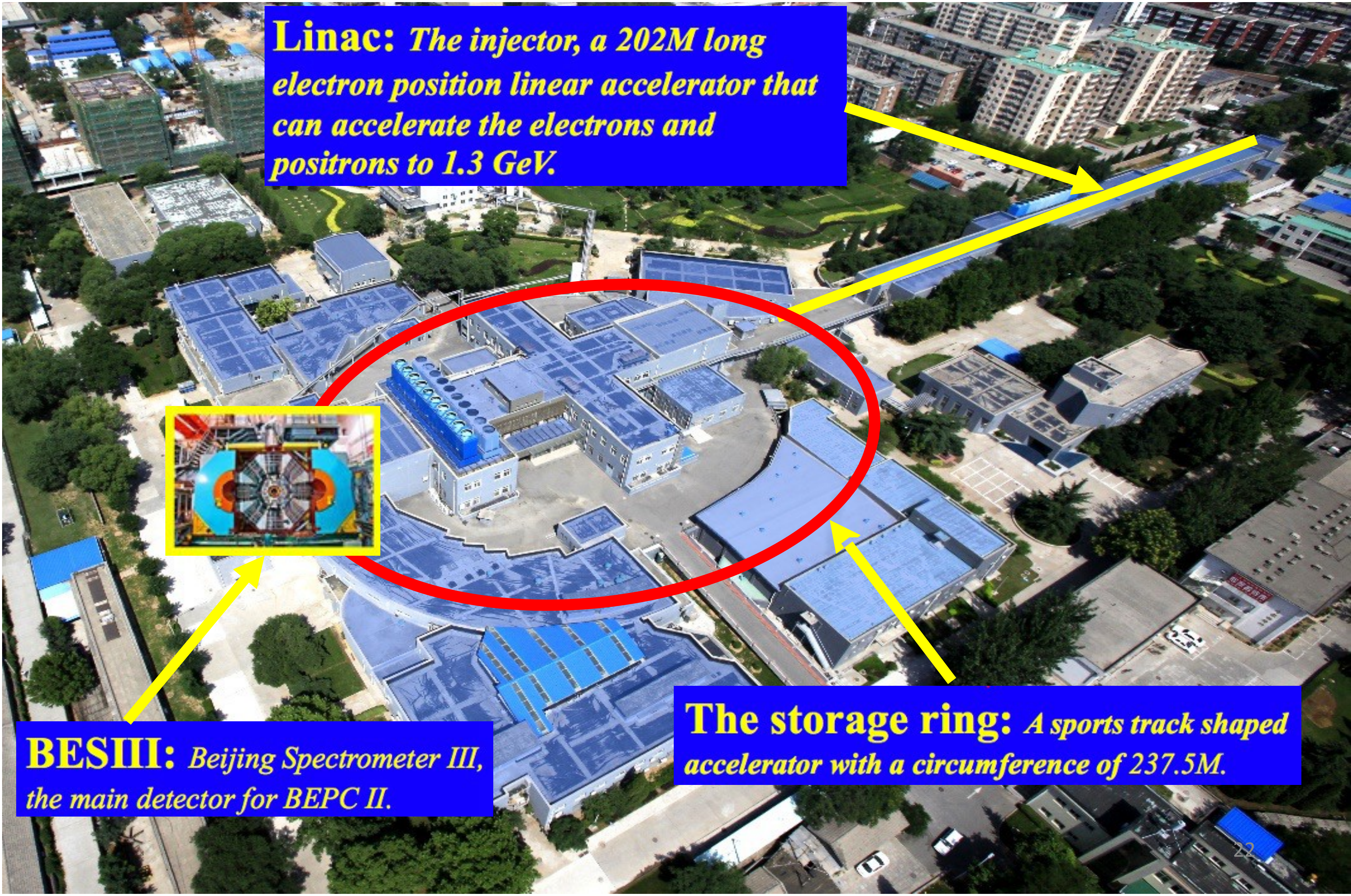
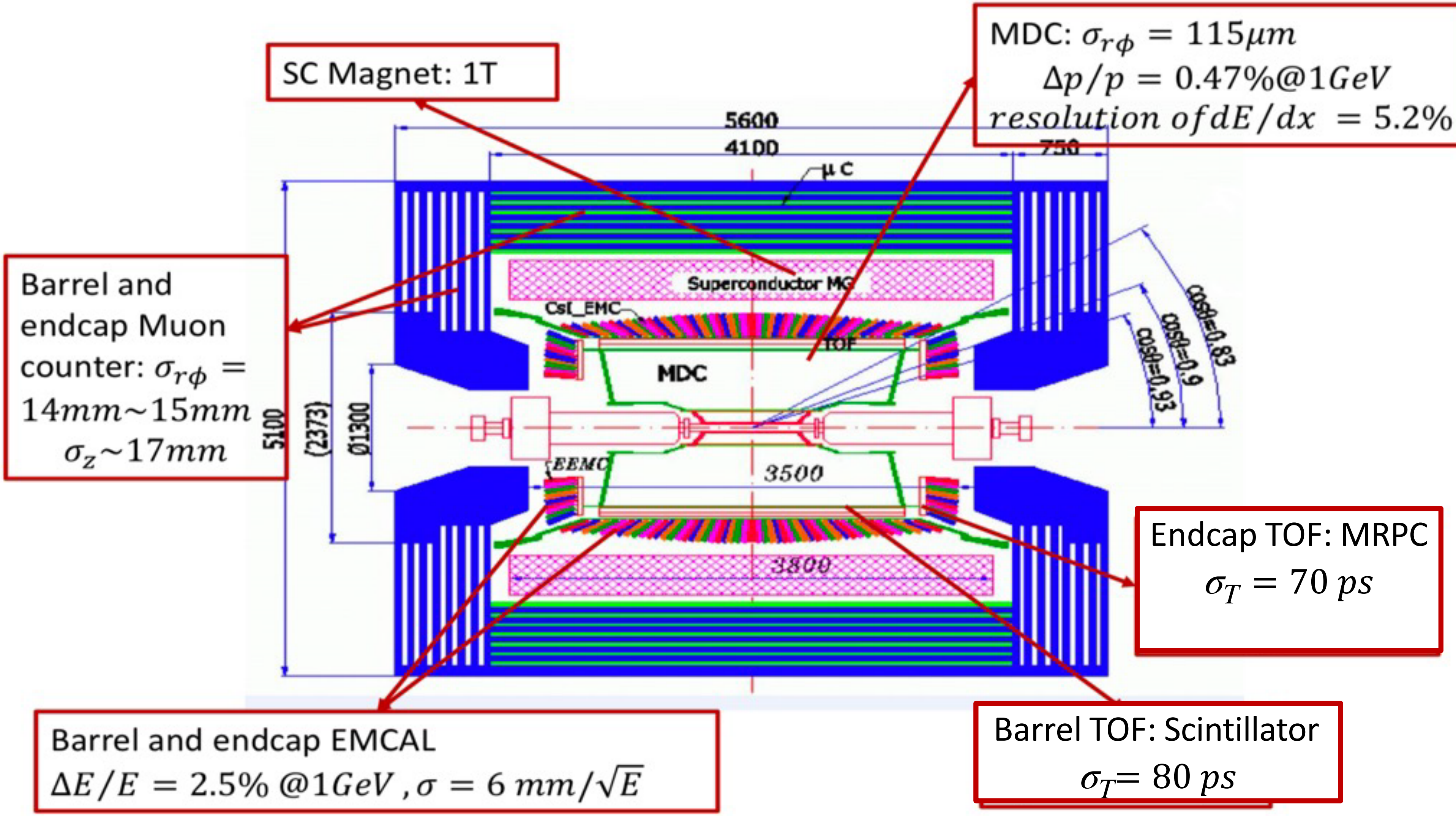
Backup Slides

Introduction:BEPCII/BESIII



Introduction:BESIII Detector



- General purpose detector at BEPCII, $E_{cm} \approx$ 2-4.6 GeV, $L_{peak} \approx 10^{33}/cm^2/s$
- Versatile researches in τ-charm physics

Introduction:BESIII Collaboration

Europe (18)

Germany(6): Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster

Italy(3): Ferrara University, INFN, University of Turin,

Netherlands(1): KVI/University of Groningen

Russia(2): Budker Institute of Nuclear Physics, Dubna JINR

Sweden(1): Uppsala University

Turkey (1): Turkish Accelerator Center Particle Factory Group

UK(3): University of Manchester, University of Oxford, University of Bristol

Poland(1): National Centre for Nuclear Research

Pakistan(2)

COMSATS Institute of Information Technology
University of the Punjab

India(1)

Indian Institute of Technology madras

Thailand(1)

Suranaree University of Technology

Mongolia(1)

Institute of Physics and Technology

Korea(1)

Chung-Ang University

USA(3)

Carnegie Mellon University
Indiana University
University of Hawaii

Chile(1)

University of Tarapaca

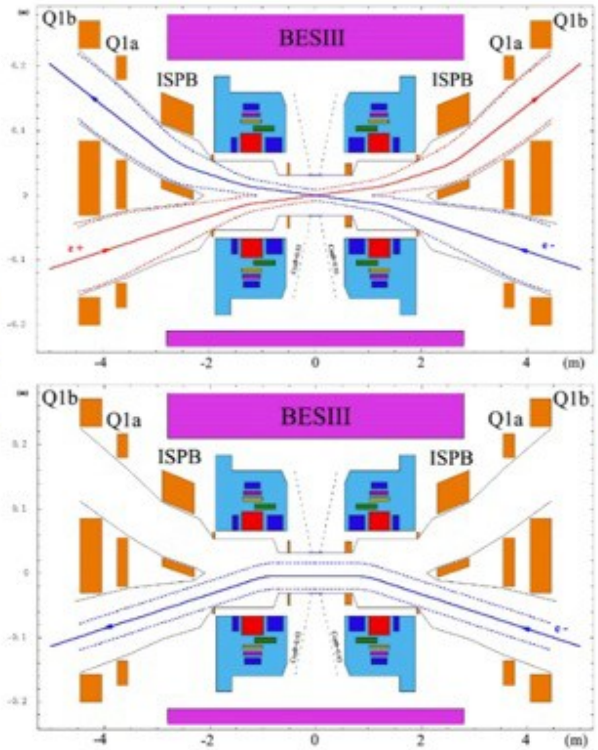
China (54)

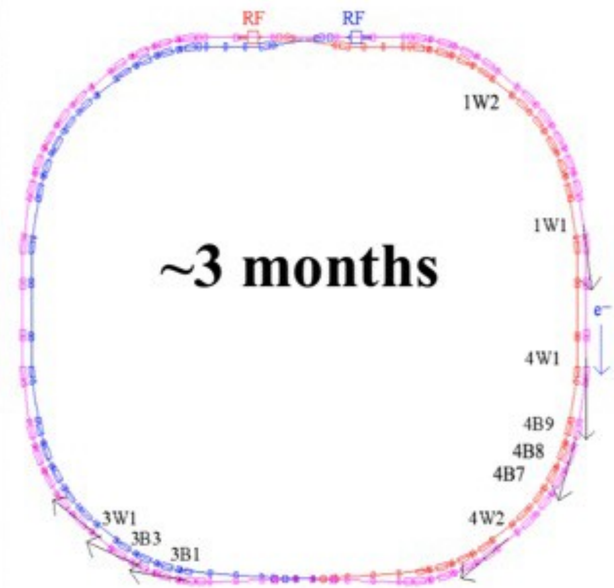
Beihang University, Central China Normal University, Central South University, China Center of Advanced Science and Technology, China University of Geosciences, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Hebei University, Henan University, Henan Normal University, Henan University of Science and Technology, Henan University of Technology, Huangshan College, Hunan University, Hunan Normal University, Inner Mongolia University, Institute of High Energy Physics, Institute of Modern Physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University,Peking University, Qufu Normal University, Renmin University of China, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, handong University of Technology,Shanghai Jiao Tong University, Soochow University,South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Yantai University , Yunnan University , Zhejiang University, Zhengzhou University

BESIII: ~600 members 85 institutes, 17 countries.

Introduction:BEPCII

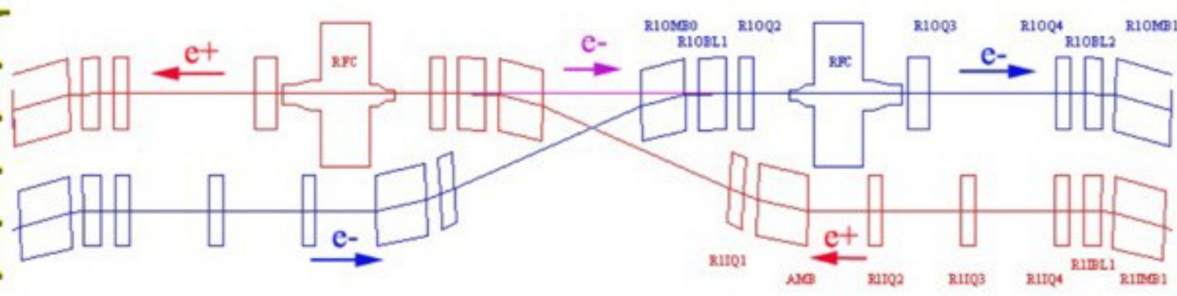
Collider





SR Facility

January 2004	Construction started
Mar.28, 2008	Installation of detector started
Jun. 22, 2008	BEPCII Commissioning started
May 13, 2009	Luminosity reached $3.3\times10^{32}cm^{-2}s^{-1}$
Apr. 5, 2016	Luminosity reached $1.0\times10^{33}cm^{-2}s^{-1}$



Data samples at BESIII

- BESIII has collected the largest data samples of J/ψ and $\psi(3686)$ on the threshold in the world!
- $> 20\ \mathrm{fb}^{-1}$ data above 4.0 GeV in total