Rare charm decays at BESIII

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On behalf of the BESIII Collaboration

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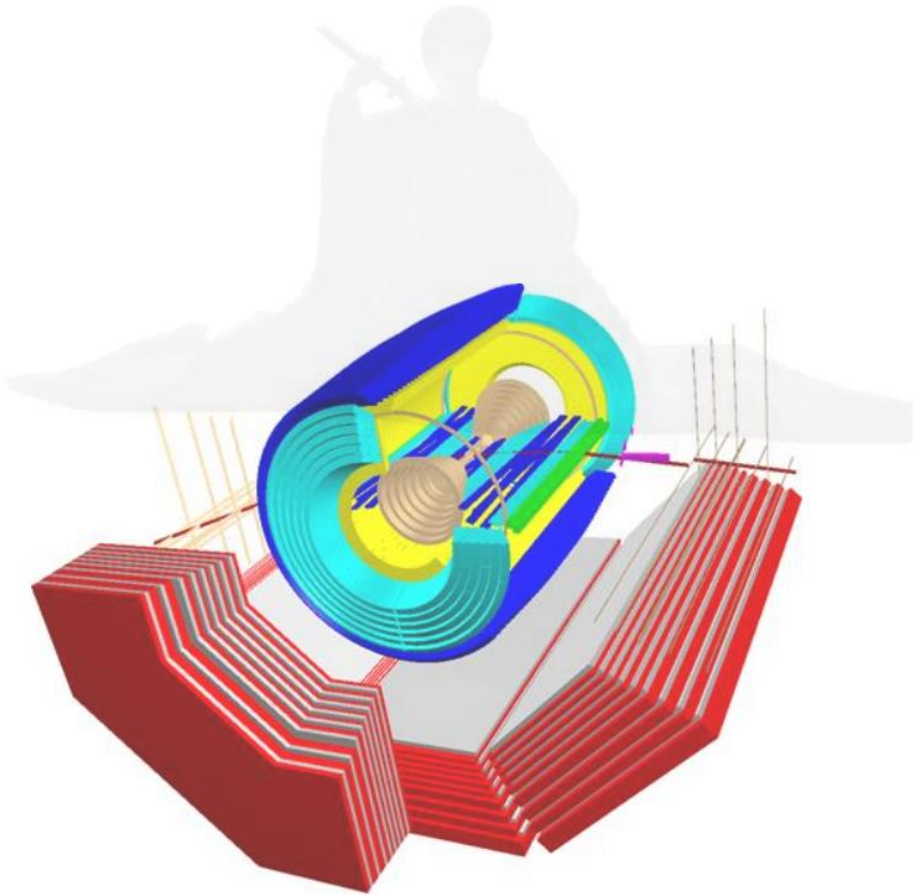
OUTLINE

- BEPCII and BESIII
- Charmonium Weak Decays
- FCNC Processes
- Baryon/Lepton Number Violation
- Charged Lepton Flavor Violation
- Summary



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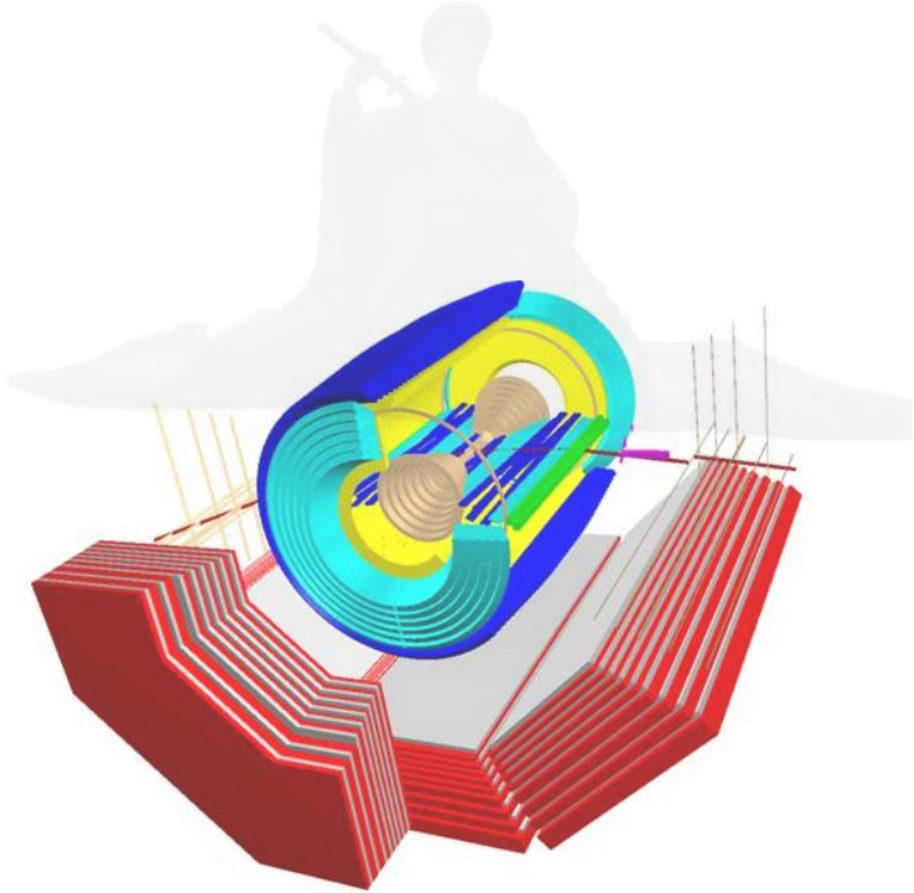

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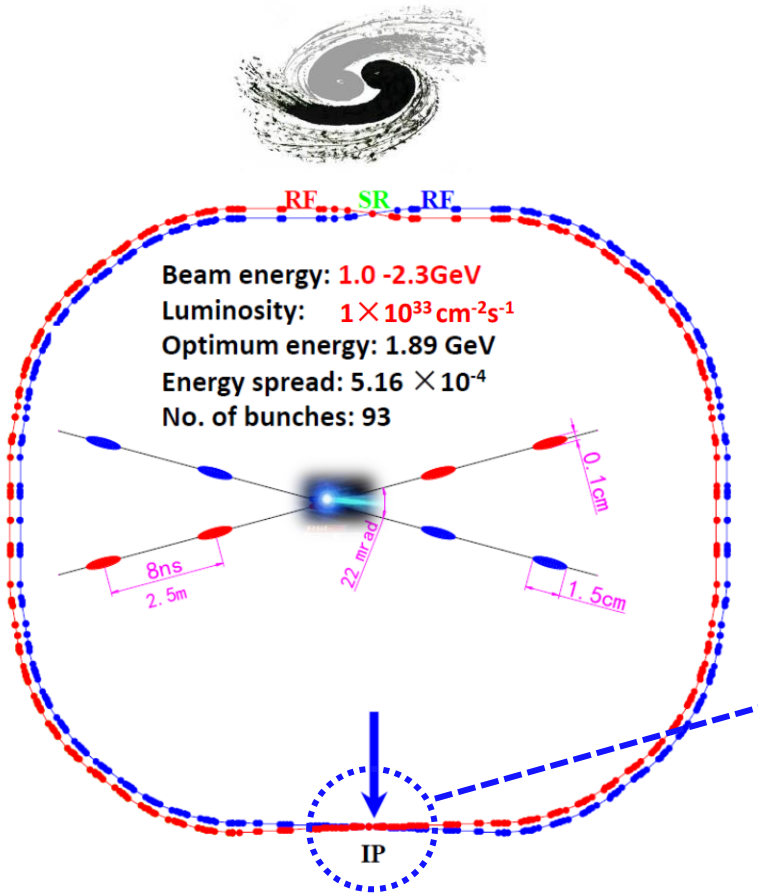
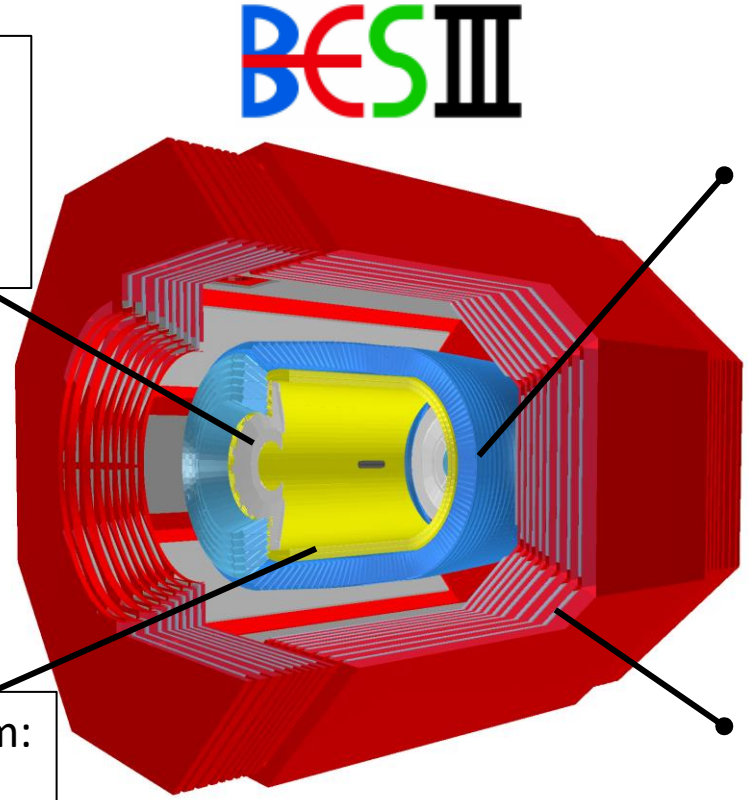
BEPCII and BESIII



✓ **B**eijing **E**lectron **P**ositron **C**ollider **II**

Multilayer **D**rift **C**hamber:
Δp/p=0.5% @ 1GeV
dE/dx: ~6%

Time-**O**f-**F**light system:
σT=68(60)ps
barrel(endcap)

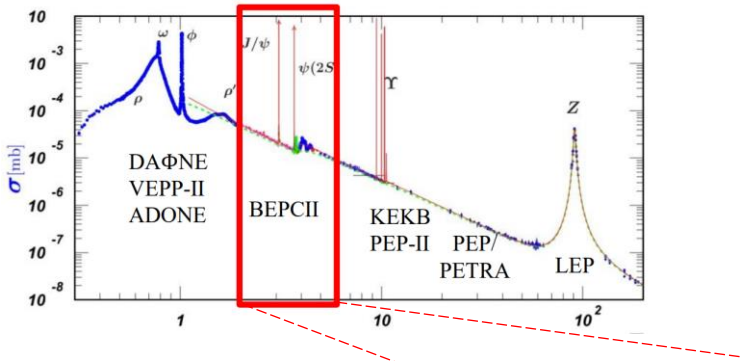


Electro**M**agnetic **C**alorimeter:
CsI(Tl) 2.5%(5.0%)
Barrel(endcap)
@ 1GeV

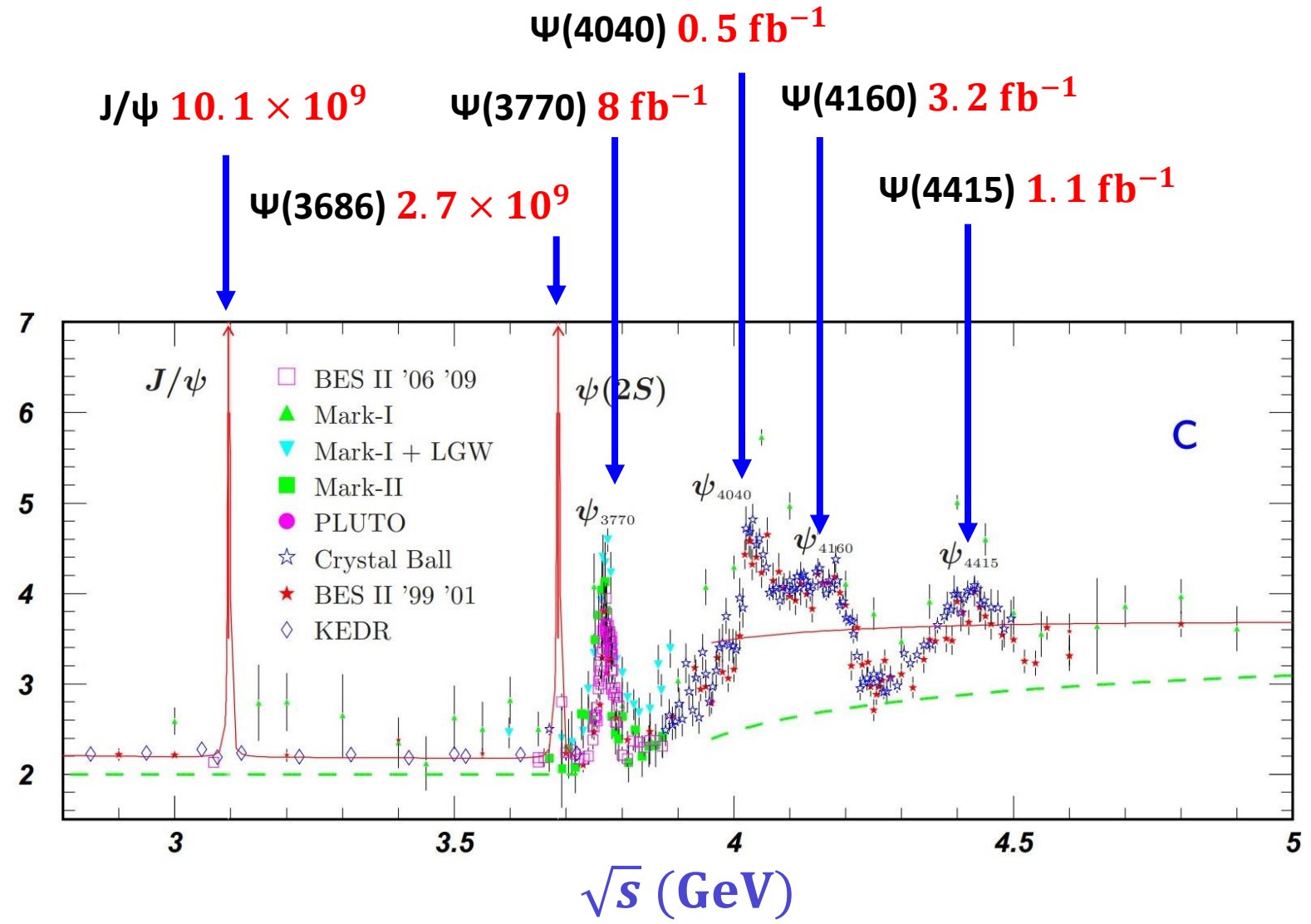
MUon **C**hamber:
RPC 9(8) layers
barrel(endcap)

✓ **BE**ijing **S**pectrometers **III**

Data samples at BESIII



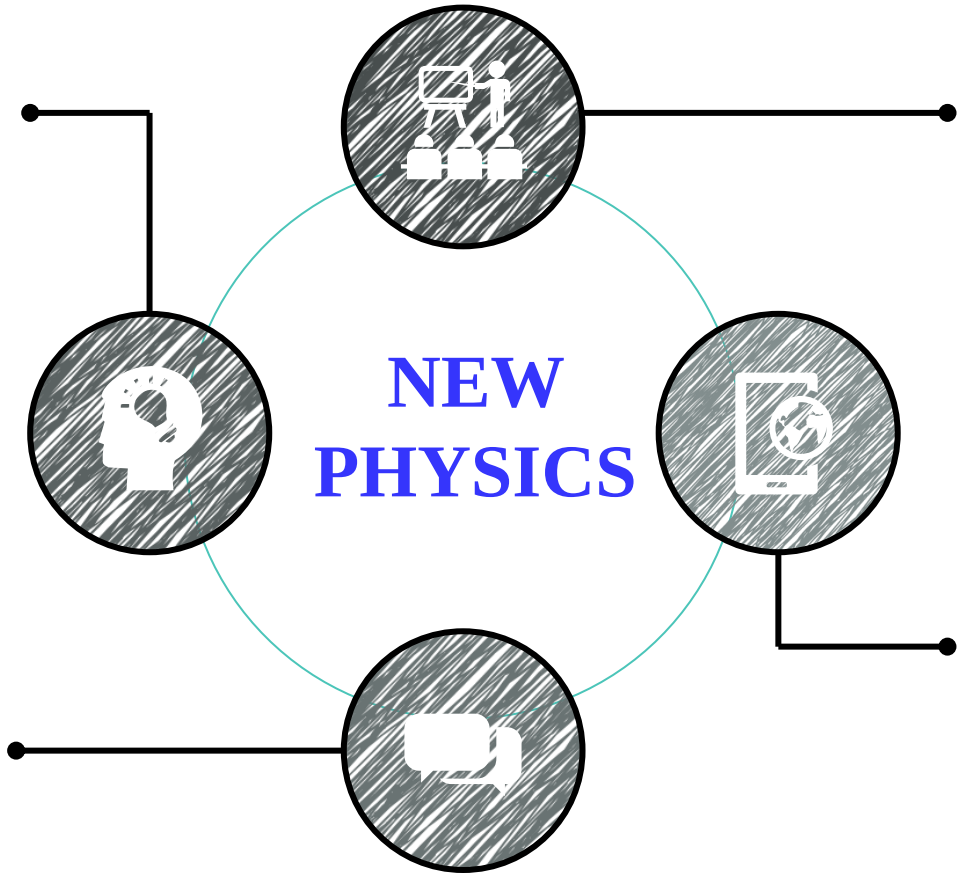
- ✓ BESIII has collected the largest charmonium data samples on threshold
- ✓ > 20 fb^{-1} data above 4.0 GeV in total
- ✓ **20 fb^{-1} Ψ(3770) will be coming in 2024, large D meson sample from $\psi \to D\bar{D}$**



New physics searches at BESIII

Symmetry violation
- ✓ **C**harged **L**epton **F**lavor **V**iolation
- ✓ **L**epton **N**umber **V**iolation
- ✓ **B**aryon **N**umber **V**iolation
- ✓ CP violation
- ✓ C parity violation
- ✓ …

Vary rare decay
- ✓ Charmonium weak decay
- ✓ **F**lavor **C**hanging **N**eutral **C**urrent process
- ✓ …



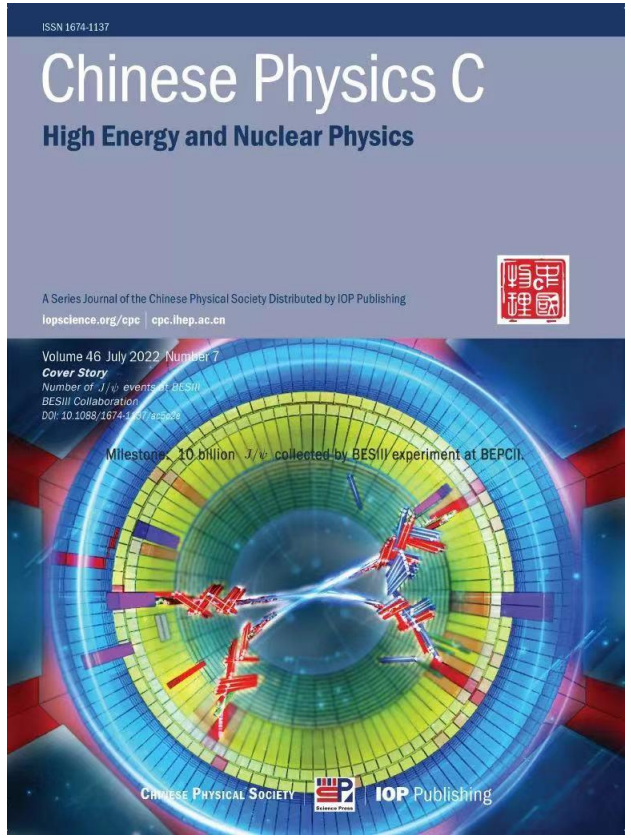
Exotic particle
- ✓ Dark photon γ'
- ✓ Axion-like particle a
- ✓ Light Higgs Z^0
- ✓ SUSY particles
- ✓ …

Other process
- ✓ Invisible decay
- ✓ Lepton universality test
- ✓ …

BESIII physics data

- ✓ Physics of BESIII
- NSR 8 (11) 2021

- ✓ 10 billion J/ψ collected by BESIII
- CPC 46 074001 (2022)



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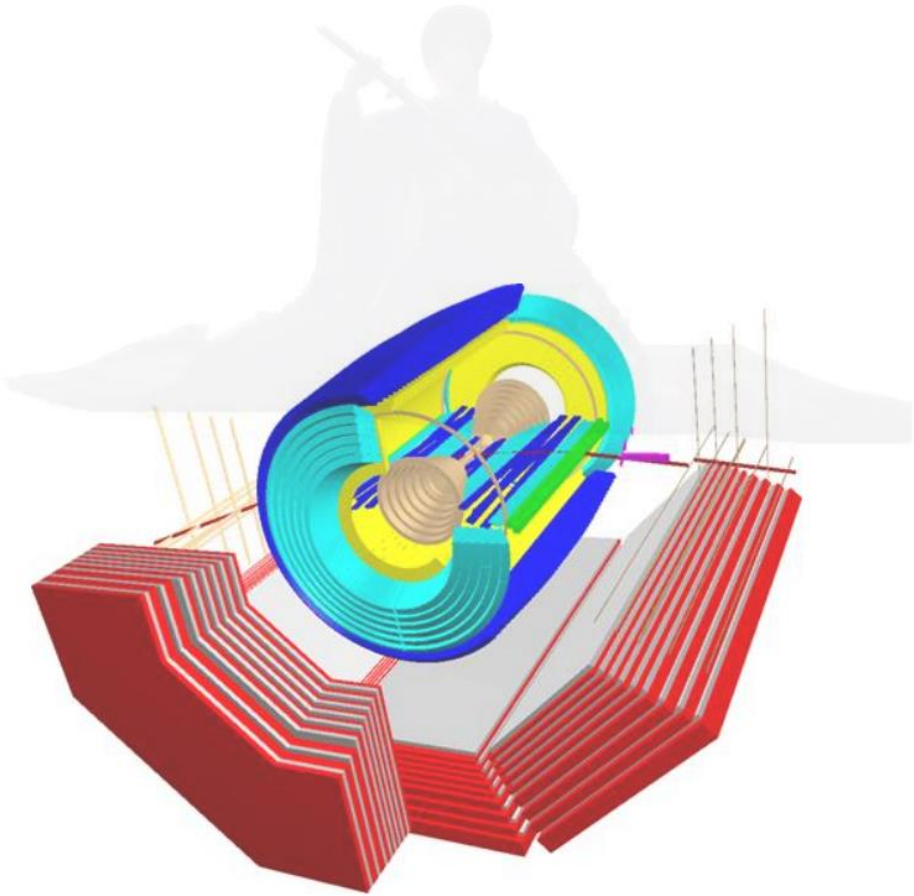

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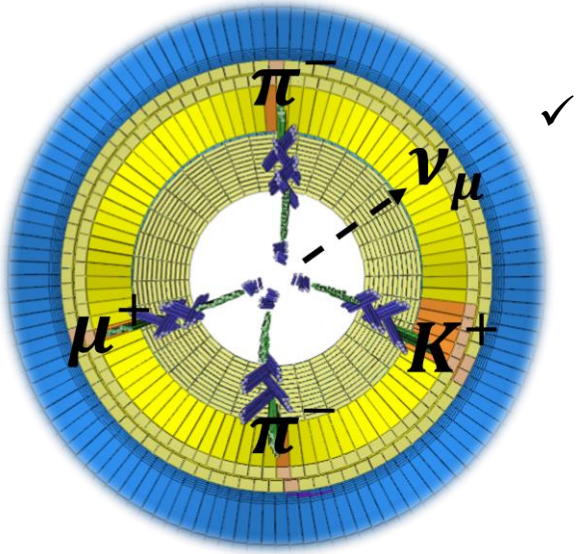
Charmonium weak decay

- Charmonium weak decays are **allowed in SM**, but highly suppressed by strong and EM decays
- The inclusive J/ψ weak decay branching fraction is predicted to be at the order of 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}, e.g. Top-color model, two-Higgs doublet model PLB 345, 483 (1995) PLB 119, 136 (1982) PRD 15, 1958 (1977) PRD, 60, 014011 (1999)



✓ An event display of $J/\psi \to D^-\mu^+\upsilon_\mu$, $D^- \to K^+\pi^-\pi^-$

EPJC,54,107,2008
PRD,78:074012,2008
AHEP,2013:706543,2013
PRD,92:074030,2015
JPG:NPP,44:045004,2017

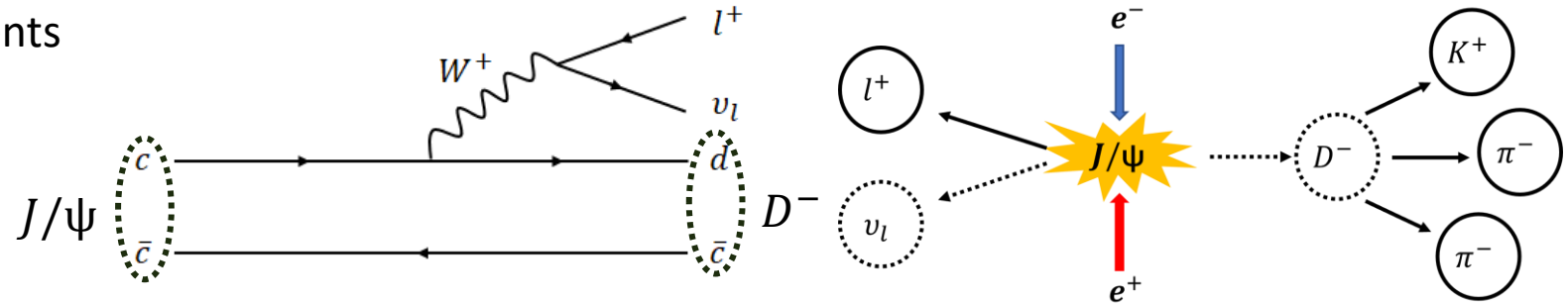
- Semi-leptonic weak decay
  - $J/\psi \to D_{(s)}^{(*)-} l^+ \upsilon_l$
  - $l = e, \mu$
- Hadronic weak decay
  - $\psi(2S) \to \Lambda_c^+ \bar{\Sigma}^-$
  - $J/\psi \to D_{(s)}^{(*)-} \pi^+$

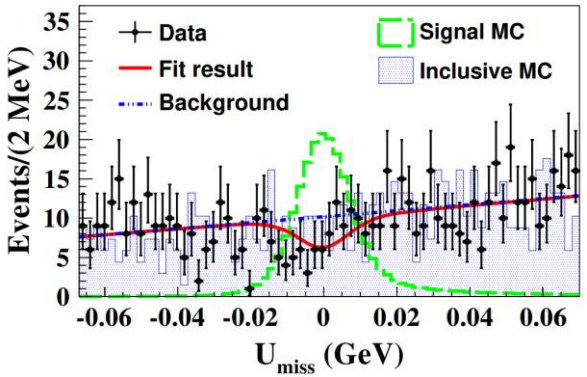
Theoretical model (SM)	QCDSR ($\times 10^{-11}$)	CLFQ ($\times 10^{-11}$)	BSW ($\times 10^{-11}$)	CCQW ($\times 10^{-11}$)	BSM ($\times 10^{-11}$)
$J/\psi \to D^- e^+ \upsilon_e$	$0.73^{+0.43}_{-0.22}$	$5.1 - 5.7$	$6.0^{+0.8}_{-0.7}$	1.71	$2.03^{+0.29}_{-0.25}$
$J/\psi \to D^- \mu^+ \upsilon_\mu$	$0.71^{+0.42}_{-0.22}$	$4.7 - 5.5$	$5.8^{+0.8}_{-0.6}$	1.66	$1.98^{+0.28}_{-0.24}$
$J/\psi \to D_s^- e^+ \upsilon_e$	18^{+7}_{-5}	$53 - 58$	$104.0^{+9.0}_{-7.5}$	33	$36.7^{+5.2}_{-4.4}$
$J/\psi \to D_s^- \mu^+ \upsilon_\mu$	17^{+7}_{-5}	$55 - 57$	$99.3^{+9.5}_{-6.5}$	32	$35.4^{+5.0}_{-4.3}$

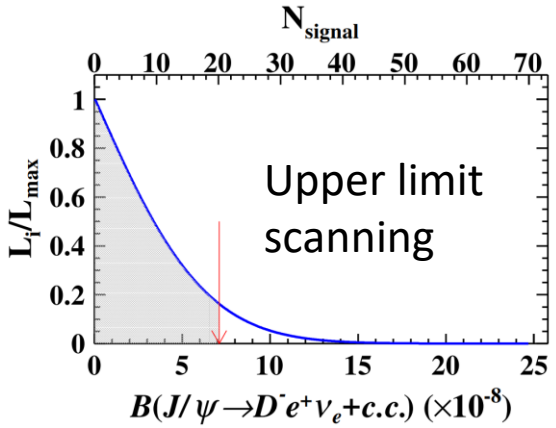
✓ **SM prediction for $J/\psi \to D_{(s)}^- l^+ \upsilon_l$: $\sim 10^{-10} - 10^{-11}$**

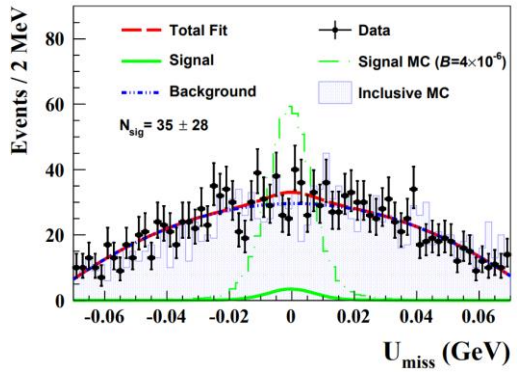
Search for $J/\psi \to D^- l^+ \nu_l + c.c.$

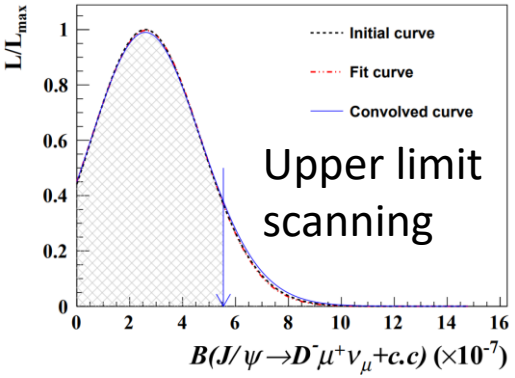
- Analyzing $(\mathbf{10087 \pm 44}) \times \mathbf{10^6}$ J/ψ events
- Using $D^- \to K^+\pi^-\pi^-$ to reconstruct D
- Fit in $U_{miss}(= E_{miss} - c \cdot |P_{miss}|)$











- $\mathcal{B}(J/\psi \to D^- e^+ \nu_e + c.c.) < 7.1 \times 10^{-8}$ @90% C.L.
- **The upper Limit (UL) is improved by more than two orders of magnitude**

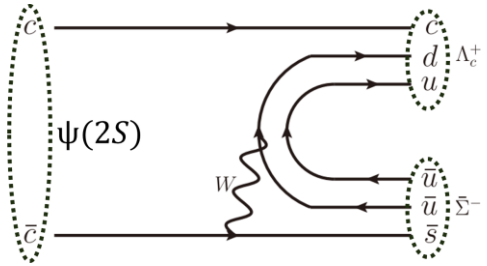
JHEP 06, 157 (2021)

- $\mathcal{B}(J/\psi \to D^- \mu^+ \nu_\mu + c.c.) < 5.6 \times 10^{-7}$ @90% C.L.
- **The first search for the charmonium weak decay with a muon in the final state.**

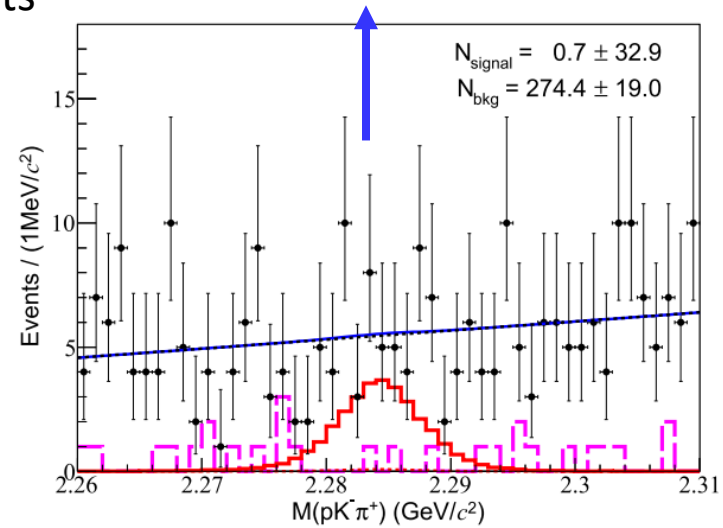
arXiv:2307.02165

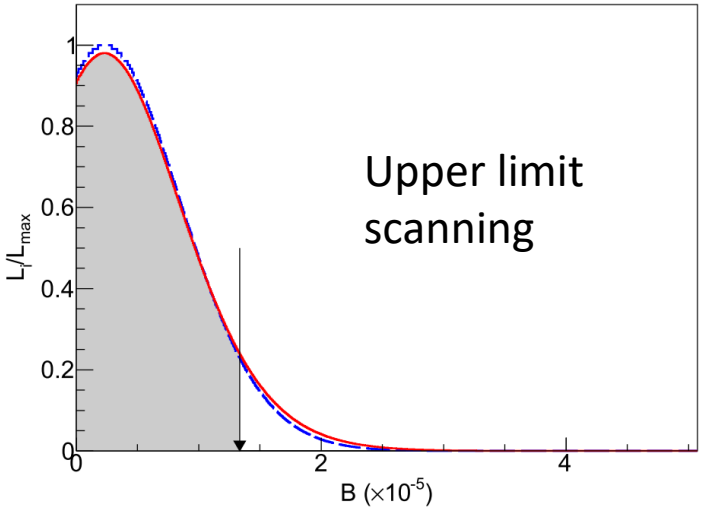
Search for $\psi(2S) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.$

- Analyzing $(448.1 \pm 2.9) \times 10^6$ ψ(2S) events
- Using $\Lambda_c^+ \to pK^-\pi^+, \bar{\Sigma}^- \to \bar{p}\pi^0$
- Fit in $M(pK^-\pi^+)$ to extract signals



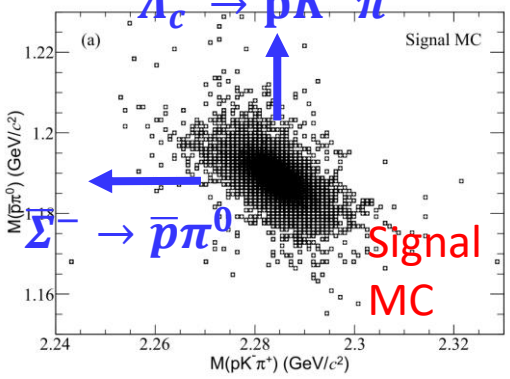
Will have a Λ_c^+ peak if signals exist



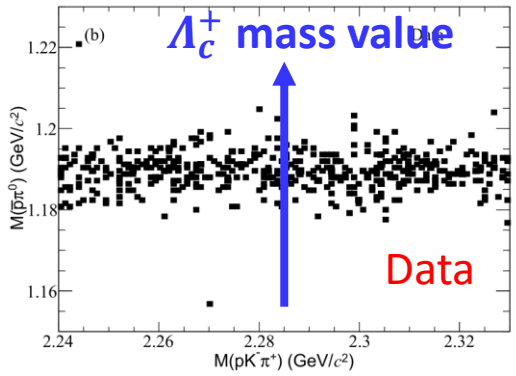


$\Lambda_c^+ \to pK^-\pi^+$

$\bar{\Sigma}^- \to \bar{p}\pi^0$



Signal MC



Data

- $\mathcal{B}(\psi(3686) \to \Lambda_c^+\bar{\Sigma}^- + c.c.) < 1.4 \times 10^{-5}$ @90% C. L.
- **The first search for the charmonium baryonic weak decay**
- An additional 2.3 billion events at BESIII are available now. This larger data sample offers an opportunity to further improve the sensitivity.

Chin Phy C, 47, 013002 (2023)

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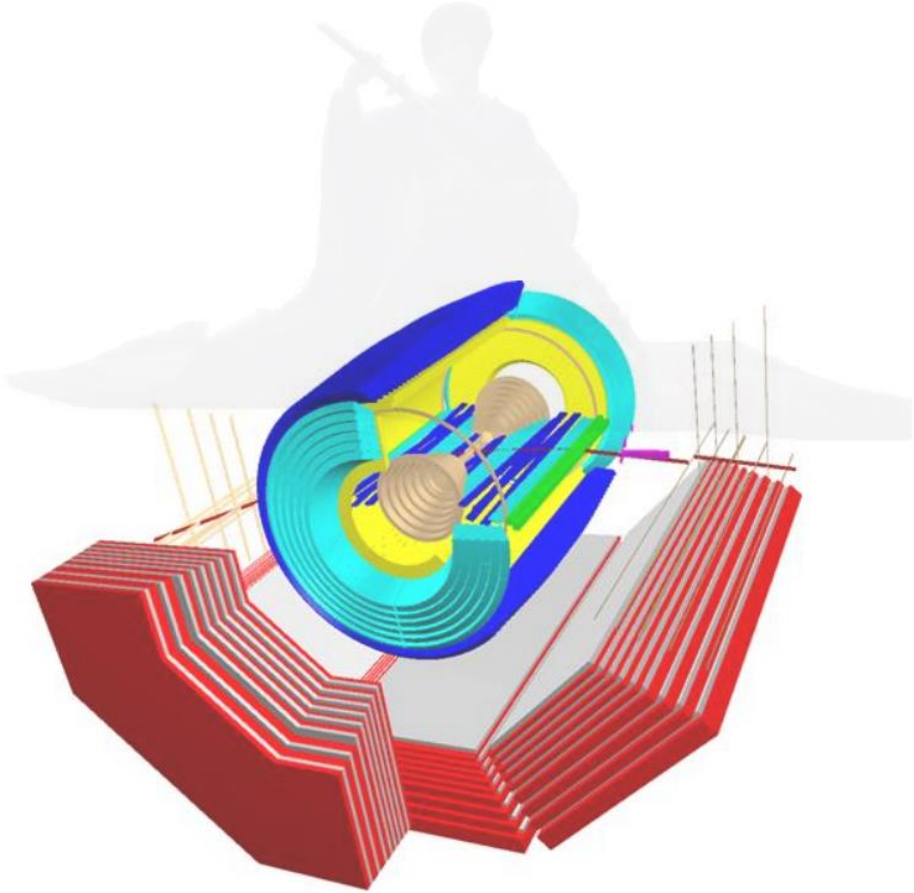

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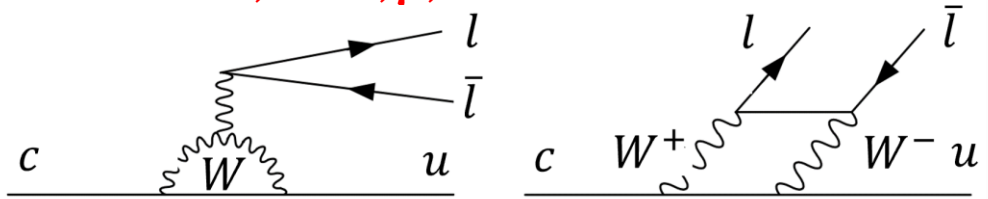
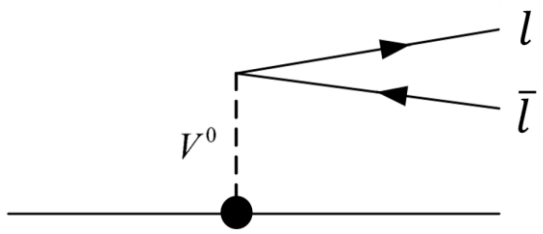
D meson and FCNC process

- Flavor changing neutral current (**FCNC**) process
- ✓ FCNC is strongly suppressed by GIM mechanism and can happen only through loop diagram:
- **BF $10^{-9}\sim10^{-15}$ in SM for D meson**
- ✓ The suppression in charm decay is much stronger than B & K system, stronger diagram cancellation due to the down-type quarks involved
- ✓ $c \to u l\bar{l}, l = e, \mu, \upsilon$

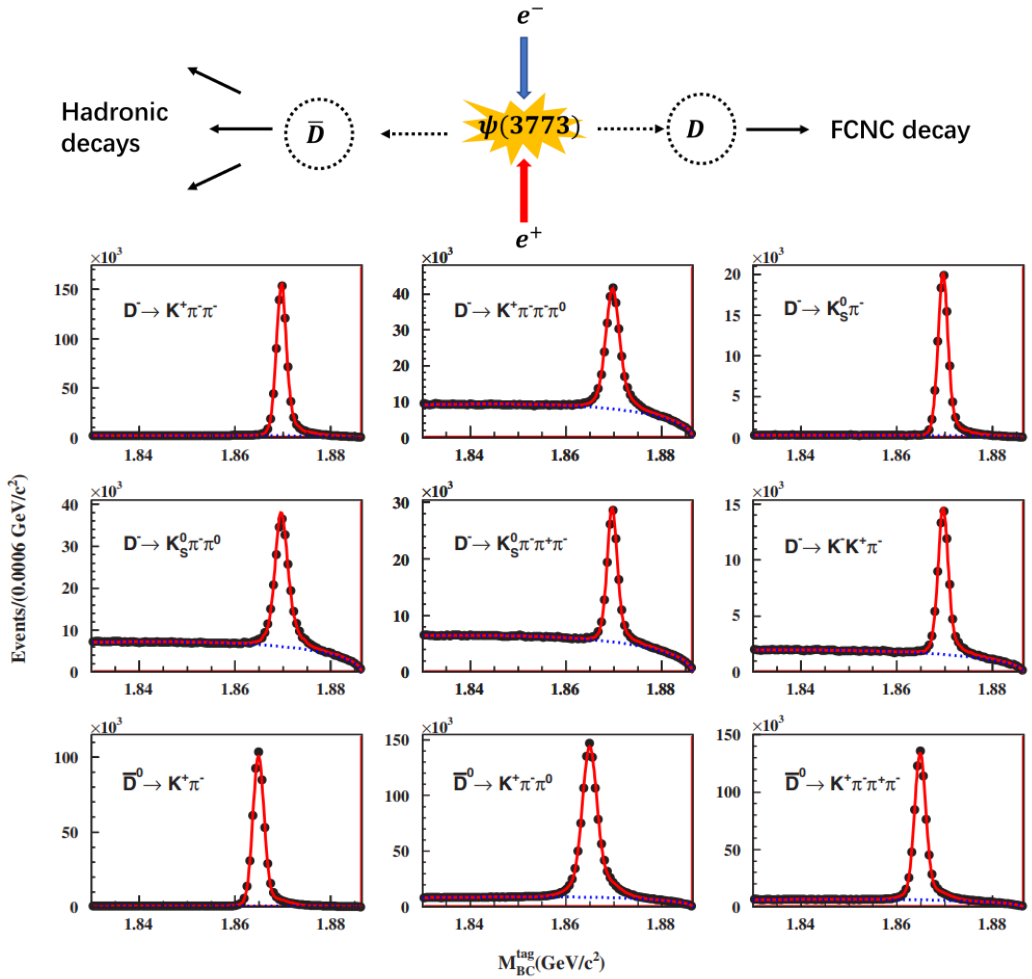


- ✓ Short distance (**SD**) process: FCNC



- ✓ Long distance (**LD**):
- Non-FCNC,
- Through vector meson
- $D \to hV, V \to l\bar{l}$

- D meson at **BESIII: Double tag method (less background)**

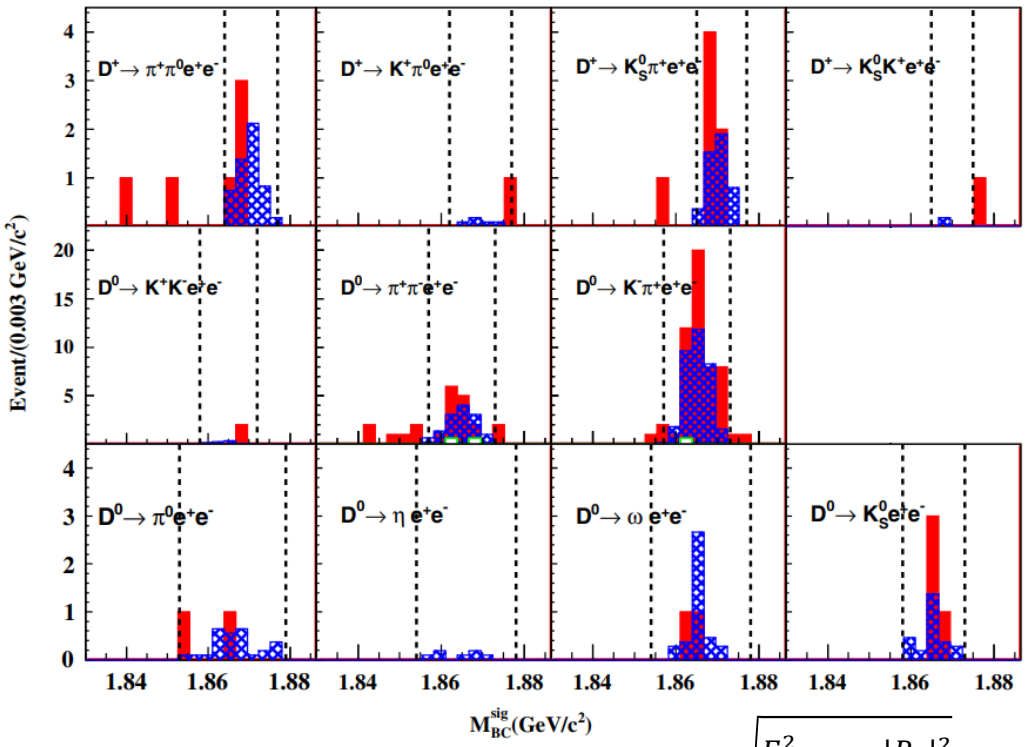


- ✓ Tag D meson by hadronic decays at BESIII

Search for $D \to h(h^{(\prime)})e^+e^-$ and $D^0 \to \pi^0\nu\bar{\nu}$

$D \to h(h^{(\prime)})e^+e^-$

- Analyzing $2.93\ fb^{-1}$ data at $\sqrt{s} = 3.773$ GeV



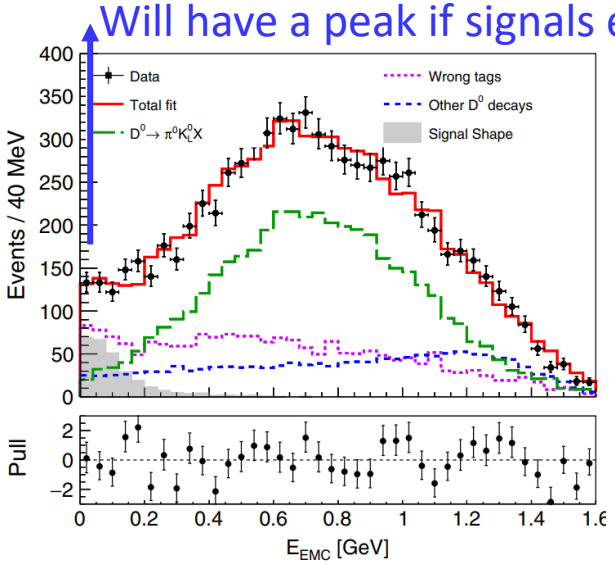
$$M_{BC}^{sig} = \sqrt{\frac{E_{beam}^2}{c^4} - \frac{|P_D|^2}{c^2}}$$

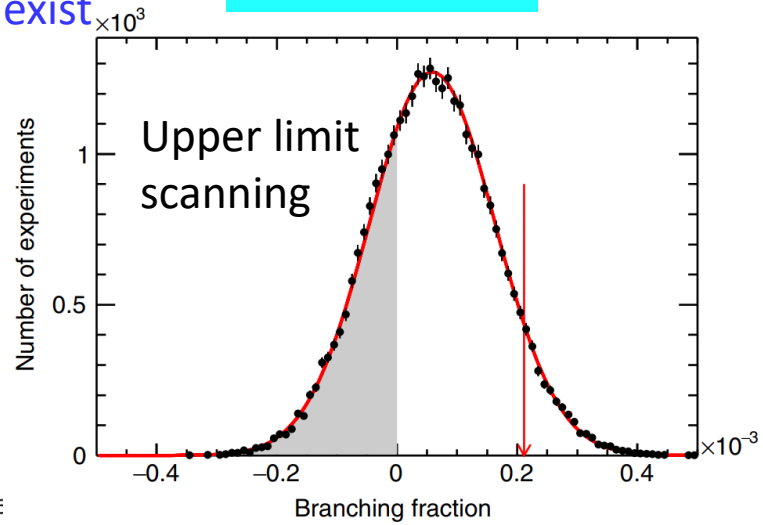
- ✓ Red: data
- ✓ Blue: background MC
- ✓ Upper limit of $\mathcal{B}(D \to h(h^{(\prime)})e^+e^-)$:
- At the level $< 10^{-5} \sim 10^{-6}$

Phys. Rev. D 97, 072015 (2018)

$D^0 \to \pi^0\nu\bar{\nu}$

Will have a peak if signals exist





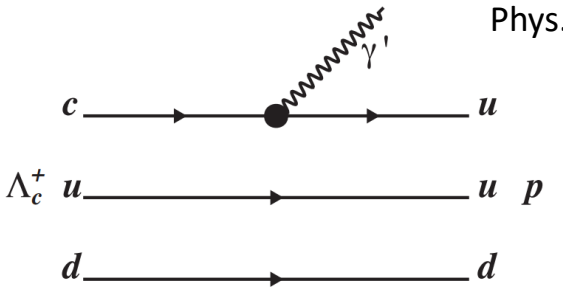
- ✓ E_{EMC}: EMC energy not associated with π^0 and tag D decays
- ✓ **If has signals, it will have events exceeding zero in E_{EMC}**
- ✓ $\mathcal{B}(D^0 \to \pi^0\nu\bar{\nu}) < 2.1 \times 10^{-4}$ @90% C. L.
- ✓ The first experimental results of search for $c \to u\nu\bar{\nu}$ processes

Phys. Rev. D 105, L071102 (2022)

$20\ fb^{-1}$ samples at BESIII are coming soon. This larger data sample offers an opportunity to further improve the sensitivity.

Search for massless dark photon via $\Lambda_c \to p\gamma'$

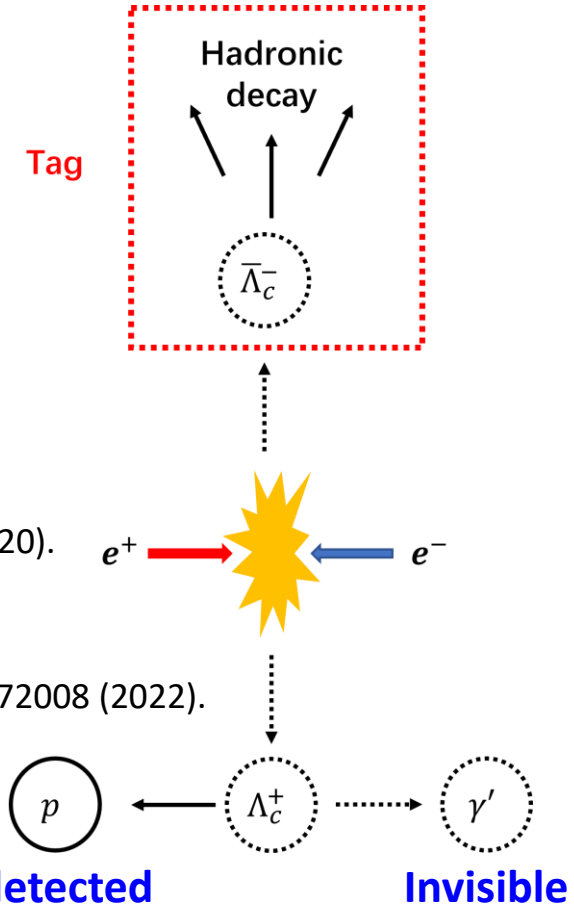
- ✓ New physics: An extra Abelian gauge group, $U(1)_D$, Causing the associated gauge boson, the dark photon
- ✓ If symmetry remains unbroken, it will cause a massless dark photon γ'
- ✓ γ' can be produced via FCNC process $c \to u\gamma'$ (**BF 10^{-5} in new physics**)

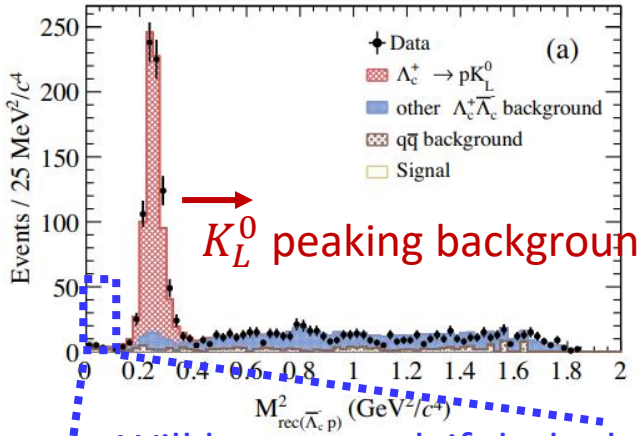


Phys. Rev. D 102, 115029 (2020).

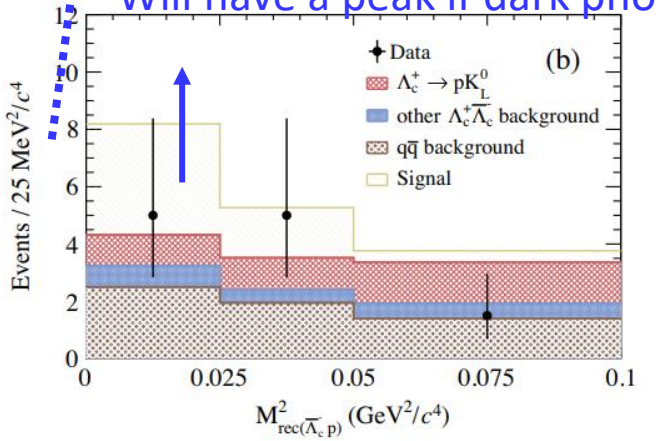
Phys. Rev. D 106, 072008 (2022).

- ✓ Double tag method





Will have a peak if dark photon exist



- ✓ The first search for massless dark photon
- ✓ $\mathcal{B}(\Lambda_c \to p\gamma') < 8.0 \times 10^{-5}$@90% C. L.
- ✓ New physics prediction: $\sim 10^{-5}$

- ☐ Analyzing $\mathbf{4.5\ fb^{-1}}$ data @4.6~4.699 GeV

$$M^2_{rec} = |(E_{\Lambda_c} - E_p)^2 - (\vec{P}_{\Lambda_c} - \vec{P}_p)^2|$$

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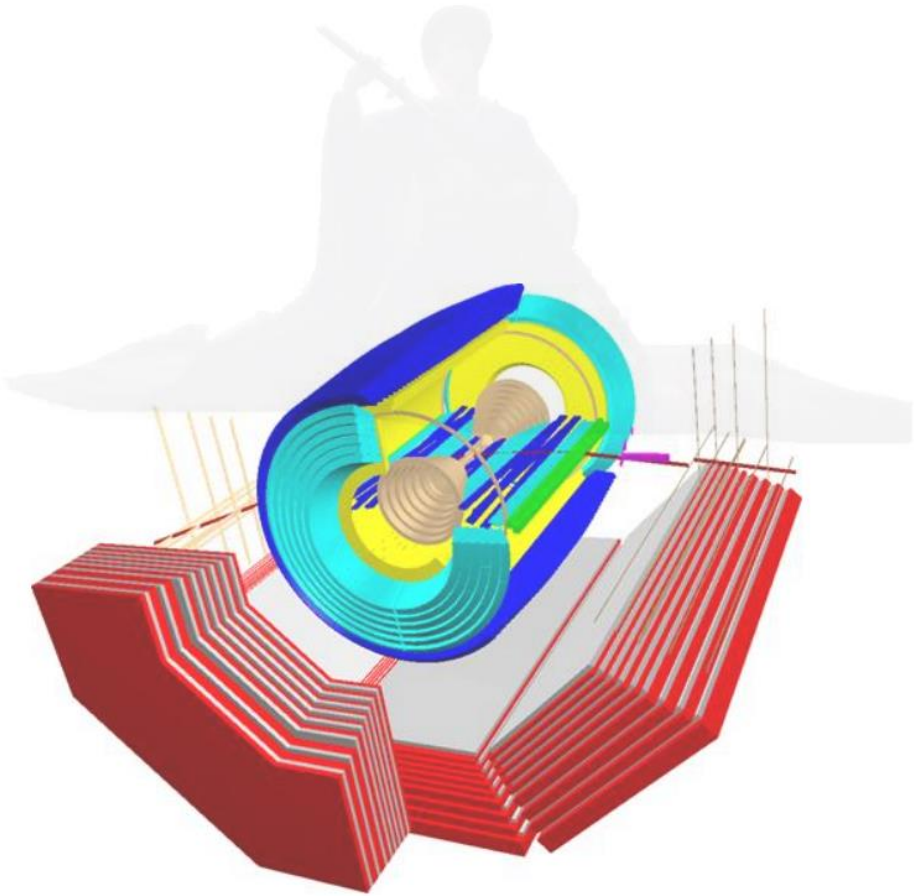

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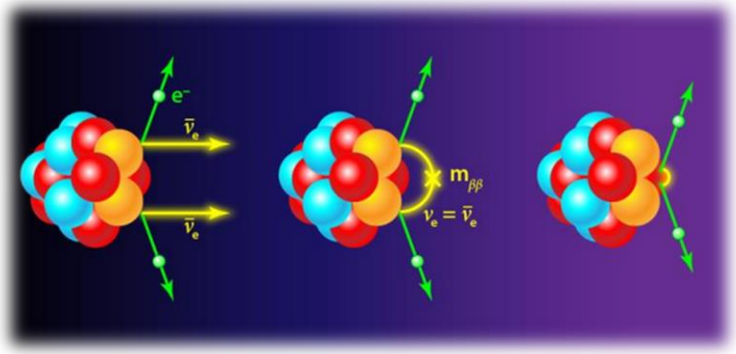
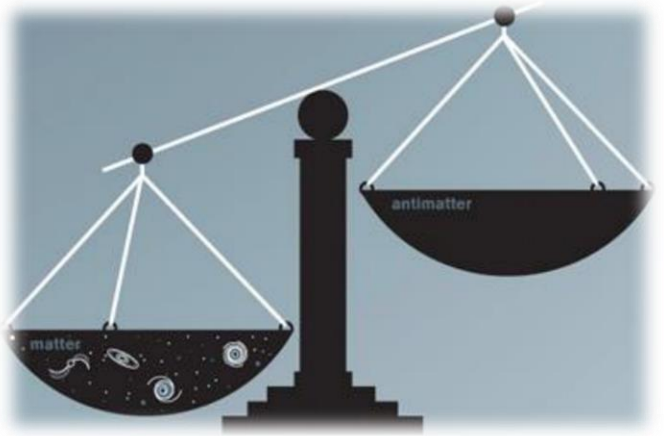
Lepton / Baryon Number Violation

- ✓ Lepton Number Violation (**LNV**) processes can be used to test the nature of neutrino, **Dirac or Majorana**?
- ✓ Neutrinoless double beta decay is the most promising
- ✓ LNV can also be probed with hadron/lepton decays



- ✓ In the SM, baryon number is always conserved.
- ✓ However, baryon anti-baryon number is highly asymmetric in the universe. Baryon Number Violation? (**BNV**)
- ✓ BNV is allowed in GUT and SM extensions $\Delta(B-L)=0$
  - BF: $10^{-29}\sim10^{-39}$
- ✓ Furthermore, another BNV under dimension seven operators allow $\Delta(B-L)=2$



PRD 22 1694 (1980)
PRD 101 015017 (2020)
PRD 72 095001 (2005)
PRD 59 091303 (1999)
JHEP 05 030 (2009)
PRL 120 132501 (2018)
PRD 93 094026 (2016)
JHEP 08 068 (2011)

Search for LNV decay $D \to K\pi e^+e^+ + c.c.$

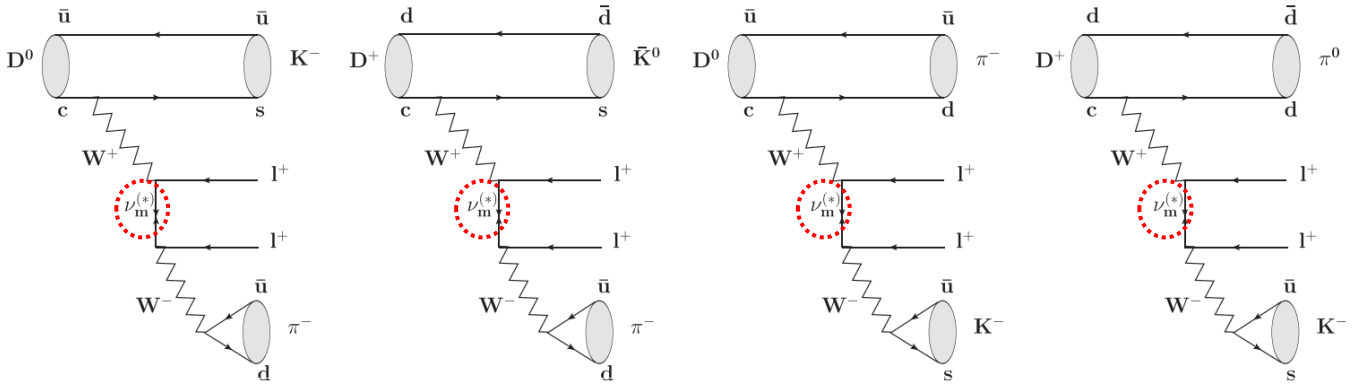
- ✓ LNV processes is given by exchanging a single **Majorana neutrino**
- ✓ Analyzing $\mathbf{2.93\ fb^{-1}}$ data at $\sqrt{s} = 3.773$ GeV

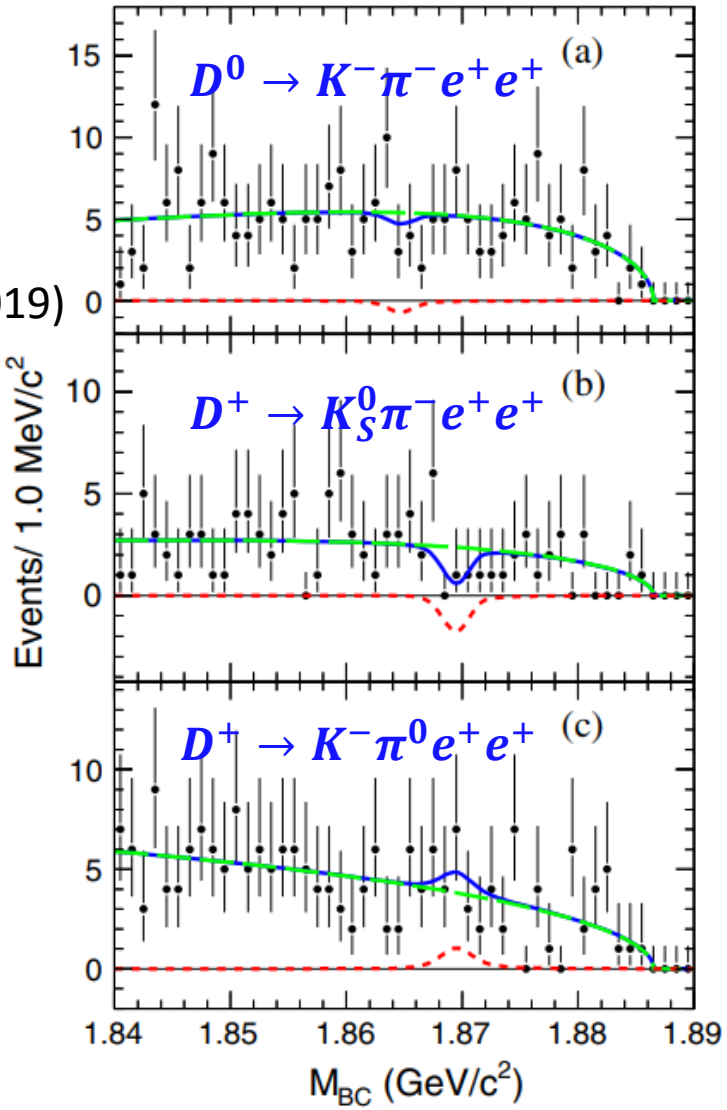
$$M_{BC}^{sig} = \sqrt{\frac{E_{beam}^2}{c^4} - \frac{|P_D|^2}{c^2}}$$

PRD 99 112002 (2019)

- $\mathcal{B}(D^0 \to K^-\pi^-e^+e^+) < \mathbf{2.8 \times 10^{-6}}$ @90%C.L.
- $\mathcal{B}(D^+ \to K_S^0\pi^-e^+e^+) < \mathbf{3.3 \times 10^{-6}}$ @90%C.L.
- $\mathcal{B}(D^+ \to K^-\pi^0e^+e^+) < \mathbf{8.5 \times 10^{-6}}$ @90%C.L.

- ✓ Majorana neutrino is searched for with different mass assumptions





Search for BNV decay $D^0 \to pe$

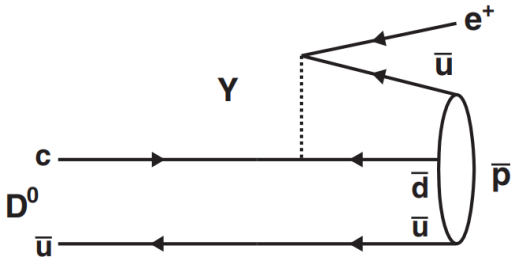
- ✓ Baryon anti-baryon number is highly asymmetric in the universe. Baryon Number Violation? (**BNV**)

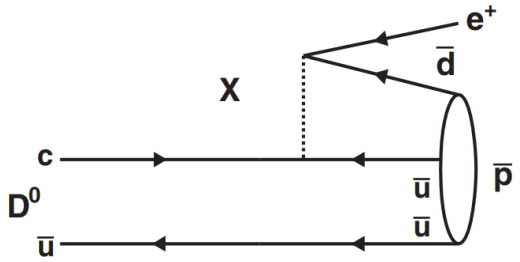
- ✓ BNV is allowed in GUT and SM extensions $\Delta(B-L)=0$
- BF: 10^{-39}

$$M_{BC}^{sig} = \sqrt{\frac{E_{beam}^2}{c^4} - \frac{|P_D|^2}{c^2}}$$

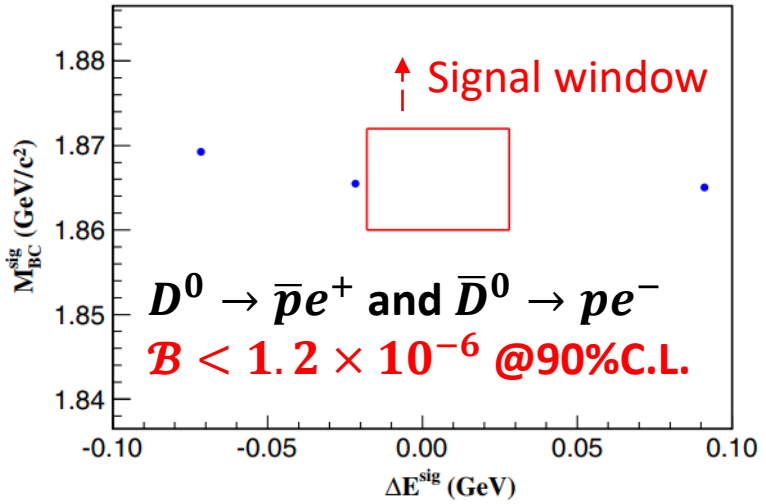
$$\Delta E^{sig} = E_D - E_{beam}$$

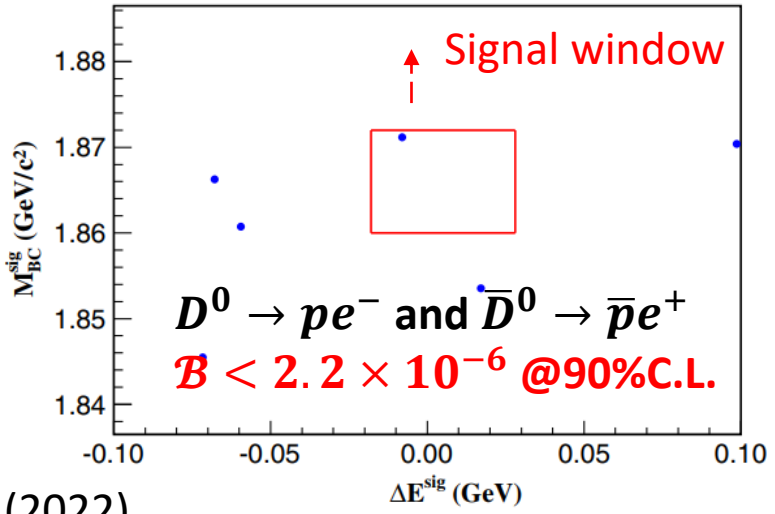
- ✓ Analyzing **2.93** fb^{-1} 3.773 GeV data
- Double Tag mothed is applied, very clean background





- ✓ $D^0 \to \bar{p}e^+$ in SU(5)
- X, Y : **leptoquarks** with electric charge $\frac{4}{3}e$ or $\frac{1}{3}e$



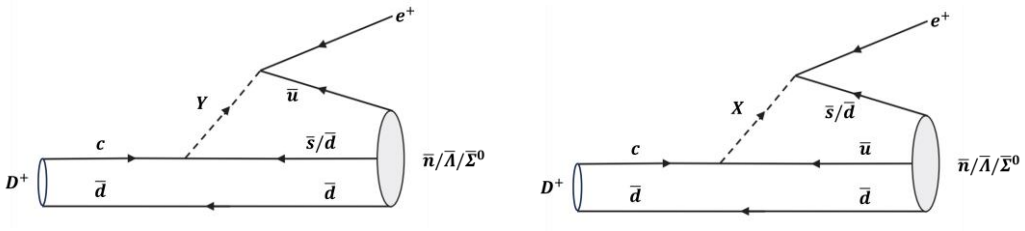


Phys. Rev. D 105, 032006 (2022)

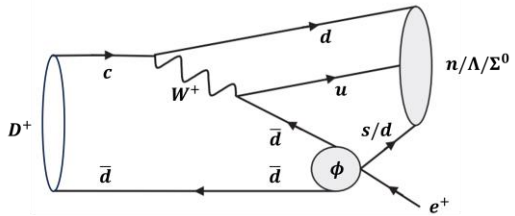
Search for BNV decay $D^+ \to (\text{anti}-)n/\Lambda/\Sigma^0 e^+$

- ✓ BNV is allowed in GUT and SM extensions $\Delta(B-L)=0$
- BF: 10^{-29} for $D^+ \to \bar{\Lambda} e^+$
  10^{-39} for $D^+ \to \bar{n} e^+$

- ✓ Another BNV under dimension seven operators allow $\Delta(B-L)=2$



- X, Y : **leptoquarks** with electric charge $\frac{4}{3}e$ or $\frac{1}{3}e$

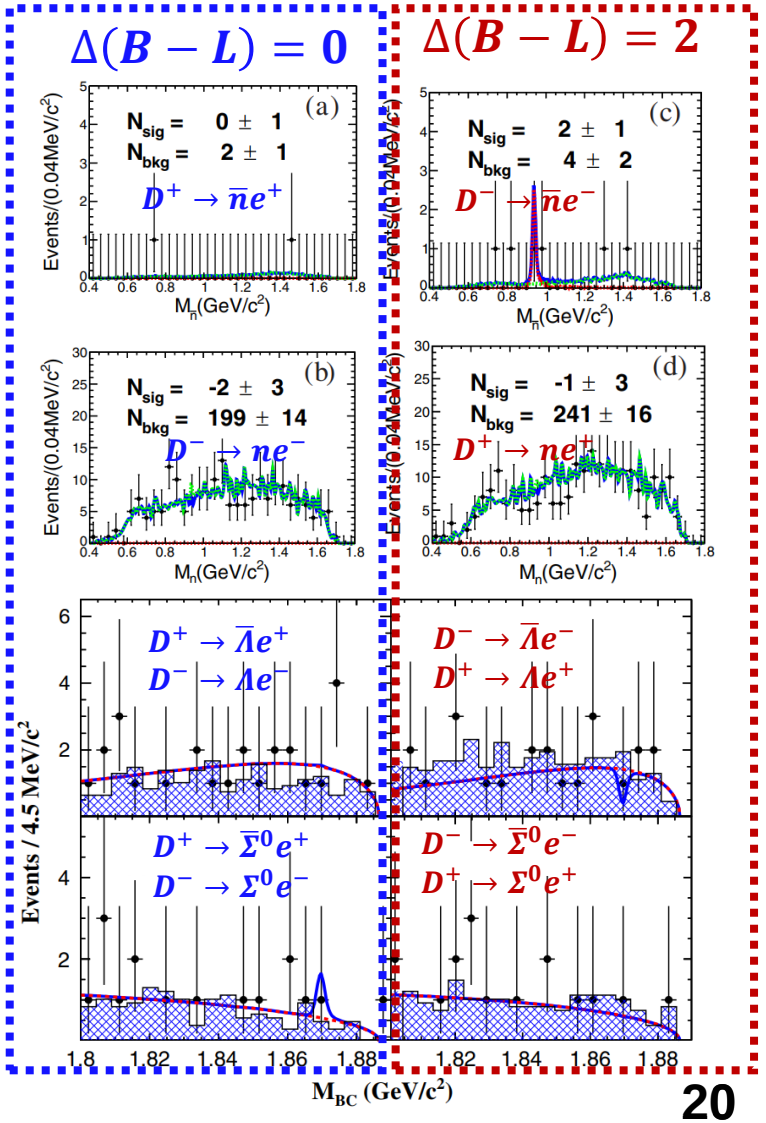


- elementary scalar field ϕ

- ✓ Analyzing **2.93** fb^{-1} 3.773 GeV data
- Double Tag mothed is applied

- ✓ $n, \bar{n}$ are regarded as missing particle
- ✓ Using $\Lambda \to p\pi^-$ to reconstruct Λ
- ✓ Using $\Sigma^0 \to \gamma\Lambda$ to reconstruct Σ^0

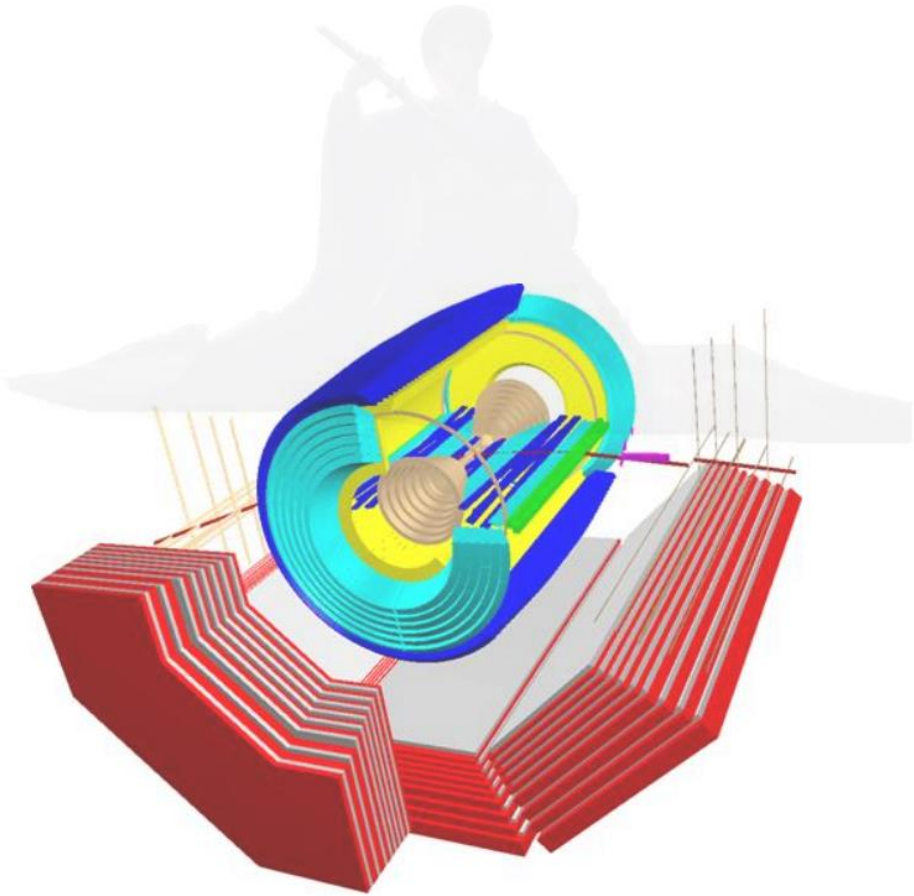
Mode (+c.c.)	$\mathcal{B}^{UL}$ @90%C.L.
$D^+ \to \bar{n}e^+$	$< 1.4 \times 10^{-5}$
$D^+ \to \bar{\Lambda}e^+$	$< 6.5 \times 10^{-7}$
$D^+ \to \bar{\Sigma}^0 e^+$	$< 1.3 \times 10^{-6}$
$D^+ \to ne^+$	$< 2.9 \times 10^{-5}$
$D^+ \to \Lambda e^+$	$< 1.1 \times 10^{-6}$
$D^+ \to \Sigma^0 e^+$	$< 1.7 \times 10^{-6}$



Phys. Rev. D 101, 031102(R) (2020)
Phys. Rev. D 106, 112009 (2022)

OUTLINE

- BEPCII and BESIII
- Charmonium Weak Decays
- FCNC Processes
- Baryon/Lepton Number Violation
- **Charged Lepton Flavor Violation**
- Summary



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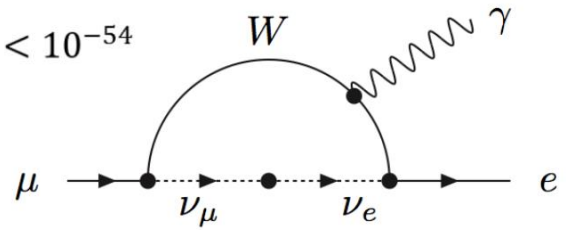
CLFV of J/ψ

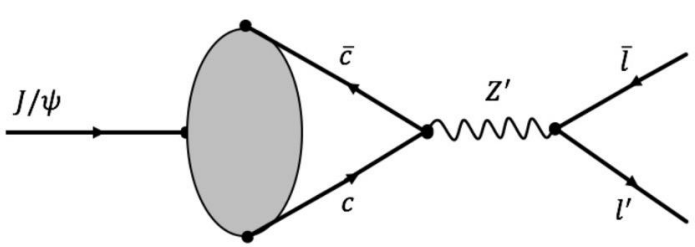
✓ With neutrino mixing, Charged Lepton Flavor Violation (**CLFV**) is allowed in extended SM, but very rare to be detected.

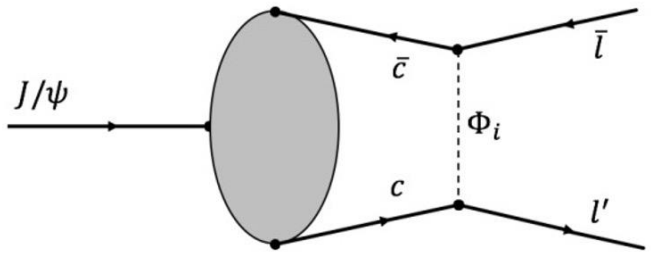
$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$



✓ Some new physics models can enhance the BF of CLFV to a detectable level:

- $BF(J/\psi \to e\mu)$ @ 10^{-16}~10^{-9}
- $BF(J/\psi \to e\tau)$ @ 10^{-10}~10^{-8}





✓ CLFV via Z' or leptoquarks

- Model-independent prediction
- Rotating mass matrix
- Unparticle physics
- Effective Lagrangian
- MSSM with gauged baryon and lepton number

Phys. Lett. B 496, 89 (2000)

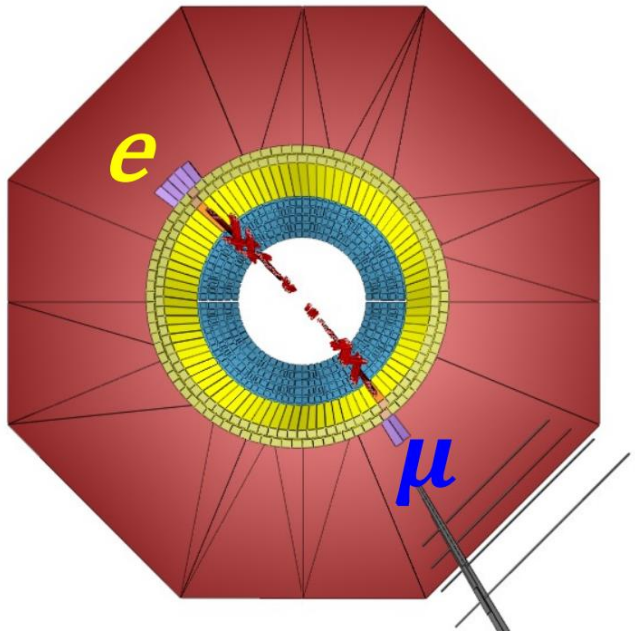
Phys. Rev. D 63, 016003 (2000).
Rev. D 83, 115015 (2011).
Phys. Rev. D 63, 016006 (2000).

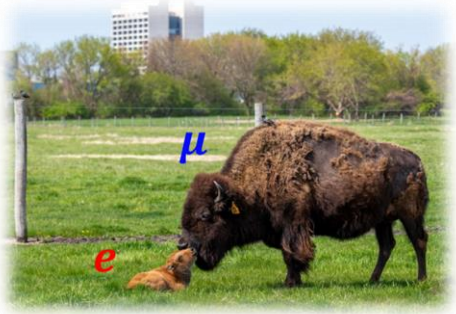
Phys. Lett. A 27, 1250172 (2012).
Phys. Rev. D 94, 074023 (2016).
Phys. Rev. D 97, 056027 (2018).

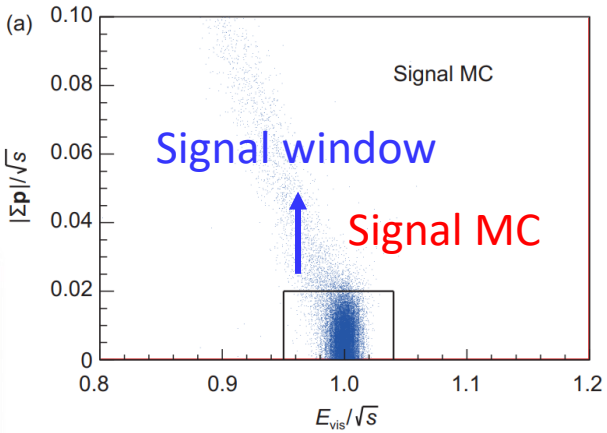
BESIII has collected 10^{10} J/ψ, offering an opportunity to search them

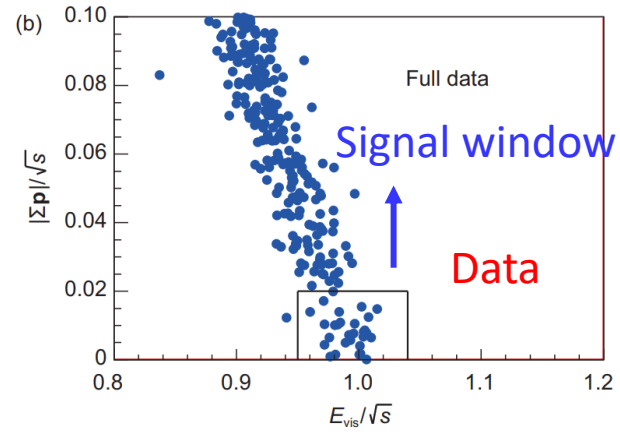
Search for $J/\psi \to e\mu$

- ✓ Analyzing $\mathbf{8.998 \times 10^9}$ J/ψ events
- ✓ **29 candidate events** are observed
- ✓ Estimated background: 36.8 ± 4.0





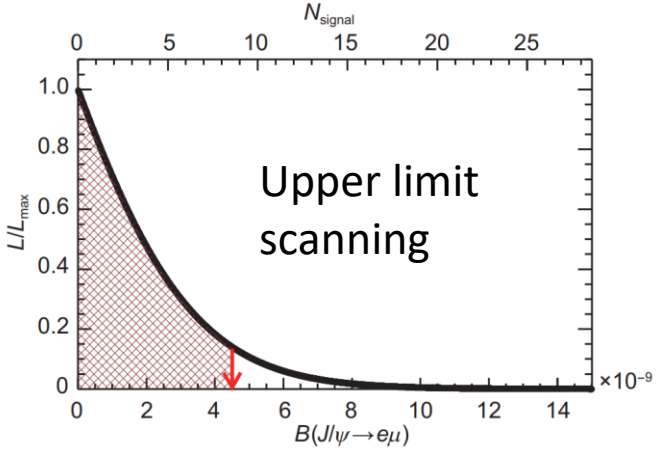




- $\sum \vec{p}$: the magnitude of the vector sum of the momenta
- E_{vis}: the total reconstructed energy of e and μ

- ✓ $\mathcal{B}(J/\psi \to e\mu) < \mathbf{4.5 \times 10^{-9}}$@90% C. L.
- ✓ **New physics prediction: $\mathbf{10^{-16} \sim 10^{-9}}$**

- ✓ Improves the previous published limits by a factor of more than 30
- ✓ The most precise CLFV search in heavy quarkonium

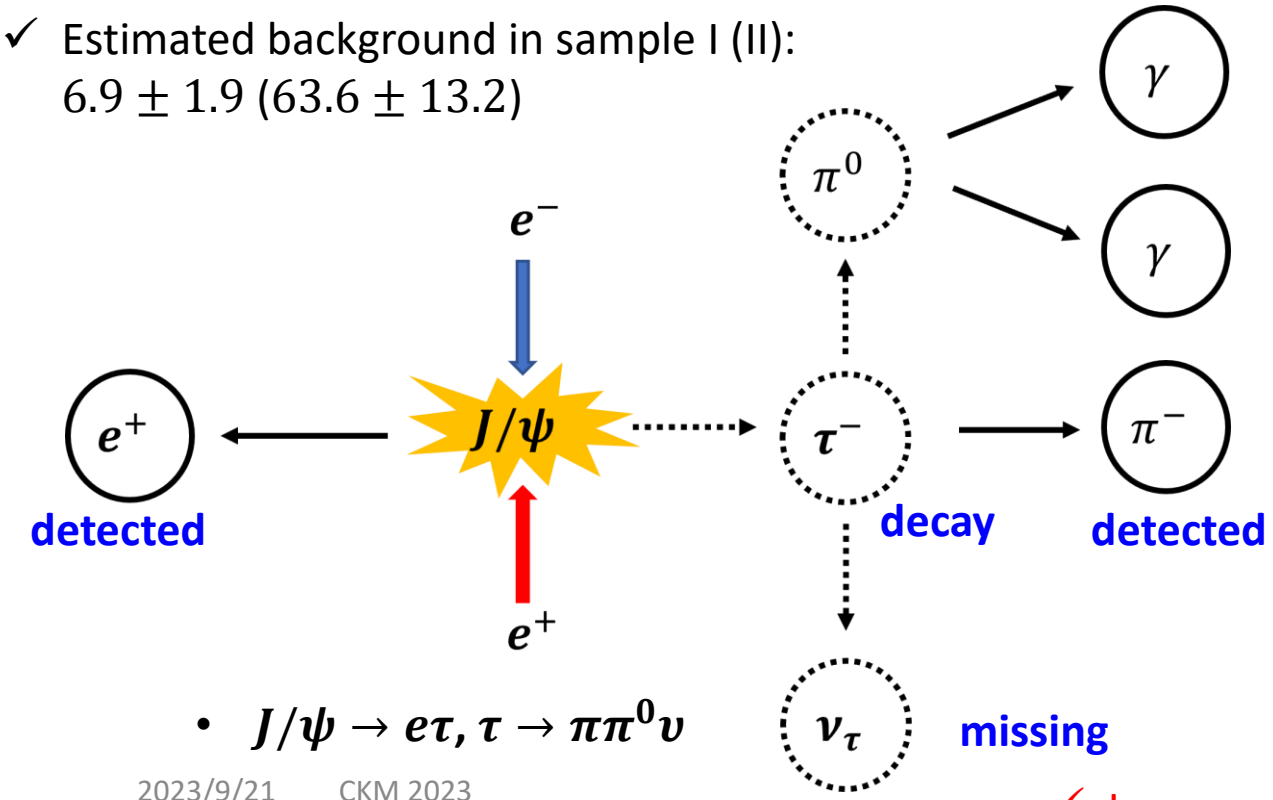


Sci. Chin. Phys. Mech. Astron. 66 2 (2023)

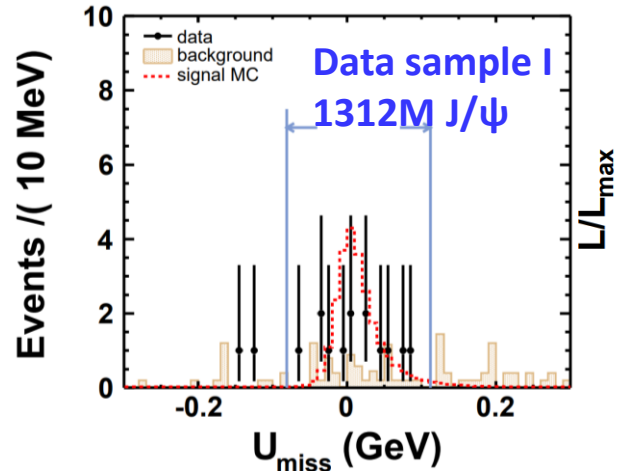
Search for $J/\psi \to e\tau$

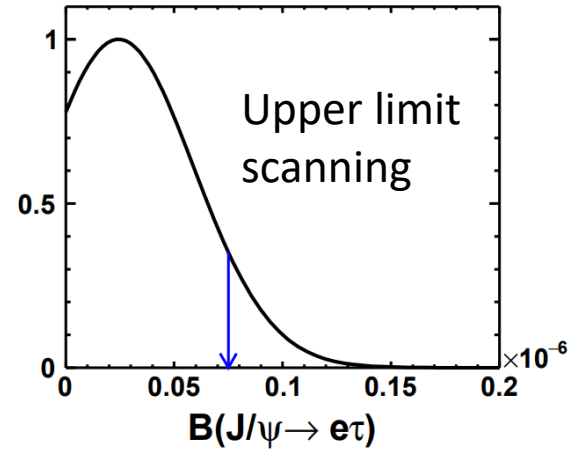
- ✓ Analyzing $\mathbf{10.1 \times 10^9}$ J/ψ events
- ✓ **13 (69) candidate events** are observed in sample I (II)
- ✓ Estimated background in sample I (II): 6.9 ± 1.9 (63.6 ± 13.2)

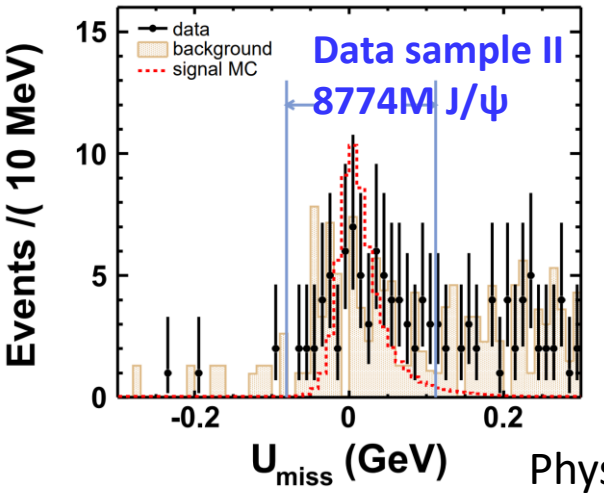
- ✓ $U_{miss} = E_{miss} - c|\vec{P}_{miss}|$
  - E_{miss}: missing energy
  - $\vec{P}_{miss}$: missing momentum



- $J/\psi \to e\tau, \tau \to \pi\pi^0\upsilon$







- ✓ $\mathcal{B}(J/\psi \to e\tau)$ $< 7.5 \times 10^{-8}$ @90% $C.L.$
- ✓ **New physics prediction:** $\mathbf{10^{-10} \sim 10^{-8}}$

Phys. Rev. D 103,112007 (2021)

- ✓ Improve the previous best limit by two orders of magnitude

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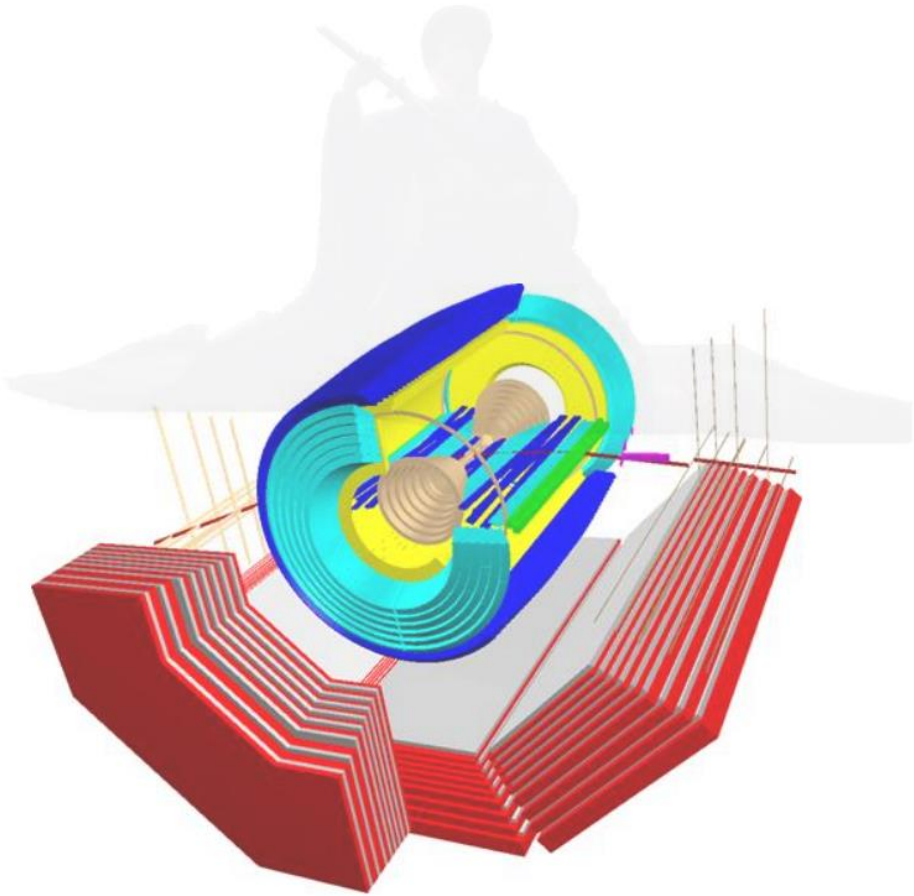

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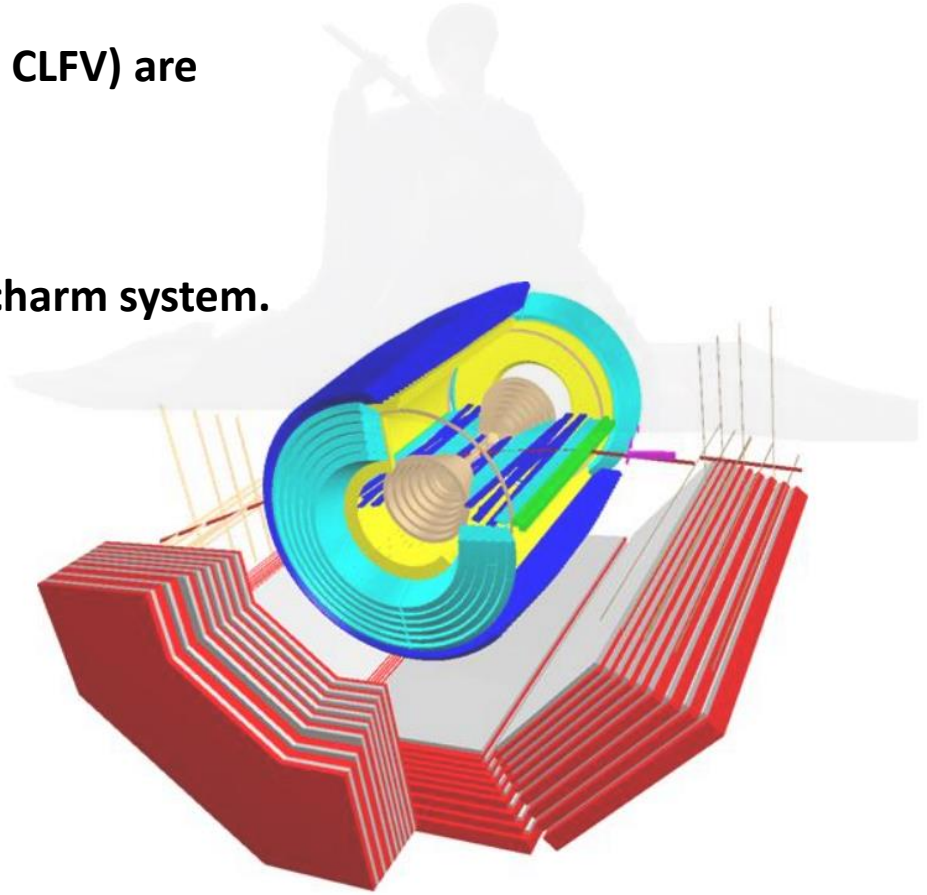
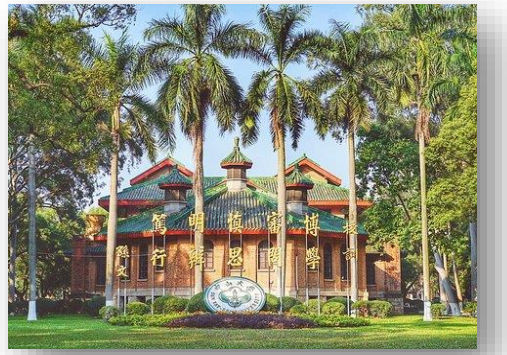
Summary

- The rare decays and symmetry violation processes (LNV, BNV, CLFV) are essential to probe New Physics beyond the Standard Model
- BESIII has performed wide studies on these processes in the charm system.
- BESIII has collected 10^{10} J/ψ and 2.7×10^{9} ψ' events
- BESIII will collect 20 fb^{-1} @ 3.773 GeV data sample ($D\bar{D}$)
- More & better results are coming soon!



Thank you



12th International Workshop on the CKM Unitarity Triangle
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