Charged lepton flavor violation searches at BESIII

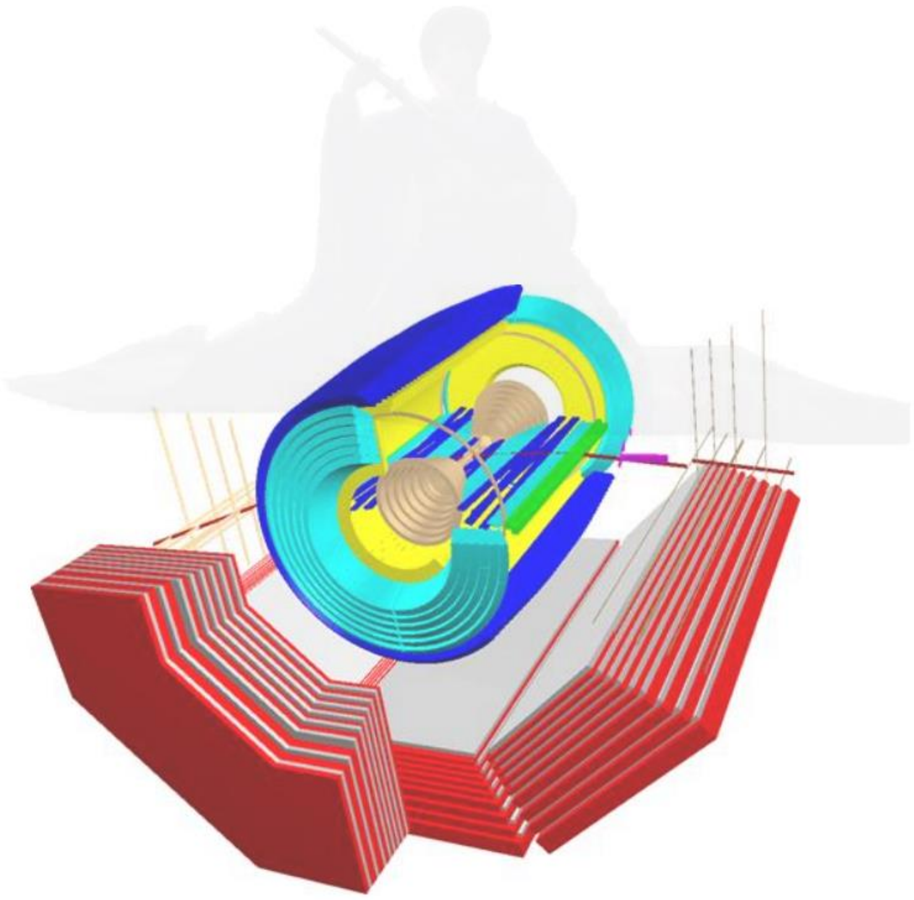
Zhengyun YOU
On behalf of the BESIII Collaboration

Sun Yat-sen University
youzhy5@mail.sysu.edu.cn

ICHEP2024, Prague, July 19th, 2024

Outline

- Charged Lepton Flavor Violation (CLFV)
- Experimental searches of CLFV
- The BESIII experiment
- Search for CLFV with charmonium decay
- Prospects
- Summary



Introduction of CLFV

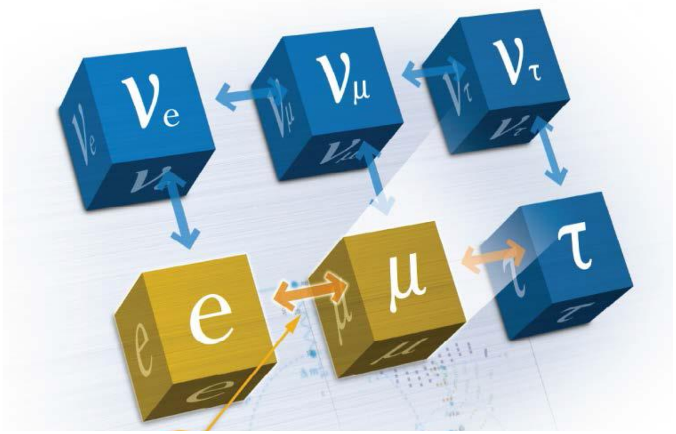
$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

M. Kobayashi &
T. Maskawa
Nobel Prize 2008

Quark mixing

T. Kajita &
A. McDonald
Nobel Prize 2015

Neutrino mixing



$$U_{PMNS} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,c_{23} \end{pmatrix}$$

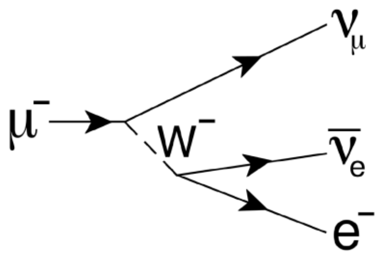
Neutrino oscillation: Uncharged Lepton Flavor Violation

$e - \mu - \tau$: Charged Lepton Flavor Violation

NOT observed yet

CLFV in the SM

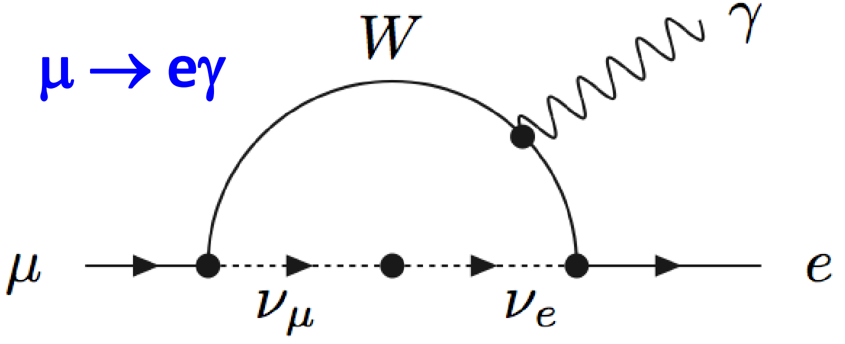
- Lepton flavor is conserved in the Standard Model (SM)
- General μ decay



	muon		muon neutrino		electron		e⁻ antineutrino
equation:	μ	$\rightarrow$	ν_μ	+	e^-	+	$\bar{\nu}_e$
electron number:	0	=	0	+	1	+	-1
muon number:	1	=	1	+	0	+	0

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

- With a minimal extension to the SM
- Considering massive neutrinos
- CLFV is allowed at loop level $\sim\mathbf{O(10^{-54})}$
- Experimentally undetectable
- Any observation of CLFV would be a clear signature of New Physics beyond the SM

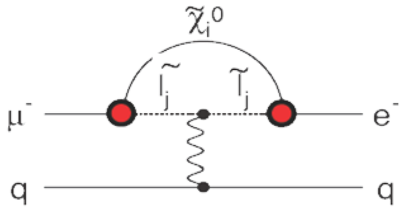


Theoretical Models

- Models provide a complementary approach, with CLFV rates predictable
  - SUSY particles
  - Compositeness
  - Leptoquark
  - Heavy neutrinos
  - Second Higgs doublet
  - Heavy Z’
  - Axion
  - …

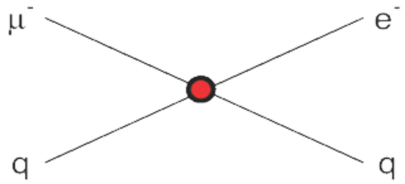
Supersymmetry

rate ~ 10^{-15}



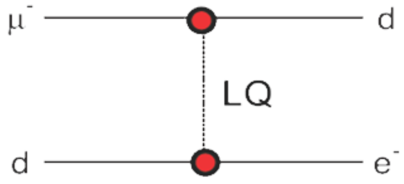
Compositeness

$\Lambda_c \sim 3000$ TeV



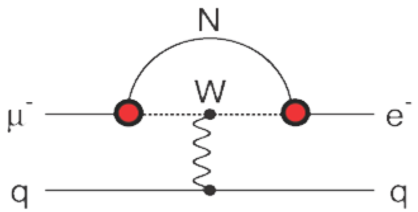
Leptoquark

$M_{LQ} = 3000\,(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



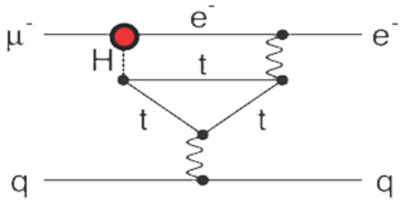
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\text{x}10^{-13}$



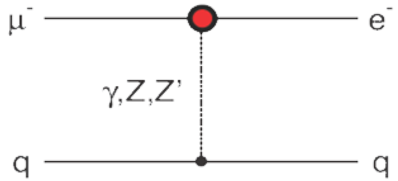
Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



Heavy Z’
Anomal. Z Coupling

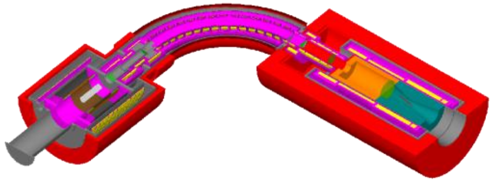
$M_{Z'} = 3000$ TeV/c^2



Search for CLFV

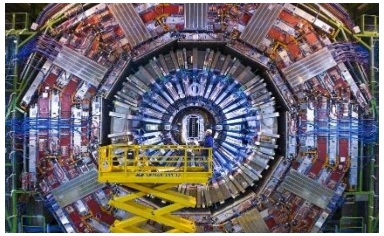
- μ transitions
  - $\mu \to e\gamma, \mu \to eee, \mu N \to eN, \mu^+ e^- \to \mu^- e^+$
- τ decays
  - $\tau \to e\gamma, \tau \to \mu\gamma, \tau \to ee\mu, \tau \to eh, \tau \to \mu h, \ldots$
- Resonance decays
  - Meson decays: $\boldsymbol{J/\psi \to e\mu/e\tau}$, $\Upsilon \to e\tau, B \to \mu\tau, \ldots$
- Heavy particles
  - Z/Higgs decays: $Z \to e\mu, H \to \mu\tau, \ldots$
  - Top decays: $t \to qll'$
  - New heavy particles: $Z' \to e\mu, \phi \to \mu\tau, \ldots$

μ beam



Low energy

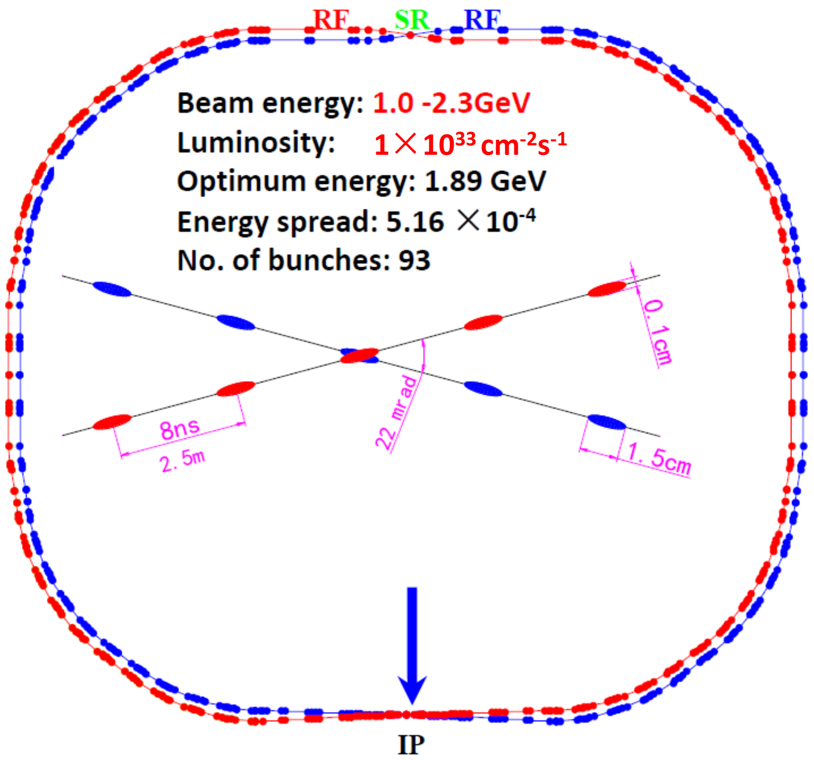
Colliders



High energy

BEPCII and BESIII

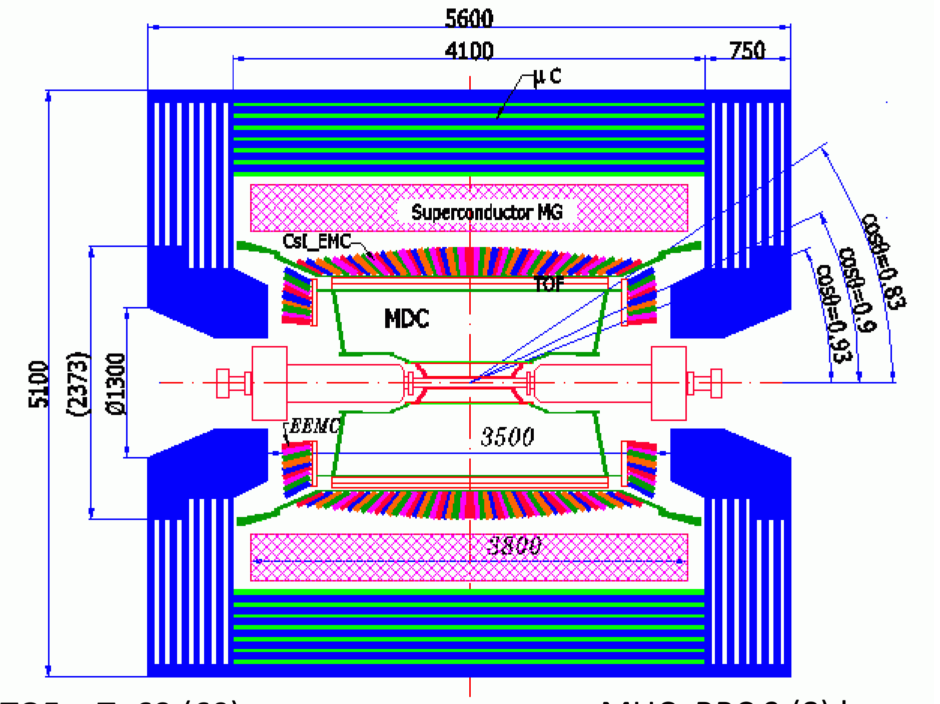
Beijing Electron Positron Collider II



BESIII Detector

MDC: Δp/p =0.5% @ 1GeV/c
dE/dx: ~ 6%

EMC: CsI (Tl) 2.5% (5.0%)
barrel (endcap) @ 1GeV



TOF: σT=68 (60) ps
barrel (endcap)

MUC: RPC 9 (8) layers
barrel (endcap)

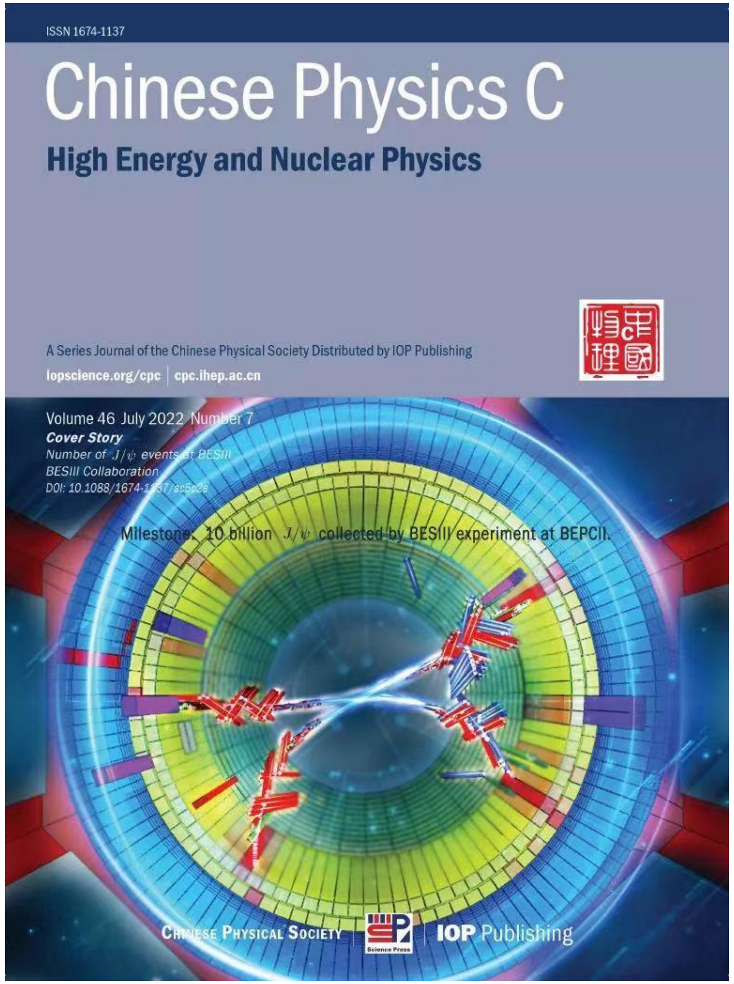
BESIII Physics Data

Physics of BESIII

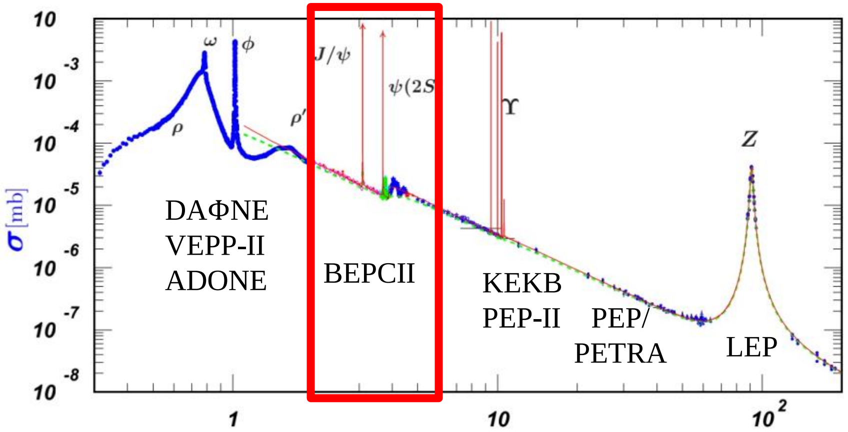
NSR 8 (11) 2021

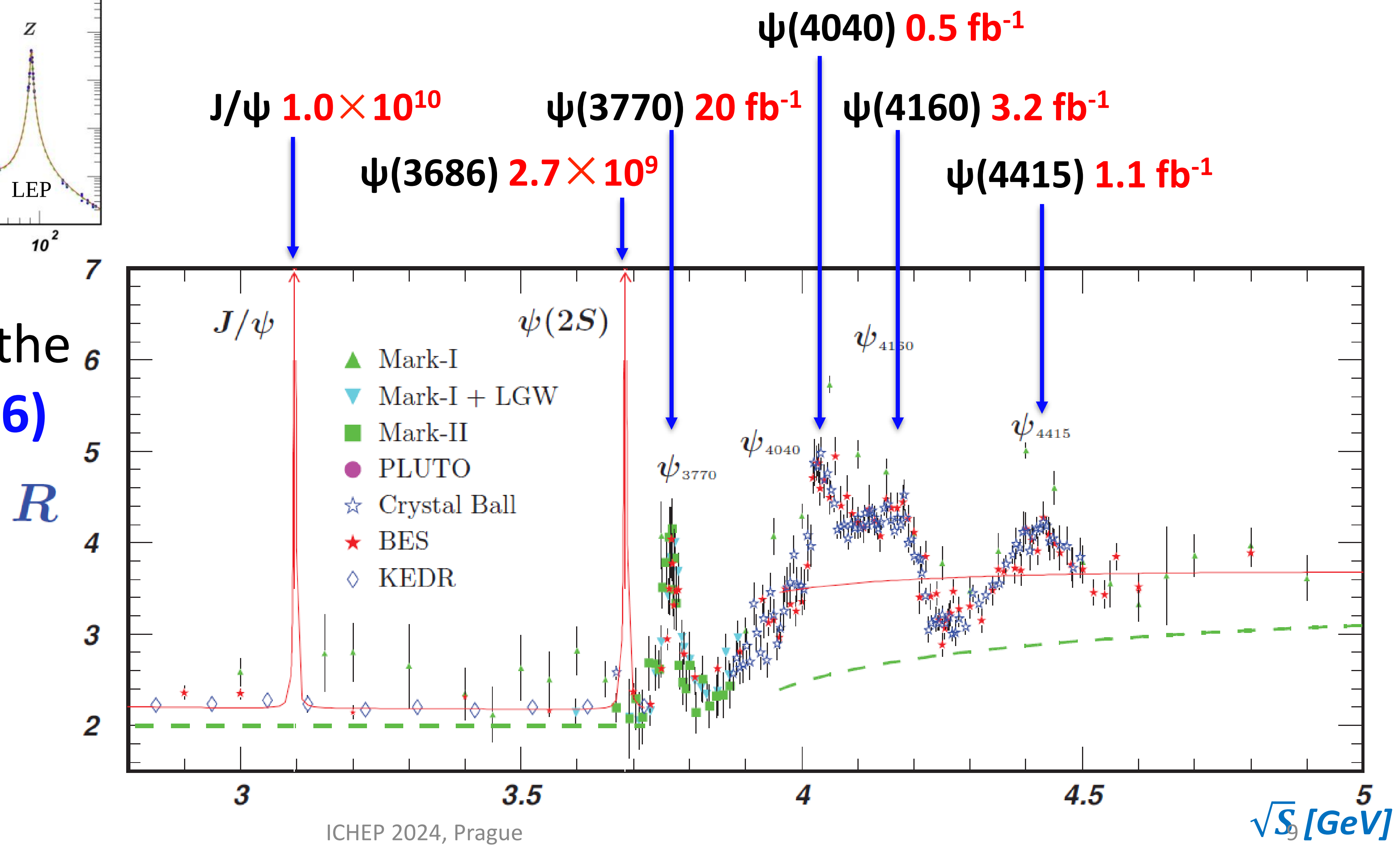
10 Billion J/ψ collected by BESIII

CPC 46 074001 (2022)



Charmonium Data at BESIII





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

New Physics Searches at BESIII

- Uniform blinding strategy and datasets
- Common statistic and standards
- Sharing methods, tools and codes

Common standards & tools

Symmetry

- BNV & LNV processes
- **LFV processes**
- Other symmetry violation

Very rare decays

New Physics

Exotic searches

Exotic

- Dark photon
- Invisible signatures
- Light Higgs, Z'
- Exotic resonances

- FCNC processes
- Charmonium weak decays
- Other rare decays

Very rare

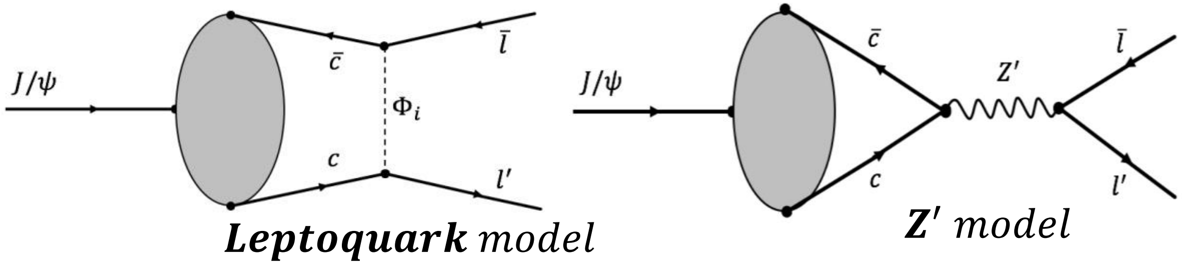
- New Physics Searches at the BESIII Experiment, S.J. Chen and S. Olsen, Nation Science Review 8, nwab189 (2021), arXiv: 2102.13290
- New Physics Program of BES, D.Y. Wang, in "30 Years of BES Physics"

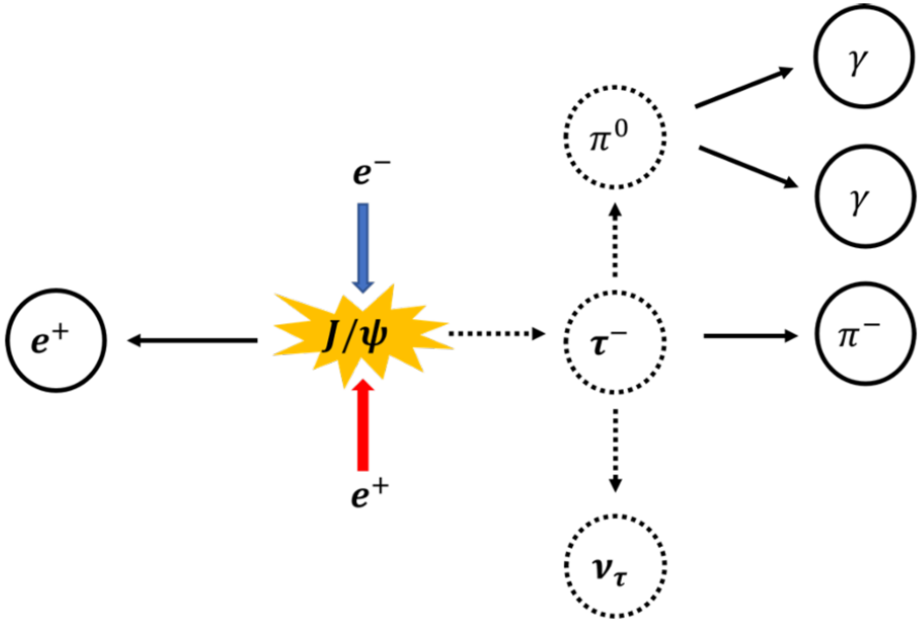
Search for CLFV decay $J/\psi \to e^{\pm}\tau^{\mp}$

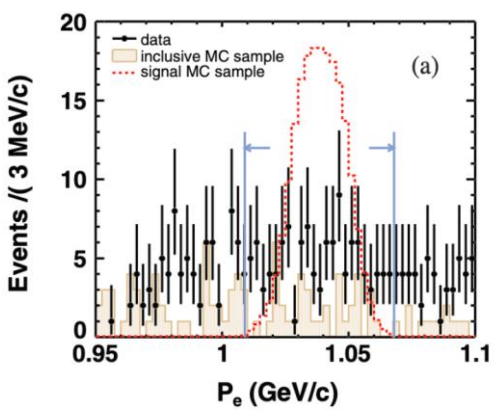
Search for $J/\psi \to e^{\pm}\tau^{\mp}$

- Analyzing **10.087×10⁹ J/ψ** events
  - Data sample I: 1.3106×10^9 in 2009 & 2012
  - Data sample II: 8.774×10^9 in 2018 & 2019
- Searching for process $J/\psi \to e\tau, \tau \to \pi\pi^0\nu$
  - Tag with one electron and one charged pion
  - At least two photons to form π^0
  - Mono-energetic electron P_e & M_{e_recoil} (@τ mass)
  - Neutrino with missing energy $E_{miss} > 0.43$ GeV

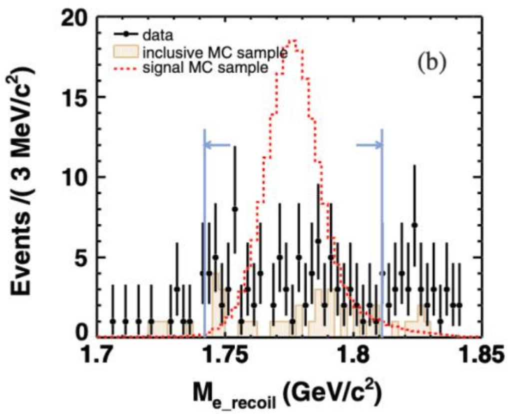
Phys. Rev. D 103 112007 (2021)







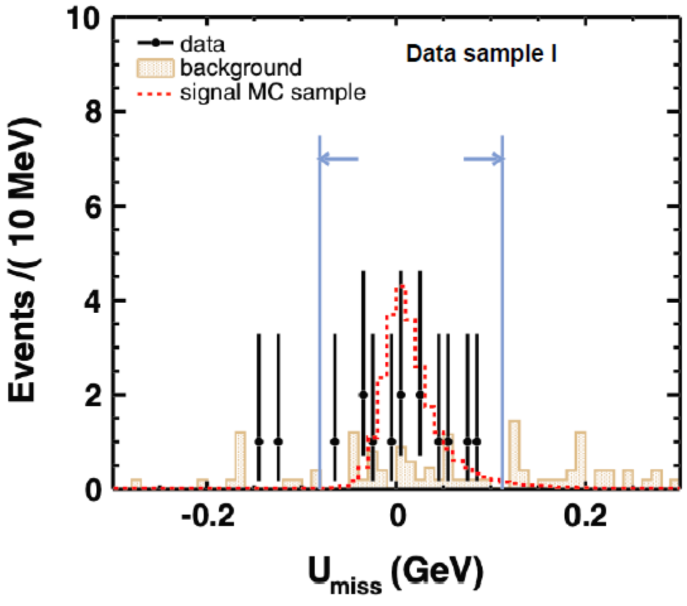
1.009 GeV/c < P_e < 1.068 GeV/c

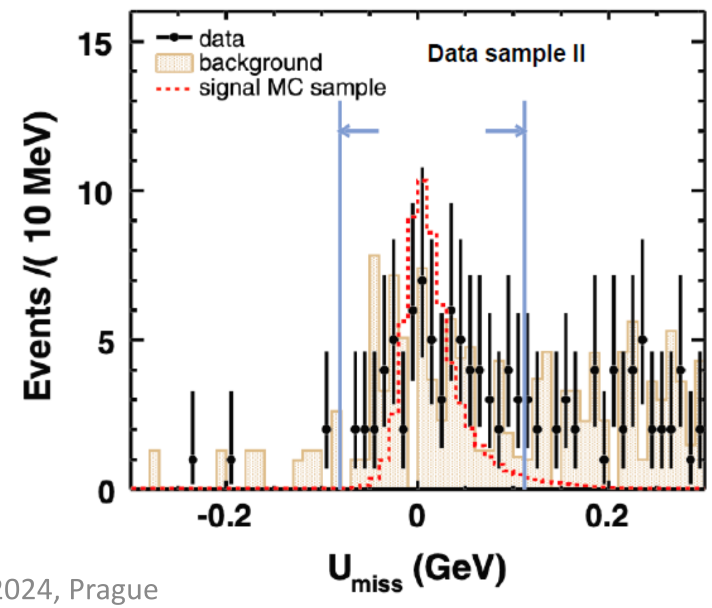


1.742 GeV/c^2 < M_{e_recoil} < 1.811 GeV/c^2

Analysis Method

- Partial reconstruction
  - Missing energy $\boldsymbol{E}_{\mathbf{miss}} = \boldsymbol{E}_{\mathbf{CMS}} - \boldsymbol{E}_{\boldsymbol{e}} - \boldsymbol{E}_{\boldsymbol{\pi}} - \boldsymbol{E}_{\boldsymbol{\pi}^{\mathbf{0}}}$
  - $\mathbf{U}_{\mathbf{miss}} = \boldsymbol{E}_{\boldsymbol{miss}} - \boldsymbol{c}\left|\overrightarrow{\boldsymbol{P}}_{\boldsymbol{miss}}\right|$
  - $\mathbf{U}_{\mathbf{miss}}$ peaking at 0 for signal events
- 13 (69) candidate events observed in data sample I (II)
  - With the expected background events of 6.9 ± 1.9 (63.6 ± 13.2) in data sample I (II)



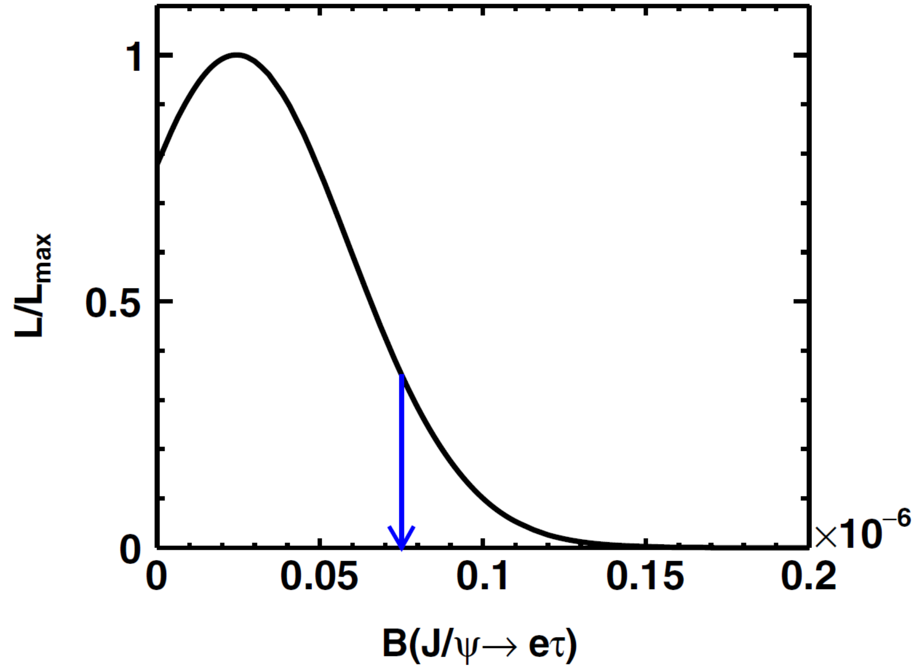


$J/\psi \to e^{\pm}\tau^{\mp}$ Upper Limit

- Signal efficiency: $(20.24 \pm 0.05)\%$ & $(19.37 \pm 0.02)\%$ for data sample I & II
- Continuum background and systematic uncertainties studied
- $\mathcal{B}(J/\psi \to e\tau) < 7.5 \times 10^{-8}$ @ 90%C. L.
- Improve the previous best limit by two orders of magnitude, comparable with theoretical predictions
- One of the best constraints from meson decay

Systematic uncertainties

Sources	Sample I	Sample II
Number of J/ψ	0.5%	0.4%
Quoted BF*	0.4%	0.4%
MC model	0.6%	...
Pion PID*	1.0%	1.0%
Pion tracking*	1.0%	1.0%
Electron PID	0.4%	0.9%
Electron tracking*	0.1%	0.1%
Photon detection*	1.0%	1.0%
π^0 reconstruction*	1.0%	1.0%
P_e and M_{e_recoil} requirements	3.0%	3.3%
E_{miss} requirement	1.0%	0.8%
Total uncertainty	3.9%	4.1%



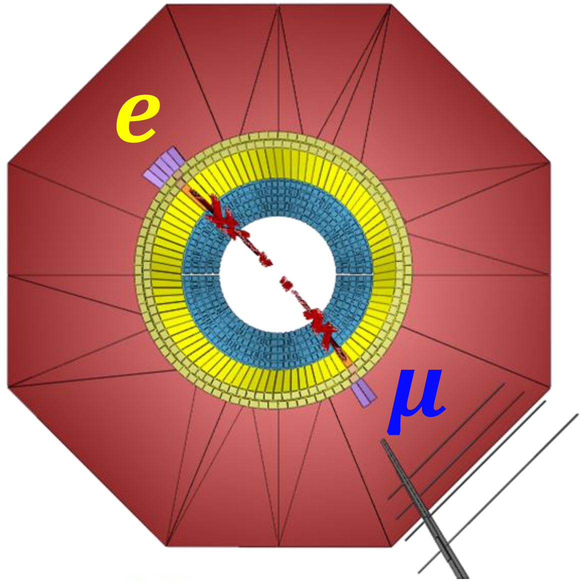
Search for CLFV decay $J/\psi \to e^{\pm}\mu^{\mp}$

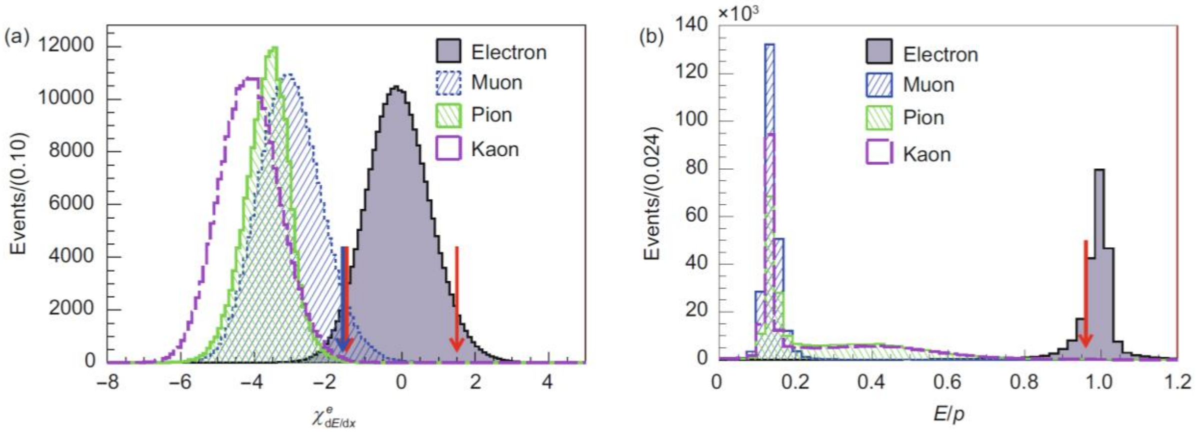
Search for $J/\psi \to e^{\pm}\mu^{\mp}$

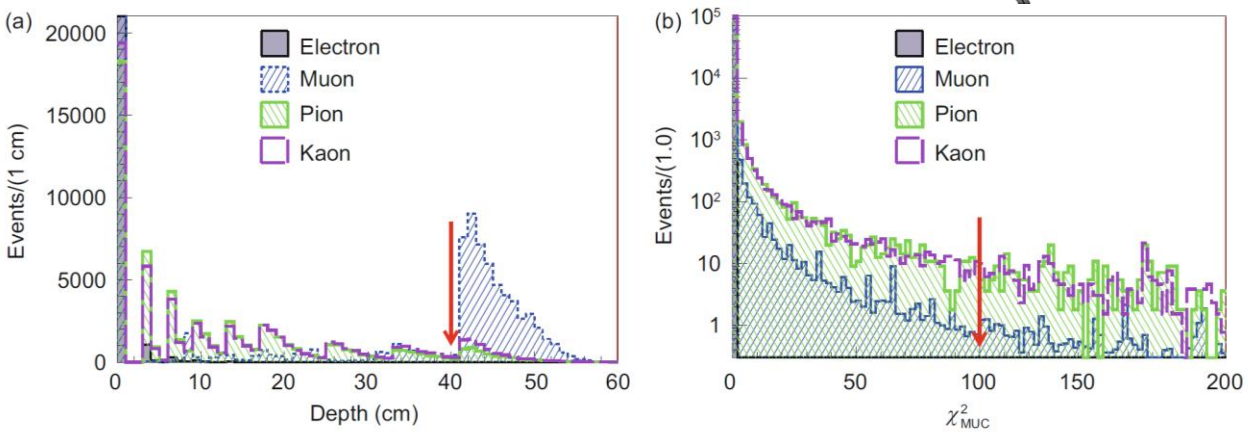
- Analyzing **8.998×10^9 J/ψ** events (no 2012 data)

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

- Searching for two back-to-back $\boldsymbol{e\ \mu}$
  - $\boldsymbol{e\ \mu}$ TOF time difference < 1.0 ns to reject cosmic ray muons
  - $\boldsymbol{e\ \mu}$ on the opposite direction $|\Delta\boldsymbol{\theta}| < \mathbf{1.2}^{\circ}, |\Delta\boldsymbol{\varphi}| < \mathbf{1.5}^{\circ}$
- $\boldsymbol{e\ \mu}$ particle identification
  - Using dE/dx, EMC deposited energy
  - MUC hits and fitting $\boldsymbol{\chi^2}$

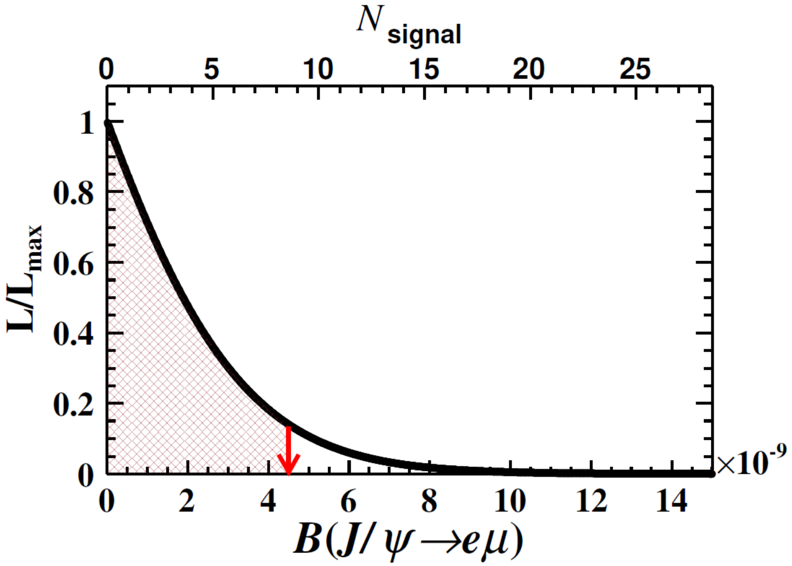


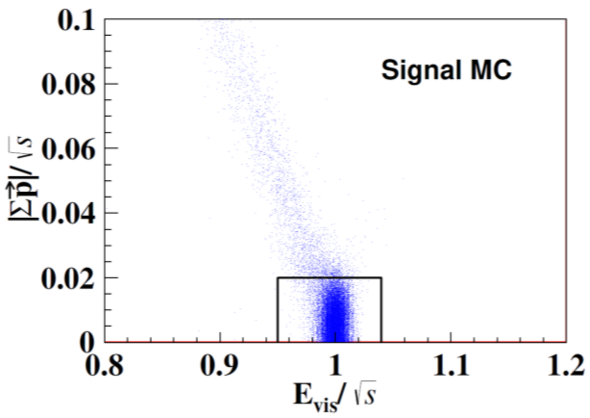


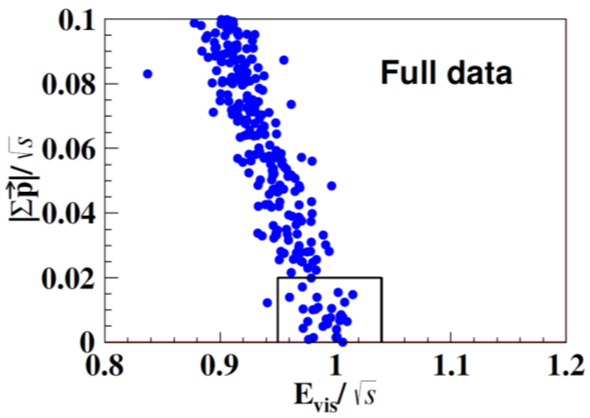


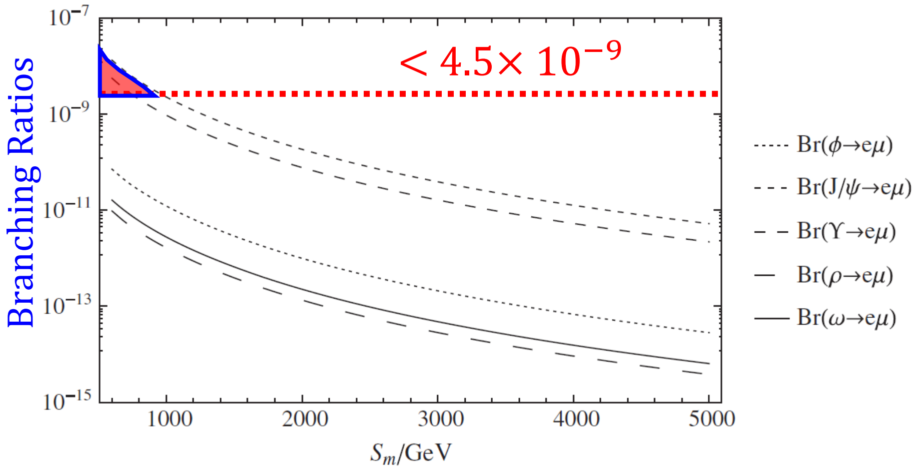
$J/\psi \to e^{\pm}\mu^{\mp}$ Upper Limit

- Signal and background
  - Expect 24.8 (J/ψ decay) + 12.0 (continuum) bkg events
  - Observe 29 candidate events in the signal window
- $\mathcal{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9}$ @ $\mathbf{90\%C.L.}$
- Improve the previous best limit by a factor of **30**
- The most precise CLFV search in heavy quarkonium
- Excluding the parameter space of some models







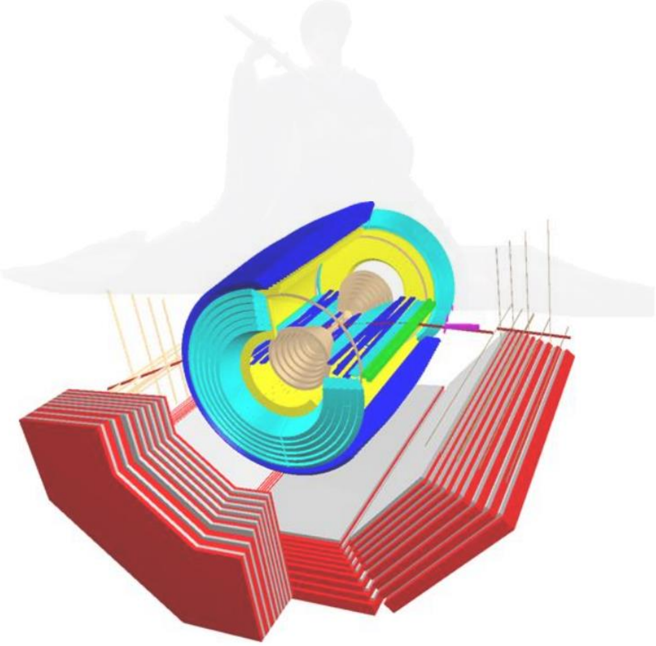


Sensitive parameters, Diagonal elements in $m_{\tilde{L}}, m_{\tilde{R}}$

Phys. Rev. D 97, 056027 (2018)

Prospects

- Charmonium CLFV decay
  - With **10^{10}** J/ψ and **2.7×10^{9}** ψ(3686) events
  - Search for $J/\psi \to \mu\tau,\ \psi(3686) \to e\mu$
  - Expected sensitivity $\mathcal{O}(10^{-8})$
- CLFV search with other mesons
  - Intermediate particles from charmonium decay
  - Sensitive to different operators in EFT
  - 0^-: $\eta, \eta', \eta_c, D, D_s$
  - 1^-: $J/\psi, \psi(3686)$
  - J^+: χ_{cJ}, h_c
- CLFV search with radiative decay
  - Sensitive to more operators



	J^P	Generate	$e\mu$	$e\tau$	$\mu\tau$	$\gamma\ell_1\bar{\ell}_2$
η'	0^-	$J/\psi \to \gamma\eta'$, $(5.25\pm0.07)\times10^{-3}$	4.7×10^{-4}	–	–	no result
$\eta_c(1S)$	0^-	$J/\psi \to \gamma\eta_c(1S)$, $(1.7\pm0.4)\,\%$	no result	no result	no result	
J/ψ	1^-	$e^+e^- \to J/\psi$, 1×10^{10}	4.5×10^{-9}	7.5×10^{-8}	2.0×10^{-6}	
$\psi(3686)$	1^-	$e^+e^- \to \psi(3686)$, 2.7×10^{9}	no result	no result	no result	
χ_{cJ}	J^+	$\psi(2S) \to \gamma\chi_{cJ}$, $\sim 10\,\%$	no result	no result	no result	
$h_c(1P)$	1^+	$\psi(2S) \to \pi^0 h_c(1P)$, $(7\pm5)\times10^{-4}$	no result	no result	no result	

Summary

- CLFV provides unique information to search for New Physics
- BESIII has great potentials in search for CLFV with charmonium data
- Currently the most stringent CLFV upper limit in heavy quarkonium sector
  - $\mathcal{B}(J/\psi \to e\tau) < 7.5 \times 10^{-8}$ @ 90%C. L.
  - $\mathcal{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9}$ @ 90%C. L.
- More BESIII CLFV results are expected in the next few years!

Thank you!