Search for Charged Lepton Flavor Violation decays at BESIII

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NPG Workshop 2023 BESIII新物理研讨会

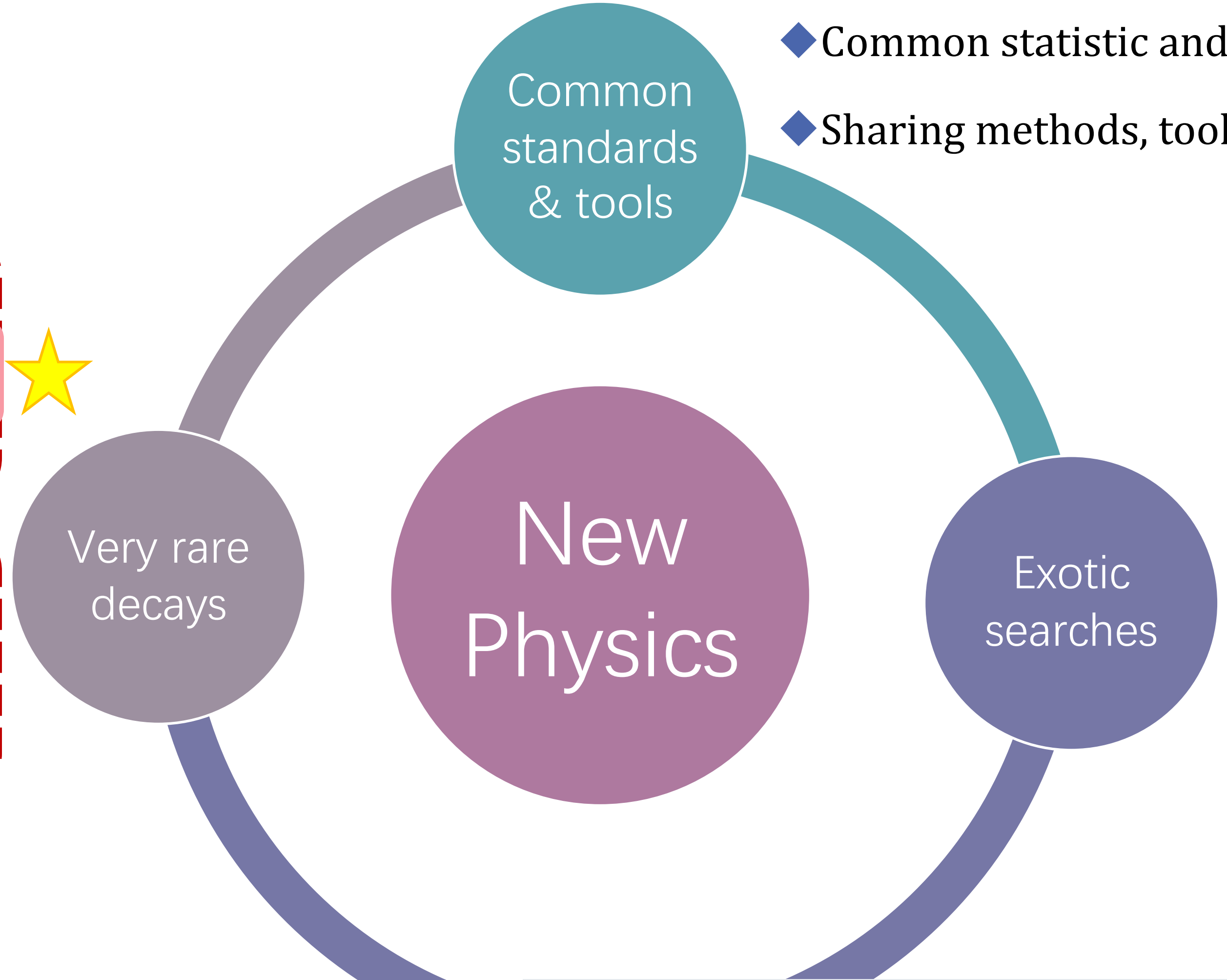
2023.10.15

Outline

- New physics searches at BESIII
- Motivation
- Search for charged lepton flavor violating decay $J/\psi \to e\tau$
- Search for charged lepton flavor violating decay $J/\psi \to e\mu$
- Ongoing CLFV analyses
- Summary

New Physics Searches at BESIII

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



Symmetry

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

Very rare

- FCNC processes
- Charmonium weak decays
- Other rare decays

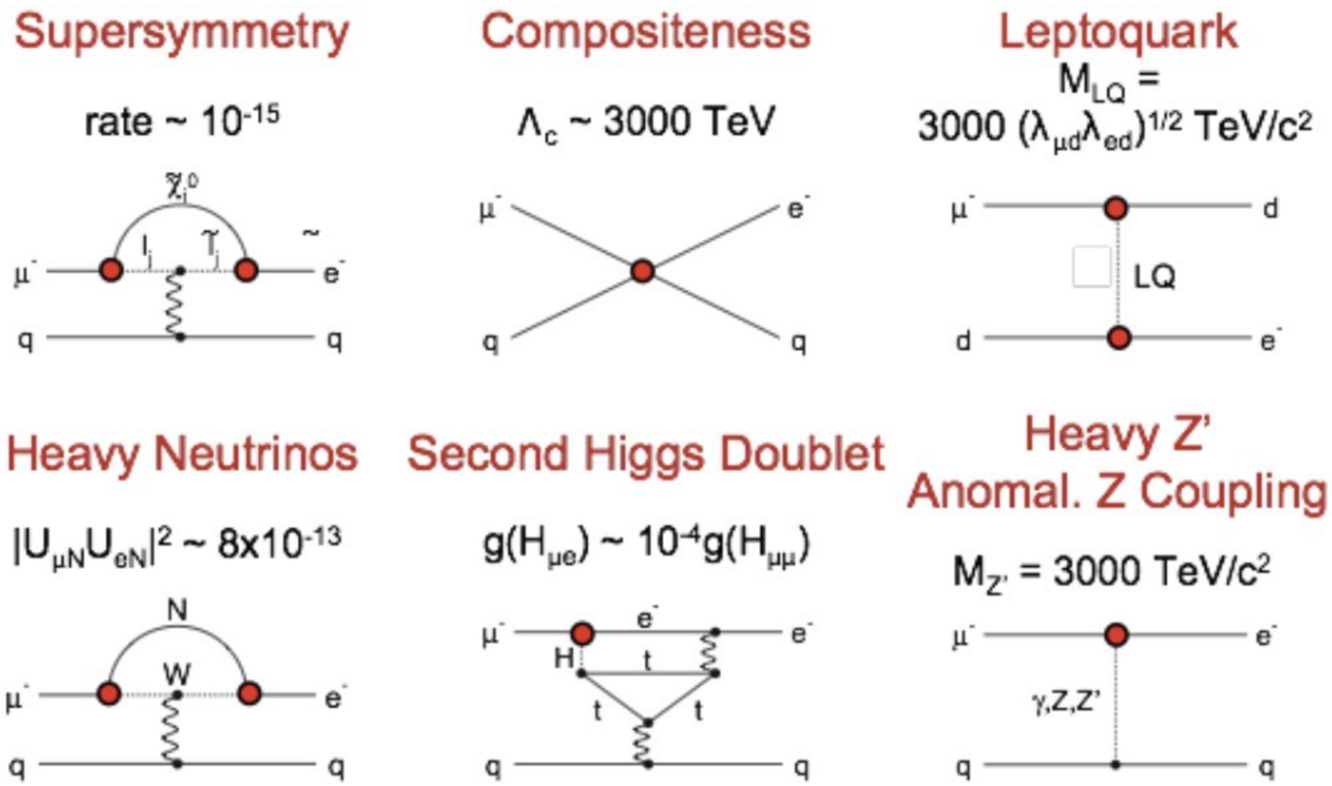
Exotic

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

- 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"

Motivation

- Since LFV decay is forbidden in the SM, the observation of any LFV decay would be a signal of new physics beyond SM.
- In SM, Lepton Flavor is conserved for zero degenerate ν masses and now we have clear indication that νs have non-zero mass.

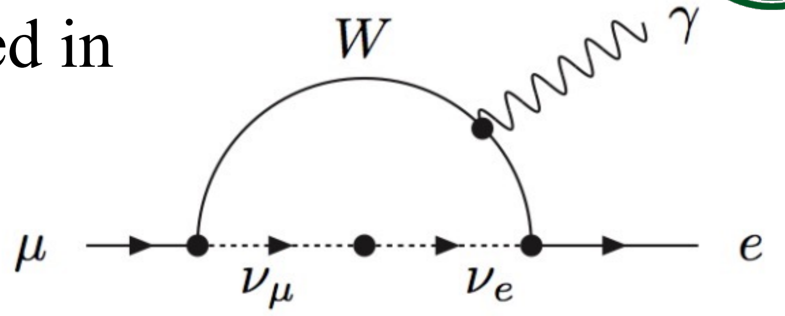


- Models may enhance LFV effects up to a detectable level, such as leptoquark, Compositeness, Supersymmetry, Heavy Z' and Anomalous boson Coupling model.

Motivation

- In the charged lepton sector, LFV is heavily suppressed in the Standard Model.

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



Neutrinoless muon decay

- Both experimental searches and upper-limit predictions, including μ, τ LFV decays, π, K LFV decays and $\phi, J/\psi$ two-body LFV decays, etc.

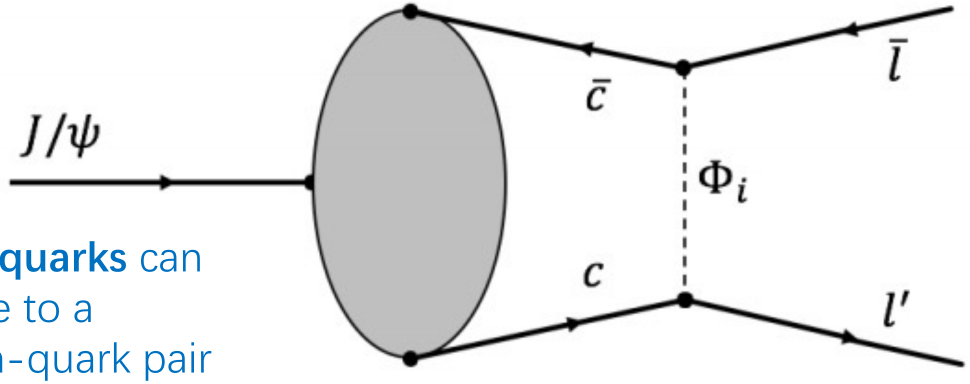


Diagram via leptoquarks

Leptoquarks can couple to a lepton-quark pair and induce the LFV two-body decays of J/ψ.

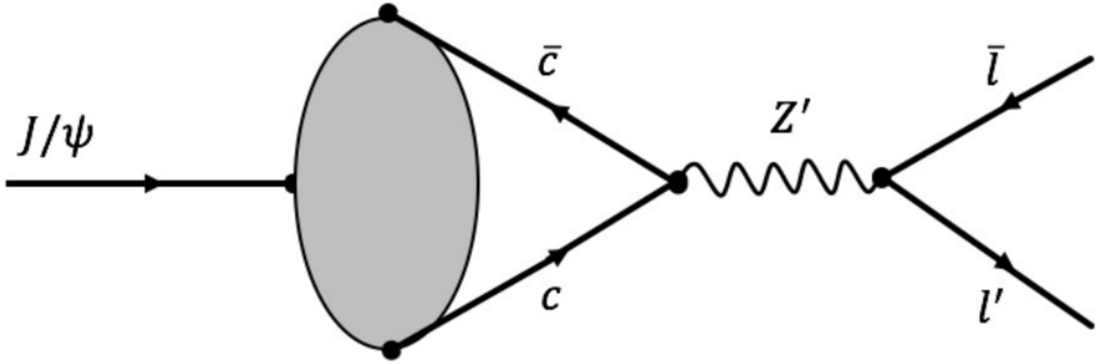


Diagram via a Z' in TC2 models

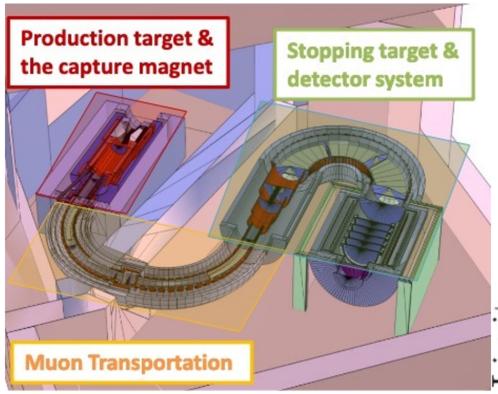
Phys. Rev. D 67, 114001 (2003)
Phys. Lett. B 496, 89 (2000)

CLFV

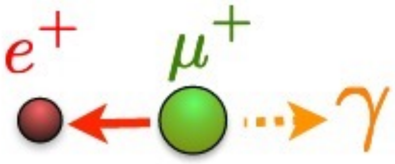
- $\mathcal{B}(\mu^+ \rightarrow e^+\gamma)<4.2\times10^{-13}$ @ 90% C.L. MEG
- $\mathcal{B}(\tau^+ \rightarrow e^+\gamma)<3.3\times10^{-8}$ @ 90% C.L. BABAR
- $\mathcal{B}(\mu \rightarrow 3e)<1.0\times10^{-12}$ @ 90% C.L. SINDRUM
- $\mathcal{B}(Z \rightarrow e^\pm\mu^\mp)<7.5\times10^{-7}$ @ 95% C.L. ATLAS
- $\mathcal{B}(\phi \rightarrow e^\pm\mu^\mp)<2\times10^{-6}$ @ 90% C.L. SND
- $\mathcal{B}(J/\psi \rightarrow e^\pm\tau^\mp)<7.1\times10^{-8}$ @ 90% C.L. BESIII
- $\mathcal{B}(J/\psi \rightarrow e^\pm\mu^\mp)<4.5\times10^{-9}$ @ 90% C.L. BESIII

Current best limit

Eur. Phys. J. C 76, 434 (2016)
Phys. Rev. Lett. 104, 021802 (2010)
Nucl. Phys. B 299, 1 (1988).
Phys. Rev. D 90, 072010 (2014)
Phys. Rev. D 81, 057102 (2010)
Phys. Lett. B 598, 172 (2004)
Phys. Rev. D 103, 112007 (2021)
Sci. Chin. Mech. Astron. 66 2 (2023)



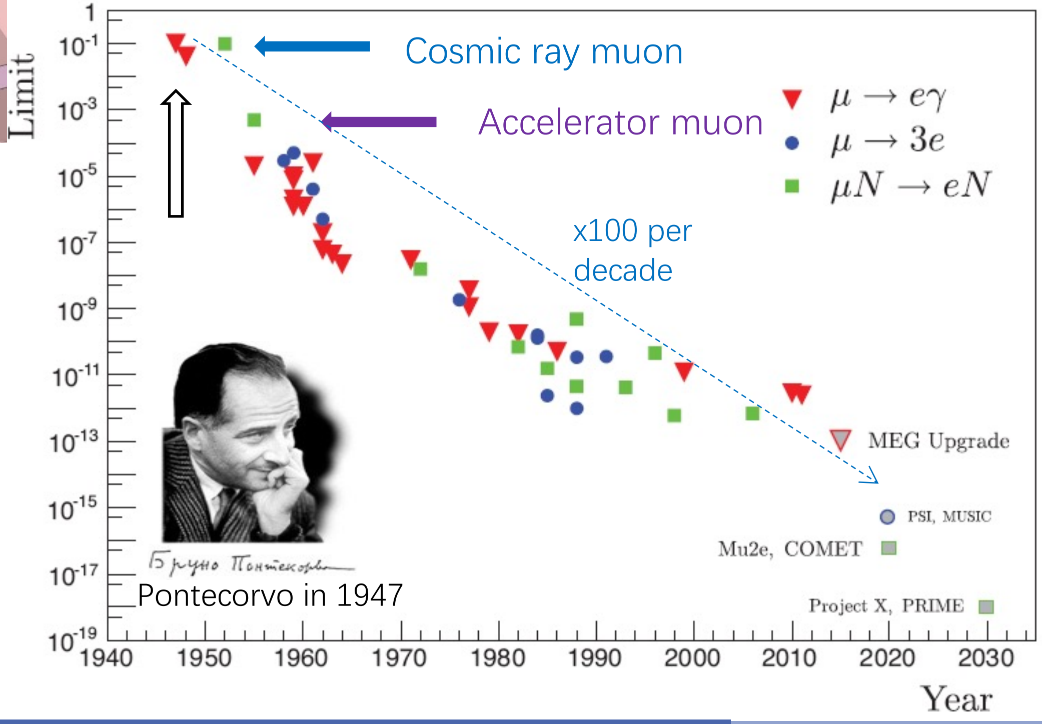
COMET



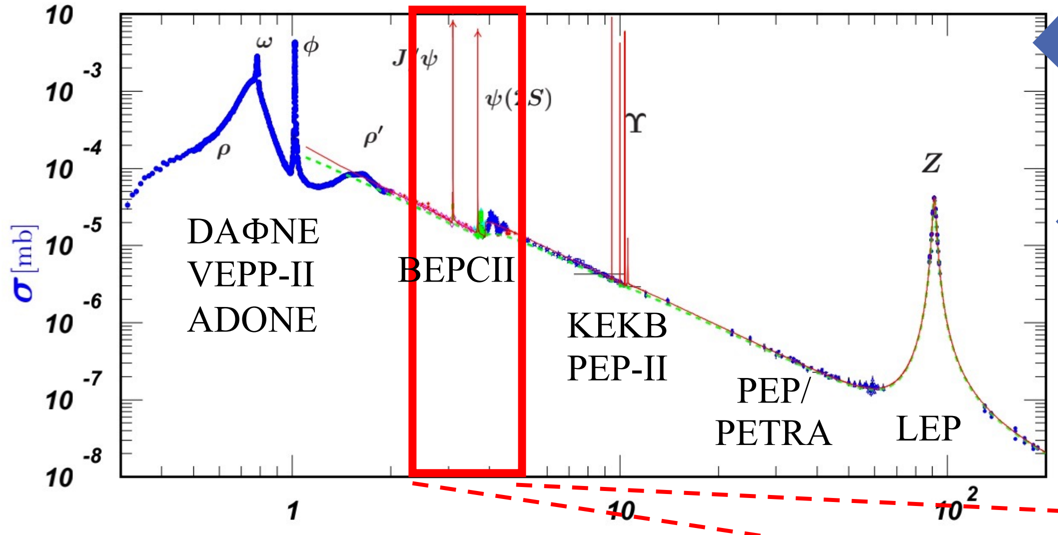
MEGII process

- Mu2e and COMET will search for CLFV with $\mu N \rightarrow eN$
  Improve the current limit by a factor of **10^4**
  Next goal <6x10^{-17} (90%C.L.)
  Search for New Physics with energy scale up to 10^4 TeV

- MEGII and Mu3e has similar beam requirements.
  Intensity O(10^8 muon/s), low momentum p = 28 MeV/c
  MEGII was started in 2021 and will continue to run until 2026 aiming at a sensitivity down to 6x10^{-14} (90%C.L.)



BESIII data samples



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

ψ(3770) 2.9 fb^{-1}

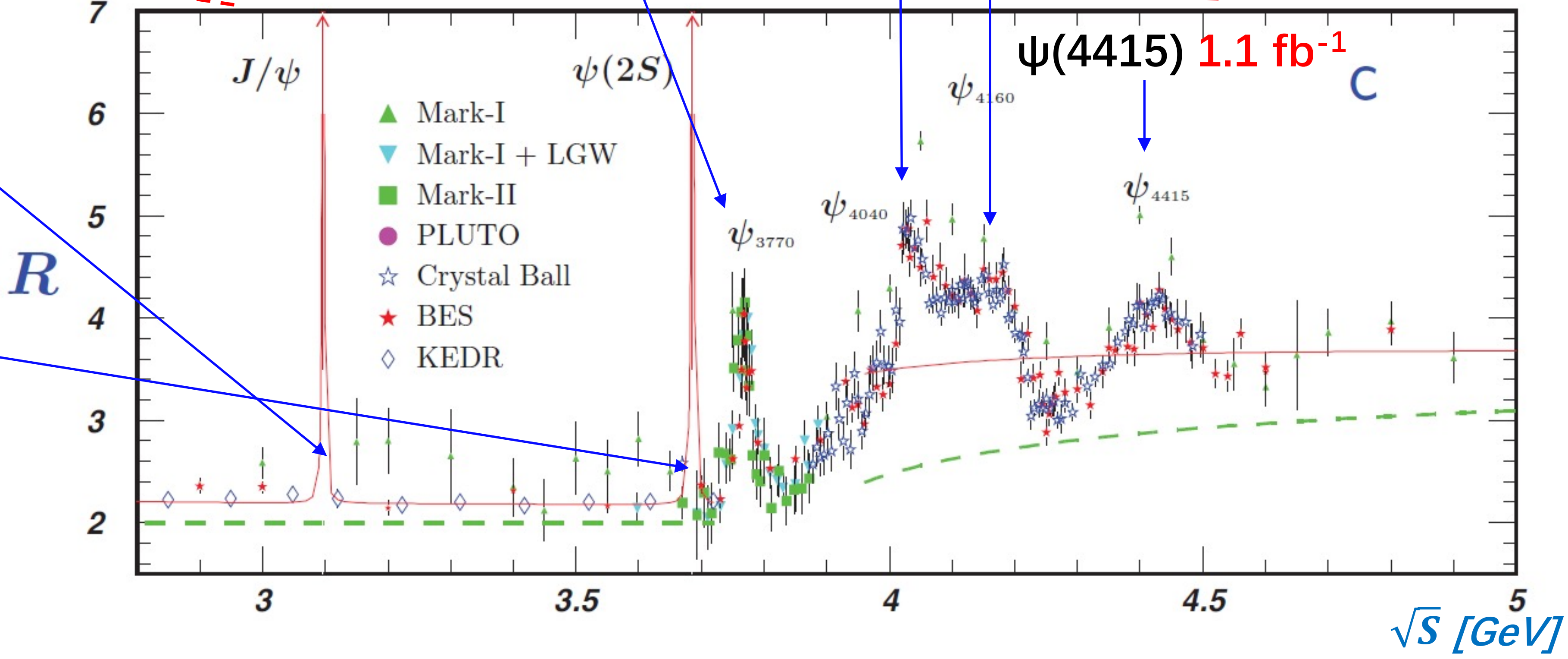
ψ(4040) 0.5 fb^{-1}

ψ(4160) 3.2 fb^{-1}

ψ(4415) 1.1 fb^{-1}

J/ψ 1.0×10^{10}

ψ(3686) 2.7×10^{9}



Motivation

- The cLFV decays of vector mesons $V \to l_i l_j$ are also predicted in various of extension models of SM:

$$\mathcal{B}(J/\psi \to e\mu) \text{ to } 10^{-16} \sim 10^{-9} \text{ @ 90\% C.L.}$$

$$\mathcal{B}(J/\psi \to e(\mu)\tau) \text{ to } 10^{-10} \sim 10^{-8} \text{ @ 90\% C.L.}$$

Phys. Rev. D 63, 016003.
Phys. Rev. D 63, 016006
Phys. Rev. D 83, 115015
Phys. Lett. A 27, 1250172
Phys. Rev. D 94, 074023.
Phys. Rev. D 97, 056027

- Experimental results before:

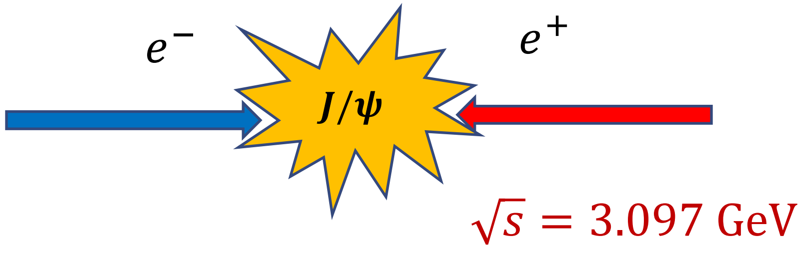
Decay mode	BESII UL (90%)	BESIII UL (90%)
Number of J/ψ	58×10^6	225.3×10^6
$\mathcal{B}(J/\psi \to e\mu)$	$< 1.1\times10^{-6}$	$< 1.6\times10^{-7}$
$\mathcal{B}(J/\psi \to e\tau)$	$< 8.3\times10^{-6}$	-
$\mathcal{B}(J/\psi \to \mu\tau)$	$< 2.0\times10^{-6}$	-

Phys. Lett. B 561, 112007
Phys. Lett. B 598, 172
Phys. Rev. D 87, 112007

Search for charged lepton flavor violating decay $J/\psi \to e\tau$

Data samples

- Based on **10 billion** data set: 1310.6M collected @2009+2012 (sample I), 8774.01M collected @2017-2019 (sample II).



Decay chain	Generator	Generated
$J/\psi \to \omega f_2(1270), \omega \to \pi^0\gamma, f_2(1270) \to \pi^+\pi^-$	PHSP, VSP_PWAVE, TSS	5.8M
$J/\psi \to \eta n\bar{n}, \eta \to \gamma\gamma$	PHSP	5.8M
$J/\psi \to \pi^+\pi^-\pi^0$	OMEGA-DALITZ	29M
$J/\psi \to \rho\pi$	HELAMP	29M
$J/\psi \to \pi^0 e^+ e^-$	PHSP	29M
$J/\psi \to \bar{p} n \pi^+$	PHSP	5.8M
$J/\psi \to K^* \bar{K}^0 (K^* \to K^+\pi^-) + c.c.$	HELAMP, VSS	11.6M

Generator and number of events list for exclusive MC samples of 2009 and 2012

Decay chain	Generator	Generated
$J/\psi \to \omega f_2(1270), \omega \to \pi^0\gamma, f_2(1270) \to \pi^+\pi^-$	PHSP, VSP_PWAVE, TSS	19M
$J/\psi \to \rho\pi$ (include direct $\pi^+\pi^-\pi^0$)	HELAMP, OMEGA-DALITZ	190M
$J/\psi \to \bar{p} n \pi^+$	PHSP	38M

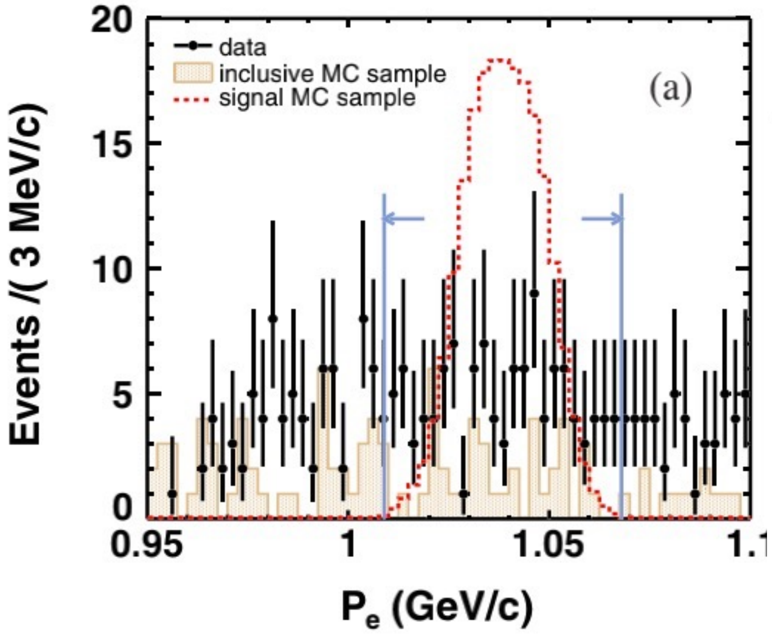
Generator and number of events list for exclusive MC samples of 2018 and 2019

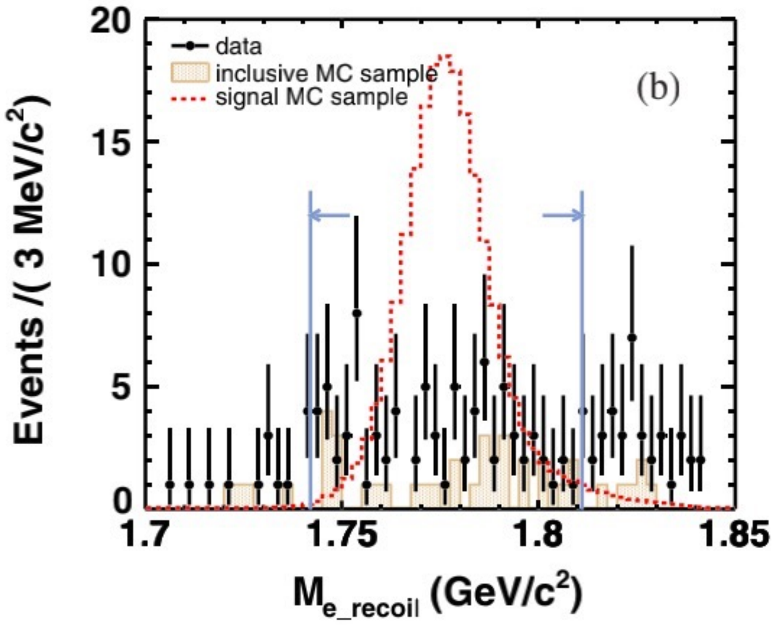
- Inclusive samples:
  225 million @ 2009
  1000 million @ 2012
  4600 million @ 2018
  4100 million @ 2019
- 1 million τ inclusive events with $J/\psi \to e\tau$ and τ inclusive decays to any decay channels

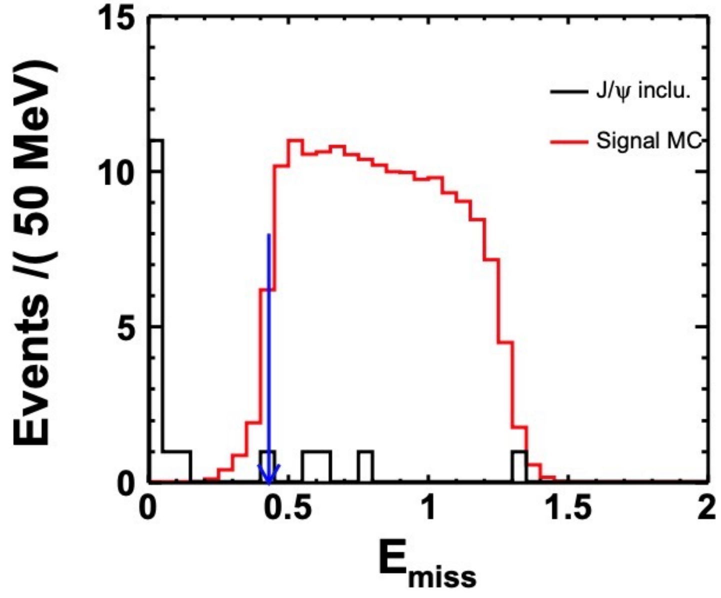
Event Selection

- $J/\psi \rightarrow e\tau, \tau \rightarrow \pi\pi^0\nu$
  - Select one electron and one charged pion
  - At least two photon showers and one π^0
  - The final-state electron from the process $J/\psi \rightarrow e\tau$ is monochromatic, therefore the momentum of the electron P_e and the recoiling mass against the electron M_{e_recoil}
  - One undetected neutrino with missing energy $E_{\text{miss}} > 0.43GeV$

$$E_{\text{miss}} = E_{\text{CMS}} - E_e - E_\pi - E_{\pi^0}$$
$$\vec{p}_{\text{miss}} = \vec{p}_{J/\psi} - \vec{p}_e - \vec{p}_\pi - \vec{p}_{\pi^0}$$

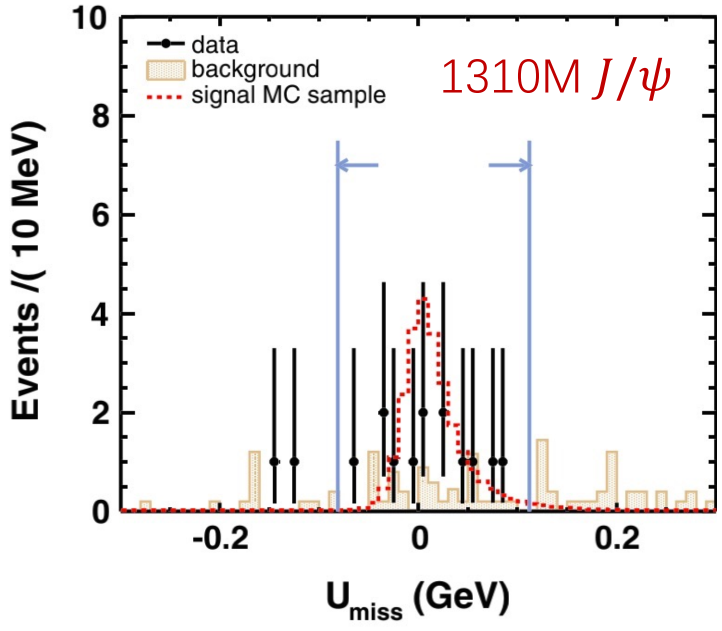


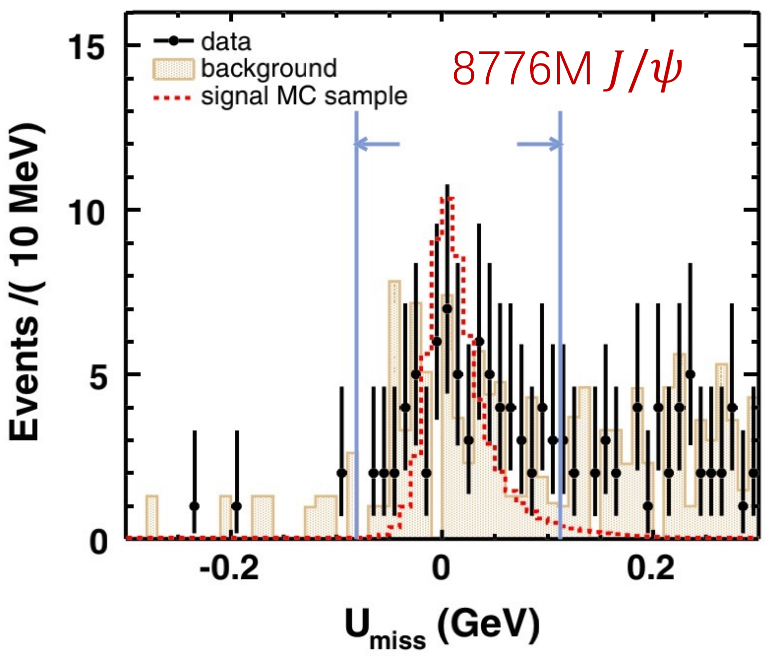




Background study

- The dominant background contaminations stem from the continuum process (e.g. radiative Bhabha) and from hadronic J/ψ decays such as $J/\psi \to \pi^+\pi^-\pi^0$
- $U_{miss} = E_{miss} - c|\vec{P}_{miss}|$, The areas between the arrows represent the signal region.
- In total, $\mathbf{6.9 \pm 1.9}$ ($\mathbf{63.6 \pm 13.2}$) background events are expected for the data sample I (II).





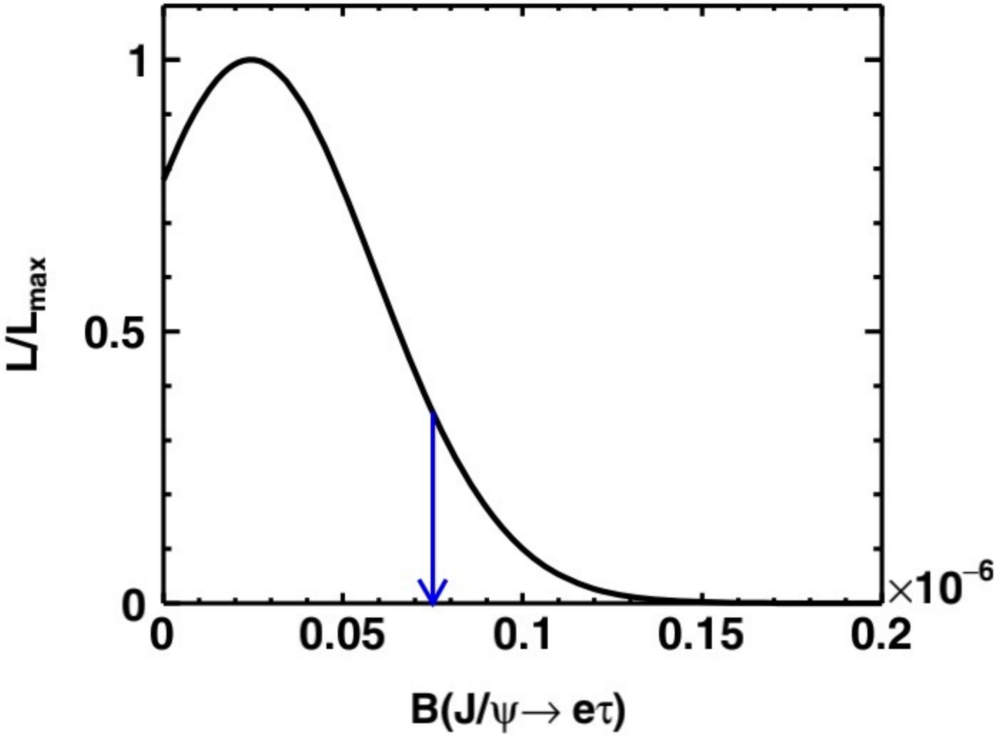
Results

◆Determination of upper limit at 90% confidence level (C.L.) with Bayesian method. Combined result:

$\mathcal{B}(J/\psi \to e\tau) < 7.5 \times 10^{-8}$ @ 90% C.L.

◆The 1st submitted paper based on full 10 billion J/ψ data of BESIII

◆This result improves the previous published limits by two orders of magnitude and is comparable with the theoretical predictions.

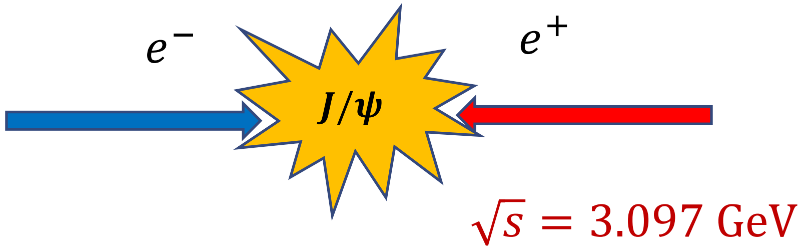


Phys. Rev. D 103, 112007 (2021)

Search for charged lepton flavor violating decay $J/\psi \to e\mu$

Data samples

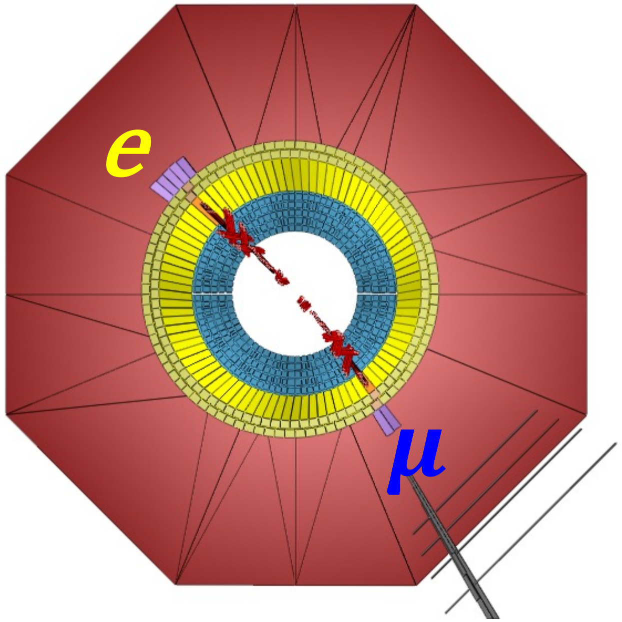
	Data size 09+17-19 (10^6)	
➢ Data: Full J/ψ	**8998**	
$\psi(3770)$	$2.93\ \mathrm{fb}^{-1}$	
$\chi_{c1}(1P)$	$458.21\ \mathrm{pb}^{-1}$	
3.080GeV data	$168.58\ \mathrm{pb}^{-1}$	
➢ Signal MC: $J/\psi \to e\mu$	0.1+0.1+0.1	PHOTOS VLL
➢ Exclusive MC		
$J/\psi \to ee$	133.8+5239	PHOTOS VLL
$J/\psi \to \mu\mu$	133.6+5230	PHOTOS VLL
$J/\psi \to \pi\pi$	0.33+12.90	VSS
$J/\psi \to KK$	0.64+25.10	VSS
$J/\psi \to pp$	4.75+1860	J2BB1
➢ Continuum MC:		
$ee \to ee(\gamma)$	81+526.1	Babayaga
$ee \to \mu\mu(\gamma)$	0.3+1.9	Babayaga
➢ Inclusive MC: Full J/ψ	230+8774	Evtgen & LundCharm



Preliminary Selection

➢ Good charged track:

- $|V_r| < 1.0\ cm$;
- $|V_z| < 10.0\ cm$;
- $|cos\theta| < 0.93$;
- $N_{charge}^{good} = 2, \Sigma Q = 0$;
- Two charged tracks $\Delta T \leq 1.0\ ns$



➢ Good photon:

- Barrel ($|cos\theta| < 0.80$) $E_{\gamma 1} > 25\ MeV$;
- Endcap ($0.86 < |cos\theta| < 0.92$) $E_{\gamma 2} > 50\ MeV$;
- Gap ($0.80 < |cos\theta| < 0.86$) $E_{\gamma 3} > 50\ MeV$;
- TDC time window [0, 700] ns;
- Angle with nearest charged track $> 20^{\circ}$;
- Reject the events with $N_\gamma > 0$

➢ Particle ID:

- π: $\text{prob}(\pi) \geq 0$ && $\text{prob}(\pi) \geq \text{prob}(K)$;
- K: $\text{prob}(K) \geq 0$ && $\text{prob}(K) \geq \text{prob}(\pi)$;
- p: $\text{prob}(p) \geq 0$ && $\text{prob}(p) \geq \text{prob}(K)$ && $\text{prob}(p) \geq \text{prob}(\pi)$

Event Selection

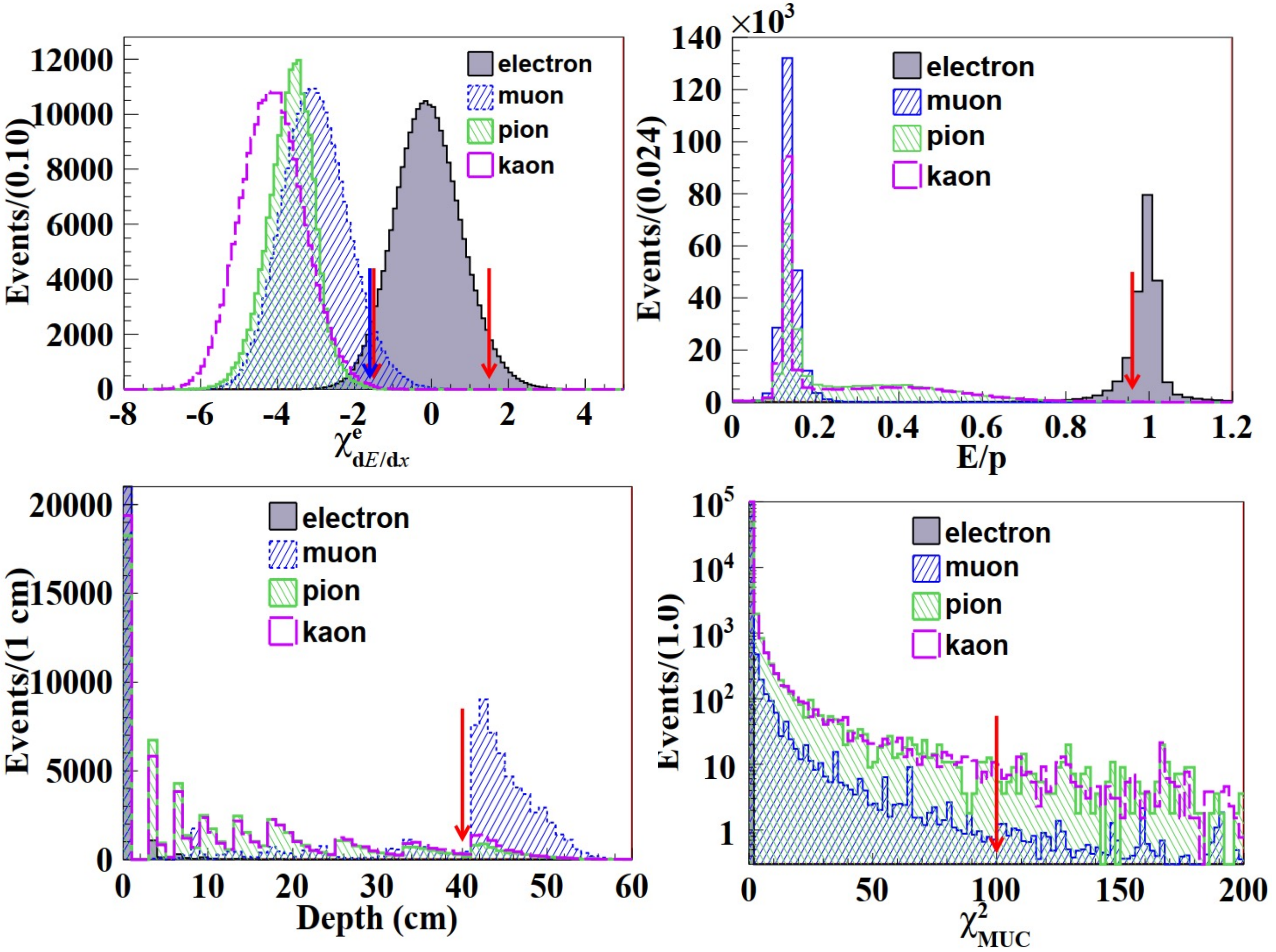
◆ Each J/ψ candidate is reconstructed with two back-to-back good charged tracks, which will be further identified as electron and muon.

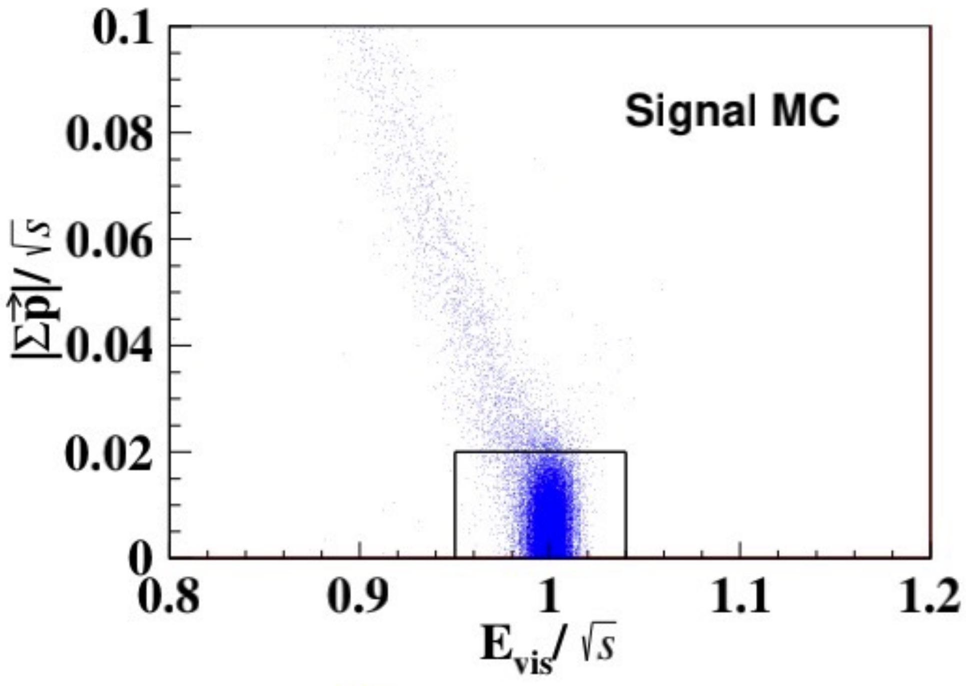
Electron identification :

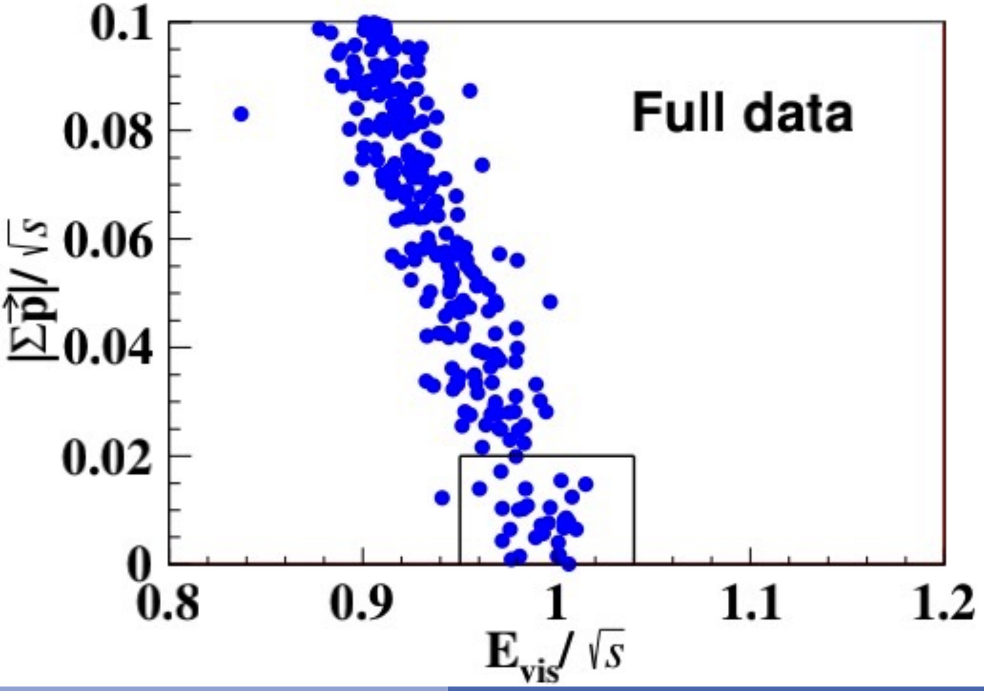
- Not associated in the MUC
- $-1.5 < \chi^e_{dE/dx} < 1.5$ ($\chi^e_{dE/dx}$ is defined as the difference between measured and expected $d\mathrm{E}/dx$ under the electron hypothesis normalized by the $d\mathrm{E}/dx$ resolution)
- $E/p > 0.96$ (E is the deposite energy in the EMC and p is the modulus of the momentum from the MDC)

Muon identification :

- $0.1 < E < 0.3$ GeV, $\chi^e_{dE/dx} < -1.6$
- The penetration depth of the track in the MUC > 40 cm
- Each candidate track must penetrate more than three layers in the MUC, and $\chi^2_{MUC} < 100$







Selection and Background study

- The signal region is defined with $|\sum\vec{p}|/\sqrt{s} \leq 0.02$ and $0.95 \leq E_{vis}/\sqrt{s} \leq 1.04$
  - $|\sum\vec{p}|$: the magnitude of the vector sum of the momenta
  - E_{vis} : the total reconstructed energy of e and μ in the event
- J/ψ MC events → J/ψ decay background (N_{bkg1})
- $\psi(3770)$, $\chi_{c1}(1P)$ and $3.080 GeV$ data → Continuum background (N_{bkg2})
- The normalized background is estimated to be $N_{bkg1}^{norm} = 24.8 \pm 1.5$ and $N_{bkg2}^{norm} = 12.0 \pm 3.7$.
- By analyzing the full data, **29 candidate events** are observed, consistent with background estimation.

Systematic uncertainty

Sources	Δ_{sys} [%]
Tracking and PID	13
TOF timing	0.52
Photon veto	0.83
$\|\Delta\theta\|$ and $\|\Delta\phi\|$	2.6
Total	**14**

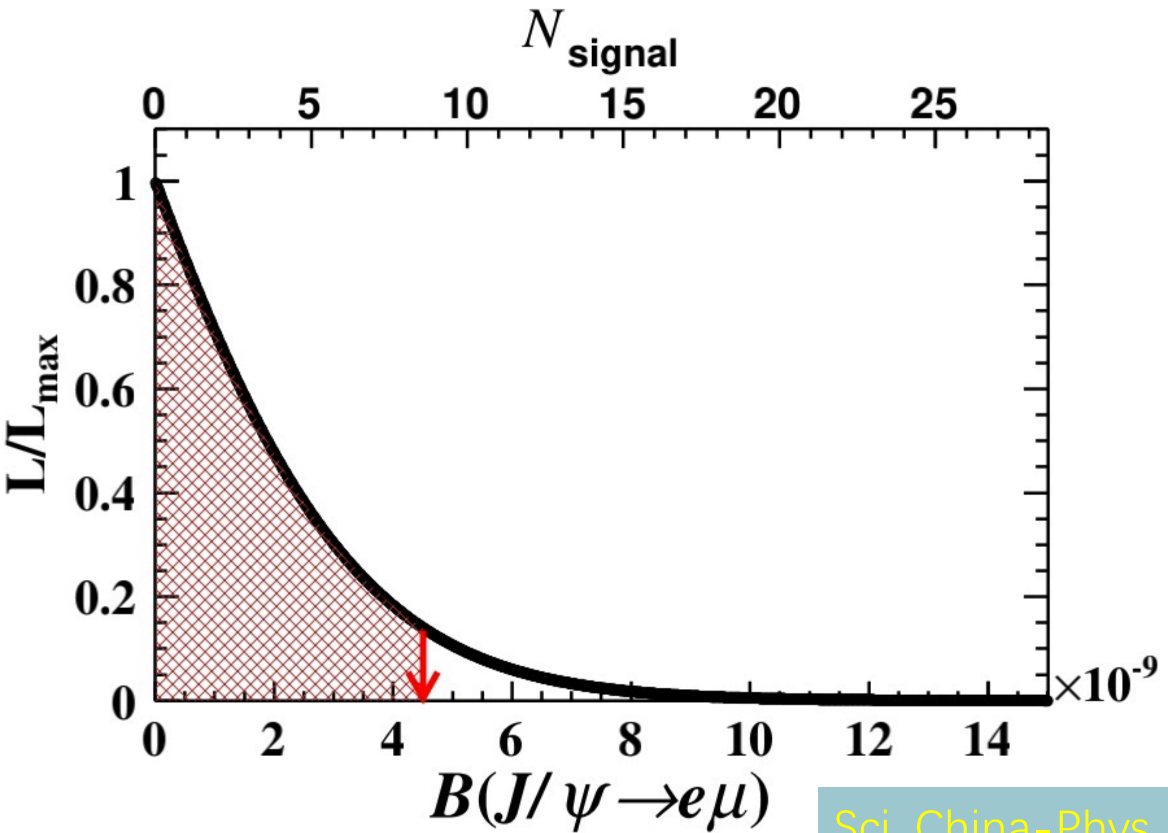
- Control samples $J/\psi(e^+e^-) \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ are used to estimate the systematic uncertainties of tracking and PID of electron and muon, TOF timing, γ veto, and $|\Delta\theta|$ and $|\Delta\phi|$ requirement.
- They are added in quadrature to the total efficiency-related systematic uncertainty of 14%.

Upper limit

$$L = P\left(N_{obs}|N_{J/\psi}\cdot\mathcal{B}\cdot\hat{\varepsilon}_{sig}+\widehat{N}_{bkg1}+\widehat{N}_{bkg2}\right)\cdot G\left(\hat{\varepsilon}_{sig}|\varepsilon_{sig}^{MC},\varepsilon_{sig}^{MC}\cdot\sigma_{sig}^{MC}\right)$$
$$\cdot P\left(N_{inc}^{J/\psi-\mathrm{MC}}|\widehat{N}_{bkg1}\cdot f_1\right)\cdot\prod_k P\left(N_{cont}^{k}|\widehat{N}_{bkg2}\cdot f_2\right)\cdot G\left(N_{J/\psi}|N_{J/\psi}^{data},\delta N_{J/\psi}^{data}\right)$$

Parameter	Value
N_{obs}	29
$N_{J/\psi}^{\mathrm{data}}$	8.998×10^9
$\delta N_{J/\psi}^{\mathrm{data}}$	0.040×10^9
$\epsilon_{\mathrm{sig}}^{\mathrm{MC}}$	21%
$\sigma_{\mathrm{sig}}^{\mathrm{EFF}}$	14%
$N_{\mathrm{bkg1}}^{J/\psi-\mathrm{MC}}$	275
$N_{\mathrm{cont}}^{3.773}$	10
$N_{\mathrm{cont}}^{3.510}$	1
$N_{\mathrm{cont}}^{3.080}$	0
f_1	0.09090
$f_2^{3.773}$	1.3416
$f_2^{3.510}$	7.4390
$f_2^{3.080}$	15.553

N_{cont}^{k}: Continuum background at different energy points



ε_{sig}^{MC}: Detection efficiency

$N_{inc}^{J/\psi}$: J/ψ decay background

N_{obs}: Observed events

σ_{sig}^{MC}: Relative systematics

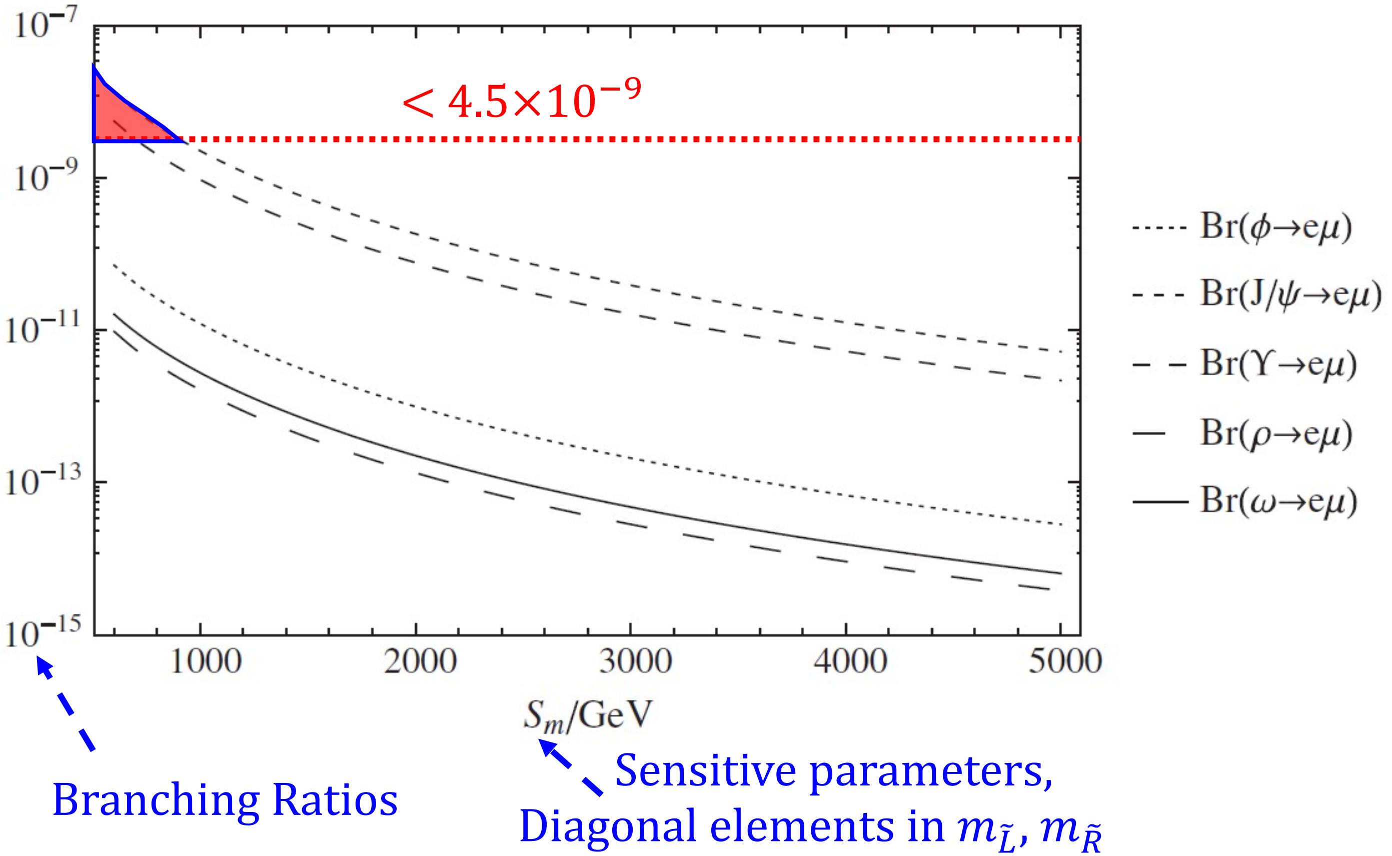
- $\mathcal{B}(J/\psi\to e\mu)$

$<4.5\times10^{-9}$ @ 90% C.L.

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

Comparison with theory

$\mathcal{B}(J/\psi \to e\mu) < 4.5\times10^{-9}$ @ 90% C.L.



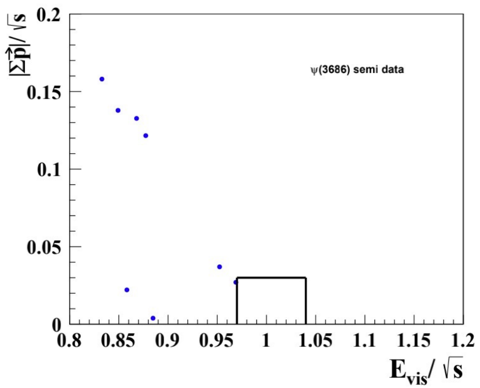
Phys. Rev. D 97, 056027 (2018)

- Excluding the parameter space of some models, such as BLMSSM model, a supersymmetric model where baryon (B) and lepton (L) numbers are local gauge symmetries.
- Improves the previous published limits by a factor of more than 30 and comparable with the theoretical predictions
- The most precise result of CLFV search in heavy quarkonium systems

Ongoing CLFV analyses

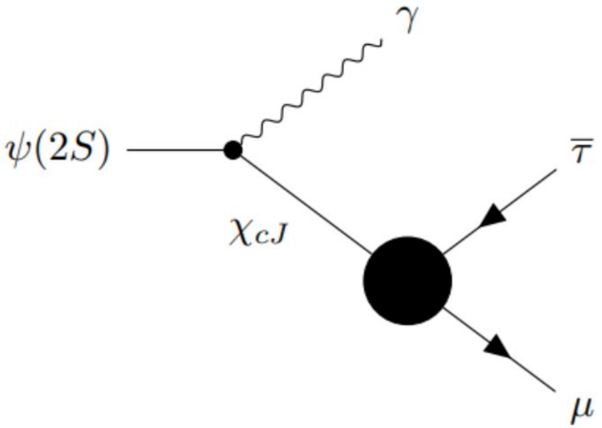
$\psi' \to e\mu$

- For the decay $\psi(3686) \to e\mu$, a variety of new physics models could enhance the BF to $(10^{-16} \sim 10^{-13})$
- Based on semi-blind $\psi(3686)$ data, 2.578×10^8 events
- Using $|\sum\vec{p}|/\sqrt{s}$ and $E_{vis}/\sqrt{s}$ to define signal box



- Expected sensitivity is $\mathcal{O}(10^{-8})$ with full dataset

$\chi_{CJ} \to \tau e, \tau\mu$



- Signal process: $\psi(2s) \to \gamma\chi_{c0}(1P)$, $\gamma\chi_{c1}(1P)$, $\gamma\chi_{c2}(1P)$,
- $\mu\tau$ via $\tau \to e\nu\nu$, $e\tau$ via $\tau \to \mu\nu\nu, \pi\nu, \pi\pi^0\nu$
- Cut optimization is done based on the τ – mass signal region using the Punzi Figure of Merit.
- Upper limit is set using counting and the Rolke method
- Expected sensitivity is $\mathcal{O}(10^{-8} \sim 10^{-7})$ with full dataset.

◆To unify different models and experimental results, effective field theory can be used to describe CLFV.

◆ CLFV decays of quarkonium with different quantum numbers are sensitive to different Wilson coefficients .

◆CLFV of quarkonium with different quantum numbers have been search a lot, but not for scalar states, which are sensitive to fewer operators, thus give better constraints.

$$\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[\left(C_{VR}^{q\ell_1\ell_2}\,\bar{\ell}_1\gamma^\mu P_R \ell_2 + C_{VL}^{q\ell_1\ell_2}\,\bar{\ell}_1\gamma^\mu P_L \ell_2 \right) \bar{q}\gamma_\mu q \quad \psi, \Upsilon$$

$$+ \left(C_{AR}^{q\ell_1\ell_2}\,\bar{\ell}_1\gamma^\mu P_R \ell_2 + C_{AL}^{q\ell_1\ell_2}\,\bar{\ell}_1\gamma^\mu P_L \ell_2 \right) \bar{q}\gamma_\mu\gamma_5 q \quad \eta, \eta', \eta_b, \eta_c$$

$$+ m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\,\bar{\ell}_1 P_L \ell_2 + C_{SL}^{q\ell_1\ell_2}\,\bar{\ell}_1 P_R \ell_2 \right) \bar{q}q \quad \chi_{b0}, \chi_{c0}$$

$$+ m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\,\bar{\ell}_1 P_L \ell_2 + C_{PL}^{q\ell_1\ell_2}\,\bar{\ell}_1 P_R \ell_2 \right) \bar{q}\gamma_5 q$$

$$+ m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\,\bar{\ell}_1\sigma^{\mu\nu} P_L \ell_2 + C_{TL}^{q\ell_1\ell_2}\,\bar{\ell}_1\sigma^{\mu\nu} P_R \ell_2 \right) \bar{q}\sigma_{\mu\nu} q + h.c. \Big].$$

$\chi_{cJ} \to e\mu$

◆Background: $\chi_C \to \pi\pi, \chi_C \to KK, \psi(2s)$ inclusive MC excluding $\chi_C \to \pi\pi/KK$, $\psi(3770)$ data

◆Have been searched for the first time

◆Expected sensitivity is $\mathcal{O}(10^{-8}\sim10^{-7})$ with full dataset.

$\eta'/\eta_c/h_c \to e\mu/e\tau/\mu\tau(\gamma)$

(Beginning)

◆ Expected sensitivity is $\mathcal{O}(10^{-8}\sim10^{-6})$ with full dataset.

Summary

◆BESIII has great potentials with unique (and increasing) datasets and analysis techniques, performed wide range study of new physics, with many first searches or best limits.

◆Some new physics models can inspire the CLFV decay rate up to a detectable level.

◆The latest searching results and ongoing analyses for CLFV decays are reported.

◆The UL is set to be $\mathcal{B}(J/\psi \to e\tau) < 7.5\times10^{-8}$ @ 90% CL.

◆The UL is set to be $\mathcal{B}(\mathrm{J}/\psi \to \mathrm{e}\mu) < 4.5\times10^{-9}$ @ 90% CL, which is the most stringent CLFV result in heavy quarkonium sector up to now.

Thank you

Back up

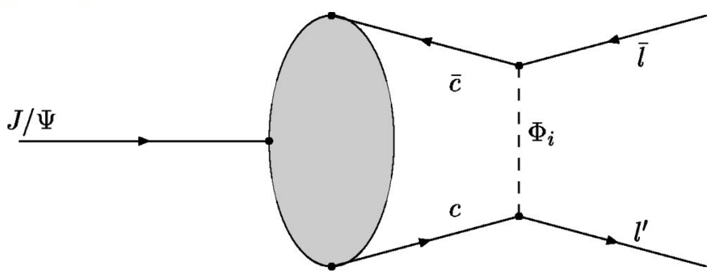
Leptoquark model

PRD.67,114001

Lagrangian: $\mathcal{L}_{\text{eff}}^{\text{leptoquark}} = \bar{c}(\lambda_L^A P_L + \lambda_R^A P_R)\mu\Phi_A + \bar{c}(\lambda_L^A P_L + \lambda_R^A P_R)\tau\Phi_A + \text{H.c.},$

$$\Phi_1 : [\lambda_{ij}^{(1)} \bar{Q}_{Lj} e_{Ri} + \tilde{\lambda}_{ij}^{(1)} \bar{u}_{Rj} L_{Li}]\Phi_1 ,$$

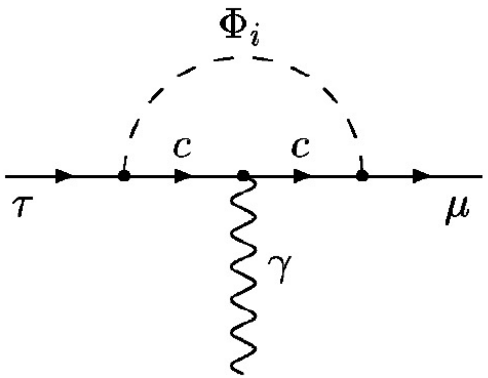
$$\Phi_3 : [\lambda_{ij}^{(3)} \bar{Q}_{Lj}^c L_{Li} + \tilde{\lambda}_{ij}^{(3)} \bar{u}_{Rj}^c e_{Ri}]\Phi_3 .$$



$$\Gamma(J/\psi \to \mu\tau) = \frac{|\mathbf{p}|}{32\pi^2 M_{J/\psi}} \int |\mathcal{M}|^2 d\Omega$$

$$= \frac{g_{J/\psi}^2}{96\pi} \frac{m_\tau^2}{M_{J/\psi}} \left(1 + 2\frac{M_{J/\psi}^2}{m_\tau^2}\right) \times \left(1 - \frac{m_\tau^2}{M_{J/\psi}^2}\right)^2 \cdot \frac{|\lambda_L^{c\mu}\lambda_L^{c\tau}|^2 + |\lambda_R^{c\mu}\lambda_R^{c\tau}|^2}{M_\Phi^4},$$

$$\text{Br}(J/\psi \to \mu\tau) = \frac{9}{2^9\pi^2\alpha^2} m_\tau^2 M_{J/\psi}^2 \left(1 + 2\frac{M_{J/\psi}^2}{m_\tau^2}\right) \times \left(1 - \frac{m_\tau^2}{M_{J/\psi}^2}\right)^2 \cdot \frac{|\lambda_L^{c\mu}\lambda_L^{c\tau}|^2 + \lambda_R^{c\mu}\lambda_R^{c\tau}|^2}{M_\Phi^4} \times \text{Br}(J/\psi \to e^+e^-).$$



$$\frac{|\lambda_L^{c\mu}\lambda_L^{c\tau}|^2 + |\lambda_R^{c\mu}\lambda_R^{c\tau}|^2}{M_\Phi^4} < 1.5 \times 10^{-10}.$$

$$\Gamma(J/\psi \to e^+e^-) = \frac{16\pi}{27}\alpha^2 \frac{g_{J/\psi}^2}{M_{J/\psi}^3},$$

$$\text{Br}(\tau \to \mu\gamma) = \frac{3}{2^9\pi^2 G_F^2} \frac{|\lambda_L^{c\mu}\lambda_L^{c\tau}|^2 + \lambda_R^{c\mu}\lambda_R^{c\tau}|^2}{M_\Phi^4} \times \text{Br}(\tau \to \mu\nu_\tau\bar{\nu}_\mu),$$

$$\mathcal{B}(J/\psi \to e\mu) < 3.5\times10^{-15}$$

Back up

CLFV in SM

$$\Gamma(\mu \to e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left(\frac{\alpha}{2\pi}\right) sin^2 2\theta sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)$$

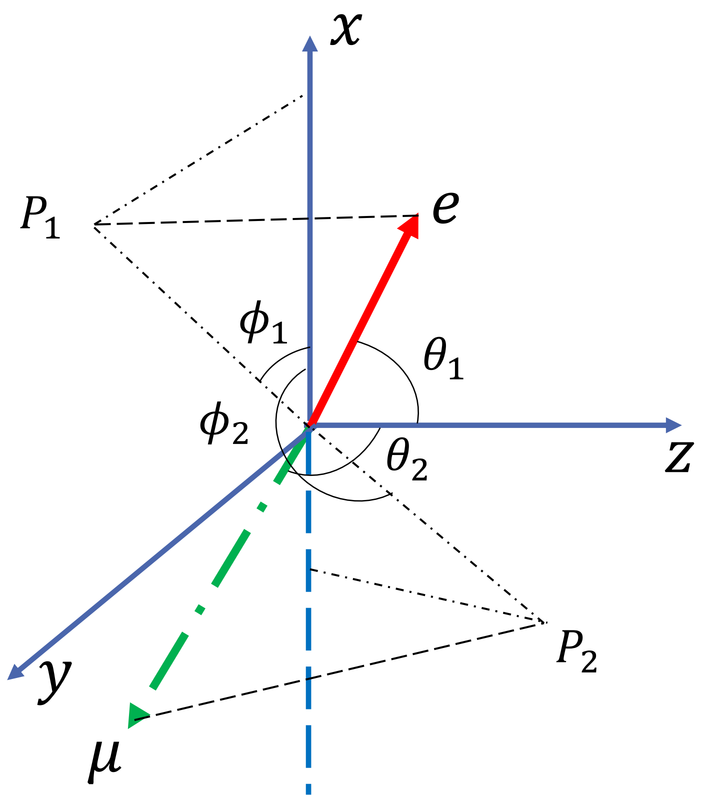
$\mu - decay$ $\quad \gamma - vertex$ $\quad \vartheta - oscillation$

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left(\frac{3\alpha}{32\pi}\right) \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

with $\Delta \sim 10^{-3} eV^2, M_W \sim O(10^{11}) eV \approx \boldsymbol{O(10^{-54})}$

$J/\psi \to e\mu$ angle

- $|\Delta\boldsymbol{\theta}| = |180° - (\theta_1 + \theta_2)|$
- $|\Delta\boldsymbol{\phi}| = \left|180° - |\phi_1 - \phi_2|\right|$



Backup

$J/\psi \to e\mu$ cut flow

Cut flow	Efficiency 2009 (%)	Efficiency 2017-2019 (%)
Generated(100000, 200000)	100	100
$N^{good}_{charged} = 2, \sum Q = 0$	88.00	87.27
$\Delta TOF \leqslant 1.0\,\mathrm{ns}$	86.45	85.67
$E/P > 0.5$ for electron, $E/P < 0.5$ for muon	83.31	82.60
$E_{\gamma B} < 0.025$ GeV, $E_{\gamma G} < 0.050$ GeV, $E_{\gamma E} < 0.050$ GeV	76.00	74.47
$N^{e}_{hits} = 0$ for electron in MUC	73.33	71.15
$E/P > 0.96$ for electron	60.34	59.09
$\lvert\chi^{e}_{dE/dx}\rvert < 1.5$ for electron	55.37	53.37
0.1 GeV $< E_{deposited} <$ 0.3 GeV for muon	54.35	52.35
$0 < \chi^2_{MUC} < 100$ for muon	32.35	40.33
$d_\mu > 40\,\mathrm{cm}$ for muon	27.38	30.06
$\chi^{e}_{dE/dx} < -1.6$ for muon	26.04	28.42
$\lvert\Delta\theta\rvert < 1.2^\circ, \lvert\Delta\phi\rvert < 1.5^\circ$	24.21	24.96
$\lvert\Sigma\vec{p}\rvert/\sqrt{s} \leqslant 0.02$, $0.95 \leqslant E_{vis}/\sqrt{s} \leqslant 1.04$	20.67	21.20

- $\chi^{e}_{dE/dx}$: difference between the measured and expected χ_{dedx} for the electron hypothesis.
- d_μ: penetration depth in MUC **NumLayers**: penetration layers **MaxHitsInLayer**: Max hits in one layer

- **Signal efficiency:** $\varepsilon^{MC}_{sig} = \sum \epsilon^{i}_{sig} \times \frac{n^i}{N} = (21.18 \pm 0.13)\%$

Backup

$J/\psi \to e\mu$ background

Sample	Mode	Size 09+17-19 (M)	Survived	Scale factor	Normalized
Exclusive MC	$J/\psi \to e^+e^-$	133.8+5239	0+58	1/10.0	$\mathbf{5.80 \pm 0.76}$
	$J/\psi \to \mu^+\mu^-$	133.6+5230	1+174	1/10.0	$\mathbf{17.40 \pm 1.32}$
	$J/\psi \to \pi^+\pi^-$	0.33+12.90	0+27	1/10.0	$\mathbf{2.70 \pm 0.52}$
	$J/\psi \to K^+K^-$	0.64+25.10	0+0	1/10.0	**0**
	$J/\psi \to p^+p^-$	4.75+1860	0+0	1/10.0	**0**
Inclusive MC	$J/\psi \to anything$	230+8774	0+6+9=15	8.2	$\mathbf{1.83 \pm 0.47}$
Continuum MC	$e^+e^- \to e^+e^-(\gamma)$	81+274.8+251.3	0	9.0	**0**
	$e^+e^- \to \mu^+\mu^-(\gamma)$	0.3+1.0+0.9	0+0+0	9.0	**0**
Data	$\psi(3770)$ data → 09	$2.93\ \mathrm{fb}^{-1}$	10	1.3416	$\mathbf{13.42 \pm 4.24}$
	$\chi_{c1}(1P)$ data → 18,19	$458.21\ \mathrm{pb}^{-1}$	1	7.4390	$\mathbf{7.44 \pm 7.44}$
	3.080GeV data	$224.04 + 877.52$	0	15.5533	**-**

$$\hat{\mu} = \frac{\sum_{i=1}^{n} \frac{\mu_i}{\sigma_i^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}} = \frac{\sum_{i=1}^{n} \omega_i \mu_i}{\sum_{i=1}^{n} \omega_i}, V(\hat{\mu}) = \frac{1}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}} = \frac{1}{\sum_{i=1}^{n} \omega_i}$$

Back up

$J/\psi \to e\mu$ background

- The normalized background in the signal region N_{bkg1}^{norm} is calculated as,

$$N_{bkg1}^{norm} = N_{bkg1}^{J/\psi-MC} \cdot f_1, \qquad f_1 = \frac{N_{J/\psi}^{data}}{N_{J/\psi}^{MC}}$$

- $N_{bkg1}^{J/\psi-MC}$: the number of J/ψ background decays in the J/ψ inclusive and exclusive MC samples
- $N_{J/\psi}^{data}$: the total number of J/ψ events in the data
- $N_{J/\psi}^{MC}$: the total number of equivalent J/ψ events in the J/ψ inclusive and exclusive MC samples

The normalized number in the signal region is estimated to be $\mathbf{N_{bkg1}^{norm} = 24.8 \pm 1.5}$.

- By assuming a $1/s$ energy-dependence of the cross sections, the normalized number of continuum backgrounds at the J/ψ peak, $N_{bkg2}^{norm,k}$, can be obtained by

$$N_{bkg2}^{norm,k} = N_{cont}^{k} \times f_2^k, \qquad f_2^k = \frac{\mathcal{L}_{J/\psi}}{\mathcal{L}_k} \times \frac{s_k}{s_{J/\psi}}$$

- N_{cont}^{k} : the number of background events survived in the signal region at the energy with index k
- $\mathcal{L}_k, \mathcal{L}_{J/\psi}$: the integrated luminosities at energies k and at the J/ψ peak

The normalized number is estimated to be $\mathbf{N_{bkg2}^{norm} = 12.0 \pm 3.7}$.

Back up

BLMSSM

$$G_{BL} = SU(3)_C \bigotimes SU(2)_L \bigotimes U(1)_Y \bigotimes U(1)_B \bigotimes U(1)_L$$

In the BLMSSM, the local B and L are spontaneously broken at the TeV scale.

The superpotential of the BLMSSM is written as:

$$\mathcal{W}_{\text{BLMSSM}} = \mathcal{W}_{\text{MSSM}} + \mathcal{W}_B + \mathcal{W}_L + \mathcal{W}_X$$

$$(m^2_{\tilde{L}})_{ii} = (m^2_{\tilde{R}})_{ii} = S^2_m$$