Search for charged Lepton Flavor Violation in J/ψ decays at BESIII

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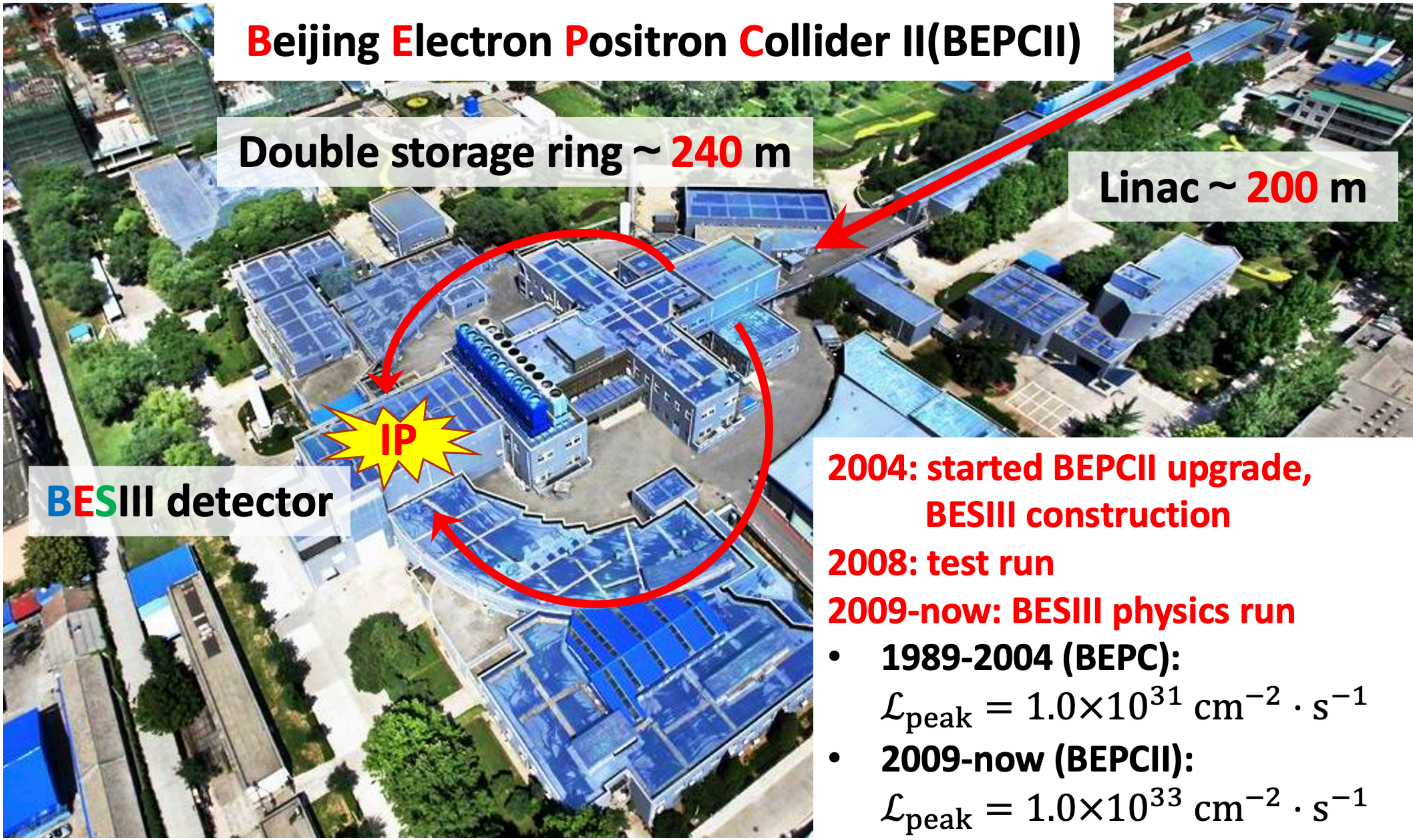
Outline

- ➔ Introduction
  - ❖ BESIII experiment
  - ❖ Physics motivation
- ➔ Highlight results of cLFV at BESIII
  - ❖ $J/\psi \to e\tau$
  - ❖ $J/\psi \to e\mu$
- ➔ Summary

Introduction

BEPCII



2004: started BEPCII upgrade,
BESIII construction
2008: test run
2009-now: BESIII physics run

- **1989-2004 (BEPC):**
  $\mathcal{L}_{\text{peak}} = 1.0\times10^{31}\ \text{cm}^{-2}\cdot\text{s}^{-1}$
- **2009-now (BEPCII):**
  $\mathcal{L}_{\text{peak}} = 1.0\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

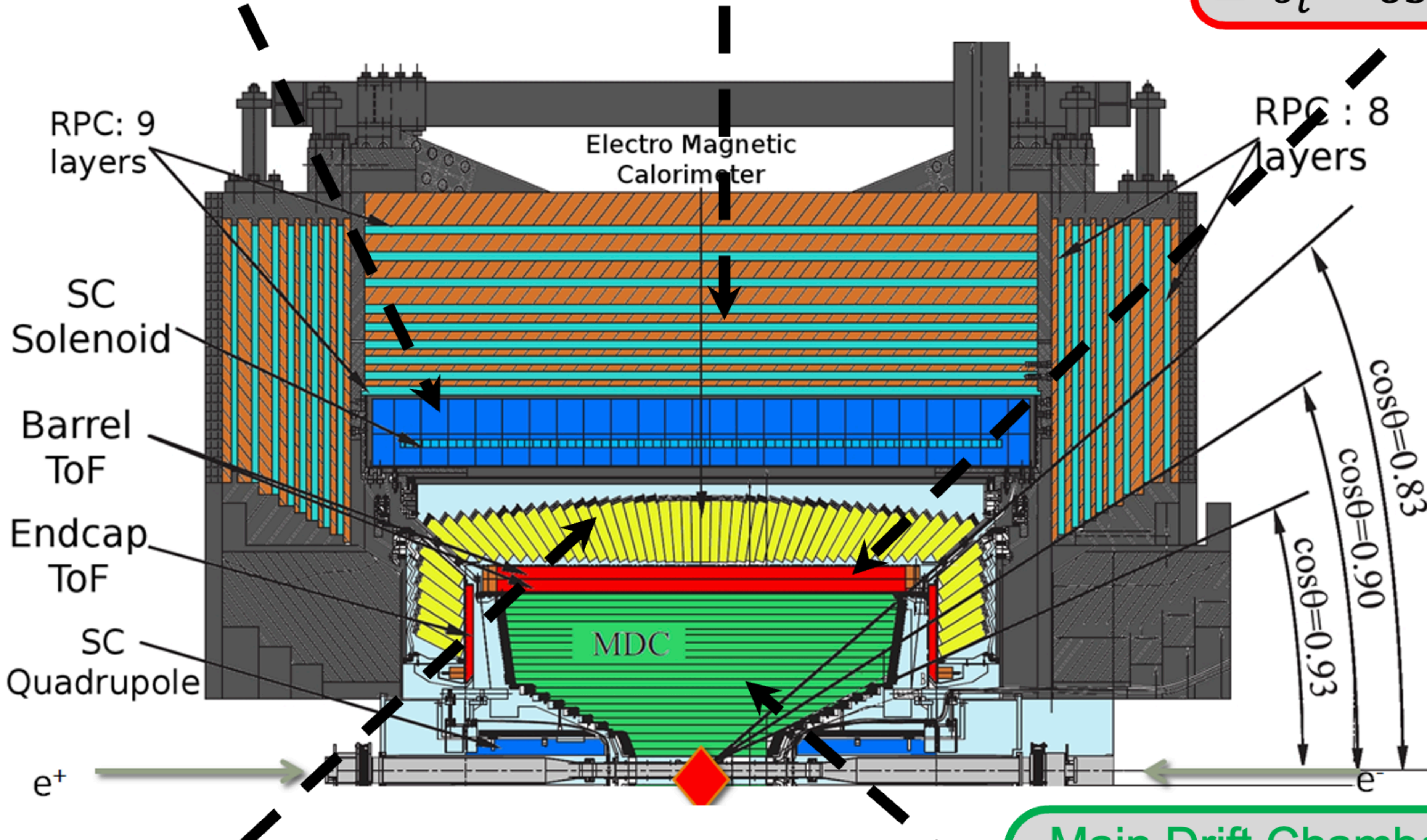
Beam energy: 1.0-2.475 GeV
Optimum energy: 1.89 GeV

BESIII detector

Superconducting solenoid
- 0.9~1.0 T

Muon Counter (MUC)
- 9 layers (barrel) + 8 layer (end-cap)

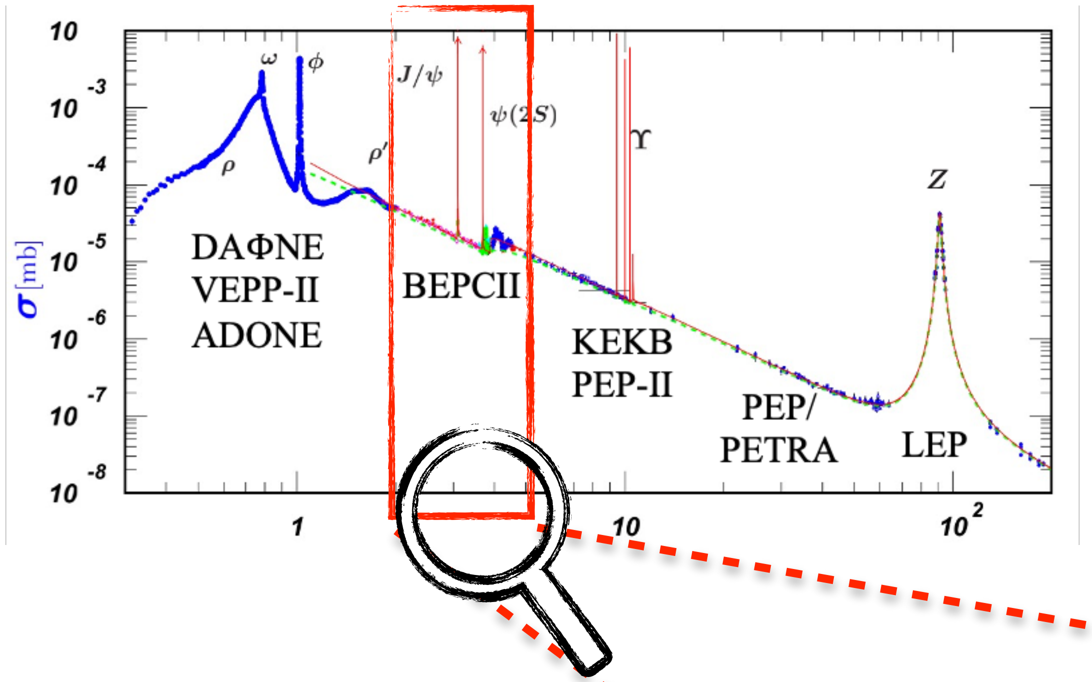
Time Of Flight (TOF)
- $\sigma_t = 90$ ps (barrel)
- $\sigma_t = 65$ ps (end cap)



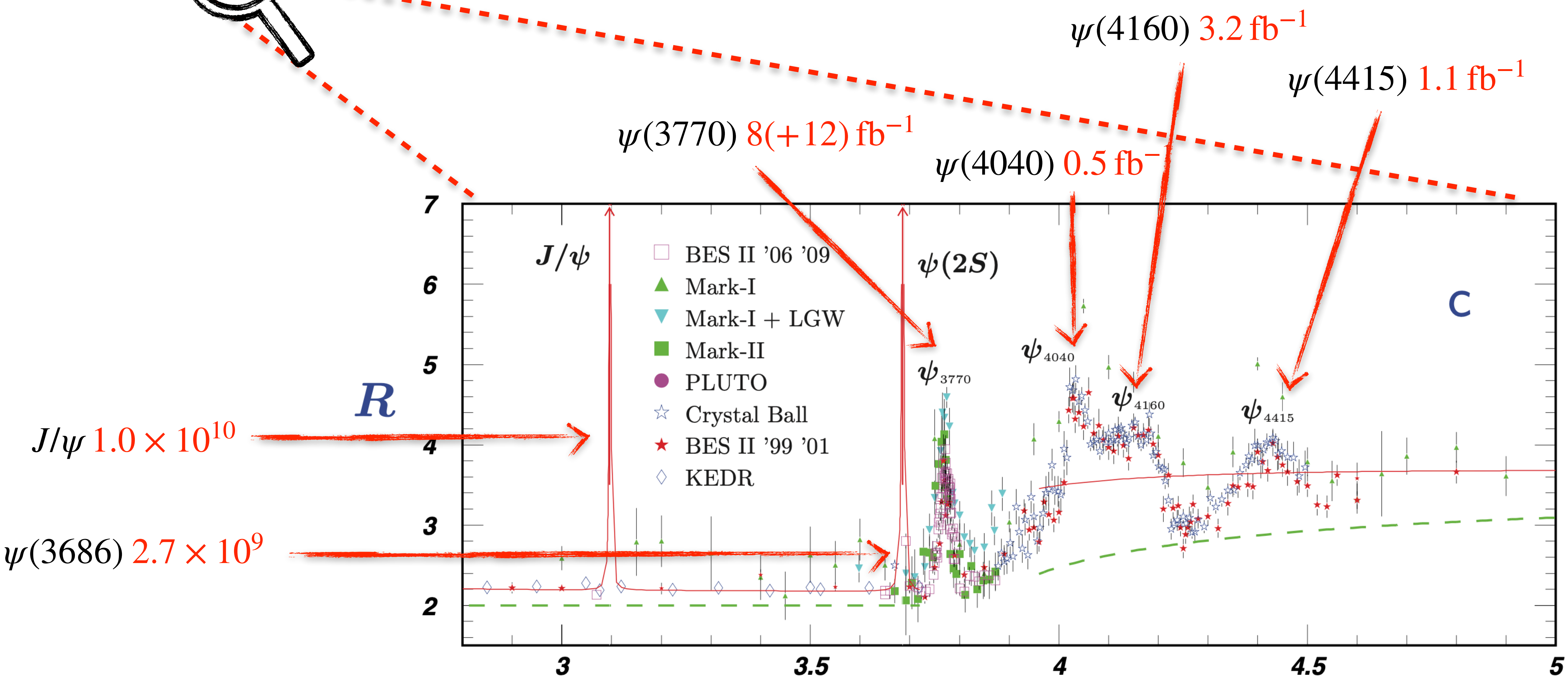
Electromagnetic Calorimeter(EMC)
- $\Delta E/E = 2.5\%$ @ 1.0 GeV
- $\sigma_{\phi z} = 0.6$ cm @ 1.0 GeV

Main Drift Chamber (MDC)
- $\sigma_{xy} = 130$ μm
- $\Delta P/P = 0.5\%$ @ 1.0 GeV
- $\sigma_{dE/dx} = 6-7\%$

Data samples at BESIII

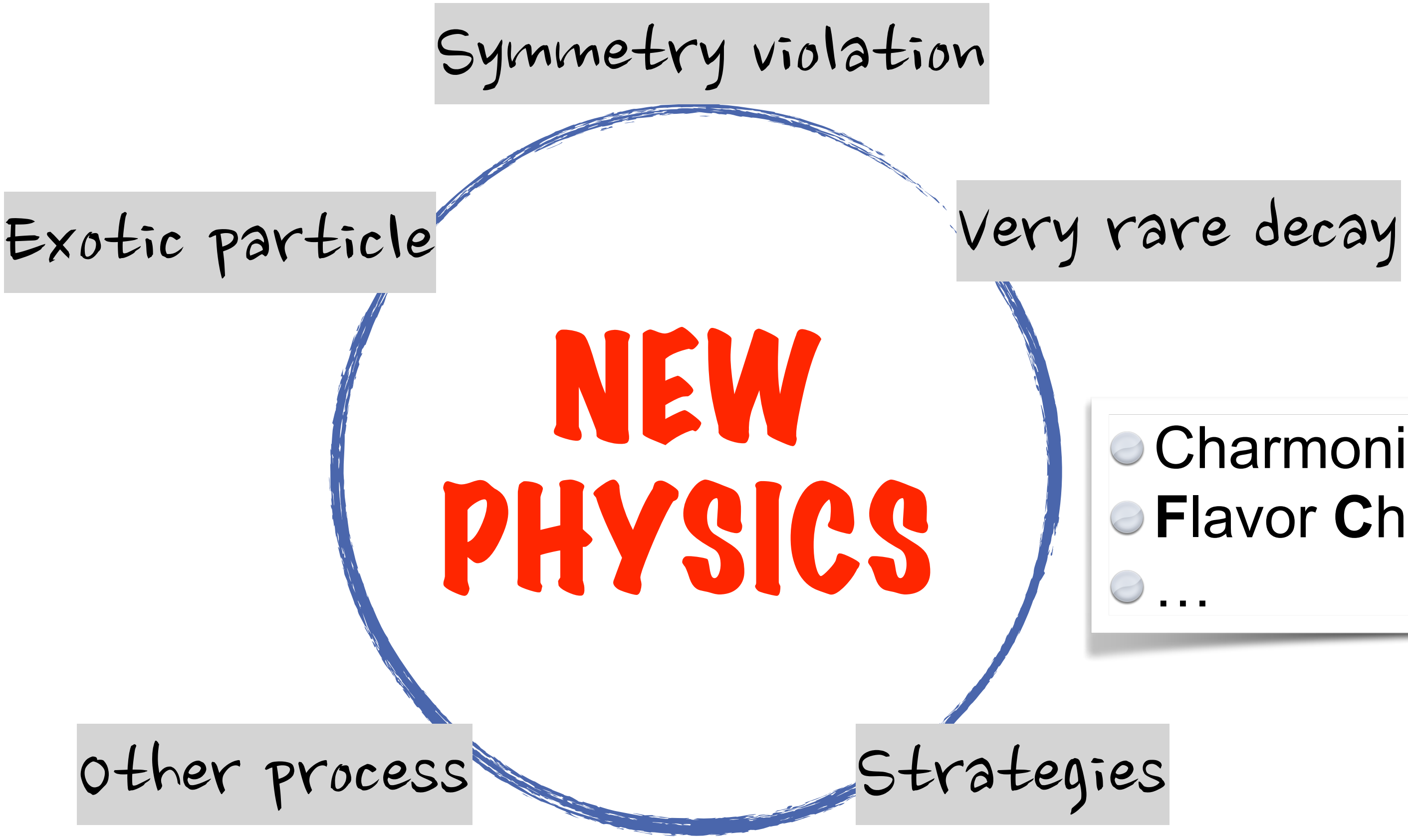


- BESIII has collected the largest data samples of J/ψ and $\psi(3686)$ on the threshold in the world!
- $> 20\ \mathrm{fb}^{-1}$ data above 4.0 GeV in total
- $20\ \mathrm{fb}^{-1}$ $\psi(3770)$ will be available in 2024



New physics searches at BESIII

- **c**harged **L**epton **F**lavor **V**iolation ← This talk
- **L**epton/**B**aryon **N**umber **V**iolation
- C/CP violation
- …



- Dark photon
- Axion-like particle
- Light Higgs
- SUSY particles
- …

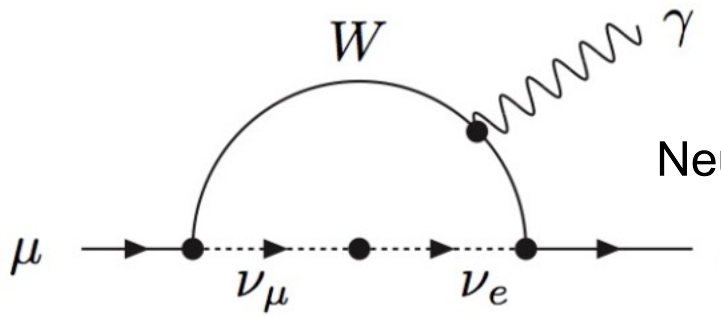
- Charmonium weak decay
- **F**lavor **C**hanging **N**eutral **C**urrent
- …

- Invisible decay
- **L**epton **U**niversality **V**iolation
- …

- Common statistic and standards
- Sharing methods, tool and codes
- Uniform semi-blind strategy and datasets

- Nation Science Review 8, nwab189 (2021), arXiv: 2102.13290
- New Physics Program of BES, D.Y. Wang, in “30 Years of BES Physics”

cLFV

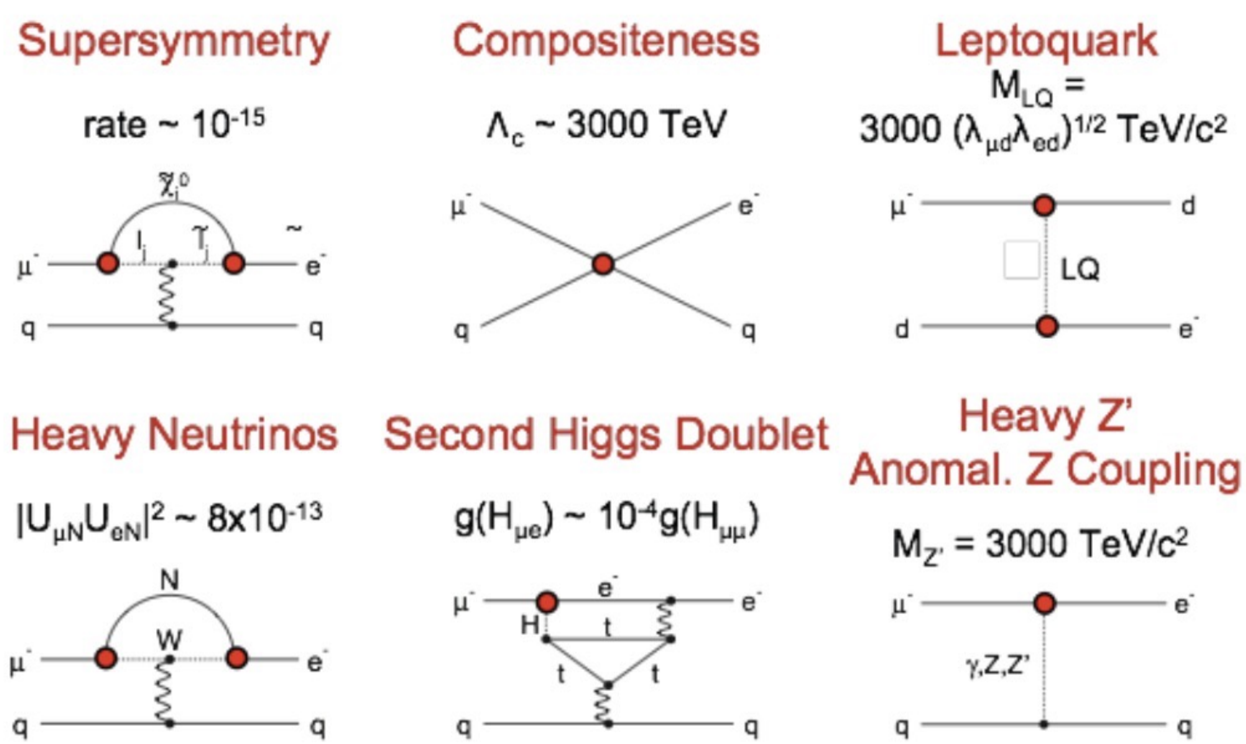


Neutrinoless muon decay

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

LFV: forbidden in SM, signal of new physics BSM

Non-zero neutrino mass ⇒ cLFV is heavily suppressed



J/ψ cLFV models

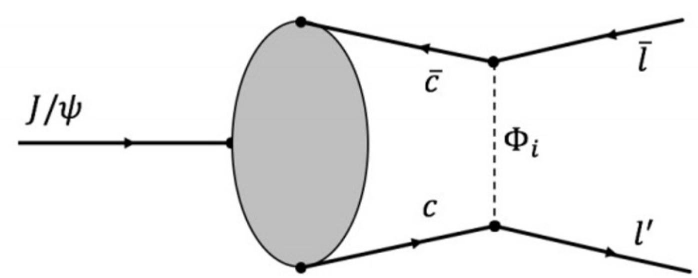


Diagram via leptoquarks

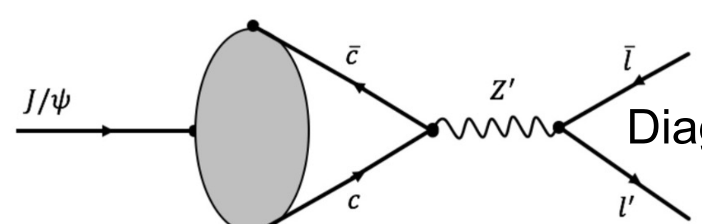


Diagram via a Z' in TC2 models

Many models enhance LFV effects up to detectable level

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

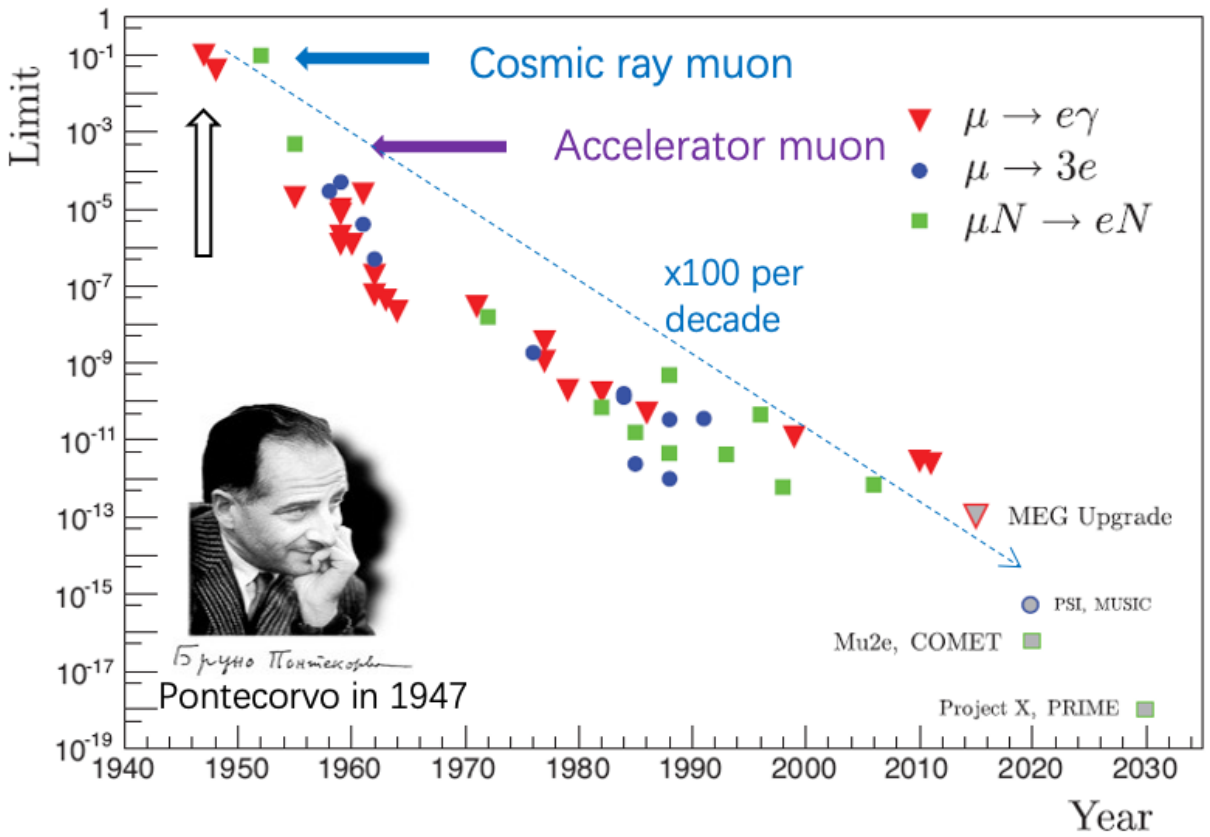
cLFV - experimental search

➔ Experimental searches in leptons (μ, τ), pseudoscalar mesons (K, π, B), vector mesons ($\phi, J/\psi, \Upsilon$), Z and H^0 decays

- $\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ @ 90 % CL MEG
- $\mathcal{B}(\tau^+ \to e^+\gamma) < 3.3 \times 10^{-8}$ @ 90 % CL BABAR
- $\mathcal{B}(\mu \to 3e) < 1.0 \times 10^{-12}$ @ 90 % CL SINDRUM
- $\mathcal{B}(Z \to e^\pm\mu^\mp) < 7.5 \times 10^{-7}$ @ 90 % CL ATLAS
- $\mathcal{B}(H^0 \to e^\pm\mu^\mp) < 6.2 \times 10^{-5}$ @ 90 % CL ATLAS
- $\mathcal{B}(\phi \to e^\pm\mu^\mp) < 2 \times 10^{-6}$ @ 90 % CL SND
- $\mathcal{B}(J/\psi \to e^\pm\tau^\mp) < 7.1 \times 10^{-8}$ @ 90 % CL BESIII
- $\mathcal{B}(J/\psi \to e^\pm\mu^\mp) < 4.5 \times 10^{-9}$ @ 90 % CL BESIII
- …

This talk

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. Lett. B 801, 135148 (2020)
Phys. Rev. D 103, 112007 (2021)
Sci. Chin. Mech. Astron. 66, 2 (2023)



➔ Prospect on future experiments

- Mu2e & COMET: $\mu N \to eN$
  - Improve current limit by a factor of 10^4
  - Search for New Physics with mass scale up to 10^4 TeV
  - Next goal: $< 6 \times 10^{-17}$ @ 90 % CL
- MEGII & Mu3e: similar beam requirements
  - Intensity $\mathcal{O}(10^8\ \mathrm{muons}/s)$, low momentum $p = 28\ \mathrm{MeV}/c$
  - MEGII aiming at sensitivity down to 6×10^{-14} @ 90 % CL

cLFV - J/ψ decays

➔ Theoretical predictions in various extension SM

- Model-independent methods, rotating mass matrix, unparticle physics, effective Lagrangian, BLMSSM
- $\mathscr{B}(J/\psi \to e\mu) : 10^{-16} \sim 10^{-9} @ 90\,\%\,\mathrm{CL}$
- $\mathscr{B}(J/\psi \to e(\mu)\tau) : 10^{-10} \sim 10^{-8} @ 90\,\%\,\mathrm{CL}$

Phys. Rev. D 63, 016003 (2000)
Phys. Rev. D 63, 016006 (2001)
Phys. Rev. D 83, 115015 (2011)
Mod. Phys. Lett. A 27, 1250172 (2012)
Phys. Rev. D 94, 074023 (2016)
Phys. Rev. D 97, 056027 (2018)

➔ Previous experimental results:

Decay mode	BESII UL (90% CL)	BESIII UL (90% CL)
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, 49 (2003)
Phys. Lett. B 598, 172 (2013)
Phys. Rev. D 87, 112007 (2013)

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

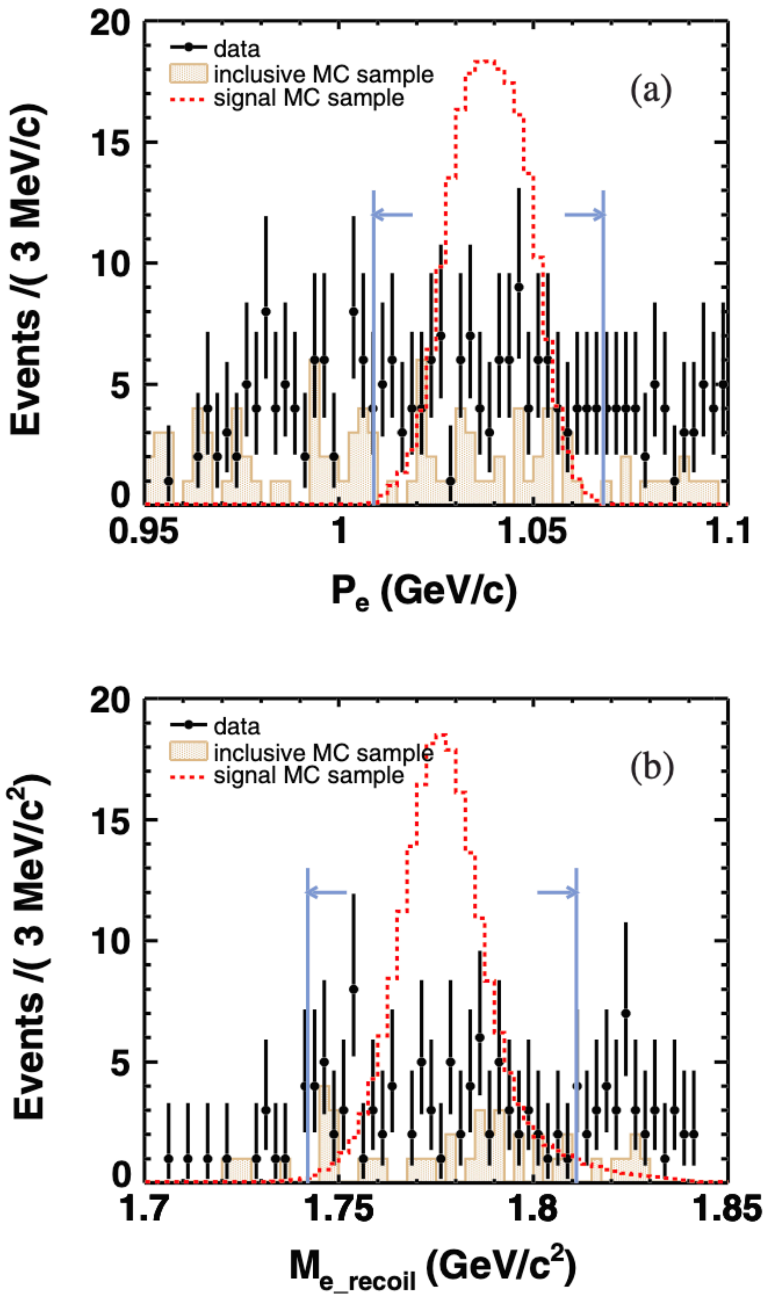
$J/\psi \to e\tau$

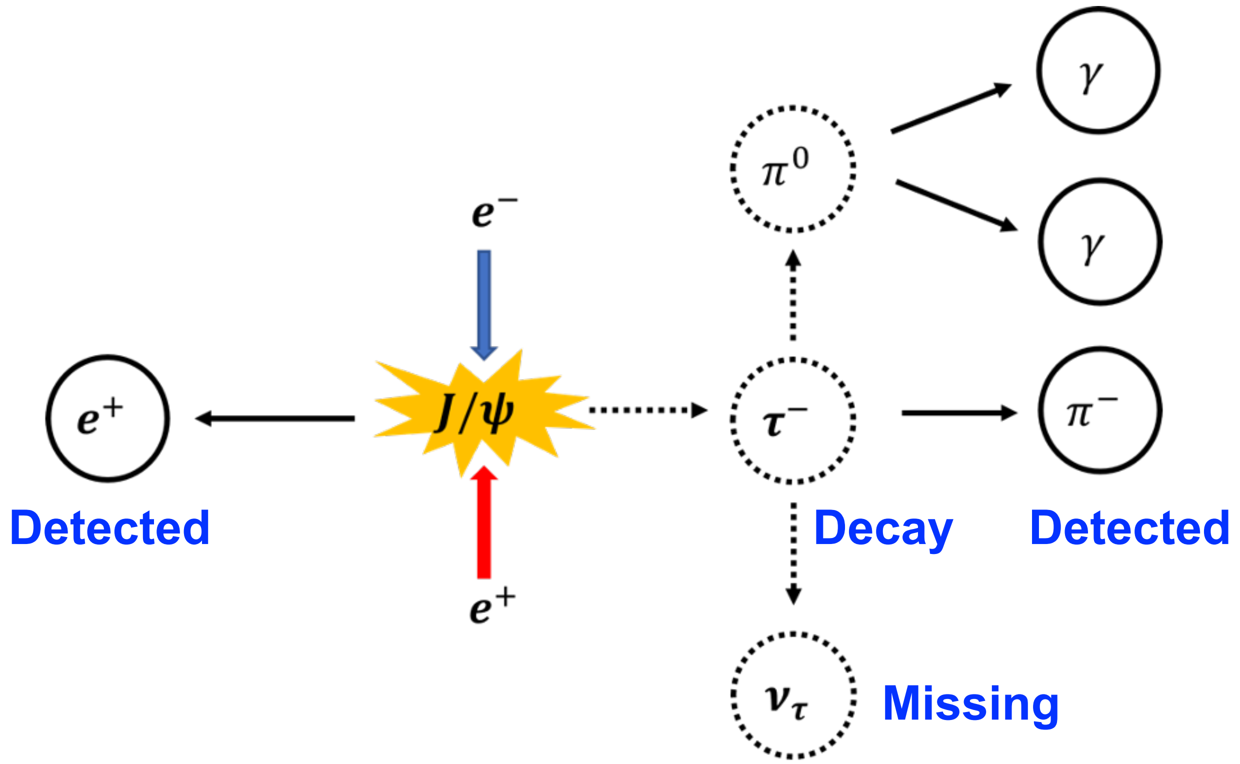
Phys. Rev. D 103, 112007 (2021)

- Analyzing 10 billion J/ψ data at BESIII
  - Data sample I: 1310.6 Million J/ψ in 2009 and 2012
  - Data sample II: 8774.0 Million J/ψ in 2018 and 2019

- Decay topology: $J/\psi \to e\tau, \tau \to \pi\pi^0\nu_\tau$

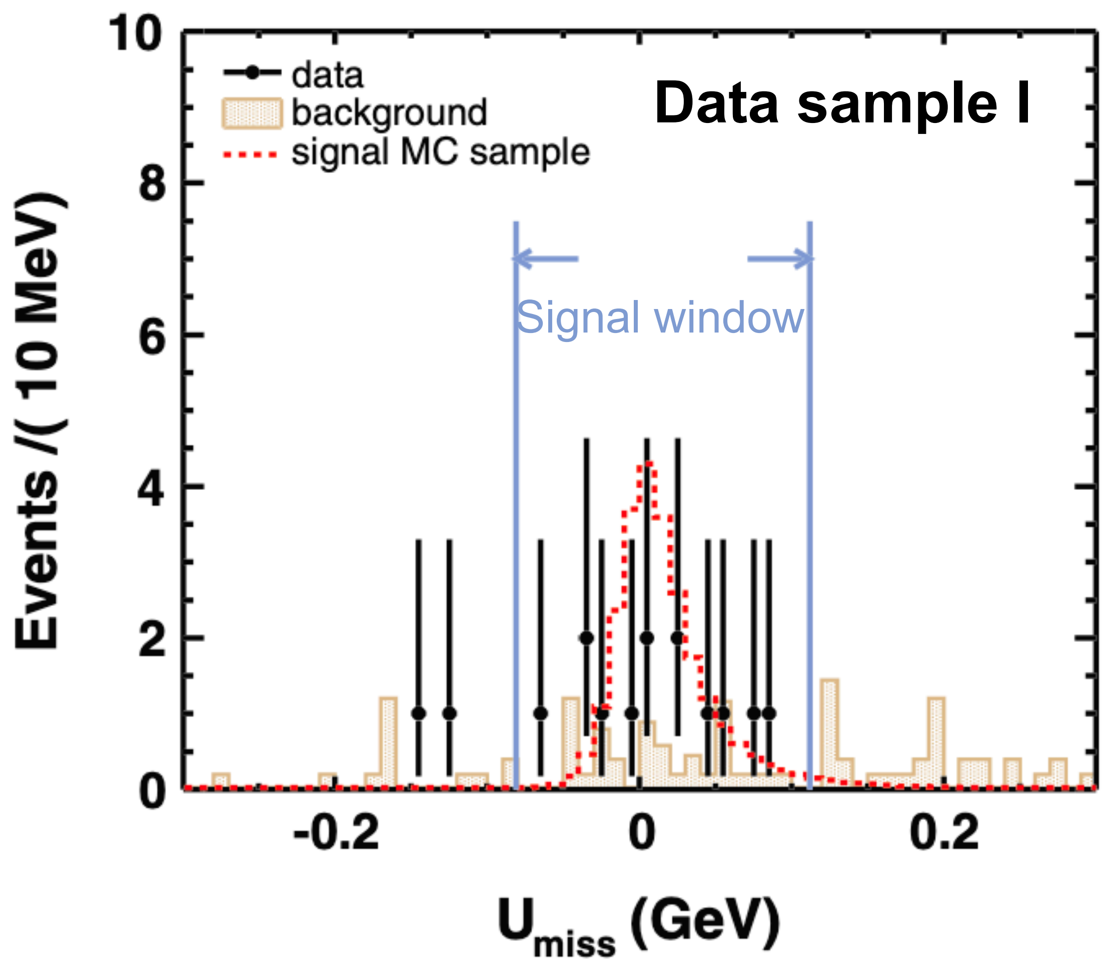
- Monochromatic electron $\Rightarrow P_e$ & $M_{\text{e\_recoil}}$

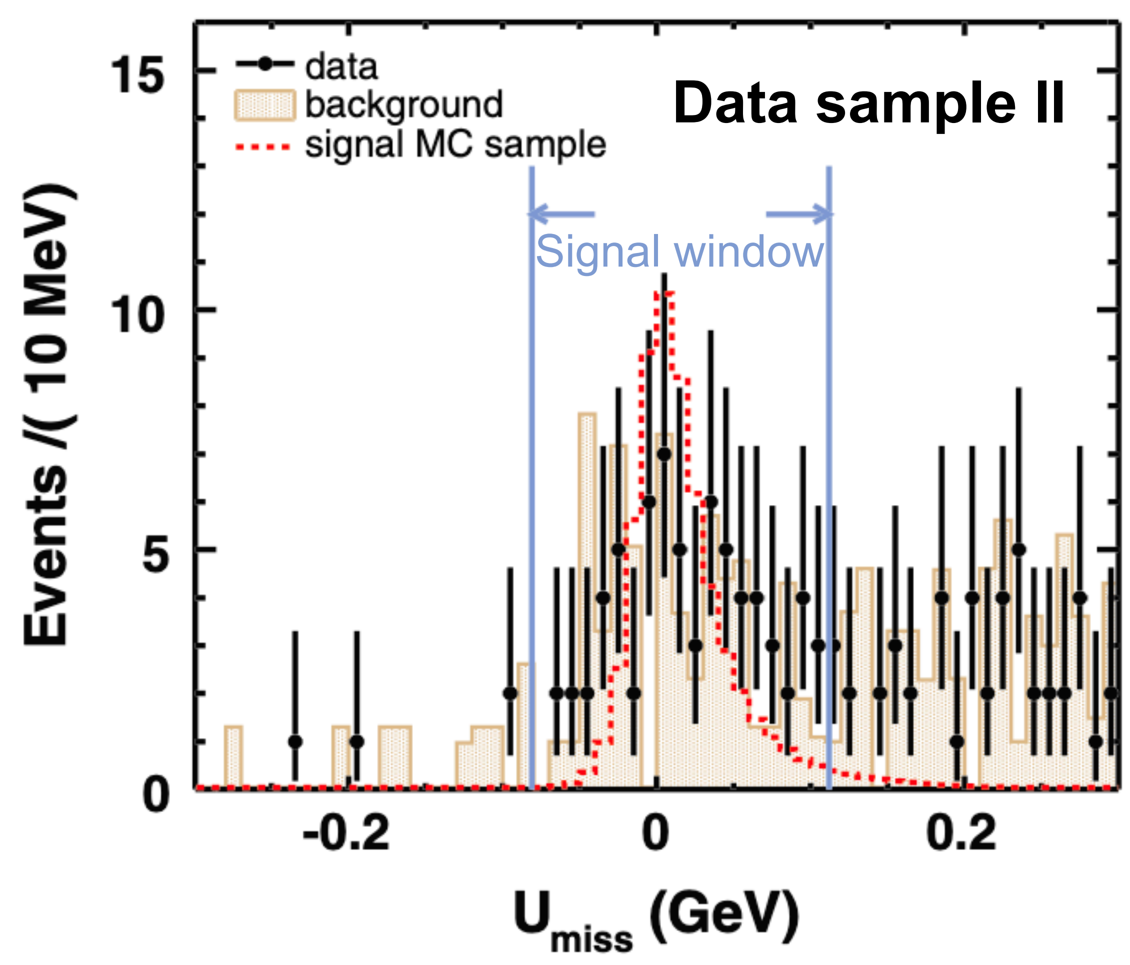




Analysis method

- ➔ Partial reconstruction
  - ❖ Missing energy $E_{\rm miss} = E_{\rm CMS} - E_e - E_\pi - E_{\pi^0}$
  - ❖ $U_{\rm miss} = E_{\rm miss} - c\,|\,\overrightarrow{P}_{\rm miss}\,|$
- ➔ 13 (69) candidate events are observed in data sample I (II)





Background study & signal efficiency

- Continuum background (radiative Bhabha)
  - Control sample: 150 pb^{-1} $\sqrt{s} = 3.08\,\mathrm{GeV}$ and 2.93 fb^{-1} $\sqrt{s} = 3.773\,\mathrm{GeV}$
  - Normalized by $1/s$ (uncertainty has been considered)
  - $N_{\mathrm{cont}} = 5.8 \pm 1.8 (37.9 \pm 11.5)$ for data sample I (II)

- J/ψ decay background
  - Inclusive MC + exclusive MC ($J/\psi \to \pi^+\pi^-\pi^0, \rho\pi, \omega f_2(1270), \bar{p}n\pi^+$)
  - The uncertainty in J/ψ decay modeling has been considered by LUNDCHARM
  - $N_{\mathrm{bkg}}^{J/\psi} = 1.1 \pm 0.8 (25.7 \pm 6.4)$ for data sample I (II)

- Signal efficiency
  - $(20.24 \pm 0.05)\,\%$ ($(19.37 \pm 0.02)\,\%$) for data sample I (II)
  - Systematic uncertainties are studies

Systematic uncertainties

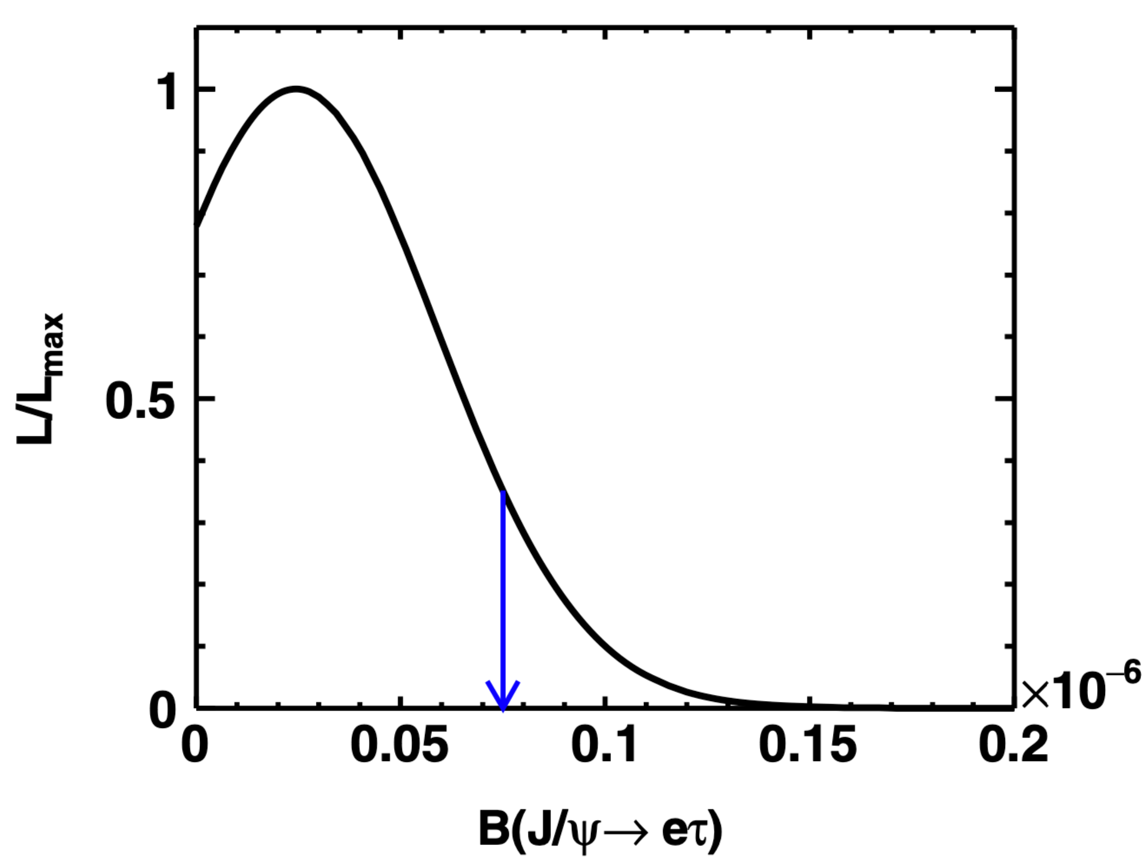
Sources	Sample I	Sample II
Number of J/ψ	0.5%	0.4%
Quoted BF*	0.4%	0.4%
MC model	0.6%	...
Pion PID*	1.0%	1.0%
Pion tracking*	1.0%	1.0%
Electron PID	0.4%	0.9%
Electron tracking*	0.1%	0.1%
Photon detection*	1.0%	1.0%
π^0 reconstruction*	1.0%	1.0%
P_e and M_{e_recoil} requirements	3.0%	3.3%
E_{miss} requirement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

Upper limit result

- ➔ Maximum likelihood estimator, extended from the profile-likelihood approach
  - ❖ Parameter of interest $\mathscr{B}(J/\psi \to e\tau)$
  - ❖ Nuisance parameters $\theta = (\epsilon_{\rm eff}, N_{\rm bkg})$

$$\mathcal{L}(\mathcal{B}(J/\psi \to e^{\pm}\tau^{\mp}),\boldsymbol{\theta}) = P(N_{\rm obs}, \mathcal{B}(J/\psi \to e^{\pm}\tau^{\mp}) \cdot N_{J/\psi} \cdot \mathcal{B}_{\tau^{\mp}\to\pi^{\mp}\pi^{0}\nu_{\tau}} \cdot \epsilon_{\rm eff} + N_{\rm bkg}) \cdot G(\epsilon_{\rm eff}^{\rm mc}, \epsilon_{\rm eff}, \sigma_{\rm eff}^{\rm mc}) \cdot G(N_{\rm bkg}^{\rm exp}, N_{\rm bkg}, \sigma_{\rm bkg}^{\rm exp}),$$

- ➔ $\mathscr{B}(J/\psi \to e\tau) < 7.5 \times 10^{-8} @ 90\,\%\,\mathrm{CL}$
  - ❖ **Improve the previous best limit by two orders of magnitude**
  - ❖ comparable with the theoretical prediction



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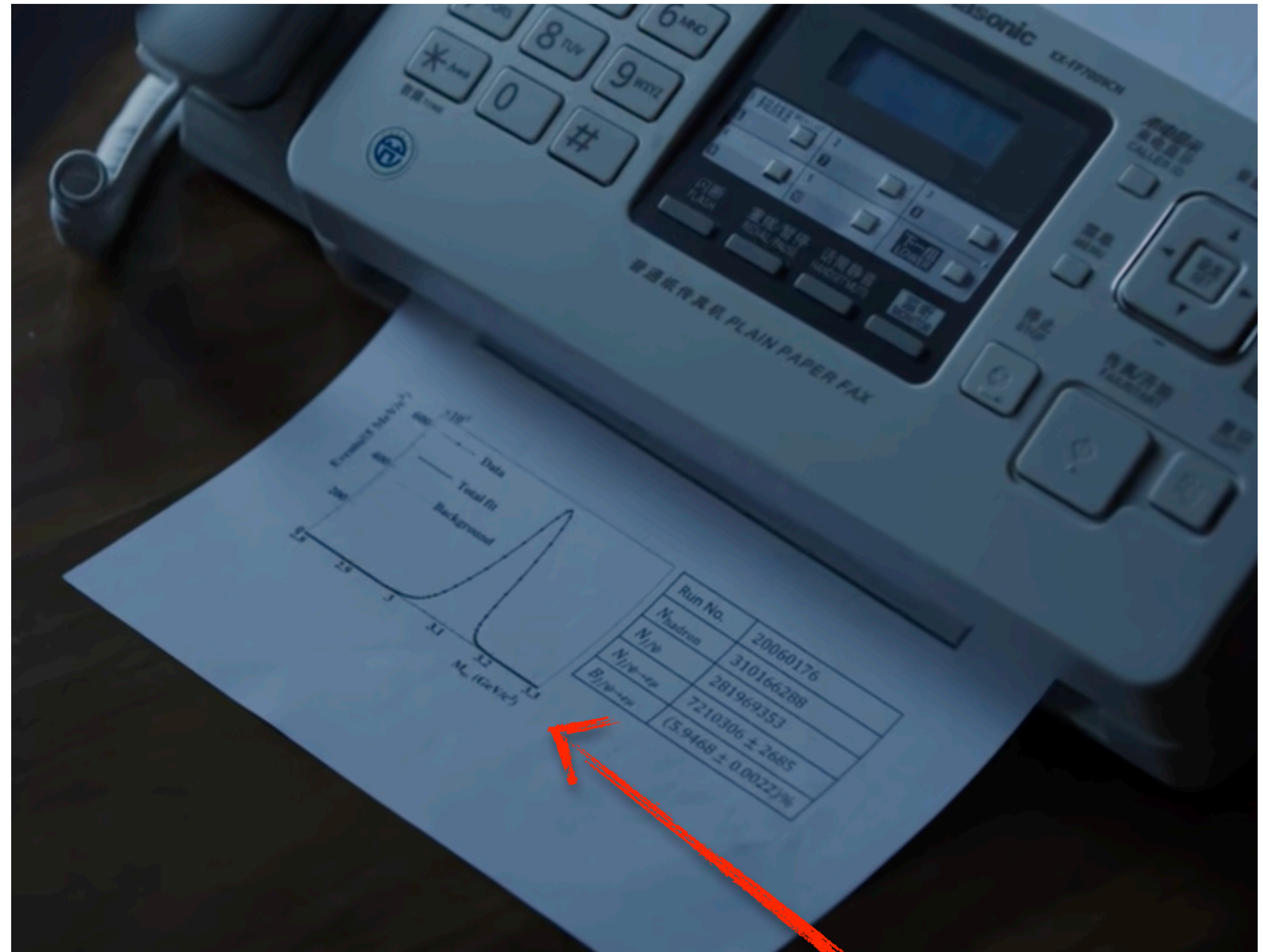
$J/\psi \to e\mu$

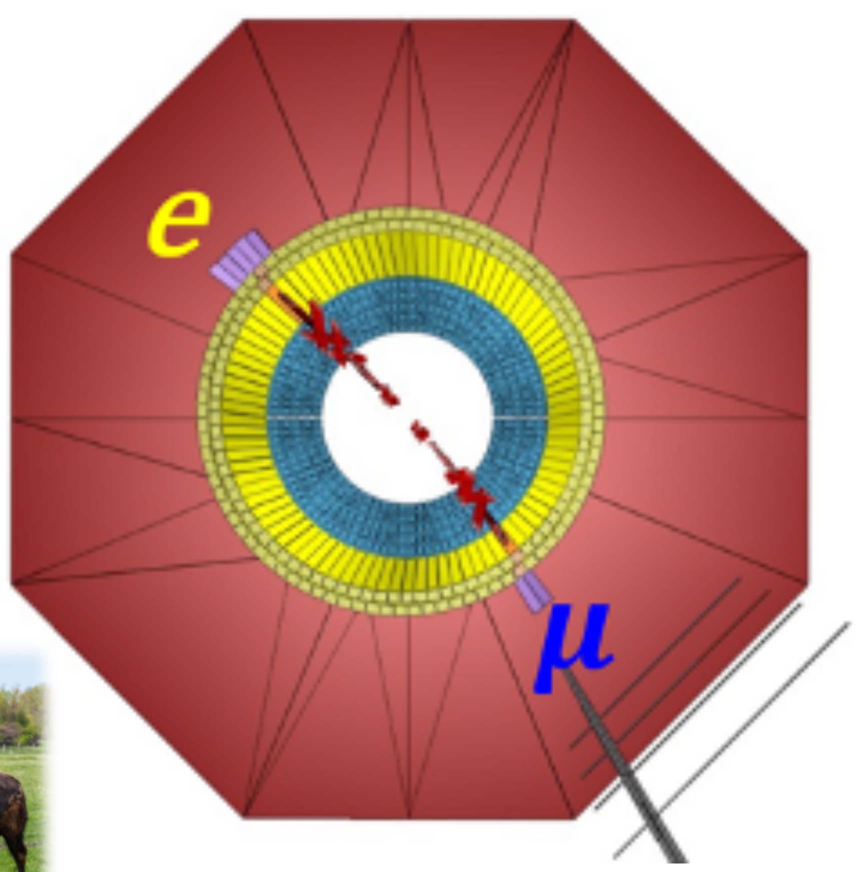
THREE-BODY!

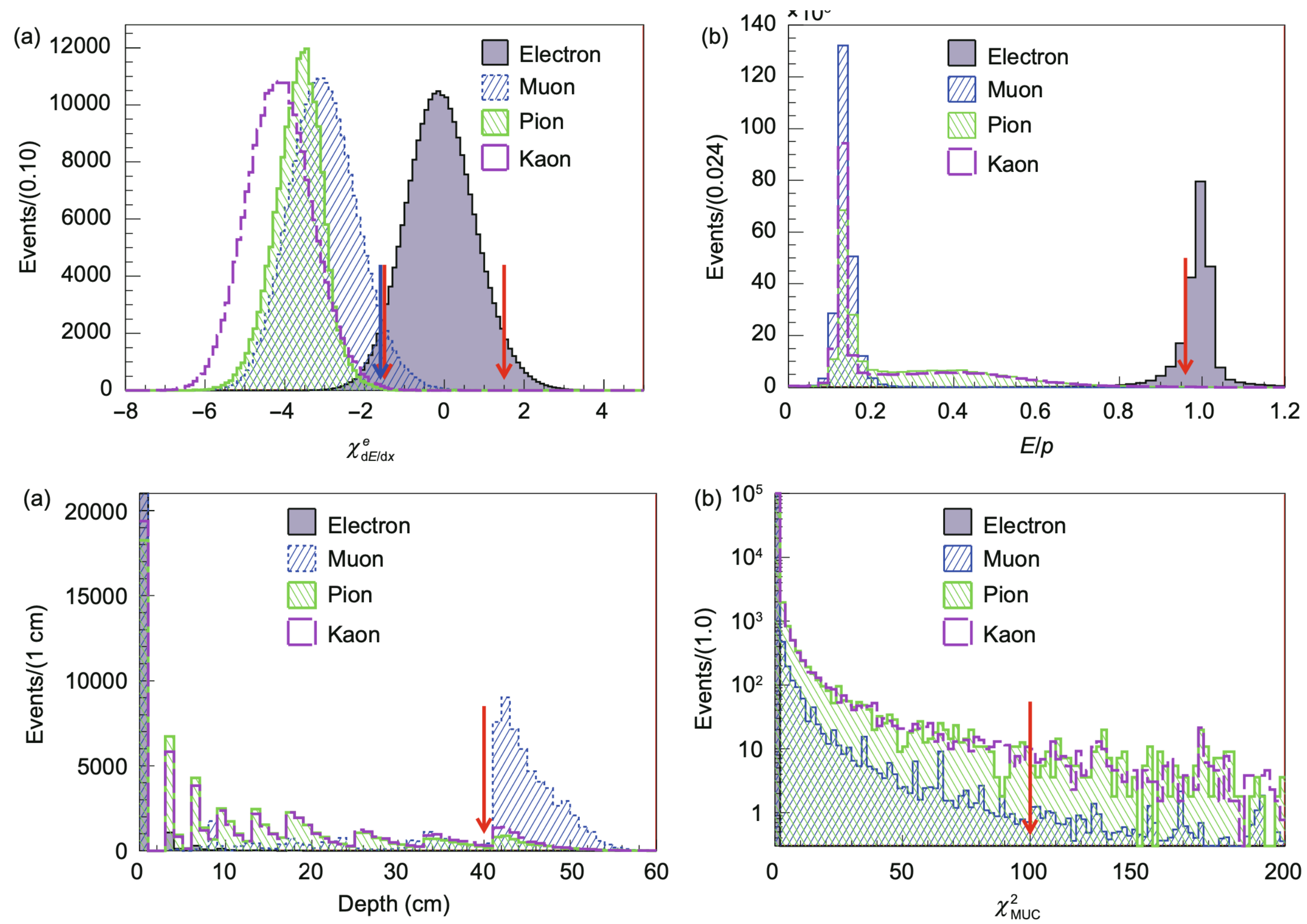


$J/\psi \to e\mu$ observed!
Physics doesn't exist!😨😱💀

$J/\psi \to e\mu$

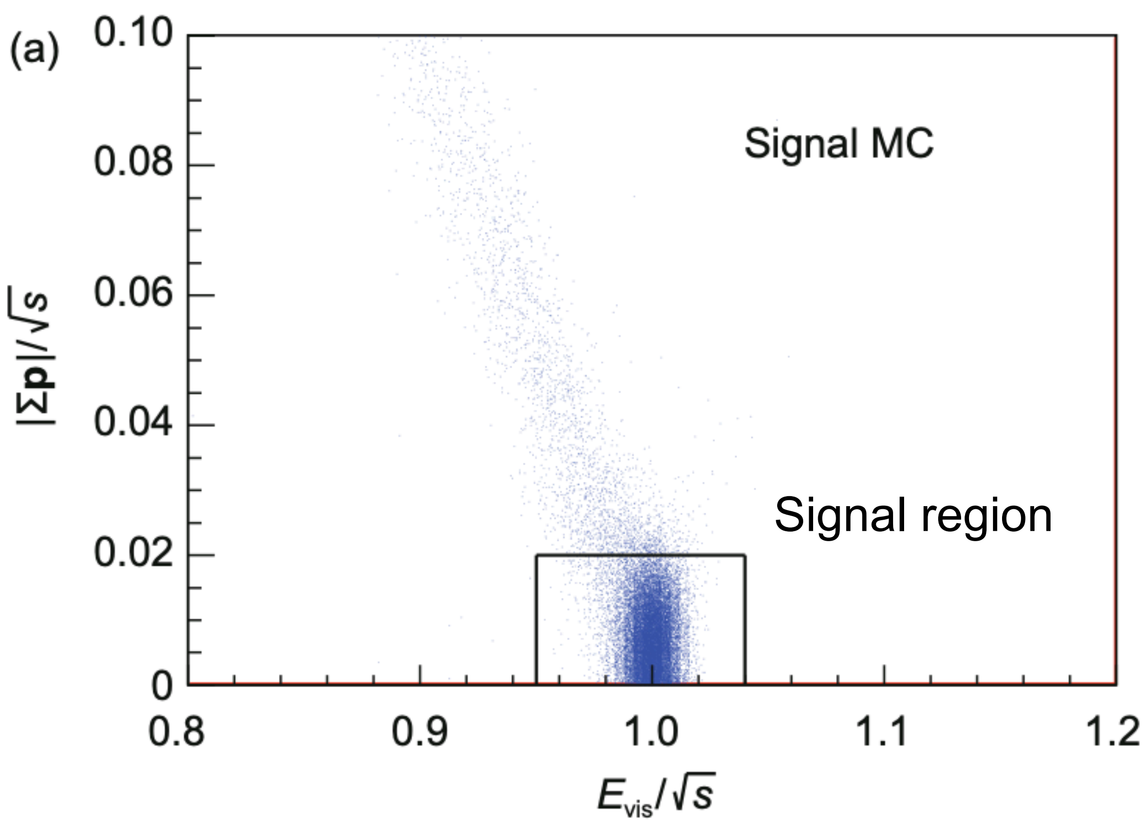
- ➔ Analyzing $(8.998 \pm 0.040) \times 10^9$ J/ψ events
- ➔ Select two back-to-back oppositely charged tracks
  - ❖ To reject cosmic rays, TOF timing difference < 1.0 ns
  - ❖ Acollinearity angle $|\Delta\theta| = |180^\circ - (\theta_1 + \theta_2)| < 1.2^\circ$
  - ❖ Acoplanarity angle $|\Delta\phi| = |180^\circ - |\phi_1 + \phi_2|| < 1.5^\circ$
- ➔ Utilizing $\mathrm{d}E/\mathrm{d}x$, deposited energy and MUC hit informations

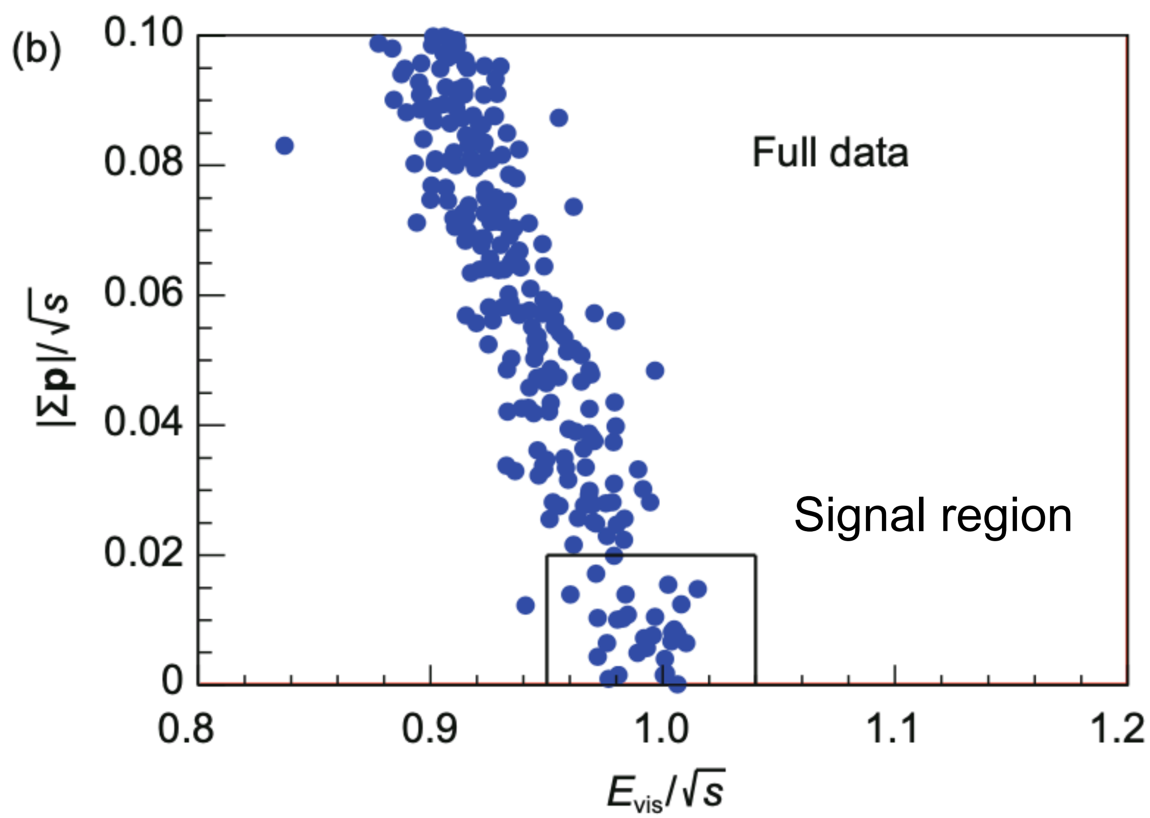




Analysis method

- Signal region: $|\sum \vec{p}|/\sqrt{s} \leq 0.02$ and $0.95 \leq E_{\text{vis}}/\sqrt{s} \leq 1.04$
  - $|\sum \vec{p}|$: The magnitude of the vector sum of the momenta
  - E_{vis}: The total reconstructed energy of e and μ
  - 85% of the signal events fall into the signal region
- 29 candidate events





Background study & signal efficiency

- Continuum background ($\rightarrow e^+e^-(\gamma), \mu^+\mu^+(\gamma)$)
  - Control sample: $\sqrt{s} = 3.773\,\mathrm{GeV}, 3.510\,\mathrm{GeV}, 3.080\,\mathrm{GeV}$
  - $1/s$ energy-dependence of cross section
  - $N_{\mathrm{bkg2}}^{\mathrm{norm}} = 12.0 \pm 3.7$

- J/ψ decay background ($\rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-, p\bar{p}$)
  - Inclusive MC + exclusive MC
  - $N_{\mathrm{bkg1}}^{\mathrm{norm}} = 24.8 \pm 1.5$

- Detection efficiency: $(21.18 \pm 0.13)\,\%$
  - Systematic uncertainties are studies

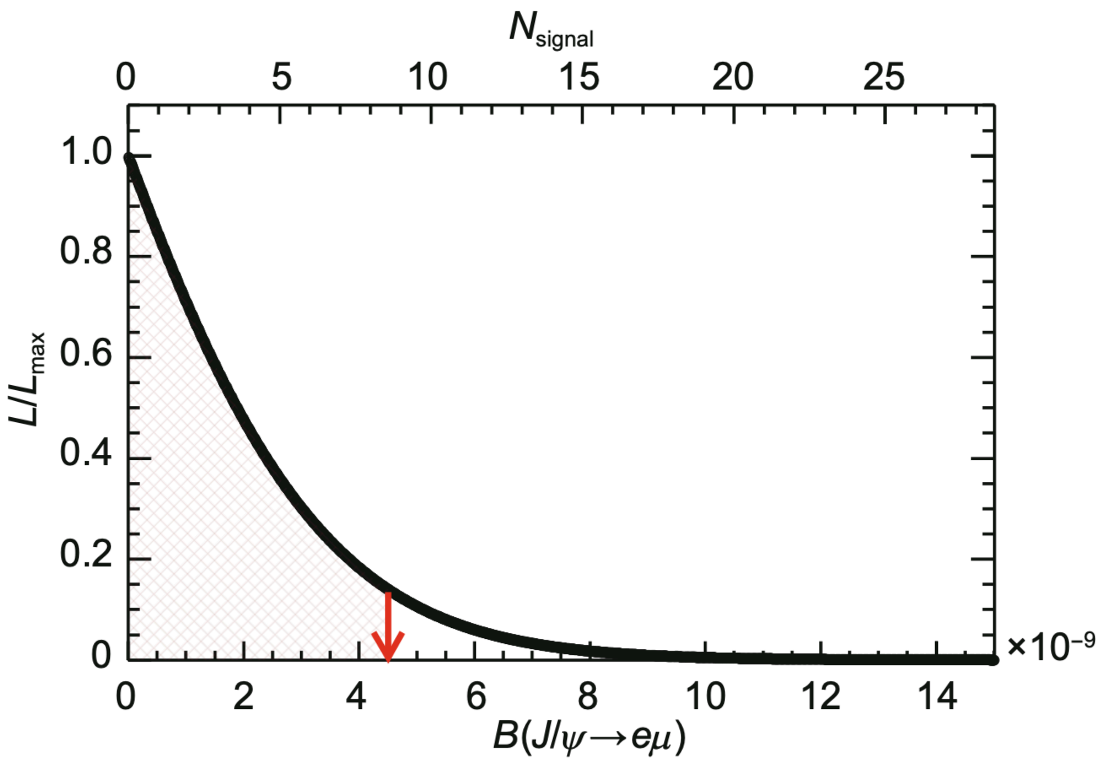
Source	Relative uncertainty (%)
Tracking and PID	13
TOF timing	0.52
Photon veto	0.83
$\lvert\Delta\theta\rvert$ and $\lvert\Delta\phi\rvert$ requirement	2.6
Total	14

Upper limit result

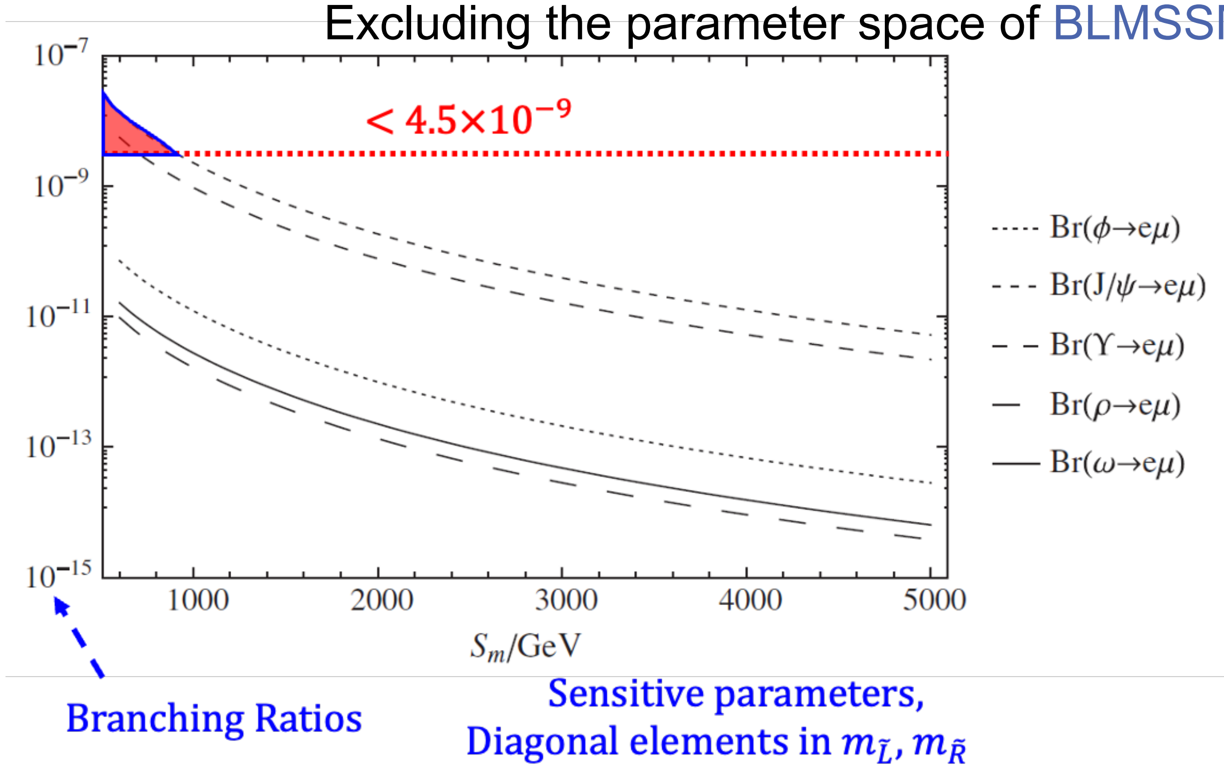
- ➔ Maximum likelihood estimator, extended from the profile-likelihood approach
  - ❖ Parameter of interest $\mathscr{B}(J/\psi \to e\mu)$
  - ❖ Nuisance parameters $\theta = (\epsilon_{\text{sig}}, N_{J/\psi}, N_{\text{bkg1}}, N_{\text{bkg2}})$

$$\mathcal{L}(\mathcal{B}, \epsilon_{\text{sig}}, N_{J/\psi}, N_{\text{bkg1}}, N_{\text{bkg2}}) = \mathcal{P}(N_{\text{obs}}|N_{J/\psi} \cdot \mathcal{B} \cdot \epsilon_{\text{sig}} + N_{\text{bkg1}} + N_{\text{bkg2}}) \cdot \mathcal{G}(\epsilon_{\text{sig}}|\epsilon^{\text{MC}}_{\text{sig}}, \epsilon^{\text{MC}}_{\text{sig}} \cdot \sigma^{\text{EFF}}_{\text{sig}}) \cdot \mathcal{P}\left(N^{J/\psi-\text{MC}}_{\text{bkg1}}|N_{\text{bkg1}}/f_1\right) \cdot \prod_k \mathcal{P}(N^k_{\text{cont}}|N_{\text{bkg2}}/f^k_2) \cdot \mathcal{G}(N_{J/\psi}|N^{\text{data}}_{J/\psi}, \delta N^{\text{data}}_{J/\psi}).$$

- ➔ $\mathscr{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9}$ @ 90 % CL
  - ❖ Improve the previous limit by **a factor of more than 30**
  - ❖ The **most stringent limit** on cLFV in heavy quarkonium systems
  - ❖ Provides constraints on the parameter spaces of new physics models



Excluding the parameter space of BLMSSM model



Phys. Rev. D 97, 056027 (2018)

Summary

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.

- ➔ The latest searching results for cLFV decays are reported.

- ➔ $\mathscr{B}(J/\psi \to e\tau) < 7.5 \times 10^{-8}$ @ 90 % CL

- ➔ $\mathscr{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9}$ @ 90 % CL, currently the most stringent limit on cLFV in heavy quarkonium sector

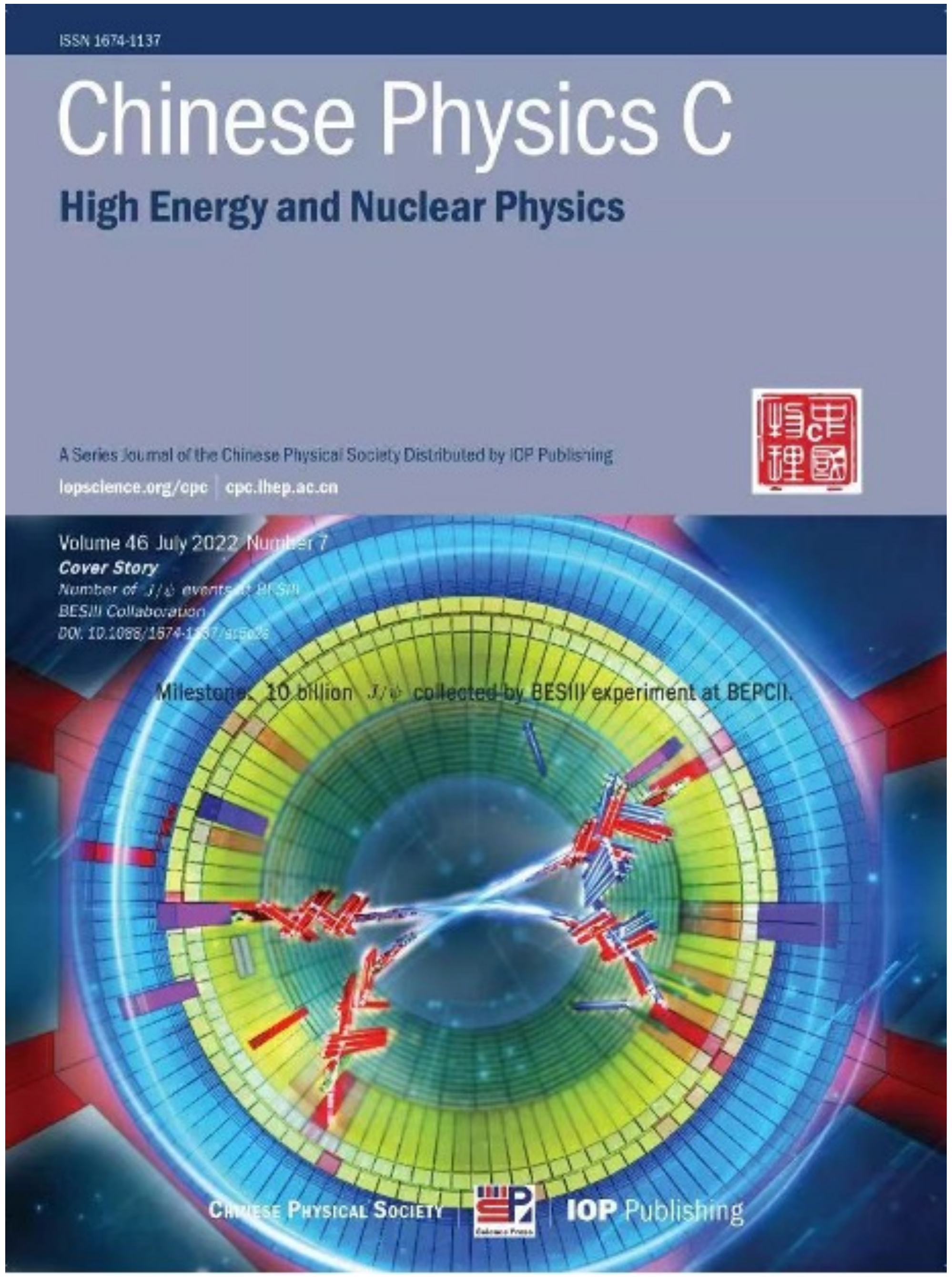
Thanks for your attention!

Backup

BESIII physics data

Physics of BESIII
NSR 8, (11) 2021

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



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:

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

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