PEKING UNIVERSITY

Search for charged Lepton Flavor Violation at BESIII

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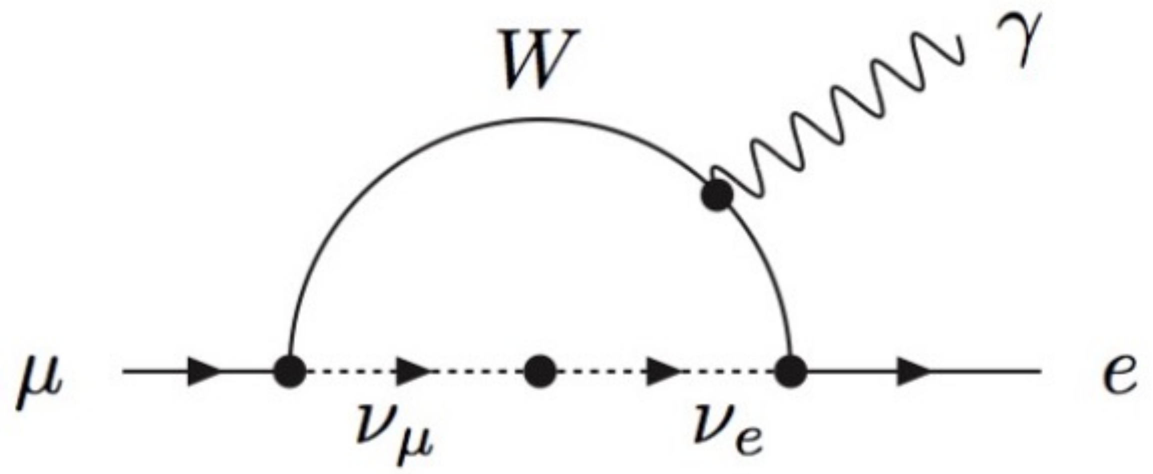
(On behalf of BESIII collaboration)

Outline

- Introduction
- BESIII experiment
- Highlight results of cLFV at BESIII
  - $J/\psi \to e\tau$
  - $J/\psi \to e\mu$
- Prospect and ongoing analysis
- Summary & outlook

Introduction

cLFV

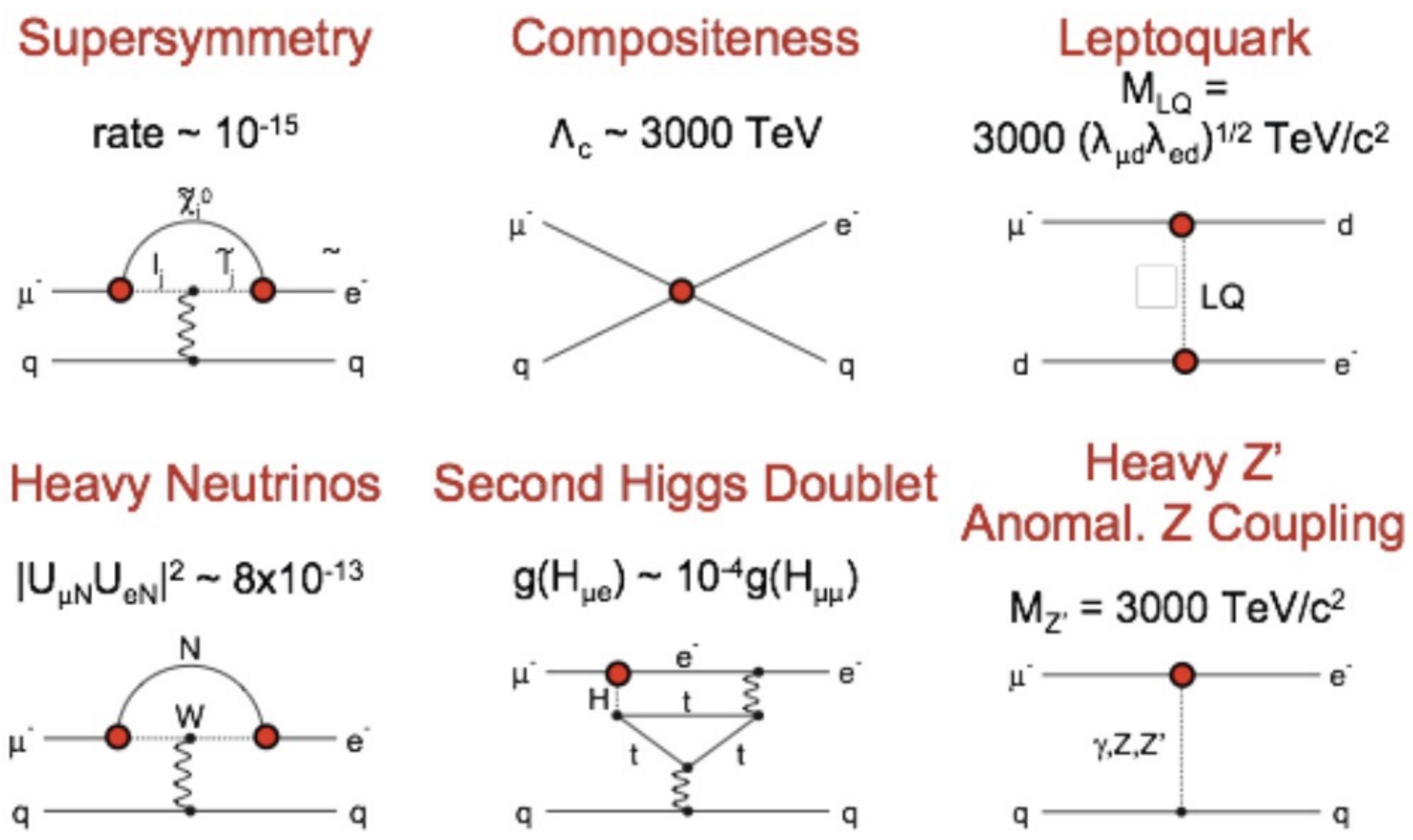


LFV: forbidden in SM, signal of new physics BSM

Non-zero neutrino mass ⇒ cLFV is heavily suppressed

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

Neutrinoless muon decay



Many models enhance LFV effects up to detectable level

J/ψ cLFV models

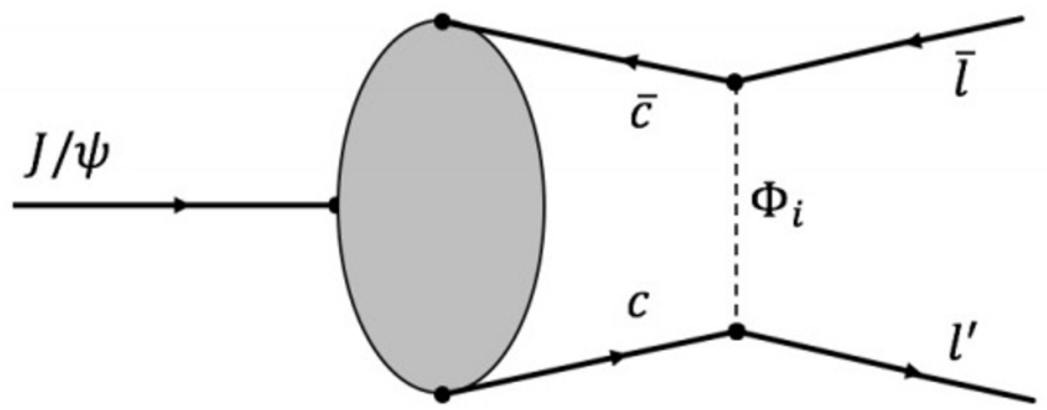


Diagram via leptoquarks

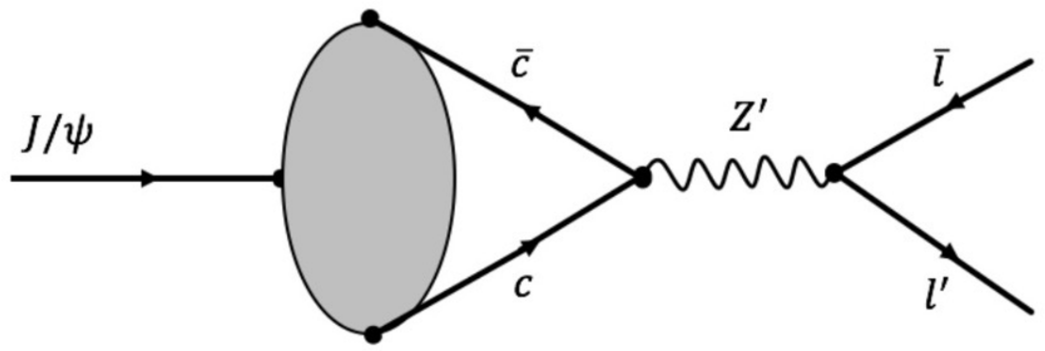


Diagram via a Z' in TC2 models

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

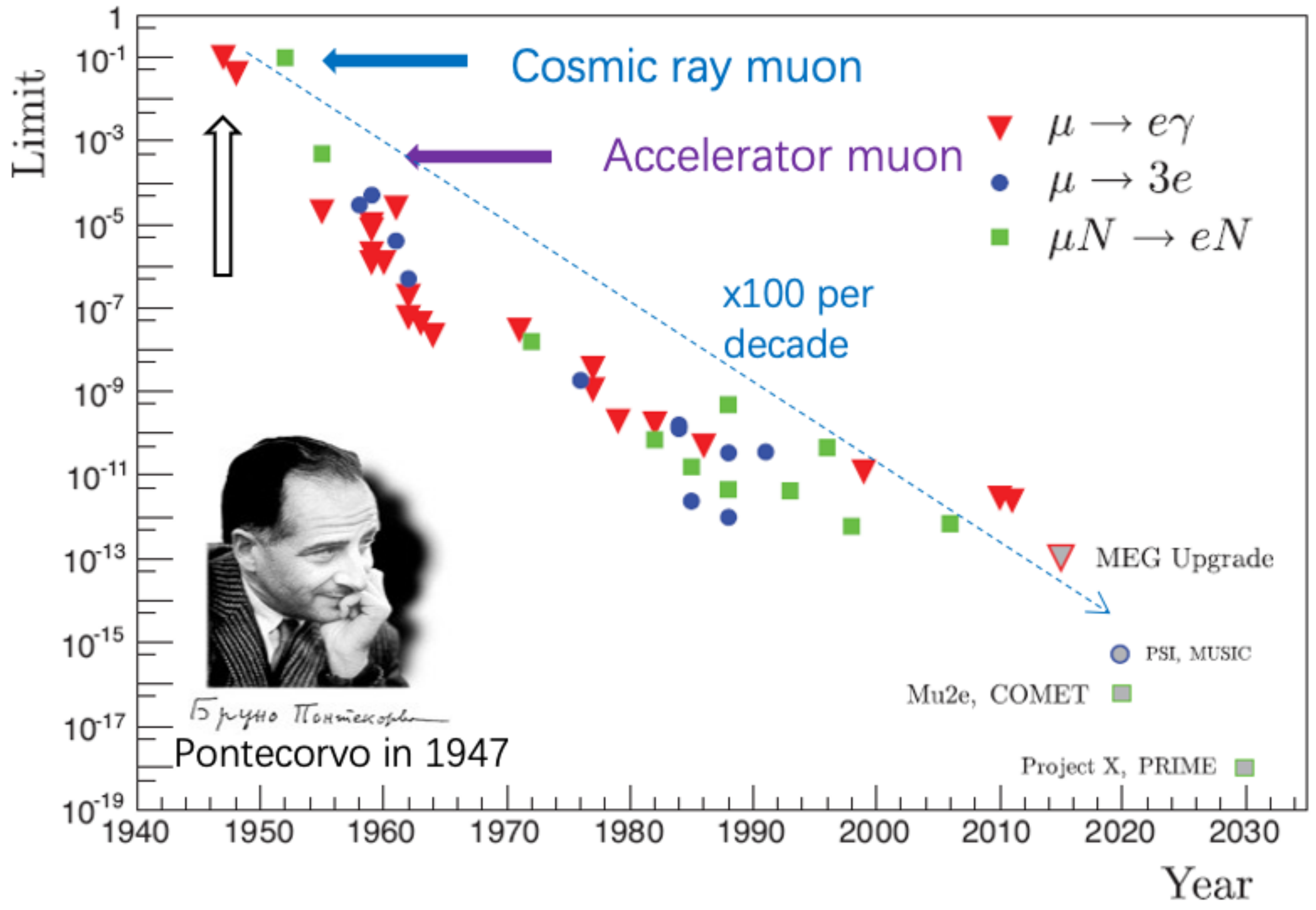
cLFV - experimental search

- ➔ Experimental searches in leptons (μ, τ), pseudoscalar mesons (K, π, B), vector mesons ($\phi, J/\psi, \Upsilon$), Z and H^0 decays
  - $\mathscr{B}(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13}$ @ 90 % CL — MEG II
  - $\mathscr{B}(\tau^+ \to e^+\gamma) < 3.3 \times 10^{-8}$ @ 90 % CL — BABAR
  - $\mathscr{B}(\mu \to 3e) < 1.0 \times 10^{-12}$ @ 90 % CL — SINDRUM
  - $\mathscr{B}(Z \to e^\pm\mu^\mp) < 2.62 \times 10^{-7}$ @ 95 % CL — ATLAS
  - $\mathscr{B}(H^0 \to e^\pm\mu^\mp) < 4.7 \times 10^{-5}$ @ 95 % CL — CMS
  - $\mathscr{B}(\phi \to e^\pm\mu^\mp) < 2 \times 10^{-6}$ @ 90 % CL — SND
  - $\mathscr{B}(\Upsilon(1S) \to e^\pm\mu^\mp) < 3.6 \times 10^{-7}$ @ 90 % CL — Belle
  - $\mathscr{B}(J/\psi \to e^\pm\tau^\mp) < 7.1 \times 10^{-8}$ @ 90 % CL — BESIII
  - $\mathscr{B}(J/\psi \to e^\pm\mu^\mp) < 4.5 \times 10^{-9}$ @ 90 % CL — BESIII
  - …

THIS TALK

- ➔ 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 $\mathscr{O}(10^8\ \mathrm{muons/s})$, low momentum $p = 28\ \mathrm{MeV}/c$
    - MEGII aiming at sensitivity down to 6×10^{-14} @ 90 % CL

Eur. Phys. J. C 84, 216 (2024)
Phys. Rev. Lett. 104, 021802 (2010)
Nucl. Phys. B 299, 1 (1988)
Phys. Rev. D 108, 032015 (2023)
Phys. Rev. D 108, 072004 (2023)
Phys. Rev. D 81, 057102 (2010)
JHEP 05, 095 (2022)
Phys. Rev. D 103, 112007 (2021)
Sci. Chin. Mech. Astron. 66, 2 (2023)



cLFV - J/ψ decays

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

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)

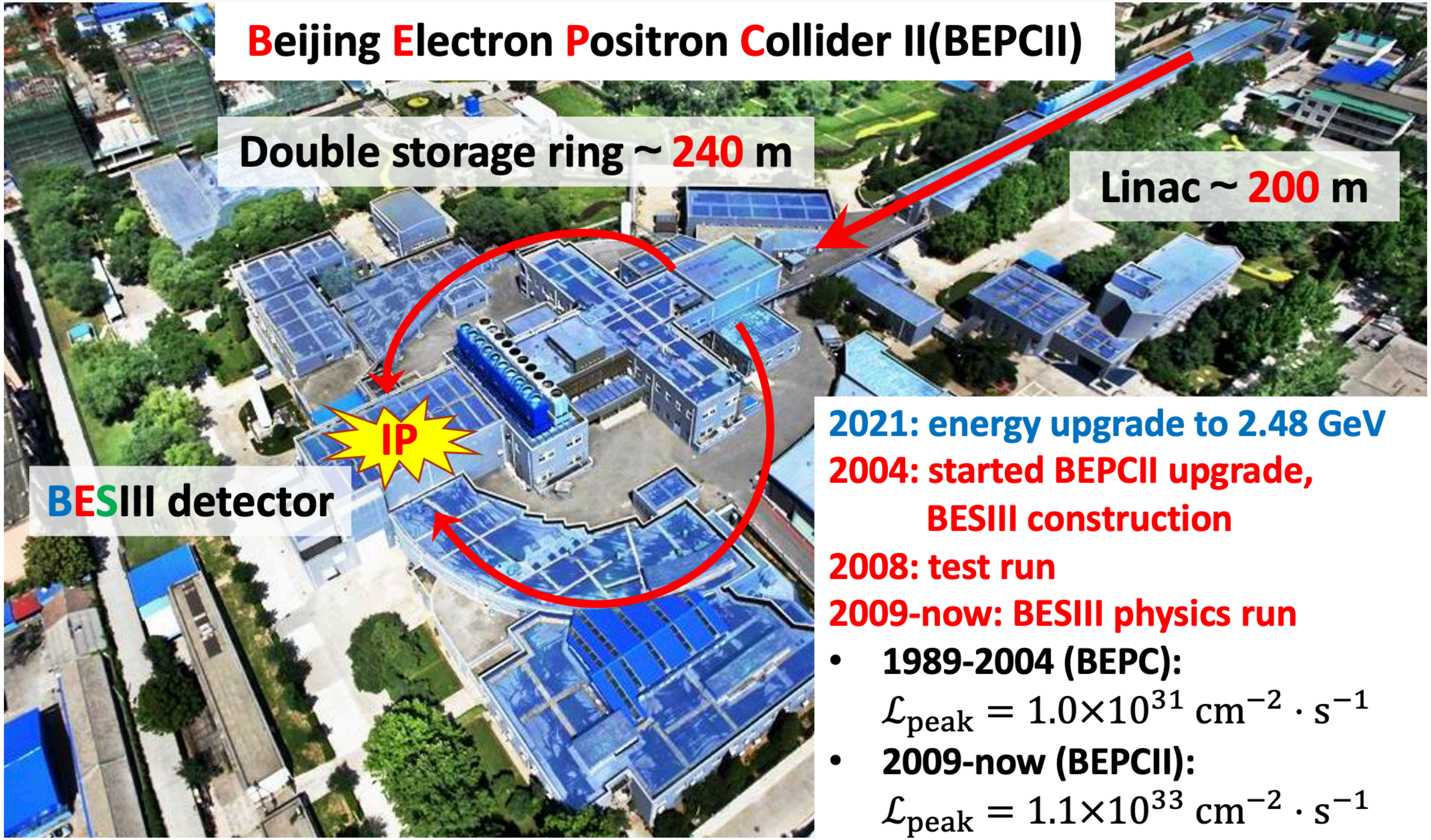
- Previous experimental results:

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)

BESIII experiment

BEPCII



2021: energy upgrade to 2.48 GeV

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):** $\mathcal{L}_{\text{peak}} = 1.1\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

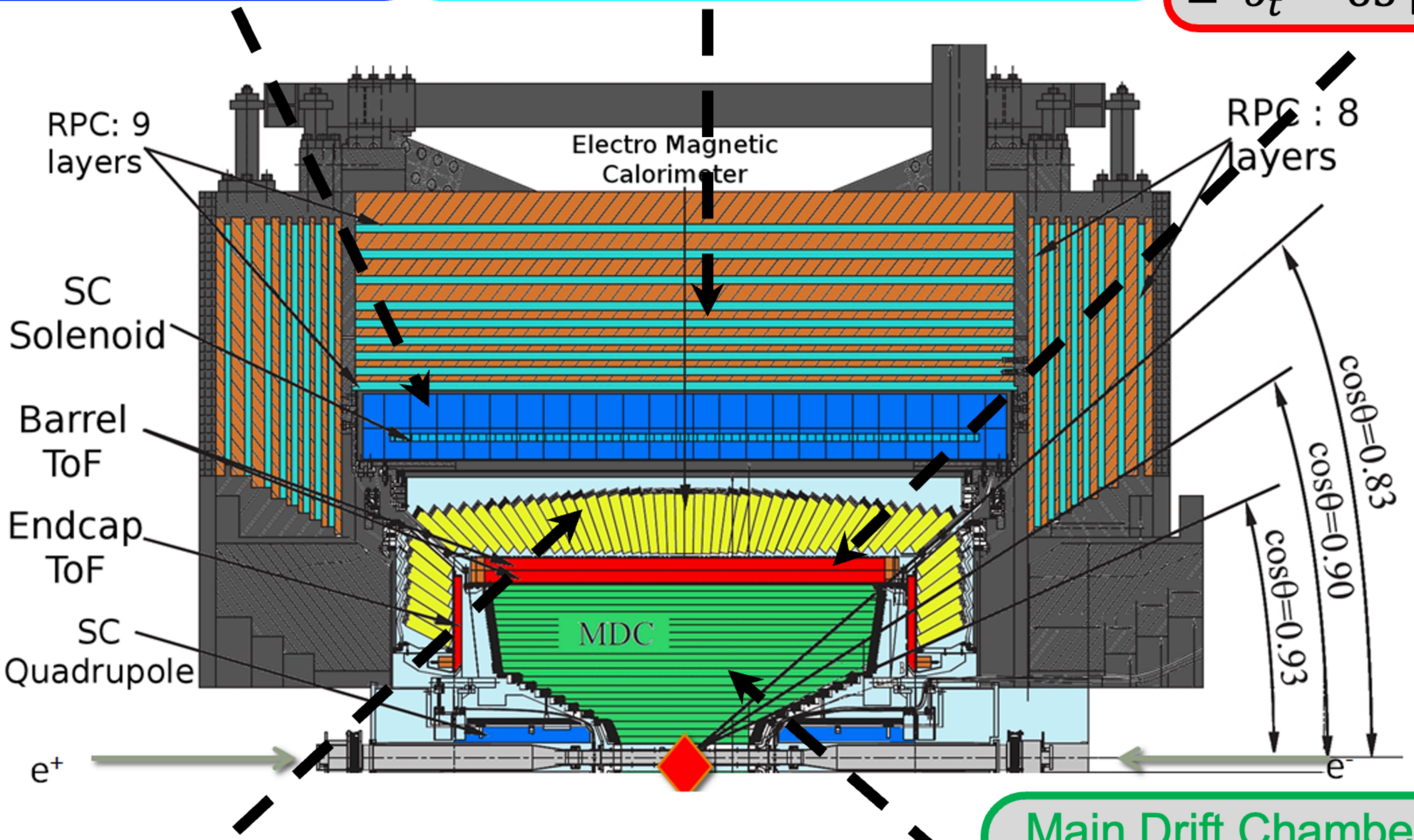
Beam energy: 1.0-2.475 GeV
Optimum energy: 1.89 GeV

BESIII detector

Superconducting solenoid
- **1.0 T**

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

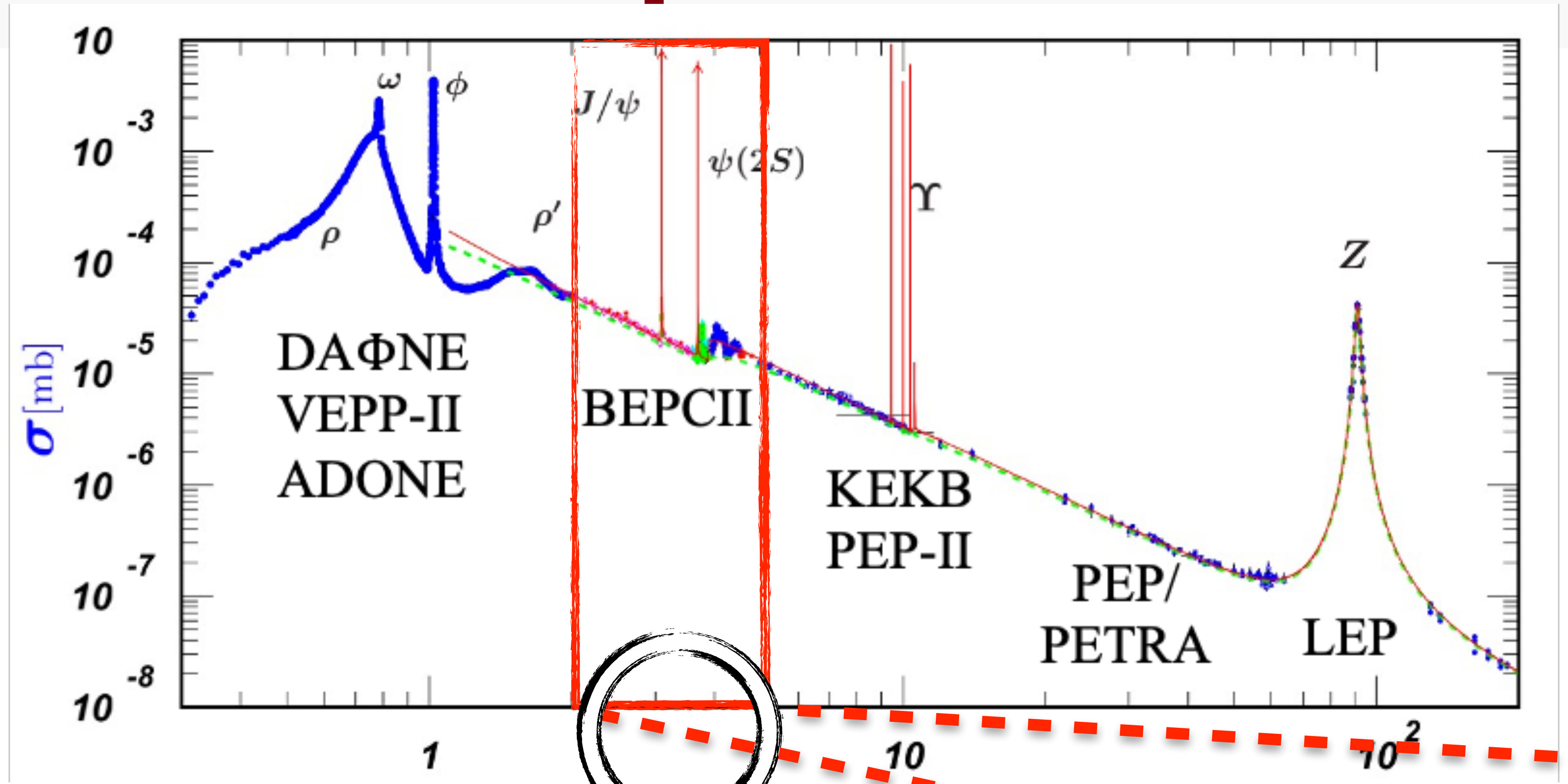
Time Of Flight (TOF)
- $\sigma_t = 90$ ps (barrel)
- $\sigma_t = 65$ ps (end cap)



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

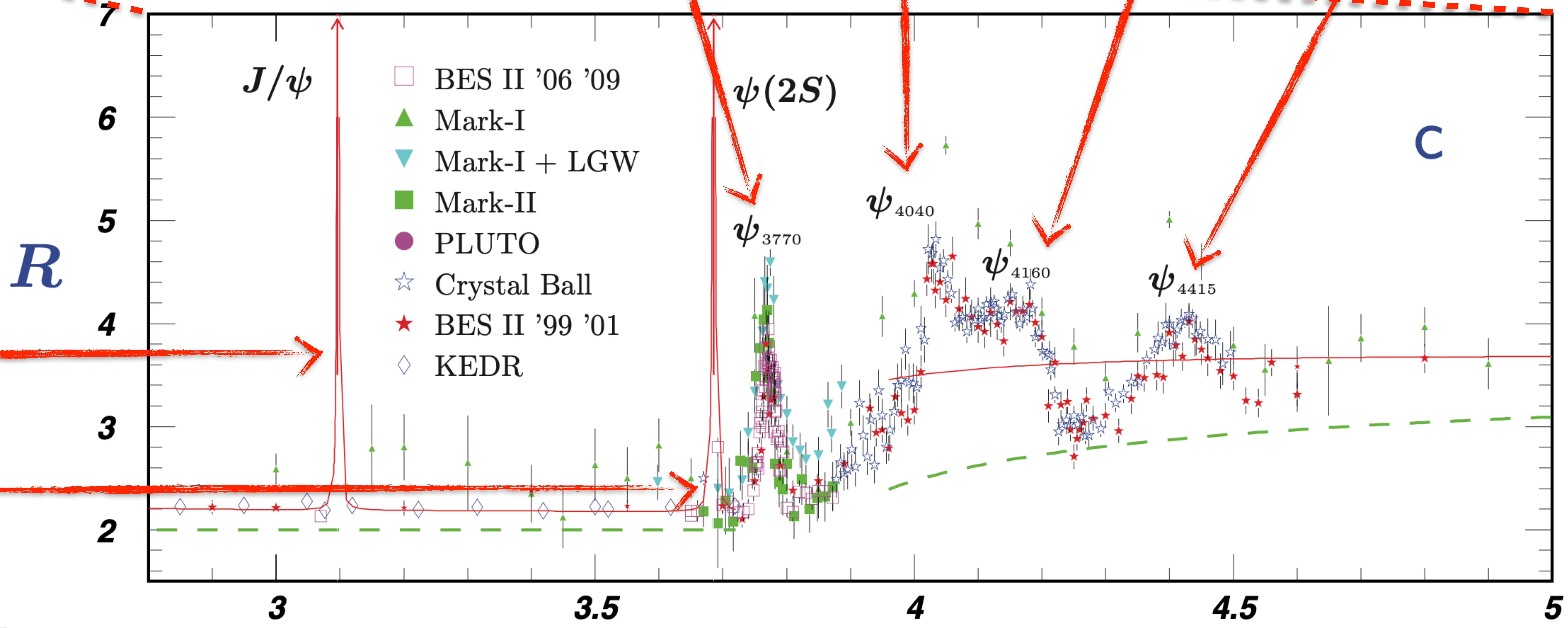


- BESIII has collected the largest data samples of J/ψ and $\psi(3686)$ on the threshold in the world!
- $> 20\,\mathrm{fb}^{-1}$ data above 4.0 GeV in total

$\psi(3770)$ $20\,\mathrm{fb}^{-1}$ $\psi(4040)$ $0.5\,\mathrm{fb}^{-1}$ $\psi(4160)$ $3.2\,\mathrm{fb}^{-1}$ $\psi(4415)$ $1.1\,\mathrm{fb}^{-1}$

J/ψ 1.0×10^{10}

$\psi(3686)$ 2.7×10^{9}



New physics searches at BESIII

- charged **L**epton **F**lavor **V**iolation
- **L**epton/**B**aryon **N**umber **V**iolation
- C/CP violation
- …

THIS TALK

Symmetry violation

Exotic particle

Very rare decay

NEW PHYSICS

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

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

Other process

Strategies

- 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”

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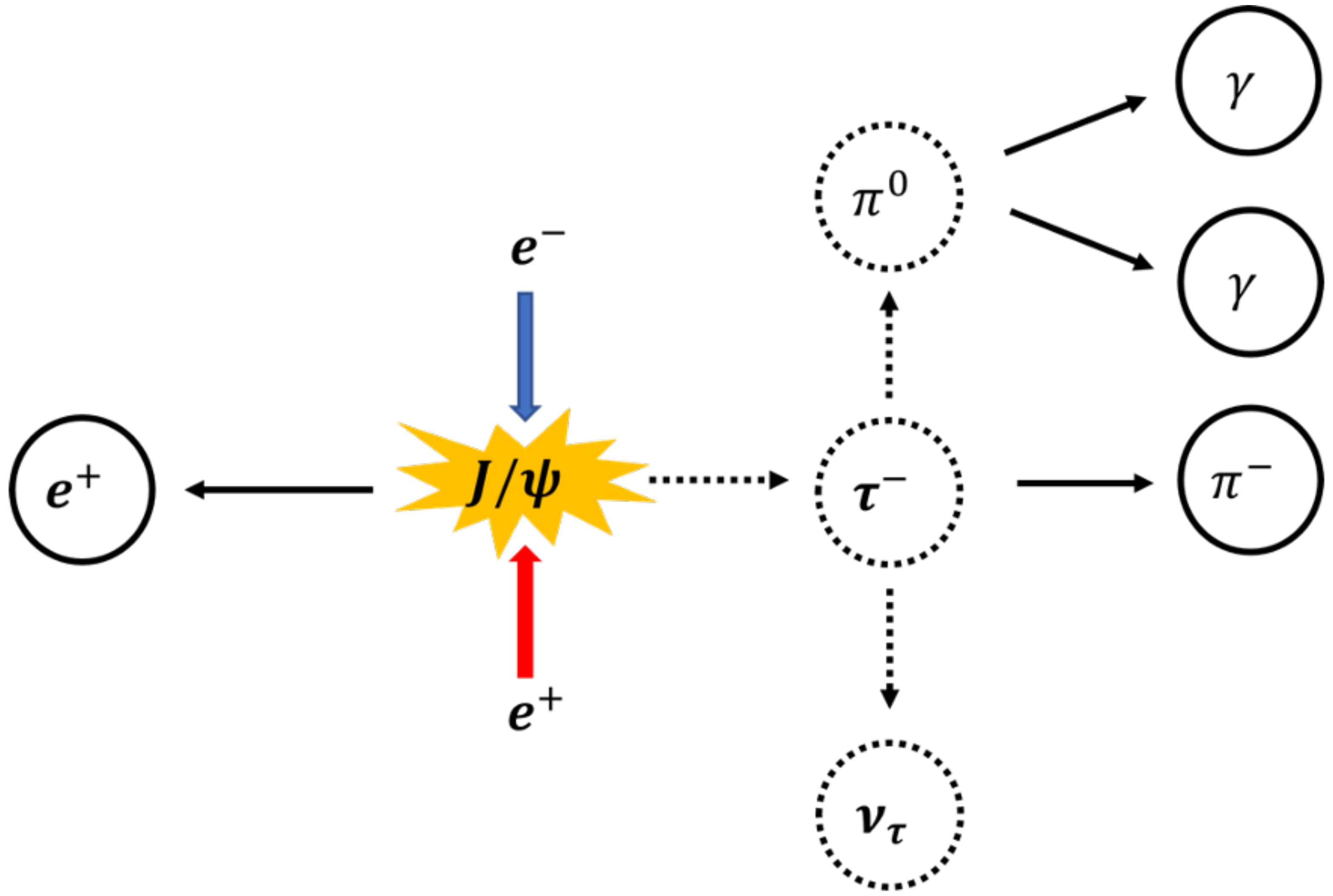
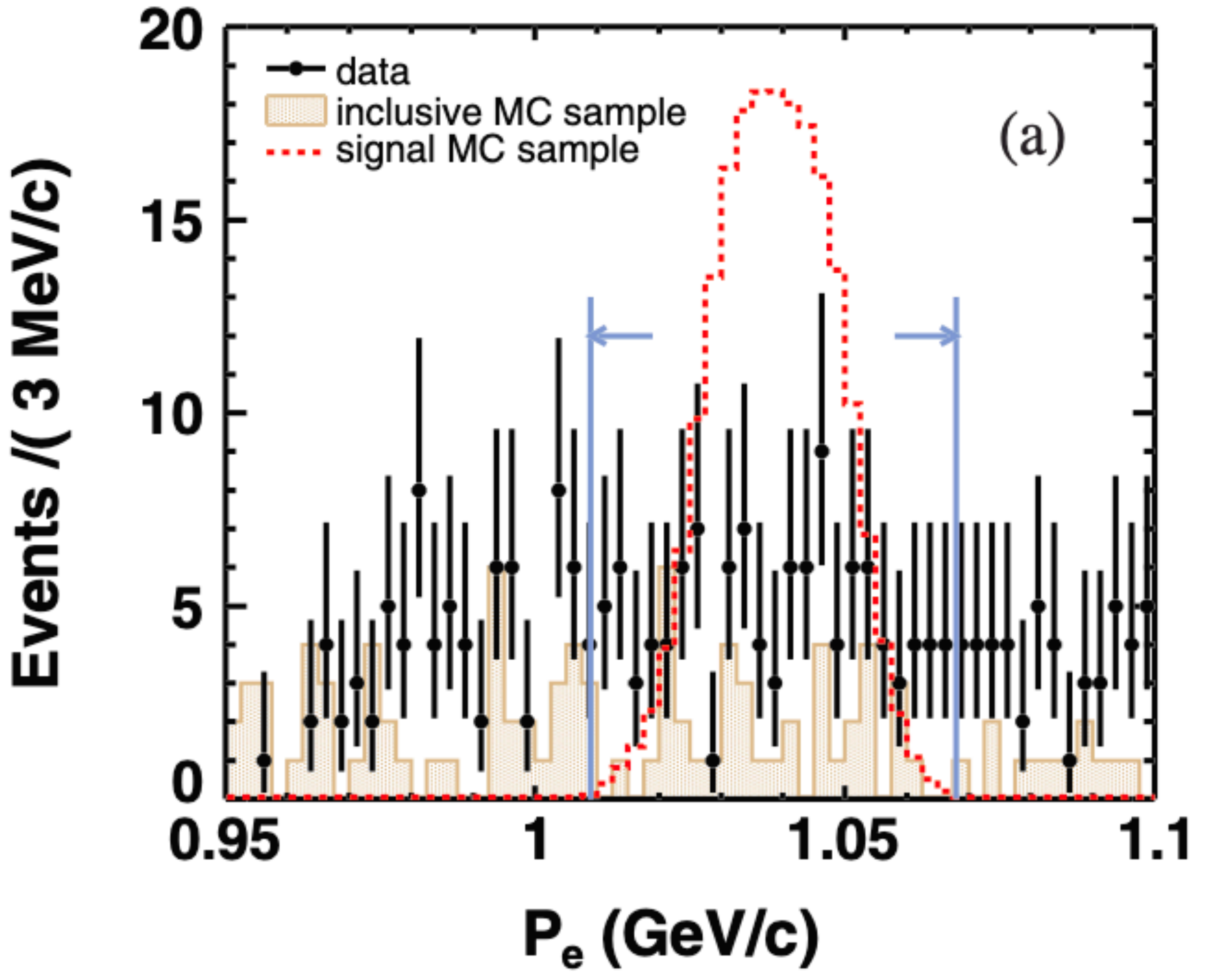
$J/\psi \to e\tau$

$J/\psi \to e\tau$

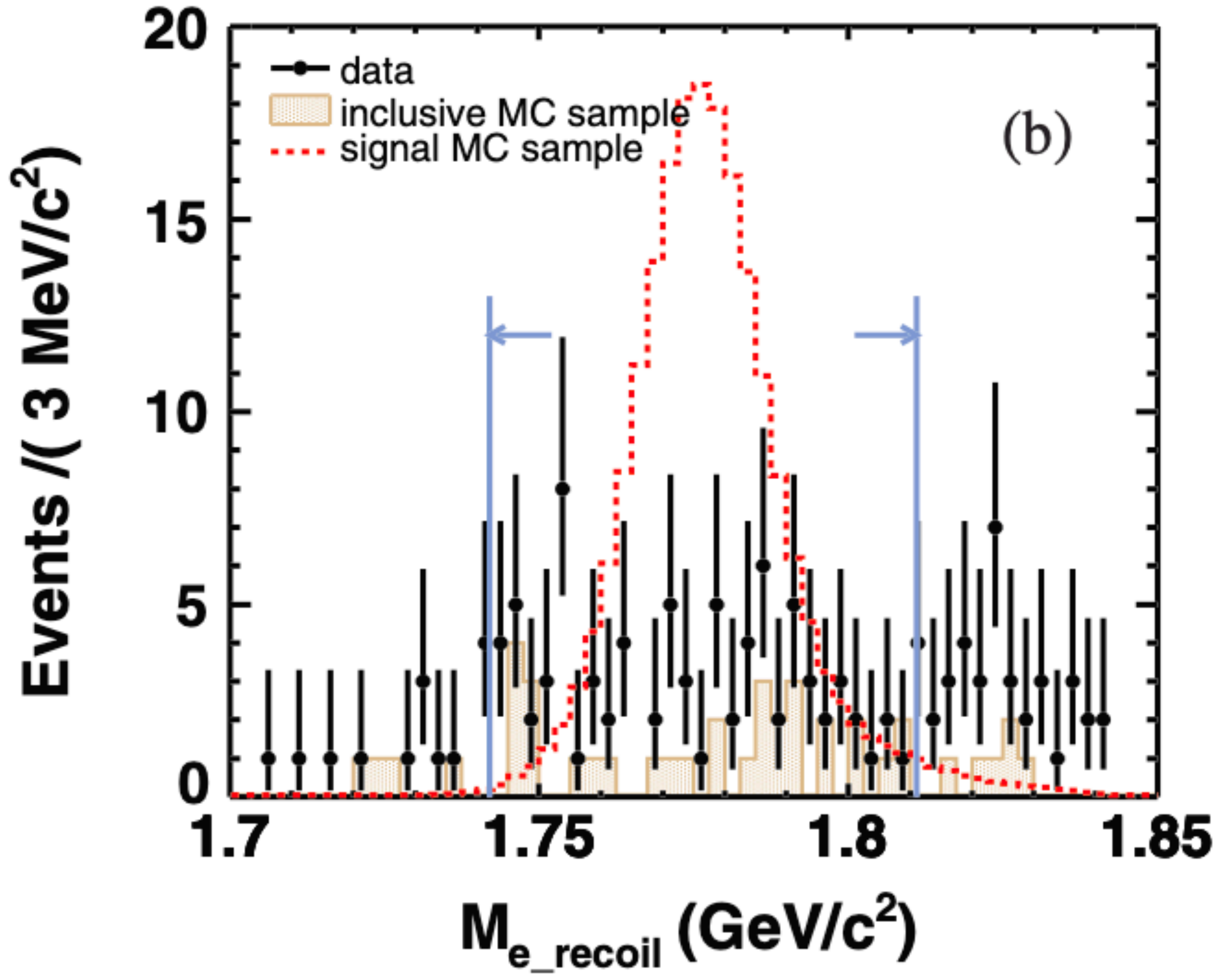
Phys. Rev. D 103, 112007 (2021)

- 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: $J/\psi \to e\tau, \tau \to \pi\pi^0\nu_\tau$
  - Select one electron and one charged pion
  - At least two photon showers and one π^0
  - Monochromatic electron $\Rightarrow P_e$ & $M_{\text{e\_recoil}}$
  - One undetected neutrino with missing energy $E_{\text{miss}} > 0.43\,\text{GeV}$





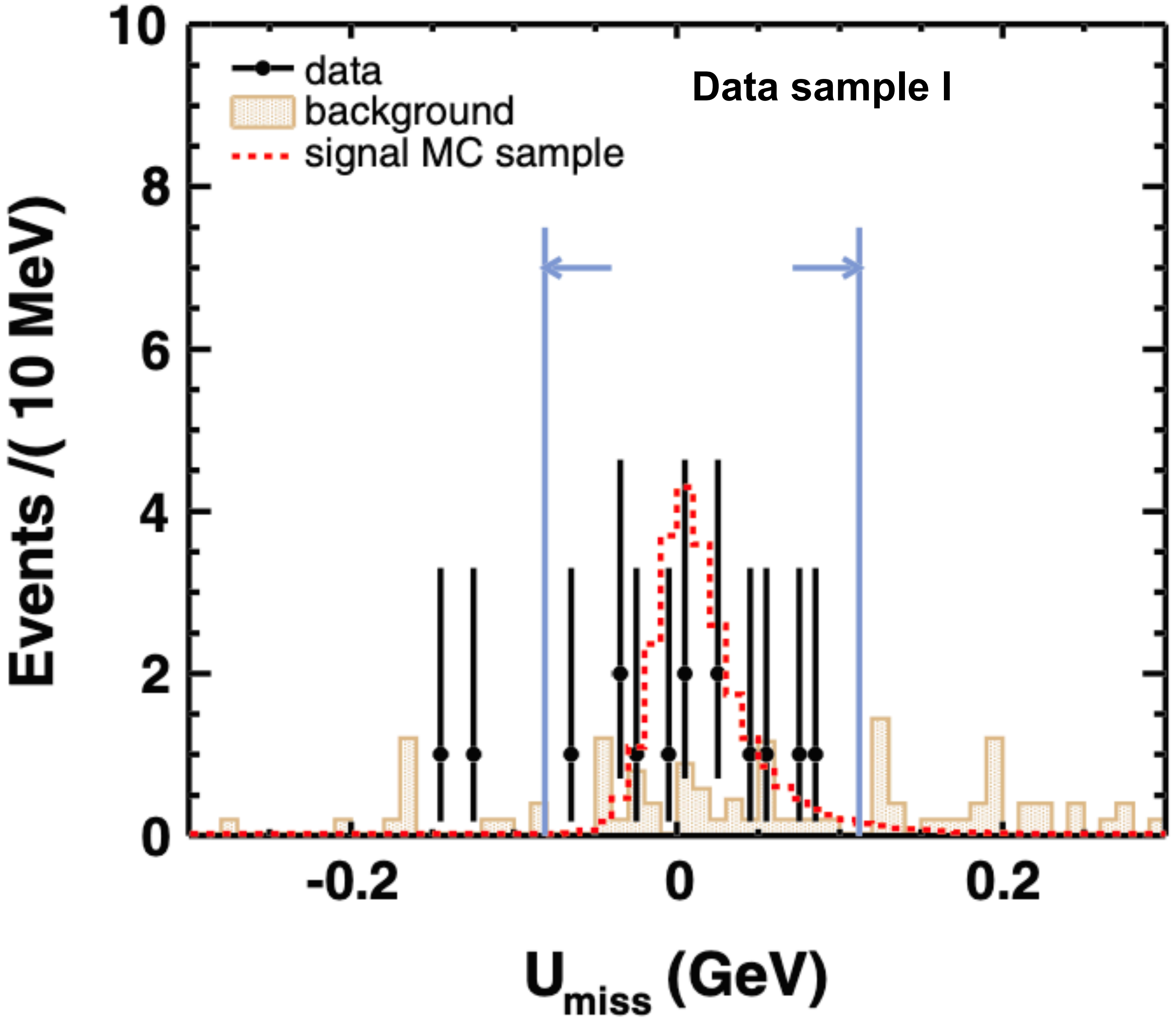
1.009 GeV/c < P_e < 1.068 GeV/c

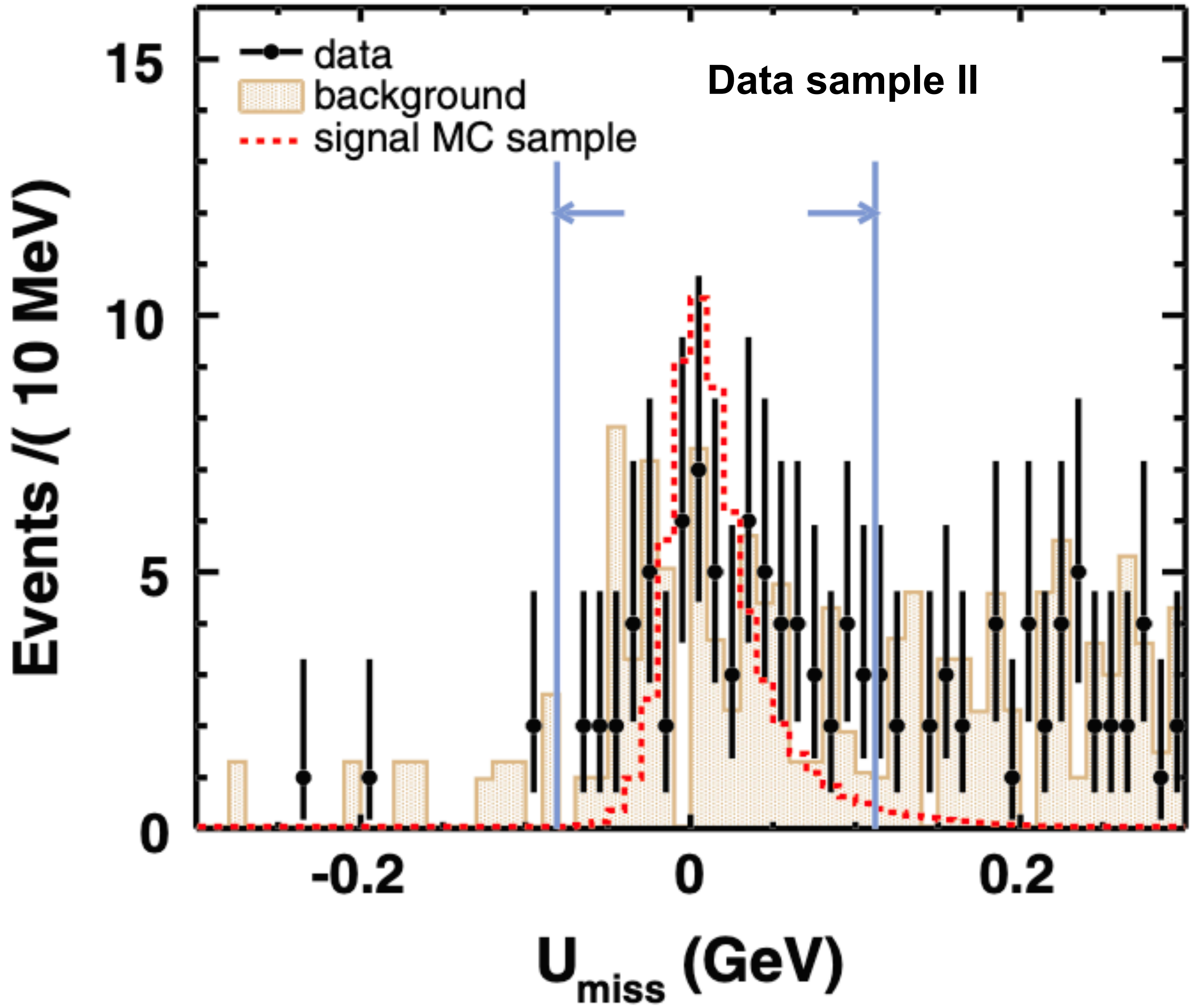


1.742 GeV/c^2 < $M_{\text{e\_recoil}}$ < 1.811 GeV/c^2

Analysis method

- ➔ Partial reconstruction
  - ❖ Missing energy $E_{\text{miss}} = E_{\text{CMS}} - E_e - E_\pi - E_{\pi^0}$
  - ❖ $U_{\text{miss}} = E_{\text{miss}} - c\,|\overrightarrow{P}_{\text{miss}}|$
- ➔ 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

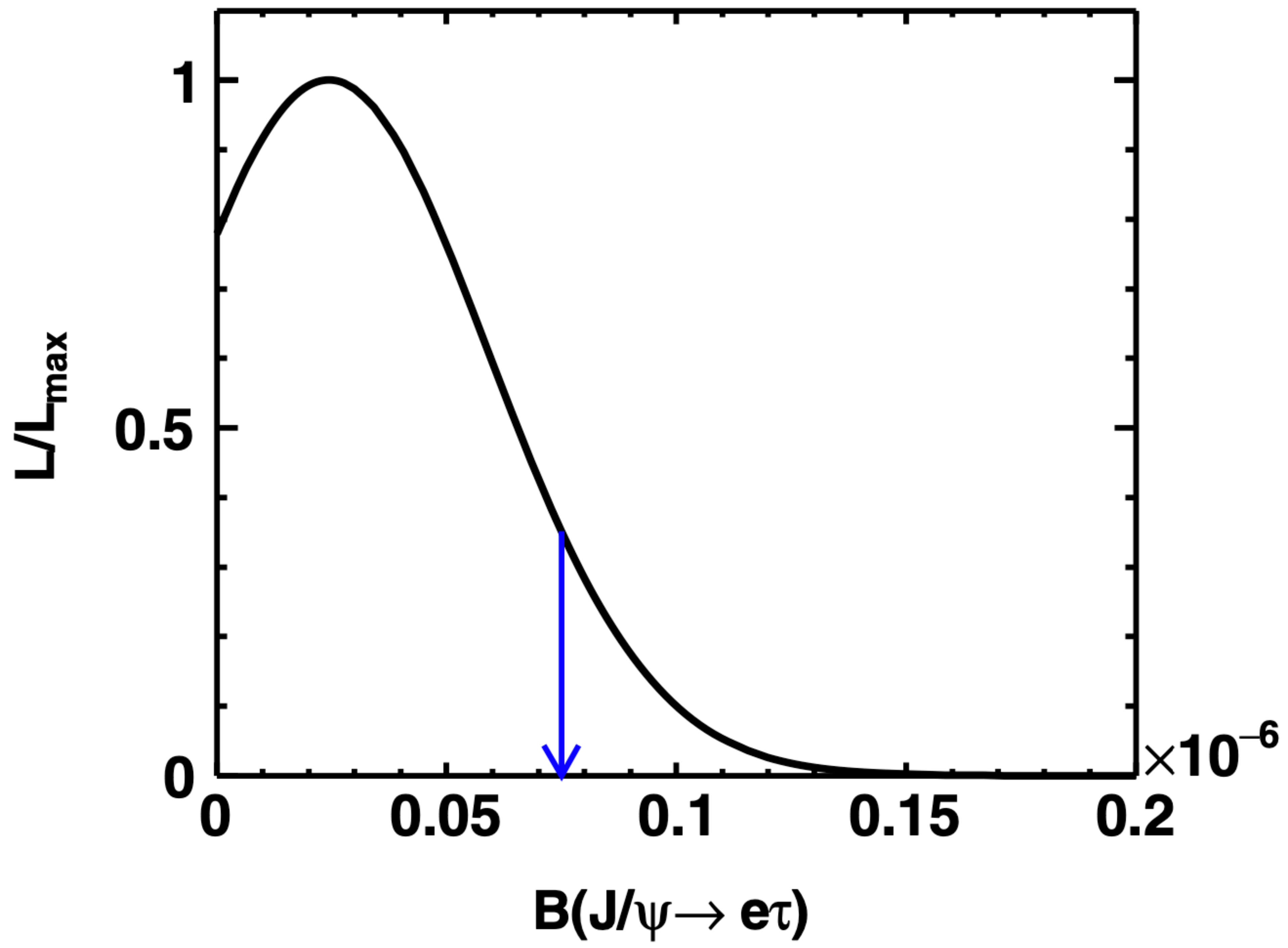
Sources	Sample I	Sample II
Number of J/ψ	0.5%	0.4%
Quoted BF*	0.4%	0.4%
MC model	0.6%	…
Pion PID*	1.0%	1.0%
Pion tracking*	1.0%	1.0%
Electron PID	0.4%	0.9%
Electron tracking*	0.1%	0.1%
Photon detection*	1.0%	1.0%
π^0 reconstruction*	1.0%	1.0%
P_e and M_{e_recoil} requirements	3.0%	3.3%
E_{miss} requirement	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 $\theta = (\epsilon_{\mathrm{eff}}, N_{\mathrm{bkg}})$

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

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



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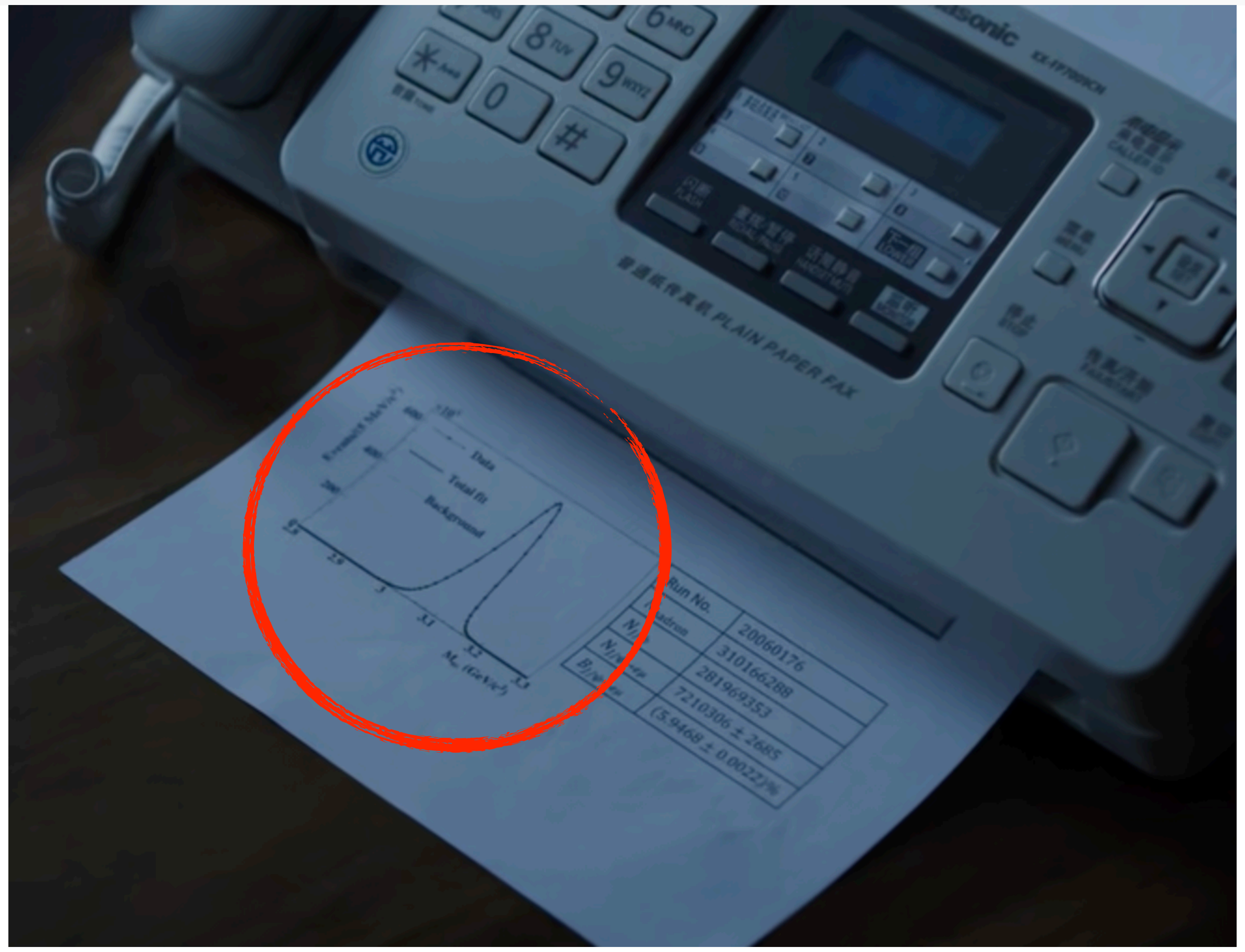
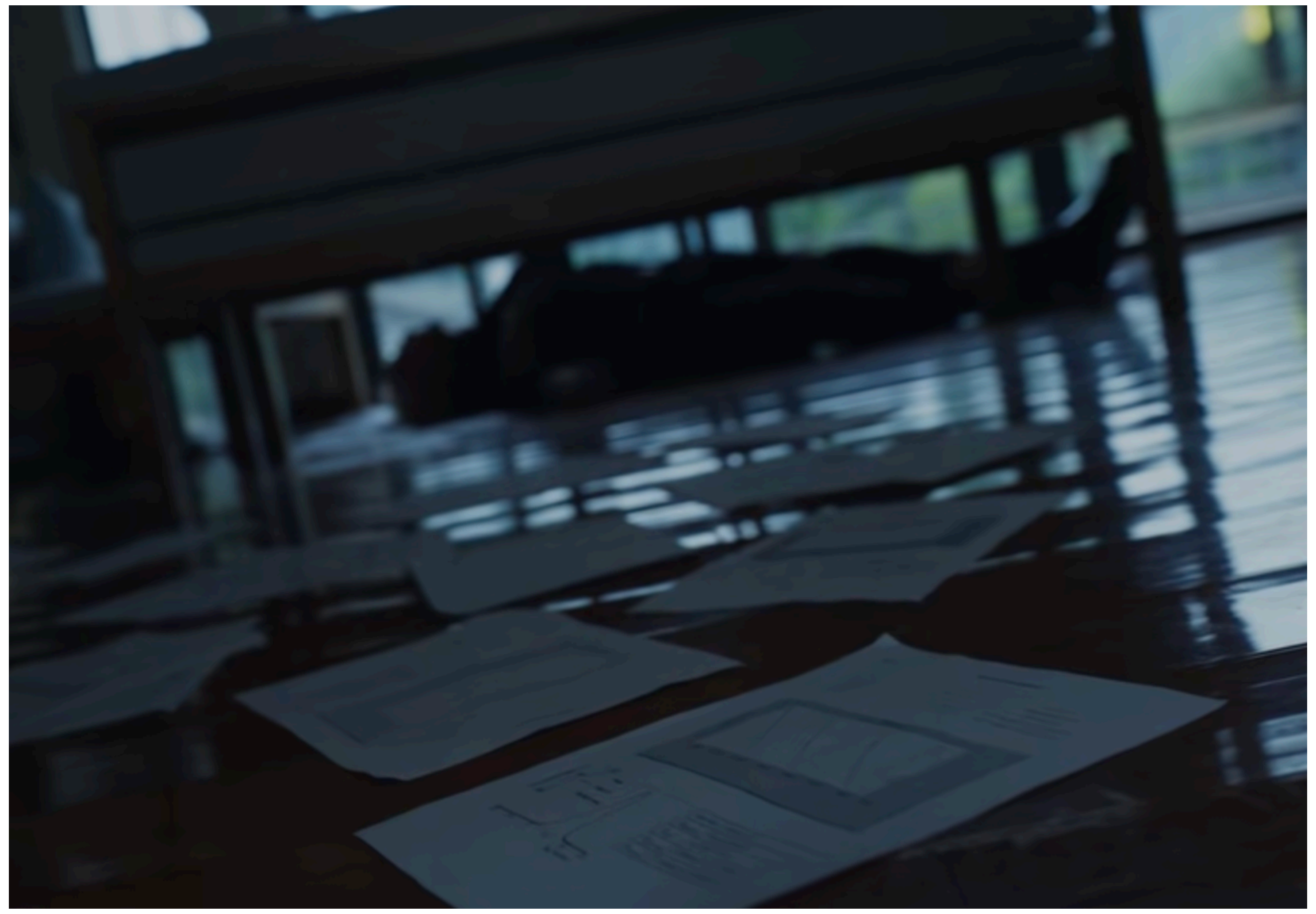
$$J/\psi \rightarrow e\mu$$

THREE-BODY!

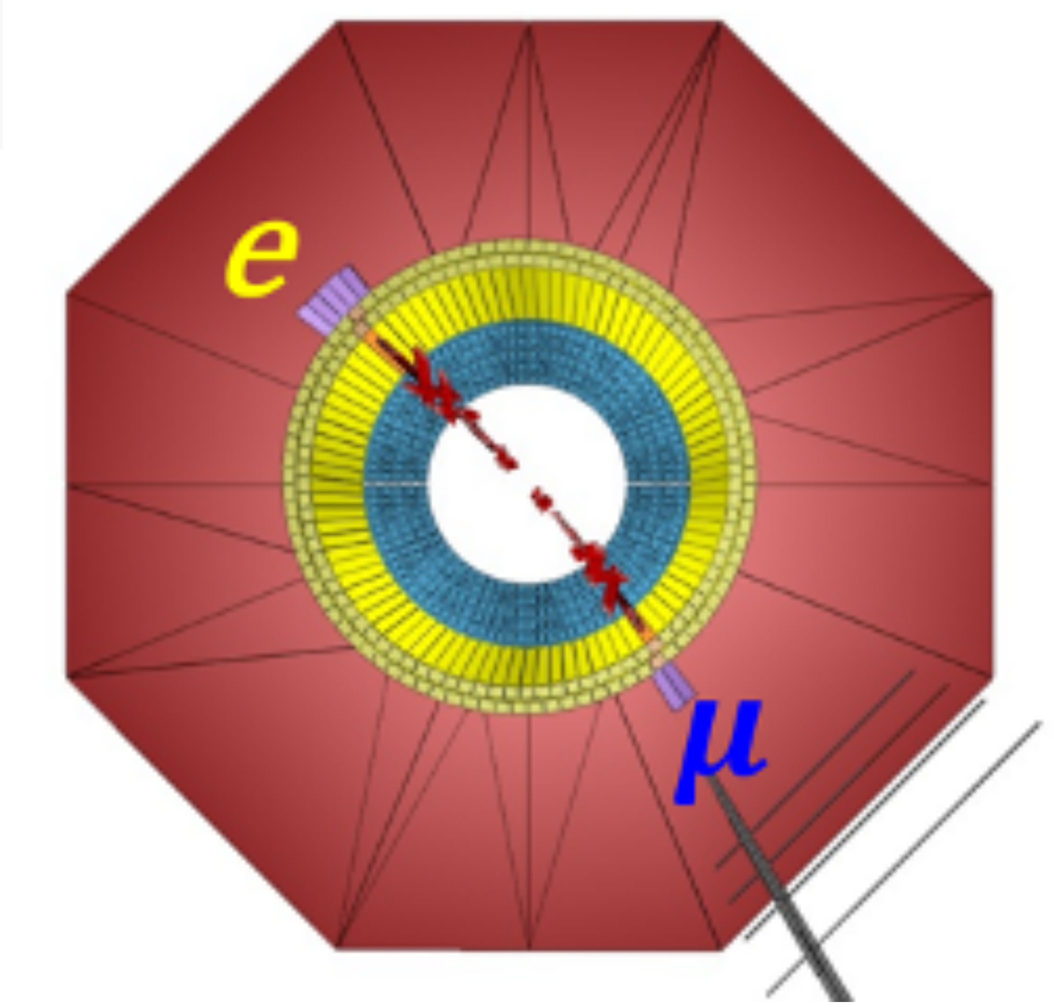




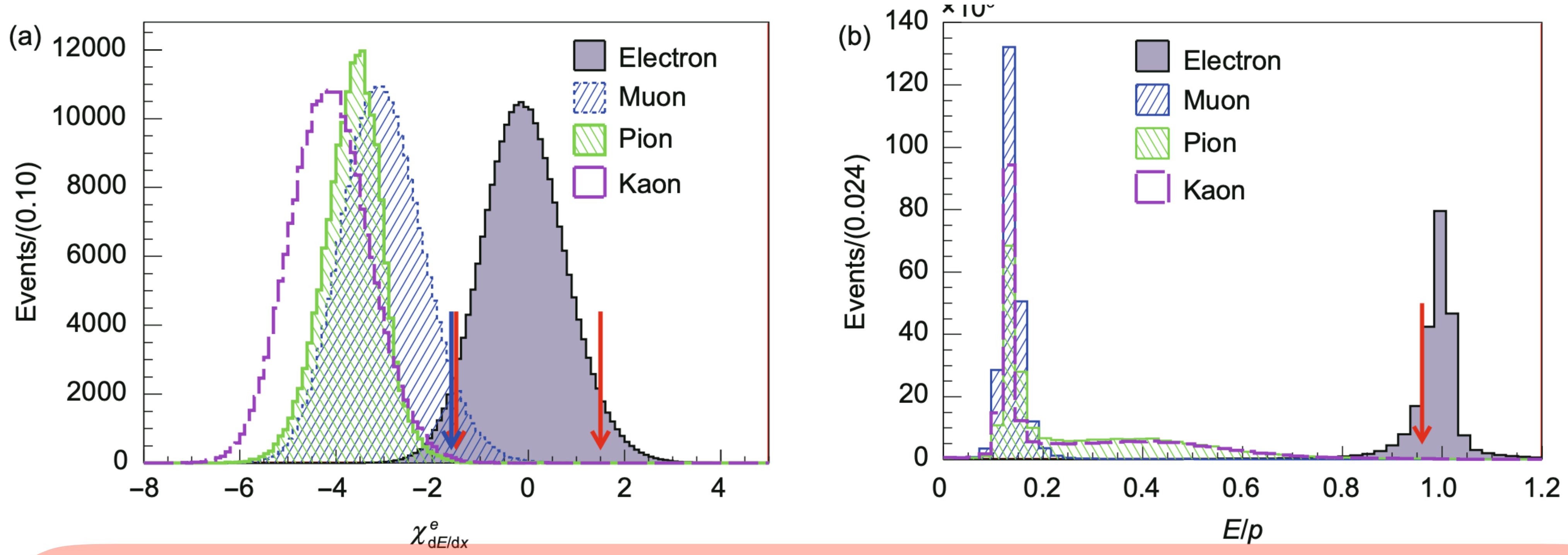
$J/\psi \to e\mu$ observed!
Physics doesn't exist!😨😱💀

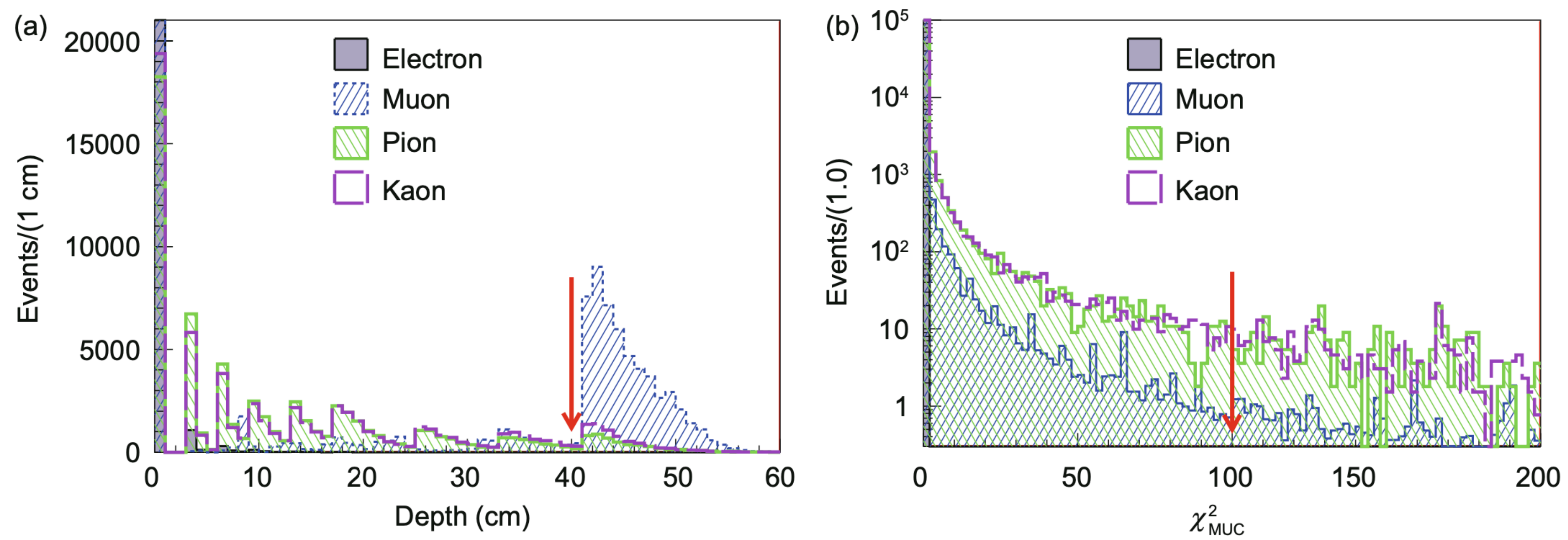
NOTE: Three-body is a scientific fiction written by Cixin Liu.
In 2023 and 2024, it was adapted for television.

$J/\psi \to e\mu$



- ➔ Analyzing $(8.998 \pm 0.040) \times 10^9$ J/ψ events (without 2012 data)
- ➔ 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 for PID





Electron ID

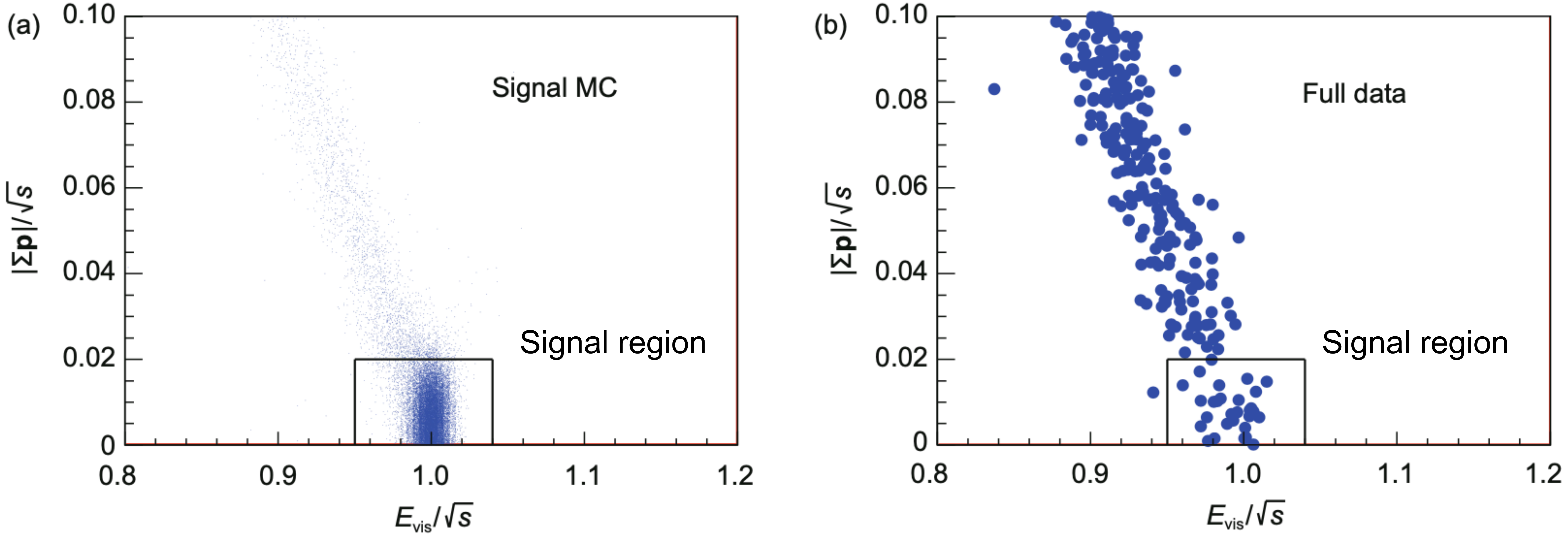
- Not associated in the MUC
- $-1.5 < \chi^e_{\mathrm{d}E/\mathrm{d}x} < 1.5$
  - $\chi^e_{\mathrm{d}E/\mathrm{d}x}$: the difference between measured and expected $\mathrm{d}E/\mathrm{d}x$ under the electron hypothesis normalized by the $\mathrm{d}E/\mathrm{d}x$ resolution)
- $E/p > 0.96$
  - E: the deposited energy in the EMC; p: the modulus of the momentum measured from MDC

Muon ID

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

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 are observed in data sample



Background study & signal efficiency

- ➔ Continuum background ($e^+e^- \to e^+e^-(\gamma), \mu^+\mu^-(\gamma)$)
  - Control sample: $\sqrt{s} = 3.773\,\mathrm{GeV}, 3.510\,\mathrm{GeV}, 3.080\,\mathrm{GeV}$
  - $1/s$ energy-dependence of cross section
  - $N^{\mathrm{norm}}_{\mathrm{bkg2}} = 12.0 \pm 3.7$
- ➔ J/ψ decay background ($J/\psi \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-, p\bar{p}$)
  - Inclusive MC + exclusive MC
  - $N^{\mathrm{norm}}_{\mathrm{bkg1}} = 24.8 \pm 1.5$
- ➔ Detection efficiency: $(21.18 \pm 0.13)\,\%$
  - Systematic uncertainties are studied

Systematic uncertainties

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

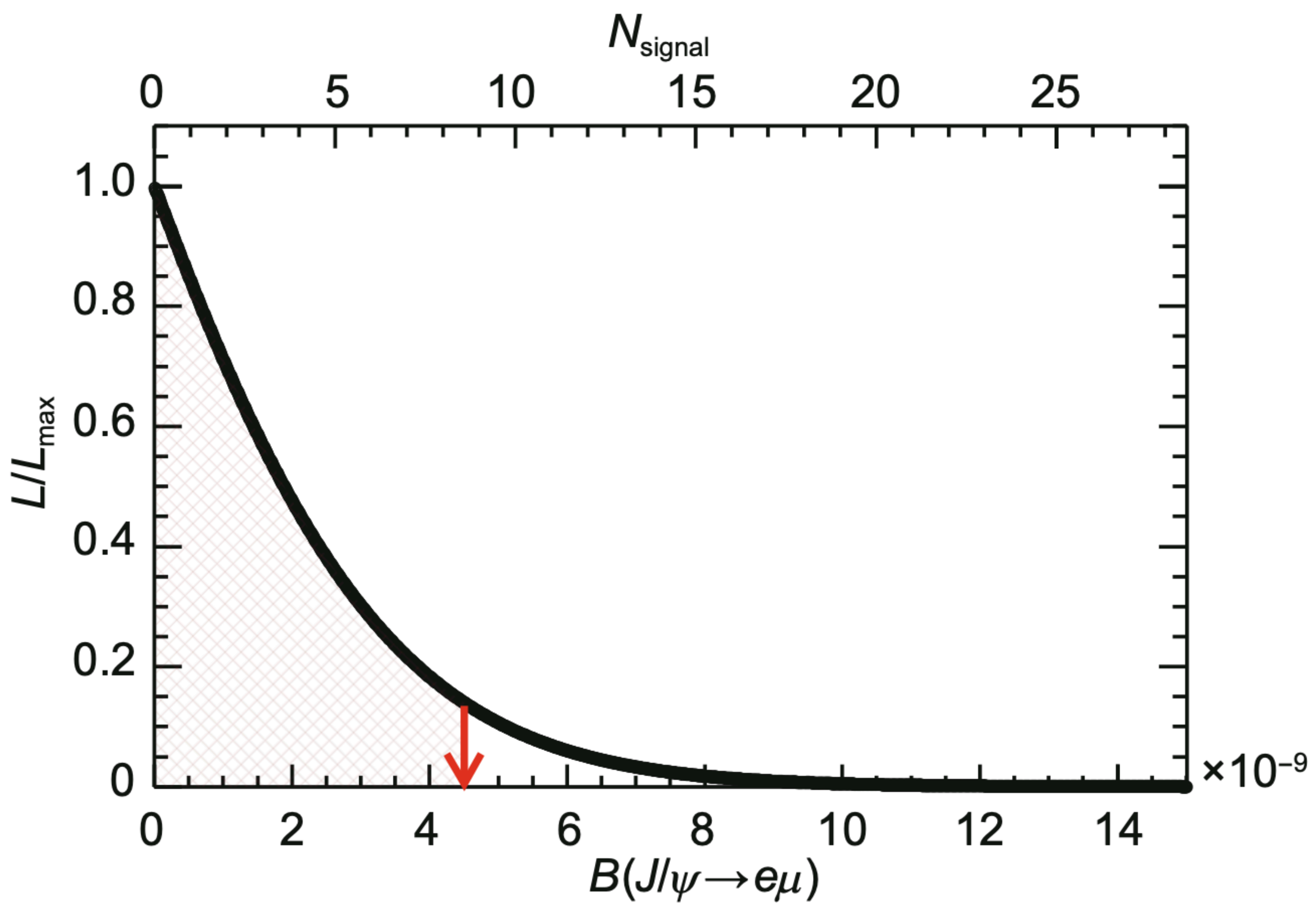
Control sample $e^+e^-(J/\psi) \to e^+e^-/\mu^+\mu^-$ are used

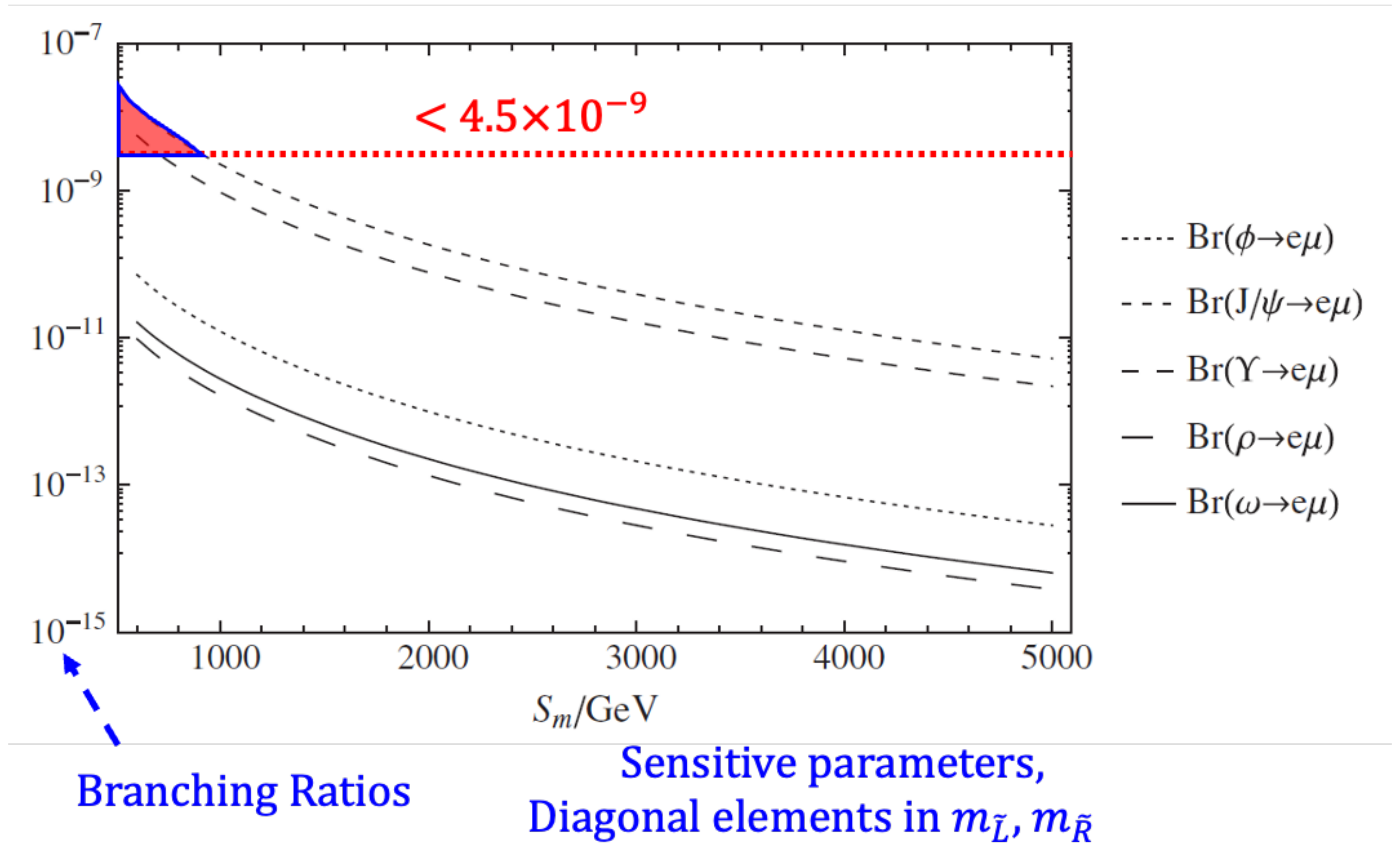
Upper limit result

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

$$\mathcal{L}(\mathcal{B}, \epsilon_{\text{sig}}, N_{J/\psi}, N_{\text{bkg1}}, N_{\text{bkg2}}) = \mathcal{P}(N_{\text{obs}} | N_{J/\psi} \cdot \mathcal{B} \cdot \epsilon_{\text{sig}} + N_{\text{bkg1}} + N_{\text{bkg2}}) \cdot \mathcal{G}(\epsilon_{\text{sig}} | \epsilon_{\text{sig}}^{\text{MC}}, \epsilon_{\text{sig}}^{\text{MC}} \cdot \sigma_{\text{sig}}^{\text{EFF}}) \cdot \mathcal{P}\left(N_{\text{bkg1}}^{J/\psi\text{-MC}} | N_{\text{bkg1}}/f_1\right) \cdot \prod_k \mathcal{P}(N_{\text{cont}}^k | N_{\text{bkg2}}/f_2^k) \cdot \mathcal{G}(N_{J/\psi} | N_{J/\psi}^{\text{data}}, \delta N_{J/\psi}^{\text{data}}).$$

- ➔ $\mathscr{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9} @ 90\,\%\,\text{CL}$
  - ❖ 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

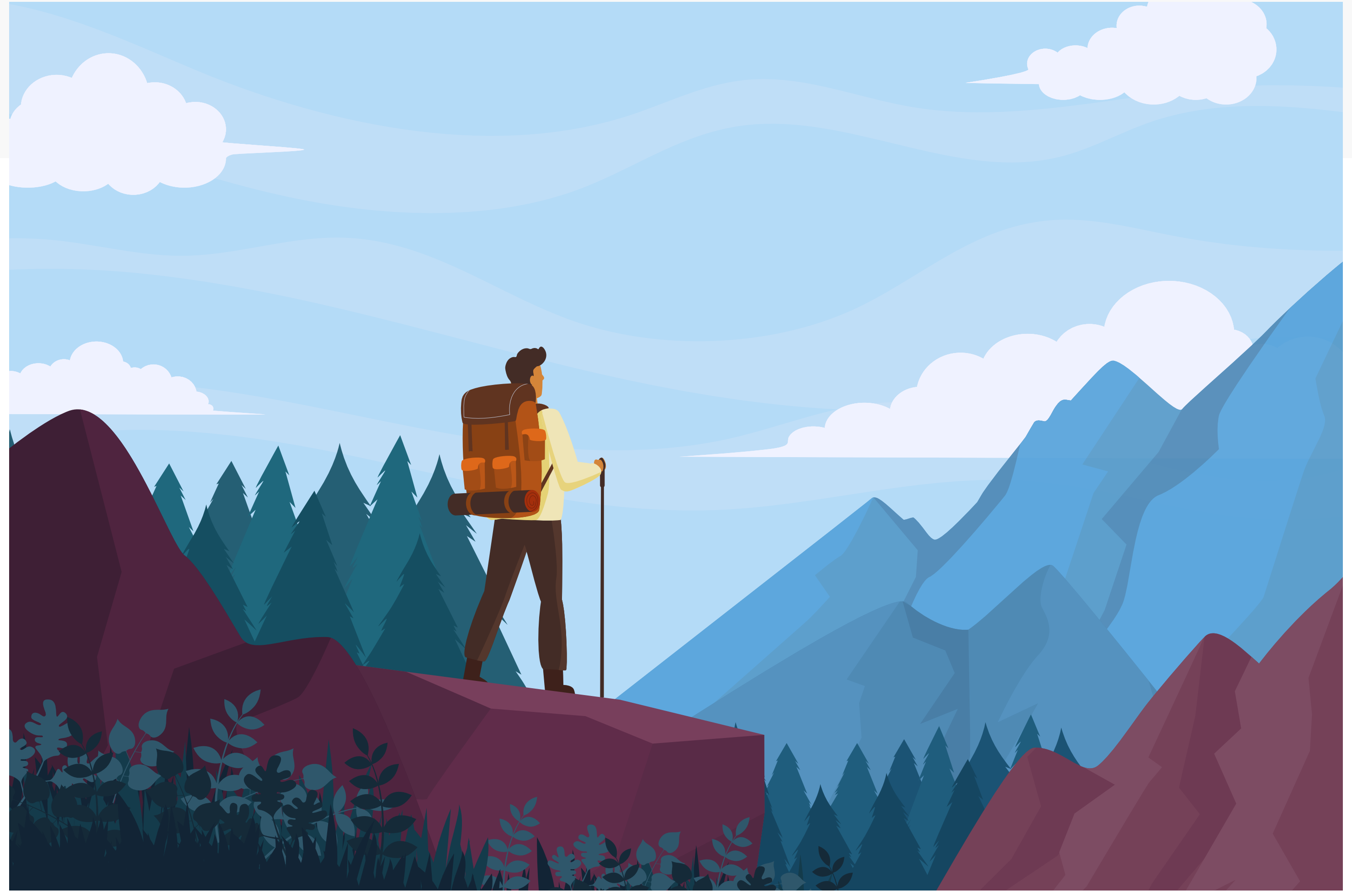




Phys. Rev. D 97, 056027 (2018)

Prospect and ongoing analysis

Prospect and ongoing analysis



- Update of J/ψ two-body cLFV decays with 10B events is ongoing
  - $J/\psi \to e\tau, \tau \to \mu\nu\nu$
  - $J/\psi \to \mu\tau$
  - Expected sensitivity $\mathcal{O}(10^{-8})$
- With large J/ψ, $\psi(3686)$, $\psi(3770)$ etc. samples, cLFV searches in many other states also ongoing
  - States with different quantum numbers sensitive to different operators in EFT [PRD 94, 074023 (2016)]
  - 0^- : $\eta', \eta_c(1S), D, D_s$
  - 1^- : $J/\psi, \psi(3686)$
  - J^+ : $\chi_{cJ}, h_c(1P)$
- Radiative cLFV also possible
  - 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	

Most of them not searched

Summary & outlook

Summary & outlook

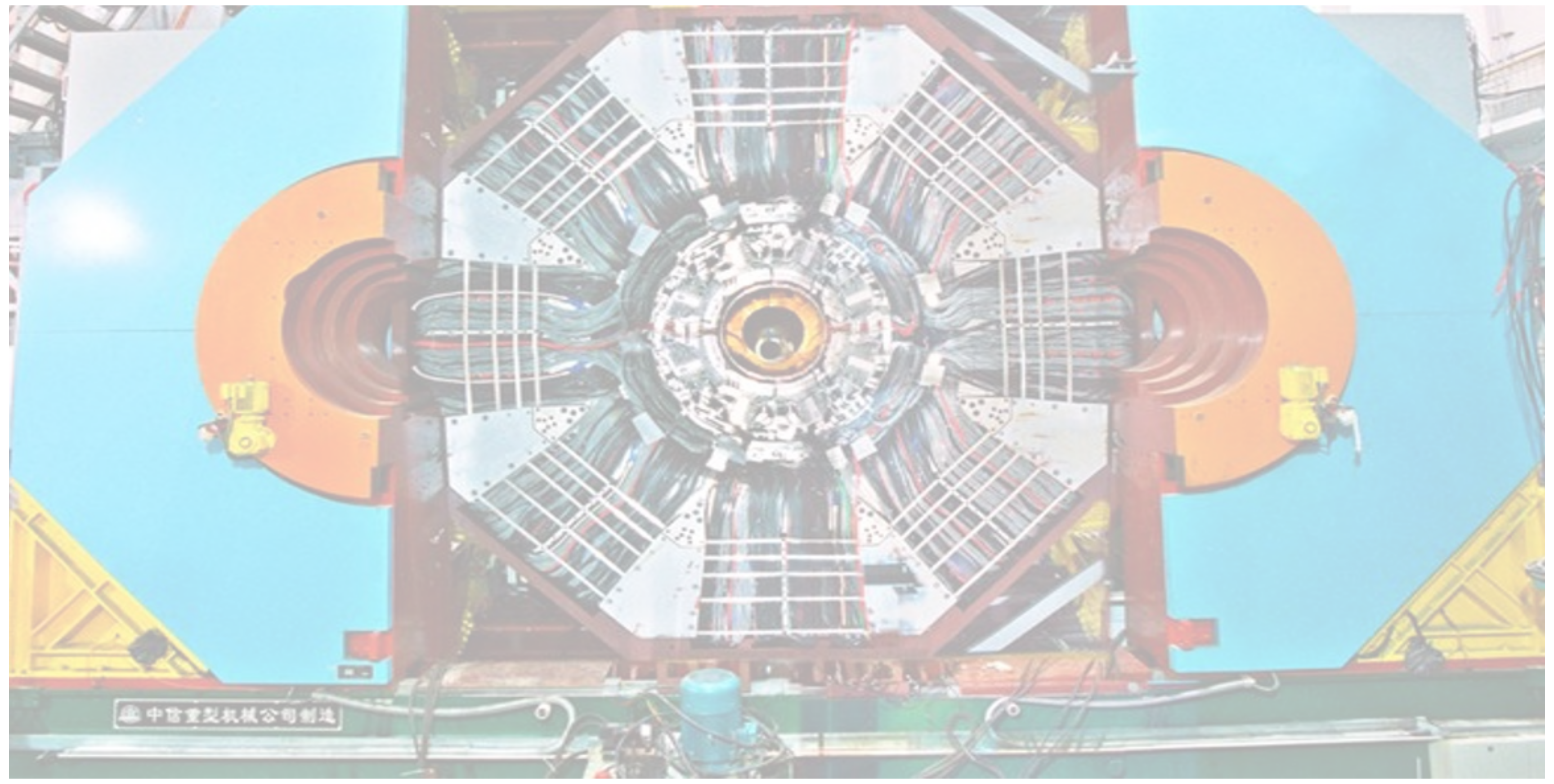
- BESIII has great potentials with unique (and increasing) datasets and analysis techniques, performed wide range study of new physics.

- 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!

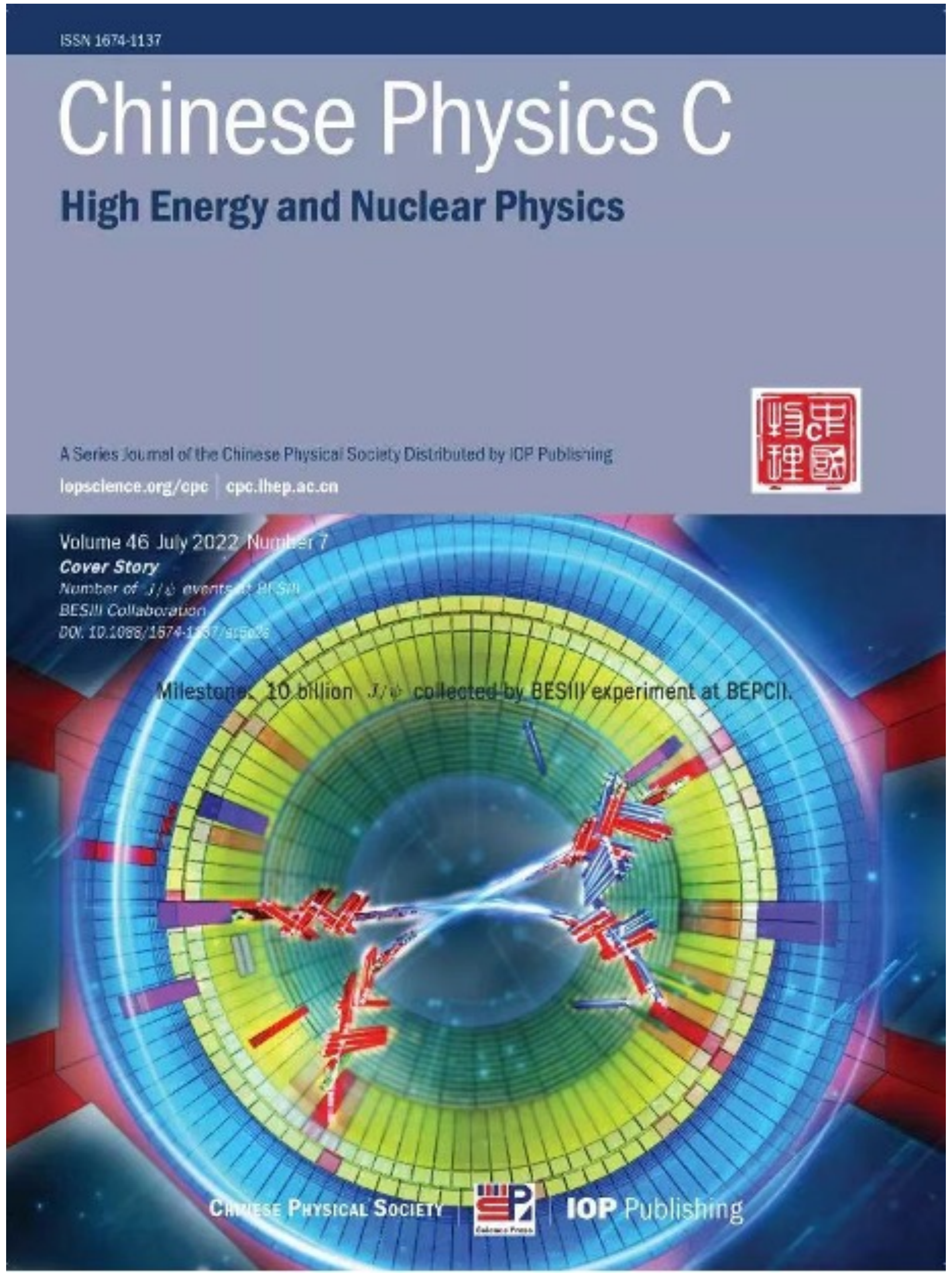


Backup

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:

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

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

Parameters in likelihood function

$J/\psi \to e\tau$

TABLE II. A summary of the analysis results. See the text for details.

Results	Sample I	Sample II
$N_{\rm obs}$	13	69
$N_{\rm bkg}^{\rm exp}$	6.9	63.6
$\sigma_{\rm bkg}^{\rm exp}$	1.9	13.2
$\epsilon_{\rm eff}^{\rm mc}$	20.24%	19.37%
$\sigma_{\rm eff}^{\rm mc}$	0.79%	0.79%
BF (90% C.L.)	7.5×10^{-8}	

$J/\psi \to e\mu$

Table 2 The values of the parameters for the likelihood function in eq. (4)

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