cLFV Searches at BESIII and Super Tau-Charm Factory

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LFV and LUV in meson and baryon decays
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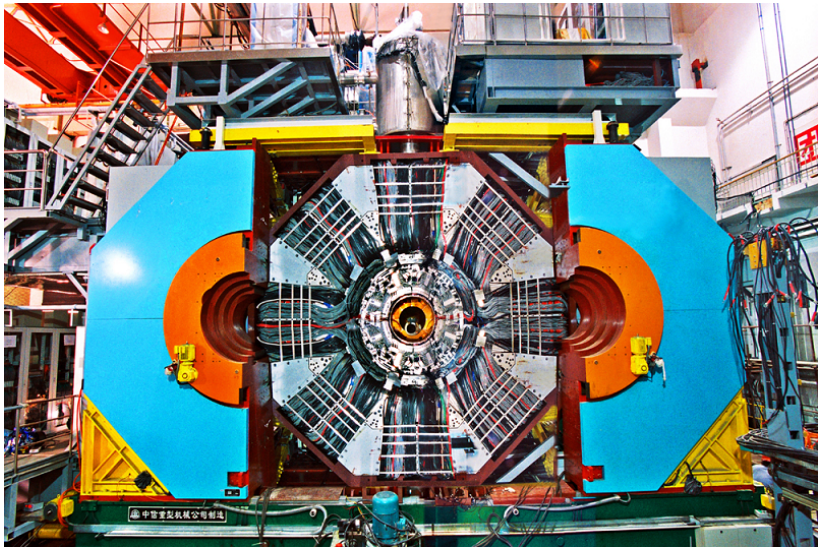
Outline

- About BESIII Exp
- Example: $J/\psi \rightarrow e\mu$ Analysis
- Ongoing and Potential cLFV topics
- Future prospects at BESIII & STCF
- Summary

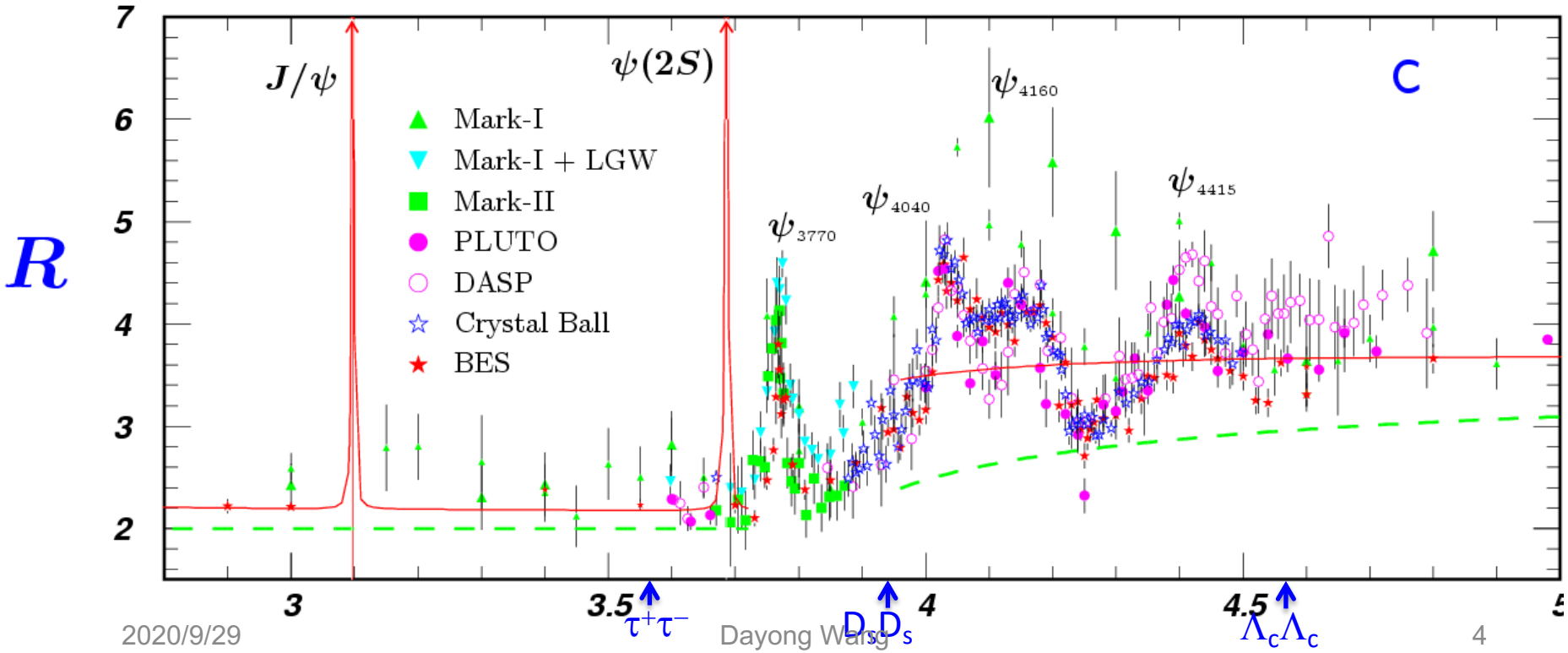
BEPCII and BESIII Exp



- BEPCII is an e+e- collider currently running at τ-charm energy
- First collision in 2008, physics run started in 2009
- BEPCII reached peak lumi of $1x10^{33}$ $cm^{-2}s^{-1}$@1.89GeV in April 2016
- More than 300 journal publications
- BESIII collaboration includes ~500 collaborators, still growing

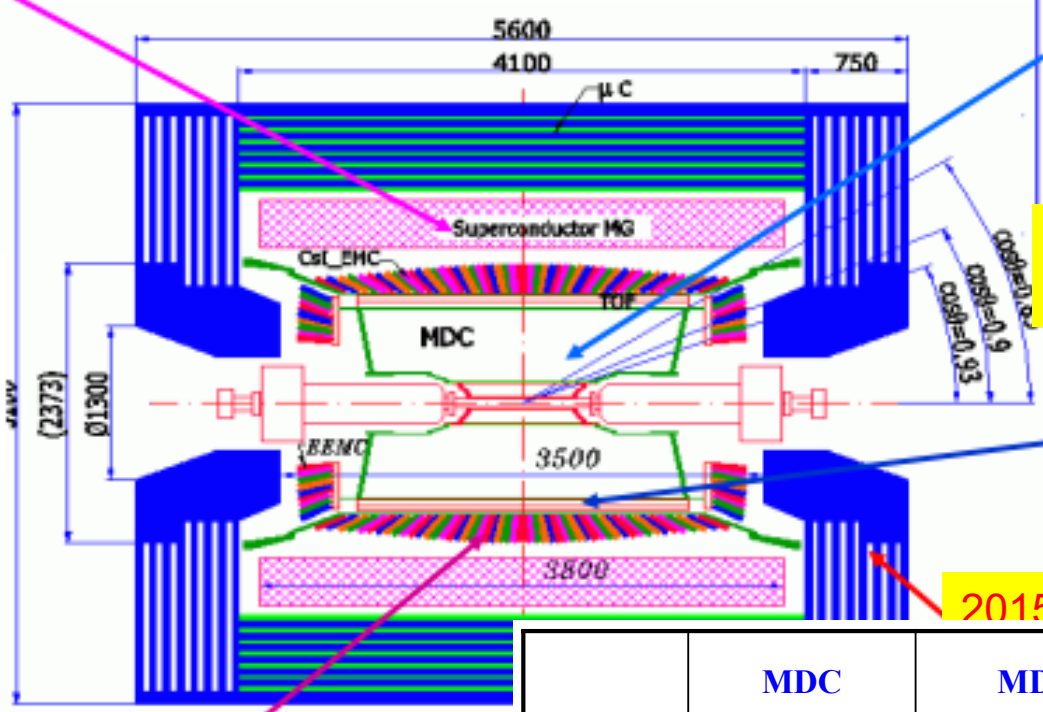
BEPCII: a τ-c Factory

- Rich of **resonances**, charmonia and charmed mesons.
- **Threshold** characteristics (pairs of τ, D, D_s, charmed baryons…).
- **Transition** between perturbative and non-perturbative **QCD**.
- **New hadrons**: glueballs, hybrids, multi-quark states
- **New Physics: high lumi, large datasets, hermetic detector with good performance**



BESIII Detector

Solenoid Magnet: 1 T Super conducting



MDC: small cell & He gas
σ_{xy}=130 μm
$\delta p/p$ = 0.5% @1GeV
dE/dx=6%

2022: Inner tracker upgrade

Ref:
NIM A614, 345 (2010)

TOF:
σ_T = 90 ps Barrel
110 ps Endcap

2015 ETOF upgrade: 60ps

EMCAL: CsI crystal
ΔE/E = 2.5% @1 GeV
$\sigma_{\varphi,z}$ = 0.5~0.7 cm/√E

Data Acquisi
Event rate =
Throughput

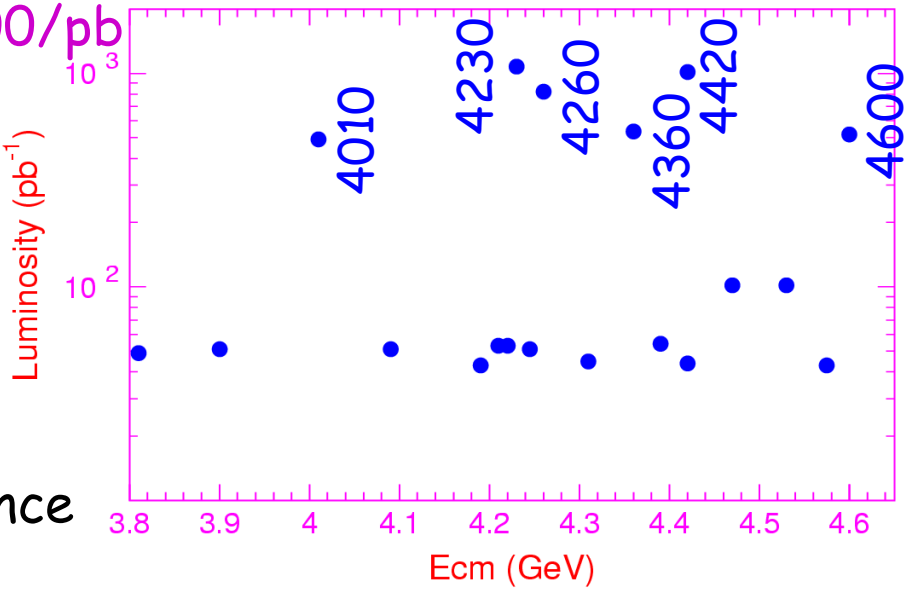
Clean environment and h
helpful for indirect

Exps.	MDC Spatial resolution	MDC dE/dx resolution	EMC Energy resolution
CLEO-c	110 μm	5%	2.2-2.4 %
BaBar	125 μm	7%	2.67 %
Belle	130 μm	5.6%	2.2 %
BESIII	115 μm	<5% (Bhabha)	2.4%

BESIII data samples

~ 0.5 B	$\psi(3686)$ events	~ 24×CLEO-c
~ 1.3 B	J/ψ events	~ 21×BESII
~ 2.9/fb	$\psi(3770)$	~ 3.5×CLEO-c
~16/fb	**XYZ** states above 4 GeV	Unique

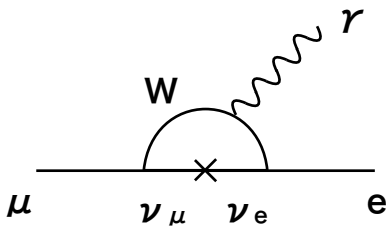
- 20 points for R &QCD Scan: 500/pb in 2015
- Y(2175) resonance: 100 /pb :
- 3/fb Ds data at 4170 MeV ~ 5×CLEO-c
- 3/fb 4.6-4.7GeV data in 2020



~ other data sets: tau, Λ_c, resonance scan and continuum, etc.

General: Search for cLFV

Considering neutrino mixing, extended νSM

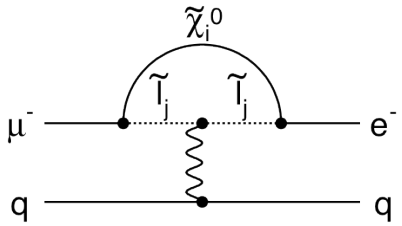


$$\mathcal{M} \propto \sum_j U_{ej} U^*_{\mu j} \frac{m_j^2}{M_W^2}$$

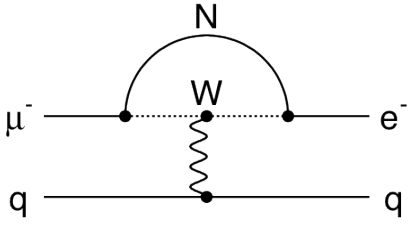
$$\sim \mathcal{O}(10^{-54})$$

Possible CLFV from NP models

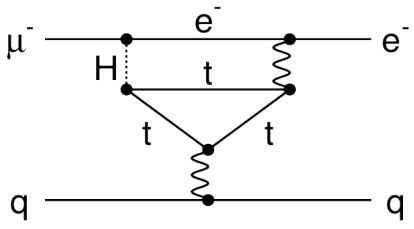
Loops



Supersymmetry

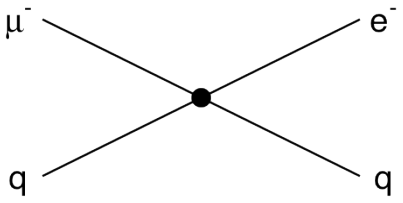


Heavy Neutrinos

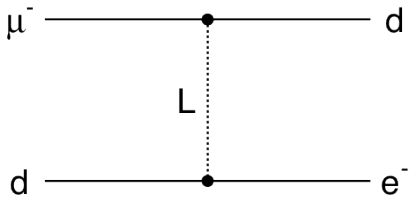


Extended higgs models

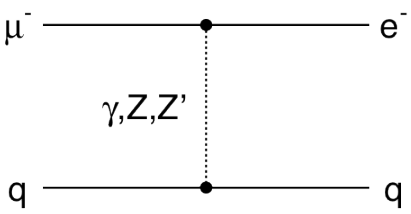
Contact Terms



Compositeness



Leptoquarks



New Heavy Bosons / Anomalous Couplings

cLFV in Jpsi decays

- The cLFV search in lepton decay, pseudoscalar meson decay and vector meson decay etc with no evidence. Equally important to search it in heavy quarkonium decays.

- The cLFV decays of vector mesons $V \to l_i l_j$ are also predicted **in various of extension models** of SM[1]:

$$\mathcal{B}_{UL}^{90}(J/\psi \to e\mu) < 10^{-13}$$

$$\mathcal{B}_{UL}^{90}(J/\psi \to e(\mu)\tau)\ ) < 10^{-9}$$

- J/ψ LFV decays have been measured by BES collaboration.

	BES	BESIII
$J/\psi \to e\mu$	$< 1.1\times10^{-6}$	$< 1.6\times10^{-7}$
$J/\psi \to e\tau$	$< 8.3\times10^{-6}$	-
$J/\psi \to \mu\tau$	$< 2.0\times10^{-6}$	-

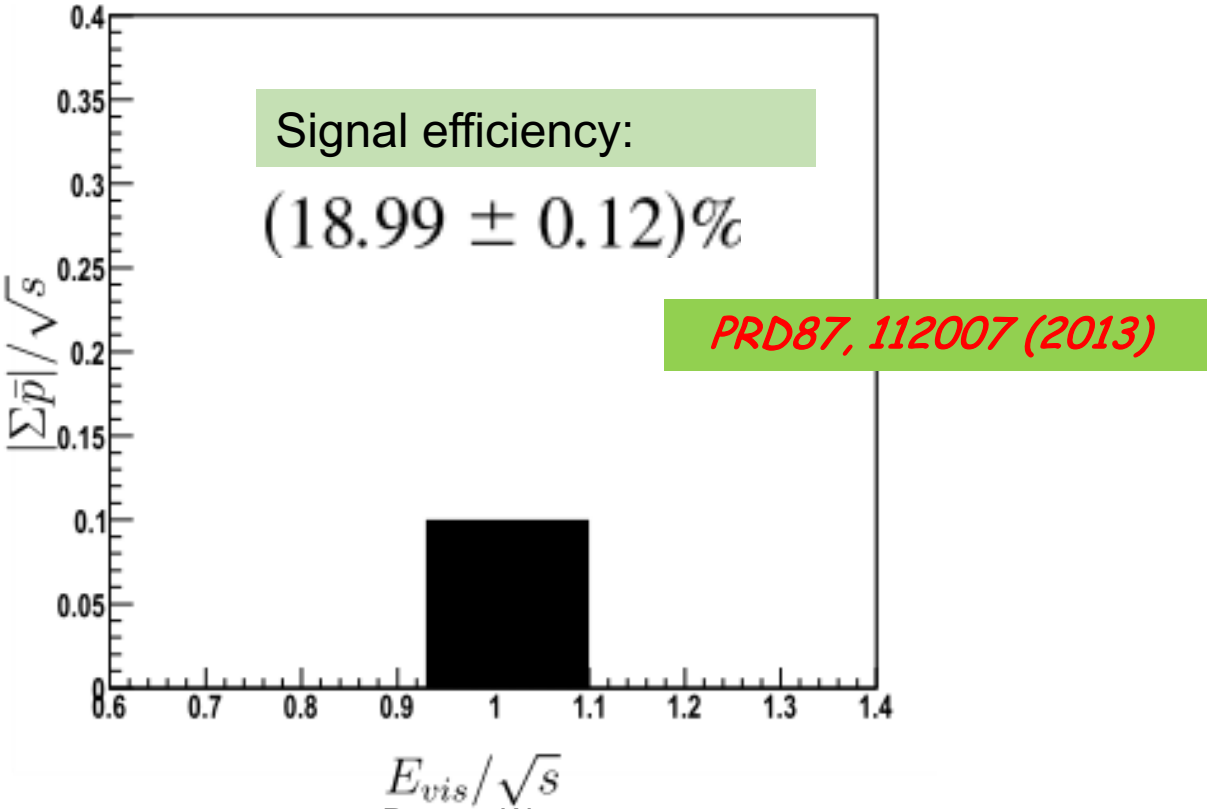
[1]: Phys. Rev. D 63, 016003, Phys. Rev. D 83, 115015, Phys. Lett. A 27, 1250172, Phys. Rev. D 97, 056027

Search for J/ψ → eμ(w/ 225M Jpsi)

Signal box definition based on MC

$$|\Sigma\vec{p}|/\sqrt{s} \pm 2\sigma \text{ and } E_{vis}/\sqrt{s} \pm 2\sigma$$

$$0.93 \leq E_{vis}/\sqrt{s} \leq 1.10 \text{ and } |\Sigma\vec{p}|/\sqrt{s} \leq 0.1$$



Signal efficiency:

$(18.99 \pm 0.12)\%$

PRD87, 112007 (2013)

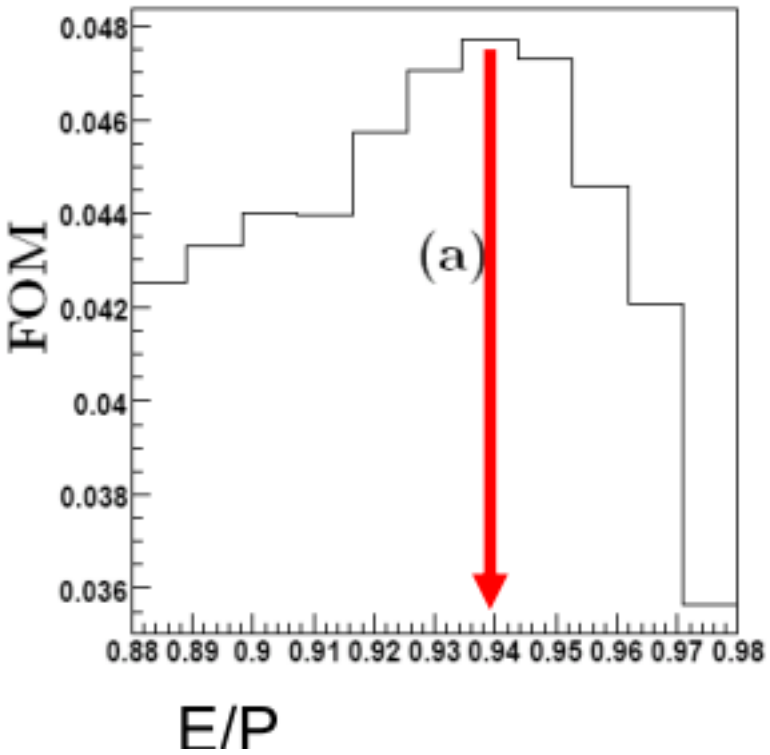
Event Selection Optimization

cut optimization

$$\mathrm{FOM} = \frac{\epsilon}{\sum_{N_{\mathrm{obs}}=0}^{\infty} P(N_{\mathrm{obs}}|N_{\mathrm{exp}}) \cdot UL(N_{\mathrm{obs}}|N_{\mathrm{exp}})}$$

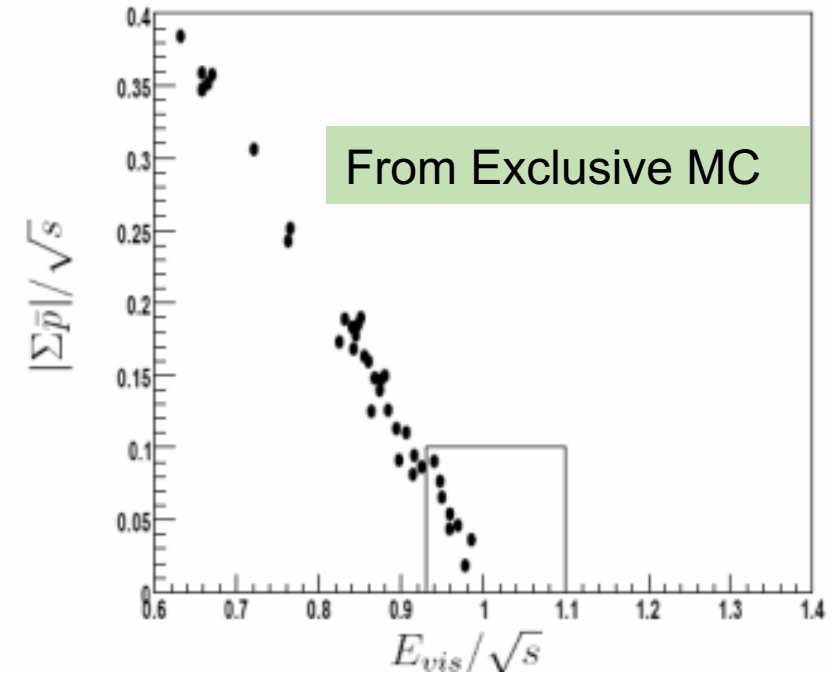
The optimized cuts after maximizing the FOM

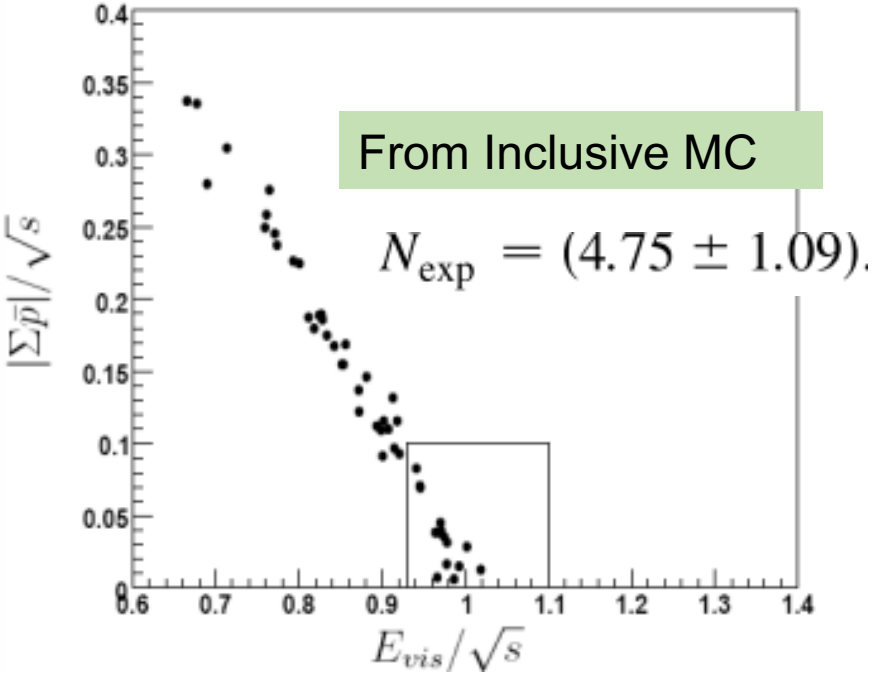
Criteria	optimized value
$\lvert\Delta\theta\rvert <$	0.9°
$\lvert\Delta\phi\rvert <$	1.4°
egam <	15 MeV
egam1 <	50 MeV
egam2 <	15 MeV
for e: $E/P >$	0.94
for e: $\lvert\chi^e_{dE/dx}\rvert <$	1.8
for μ: $\chi^e_{dE/dx} <$	-1.8
for μ: Depth >	40 cm



Background study

Background channel	normalized number	Model
$J/\psi \to e^+e^-$	2.7×10^7	PHOTOS and VLL[13]
$J/\psi \to \mu^+\mu^-$	2.7×10^7	PHOTOS and VLL[13]
$J/\psi \to \pi^+\pi^-$	1.0×10^5	PHSP[13]
$J/\psi \to K^+K^-$	7.0×10^4	PHSP[13]
$e^+e^- \to e^+e^-(\gamma)$	2.7×10^7	Babayaga[15]
$e^+e^- \to \mu^+\mu^-(\gamma)$	1.0×10^5	Babayaga[15]

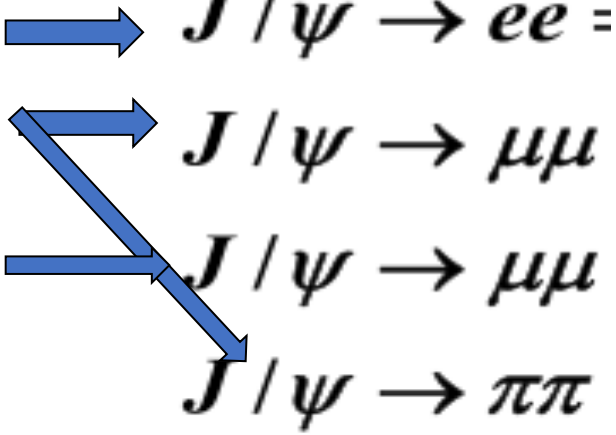




Systematic Uncertainties

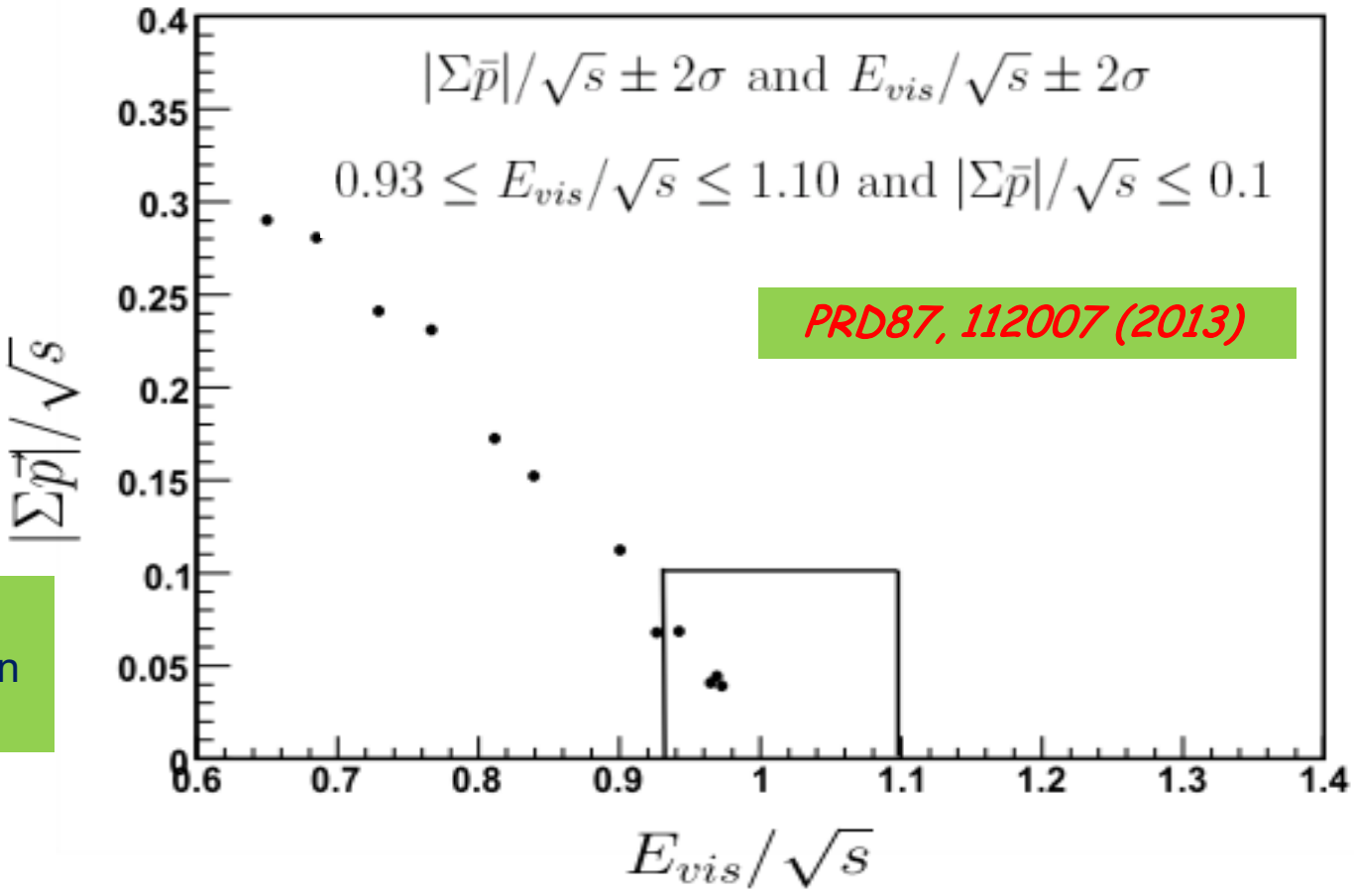
Sources	Error
$e^{\pm}$ tracking	1.00
$\mu^{\pm}$ tracking	1.00
$e^{\pm}$ ID	0.62
$\mu^{\pm}$ ID	0.04
Acollinearity, acoplanarity	5.36
Photon veto	1.19
$N_{J/\psi}$	1.24
Total	5.84

$\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to e^+e^-$, $\mu^+\mu^-$



Relative, most from control samples, in percentage

J/ψ → eμ: Unblinded Results



Among 225M J/ψ, 4 events in the signal box

$$\mathcal{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7} \text{ (90\% C.L.)}$$

Future BESIII upgrade & data sets

Extended running of another 5-8 years, with upgrade in both energy and lumi
Top-up injection since 2019, energy increase up to 4.9GeV soon

Energy	Physics motivations	Expected final data
1.8 - 2.0 GeV	R values Nucleon cross-sections	0.1 fb^{-1} (fine scan)
2.0 - 3.1 GeV	R values Cross-sections	omplete scan (additional points)
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	4.5 fb^{-1} (3.0 billion)
$\psi(3770)$ peak	$D^0/D^{\pm}$ decays	20.0 fb^{-1}
3.8 - 4.6 GeV	R values XYZ/Open charm	No requirement
4.180 GeV	D_s decay XYZ/Open charm	6 fb^{-1}
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	30 fb^{-1} at different $\sqrt{s}$
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	15 fb^{-1} at different $\sqrt{s}$
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	1.0 fb^{-1}
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	1.0 fb^{-1}
4.95 GeV	Ξ_c decays	1.0 fb^{-1}

Chinese Phys. C **44**, 040001 (2020).

Jspi cLFV decay beyond eμ

$J/\psi \to e^+\tau^- \quad \tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau + cc.$

$J/\psi \to \mu^+\tau^- \quad \tau^- \to e^-\bar{\nu}_e\nu_\tau + cc.$

$J/\psi \to \gamma e^+\tau^- \quad \tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau + cc.$

$J/\psi \to \gamma\mu^+\tau^- \quad \tau^- \to e^-\bar{\nu}_e\nu_\tau + cc.$

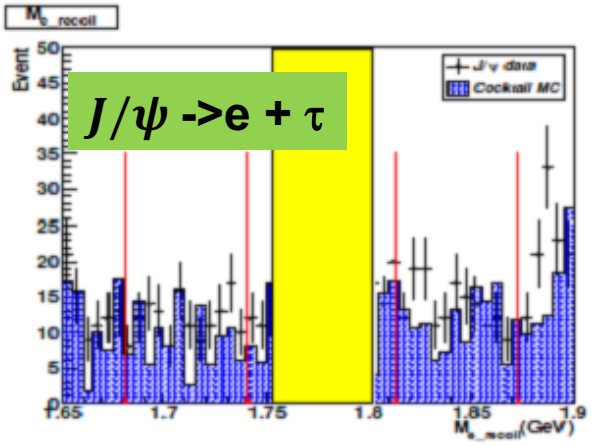
- ✓ From preliminary MC studies, the efficiencies could reach ~30-35%, and the BR sensitivity could be in the level of 1E-8 to 1E-7
- ✓ Better up limit could be achieved if QED description & PID on muons improved

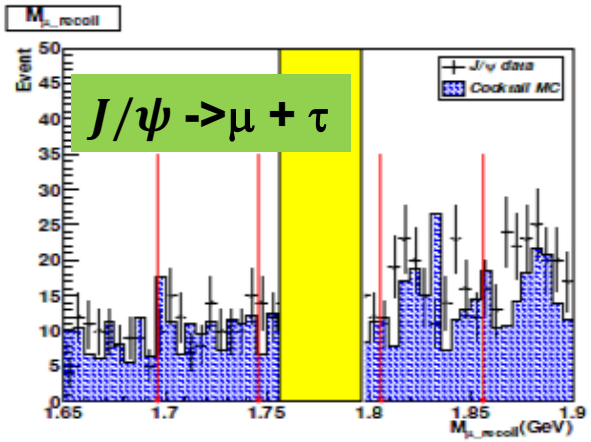
- ✓ **Detailed data analysis without photons is being performed (J/ψ-> e τ/μτ)**
- ✓ **Channels with photons are also in investigation (J/ψ-> γeτ/γμτ)**

cLFV processes from psi(2S), D, η and η′ decays are also possibly to search at BESIII, esp for final datasets

cLFV searches in J/ψ: Prospects

$$\mathcal{A}(V \to \ell_1\bar{\ell}_2) = \bar{u}(p_1, s_1)\left[A_V^{\ell_1\ell_2}\gamma_\mu + B_V^{\ell_1\ell_2}\gamma_\mu\gamma_5 + \frac{C_V^{\ell_1\ell_2}}{m_V}(p_2 - p_1)_\mu + \frac{iD_V^{\ell_1\ell_2}}{m_V}(p_2 - p_1)_\mu\gamma_5\right] v(p_2, s_2)\ \epsilon^\mu(p)$$





$J/\psi \to$ e(μ) τ
$J/\psi \to$ e μ
$J/\psi \to \gamma$ e(μ) τ
$\psi(2s) \to \gamma$ e(μ) τ

Expected to *improve the UL by ~10^2*

$\ell_1\ell_2$	$\mu\tau$	$e\tau$	$e\mu$
Current UL	2.0×10^{-6}	8.3×10^{-6}	1.6×10^{-7}
BESIII projected(CC)	3.0×10^{-8}	4.5×10^{-8}	1.0×10^{-8}
BESIII projected(MVA/ML)	1.5×10^{-8}	2.5×10^{-8}	6.0×10^{-9}

Phys. Rev. D **87**, 112007 (2013).

Wilson coeff (GeV^{-2})	Leptons $\ell_1\ell_2$	Constraints Current	Projected
$\left\|C_{VL}^{cc\ell_1\ell_2}/\Lambda^2\right\|$	$\mu\tau$	5.5×10^{-5}	$[5.0, 7.1] \times 10^{-6}$
	$e\tau$	1.1×10^{-4}	$[6.5, 8.7] \times 10^{-6}$
	$e\mu$	1.0×10^{-5}	$[2.8, 3.7] \times 10^{-6}$

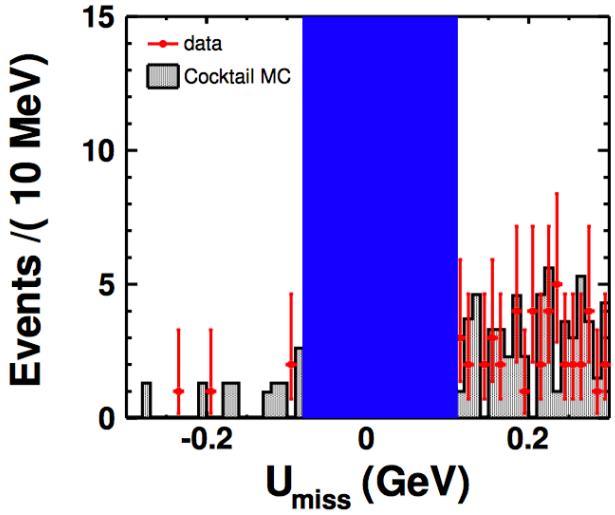
efficiencies ~30-35%

$J/\psi \rightarrow e\tau$ via hadronic modes

- Search for Charged Lepton Flavor Violation Process $J/\psi \rightarrow e\tau$ with $\tau \rightarrow \pi\pi^0\nu$ with 10 billions J/ψ events.
- Semi-blind analysis is used in this study to avoid possible biases from the experimentalist.
- Signal MC sample, J/ψ inclusive MC sample, J/ψ exclusive MC samples, and continuum data are used to optimize event selection criteria and study background.
- Most systematic uncertainties are determined from comparisons of MC with clean, high statistics control samples.
- Small portion (~10%) of data are used for validation. The upper limit is given with a profile likelihood method.
- After verifying the analysis strategies, the whole data set is unblinded and the final upper limit is given.

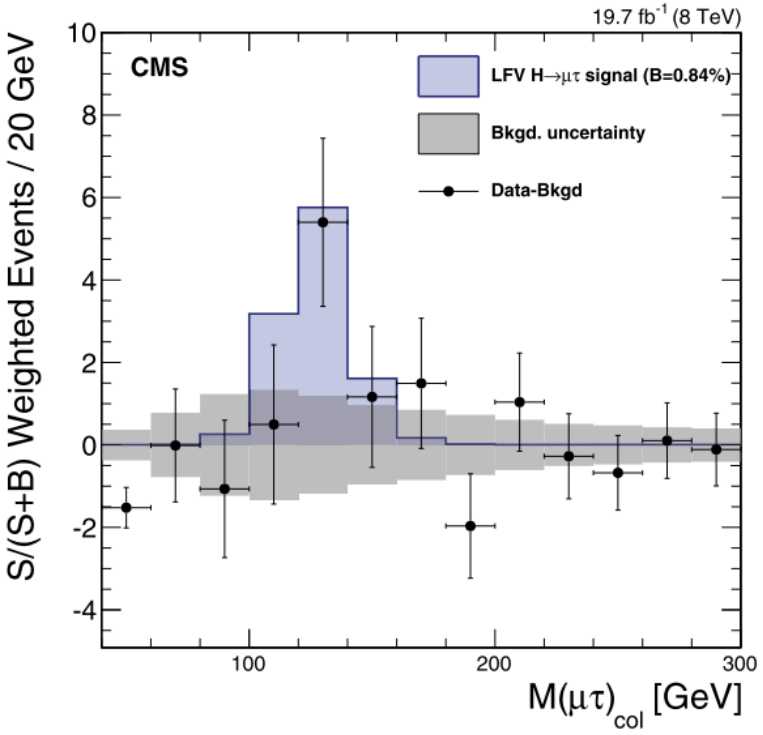
Sensitivity projection

- Cocktail MC sample is comparable with the J/ψ data sample in the sideband regions.



- The upper limit of branching ratio could be up to 10^{-8} with 10 billion J/ψ data.

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



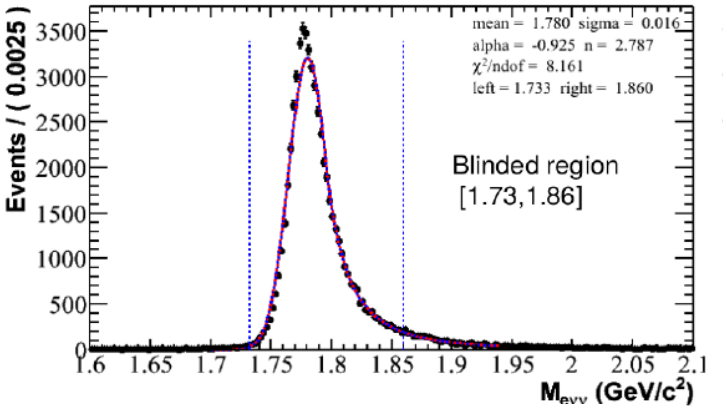
$$BR(h \to \tau\mu) < 1.51\%\ (\ 95\%\ C.L.\ )$$
$$BR(h \to \tau\mu) = 0.89^{+0.39}_{-0.37}\%\ (\ 2.46\sigma\ )$$
$$|y_{\tau\mu}| \leq 3.6 \times 10^{-3}$$

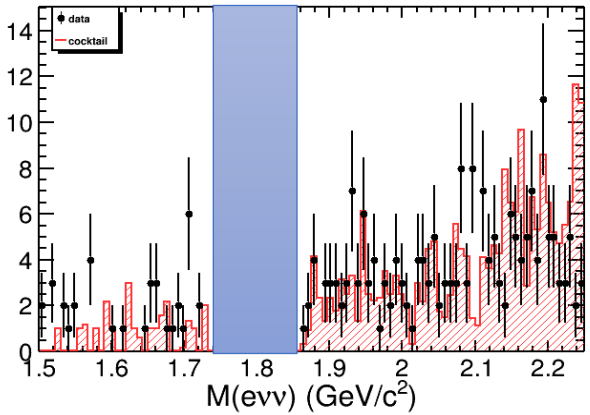
Phys. Lett. B 749 (2015) 337

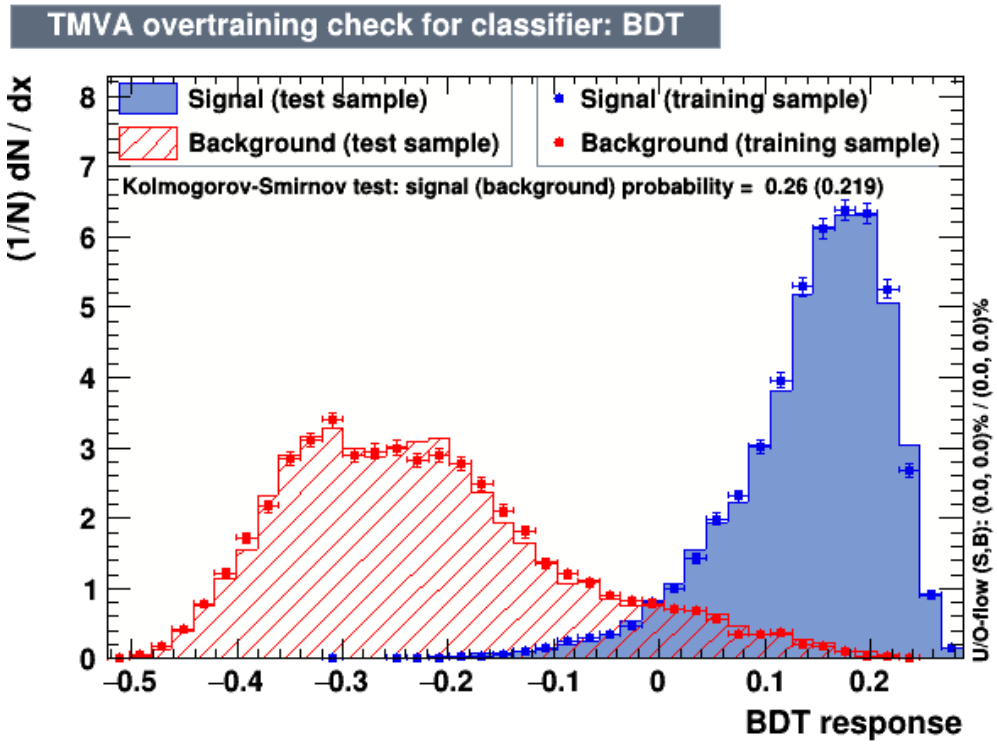
- Non-trival Yukawa coupling? enhance flavor changing rates
- Higgs induced CLFV with the Cheng-Sher Ansatz
- Inspire search in heavy quarkonium decays

Sensitivity projection

- Set 3σ band in $M_{e\nu\nu}$ distribution as signal region.
- MVA method with cocktail MC and toy model
- Sensitivity projection with 10 billion J/ψ sample: 10^{-8}

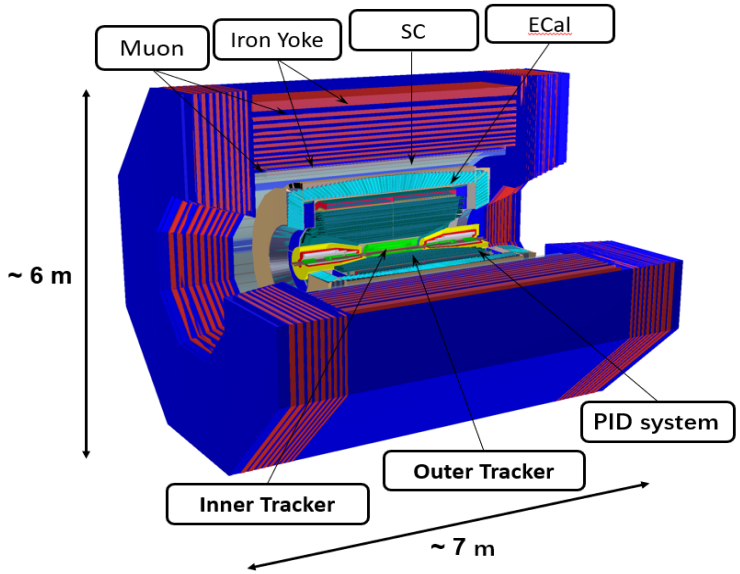






Proposed STCF in China

- Peaking luminosity (0.5-1)×10^{35} $cm^{-2}s^{-1}$ at 4 GeV
- Energy range E_{cm} = 2-7 GeV
- Potential to increase luminosity and realize beam polarization



J/ψ LFV decays at STCF

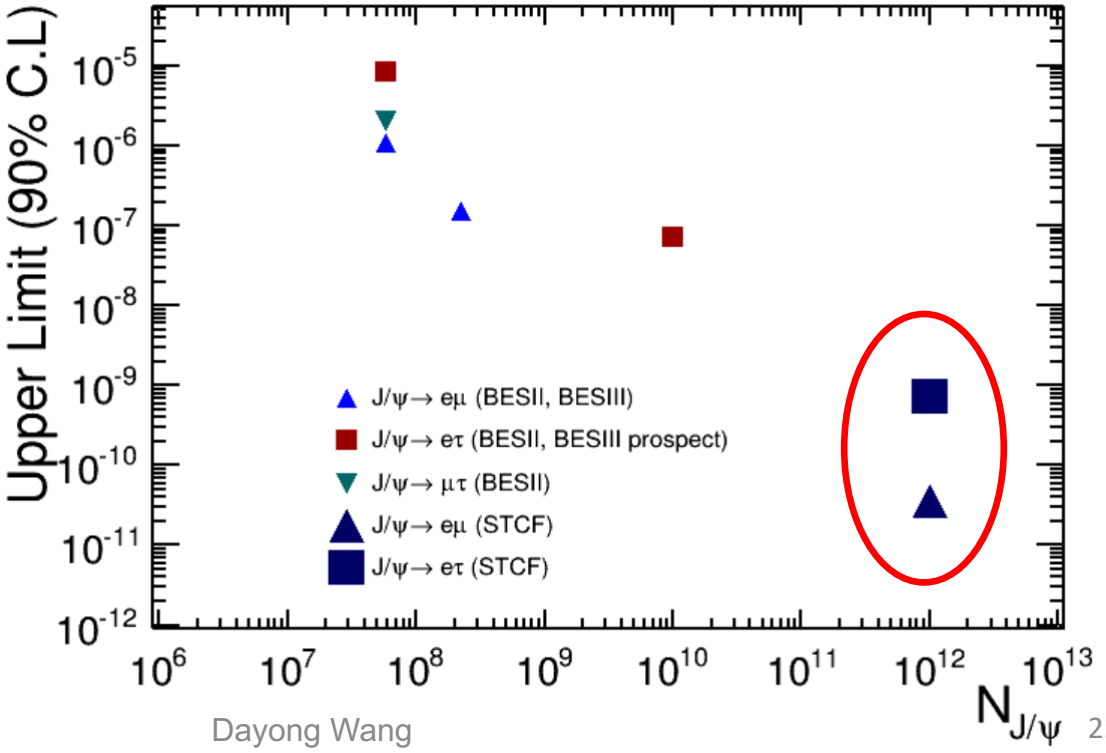
- At **STCF**, **1 trillion J/ψ** can be obtained per year, taken efficiency from BESIII, the upper limit can be predicted to be:

$$\mathcal{B}_{UL}^{90}(J/\psi \to e\mu) < 4\times10^{-11}$$

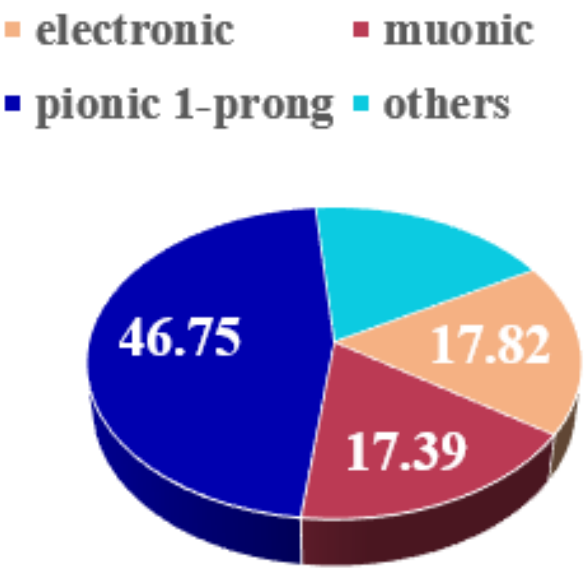
$$\mathcal{B}_{UL}^{90}(J/\psi \to e\tau)\ ) < 7\times10^{-10}$$

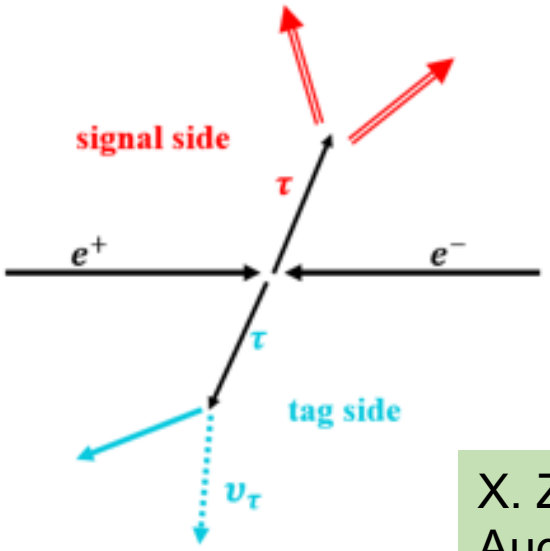
- The $\mathcal{B}_{UL}^{90}(J/\psi \to e\tau)\ )$ can be further **optimized** with better e/π id.

The LFV decay of $J/\psi \to e\tau$ at STCF is promising to probe the new physics!



LFV decay of τ at STCF





X. Zhou @ RF5 workshop
Aug 26. 2020

- **STCF with 1ab^{-1}:**

$$\mathcal{B}_{UL}^{90}(\tau \to \mu\mu\mu) < \frac{N_{UL}^{90}}{2\varepsilon N_{\tau\tau}} \sim 1.4\times10^{-9}$$

$$\mathcal{B}_{UL}^{90}(\tau \to \gamma\mu) < \frac{N_{UL}^{90}}{2\varepsilon N_{\tau\tau}} \sim 3\times10^{-8}$$

Summary

- High lumi and good detector enables BESIII sensitive to LFV in meson decays
- The published results on $J/\psi \rightarrow e\mu$ yield the best limit from Heavy Quarkonium decays, updates with 10B Jpsi is ongoing.
- LFV J/ψ decays involving τ are going on, would be more close to probe some models
- With further BESIII operation and STCF, more possibility will be further explored