Charmonium Rare Decay at BESIII

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Outline

- Why Rare Decay is Interesting
- The Rare Decays of Charmonium at BESIII
- Outlook and Summary

Why Rare Decay is Interesting

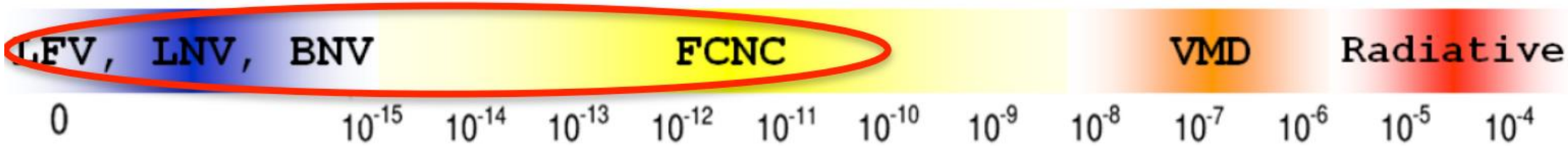
- The huge J/ψ and $\psi(2S)$ data sample is one possible way for us to approach a precious level where the charmonium rare decay can provide important tests of the SM.
- Rare decays in low energy region may be complementary to high energy colliders.
- Predicted to be unobservable in SM, but the BF may enhanced in the presence of new physics. A good window for NP beyond the SM.

Charmonium Rare Decays

- Flavor changing weak decays
  - Semi-leptonic decays of charmonium, $J/\psi \to D_s^* e\nu$.
  - Non-leptonic two-body weak decays, $J/\psi \to D_s^- \rho^+ / \bar{D}^0 \bar{K}^{*0}$
- C/P violating decays
  - $J/\psi \to \gamma\gamma / \gamma\phi$
  - $\eta_c \to \pi\pi$
- Lepton flavor violating decays
  - $J/\psi \to e\mu$
- Invisible decays in charmonium
  - $J/\psi \to \phi\eta^{(\prime)}, \eta^{(\prime)} \to$ invisible

$\psi(2S) \to \gamma\eta'$
$\psi(2S) \to \gamma\eta$

$\psi(2S) \to \gamma\chi_{c1/2}$
$J/\psi \to \gamma\eta_c$



$J/\psi \to e\mu$

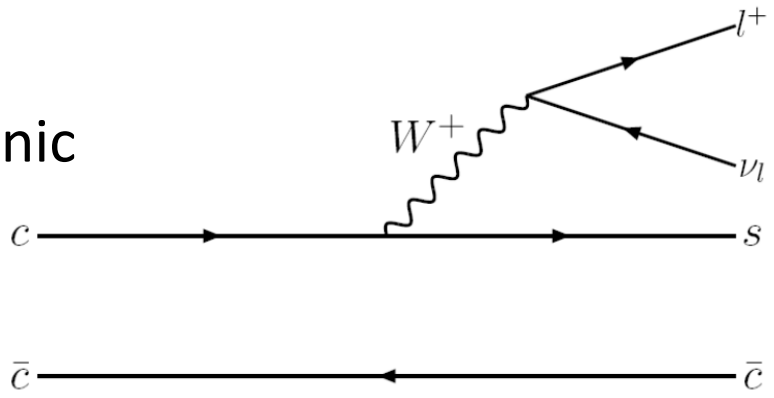
$J/\psi \to D_s^* e\nu$

$h_c \to \gamma\eta'$
$h_c \to \gamma\eta$

Semi-leptonic Decays

- In the SM, the inclusive BF of J/ψ decay to single D or D_s^- are predicted to be 10^{-8}. Using sum rules the BF are predicted to be ~10^{-10}.

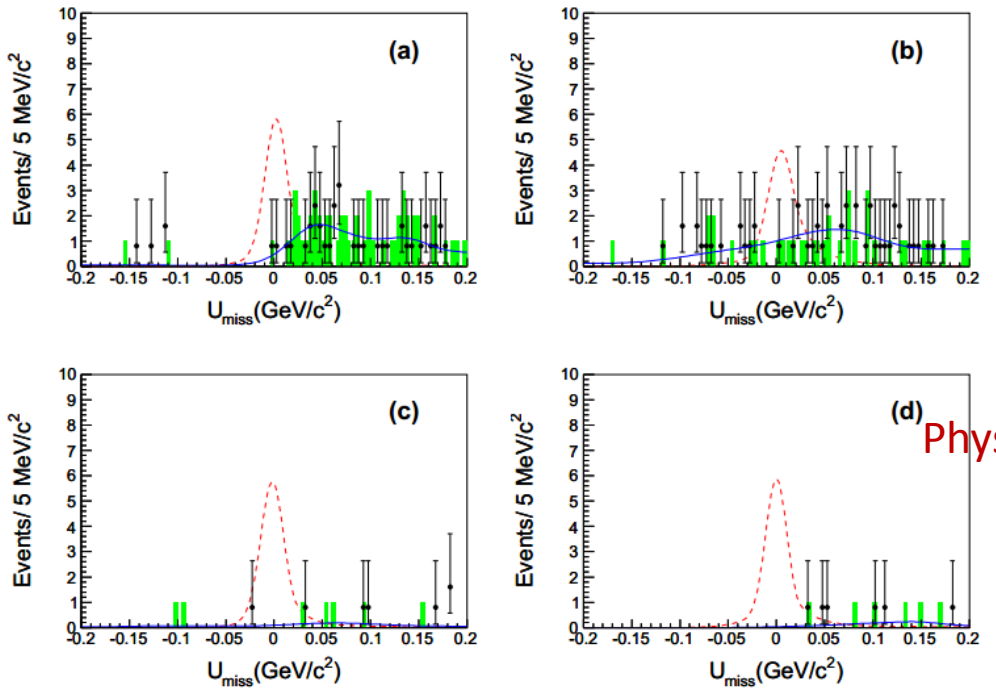
- With 2.25×10^8 J/ψ events collected at BEPCII, 4 hadronic decay channels are used to reconstruct D_s: $K_S K$, $KK\pi$, $KK\pi\pi^0$, $K_S K\pi\pi$, and D_s^* is reconstructed by $D_s^* \to \gamma D_s$.



Semi-leptonic Decays

The D_s and lepton are fully constructed and the missing U is used to extract the signal.

$$E_{\text{miss}} = E_{J/\psi} - E_{D_s^-} - E_{e^+} \qquad \vec{p}_{\text{miss}} = \vec{p}_{J/\psi} - \vec{p}_{D_s^-} - \vec{p}_{e^+} \qquad U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$



Phys. Rev. D **90**, 112014

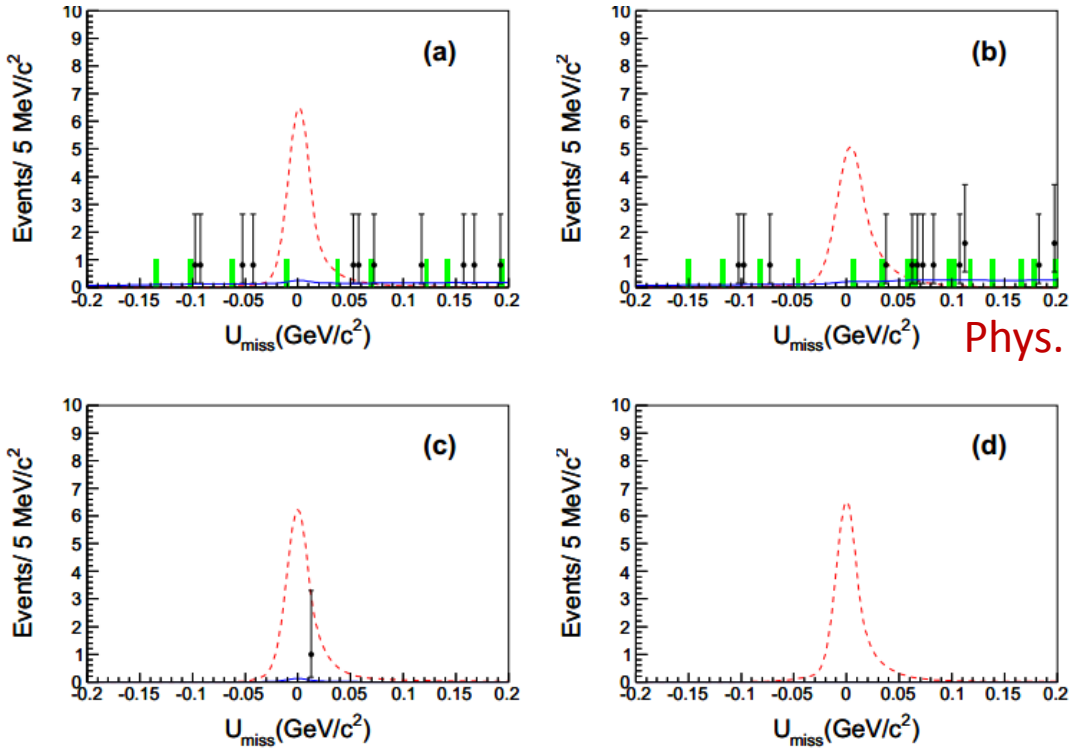
A simultaneous unbinned likelihood fit is used determined the signal yields.

$$\mathcal{L}_k = \prod_{i=1}^{N_k} \frac{N_{\text{total}} \mathcal{B}_k \epsilon_k \mathcal{P}_{i,k}^{\text{sig}} + N_k^{\text{bkg}} \mathcal{P}_{i,k}^{\text{bkg}}}{N_{\text{total}} \mathcal{B}_k \epsilon_k + N_k^{\text{bkg}}} ,$$

The Bayesian method with a uniform prior is used to estimate the upper limits.

$$\frac{\int_0^{N_{\text{total}}^{\text{up}}} \mathcal{L}(N_{\text{total}}) dN_{\text{total}}}{\int_0^{\infty} \mathcal{L}(N_{\text{total}}) dN_{\text{total}}} = 0.90 ,$$

Semileptonic Decays



$D_s^* \to \gamma D_s$

The same method as that in D_s to extract the signal and estimate the upper limits.

Phys. Rev. D **90**, 112014

	$J/\psi \to D_s^- e^+ \nu_e$	$J/\psi \to D_s^{*-} e^+ \nu_e$
$\bar{N}^{\rm up}_{\rm total}$	244	335
$\sigma_{\rm total}$	31	43
$N^{\rm up\ \prime}_{\rm total}$	275	378
$\sigma^{\rm sys}_{\rm common}$	3.3%	3.9%
$N_{J/\psi}$	2.25×10^8	
$\mathcal{B}$(90%C.L.)	$< 1.3 \times 10^{-6}$	$< 1.8 \times 10^{-6}$

$$\mathcal{B} < \frac{N^{\rm up\ \prime}_{\rm total}}{(1-\sigma^{\rm sys}_{\rm common})N_{J/\psi}}$$

Best results ever: $<3.5 \times 10^{-5}$.

Two-body Hadronic Weak Decays

- Consider QCD correction to hadronic matrix elements with QCD factorization approach, BF of $J/\psi \to D(\overline{D})X$ could $\geq 10^{-10}$.

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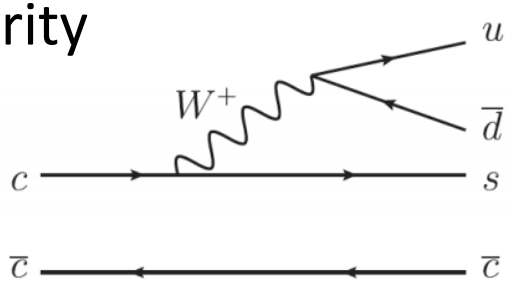
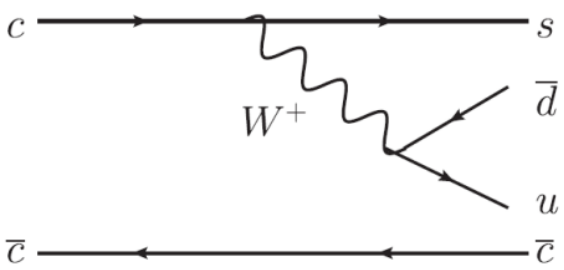
DOI: 10.1142/S0217751X15500943

$$\frac{\mathcal{B}F(J/\psi \to D_s^- \rho^+)}{\mathcal{B}F(J/\psi \to D_s^- \pi^+)} = 4.2$$

Int. J. Mod. Phys. A **14**, 937

- New physics, the BF of $J/\psi \to D(\overline{D})X$ could be enhanced ($10^{-5} \sim 10^{-6}$):
  - Minimal super-symmetric SM with R-parity violation,
  - Two-Higgs-doublet model.



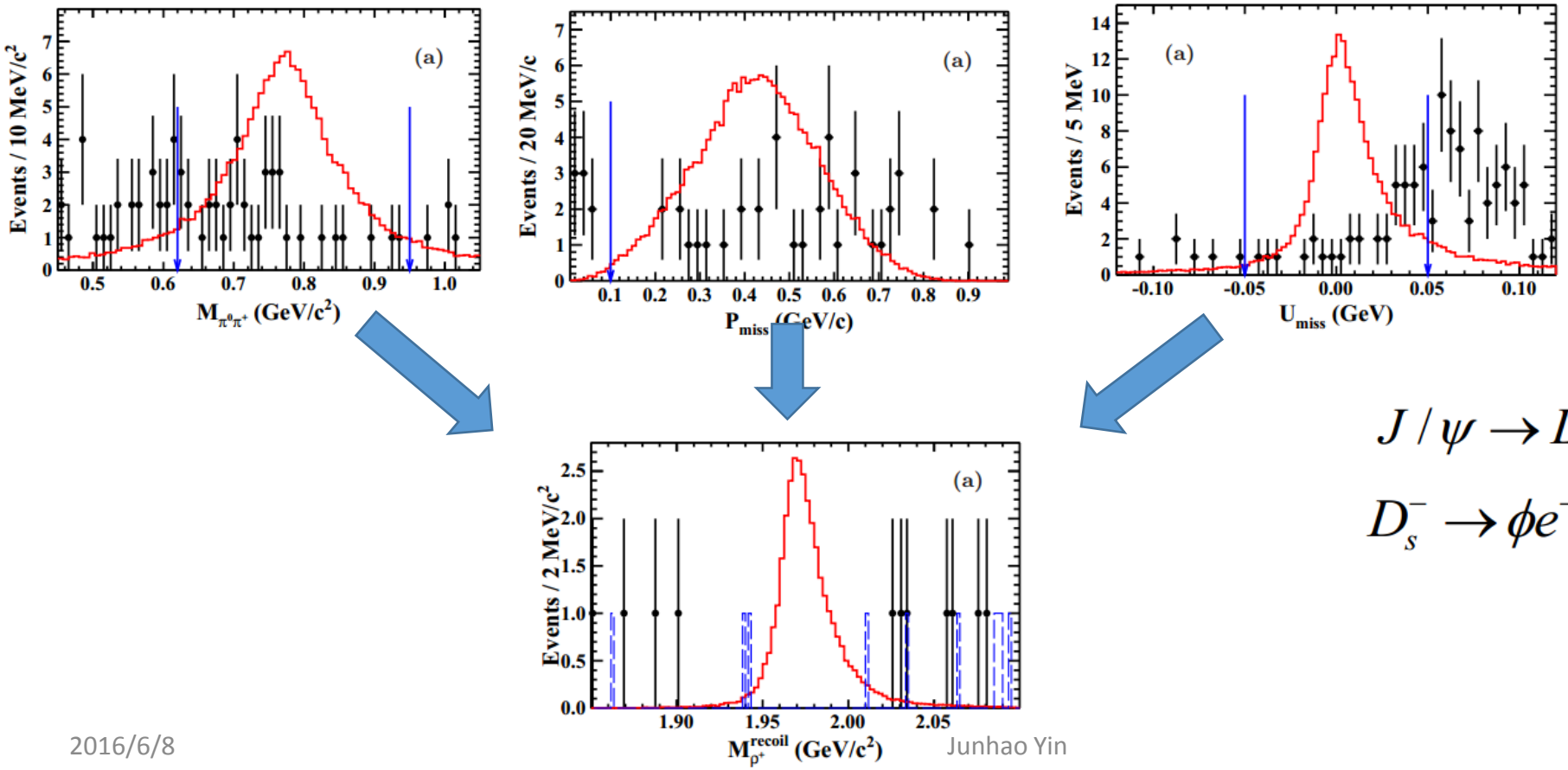


- Use 2.25×10^8 J/ψ events collected at BEPCII to search the decay $J/\psi \to D_s^- \rho^+$ and $\overline{D}^0 \overline{K}^{*0}$.
- The D_s and D^0 mesons are identified by their semi-leptonic decays: $D_s \to \phi e \nu$, $D^0 \to K e \nu$.

Two-body Hadronic Weak Decays

- Select candidates of ρ and K^{*0}.
- Use the electrons to tag the events and the missing momentum to suppress the background.

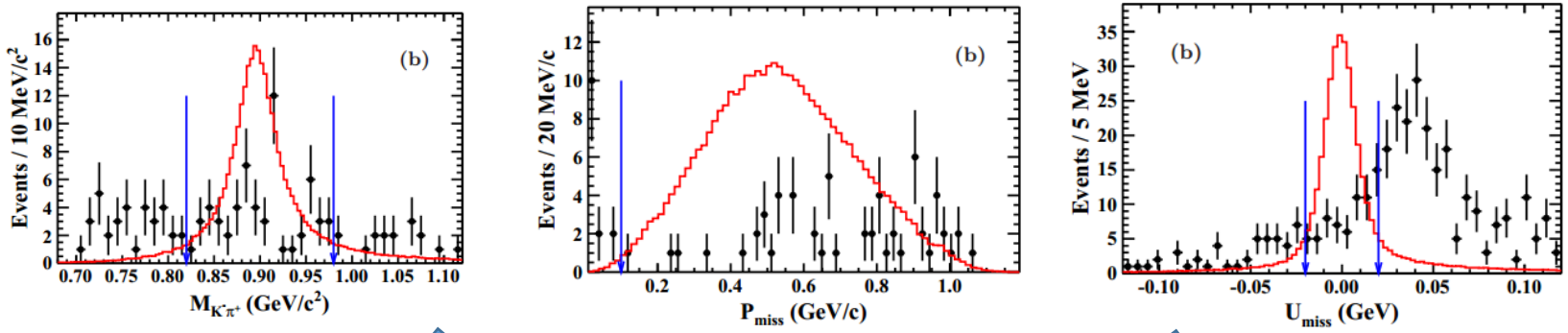
Phys. Rev. D **89**, 071101



$$J/\psi \to D_s^- \rho^+$$

$$D_s^- \to \phi e^- \bar{\nu}_e, \phi \to K^+ K^-$$

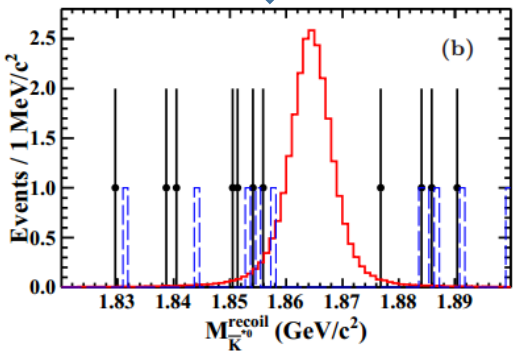
Two-body Hadronic Weak Decays



$$J/\psi \to \bar{D}^0 \bar{K}^{*0}$$

$$\bar{D}^0 \to K^+ e^- \nu_e$$

$$\bar{K}^{*0} \to K^- \pi^+$$



Phys. Rev. D **89**, 071101

Given for the first time.

Decay mode	Intermediate decay	ε	$\mathcal{B}_{inter}$	σ^{sys}	N_{UL}	$\mathcal{B}$ (90% C.L.)
$J/\psi \to D_s^- \rho^+$	$D_s^- \to \phi e^- \overline{\nu}_e,\ \phi \to K^+K^-,$ $\rho^+ \to \pi^+\pi^0,\ \pi^0 \to \gamma\gamma$	7.79%	1.20%	8.6%	2.5	$< 1.3 \times 10^{-5}$
$J/\psi \to \overline{D}^0 \overline{K}^{*0}$	$\overline{D}^0 \to K^+ e^- \overline{\nu}_e,\ \overline{K}^{*0} \to K^- \pi^+$	21.83%	2.37%	7.5%	2.7	$< 2.5 \times 10^{-6}$

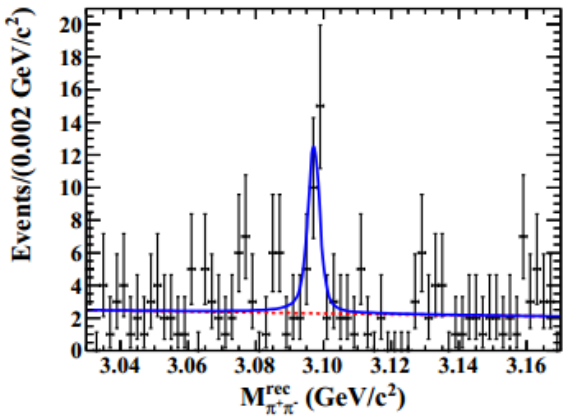
C/P-parity Violating Decays

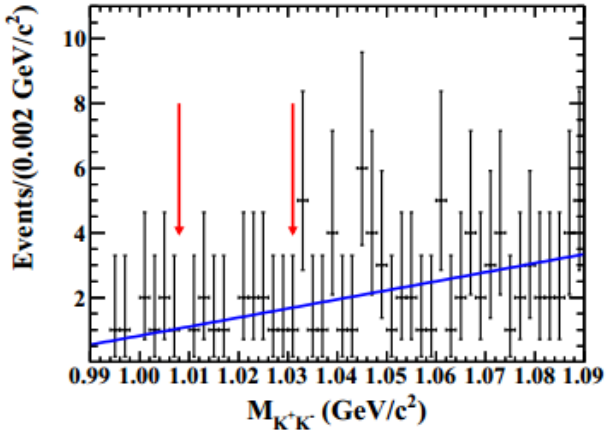
- $J/\psi \to \gamma\gamma/\gamma\phi$

Phys. Rev. D **90**, 092002

- In the SM, C invariance is held in strong and EM interactions. Evidence for C violation would immediately indicate physics beyond the SM.
- Use 1.06×10^8 $\psi(2S)$ data, where J/ψ from $\psi(2S) \to \pi^+\pi^- J/\psi$.
- The peak in $J/\psi \to \gamma\gamma$ is dominated by background with similar final states .

	$\gamma\gamma$	$\gamma\phi$
$N^{\rm obs}$	29.2 ± 7.1	0.0 ± 4.6
$N^{\rm bkg}$	46.5 ± 2.5	negligible
$N^{\rm up}_{\rm sig}$(90% C.L.)	2.8	6.9
ϵ (%)	30.72 ± 0.07	30.89 ± 0.07
$\mathcal{B}(J/\psi \to)$ (this work)	$< 2.7 \times 10^{-7}$	$< 1.4 \times 10^{-6}$
$\mathcal{B}(J/\psi \to)$ (PDG [1])	$< 50 \times 10^{-7}$	-





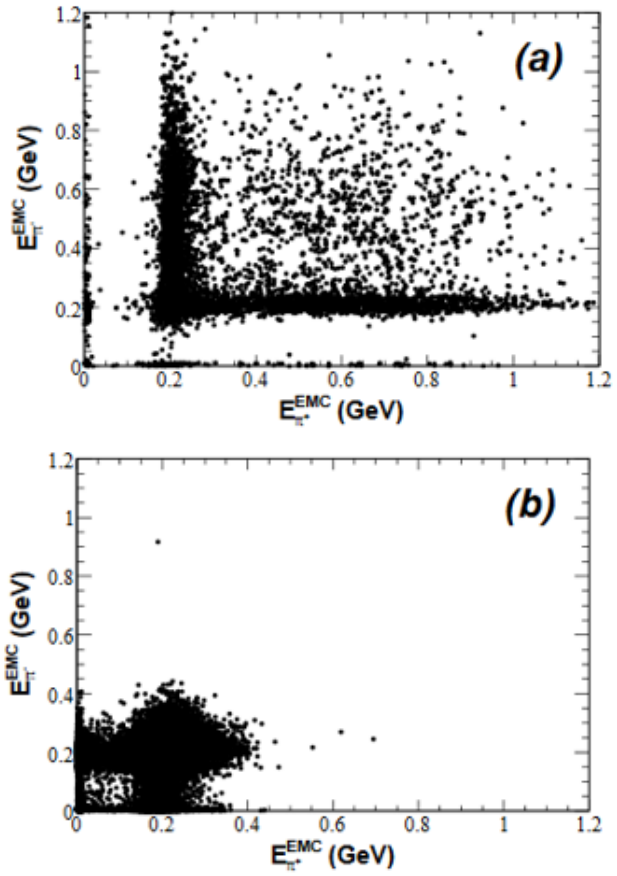
- The upper limit of $J/\psi \to \gamma\gamma$ is one order of the magnitude more stringent than the previous one.

C/P-parity Violating Decays

- $\eta_c \to \pi\pi$

- The decay $\eta_c \to \pi^+\pi^-/\pi^0\pi^0$ violates both P and CP invariance and provides an excellent laboratory for testing the validity of symmetries. BF~10^{-27}.
- Higher branching fractions are possible by introducing a CP violating term in the QCD lagrangian (BF~10^{-17}) or allowing CP vilation in the extended Higgs sector (BF~10^{-15}).

  Phys. Scripta T **99**, 104
- Based on 2.25×10^8 J/ψ events, via $J/\psi \to \gamma\eta_c$.
  - In $\pi^+\pi^-$ mode, $0.4\ \mathrm{GeV} < E_\pi < 1.2\ \mathrm{GeV}$ is required to suppress $J/\psi \to l^+l^-$ background.

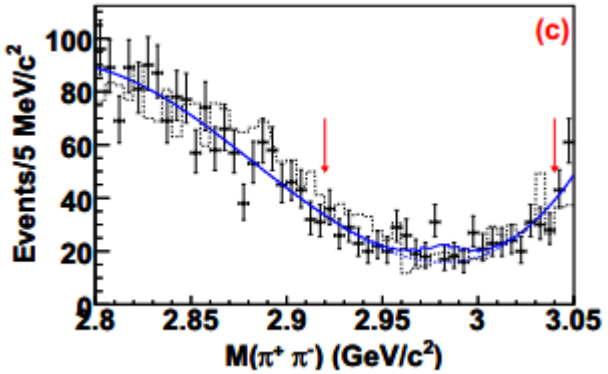


C/P-parity Violating Decays

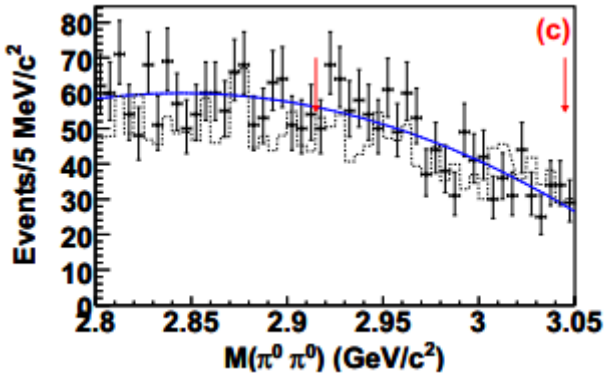
- $\eta_c \to \pi\pi$

Phys. Rev. D **84**, 032006

Process	$N_{\rm sig}^{\rm UP}$	ε (%)	$\sigma_{\rm sys}$(%)	S	$\mathcal{B}^{\rm UP}$	$\mathcal{B}^{\rm UP}_{PDG}$
$\eta_c \to \pi^+\pi^-$	92	25.27	27	1.5σ	1.3×10^{-4}	6×10^{-4}
$\eta_c \to \pi^0\pi^0$	40	35.70	28	0.1σ	4.2×10^{-5}	4×10^{-4}

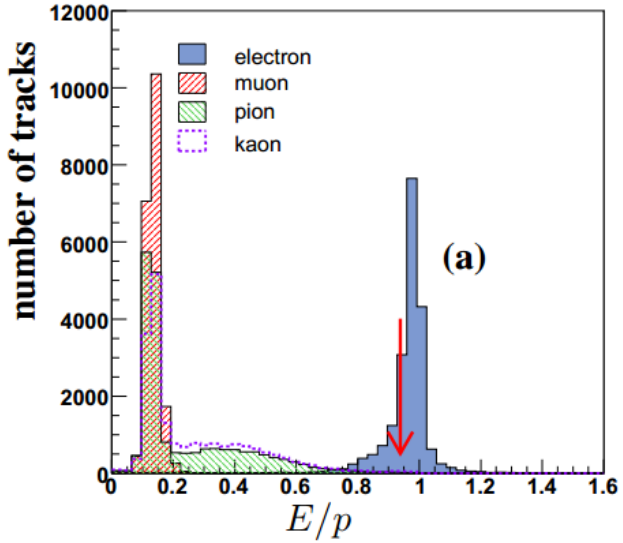


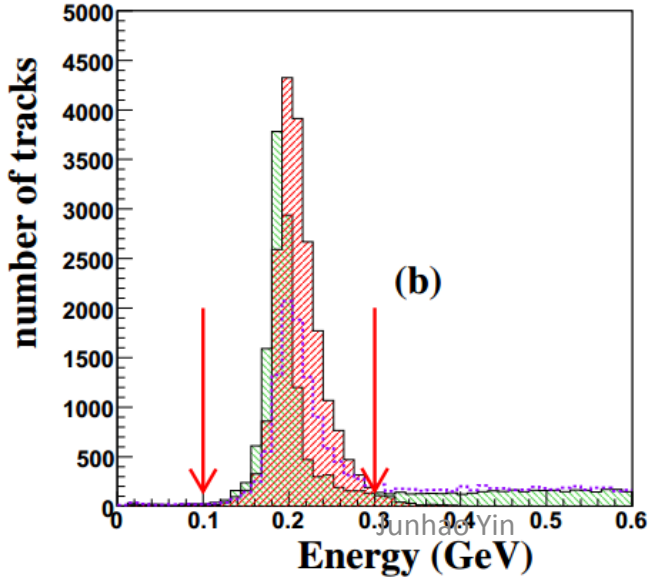
- The systematic error mainly comes from the BF of $J/\psi \to \gamma\eta_c$.
- Our result is smaller compared to the upper limits provided in PDG.
- Provide experimental limit for theoretical models predicting how much CP and P violation there may be in η_c meson decays.

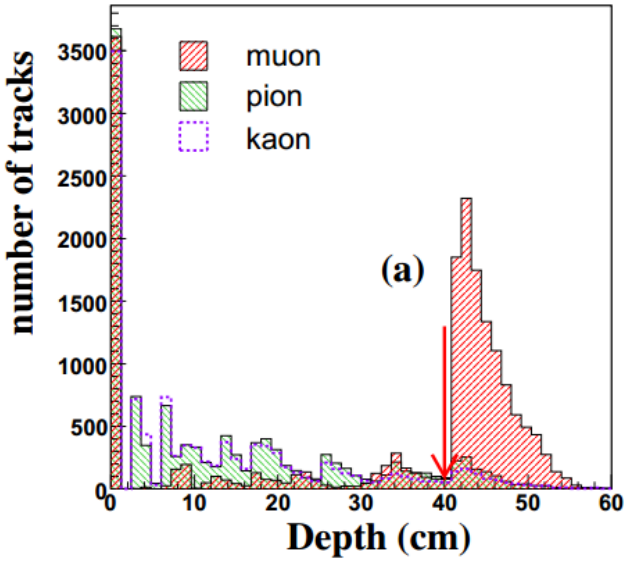


Lepton Flavor Violating Decays

- $J/\psi \to e\mu$
  - With finite neutrino masses included, the SM allows for LFV, yet which is beyond current experimental sensitivity.
  - Theoretical models of SUSY enhance LFV.
  - The result is with 2.25×10^8 J/ψ events for $J/\psi \to e\mu$.







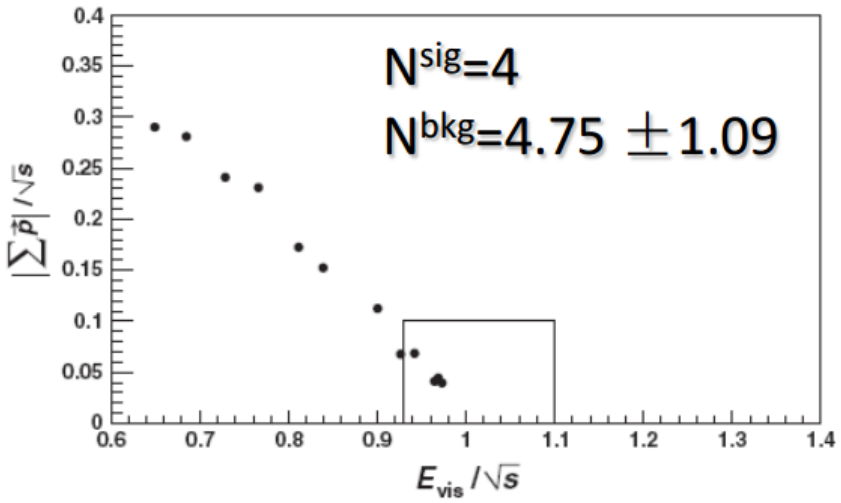
Lepton Flavor Violated Decays

- The reconstructed total momentum and energy are used to extract the signal.
- The selection criteria are optimized using a blind fashion with a sensitive FOM:

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

- Background is studied using an inclusive MC with four times the size of data.

Sources	Error
$e^{\pm}$ tracking	1.00
$\mu^{\pm}$ tracking	1.00
$e^{\pm}$ ID	0.62
$\mu^{\pm}$ ID	0.04
Acollinearity, acoplanarity	2.83
Photon veto	1.19
$N_{J/\psi}$	1.24
Total	3.65



Phys. Rev. D **87**, 112007

$\mathcal{B}F(J/\psi \to e\mu) < 1.5 \times 10^{-7}$

Most stringent limit obtained.

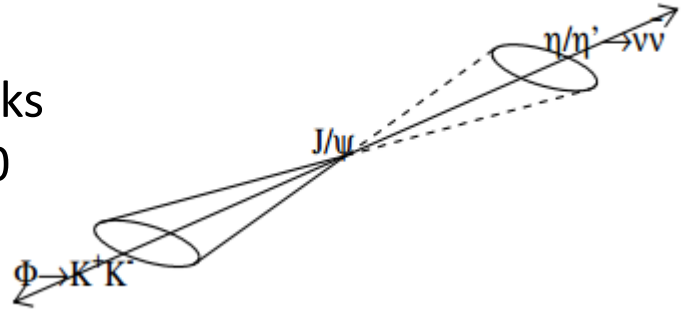
$< 1.1 \times 10^{-6}$

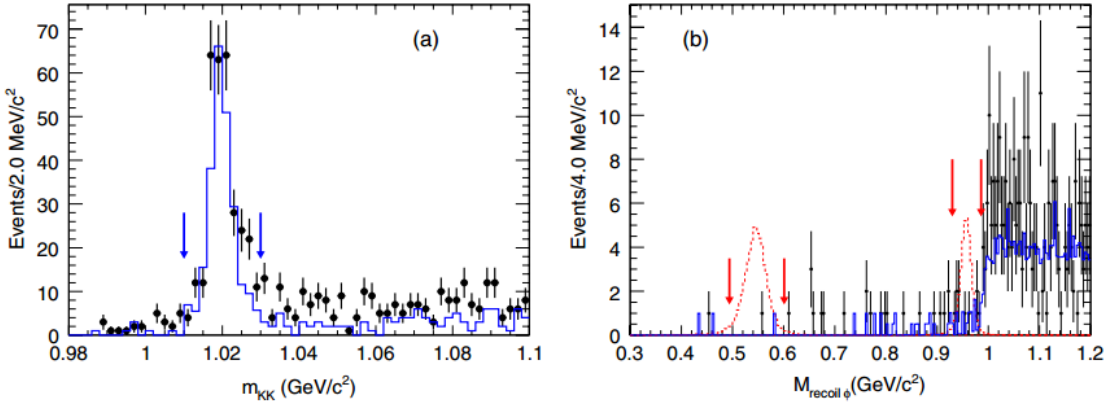
(best results before)

Invisible Decays in Charmonium

- $J/\psi \to \eta(\eta')\phi, \eta(\eta') \to invisible$

- The invisible decays of J/ψ and other mesons provide a good field to search for new physics beyond the SM.
- Could be light dark matter constituents according to $q\bar{q} \to (\gamma)\chi\chi$.
- The results are based on 2.25×10^8 J/ψ events. No good charged tracks allowed except for the K^+K^- and no good photons inside a cone of 1.0 rad around the recoil direction against the ϕ candidate.





$$\frac{\mathcal{B}r(\eta(\eta') \to invisible)}{\mathcal{B}r(\eta(\eta') \to \gamma\gamma)} < 2.6(2.4) \times 10^{-4(2)}$$

- The $N_\eta^{up} = 3.34$ and $N_{\eta'}^{up} = 10.1$. And give the upper limits of the ratio to the $\mathcal{B}r(\eta(\eta') \to \gamma\gamma)$ to cancel the common systematic error.

Phys. Rev. D **87**, 012009

Summary and Outlook

- BESIII collaboration has studied charmonium rare decays and the best upper limits for branching fractions are obtained with 225 M J/ψ and 106 M $\psi(2S)$. By now the results are still consistent with the SM.
- 1.3 B J/ψ and 0.45 B $\psi(2S)$ events have been collected and better precision can be obtained.
- The invisible decays of J/ψ can be searched with the largest J/ψ and $\psi(2S)$ samples.

Thanks!