Charmonium rare decay

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outline

- Why rare decay is interesting
- The rare decay of charmonium on BESIII
- Outlook and summary

Why rare decay is interesting

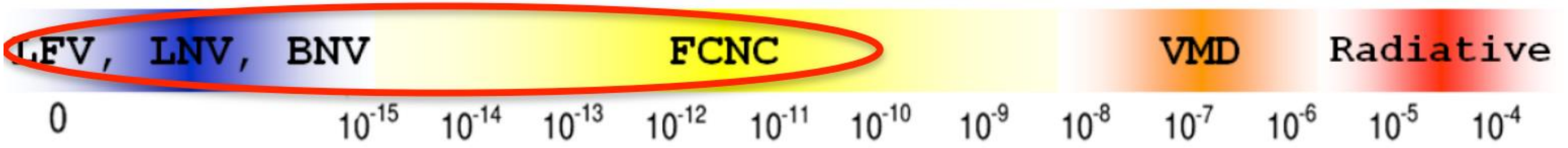
- The huge J/ψ and ψ(2S) data sample is one possible way for us to approach a precious level where the charmonium rare decay can provide important tests of the SM.
- Rare decays in low energy region may be complementary to high energy colliders.
- A good window for new physics beyond the standard model.

Charmonium rare decays

- Flavor changing weak decays
  - Semileptonic 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 violation decays
  - $J/\psi \to \gamma\gamma / \gamma\phi$
  - $\eta_c \to \pi\pi$
- Lepton flavor violated decays
  - $J/\psi \to e\mu$
- Invisible decays in charmonium
  - $J/\psi \to \phi\eta^{(\prime)}, \eta^{(\prime)} \to$ invisible

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

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



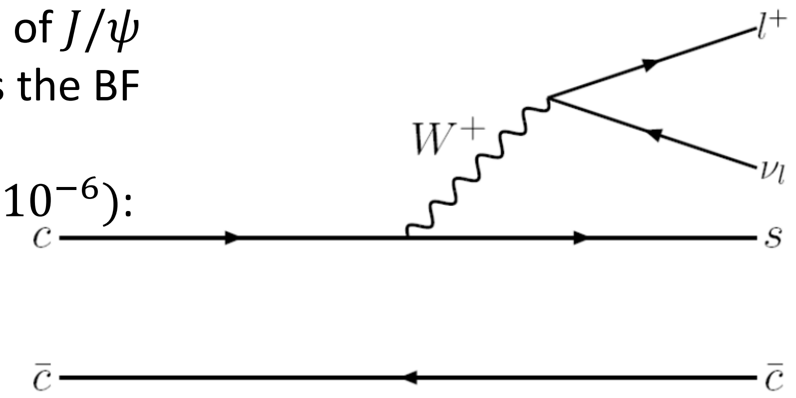
$J/\psi \to e\mu$

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

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

Semileptonic decays

- J/ψ can decay to charm meson via weak interaction through virtual intermediate bosons in SM framework. 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},
- New physics, the BF of $J/\psi \to D(\overline{D})X$ could be enhanced (10^{-5}~10^{-6}):
  Top-color models,
  Minimal super-symmetric SM with R-parity violation,
  Two-Higgs-doublet model

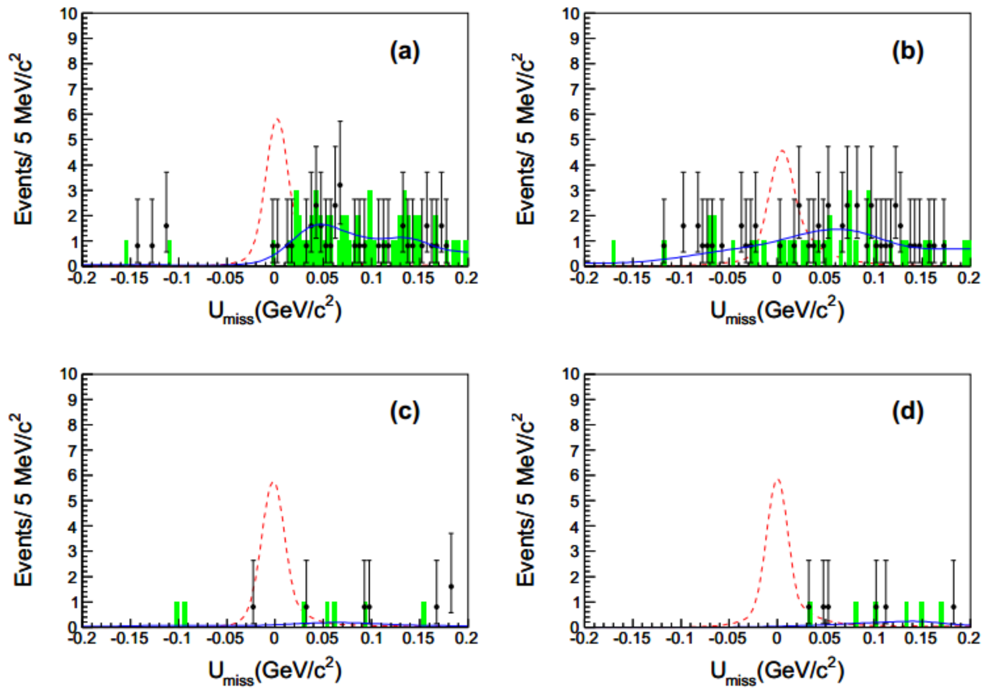


- Ratio between $J/\psi \to D_s^* l\nu$ and $D_s l\nu$ is predicted to be 1.5~3.1.
- With 2.25×10^8 J/ψ events collected at BEPCII, 4 hadronic decay channels is used to reconstruct D_s: $K_S K$, $KK\pi$, $KK\pi\pi^0$, $K_S K\pi\pi$, and D_s^* is reconstructed by $D_s^* \to \gamma D_s$.

Semileptonic decays

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

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



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

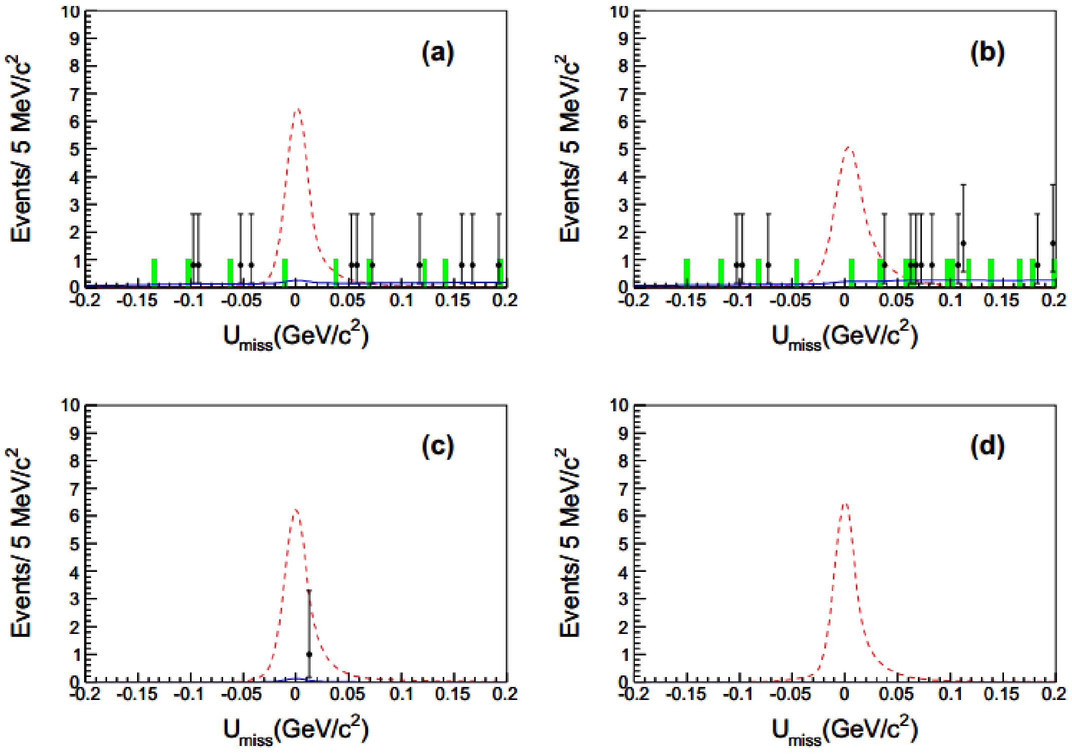
$$\mathcal{L}_k = \prod_{i=1}^{N_k} \frac{N_{\text{total}} \mathcal{B}_k \epsilon_k \mathcal{P}_{i,k}^{\text{sig}} + N_k^{\text{bkg}} \mathcal{P}_{i,k}^{\text{bkg}}}{N_{\text{total}} \mathcal{B}_k \epsilon_k + N_k^{\text{bkg}}} ,$$

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

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

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

Semileptonic decays



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$D_s^* \to \gamma D_s$

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

Source	$J/\psi \to D_s^- e^+ \nu_e$ (%)	$J/\psi \to D_s^{*-} e^+ \nu_e$ (%)
Physics model	0.9	0.8
Resolutions	1.6	1.8
e tracking	2.1	2.1
e PID	1.0	1.0
E/p cut	0.6	1.7
Photon efficiency	-	1.0
$\mathcal{B}(D_s^{*-} \to D_s^- \gamma)$	-	0.7
J/ψ events	1.2	1.2
Trigger	Negligible	Negligible
Total	3.3	3.9

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

$$\mathcal{B} < \frac{N_{\text{total}}^{\text{up}\,\prime}}{(1-\sigma_{\text{common}}^{\text{sys}})N_{J/\psi}}$$

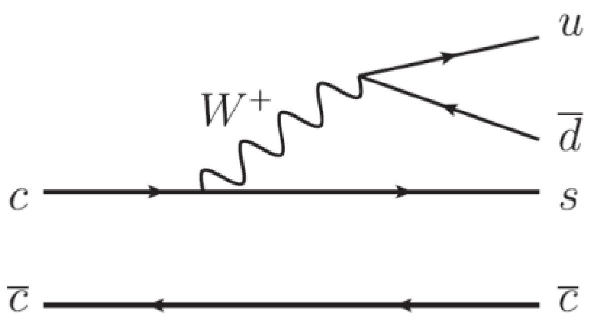
Best results ever: $<3.5 \times 10^{-5}$.

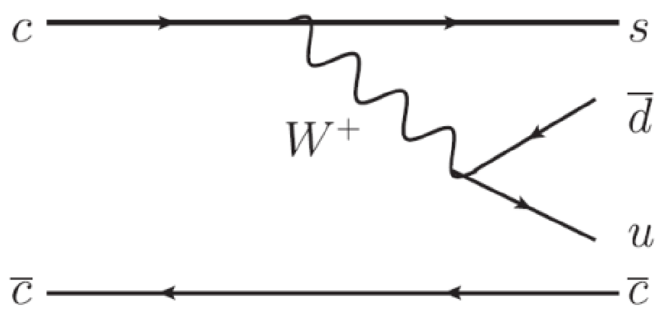
Two-body hadronic weak decays

- 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 semileptonic decays: $D_s \to \phi e \nu$, $D^0 \to K e \nu$.

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

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

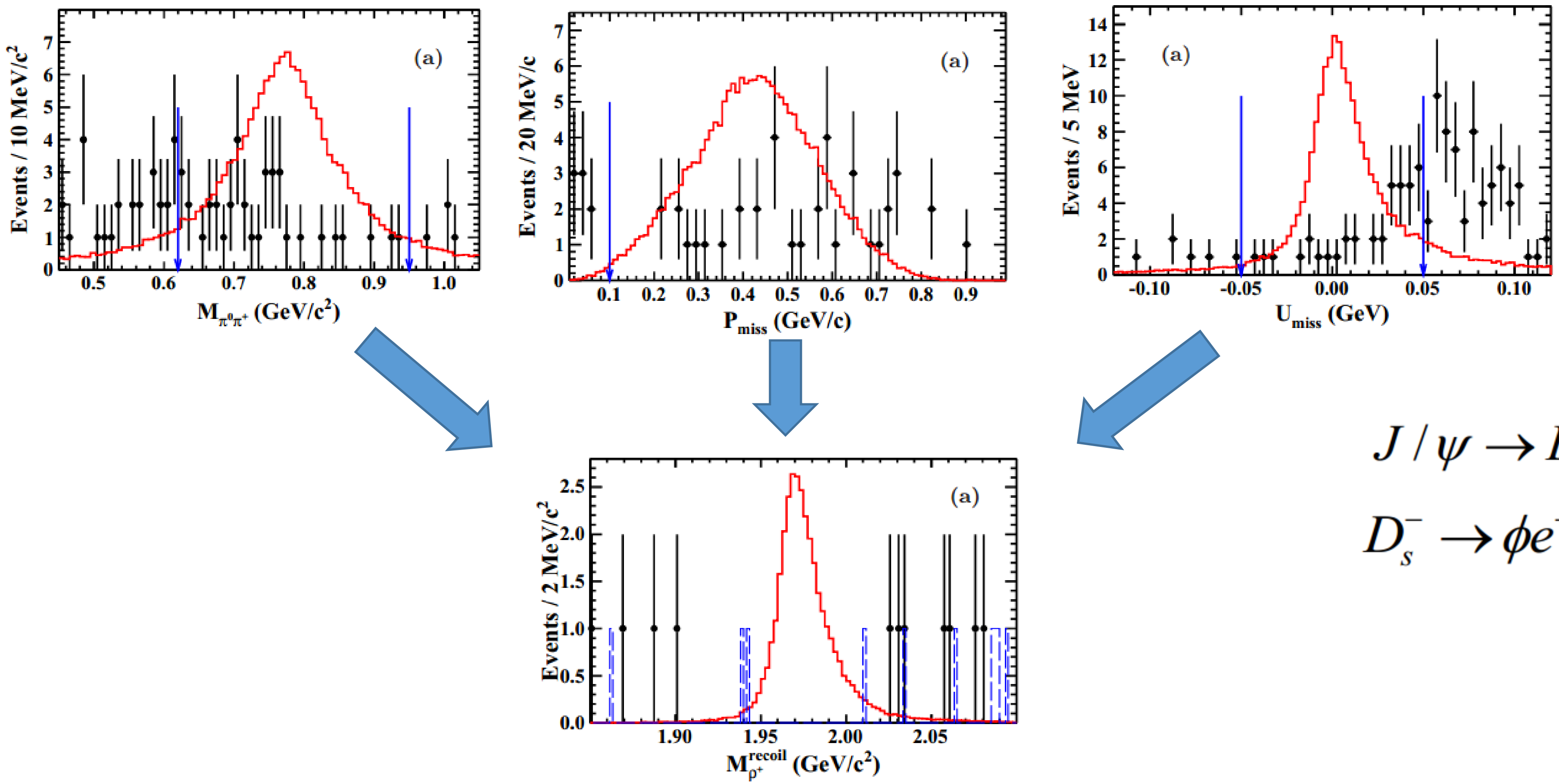




Two-body hadronic weak decays

- Select candidates of ρ and K^{*0}, use the recoiling side of ρ and K^{*0}.
- Use the electrons to tag the events and the missing momentum to suppress the backgrounds.

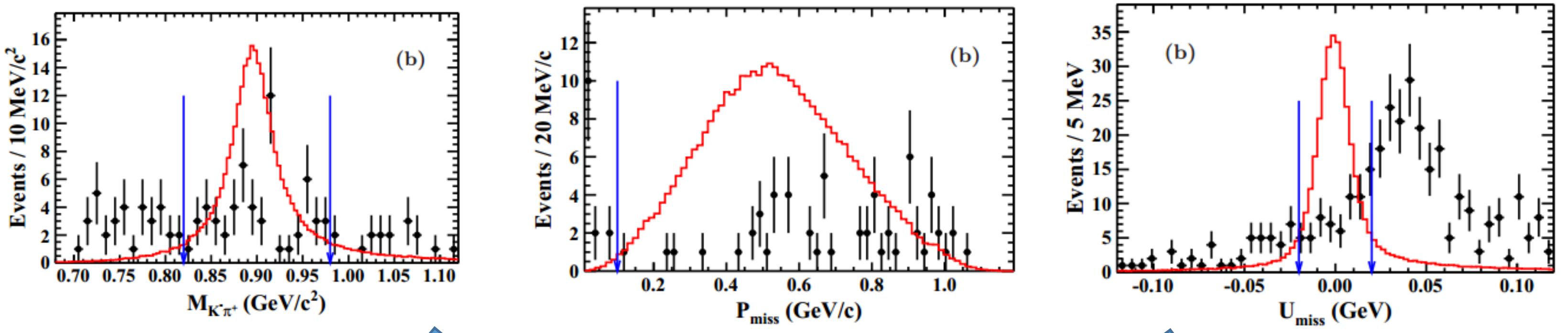
Phys. Rev. D **89**, 071101



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

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

Two-body hadronic weak decays



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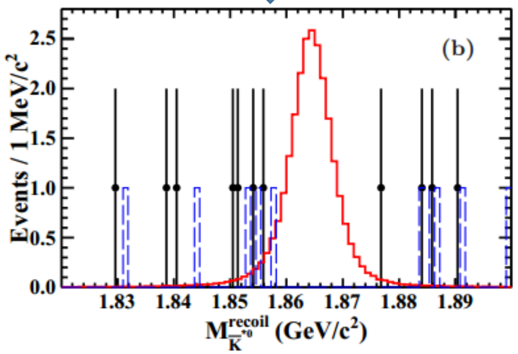
Sources	$J/\psi \to D_s^- \rho^+$	$J/\psi \to \overline{D}^0 \overline{K}^{*0}$
MDC tracking	4.0	4.0
Photon detection	2.0	2.0
Particle ID	4.0	4.0
π^0 kinematic fit	0.2	1.0
ϕ mass window	1.0	–
ρ^+ mass window	1.0	–
$\overline{K}^{*0}$ mass window	–	0.5
U_{miss} window	1.0	4.0
Intermediate decays	5.7	1.1
MC statistics	0.5	0.3
Number of J/ψ events	1.2	1.2
Total	8.6	7.5

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

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

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



Given for the first time.

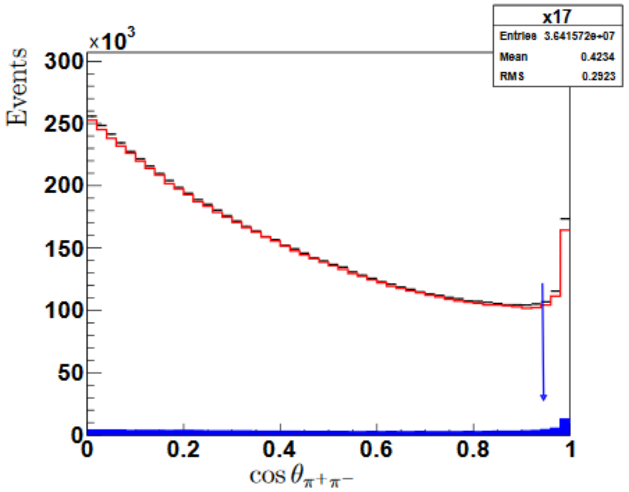
Decay mode	Intermediate decay	ε	$\mathcal{B}_{inter}$	σ^{sys}	N_{UL}	$\mathcal{B}$ (90% C.L.)
$J/\psi \to D_s^- \rho^+$	$D_s^- \to \phi e^- \overline{\nu}_e$, $\phi \to K^+K^-$, $\rho^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$	7.79%	1.20%	8.6%	2.5	$< 1.3 \times 10^{-5}$
$J/\psi \to \overline{D}^0 \overline{K}^{*0}$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

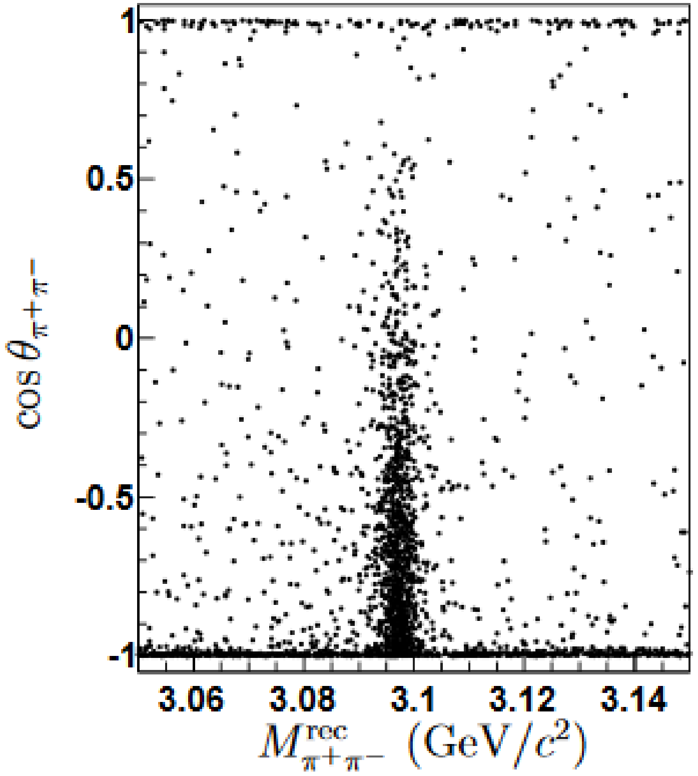
C/P-parity violation decays

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

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

- ➢ In SM, C invariance is held in strong and EM interactions.
- ➢ Evidence for C violation in the EM sector would immediately indicate physics beyond the SM.
- ➢ Use 1.06×10^8 $\psi(2S)$ data and via $\psi(2S) \to \pi^+\pi^-\ J/\psi$ to study the decay $J/\psi \to \gamma\gamma/\gamma\phi$.
- ➢ Require $|cos_{\pi^+\pi^-}| < 0.95$ exactly two photons for $\gamma\gamma$ channel. $cos_{\pi^+\pi^-} < 0.95$ and $E_\gamma > 1.0$ GeV for $\gamma\phi$ channel.





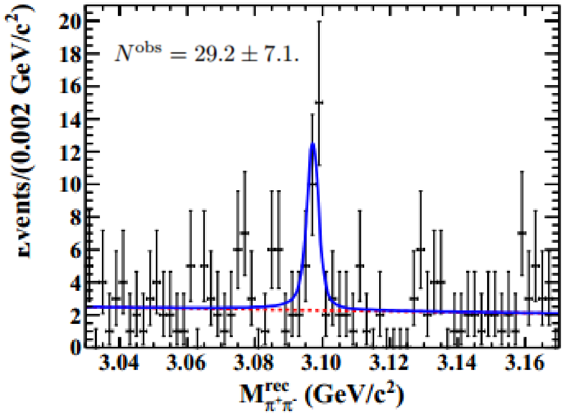
C/P-parity violation decays

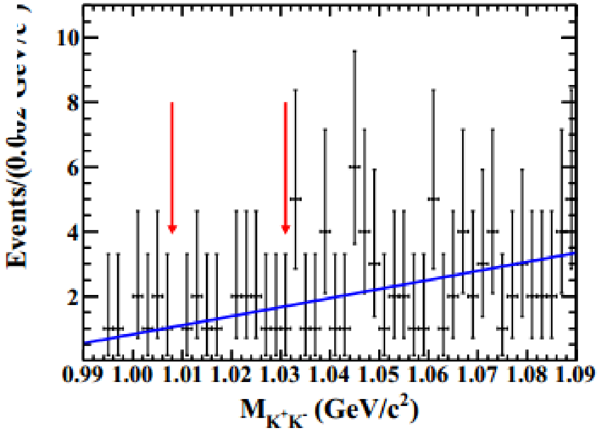
- $J/\psi \to \gamma\gamma/\gamma\phi$

  - The peak in $J/\psi \to \gamma\gamma$ is dominated by background with similar final states .
  - MC study for $J/\psi \to \gamma\phi$ shows that there are no peaking background.

Background channel	Expected counts (N^{bkg})
$J/\psi \to \gamma\pi^0, \pi^0 \to 2\gamma$	18.5 ± 1.9
$J/\psi \to \gamma\eta, \eta \to 2\gamma$	24.6 ± 1.6
$J/\psi \to \gamma\eta_c, \eta_c \to 2\gamma$	1.3 ± 0.3
$J/\psi \to 3\gamma$	0.9 ± 0.3
Total	45.3 ± 2.5

	$\gamma\gamma$	$\gamma\phi$
N^{obs}	29.2 ± 7.1	0.0 ± 4.6
N^{bkg}	46.5 ± 2.5	negligible
$N^{\text{up}}_{\text{sig}}$(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 limits of $J/\psi \to \gamma\gamma$ is one order of the magnitude more stringent than the previous one.

C/P-parity violation decays

- $\eta_c \to \pi\pi$

➢ The decay $\eta_c \to \pi^+\pi^-/\pi^0\pi^0$ violate both P and CP invariance and provide 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 $J/\psi \to \gamma\eta_c$. For $\eta_c \to \pi^+\pi^-$:

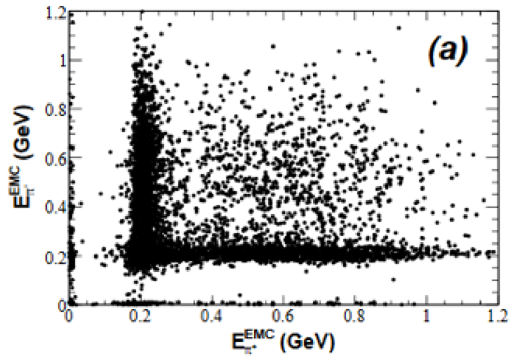
  ➢ Paring the photons in an event and reject the background of $J/\psi \to \pi^+\pi^-\pi^0$.

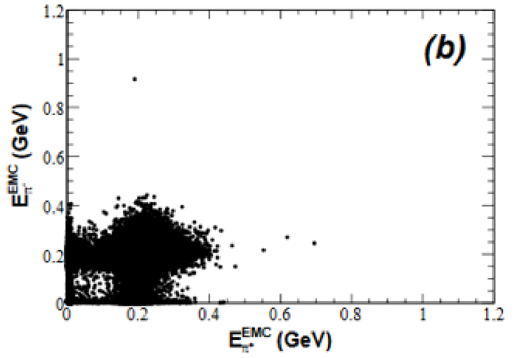
  ➢ $0.4\ \text{GeV} < E_\pi^{EMC} < 1.2\ \text{GeV}$ to suppress the $J/\psi \to e^+e^-/\mu^+\mu^-$ background.

For $\eta_c \to \pi^0\pi^0$:

  ➢ The photon pairs with minimized $\chi = \sqrt{(M(\gamma\gamma)_1 - M_{\pi^0})^2 + (M(\gamma\gamma)_2 - M_{\pi^0})^2}$ is chosen.

  ➢ Events satisfied $0.72 < M(\gamma\pi^0) < 0.82\ \text{GeV}/c^2$ is rejected to reduce the $J/\psi \to \omega\pi^0$ background.



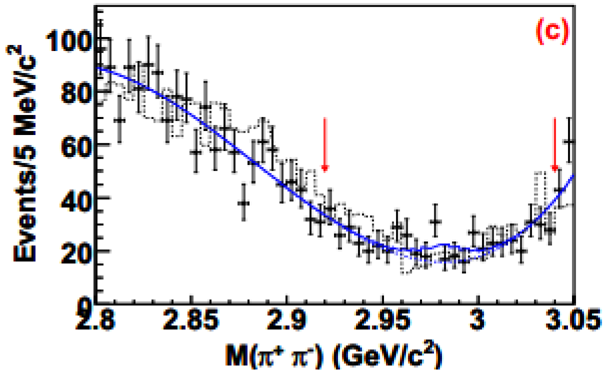


C/P-parity violation decays

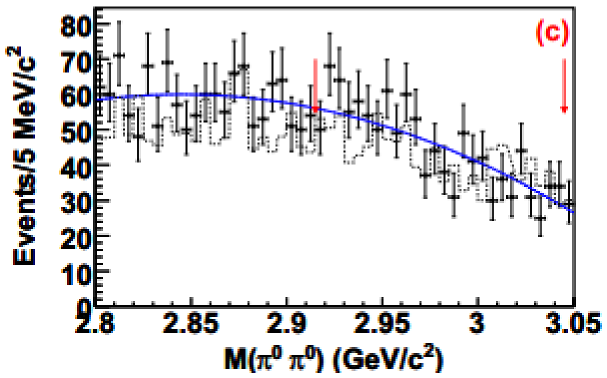
- $\eta_c \to \pi\pi$

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

Process	$N_{\text{sig}}^{\text{UP}}$	ε (%)	σ_{sys}(%)	S	$\mathcal{B}^{\text{UP}}$	$\mathcal{B}_{PDG}^{\text{UP}}$
$\eta_c \to \pi^+\pi^-$	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}



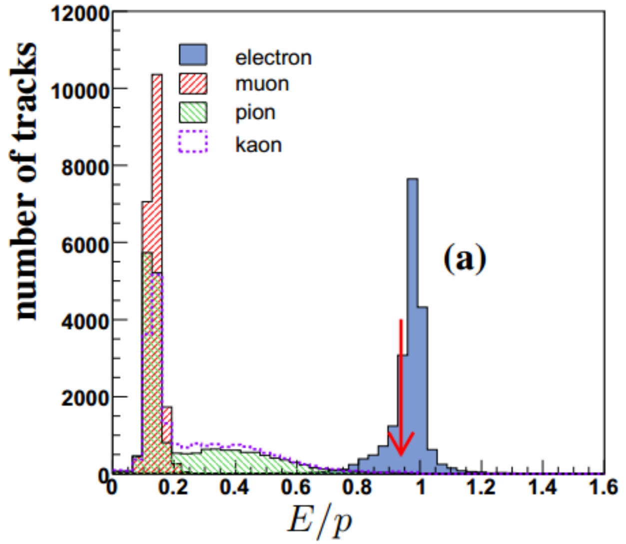
- The systematic error mainly come from the BF of $J/\psi \to \gamma\eta_c$.
- Our results is smaller compared to the upper limits provided in PDG.
- Provide experimental limits for theoretical models predicting how much CP and P violation there may be in η_c meson decays.

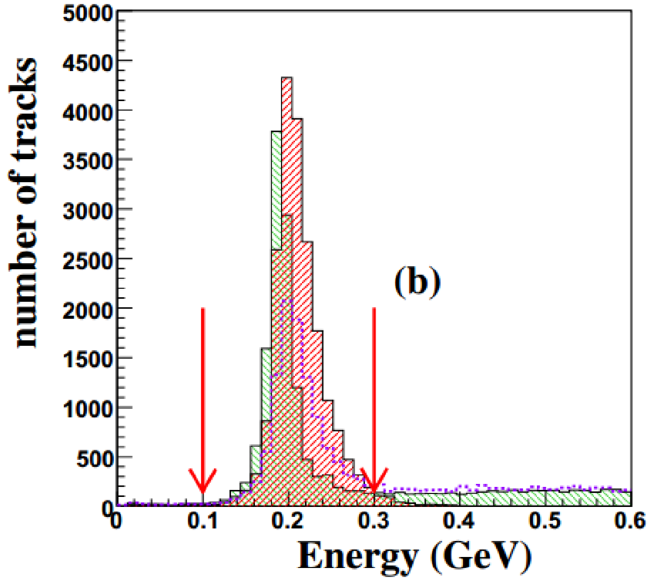


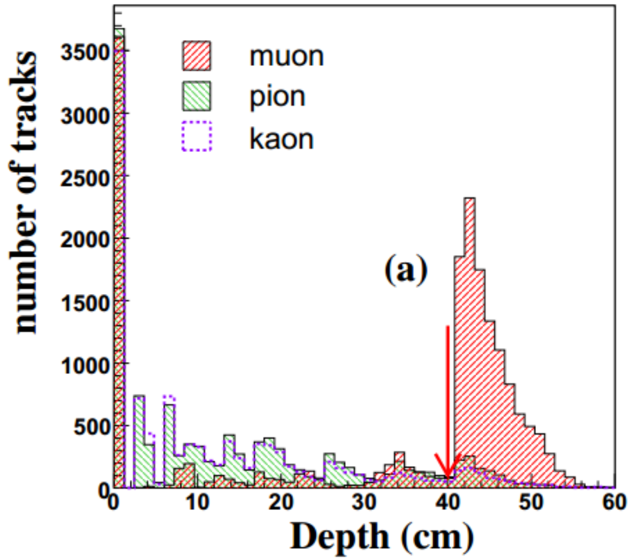
Lepton flavor violated decays

- $J/\psi \to e\mu$
  - With finite neutrino masses included, the SM allows for LFV, yet which is beyond current experimental sensitivity.
  - Theoretical models enhance LFV:

    SUSY, include SUSY-based grand unified theories, SUSY with a right-handed neutrino, gauge-mediated SYSY breaking, SUSY with vector-like leptons, SUSY with R-parity violation, models with a Z' and models violating Lorentz invariance.
  - We present our results here with 2.25×10^{8} J/ψ events for $J/\psi \to e\mu$.







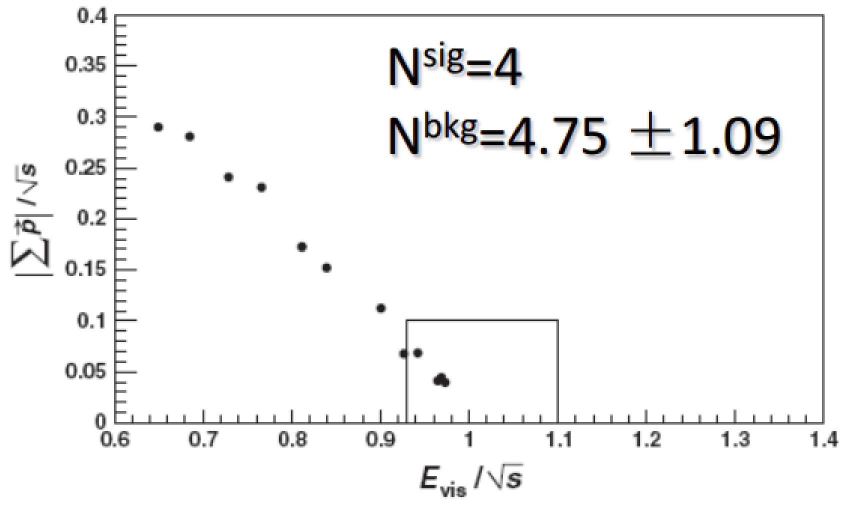
Lepton flavor violated decays

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

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

- The 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

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

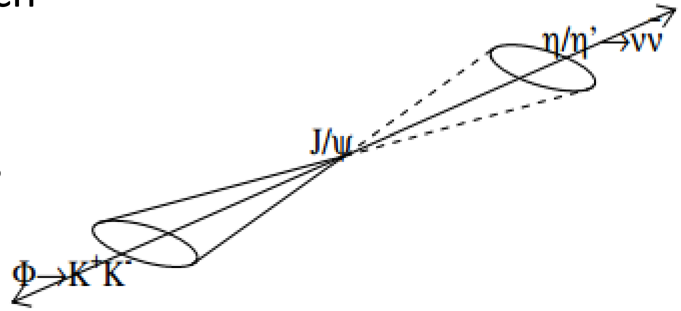
Most stringent limit obtained.

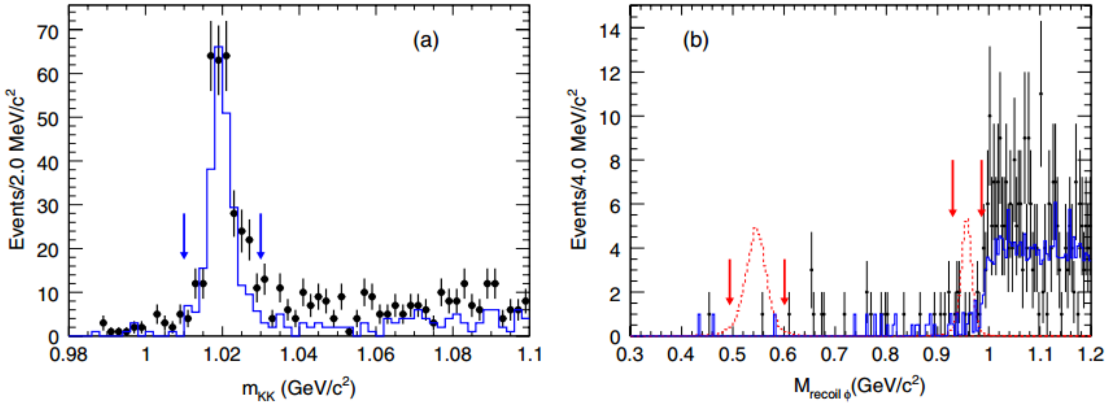
$< 1.1 \times 10^{-6}$

(best results before)

Invisible decays in charmonium

- $J/\psi \rightarrow \eta\phi, \eta \rightarrow invisible$
  - The invisible decays of J/ψ and other mesons provide a good filed to search for new physics beyond the SM.
  - Could be light dark matter constituents according to $q\bar{q} \rightarrow (\gamma)\chi\chi$.
  - Based on 2.25×10^8 J/ψ events. No good charged tracks allowed besides the K^+K^- and no good photons inside a cone of 1.0 rad around the recoil direction against the ϕ candidate and $|cos\theta_{recoil}| < 0.7$.
  - The $N_\eta^{up} = 3.34$ and $N_{\eta'}^{up} = 10.1$. And give the upper limits of the ratio to the $\mathcal{B}r(\eta(\eta') \rightarrow \gamma\gamma)$ to cancel the common systematic error.





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

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

Summary and outlook

- BESIII collaboration has performed dedicated studies on charmonium rare decays and the best upper limits branching fractions of the world 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 has been collected and more searches of charmonium rare decays with better precision can be obtained.
- The invisible decays of J/ψ or other particles can be searched with the largest J/ψ and $\psi(2S)$ samples in the world.

Thanks!