Charmonium hadronic weak decay at BESIII

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Rare decays of charmonium

- Semileptonic weak decays

$$\psi \to D_q l\nu,\ \psi \to \bar{D}^{0/*} l^+ l^-$$

- Two-body hadronic weak decays

$$J/\psi \to D_s^- \pi^+ / K^+ + c.c.,\ J/\psi \to D_s^{(*)+} \rho^- / K^- + c.c., \ldots$$

- C/P violation decays

$$J/\psi \to \gamma\gamma, \gamma V, VV, PP$$

- Lepton flavor violation decays

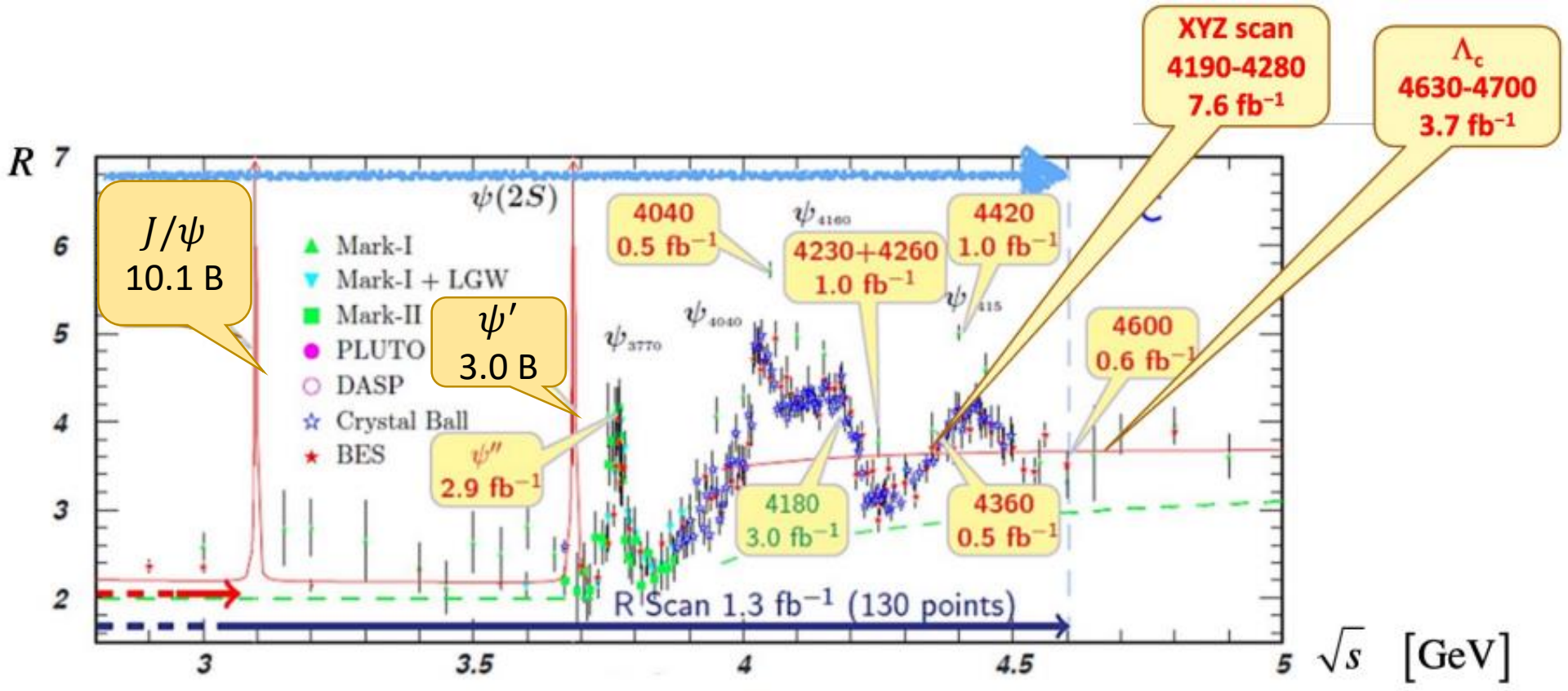
$$J/\psi \to e\mu, e\tau, \mu\tau$$

Outline

- Motivation
- Overview of recent charmonium hadronic weak decays
  - Search for the weak decay $J/\psi \to D_S^- \rho^+, \bar{D}^0 \bar{K}^{*0}$
  - Search for the weak decay $J/\psi \to \bar{D}^0 \pi^0, \bar{D}^0 \eta, \bar{D}^0 \rho^0, D^- \pi^+, D^- \rho^+$
  - Search for the weak decay $\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.$
- Summary

Motivation

- BEPCII: The double-ring collider with high luminosity, Center-of-mass energy: 2.9 - 4.9 GeV
- BESIII: Collected the world largest J/ψ, $\psi(3686)$ data samples.



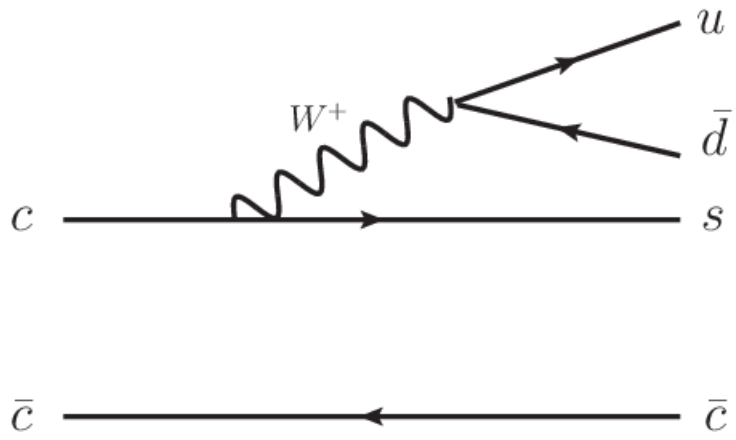
Motivation

- With the large statistic events collected at BESIII, which provides the opportunity to search for the charmnoium weak decays.

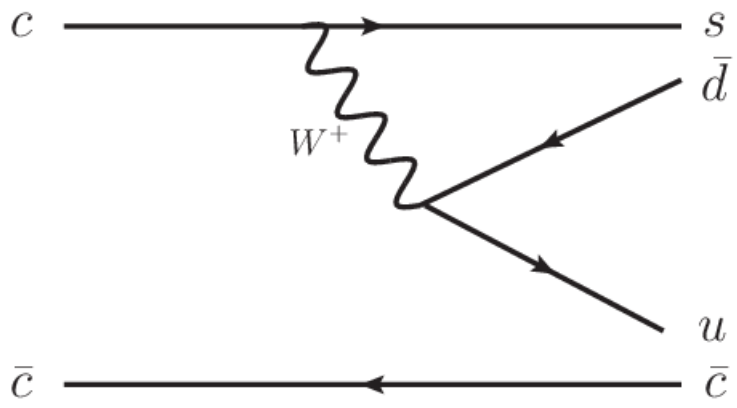
- Predicted to be unobservable in SM, but the branching fraction may be enhanced in the presence of New Physics. (as large as $10^{-5} - 10^{-6}$, can be marginally measured by BESIII)

- Searching for these decays not only tests the SM prediction but also probes new physics theories beyond the SM.

$J/\psi \to D_S^- \rho^+, \bar{D}^0 \bar{K}^{*0}$ PRD 89(2014)071101



(a) $J/\psi \to D_S^- \rho^+$



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

- **With Standard Model**
  Factorization model: $10^{-9} - 10^{-10}$
- **New Physics:** $10^{-5} - 10^{-6}$
  Topo color model
  Minimal Supersymmetric model
  Two-Higgs-double model

- $\frac{Br(J/\psi \to D_S \rho)}{Br(J/\psi \to D_S \pi)} \approx 4.2$

Int.J.Mod.Phys.A 14 (1999) 937-946

- $\frac{Br(J/\psi \to D_S \rho)}{Br(J/\psi \to D_S \pi)} \approx 6.3$

Eur.Phys.J.C 55 (2008) 607-613

$J/\psi \to D_S^- \rho^+, \bar{D}^0 \bar{K}^{*0}$ PRD 89(2014)071101

Event selection

- Good charged track: $|V_{xy}| < 2$ cm $|V_z| < 20$ cm $|cos\theta| < 0.93$
- NGood=4
- Particle identification (dE/dx +TOF)

  $K^{\pm}$: $CL_K > CL_\pi \&\& CL_K > CL_p$

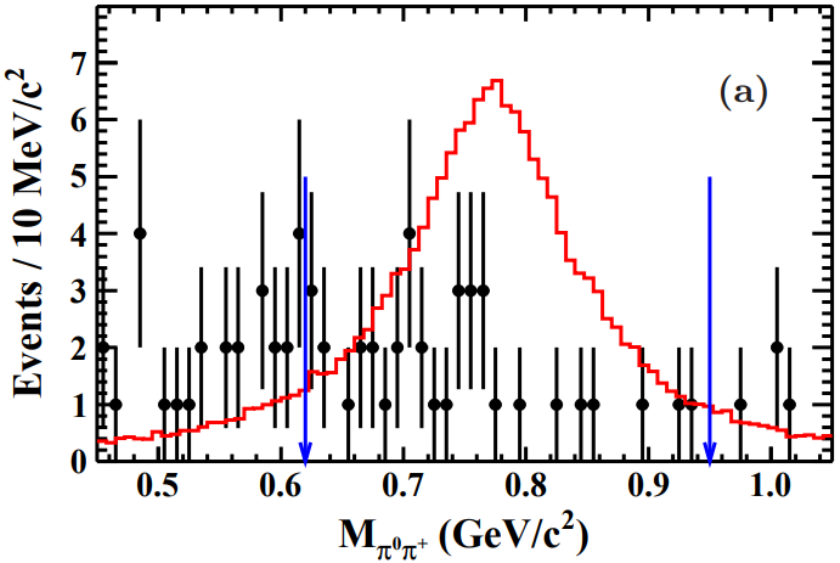
  $\pi^{\pm}$: $CL_\pi > CL_K \&\& CL_\pi > CL_p \&\& CL_\pi > CL_e$

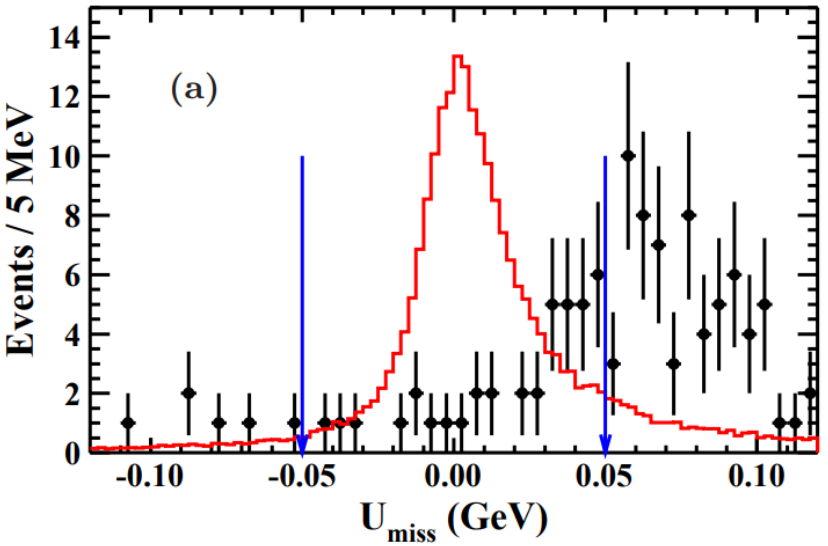
  $e^{\pm}$: $CL_e > CL_\pi \&\& CL_e > CL_K$, e/p>0.8, $|\cos\theta| < 0.8$
- Photon:

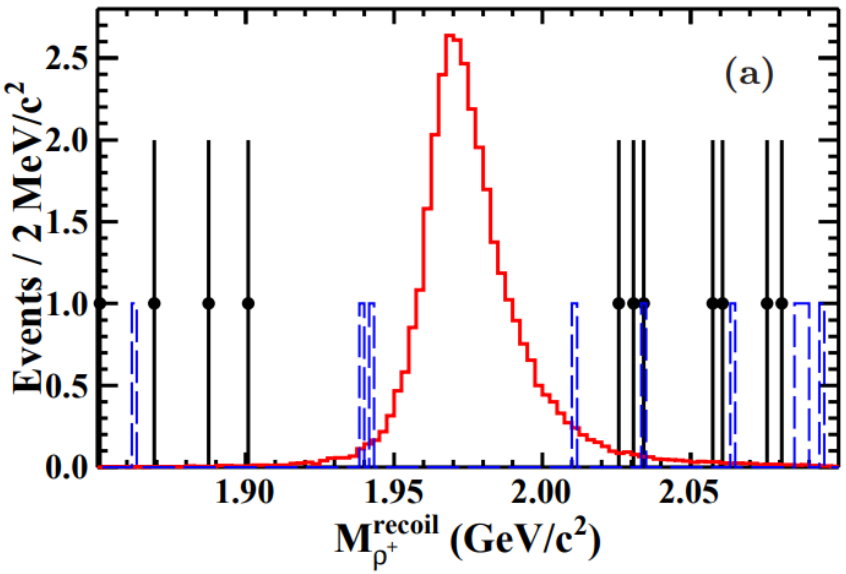
  $|\cos\theta| < 0.8 (0.86 < |\cos\theta| < 0.92)$, $E_\gamma > 25(50)$ MeV for barrel(endcap)

  NPhoton ≥ 2, $\theta_{c\gamma} > 10°$, $0 \leq$ TDC ≤ 14
- π^0 reconstruction: 1-C: $\chi^2 < 200$
- $J/\psi \to D_S^- \rho^+, D_S^- \to \phi e^- \nu_e, \phi \to K^+K^-, \rho^+ \to \pi^0\pi^+$
- $J/\psi \to \bar{D}^0 \bar{K}^{*0}, \bar{D}^0 \to K^+ e^- \bar{\nu}_e$, $\bar{K}^{*0} \to K^-\pi^+$

$J/\psi \to D_S^- \rho^+, \overline{D}^0 \overline{K}^{*0}$ PRD 89(2014)071101

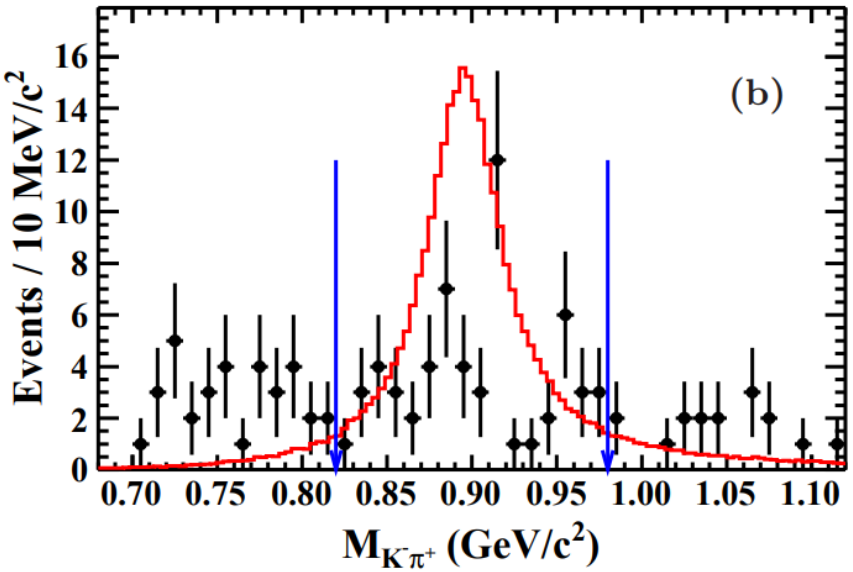


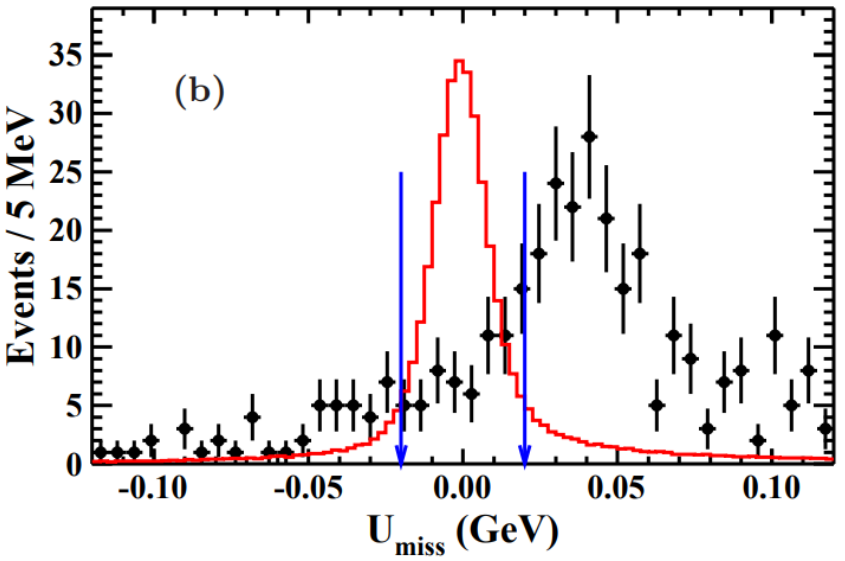


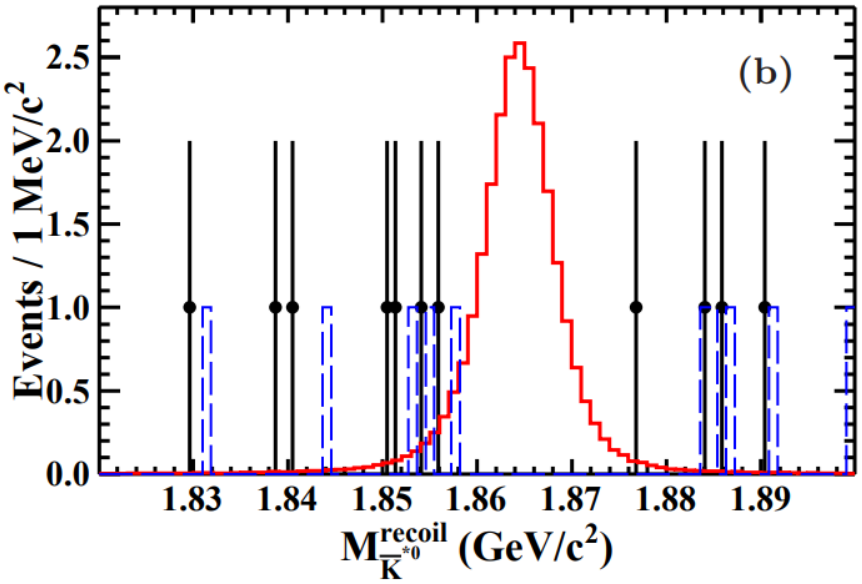


- $J/\psi \to D_S^- \rho^+$
  $D_S^- \to \phi e^- \nu_e, \phi \to K^+ K^-, \rho^+ \to \pi^0 \pi^+$

$J/\psi \to D_S^- \rho^+, \bar{D}^0 \bar{K}^{*0}$ PRD 89(2014)071101

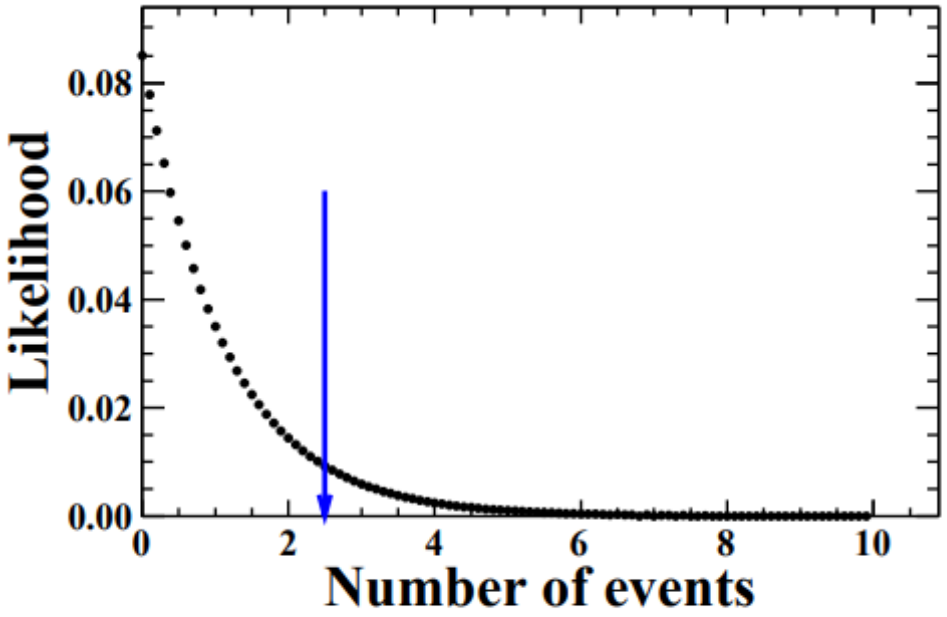




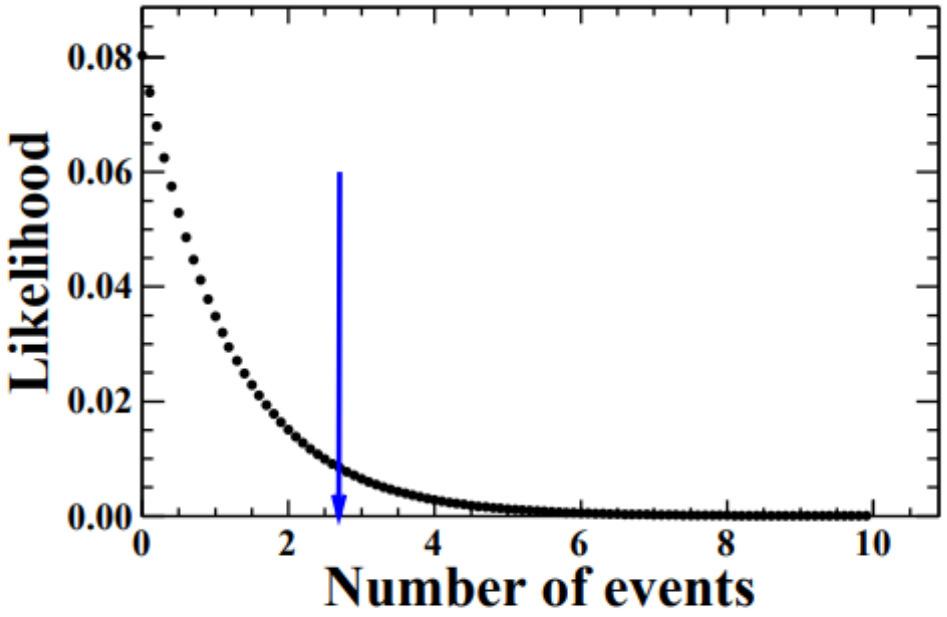


- $J/\psi \to \bar{D}^0 \bar{K}^{*0}$
  $\bar{D}^0 \to K^+ e^- \bar{\nu}_e$, $\bar{K}^{*0} \to K^- \pi^+$

$J/\psi \to D_S^- \rho^+, \overline{D}^0 \overline{K}^{*0}$ PRD 89(2014)071101



(a) $J/\psi \to D_s^- \rho^+$



(b) $J/\psi \to \overline{D}^0 \overline{K}^{*0}$

- $\mathcal{B}(J/\psi \to D_S^- \rho^+) < 1.3 \times 10^{-5}$
- $\mathcal{B}(J/\psi \to \overline{D}^0 \overline{K}^{*0}) < 2.5 \times 10^{-6}$

$J/\psi \to D_S^- \pi^+, D_S^- \rho^+$

- Ongoing analysis of $J/\psi \to D_S^- \pi^+ + c.c.$ and $J/\psi \to D_S^- \rho^+ + c.c.$.
- With full data of 10.1B J/ψ events, expect to improve the branching fractions.
- The analysis will be published in 2023.

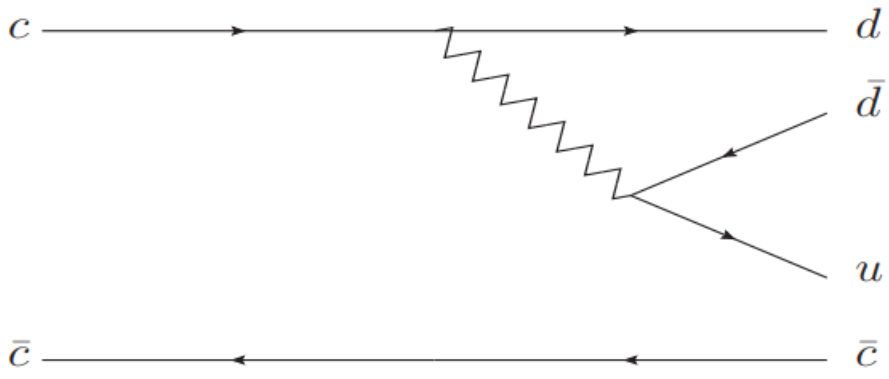
arXiv:1912.05983

Decay	Predict $\mathcal{B}$ $(\times 10^{-10})$	Data $(\times 10^{8})$	$\mathcal{B}$ $(\times 10^{-4})$	Exp.sensitivity (use full data)$(\times 10^{-6})$
$J/\psi \to D_S^- \pi^+ + c.c.$	2.00 ~ 8.74	0.577	1.3[1]	9.9
$J/\psi \to D_S^- \rho^+ + c.c.$	12.60 ~ 50.50	2.250	0.13[2]	2.0

[1] Phys. Lett. B 663(2008) 297.

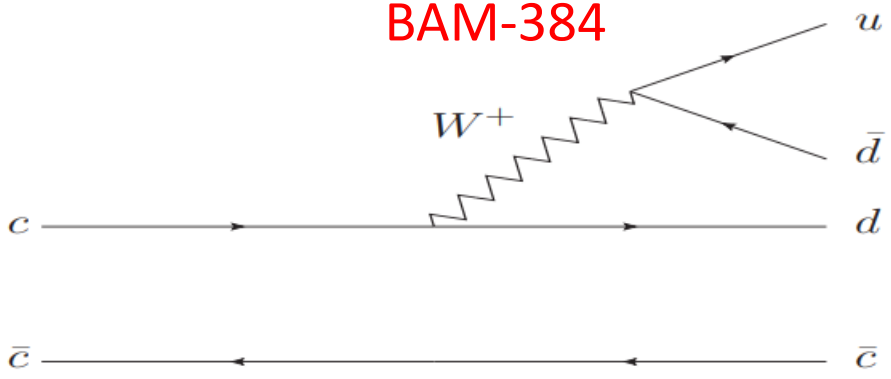
[2] Phys. Rev. D 89(2014) 071101.

$J/\psi \to \bar{D}^0\pi^0, \bar{D}^0\eta, \bar{D}^0\rho^0, D^-\pi^+, D^-\rho^+$



(a) $J/\psi \to \bar{D}^0\pi^0, \bar{D}^0\eta$ and $\bar{D}^0\rho^0$

BAM-384



(b) $J/\psi \to D^-\pi^+$ and , $D^-\rho^+$

- $c \to u/s$ processes such as $J/\psi \to D^0e^+e^-$, $J/\psi \to D^0K^0$, and $J/\psi \to D_s^-\rho^+$ and $J/\psi \to D^0K^{*0}$ have been studied at BESII/BESIII;
- More $c \to d$ processes such as $J/\psi \to \bar{D}^0\pi^0, \bar{D}^0\eta, \bar{D}^0\rho^0, D^-\pi^+, D^-\rho^+$ have not reported yet; Searching for weak decays of charmonium to single D mesons provides tests of standard model theory and serves as a probe of new physics.
- Multiple models[123] predict the order of branching fraction at $10^{-10} - 10^{-12}$.

[1]EPJC55 607 , [2] Int. J. Mod. Phys. A 14, 937(1997),
[3] Int. J. Mod. Phys. A30, 1550094 (2015)

$J/\psi \to \bar{D}^0\pi^0, \bar{D}^0\eta, \bar{D}^0\rho^0, D^-\pi^+, D^-\rho^+$

Event selection

BAM-384

- Good charged track: $|V_{xy}| < 1$ cm $|V_z| < 10$ cm $|cos\theta| < 0.93$
- Particle identification (dE/dx +TOF)

  $K^{\pm}$: $CL_K > CL_\pi$, $CL_K > 0$

  $\pi^{\pm}$: $CL_\pi > CL_K$, $CL_\pi > 0$

  $e^{\pm}$: $CL_e > CL_\pi \&\& CL_e > CL_K$, $CL_e > 0.001$, e/p>0.8
- Photon:

  $|\cos\theta| < 0.8 (0.86 < |\cos\theta| < 0.92)$, $E_\gamma > 25(50)$ MeV for barrel(endcap)

  $\theta_{c\gamma} > 10°$, $0 \leq$ TDC ≤ 14
- π^0 reconstruction: 1-C: $\chi^2 < 200$
- $J/\psi \to \bar{D}^0 M$, $\bar{D}^0 \to K^+ e^- \bar{\nu}_e$, $M \to \pi^+\pi^-(\rho^0), \gamma\gamma(\pi^0, \eta)$
- $J/\psi \to D^- M^+, D^- \to K_S^0 e^- \bar{\nu}_e, K_S^0 \to \pi^+\pi^-, M^+ \to \pi^+ (\rho^+)$

$J/\psi \to \overline{D}^0\pi^0, \overline{D}^0\eta, \overline{D}^0\rho^0, D^-\pi^+, D^-\rho^+$

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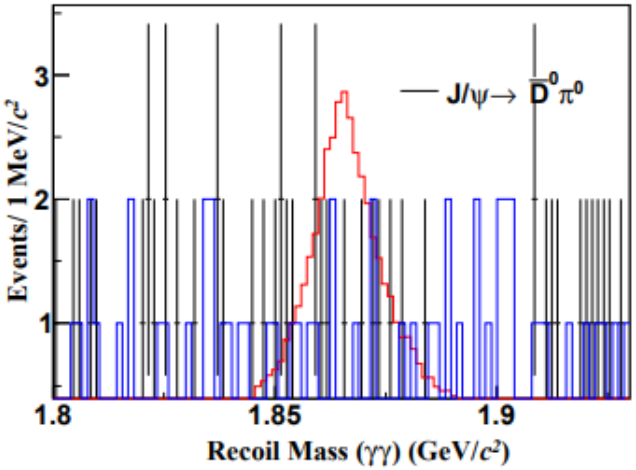

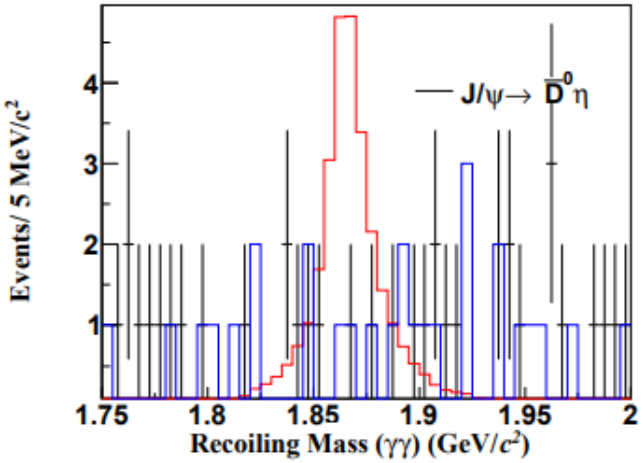

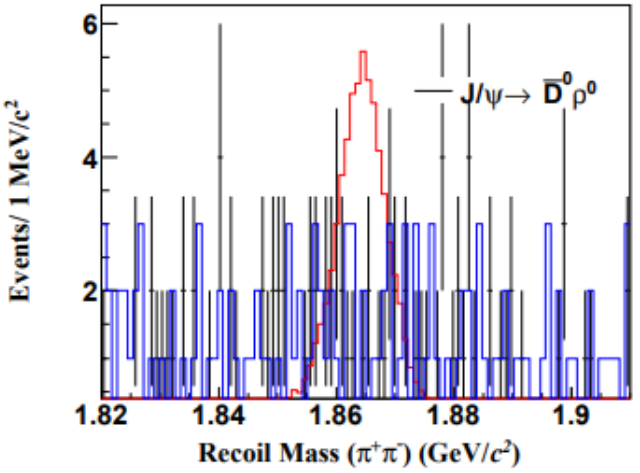

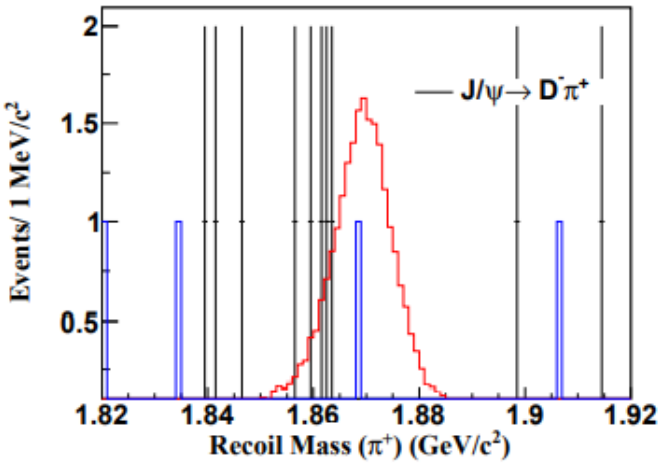

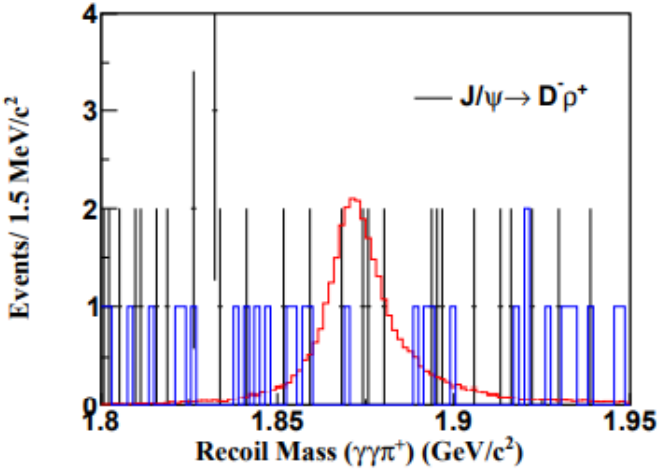

- The distributions of recoiling invariant mass.

$J/\psi \to \bar{D}^0\pi^0, \bar{D}^0\eta, \bar{D}^0\rho^0, D^-\pi^+, D^-\rho^+$

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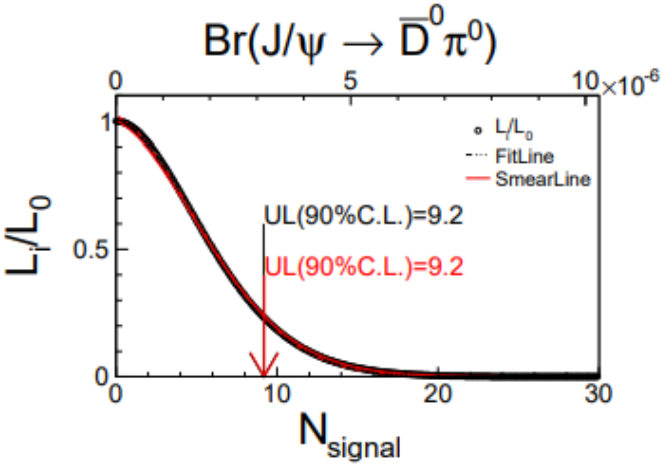
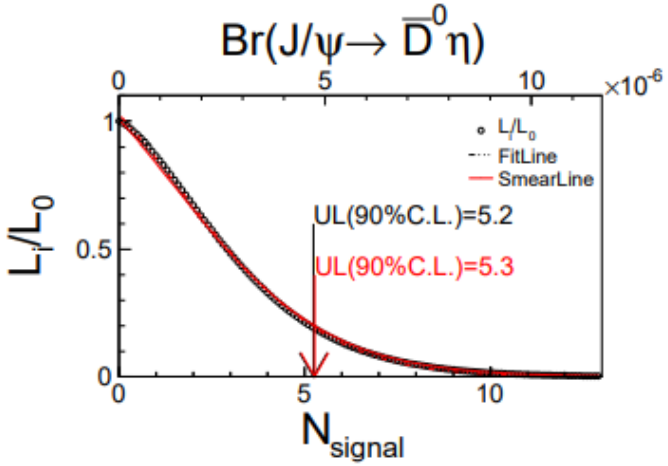
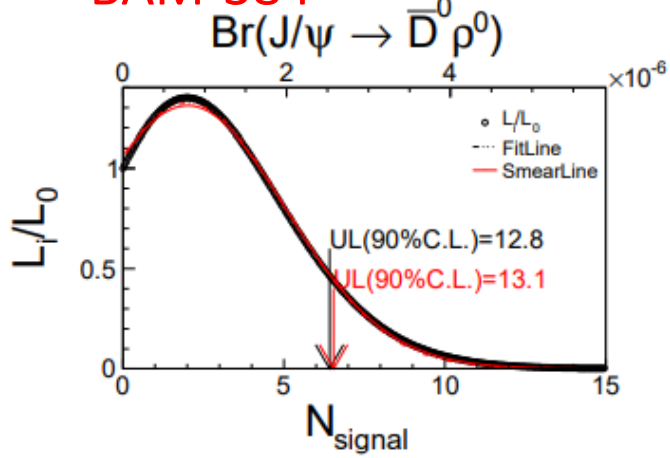
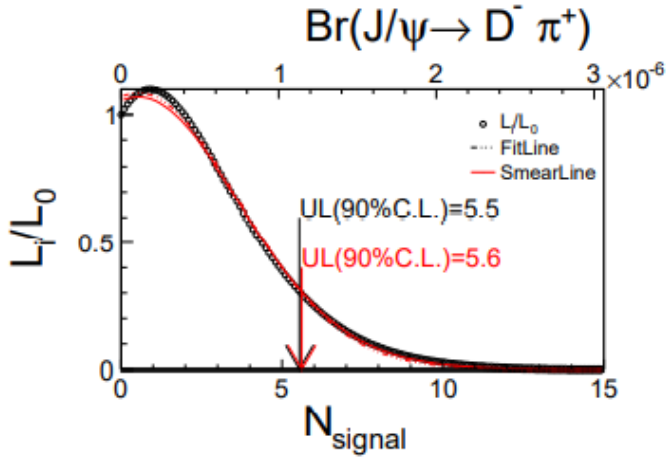
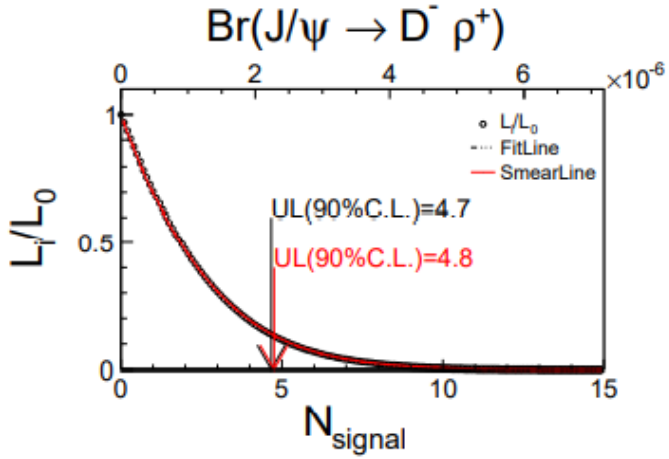










- Bayesian approaches
- The upper limit of number of signal at the 90% C.L: 9.2, 5.3, 13.1, 5.6, 4.8

$J/\psi \to \bar{D}^0\pi^0, \bar{D}^0\eta, \bar{D}^0\rho^0, D^-\pi^+, D^-\rho^+$

BAM-384

- With full data of 10.1B J/ψ events, expect to improve the branching fractions.
- The analysis will be published in 2023.

arXiv:1912.05983

Decay	Predict $\mathcal{B}$ $(\times 10^{-10})$	Data $(\times 10^{8})$	$\mathcal{B}$ $(\times 10^{-6})$	Exp.sensitivity (use full data) $(\times 10^{-6})$
$J/\psi \to \bar{D}^0\pi^0 + c.c$	0.24 ~ 0.055	2.250	3.2[1]	0.48
$J/\psi \to \bar{D}^0\eta + c.c$	0.016 ~ 0.070		4.7[1]	0.72
$J/\psi \to \bar{D}^0\rho^0 + c.c$	0.18 ~ 0.22		5.1[1]	0.77
$J/\psi \to D^-\pi^+ + c.c$	0.08 ~ 0.55		1.2[1]	0.21
$J/\psi \to D^-\rho^+ + c.c.$	0.42 ~ 2.20		2.3[1]	0.35

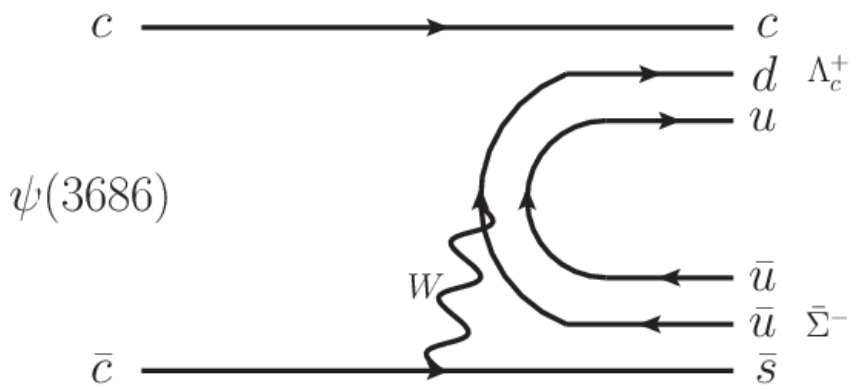
[1] Y.H. Yang, C.W Wang, Search for the J/ψ weak decays. BESIII-BAM-00384.

$\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.$

arxiv: 2207.10877

- A thorough study of the production and decay processes of baryons will provide a clearer insight into the structure of hadrons, the underlying physics , the mechanism and the fundamental interactions, and such processes may be more sensitive to new physics beyond the SM.
- Searches for purely baryonic weak $\psi(3686)$ decays involving a charmed baryon Λ_c^+ in the final state have never previously been performed.
- SM : $\mathcal{B}(\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.) \sim 10^{-10}$ [1] [1] Chin.Phys.Lett. 28 071301

  BSM: $\mathcal{B}(\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.) \sim 10^{-5} - 10^{-6}$.



$\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.$

arxiv: 2207.10877

Event selection

- Good charged track of Λ_c^+: $|V_{xy}| < 1$ cm $\quad |V_z| < 10$ cm $\quad |cos\theta| < 0.93$
- Good charged track of $\bar{\Sigma}^-$: $|V_{xy}| < 10$ cm $\quad |V_z| < 20$ cm $\quad |cos\theta| < 0.93$
- Particle identification (dE/dx +TOF)

  $K^{\pm}$: $CL_K > CL_\pi \&\& CL_K > CL_p$

  $\pi^{\pm}$: $CL_\pi > CL_K \&\& CL_\pi > CL_p$

  $p/\bar{p}$: $CL_p > CL_K \&\& CL_p > CL_\pi$
- Photon:

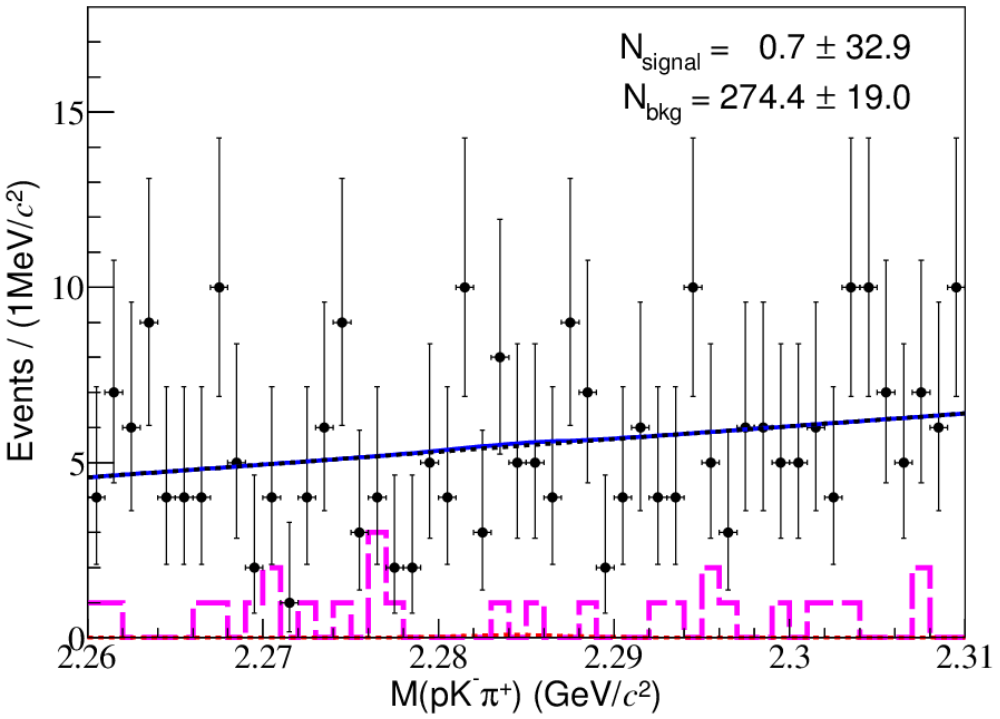
  $|\cos\theta| < 0.8 (0.86 < |\cos\theta| < 0.92)$, $E_\gamma > 25(50)$ MeV for barrel(endcap)

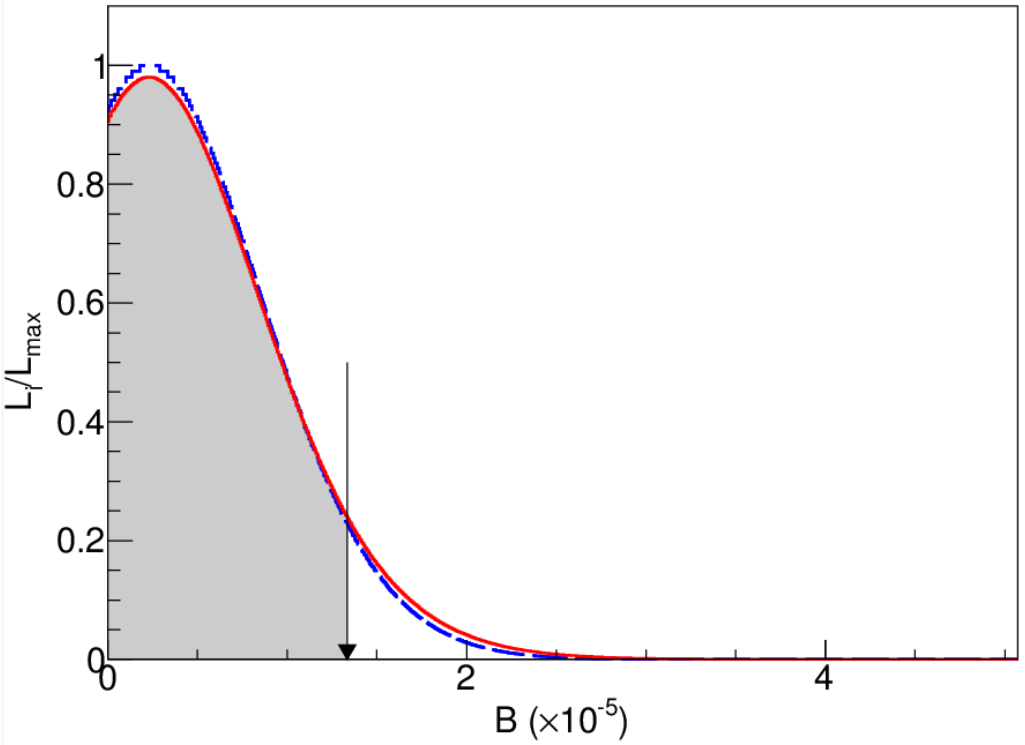
  $\theta_{c\gamma} > 10°$, $0 \leq \mathrm{TDC} \leq 14$
- π^0 reconstruction: 1-C: $\chi^2 < 200$
- $\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^-$, $\bar{\Sigma}^- \to \bar{p}\pi^0$ PHSP

  $\Lambda_c^+ \to pK^-\pi^+$ Amplitude analysis model
- Analysis strategy: Blinded method

$\psi(3686) \rightarrow \Lambda_c^+ \bar{\Sigma}^- + c.c.$

arxiv: 2207.10877





- $\psi(3686) \rightarrow \Lambda_c^+ \bar{\Sigma}^-$

  $\bar{\Sigma}^- \rightarrow \bar{p}\pi^0,\ \Lambda_c^+ \rightarrow pK^-\pi^+$

- $\mathcal{B}(\psi(3686) \rightarrow \Lambda_c^+ \bar{\Sigma}^- + c.c.) < 1.3 \times 10^{-5}$

Summary

- BESIII collaboration has performed studies on charmoium rare decay and the upper limit of branching fractions (@90% C.L) are obtained, with $(225.3 \pm 2.8) \times 10^6$ J/ψ events taken at $\sqrt{s}$=3.097 GeV and $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events taken at $\sqrt{s}$=3.686 GeV. PRD 89(2014)071101
  - $Br(J/\psi \to D_S^- \rho^+) < 1.3 \times 10^{-5}$, $Br(J/\psi \to \bar{D}^0 \bar{K}^{*0}) < 2.5 \times 10^{-6}$
  - $Br(J/\psi \to \bar{D}^0 \pi^0 + c.c) < 3.2 \times 10^{-6}$

    $Br(J/\psi \to \bar{D}^0 \eta + c.c) < 4.7 \times 10^{-6}$

    $Br(J/\psi \to \bar{D}^0 \rho^0 + c.c) < 5.1 \times 10^{-6}$ BAM-384

    $Br(J/\psi \to D^- \pi^+ + c.c) < 1.2 \times 10^{-6}$

    $Br(J/\psi \to D^- \rho^+ + c.c) < 2.3 \times 10^{-6}$
  - $Br(\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.) < 1.3 \times 10^{-5}$ arxiv: 2207.10877
- With full data of 10.1B J/ψ events, with improve the upper limit by 1-3 orders of magnitude.

Summary

- Predicted branching fractions and expected sensitivities with a sample of 10.1B J/ψ events and 3.0B $\psi(3686)$ events.

	Decay type	Example	exp. sensitivity ($\times 10^{-6}$)	predicted $\mathcal{B}$ [7–10] ($\times 10^{-10}$)
$c \to s$	$D_{(s)}P$	$J/\psi \to D_s^- \pi^+$	9.9	$2.00 \sim 8.74$
		$J/\psi \to D^0 K^0$	13.0	$0.36 \sim 2.80$
	$D_{(s)}V$	$J/\psi \to D_s^- \rho^+$	2.0	$12.60 \sim 50.50$
		$J/\psi \to D^0 K^{*0}$	0.38	$1.54 \sim 10.27$
	$D_{(s)}^* V$	$J/\psi \to D_s^{*-} \rho^+$	1.7	52.60
$c \to d$	$D_{(s)}P$	$J/\psi \to D_s^- K^+$	9.8	$0.16 \sim 0.55$
		$J/\psi \to D^- \pi^+$	0.21	$0.08 \sim 0.55$
		$J/\psi \to D^0 \eta$	0.72	$0.016 \sim 0.070$
		$J/\psi \to D^0 \eta'$	0.25	$0.003 \sim 0.004$
		$J/\psi \to D^0 \pi^0$	0.48	$0.024 \sim 0.055$
	$D_{(s)}V$	$J/\psi \to D_s^- K^{*+}$	5.4	$0.82 \sim 2.79$
		$J/\psi \to D^- \rho^+$	0.35	$0.42 \sim 2.20$
		$J/\psi \to D^0 \rho^0$	0.77	$0.18 \sim 0.22$
		$J/\psi \to D^0 \omega$	0.35	$0.16 \sim 0.18$
		$J/\psi \to D^0 \phi$	0.22	$0.41 \sim 0.65$
	$D_{(s)}^* V$	$J/\psi \to D_s^{*-} K^{*+}$	4.5	2.6
		$J/\psi \to D^{*-} \rho^+$	0.083	2.8
		$J/\psi \to D^{*-} K^{*+}$	0.027	9.6

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These weak decays can also be searched for in expected 3.0B $\psi(3686)$ events.

Thank you !