Charmonium semi-leptonic weak decay at BESIII

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Outline

- **Introduction**
- Search for $\psi \to D^- l^+ \upsilon_l + c.c.$
- Search for $\psi \to D_s^{(*)-} l^+ \upsilon_l + c.c.$
- Search for $\psi \to D_0 l^+ l^- + c.c.$
- Summary

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Semi-leptonic weak decay of charmonium

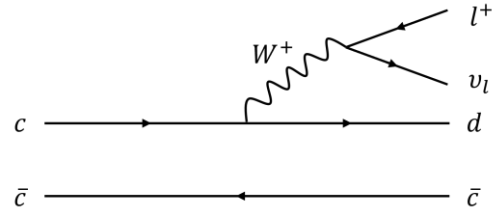
- **Calculation from standard model：** $10^{-9}\sim10^{-12}$

  ✓ Kinematically allowed but suppressed by strong interactions

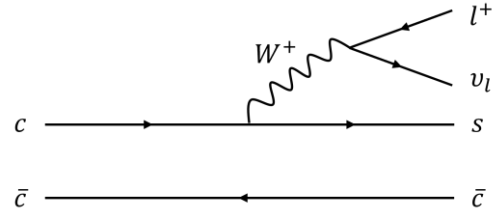
EPJC,54,107,2008
PRD,78:074012,2008
AHEP,2013:706543,2013
PRD,92:074030,2015
JPG:NPP,44:045004,2017

Theoretical model	QCDSR ($\times 10^{-11}$)	CLFQ ($\times 10^{-11}$)	BSW ($\times 10^{-11}$)	CCQM ($\times 10^{-11}$)	BSM ($\times 10^{-11}$)
$J/\psi \to D^- e^+ \nu_e$	$0.73^{+0.43}_{-0.22}$	$5.1-5.7$	$6.0^{+0.8}_{-0.7}$	1.71	$2.03^{+0.29}_{-0.25}$
$J/\psi \to D^- \mu^+ \nu_\mu$	$0.71^{+0.42}_{-0.22}$	$4.7-5.5$	$5.8^{+0.8}_{-0.6}$	1.66	$1.98^{+0.28}_{-0.24}$
$J/\psi \to D_s^- e^+ \nu_e$	18^{+7}_{-5}	$53-58$	$104.0^{+9.0}_{-7.5}$	33	$36.7^{+5.2}_{-4.4}$
$J/\psi \to D_s^- \mu^+ \nu_\mu$	17^{+7}_{-5}	$55-57$	$99.3^{+9.5}_{-6.5}$	32	$35.4^{+5.0}_{-4.3}$

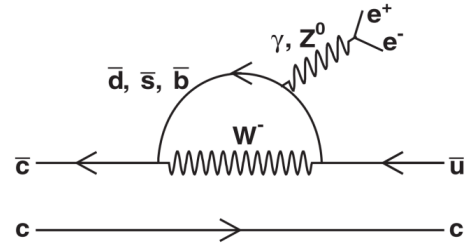
✓ $\psi \to D^- l^+ \upsilon_l + c.c.$



✓ $\psi \to D_s^{(*)-} l^+ \upsilon_l + c.c.$



✓ $\psi \to D_0 e^+ e^- + c.c.$



- **New physics beyond the stand model：**

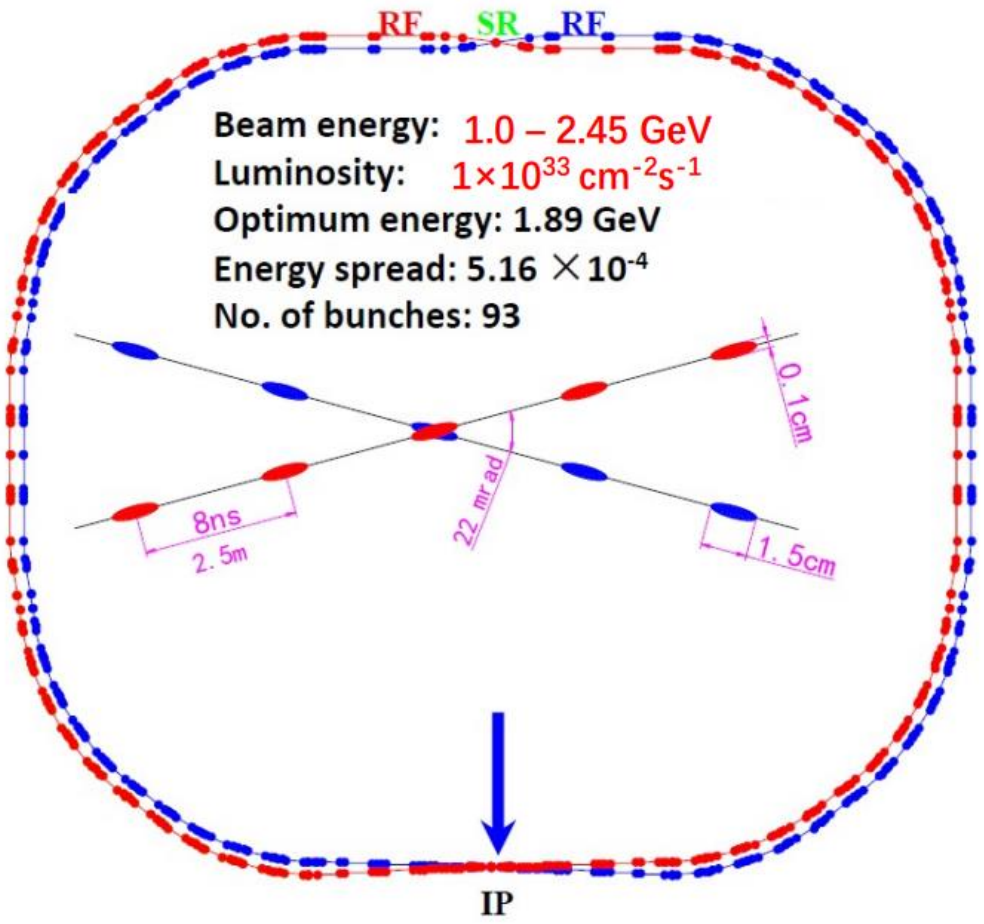
  Branching fraction could be enhanced by 2 or 3 orders of magnitude,

  e.g. Top-color model, two-Higgs doublet model..

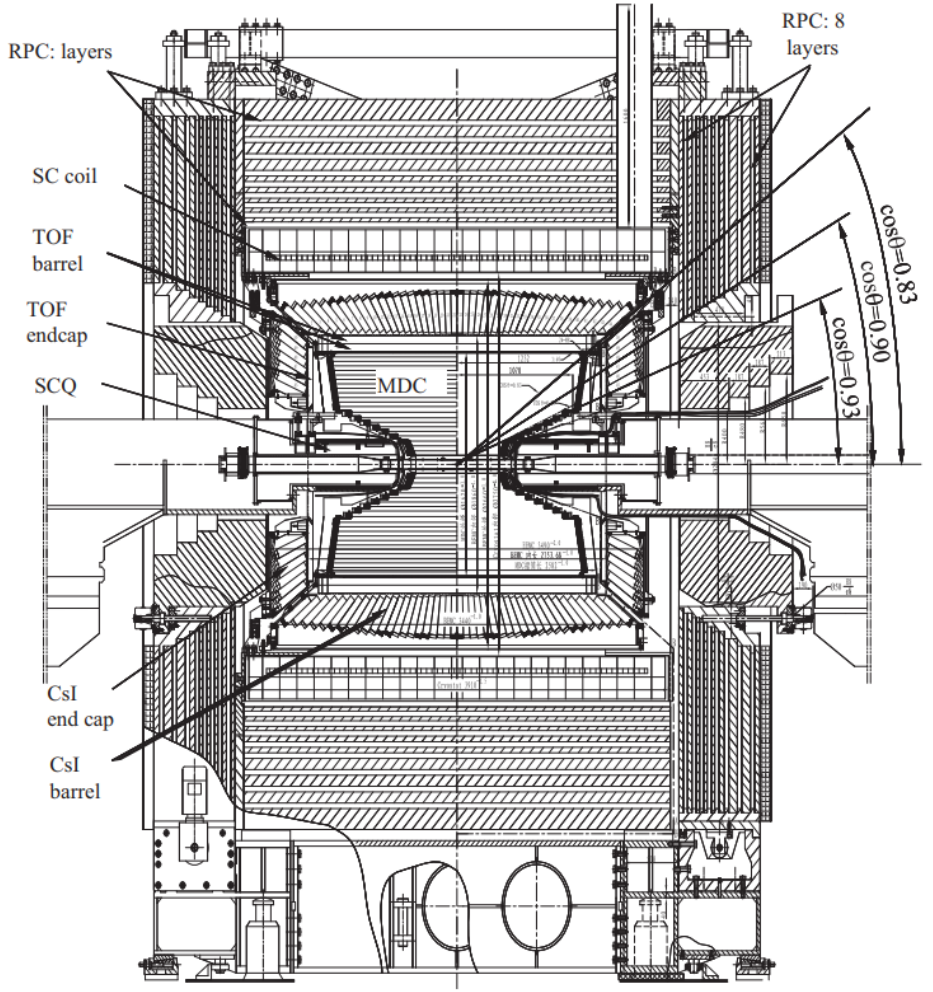
Phys. Lett. B 345, 483 (1995).
Phys. Rev. D 60, 014011 (1999).
Chin. Phys. C 36, 932 (2012).

➢ Weak decay of charmonium is a good prob to test the SM theory or search for new physics beyond SM

BEPCII and BESIII

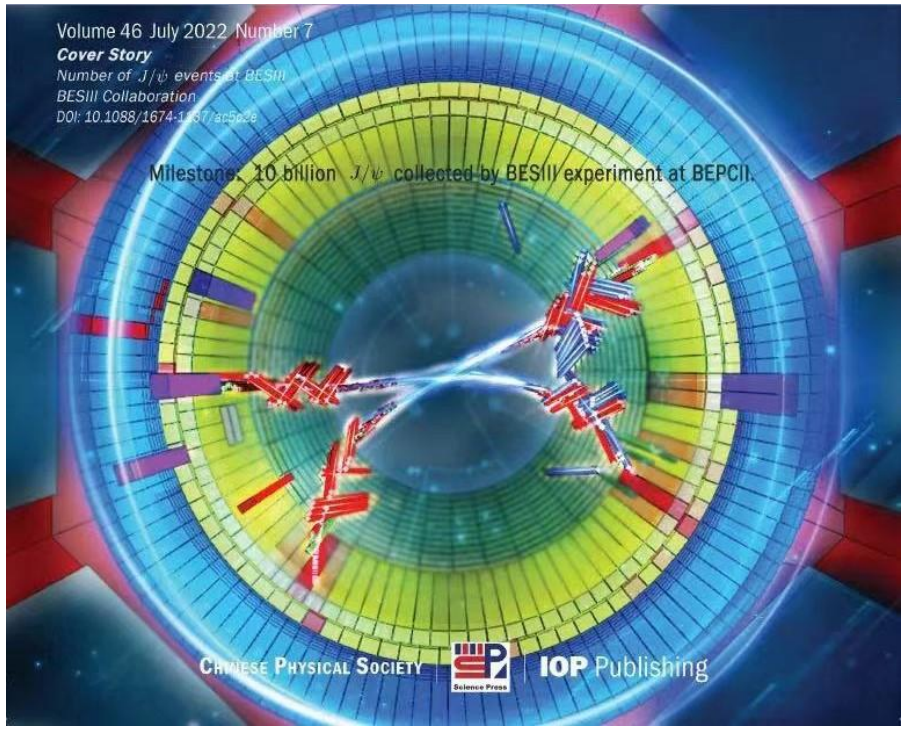


✓ **B**eijing **E**lectron **P**ositron **C**ollider **II**



✓ **BE**ijing **S**pectrometers **III**

Charmonium at BESIII



$Year$	J/ψ $events$ $(\times 10^6)$	$\psi(2S)events$ $(\times 10^6)$
2009	224.0 ± 1.3	107.0 ± 0.8
2012	1088.5 ± 4.4	341.1 ± 2.1
$2017-2019$	8774.0 ± 39.4	$-$
2021	$-$	~ 2300
$Total$	10087 ± 44	~ 2748.1

- ✓ A real J/ψ event at BESIII
- ✓ Drawn with Besvis,
- ✓ developed by Z.Y. You, S.H.Huang @SYSU, P.X. Long, Y. Zhang, etc @IHEP

https://docbes3.ihep.ac.cn/~offlinesoftware/index.php/Event_Display

- ✓ J/ψ events @3.097 GeV: $\sim 1 \times 10^{10}$ *Chin.Phys.C* 46 (2022) 7, 074001
- ✓ Ψ(2S) events @3.686 GeV: $\sim 3 \times 10^{9}$ *Chin.Phys.C* 42 (2018) 2, 023001

- ✓ **A large charmonium sample to search for the rare weak decay**

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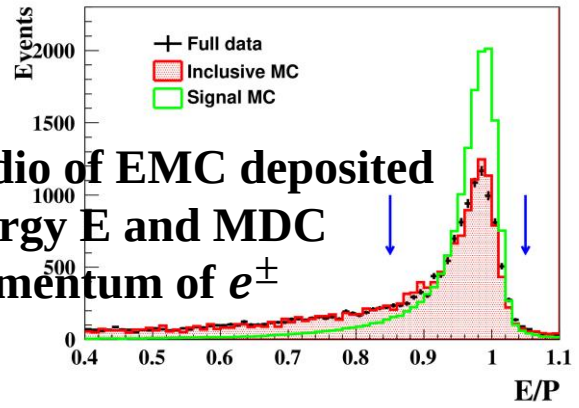
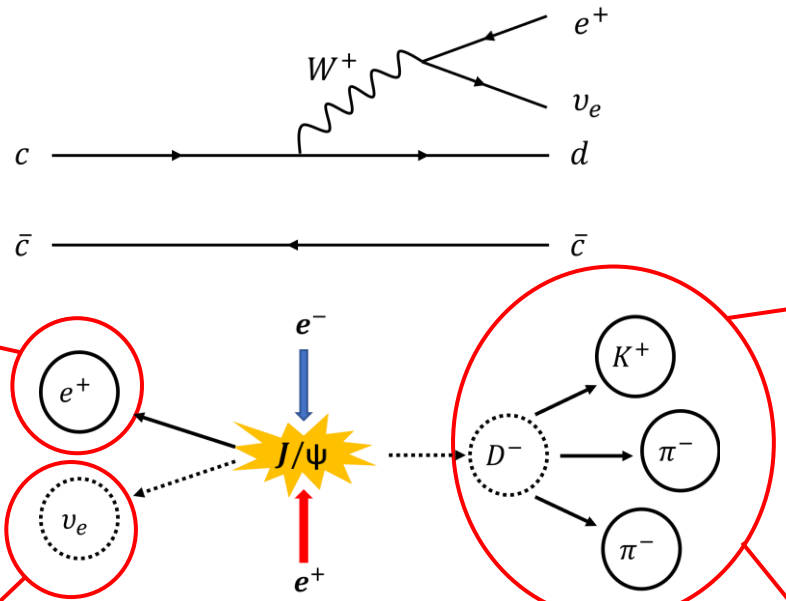
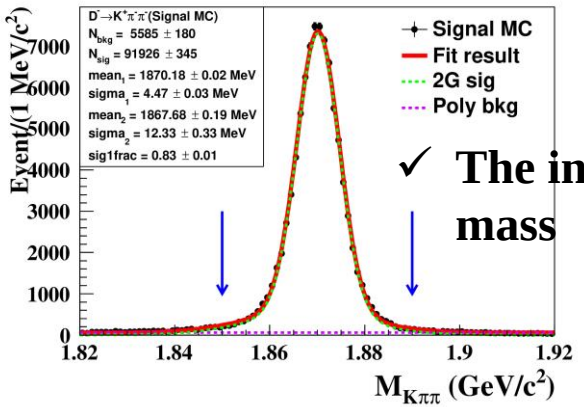
JHEP06(2021)157
BAM-459
Base on full J/ψ data @3.097 GeV

Event selection

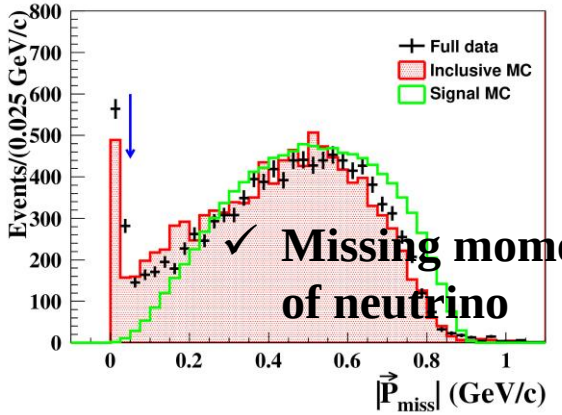


✓ Radio of EMC deposited energy E and MDC momentum of $e^{\pm}$

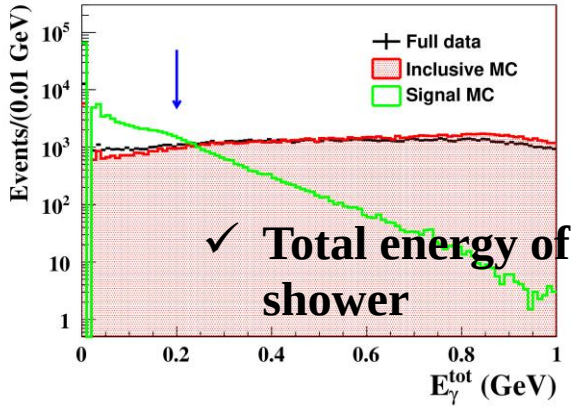




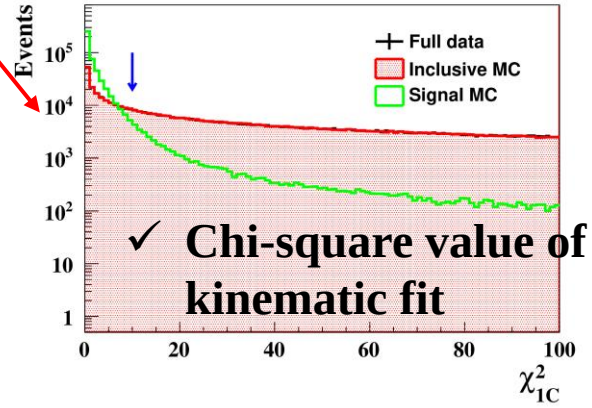
✓ The invariant mass



✓ Missing momentum of neutrino



✓ Total energy of good shower



✓ Chi-square value of kinematic fit

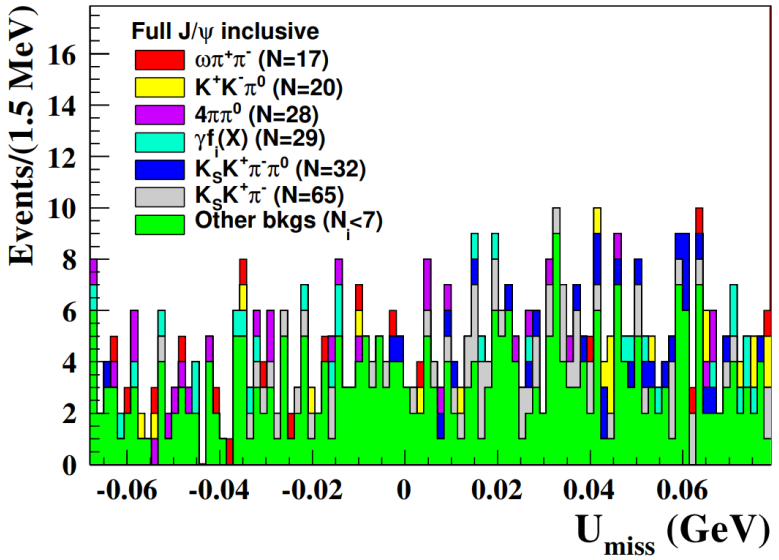
JHEP06(2021)157
BAM-459
Base on full J/ψ data @3.097 GeV

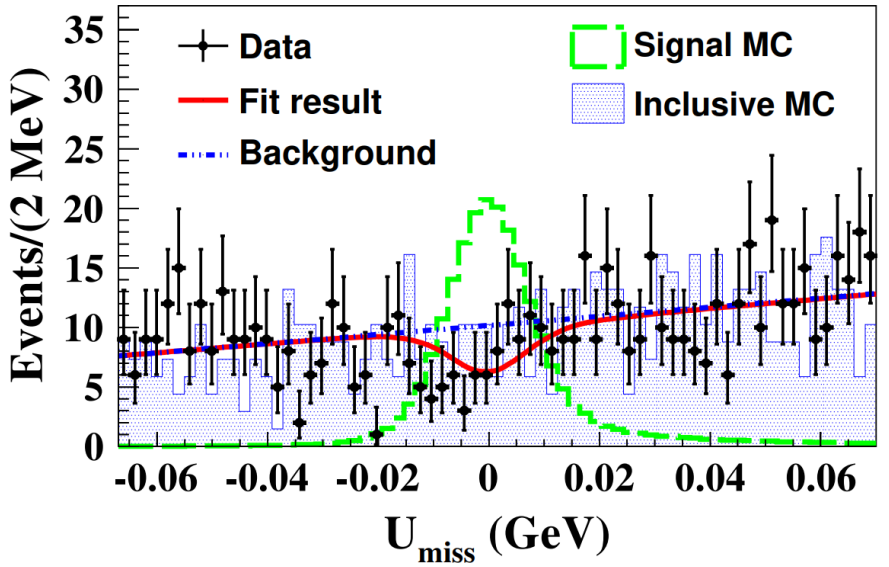
Background and signal study

- Two main backgrounds:

(1) Gamma conversion with e misidentified as π/K: $J/\psi \to \rho\pi \to \gamma\gamma\pi\pi \to \gamma e^+e^-\pi\pi$;
(2) π/K misidentified as e: $J/\psi \to \gamma\eta(1405) \to \gamma K K^0\pi \to \gamma\pi\pi\pi K$

- Define $U_{miss} = E_{miss} - c|\vec{p}_{miss}|$
  - ✓ Neutrino missing-energy: $E_{miss} = E_{J/\psi} - E_{D^-} - E_{e^+}$
  - ✓ Neutrino missing-momentum: $\vec{p}_{miss} = \vec{p}_{J/\psi} - \vec{p}_{D^-} - \vec{p}_{e^+}$
  - ✓ If there are signals in real data, it will have a peak around 0 in U_{miss}





- ✓ $PDF_{total} = \sum PDF^i_{sig} + poly(c_0)$
- ✓ $BF(J/\psi \to D^- e^+ \nu_e + c.c.) = \frac{N_{signal}}{N_{J/\psi} \times \epsilon \times BF(D^- \to K^+\pi^-\pi^-)}$

where signal efficiency $\epsilon = (29.93 \pm 0.10)\%$, which is determined from MC samples and N_{signal} is determined from fitting.

✓ **No excess of events is observed above the background.**

JHEP06(2021)157
BAM-459
Base on full J/ψ data @3.097 GeV

Uncertainty and upper limit

Sources	Relative uncertainties
Tracking	4.0
Particle ID	4.0
Signal MC model	3.0
$E_\gamma^{\rm tot}$ requirement	2.1
E/p requirement	0.3
$\lvert\vec{p}_{\rm miss}\rvert$ requirement	0.3
BF of the $D^- \to K^+\pi^-\pi^-$ decay	1.7
Number of J/ψ events	0.5
Total	7.0

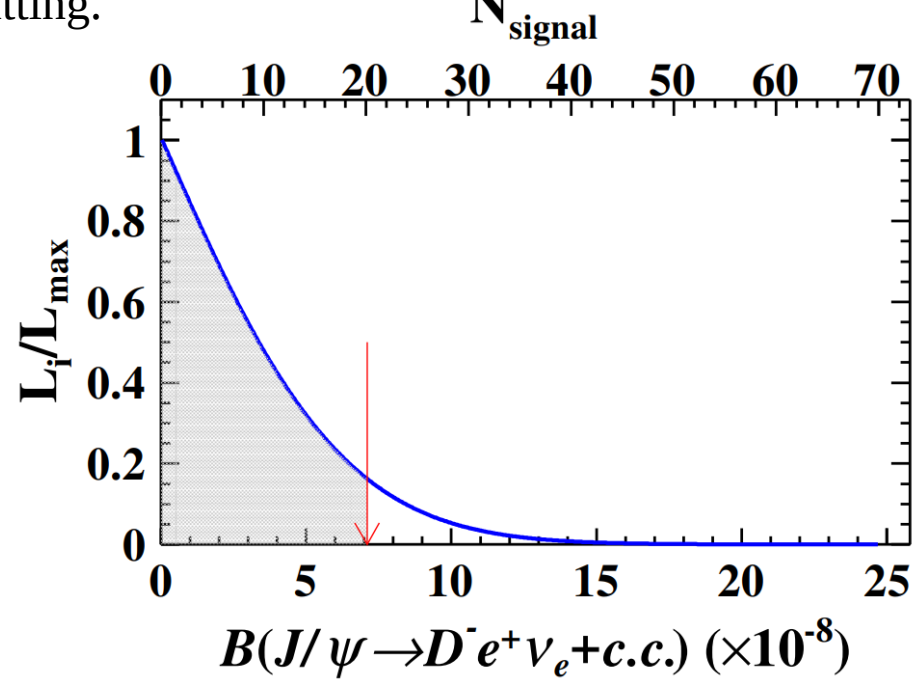
✓ Summary of systematic uncertainties (%).

- $\mathcal{B}(J/\psi \to D^- e^+ \nu_e + c.c.) < 7.1 \times 10^{-8}$ at 90% CL
- **The most sensitive result of charmonium weak decay**

✓ $PDF_{total} = \sum PDF_{sig}^{i} + poly(c_0)$

✓ $BF(J/\psi \to D^- e^+ \nu_e + c.c.) = \frac{N_{signal}}{N_{J/\psi} \times \epsilon \times BF(D^- \to K^+\pi^-\pi^-)}$

where signal efficiency $\epsilon = (29.93 \pm 0.10)\%$, which is determined from MC samples and N_{signal} is determined from fitting.



✓ The likelihood curve and UL at 90% CL.

Reply to PSM
Ongoing

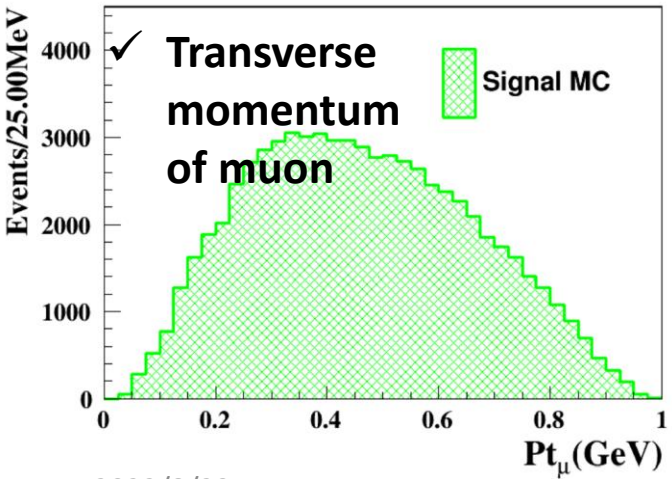
$J/\psi \to D^- \mu^+ \upsilon_\mu$ vs $J/\psi \to D^- e^+ \upsilon_e$

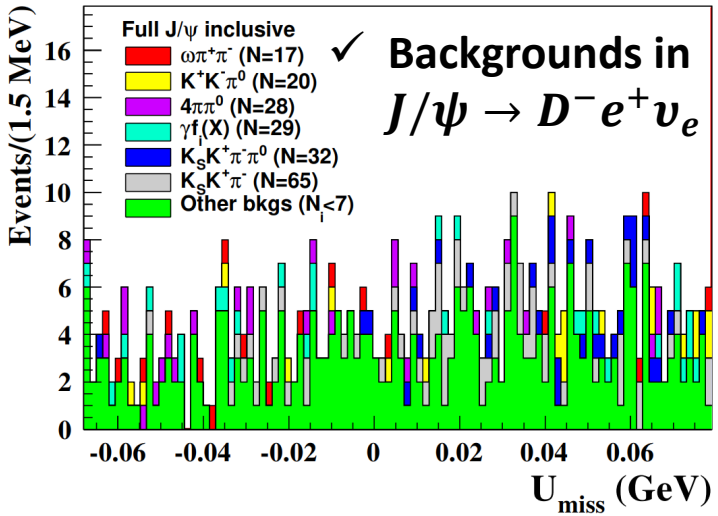
- μ/e will be Similar in standard model.
- μ/e will be different beyond the standard model.

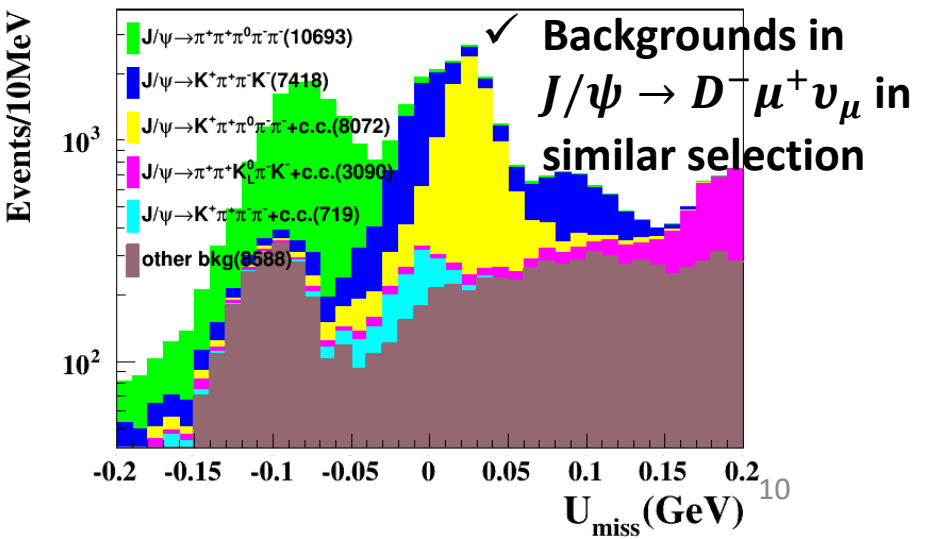
- Some experiments have found some deviations in muon between electron, like muon g-2, B meson weak decay with a μ Phys. Rev. Lett. 126.141801 Nature Phys., 2022, 18 (3): 277-282.

- Charmonium weak decay with a μ has never been searched before

- In $J/\psi \to D^- \mu^+ \upsilon_\mu$
  - MDC, EMC, TOF can not identify μ/π well
  - Muon with low momentum can't have hit information in MUC
  - MUC also does not help much in selecting muon in $J/\psi \to D^- \mu^+ \upsilon_\mu$
  - Large μ/π mis-identification hadron backgrounds from J/ψ decay

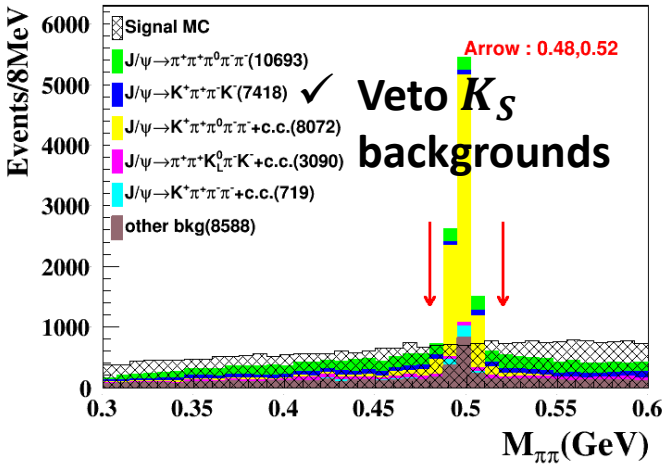




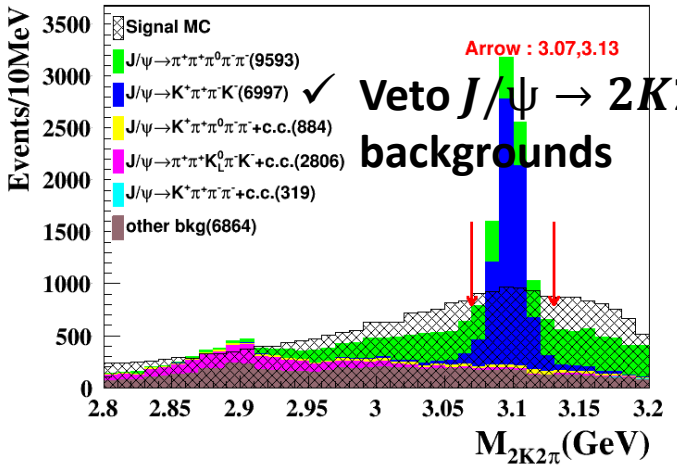


Reply to PSM
Ongoing

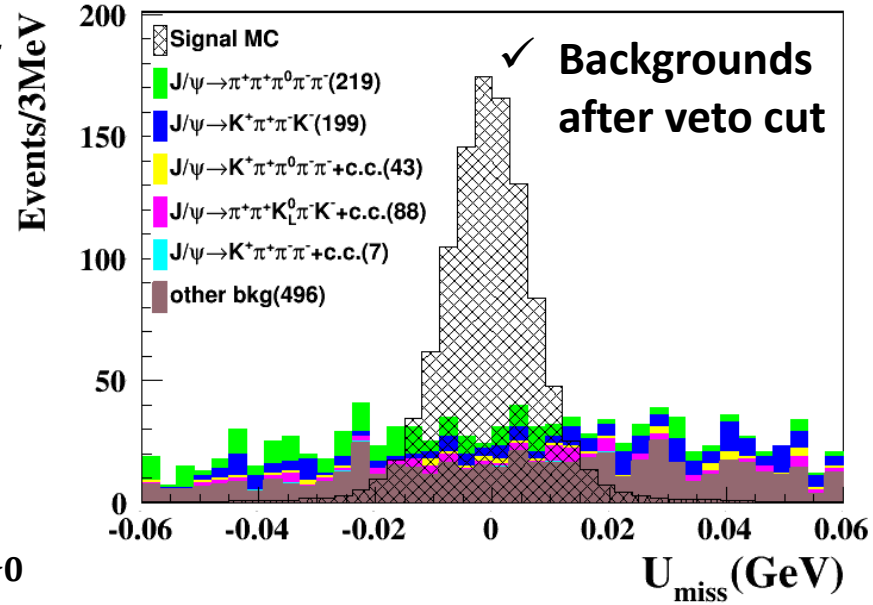
Backgrounds study



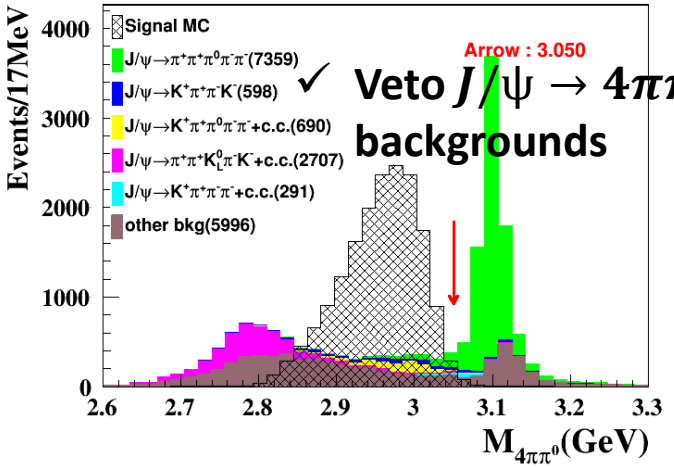
✓ Veto K_S backgrounds



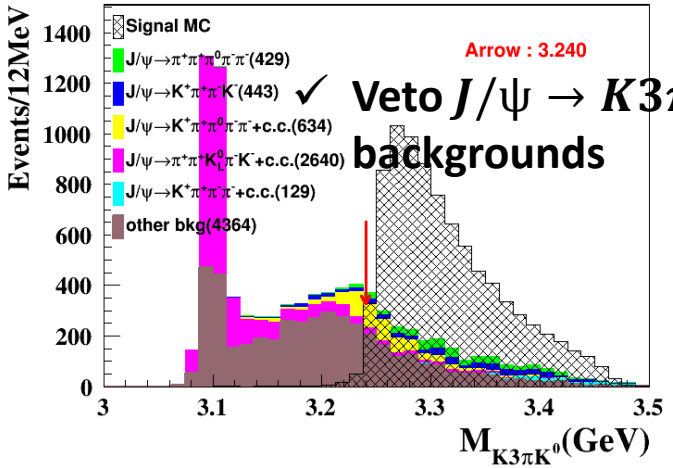
✓ Veto $J/\psi \to 2K2\pi$ backgrounds



✓ Backgrounds after veto cut



✓ Veto $J/\psi \to 4\pi\pi^0$ backgrounds



✓ Veto $J/\psi \to K3\pi K^0$ backgrounds

✓ The first result of $\mathcal{B}(J/\psi \to D^- \mu^+ \nu_\mu + c.c.)$ will come soon

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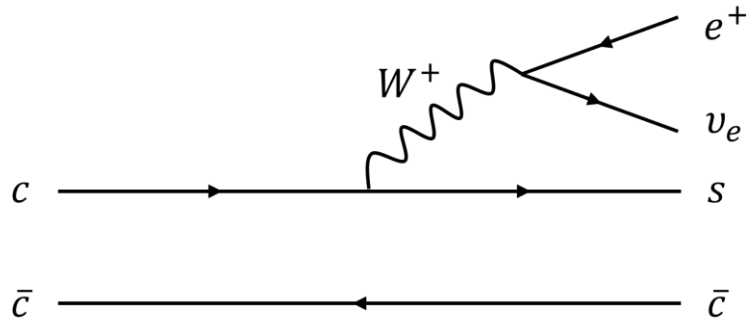
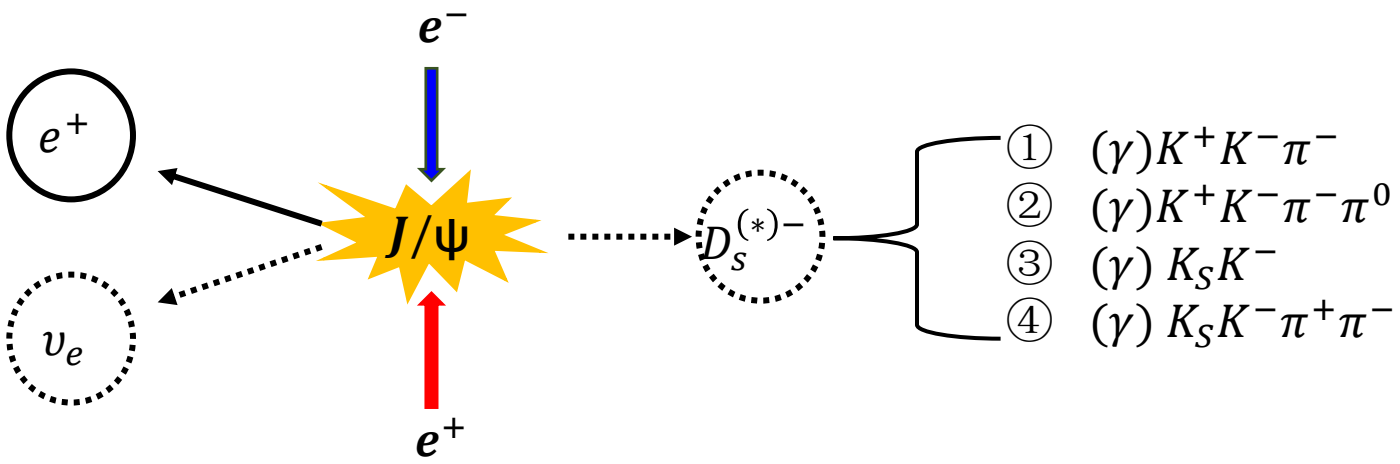
PRD, 2014, 90(11): 112014.
BAM-96
Base on J/ψ data @3.097 GeV in 2009

Event selection



➢ $J/\psi \to D_s^{(*)-} e^+ \nu_e + c.c.\,(c \to d)$ will have larger branch fraction than $J/\psi \to D^- e^+ \nu_e + c.c.\,(c \to s)$

☐ Reconstruction of $J/\psi \to D_s^{(*)-} e^+ \nu_e + c.c.$



Rec Model	signal events	efficiency(%)
$D_s^- \to K^+K^-\pi^-$	24457 ± 174	24.46 ± 0.17
$D_s^- \to K_s^0K^-$	29898 ± 188	29.90 ± 0.19
$D_s^- \to K^+K^-\pi^-\pi^0$	11075 ± 126	11.08 ± 0.13
$D_s^- \to K_s^0K^-\pi^+\pi^-$	13744 ± 118	13.74 ± 0.12

☐ Efficiency of $J/\psi \to D_s^- e^+ \nu_e + c.c.$
(simulation of signal MC in each mode: 1×10^5)

Rec Mode	signal events	efficiency(%)
$D_s^- \to K^+K^-\pi^-$	16594 ± 169	16.59 ± 0.17
$D_s^- \to K_s^0K^-$	19622 ± 167	19.62 ± 0.17
$D_s^- \to K^+K^-\pi^-\pi^0$	7402 ± 145	7.40 ± 0.15
$D_s^- \to K_s^0K^-\pi^+\pi^-$	8201 ± 108	8.20 ± 0.11

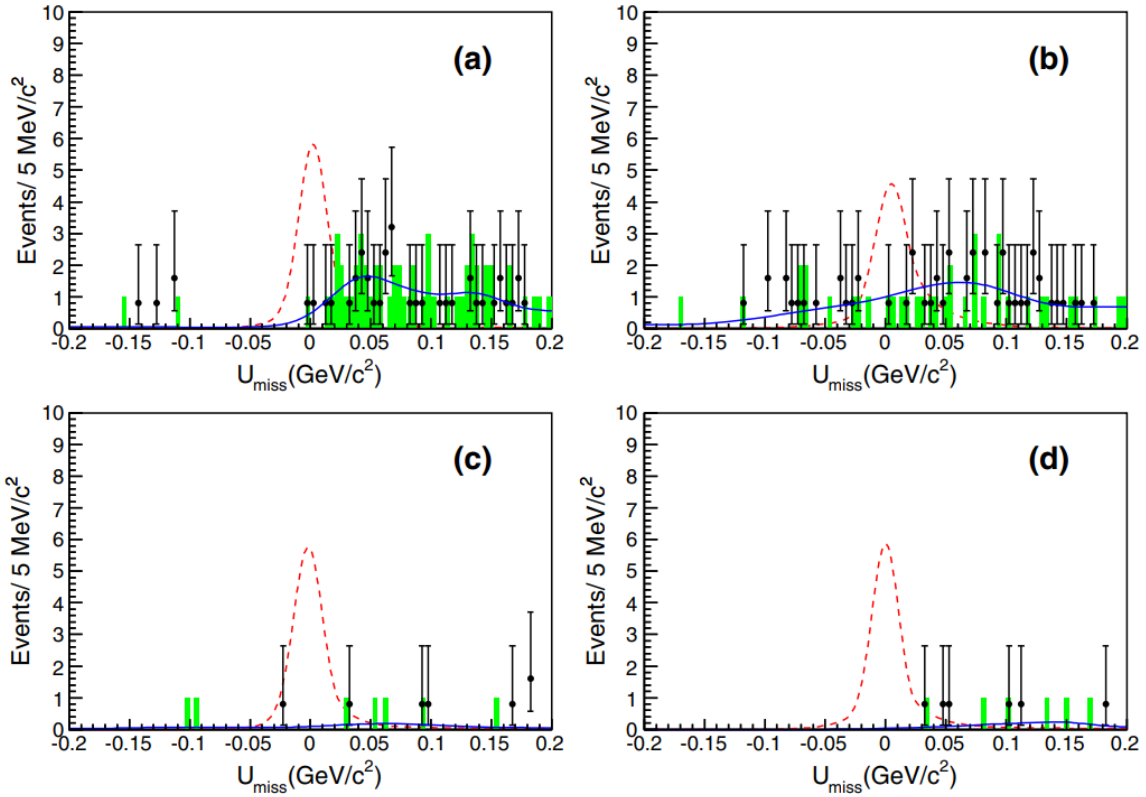
☐ Efficiency of $J/\psi \to D_s^{*-} e^+ \nu_e + c.c.$
(simulation of signal MC in each mode: 1×10^5)

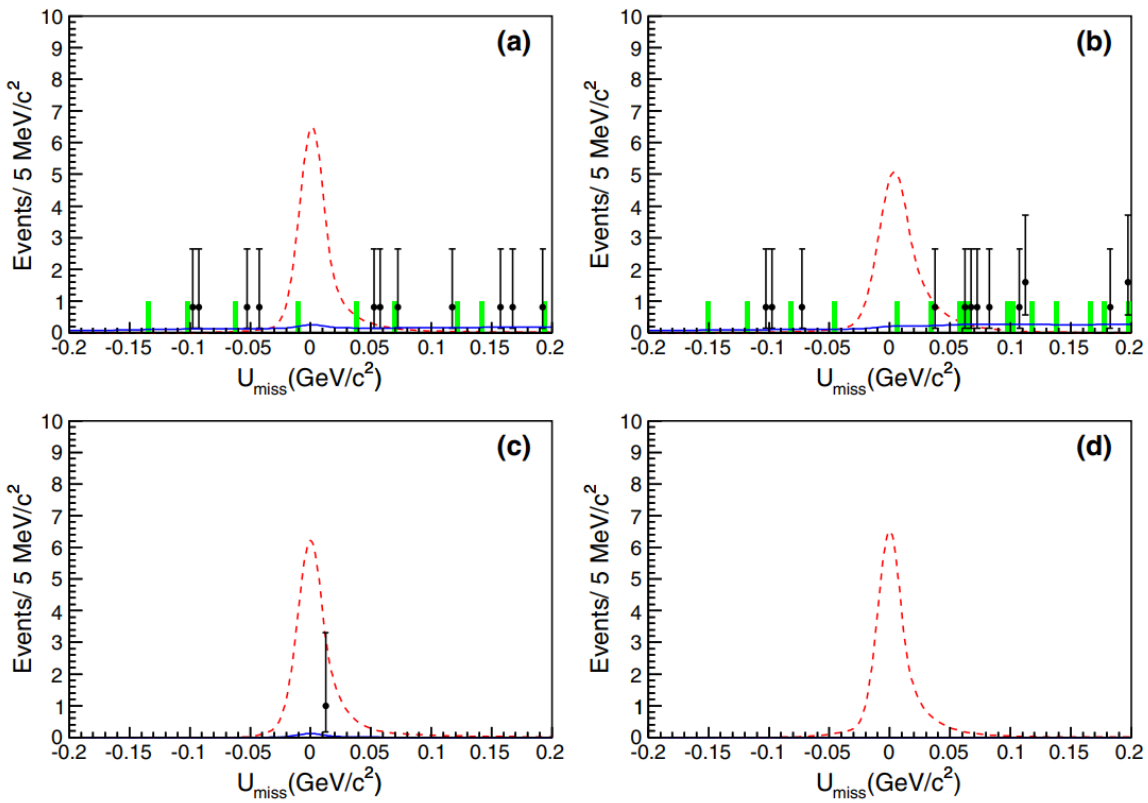
$J/\psi \to D_s^{(*)-} e^+ \nu_e + c.c.$

Signal study

(a) $D_s^- \to K^+K^-\pi^-$
(b) $D_s^- \to K^+K^-\pi^-\pi^0$
(c) $D_s^- \to K_S K^-$
(d) $D_s^- \to K_S K^-\pi^+\pi^-$

PRD, 2014, 90(11): 112014.
BAM-96
Base on J/ψ data @3.097 GeV in 2009





- ✓ $J/\psi \to D_s^- e^+ \nu_e + c.c.$
- ✓ Simultaneous fitting on the U_{miss} from data

- ✓ $J/\psi \to D_s^{*-} e^+ \nu_e + c.c.$
- ✓ Simultaneous fitting on the U_{miss} from data

✓ **No excess of events is observed in 2.24×10^8 J/ψ**

PRD, 2014, 90(11): 112014.
BAM-96
Base on J/ψ data @3.097 GeV in 2009

Uncertainty and upper limit

➢ Uncertainty of $J/\psi \to D_s^- e^+ \nu_e + c.c.$

Sources\modes	$K^+K^-\pi^-$	$K^+K^-\pi^-\pi^0$	$K_S^0K^-$	$K_S^0K^-\pi^+\pi^-$
Reconstruction ϵ	6.8	16.2	16.6	18.6
$\mathcal{B}(D_s^- \to X)$	3.9	11.1	4.0	6.6
Background shape	2.3	2.4	3.2	2.9
Fitting range	0.3	0.4	0.5	0.6
MC statistic	0.7	1.2	0.6	0.9
Total	8.2	19.8	17.4	20.0

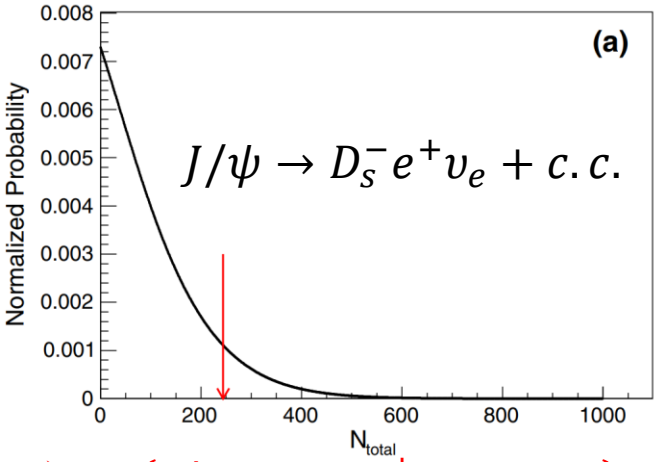
➢ Uncertainty of $J/\psi \to D_s^{*-} e^+ \nu_e + c.c.$

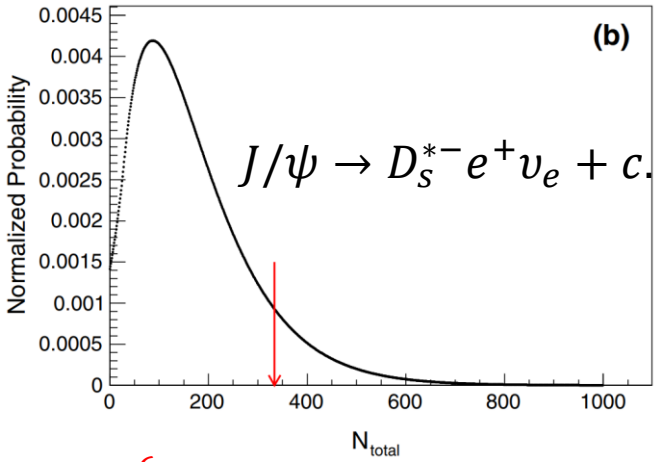
Sources\modes	$K^+K^-\pi^-$	$K^+K^-\pi^-\pi^0$	$K_S^0K^-$	$K_S^0K^-\pi^+\pi^-$
Reconstruction ϵ	6.8	16.2	16.6	18.6
$\mathcal{B}(D_s^- \to X)$	3.9	11.1	4.0	6.6
Background shape	2.5	2.5	2.7	3.2
Fitting range	0.2	0.6	0.4	0.4
MC statistic	1.0	1.9	0.9	1.4
Total	8.3	20.0	17.4	20.1

➢ Upper limit of $J/\psi \to D_s^{(*)-} e^+ \nu_e + c.c.$

	$J/\psi \to D_s^- e^+ \nu_e$	$J/\psi \to D_s^{*-} e^+ \nu_e$
$\bar{N}_{\text{total}}^{\text{up}}$	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	
$\mathcal{B}(90\%\,\text{C.L.})$	$< 1.3 \times 10^{-6}$	$< 1.8 \times 10^{-6}$

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





➢ $\mathcal{B}(J/\psi \to D_s^- e^+ \nu_e + c.c.) < 1.3 \times 10^{-6}$ at 90% CL
➢ $\mathcal{B}(J/\psi \to D_s^{*-} e^+ \nu_e + c.c.) < 1.8 \times 10^{-6}$ at 90% CL
(Only base on J/ψ data @3.097 GeV in 2009, 2.25×10^8)

Beginning
Will use full J/ψ data @3.097 GeV

More data sample for $J/\psi \to D_s^- e^+ \nu_e + c.c.$

- Prediction from SM: $10^{-9} - 10^{-10}$
- Number of J/ψ number: $\sim 10^{10}$

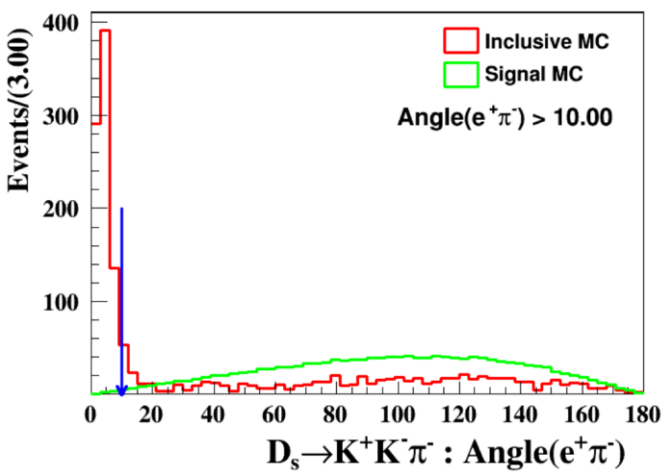
- Very close to the standard model
- Cover most of the remaining region of the new physics model

- If use full J/ψ data, some of the backgrounds can no longer be ignored

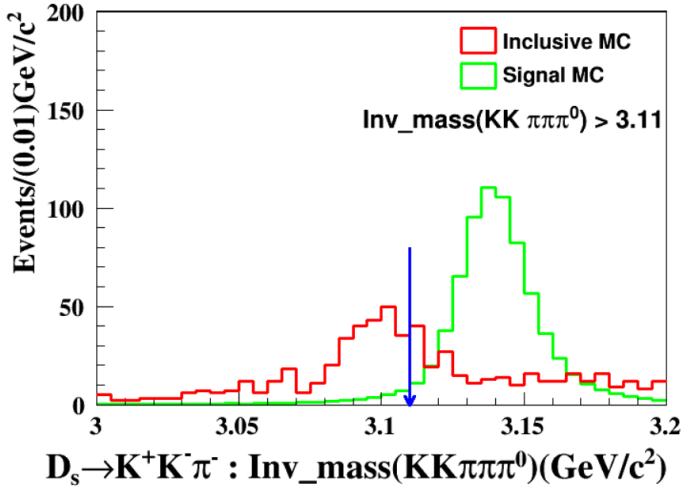
✓ **New result of $\mathcal{B}(J/\psi \to D_s^- e^+ \nu_e + c.c.)$ with more J/ψ data will come soon.**

✓ Study of $\psi(2S) \to D_s^- e^+ \nu_e + c.c.$ will also begin soon.

✓ Some backgrounds should be veto if open full data now



eg. γ conversion to e^+e^- and one of e will be mis-identified as π



eg. $J/\psi \to K^+K^-\pi^+\pi^-\pi^0$ backgrounds and one of π will be mis-identified as e

Outline

- Introduction
- Search for $\psi \to D^- l^+ \upsilon_l + c.c.$
- Search for $\psi \to D_s^{(*)-} l^+ \upsilon_l + c.c.$
- **Search for $\psi \to D_0 l^+ l^- + c.c.$**
- Summary

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$\psi \to D^0 e^+ e^- + c.c.$

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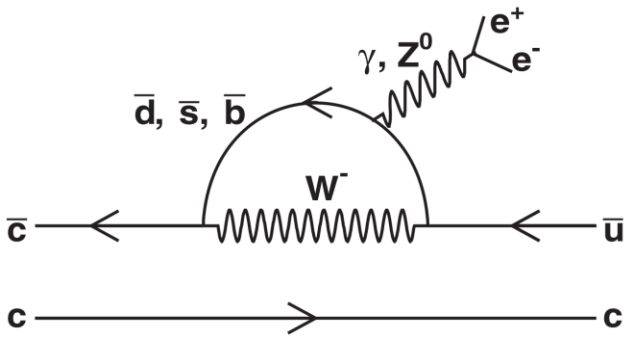
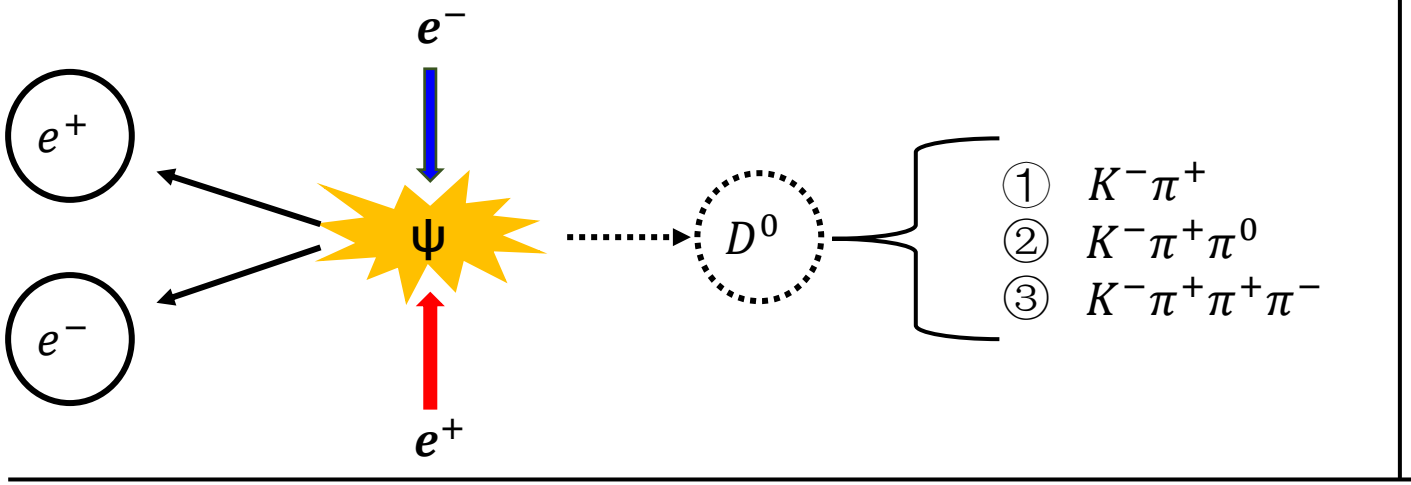
BAM-237
Base on J/ψ data @3.097 GeV in 2009, 2012
and ψ(2S) data @3.686 GeV in 2009, 2012

Event selection and signal study



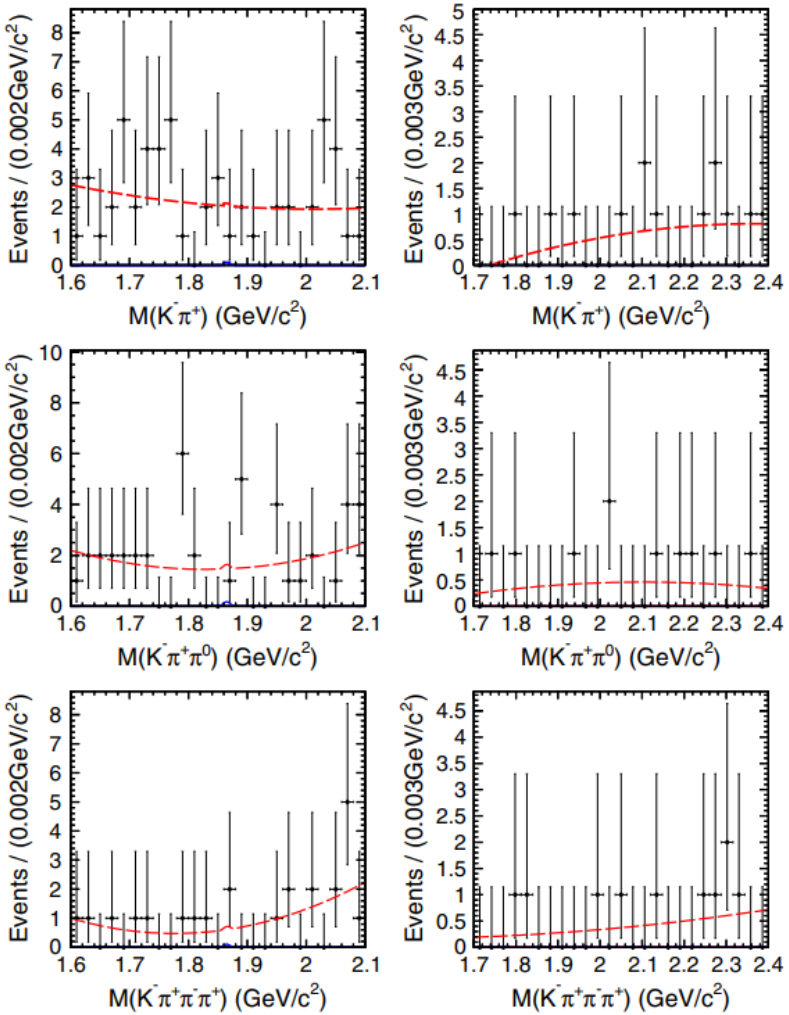
- $c \to u$ (FCNCs)
- **F**lavor **C**hanging **N**eutral **C**urrents

- Forbidden at the tree level due to the GIM mechanism
- Can occur at the loop level



- Simultaneous fitting on the M_{D^0} from data

- **No excess of events is observed in 1310.6×10^6 J/ψ and 448.1×10^6 ψ(2S)**



✓ $J/\psi \to D^0 e^+ e^-$ ✓ $\psi(2S) \to D^0 e^+ e^-$

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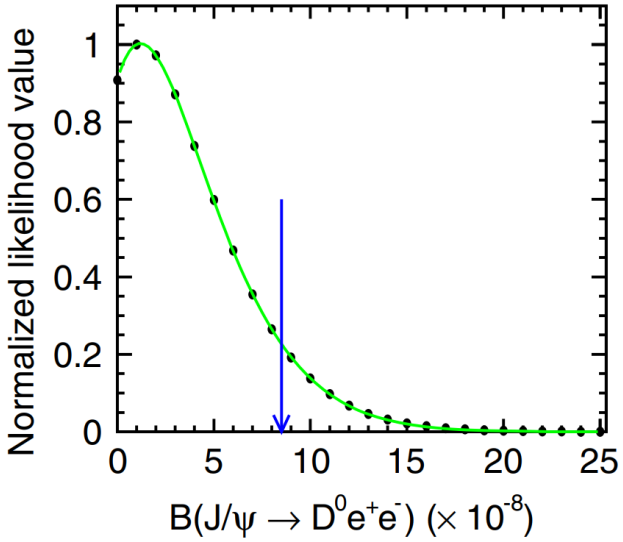
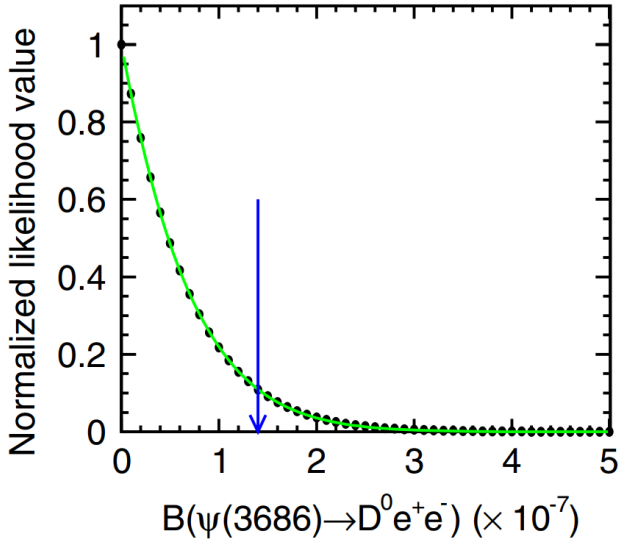
Event selection and signal study

	$D^0 \to K^-\pi^+$		$D^0 \to K^-\pi^+\pi^0$		$D^0 \to K^-\pi^+\pi^+\pi^-$	
	J/ψ	$\psi(3686)$	J/ψ	$\psi(3686)$	J/ψ	$\psi(3686)$
Tracking*	4.0	4.0	4.0	4.0	6.0	6.0
PID*	6.0	6.0	6.0	6.0	8.0	8.0
γ detection	···	···	1.2	1.2	···	···
Kinematic fit	1.7	1.6	1.1	1.8	2.2	2.0
Veto γ conversion*	1.7	1.7	1.7	1.7	1.7	1.7
Veto $K_S \to \pi^0\pi^0$	···	···	0.6	···	···	
Veto $K_S \to \pi^+\pi^-$	···	···	···	···	2.1	2.2
Veto $J/\psi \to e^+e^-$	···	0.1	···	···		···
Branching fraction	1.3	1.3	3.6	3.6	2.6	2.6
ψ total number*	0.55	0.62	0.55	0.62	0.55	0.62
Others	1.0	1.0	1.0	1.0	1.0	1.0
Total	7.8	7.8	8.5	8.7	11.0	10.9





✓ Summary of systematic uncertainties (%).

✓ The likelihood curve and UL at 90% CL.

- $\mathcal{B}(J/\psi \to D^0 e^+ e^- + c.c.) < 8.5 \times 10^{-8}$ at 90% CL
- $\mathcal{B}(\psi(2S) \to D^0 e^+ e^- + c.c.) < 1.4 \times 10^{-7}$ at 90% CL

  (Only base on J/ψ data @3.097 GeV in 2009,2012 which is 1310.6×10^6 and ψ(2S) data @3.686 GeV in 2009, 2012 which is 448.1×10^6)

- The study of $\psi \to D^0 l^+ l^- + c.c.$ with more data will begin soon.

Outline

- Introduction
- Search for $\psi \to D^- l^+ \upsilon_l + c.c.$
- Search for $\psi \to D_s^{(*)-} l^+ \upsilon_l + c.c.$
- Search for $\psi \to D_0 l^+ l^- + c.c.$
- **Summary**

Summary

✓ J/ψ weak decay is rare ($\mathbf{10^{-9}\sim10^{-12}}$) but allowed in SM
✓ If new physics exists, it can be enhanced by 2 or 3 orders of magnitude

✓ Charmonium semi-leptonic weak decay: $c \to d, c \to s, c \to u$

✓ Test the SM theory or search for new physics beyond SM

✓ $\mathcal{B}(J/\psi \to D^- e^+ \nu_e + c.c.) < 7.1 \times 10^{-8}$ at 90% CL ($\sim 10^{10}$ J/ψ)
✓ $\mathcal{B}(J/\psi \to D_s^- e^+ \upsilon_e + c.c.) < 1.3 \times 10^{-6}$ at 90% CL ($\sim 10^{8}$ J/ψ)
✓ $\mathcal{B}(J/\psi \to D_s^{*-} e^+ \upsilon_e + c.c.) < 1.8 \times 10^{-6}$ at 90% CL ($\sim 10^{8}$ J/ψ)
✓ $\mathcal{B}(J/\psi \to D^0 e^+ e^- + c.c.) < 8.5 \times 10^{-8}$ at 90% CL ($\sim 10^{9}$ J/ψ)
✓ $\mathcal{B}(\psi(2S) \to D^0 e^+ e^- + c.c.) < 1.4 \times 10^{-7}$ at 90% CL ($\sim 10^{8}$ $\psi(2S)$)

✓ **More results with full data now will come soon.** ($\sim 1 \times 10^{10}$ J/ψ and $\sim 3 \times 10^{9}$ $\psi(2S)$)

THANKS

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