Status and perspective of rare charm decays at BESIII

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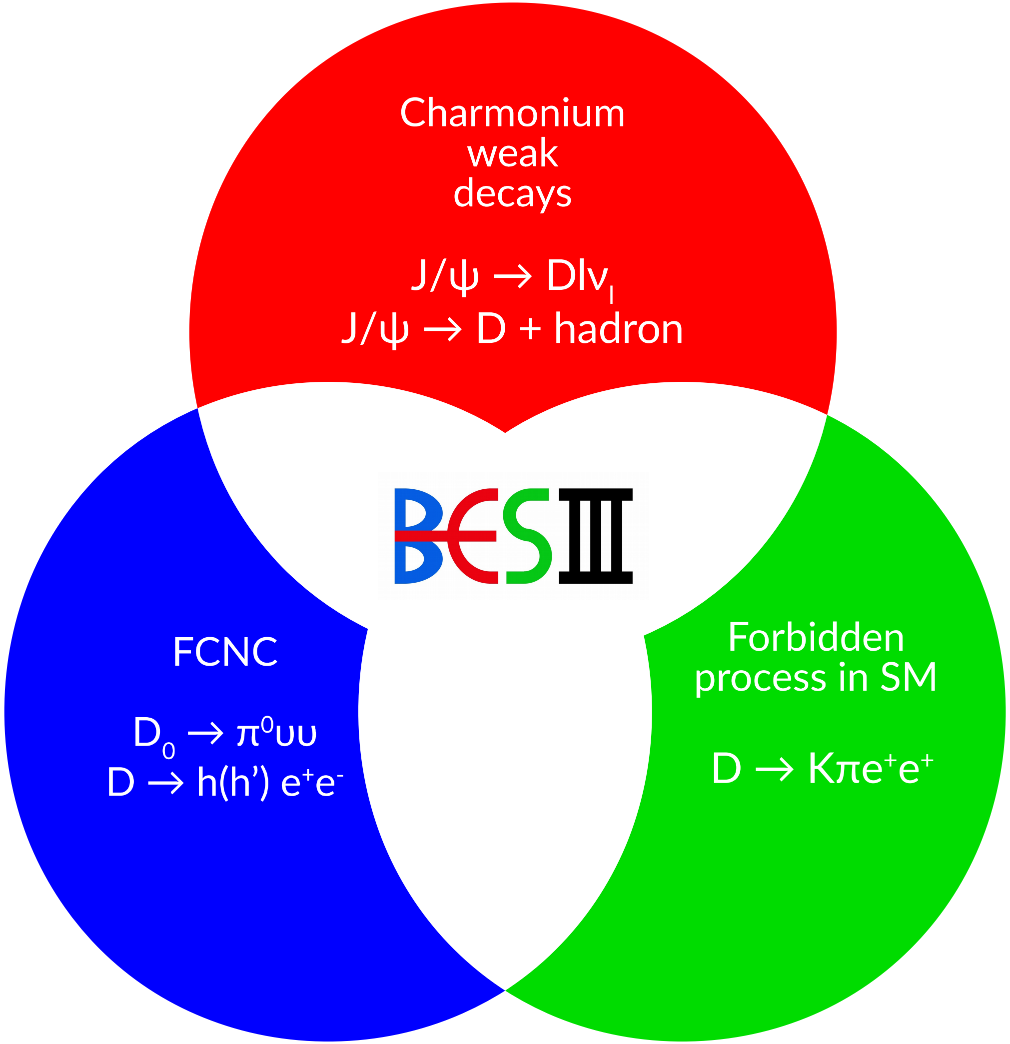
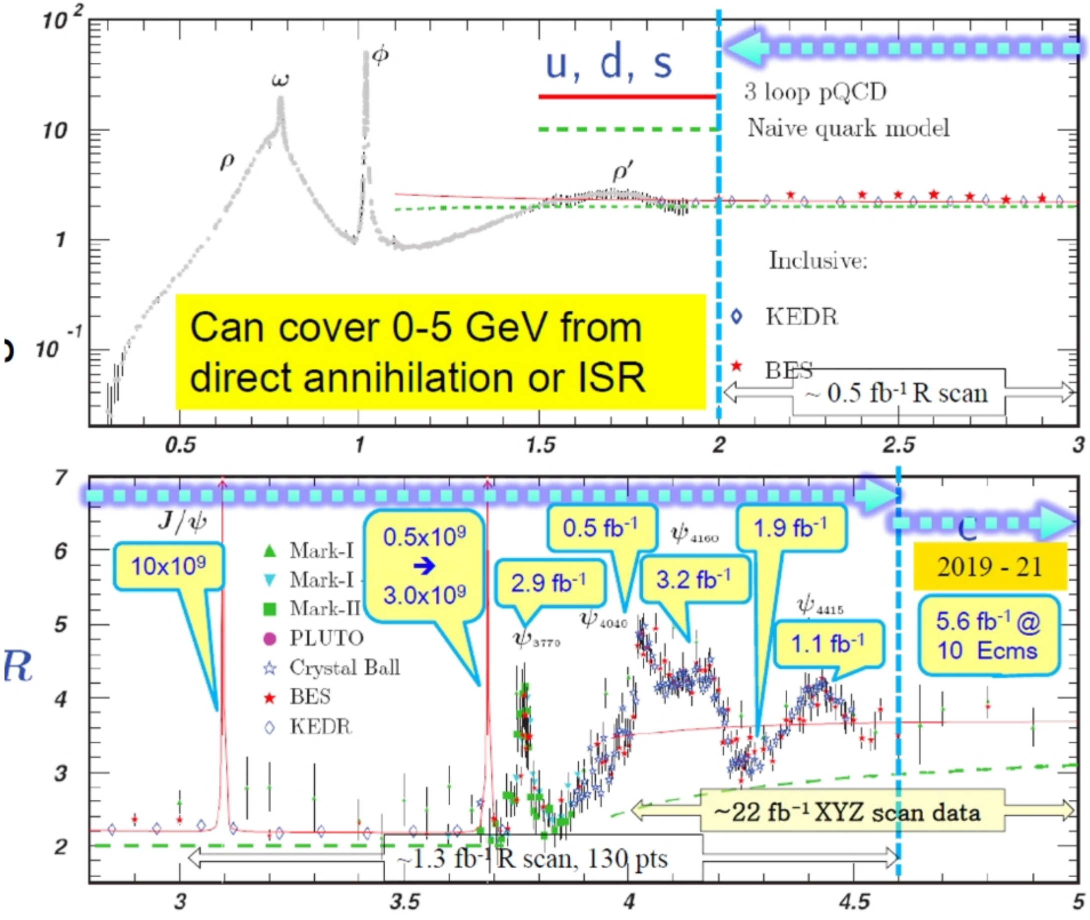
on behalf of the BESIII collaboration

WIFAI 2023 – 2023/11/09 - Roma

Outline


Charmonium
weak
decays
$J/\psi \rightarrow Dl\nu_l$
$J/\psi \rightarrow D$ + hadron
BESIII
FCNC
$D_0 \rightarrow \pi^0 \upsilon\upsilon$
$D \rightarrow h(h') e^+e^-$
Forbidden
process in SM
$D \rightarrow K\pi e^+e^+$

BESIII Datasets



Rich datasets allow for diverse studies

Today we focus on:

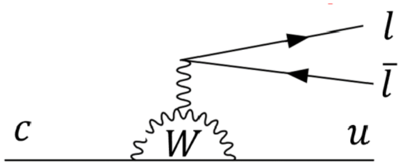
- 10B J/ψ
- 2.93/fb at ψ(3770) for D studies

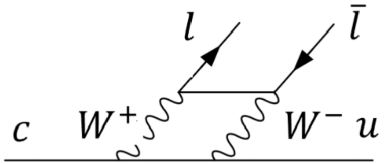
Status of FCNC decays

10.6M $D^0\overline{D}^0$ pairs – 8.3M D^+D^- pairs

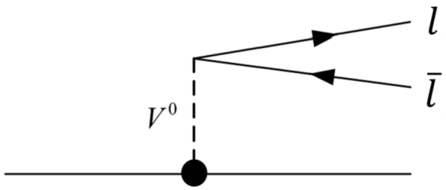
- $D^0 \to \pi^0\nu\nu$ - PRD 105 (2022) L071102
- $D \to h(h^{(\prime)})e^+e^-$ - PRD 97 (2018) 072015

FCNC in u-type quarks





✓ Short distance (**SD**) process: FCNC



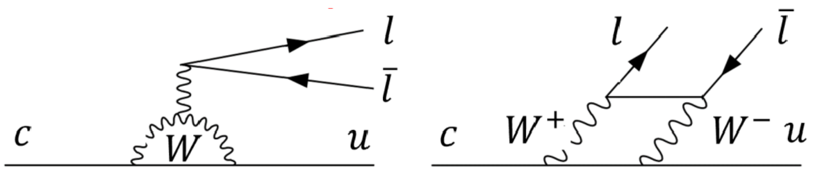
✓ Long distance (**LD**):
- Non-FCNC,
- Through vector meson
- $D \to hV, V \to l\bar{l}$

Strong suppression from **GIM mechanism** in SD processes. BF 10^{-8}~10^{-15} for D decays.

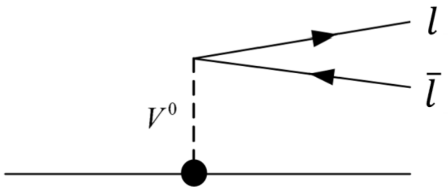
However, LD effect can increase this rate, as shown by recent observation of four-body D decays with muons in the final state at LHCb at 10^{-7} level

PRL. 119, 181805 (2017), Phys. Lett. B 757, 558 (2016)

FCNC in u-type quarks @ BESIII



✓ Short distance (**SD**) process: FCNC



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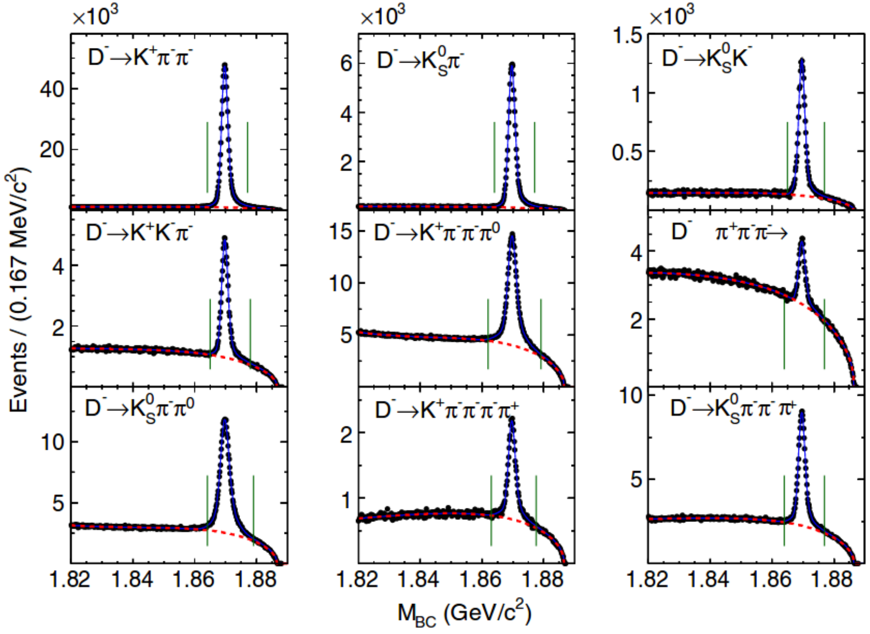
PRL. 119, 181805 (2017), Phys. Lett. B 757, 558 (2016)

Profit of production at threshold.
Double tag:
- Tag one D
- Search for the FCNC decay in the other side.

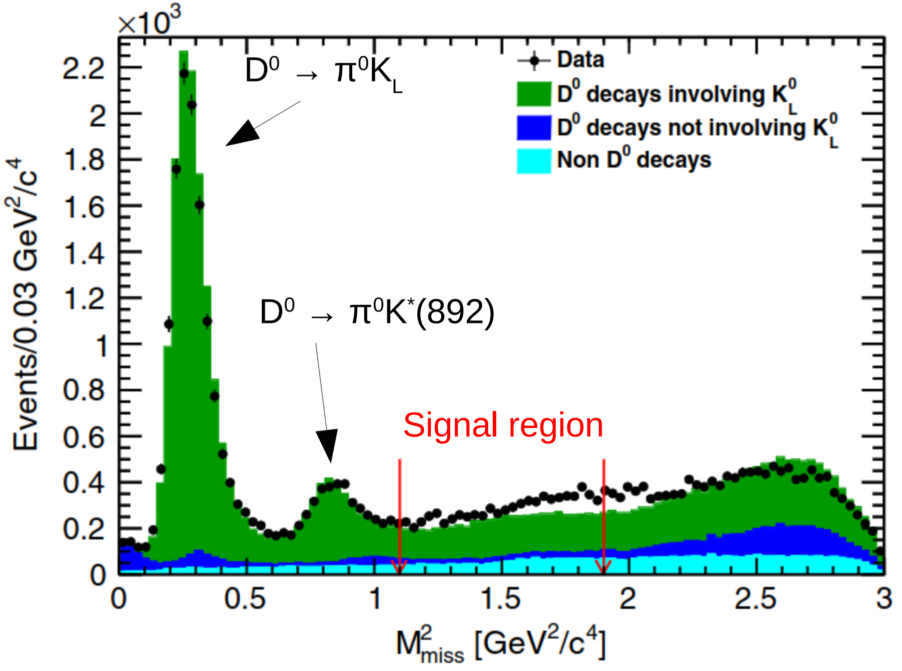


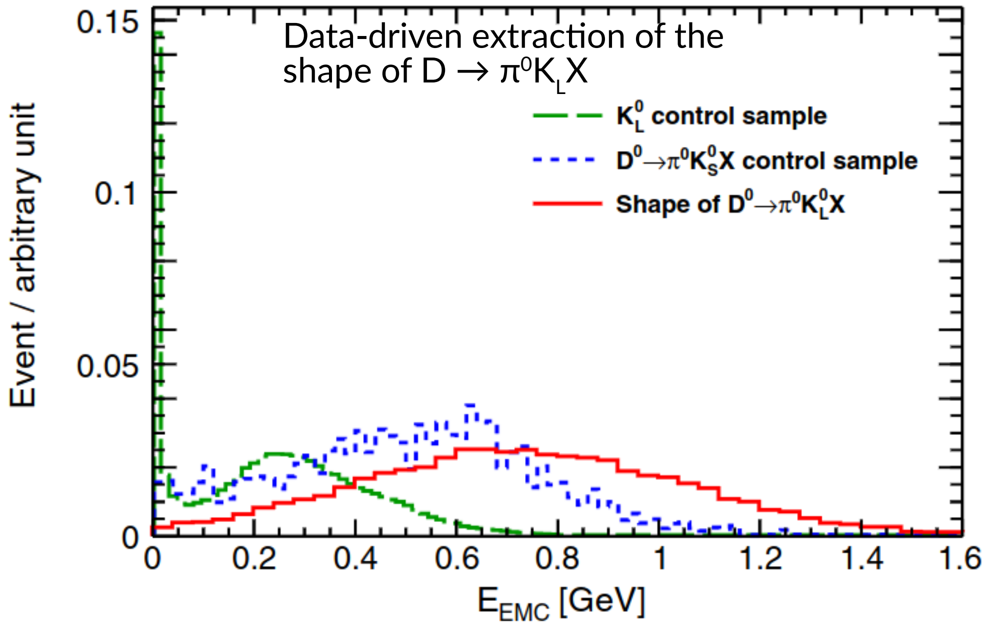
$D^0 \to \pi^0 \nu\nu$

PRD 105 (2022) L071102

Since there is no LD contribution, SM BR expected to be of order 10^{-15}.

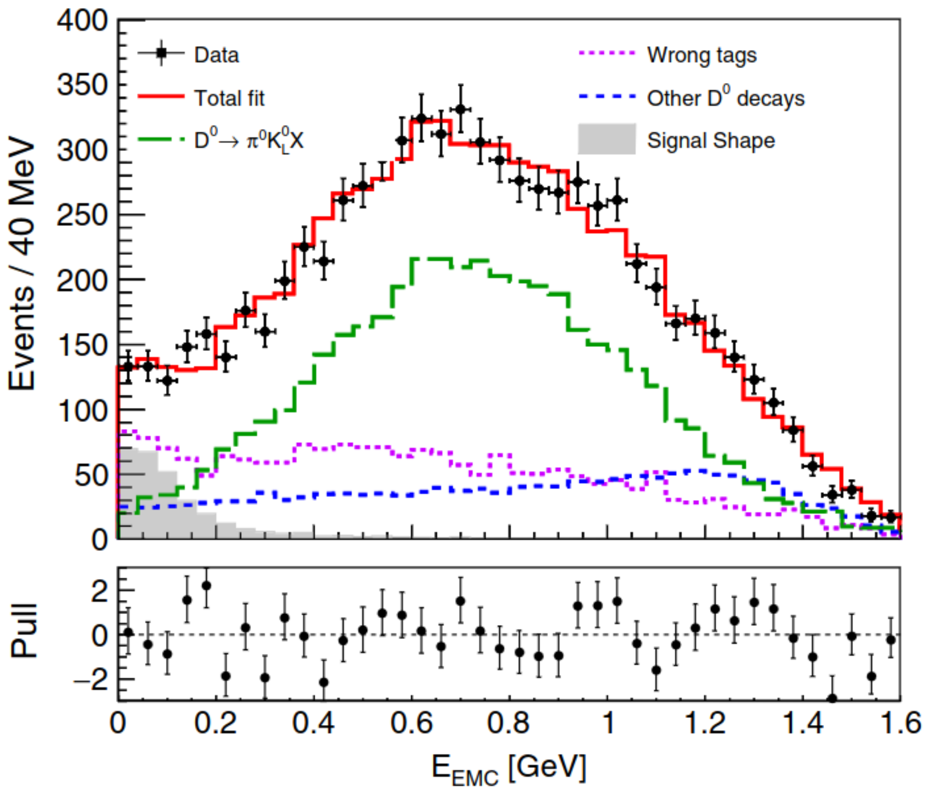
First ever study of di-neutrino FCNC. Discriminate using EMC signal and missing mass.
Dominant background from D decays with K_L in the final state





$D^0 \to \pi^0 \nu\nu$

PRD 105 (2022) L071102



Extended maximum likelihood fit to E_{EMC} to extract the number of events.

Fixed number of wrong tags events from MC estimation

U.L. $B(D^0 \to \pi^0\nu\nu) < 2.1 \times 10^{-4}$ @ 90 C.L.
First ever measurement of $c \to u\nu\nu$ process

More stringent than UL presented in *J. High Energy Phys. 04 (2021) 246* providing constrains on the fermionic coupling strength of leptoquarks to the sterile neutrinos

By early 2024, 20/fb ψ(3770) on tape to put even more stringent limits (with additional ~60M D^0D^0 pairs)

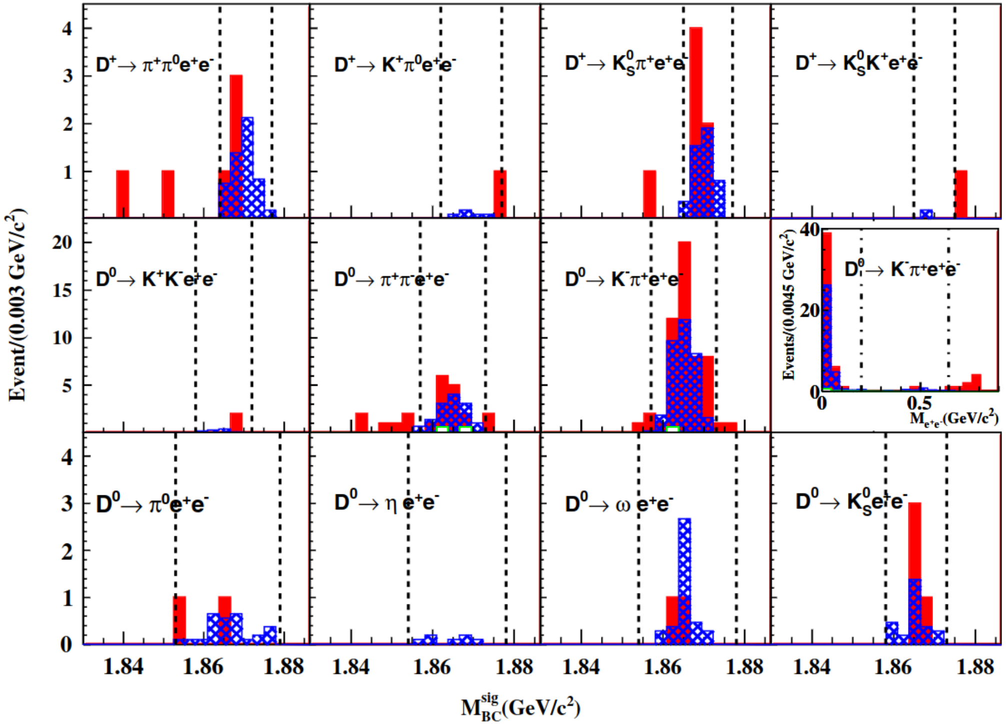
$D \to h(h^{(\prime)})e^+e^-$

PRD 97 (2018) 072015

Processes with both SD and LD contributions. Few results are available for three(four) body decay of neutral (charged) D decay.

Fully blind analysis using 2.93/fb data.

DATA / INC MC



Signal decays	$\mathcal{B}$ ($\times 10^{-5}$)	PDG [9] ($\times 10^{-5}$)
$D^+ \to \pi^+\pi^0 e^+e^-$	<1.4	...
$D^+ \to K^+\pi^0 e^+e^-$	<1.5	...
$D^+ \to K^0_S\pi^+ e^+e^-$	<2.6	...
$D^+ \to K^0_S K^+ e^+e^-$	<1.1	...
$D^0 \to K^-K^+ e^+e^-$	<1.1	<31.5
$D^0 \to \pi^+\pi^- e^+e^-$	<0.7	<37.3
$D^0 \to K^-\pi^+ e^+e^{-\dagger}$	<4.1	<38.5
$D^0 \to \pi^0 e^+e^-$	<0.4	<4.5
$D^0 \to \eta e^+e^-$	<0.3	<11
$D^0 \to \omega e^+e^-$	<0.6	<18
$D^0 \to K^0_S e^+e^-$	<1.2	<11
† in $M_{e^+e^-}$ regions:		
$[0.00, 0.20)$ GeV/c^2	<3.0 $(1.5^{+1.0}_{-0.9})$	...
$[0.20, 0.65)$ GeV/c^2	<0.7	...
$[0.65, 0.90)$ GeV/c^2	<1.9 $(1.0^{+0.5}_{-0.4})$	...

Improved U.L. on all the final state studied, and still above SM prediction.

$D^0 \to K^-\pi^+e^+e^-$ studied also in 3 bin of M_{ee}

Status of Rare charmonium weak decays

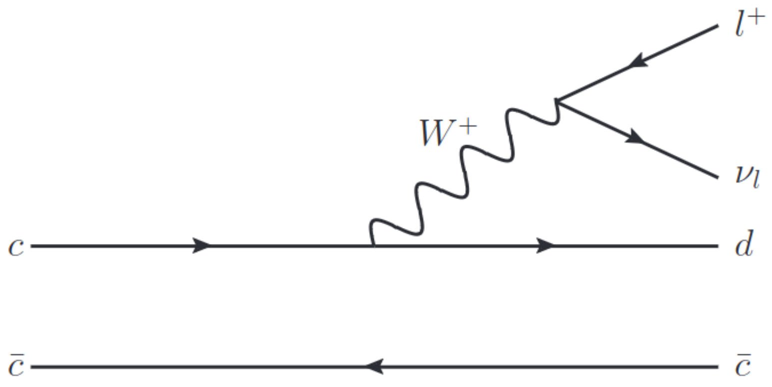
10B J/ψ

- $J/\psi \to D e \upsilon_e$ + c.c. – JHEP 06 (2021) 157
- $J/\psi \to D \mu \nu_\mu$ + c.c. – Arχiv: 2307.02165
- $J/\psi \to D$ + hadron – Arχiv: 2310.07277

$J/\psi \to Dl\nu$

Rare SM allowed process. **BR ~ 10^{-8} or lower.** Two independent analyses using 10B J/ψ dataset

- D is reconstructed in $D \to K\pi\pi$ final state
- Fit to missing mass to search for the neutrino



In the generation with EVTGEN (Nucl. Instrum. Meth. A 462,152 (2001)), we assumed that decay is governed by weak interaction via a $c \to d$ charged current process, ignoring hadronization effect and spin-flip

JHEP 06 (2021) 157

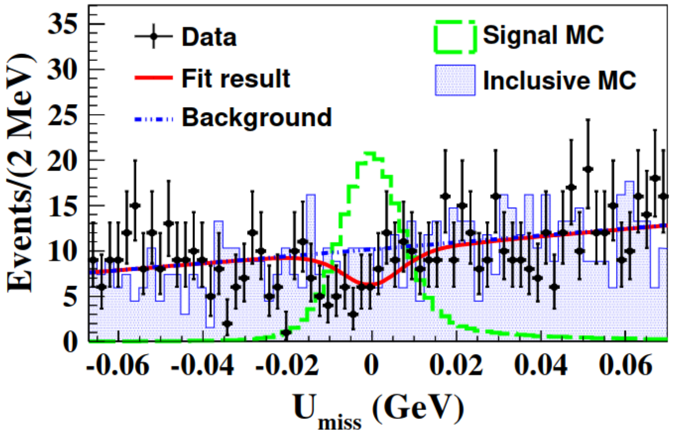
J/ψ → Deυ

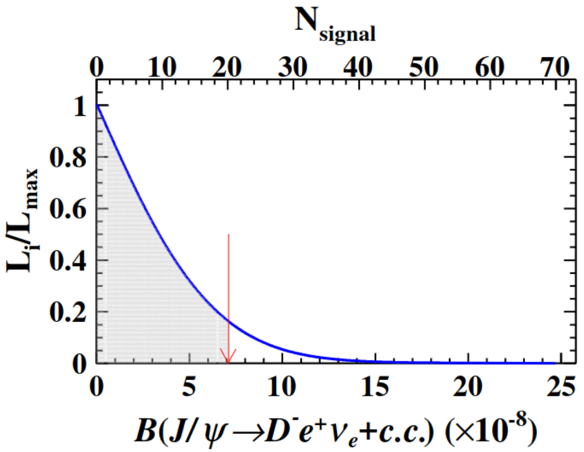
Rare SM allowed process. **BR ~ 10^{-8} or lower.** Two independent analyses using 10B J/ψ dataset

- D is reconstructed in D → Kππ final state
- Fit to missing mass to search for the neutrino
- E^{γ}_{tot} < 0.2 GeV

SM predictions (x10^{-11})

Decay mode	QCDSR [6]	LFQM [7]	BSW [8]	CCQM [9]	BSM [10]
$J/\psi \to D^- e^+ \nu_e$	$0.73^{+0.43}_{-0.22}$	5.1–5.7	$6.0^{+0.8}_{-0.7}$	1.71	$2.03^{+0.29}_{-0.25}$





U.L. $B(J/\psi \to D^- e^+ \nu + c.c.) < 7.1 \times 10^{-8}$ (@90% C.L.) improves previous measurement by 170 times

Exclude some older NP models prediction (Phys.Rev. D60 (1999) 014011, Phys. Lett. B 345, 483 (1995))

Arχiv: 2307.02165

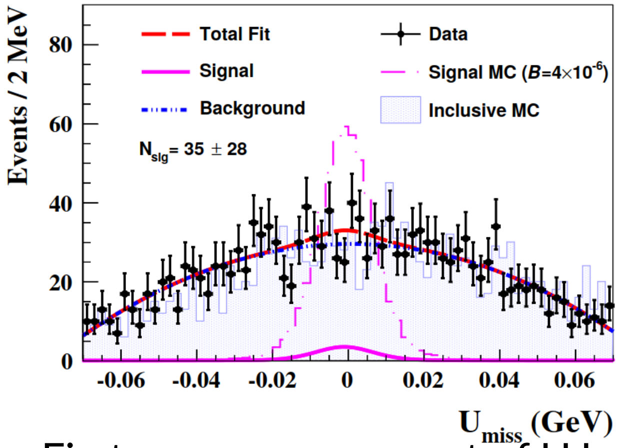
J/ψ → Dμυ

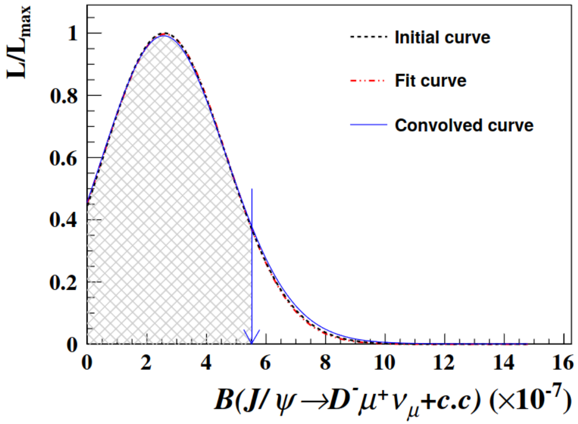
Rare SM allowed process. **BR ~ 10^{-8} or lower.** Two independent analyses using 10B J/ψ dataset

- D is reconstructed in D → Kππ final state
- Fit to missing mass to search for the neutrino
- 0.98 GeV/c < $|P_{miss}| + |P_{\mu}|$ < 1.23 GeV/c

SM predictions ($\times10^{-11}$)

Model	QCDSR [8]	LFQM [9]	BSW [10]	CCQM [11]	BSM [12]
BF ($\times10^{-11}$)	$0.71^{+0.42}_{-0.22}$	4.7 – 5.5	$5.8^{+0.8}_{-0.6}$	1.66	$1.98^{+0.28}_{-0.24}$



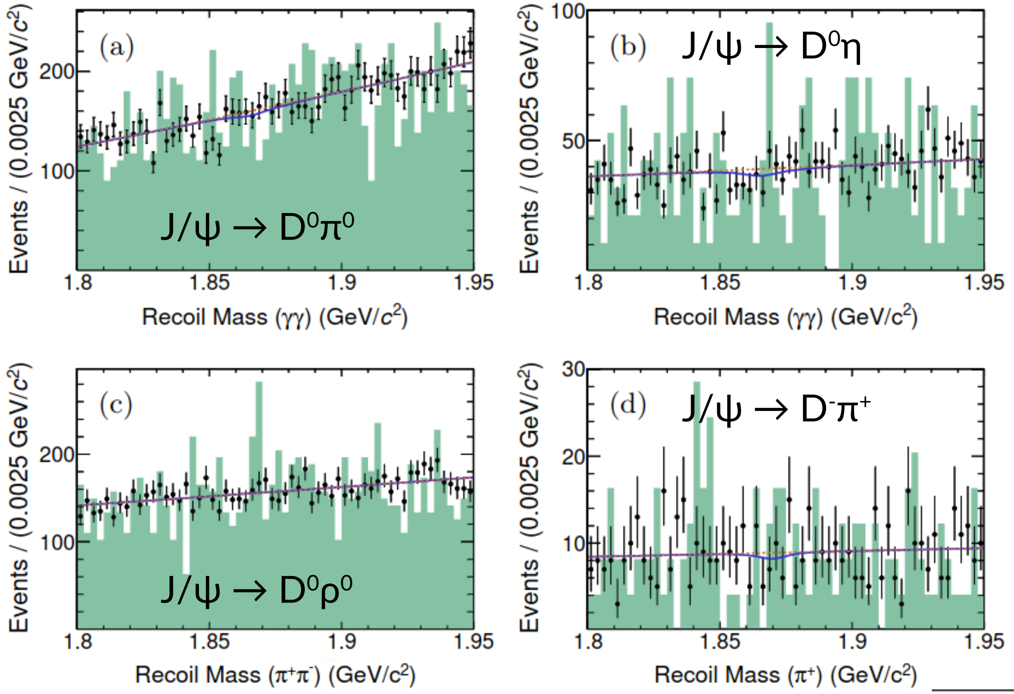


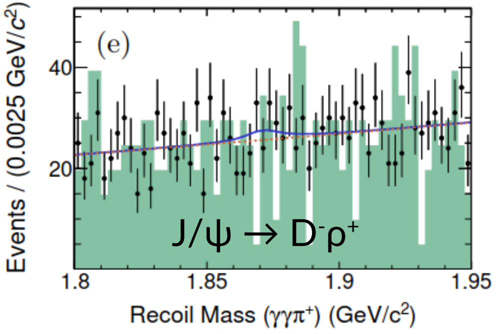
First ever measurement of U.L. **B(J/ψ → $D^-\mu^+\nu$ + c.c.) < 5.6 $\times10^{-7}$ (@90% C.L.)**

Exclude some older NP models prediction (Phys.Rev. D60 (1999) 014011, Phys. Lett. B 345, 483 (1995))

Arχiv: 2310.07277

$J/\psi \to$ D+hadron





Search for weak decays with fully hadronic final state

To avoid background from strong J/ψ decays, D mesons are tagged by their semileptonic decays

$D^0 \to K^+ e^- \upsilon_e$

$D^- \to K_s e^- \upsilon_e$

Fit the recoil mass to extract number of events

Mode	N_{sig}	$N_{\text{sig}}^{\text{UL}}$	$\mathcal{B}$ (90% C.L.)	$\mathcal{B}$ (90% C.L.)
$J/\psi \to \bar{D}^0\pi^0$	-49.5 ± 69.3	< 68.8	$< 4.7 \times 10^{-7}$	$\cdots$
$J/\psi \to \bar{D}^0\eta$	-28.9 ± 34.5	< 32.9	$< 6.8 \times 10^{-7}$	$\cdots$
$J/\psi \to \bar{D}^0\rho^0$	2.0 ± 37.1	< 59.9	$< 5.2 \times 10^{-7}$	$\cdots$
$J/\psi \to D^-\pi^+$	-4.3 ± 10.3	< 14.4	$< 7.0 \times 10^{-8}$	$< 7.5 \times 10^{-5}$
$J/\psi \to D^-\rho^+$	18.6 ± 26.2	< 51.4	$< 6.0 \times 10^{-7}$	$\cdots$

PLB 663, 297 (2008) with 58M J/ψ

First measurements or great improvements, close to the 10^{-8} level to start constraining paramenters of NP models

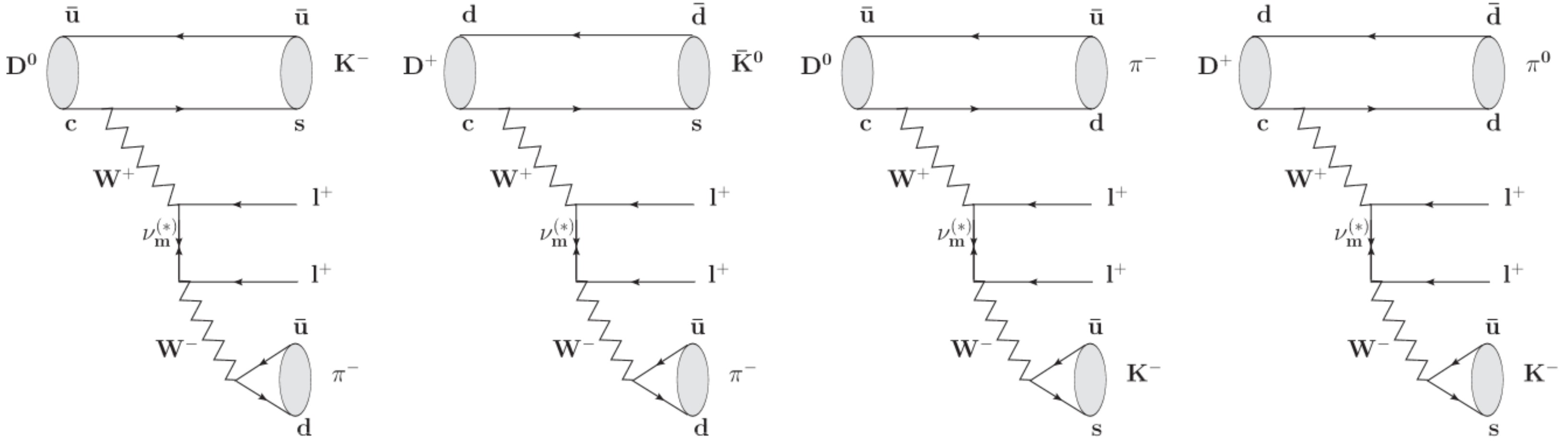
Status of Forbidden process in SM

10.6M $D^0\overline{D}^0$ pairs – 8.3M D^+D^- pairs

- $D \rightarrow K\pi e^+e^+$ - PRD 99 (2019) 112002

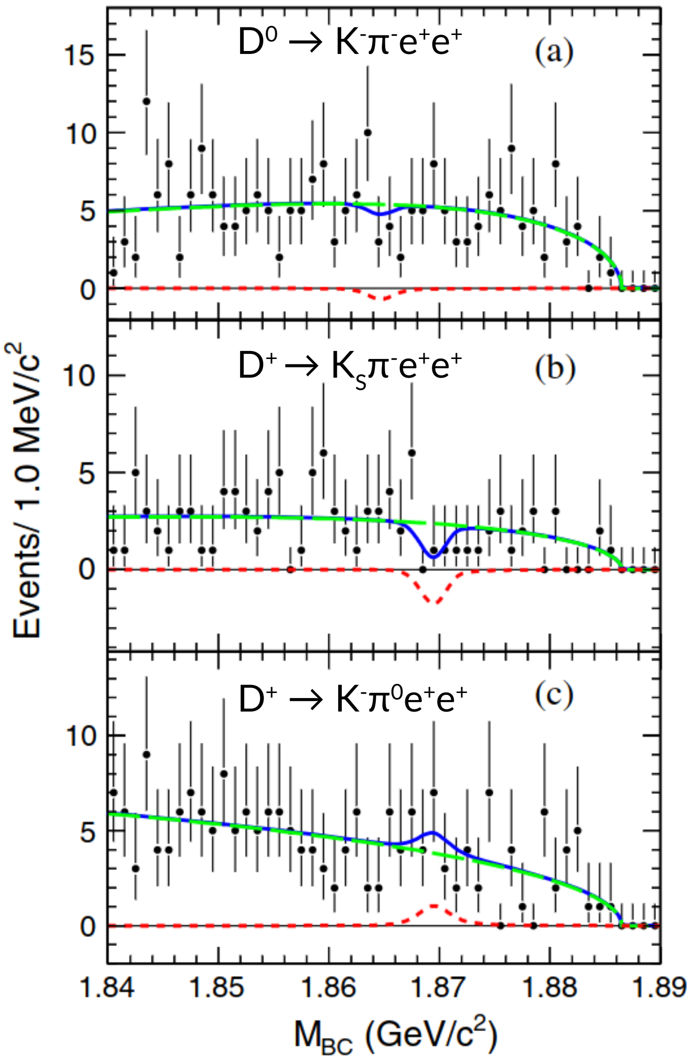
$D \to K\pi e^+e^+$

Search for SM-forbidden |ΔL = 2| transition to study possible contribution of Mayorana neutrinos with mass at the heavy flavor scale (200 MeV/c^2 to 1 GeV/c^2)



(a) $D^0 \to K^-\pi^-l^+l^+$ (CF) (b) $D^+ \to \bar{K}^0\pi^-l^+l^+$ (CF) (c) $D^0 \to K^-\pi^-l^+l^+$ (DCS) (d) $D^+ \to K^-\pi^0l^+l^+$ (DCS)

From model on Chin. Phys. C 39 (2015) 013101, BR of $Kl^+l^-\pi$ have upper limits in the range (10^{-9},10^{-12})



PRD 99 (2019) 112002

$D \to K\pi e^+e^+$

Single tag study using 2.93/fb at ψ(3770).
Both charged and neutral D mesons are studied.

Fit to M_{bc} variable with some additional requirements

$$M_{bc} = \sqrt{E_{beam}^2 - p_{candidate}^2}$$

Channel	ΔE (MeV)
$D^0 \to K^-\pi^-e^+e^+$	[−33.0, 19.7]
$D^+ \to K_S^0\pi^-e^+e^+$	[−30.6, 19.3]
$D^+ \to K^-\pi^0e^+e^+$	[−54.8, 24.4]

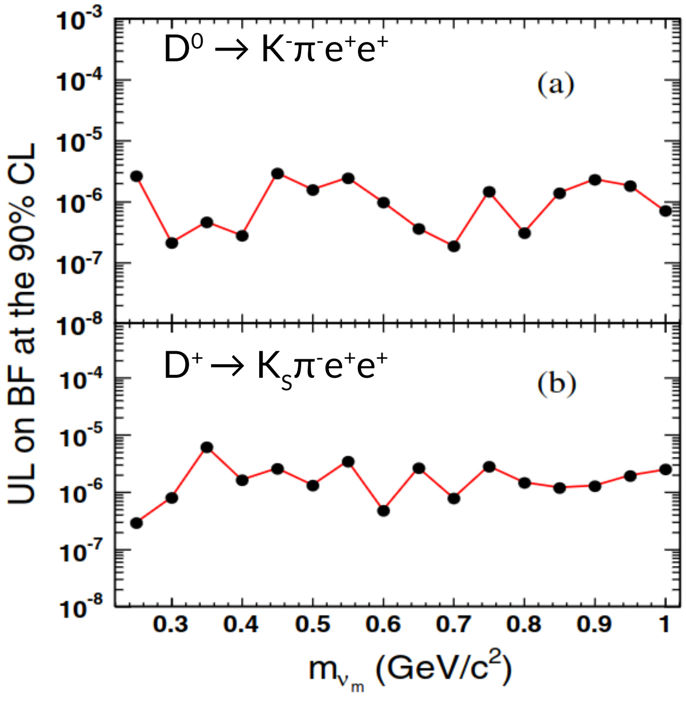
$$dE = E_{candidate} - E_{beam}$$

Final number of events extracted from both charge conjugated modes

Channel	$\epsilon(\%)$	N_{sig}^{UL}	$\mathcal{B}_{sig}^{UL}(\times 10^{-6})$
$D^0 \to K^-\pi^-e^+e^+$	16.8	10.0	<2.8
$D^+ \to K_S^0\pi^-e^+e^+$	11.5	4.4	<3.3
$D^+ \to K^-\pi^0e^+e^+$	10.6	14.8	<8.5

$D \to K e^+ \nu_m (\pi e^+)$

Count the number of events within $[\nu_m - 3\sigma, \nu_m + 3\sigma]$ with fixed signal M_{bc} and extract the upper limit.

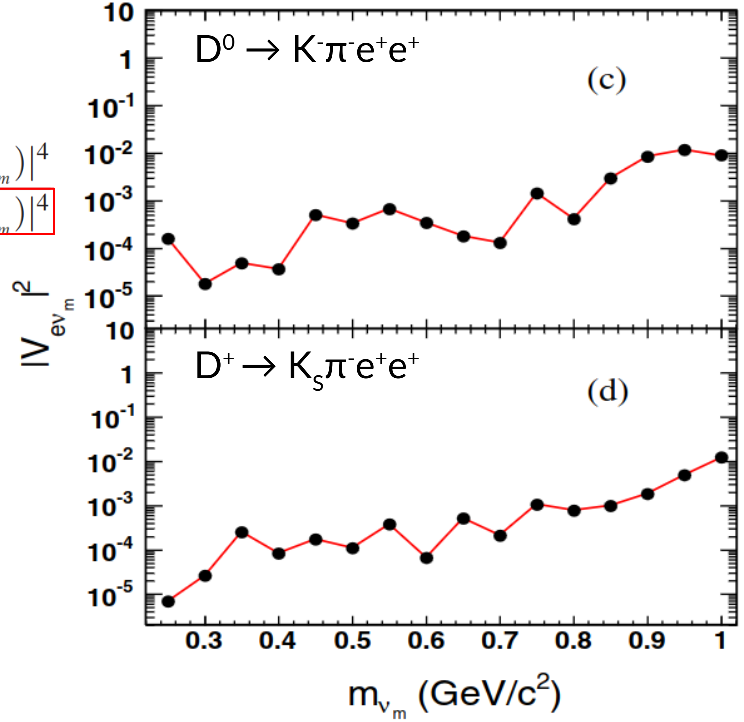


$$\frac{\Gamma(m_{\nu_m}, V_{e\nu_m}(m_{\nu_m}))}{\Gamma(m_{\nu_m}, V'_{e\nu_m}(m_{\nu_m}))} = \frac{|V_{e\nu_m}(m_{\nu_m})|^4}{|V'_{e\nu_m}(m_{\nu_m})|^4}$$

BR from this measure

BR from CPC 39 (2015) 013101

0νββ decay reanalysis from PRD 71 (2005) 077901



Final remarks, perspective from BESIII

- Rare decays in charm sector are REALLY tiny
  - New physics model may enhance the BR, but at present experimental precision we are just fighting with the statistics

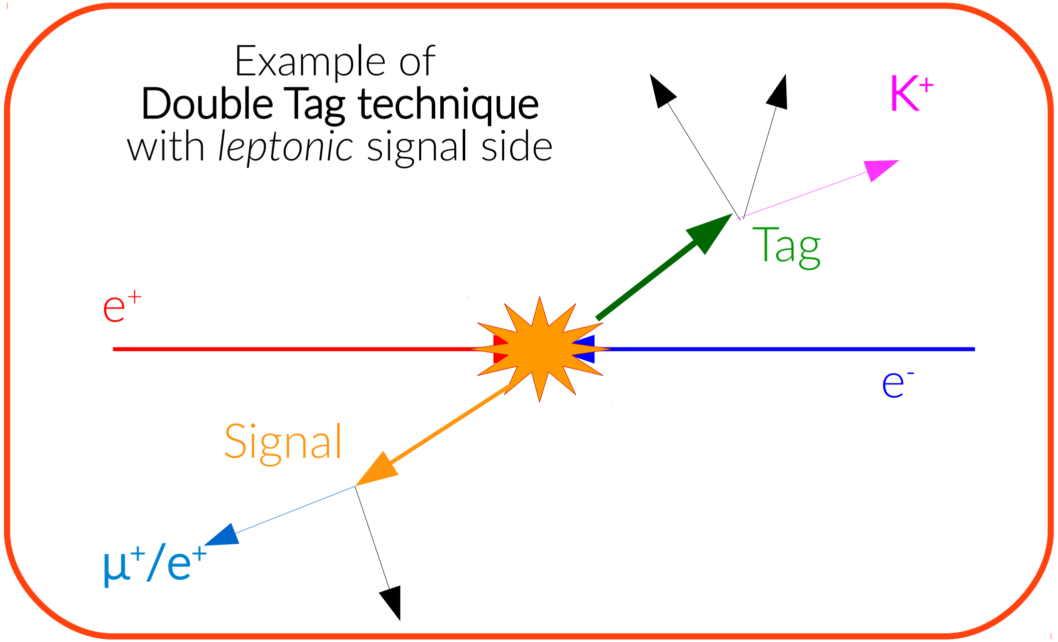
- BESIII has a wider program that includes also cLFV, axions, dark matter searches with a growing dataset
  - First results with 10B J/ψ, more to come
  - Finalization of full 2.8B ψ(2S) dataset
  - Almost finished the data taking of additional 17/fb at ψ(3770) (likely 5 times more event) to push further the upper limits and test the models
  - More details on our program in Chinese Phys. C 44 (2020) 040001 – chapter 6

https://iopscience.iop.org/article/10.1088/1674-1137/44/4/040001/pdf

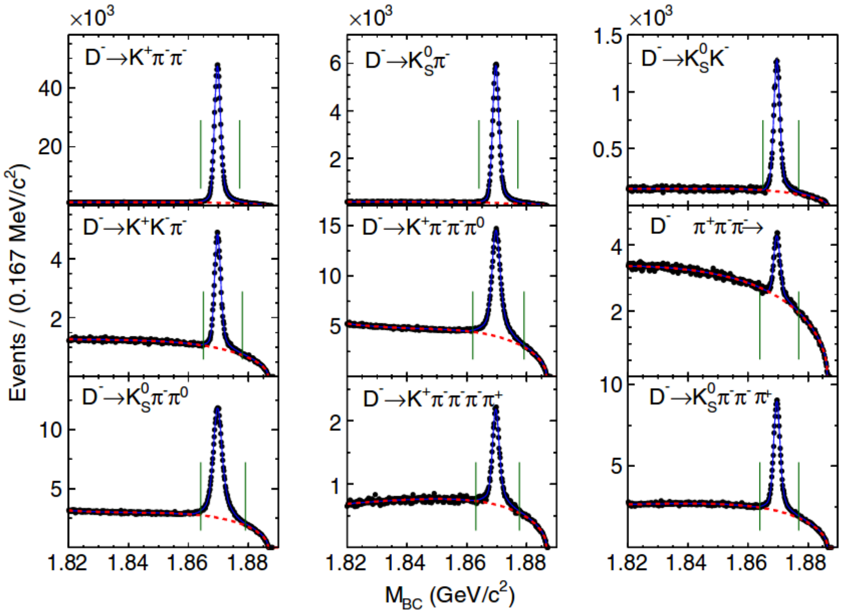

謝謝
xie xie.
THANKS

Back-up slides

Charmed meson decay at threshold at BESIII



Example D- Tag mode



Variables of interest (calculated in e^+e^- reference frame)

Mass beam constrained

$$M_{bc} = \sqrt{E_{beam}^2 - p_{candidate}^2}$$

Energy difference

$$\mathrm{dE} = \mathrm{E_{candidate}} - \mathrm{E_{beam}}$$

Missing mass

$$\mathrm{U_{miss}} = \mathrm{E_{miss}} - |\vec{p}_{\mathrm{miss}}|$$

Analysis jargon

Single tag analysis:

In charmed hadron production at threshold, quantum numbers conservation allows to reconstruct only one side of the decay.

- High efficiency
- Higher backgrounds

Double tag analysis:

In charmed hadron production, first reconstruct the D^- to tag the decay. Within the reconstructed candidates associate the signal candidate.

- Low background and possibility to search for events with missing tracks
- Lower efficiency

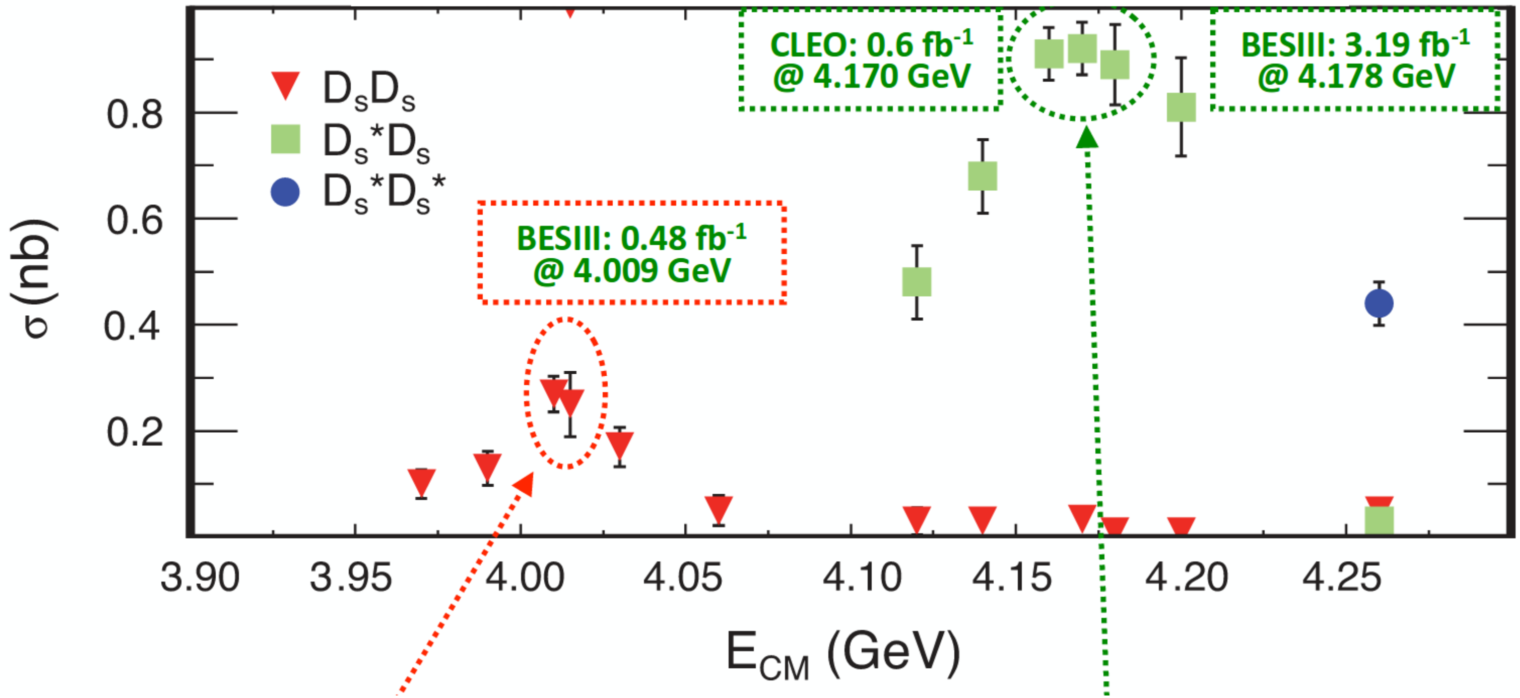
Charmonium studies:

Direct production of these states, hermetic detector and closed kinematics allows for search for missing tracks

- Semi-blind analysis

D_s data samples

CLEO PRD80, 072001 (2009)



Clean sample, low production rate
~0.4 M D_s produced

Higher production rate, BF($D^*_s \rightarrow \gamma D_s$)
~6 M D_s produced

Rare D decays as Null Tests of the Standard Model

- $D \to \mu^+\mu^-$
  - short distance contribution not observable (10^{-18})
  - long distance dominated by two-photon exchange: $BR(D\to\mu^+\mu^-) \sim 3\ 10^{-5}\ BR(D\to\gamma\gamma)$, could be around few times 10^{-13} Burdman et al., hep-ph/0112235
- $D \to P\nu\bar{\nu}$
  - unobservably small, except for the possible LD τ contribution in charged D decays

Burdman et al., hep-ph/0112235

From L. Silvestrini, last year workshop

https://agenda.infn.it/event/31592/contributions/174857/attachments/98994/137183/silvestrini@HI.pdf

Rare D decays as Null Tests of the Standard Model

- $D \to P l^+ l^-$, $\Lambda_c \to p l^+ l^-$
  - given the smallness of SM short-distance contributions, one has $C_{10}^A \sim 0$ and therefore

    $A_{FB} = 0$
  - in the baryonic channel, one also has

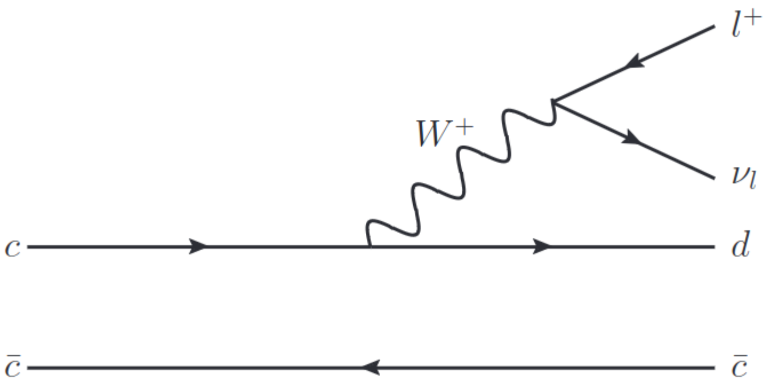
    $F_L = 1/3$

    at the kinematic endpoints

Hiller et al. '21, '22

$J/\psi \to Dl\upsilon$

Rare allowed SM process



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Model	QCDSR	LFQM	BSW	CCQM	BSM
BF ($\times 10^{-11}$)	$0.71^{+0.42}_{-0.22}$	4.7 – 5.5	$5.8^{+0.8}_{-0.6}$	1.66	$1.98^{+0.28}_{-0.24}$

QCDSR: Eur. Phys. J. C 54, 107 (2008)

LFQM: Phys. Rev. D 78, 074012 (2008)

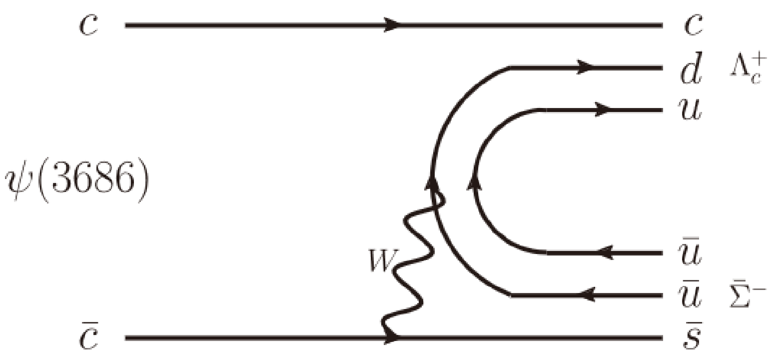
BSW: Adv. High Energy Phys. 2013, 706543 (2013)

CCQM: Phys. Rev. D 92, 074030 (2015)

BSM: J. Phys. G: Nucl. Part. Phys. 44, 045004 (2017)

Chin. Phys. C 47 (2023) 013002

$\psi(2S) \rightarrow \Lambda_c \Sigma$



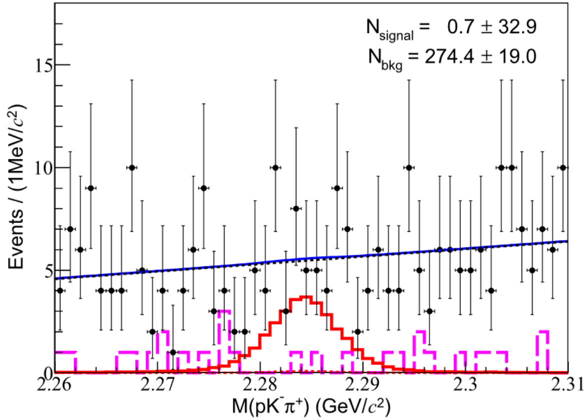
First weak baryonic decay investigated for ψ(3686)

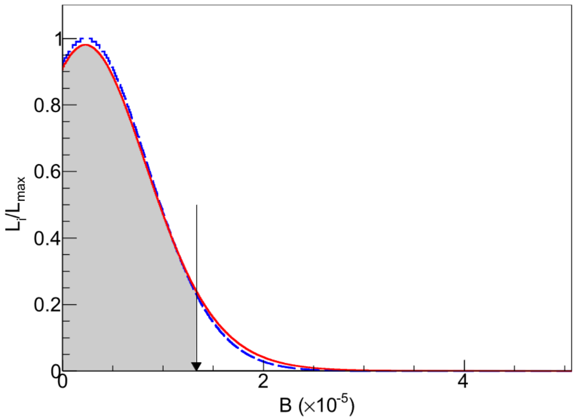
Rare allowed SM, with prediction for BR~(10^{-8},10^{-11})

Reconstructed $\Lambda_c \rightarrow pK\pi$, $\Sigma \rightarrow p\pi^0$

Backgrounds: ψ(2S) decays with K*(892)-p-hyperon type final state

Signal extracted with unbinned maximum likelihood fit to M(pKπ)





U.L. $B(\psi(2S) \rightarrow \Lambda_c\Sigma) < 1.4 \times 10^{-5}$ @ 90% C.L.. Plan to use full 2.8B psi(2S) dataset

Other opportunities at BESIII

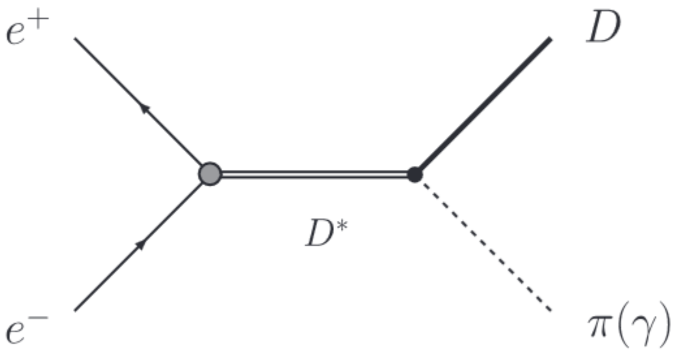
- Direct production of D*(2007)
  - Feasible in terms of accelerator energies,
  - Ideally sensible to BR larger that 4×10^{-13} with one year of data taking
  - In present accelerator conditions, few order of magnitude less due to beam spread wider than D* width

$$\mathcal{B}_{D^*\to e^+e^-} \geqslant \left(\frac{1}{\epsilon\int L dt}\right) \times \frac{m_{D^*}^2}{12\pi\,\mathcal{B}_{D^*\to D\pi}}$$

To estimate the NP scale sensitivity implied by Eq. (6.39), one can assume single operator dominance with the Wilson coefficient C to obtain [133]

$$\Lambda \sim \left(\frac{1}{3\pi}\frac{m_{D^*}^3 f_{D^*}^2}{32\Gamma_0}\frac{C^2}{\mathcal{B}(D^*\to e^+e^-)}\right)^{1/4}. \qquad (6.40)$$

With the upper bound of 4×10^{-13}, the observation of a single event in a year of running would probe NP scales of the order of $\Lambda \sim 2.7$ TeV, provided that $C \sim 1$. Taking into account the current experimental bound $\mathcal{B}_{D\to e^+e^-} = 7.9\times10^{-8}$, one finds that only the scale $\Lambda \sim 200$ GeV is currently probed by the $D \to e^+e^-$ decay.



PHYSICAL REVIEW D 104, 112012 (2021)

$D^* \to D^0e^+e^-$

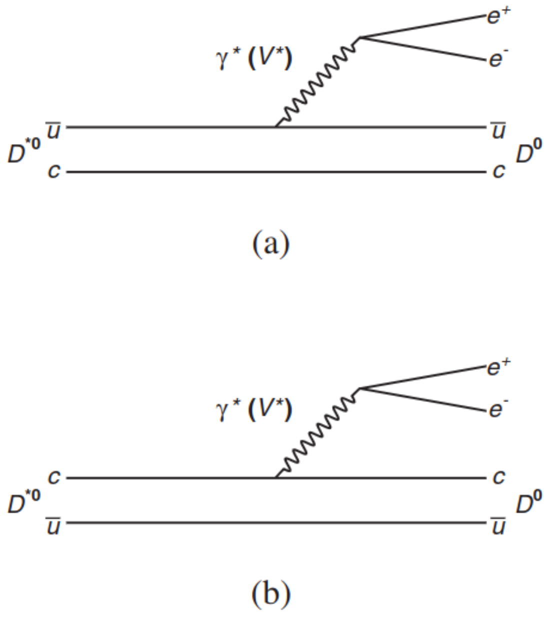


FIG. 1. Diagrams of the decay $D^{*0} \to D^0e^+e^-$. The symbol V^* indicates the virtual ρ, ω, ϕ, or J/ψ meson.

$$R_{ee} = \frac{\mathcal{B}(D^{*0} \to D^0e^+e^-)}{\mathcal{B}(D^{*0} \to D^0\gamma)}. \qquad (1)$$

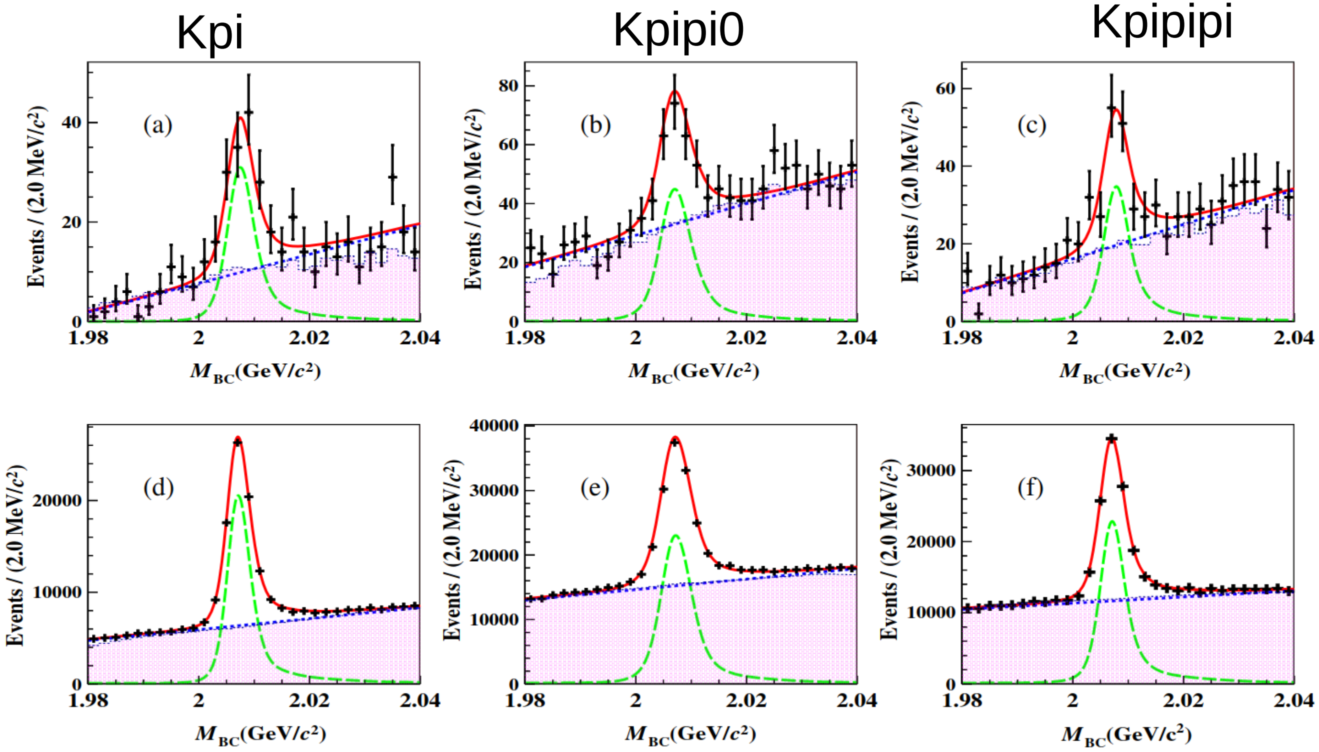
Calculations using the VMD model give $R_{ee} = 0.67\%$ along with the following differential decay rate [1]:

$$\frac{dR_{ee}}{dq^2} = \frac{\alpha}{3\pi q^2}\left|\frac{f(q^2)}{f(0)}\right|^2\left[1-\frac{4m_e^2}{q^2}\right]^{\frac{1}{2}}\left[1+\frac{2m_e^2}{q^2}\right] \times\left[\left(1+\frac{q^2}{A}\right)-\frac{4m_{D^{*0}}^2q^2}{A^2}\right]^{\frac{3}{2}}. \qquad (2)$$

Here, α is the fine structure constant, $A = m_{D^{*0}}^2 - m_{D^0}^2$, $f(q^2)$ is the transition form factor for D^{*0} to D^0, m_e is the mass of electron and $m_{D^{*0}}$ (m_{D^0}) is the mass of D^{*0} (D^0). The form-factor ratio $\frac{f(q^2)}{f(0)}$ is equal to $(1-\frac{q^2}{m_\rho^2})^{-1}$, where m_ρ is the ρ resonance mass.

PHYSICAL REVIEW D 104, 112012 (2021)

$D^* \to D^0 e^+ e^-$



$R_{ee} = (11.08 \pm 0.76 \pm 0.49) \times 10^{-3}$

3.6σ larger than prediction, but agreement the q^2 distribution. More data needed