南開大學
Nankai University

BESIII

New Physics Beyond the SM @BESIII

Minggang Zhao
(on behalf of the BESIII Collaboration)

School of Physics, Nankai University, Tianjin, China

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BESIII Experiment

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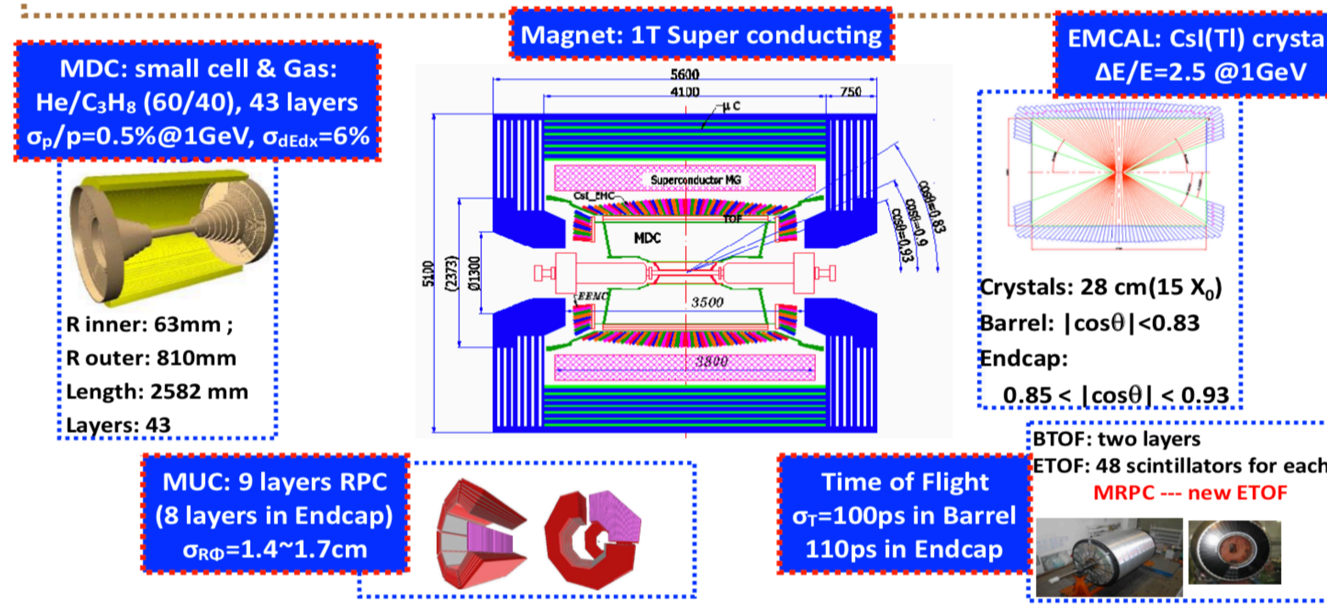
- A powerful general purpose detector.
- Excellent neutral/charged particle detection/identification with a large coverage.
  - ✓ Precision tracking
  - ✓ CsI calorimeter
  - ✓ PID via dE/dx & Time of Flight



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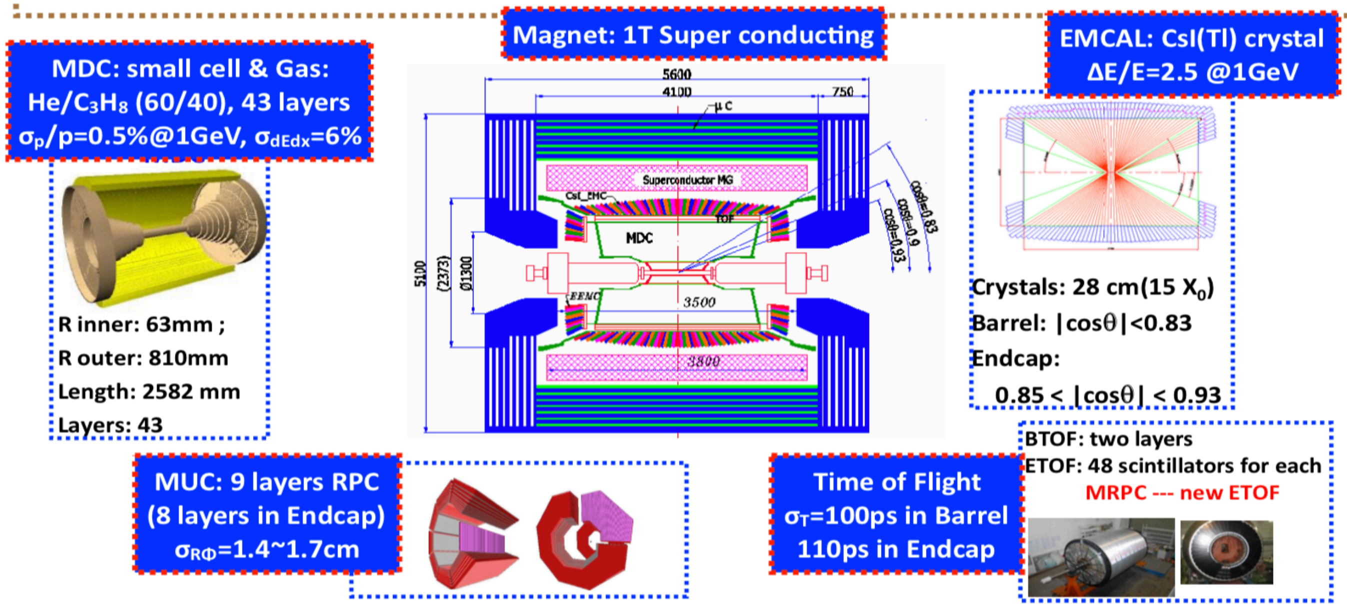
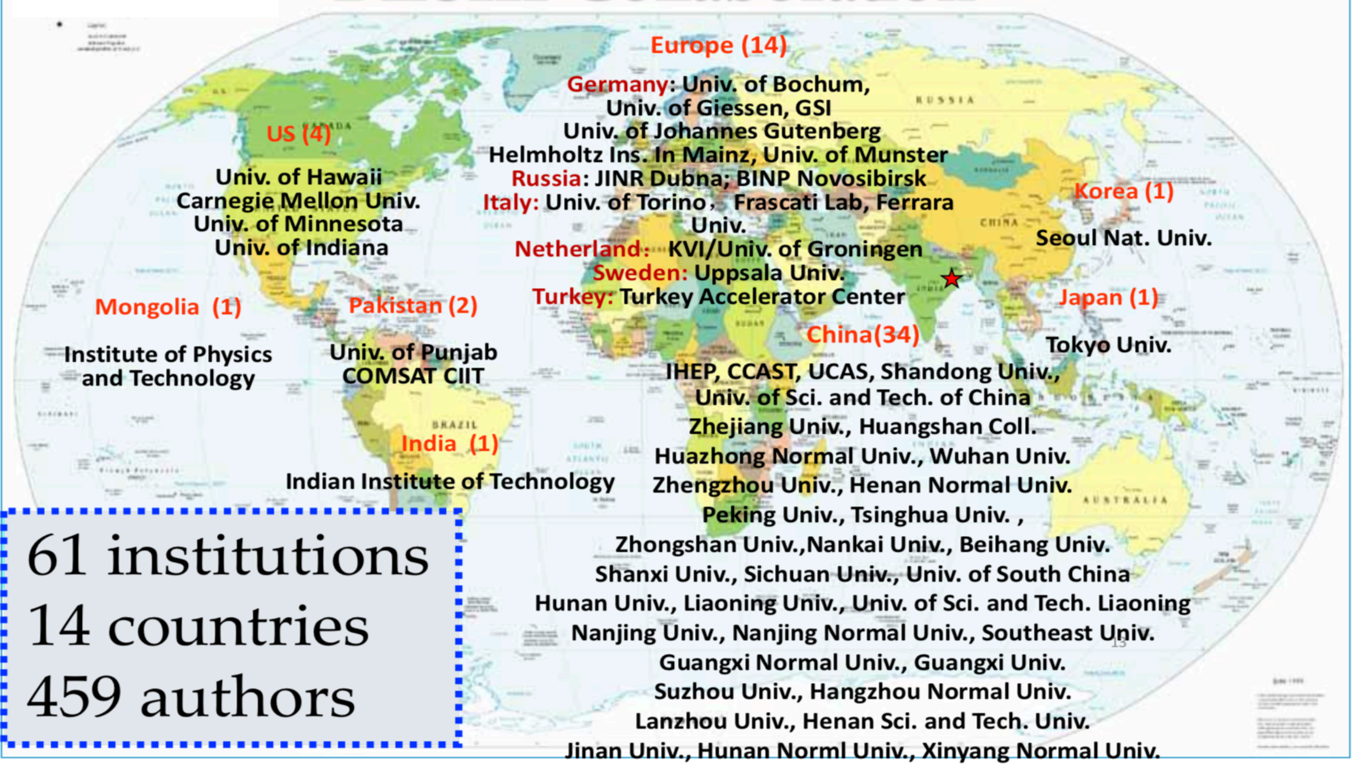


BESIII Collaboration



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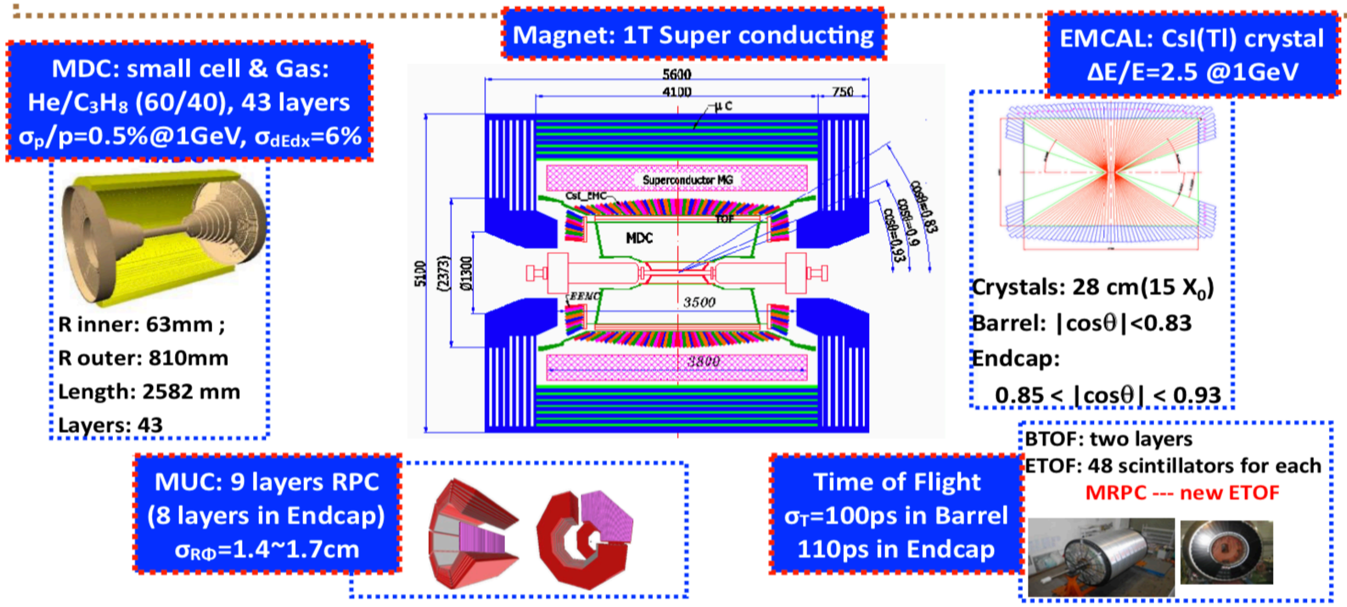

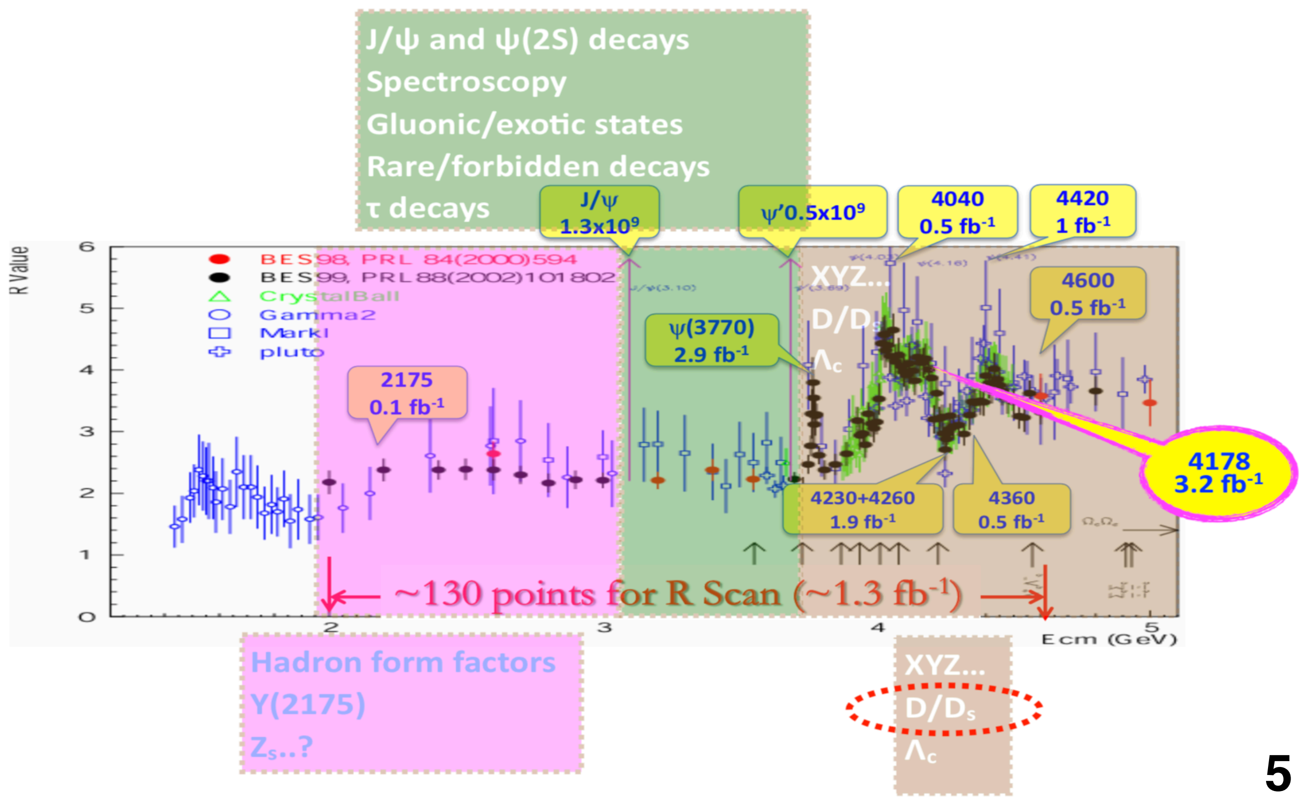

New Physics Searches at BESIII

New Physics	Channels	Publications
Dark Photons	$e^+e^- \to \gamma_{\rm ISR}\gamma', \gamma' \to l^+l^-$ $e^+e^- \to \eta\gamma', \gamma' \to e^+e^-$ $e^+e^- \to \eta'\gamma', \gamma' \to e^+e^-$	PLB774, 252 (2017) PRD99, 012006 (2019) PRD99, 012013 (2019)
Invisible Decays	$J/\psi \to \phi\eta/\eta', \eta/\eta' \to invisible$ $J/\psi \to \eta\omega/\phi, \omega/\phi \to invisible$	PRD87, 012009 (2013) PRD98, 032001 (2018)
Light Higgs	$\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \gamma A^0, A^0 \to \mu^+\mu^-$ $J/\psi \to \gamma A^0, A^0 \to \mu^+\mu^-$	PRD85, 092012 (2012) PRD93, 052005 (2016)
BNV/LNV	$J/\psi \to \Lambda_c^+ e^- + c.c.$ $D \to K\pi e^+e^+$	arXiv: 1803.04789 arXiv: 1902.02450
LFV	$J/\psi \to e^+\mu^- + c.c.$	PRD87, 112007 (2013)
CV	$J/\psi \to \gamma\gamma, \gamma\phi$	PRD90, 092002 (2014)
FCNC	$D^0 \to \gamma\gamma$ $J/\psi/\psi(3686) \to D^0 e^+e^-$ $D \to h(h')e^+e^-$ $\psi(3686) \to \Lambda_c^+ \bar{p} e^+e^- + c.c.$	PRD91, 112015 (2015) PRD96,111101-R (2017) PRD97, 072015 (2018) PRD97, 091102-R (2018)

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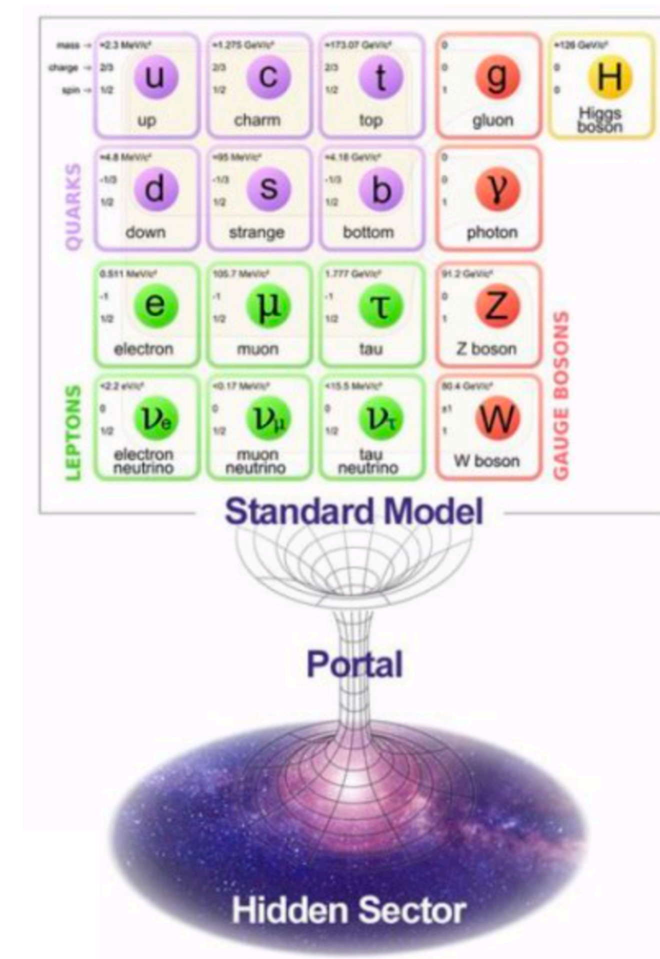
	$\psi(3686) \to \Lambda_c^+ \bar{p} e^+e^- + c.c.$	PRD97, 091102-R (2018)

01 Dark Sector

- Numerous astrophysical observations strongly suggest the existence of Dark Matter(DM) which provides a hint of dark sector (hidden sector).
- There might exist some "portals" that connect the SM sector to DM sector



Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

R. Essig et al., arXiv: 1311.0029 (2013)

01 Dark Sector

- Postulate an extra $\mathrm{U}(1)$ gauge symmetry, and the corresponding gauge boson is called dark photon or U boson, γ', A', Z'_d
- It can decay into light DM particles $\chi\chi$
- or decay into the SM $q\bar{q}, \ell^+\ell^-, \nu\bar{\nu}$
  - direct and very weak interaction
  - kinetic mixing with the SM photon, or mass mixing with the Z

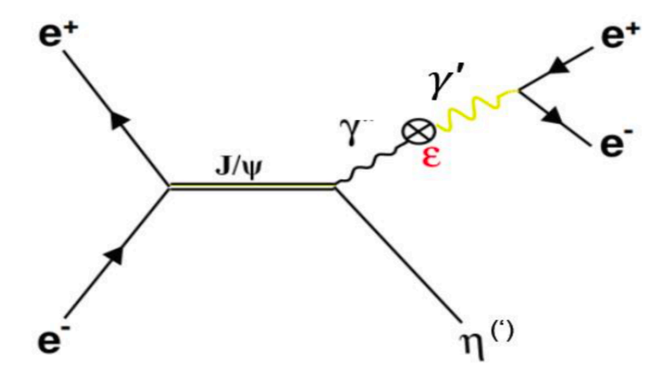
$$\mathcal{L}_{\text{int}} = -\left(\varepsilon e J_\mu^{\text{EM}} + \varepsilon_Z \frac{g}{2\cos\theta_W} J_\mu^{\text{NC}} \right) Z_d^\mu$$

- mixing strength $\varepsilon = \sqrt{\alpha'/\alpha} \sim 10^{-2} - 10^{-5}$ (could be smaller)
- mass ranges: $\mathrm{MeV}/c^2 - \mathrm{GeV}/c^2$ (ε_Z suppressed by $(m_{A'}/m_Z)^2$)

A resonant structure in the invariant mass spectrum

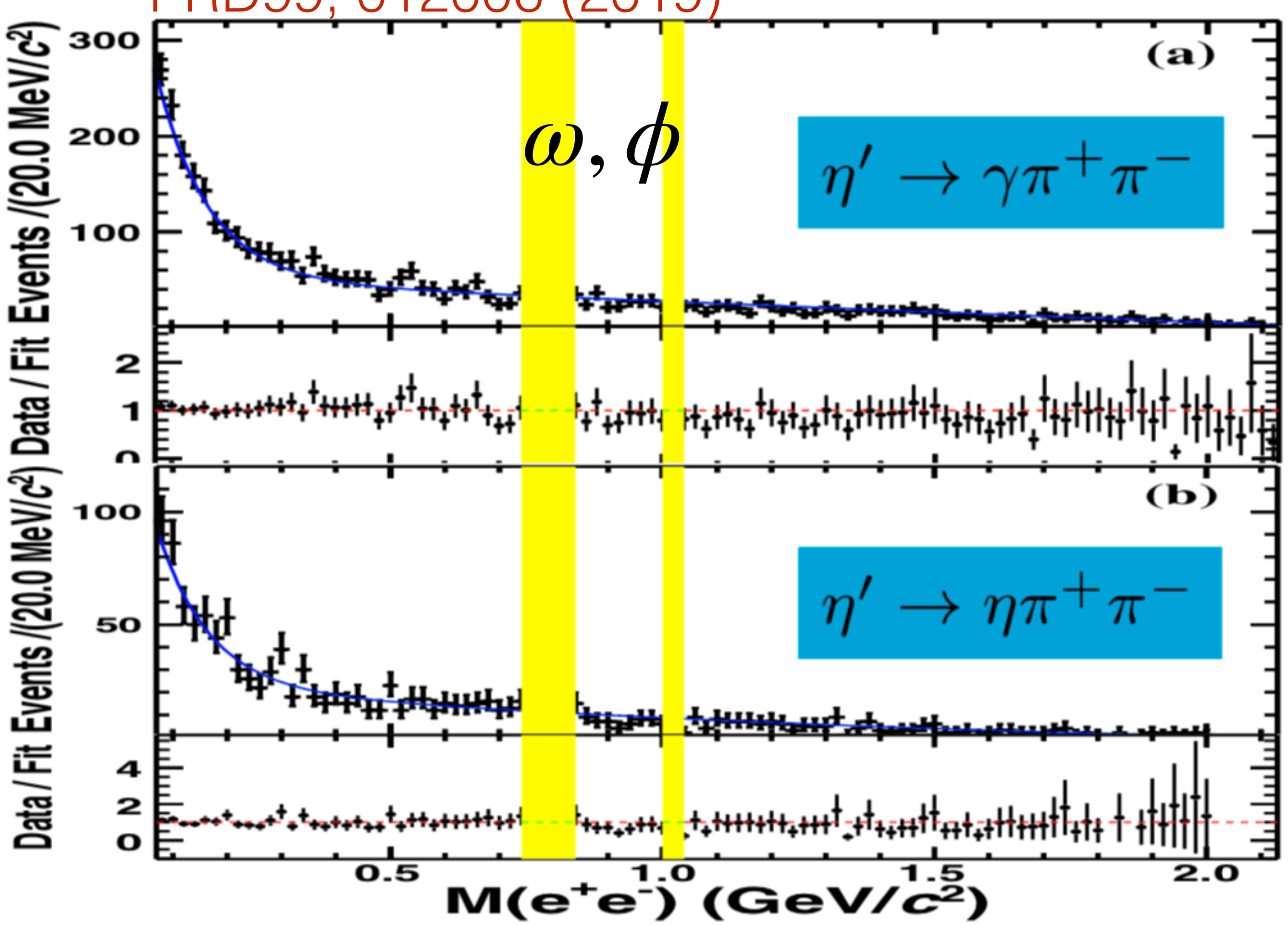
01 Dark Sector: dark photons

- First search for dark photon in E.M. Dalitz decays
  - $J/\psi \to \eta\gamma', \gamma' \to e^+e^-$ PRD99, 012013 (2019)
  - $J/\psi \to \eta'\gamma', \gamma' \to e^+e^-$ PRD99, 012006 (2019)



- Check narrow peaking structures in the $m_{e^+e^-}$ distribution

PRD99, 012006 (2019)



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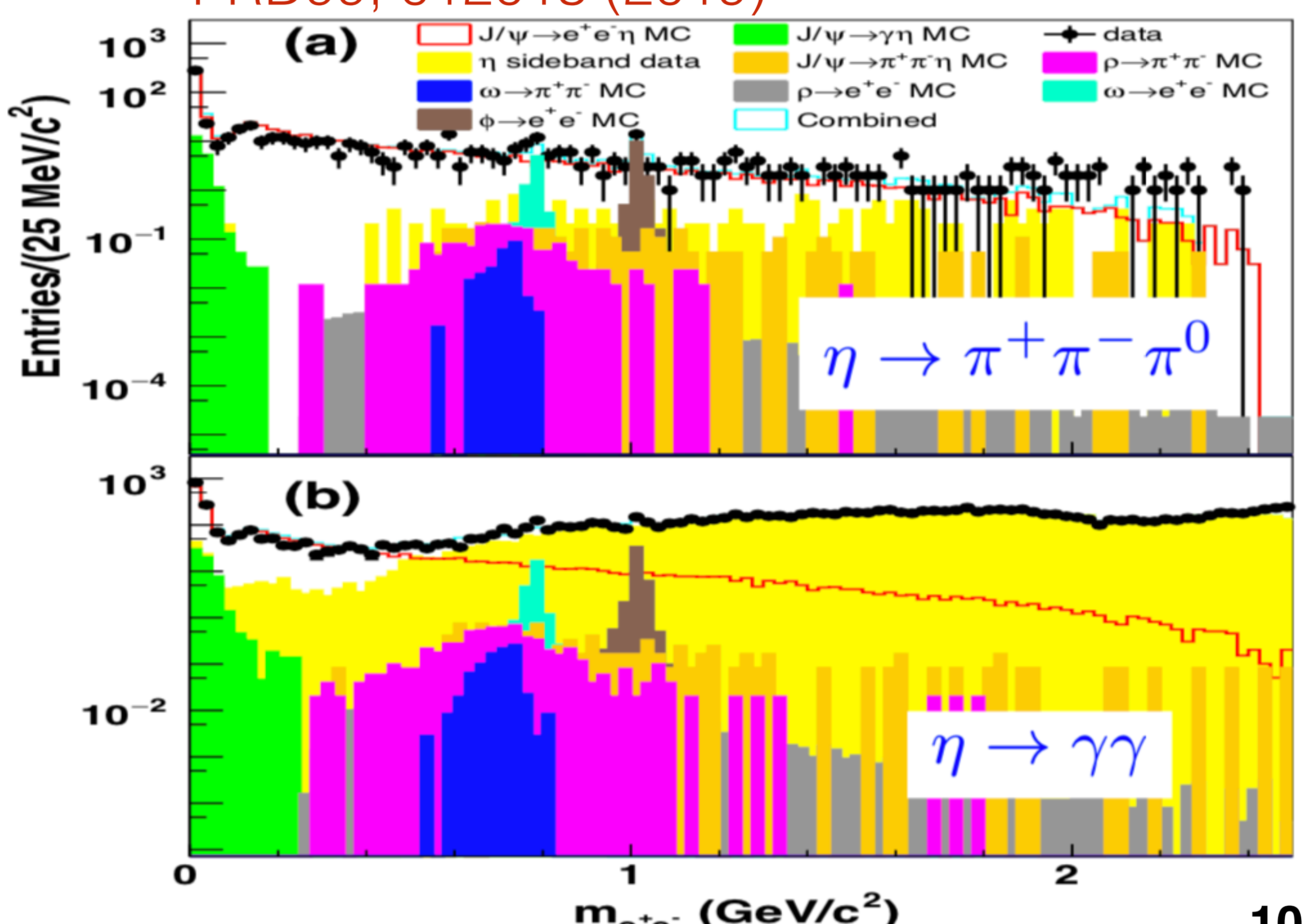
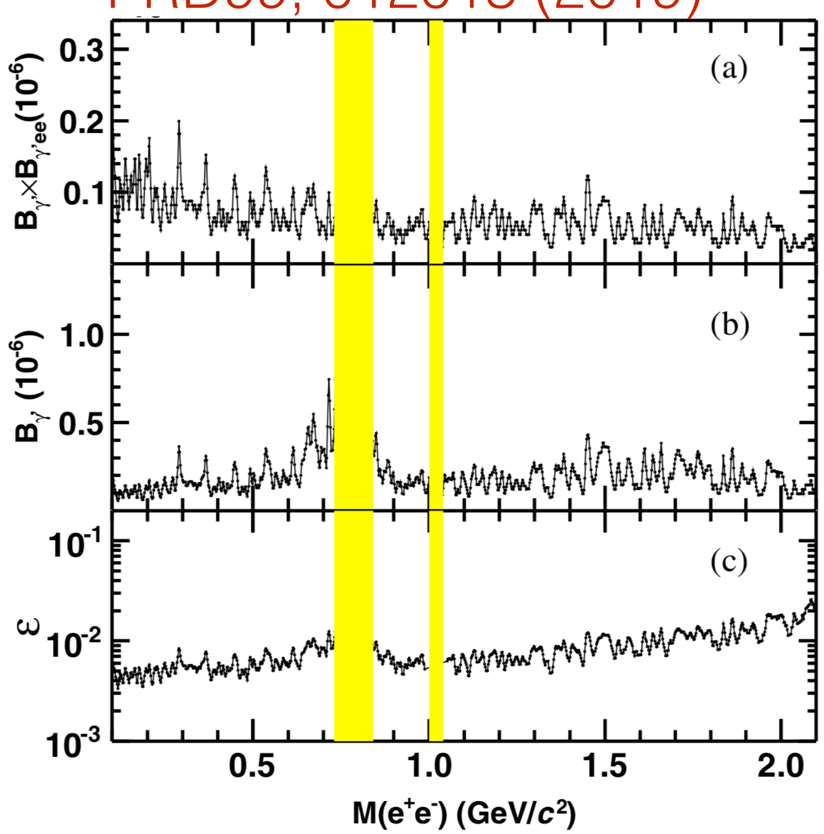


01 Dark Sector: dark photons

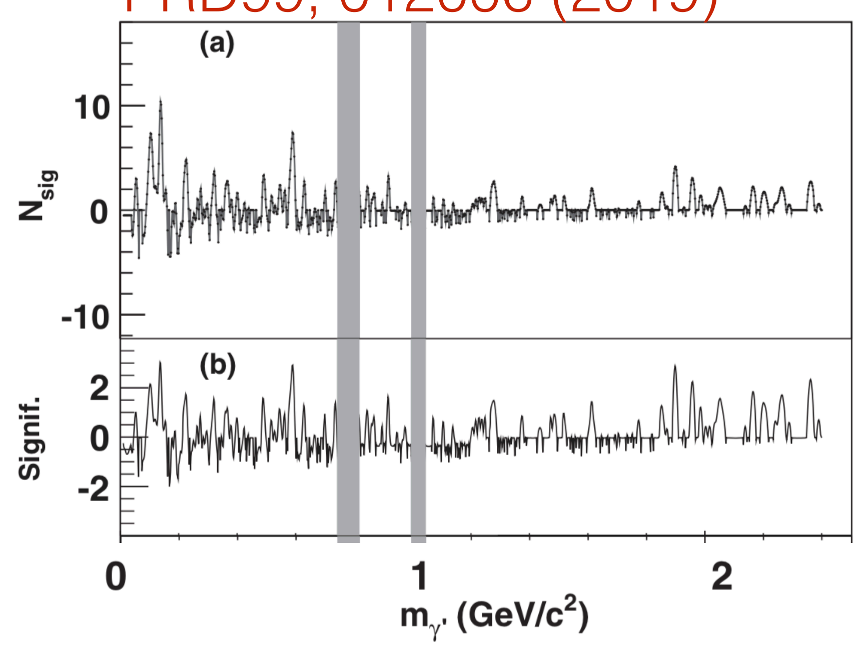
- No obvious peaking structures observed
- Fit to m_{e+e-} of data to obtain signal yields (ω, ϕ regions excluded)
- Combined limits at 90% C.L. on BF and ϵ (Bayesian approach)

	$\mathcal{B}(\psi \to P\gamma')\mathcal{B}(\gamma' \to e^+e^-)$	$\mathcal{B}(\psi \to P\gamma')$	ε
$P = \eta'$	$< 1.8\times10^{-8} - 2.0\times10^{-7}$	$< 6.0\times10^{-8} - 7.8\times10^{-7}$	$3.4\times10^{-3} - 2.6\times10^{-2}$
$P = \eta$	$< 1.9\times10^{-8} - 9.1\times10^{-7}$		$10^{-3} - 10^{-2}$

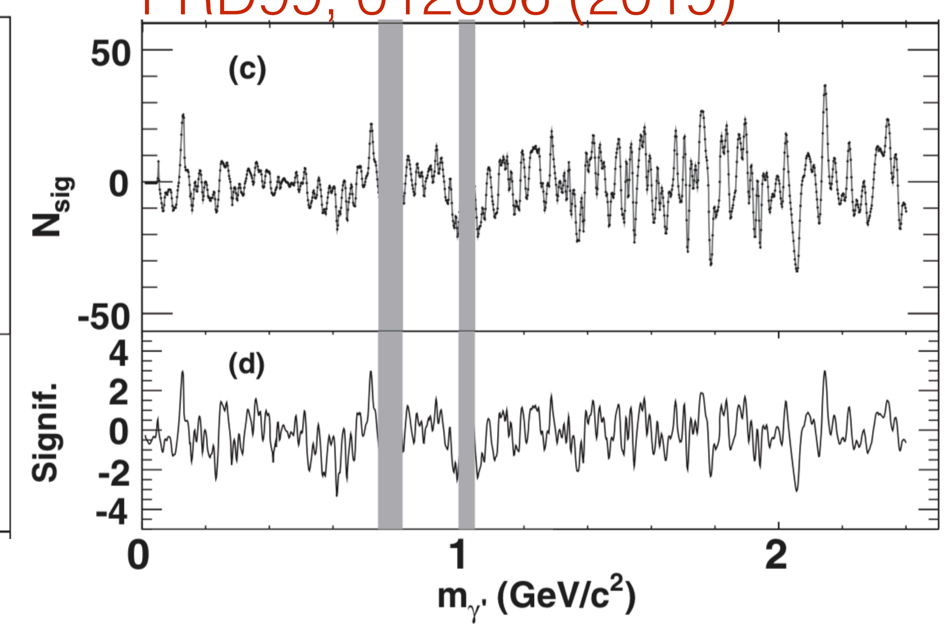
PRD99, 012013 (2019)



PRD99, 012006 (2019)



PRD99, 012006 (2019)



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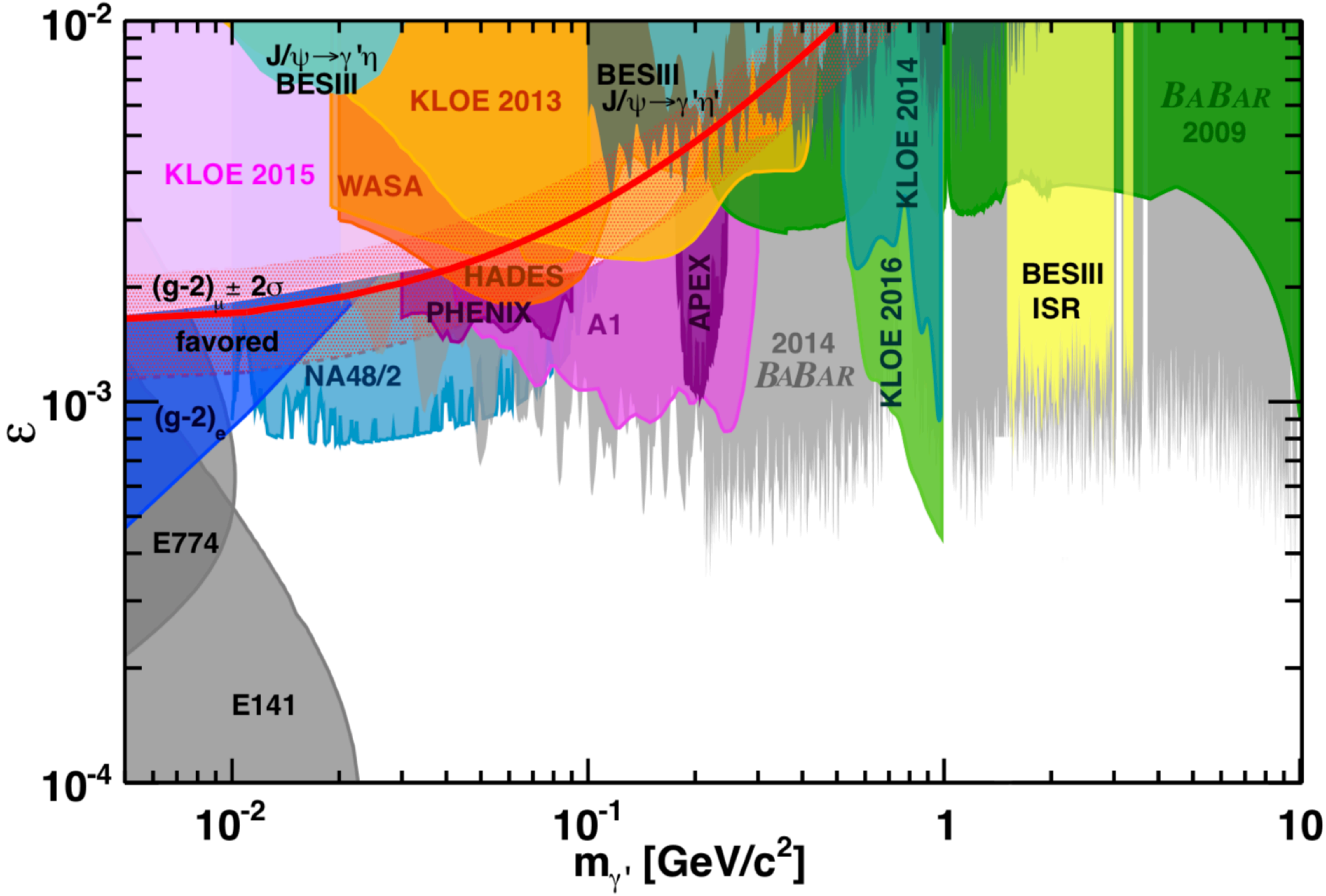


01 Dark Sector: invisible decay

- In the SM, quarkonium states can decay into neutrino and anti-neutrino pair via virtual Z^0 boson with very low expected BFs

$$\mathscr{B}(\omega \to \nu\nu) = 8.4 \times 10^{-14}, \mathscr{B}(\phi \to \nu\nu) = 5.8 \times 10^{-12}$$

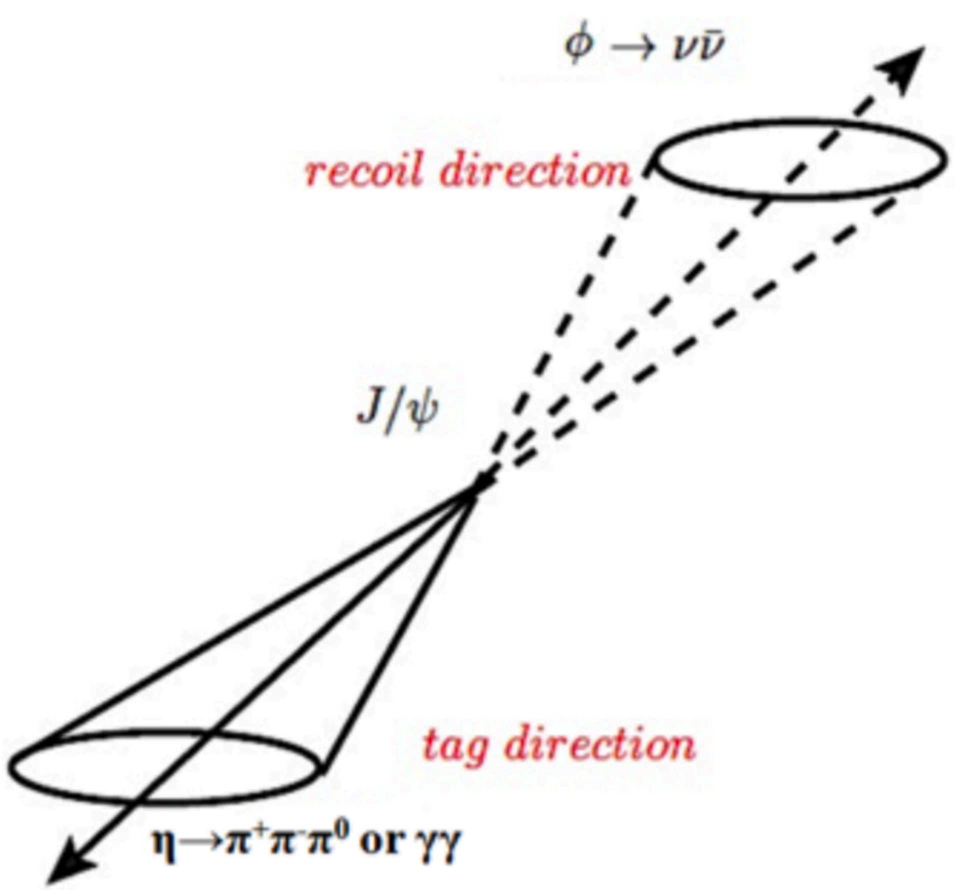
- However, if singlet scalar, pseudo-scalar or vector (portals) exists, and mediates the SM-DM interaction, it can allow invisible decays of SM particles to DM particles.
- The branching fraction of invisible decay might be enhanced in the presence of light DM particles.

mode	s-wave	p-wave
$\mathrm{BR}(\Upsilon(1S) \to \chi\chi)$	4.2×10^{-4}	1.8×10^{-3}
$\mathrm{BR}(\Upsilon(1S) \to \nu\bar{\nu})$	9.9×10^{-6}	
$\mathrm{BR}(J/\Psi \to \chi\chi)$	2.5×10^{-5}	1.0×10^{-4}
$\mathrm{BR}(J/\Psi \to \nu\bar{\nu})$	2.7×10^{-8}	
$\mathrm{BR}(\eta \to \chi\chi)$	3.4×10^{-5}	1.4×10^{-4}
$\mathrm{BR}(\eta' \to \chi\chi)$	3.7×10^{-7}	1.5×10^{-6}
$\mathrm{BR}(\eta_c \to \chi\chi)$	1.3×10^{-7}	5.3×10^{-7}
$\mathrm{BR}(\chi_{c0}(1P) \to \chi\chi)$	2.7×10^{-8}	1.2×10^{-7}
$\mathrm{BR}(\phi \to \chi\chi)$	1.9×10^{-8}	7.8×10^{-8}
$\mathrm{BR}(\omega \to \chi\chi)$	7.2×10^{-8}	3.0×10^{-8}

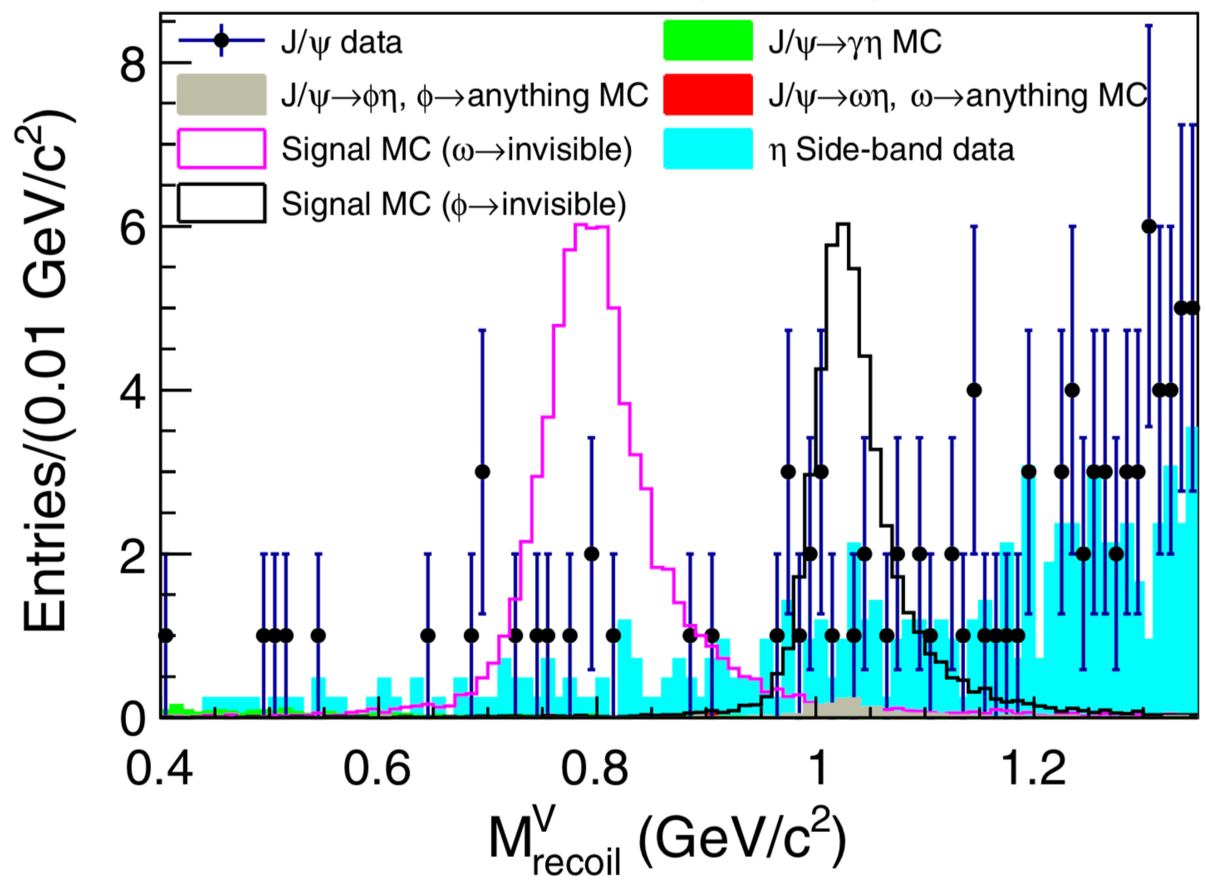
B. McElrath, eConf C070805, 19 (2007)

01 Dark Sector: invisible decay

- First search for $J/\psi \to \eta\omega/\phi, \omega/\phi \to invisible$ PRD98, 032001 (2018)
- Recoiling mass (against η) is defined as $M^{V}_{\rm recoil} \equiv \sqrt{(E_{\rm CM} - E_{3\pi})^2 - |\vec{p}|^2_{3\pi}}$



PRD98, 032001 (2018)



01 Dark Sector: invisible decay

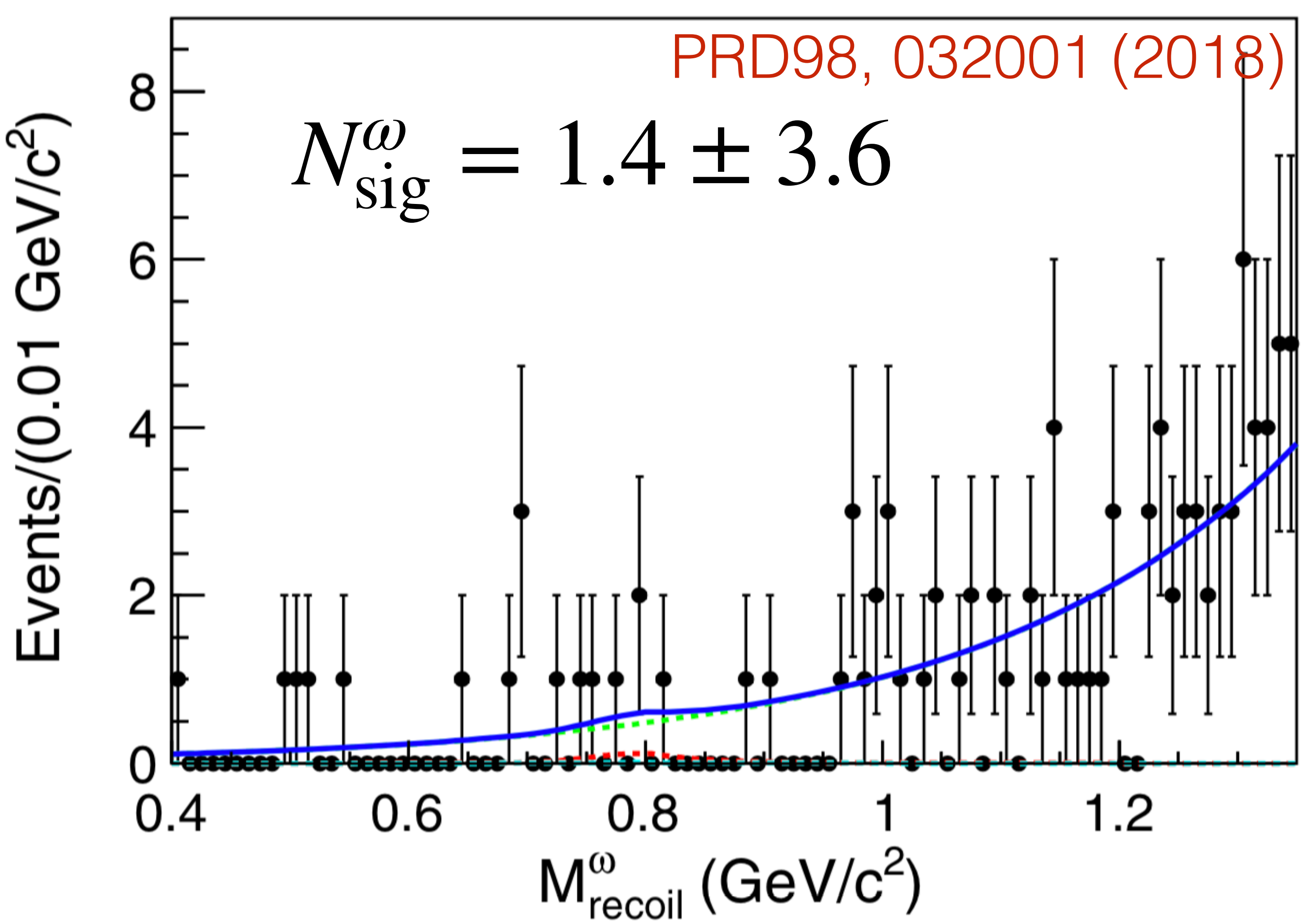
- Fit to $M^{V}_{\rm recoil}$ to obtain signal yields
- No obvious signals found, upper limits set at 90% C.L.

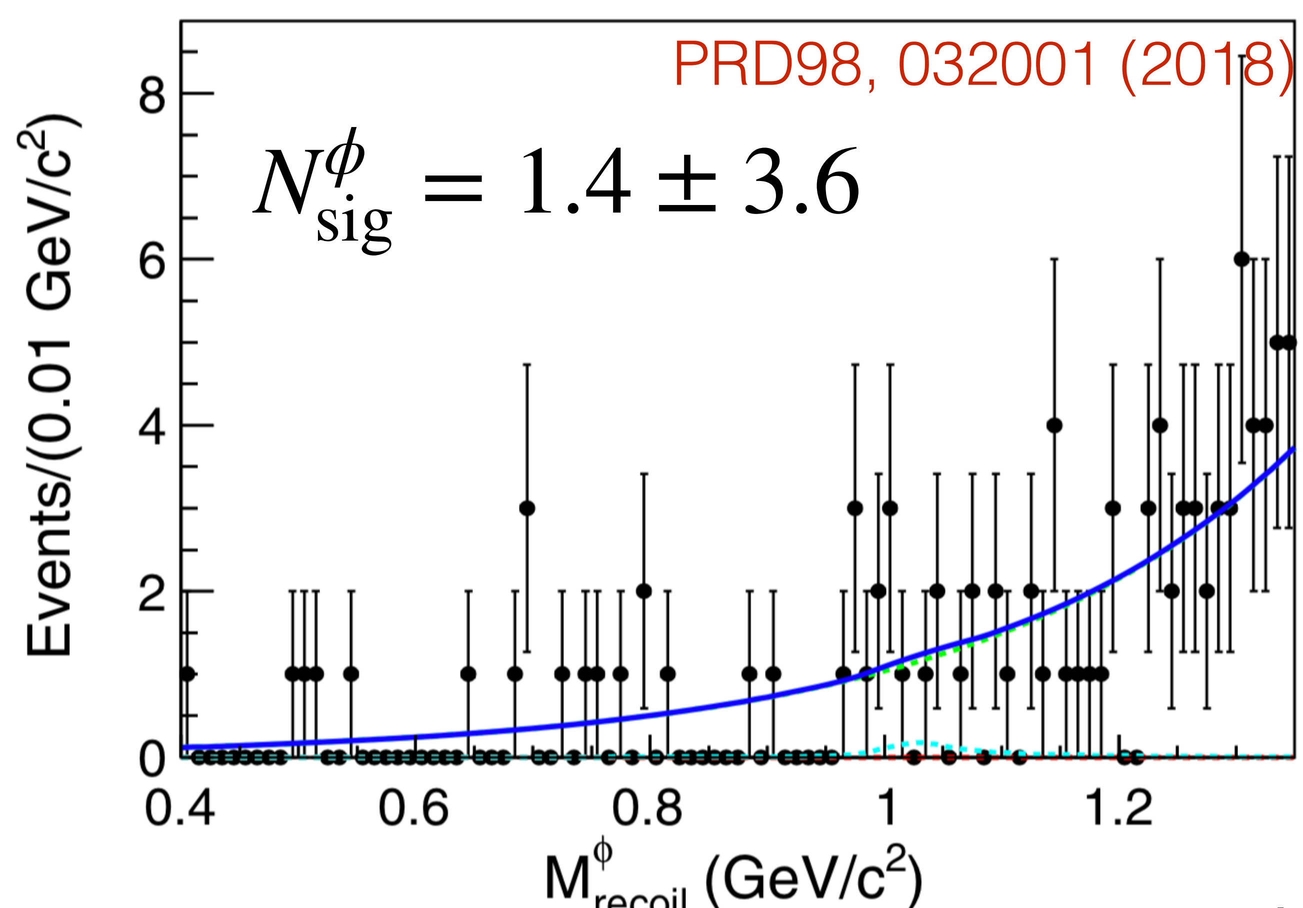
$$\frac{\mathcal{B}(\omega \to invisible)}{\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)} < 8.1 \times 10^{-5}$$

$$\frac{\mathcal{B}(\phi \to invisible)}{\mathcal{B}(\phi \to K^+K^-)} < 3.4 \times 10^{-4}$$

$$\mathcal{B}(\omega \to invisible) < 7.3 \times 10^{-5}$$

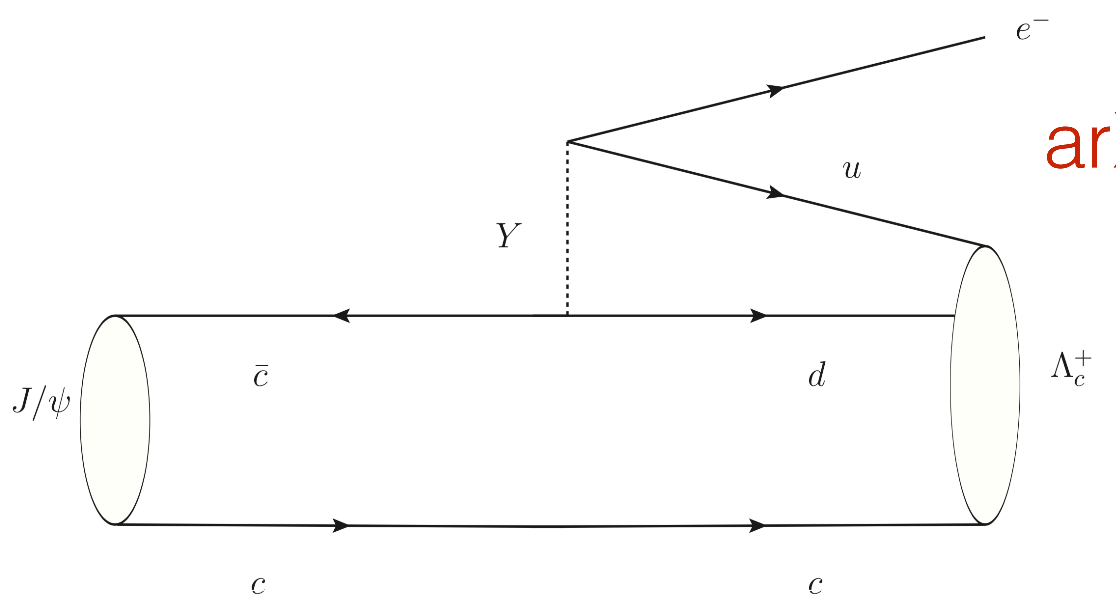
$$\mathcal{B}(\phi \to invisible) < 1.7 \times 10^{-4}$$



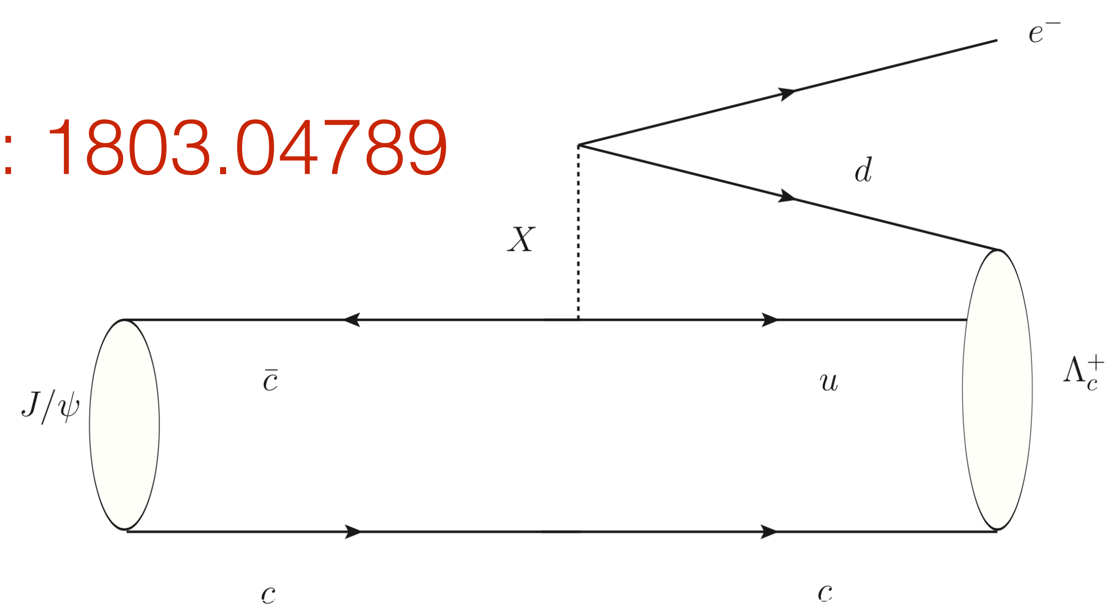


02 BNV/LNV: $J/\psi \to \Lambda_c^+ e^- + c.c.$

- Many SM extensions and Grand Unified Theories, such as superstring or SUSY, predict proton decays. In this case, baryon number is violated while the difference Δ(B-L) is conserved.
- Since the matter–antimatter asymmetry in the universe is an observable fact, the negative result from proton decay experiment does not imply BN is conserved.
- Searches for new physics at collider experiments are complementary to those at specifically designed non-collider experiments.



arXiv: 1803.04789



02 BNV/LNV: $J/\psi \to \Lambda_c^+ e^- + c.c.$

arXiv: 1803.04789

- First search for

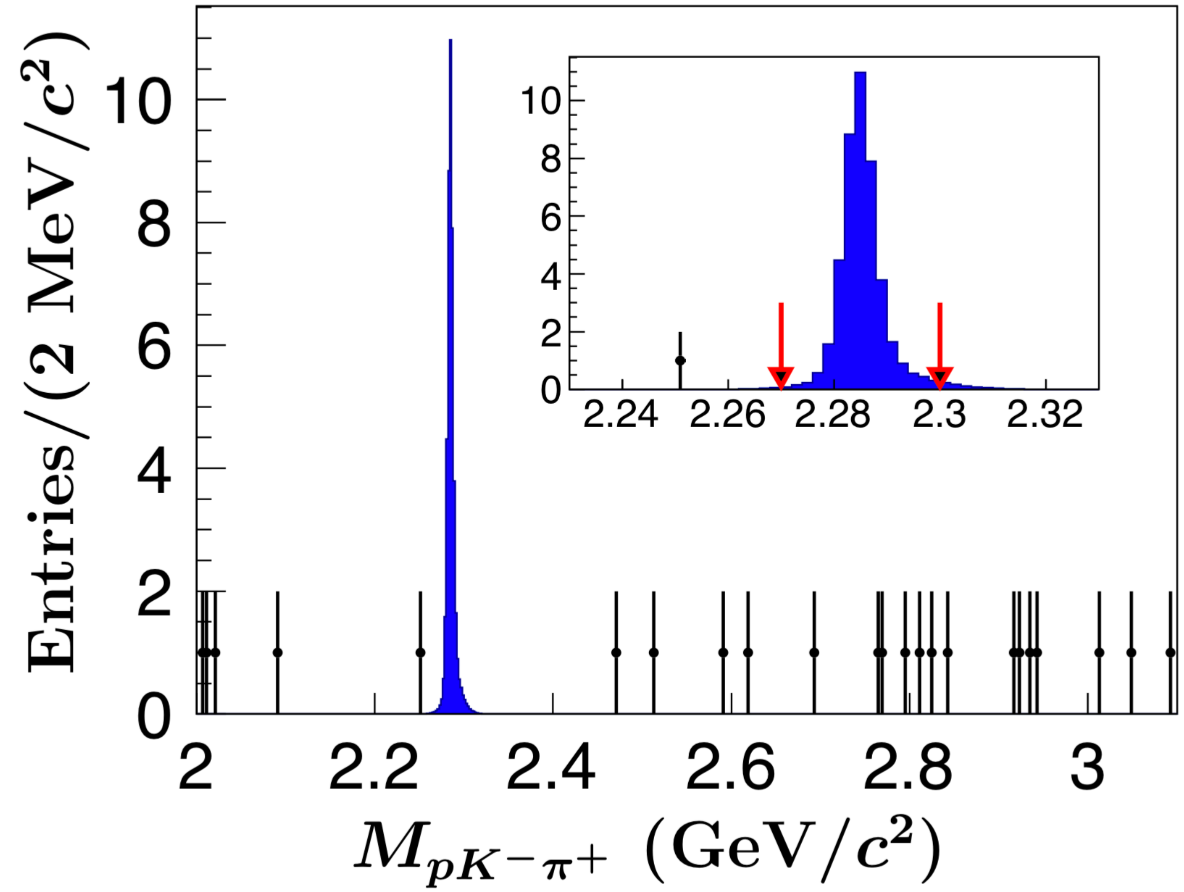
  $J/\psi \to \Lambda_c^+ e^- + c.c., \Lambda_c^+ \to pK^-\pi^+$

- Check $M_{pK^-\pi^+}$ distribution

- No events found in the signal window

- Upper limit at 90% C.L. on BF

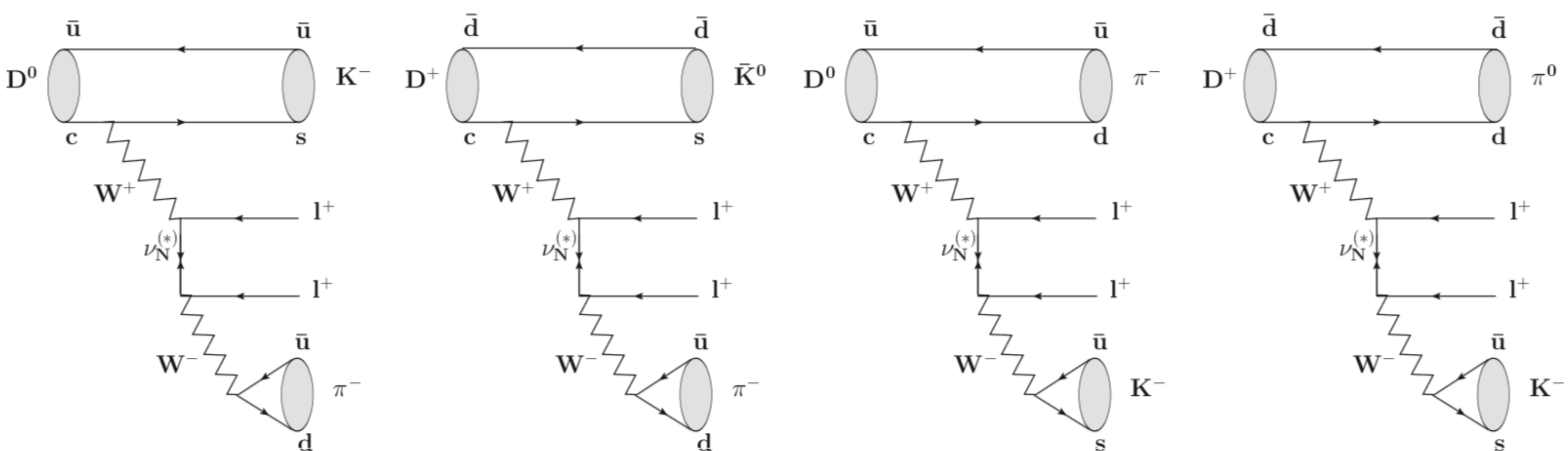
  $\mathscr{B}(J/\psi \to \Lambda_c^+ e^- + c.c.) < 6.9 \times 10^{-8}$



- The first BNV search in quarkonium decay products.
- More than two orders of magnitude than that of CLEO's measurement in the analogous process $D^0 \to \bar{p}e^+ + c.c.$

02 BNV/LNV: $D \to K\pi e^+ e^+$

- Observations of neutrino oscillation shown that the masses of neutrino should not be zero.
- Theoretically, the leading model accommodating the neutrino masses is the "see-saw" mechanism, in which the SM neutrinos can be Majorana particles.
- The Majorana neutrinos can be searched through the process violating the lepton-number (LN) conservation by two units ($\Delta L = 2$).



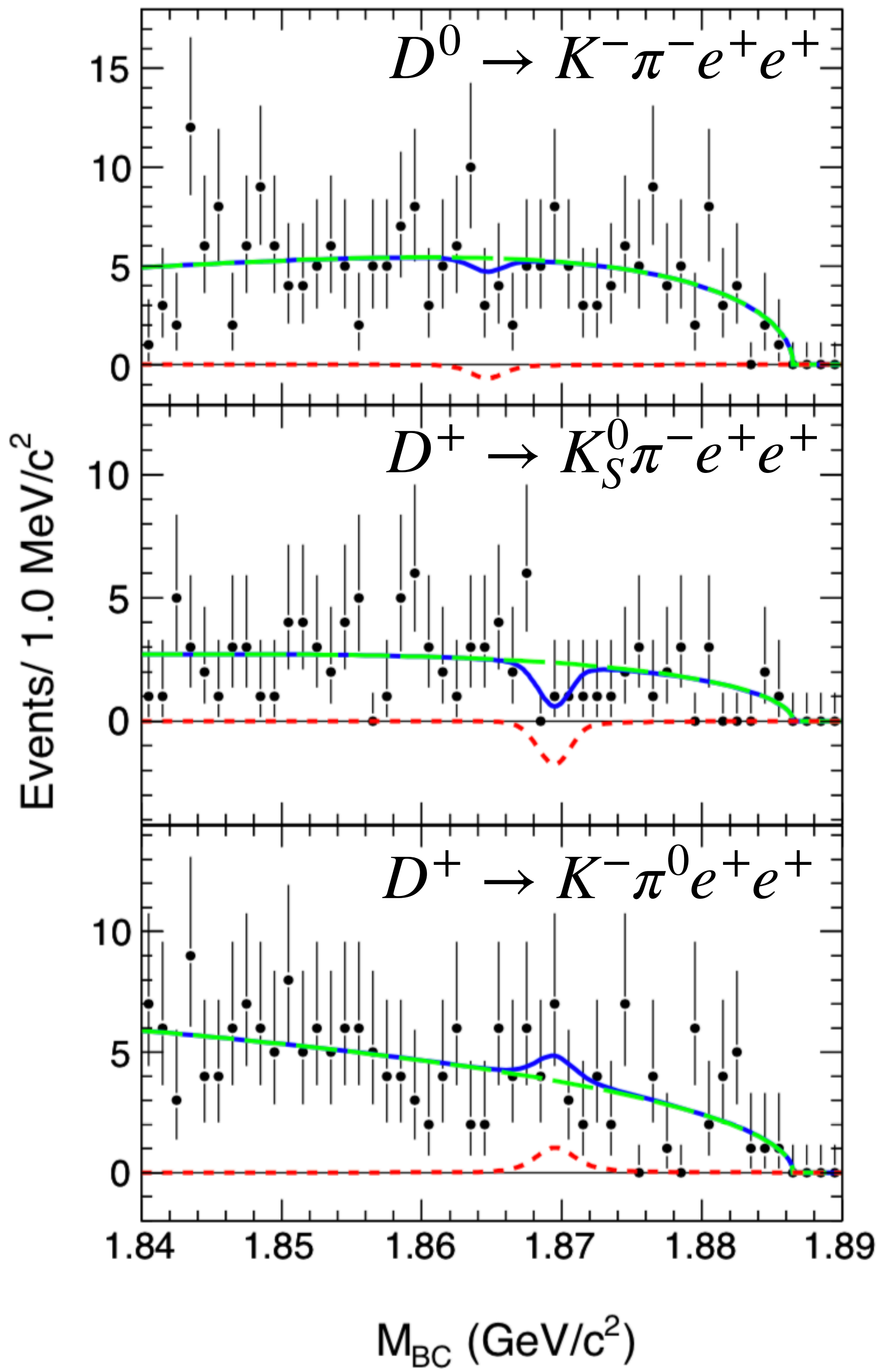
(a) $D^0 \to K^-\pi^- l^+ l^+$ (CF) (b) $D^+ \to \bar{K}^0\pi^- l^+ l^+$ (CF) (c) $D^0 \to K^-\pi^- l^+ l^+$ (DCS) (d) $D^+ \to K^-\pi^0 l^+ l^+$ (DCS)

H.R. Dong et al Chin, Phys. C **39** 013101 (2015).

02 BNV/LNV: $D \to K\pi e^+ e^+$

arXiv: 1902.02450

- Check m_{BC}, no signals found



02 BNV/LNV: $D \to K\pi e^+ e^+$

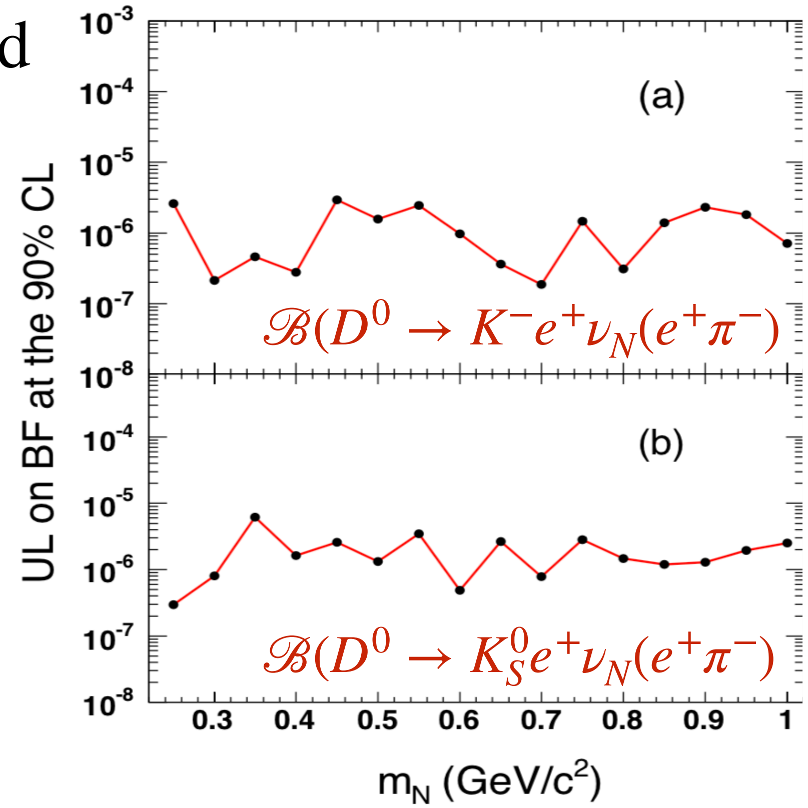
- Check m_{BC}, no signals found
- UL at 90% C.L. on BFs

$\mathcal{B}(D^0 \to K^- \pi^- e^+ e^+) < 2.7 \times 10^{-6}$

$\mathcal{B}(D^+ \to K_S^0 \pi^- e^+ e^+) < 3.3 \times 10^{-6}$

$\mathcal{B}(D^+ \to K^- \pi^0 e^+ e^+) < 8.5 \times 10^{-6}$

arXiv: 1902.02450



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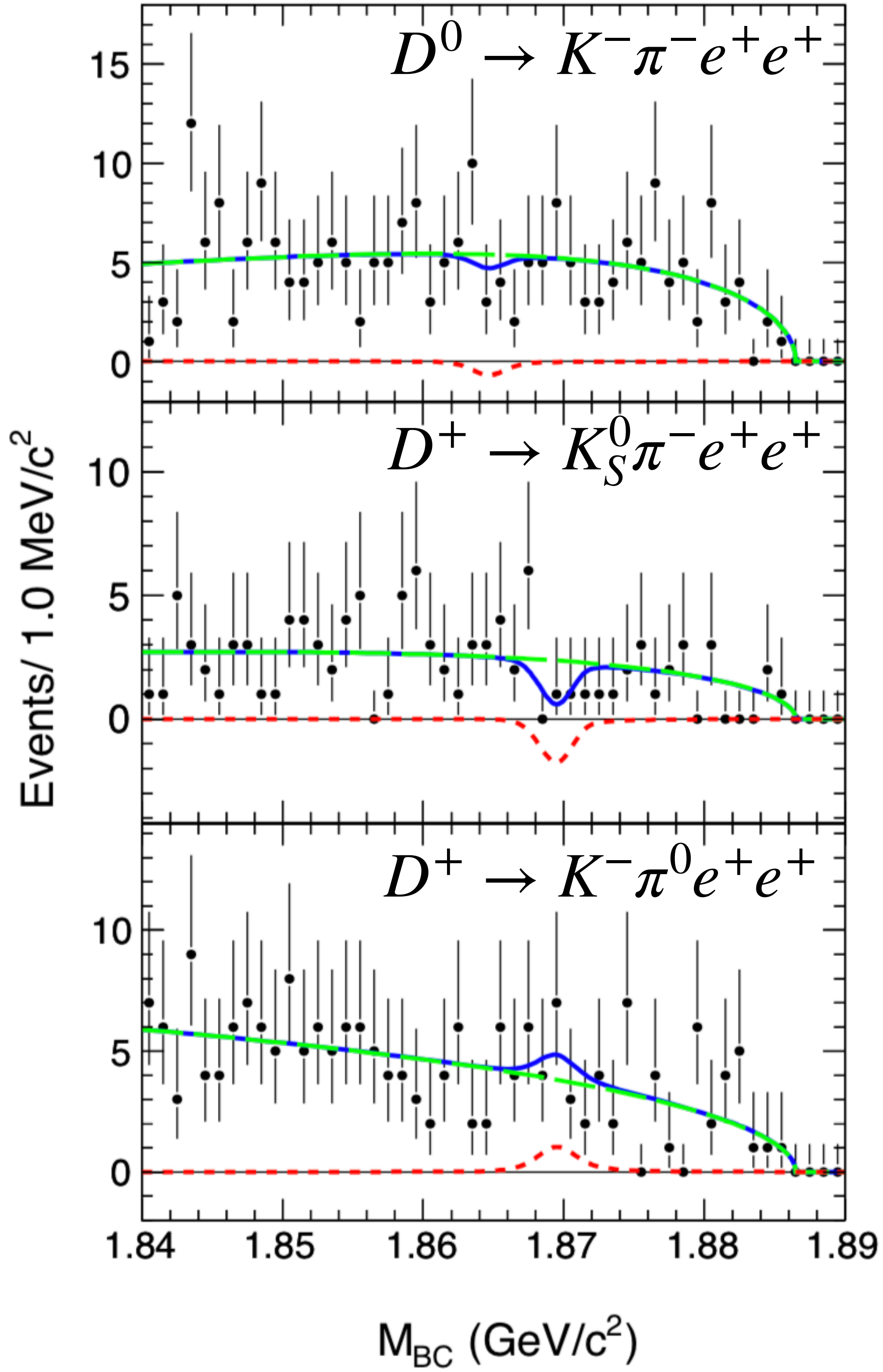

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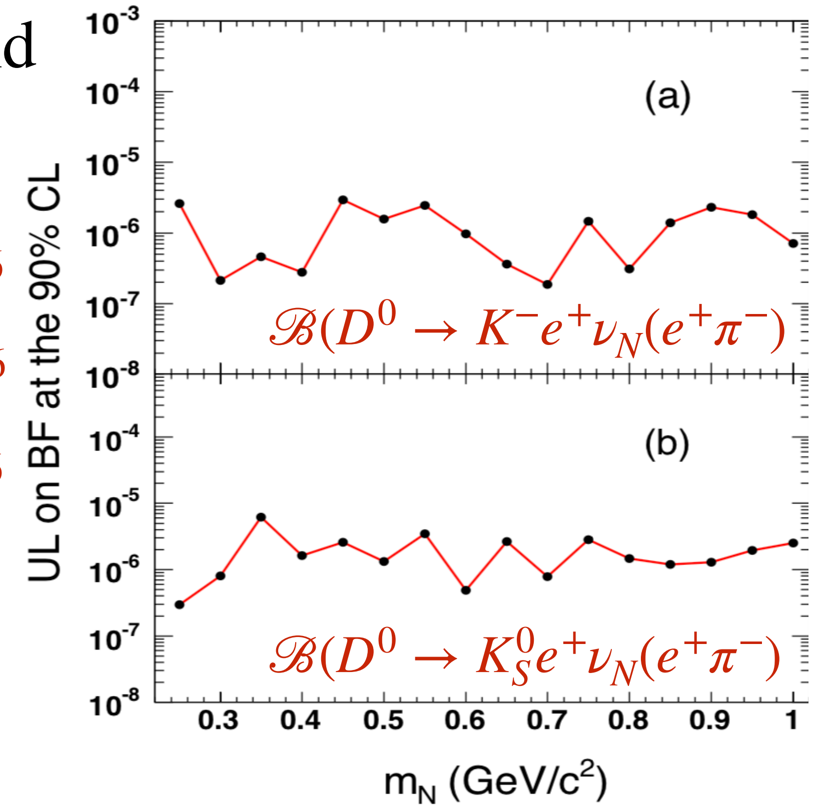
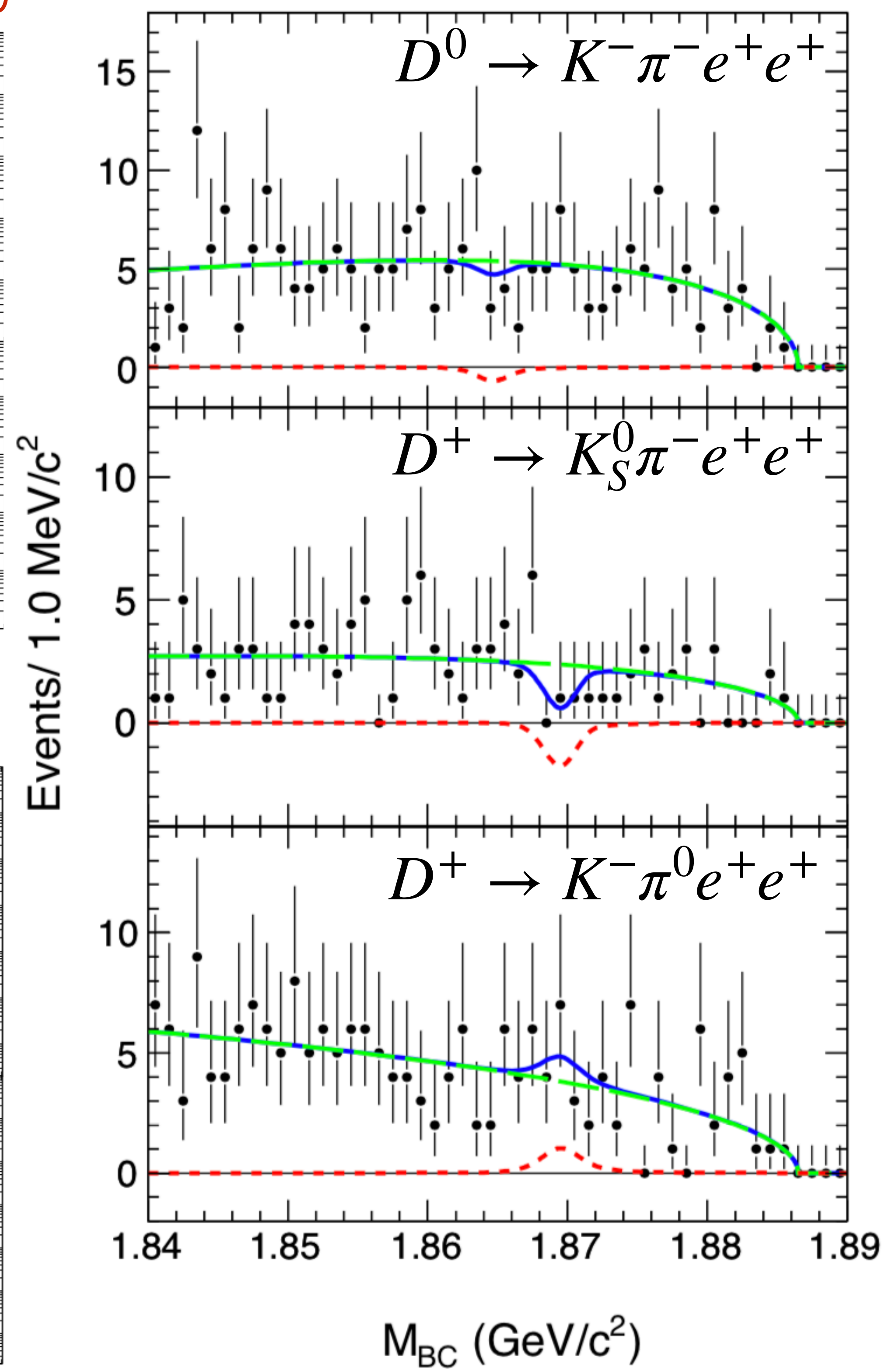
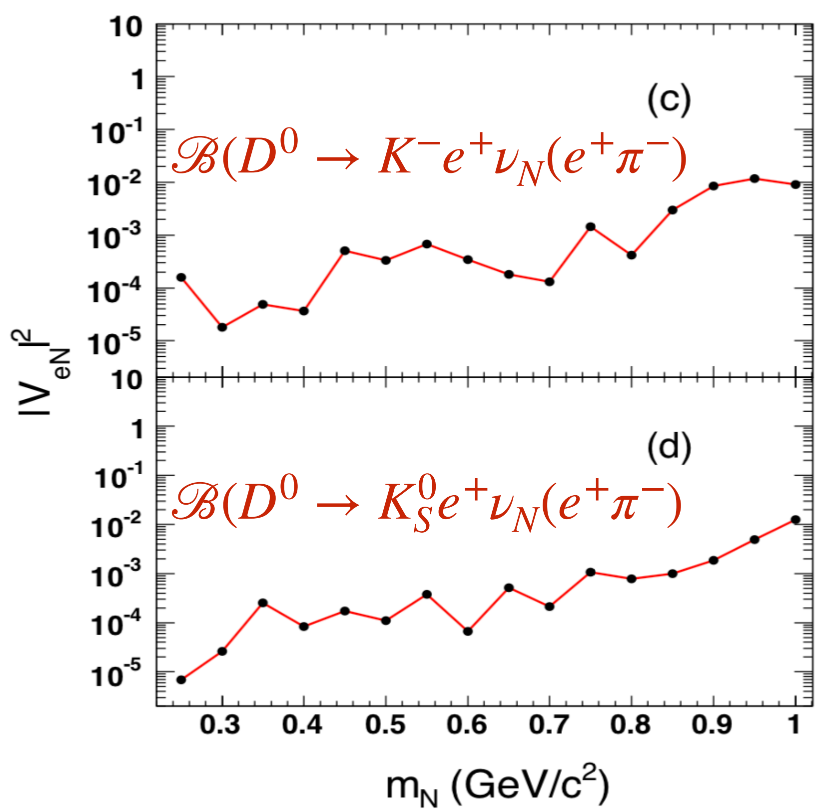


arXiv: 1902.02450



The resultant ULs on the mixing matrix element $|V_{eN}|^2$ as a function of m_N provide additional/complementary information about the bounds on the $|V_{eN}|^2$ in D meson decays

$$\frac{\Gamma(m_N, V_{eN}(m_N))}{\Gamma(m_N, V'_{eN}(m_N))} = \frac{|V_{eN}(m_N)|^4}{|V'_{eN}(m_N)|^4}$$



03 FCNC

- In SM, FCNC is strongly suppressed by GIM mechanism and can happen only through loop diagram, leading to a very small BF theoretically.
- The suppression in charm decays is much stronger than those in B and K system due to stronger diagram cancellation than the down-type quarks.
- Sensitive to New Physics.

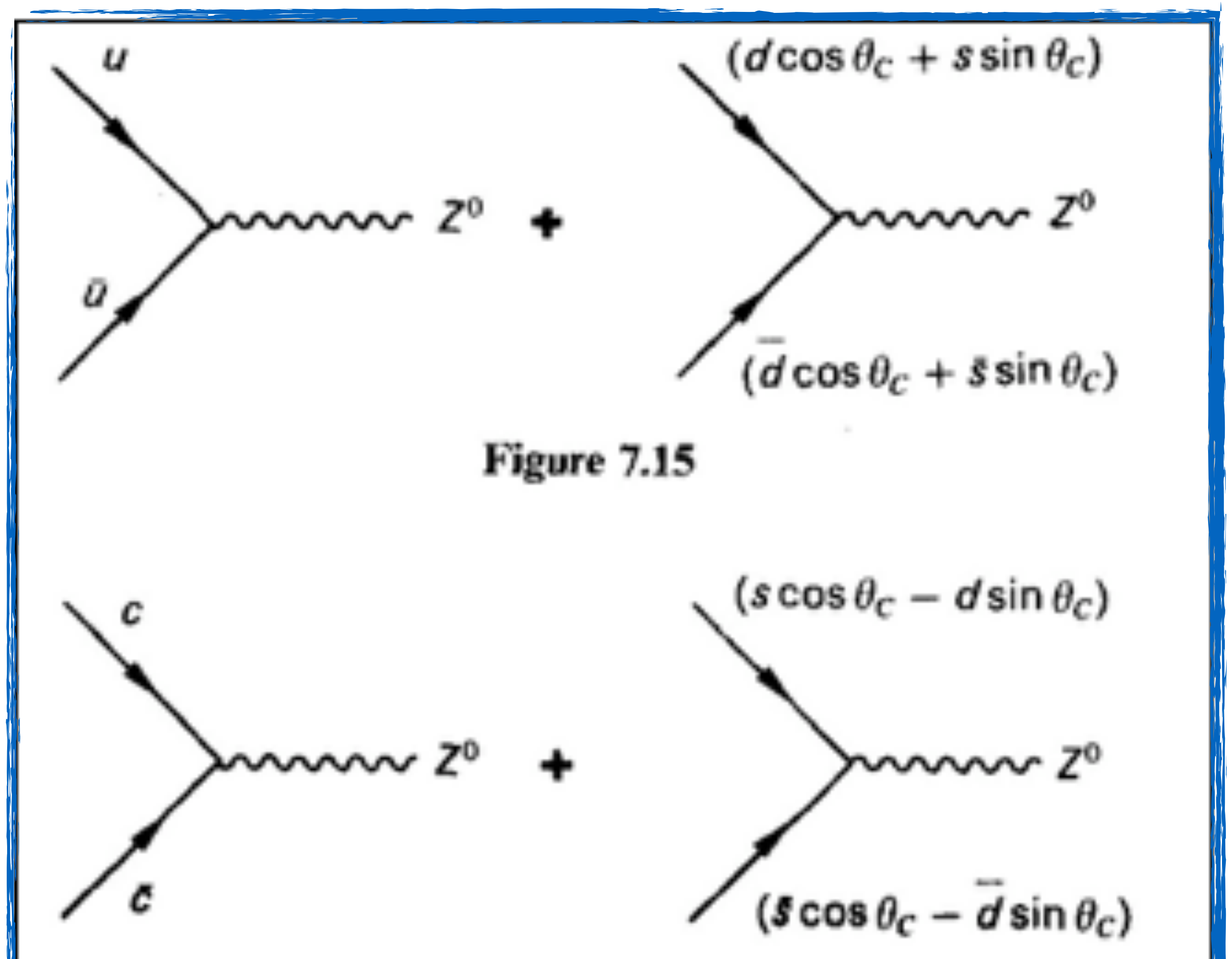
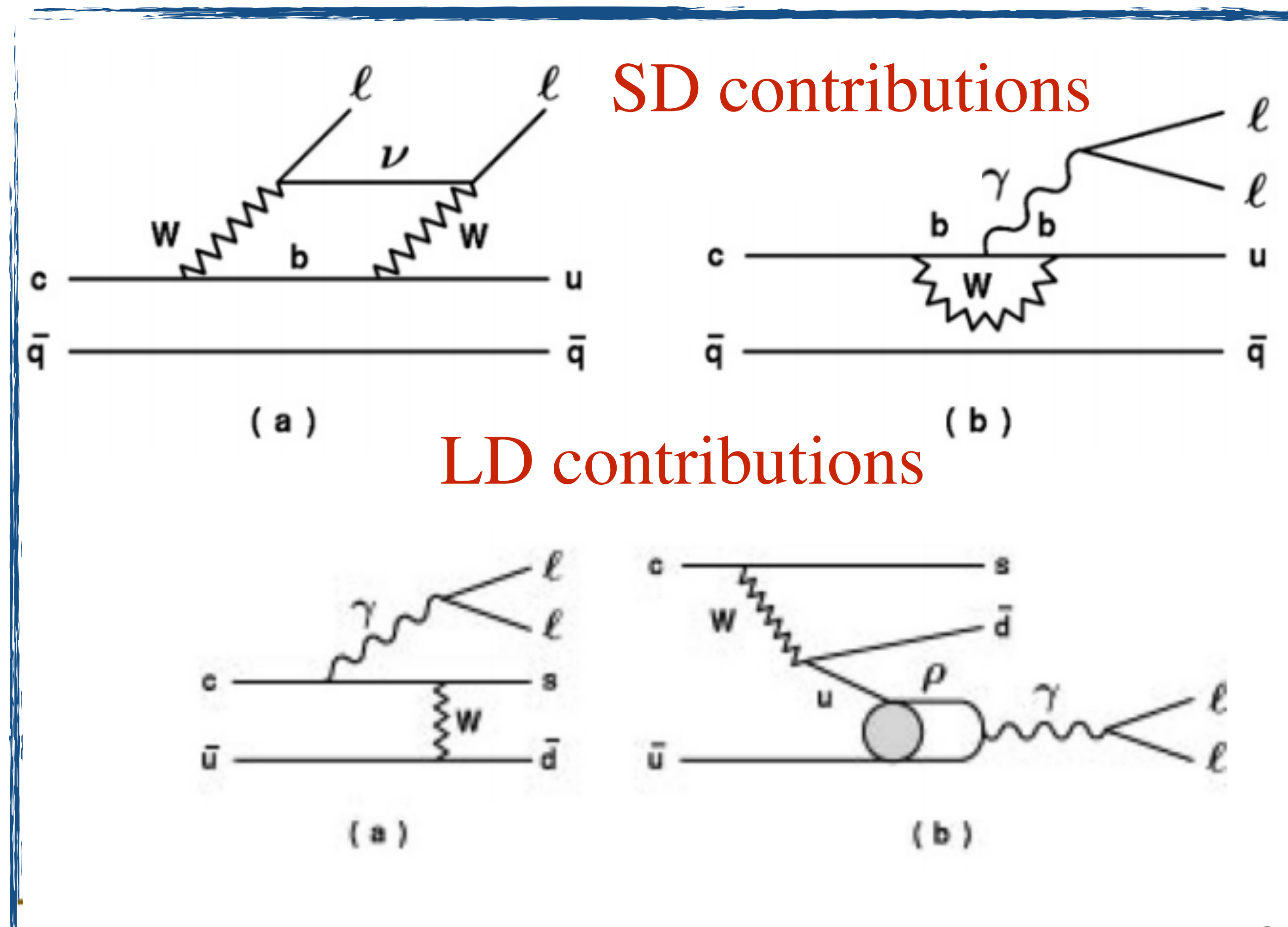


Figure 7.15



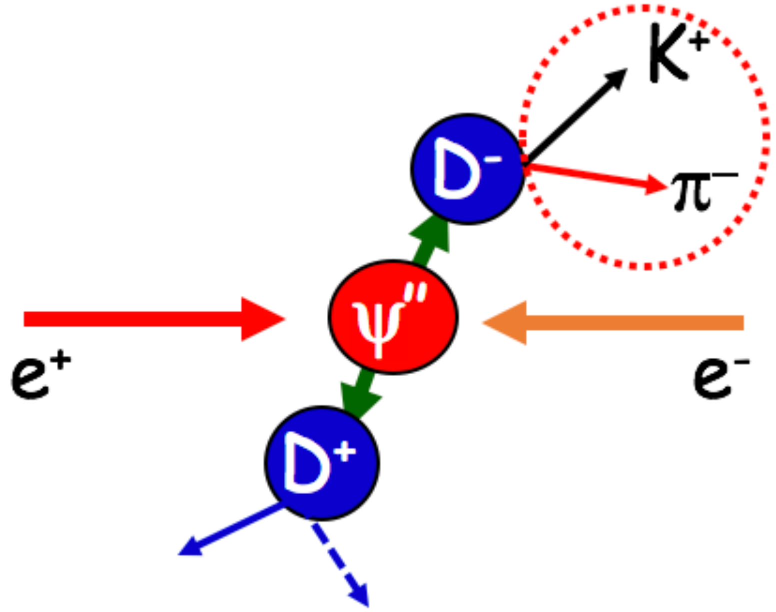
03 FCNC: $D \to h(h')e^+e^-$

- Most of the previous D^0 limits are at the level of 10^{-5} ~10^{-4}
- LHCb observed some four-body decays of $D^0 \to hh\mu^+\mu^-$ at 10^{-7} level
- BESIII could make best constraint on all of the above e+e- modes

Decay	Upper limit	Experiment	Year	Ref.
$D^0 \to \pi^0 e^+e^-$	45.0	CLEO	1996	[14]
$D^0 \to \eta e^+e^-$	110.0	CLEO	1996	[14]
$D^0 \to \omega e^+e^-$	180.0	CLEO	1996	[14]
$D^0 \to \overline{K}^0 e^+e^-$	110.0	CLEO	1996	[14]
$D^0 \to \rho e^+e^-$	124.0	E791	2001	[15]
$D^0 \to \phi e^+e^-$	59.0	E791	2001	[15]
$D^0 \to \overline{K}^{*0} e^+e^-$	47.0	E791	2001	[15]
$D^0 \to \pi^+\pi^- e^+e^-$	370.0	E791	2001	[15]
$D^0 \to K^+K^- e^+e^-$	315.0	E791	2001	[15]
$D^0 \to K^-\pi^+ e^+e^-$	385.0	E791	2001	[15]
$D^+ \to \pi^+ e^+e^-$	1.1	BaBar	2011	[16]
$D^+ \to K^+ e^+e^-$	1.0	BaBar	2011	[16]
$D^+ \to \pi^+\pi^0 e^+e^-$				
$D^+ \to \pi^+ K_S^0 e^+e^-$				
$D^+ \to K^+\pi^0 e^+e^-$				
$D^+ \to K^+\overline{K}^0 e^+e^-$				

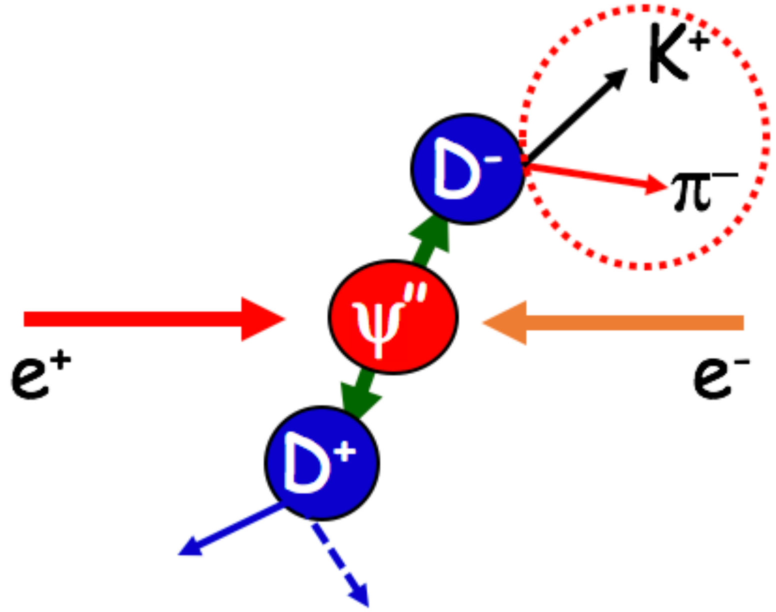
In unit of 10^{-6}

03 FCNC: $D \to h(h')e^+e^-$ PRD97, 072015 (2018)



03 FCNC: $D \to h(h')e^+e^-$ PRD97, 072015 (2018)

- Double Tag analysis
  - Absolute BFs
  - Event is very clean, bkg very low
  - High tagging efficiency
  - Many sys. uncertainties cancelled



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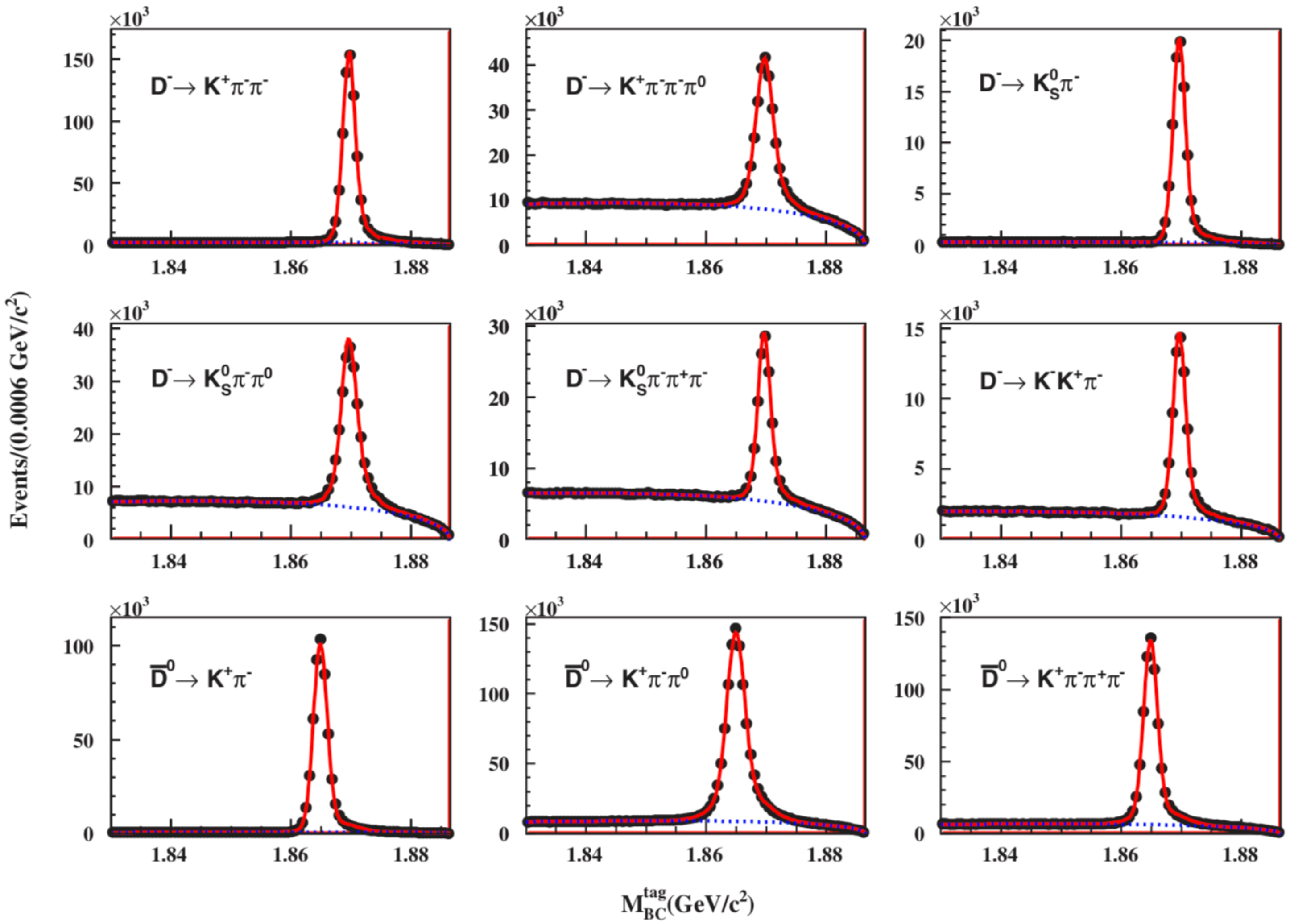
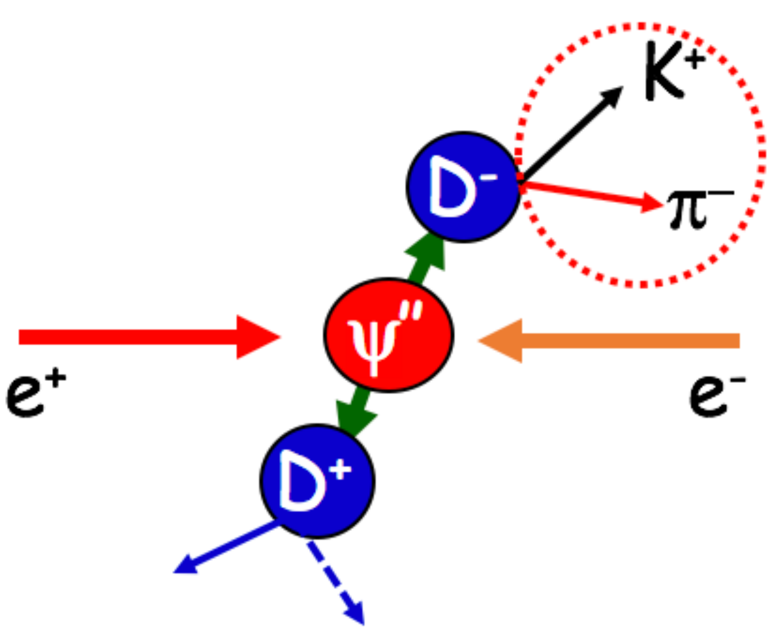
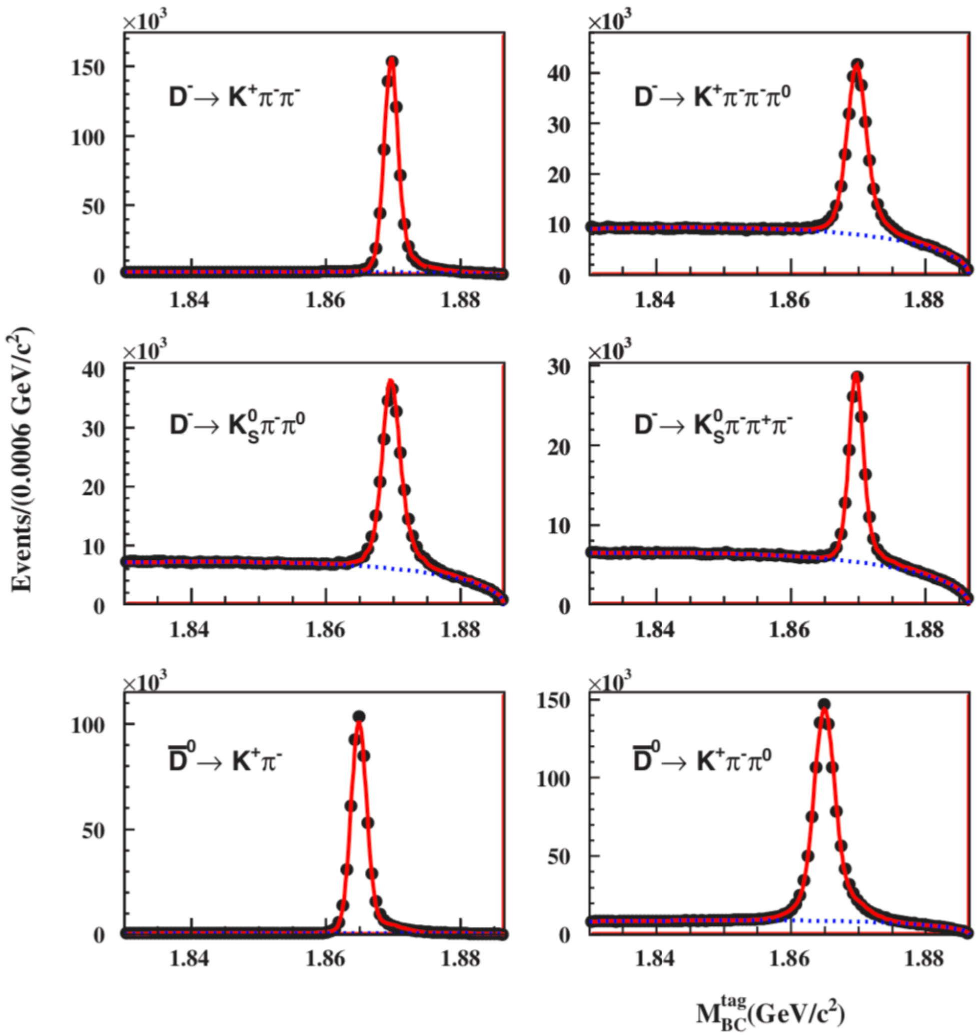


- Double Tag analysis
  - Absolute BFs
  - Event is very clean, bkg very low
  - High tagging efficiency
  - Many sys. uncertainties cancelled



03 FCNC: $D \to h(h')e^+e^-$ PRD97, 072015 (2018)



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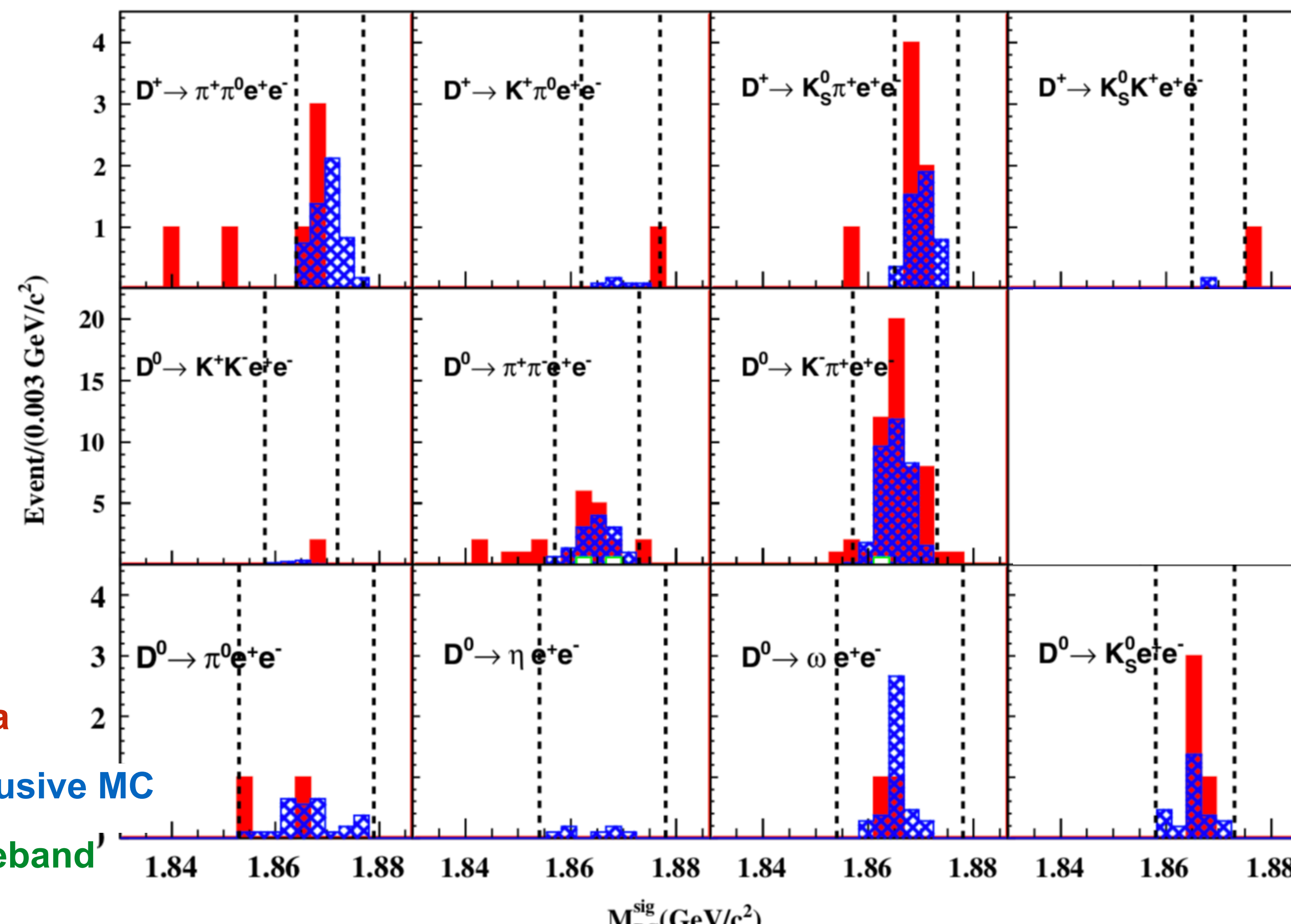
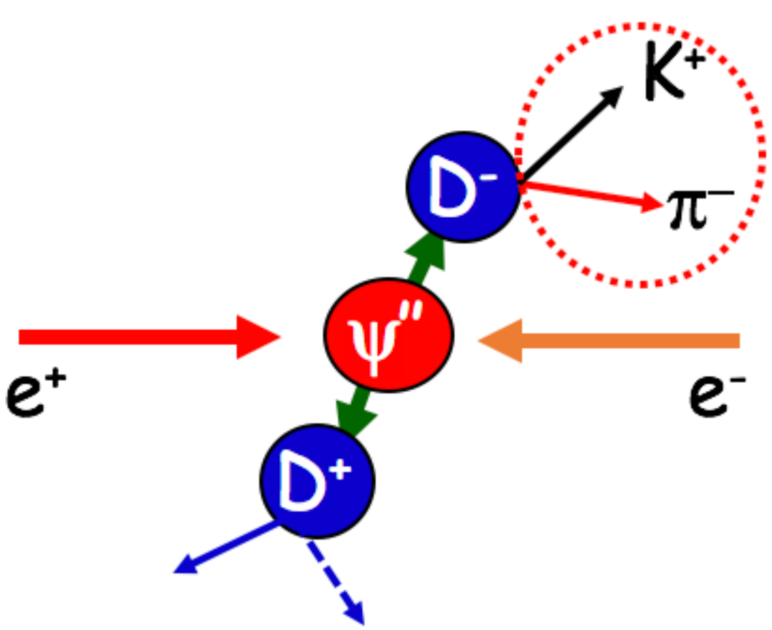


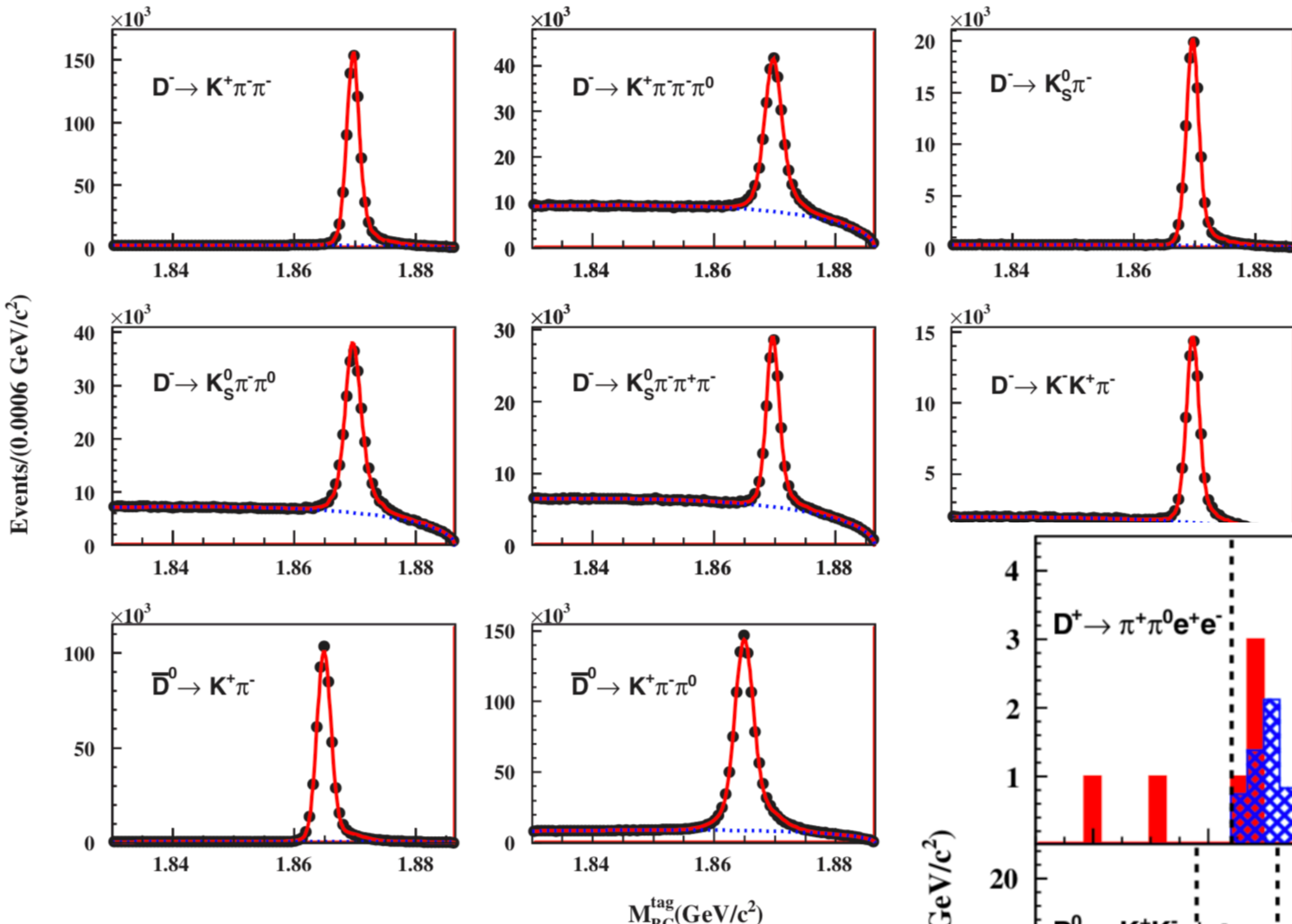


Data

Inclusive MC

Sideband

03 FCNC: $D \rightarrow h(h')e^+e^-$ PRD97, 072015 (2018)



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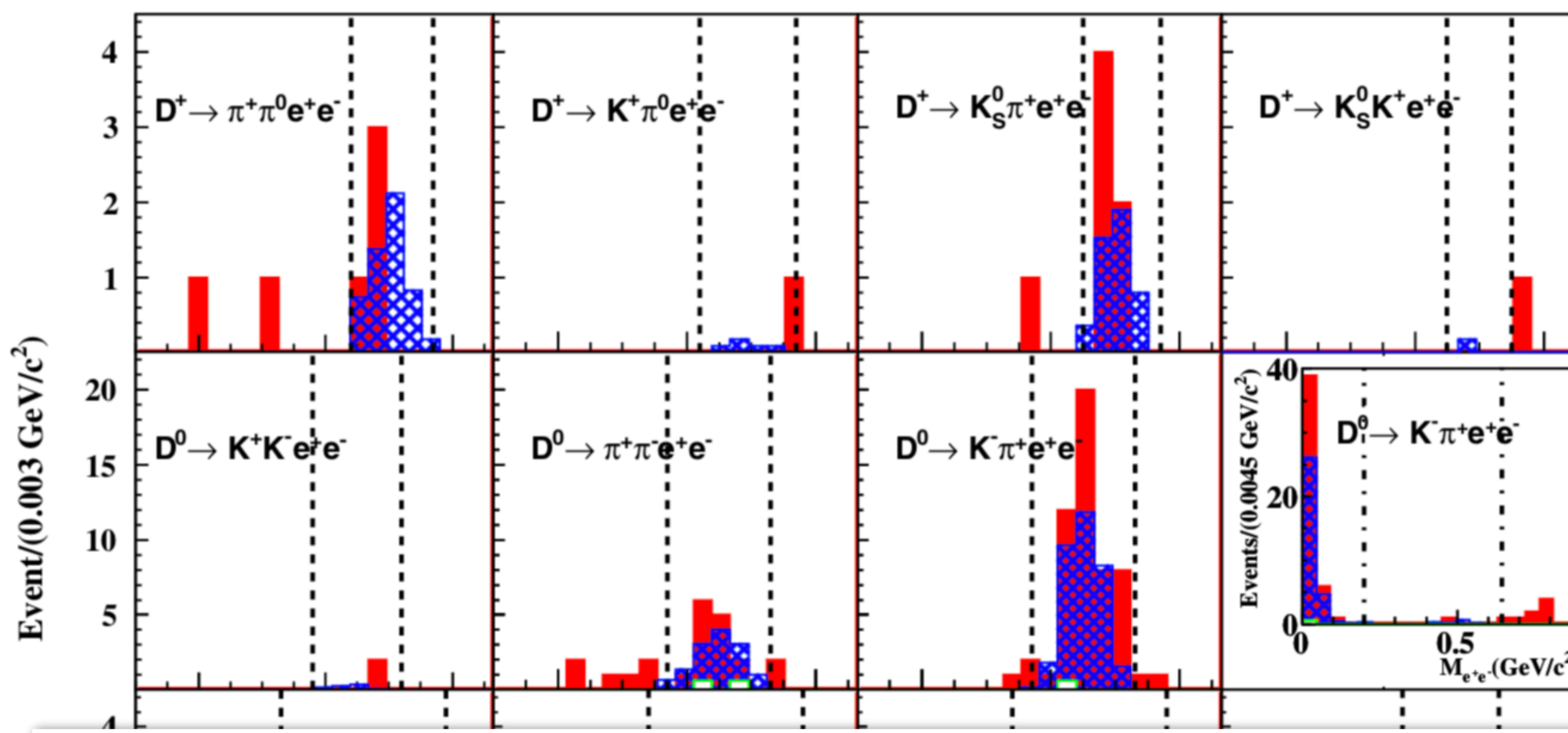
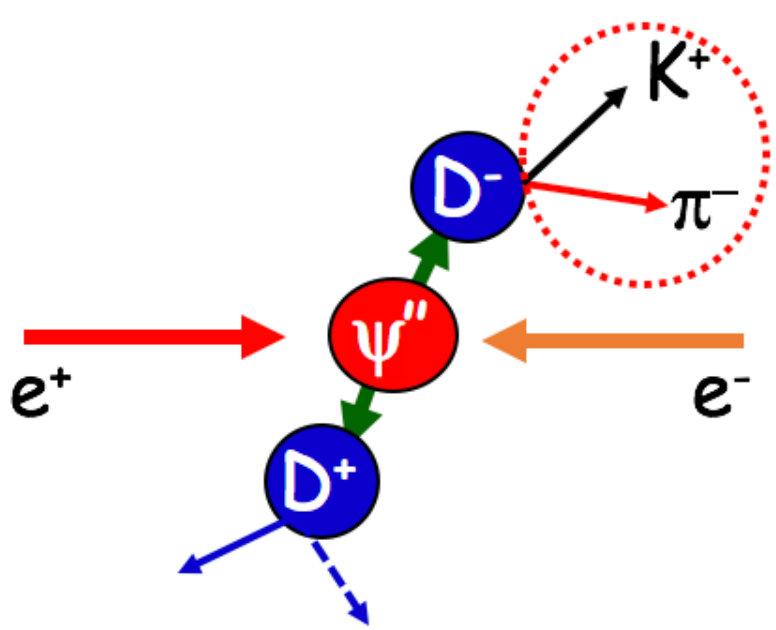
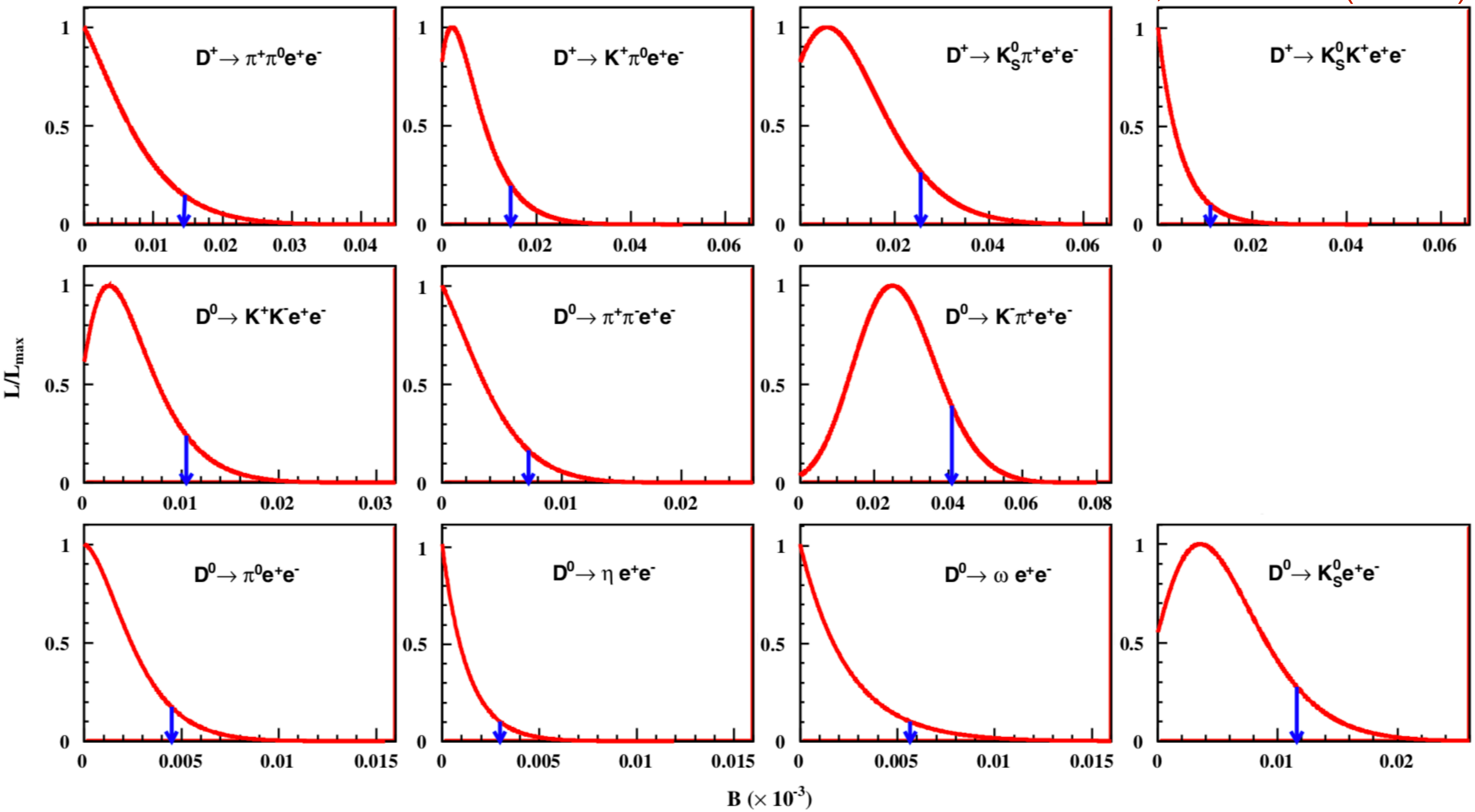




- Dominated by the LD bremsstrahlung and (virtual) resonance decay contributions in the lower and upper regions (dot lines) [JHEP, 04, 135 (2014)].
- $M_{e^+e^-}$ distribution is divided into three parts and the BFs are obtained in the individual regions.

03 FCNC: $D \to h(h')e^+e^-$

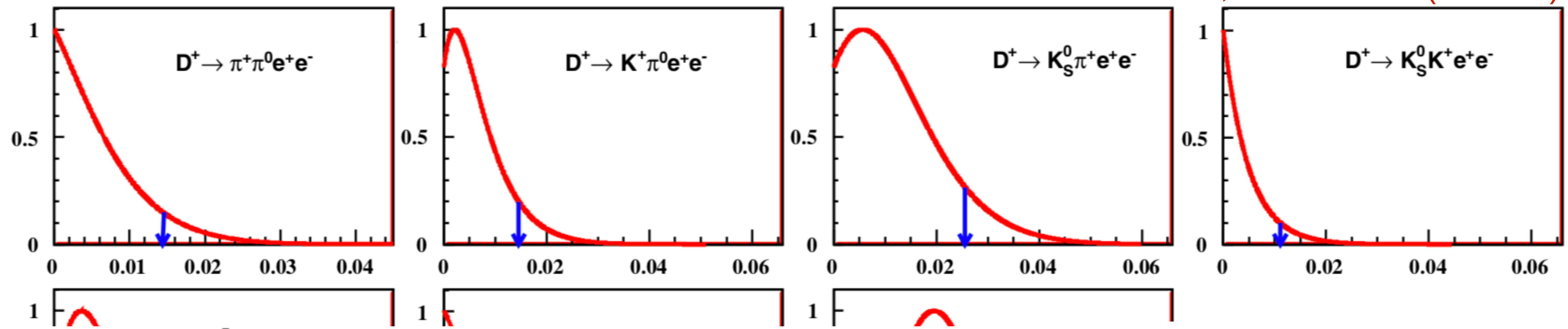
PRD97, 072015 (2018)



The likelihood distributions for all the signal modes are shown above, the ULs on the signal BFs at the 90% CL are estimated by integrating the likelihood curves in the physical region of BF>0

03 FCNC: $D \to h(h')e^+e^-$

PRD97, 072015 (2018)



Signal decays	$\mathcal{B}$ ($\times10^{-5}$)	PDG [9] ($\times10^{-5}$)
$D^+ \to \pi^+\pi^0 e^+e^-$	<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 $(1.0^{+0.5}_{-0.4})$	

- UL for D^+ are obtained for the first time.
- UL for D^0 are greatly improved.
- Divide the M_{ee} distribution of $K^-\pi^+e^+e^-$ into 3 regions to help separate LD effect.

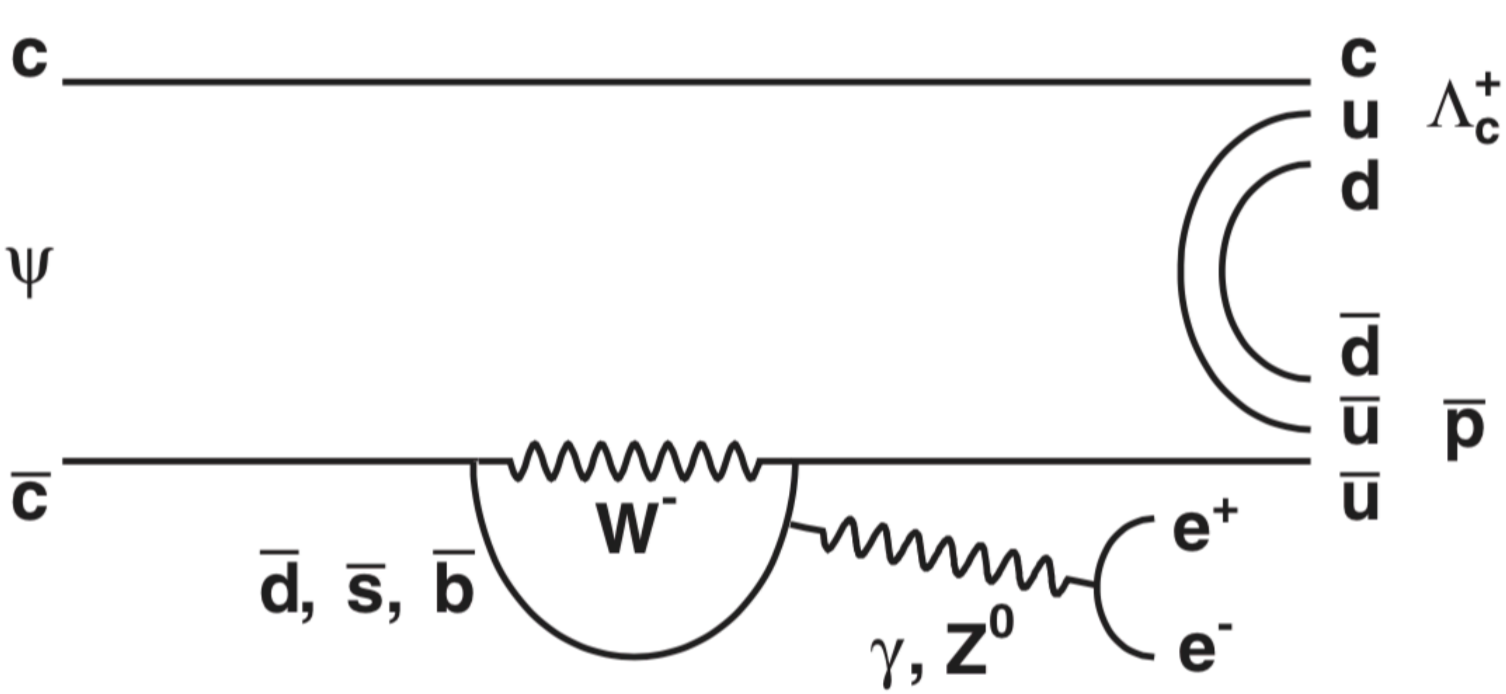
Theoretical[JHEP, 04, 135 (2014)] calculation: $\mathcal{B}^{tot}=1.6\times10^{-5}$

Experimental result: $\mathcal{B}^{tot}=(2.5\pm1.1)\times10^{-5}$

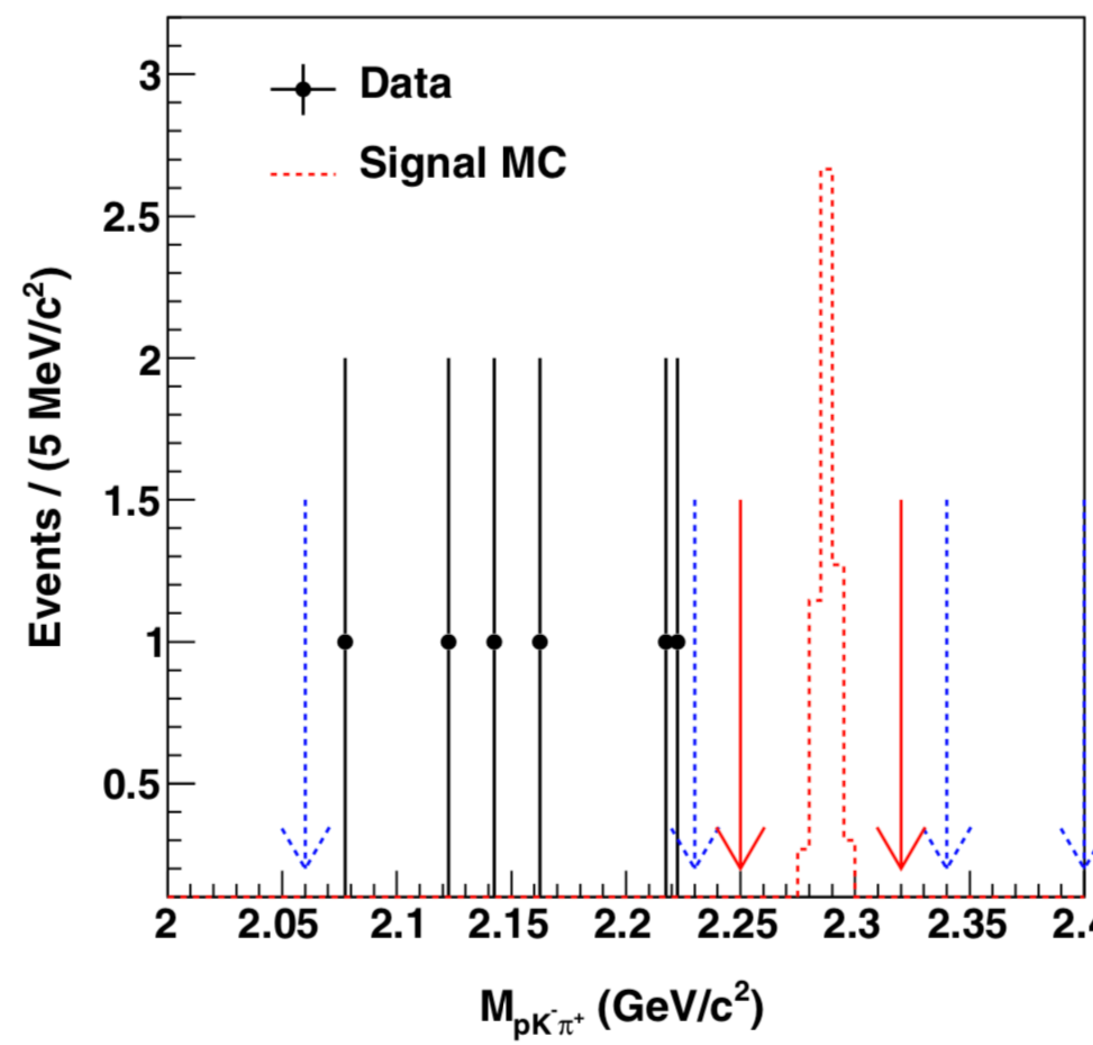
03 FCNC: $\psi(3686) \to \Lambda_c^+ \bar{p} e^+ e^- + c.c.$

- First search for $\psi(3686) \to \Lambda_c^+ \bar{p} e^+ e^- + c.c.$
- Check $M_{pK^-\pi^+}$ distribution, No events found in the signal window
- Upper limit at 90% C.L. on BF

$$\mathscr{B}(\psi(3686) \to \Lambda_c^+ \bar{p} e^+ e^- + c.c.) < 1.7 \times 10^{-6}$$



PRD97, 091102-R (2018)



Summary

- Seven latest analyses (dark, BNV/LNV, FCNC) are introduced.
- Good electron/positron ID@BESIII, thus we have currently the best constraint on the channels with e+e- pair.
- Largest threshold charm data@BESIII, thus we have almost background free results with DT method.
- We have 10 B J/ψ data@11 Feb. which is nearly ready for navigation.
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Thanks for your attention!

01 Dark Sector: dark photons

Upper limit of number of γ' signal

Total number of J/ψ

$$B(J/\psi \to \gamma'\eta^{(\prime)}) \times B(\gamma' \to e^+e^-) < \frac{N_{\gamma'}}{N_{J/\psi} \cdot B(\eta^{(\prime)} \to \mathrm{F}) \cdot \epsilon}$$

Branching fraction of $\eta^{(\prime)}$ to a final state

Detection efficiency

Mixing strength

$$\frac{B(J/\psi \to \gamma'\eta^{(\prime)})}{B(J/\psi \to \gamma\eta^{(\prime)})} = \varepsilon^2 |F_{J/\psi\eta^{(\prime)}}(m_{\gamma'}^2)|^2 \cdot \frac{\Lambda^{3/2}(m_{J/\psi}^2, m_{\eta^{(\prime)}}^2, m_{\gamma'}^2)}{\Lambda^{3/2}(m_{J/\psi}^2, m_{\eta^{(\prime)}}^2, 0)}$$

M. Reece, L.-T Wang, JHEP 07, 051 (2009)

Form factor for $J/\psi \to \gamma^*\eta^{(\prime)}$ transition evaluated at γ' mass

$$|F_{J/\psi\eta^{(\prime)}}(m_{\gamma'}^2)|^2 = \frac{\Lambda^2}{\Lambda^2 - m_{\gamma'}^2} \qquad \Lambda^2 = m_{\psi(2S)}$$

$$\Lambda^{3/2}(m_1^2, m_2^2, m_3^2) = \left(1 + \frac{m_3^2}{m_1^2 - m_2^2}\right)^2 - \frac{4m_1^2 m_3^2}{(m_1^2 - m_2^2)^2}$$