Radiative and Rare Charm Decays @ BESIII

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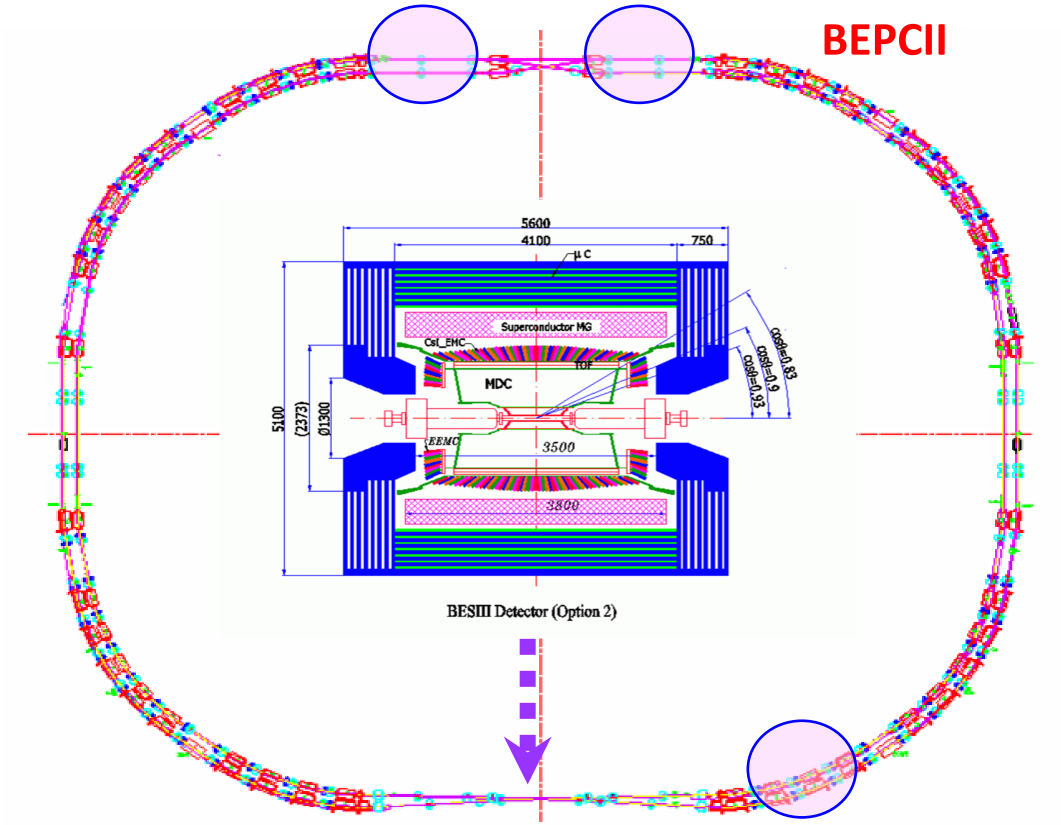
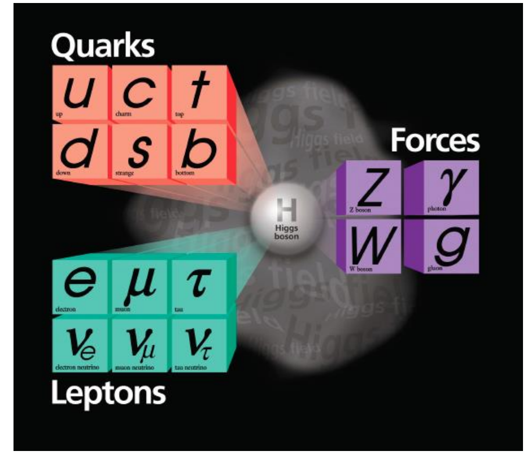
Outline

- Introduction of BEPCII/BESIII
- Charm LNV and BNV decays
- Charm radiative decays
- Rare semi-leptonic Ds decays
- Charm DCS decays
- Summary

BEPCII/BESIII





MDC: σ_{xy}=130 μm, dE/dx=6%
σ_p/p = 0.5% at 1 GeV

TOF:
Plastic scintillator :σ_T(barrel): 80 ps
MRPC: σ_T(endcap): 70 ps

EMC: CsI(Tl)

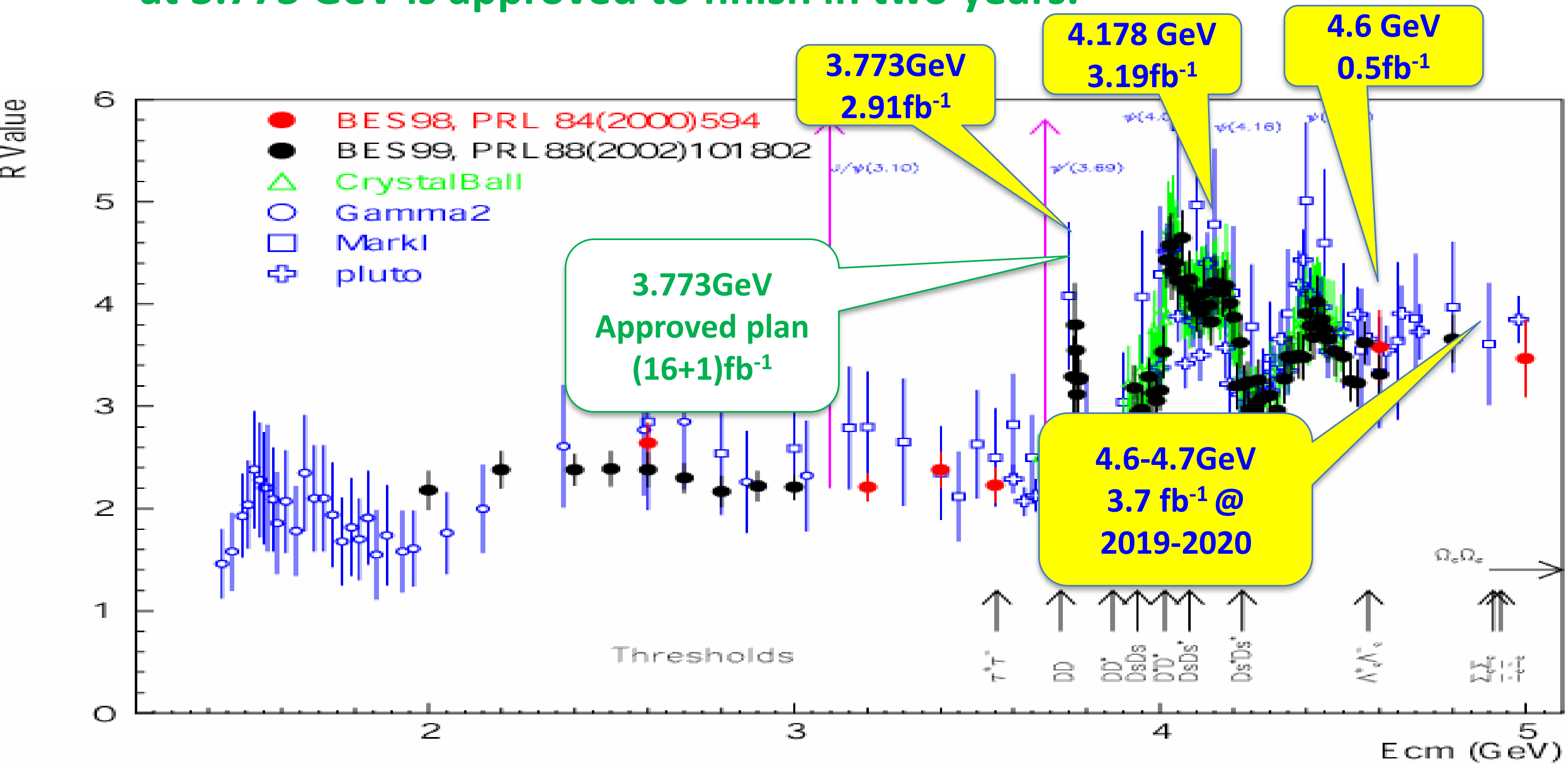
At 1 GeV	σ_E (%)	σ_l(mm)
Barrel:	2.5	6.1
Endcap:	5	9

MUC: $\sigma_{spatial}$: 1.48 cm

The BEPCII has achieved the designed luminosity 1×10^{33} $cm^{-2}s^{-1}$ at Apr. 2016.

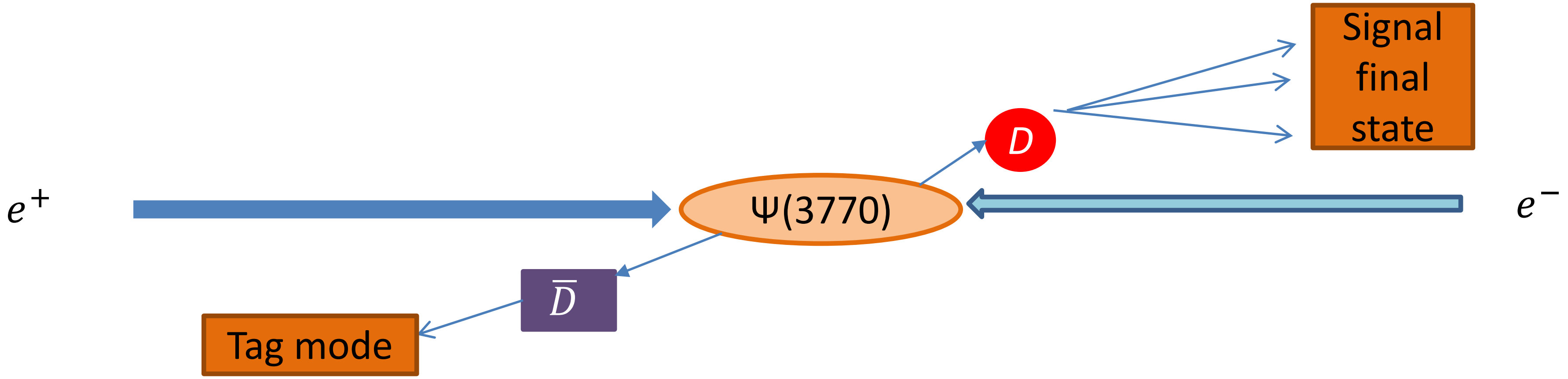
Charm Data Sets @ BESIII

BESIII has collected charm data sets for D^0, D^+, D_s^+ and Λ_c^+ studies at 3.773, 4.178 GeV and around 4.6 GeV. A data taken plan of (16+1) fb^{-1} at 3.773 GeV is approved to finish in two years.



Study method

Due to the pair production of charmed mesons above the threshold, double/single tag method can be employed



Single Tag : $$\mathrm{B}(D \to f) = \frac{N_{sig}}{2 \times N_{D\bar{D}}^{tot} \times \epsilon}$$ For channels with few bkgs, etc

double Tag : $$\mathrm{B}(D \to f) = \frac{N_{sig}}{N_{ST}^{tot} \times \epsilon}$$ For channels cannot be studied with single tag method (high bkg levels, undetectable particles …)

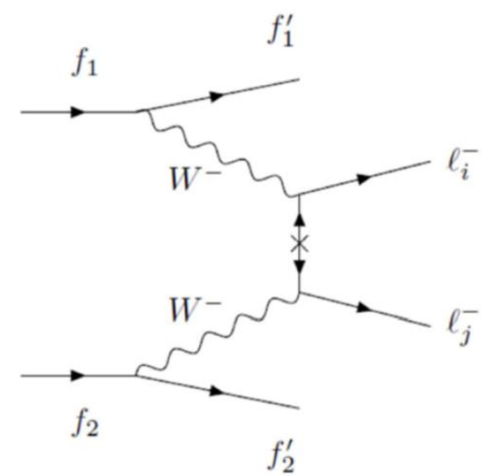
Search for LNV in D decays

- Lepton number is conserved in the Standard Model
- evidence from neutrino oscillation → neutrinos are massive particles
- New physics scenarios are explored to explain neutrino mass generation
- LNV is introduced in many New Physics models:
  - 4^{th} quark generation
  - SO(10) SUSY GUT
  - Exotic higgs
  - ……
- Majorana neutrinos violate Lepton Number: neutrinoless double beta decay expt.
- Three/Four-body ΔL=2 processes in K, D, B, Bc has been searched widely

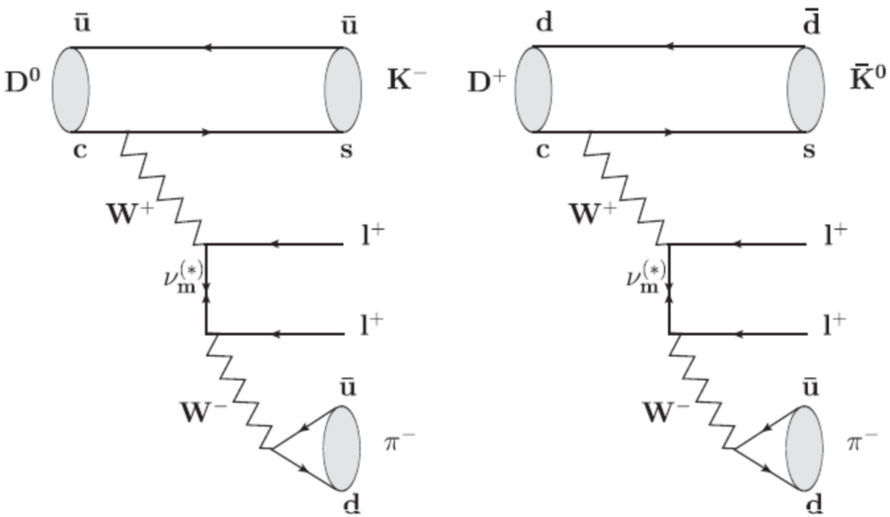
$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \bar{\nu}_\uparrow \\ \bar{\nu}_\downarrow \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

Dirac Majorana

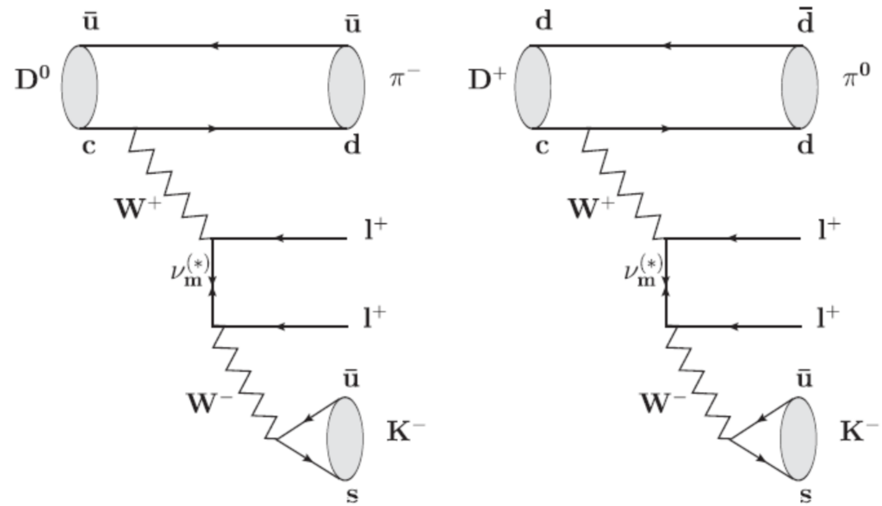
PRD 93 094026 (2016)
JHEP 08 068 (2011)
PRD 51 6524 (1995)
PLB 93 389 (1980)
……



Feynman diagram for ΔL=2 processes via Majorana neutrino exchange



Feynman diagram of four-body Cabibbo favored decay for ΔL=2 processes via Majorana neutrino exchange



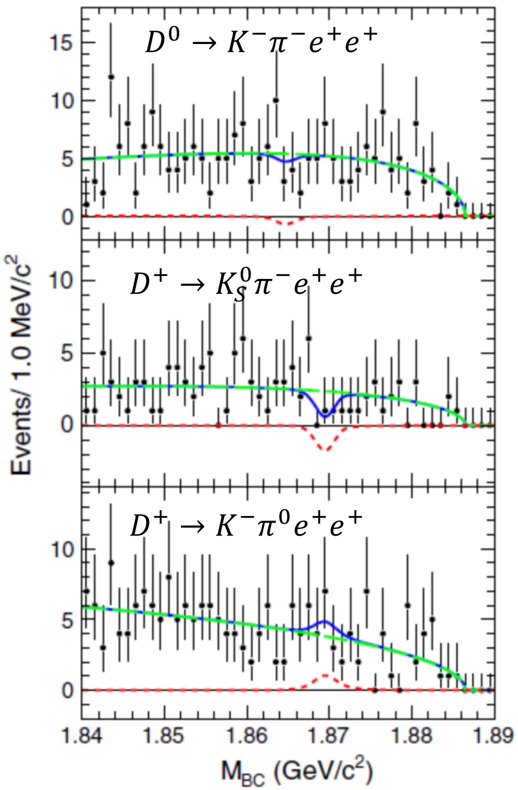
Feynman diagram of four-body double Cabibbo suppressed decay for ΔL=2 processes via Majorana neutrino exchange

Studied channels: $D^0 \rightarrow K^-\pi^-e^+e^+, D^+ \rightarrow K_S^0\pi^-e^+e^+, D^+ \rightarrow K^-\pi^0e^+e^+$

Single tag method is used

$$\Delta E = E_D - E_{\text{beam}}$$

$$M_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D|^2}$$

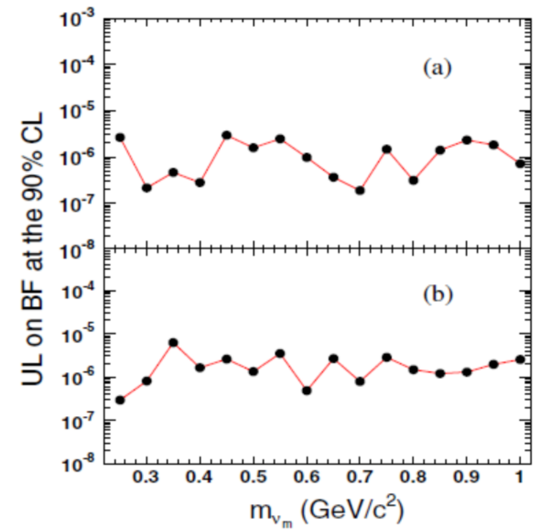


2.93 fb^{-1} data @ 3.773 GeV

PRD 99 112002 (2019)

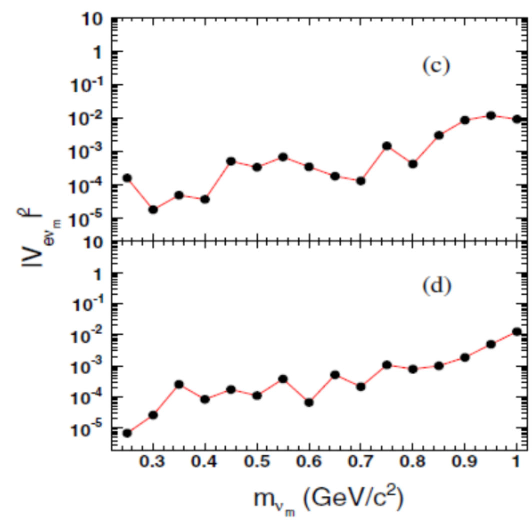
Upper limit determination:

$$\int_0^{B^{UL}} L(B)dB = 90\%$$



mixing matrix element $|\nu_{e\nu_m}|^2$

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



Channels	Upper limits
$D^0 \to K^-\pi^-e^+e^+$	$< 2.8 \times 10^{-6}$
$D^+ \to K_S^0\pi^-e^+e^+$	$< 3.3 \times 10^{-6}$
$D^+ \to K^-\pi^0e^+e^+$	$< 8.5 \times 10^{-6}$

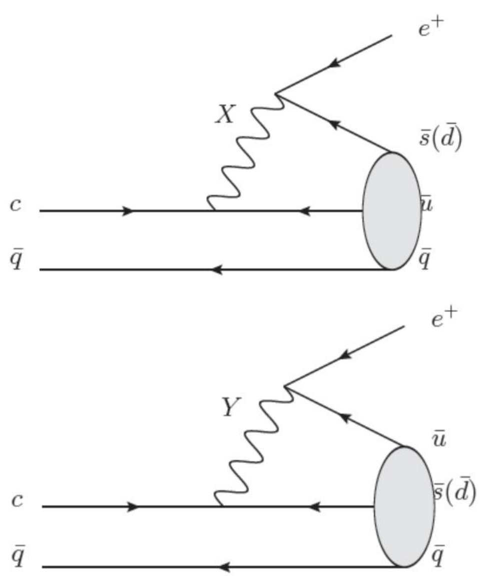
First search or best limits on these channels up to now!

Search for BNV in D decays

- Unlike conservation of charge, momentum, energy and so on, no priori principle requires that the baryon number conservation
- The excess of matter over anti-matter requires BNV
- BNV can present in some Standard Model extensions and GUTs:

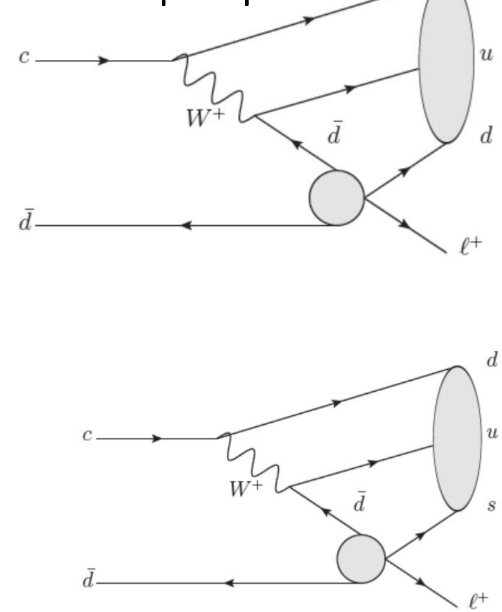
PRD 25 266 (1982)
PRD 22 1694 (1980)
PRD 101 015017(2020)
……

B-L=0



Feynman diagram under operators with dimension six

|B-L|=2



Feynman diagram under operators with dimension seven

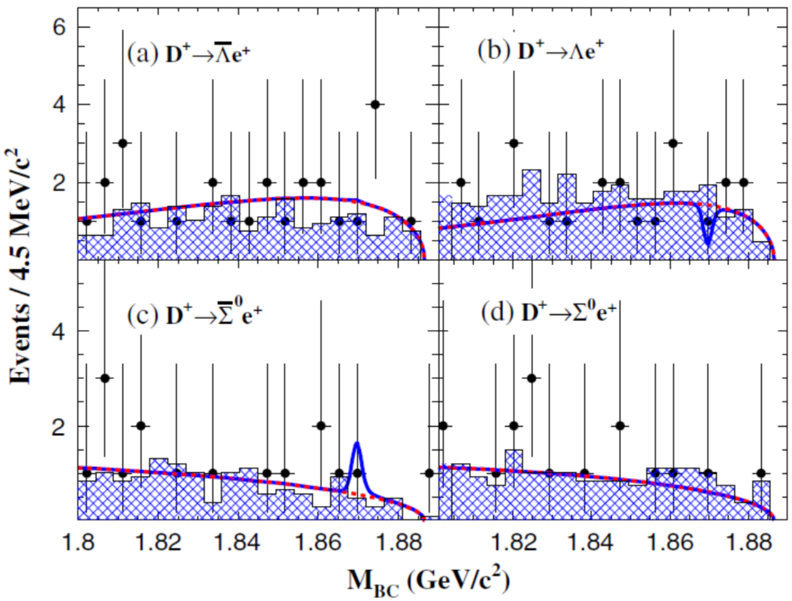
2.93 fb^{-1} data @ 3.773 GeV

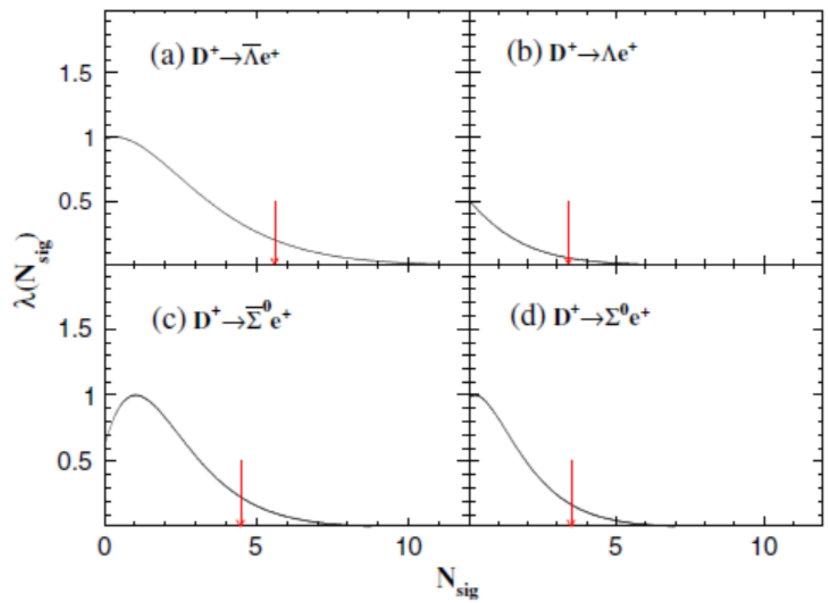
PRD 101 031102 (2020)

Single tag method is used

$$\Delta E = E_D - E_{\text{beam}}$$

$$M_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D|^2}$$





Upper limit determination:

$$\int_0^{N_{\text{sig}}^{\text{UL}}} N_{\text{sample}} dN_{\text{sig}} \Big/ \int_0^{\infty} N_{\text{sample}} dN_{\text{sig}} = 90\%$$

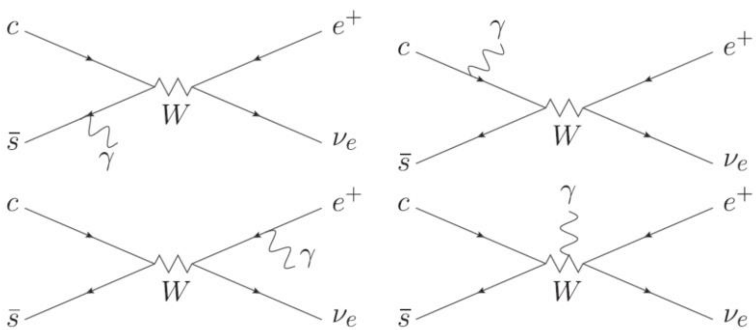
First searches of these channels

Channels	Upper limits
$D^+ \to \Lambda e^+$	$< 1.1 \times 10^{-6}$
$D^+ \to \bar{\Lambda} e^+$	$< 6.5 \times 10^{-7}$
$D^+ \to \Sigma^0 e^+$	$< 1.7 \times 10^{-6}$
$D^+ \to \bar{\Sigma}^0 e^+$	$< 1.3 \times 10^{-6}$

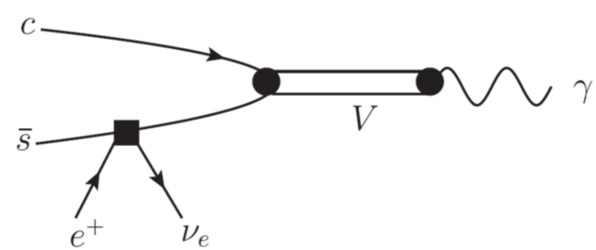
Charm radiative decays

- The leptonic decay is of great interest both theo. & expt.
  - Extract CKM element (Vcd/Vub) or determine decay constant f_D/f_B
  - Small BFs due to helicity suppression as well as GIM effect
  - Backgrounds from radiative leptonic decays
- For $D_s^+/D^+ \to \gamma e^+ \nu_e$
  - Avoid helicity suppression
  - Long distance contributions can affect the decay rates
  - Predicted to be 10^{-4}~10^{-5} by different models

Phys. Rev. D 51, 111 (1995)
Mod. Phys. Lett. A 15, 2087 (2000)
Phys. Lett. B 562, 75 (2003)
Mod. Phys. Lett. A 27, 1250120 (2012)
Phys. Rev. D 61, 114510 (2000)
Nucl. Phys. B650, 356 (2003)
…….



Tree-level Feynman diagrams

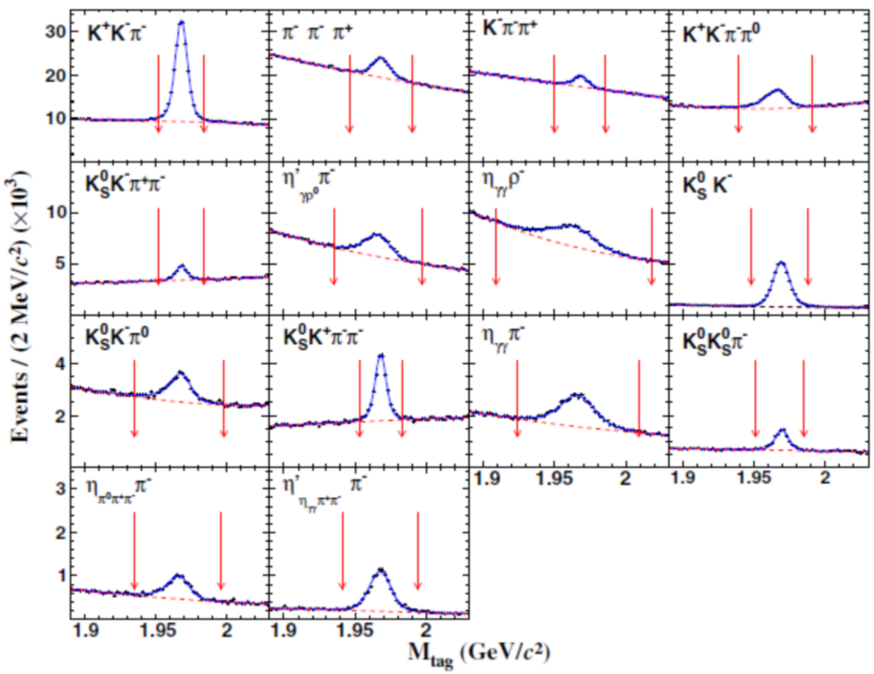


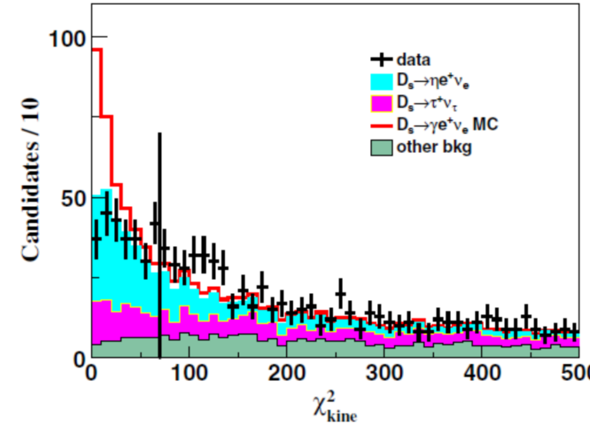
Long distance contributions

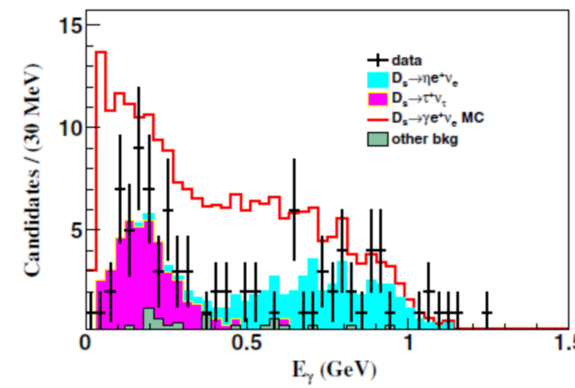
PRD 95 071102 (2017) (BESIII): $B(D^+ \to \gamma e^+ \nu_e) < 3.0 \times 10^{-5}$

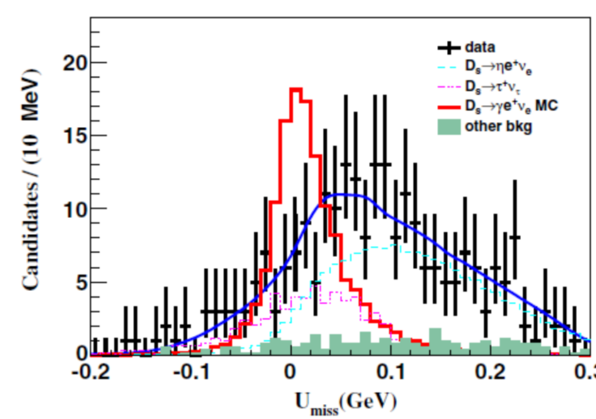
$3.19\ \mathrm{fb}^{-1}$ data @ 4.178 GeV

PRD 99 072002 (2019)









For $D_s^+ \to \gamma e^+ \nu_e$, 14 single tag channels are used,
The single tag yields are N_{ST}^{tot}=395412 $\pm$ 1931

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

First search of this channel and the upper limit :

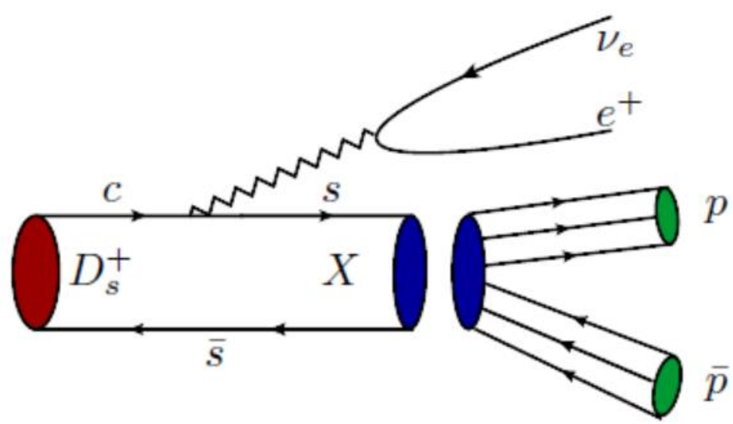
$$\int_0^{B^{UL}} L(B)dB = 90\%$$

$$B(D_s^+ \to \gamma e^+ \nu_e) < 1.3 \times 10^{-4}$$

Rare semi-leptonic Ds decays

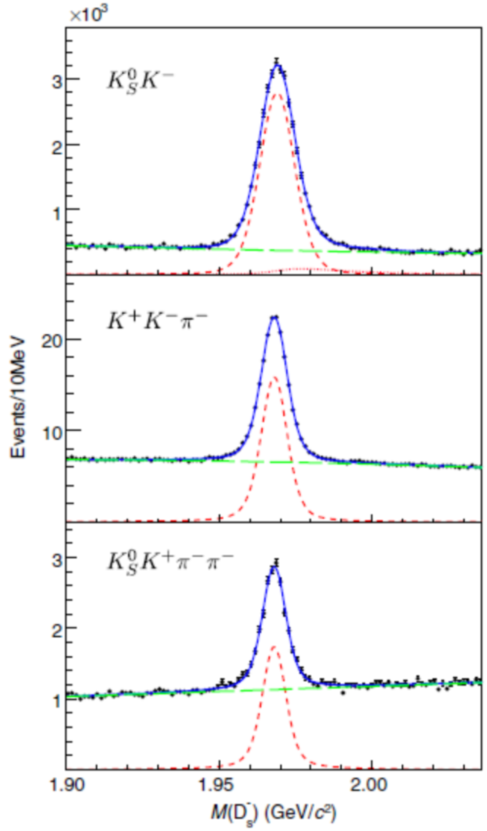
- Possible baryonic Ds decays:$D_s^+ \to p\bar{n}, D_s^+ \to p\bar{p}e^+\nu_e, D_s^+ \to n\bar{n}e^+\nu_e$
- the first observation of $D_s^+ \to p\bar{n}$ by CLEO (PRL 100 181802(2008))and confirmed by BESIII (PRD 99 031101(2019)).
- Belle claimed the evidence of $B^+ \to p\bar{p}e^+\nu_e$ (PRD 89 011101 (2014))
- Play an important role in study of X(1835)
- Suppressed by phase space:

$$\frac{d\Gamma(D_s^+ \to Xe^+\nu_e)}{dq^2} = \frac{G_F^2|V_{cs}|^2}{24\pi^3} p_X^3 |f_+(q^2)|^2$$



Feynman diagram of $D_s^+ \to Xe^+\nu_e \to p\bar{p}e^+\nu_e$

3.19 fb^{-1} data @ 4.178 GeV



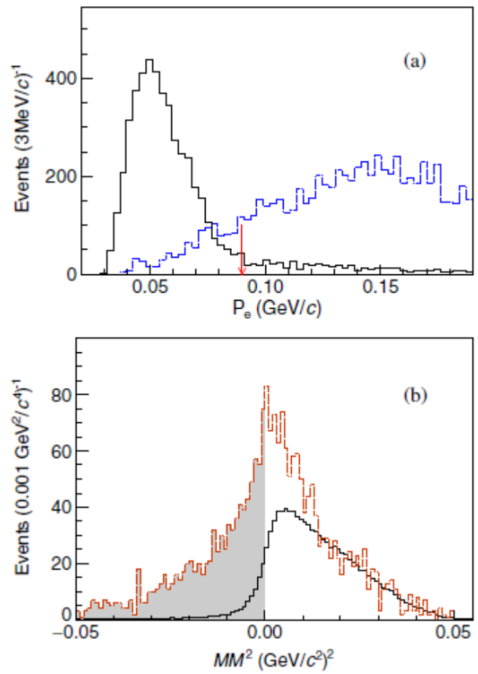
N_{ST}^{tot}=186091 ± 719

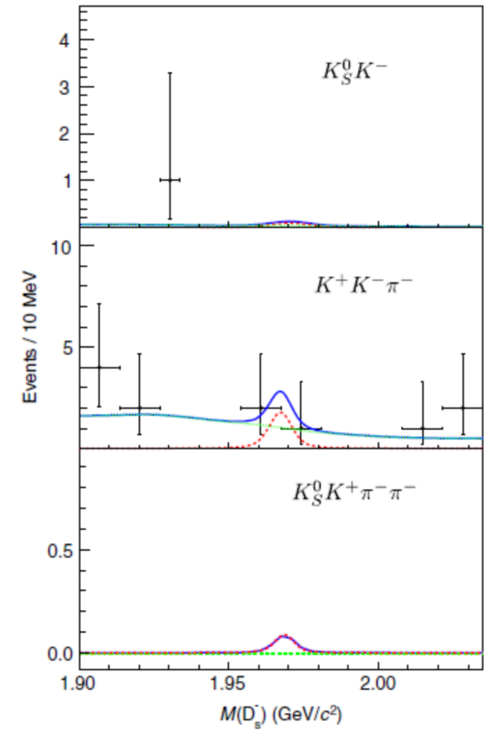
$$\frac{\int_0^{\mathrm{UL}} L(\mathcal{B})d\mathcal{B}}{\int_0^1 L(\mathcal{B})d\mathcal{B}} = 0.9$$

PRD 100 112008 (2019)

- Recoil side: a pair of baryon (and a electron without PID) are reconstructed

$$MM^2 = (\sqrt{s} - E_{tag} - E_{sig})^2 - (\vec{p}_{tag} - \vec{p}_{sig})^2$$





$$\mathcal{L}^\alpha = \frac{e^{-(N_{\mathrm{sig}}^\alpha + N_{\mathrm{bkg}}^\alpha)}}{n^\alpha!} \times \prod_{i=1}^{n^\alpha} (N_{\mathrm{sig}}^\alpha \mathcal{P}_{\mathrm{sig}}^\alpha(M_{D_s^-}) + N_{\mathrm{bkg}}^\alpha \mathcal{P}_{\mathrm{bkg}}^\alpha(M_{D_s^-}))$$

$$B(D_s^+ \to p\bar{p}e^+\nu_e) < 2.0 \times 10^{-4}$$

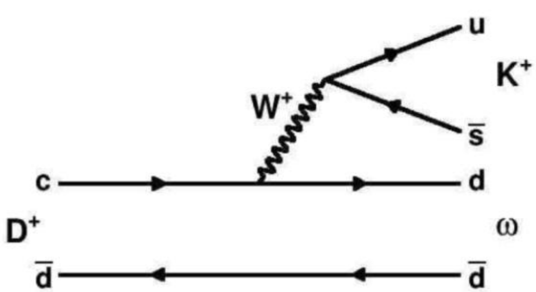
DCS of D decays

- Doubly Cabibbo suppressed decay is hardly explored
- DCS to Cabibbo-favored counterpart is of order $\tan^4\theta_C \sim 0.29\%$
- CP asymmetry in DCS or CF channels will be tiny, anyhow, it can provide complementary information for CP violation in D sector
- Search for two-body DCS $D^+ \to K^+\omega$ will give more constraint to understand SU(3) flavor symmetry and its break effects

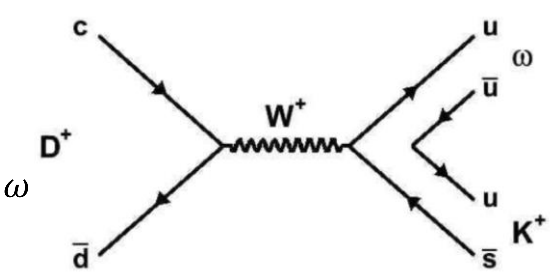
PRD 75 036008 (2007)
PRD 89 054006 (2014)
JPG 42 105002 (2015)
PRD 93 114010 (2016)
PRD 81 074021 (2010)
……

PDG2020

DCS	BF($\times 10^{-4}$)	CF	BF($\times 10^{-2}$)	Ratio($\times 10^{-3}$)
$D^0 \to K^+\pi^-$	1.48 ± 0.07	$D^0 \to K^-\pi^+$	3.89 ± 0.04	3.80 ± 0.18
$D^0 \to K^+\pi^-\pi^0$	3.01 ± 0.15	$D^0 \to K^-\pi^+\pi^0$	14.2 ± 0.5	2.12 ± 0.13
$D^0 \to K^+\pi^-\pi^-\pi^+$	2.61 ± 0.06	$D^0 \to K^-\pi^+\pi^-\pi^+$	8.11 ± 0.15	3.22 ± 0.10
$D^+ \to K^+\pi^-\pi^+$	5.19 ± 0.26	$D^+ \to K^-\pi^+\pi^+$	8.98 ± 0.28	5.78 ± 0.34

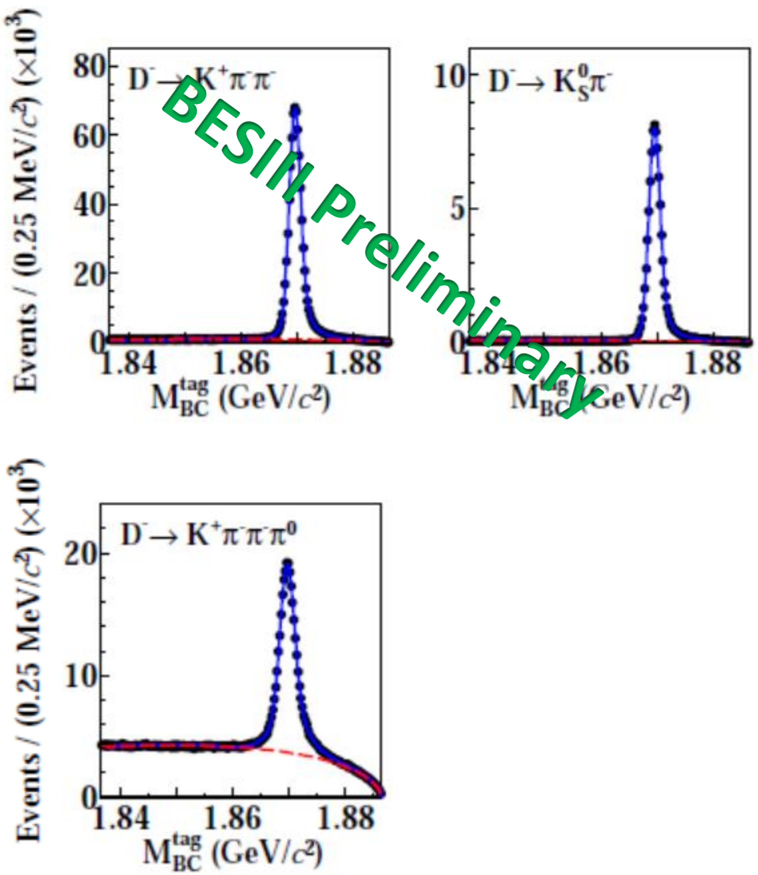


Feynman diagram of DCS channel $D^+ \to K^+\omega$



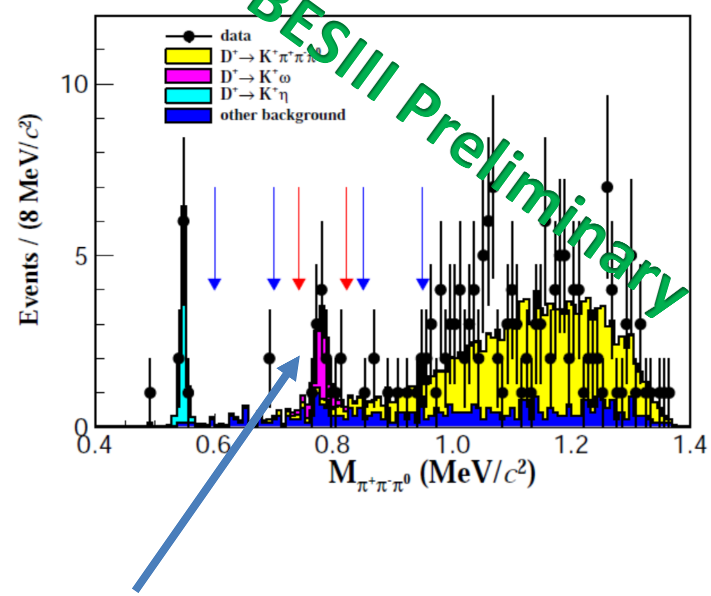
Three single tag channels: $M_{\rm BC} = \sqrt{E_{\rm beam}^2 - |\vec{p}_D|^2}$

2.93 fb^{-1} data @ 3.773 GeV



Recoil side: $D^+ \to K^+\pi^+\pi^-\pi^0$

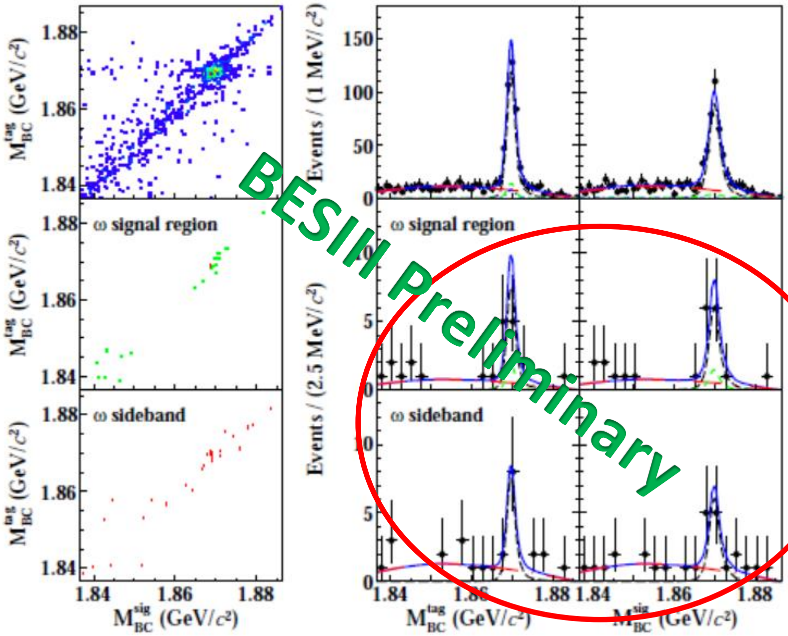
The invariant mass of $\pi^+\pi^-\pi^0$ from candidate events



ω signal

Single tag yields: N_{ST}^{tot}=1150287 $\pm$ 1484

Arxiv:2007.07674



two-dimensional (2D)
unbinned maximum likelihood fit

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}}{\sum_i N^i_{\rm ST}(\epsilon^i_{\rm DT}/\epsilon^i_{\rm ST})}$$

3.3σ

Definition of CP asymmetry

$$\mathcal{A}_{CP}^{D^\pm\to K^\pm\pi^\pm\pi^\mp\pi^0} = \frac{\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0} - \mathcal{B}_{D^-\to K^-\pi^-\pi^+\pi^0}}{\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0} + \mathcal{B}_{D^-\to K^-\pi^-\pi^+\pi^0}}$$

$$A_{CP}^{D^\pm\to K^\pm\pi^\pm\pi^\mp\pi^0} = -(0.04 \pm 0.06 \pm 0.01)$$

First measurement of CP asymmetry in this channel

* represents the BF removed the resonance contribution

channel	BF	BF*	Predicted
$D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0$	$(1.21 \pm 0.08)\times 10^{-3}$	$(1.13 \pm 0.08)\times 10^{-3}$	
$D^\pm \to K^\pm\omega$	$(5.7^{+2.5}_{-2.1})\times 10^{-5}$		$(2.4 \pm 0.6)\times 10^{-4}$ PRD 81 074021 $(1.8 \pm 0.5)\times 10^{-4}$ PRD 84 074019
$D^- \to K^-\pi^-\pi^+\pi^0$	$(1.25 \pm 0.11)\times 10^{-3}$		
$D^+ \to K^+\pi^+\pi^-\pi^0$	$(1.16 \pm 0.11)\times 10^{-3}$		

6.5σ of the CF channel, deviate native prediction (1 or 2) significantly

Summary

With the world largest charm threshold data set, BESIII has performed many searches on charm rare decays and produces many results.

$B(D^0 \to K^-\pi^-e^+e^+) < 2.8 \times 10^{-6}$

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

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

$B(D_s^+ \to p\bar{p}e^+\nu_e) < 2.0 \times 10^{-4}$

$B(D_s^+ \to \gamma e^+\nu_e) < 1.3 \times 10^{-4}$

$B(D^+ \to \Lambda e^+) < 1.1 \times 10^{-6}$

$B(D^+ \to \bar{\Lambda} e^+) < 6.5 \times 10^{-7}$

$B(D^+ \to \Sigma^0 e^+) < 1.7 \times 10^{-6}$

$B(D^+ \to \bar{\Sigma}^0 e^+) < 1.3 \times 10^{-6}$

$A_{CP}^{D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0} = -(0.04 \pm 0.06 \pm 0.01)$

Observed the DCS channel $D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0$ for the first time!

World largest charm threshold data set at BESIII provide opportunity to absolutely precise measurements of charm decays and searches for charm rare decays: **high statistics, low background …**

More are promising with coming 17 fb^{-1} data taken at 3.773 GeV!

Thanks for your attention!