BESIII上粲强子稀有衰变的寻找

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BESIII粲强子物理研讨会
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Outline

- Introduction

- BESIII results
  - ✓ FCNC
    - $D^0 \to \gamma\gamma$
    - $D \to h(h')e^+e^-$
    - $D^0 \to \pi^0\nu\bar{\nu}$
  - ✓ L/BNV
    - $D \to K\pi e^+e^+$
    - $D^\pm \to n(\bar{n})e^\pm$
    - $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+/\Lambda(\Sigma^0)e^+$
    - $D^0 \to \bar{p}e^+/pe^-$
  - ✓ Radiative decay
    - $\Lambda_c^+ \to \Sigma^+\gamma$

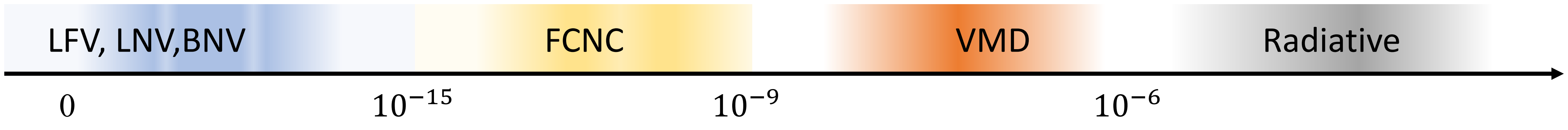
- Summary

Introduction

- Why rare and forbidden decays?
  - ✓ SM is incomplete -> DM, neutrino masses , asymmetry between matter and antimatter …
  - ✓ Rare decays are amongst the most powerful indirect probes as they are very sensitive to the presence of new particles in the virtual states.

- Rare and forbidden decays in charm sector: can be categorized as
  - ✓ flavor-changing neutral currents (FCNC)
  - ✓ Radiative decay
  - ✓ lepton-flavor-violating (LFV), lepton-number-violating (LNV), baryon- and lepton-number-violating (BNV)

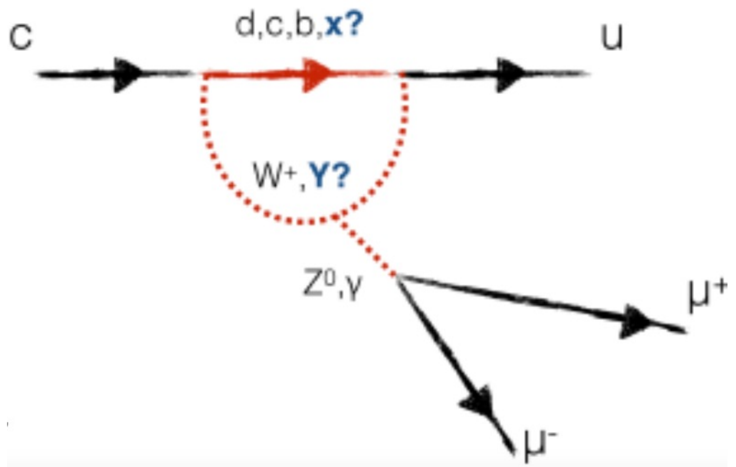
SM prediction

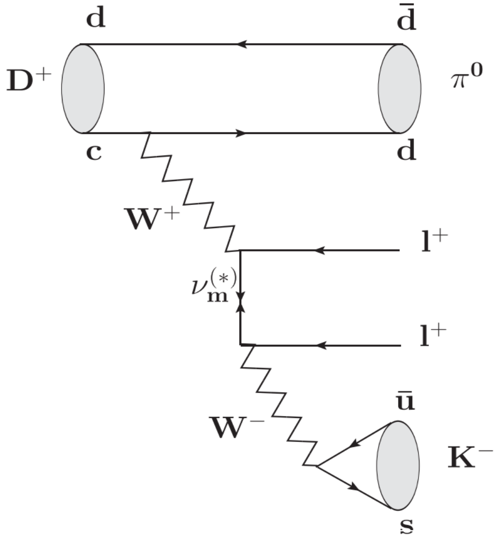


Introduction

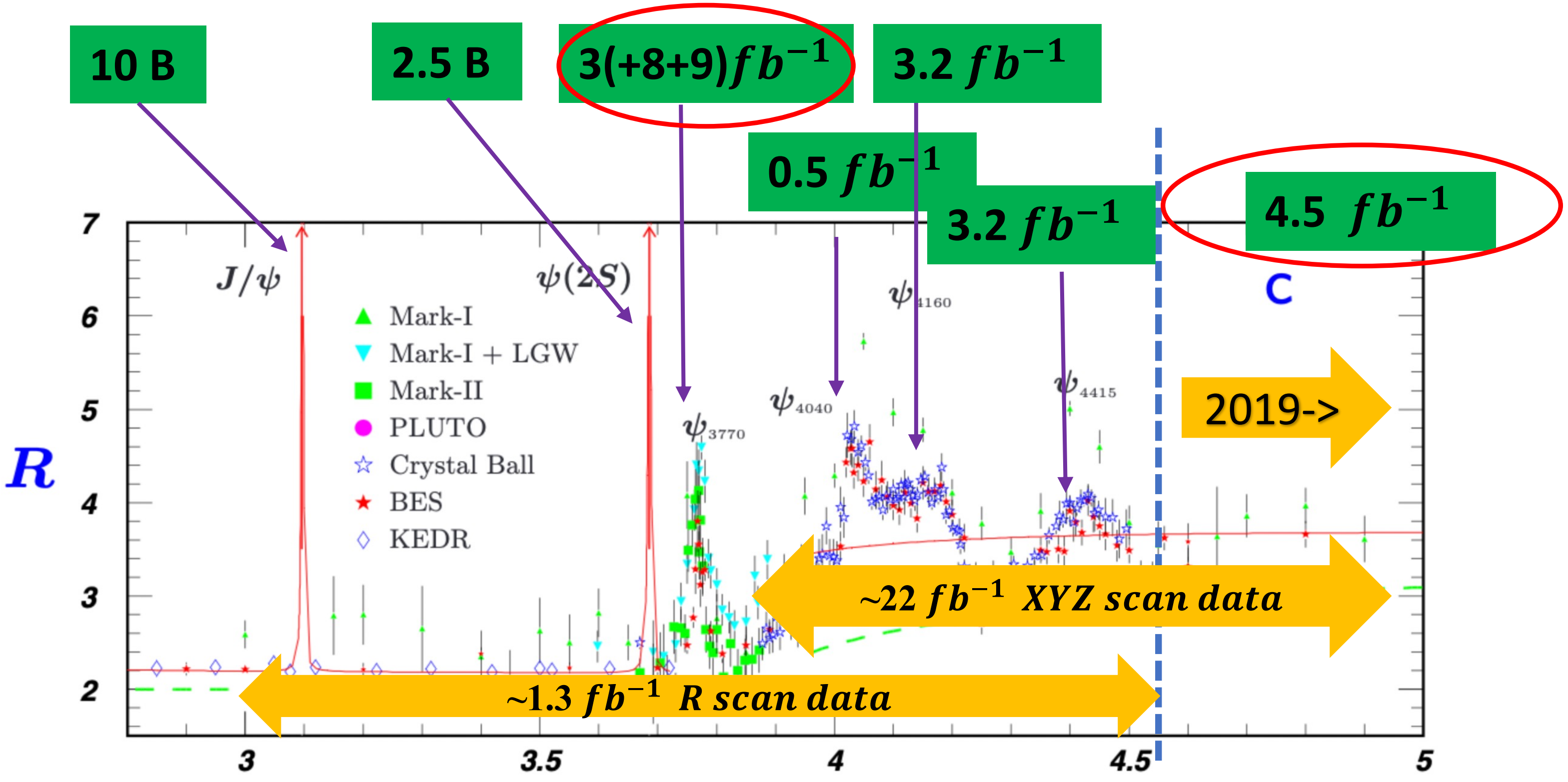
- Why charm ?
  - ✓ GIM mechanism is very strong in charm decay
  - ✓ Unique to test QCD in low energy
  - ✓ Charm hadron is the only system made of up-type heavy quark: complementary to the B and K sectors in NP searching

- New physics effect
  - ✓ Indirect: New particles (virtual, high mass) enter loops enhance BFs
  - ✓ Direct: New particles (real) can enhance BFs significantly





Data samples



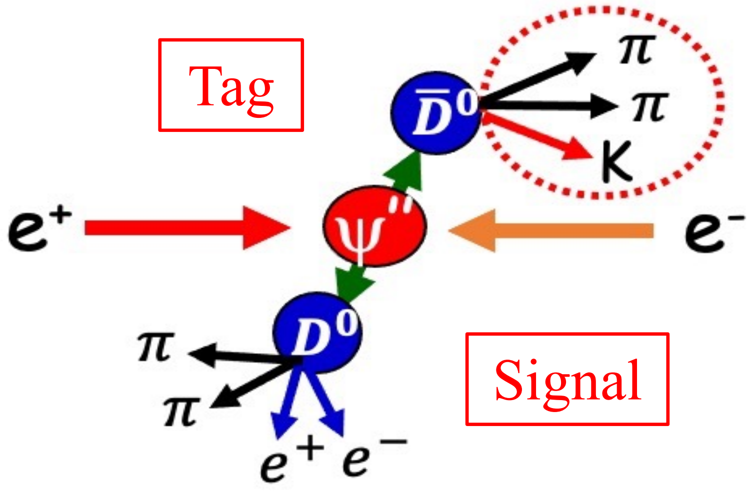
- 2.93fb^{-1} $\psi(3770)$

$$N_{D^0\bar{D}^0} = (10{,}597 \pm 28 \pm 98) \times 10^3,$$
$$N_{D^+D^-} = (8{,}296 \pm 31 \pm 65) \times 10^3,$$

- 4.5 fb^{-1} $E_{c.m.}$ =4.6 -4.7 GeV

$N_{\Lambda_c\bar{\Lambda}_c}$~ 0.9 M

Analysis strategy



- Double tag: reconstruct both of D mesons
  - ✓ Low background level, absolute branching fraction

$$\mathcal{B}_{\rm sig} = N_{\rm DT}/(N_{\rm ST}^{\rm tot} \cdot \epsilon_{\rm sig}),$$

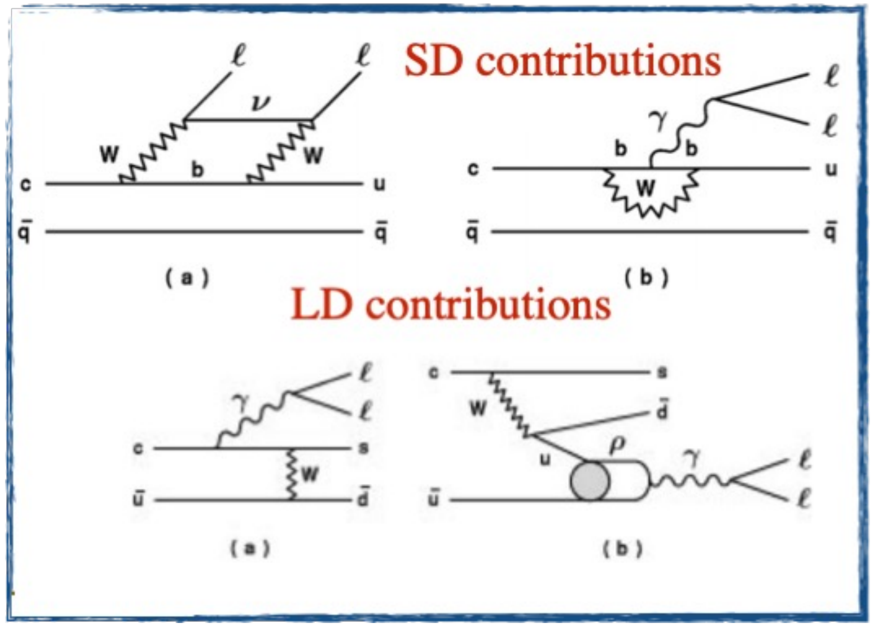
- Single tag: reconstruct one of D mesons
  - ✓ High efficiency, high signal yield, relative higher background level

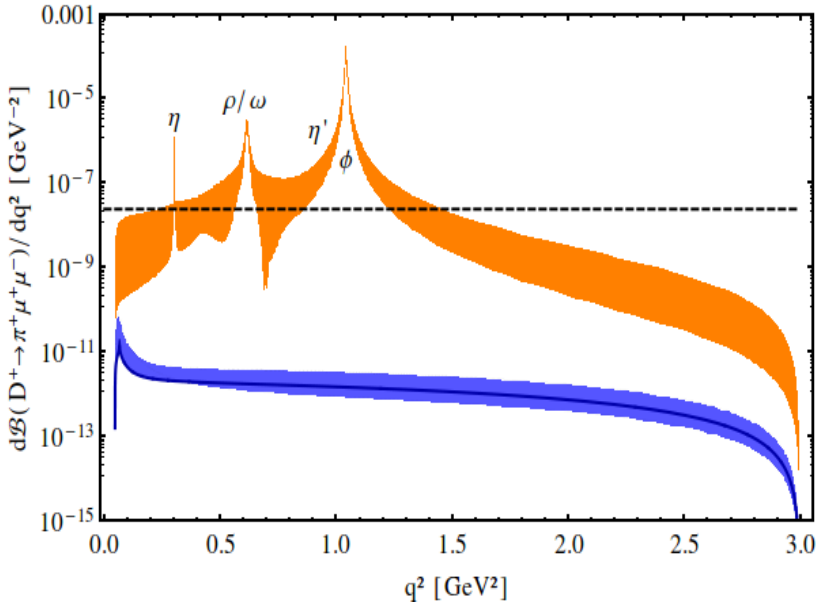
$$\mathcal{B}_{\rm sig} = \frac{N_{\rm sig}}{2 \cdot N_{D\bar{D}}^{\rm tot} \cdot \epsilon \cdot \mathcal{B}}$$

FCNC

FCNC processes

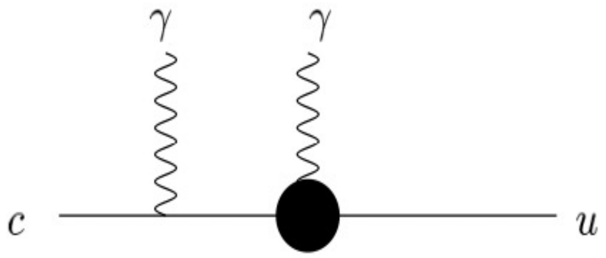
- In SM, FCNC is strongly suppressed by GIM mechanism and can happen only through loop diagram, leading to a very small BF, 10^{-9}, theoretically
- However, it can reach 10^{-6} under LD contribution
- The study of FCNC transitions is a key tool to look for physics beyond the standard model (BSM).



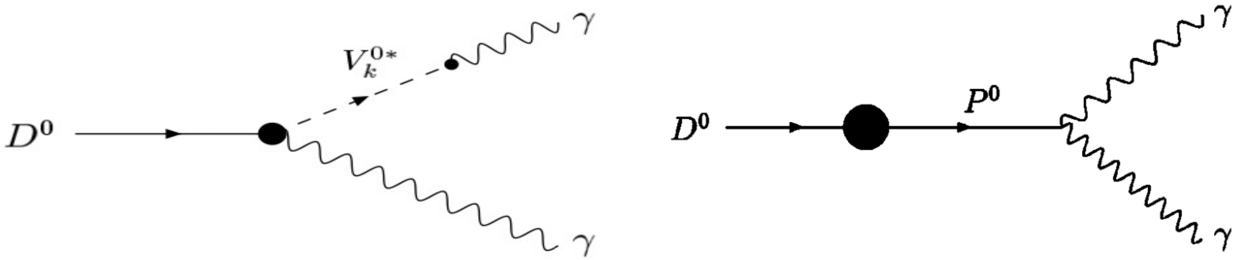


I: $D^0 \to \gamma\gamma$

PRD 91, 112015(2015)



Short distance



Long distance

- The branching fractions $B_{SD} \sim 3\times10^{-11}$ / $B_{SD+LD}(1-3)\times10^{-8}$;
- Some extensions to the SM can enhance FCNC processes by many orders of magnitude. For example, MSSM, gluino exchange can increase the branching fraction;

$D^0 \to \gamma\gamma$

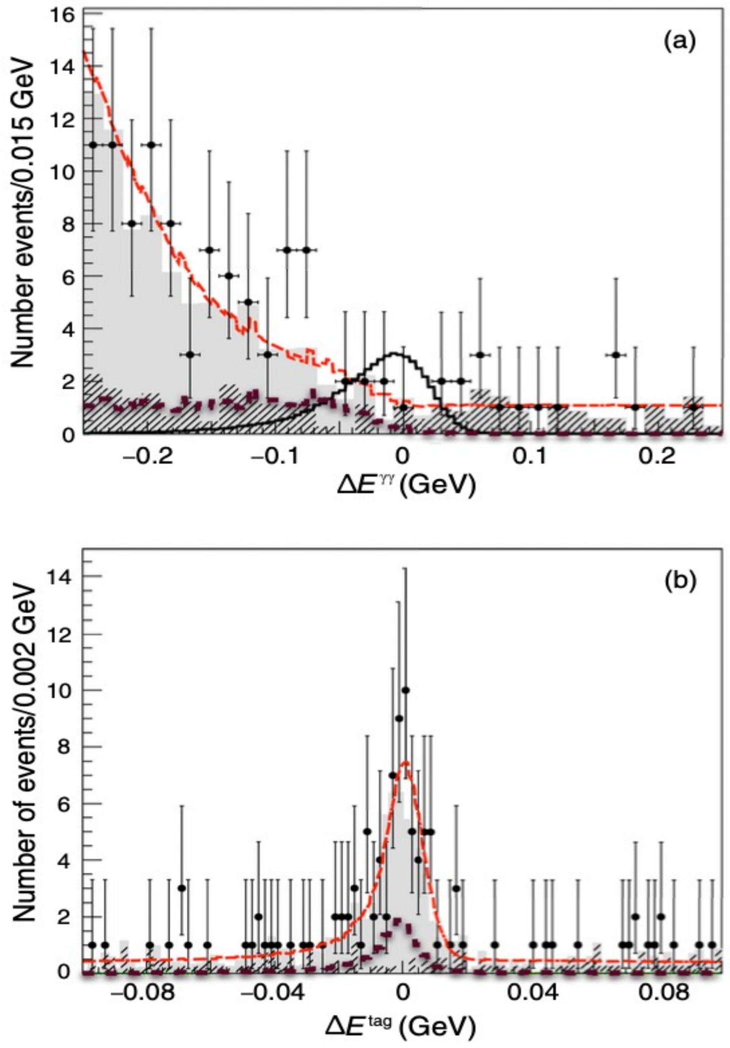
- Double-Tag method is implied
- Single tag (ST) candidate events are selected approximately 2.8 million.
- An unbinned maximum likelihood fit to the two-dimensional distribution of $\Delta E^{\gamma\gamma}$ versus ΔE^{tag}

$$\Delta E \equiv \sum_i E_i - E_{\text{beam}},$$

- An 90% CL uper limit is set to be

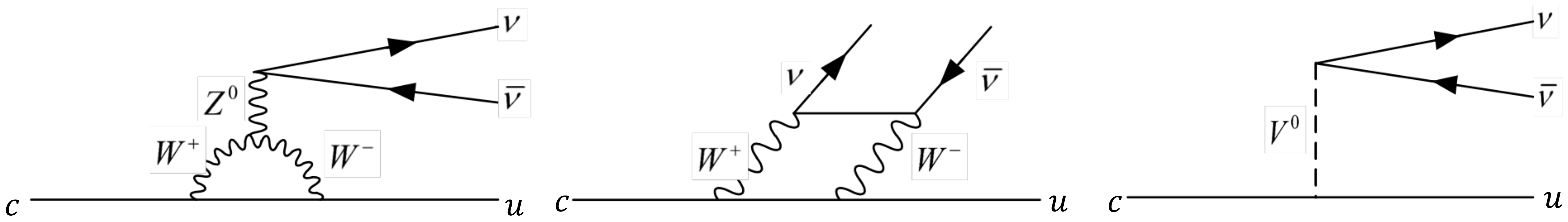
$$\mathcal{B}(D^0 \to \gamma\gamma) < 3.8 \times 10^{-6}$$

The UL is consistent with BaBar result and with the SM prediction.



II: $D^0 \to \pi^0 \nu\bar{\nu}$

PRD 105, L071102(2022)



Short distance

Long distance

- For FCNC decays $c \to u\nu\bar{\nu}$, LD contributions become insignificant and the SD contributions dominate, resulting in the branching fraction at the level of 10^{-15} in SM. Thus, $c \to u\nu\bar{\nu}$ provide a unique and clean probe to study the CP violation in the charm sector and search for NP

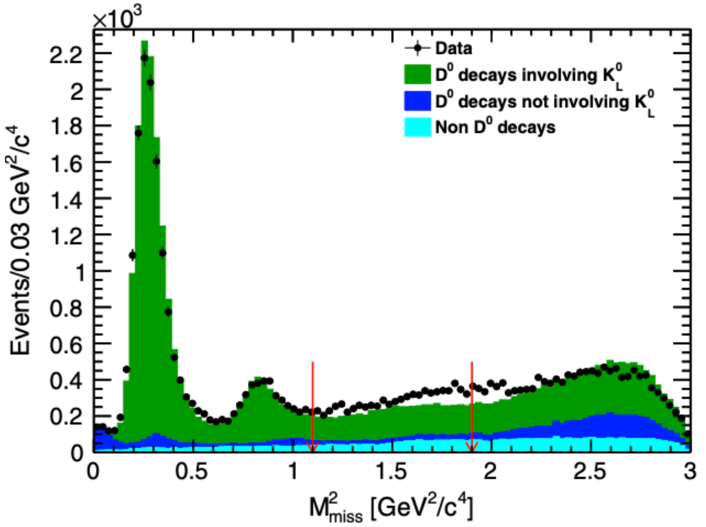
- In the scenario of leptoquarks, the branching fraction can be enhanced up to 9.7×10^{-4} with the sterile neutrinos

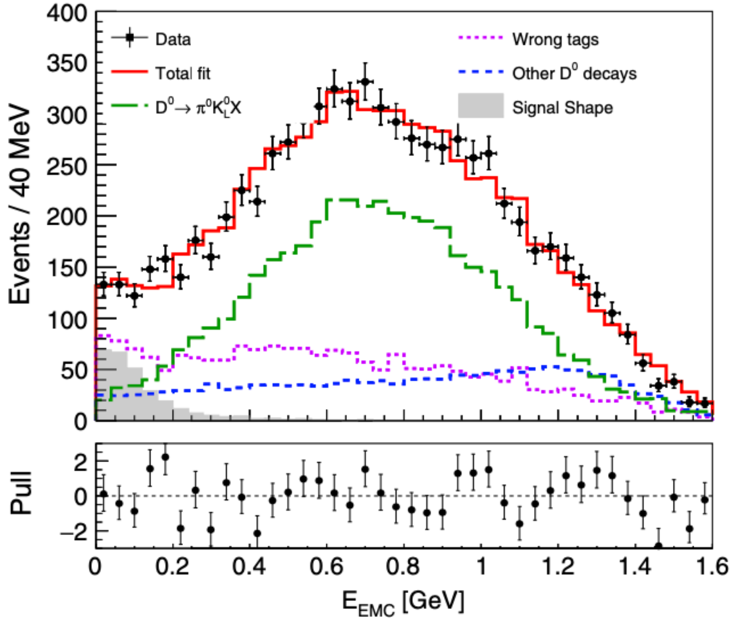
$D^0 \to \pi^0 \nu\bar{\nu}$

- Double-Tag method is implied
- Discriminating variable : E_{EMC} all the showers excluding π^0, signified a peak ~ 0.
- $N_{sig} = 14 \pm 30$, which consistent with 0. An 90% CL upper limit is estimated:

$$\mathrm{B}(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1\times10^{-4}$$

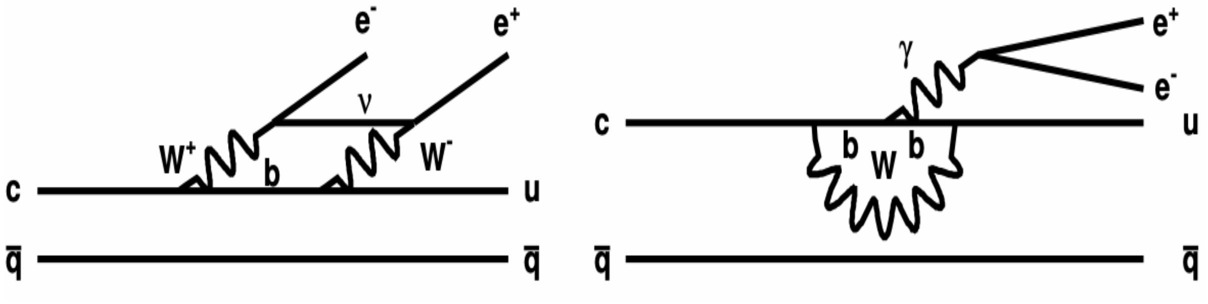
the world-first experimental in charm sector, providing constrains on the fermionic coupling strength of leptoquarks to the sterile neutrino



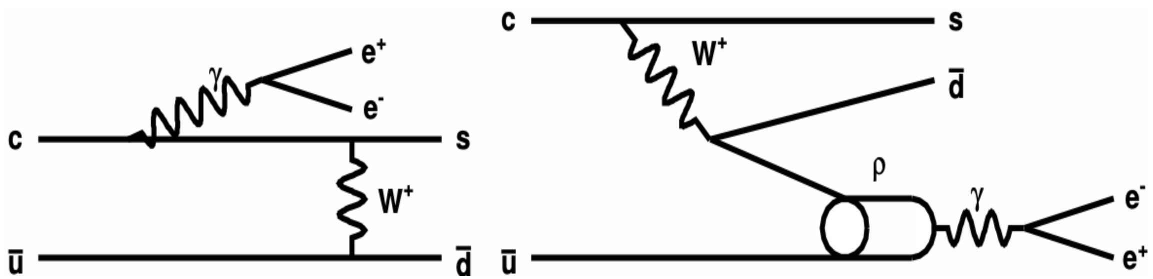


III: $D \to h(h')e^+e^-$

PRD 97, 072015 (2018)



Short distance

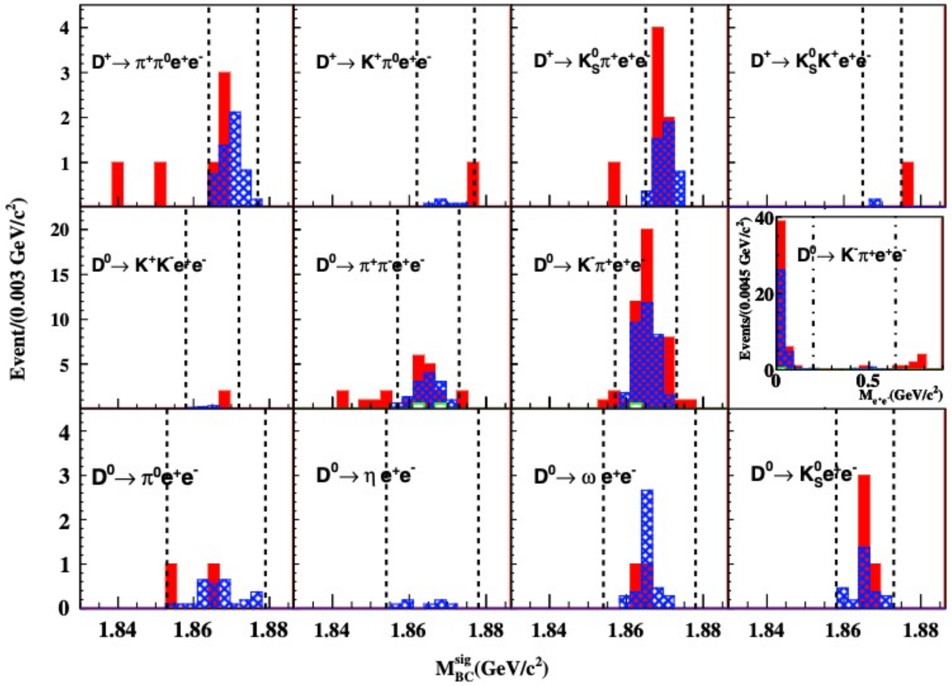


Long distance

- In SM, the FCNC process $c \to ul^+l^-$ with a BF at the level of 10^{-9}, NP can enhance the BF
- The BF with LD effect through vector meson decays at the level of 10^{-6}
- Experimentally, $D^+ \to \pi^+\mu^+\mu^-(e^+e^-)$, $D^0 \to K^-K^+\mu^+\mu^-/K^-\pi^+\mu^+\mu^-/\ \pi^-\pi^+\mu^+\mu^-$ have been observed with significant LD contribution
- 11 decays are searched in this work $D^0 \to K^-K^+e^+e^-/\pi^-\pi^+e^+e^-/K^-\pi^+e^+e^-/\pi^0e^+e^-/\eta e^+e^-/\ \omega e^+e^-/$ $K_S^0e^+e^-/\ D^+ \to \pi^+\pi^0e^+e^-/K^+\pi^0e^+e^-/K_S^0\pi^+e^+e^-/\ K_S^0K^+e^+e^-$
  the four-body D^+ decays are performed for the first time

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

- $M(e^+e^-)$ out of ϕ mass window to exclude contribution from $D \to h(h')\phi, \phi \to e^+e^-$;
- The 90% CL upper limits are at the level of $10^{-5} - 10^{-6}$. For the D^0 decays, the ULs are improved in general by a factor of 10, compared to previous measurements.
- All the measured ULs on the BFs are above the SM predictions, which include both LD and SD contributions.

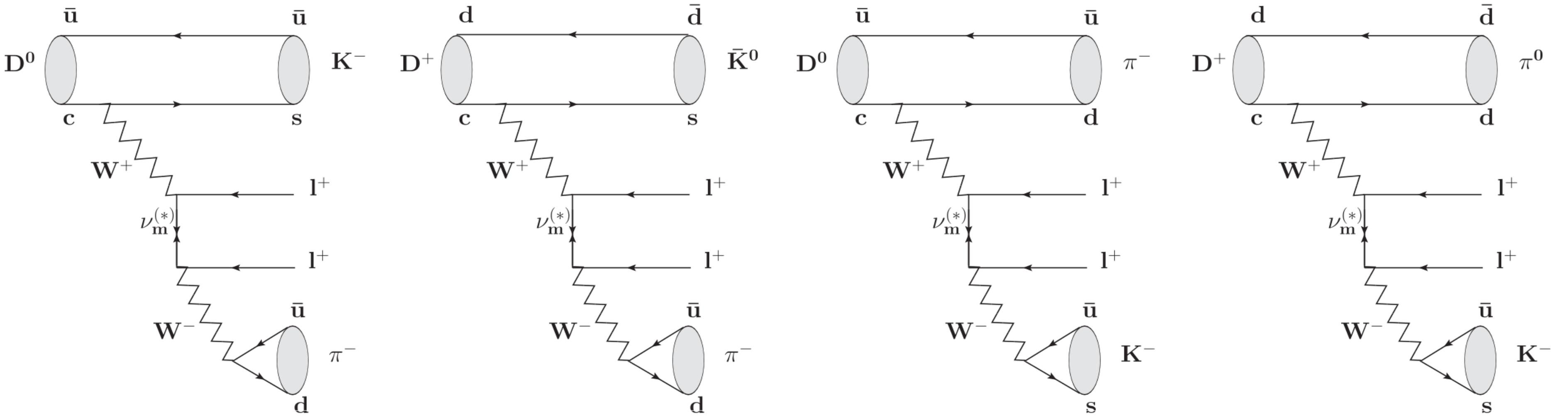


Signal decays	$\mathcal{B}$ ($\times 10^{-5}$)	PDG [9] ($\times 10^{-5}$)
$D^+ \to \pi^+\pi^0 e^+e^-$	<1.4	...
$D^+ \to K^+\pi^0 e^+e^-$	<1.5	...
$D^+ \to K^0_S\pi^+ e^+e^-$	<2.6	...
$D^+ \to K^0_S K^+ e^+e^-$	<1.1	...
$D^0 \to K^-K^+ e^+e^-$	<1.1	<31.5
$D^0 \to \pi^+\pi^- e^+e^-$	<0.7	<37.3
$D^0 \to K^-\pi^+ e^+e^{-\dagger}$	<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/c²	<3.0 ($1.5^{+1.0}_{-0.9}$)	...
[0.20, 0.65) GeV/c²	<0.7	...
[0.65, 0.90) GeV/c²	<1.9 ($1.0^{+0.5}_{-0.4}$)	...

LNV/BNV

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

PRD 99, 112002 (2018)



(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)

- Neutrino oscillation -> neutrinos have mass ->NP
  In "seesaw" mechanism, a new massive neutrino can provide a tiny mass of SM neutrinos

- Nature of neutrinos: Dirac or Majorana particles. The effects of Majorana neutrino can be manifested through violating lepton-number conservation by two units ($\Delta L = 2$)

- The LNV processes with $\Delta L = 2$: $D^0 \to K^-\pi^-e^+e^+$, $D^+ \to K_S^0\pi^-e^+e^+$, $D^+ \to K^-\pi^0e^+e^+$ are searched. These processes can occur by mediation of a Majorana neutrino.

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

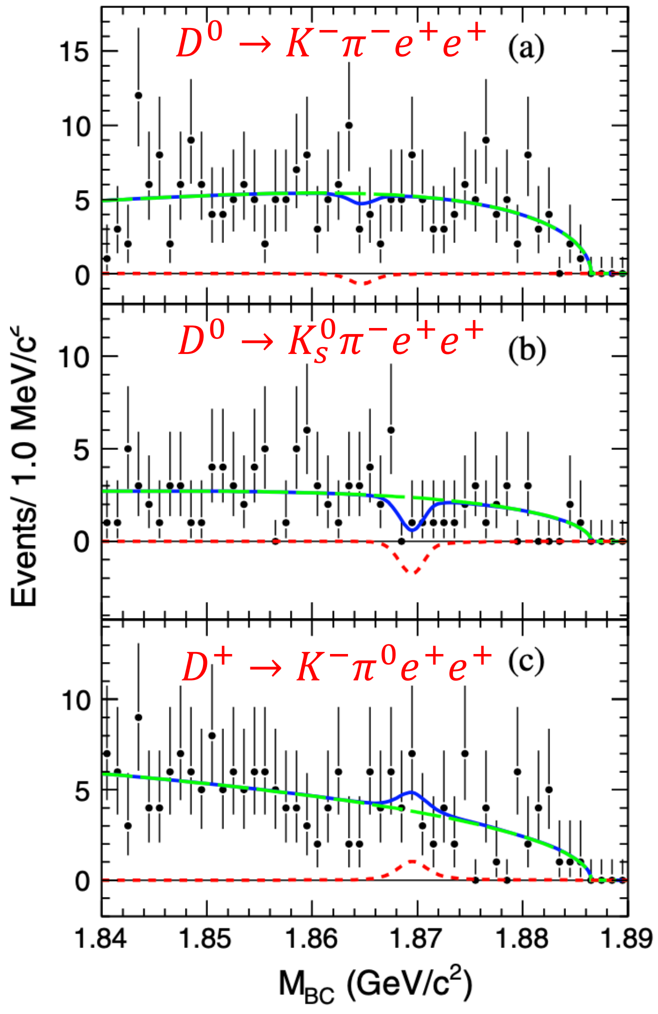
PHYS. REV. D 99, 112002 (2018)

- A Single-Tag method is implied;
- The signals are determined by performing an unbinned maximum likelihood fit on the M_{BC} distribution.

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

- No obvious signal is observed, 90% CL upper limits

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

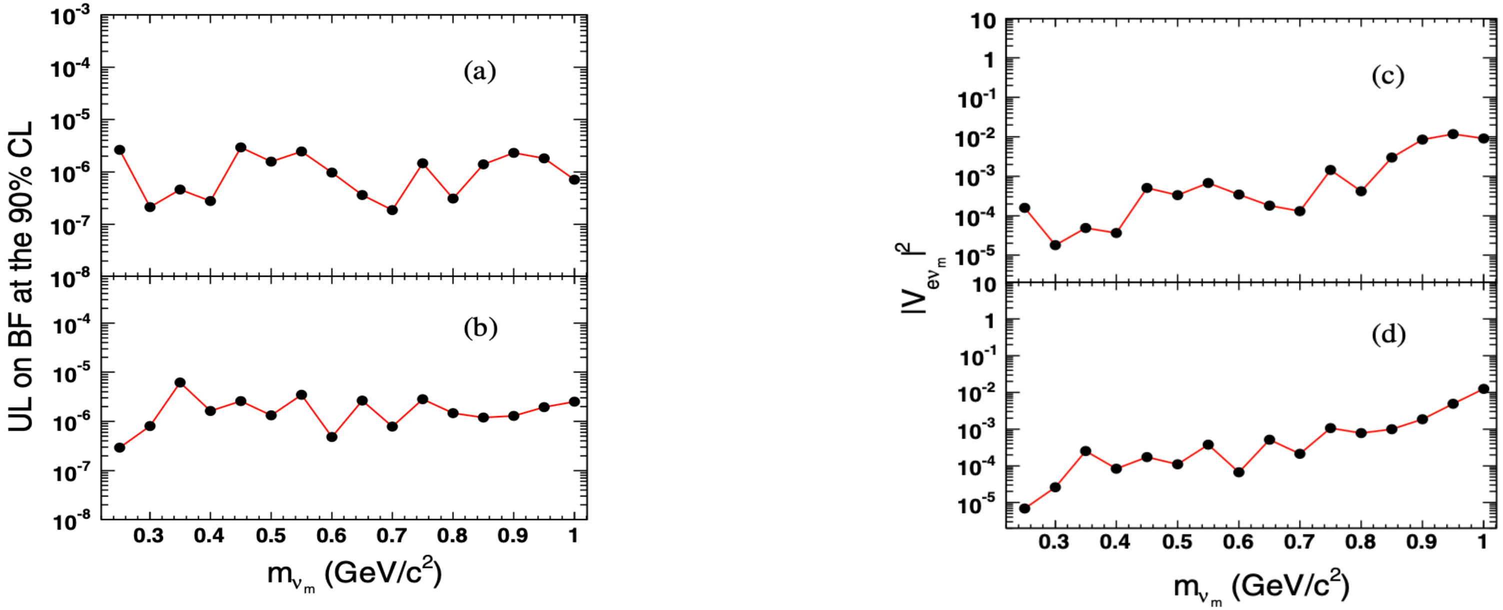


$D \to K\pi e^+ e^+$

PHYS. REV. D 99, 112002 (2018)

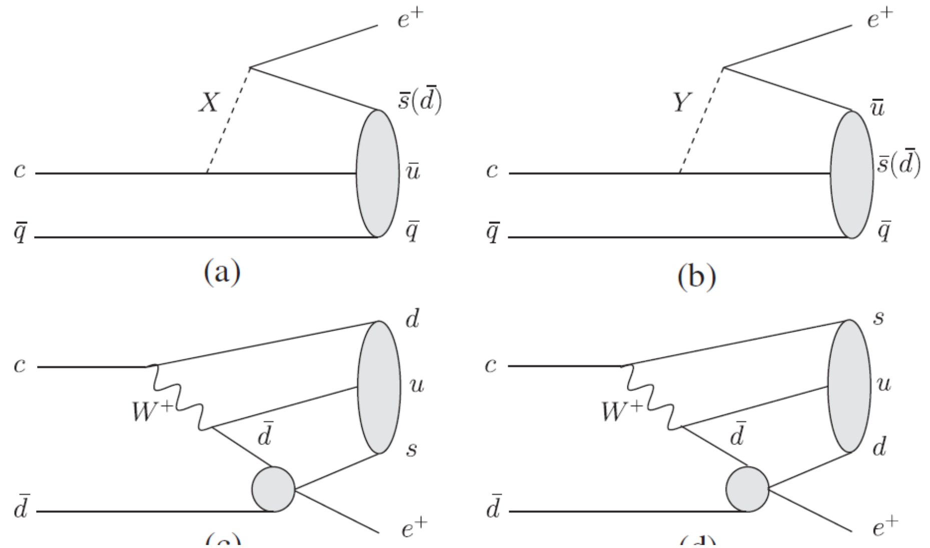
- Search for Majorana neutrino: the Majorana neutrino are searched for in the CF processes
  - ✓ $D^0 \to K^- e^+ \nu_m, \nu_m \to \pi^- e^+$
  - ✓ $D^+ \to K_S^0 e^+ \nu_m, \nu_m \to \pi^- e^+$

✓ The results on BF and mixing matrix element provide the supplementary information in the study of mixing between the heavy Majorana neutrino and the standard model neutrino in D meson decays



Search for baryon- and lepton-number violating decays

- The matter-antimatter asymmetry in the Universe suggests the existence of BNV.
- Various SM extensions, BNV processes can happen with $\Delta(L-B)=0$, $\Delta(L-B)=2$ mediated by heavy gauge bosons X or Y, called "leptoquarks" , or scalar field ϕ
- Four decays of $D^{\pm}\to\Lambda(\bar{\Lambda})e^{\pm}$, $D^{\pm}\to\Sigma\,(\bar{\Sigma}^{0})e^{\pm}$, $D^{\pm}\to p(\bar{p})e^{\pm}$ and $D^{\pm}\to n(\bar{n})e^{\pm}$are performed at BESIII



dimension-six operators - $\Delta(L-B)=0$

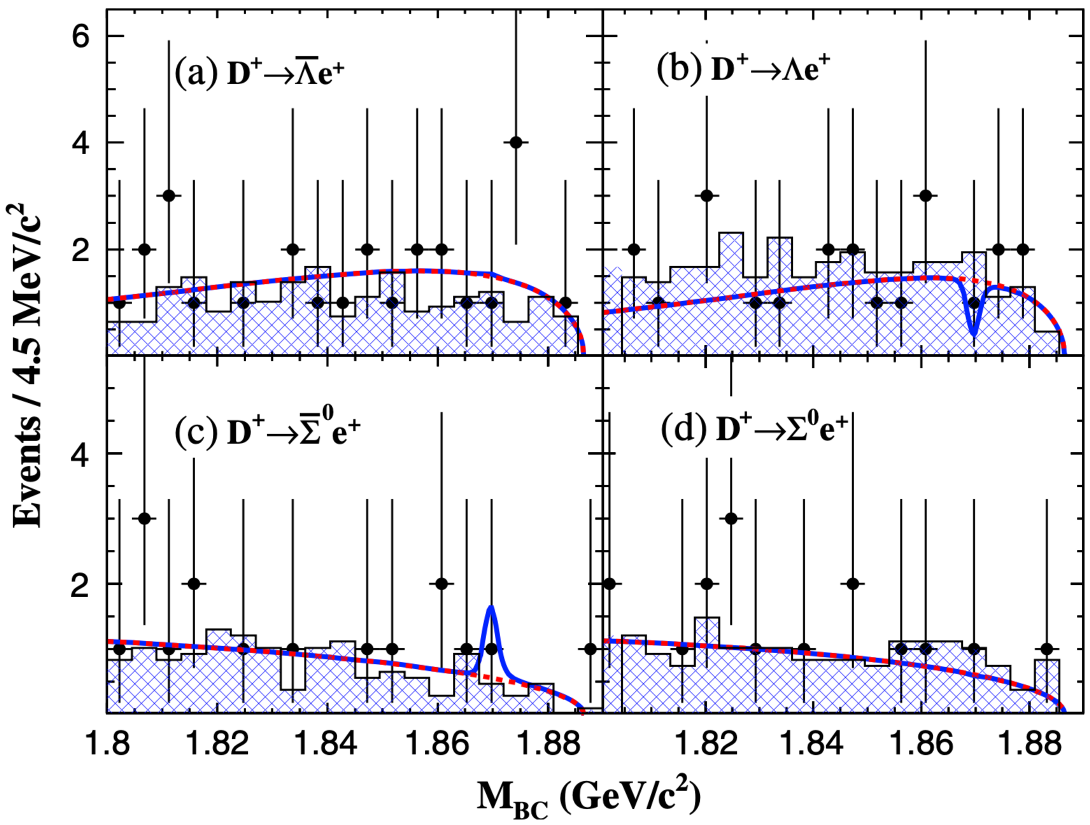
dimension-seven operators - $\Delta(L-B)=2$

I: $D^{\pm} \to \Lambda(\bar{\Lambda})e^{\pm}$, $D^{\pm} \to \Sigma\,(\bar{\Sigma}^0)e^{\pm}$

PRD 101, 031102 (2020)

- The $D^+ \to \bar{\Lambda}e^+$, $D^+ \to \bar{\Sigma}^0 e^+$ $\Delta(\mathrm{B-L}) = 0$
  $D^+ \to \Lambda e^+$, $D^+ \to \Sigma\, e^+$ $\Delta(\mathrm{B-L}) = 2$
  are searched for the first time;
- A Single-Tag method is implied;
- ULs are determined by likelihood scan

Mode	$N_{\mathrm{sig}}^{\mathrm{UL}}$	ε (%)	$\mathcal{B}^{\mathrm{UL}}$
Λe^+	5.6	31.11 ± 0.14	1.1×10^{-6}
$\bar{\Lambda}e^+$	3.4	31.18 ± 0.10	6.5×10^{-7}
$\Sigma^0 e^+$	4.5	16.31 ± 0.07	1.7×10^{-6}
$\bar{\Sigma}^0 e^+$	3.5	16.40 ± 0.07	1.3×10^{-6}



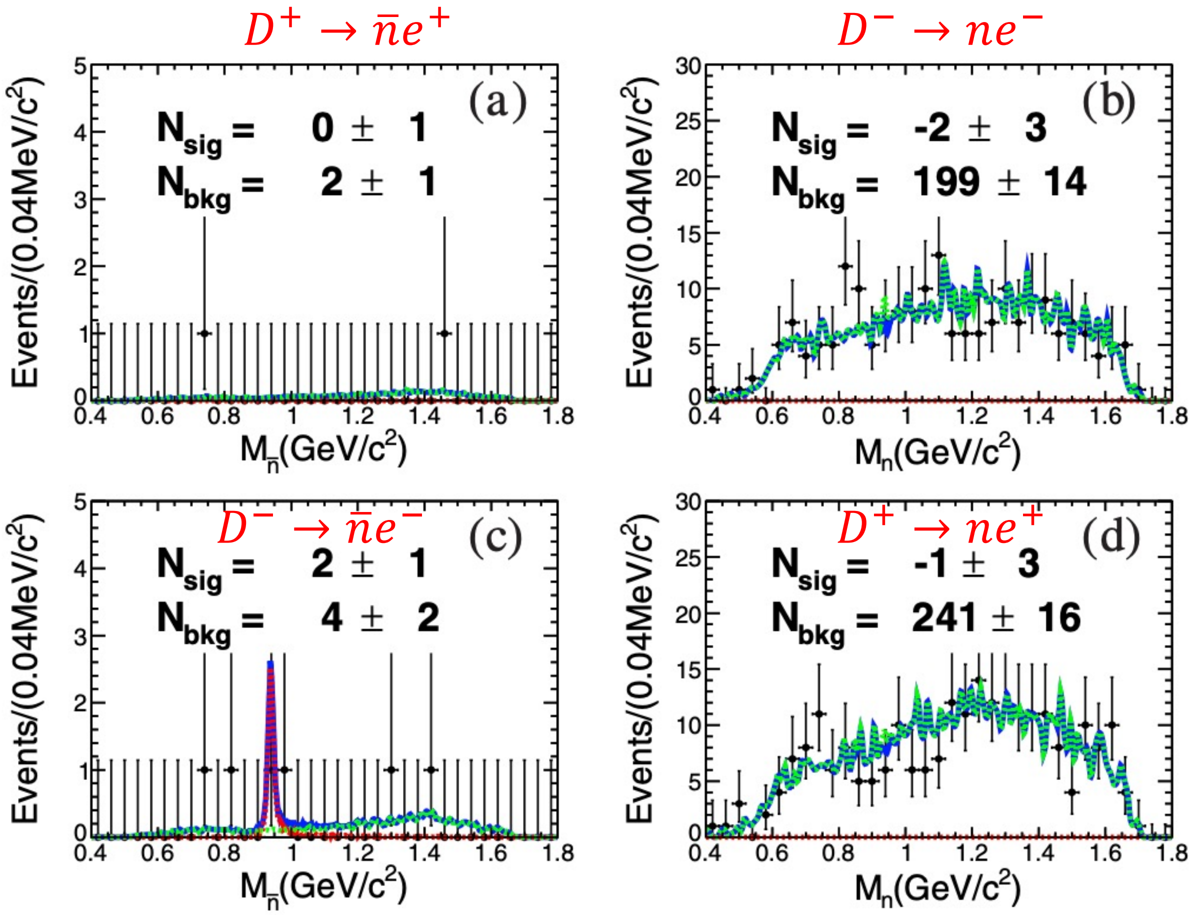
II: $D^{\pm} \to n(\bar{n})e^{\pm}$

PRD 106, 112009 (2022)

- A Double-Tag method is implied
- Single tag (ST) candidate events ~ 1.5 million
- ULs are determined by likelihood scan

$$\mathcal{B}_{D^+\to\bar{n}e^+} < 1.43 \times 10^{-5}$$
$$\mathcal{B}_{D^+\to ne^+} < 2.91 \times 10^{-5}$$

- Most stringent constraint to date



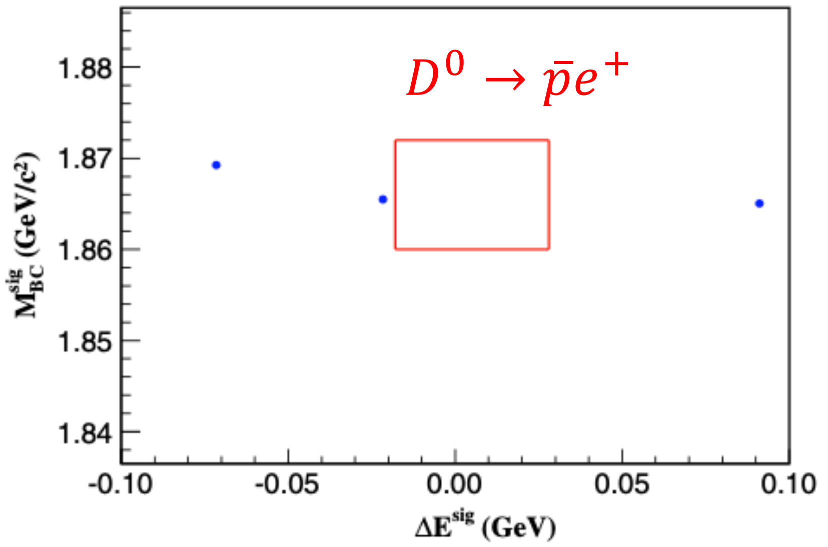
III: $D^0 \to p(\bar{p})e^{\mp}$

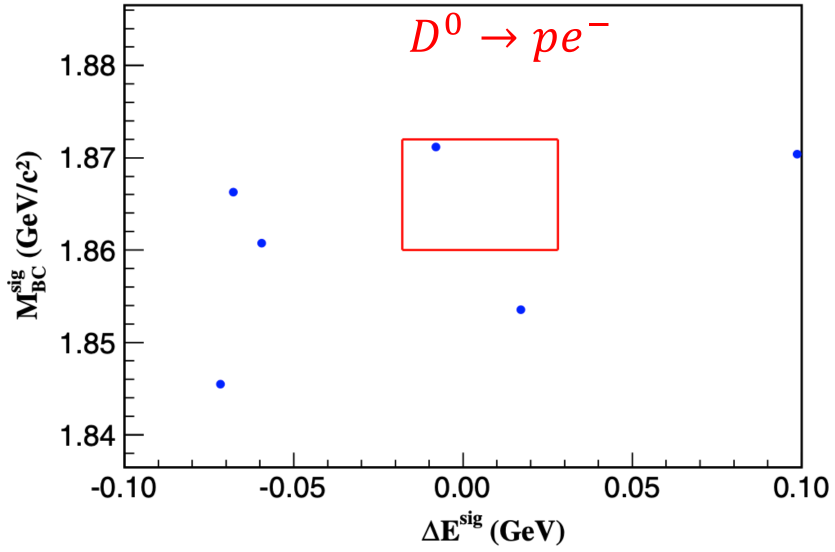
PRD 105, 032006 (2022)

- A Double-Tag method is implied;
- Single tag (ST) candidate events ~ 2.3 million
- The ULs are calculated by using a frequentist method with an unbounded profile likelihood (TROLKE).
- The ULs on the BFs:

$$\mathcal{B}_{D^0 \to pe^-} < 2.2 \times 10^{-6}$$

$$\mathcal{B}_{D^0 \to \bar{p}e^+} < 1.2 \times 10^{-6}$$



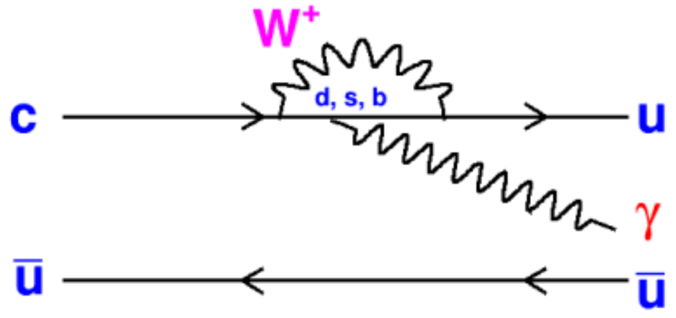


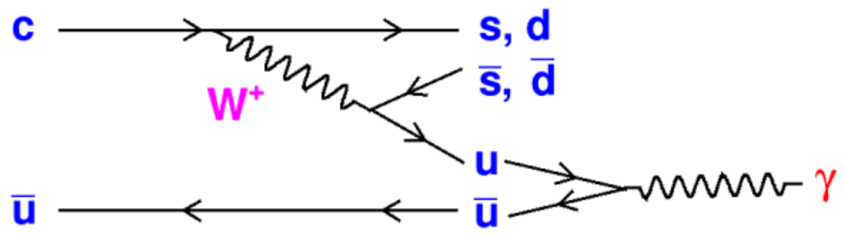
Radiative decay

Radiative decays

- Rare radiative decays are most likely dominated by the LD SM contributions
  SD (10^{-8}) LD (10^{-4})

- The rare radiative transitions could be sensitive to NP contributions:
  - ✓ the difference between different radiative transitions
  - ✓ *CP*-violating asymmetries
  - ✓ photon polarization patterns

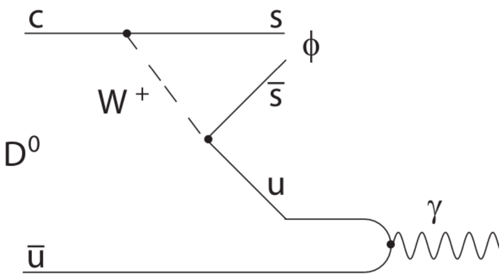


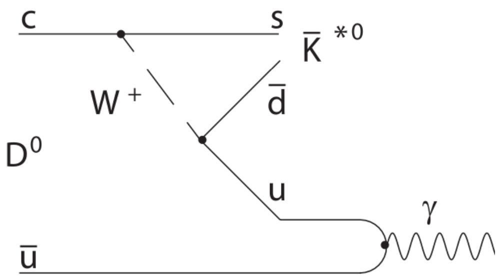


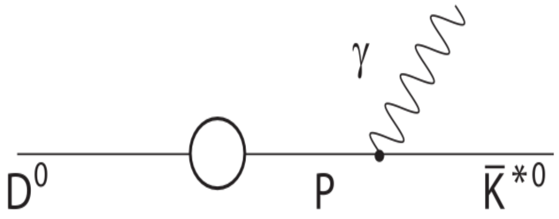
$D^0 \to \gamma\rho^0/\gamma\phi/\gamma\bar{K}^*$

PRL 118, 051801 (2017)/ PR D 78, 071101(R)

- The radiative decays of $D^0 \to \gamma\rho^0/\gamma\phi/\gamma\bar{K}^*$ have been observed by Belle and BaBar







JHEP08(2017)091

Radiative modes

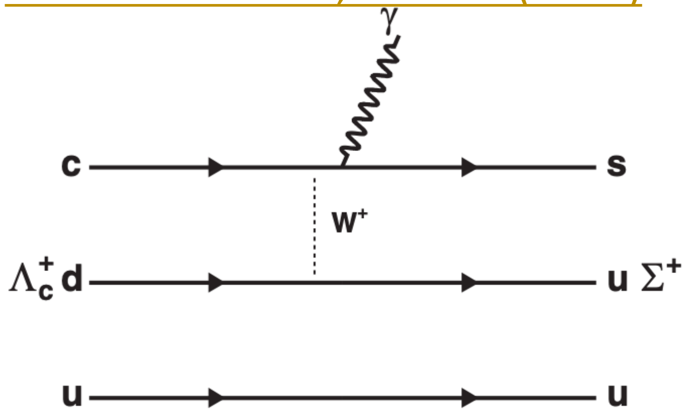
Γ_{268}	$\rho^0\gamma$	$(1.82 \pm 0.32) \times 10^{-5}$
Γ_{269}	$\omega\gamma$	$< 2.4 \times 10^{-4}$
Γ_{270}	$\phi\gamma$	$(2.81 \pm 0.19) \times 10^{-5}$
Γ_{271}	$\bar{K}^*(892)^0\gamma$	$(4.1 \pm 0.7) \times 10^{-4}$

branching ratio	$D^0 \to \phi\gamma$	$D^0 \to \bar{K}^{*0}\gamma$	$D^0 \to K^{*0}\gamma$	$D^+ \to K^{*+}\gamma$	$D_s \to \rho^+\gamma$
WA	$(0.0074-1.2)\cdot10^{-5}$	$(0.011-1.6)\cdot10^{-4}$	$(0.032-4.4)\cdot10^{-7}$	$(0.73-1.1)\cdot10^{-5}$	$(1.8-2.9)\cdot10^{-3}$
hybrid	$(0.24-2.8)\cdot10^{-5}$	$(0.26-4.6)\cdot10^{-4}$	$(0.076-1.3)\cdot10^{-6}$	$(0.48-7.6)\cdot10^{-6}$	$(0.11-1.3)\cdot10^{-3}$
[5, 6]	$(0.4-1.9)\cdot10^{-5}$	$(6-36)\cdot10^{-5}$	$(0.03-0.2)\cdot10^{-5}$	$(0.03-0.44)\cdot10^{-5}$	$(20-80)\cdot10^{-5}$
[8]	$(0.1-3.4)\cdot10^{-5}$	$(7-12)\cdot10^{-5}$	$0.1\cdot10^{-6}$	$(0.1-0.3)\cdot10^{-5}$	$(6-38)\cdot10^{-5}$
[9][a]	—	$1.8\cdot10^{-4}$	—	—	$4.7\cdot10^{-5}$
Belle [15][†]	$(2.76\pm0.21)\cdot10^{-5}$	$(4.66\pm0.30)\cdot10^{-4}$	—	—	—
BaBar [39][†b]	$(2.81\pm0.41)\cdot10^{-5}$	$(3.31\pm0.34)\cdot10^{-4}$	—	—	—

- LD contributions to radiative charm decays are expected to 10^{-5};
- With 20 fb^{-1} $\psi(3770)$ data, the radiative decays are expected to be observed;

$\Lambda_c^+ \to \Sigma^+\gamma$

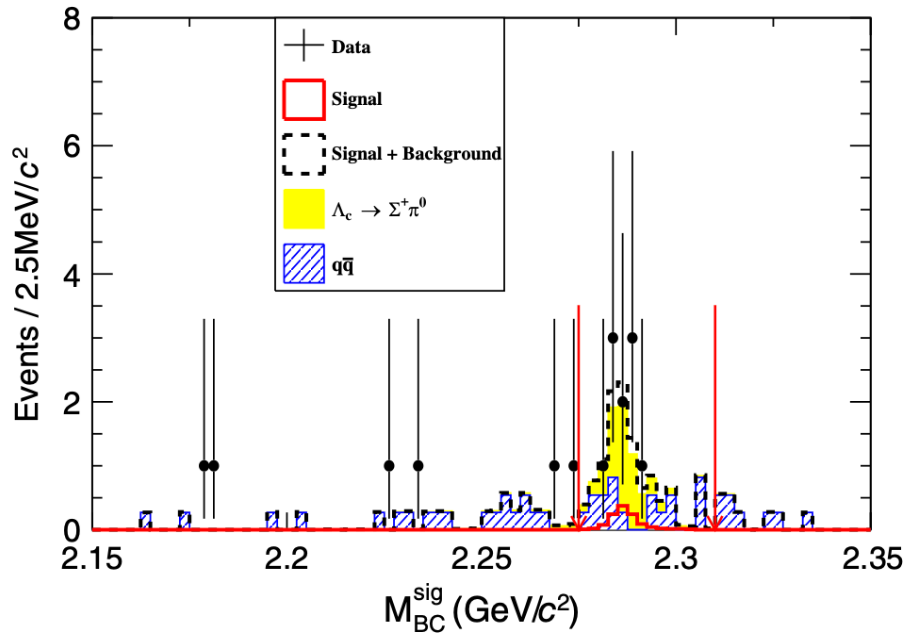
PHYS. REV. D 107, 052002 (2023)



- A Double-Tag method is implied;
- Single tag (ST) candidate events ~105K
- Since no significant signal is observed, the upper limit on the BF

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\gamma) < 4.4 \times 10^{-4}$$

- This result is consistent with the theoretical predictions from the bag model and appropriate QCD corrections, respectively, where the short-distance $cd \to \gamma su$ mechanism is expected to be dominant.



Summary

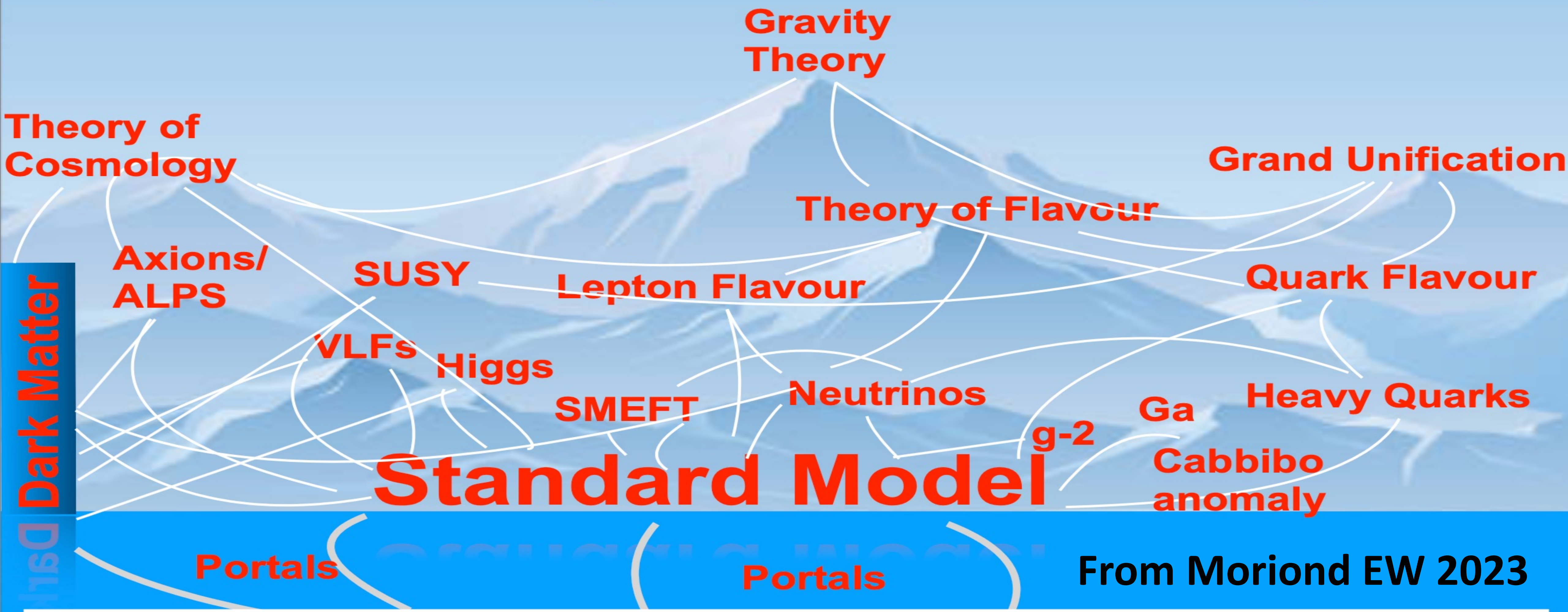
- Rare charm decays are a powerful indirect probes for NP
  - ✓ FCNC $D^0 \to \gamma\gamma, D \to h(h')e^+e^-, D^0 \to \pi^0 \nu\bar{\nu}$
  - ✓ L/BNV $D \to K\pi e^+e^+,\ D^\pm \to n(\bar{n})e^\pm,\ D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+/\Lambda(\Sigma^0)e^+, D^0 \to \bar{p}e^+/pe^-$
  - ✓ Radiative decay. $\Lambda_c^+ \to \Sigma^+\gamma$

- Ongoing
  - ✓ FCNC: $D_s^+ \to h(h')e^+e^-$ L/BNV: $D_s^+ \to h(h')e^+e^+, D_s^+ \to \Lambda e^+$
  - ✓ Radiative decay: $D_s^+ \to \gamma\rho^+(K^{*+}),\ D^0 \to \gamma\omega/\gamma\phi/\gamma\bar{K}^*$

- A more stringent constraint, or discovery (LD) , is expected with the larger dataset that BESIII expects to accumulate in the near future!

Thanks

Summary of Summary



Whatever you work on, enjoy the ride!