Charm Rare Decay at Belle

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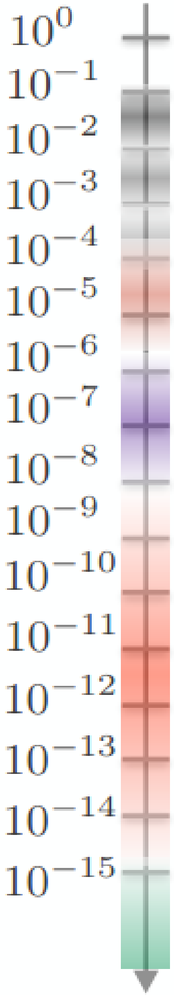
Introduction

Ref. A. Zupanc @CKM2014

Overview of measurements of selected rare decays



Cabibbo favored

Singly Cabibbo suppresed

Doubly Cabibbo suppresed

Radiative

$D^0 \to \overline{K}^{*0}\gamma,\ \phi\gamma,\ \omega\gamma,\ \rho^0\gamma$

Vector Meson Dominance

$D^0 \to \gamma\gamma$

$D^0 \to \rho V(\to \ell\ell),\ \pi^-\pi^+ V(\to \ell\ell)$

$D^0 \to \phi V(\to \ell\ell),\ K^-K^+ V(\to \ell\ell)$

$D^0 \to \overline{K}^{*0} V(\to \ell\ell),\ K^+\pi^- V(\to \ell\ell)$

Flavour Changing Neutral Current

$D^0 \to \mu^-\mu^+$

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

$D \to h\ell^+\ell^-$

$D \to hh'\ell^-\ell^+$

$D \to V\ell^+\ell^-$

Lepton/Baryon Number Violating

Lepton Flavor Violating

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

$D \to (h)\ell^+\ell^+$

Introduction

Experimental requirements

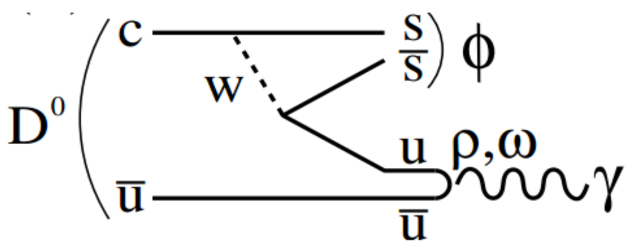
- **Statistics: very large samples**
- **Excellent detector performance:**
  - Excellent vertex resolution
  - Very high reconstruction efficiencies for charged particles and photons
  - Very good momentum resolution over the whole kinematic range
  - Precise measurements of photon energy and direction
  - Highly efficient particle ID system to separate π/K and e/μ over the full kinematic range
  - Cover the (almost) full solid angle

Available samples

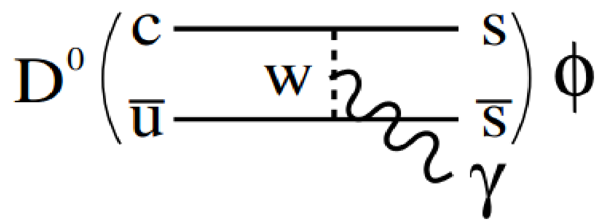
Experiment	Sample	N(D)	efficiency
LHCb, CMS	pp @ 7 TeV	5.0T	< 0.5%
DØ, CDF	$p\bar{p}$ @ 2 TeV	0.13T	
BESIII, CLEO	e^+e^- @ 3.77 GeV e^+e^- @ 4.18 GeV	10.5M 2.9M	~10-30%
BaBar, BELLE	e^+e^- @ 10.6 GeV	0.65G 1.30G	~5-10%

Radiative Charm Decay $D^0 \to V\gamma$

- Include long-range contribution (~10^{-5}) and short-range contribution (10^{-8})



long-range contribution



short-range contribution

- Vector Meson Dominance (VMD): make rough estimates of the rates

PDG: $B(D^0 \to \phi\rho^0) = (0.93 \pm 0.12) \times 10^{-3}$

$B(D^0 \to \phi\omega) < 2.1 \times 10^{-3}$@90% C.L.

The coupling of the photon to a vector: ~1%

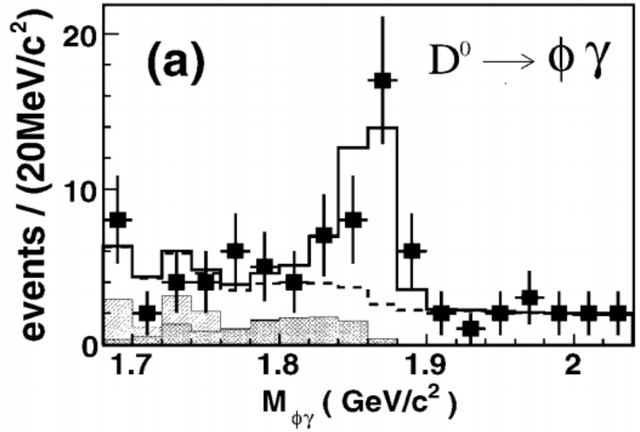
Expected rates of long-range : $\sim 10^{-5}$

- In 1998, CLEO set the upper limit on $B(D^0 \to \phi\gamma, \omega\gamma, \bar{K}^{0*}\gamma, \rho^0\gamma)$ to be 1.9×10^{-4},2.4×10^{-4},7.6×10^{-4},2.4×10^{-4}. [PRD 58, 092001(1998)]

Radiative Charm Decay $D^0 \to \phi\gamma$

- In 2004, Belle gave the first observation of $D^0 \to \gamma\phi$ with a significance of 5.4σ based on $78.1\ \mathrm{fb}^{-1}$ data [O. Tajima *et al.* PRL 92,101803 (2004)]

  - Tagged $D^{*+} \to D^0\pi_s^+$
  - $E_\gamma > 450\mathrm{MeV}, P^*(D^*) > 2.9$GeV/c
  - Main bkg. $D^0 \to \phi\pi^0$ and $\phi\eta$
  - Normalized to $D^0 \to K^+K^-$



$$B(D^0 \to \phi\gamma) = [2.60^{+0.70}_{-0.61}(\mathrm{stat})^{+0.15}_{-0.17}(\mathrm{syst})] \times 10^{-5}$$

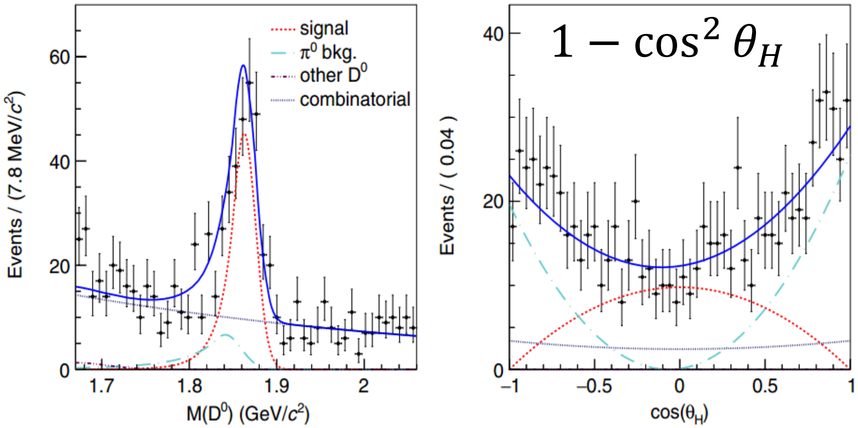
- In 2008, BABAR improved the precision of $D^0 \to \gamma\phi$ based on $387.1\mathrm{fb}^{-1}$ data [B. Aubert *et al.* PRD 78 071101(2008)]

$$B(D^0 \to \phi\gamma) = [2.78 \pm 0.30(\mathrm{stat}) \pm 0.27(\mathrm{syst})] \times 10^{-5}$$

Radiative Charm Decay $D^0 \to \phi\gamma$

- In 2017, Belle measure the $D^0 \to \phi\gamma$ based on 943 fb^{-1} data of $\Upsilon(nS)$ [T. Nanut *et al.* PRL 118, 051801(2017)]

- Tagged $D^{*+} \to D^0\pi^+$
- $E_\gamma > 540\mathrm{MeV}$, $P^*(D^*) > 2.42\mathrm{GeV/c}$
- $E_9/E_{25} > 0.94$ to reject γ from π^0
- Main bkg. $D^0 \to \phi\pi^0$ by ANN
- Charge-conjugate is included
- Normalized to $D^0 \to K^+K^-$



- Simultaneously fit D^0 candidate and the cosine of the helicity angle θ_H

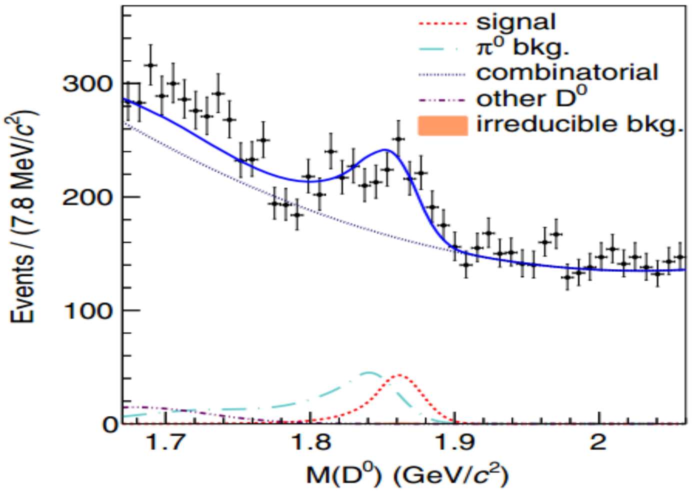
$$B(D^0 \to \phi\gamma) = [2.76 \pm 0.19(\mathrm{stat}) \pm 0.10(\mathrm{syst})] \times 10^{-5}$$

- Consistent with the world average value, and agree with the latest theoretical calculations

Radiative Charm Decay $D^0 \to \rho^0\gamma$

➢ In 2017, Belle **firstly** observed $D^0 \to \rho^0\gamma$ with a significance of 5.5σ based on a data sample of $943\ \mathrm{fb}^{-1}$ [T. Nanut *et al.* PRL 118, 051801(2017)]

- Tagged $D^{*+} \to D^0\pi^+$
- $E_\gamma > 540\mathrm{MeV}$, $P^*(D^*) > 2.72\mathrm{GeV/c}$
- $E_9/E_{25} > 0.94$ to reject γ from π^0
- Main bkg. $D^0 \to \rho^0\pi^0$ by ANN
- Charge-conjugate is included
- Normalized to $D^0 \to \pi^+\pi^-$



$$B(D^0 \to \rho^0\gamma) = [1.77 \pm 0.30(\mathrm{stat}) \pm 0.07(\mathrm{syst})] \times 10^{-5}$$

➢ The value is considerably larger than theoretical expectations ($\sim 10^{-6}$)

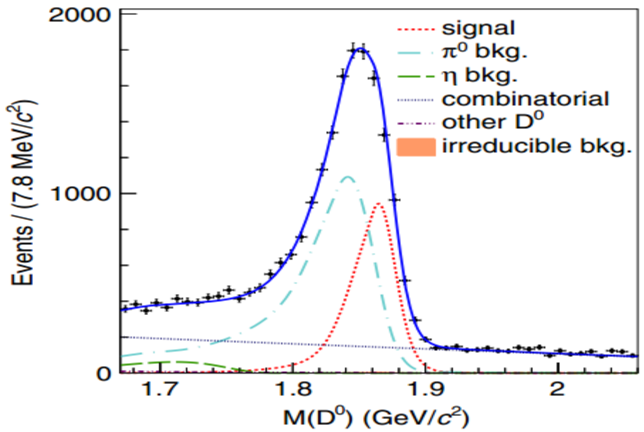
Radiative Charm Decay $D^0 \to \overline{K}^{*0}\gamma$

- In 2008, firstly observed by BABAR based on $387.1\ \mathrm{fb}^{-1}$ data [B. Aubert *et al.* PRD 78 071101(2008)]

$$B\left(D^0 \to \overline{K}^{*0}\gamma\right) = [3.28 \pm 0.20(\mathrm{stat}) \pm 0.27(\mathrm{syst})] \times 10^{-4}$$

- In 2017, Belle improved measurement of $D^0 \to \overline{K}^{*0}\gamma$ based on a data sample of $943\ \mathrm{fb}^{-1}$ [T. Nanut *et al.* PRL 118, 051801(2017)]

- Tagged $D^{*+} \to D^0\pi^+$
- $E_\gamma > 540\mathrm{MeV}$, $P^*(D^*) > 2.17\mathrm{GeV/c}$
- $E_9/E_{25} > 0.94$ to reject γ from π^0
- Main bkg. $D^0 \to K^{*0}\pi^0$ by ANN
- Charge-conjugate is included
- Normalized to $D^0 \to K^-\pi^+$



$$B\left(D^0 \to \overline{K}^{*0}\gamma\right) = [4.66 \pm 0.21(\mathrm{stat}) \pm 0.21(\mathrm{syst})] \times 10^{-4}$$

CP Violation in $D^0 \to V\gamma$

- **CP violation in weak decays arises due to the irreducible phase in CKM matrix ($< 10^{-3}$ for charm decay)**

- **Radiative charm decays $A_{CP}^{V\gamma} > 3\% \Longrightarrow$ signal of NP** [G. Isidori *et al.* PRL 109 171801(2012)]

- **In 2017, Belle report the first search for CP violation in decays $\boldsymbol{D^0 \to \rho^0\gamma}$, $\boldsymbol{\phi\gamma}$, $\boldsymbol{K^{*0}\gamma}$** [T. Nanut *et al.* PRL 118, 051801(2017)]

$$A_{\rm raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$$

$$A_{\rm raw} = A_{CP} + A_{FB} + A_{\varepsilon}^{\pm}$$

$$A_{CP}^{\rm sig} = A_{\rm raw}^{\rm sig} - A_{\rm raw}^{\rm norm} + A_{CP}^{\rm norm}$$

$$A_{CP}(D^0 \to \rho^0\gamma) = +0.056 \pm 0.152 \pm 0.006$$
$$A_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001$$
$$A_{CP}(\boldsymbol{D^0 \to \bar{K}^{*0}\gamma}) = \boldsymbol{-0.003} \pm 0.020 \pm 0.000$$

- **The results are consistent with no CP violation, be sensitive at the upcoming Belle II**

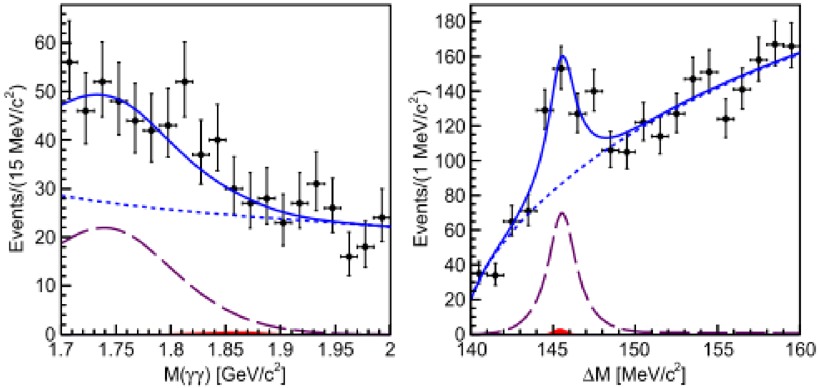
Flavor-changing neutral current $D^0 \to \gamma\gamma$

- **Flavor-changing neutral current (FCNC) processes are forbidden at tree level in SM, can occur at higher orders , and measured in K and B mesons**
- **Theory calculations based on VMD yield a decay branching fraction in the range $(1.0 \sim 3.0) \times 10^{-8}$**
- **In 2003, CLEO reported a first search for FCNC of $D^0 \to \gamma\gamma$ using 13.8 fb^{-1} and set the upper limit to be $B(D^0 \to \gamma\gamma) < 2.9 \times 10^{-5}$ at 90% C.L.. [T. E. Coan *at al.* PRL 90, 101801(2003)]**
- **In 2012, BABAR improved the upper limit to be $B(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ at 90% C.L.. using 470.5 fb^{-1} data [J. P. Lees *et al.* PRD 85, 091107(R)(2012)]**
- **Recently, BESIII also gave the upper limit of $B(D^0 \to \gamma\gamma) < 3.8 \times 10^{-6}$ at 90% C.L.. based on $2.92\mathrm{fb}^{-1}$ [M. Ablikim *et al.* PRD 91, 112015(2015)]**

Flavor-changing neutral current $D^0 \to \gamma\gamma$

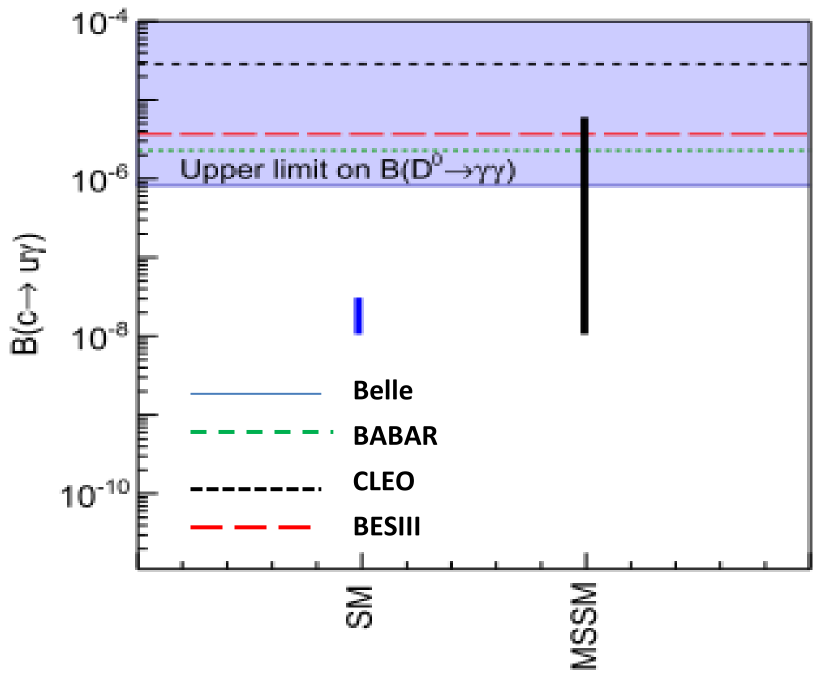
- **In 2016, Belle reported a search for $D^0 \to \gamma\gamma$ based on a data sample of $\mathbf{832fb^{-1}}$ [N. K. Nisar *et al.* PRD 93, 051102(R) (2016)]**
  - **Tagged $D^{*+} \to D^0\pi^+$**
  - **Normalized to $D^0 \to K_S^0\pi^0$**
  - **Main bkg.:**
    - **Peaking: $D^0 \to \pi^0\pi^0, \eta\pi^0, \eta\eta$; $P(\pi^0) < 0.15$**
    - **QED: $e^+e^- \to \gamma\gamma, e^+e^-\gamma$; N>4, T(ECL)<2μs**
    - **Combinatorial: $E_{\gamma 2} > 900\text{MeV}$,$P^*(D^*) > 2.9$GeV/c**

- **an unbinned extended maximum likelihood 2D fit to $M(\gamma\gamma)$ and ΔM. ($\Delta M = M(D^*) - M(D^0)$)**



$B(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$ at 90% C.L.

Flavor-changing neutral current $D^0 \to \gamma\gamma$



- This is the most restrictive limit on $D^0 \to \gamma\gamma$ decay to date
- Can be used to constrain NP parameter spaces
- This FCNC decay will be probed further at the next-generation Belle II

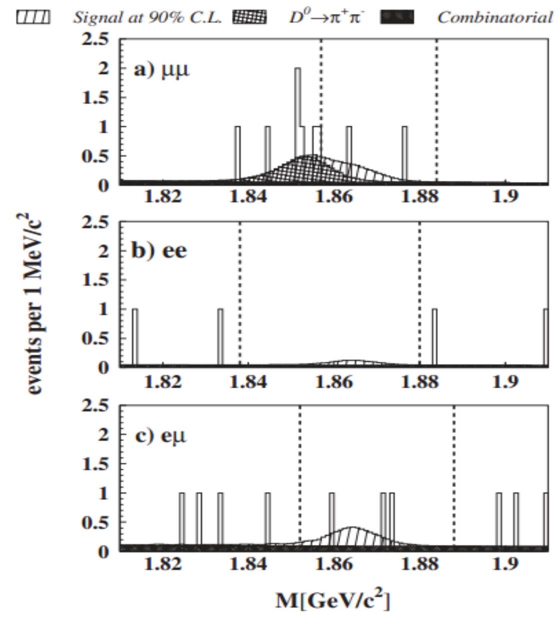
Flavor-changing neutral current $D^0 \to l^+l^-$

- **In SM, the FCNC decays of $D^0 \to l^+l^-$ are highly suppressed by GIM, $B \sim 10^{-13}$ included in long-range contributions**
- **The LFV decays are forbidden in the SM;in extensions of the SM, $B \sim 10^{-14}$; all these below the current experimental sensitivity**
- **In certain NP scenarios, FCNC decays can be enhanced by many orders. e.g. some models increase $B(D^0 \to \mu^+\mu^-)$ to 10^{-8} and $B(D^0 \to e^+e^-)$ to 10^{-12}**
- **Searching for the FCNC and LFV decays in the charm sector is a potential way to test the SM and explore NP**
- **In 2004, BABAR reported on a search for FCNC decays $D^0 \to l^+l^-$ based on $122\ \mathrm{fb}^{-1}$ data, set the upper limit on $B(D^0 \to e^+e^-) < 1.2 \times 10^{-6}$, $B(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-6}$, $B(D^0 \to e^\pm\mu^\mp) < 8.1 \times 10^{-7}$ at 90% C.L. [B. Aubert et al. PRL 93 191801(2004)]**

Flavor-changing neutral current $D^0 \to l^+l^-$

- In 2010, Belle reported a search for FCNC of $D^0 \to \mu^+\mu^-$, $D^0 \to e^+e^-$, and LFV $D^0 \to e^\pm\mu^\mp$ using 660fb^{-1} data [M. Petricˇ et al. PRD 81, 091102(R)(2010)]

- Tagged $D^{*+} \to D^0\pi^+$
- $P^*(D^*) > 2.5$GeV/c
- Main bkg.
  - Source : semileptonic B decays (80%) and D^0 decays (10%)
  - M distribution: smooth bkg and peaking bkg. from $D^0 \to \pi^+\pi^-$
- Normalized to $D^0 \to \pi^+\pi^-$
- To avoid biases, a blind analysis is used



$B(D^0 \to \mu^+\mu^-) < 1.4 \times 10^{-7}$@90%C. L.
$B(D^0 \to e^+e^-) < 7.9 \times 10^{-8}$@90%C. L.
$B(D^0 \to e^\pm\mu^\mp) < 2.6 \times 10^{-7}$@90%C. L.

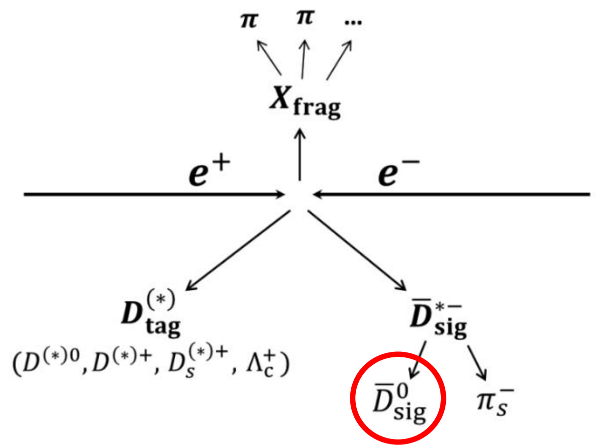
$B(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$@90%C. L.
$< 7.6 \times 10^{-9}$@95%C. L.
@LHCb [R. Aaij *et al.* PLB 725, 15(2013)]

D^0 decays to invisible final states

- **In SM, heavy (D or B) meson to $\nu\bar{\nu}$ is suppressed $\sim 10^{-30}$, beyond the reach of current experiments.**
- **Non-SM mechanisms (D decays to DM) enhance the order $\sim 10^{-15}$**
- **Indirect detection of DM: One of the D or B mesons is fully reconstructed, and then energy-momentum conservation is used to search for the other D meson into invisible final states.**
- **Use the charm tagger method to select an inclusive D^0 sample**

$e^+e^- \to c\bar{c} \to D_{tag}^{(*)} X_{frag} \overline{D}^{*-}_{sig}$ with $\overline{D}^{*-}_{sig} \to \overline{D}^0_{sig}\pi^-$

$X_{\rm frag}$ fragmentation system with light unflavored mesons

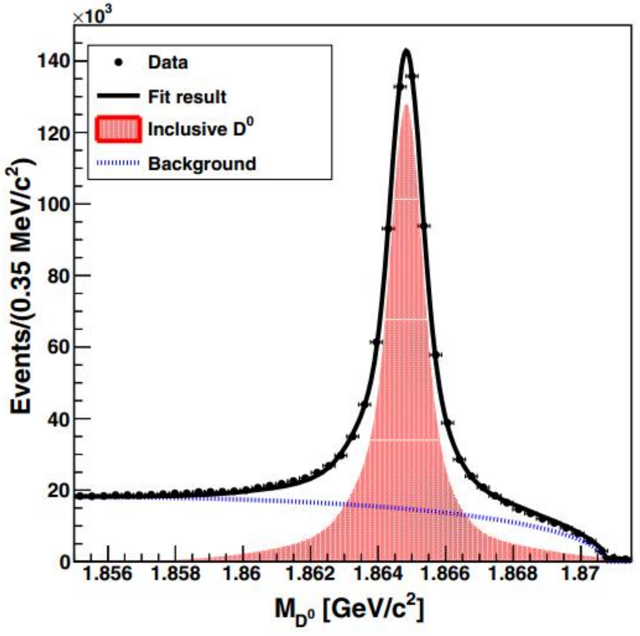


- **Any clear signal would be an indication for new physics.**

D^0 decays to invisible final states

- In 2017, Belle reported the first search for D^0 decays to invisible final states based on a data sample of 924 fb^{-1} [Y.-T. Lai *et al.* PRD 95 011102(R) (2017)]

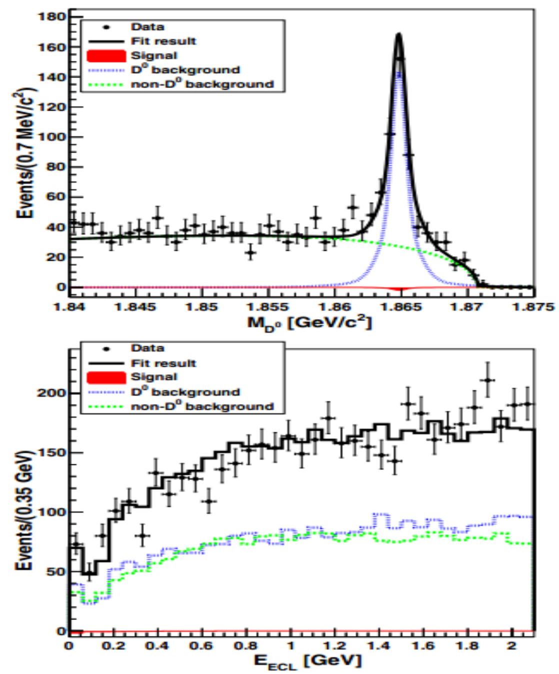
- D_{tag} : four type, 23 decay modes
- D^*_{tag} : five decay modes
- X_{frag}: $n\pi(K^+K^-)$ for $D^{(*)0,\pm}$, $n\pi\bar{p}$ for Λ_C^+, $n\pi(K^-/K_S^0)$ for $D_S^{(*)+}$
- $\bar{D}^{*-}_{\mathrm{sig}}$:by $M^{rec}(D^{(*)}_{tag}X_{\mathrm{frag}})$ in [1.86, 2.16]
- $P^*\left(D^{(*)}_{tag}X_{frag}\pi_s^-\right) > 2.0\mathrm{GeV/c}$
- $M^{rec}(D^{(*)}_{tag}X_{\mathrm{frag}})$ imposed 1C fit



- Inclusive D^0 yield is extracted from 1D maximum likelihood fit , obtain 694667^{+1494}_{-1563} inclusive D^0events

D^0 decays to invisible final states

- **Invisible D^0 decays are identified by requiring no remaining final-state particles with $\overline{D}^0_{sig}$**
- **Residual energy in the ECL is also used, the sum of E against $D^{(*)}_{tag} X_{frag} \pi^-_s$**
- **invisible D^0 is extracted by a 2D fit**
- **No significant signal yield is found**
- **Fitted signal yield of D^0 →invisible is $-6.3^{+22.5}_{-21.0}$, consistent with zero.**



$B(D^0 \rightarrow \text{invisible}) < 9.4 \times 10^{-5} @ 90\%\ \text{C.L.}$

- **Further improvement in this measurement may be possible in the near future Belle II.**

Summary (I)

- Firstly, we reviewed measurement of $D^0 - V\gamma$ at Belle

$$B(D^0 \to \phi\gamma) = [2.76 \pm 0.19(\text{stat}) \pm 0.10(\text{syst})] \times 10^{-5}$$

$$B(D^0 \to \rho^0\gamma) = [1.77 \pm 0.30(\text{stat}) \pm 0.07(\text{syst})] \times 10^{-5}$$

$$B(D^0 \to \bar{K}^{*0}\gamma) = [4.66 \pm 0.21(\text{stat}) \pm 0.21(\text{syst})] \times 10^{-4}$$

- Secondly, we reviewed CP Violation in $D^0 \to V\gamma$ at Belle, the results are consistent with no CP violation

- Thirdly, we reviewed FCNC decays $D^0 \to \gamma\gamma$ and $D^0 \to l^+l^-$ at Belle

$$B(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7} \text{ @90\% C.L.}$$

$$B(D^0 \to \mu^+\mu^-) < 1.4 \times 10^{-7} \text{@90\%C.L.} \quad < 6.2 \times 10^{-9} \text{@90\%C.L.}$$

$$B(D^0 \to e^+e^-) < 7.9 \times 10^{-8} \text{@90\%C.L.}$$

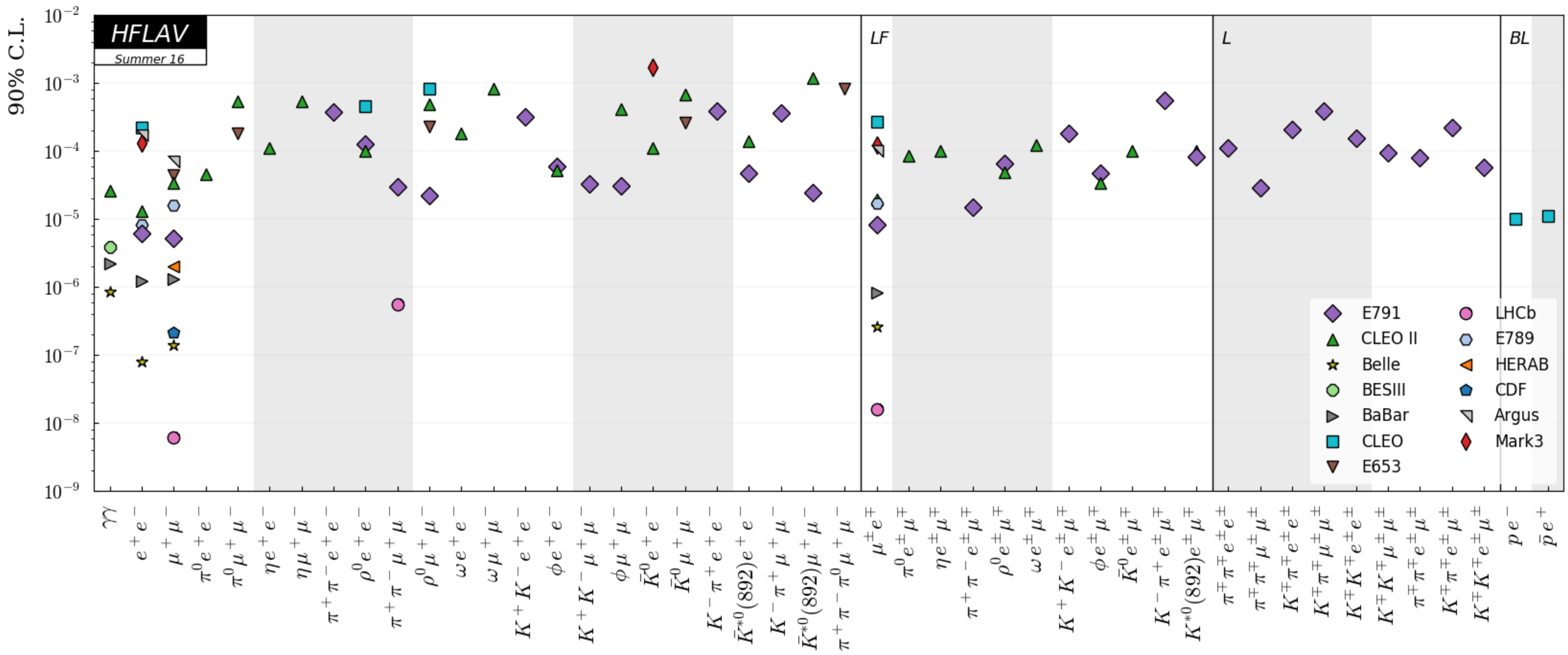
$$B(D^0 \to e^\pm\mu^\mp) < 2.6 \times 10^{-7} \text{@90\%C.L.}$$

- Finally, we reviewed D^0 invisible decay at Belle

$$B(D^0 \to \text{invisible}) < 9.4 \times 10^{-5} \text{@90\%C.L.}$$

Summary (II)

Upper limits on the branching fractions of rare D^0 decays from *HFLAV*



Thank you for your attention!