STUDIES OF RADIATIVE CHARM DECAYS AT BELLE

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on behalf of the Belle Collaboration

Les Rencontres de Physique de la Vallée d'Aoste

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Outline of the talk

We present:

- Preliminary results of the measurement of

  branching fraction and CP asymmetry in decays

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

  on 943 fb^{-1} of Belle data.

- Final results of the study of the rare decay

  $D^0 \to \gamma\gamma$

  on 832 fb^{-1} of Belle data.

Analysis $D^0 \to V\gamma$

Motivation:

- Decays $D^0 \to \rho^0\gamma$ not yet observed
- Sensitive to New Physics in terms of A_{CP} measurement:
  - SM prediction: $\mathcal{O}(10^{-3})$
  - SM extension with chromomagnetic dipole operators: up to several % for $V = \phi, \rho^0$ (Phys. Rev. Lett. 109, 171801)
- No A_{CP} measurement yet in $D^0 \to V\gamma$

Decay chains:

$D^0 \to \phi\gamma \to K^+K^-\gamma$
$D^0 \to \overline{K}^{*0}\gamma \to K^-\pi^+\gamma$
$D^0 \to \rho^0\gamma \to \pi^+\pi^-\gamma$

Normalisation channels:

$D^0 \to K^+K^-$
$D^0 \to K^-\pi^+$
$D^0 \to \pi^+\pi^-$

Analysis method

- $\mathcal{B}r$ and A_{CP} extracted through normalisation channels to avoid several sources of systematic uncertainties
  - Branching fraction:

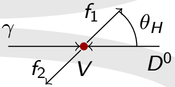
$$\mathcal{B}r_{sig} = \mathcal{B}r_{norm} \times \frac{N_{sig}}{N_{norm}} \times \frac{\varepsilon_{norm}}{\varepsilon_{sig}}$$

  - CP asymmetry:

$$A_{\text{raw}} = \frac{N(D^0) - N(\overline{D^0})}{N(D^0) + N(\overline{D^0})} = A_{CP} + A_{\text{FB}} + A_{\varepsilon}^{\pm}$$

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

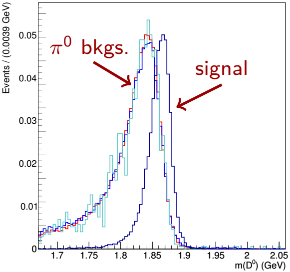
- Flavour tag: D^0 from decay $D^{*+} \to D^0 \pi_s^+$
- Signal extraction: simultaneous 2d fit in $m(D^0)$ and $\cos(\theta_H)$



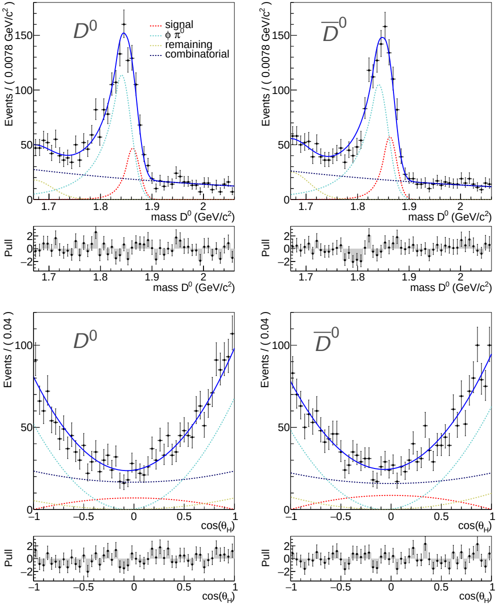
- Normalisation modes:
  - Based on previous Belle analysis of same modes (Phys.Lett. B753, 412 (2016))
  - Signal extraction: background subtraction in signal window

Dominant background

- From decays with $\pi^0(\to \gamma\gamma)$, one photon missed in reconstruction
- Main peak in $m(D^0)$ overlapping with signal peak
- Lots of decay modes (especially $\overline{K}^{*0}$, ρ^0), high $\mathcal{B}rs$
- Devise dedicated π^0 veto to suppress:
  - combine photon with all others, take diphoton mass closest to $M(\pi^0)$
  - require once $E_{\gamma_2} > 75$ MeV and once $E_{\gamma_2} > 30$ MeV
  - feed these two variables to the neural network
- Final veto rejects 60% of background and 15% of signal



Fit results ϕ mode

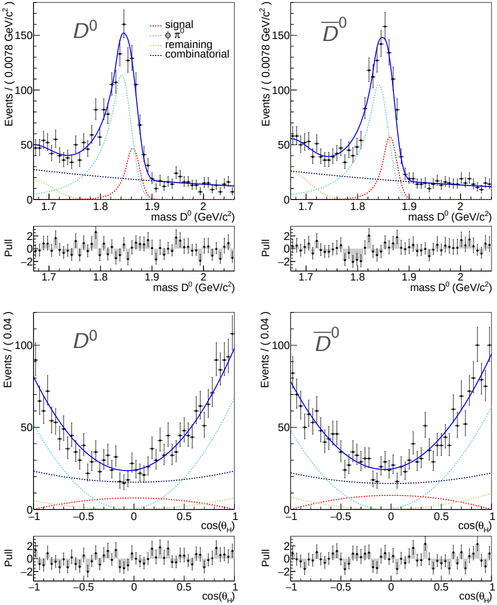


Signal yield: 524$\pm$35

Raw asymmetry: -0.091$\pm$0.066

Efficiency: 9.6%

Fit results ϕ mode



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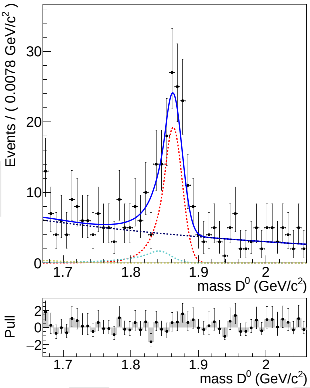
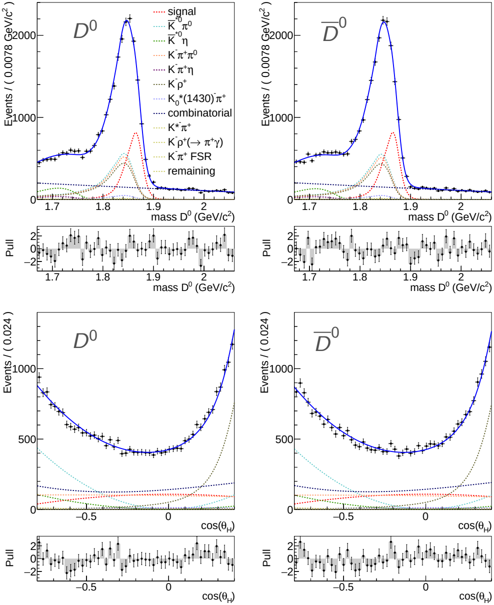
Signal enhanced:



$0.0 < \cos(\theta_H) < 0.2$

Fit results $\overline{K}^{*0}$ mode

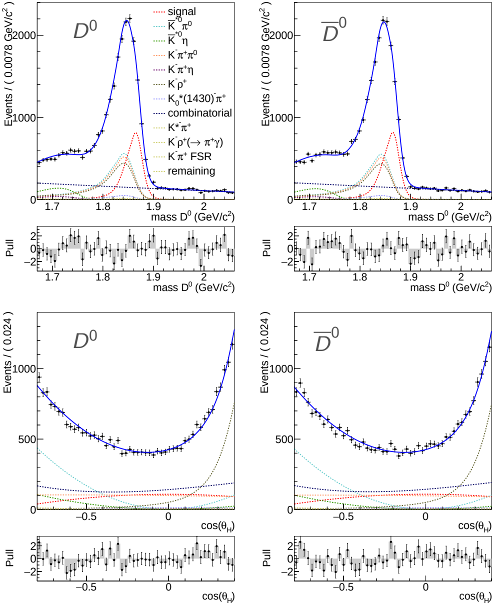


Signal yield: 9104 ± 396

Raw asymmetry: -0.002 ± 0.020

Efficiency: 7.8%

Fit results $\overline{K}^{*0}$ mode



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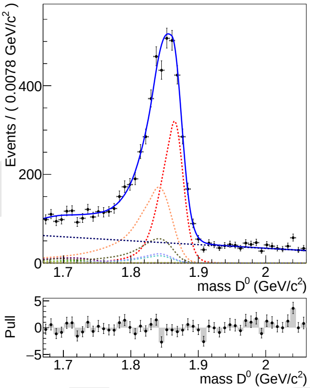
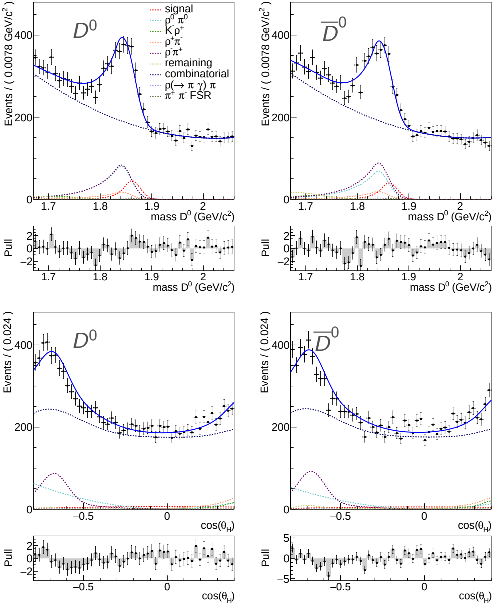


$-0.2 < \cos(\theta_H) < 0.0$

Fit results ρ^0 mode

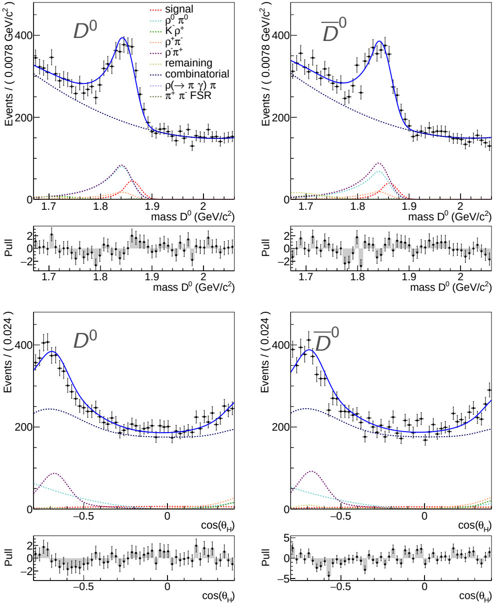


Signal yield: 500 ± 85

Raw asymmetry: 0.056 ± 0.151

Efficiency: 6.8%

Fit results ρ^0 mode



Signal yield: 500$\pm$85

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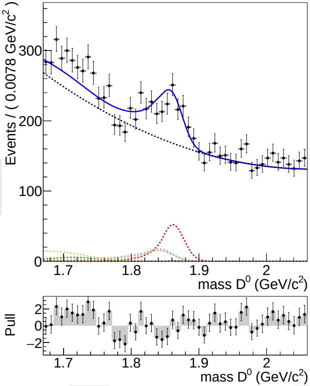
Signal enhanced:



$-0.3 < \cos(\theta_H) < 0.3$

Normalisation channels

Estimate background in signal window(SW) from sidebands(LSB, USB):

$$f = \frac{(N_{\text{SW}}^{\text{bkg}})_{MC}}{(N_{\text{LSB}} + N_{\text{USB}})_{MC}}$$

$$(N_{\text{SW}}^{\text{bkg}})_{\text{DATA}} = f \times (N_{\text{LSB}} + N_{\text{USB}})_{\text{DATA}}$$

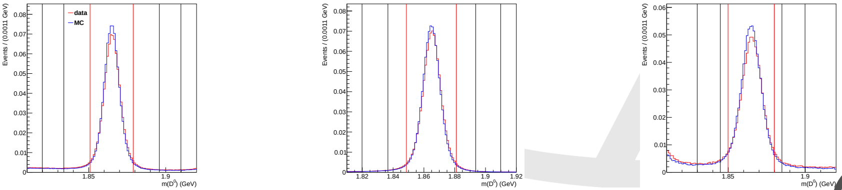
get on MC

use on data

	SW [MeV]	sidebands [MeV]	Efficiency	Yield	$A_{raw}[\times 10^{-3}]$
K^+K^-	$\pm$14.0	$\pm$(31-45)	22.7%	362274	2.2$\pm$1.7
$K^-\pi^+$	$\pm$16.2	$\pm$(28.8-45)	27.0%	4.02×10^6	1.3$\pm$0.5
$\pi^+\pi^-$	$\pm$15.0	$\pm$(20-35)	21.4%	127683	8.2$\pm$3.0

Table: Analysis of normalisation modes.

$D^0 \to K^+K^-$ $D^0 \to K^-\pi^+$ $D^0 \to \pi^+\pi^-$



Systematic uncertainties

	ϕ		$\overline{K}^{*0}$		ρ^0	
	$\mathcal{B}r[\%]$	A_{CP} [$\times 10^{-3}$]	$\mathcal{B}r[\%]$	A_{CP} [$\times 10^{-3}$]	$\mathcal{B}r[\%]$	A_{CP} [$\times 10^{-3}$]
γ rec. eff.	2	–	2	–	2	–
q	1.16	–	1.16	–	1.16	–
π^0 veto	0.5	–	0.5	–	0.5	–
E_9/E_{25}	0.96	–	0.96	–	0.96	–
signal parametrisation	1.39	0.32	–	–	2.33	4.29
π^0 bkg. parametrisation	0.95	0.30	2.79	0.36	2.97	3.78
fixed bkg. yields	–	–	0.37	0.20	0.45	0.00
norm. modes systematics	0.05	0.46	0.00	0.01	0.14	0.54
total	3.06	0.64	3.8	0.41	4.58	5.74

Table: Systematic uncertainties.

Results (PRELIMINARY)

Branching fractions:

$$\mathcal{B}r(D^0 \to \phi\gamma) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5}$$

consistent with results by Belle, BaBar

$$\mathcal{B}r(D^0 \to \overline{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}$$

3.3σ away from BaBar result

$$\mathcal{B}r(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$$

first observation

$> 5\sigma$ significance

CP asymmetries:

$$A_{CP}(D^0 \to \phi\gamma) = -(0.094 \pm 0.066 \pm 0.001)$$

$$A_{CP}(D^0 \to \overline{K}^{*0}\gamma) = -(0.003 \pm 0.020 \pm 0.000)$$

$$A_{CP}(D^0 \to \rho^0\gamma) = 0.056 \pm 0.151 \pm 0.006$$

First measurement of A_{CP}.

Results consistent with no CP violation.

Analysis $D^0 \to \gamma\gamma$

arXiv:1512.02992 (Accepted by PRD)

Motivation:

- Decay not observed yet
- Sensitive to New Physics:
  - SM prediction: $\mathcal{B}r \approx (1-3) \times 10^{-8}$ (Phys. Rev. D 66, 014009 (2002))
  - MSSM model, gluino exchange: $\mathcal{B}r \approx 6 \times 10^{-6}$ (Phys. Lett. B 500, 304 (2001))

Analysis method:

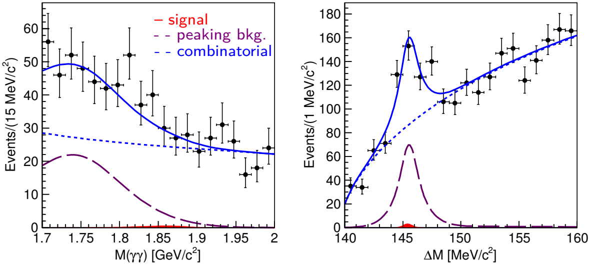
- D^0 from decay $D^{*+} \to D^0 \pi_s^+$
- 2d fit in $m(D^0)$ and Δm
- normalise $\mathcal{B}r$ w.r.t decay $D^0 \to K_S^0 \pi^0$

Peaking background:

- From decays with π^0 and/or η decaying to $\gamma\gamma$
- $D^0 \to \pi^0\pi^0$, $D^0 \to \eta\pi^0$, $D^0 \to \eta\eta$, $D^0 \to K_S^0(\to \pi^0\pi^0)\pi^0$, $D^0 \to K_L^0\pi^0$
- Suppress with $\pi^0(\eta)$ veto and suppression of merged ECL clusters

Signal extraction

- Signal fit on data:



  - Efficiency: 7.3%
  - Signal yield: 4 ± 15
- Same fit on normalisation mode:
  - Efficiency: 7.2%
  - Signal yield: 343050 ± 673
- Calculation of upper limit:
  - use frequentist method to estimate 90% C.L. upper limit

Systematics and result

Systematic uncertainties:

cut variation	$\pm 6.8\%$
signal PDF shape	$^{+4.0}_{-2.4}$ events
γ rec. eff.	$\pm 4.4\%$
K_S^0 reconstruction	$\pm 0.7\%$
π^0 identification	$\pm 4.0\%$
$\mathcal{B}r(D^0 \to K_S^0 \pi^0)$	$\pm 3.3\%$

Table: Systematic uncertainties.

Previous best result:

$$\mathcal{B}r(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6} \text{ at } 90\% \text{ C.L.}$$

BaBar collaboration (Phys. Rev. D 85, 091107 (2012))

Final result:

$$\mathcal{B}r(D^0 \to \gamma\gamma) < 8.4 \times 10^{-7} \text{ at } 90\% \text{ C.L.}$$

- most stringent upper limit to date

Summary

$D^0 \to V\gamma$ (PRELIMINARY RESULTS)

Branching fractions

$$\mathcal{B}r(D^0 \to \phi\gamma) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5}$$
$$\mathcal{B}r(D^0 \to \overline{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}$$
$$\mathcal{B}r(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$$

first observation!

CP asymmetries:

$$A_{CP}(D^0 \to \phi\gamma) = -(0.094 \pm 0.066 \pm 0.001)$$
$$A_{CP}(D^0 \to \overline{K}^{*0}\gamma) = -(0.003 \pm 0.020 \pm 0.000)$$
$$A_{CP}(D^0 \to \rho^0\gamma) = 0.056 \pm 0.151 \pm 0.006$$

First A_{CP} measurement.
No A_{CP} observed.

$D^0 \to \gamma\gamma$

$$\mathcal{B}r(D^0 \to \gamma\gamma) < 8.4 \times 10^{-7} \text{ at } 90\% \text{ C.L.}$$

Most stringent limit to date.

Backup

Current world average values for $\mathcal{B}r(D^0 \to V\gamma)$

	$\mathcal{B}r \times 10^{-5}$ (PDG)
$\phi\gamma$	(2.70 ± 0.35)
$\overline{K}^{*0}\gamma$	(32.7 ± 3.4)
$\rho^0\gamma$	< 24
$\omega\gamma$	< 24

Table: World average values of branching fractions of $D^0 \to V\gamma$ decays.

Selection criteria

$D^0 \to V\gamma$

	all	ϕ	$\overline{K}^{*0}$	ρ^0
Flavour tag	$D^{*+} \to D^0\pi_S^+$			
vertex fit	p value $> 10^{-3}$			
$p_{CMS}(D^{*+})$ [GeV/c]		>2.42	>2.17	>2.72
window in q [MeV/c^2]	± 0.6			
window in $m(V)$ [MeV/c^2]		± 11	± 60	± 150
E_γ [GeV]	>0.54			
E_9/E_{25}	>0.94			
$m(D^0)$ [GeV/c^2]	[1.67, 2.06]			
$\cos\theta_H$		[-1,1]	[-0.8, 0.4]	[-0.8, 0.4]

$D^0 \to \gamma\gamma$

$p_{CMS}(D^{*+})$	> 2.93 GeV/c
$\frac{\lvert E_{\gamma_1} - E_{\gamma_2}\rvert}{(E_{\gamma_1} + E_{\gamma_2})}$	< 0.5 GeV
E_γ	> 1 GeV
Prob(π^0)	< 0.2
dr	< 1 cm
$\lvert dz\rvert$	< 3 cm