CP violation in D meson decays at Belle

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Outline of the talk

- **Preliminary results** of the measurement of branching fraction and CP asymmetry in decays

$$\boxed{D^0 \to V\gamma}$$

(V $= \phi$, $\overline{K}^{*0}$ and ρ^0) with 943 fb^{-1} Belle data[1].

- **Results** from the rare decay analysis

$$\boxed{D^0 \to \gamma\gamma}$$

with 832 fb^{-1} Belle data[2].

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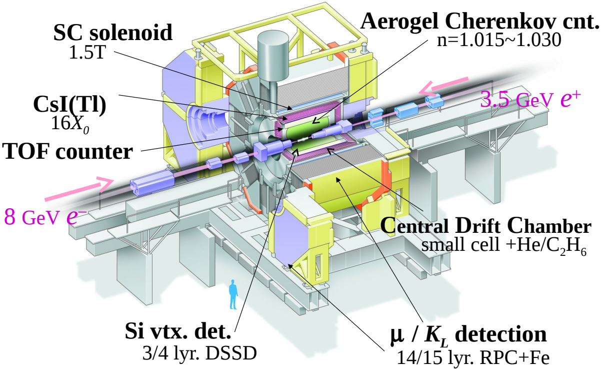
[1] arXiv:1603.03257v1 [hep-ex]
[2] Phys. Rev. D 93, **051102** (2016)

Belle detector

- Asymmetric e^+e^- collider operates at $\Upsilon(4S)$ resonance.
- More than the charm threshold, a lot of D mesons are produced.



$D^0 \to V\gamma$ decay

Motivation:

- Decay $D^0 \to \rho^0\gamma$ is not observed.
- Sensitive to new physics with A_{CP} measurements[1].
- Standard model prediction: $\mathcal{O}(10^{-3})$.
- No A_{CP} measurement yet in $D^0 \to V\gamma$ decays.

Previous results:

Collaboration	Luminosity	Decay mode	Branching fraction (BF)
Belle[2]	78 fb^{-1}	$D^0 \to \phi\gamma$	$\left(2.60^{+0.70}_{-0.61}(stat)^{+0.15}_{-0.17}(syst)\right) \times 10^{-5}$
BaBar[3]	387 fb^{-1}	$D^0 \to \phi\gamma$	$(2.73 \pm 0.30(stat) \pm 0.26(syst)) \times 10^{-5}$
BaBar[3]	387 fb^{-1}	$D^0 \to \overline{K}^{*0}\gamma$	$(3.22 \pm 0.20(stat) \pm 0.27(syst)) \times 10^{-4}$

Table : Previous BF measurements in $D^0 \to V\gamma$ decays.

[1] Phys. Rev. Lett. 109, **171801** (2010)
[2] Phys. Rev. Lett. 92, **101803** (2004)
[3] Phys. Rev. D 78, **071101** (2008)

Analysis strategy for $D^0 \to V\gamma$ decay

BF measurements:

$$\mathcal{B}_{\mathrm{sig}} = \mathcal{B}_{\mathrm{norm}} \times \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}} \times \frac{\epsilon_{\mathrm{norm}}}{\epsilon_{\mathrm{sig}}} \quad (1)$$

CP asymmetry:

$$A_{\mathrm{raw}} = \frac{N(D^0) - N(\overline{D^0})}{N(D^0) + N(\overline{D^0})} \quad (2)$$

$$A_{\mathrm{raw}} = A_{CP} + A_{FB} + A_{\epsilon}^{\pm} \quad (3)$$

$$A_{CP}^{\mathrm{sig}} = A_{\mathrm{raw}}^{\mathrm{sig}} - A_{\mathrm{raw}}^{\mathrm{norm}} + A_{CP}^{\mathrm{norm}} \quad (4)$$

• $\mathcal{B}$ and A_{CP} are extracted through **normalized** decay channels $\to$ ease the systematic studies.

Analysis strategy for $D^0 \to V\gamma$ decay (cont.)

Decay chain

$D^0 \to \phi\gamma \quad \to K^+K^-\gamma$

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

$D^0 \to \rho^0\gamma \quad \to \pi^+\pi^-\gamma$

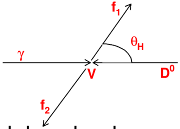
Normalization channels

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

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

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

- Flavour tagging: $D^* \to D^0\pi_{\rm slow}$.
- Background suppression with $\Delta M = M_{D^*} - M_{D^0}$ variable.
- Simultaneous 2D fit between M_{D^0} and $\cos(\theta_H)$ to extract the signal yield.



- Normalization mode: Sideband subtracted signal events from the signal window (SW).

Dominant backgrounds for $D^0 \to V\gamma$ decay

- $\pi^0 \to \gamma\gamma$ decay.
  - One photon misreconstructed as signal;
  - Overlap with the signal M_{D^0} peak.
- $D^0 \to V\pi^0$ or a different decay chain with the same final state (with high $\mathcal{B}$).
- π^0 vetos:
  - Diphoton mass close to that of M_{π^0};
  - Other photons with energies $>$ 75 MeV & 30 MeV;
  - Feed these two variables to neural network;
  - Output contains 85% signal while background rejected by 60%.

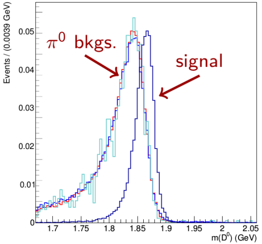


Figure : **The peaking backgrounds:** $\overline{K}^{*0}\pi^0$, $K^-\rho^+$ **and** $\overline{K}_0^*(1430)^-\pi^+$.

Results from $D^0 \to \phi\gamma$ decay

D^0 $\overline{D^0}$ D^0 $\overline{D^0}$

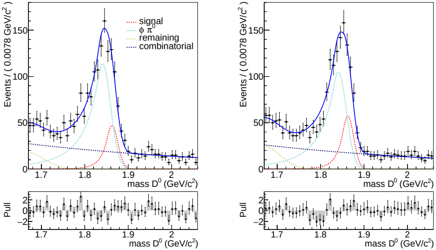


Figure : M_D distributions for ϕ mode.

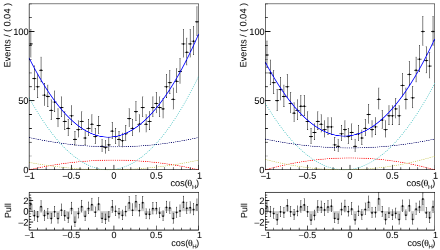


Figure : $\cos(\theta_H)$ distributions for ϕ mode.

- Efficiency $= 9.6\%$
- Signal yield $= 524 \pm 35$
- $\boxed{A_{\text{raw}} = -0.091 \pm 0.066}$

Results from $D^0 \to \overline{K}^{*0}\gamma$ decay

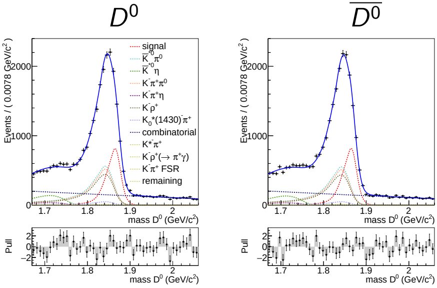


Figure : M_D distributions for $\overline{K}^{*0}$ mode.

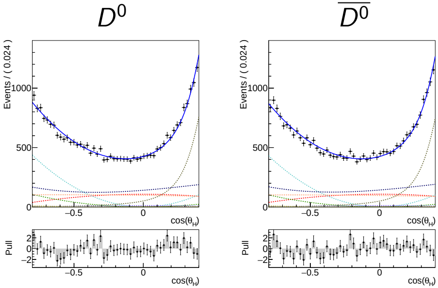


Figure : $\cos(\theta_H)$ distributions for $\overline{K}^{*0}$ mode.

- Efficiency $= 7.8\%$
- Signal yield $= 9104 \pm 396$
- $\boxed{A_{\rm raw} = -0.002 \pm 0.020}$

Results from $D^0 \to \rho^0\gamma$ decay

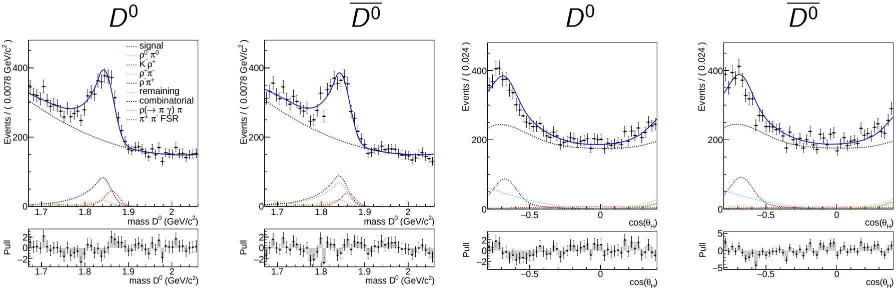


Figure : M_D distributions for ρ^0 mode.

Figure : $\cos(\theta_H)$ distributions for ρ^0 mode.

- Efficiency $= 6.8\%$
- Signal yield $= 500 \pm 85$
- $A_{\mathrm{raw}} = 0.064 \pm 0.151$

Systematics for $D^0 \to V\gamma$ decay

Source	$D^0 \to \phi\gamma$		$D^0 \to \overline{K}^{*0}\gamma$		$D^0 \to \rho\gamma$	
	$\mathcal{B}$ (%)	$A_{CP} \times 10^{-3}$	$\mathcal{B}$ (%)	$A_{CP} \times 10^{-3}$	$\mathcal{B}$ (%)	$A_{CP} \times 10^{-3}$
γ rec. eff	2	-	2	-	2	-
ΔM	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 shape	1.39	0.32	-	-	2.33	4.29
Background shape	0.95	0.30	2.81	0.41	3.00	3.78
Norm modes systematics	0.05	0.46	0.00	0.01	0.14	0.54
Total	3.06	0.64	3.80	0.41	4.58	5.74

Results (Preliminary)

Branching fractions:

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

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

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

Consistent with the previous measurements.

3.3σ difference with the BaBar result.

First observation.

A_{CP} **values:**

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

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

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

First measurement of A_{CP} in $D^0 \to V\gamma$ mode.

Results consistent with **no CP violation**.

A_{CP} is statistically dominated, so it is of great interest at **Belle II**.

$D^0 \to \gamma\gamma$ decay

Motivation:

- The decay is not observed yet.
- Sensitive to new physics.
  - Standard model (SM) prediction[1] $\mathcal{B} \approx 10^{-8}$;
  - MSSM predicts $\mathcal{B} \approx 10^{-6}$ with gluino exchange[2].

Previous best result:

- BaBar collaboration[3]:

$$\mathcal{B}(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6} \tag{5}$$

with 90% C.L with 470.5 fb^{-1} data.

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[1] Phys. Rev. D 66, **014009** (2002)
[2] Phys. Lett. B 500, **304** (2001)
[3] Phys. Rev. D 85, **091107** (2012)

Analysis strategy for $D^0 \to \gamma\gamma$ decay

- Flavour tagging: $D^* \to D^0\pi_{\rm slow}$.
- Signal extraction: From 2D fit between M_{D^0} and ΔM.
- Normalization decay channel: $D^0 \to K^0_S\pi^0$.
- Dominant (peaking) backgrounds:
  - $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$;
  - $D^0 \to \pi^0\pi^0$, $D^0 \to \eta\pi^0$, $D^0 \to \eta\eta$, $D^0 \to K^0_S\pi^0$ and $D^0 \to K^0_L\pi^0$;
  - Use $\pi^0(\eta)$ veto and E_9/E_{25} cut to reduce these backgrounds.

Signal extraction for $D^0 \to \gamma\gamma$ decay

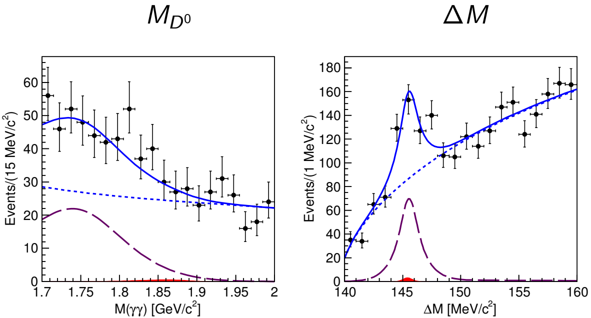

Figure : 2D fit between M_{D^0} and ΔM where combinatoric and peaking backgrounds are shown in dotted blue & magenta colours and the signal is shown in red.

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

- Efficiency = 7.3%
- Signal yield = 4 ± 15

$D^0 \to K_S^0\pi^0$:

- Efficiency = 7.2%
- Signal yield = 343050 ± 673

Systematics and result for $D^0 \to \gamma\gamma$ decay

- Cut variation $\to E_{\gamma 2}$, A_E and $\mathcal{P}(\pi^0)$ variables.

Source	Contribution
Cut variation	$\pm$ 6.8 %
signal shape	$^{+4}_{-2.4}$ events
γ rec. eff	$\pm$ 4.4 %
K_S^0 reconstruction	$\pm$ 0.7 %
π^0 identification	$\pm$ 4.0 %
$\mathcal{B}(D^0 \to K_S^0\pi^0)$	$\pm$ 3.3 %

Table : Systematic uncertainties for $D^0 \to \gamma\gamma$ study.

Result:

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

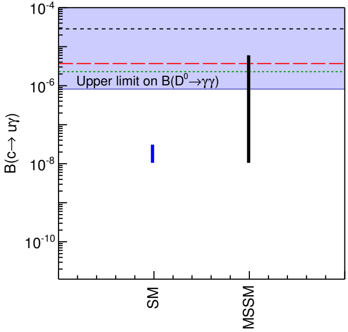

Figure : Our result, BaBar, BESIII, CLEO results. BF predictions of $c \to u\gamma$ transitions: **SM** and **MSSM**.

Summary

$D^0 \to V\gamma$ analysis:

- $\mathcal{B}(D^0 \to \phi\gamma) \to$ consistent with the previous Belle and BaBar results.
- $\mathcal{B}(D^0 \to \overline{K}^{*0}\gamma) \to$ different by 3.3σ from BaBar result.
- $\mathcal{B}(D^0 \to \rho^0\gamma) \to$ first observation.

- $A_{CP} \to$ first measurements.

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

- $\mathcal{B}(D^0 \to \gamma\gamma) \to$ most stringent limit with 90% C.L.

Back up - Normalization channels used for $D^0 \to V\gamma$ decay

Decay channel	Efficiency (%)	Yield	A_{raw} $(\times 10^{-3})$
$D^0 \to K^+K^-$	22.7	362274	2.2 ± 1.7
$D^0 \to K^-\pi^+$	27.0	4.02×10^6	1.3 ± 0.5
$D^0 \to \pi^+\pi^-$	21.4	127683	8.2 ± 3.0

Table : A_{raw} for the control samples used for $D^0 \to V\gamma$ study.