



# Search of CP violation in $D$ Decays to radiative and hadronic decays + search for rare D decay at Belle

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(On behalf of Belle Collaboration)

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# Talk Outline



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- ▶ Measurement of branching fraction and CP asymmetry in decays  
 $D^0 \rightarrow V\gamma$  ( $V = \phi, \bar{K}^{*0}, \rho^0$ )  
[Preliminary result, arXiv:1603.03257]
- ▶ Measurement of CP asymmetry in  $D^0 \rightarrow K_S^0 \bar{K}_S^0$  decay  
[Preliminary result]  
Shown for the first time
- ▶ Search for rare decay  $D^0 \rightarrow \gamma\gamma$   
[PRD 93 (2016) 051102]



# INTRODUCTION : CPV in D decays to radiative and hadronic decays



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- ▶ SM expects CP violation in charm sector to be  $\mathcal{O}(0.1)\%$
- ▶ In 2012 LHCb measured an unexpectedly high value of  $A_{CP}(D^0 \rightarrow KK(\pi\pi))$  **PRL 108 (2012) 111602**

Experiment	$\Delta A_{CP}(\%)$	References
BaBar	$+0.24 \pm 0.61 \pm 0.18$	<b>PRL 100 (2008) 061803</b>
CDF	$-0.62 \pm 0.21 \pm 0.10$	<b>PRL 109 (2012) 111801</b>
Belle	$-0.87 \pm 0.41 \pm 0.06$	<b>PoS ICHEP (2012)</b>
LHCb	$+0.14 \pm 0.16 \pm 0.08$	<b>JHEP 07(2014) 041</b>
LHCb	$-0.10 \pm 0.08 \pm 0.03$	<b>PRL 116 (2016) 19160</b>
HFAG	$-0.137 \pm 0.070$	<b>HFAG 2016</b>

- ▶ Neutral modes not easy for LHCb, limited results from CLEO
- ▶ Belle is very capable to measure neutral final states, obtain the most precise measurements:

$$A_{CP}(D^0 \rightarrow \pi^0 \pi^0) = [-0.03 \pm 0.64 \pm 0.10]\%$$

$$A_{CP}(D^0 \rightarrow K_S \pi^0) = [-0.21 \pm 0.16 \pm 0.07]\% \quad \textcolor{red}{PRL 112 (2014) 211601}$$



# Search for CP violation in $D^0 \rightarrow V\gamma$ ,

$$V = \phi, \bar{K}^{*0}, \rho^0$$



## Motivation:

- Sensitive to new physics with  $A_{CP}$  measurements

G. Isidori and J. F. Kamenik, PRL 109 (2012) 171801

- Decay  $D^0 \rightarrow \rho^0\gamma$  is not observed
  - Standard model prediction:  $\mathcal{O}(10^{-3})$ .
  - No  $A_{CP}$  measurement yet in  $D^0 \rightarrow V\gamma$  decays.

Experiment	Luminosity	Decay	$\mathcal{B} \times 10^{-5}$	References
Belle	$78 \text{ fb}^{-1}$	$D^0 \rightarrow \phi\gamma$	$2.60^{+0.70+0.15}_{-0.61-0.17}$	PRD 92 (2004) 101803
BaBar	$387 \text{ fb}^{-1}$	$D^0 \rightarrow \phi\gamma$	$2.73 \pm 0.30 \pm 0.26$	PRD 78 (2008) 071101
BaBar	$387 \text{ fb}^{-1}$	$D^0 \rightarrow \bar{K}^{*0}\gamma$	$32.2 \pm 2.00 \pm 2.70$	PRD 78 (2008) 071101



# Methods

- Decay chain

$$D^0 \rightarrow \phi\gamma \rightarrow K^+K^-\gamma$$

$$D^0 \rightarrow \bar{K}^{*0}\gamma \rightarrow K^-\pi^+\gamma$$

$$D^0 \rightarrow \rho^0\gamma \rightarrow \pi^+\pi^-\gamma$$

- Flavour tag :  $D^0$  from  $D^*$

- Background suppression with  $q \simeq m_{D^*} - m_{D^0} - M_{\pi^+}$

- Signal extraction : Simultaneous 2D fit of  $M_{D^0}$  and  $\cos(\theta_H)$

- $\cos(\theta_H)$  distribution  $\propto 1 - \cos^2(\theta_H)$

►  $\mathcal{B}$  measurement  $\mathcal{B}_{sig} = \mathcal{B}_{norm} \times \frac{N_{sig}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}}$

► CP asymmetry

$$A_{raw} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = A_{CP} + A_{FB} + A_{\epsilon}^{\pi_s^\pm}$$

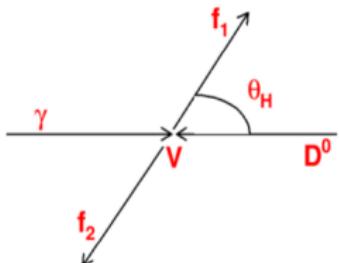
$$A_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{norm} + A_{CP}^{norm}$$

Normalization mode

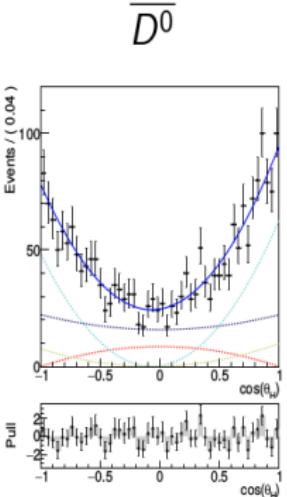
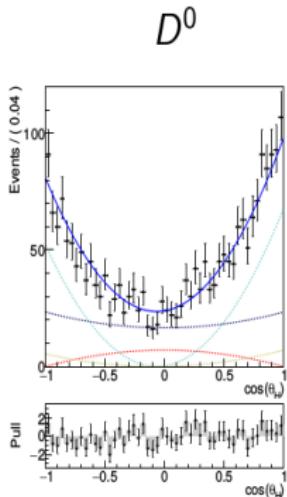
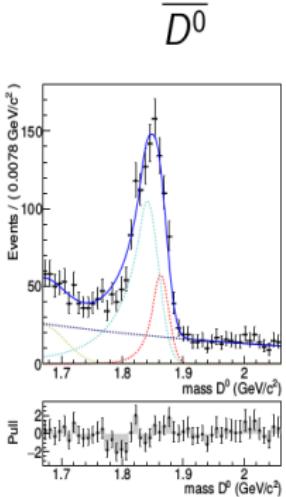
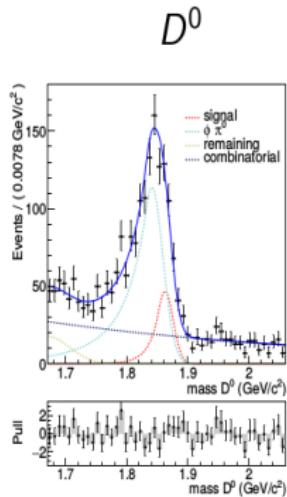
$$D^0 \rightarrow K^+K^-$$

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

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



# Results from $D^0 \rightarrow \phi\gamma$ decay



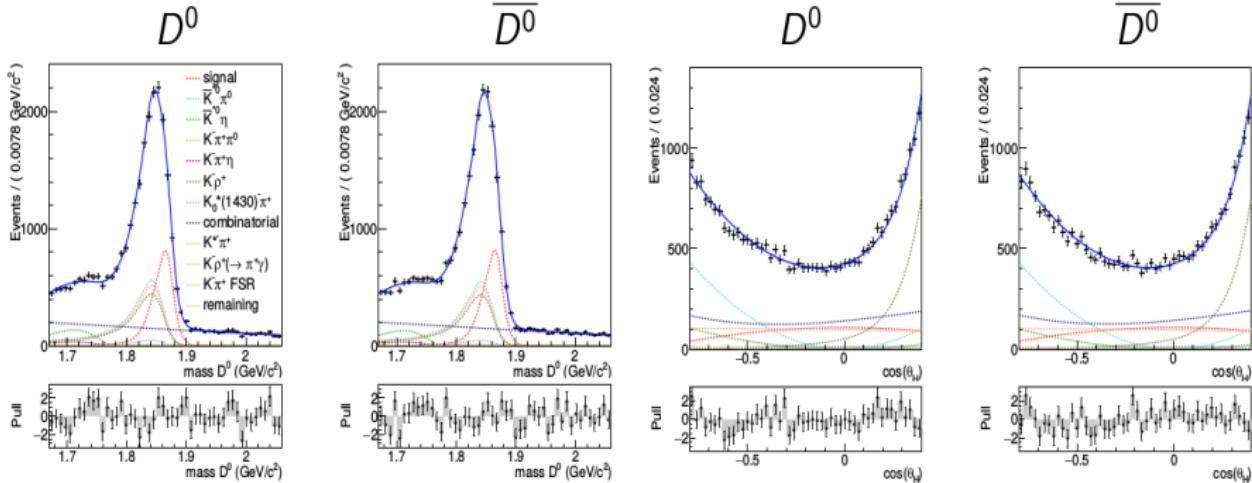
Mass  $D^0$  ( $\text{GeV}/c^2$ )

- Efficiency = 9.7%
- Signal yield =  $524 \pm 35$

$\cos(\theta_H)$



# Results from $D^0 \rightarrow \bar{K}^{*0}\gamma$ decay



Mass  $D^0$  (GeV/ $c^2$ )

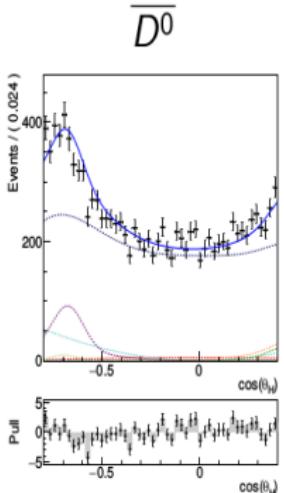
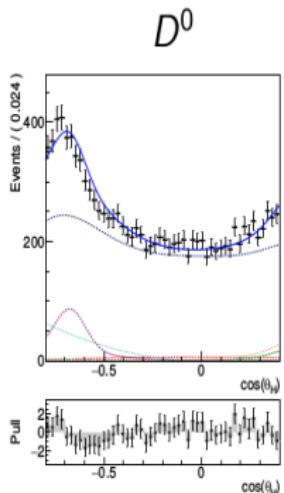
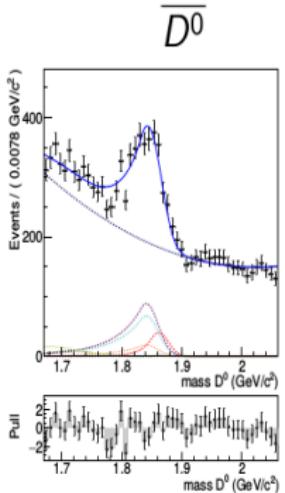
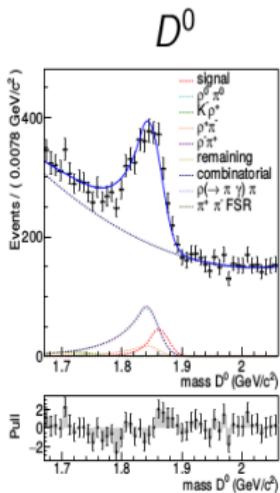
- Efficiency = 7.8%
- Signal yield =  $9104 \pm 396$

$\cos(\theta_H)$



# Results from $D^0 \rightarrow \rho^0 \gamma$ decay

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Mass  $D^0$  ( $\text{GeV}/c^2$ )

- Efficiency = 6.8%
- Signal yield =  $500 \pm 85$

$\cos(\theta_H)$



# Preliminary results of $D^0 \rightarrow V\gamma$ decay



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- Branching fractions:

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

Consistent with results by Belle, BaBar  
3.3 $\sigma$  away from the BaBar result.  
First observation

- $A_{CP}$  values :

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

First measurement of  $A_{CP}$   
Results consistent with no CPV  
 $A_{CP}$  is statistically dominated

[arXiv:1603.03257]



# Study of CP violation in $D^0 \rightarrow K_S^0 K_S^0$



- ▶ SM limit 1.1% for direct CPV in  $D^0 \rightarrow K_S^0 K_S^0$

U. Nierste and A. Schacht, PRD 92 (2015) 054036

- ▶ SCS decays (such as  $D^0 \rightarrow K_S^0 K_S^0$ ) are special interest: possible interference with NP amplitude could lead to larger nonzero CPV

- ▶ The previous measured  $A_{CP}$  ( $D^0 \rightarrow K_S^0 K_S^0$ ):

- CLEO  $(-23 \pm 19)\%$   $13.7 \text{ fb}^{-1}$  PRD 63 (2001) 071101
- LHCb  $(-2.9 \pm 5.2 \pm 2.2)\%$   $3 \text{ fb}^{-1}$  JHEP 10 (2015) 055

- ▶ Method:  $A_{CP}^{D^0 \rightarrow K_S^0 K_S^0} = (A_{D^0 \rightarrow K_S^0 K_S^0}^{rec} - A_{D^0 \rightarrow K_S^0 \pi^0}^{rec}) + (A_{CP}^{D^0 \rightarrow K_S^0 \pi^0}) + A_\epsilon^{K^0/\bar{K}^0}$

$$A_\epsilon^{K^0/\bar{K}^0} = (-0.11 \pm 0.01)\% \quad [\text{B. R. Ko et al., PRD 84 (2011) 111501}]$$

$A_\epsilon^{K^0/\bar{K}^0}$ : Asymmetry originating from the different strong interaction of  $K^0$  and  $\bar{K}^0$  mesons with nucleons of the detector material

$$A_{CP}^{D^0 \rightarrow K_S^0 \pi^0} = (-0.20 \pm 0.17)\% \quad [\text{PDG}]$$



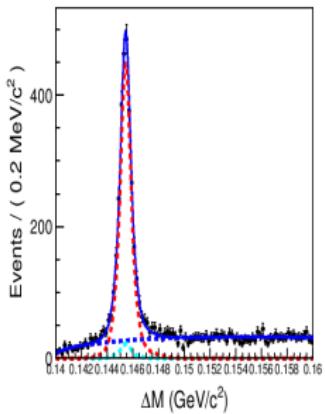
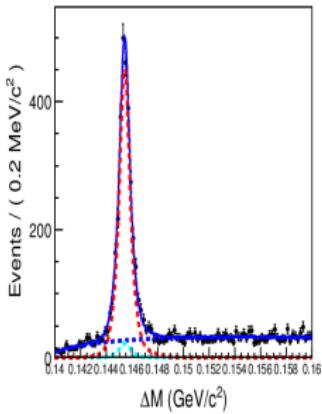
# $D^0 \rightarrow K_S^0 K_S^0$ Decay

- ▶ Cut Optimization with the Figure of merit =  $\frac{N_S}{\sqrt{N_S + N_B}}$ 
  - $N_S$  and  $N_B$  : signal (scaled with PDG  $\mathcal{B}$ ) and background yield (scaled with Data/MC in the  $\Delta M$  sideband ( $0.148 < \Delta M < 0.16 \text{ GeV}/c^2$ )) in the signal window
  - $K_S^0$  within  $15 \text{ MeV}/c^2$  of nominal ,  $D^*$  momentum at CM  $> 2.2 \text{ GeV}/c$
- ▶ Peaking background  $D^0 \rightarrow K_S^0 \pi\pi$  ( $D^0 \rightarrow \pi\pi\pi^0$ ) in  $D^0 \rightarrow K_S^0 K_S^0$  ( $D^0 \rightarrow K_S^0 \pi^0$ ) is estimated in the  $K_S^0$  mass sideband,  $0.470 < M_{\pi\pi} < 0.478 \text{ GeV}/c^2$  and  $0.516 < M_{\pi\pi} < 0.526 \text{ GeV}/c^2$  and fixed yield in the  $\Delta M$  fit
- ▶  $A_{raw}$  extraction: Simultaneous fit of  $\Delta M$  for  $D^0$  and  $\bar{D}^0$



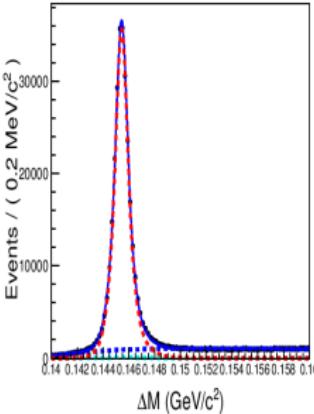
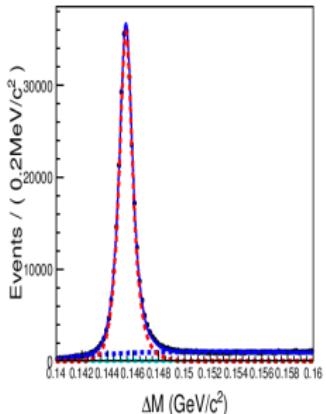
# $D^0 \rightarrow K_S^0 K_S^0$ Decay

$D \rightarrow K_S^0 K_S^0$  : Signal mode



- Efficiency =  $(11.04 \pm 0.02)\%$
- Signal Yield =  $5399 \pm 87$
- $A^{raw} = (0.45 \pm 1.53)\%$

$D \rightarrow K_S^0 \pi^0$  : Normalization mode



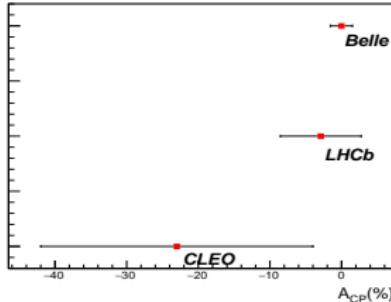
- Efficiency =  $(12.60 \pm 0.02)\%$
- Signal Yield =  $531807 \pm 796$
- $A^{raw} = (0.16 \pm 0.14)\%$



## systematic uncertainties

Source	Systematic uncertainty, in %
Signal shape	$\pm 0.01$
Peaking background	$\pm 0.01$
$K^0 / \bar{K}^0$ material effects	$\pm 0.01$
$A_{CP}$ measurement of $K_S^0 \pi^0$	$\pm 0.17$
Total	$\pm 0.17$

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.17)\% \text{ [Preliminary result]}$$



Consistent with no CPV, improve precision of previous best measurement by more than a factor 3 !!



# Search for rare decay $D \rightarrow \gamma\gamma$

- Motivation:

- ▶ SM prediction  $\mathcal{B} \sim 10^{-8}$  [G. Burdman et al., PRD 66 \(2002\) 014009](#)
- ▶ MSSM predicts  $\mathcal{B} \sim 10^{-6}$  with gluino exchange [S. Prelovsek and D. Wyler, PLB 500 \(2001\) 304](#)

Experiment	Luminosity	$\mathcal{B}$ UL at 90% C.L.	References
CLEO	$13.8 \text{ fb}^{-1}$	$2.9 \times 10^{-5}$	<a href="#">PRL 90 (2003) 101801</a>
BaBar	$470.5 \text{ fb}^{-1}$	$2.2 \times 10^{-6}$	<a href="#">PRD 85 (2012) 091107</a>
BESIII	$2.92 \text{ fb}^{-1}$	$3.8 \times 10^{-6}$	<a href="#">PRD 91 (2015) 112015</a>

- To suppress combinatorial background:  $D^{*+} \rightarrow D^0 \pi_s^+$
- Signal extraction: from 2D fit of  $M_{\gamma\gamma}$  and  $\Delta M$  ( $M_{D^*} - M_{D^0}$ )
- Normalization mode:  $D^0 \rightarrow K_S^0 \pi^0$ .
- Dominant peaking backgrounds :  $D^0 \rightarrow \pi^0 \pi^0$ ,  $D^0 \rightarrow \eta \pi^0$ ,  $D^0 \rightarrow K_S^0 \pi^0$  and



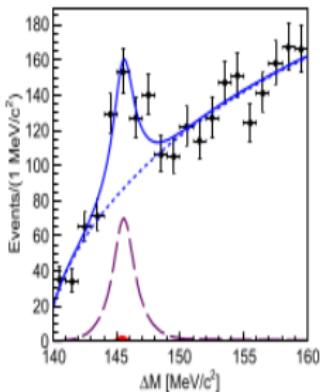
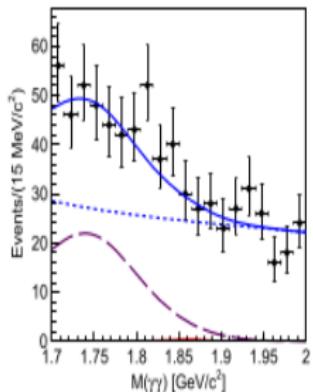
$D^0 \rightarrow K_L^0 \pi^0$  : Use  $\pi^0$  veto and  $\frac{E_9}{E_{25}}$  cut to reduce these backgrounds



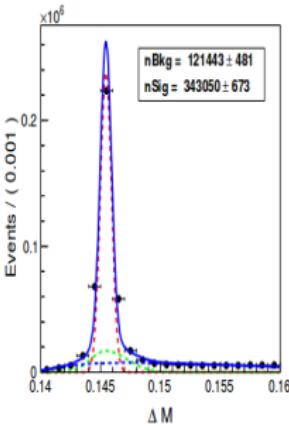
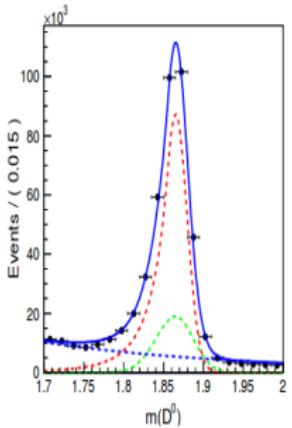
# Search for rare decay $D \rightarrow \gamma\gamma$

Signal extraction : Data sample  $832 \text{ fb}^{-1}$ ,  $\Upsilon(4S)$  and  $\Upsilon(5S)$  resonances

$D \rightarrow \gamma\gamma$  : Signal mode



$D \rightarrow K_S^0 \pi^0$  : Normalization mode



- Efficiency = 7.3%
- Signal Yield =  $4 \pm 15$

- Efficiency = 7.2%
- Signal Yield =  $343050 \pm 673$

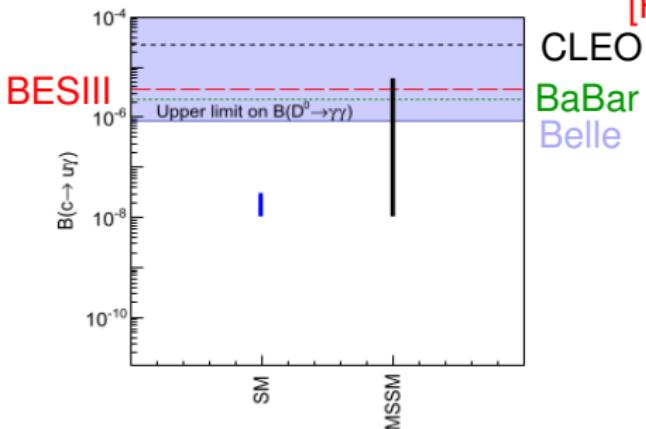
- Dominant peaking backgrounds :  $D^0 \rightarrow \pi^0 \pi^0$ ,  $D^0 \rightarrow \eta \pi^0$ ,  $D^0 \rightarrow \eta \eta$ ,  $D^0 \rightarrow K_S^0 (\pi^0 \pi^0) \pi^0$  and  $D^0 \rightarrow K_L^0 \pi^0$



# Result for $D \rightarrow \gamma\gamma$ decay

Result :  $\mathcal{B}(D \rightarrow \gamma\gamma) < 8.5 \times 10^{-7}$  with 90 % C.L

[PRD 93 (2016) 051102]



BF predictions of  $c \rightarrow u\gamma$  transitions: SM and MSSM

- Most restrictive limit on  $D \rightarrow \gamma\gamma$  to date
- Can be used to constrain NP parameter space
- Probe further at the next-generation Belle II experiment



# Summary

- ▶  $D^0 \rightarrow V\gamma$  decay : [arXiv:1603.03257]
  - $\mathcal{B}(D^0 \rightarrow \phi\gamma) \rightarrow$  consistent with the previous Belle and BaBar results
  - $\mathcal{B}(D^0 \rightarrow \bar{K}^{*0}\gamma) \rightarrow$  different by  $3.3\sigma$  from BaBar result
  - $\mathcal{B}(D^0 \rightarrow \rho\gamma) \rightarrow$  first observation
  - $A_{CP} \rightarrow$  first measurements and consistent with SM
  - $A_{CP}$  is statistically dominated, great interest at Belle II.
- ▶  $D^0 \rightarrow K_S^0 K_S^0$  decay : [New result, shown for the first time]
  - $A_{CP} \rightarrow$  consistent with SM
  - significant improvement compared to the previous measurement of CLEO and LHCb Collaborations
- ▶ Rare decay  $D^0 \rightarrow \gamma\gamma$  decay : [PRD 93 (2016) 051102]
  - $\mathcal{B}(D^0 \rightarrow \gamma\gamma) \rightarrow$  most stringent limit with 90% C.L.
  - Interesting analysis for Belle II

THANK YOU...



38th INTERNATIONAL CONFERENCE  
ON HIGH ENERGY PHYSICS  
AUGUST 3 - 10, 2016  
CHICAGO



# BACKUP

- Cut variation:  $E_{\gamma 2}$  (lower energy photon),  $A_E$  (energy asymmetry between the two  $\gamma$ ) and probabilities  $P_{\pi^0}$  variables.

TABLE I. Summary of systematic uncertainties for  $D^0 \rightarrow \gamma\gamma$ .

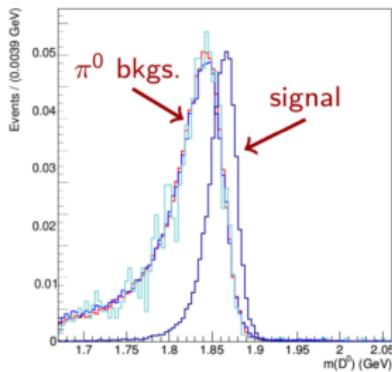
Source	Contribution
Cut variation	$\pm 6.8\%$
PDF shape	$^{+4.0}_{-2.4}$ events
Photon detection	$\pm 4.4\%$
$K_S^0$ reconstruction	$\pm 0.7\%$
$\pi^0$ identification	$\pm 4.0\%$
$\mathcal{B}(D^0 \rightarrow K_S^0 \pi^0)$	$\pm 3.3\%$

[PRD 93 (2016) 051102]



- Dominant backgrounds for  $D^0 \rightarrow V\gamma$  decay

- $\pi^0 \rightarrow \gamma\gamma$  decay.
  - One photon misreconstructed as signal.
  - Overlap with the signal  $M_{D^0}$  peak.
- $D^0 \rightarrow V\pi^0$  or a different decay chain with the same final stage (with high ( $\mathcal{B}$ ))).
- $\pi^0$  vetos:
  - Diphoton mass close to that of  $M_{\pi^0}$ ;
  - Other photons with energies >75 MeV & 30 MeV
  - Feed these two variables to neural network
  - Output contains 85% signal while background rejected by 60%.
- Peaking backgrounds :  $D^0 \rightarrow K^{*-0}\pi^0$ ,  $D^0 \rightarrow K^-\rho^+$  and  $D^0 \rightarrow \bar{K}_0^*(1430)^-\pi^+$



# Systematics for $D^0 \rightarrow V\gamma$ decay

Source	$D^0 \rightarrow \phi\gamma$		$D^0 \rightarrow \bar{K}^{*0}\gamma$		$D^0 \rightarrow \rho\gamma$	
	$\mathcal{B}$ (%)	$A_{CP} \times 10^{-3}$	$\mathcal{B}$ (%)	$A_{CP} \times 10^{-3}$	$\mathcal{B}$ (%)	$A_{CP} \times 10^{-3}$
$\gamma$ rec. eff	2	-	2	-	2	-
$\Delta M$	1.16	-	1.16	-	1.16	-
$\pi^0$ 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

