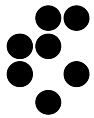
SEARCH FOR CP VIOLATION IN RADIATIVE AND HADRONIC D^0 DECAYS AT BELLE

Tara Nanut



on behalf of the Belle Collaboration

The XIIIth International Conference on Heavy Quarks and Leptons

26 May 2016

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.

- Results of the study of the rare decay

  $D^0 \to \gamma\gamma$

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

- Results of the measurement of *CP* asymmetry in decay

  $D^0 \to \pi^0\pi^0$

  on 966 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 $D^0 \to V\gamma$

Previous results:

- Belle (PRL 92, 101803 (2004)):
  $\mathcal{B}(D^0 \to \phi\gamma) = 2.60^{+0.70}_{-0.61}(stat.)^{+0.15}_{-0.17}(syst.) \times 10^{-5}$
- BaBar (PRD 78, 071101 (2008)):
  $\mathcal{B}(D^0 \to \phi\gamma) = 2.73 \pm 0.30 \pm 0.26 \times 10^{-5}$
  $\mathcal{B}(D^0 \to \overline{K}^{*0}\gamma) = 3.22 \pm 0.20 \pm 0.27 \times 10^{-4}$

Analysis method

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

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:

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

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

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

- Branching fraction:

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

- *CP* asymmetry:

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

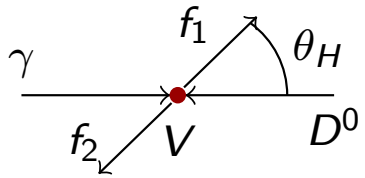
$$A_{\text{raw}} = A_{CP} + A_{\text{FB}} + A_{\varepsilon}^{\pm}$$

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

Analysis method

- Flavour tag: D^0 from decay $D^{*+} \to D^0 \pi_s^+$
  (also background suppression with requirement on $\Delta m = m(D^{*+}) - m(D^0)$)

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

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

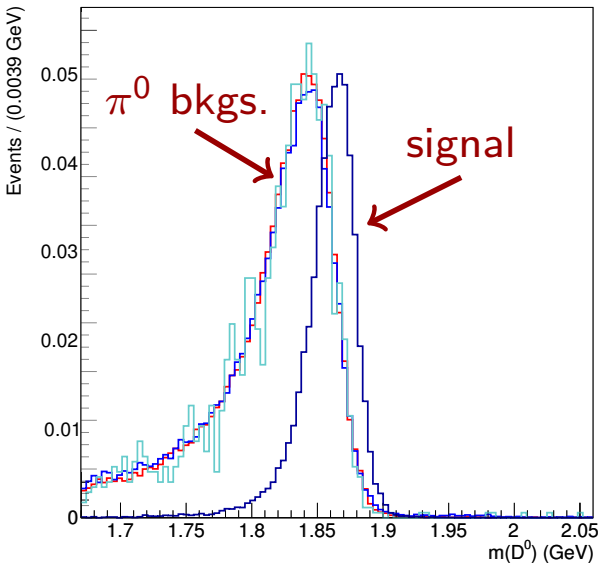
get on MC

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

use on data

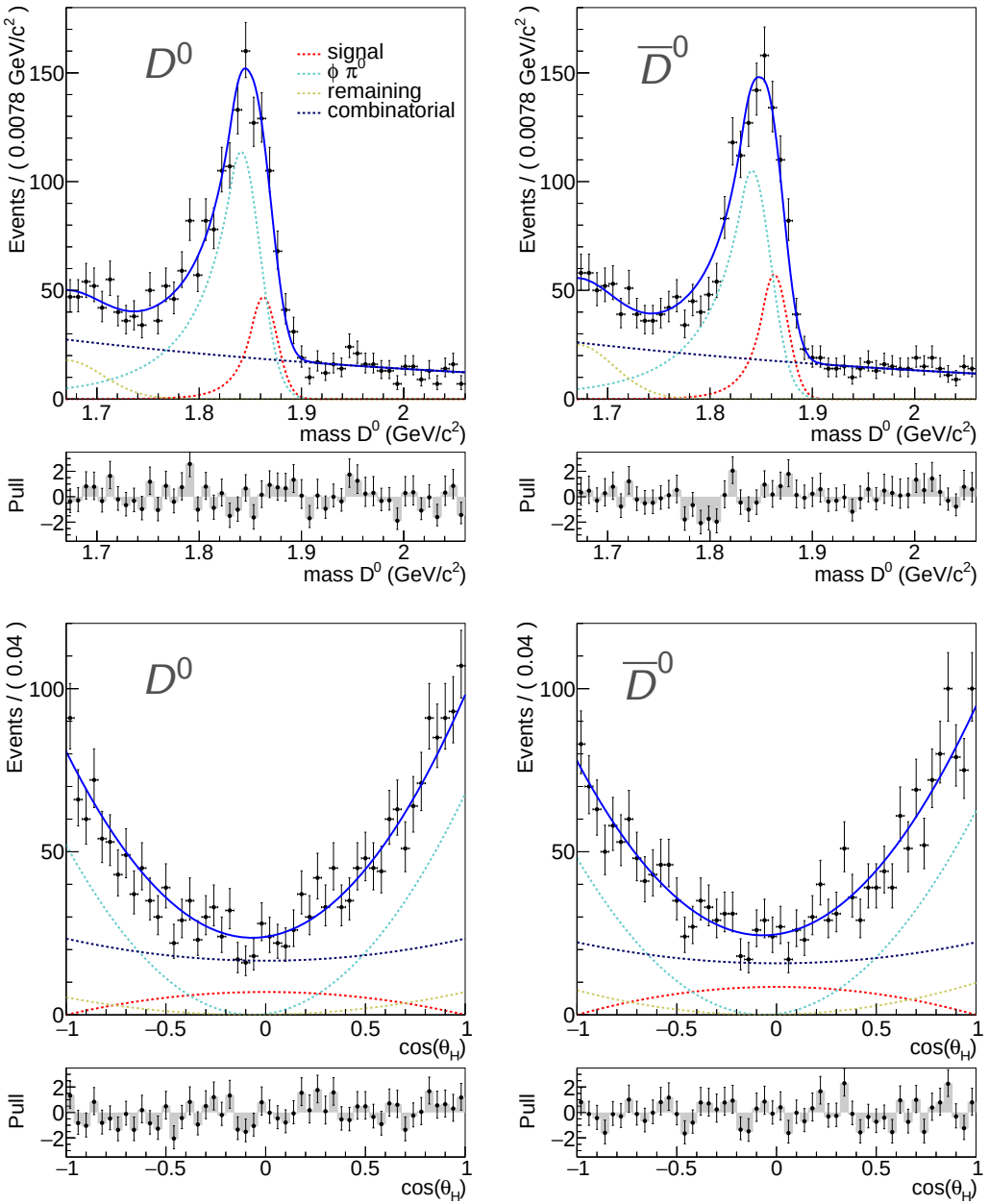
Dominant background

- 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 $D^0 \to \phi\gamma$

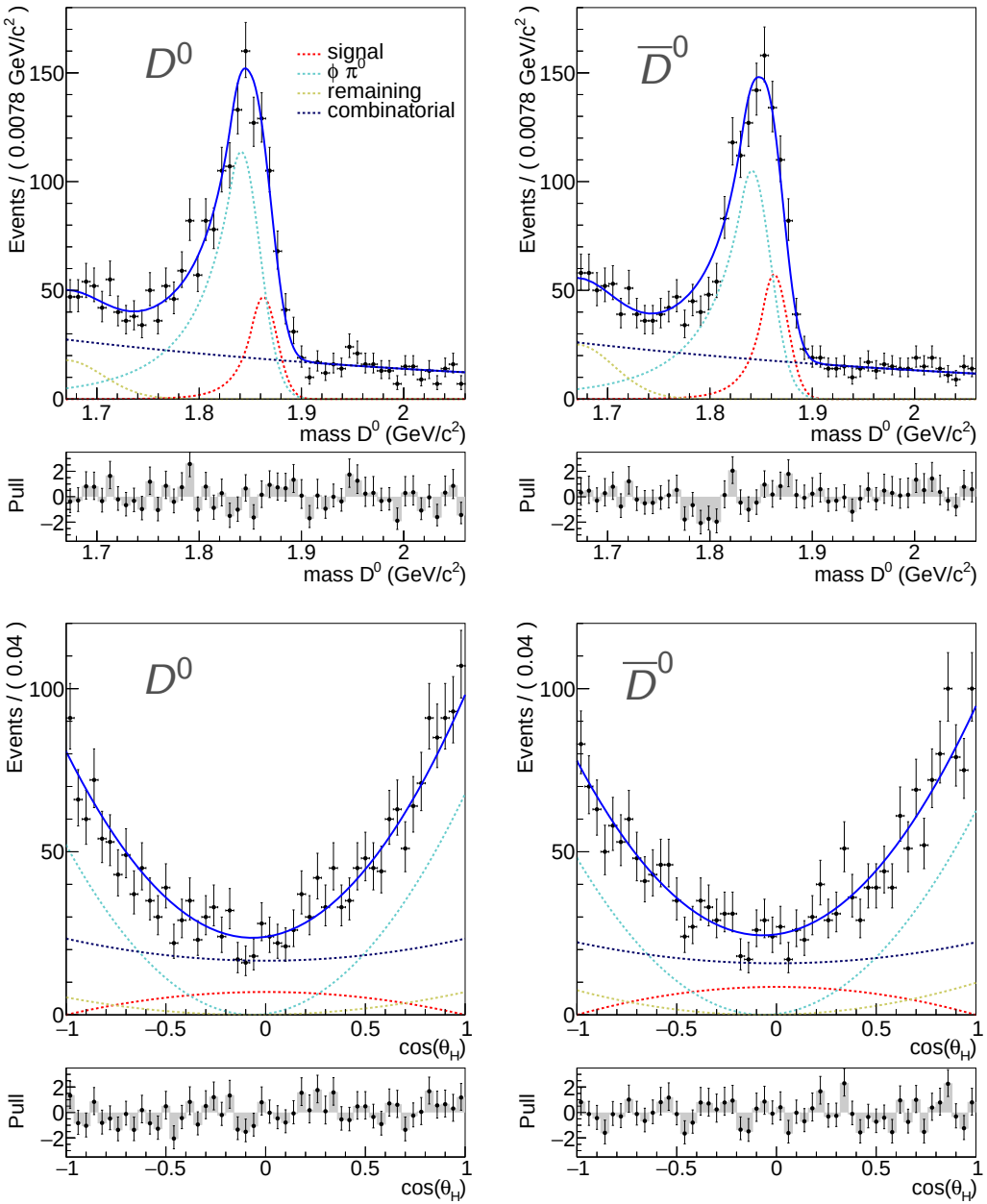


Efficiency: 9.6%

Signal yield: 524$\pm$35

Raw asymmetry: -0.091$\pm$0.066

Fit results $D^0 \to \phi\gamma$

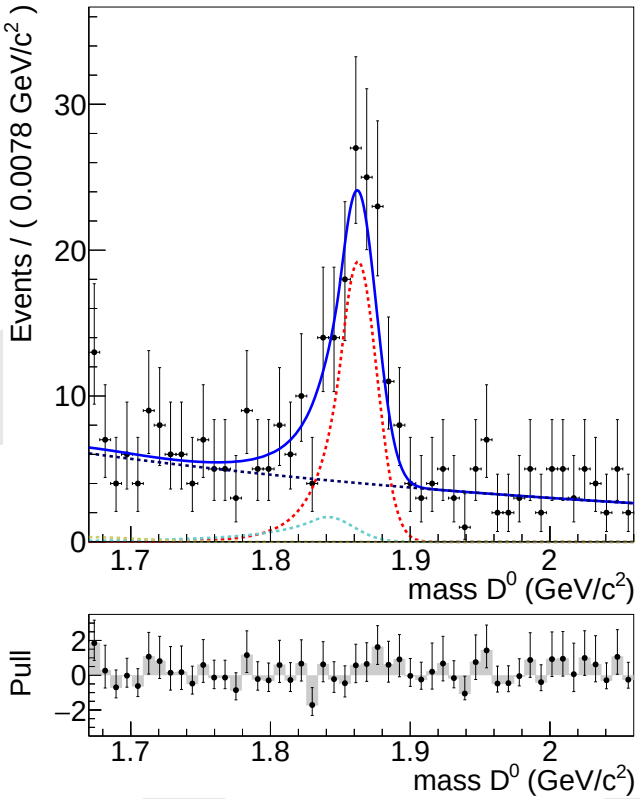


Efficiency: 9.6%

Signal yield: 524±35

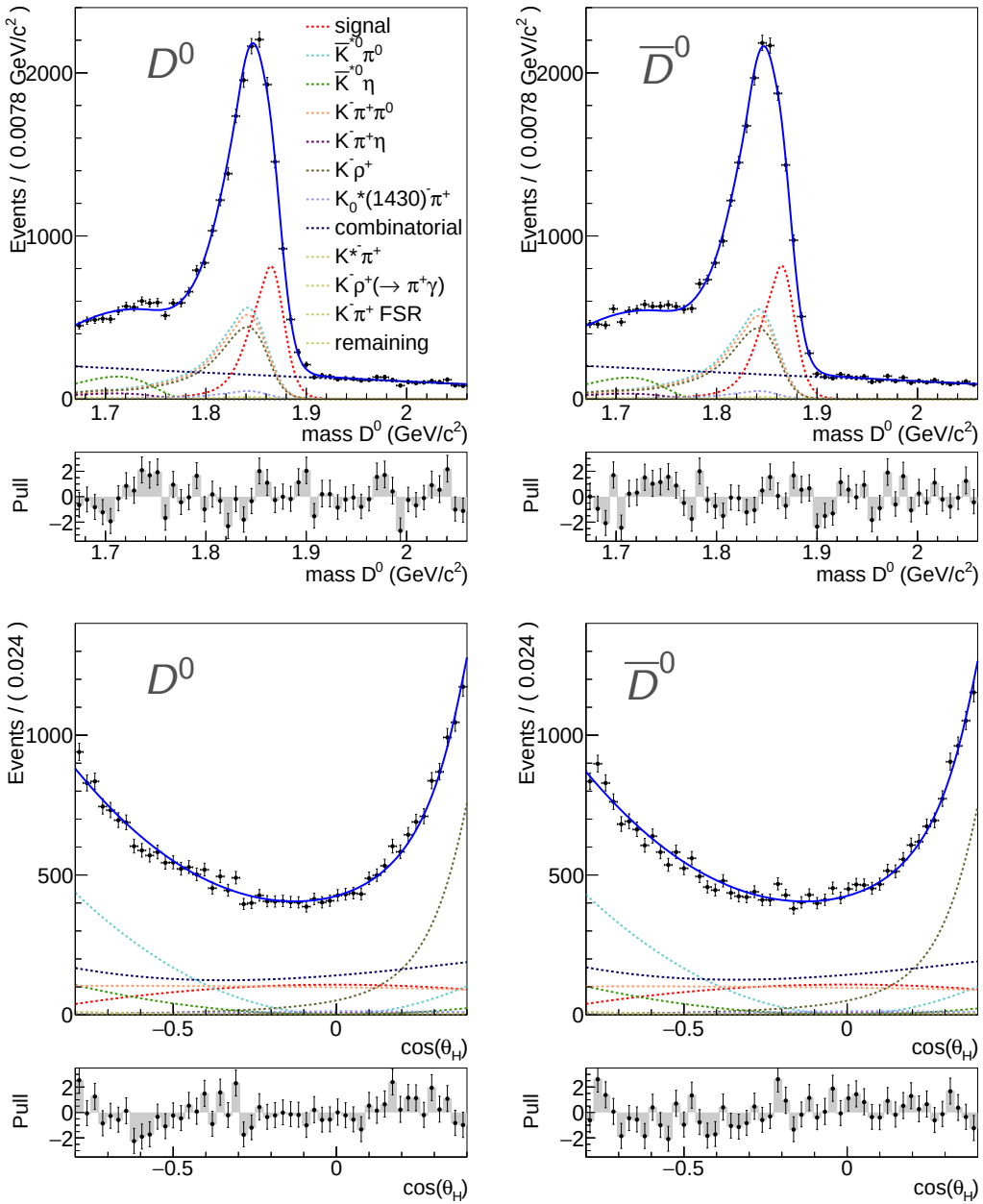
Raw asymmetry: -0.091±0.066

Signal enhanced:



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

Fit results $D^0 \to \overline{K}^{*0}\gamma$

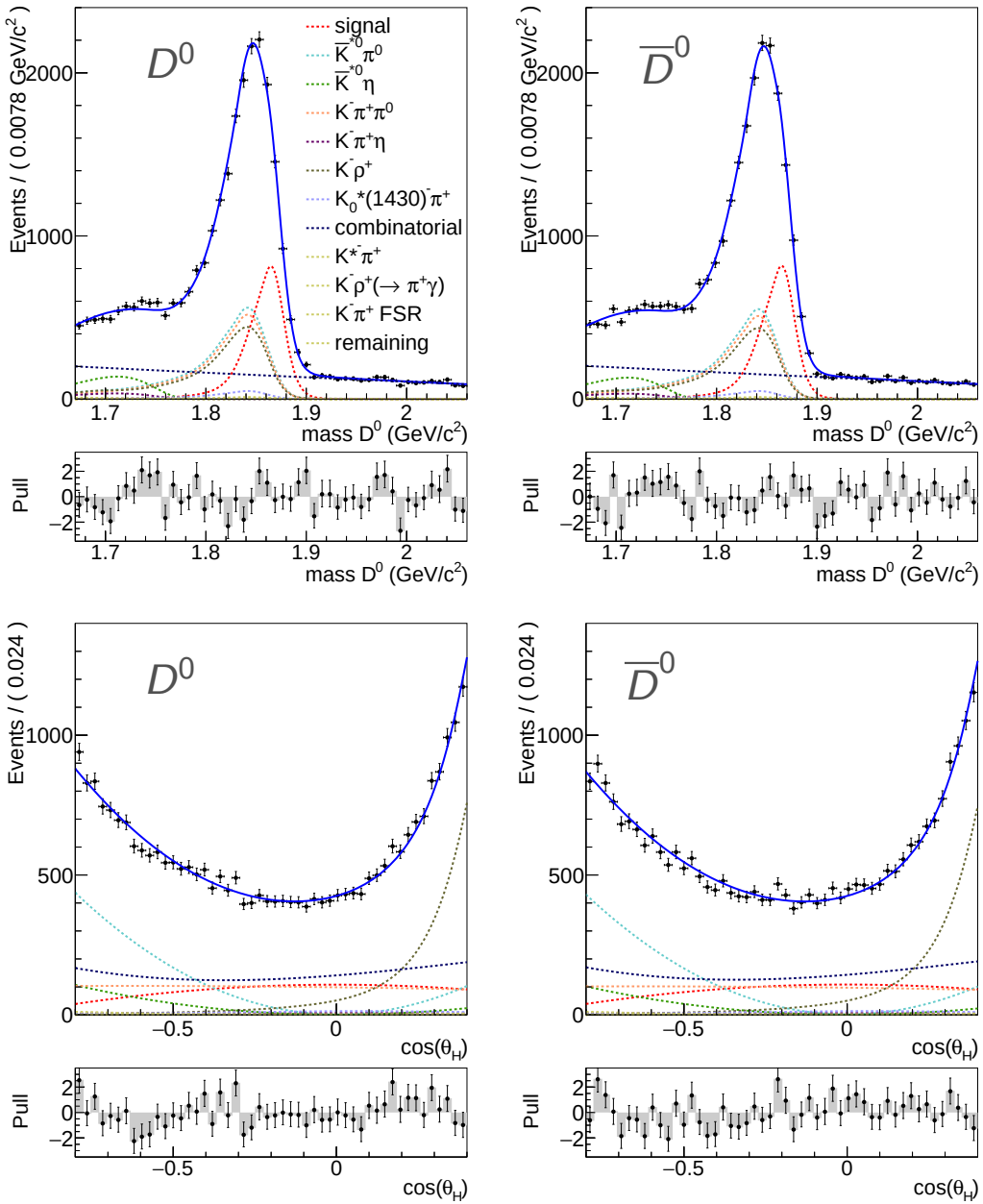


Efficiency: 7.8%

Signal yield: 9104$\pm$396

Raw asymmetry: -0.002$\pm$0.020

Fit results $D^0 \to \overline{K}^{*0}\gamma$



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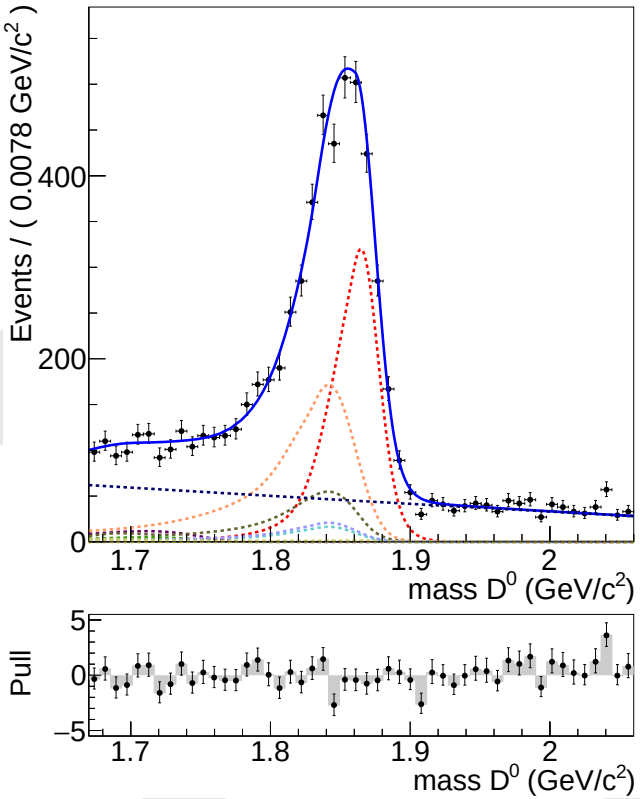
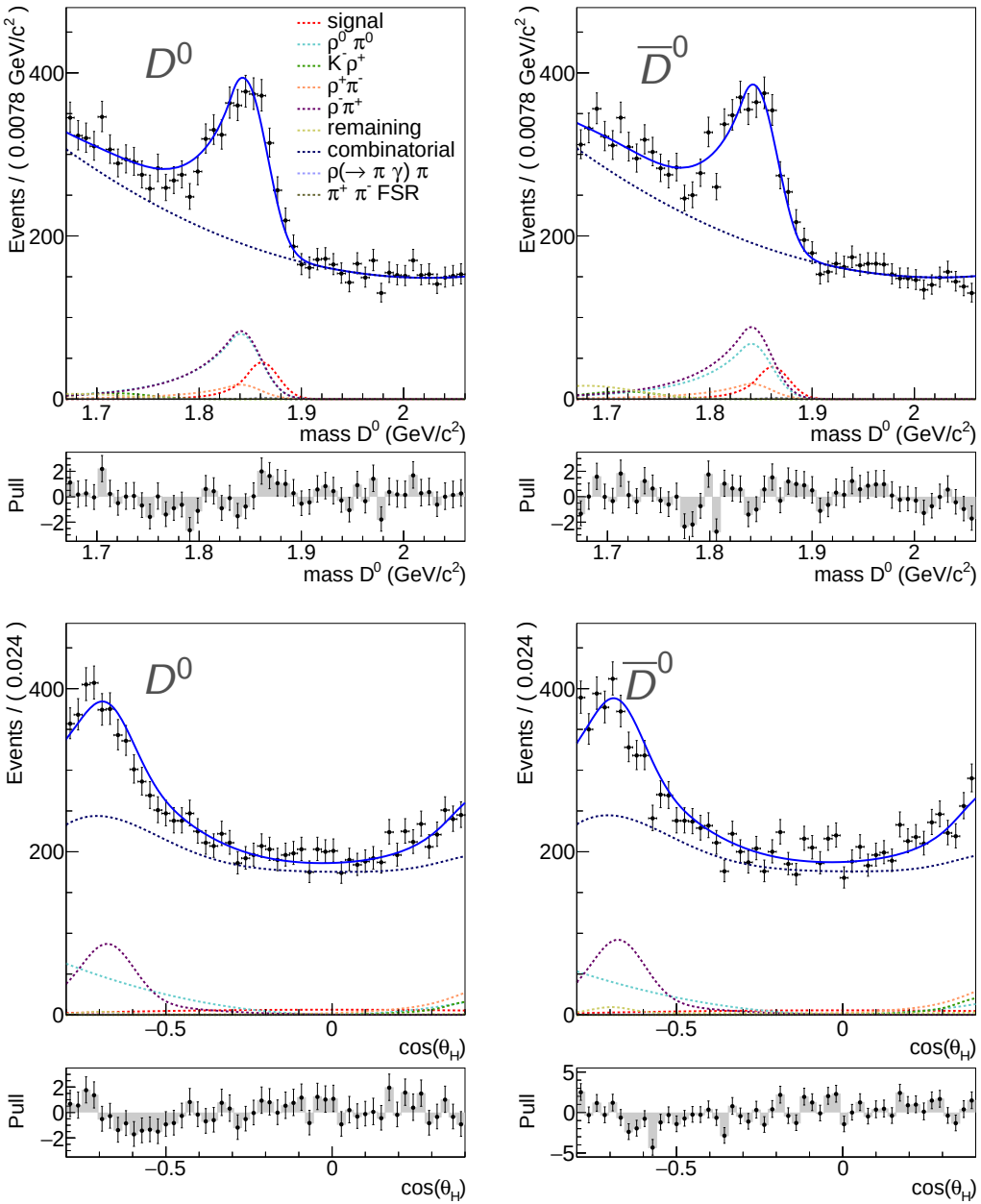


$-0.2 < \cos(\theta_H) < 0.0$

Fit results $D^0 \to \rho^0\gamma$

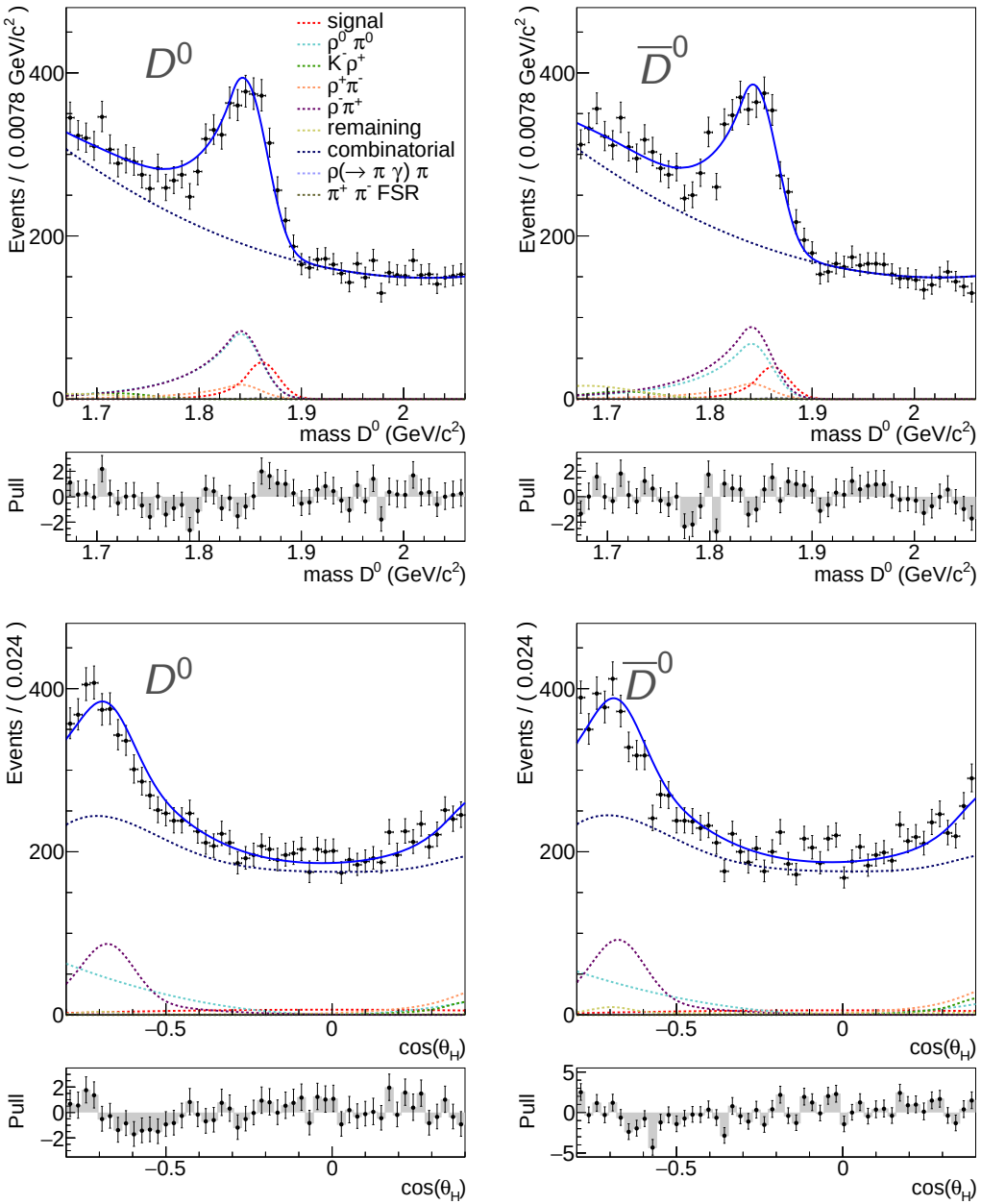


Efficiency: 6.8%

Signal yield: 500 ± 85

Raw asymmetry: 0.064 ± 0.151

Fit results $D^0 \to \rho^0\gamma$



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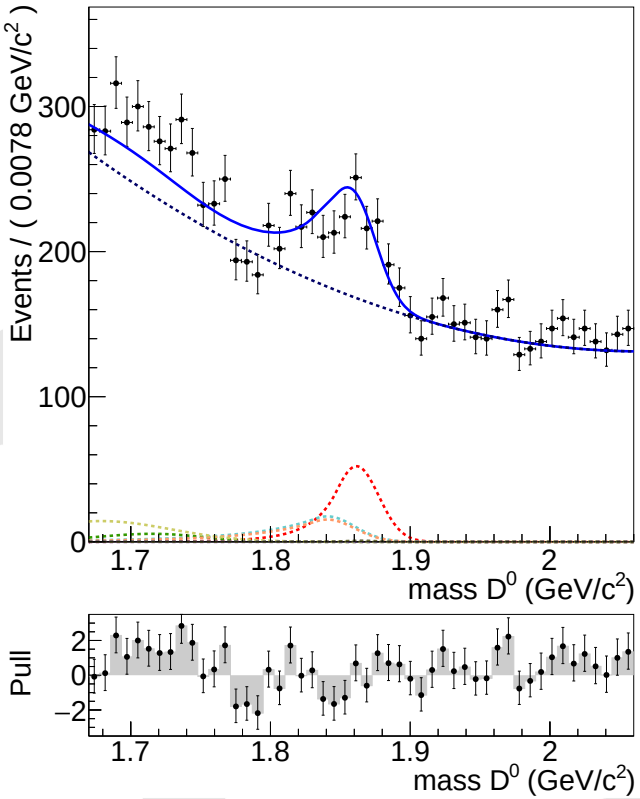
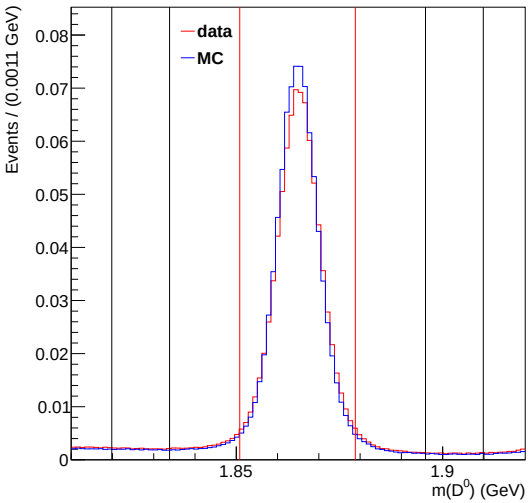


$-0.3 < \cos(\theta_H) < 0.3$

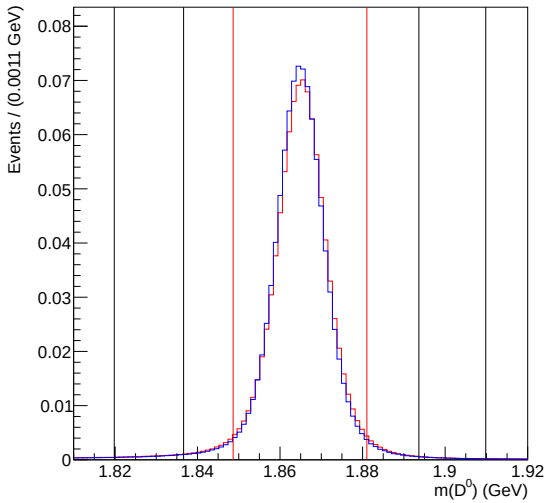
Normalisation channels

	Efficiency	Yield	$A_{raw}[\times 10^{-3}]$
K^+K^-	22.7%	362274	2.2 ± 1.7
$K^-\pi^+$	27.0%	4.02×10^6	1.3 ± 0.5
$\pi^+\pi^-$	21.4%	127683	8.2 ± 3.0

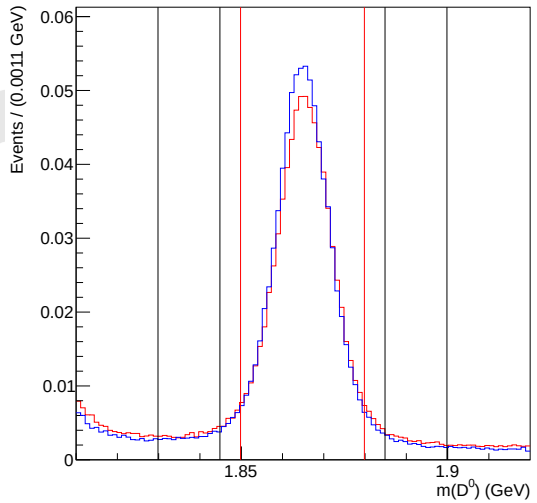
$D^0 \to K^+K^-$



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



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



Systematic uncertainties

	$D^0 \to \phi\gamma$		$D^0 \to \overline{K}{}^{*0}\gamma$		$D^0 \to \rho^0\gamma$	
	$\mathcal{B}r$[%]	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	–
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 parametrisation	1.39	0.32	–	–	2.33	4.29
bkg. parametrisation	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	3.8	0.41	4.58	5.74

Table: Systematic uncertainties.

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 results by Belle, BaBar

3.3σ away from BaBar result
$((3.22 \pm 0.20 \pm 0.27) \times 10^{-4})$

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: $\mathcal{B} \approx (1-3) \times 10^{-8}$ (Phys. Rev. D 66, 014009 (2002))
  - MSSM model, gluino exchange: $\mathcal{B} \approx 6 \times 10^{-6}$ (Phys. Lett. B 500, 304 (2001))

Previous best result:

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

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

Analysis method

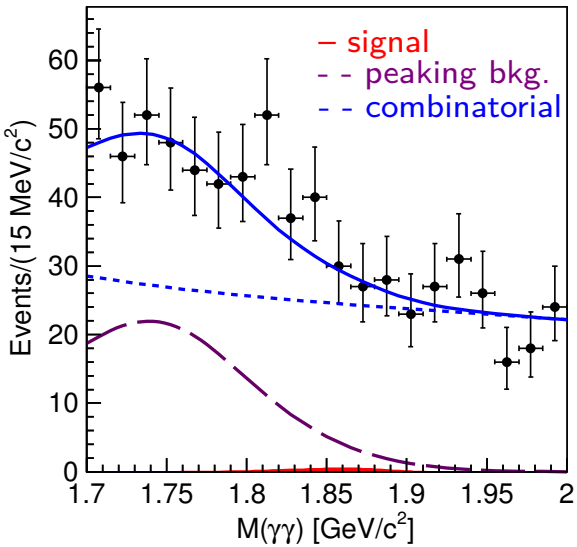
- D^0 from decay $D^{*+} \to D^0 \pi_s^+$
- 2d fit in $m(D^0)$ and Δm
- normalise $\mathcal{B}$ w.r.t decay $D^0 \to K_S^0 \pi^0$

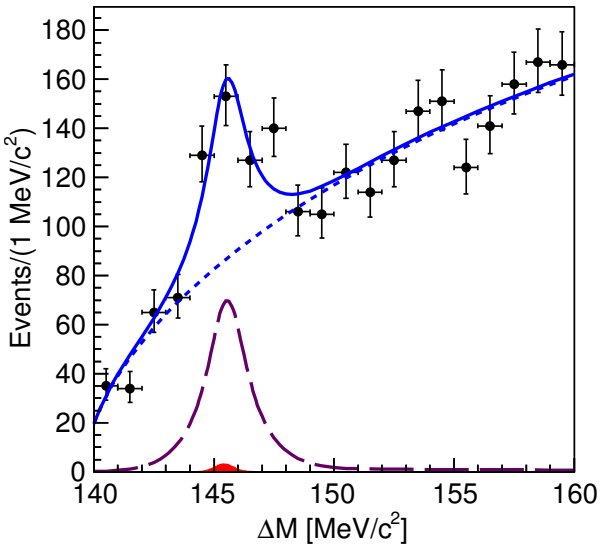
Peaking background:

- 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

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^0_S reconstruction	$\pm 0.7\%$
π^0 identification	$\pm 4.0\%$
$\mathcal{B}(D^0 \to K^0_S \pi^0)$	$\pm 3.3\%$

Table: Systematic uncertainties.

- Calculation of upper limit:
  - use frequentist method to estimate 90% C.L. upper limit

Final result:

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

- most stringent upper limit to date

Analysis $D^0 \to \pi^0\pi^0$

Phys. Rev. Lett. 112, 211601 (2014)

Motivation:

- Singly Cabibbo-suppressed: enhanced possibility of New Physics contributions to A_{CP}
- Not measured at B-factories before

Only previous result:
by CLEO collaboration (Phys. Rev. D 63, 071101 (2001)):

$$A_{CP}(D^0 \to \pi^0\pi^0) = (0.1 \pm 4.8)\%$$

Analysis method

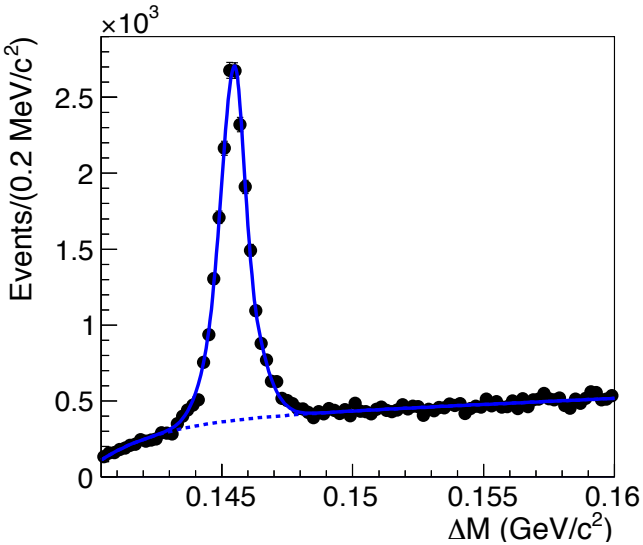
- Flavour tag: D^0 from decay $D^{*+} \to D^0 \pi_s^+$
- Fit Δm simultaneously for $D^0, \overline{D}^0$, in bins of $(\cos(\theta^*), p_T^{\pi S}, \cos(\theta^{\pi S}))$, extract A_{raw} for each bin
- $A_{\text{raw}} = A_{CP} + A_{\text{FB}} + A_{\varepsilon}^{\pi_s^+}$
  - Determine $A_{\varepsilon}^{\pi_s^+}$ from tagged and untagged $D^0 \to K^-\pi^+$, subtract and obtain $A_{raw}^{corr} = A_{CP} + A_{\text{FB}}$ in $\cos(\theta^*)$ bins
  - A_{FB} is an odd function in $\cos(\theta^*)$, therefore

$$A_{CP} = \frac{1}{2}(A_{raw}^{corr}(\cos(\theta^*)) + A_{raw}^{corr}(-\cos(\theta^*))$$

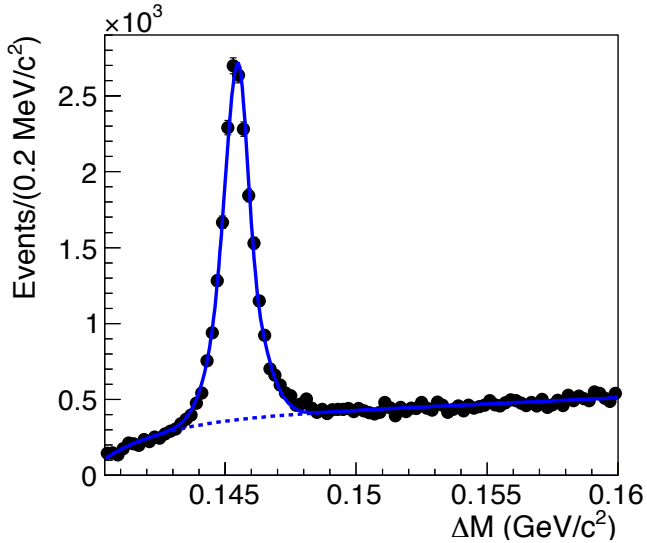
- Obtain average A_{CP} via a χ^2 fit on values in bins of $\cos(\theta^*)$

Fit results

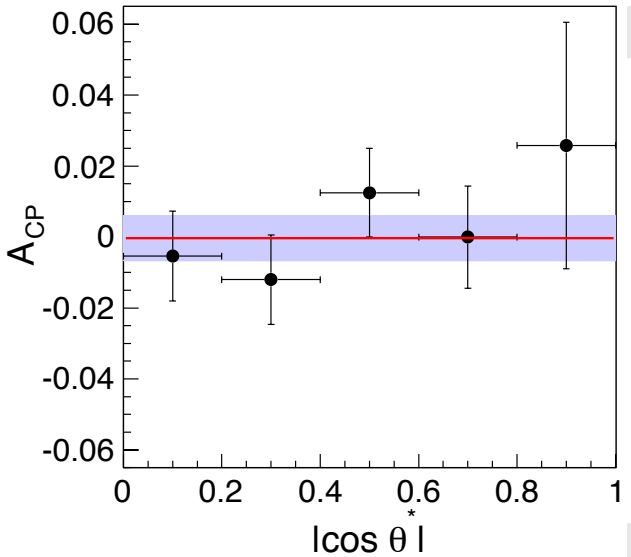
D^0



$\overline{D}^0$



Combined signal yield: 34460 ± 273



Systematics and result

signal shape	0.03
π_S correction	0.07
A_{CP} extraction method	0.07
Total	0.10

Table: Systematic uncertainties.

Final result:

$$A_{CP} = [-0.03 \pm 0.64(stat.) \pm 0.10(syst.)]\%$$

Result is consistent with no CPV.

Summary

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

Branching fractions

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

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.

$D^0 \to \gamma\gamma$

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

Most stringent limit to date.

$D^0 \to \pi^0\pi^0$

$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.1)\%$

No A_{CP} observed.