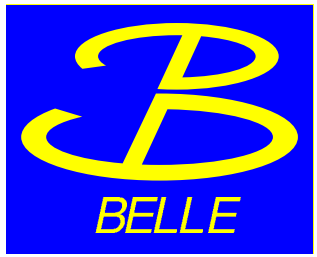
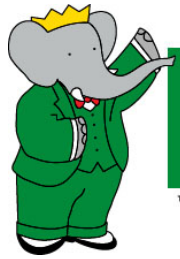
Charm Physics at B-factories: rare, mixing and CPV

Longke Li[1] (李龙科)
(On behalf of Belle Collaboration)

[1]University of Science and Technology of China (USTC)





BABAR™

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The 16th International Conference on B-physics at Frontier Machines
2 - 6 May 2016, Marseille, France

Outline

1. Belle and BABAR at B-factories

2. neutral D mixing and CP violation
   - CP-eigenstates decays $D^0 \to KK/\pi\pi$
   - Wrong-Sign decay $D^0 \to K^+\pi^-$
   - Three-body self-conjugated decays

3. direct CP violation in charm decays
   - direct CP violation in $D^0 \to \pi^0\pi^0$
   - direct CP violation in $D^+_{(s)}$ decays

4. Rare or radiative charm decays
   - Flavor-changing radiative decays $D^0 \to V\gamma$
   - Branch ratio of $D^0 \to \gamma\gamma$

Available Charm samples from Charm factories, B-factories, hadron colliders

Experiment	Machine	Operation	C.M (GeV)	Lumin.	N(D)	efficiency
CLEO	CESR (e^+e^-)	2003-2008	3.77	0.8 fb^{-1}	2.9 M 2.3 M($D^{\pm}$)	∼10-30%
			4.17	0.6 fb^{-1}	0.6 M	
BESIII	BEPC-II (e^+e^-)	2010-2011	3.77	2.92 fb^{-1}	10.5 M 8.4 M ($D^{\pm}$)	
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BELLE	KEKB (e^+e^-)	1999-2008	10.58	1000 fb^{-1}	1.3 G	∼5-10%
	PEP-II (e^+e^-)	1999-2008	10.58	500 fb^{-1}	0.65 G	
					★★	★★
CDF II	Tevatron ($p\bar{p}$)	2002-2011	1960	9.6 fb^{-1}	0.13 T	<0.5%
LHCb	LHC (pp)	2011	7000	1.0 fb^{-1}	5.0 T	
		2012	8000	2.0 fb^{-1}		
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here we used $\sigma(D^0\bar{D}^0@3.77\ GeV)$=3.61 nb, $\sigma(D^+D^-@3.77\ GeV)$=2.88 nb, $\sigma(D^*D_s@4.17\ GeV)$=0.967 nb, $\sigma(c\bar{c}@10.58\ GeV)$=1.3 nb, $\sigma(D^0@LHCb)$=1.661 nb. The table mainly refers to Int. J. Mod. Phys. A **29** (2014) 24, 14300518.

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@B-factories

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D^0-$\bar{D}^0$ mixing and CP violation

- Flavor eigenstates (D^0, $\bar{D}^0$) $\neq$ mass eigenstates ($D_{1,2}$ with $m_{1,2}$ and $\Gamma_{1,2}$).

$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle \text{ (CPT: } p^2 + q^2 = 1).$$

- Mixing parameters:

$$\mathbf{x} \equiv 2\frac{m_1 - m_2}{\Gamma_1 + \Gamma_2}, \quad \mathbf{y} \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

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$$D_{\text{no-mixing}}(t) = \left|\langle D^0|D^0(t)\rangle\right|^2 = e^{-\Gamma t}\frac{\cosh(y\Gamma t)+\cos(x\Gamma t)}{2}$$

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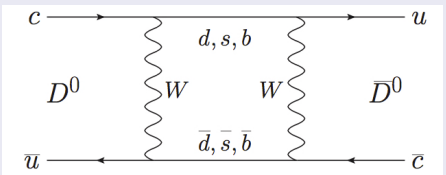

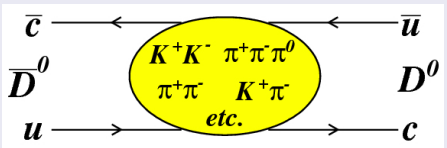

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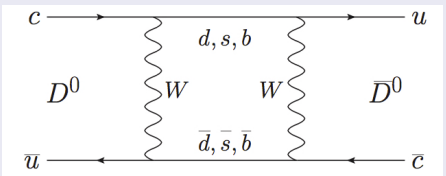

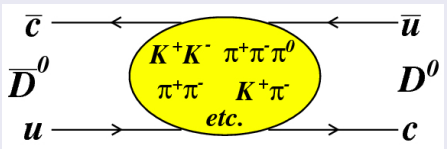

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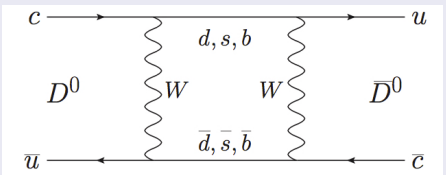

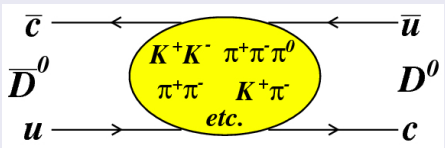

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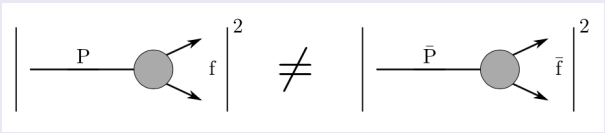
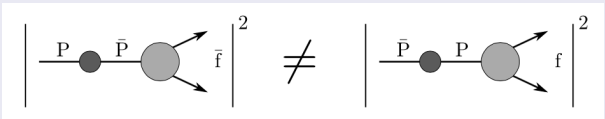
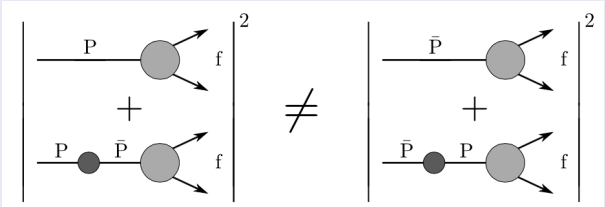


- in mixing (indirect): $r_m = |q/p| \neq 1$



- in the interference: $\arg(q/p) \neq 0$



Regular analysis techniques at B-factories

- tag D^0 flavor using the charge of slow pions from $D^{*\pm}(\to D^0\pi_s^+/\bar{D}^0\pi_s^-)$.
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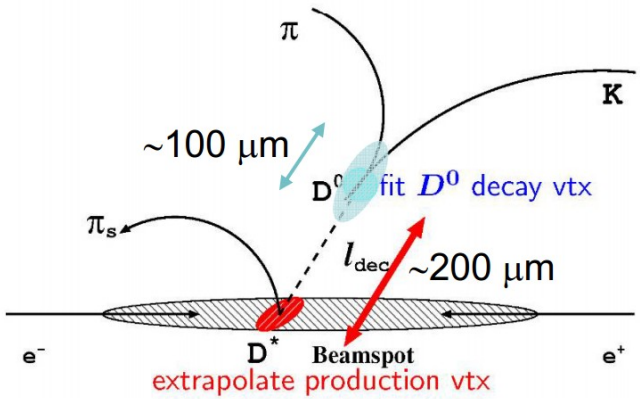
(Time-dependent) method to extract mixing parameters

- CP eigenstates using D^0 lifetime analysis relative to non-CP eigenstates.
  - $y_{cp} = \frac{\tau_{K\pi}}{<\tau_{hh}>} - 1$ (h=K/π in CPC $y_{cp} = y$)
  - $A_\Gamma = \frac{\tau(\bar{D}^0 \to h^-h^+) - \tau(D^0 \to h^+h^-)}{\tau(\bar{D}^0 \to h^-h^+) + \tau(D^0 \to h^+h^-)}$
- WS-to-RS decay rate ratio under CP conservation:
  - $R_{WS}(t) = R_D + y'\sqrt{R_D}\Gamma t + \frac{x'^2+y'^2}{4}\Gamma^2 t^2$
  - $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$, $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$



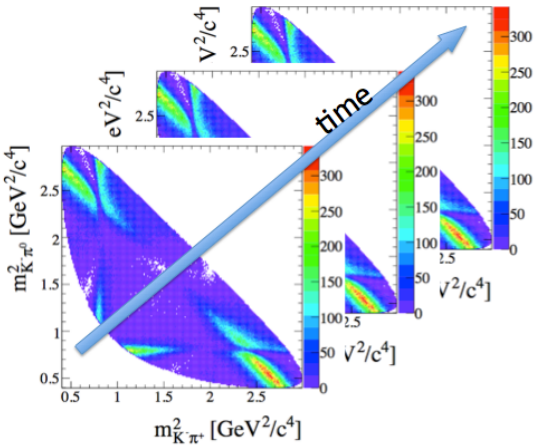
analysis techniques at B-factories (cont')

- Time evolution of amplitude (see backup)

$$|\mathcal{M}(f,t)|^2 = e^{-\Gamma t}\Big\{(|\mathcal{A}_f|^2 + |\frac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cosh(\Gamma y t) - 2\Re(\frac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f^*)\sin(\Gamma y t) + (|\mathcal{A}_f|^2 - |\frac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cos(\Gamma x t) + 2\Im(\frac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f^*)\sin(\Gamma x t)\Big\}.$$

if no CPV, $|q/p| = 1$ and $\arg(q/p) = 0$.
Dalitz variables: invariant mass-square of two final particles.

Dalitz model is usually performed by time-indep. Dalitz fit on real data.



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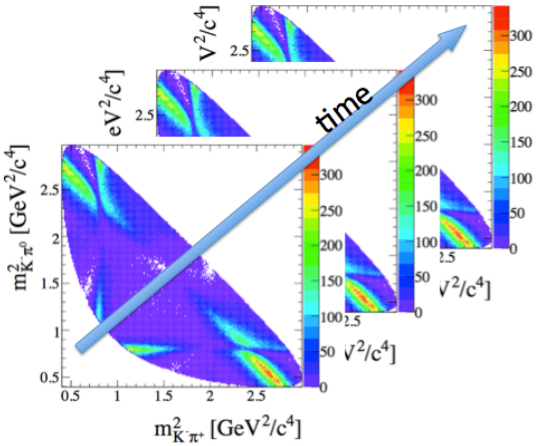

- TDDA in D^0 WS 3-body decay (assuming no CPV and $|x|,|y| \ll 1$) :

$$\frac{dN_f(s_{12},s_{13},t)}{ds_{12}ds_{13}dt} = e^{-\Gamma t}r_0^2\left[|A_f^{DCS}|^2 + |A_f^{DCS}||A_f^{CF}|(c_y\cos\delta_f - c_x\sin\delta_f)\Gamma t + \frac{c_x^2+c_y^2}{4}|A_f^{CF}|^2(\Gamma t)^2\right]$$

where $c_x = x/r_0$ and $c_y = y/r_0$, $r_0^2 = \int|A_f|^2 ds_{12}ds_{13} / \int|\bar{A}_f|^2 ds_{12}ds_{13}$

- TDDA in self-conjugated 3-body decays (assuming no CPV):

$$|\mathcal{M}(t)|^2 = \left\{|\mathcal{A}_1|^2 e^{-y\Gamma t} + |\mathcal{A}_2|^2 e^{yt} + 2\Re[\mathcal{A}_1\mathcal{A}_2^*]\cos(x\Gamma t) + 2\Im[\mathcal{A}_1\mathcal{A}_2^*]\sin(x\Gamma t)\right\}e^{-\Gamma t}$$

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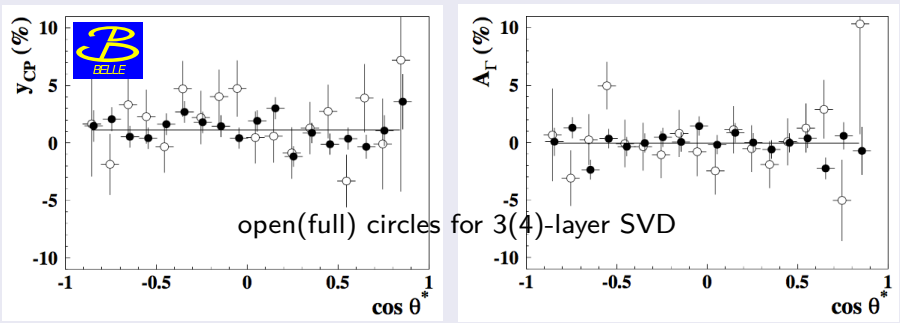
recent published result with full dataset

[M. Staric *et al.* PLB **753**, 412 (2016)]

- tagged D^0 flavor by charge of π_s from D^*
- twice data (976 fb^{-1}) than first evidence result based on 540 fb^{-1} data:
  - y_{CP}=(+1.31±0.32±0.25)%
    [M. Staric *et al.* PRL **98**, 211801 (2007)]
- asymmetric time resolution function depends on D^* polar angle in CMS
- different configurations for SVD
- y_{CP}=[1.11±0.22±0.09]%(4.7σ)
- A_Γ=[-0.03±0.20±0.07]%



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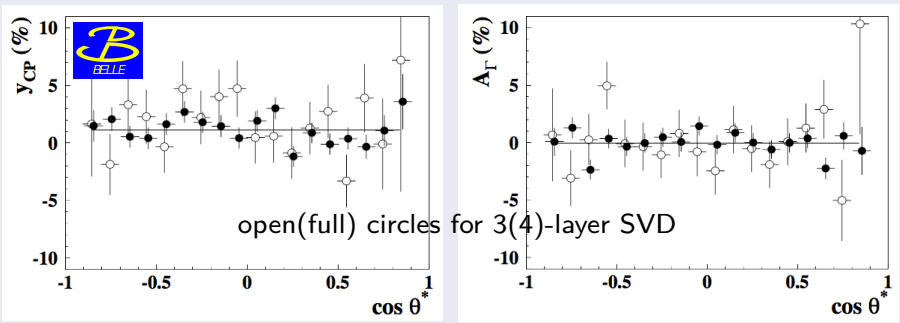
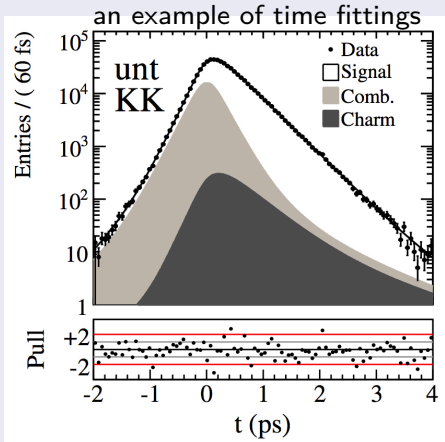


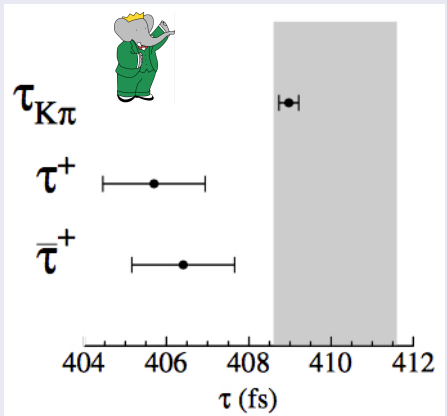
using both tagged/untagged samples

[B. Aubert *et al.* PRL **87**, 012004 (2013)]

- more data (468 fb^{-1}) than previous papers based on 384 fb^{-1} data :
  - tagged: y_{CP}=(1.24±0.39±0.13)%(3σ)
    [B. Aubert *et al.* PRD **78**, 011105(R) (2008)]
  - untagged: y_{CP}=(1.12±0.26±0.22)%(3.3σ)
    [B. Aubert *et al.* PRD **80**, 071103(R) (2009)]
- tagged/untagged: $KK/K\pi$, tagged: $\pi\pi$ for poor S/B in untagged
- y_{CP}=[0.72±0.18±0.12]%(3.3σ)
- ΔY=-A_Γ/2=[0.09±0.26±0.06]%

an example of time fittings



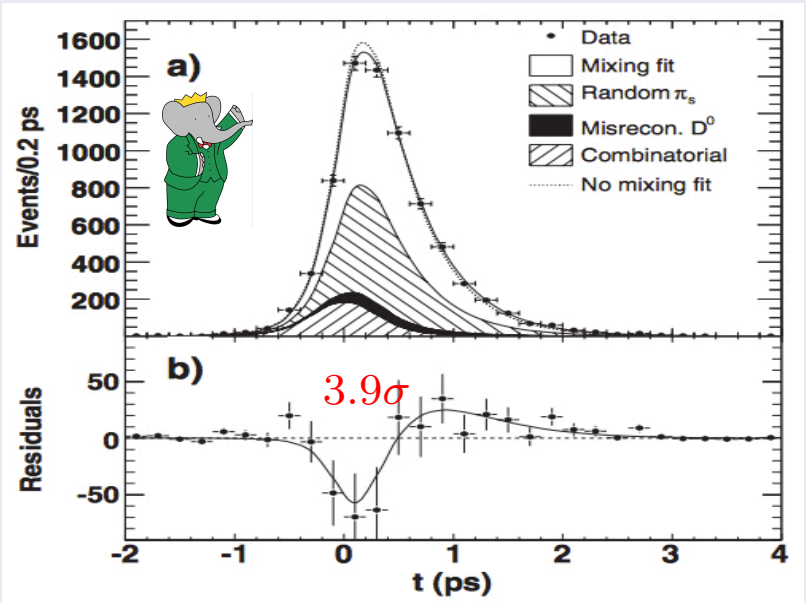


WS decay $D^0 \to K^+\pi^-$ (for 3-body WS, see backup)

first evidence for D^0-$\bar{D}^0$ mixing

[B. Aubert *et al.* PRL **98**, 211802 (2007)]

- fitting D^0 proper-time distribution of WS sample based on 384 fb^{-1} of data
- R_D=(0.303±0.016(stat)±0.010(syst))%
- x'^2=(-0.22±0.30(stat)±0.21(syst))$\times 10^{-3}$
- y'=(9.7±4.4(stat)±3.1(syst))$\times 10^{-3}$
- (x'^2, y') with correlation -0.95



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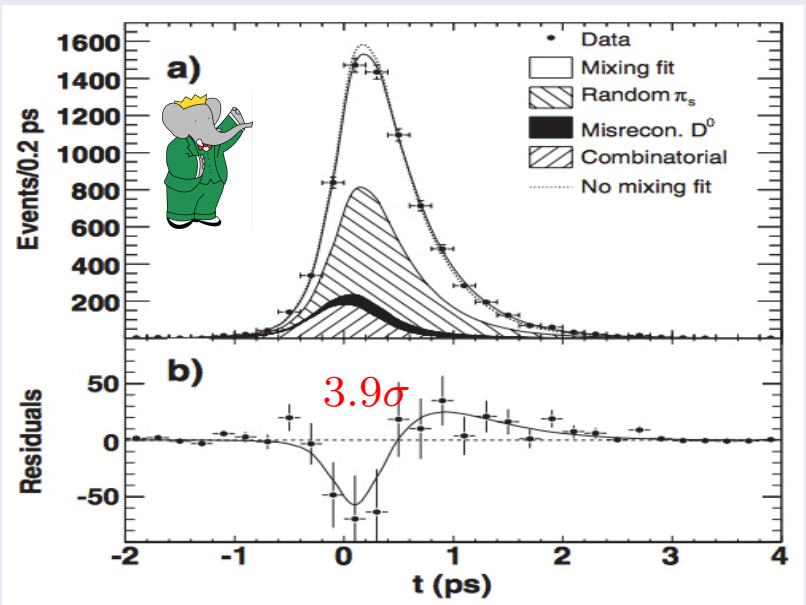
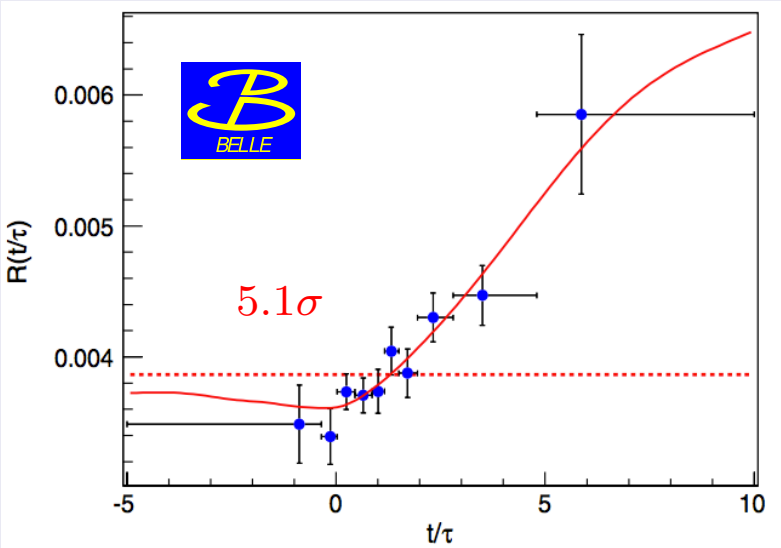


first observation in e^+e^- collisions

[B.R. Ko *et al.* PRL **112**, 111801 (2014)]

- fitting time-dependent ratio of WS-to-RS decay rates based on 976 fb^{-1} of data
- R_D=(0.353±0.013(stat+syst))%
- x'^2=(0.09±0.22(stat+syst))$\times 10^{-3}$
- y'=(4.6±3.4(stat+syst))$\times 10^{-3}$
- (x'^2, y') with correlation -0.948



self-conjugated three-body decays $D^0 \to K^0_S\pi\pi$

Belle $K^0_S\pi^+\pi^-$ by time-dependent Dalitz analysis (see backup) [T. Peng *et al.* PRD **89**, 091103(R) (2014)]

- (1) provide direct measurement of x and y; (2) search for CPV: $q/p \neq 1$
- 921 fb^{-1} dataset: $\sim$1.23M signals with high purity 95.5%

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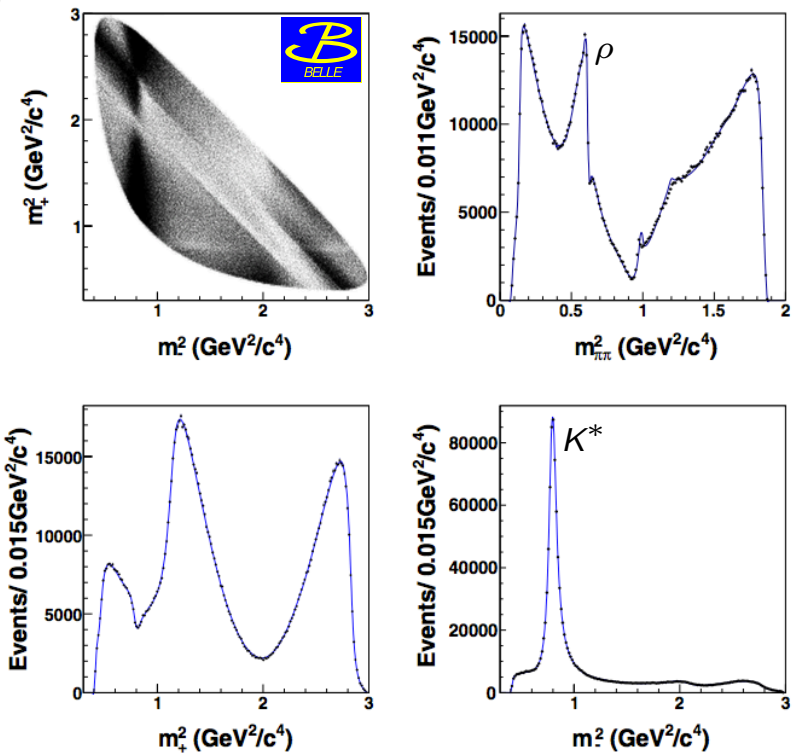
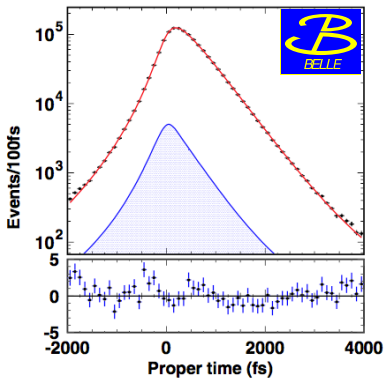
- isobar model with form factor (Blatt-Weisskopt), angular dependence (Zemach tensor)





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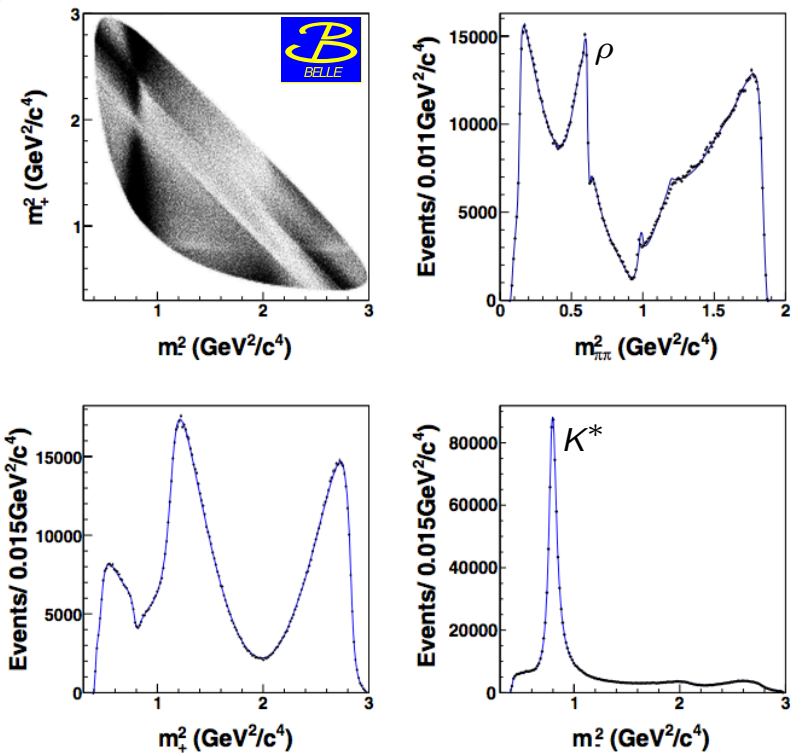

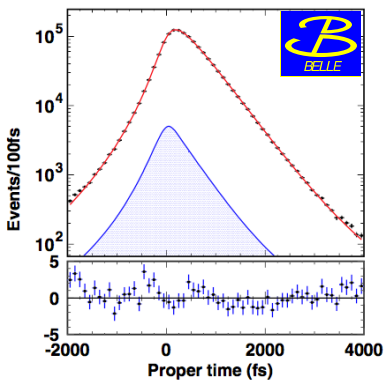

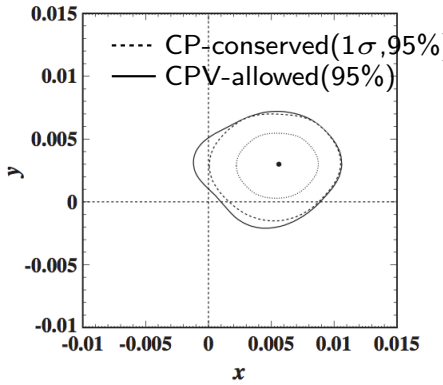

No CPV(2.5σ)	x(%)	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	y(%)	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
indirect CPV	x(%)	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	y(%)	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
	$\lvert q/p\rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	arg(q/p)	$-6 \pm 11 \pm 3^{+3}_{-4}$

Short summary for D^0-$\bar{D}^0$ mixing and CPV [mainly ref. charm physics at HFAG]

Decay Type	Final State	LHCb	BELLE		CDF II	CLEO	BESIII
DCS 2-body(WS)	$K^+\pi^-$	★	★	☆	★	✓	✓ $_{\delta K\pi}$
DCS 3-body(WS)	$K^+\pi^-\pi^0$		✓ $_{A_{CP}}$	☆		✓ $_{A_{CP}}$	
CP-eigenstates	K^+K^-, $\pi^+\pi^-$	☆ $^{(a)}_{A_{CP}}$	☆	☆	✓ $_{A_{CP}}$	✓	
Self-conjugated 3-body decay	$K^0_S\pi^+\pi^-$		✓	✓	✓ $_{A_{CP}}$	✓	
	$K^0_SK^+K^-$		✓ $^{(b)}$	✓			
Self-conjugated SCS 3-body decay	$\pi^+\pi^-\pi^0$	✓ $_{A_{CP}}$	✓ $_{A_{CP}}$	✓ $_{A_{CP}}$			
	$K^+K^-\pi^0$			✓ $_{A_{CP}}$			
SCS 3-body	$K^0_SK^\pm\pi^\mp$	✓ $_{\delta^{K^0_SK\pi}}$				✓ $_{\delta^{K^0_SK\pi}}$	
Semileptonic decay	$K^+\ell^-\nu_\ell$		✓	✓		✓	
Multi-body(n≥4)	$\pi^+\pi^-\pi^+\pi^-$	✓ $_{A_{CP}}$					
	$K^+\pi^-\pi^+\pi^-$		✓ $_{A_{CP}}$	✓			
	$K^+K^-\pi^+\pi^-$	✓ $^{(c)}_{A_{CP}}$		✓ $_{A_T}$		✓ $_{A_{CP}}$	
$\psi(3770) \to D^0\bar{D}^0$ via correlations						✓ $_{\delta K\pi}$	✓ $_{y_{CP}}$

★ for observation ($> 5\sigma$); ☆ for evidence ($> 3\sigma$); ✓ for measurement finished; Measurement on going not included.

The related references are linked under their corresponding signs.

(a) LHCb also give the measurement of indirect CP asymmetry in $D^0 \to h^-h^+$ decay in PRL **112**, 041801 (2014).

(b) Belle measured y_{CP} in $D^0 \to K^0_S\phi$ in PRD **80**, 052006 (2009), the amplitude analysis for mixing parameters (x, y) is on going.

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search for CPV in SCS decay: $D^0 \to \pi^0\pi^0$ [N.K. Nisar *et al.* PRL **112**, 211601 (2014)]

Measured asymmetry A_{rec} and obtain A_{CP} based on 966 fb^{-1} of Belle data

$$A_{rec} = \frac{N_{rec}^{D^{*+}\to D^0\pi_s^+} - N_{rec}^{D^{*-}\to \bar{D^0}\pi_s^-}}{N_{rec}^{D^{*+}\to D^0\pi_s^+} + N_{rec}^{D^{*-}\to \bar{D^0}\pi_s^-}}$$

$$A_{rec}^{cor} = A_{rec} - A_\epsilon^{\pi_s} = A_{CP} + A_{FB}(\cos\theta^*)$$

$$A_{CP/FB} = [A_{rec}^{cor}(\cos\theta^*) \pm A_{rec}^{cor}(-\cos\theta^*)]/2$$

A_{CP}: indept of all kinematic variables;

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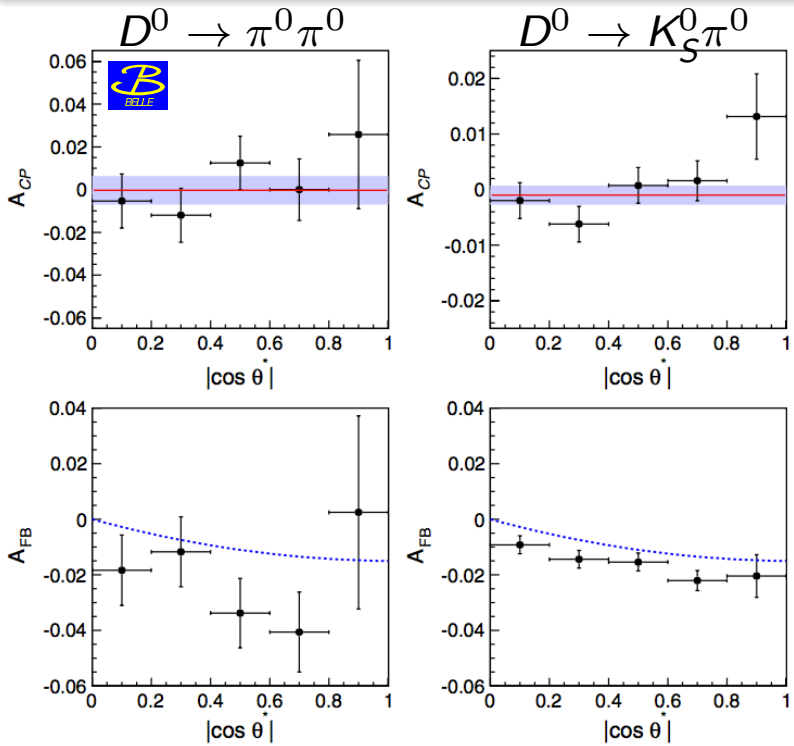
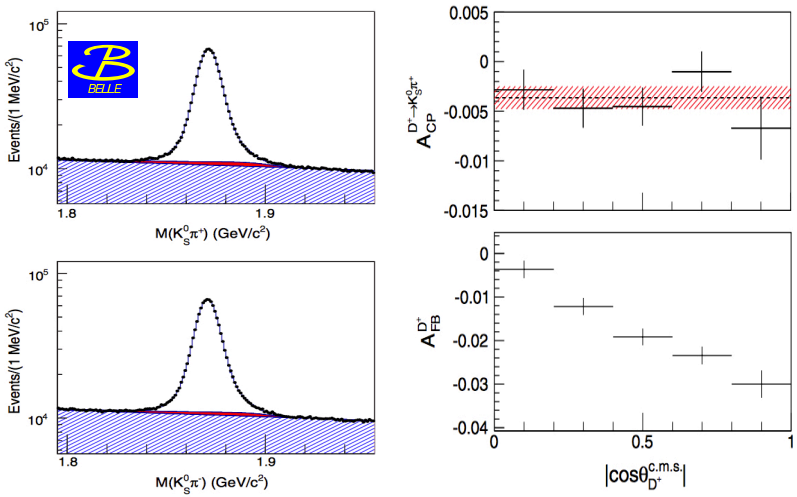


- $D^0/\bar{D}^0$ yields from simultaneous fit to ΔM in 3D bins of $(\cos\theta^*,\ p_T^{\pi_s},\ \cos\theta^{\pi_s})(10\times7\times8)$.
- $A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$
  (1) an order of magnitude improvement.
  (2) no evidence for CP violation.
- $A_{CP}(D^0 \to K^0_S\pi^0) = (-0.21 \pm 0.16 \pm 0.07)\%$

direct CP violation in $D^+_{(s)}$ decays (no new measurement)

review A_{CP} in $D^+ \to K^0_S\pi^+$ [PRL **109**, 119903 (2012)]

- $A_{raw} = A_{CP} + A_{FB} + A^{\pi}_{\epsilon} + A^{K^0}_{mat}$
- Pion and K^0-material asymmetries corrected by event weighting
- in $\cos\theta^*_{D^+}$ bins using simultaneous fit to M($K^0_S\pi^{\pm}$)
- $A_{CP}^{K^0_S\pi^+}$ =(-0.363$\pm$0.094$\pm$0.067)% (3.2σ)
- consistent with expected CPV due to K^0-mixing (-0.345$\pm$0.008)%



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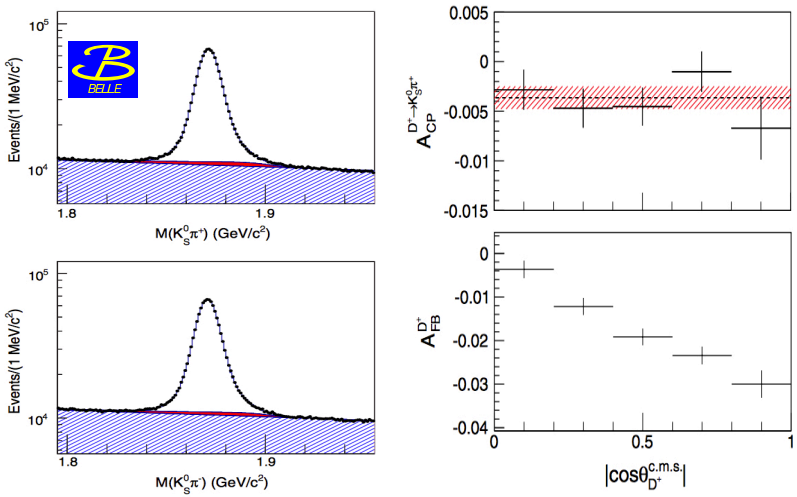


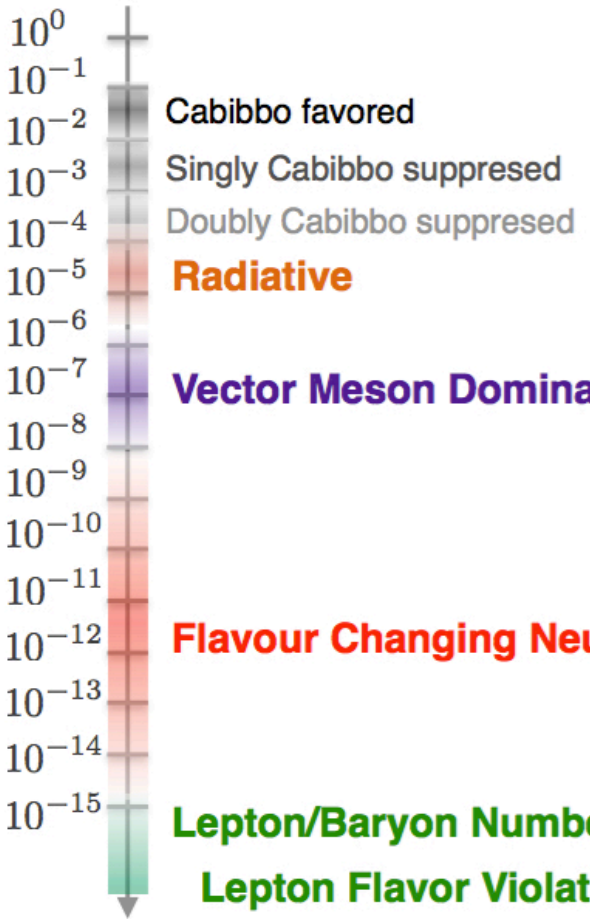
Table: Short summary of A_{CP} measurements [ref. HFAG:CP Asymmetries].

meson	final	$\mathcal{L}$(/fb)	A_{CP}(%)	references
$D^+ \to$	$\phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	Belle PRL **108**, 071801 (2012)
	$\eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	Belle PRL **107**, 221801 (2011)
	$\eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	Belle PRL **107**, 221801 (2011)
	$K^0_S\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	Belle PRL **109**, 021601 (2012)
	$K^0_S\pi^+$	469	$-0.44 \pm 0.13 \pm 0.10$	BABAR PRD **83**, 071103 (2011)
	$K^0_SK^+$	977	$-0.25 \pm 0.28 \pm 0.14$	Belle JHEP **02**, 98 (2013)
	$K^0_SK^+$	469	$+0.13 \pm 0.36 \pm 0.25$	BABAR PRD **87**, 052012 (2013)
	$K^0_S\pi^+\pi^0$	476	$+0.51 \pm 0.28 \pm 0.05$	BABAR PRD **87**, 052010 (2013)
$D^+_s \to$	$K^0_S\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	Belle PRL **104**, 181602 (2010)
	$K^0_S\pi^+$	469	$+5.45 \pm 2.50 \pm 0.33$	BABAR PRD **87**, 052012 (2013)
	$K^0_SK^+$	673	$+0.12 \pm 0.36 \pm 0.22$	Belle PRL **104**, 181602 (2010)
	$K^0_SK^+$	469	$+0.12 \pm 0.36 \pm 0.22$	BABAR PRD **87**, 052012 (2013)

Rare or radiative charm decays

To probe the BSM Physics processes

Figure ref. A. Zupanc @CKM2014



Overview of measurements of selected rare decays

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

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

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

$D^0 \to \gamma\gamma$

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

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

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

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

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

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

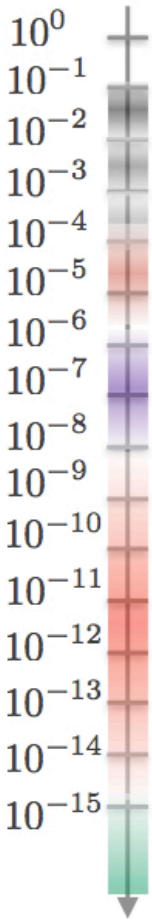
$D \to (h)e^-\mu^+$

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

Rare or radiative charm decays

To probe the BSM Physics processes

Figure ref. A. Zupanc @CKM2014



Cabibbo favored

Singly Cabibbo suppresed

Doubly Cabibbo suppresed

Radiative

Vector Meson Dominance

Flavour Changing Neutral Current

Lepton/Baryon Number Violating

Lepton Flavor Violating

Overview of measurements of selected rare decays

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

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

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

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

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

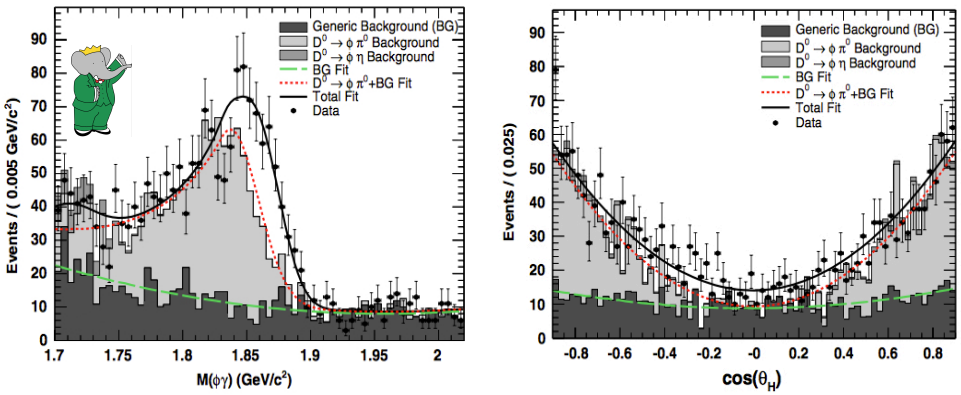
$D \to (h)e^-\mu^+$

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

Flavor-changing radiative decays $D^0 \to V\gamma$

$D^0 \to \phi\gamma/\bar{K}^{*0}\gamma/\rho^0\gamma$ at Belle [A. Abdesselam *et al.*, arXiv:1603.03257] (Preliminary)

- dominated by long-range contribution (10^{-5}, whereas short-range 10^{-8})
- Belle gave first observation of $D^0 \to \phi\gamma$ with 78.1/fb data [O. Tajima *et al.* PRL **92**,101803 (2004)]
- BABAR give first observation of $D^0 \to \bar{K}^{*0}\gamma$ with 387.1/fb data [B. Aubert *et al.*, PRD**78**,071101(R) (2008)]



$M_{V\gamma}$ and $\cos\theta_H$ 2-dimension fit:

$$\mathcal{B}(D^0 \to \phi\gamma) = (2.78 \pm 0.30 \pm 0.27) \times 10^{-5}$$

only $M_{V\gamma}$ fit, and $\cos\theta_H$ consistency check:

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (3.28 \pm 0.20 \pm 0.27) \times 10^{-4}$$

(first observation)

Flavor-changing radiative decays $D^0 \to V\gamma$

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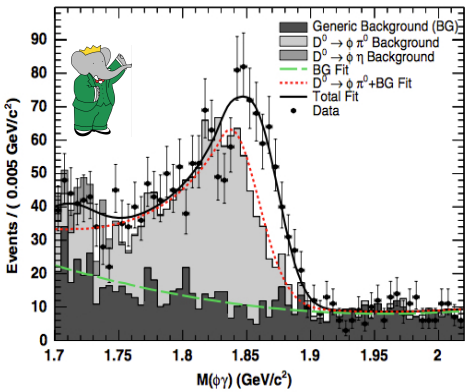
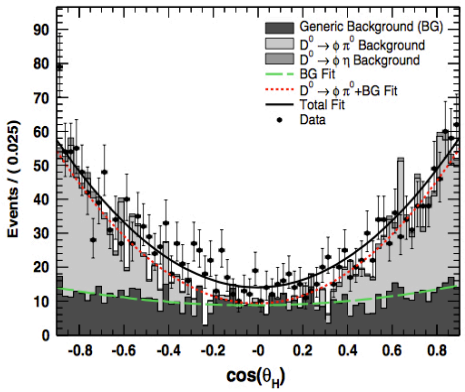
- using 943 fb^{-1} of data; normalize to $D^0 \to K^+K^-/K^-\pi^+/\pi^+\pi^-$ respectively.
- $M_{V\gamma}$ and $\cos\theta_H$ 2-dimension fit





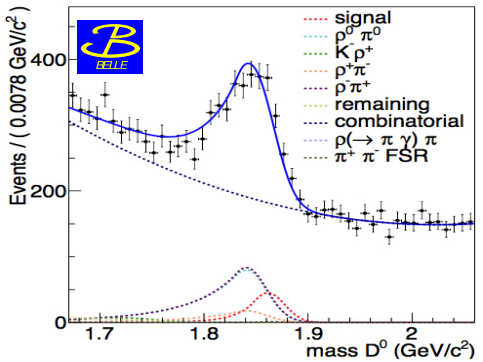
$M_{V\gamma}$ and $\cos\theta_H$ 2-dimension fit:

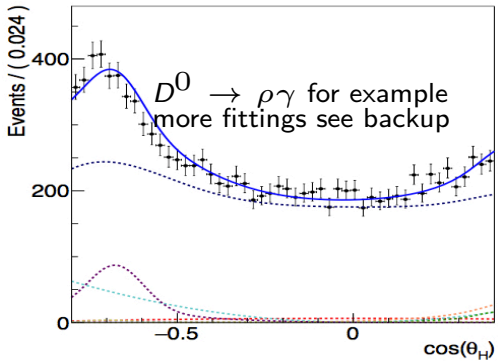
$\mathcal{B}(D^0 \to \phi\gamma) = (2.78 \pm 0.30 \pm 0.27) \times 10^{-5}$

only $M_{V\gamma}$ fit, and $\cos\theta_H$ consistency check:

$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (3.28 \pm 0.20 \pm 0.27) \times 10^{-4}$

(first observation)





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

(improved Belle result, $\simeq$ W.A)

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

(3.3σ away from BABAR analysis)

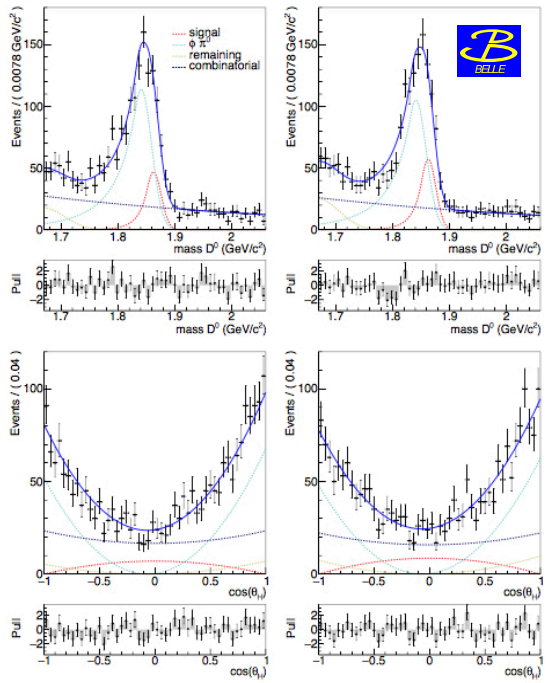
$\mathcal{B}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$

(first observation, $\simeq$ theoretical predictions)

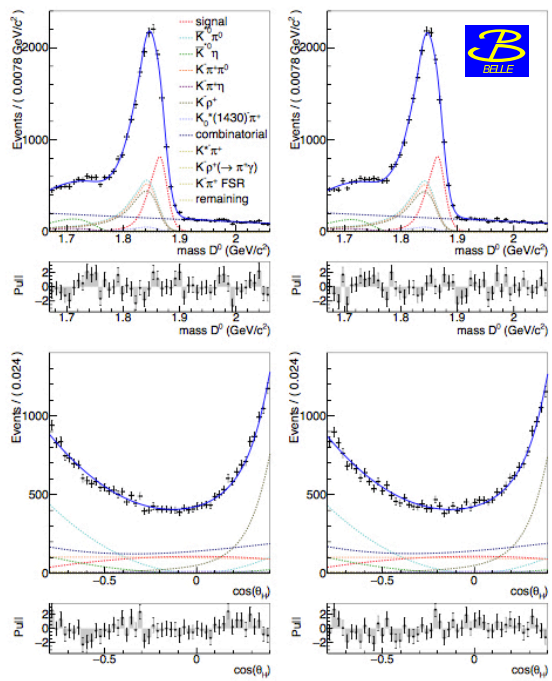
Flavor-changing radiative decays $D^0 \to V\gamma$(cont')

Belle: First measurement of $\mathcal{A}_{CP}$ in $D^0 \to V\gamma$ [A. Abdesselam *et al.*, arXiv:1603.03257] (Preliminary)

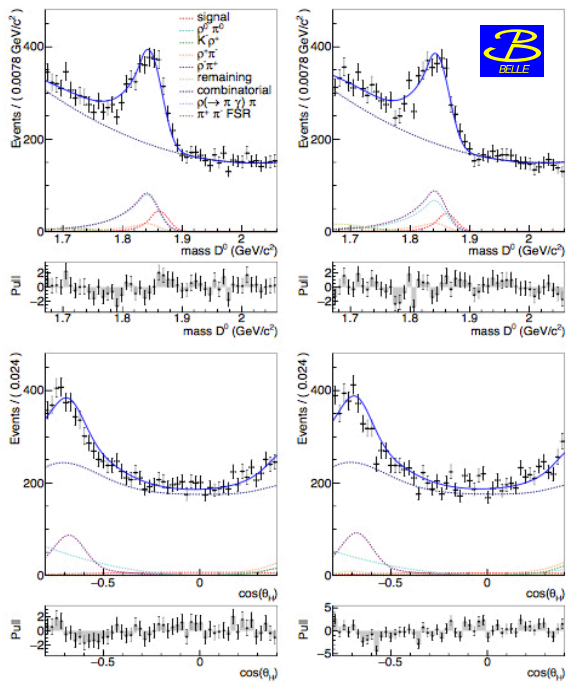
- in radiative charm decays: $\mathcal{A}_{CP}^{V\gamma} > 3\% \Rightarrow$ signal of NP [RPL**109**,171801(2012)].
- raw asym.: $A_{raw} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = \mathcal{A}_{CP} + A_{FB} + A_{\epsilon}^{\pm}$
- A_{FB}, $A_{\epsilon}^{\pm}$: be eliminated through a relative measurement of $\mathcal{A}$: $\mathcal{A}_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{norm} + \mathcal{A}_{CP}^{norm}$



$\mathcal{A}_{CP}^{\phi\gamma} = -0.094 \pm 0.066 \pm 0.001$



$\mathcal{A}_{CP}^{\bar{K}^{*0}\gamma} = -0.003 \pm 0.020 \pm 0.000$



$\mathcal{A}_{CP}^{\rho^0\gamma} = +0.056 \pm 0.151 \pm 0.006$

Branch ratio of $D^0 \to \gamma\gamma$

- FCNC are forbidden at tree level in SM; GIM mechanism suppress at loop level
- NP models allow FCNC even at tree level and can lead to significant enhancements
- Theory predict this decay is dominated by long-distance effects.

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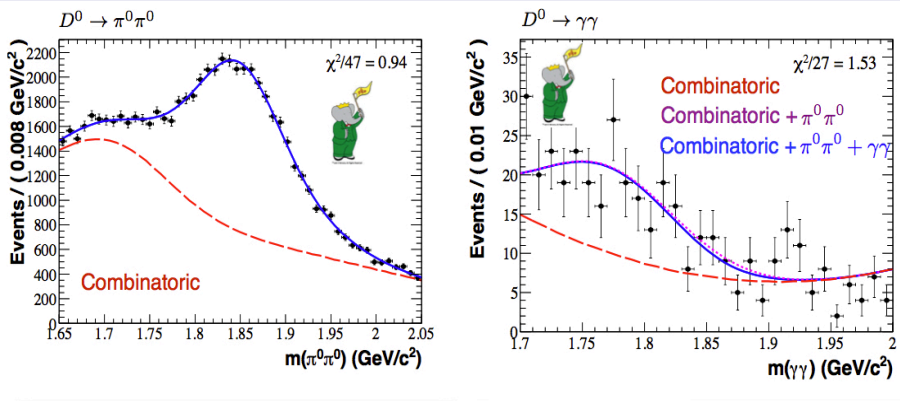
BABAR result [J.P. Lees *et al.* PRD **85**, 091107(R) (2012)]

- using $D^{*+} \to D^0\pi^+$ with 470.5 fb^{-1} data
- normalize to $D^0 \to K^0_S\pi^0$
- measure main BKG as well $D^0 \to \pi^0\pi^0$
  π^0 veto: reject all γ's that can be used for a good π^0.



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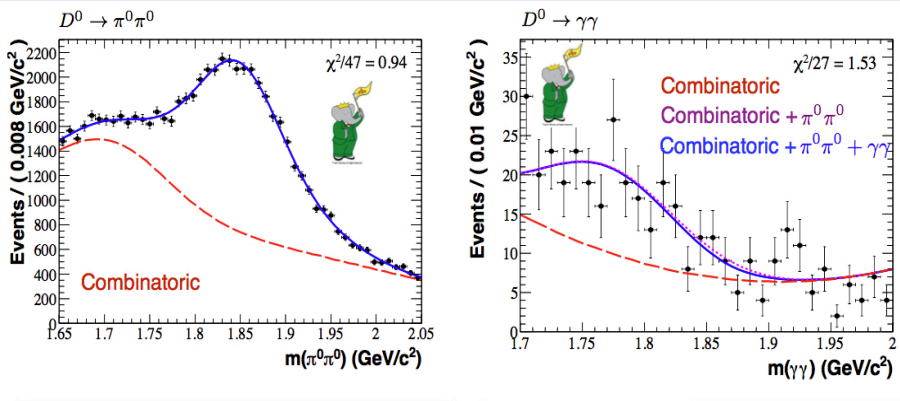
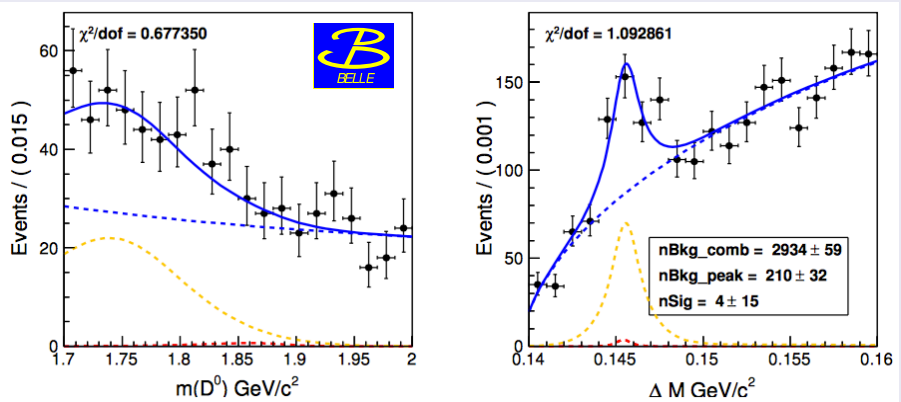


Belle result [N.K. Nisar *et al.* PRD**93**, 051102(R) (2016)]

- using $D^{*+} \to D^0\pi^+$ with 832 fb^{-1} data
- extract signal yield: unbinned extended ML fit to $M_{\gamma\gamma}$ and $\Delta M = M_{D^*} - M_{D^0}$
- correlation: negligible for signal/cmb. BKG; significant for peak BKG.



Branch ratio of $D^0 \to \gamma\gamma$(cont')

The upper-limited on branch ratio:

$$B_{UL}^{90\%}(D^0 \to \gamma\gamma) < \frac{N_{UL}^{90\%}(D^0 \to \gamma\gamma)/\epsilon_{\gamma\gamma}}{N(D^0 \to K_S^0\pi^0)/\epsilon_{K_S^0\pi^0}} \times B(D^0 \to K_S^0\pi^0)_{WA}$$

BABAR: $< 2.2 \times 10^{-6}$; Belle: $< 8.5 \times 10^{-7}$ approaching SM prediction.

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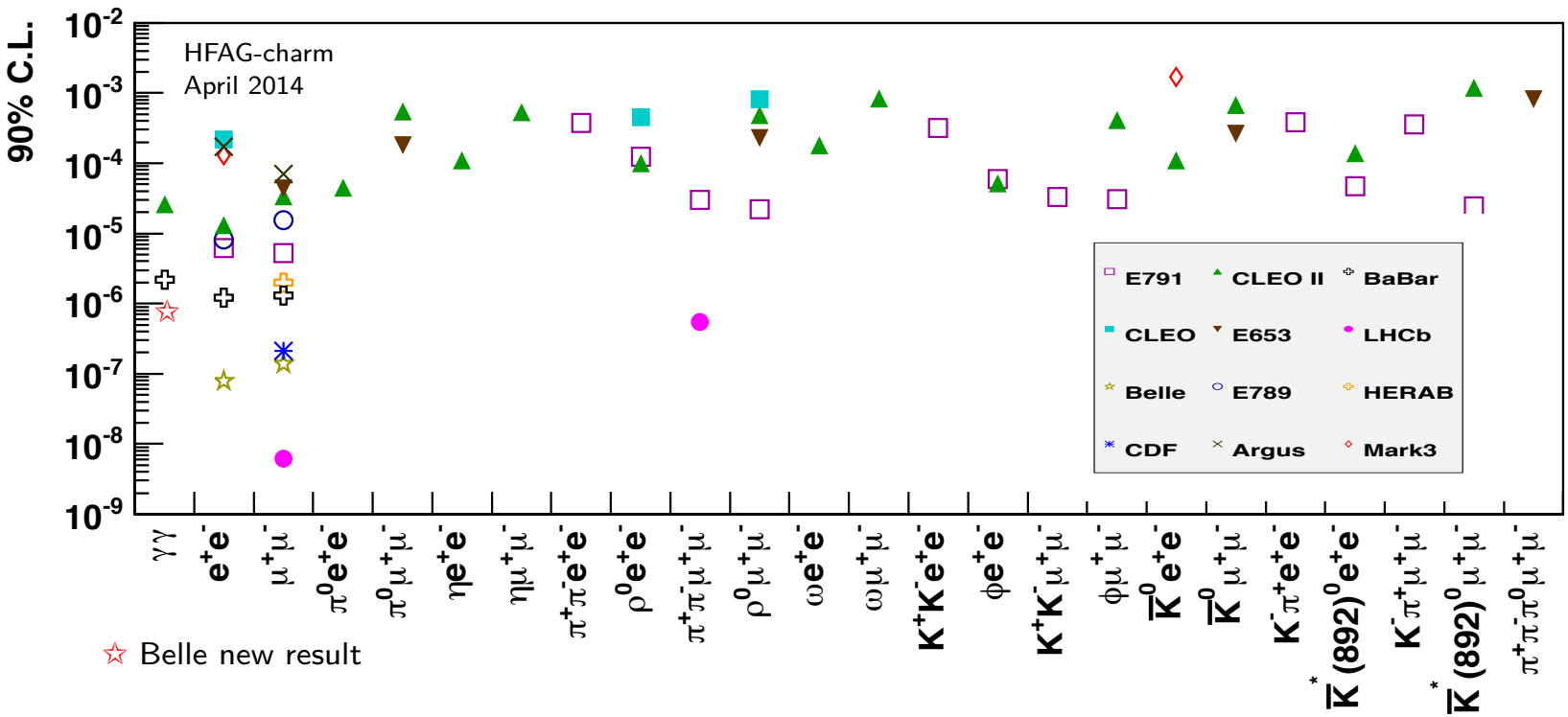
Short summary for D^0 rare decay ref. HFAG [link]



Summary

D^0-$\bar{D}^0$ mixing and CPV measurement

- CP-eigenstate $D^0 \to h^+h^-$
  Belle: y_{CP}=(+1.11±0.22±0.09)%(4.7σ);
  A_Γ=(-0.03±0.20±0.07)% BABAR:
  y_{CP}=(+0.72±0.18±0.12)%(3.3σ)
- WS decay $D^0 \to K^+\pi^-$:
  BABAR (3.9σ):
  x'^2=(-0.22±0.30±0.21)$\times 10^{-3}$
  y'=(9.7±4.4±3.1)$\times 10^{-3}$;
  Belle (5.1σ):
  x'^2=(0.09±0.22(stat+syst))$\times 10^{-3}$
  y'=(4.6±3.4(stat+syst))$\times 10^{-3}$
- self-conjugated decay $D^0 \to K^0_S\pi^+\pi^-$
  Belle w/o CPV (2.5σ):
  $x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$
  $y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$
  CPV: $|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$,
  $\arg(q/p) = (-6 \pm 11 \pm 3^{+3}_{-4})^o$.

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direct CP violation in charm decays

- $D^0 \to \pi^0\pi^0$ at Belle:
  A_{CP}=(-0.03±0.64±0.10)%.
- $D^+_{(s)}$ decay: statistical limited.
- no evidence for CPV in charm sector.

Summary

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Rare or radiative charm decays

- BR($D^0 \to V\gamma$)
  $\phi\gamma$: (2.78±0.30±0.27)$\times 10^{-5}$(BABAR)
  (2.76±0.20±0.08)$\times 10^{-5}$(Belle)
  $\bar{K}^*\gamma$: (3.28±0.20±0.27)$\times 10^{-4}$(BABAR)
  (4.66±0.21±0.18)$\times 10^{-4}$(Belle)
  $\rho\gamma$: (1.77±0.30±0.08)$\times 10^{-5}$(Belle)
- $A_{CP}(D^0 \to \phi\gamma/\bar{K}^*\gamma/\rho\gamma)$ at Belle
  first measurement, no observation.
- BR($D^0 \to \gamma\gamma$)
  BABAR: $<2.2\times 10^{-6}$
  Belle: $<8.5\times 10^{-7}$ →SM prediction.

Back up

Thank you for your attention.

谢谢!

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Univ. of Science and Technology of China (USTC)
No. 96, Jinzhai Road, Hefei City, 230026, P. R. China
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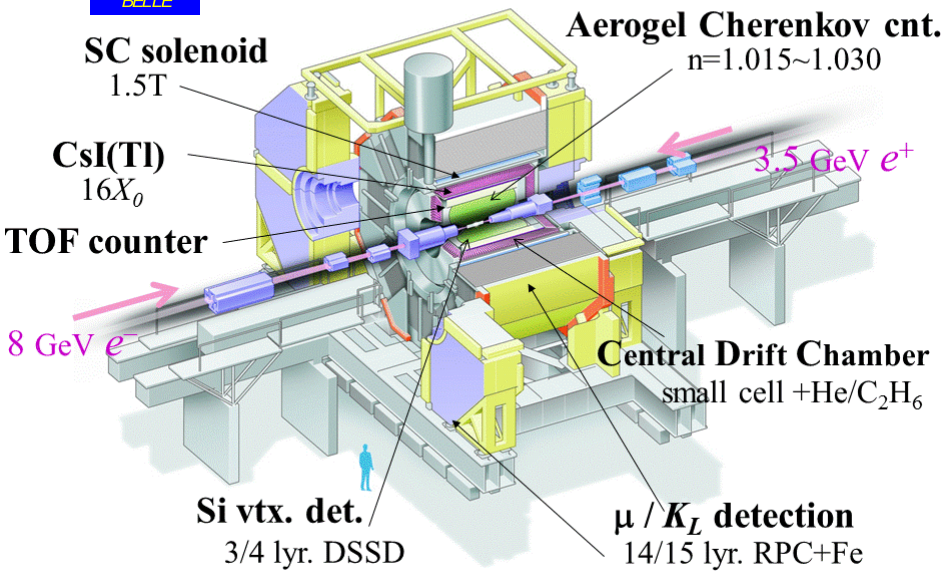
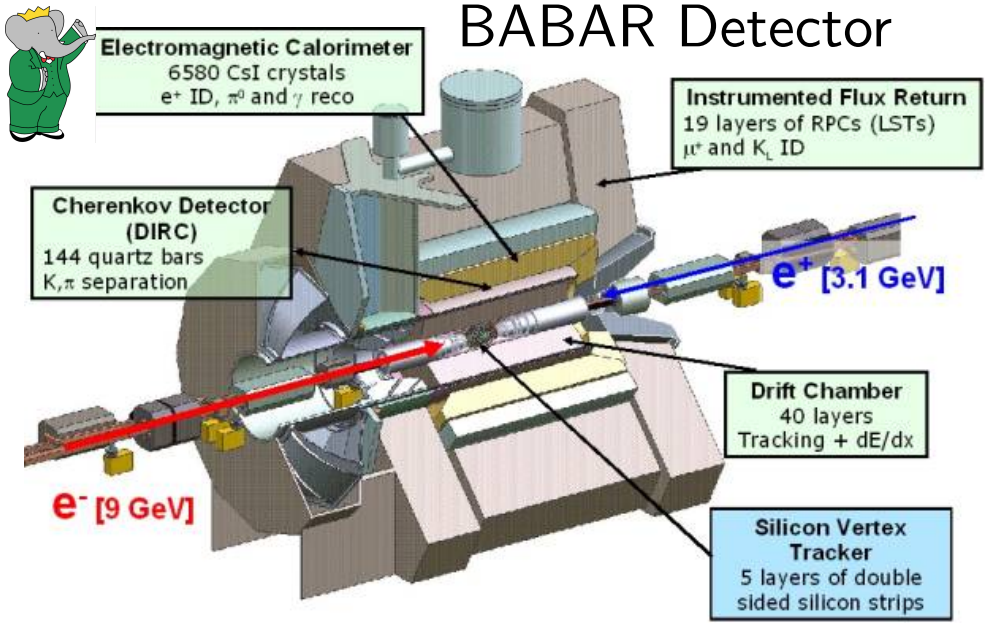
E-mail: lilongke@mail.ustc.edu.cn

Belle Detector



BABAR Detector



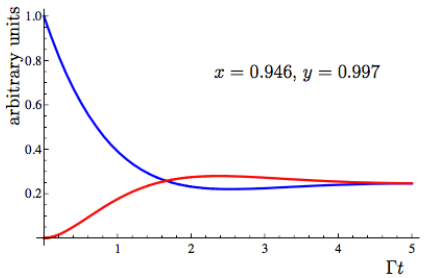
- asymmetric-energy e^+e^- collider with 22(0) mrad cross angle for Belle(BABAR).
- Belle(BABAR) has high peak luminosity $2.1(1.2) \times 10^{34}\ cm^{-2}s^{-1}$
- good momentum/vertex resolution (K/π separation up to 3.5 GeV/c)
- final state with $\gamma/K^0_S/\pi^0$ can be well reconstructed that are difficult/impractical to reconstruct at hadron machine
- low background(BKG), high trigger/rec. efficiencies, minimal decay time bias

Different neutral meson mixing phenomena

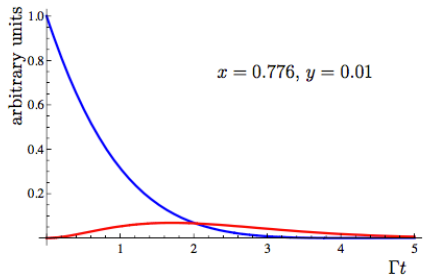
Table: neutral mesons mass and width information

Meson	M(MeV)	ΔM(MeV)	Γ(MeV)	$\Delta\Gamma$(MeV)
K^0	497.6	3.48×10^{-12}	3.68×10^{-12}	7.34×10^{-12}
D^0	1864.9	9.45×10^{-12}	1.6×10^{-9}	2.57×10^{-11}
B_d^0	5279.6	3.34×10^{-10}	4.43×10^{-10}	$\sim$
B_s^0	5366.8	1.16×10^{-8}	4.39×10^{-10}	6.58×10^{-11}

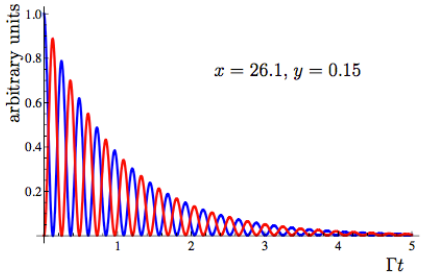
- the right figures is for different neutral meson time-dep. mixing and no-mixing rate distribution with some mixing parameters value under no CP violation.
- we can see D^0-$\bar{D}^0$ mixing is most difficult to measure.



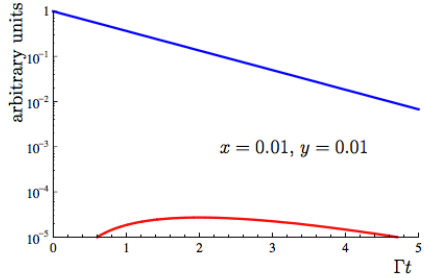
(a) $K^0 - \overline{K}^0$



(b) $B_d^0 - \overline{B}_d^0$



(c) $B_s^0 - \overline{B}_s^0$



(d) $D^0 - \overline{D}^0$

Why named Dalitz?

Richard Henry Dalitz (28 Feb. 1925 - 13 Jan. 2006)
Australian Physicst;
To study "$\tau \to 3\pi$"(kaon) decays:
$\Longrightarrow$ Dalitz technique (as called today).

"On the analysis of τ-meson data and the nature of the τ-meson.
Author: R. H. Dalitz
DOI: 10.1080/14786441008520365

Published: Philosophical Magazine Series 7, V. 44, Issue 357, Oct. 1953, p1068-1080.

Degree of freedom

Decay types	$S \to SSS$	$S \to SSSS$	$S \to VSS$
Examples	$D^0 \to K^-\pi^+\pi^0$	$D^0 \to 4\pi$	$B^0 \to \psi(2S)K^-\pi^+$
4-vectors	3×4	4×4	3×4
E-p const. laws	-4	-4	-4
final state mass	-3	-4	-3
arbitrary rotations	-3	-3	-1(2 vector helicity)
Total	2	5	4

standard Dalitz analysis formalism

Lorentz Invariant Phase Space for n-body decay,

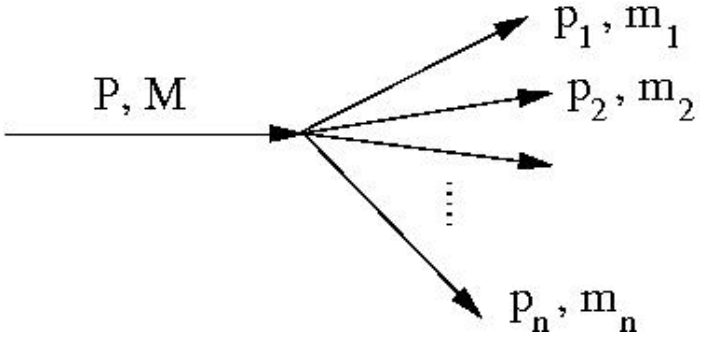
$$d\Phi_n(P; p_1, p_2, p_n) = \delta^4(P - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

For 3-body decay ($P_M \to P_1 P_2 P_3$):

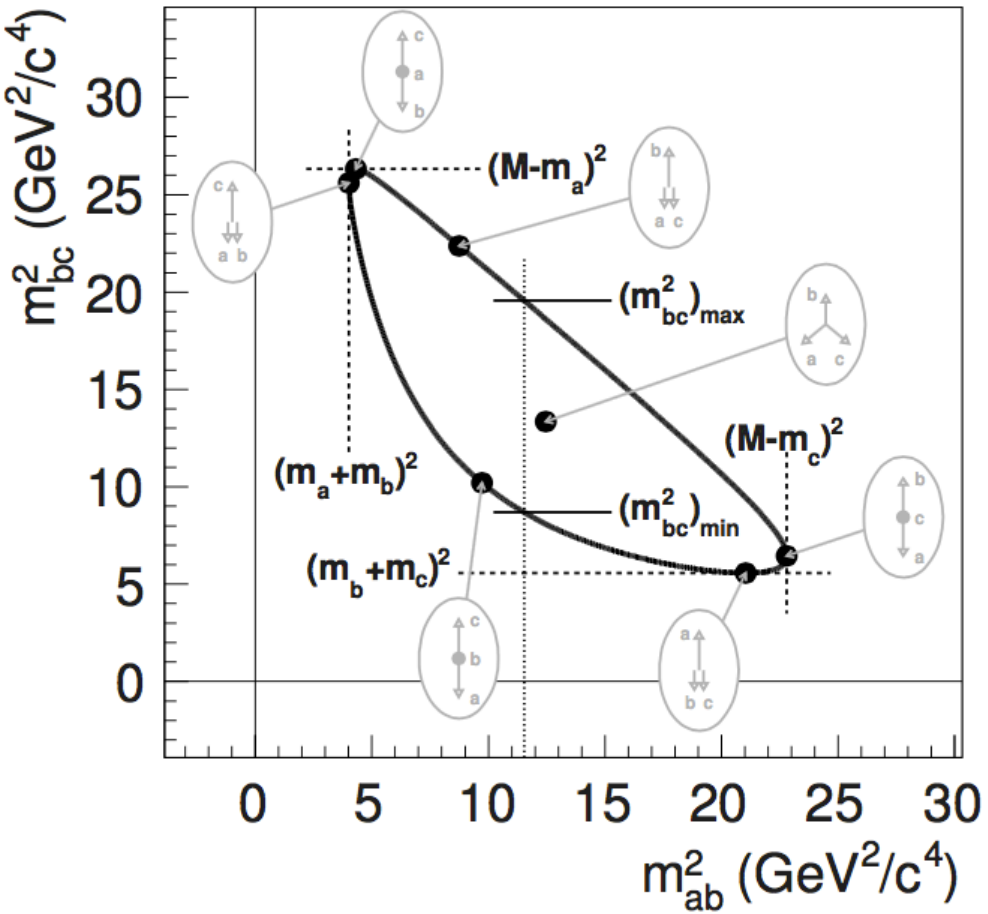
$$m_{12}^2 + m_{13}^2 + m_{23}^2 = M^2 + m_1^2 + m_2^2 + m_3^2 = const.$$

So for take two inv. masses as independent variables to obtain the standard form of Dalitz plot:

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathcal{M}|^2} dm_{12}^2 dm_{23}^2$$



Kinematics limit on DP



kinematic limit:

$$(m^2_{bc})_{max} = (E^*_b + E^*_c)^2 - (p^*_b - p^*_c)^2$$
$$(m^2_{bc})_{min} = (E^*_b + E^*_c)^2 - (p^*_b + p^*_c)^2$$

$$E^*_b = \frac{m^2_{ab} - m^2_a + m^2_b}{2m_ab}, \qquad E^*_c = \frac{M^2 - m^2_{ab} - m^2_c}{2m_{ab}}$$

$$p^*_b = \sqrt{E^{*2}_b - m^2_b} \qquad p^*_c = \sqrt{E^{*2}_c - m^2_c}$$

The form related to Helicity angle:

$$m^2_{23} = (m^2_{23})_{min}\frac{1+\cos\theta_{hel}}{2} + (m^2_{23})_{max}\frac{1-\cos\theta_{hel}}{2}$$

$\cos\theta_{hel} = -1 \Longrightarrow (m^2_{23})_{min}$

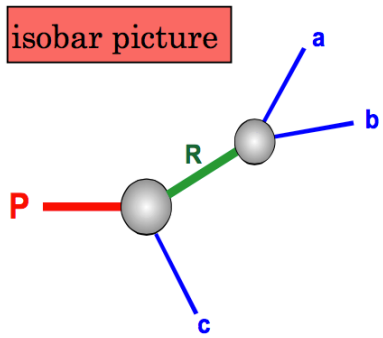
$\cos\theta_{hel} = +1 \Longrightarrow (m^2_{23})_{max}$

resonance description: Isobar model (1)

Isobar model

total decay amplitude as a coherent sum of processes where one daughter is spectator.

$$\mathcal{A}(m_{ab}^2, m_{bc}^2) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m_{ab}^2, m_{bc}^2) + a_{NR} e^{i\phi_{NR}} \mathcal{A}_{NR}(m_{ab}^2, m_{bc}^2)$$



Amplitude describe of resonance r by Isobar model

$$\mathcal{A}_r = F_D \times F_r \times T_r \times W_r$$

Breit-Wigner formalism

$$T_r = \frac{1}{m_r^2 - m_{ab}^2 - i m_r \Gamma_{ab}}$$

$$\Gamma_{ab} = \Gamma_r \left(\frac{q_{ab}}{q_r}\right)^{2J+1} \left(\frac{m_r}{m_{ab}}\right) F_r^2 .$$

$$p_{ab} = \frac{1}{2m_{ab}} \sqrt{[m_{ab}^2 - (M_a + M_b)^2][m_{ab}^2 - (M_a - M_b)^2]}$$

$$p_r = \frac{1}{2M_r} \sqrt{[M_r^2 - (M_a + M_b)^2][M_r^2 - (M_a - M_b)^2]}$$

Blatt-Weisskopf form factors

$$J = 0: \quad F = 1$$

$$J = 1: \quad F = \frac{\sqrt{1 + R^2 q_r^2}}{\sqrt{1 + R^2 q_{ab}^2}}$$

$$J = 2: \quad F = \frac{\sqrt{9 + 3R^2 p_r^2 + R^4 p_r^4}}{\sqrt{9 + 3R^2 p_{ab}^2 + R^4 p_{ab}^4}}$$

here R: phenomenological factor, for D^0, $R = 0 \sim 10\ GeV^{-1}$, for resonances r, $R = 0 \sim 3\ GeV^{-1}$.

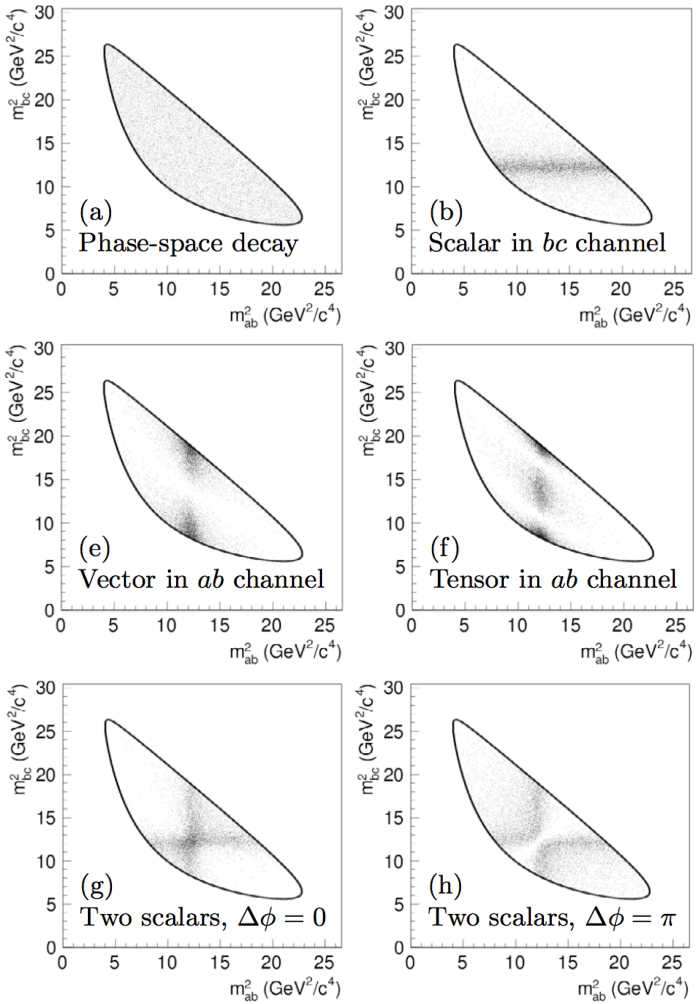
resonance description: Isobar model (2)

angular distribution for spin-J particles

$$J = 0: \quad W_r = 1$$

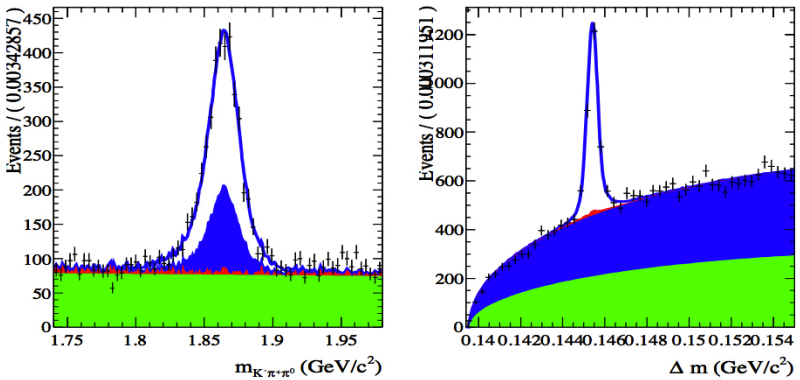
$$J = 1: \quad W_r = m_{ac}^2 - m_{bc}^2 + \frac{(M_D^2 - M_c^2)(M_b^2 - M_a^2)}{M_r^2}$$

$$J = 2: \quad W_r = \left[m_{bc}^2 - m_{ac}^2 + \frac{(M_D^2 - M_c^2)(M_a^2 - M_b^2)}{M_r^2} \right]^2 - \frac{1}{3} \left[m_{ab}^2 - 2M_D^2 - 2M_c^2 + \frac{(M_D^2 - M_c^2)^2}{M_r^2} \right] \times \left[m_{ab}^2 - 2M_a^2 - 2M_b^2 + \frac{(M_a^2 - M_b^2)^2}{M_r^2} \right]$$

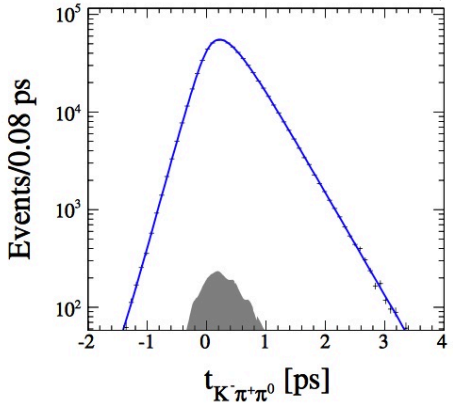


TDDP analysis of WS $D^0 \to K^+\pi^-\pi^0$ at BABAR

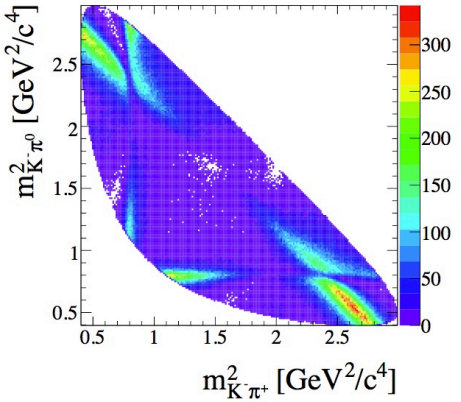
WS M-Q fit to obtain $f_{sig,bkg}$

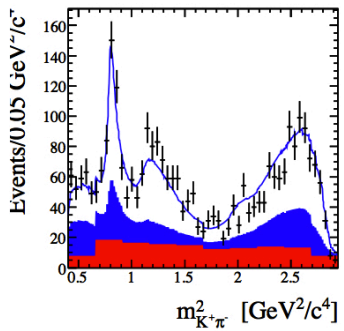


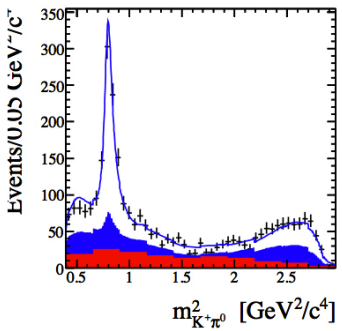
RS D^0 time fitting to obtain $pdf(t)_{sig}$

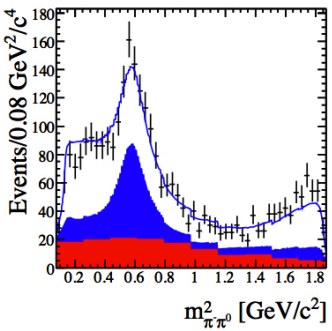


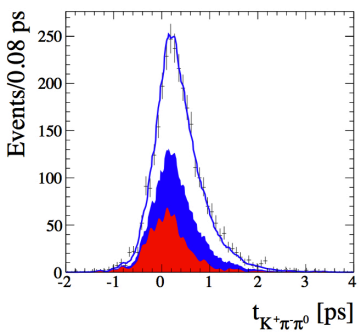
RS TIDA to obtain WS CF process A_f^{CF}

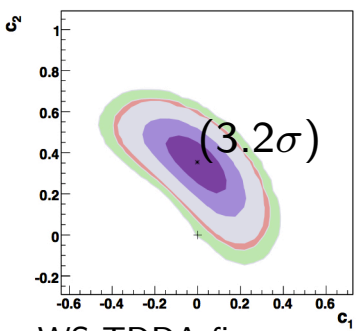












WS TDDP fit: Dalitz projections and time projection

7 res. in DCS process with $\sum FF = 102\%$

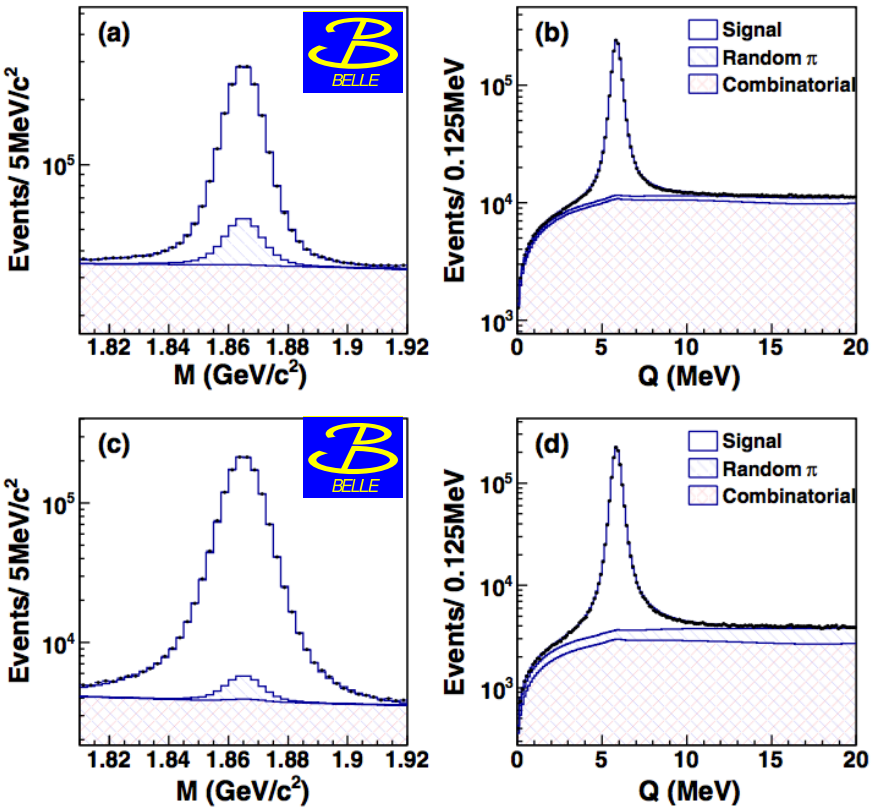
signal time par. fixed to RS signal's

WS TDDA fit: extract

$x'/r_0 = 0.353 \pm 0.091 \pm 0.066$

$y'/r_0 = -0.002 \pm 0.090 \pm 0.05$

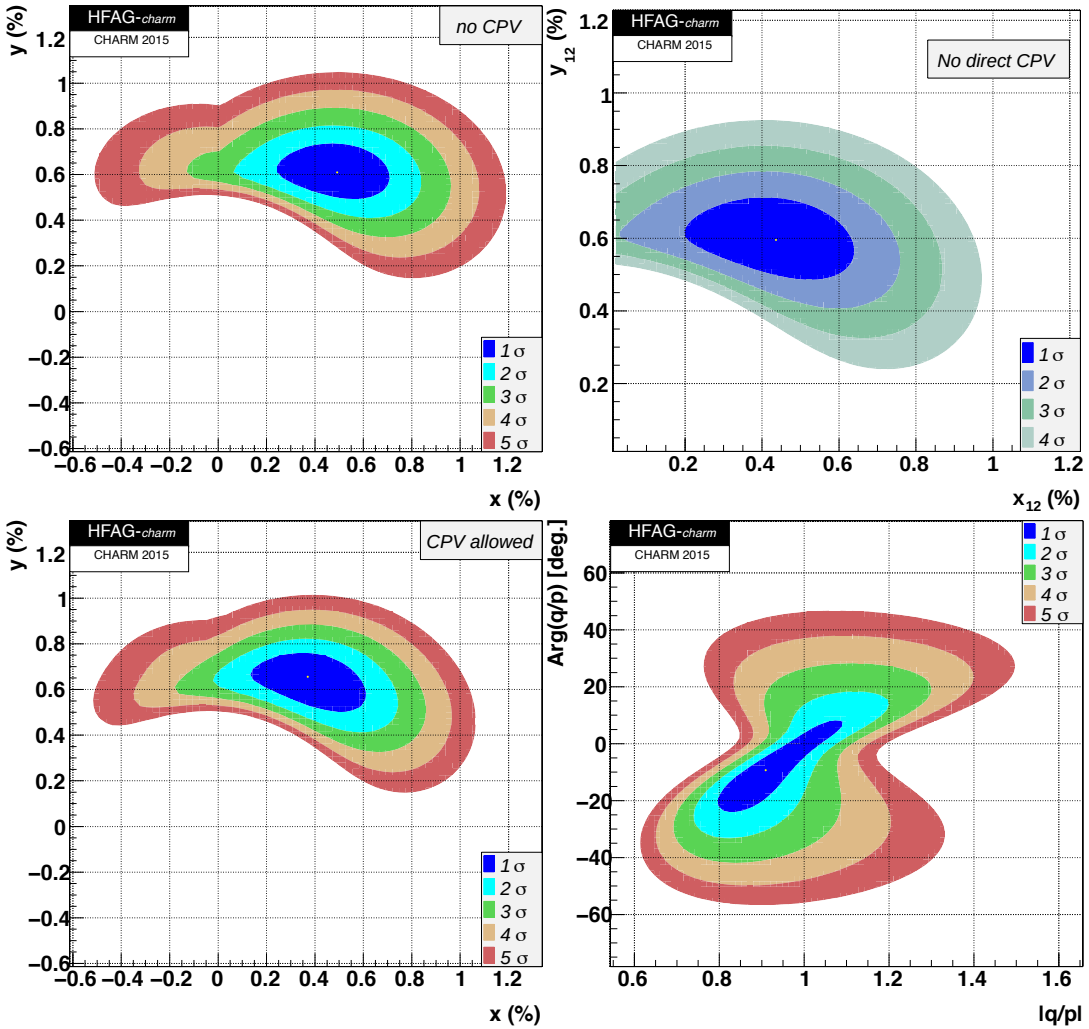
Projections of M and Q for signal and BG M-Q fit to obtain the fraction of events:



Dalitz plot fitting results:

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K_2^*(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 0.002	-42.1 ± 0.7	0.0046
$K_0^*(1430)^+$	0.176 ± 0.007	-102.3 ± 2.1	0.0005
$K_2^*(1430)^+$	0.077 ± 0.007	-32.2 ± 4.7	0.0001
$K^*(1410)^+$	0.248 ± 0.010	-145.7 ± 2.9	0.0007
$K^*(1680)^+$	1.407 ± 0.053	86.1 ± 2.7	0.0013
$\rho(770)$	1 (fixed)	0 (fixed)	0.2000
$\omega(782)$	0.0370 ± 0.0004	114.9 ± 0.6	0.0057
$f_2(1270)$	1.300 ± 0.013	-31.6 ± 0.5	0.0141
$\rho(1450)$	0.532 ± 0.027	80.8 ± 2.1	0.0012
$\pi\pi$ S wave			0.1288
β_1	4.23 ± 0.02	164.0 ± 0.2	
β_2	10.90 ± 0.02	15.6 ± 0.2	
β_3	37.4 ± 0.3	3.3 ± 0.4	
β_4	14.7 ± 0.1	-8.9 ± 0.3	
f_{11}^{prod}	12.76 ± 0.05	-161.1 ± 0.3	
f_{12}^{prod}	14.2 ± 0.2	-176.2 ± 0.6	
f_{13}^{prod}	10.0 ± 0.5	-124.7 ± 2.1	
$K\pi$ S wave	Parameters		
M (MeV/c^2)	1461.7 ± 0.8		
Γ (MeV/c^2)	268.3 ± 1.1		
F	0.4524 ± 0.005		
ϕ_F (rad)	0.248 ± 0.003		
R	1(fixed)		
ϕ_R (rad)	2.495 ± 0.009		
a (GeV/c^{-1})	0.172 ± 0.006		
r (GeV/c^{-1})	-20.6 ± 0.3		
$K^*(892)$	Parameters		
$M_{K^*(892)}$ (MeV/c^2)	893.68 ± 0.04		
$\Gamma_{K^*(892)}$ (MeV/c^2)	47.49 ± 0.06		

HFAG: D^0-$\bar{D}^0$ mixing and CPV: mixing [link], mixing with CPV [link]



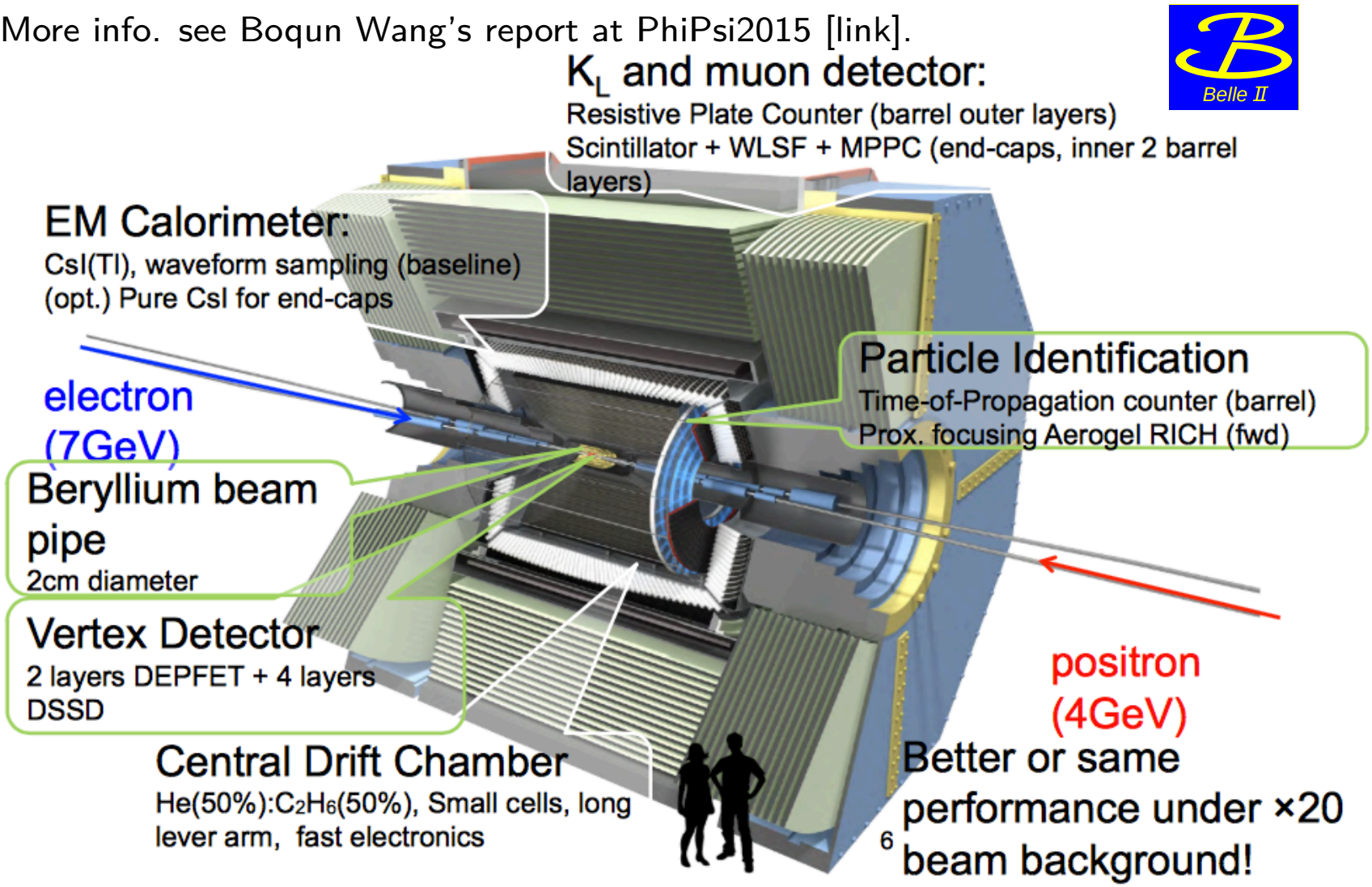
CP-allowed plot: no mixing (x,y)=(0,0) excluded at $\gg 11.5\sigma$

Uncertainty of A_{CP} measurements in $D^0 \to V\gamma$ (preliminary)

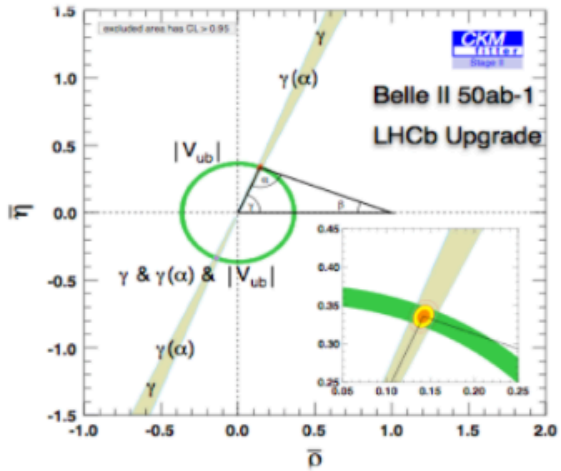
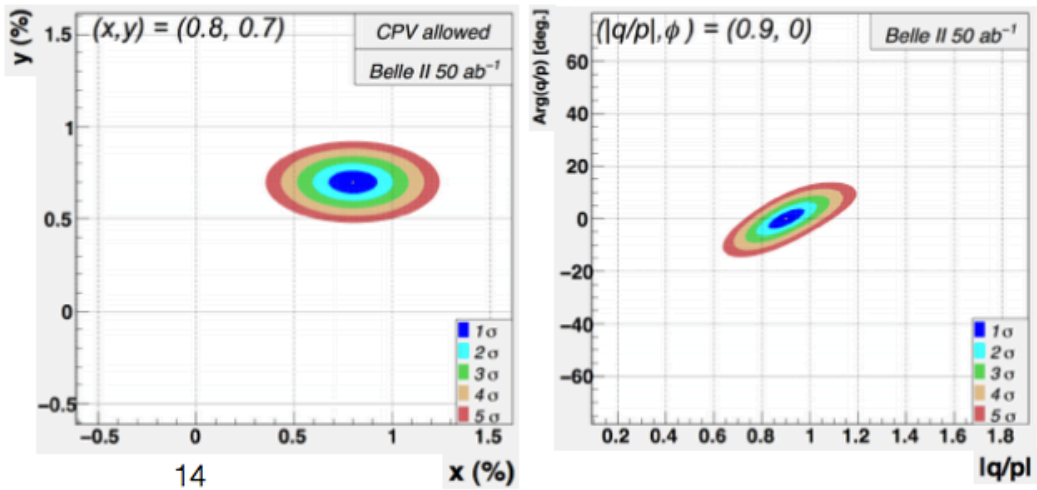
Table I. The systematic uncertainties.

	$\mathcal{B}$ [%]	$\mathcal{A}_{CP}$ [$\times 10^{-3}$]	$\mathcal{B}$ [%]	$\mathcal{A}_{CP}$ [$\times 10^{-3}$]	$\mathcal{B}$ [%]	$\mathcal{A}_{CP}$ [$\times 10^{-3}$]
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

More info. see Boqun Wang's report at PhiPsi2015 [link].



More info. see Boqun Wang's report at PhiPsi2015 [link].

Physics Opportunities

- Potential signals for new physics:
  - Flavor changing neutral currents
  - Probing charged Higgs
  - New sources of CPV
  - Lepton Flavour Violation decays
  - Dark sectors
- Belle II physics programme will be complementary with LHCb.