Charm Mixing and *CP* Violation at B-factories

李龙科
lilongke@ihep.ac.cn
中国科学院高能物理研究所

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Outline

- *Belle @KEKB and Belle II @SuperKEKB*
  - *Accelerator; detectors; data set etc.*
- *D^0-$\bar{D}^0$ mixing and CP violation*
  - *Formalism and status*
  - *Hadronic WS decay D^0->$K^+\pi^-$*
  - *Time-dependent analyses*
- *Time-integrated CP asymmetry*
  - *summary table of measurements*
  - *Search for CPV in D^0->K_SK_S*
  - *CPV in radiative decays D^0->γV*
  - *T-odd asymmetry in D^0->$K_S\pi\pi\pi^0$*
- *ROE method for D^0 flavor tagging at Belle II*
- *Summary*

Experimental Charm Data set

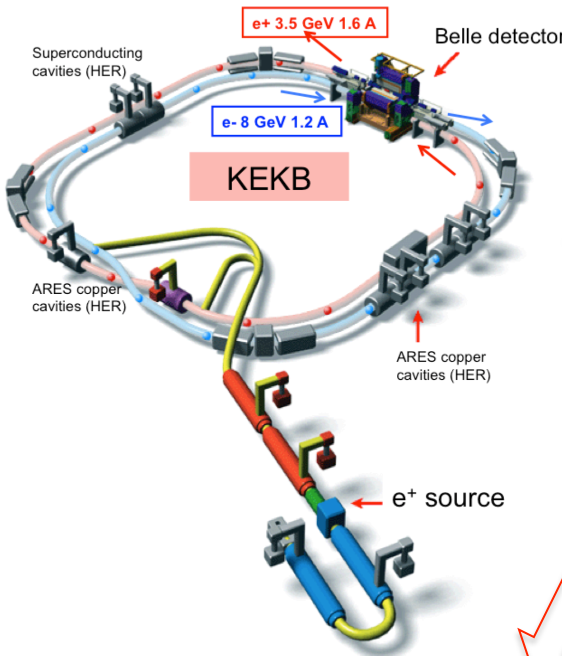
- Available data sets from Charm factories, B-factories and hadron colliders

Experiment	Machine	C.M	Lumin.	N(D)	efficiency	☺advantage / ☹disadvantage
CLEOc	CESR (e^+e^-)	3.77 GeV 4.17 GeV	0.8 fb^{-1} 0.6 fb^{-1}	2.9×10^6 $2.3 \times 10^6 (D^{\pm})$ 0.6×10^6	~10-30%	☺ extremely clean enviroment ☺ pure D-beam, almost no bkg ☺ quantum coherence ☹ no CM boost, no T-dep analyses
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18 GeV	2.92 fb^{-1} 3 fb^{-1}	10.5×10^6 8.4×10^6 $(D^{\pm})$ 3×10^6 ★	★★★	
BELLE	KEKB (e^+e^-)	10.58 GeV	1 ab^{-1}	1.3×10^9	~5-10%	☺ clear event environment ☺ high trigger efficiency ☺ high-efficiency detection of neutrals ☺ many high-statistics control samples ☺ time-dependent analysis ☹ smaller cross-section than pp colliders
BaBar	PEP-II (e^+e^-)	10.58 GeV	0.5 ab^{-1}	6.5×10^8 ★★	★★	
CDF	Tevatron ($p\bar{p}$)	1.96 TeV	9.6 fb^{-1}	1.3×10^{11}	<0.5%	☺ large production cross-section ☺ large boost: excellent time resolution ☹ dedicated trigger required ☹ hard to do neutrals and neutrinos
LHCb	LHC (pp)	7 TeV 8 TeV	1.0 fb^{-1} 2.0 fb^{-1}	5.0×10^{12} ★★★	★	

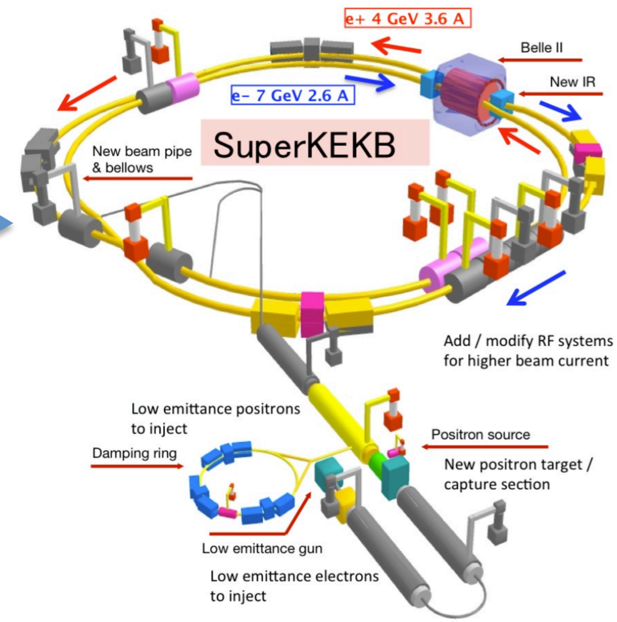
here we used $\sigma(D^0\bar{D}^0@3.77\ GeV)$=3.61 nb, $\sigma(D^+D^-@3.77\ GeV)$=2.88 nb, $\sigma(D^*D_s@4.17\ GeV)$=0.967 nb, $\sigma(c\bar{c}@10.58\ GeV)$=1.3 nb, $\sigma(D^0@LHCb)$=1.661 nb. This table mainly refers to IJMP **A 29** (2014) 24, 14300518 and G. Casarosa's report at SLAC experimental seminar 2016.

B-factories at KEK

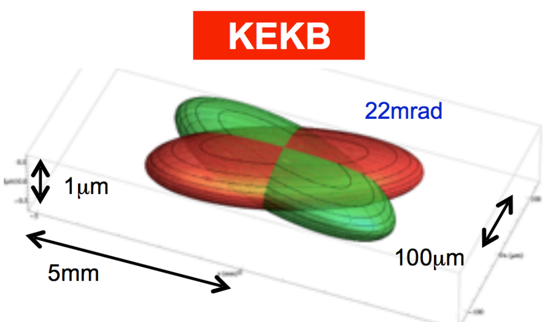
- 1^{st} Vs. 2^{nd} generation B-factory

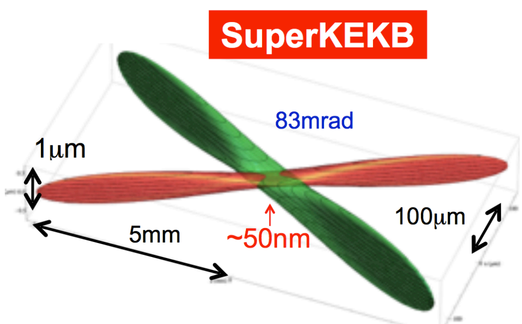


boost:
$\beta\gamma \sim 2/3$
Current × 2
IP impact par.
$\beta^*_y \times 1/20$



- Nano-beam design (by P. Raimondi for SuperB)



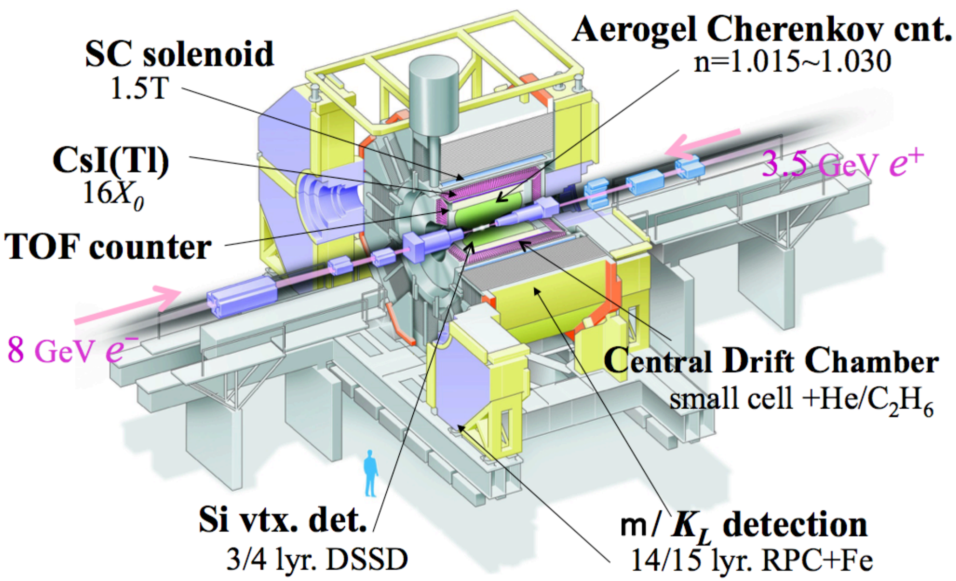


$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

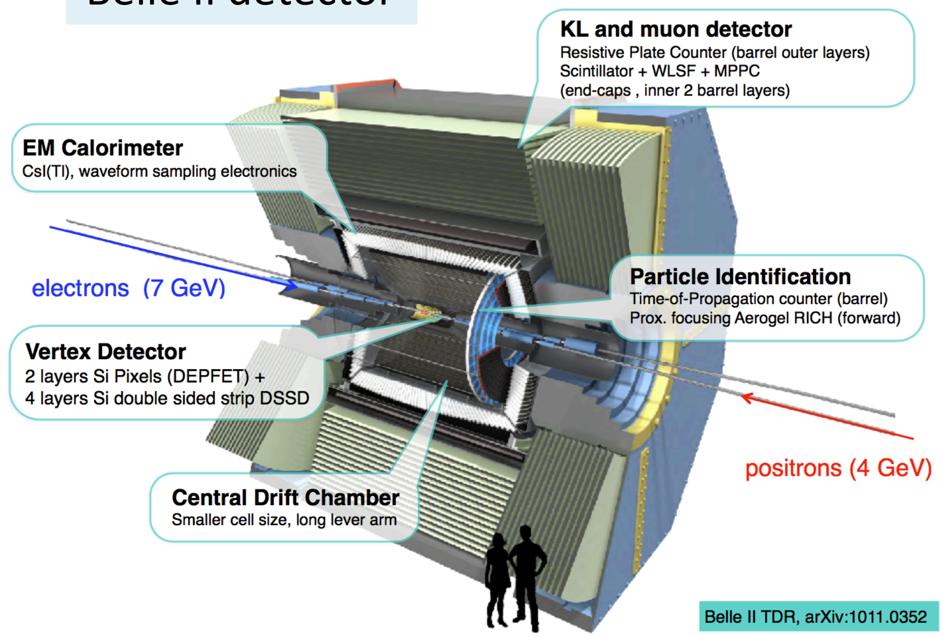
	Lumin. ($cm^{-2}s^{-1}$)
KEKB	2.1×10^{34}
SuperKEKB	80×10^{34}
	$\times 40$

Detectors at (Super)KEKB

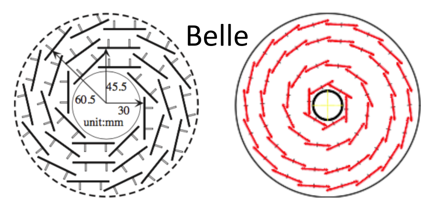
Belle detector

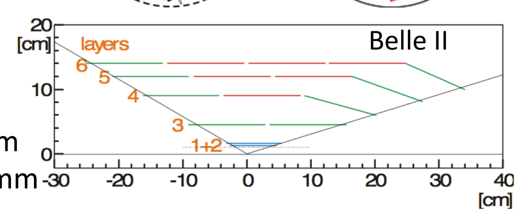


Belle II detector

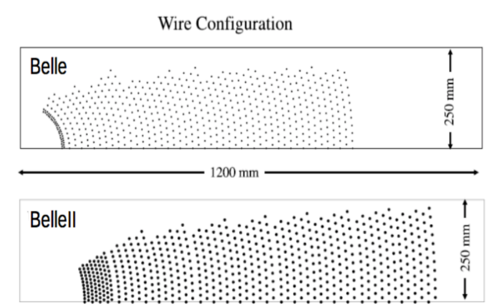


- SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
- CDC: small cell, long lever arm
- ACC+TOF → imaging "TOP"+Aerogel RICH
- ECL: waveform sampling
- KLM: RPC → Scintillator +SiPM (end-caps)

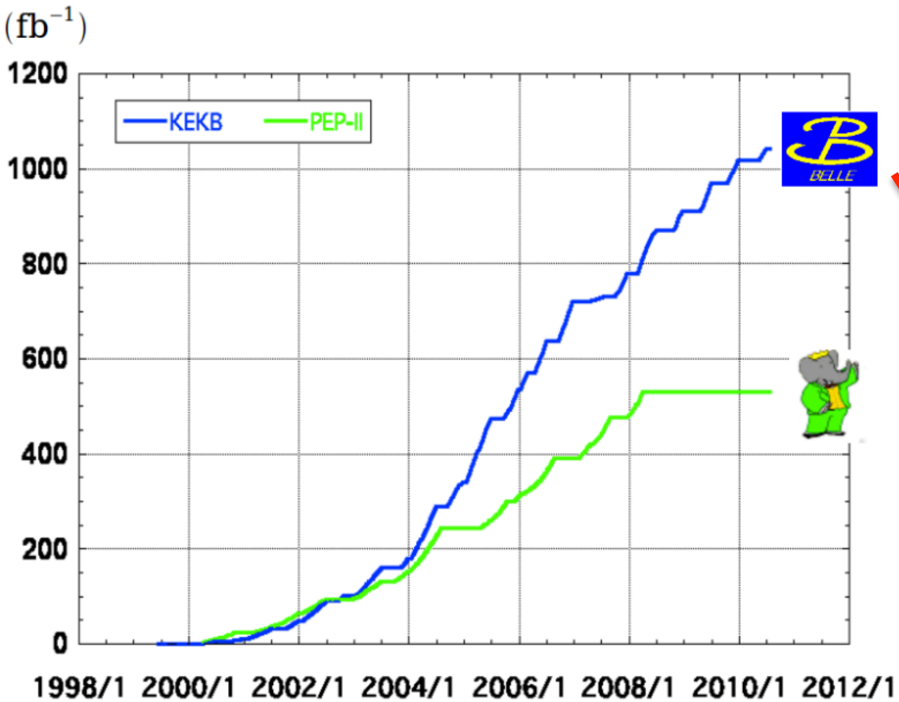


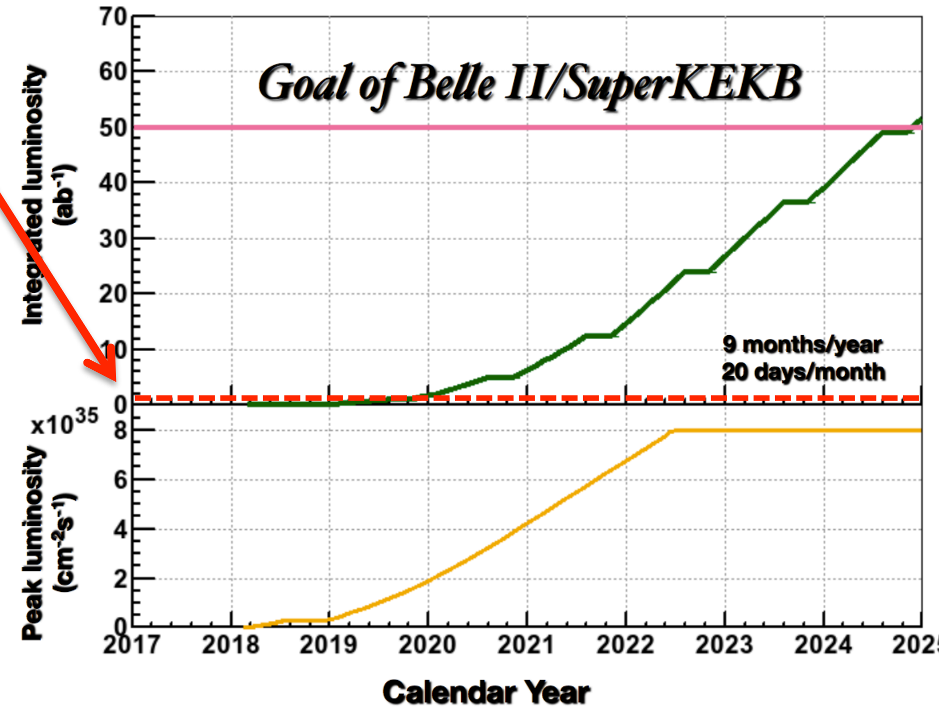


inner layer: r=20 mm → 14 mm
outer layer: r=88 mm → 135 mm



data set at Belle and Belle II





Each 1 ab^{-1} experimental data provides

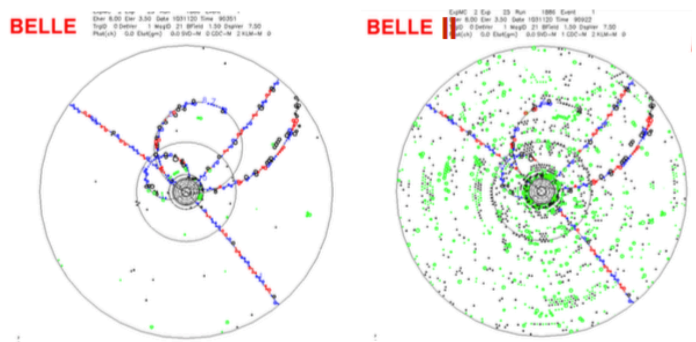
- $\sim 1.1 \times 10^9$ $B\bar{B} \Rightarrow$ a super B-factory;
- $\sim 1.3 \times 10^9$ $c\bar{c} \Rightarrow$ a super charm factory;
- $\sim 0.9 \times 10^9$ $\tau^+\tau^- \Rightarrow$ a super τ factory;
- wide effective $E_{c.m}$=[0.5-10] GeV via ISR process.

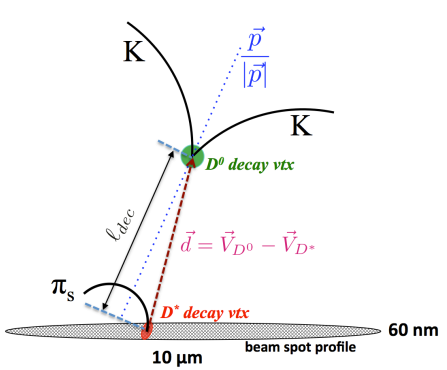
A rich platform for Charm physics

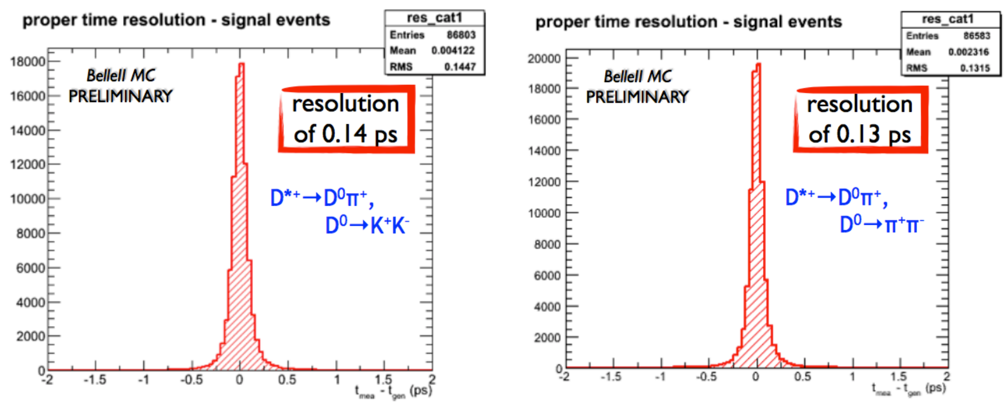
- ✓ *Hadronic Modes*
  - ✓ *time-dependent CPV & mixing*
  - ✓ *time-integrated Acp*
- ✓ *semi-leptonic Modes*
- ✓ *Leptonic and Radiative Decays*
- ✓ *More exotic stuff (missing energy...)*

Improved performance

- Higher beam-related and QED background(x20)
- Higher event rate (x10):
  - ✓ L1 trigger: 500Hz(Belle) Vs. 30kHz(Belle II)
- Improved performance:
  - ✓ vertex resolution; tracking;
  - ✓ particle identification;
  - ✓ ...
- Important effects on Charm mixing and CPV







- Based on MC study, time resolution = 140 fs: 2× better than BaBar (270 fs)
- Time error σ_t: factor 3 improvement; and RMS(σ_t): reduced by a factor 2.
  - $Res = Gauss(\mu, k\sigma_t)$, so reduced RMS($\sigma_t$) (higher weight in the fit) results in an increased statistics

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Introduction to D⁰-D̄⁰ mixing and *CP* violation

- Open-flavor neutral meson transforms to anti-meson:

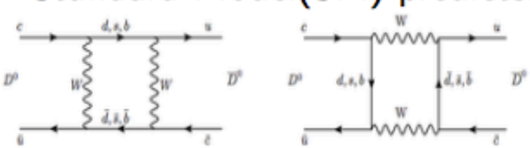
$$K^0 \Leftrightarrow \overline{K^0},\ B^0_d \Leftrightarrow \overline{B^0_d},\ B^0_s \Leftrightarrow \overline{B^0_s},\ D^0 \Leftrightarrow \overline{D^0}$$

- Flavor eigenstate ($|D^0\rangle$, $|\overline{D^0}\rangle$) $\neq$ mass eigenstate $|D_{1,2}\rangle$ with $M_{1,2}$ and $\Gamma_{1,2}$)

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

- Mixing parameters: $$x \equiv 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

- Unique system: only up-type meson for mixing
- Standard Model(SM) predicts: $\sim \mathcal{O}(1\%)$



(1) short distance ($< 0.1\%$)

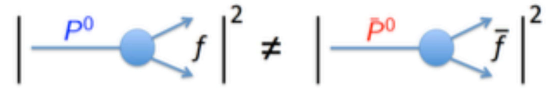
(2) long distance ($\sim 1\%$)

- Precise measurement of x, y: effectively limit the New Physics(NP) modes; and search for NP, eg: $|x| \gg |y|$

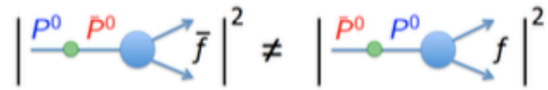
► Three types of Charged-conjugated-Parity combined symmetry Violation (CPV):

$$A^f_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} = a^f_d + a^f_m + a^f_i$$

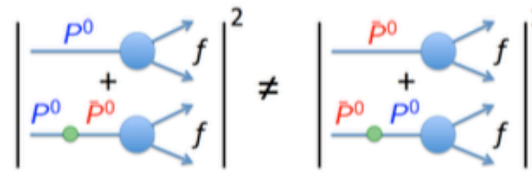
- a^f_d: (direct CPV) CPV in decay $|\bar{A}_{\bar{f}}/A_f| \neq 1$



- a^f_m: CPV in mixing with $r_m = |q/p| \neq 1$



- a^f_i: CPV in interference with $\arg(q/p) \neq 0$



- SM with only a source: the phase in CKM
- in charm sector, it's predicted at $\sim \mathcal{O}(10^{-3})$
- $\sim 1\%$ exp. sensitivity to observe CPV→NP

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

- summary table Mainly basing on HFLAV group

Decay Type	Final State	BELLE	BaBar	LHCb	CDF II	CLEO	BESIII
DCS 2-body(WS)	$K^+\pi^-$	★	☆	★[a]	★	✓	✓ $_{\delta K\pi}$
DCS 3-body(WS)	$K^+\pi^-\pi^0$	○[c]	☆			✓ A_{CP}	○ $_{\delta RS}$
CP-eigenstate	(even) h^+h^-	☆	☆	☆[b] A_{CP}	✓ A_{CP}	✓	
	(odd) $K_S^0\phi$	✓					
Self-conj. 3-body decay	$K_S^0\pi^+\pi^-$	✓	✓	✓	✓ A_{CP}	✓	○ $_\delta$
	$K_S^0K^+K^-$	○	✓	○			○ $_\delta$
	$K_S^0\pi^0\pi^0$					✓ Dalitz	○ y_{CP}
Self-conj. SCS 3-body decay	$\pi^+\pi^-\pi^0$	✓ A_{CP}	✓ mixing A_{CP}	✓ A_{CP}			○ $_\delta$
	$K^+K^-\pi^0$		✓ A_{CP}				○ $_\delta$
SCS 3-body	$K_S^0K^\pm\pi^\mp$			✓ A_{CP}		✓ $_\delta$	○ $_\delta$
Semileptonic decay	$K^+\ell^-\nu_\ell$	✓	✓			✓	
Multi-body(n≥4)	$K^+\pi^-\pi^+\pi^-$	✓ R_{WS}	✓	★			○ $_{\delta RS}$
	$\pi^+\pi^-\pi^+\pi^-$	○ A_{CP}		✓[d] A_{CP}			
	$K^+K^-\pi^+\pi^-$	○ A_T	✓ A_T	✓[e] A_{CP}		✓ A_{CP}	○
	$K_S^0\pi^+\pi^-\pi^0$	✓ A_T					
$\psi(3770)\to D^0\overline{D^0}$ via correlations						✓ $_{\delta K\pi}$	✓ y_{CP}

In D^0-$\overline{D^0}$ mixing measurements: ★ for observation ($>5\sigma$); ☆ for evidence ($>3\sigma$); ✓ for measurement published; ○ for analysis on going. A_T stands for measuring CP asymmetry using T-odd correlations.

(a) LHCb gave the measurement of charm mixing and CP violation in $D^0\to K^\pm h^\mp$ decay in PRD **95**, 052004 (2017).

(b) LHCb gave the measurements of CP violation in $D^0\to h^-h^+$ decay in PRL **112**, 041801 (2014) and PRL **118**, 261803 (2017).

(c) Belle measured WS-to-RS ratio R_{WS} and A_{CP} in $D^0\to K^\mp\pi^\pm\pi^0$ in PRL **95**, 231801 (2005).

(d) LHCb also searched for CP violation in phase space of $D^0\to\pi^+\pi^-\pi^+\pi^-$ decays in PLB **769**(2017) 345.

(e) LHCb also searched for CP violation using T-odd correlations in $D^0\to K^+K^-\pi^+\pi^-$ decays in JHEP **10**(2014)005.

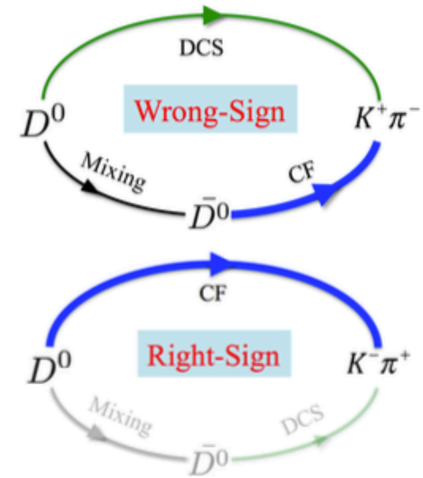
Hadronic WS decay for mixing & CPV

- Wrong-sign(WS) decay rates with D^0-$\overline{D^0}$ mixing or CPV-allowed:

$$\frac{N(D^0 \to f)}{dt} = e^{-\Gamma t}\left[R_D + \left|\frac{q}{p}\right|\sqrt{R_D}(y'\cos\phi - x'\sin\phi)(\Gamma t) + \left|\frac{q}{p}\right|^2\frac{(x'^2+y'^2)}{4}(\Gamma t)^2\right]$$

$$\frac{N(D^0 \to f)}{dt} = e^{-\Gamma t}\left[R_D + \sqrt{R_D}y'(\Gamma t) + \frac{(x'^2+y'^2)}{4}(\Gamma t)^2\right] \text{ (no CPV)}$$

where $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$ with strong phase difference δ



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

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

- fitting D^0 proper time distribution of WS sample (384 fb^{-1})

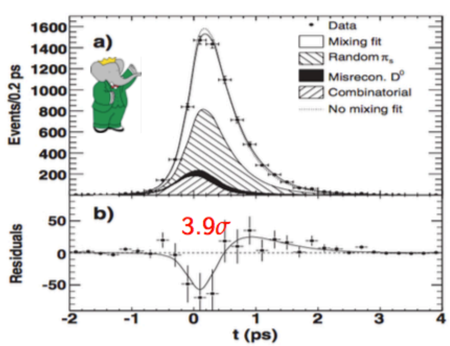
$$\frac{T_{WS}(t)}{e^{-\Gamma t}} \propto R_D + \sqrt{R_D}y'\Gamma t + \frac{x'^2+y'^2}{4}(\Gamma t)^2$$

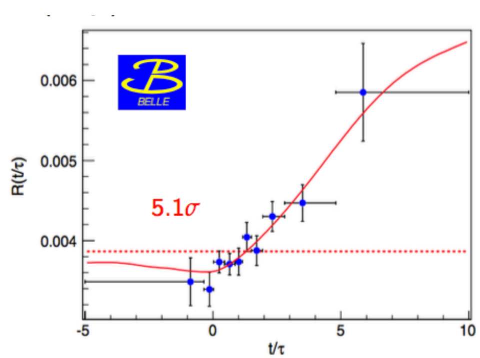
first observation in e^+e^- collisions

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

- fitting time-dependent ratio of WS-to-RS decay (976 fb^{-1})

$$R_{WS}(t) = \frac{\Gamma_{WS}(t)}{\Gamma_{RS}(t)} \approx R_D + \sqrt{R_D}y'\Gamma t + \frac{x'^2+y'^2}{4}(\Gamma t)^2$$





Parameter		Belle 976 /fb	Belle II 5 /ab	20 /ab	50 /ab
no CPV	$\sigma(x'^2)(10^{-5})$	22	7.5	3.7	2.3
	$\sigma(y')(\%)$	0.34	0.11	0.056	0.035
CPV-allowed	$\sigma(x')(\%)$		0.37	0.23	0.15
	$\sigma(y')(\%)$		0.26	0.17	0.10
	$\sigma(\|q/p\|)$		0.197	0.089	0.051
	$\sigma(\phi)(^\circ)$		15.5	9.2	5.7

One order magnitude improvement at Belle II

Time-dept. analyses for mixing and CPV

- Time-dependent Dalitz plot(TDDP) provides an essential tool in studying D^0-$\overline{D^0}$ mixing.
- Only method: sensitive to linear order in both mixing parameters, especially self-conjugated decays like $K^0_S hh$ (not rotated by an unknown δ)

- TDDP fit on $D^0 \to K^+\pi^-\pi^0$ WS decays to extract mixing par. $(x''/r_0,\ y''/r_0)$

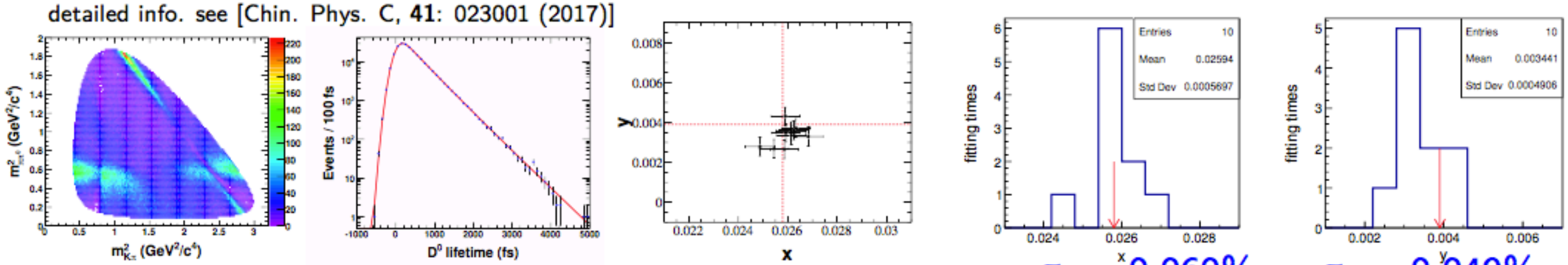
$$|\mathcal{A}_{\bar f}|^2 = \left[|\mathcal{A}^{DCS}_{\bar f}|^2 e^{-\Gamma t} + \frac{(x^2+y^2)}{4r_0^2}|\bar{\mathcal{A}}^{CF}_{\bar f}|^2(\Gamma t)^2 e^{-\Gamma t} + \left(\frac{y''}{r_0}\mathrm{Re}[\mathcal{A}^{DCS}_{\bar f}\bar{\mathcal{A}}^{*CF}_{\bar f}] + \frac{x''}{r_0}\mathrm{Im}[\mathcal{A}^{DCS}_{\bar f}\bar{\mathcal{A}}^{*CF}_{\bar f}]\right)(\Gamma t)e^{-\Gamma t}\right] \otimes_t Res(t)$$

$$x'' = x\cos\delta_{K\rho} + y\sin\delta_{K\rho},\ y'' = y\cos\delta_{K\rho} - x\sin\delta_{K\rho},\ r_0 = |A^{CF}|/|A^{DCS}|$$

- BaBar: the evidence (3.2σ) with 384 fb^{-1}: $\sigma(x'', y'') = ({}^{+0.57}_{-0.68}, {}^{+0.55}_{-0.64})\%$ [PRL **103**, 211801 (2009)]

- ToyMC: smear lifetime with Gauss(σ=140 fs); without considering bkg effects.
- Sensitivity estimation: one order of magnitude improvement than BaBar

detailed info. see [Chin. Phys. C, **41**: 023001 (2017)]



$\sigma_x = 0.060\%$, $\sigma_y = 0.049\%$

- More t-dept. measurements, like $D^0 \to K^+K^-, \pi^+\pi^-$ (y_{CP}, A_Γ), $D^0 \to K^0_S\pi^+\pi^-$ (x,y,|q/p|,ϕ) etc. in backup.

Time-dept. analyses for mixing and CPV

L.M. Zhang *et al.* PRL **99**, 131803 (2007)
T. Peng *et al.* PRD **89**, 091103(R) (2014)

- TDDA in self-conjugated decays:
  (1) direct measurement for x and y; (2) search for CPV: $q/p \neq 1$
- $D^0 \to K_S^0 \pi^+\pi^-$ with qusai-two-body decays with difference physics process:

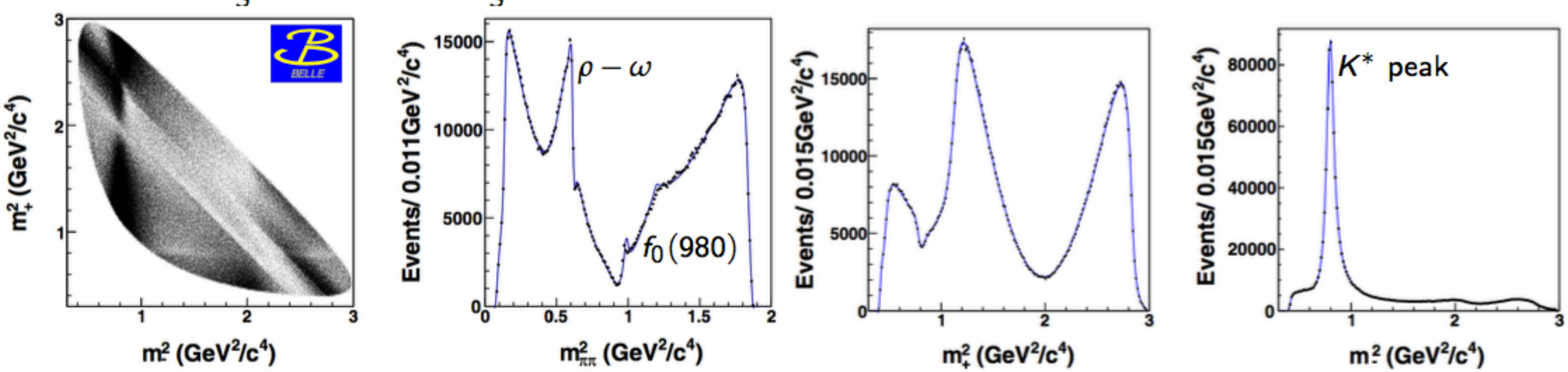
RS: $\mathcal{A}_f = \langle f|\mathcal{H}|D^0\rangle$; $\frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} = \left|\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}\right| \frac{1-\epsilon}{1+\epsilon} e^{i(\delta+\phi)}$; eg: $D^0 \to K^{*-}\pi^+$ etc.

WS: $\mathcal{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|D^0\rangle$; $\frac{q}{p}\frac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_{\bar{f}}} = \left|\frac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_{\bar{f}}}\right| \frac{1-\epsilon}{1+\epsilon} e^{-i(\delta-\phi)}$; eg: $D^0 \to K^{*+}\pi^-$ etc.

CP: $\mathcal{A}_+ = \langle +|\mathcal{H}|D^0\rangle$ $\frac{q}{p}\frac{\bar{\mathcal{A}}_+}{\mathcal{A}_+} = +\frac{1-\epsilon}{1+\epsilon} e^{+i\phi}$; eg: $D^0 \to K_S^0 f_0$ etc.

CP: $\mathcal{A}_- = \langle -|\mathcal{H}|D^0\rangle$ $\frac{q}{p}\frac{\bar{\mathcal{A}}_-}{\mathcal{A}_-} = -\frac{1-\epsilon}{1+\epsilon} e^{-i\phi}$; eg: $D^0 \to K_S^0\rho/K_S^0\omega$ etc.

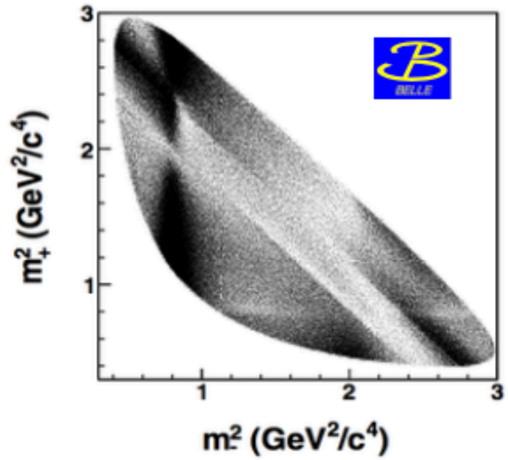
- DP Model with Isobar: 12 BW+K-matrix($\pi\pi$ S-wave)+LASS($K\pi$ S-wave)
- DP $m_-^2 = m^2_{K_S^0\pi^-}$, $m_+^2 = m^2_{K_S^0\pi^+}$ for D^0, exchange for $\overline{D^0}$.

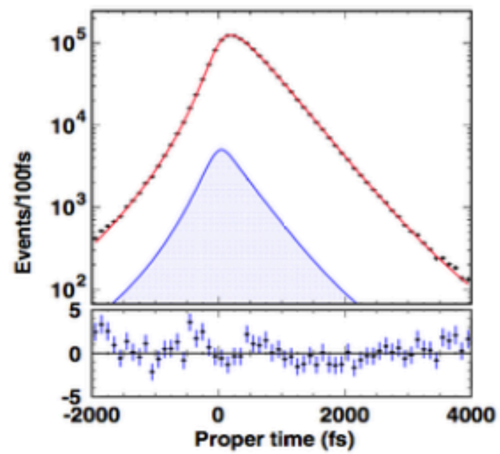


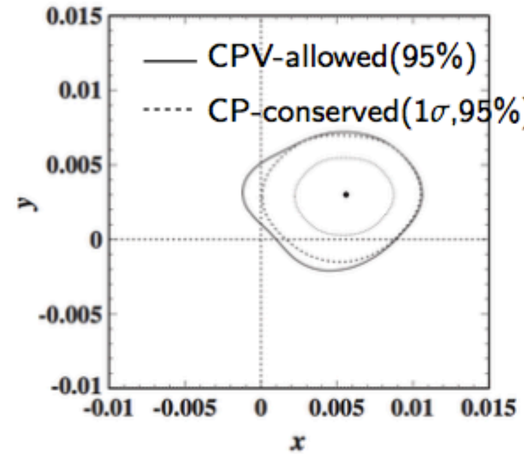
Time-dept. analyses for mixing and CPV

- Time-dependent DP fit on (m^2_-, m^2_+, t) to extract (x,y) and $(|q/p|, \arg(q/p))$

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







- fit results and prospect estimation:

Fit type	Para.	Belle Fit result 921 fb^{-1}	Belle II prospect 5 ab^{-1}	Belle II prospect 50 ab^{-1}	model-indept. 100 M signals	LHCb 50 fb^{-1}
No CPV	x(%)	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$	$\pm 0.08 \pm 0.11$	$\pm 0.03 \pm 0.11$	± 0.017	
	y(%)	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$	$\pm 0.06 \pm 0.05$	$\pm 0.02 \pm 0.04$	± 0.019	
indirect	x(%)	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$	$\pm 0.08 \pm 0.11$	$\pm 0.03 \pm 0.11$		0.04
	y(%)	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$	$\pm 0.06 \pm 0.05$	$\pm 0.02 \pm 0.04$		0.004
CPV	$\|q/p\|$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$	$\pm 0.069 \pm 0.073$	$\pm 0.022 \pm 0.069$		0.04
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$	$\pm 4.7 \pm 4.2$	$\pm 1.5 \pm 3.8$		3

Outline

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  - *Hadronic WS decay D^0->$K^+\pi^-$*
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- *Time-integrated CP asymmetry*
  - *summary table of measurements*
  - *Search for CPV in D^0->K_SK_S*
  - *CPV in radiative decays D^0->γV*
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- *ROE method for D^0 flavor tagging at Belle II*
- *Summary*

Time-integrated *CP* asymmetry measurement

- Time-integrated *CP* asymmetries are measured based on partial decay rates:

$$A^f_{CP} = \frac{\Gamma(D\to f) - \Gamma(\overline{D}\to \overline{f})}{\Gamma(D\to f) + \Gamma(\overline{D}\to \overline{f})} = a^f_d + a^f_{ind}$$ e.g: in $D^0 \to K^0_S h^+$, measured asym.: $A_{raw} = A_{CP} + A_{FB} + A^{h^+}_{\epsilon} + A^{K^0}_{CP}$

- Several measurements are performed at Belle

Channel	Current measurement			Belle II	LHCb
	$\mathcal{L}$(/fb)	value(%)	References	50 ab^{-1}(%)	50 fb^{-1}(%)
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	PoS ICHEP2012 (2013) 353	± 0.05	± 0.03
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	PoS ICHEP2012 (2013) 353	± 0.03	± 0.03
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	PRL **112**, 211601 (2014)	± 0.09	
$D^0 \to K^0_S K^0_S$	921	$-0.02 \pm 1.53 \pm 0.17$	PRL **119**, 171801 (2017)	± 0.20	
$D^0 \to K^0_S \pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	PRL **112**, 211601 (2014)	± 0.03	
$D^0 \to K^0_S \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	PRL **106**, 211801 (2011)	± 0.07	
$D^0 \to K^0_S \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	PRL **106**, 211801 (2011)	± 0.09	
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 0.41 \pm 1.23$	PLB **662**, 102 (2008)	± 0.13	
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	PRL **95**, 231801 (2005)	± 0.40	
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	$+0.43 \pm 1.30$	PRL **95**, 231801 (2005)	± 0.33	
$D^+ \to \pi^0\pi^+$	921	$+2.31 \pm 1.24 \pm 0.23$	Belle Preliminary	± 0.40	
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	PRL **108**, 071801 (2012)	± 0.04	
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	PRL **107**, 221801 (2011)	± 0.14	± 0.01
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	PRL **107**, 221801 (2011)	± 0.14	
$D^+ \to K^0_S \pi^+$	977	$-0.363 \pm 0.094 \pm 0.067 (3.2\sigma)$	PRL **109**, 021601 (2012)	± 0.03	± 0.03
$D^+ \to K^0_S K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	JHEP **02** (2013) 098	± 0.05	
$D^+_s \to K^0_S \pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	PRL **104**, 181602 (2010)	± 0.29	± 0.03
$D^+_s \to K^0_S K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	PRL **104**, 181602 (2010)	± 0.05	

- Belle II: precision of $\mathcal{O}(0.01\%)$ (down to SM level). $\sigma_{Belle\ II} = \sqrt{(\sigma^2_{stat} + \sigma^2_{syst}) \cdot (\mathcal{L}_{Belle}/50\ ab^{-1}) + \sigma^2_{irred}}$
- With respect to LHCb, Belle II has advantages of excellent γ and π^0 reconstruction.

Search for CPV in $D^0 \to K_S^0 K_S^0$

PRL **119**, 171801 (2017)

- The measured raw asymmetry:

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

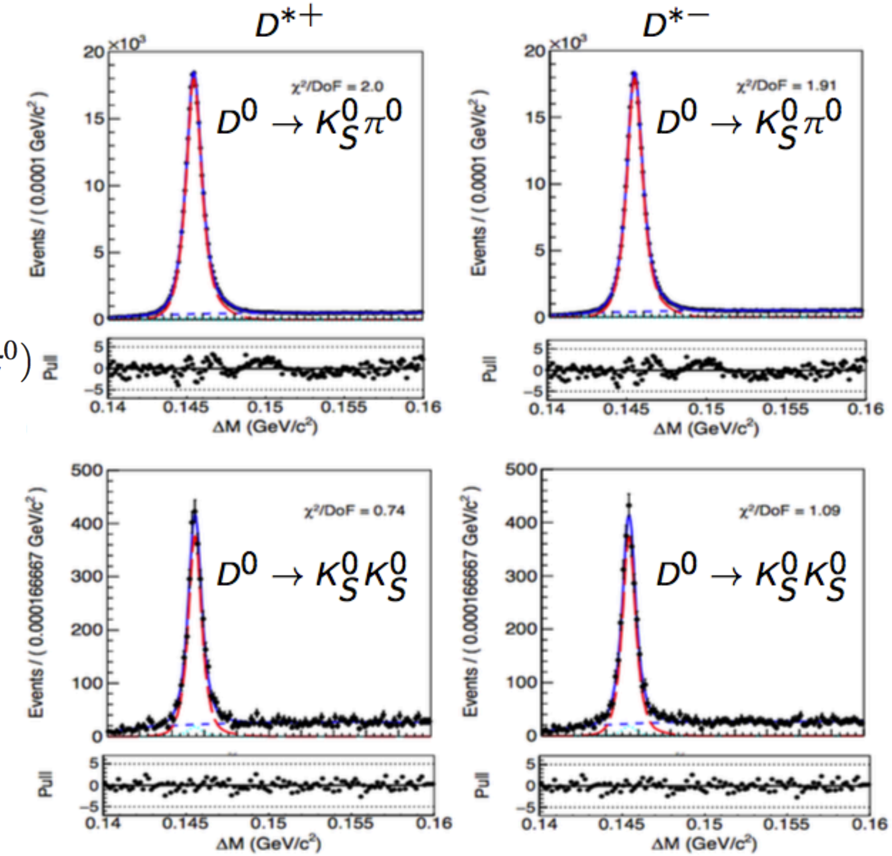
- Choose normalization mode: $D^0 \to K_S\pi^0$:

$$A_{CP}(D^0 \to K_S^0 K_S^0) = A_{\rm raw}(D^0 \to K_S^0 K_S^0) - A_{\rm raw}(D^0 \to K_S^0 \pi^0) + A_{CP}(D^0 \to K_S^0 \pi^0) + A_\epsilon^K,$$

$$\frac{\mathcal{B}(D^0 \to K_S^0 K_S^0)}{\mathcal{B}(D^0 \to K_S^0 \pi^0)} = \frac{(N/\epsilon)_{D^0 \to K_S^0 K_S^0}}{(N/\epsilon)_{D^0 \to K_S^0 \pi^0}}$$

- most precise measurement on both A_{CP} and BR for $D^0 \to K_S K_S$ mode:

  $A_{CP} = (-0.02 \pm 1.53 \pm 0.02 \pm 0.07)\%$
  BR $= (1.32 \pm 0.02 \pm 0.04 \pm 0.04) \times 10^{-4}$



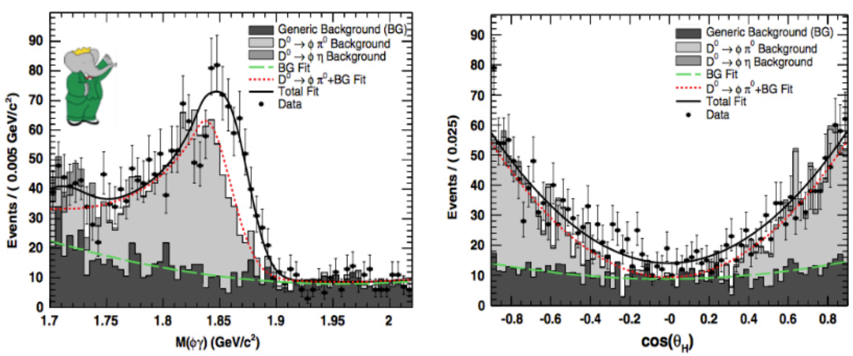
  - A_{CP}: consistent with SM expectation (improved to LHCb in 2015: $(-2.9 \pm 5.2 \pm 2.2)\%$)
  - BR: consistent with PDG: $(1.8 \pm 0.4) \times 10^{-4}$, but 2.3σ away from BESIII result $(1.67 \pm 0.11 \pm 0.11) \times 10^{-4}$ [PLB **765** (2017) 231]

- A_{CP} uncertainty dominated by stat. error → Prospect at Belle II: expect a precision of 0.2%

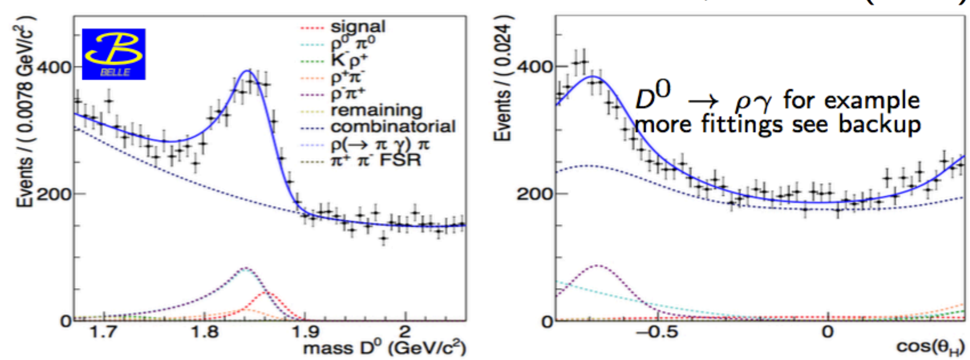
CPV in D^0 radiative decays

- branch ratio measurement in D^0->γV
  - 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)]
  - 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

PRD**78**,071101(R) (2008)



PRL **118**, 051801 (2017)



$M_{V\gamma}$ 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)

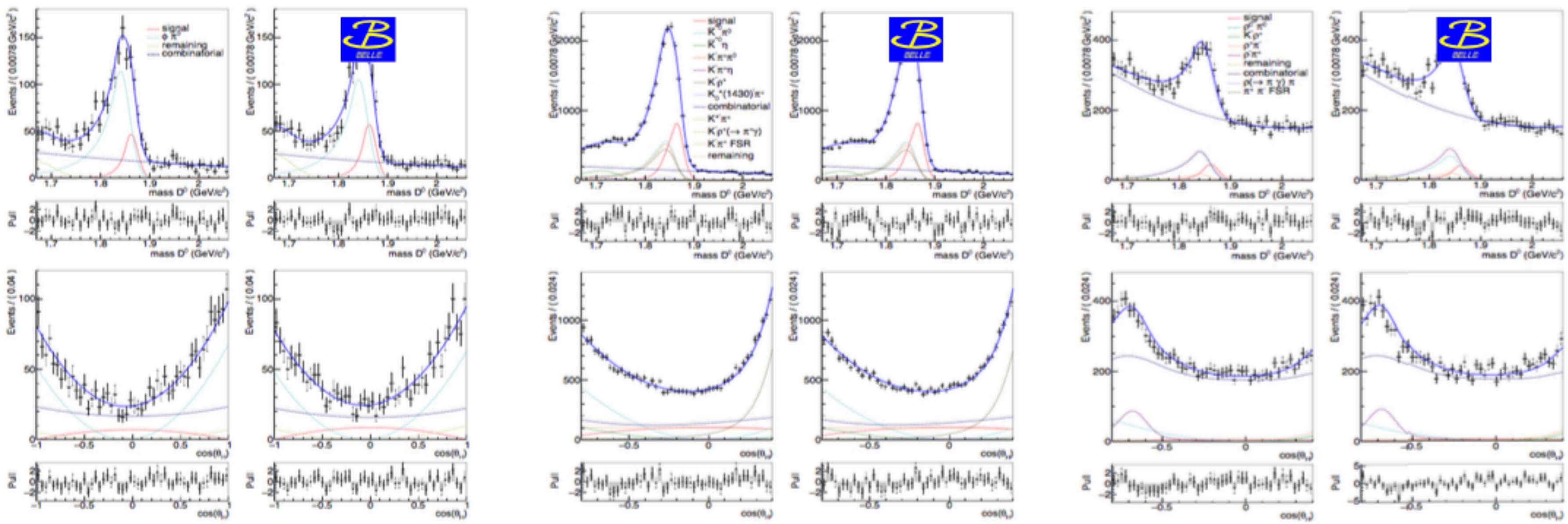
$\mathcal{B}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$

(first observation, $\simeq$ theoretical predictions)

CPV in D^0 radiative decays

Belle: First measurement of $\mathcal{A}_{CP}$ in $D^0 \to V\gamma$ [T. Nanut *et al.*, PRL **118**, 051801 (2017)]

- 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}, $A_{\epsilon}^{\pm}$: eliminated through a relative measurement: $\mathcal{A}_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{norm} + \mathcal{A}_{CP}^{norm}$



$\mathcal{A}_{CP}^{\phi\gamma} = -0.094 \pm 0.066 \pm 0.001$ $\mathcal{A}_{CP}^{\bar{K}^{*0}\gamma} = -0.003 \pm 0.020 \pm 0.000$ $\mathcal{A}_{CP}^{\rho^0\gamma} = +0.056 \pm 0.151 \pm 0.006$

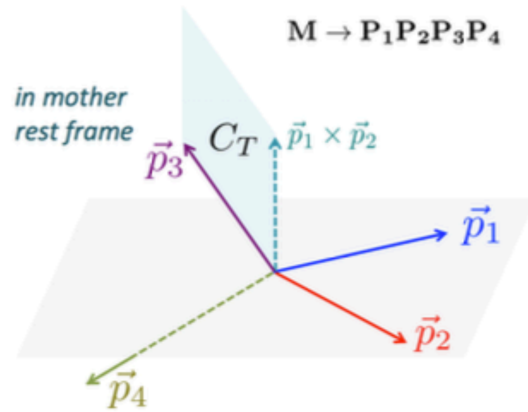
Belle II(50 ab^{-1}): σ=±0.01 σ=±0.003 σ=±0.02

T-odd asymmetry in $D^0 \to K_S\pi^+\pi^-\pi^0$

PRD **95**, 091101(R) (2017)

- T-odd correlations provides a powerful tool to indirectly search for *CP* violation:
  (1) a triple product of momenta; (2) assuming CPT symmetry conservation
- Parity-odd observable $C_T = (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$ and its CP-conjugated observable $\overline{C}_T$

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \qquad \overline{A}_T = \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) + \Gamma(-\overline{C}_T < 0)}$$



- T-odd asymmetry: remove strong phase introduced by FSI

$$a_{CP}^{\text{T-odd}} = \frac{1}{2}(A_T - \overline{A}_T)$$

- Observing a T-odd asymmetry would be a signal for processes beyond the SM.
- Status of T-odd asymmetries in charmed mesons decay-rates:

$D^0 \to K_S^0\pi^+\pi^-\pi^0$	$a_{CP}^{\text{T-odd}} = (-0.28 \pm 1.38^{+0.23}_{-0.76}) \times 10^{-3}$	Belle[1]
$D^0 \to K^+K^-\pi^+\pi^-$	$a_{CP}^{\text{T-odd}} = (+1.7 \pm 2.7) \times 10^{-3}$	LHCb[2], BaBar[3], Focus[4]
$D^+ \to K_S^0K^+\pi^+\pi^-$	$a_{CP}^{\text{T-odd}} = (-1.10 \pm 1.09) \times 10^{-2}$	BaBar[5], Focus[4]
$D_s^+ \to K_S^0K^+\pi^+\pi^-$	$a_{CP}^{\text{T-odd}} = (-1.39 \pm 0.84) \times 10^{-2}$	BaBar[5], Focus[4]

[1] K. Prasanth *et al.*(Belle Collab.), Phys. Rev. D **95**, 091101(R) (2017)
[2] R. Aaij *et al.*(LHCb Collab.), JHEP **10**, 5 (2014)
[3] P. del Amo Sanchez *et al.*(BaBar Collab.), Phys. Rev. D **81**, 111103(R) (2010)
[4] J.M. Link *et al.*(FOCUS Collab.), Phys. Lett. B **622**, 239 (2005)
[5] J.P. Lees *et al.*(BaBar Collab.), Phys. Rev. D **84**, 031103(R) (2011)

Belle II could improve these results with more precision benefited from the increased dataset.

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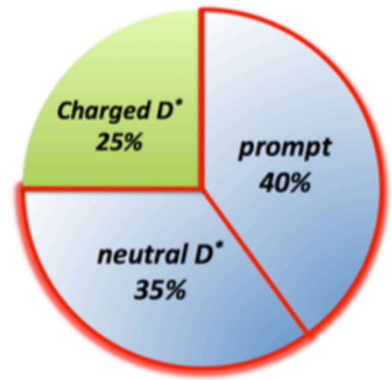
- ***ROE method for D^0 flavor tagging at Belle II***
- *Summary*

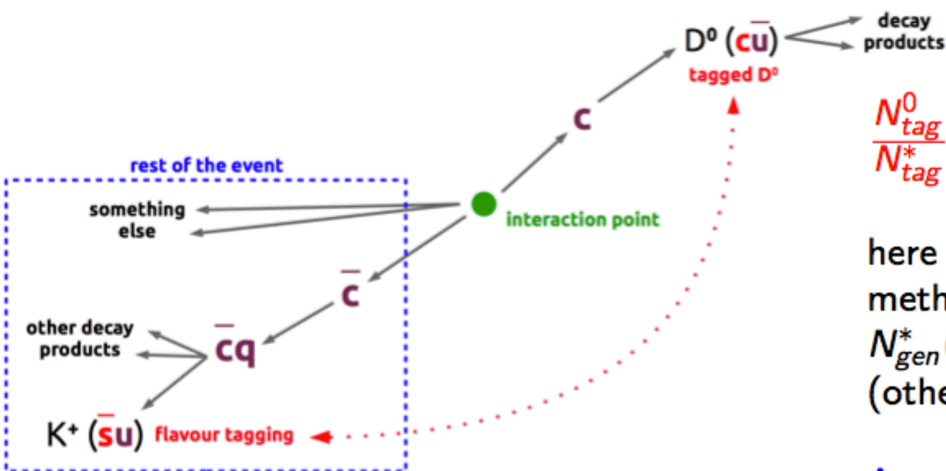
ROE method

- To measure CPV, the flavor of D^0 is determined effectively.
- At B-factories, the charge of π_s from $D^{*+} \to D^0\pi_s^+$ is used to tag the flavor of D^0; but D^0 mesons from B decays are excluded.
  $\Rightarrow$ only D^0 from $D^{*\pm}$ in $c\bar{c}$ events (25%) were used.



$c\bar{c} \to D^{*+}X,\ D^{*+} \to D^0\pi_s^+$
$c\bar{c} \to D^{*0}X,\ D^{*0} \to D^0\pi^0/D^0\gamma$
$c\bar{c} \to D^0 D^- X/D^0\bar{\Lambda}_c^- X$

- ROE method: select events with only one $K^\pm$ in the Rest Of Event;
- the charge of this $K^\pm$ in ROE to determine the flavor of D^0.



$$\frac{N^0_{tag}}{N^*_{tag}} = \frac{\epsilon^0_{tag}}{\epsilon^*_{tag}} \cdot \frac{N^0_{gen}+(1-\epsilon^*_{tag})\cdot N^*_{gen}}{N^*_{gen}} \sim 1$$

here $\epsilon^*_{tag}(\epsilon^0_{tag})$: tagging efficieny of D^*(ROE) method with 80%($\leqslant$ 20%).
$N^*_{gen}(N^0_{gen})$: number of D^0 produced by a D^* (other $c\bar{c}$ event) with $N^0_{gen} : N^*_{gen} \simeq 3:1$

A reduction of $\sim 15\%$ of $\sigma(stat)$ on A_{CP}

An additional D^0 sample from ROE for mixing and CPV measurements.

Summary

- *Belle at KEKB have proven to be an excellent tool for charm physics*
  - *first (only) observation of D^0-$\bar{D}^0$ mixing in e^+e^- collision*
  - *no hints for indirect CPV and no clear evidence for direct CPV*
  - *fruitful results on mixing/CPV measurement, but mostly under statistical limit*
- *Major upgrade at KEKB in 2010-17 → SuperKEKB $\mathcal{L}\times 40 = 50\ ab^{-1}$ before 2025. Belle II at SuperKEKB will have a rich charm physics program with much improved performance:*
  - *improve precision of mixing and CPV parameters, direct CP asymmetries.*
  - *Many final states studies (e.g. with $\pi^0/\eta/\eta'$ etc.) complementary to LHCb.*
  - *Some new techniques are developing, like ROE method.*
- *Detector is mostly installed and commissioned, will collect the first data in 2018.*

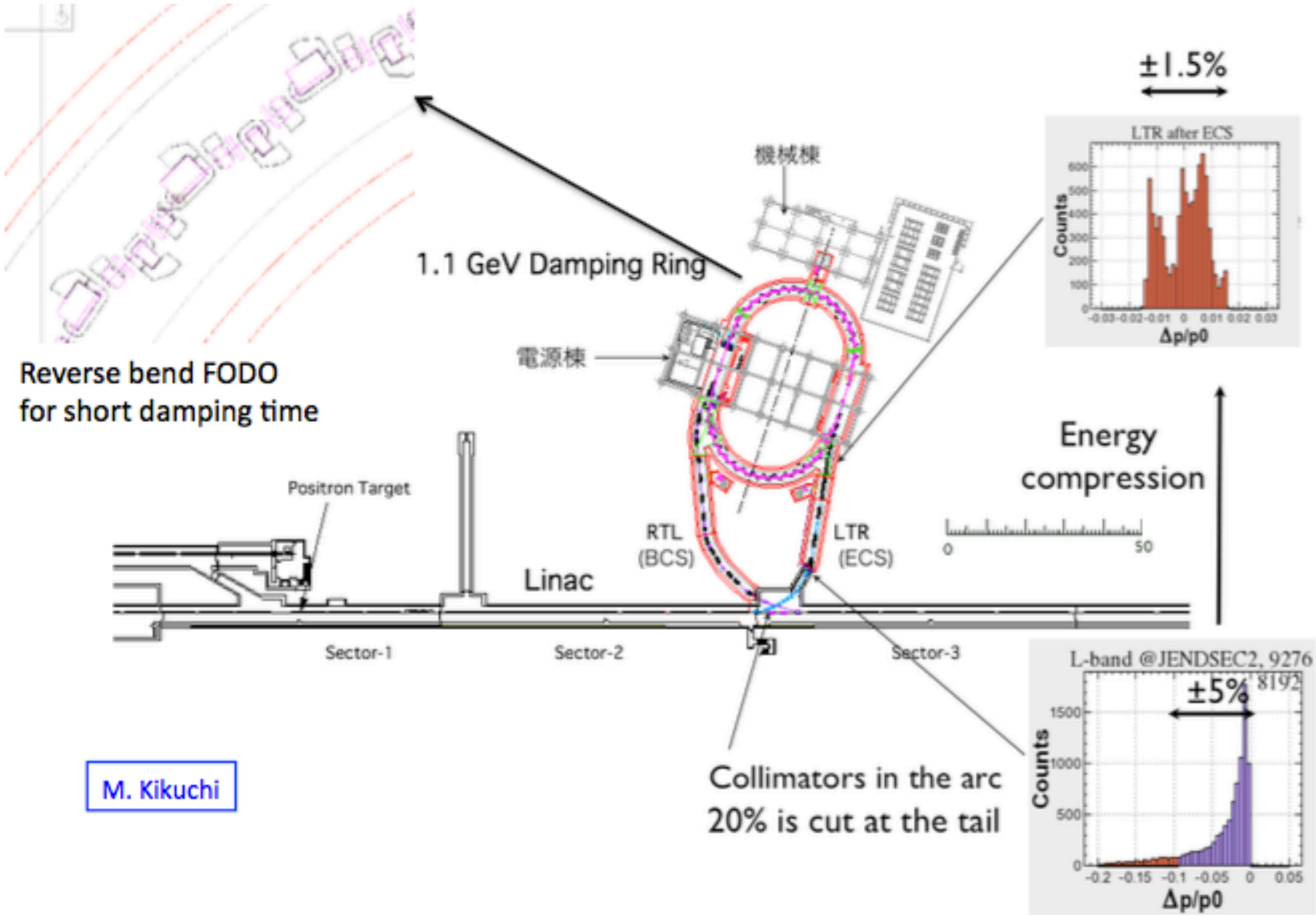
Let's look forwards to the charming news of charm physic from Belle II (绝世美女二世).

今夕何夕，见此粲者？
子兮子兮，如此粲者何？
--《诗经•绸缪》

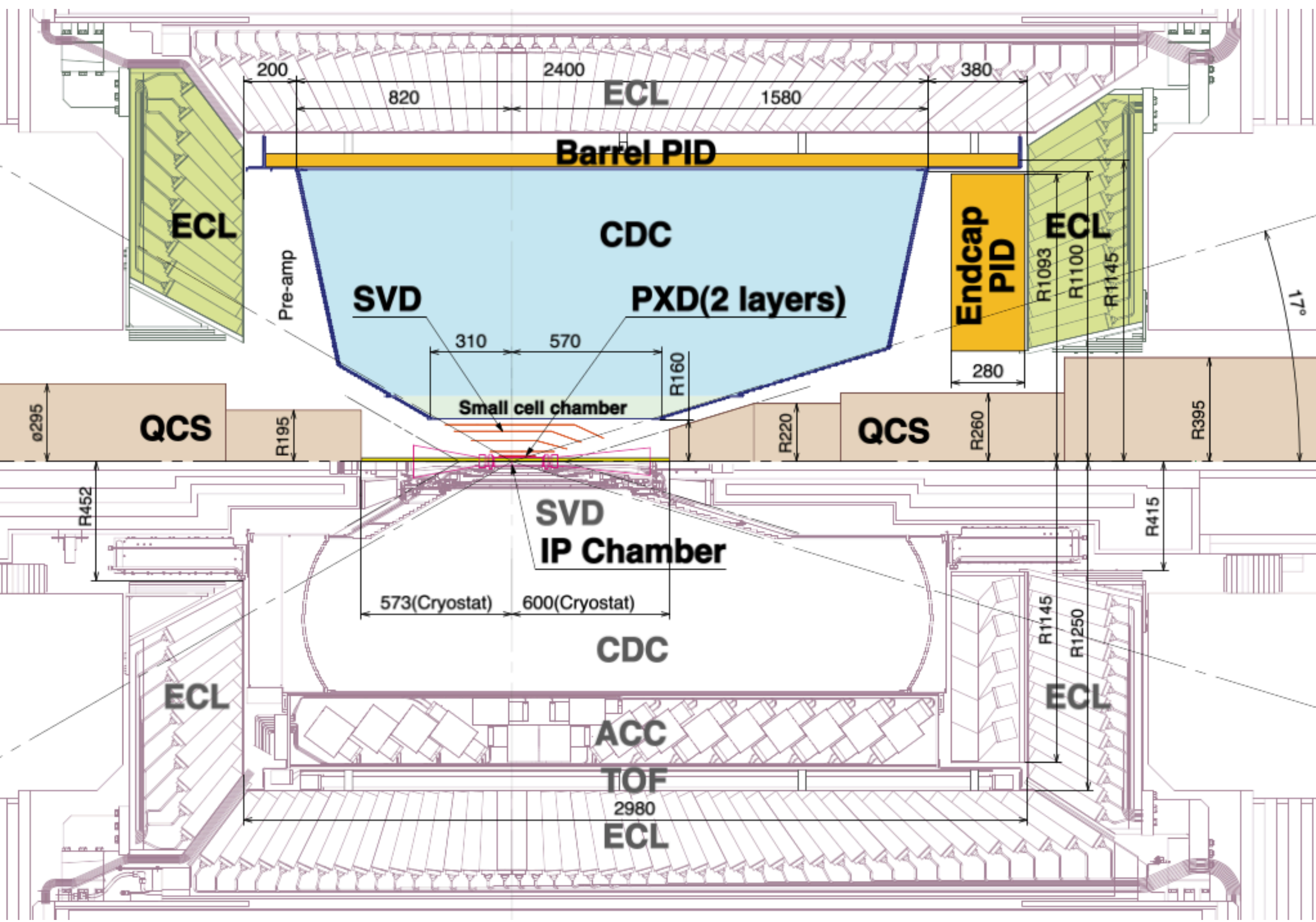
backup

Longke LI (李龙科)
Room A519, Main Building
Institute of High Energy Physics, CAS (IHEP)
19B, Yuquan Road, Shijingshan District
Beijing City, 100049, P. R. China
(+86)-159-5693-4447
lilongke_ustc
lilongke@ihep.ac.cn

Damping Ring



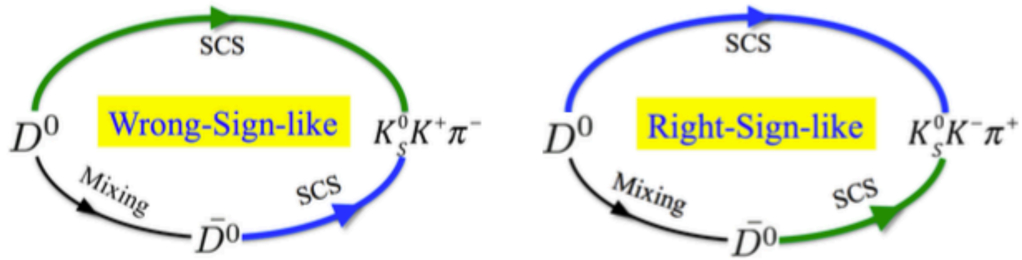
M. Kikuchi



200
2400
380
820
ECL
1580
Barrel PID
ECL
CDC
ECL
Pre-amp
SVD
PXD(2 layers)
Endcap PID
R1093
R1100
R1145
17°
310
570
R160
280
Small cell chamber
ø295
QCS
R195
R220
QCS
R260
R395
R452
SVD
IP Chamber
R415
573(Cryostat)
600(Cryostat)
R1145
R1250
CDC
ECL
ECL
ACC
TOF
2980
ECL

prospect of mixing in three-body SCS decays

- decay rate of WS-like and RS-like:



  - $\Gamma(D^0 \to K_S^0 K^+ \pi^-) = e^{-\Gamma t}\left[r_D^2 + r_D R_D y' \Gamma t + \frac{(1-r_D^2)x'^2 + (1+r_D^2)y'^2}{4}(\Gamma t)^2\right]$
  - $\Gamma(D^0 \to K_S^0 K^- \pi^+) = e^{-\Gamma t}\left[1 + r_D R_D y' \Gamma t + \frac{(1+r_D^2)x'^2 - (1-r_D^2)y'^2}{4}(\Gamma t)^2\right]$

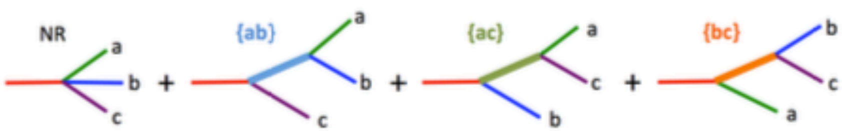
  where $r_D = A_{sup.}/\bar{A}_{fav.}$, $y' = y\cos\delta_D - x\sin\delta_D$, coherence factor R_D: $A_f \bar{A}_f R_D e^{-i\delta_D} = A_f \bar{A}_f^*$

- Comparing with WS decays $D^0 \to K^+\pi^-$: $r_D^{K\pi} \ll 1$ Vs. $r_D^{K_S^0 K\pi} \sim 1$
- $D^0 \to K_S^0 K\pi$: effectively sensitive to y'(large R_D); higher purity (large r_D)
- CLEO gave in $D^0 \to K_S^0 K\pi$, $R_D = 0.73 \pm 0.09$ and $\delta_D = (8.2 \pm 15.2)^o$ [PRD 85, 092016(2012)]
- sensitivity estimation of mixing: $\sigma(y') = 0.55\%$ (80K signals) [PLB 701(2011)353]
- LHCb has performed Dalitz plot fit on these two decays. [PRD 93, 052018 (2016)]
- mixing and CPV measurement in these decays......

Time-dependent Dalitz analysis

- DP of 3-body decay described by Isobar model:

Phys. Rev. **123**, 333 (1961)

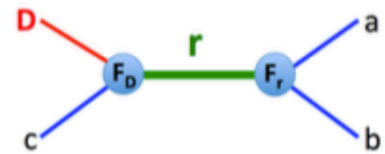


$$\mathcal{M}(m^2_{ab}, m^2_{bc}) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m^2_{ab}, m^2_{bc}) + a_{NR} e^{i\phi_{NR}}$$

here $a_r(\phi_r)$ is magnitude (phase) of resonance r.

- $\mathcal{A}_r$: dynamics of $D \to (r \to ab)c$

PRD **63**, 092001 (2001)



$$\mathcal{A}_r(m^2_{ab}, m^2_{bc}) = F_D \times F_r \times T_r \times W_r$$

▷ T_r: resonance lineship

usually use relativistic Breit-Wigner with mass dept. width
For wide width or special resonances:
mass-threshold: Flatté model, eg: $f_0(980)(KK)$ / $a_0(980)(KK/\eta'\pi)$
$\pi\pi$ S-wave overlapping res.: K-matrix model EPJ **A16** (2003) 229-258
$\pi\pi$ P-wave: ρ with Gounaris-Sakurai (GS) model PRL **24**,244(1968)
$K\pi$ S-wave: $K^*_0(1430)$ with LASS model EPJ **C74** (2014): 3026

▷ W_r angular distribution:

(1)Helicity form [PRD **78**, 052001 (2008)]
(2)Zemach covariant tensor form [PR **133**, B1201 (1964), PR **140**, B109 (1965)]

▷ F_r, F_D form factor: PR D **63**, 092001 (2001)

using Blatt-Weisskopt Barrier form factor, depend on orbital angular momentum ℓ(here $\ell = J$(spin of res.)

$F_{J=0} = 1$

$F_{J=1} = \frac{\sqrt{1+z_r}}{\sqrt{1+z_{ab}}}$

$F_{J=2} = \frac{\sqrt{(z_r-3)^2+9z_r}}{\sqrt{(z_{ab}-3)^2+9z_{ab}}}$

$F_{J=3} = \frac{\sqrt{z_r(z_r-15)^2+9(2z_r-5)}}{\sqrt{z_{ab}(z_{ab}-15)^2+9(2z_{ab}-5)}}$

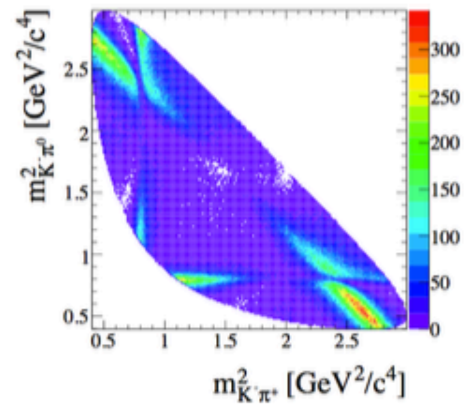
$F_{J=4} = \frac{\sqrt{(z_r^2-45z_r+105)^2+15z_r(21z_r-21)^2}}{\sqrt{(z_{ab}^2-45z_{ab}+105)^2+15z_{ab}(21z_{ab}-21)^2}}$

here $z = (R \cdot q)^2$, R is the radius of D or res. r

Time-dependent Dalitz analysis

- Dalitz plot(DP) fit
  - p.d.f of signal DP:
    - (1) efficiency plane ϵ correction
    - (2) considering mass resolution $Res(m)$
    - (3) normalization

$$p_{\rm sig}(m^2_{12,i}, m^2_{23,i}) = \frac{|\mathcal{M}(m^2_{12,i},m^2_{23,i})|^2 \otimes_m Res(m)\cdot\epsilon(m^2_{12,i},m^2_{23,i})}{\iint_{DP} dm^2_{12}dm^2_{23}\ |\mathcal{M}(m^2_{12},m^2_{23})|^2 \otimes_m Res(m)\cdot\epsilon(m^2_{12},m^2_{23})}$$



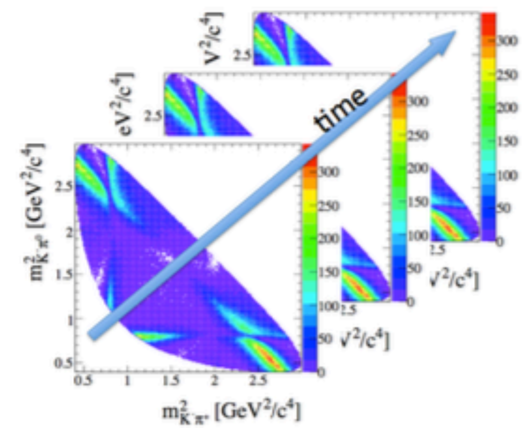
  - fit method: unbinned maximum likelihood (UML)

$$2\ln\mathcal{L} = 2\sum_{i=1}^{n}\ln\left[f^i_{sig}p_{\rm sig}(m^2_{12,i}, m^2_{23,i}) + \sum_{X=bg} f^i_X p_X(m^2_{12,i}, m^2_{23,i})\right]$$

signal-to-bkg f^i determined by kinematic variable fit result, like M-Q。

- time-dependent Dalitz plot(TDDP) fit
  - p.d.f of signal TDDP with considering time resolution : $R_{sig}(t)$

$$p_{\rm sig}(m^2_{12,i}, m^2_{23,i}, t_i, \sigma^i_t) = \frac{\int dt' R_{\rm sig}(t_i - t', \sigma^i_t)\left|\mathcal{M}_f(m^2_{12,i},m^2_{23,i},t')\right|^2\cdot\epsilon(m^2_{12,i},m^2_{23,i})}{\int dt \iint_{DP} dm^2_{12}dm^2_{23}\ \left|\mathcal{M}_f(m^2_{12},m^2_{23},t)\right|^2\epsilon(m^2_{12},m^2_{23})}$$



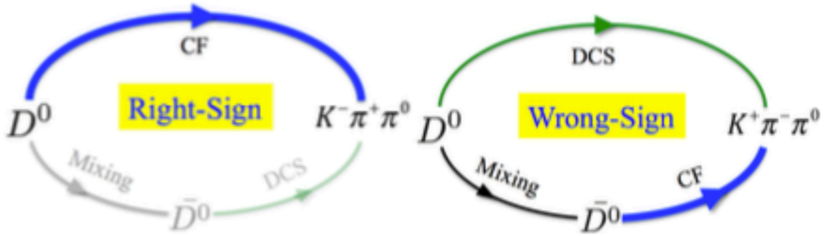
  - fit method: unbinned maximum likelihood (UML)

$$2\ln\mathcal{L} = 2\sum_i^n\{\ln(f^i_{\rm sig}p_{\rm sig}(m^2_{12,i}, m^2_{23,i}, t_i, \sigma^i_t; x, y)p^{nc}_{sig}(\sigma^i_t) + \sum_{x=bg} f^i_x p_x(m^2_{12,i}, m^2_{23,i}, t_i)p^{nc}_x(\sigma^i_t))\}$$

here $p^{nc}_x(\sigma^i_t)$ is global function for time error, independent on others.

Time-dependent Dalitz analysis

- Right-Sign(RS) abd Wrong-Sign(WS) decays

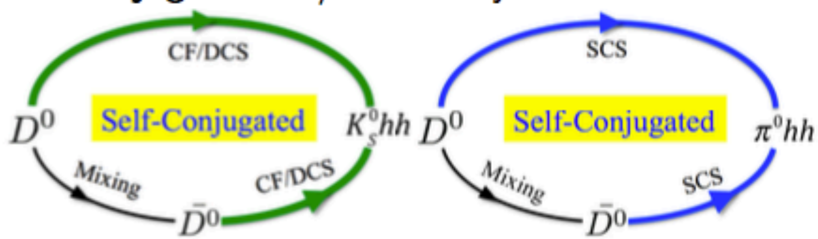


$$|\mathcal{M}_f(RS,t)|^2 = e^{-\Gamma t}|\bar{\mathcal{A}}_{\bar{f}}^{CF}|^2$$

$$\mathcal{A}_{\bar{f}}/\bar{\mathcal{A}}_{\bar{f}} = -\sqrt{R_D}e^{-i\delta};\ x'' = x\cos\delta + y\sin\delta;\ y'' = y\cos\delta - x\sin\delta$$

$$|\mathcal{M}_{\bar{f}}(WS,t)|^2 = e^{-\Gamma t}\left\{|\mathcal{A}_{\bar{f}}^{DCS}|^2 - (\frac{y''}{r_0}\mathrm{Re}[\mathcal{A}_{\bar{f}}^{DCS}\bar{\mathcal{A}}_{\bar{f}}^{CF*}] + \frac{x''}{r_0}\mathrm{Im}[\mathcal{A}_{\bar{f}}^{DCS}\bar{\mathcal{A}}_{\bar{f}}^{CF*}])\Gamma t + \frac{x''^2+y''^2}{4r_0^2}|\bar{\mathcal{A}}_{\bar{f}}^{CF}|^2(\Gamma t)^2\right\}$$

- Self-conjugated CF/SCS decays



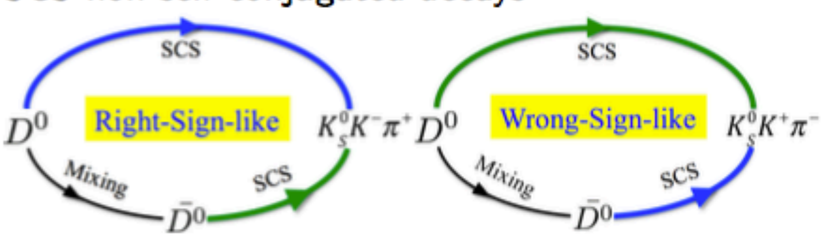
RS: $\mathcal{A}_f = \langle f|\mathcal{H}|D^0\rangle$; WS: $\mathcal{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|D^0\rangle$; CP: $\mathcal{A}_\pm = \langle \pm|\mathcal{H}|D^0\rangle$

D^0: $m_+^2 = m^2_{K^0_S h^+}$; $m_-^2 = m_{K^0_S h^-}$; $\overline{D^0}$: $m_-^2 = m^2_{K^0_S h^+}$; $m_+^2 = m_{K^0_S h^-}$

$$|\mathcal{M}_f|^2 = \left\{|A_1|^2 e^{-y\Gamma t} + |A_2|^2 e^{y\Gamma t} + 2\,\mathrm{Re}[A_1 A_2^*]\cos(x\Gamma t) + 2\,\mathrm{Im}[A_1 A_2^*]\sin(x\Gamma t)\right\}e^{-\Gamma t}$$

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

- SCS non-self-conjugated decays



(very difficult! No one experiment gives time-dept. amplitude analysis to date.)

$A = \langle K^0_S K^-\pi^+|\mathcal{H}|D^0\rangle = \langle K^0_S K^+\pi^-|\mathcal{H}|\bar{D}^0\rangle$; $B = \langle K^0_S K^+\pi^-|\mathcal{H}|D^0\rangle = \langle K^0_S K^-\pi^+|\mathcal{H}|\bar{D}^0\rangle$

$$|\mathcal{M}(RS,t)|^2 = e^{-\Gamma t}\left\{|A|^2 + \frac{x^2+y^2}{4}r_D^2|B|^2(\Gamma t)^2 + r_D(y'\,\mathrm{Re}[AB^*] + x'\,\mathrm{Im}[AB^*])\Gamma t\right\}$$

$$|\mathcal{M}(WS,t)|^2 = e^{-\Gamma t}\left\{r_D^2|B|^2 + \frac{x^2+y^2}{4}|A|^2(\Gamma t)^2 + r_D\cdot(y'\,\mathrm{Re}[BA^*] + x'\,\mathrm{Im}[BA^*])\Gamma t\right\}$$

search for CPV in $D^0 \to K_S^0 K_S^0$

SM limit 1.1% for direct CPV in $D^0 \to K_S^0 K_S^0$

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

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

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

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

Method: $A_{CP}(D^0 \to K_S^0 K_S^0) = (A_{rec}(K_S^0 K_S^0) - A_{rec}(K_S^0 \pi^0)) + A_{CP}(D^0 \to K_S^0 \pi^0) + A_{K0/\bar{K}0}$

$A_{K0/\bar{K}0}$: Asymmetry originating from the different strong interaction of K0 and $\overline{K0}$ mesons with nucleons of the detector material = $(-0.11 \pm 0.01)\%$

[B. R. Ko et al., PRD 84 (2011) 111501]

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

N. Dash, ICHEP 2016