

Measurement of $\cos 2\beta \equiv \cos 2\varphi_1$ in $B^0 \rightarrow D^{(*)0} h^0$ with $D \rightarrow K_S^0 \pi^+ \pi^-$ decays by a time-dependent Dalitz analysis using BaBar and Belle combined data



Vitaly Vorobyev on behalf of the Belle Collaboration

ICHEP 2018, July 6th 2018, Seoul

Outline

- Introduction
- Analysis of $B^0 \rightarrow D^{(*)} h^0$, $D \rightarrow K_S^0 \pi^+ \pi^-$ with combination of the complete Belle and BaBar data sets

- Future prospects

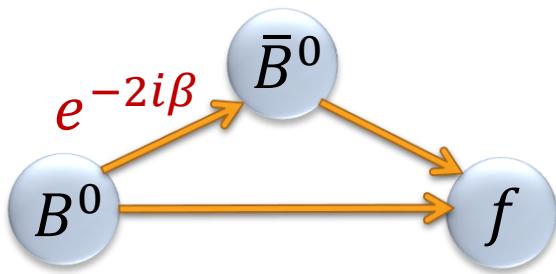
- Conclusions



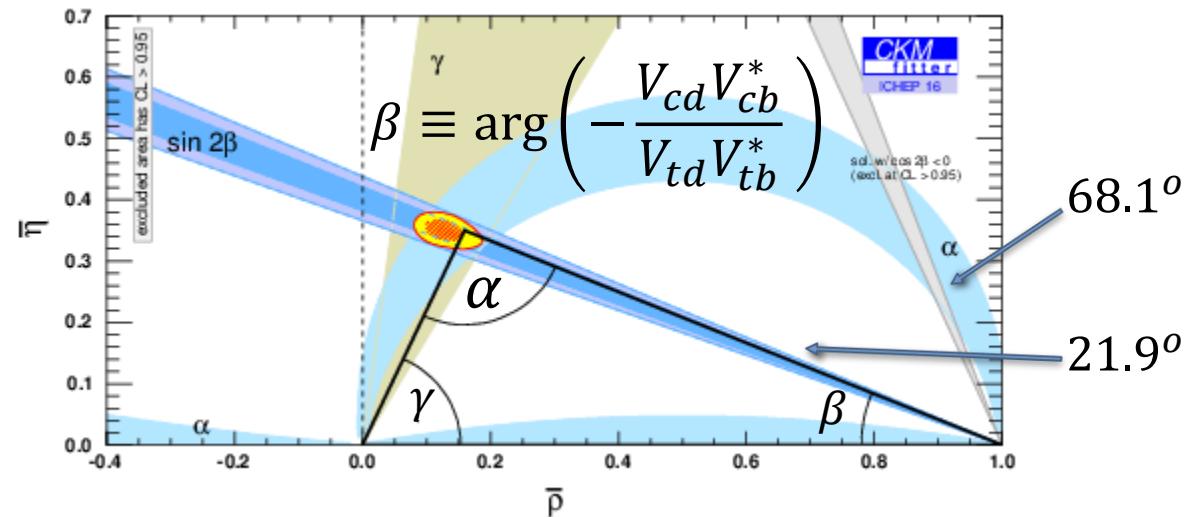
arXiv:1804.06152 [hep-ex] (submitted to PRL)
arXiv:1804.06153 [hep-ex] (submitted to PRD)

Determination of the CKM phase β

- Time-dependent interference between decays w/ and w/o oscillation



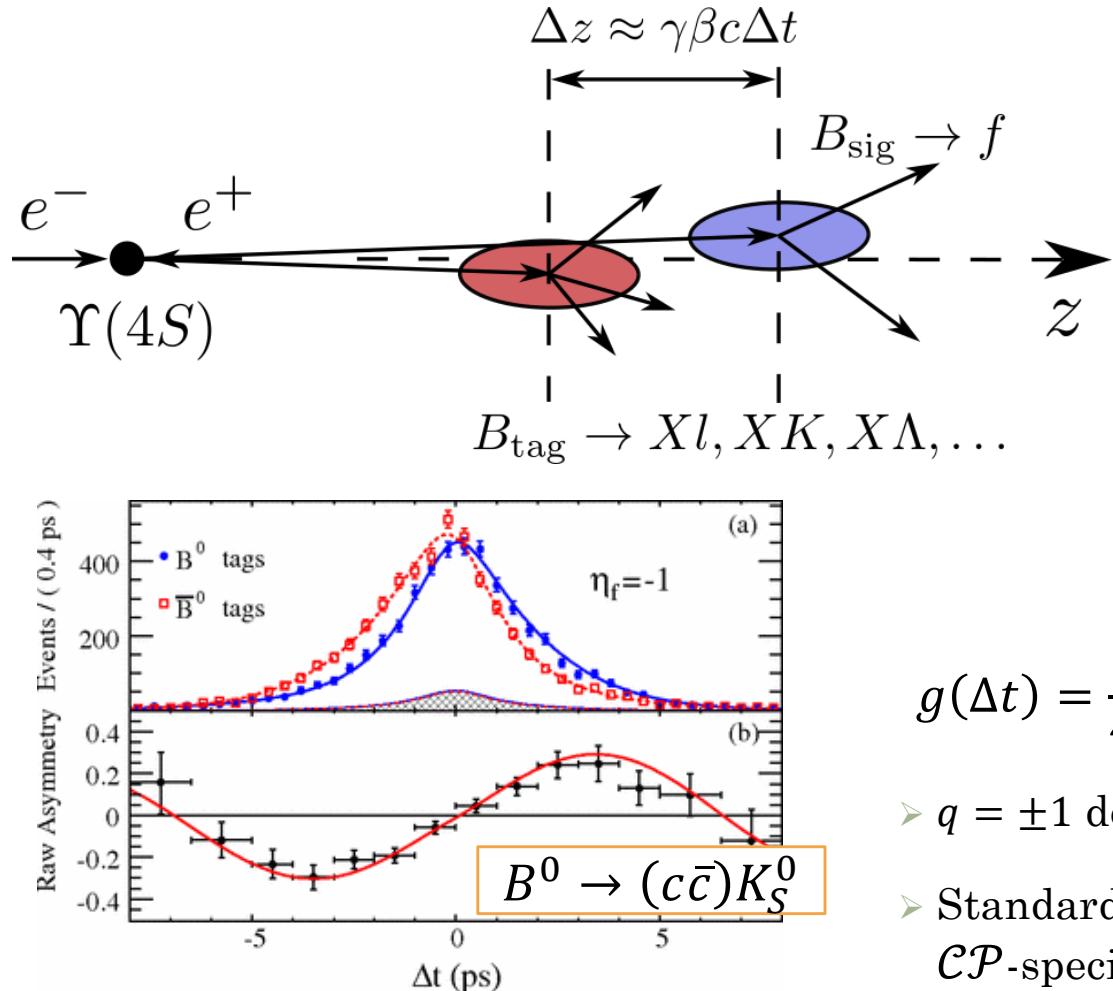
- A \mathcal{CP} -specific final state f provides sensitivity only to $\sin(2\beta)$
- Tagging of the initial B^0 flavor is necessary
- Measurement of B^0 decay vertex is needed for a time-dependent analysis



- The value of $\sin(2\beta)$ is measured precisely in $b \rightarrow c\bar{c}s$ ($B^0 \rightarrow J/\psi K_S^0, \dots$) transitions:

$$\sin(2\beta)_{b \rightarrow c\bar{c}s} = 0.691 \pm 0.017$$
- Trigonometric ambiguity: $2\beta \rightarrow \pi - 2\beta$

Time-dependent \mathcal{CP} violation at an asymmetric B -factory



- Flight distance $\Delta z \approx 200 \mu\text{m}$
- Spatial resolution $\sigma(\Delta z) \approx 130 \mu\text{m}$
- Correct flavor tagging for $\approx 80\%$ events
- Boost factor:
 - ❖ $\beta\gamma = 0.425$ at Belle
 - ❖ $\beta\gamma = 0.560$ at BaBar

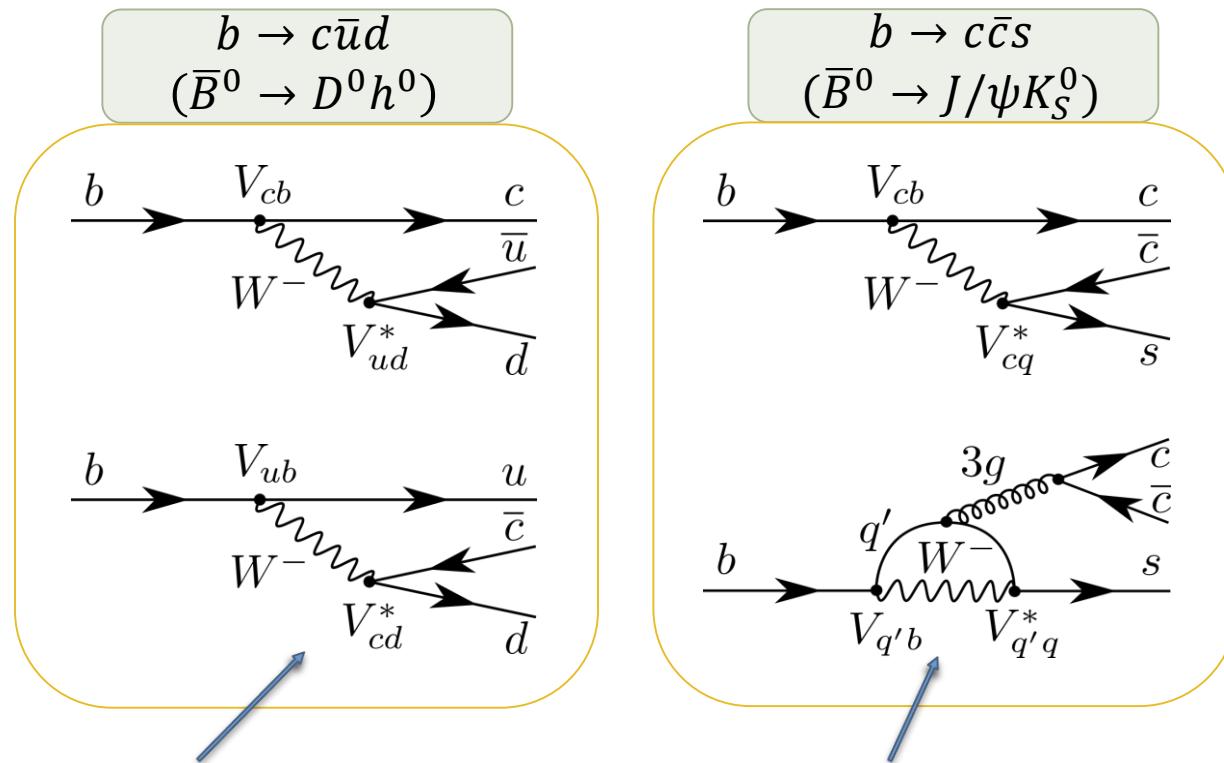
Time-dependent B decay rate

$$g(\Delta t) = \frac{1}{4\tau_B} e^{-\frac{|\Delta t|}{\tau_B}} (1 + q[\mathcal{S} \sin(\Delta m\Delta t) - \mathcal{C} \cos(\Delta m\Delta t)])$$

- $q = \pm 1$ denotes the initial flavor of signal B meson
- Standard model predicts $\mathcal{S} = -\eta_f \sin(2\beta)$ and $\mathcal{C} = 0$ for a \mathcal{CP} -specific final state with \mathcal{CP} parity η_f

Features of the $b \rightarrow c\bar{u}d$ transition

- Provides a complementary and theoretically clean approach to access β
- Dominated by tree amplitudes and not sensitive to most of physics beyond standard model (BSM)
- Time-dependent Dalitz analysis of the $B^0 \rightarrow D\{h^0, \pi^+\pi^-\}$ with $D \rightarrow K_S^0\pi^+\pi^-$ decays resolves the trigonometric ambiguity.
- A discrepancy between \mathcal{CP} asymmetries measured with $b \rightarrow c\bar{u}d$ and $b \rightarrow c\bar{c}s$ would indicate a BSM effect



The DCS transition is suppressed by ≈ 0.02

A sizable contribution from loop diagrams

\mathcal{CP} violation with $b \rightarrow c\bar{u}d$: history

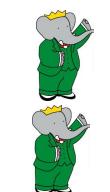
- Bondar, Gershon and Krokovny, [PLB 624 \(2005\) 1](#)

✓ The idea of time-dependent Dalitz plot analysis of $B^0 \rightarrow \bar{D}^0 h^0$,
 $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays is proposed



- Belle (Krokovny et al.), [PRL 97 \(2006\) 081801](#)

✓ First time-dependent Dalitz plot analyses of $B^0 \rightarrow \bar{D}^0 h^0$,
 $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays



- BaBar (Aubert et al.), [PRL 99 \(2007\) 081801](#)

✓ First observation of \mathcal{CP} violation in $B^0 \rightarrow \bar{D}_{\mathcal{CP}}^{(*)0} h^0$ decays. Analysis by M. Röhrken



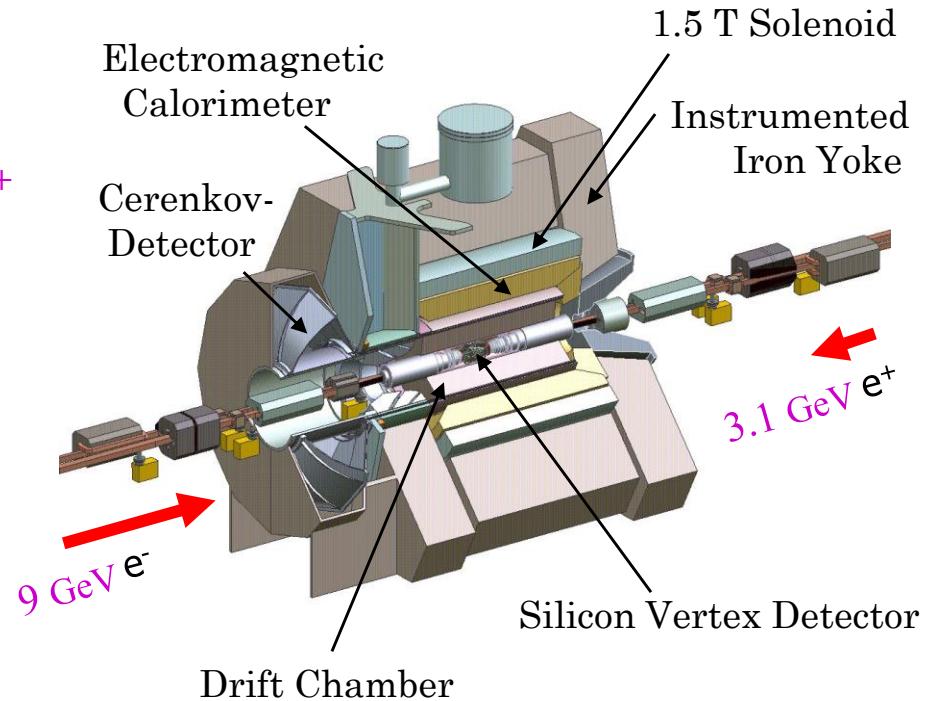
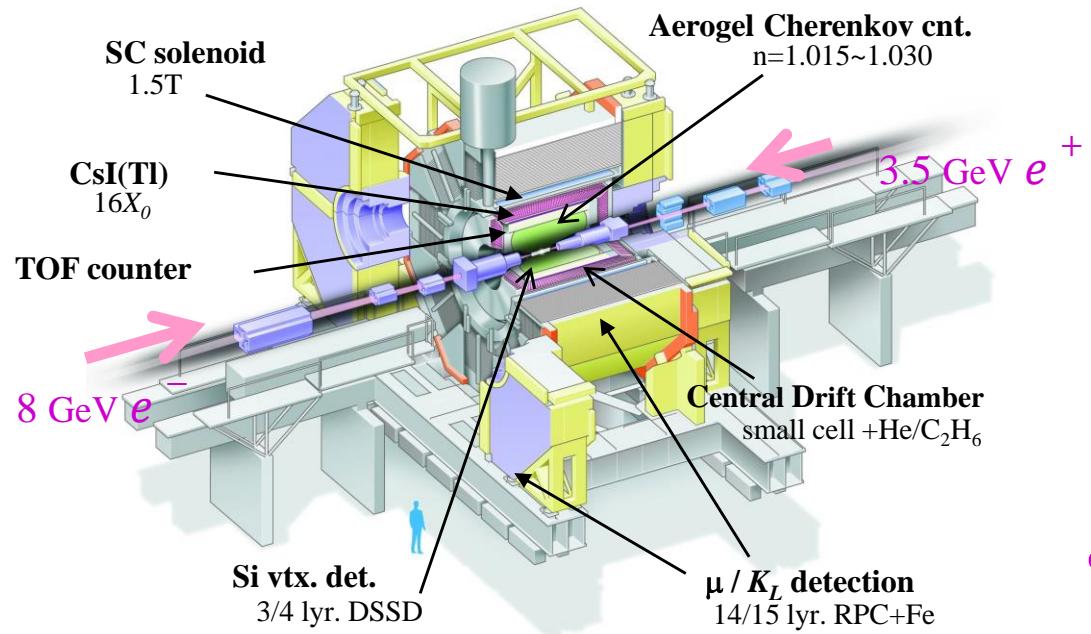
- Belle + BaBar (Abdesselam et al.), [PRL 115 \(2015\) 121604](#)
 $\sin(2\beta) = 0.66 \pm 0.10 \text{ (stat)} \pm 0.06 \text{ (syst)}$



- Belle (Vorobyev et al.), [PRD 94 \(2016\) 091503](#)
 $\sin(2\beta) = 0.43 \pm 0.27 \text{ (stat)} \pm 0.08 \text{ (syst)}$
 $\cos(2\beta) = 1.06 \pm 0.33 \text{ (stat)} {}^{+0.21}_{-0.15} \text{ (syst)}$
 $\beta = (11.7 \pm 7.8 \text{ (stat)} \pm 2.1 \text{ (syst)})^\circ$

✓ Direct exclusion of the 2nd solution @ 5.1σ
✓ First model-independent measurement of $\cos(2\beta)$

The Belle and BaBar experiments



➤ The Belle experiment:



- ✓ Operation period: 1999 – 2010
- ✓ 1.04 ab⁻¹ integrated luminosity
- ✓ $772 \times 10^6 B\bar{B}$ pairs

➤ The BaBar experiment:



- ✓ Operation period: 1999 – 2008
- ✓ 0.541 ab⁻¹ integrated luminosity
- ✓ $471 \times 10^6 B\bar{B}$ pairs

The $B^0 \rightarrow Dh^0$, $D \rightarrow K_S^0\pi^+\pi^-$ analysis

Time-dependent Dalitz plot analysis

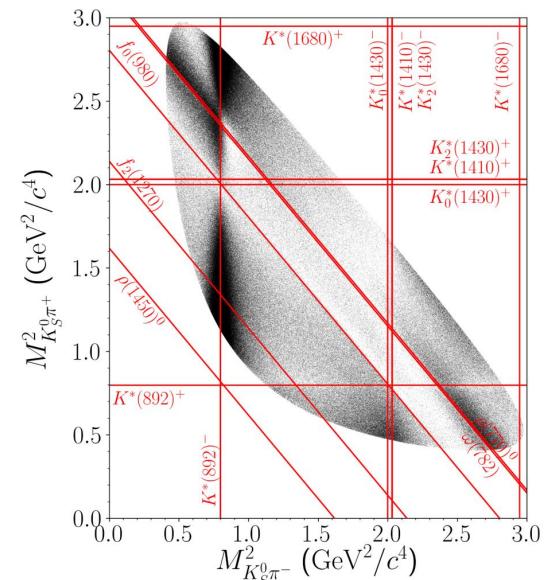
$$g(\Delta t, M_{K_S^0\pi^+}^2, M_{K_S^0\pi^-}^2) \propto e^{-\frac{|\Delta t|}{\tau_B}} [U - q(C \cos(\Delta m \Delta t) + S \sin(\Delta m \Delta t))]$$

$$U = |\mathcal{A}_{\bar{D}^0}^2|^2 + |\mathcal{A}_{D^0}^2|^2, \quad C = |\mathcal{A}_{\bar{D}^0}^2|^2 - |\mathcal{A}_{D^0}^2|^2,$$

$$S = 2q\eta_{h^0}(-1)^L [\text{Im}(\mathcal{A}_{D^0}\mathcal{A}_{\bar{D}^0}^*) \cos 2\beta - \text{Re}(\mathcal{A}_{D^0}\mathcal{A}_{\bar{D}^0}^*) \sin 2\beta]$$

- Variation of the $D^0 \rightarrow K_S^0\pi^+\pi^-$ decay amplitude **phase** provides a good sensitivity to $\sin 2\beta$ and $\cos 2\beta$ [Phys. Lett. B 624 (2005) 1]
- A $D^0 \rightarrow K_S^0\pi^+\pi^-$ **decay model** is needed to obtain the phase (phase difference between \mathcal{A}_{D^0} and $\mathcal{A}_{\bar{D}^0}$ amplitudes)
- Absence of \mathcal{CP} violation in mixing as and direct \mathcal{CP} violation the B and D decays are assumed

$$\mathcal{A}_{D^0}(M_{K_S^0\pi^+}^2, M_{K_S^0\pi^-}^2) \equiv \mathcal{A}_{\bar{D}^0}(M_{K_S^0\pi^-}^2, M_{K_S^0\pi^+}^2)$$

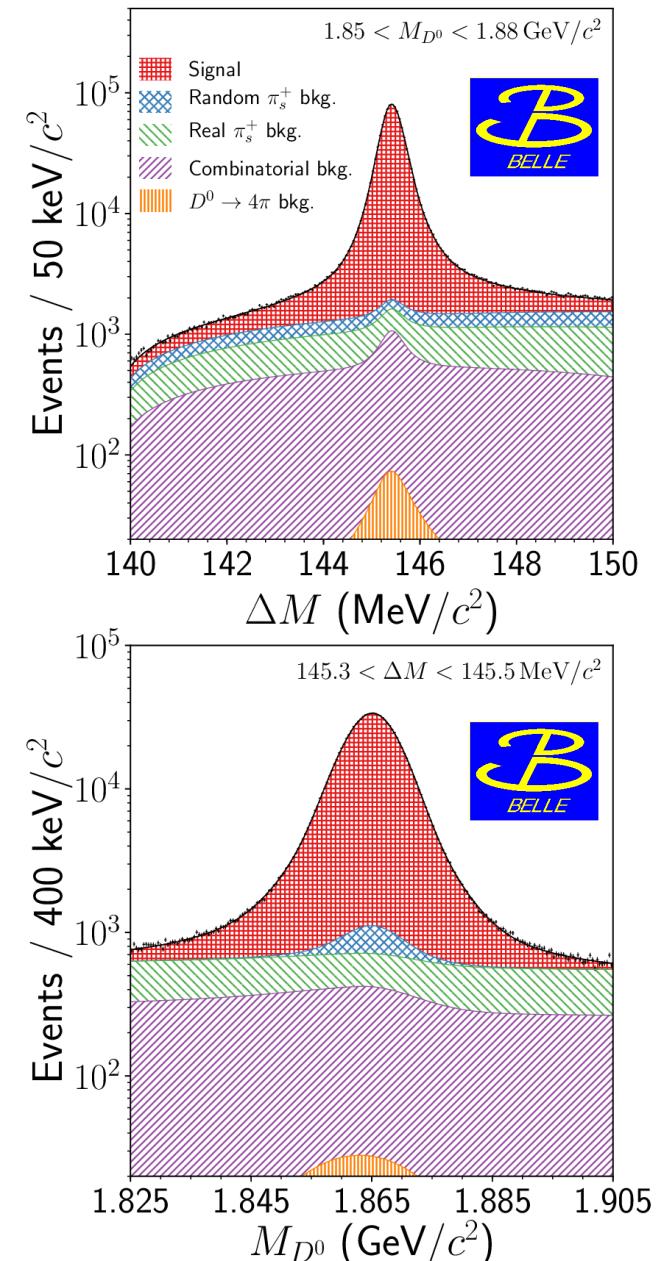


$$\mathcal{A}_{D^0} \equiv \mathcal{A}(D^0 \rightarrow K_S^0\pi^+\pi^-)$$

$$\mathcal{A}_{\bar{D}^0} \equiv \mathcal{A}(\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-)$$

The $D^{*+} \rightarrow D^0\pi_S^+$, $D^0 \rightarrow K_S^0\pi^+\pi^-$ data set

- Promptly produced D^{*+} in $e^+e^- \rightarrow c\bar{c}$ events (924 fb^{-1} of Belle data at $\Upsilon(4S)$ and $\Upsilon(5S)$)
- 2D fit of M_{D^0} and $\Delta M \equiv (M_{D^{*+}} - M_{D^0})$ distributions
- Background categories
 - ❖ Random slow pion with correct $D^0 \rightarrow K_S^0\pi^+\pi^-$ candidate
 - ❖ Correct π_S^+ from $D^{*+} \rightarrow D^0\pi_S^+$ with wrong D^0 candidate
 - ❖ $D^0 \rightarrow 4\pi$
 - ❖ Combinatorial
- The signal region
 - ✓ Signal yield: $(1.2173 \pm 0.0020) \times 10^6$ events
 - ✓ Signal purity: 94%



The $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay model

Signal model

- The K -matrix and LASS formalisms for the $\pi\pi$ and $K\pi$ S -waves, respectively
- The isobar ansatz for the set of resonances

$$\begin{aligned} & \rho(770), \omega(782), f_2(1270), \rho(1450)^0 \\ & K^*(892)^-, K_2^*(1430)^-, K^*(1680)^-, K^*(1410)^- \\ & K^*(892)^+, K_2^*(1430)^+, K^*(1410)^+ \end{aligned}$$

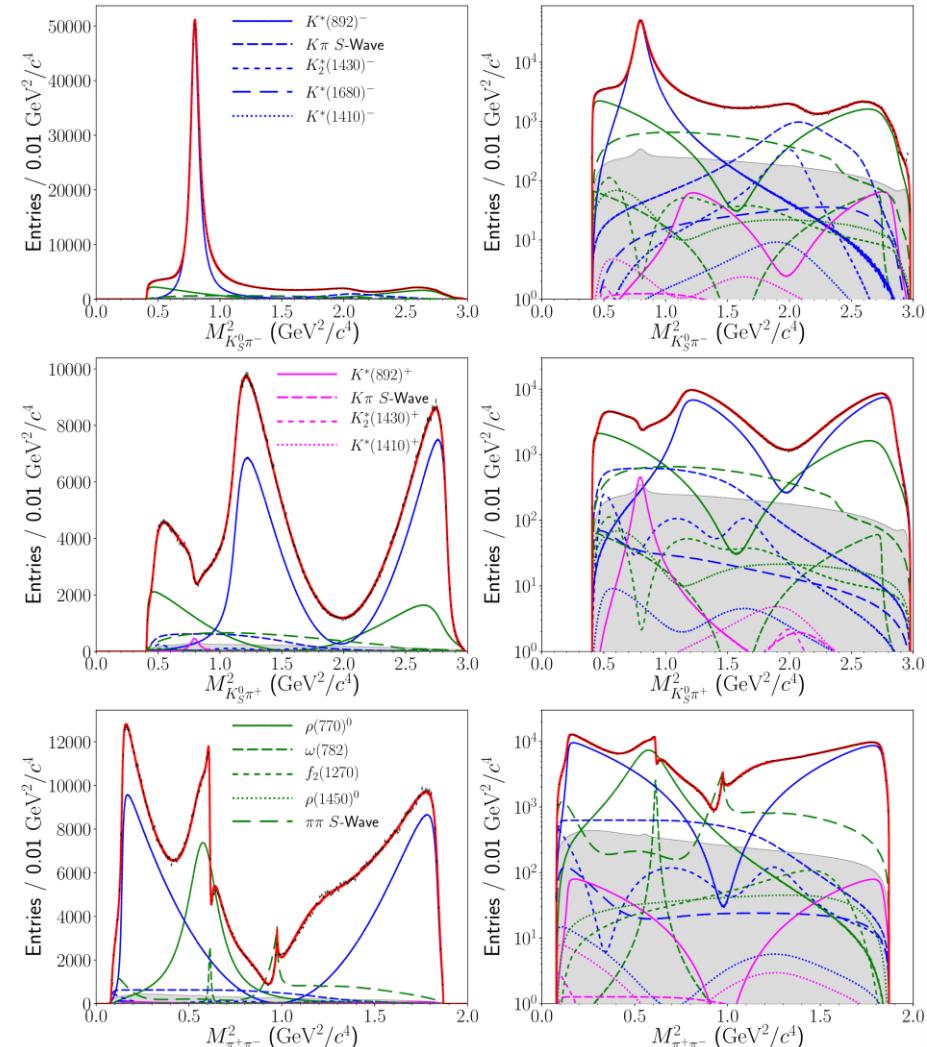
Background description

- Fit in two $(M_{D^0}, \Delta M)$ sideband regions: 6th order polynomial and BWs for $K^*(892)^-$, $\rho(770)$ and kaon states near 1410 MeV/ c^2

Unbinned ML fit

- ✓ 49 parameters using 64 CPUs in parallel
- ✓ 2D $\chi^2/n. d. f.$ = 1.05

[arXiv:1804.06152](https://arxiv.org/abs/1804.06152) [hep-ex]
[arXiv:1804.06153](https://arxiv.org/abs/1804.06153) [hep-ex]



The $B^0 \rightarrow Dh^0$, $D^0 \rightarrow K_S^0\pi^+\pi^-$ data set

Data set

Combination of full Belle and BaBar data at $\Upsilon(4S)$, more than 1 ab^{-1}

Signal modes

- $D^0 h^0$, with h^0 in
 - ✓ $\pi^0 \rightarrow \gamma\gamma$
 - ✓ $\eta \rightarrow \gamma\gamma$, $\pi^+\pi^-\pi^0$
 - ✓ $\omega \rightarrow \pi^+\pi^-\pi^0$
- $D^{*0} h^0$ with
 - ✓ $D^{*0} \rightarrow D^0\pi^0$
 - ✓ $h^0 \in \{\pi^0, \eta\}$

The main variables

- Energy difference

$$\Delta E \equiv E_B^* - E_{\text{beam}}^*$$

asterisk denotes the center-of-mass system

- (Modified) beam-energy-constrained mass

$$M'_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^{*2} - \left(\vec{p}_{D^{(*)}}^* + \frac{\vec{p}_{h^0}^*}{|\vec{p}_{h^0}^*|} \sqrt{(E_{\text{beam}}^* - E_{D^{(*)}}^*)^2 - M_{h^0}^2} \right)^2}$$

- Modified output of the neural network classifier C'_{NNout}
- ✓ The parameters ΔE , M'_{bc} and C'_{NNout} are (almost) not correlated

[arXiv:1804.06152](https://arxiv.org/abs/1804.06152) [hep-ex]
[arXiv:1804.06153](https://arxiv.org/abs/1804.06153) [hep-ex]

The $B^0 \rightarrow Dh^0, D^0 \rightarrow K_S^0\pi^+\pi^-$ data set

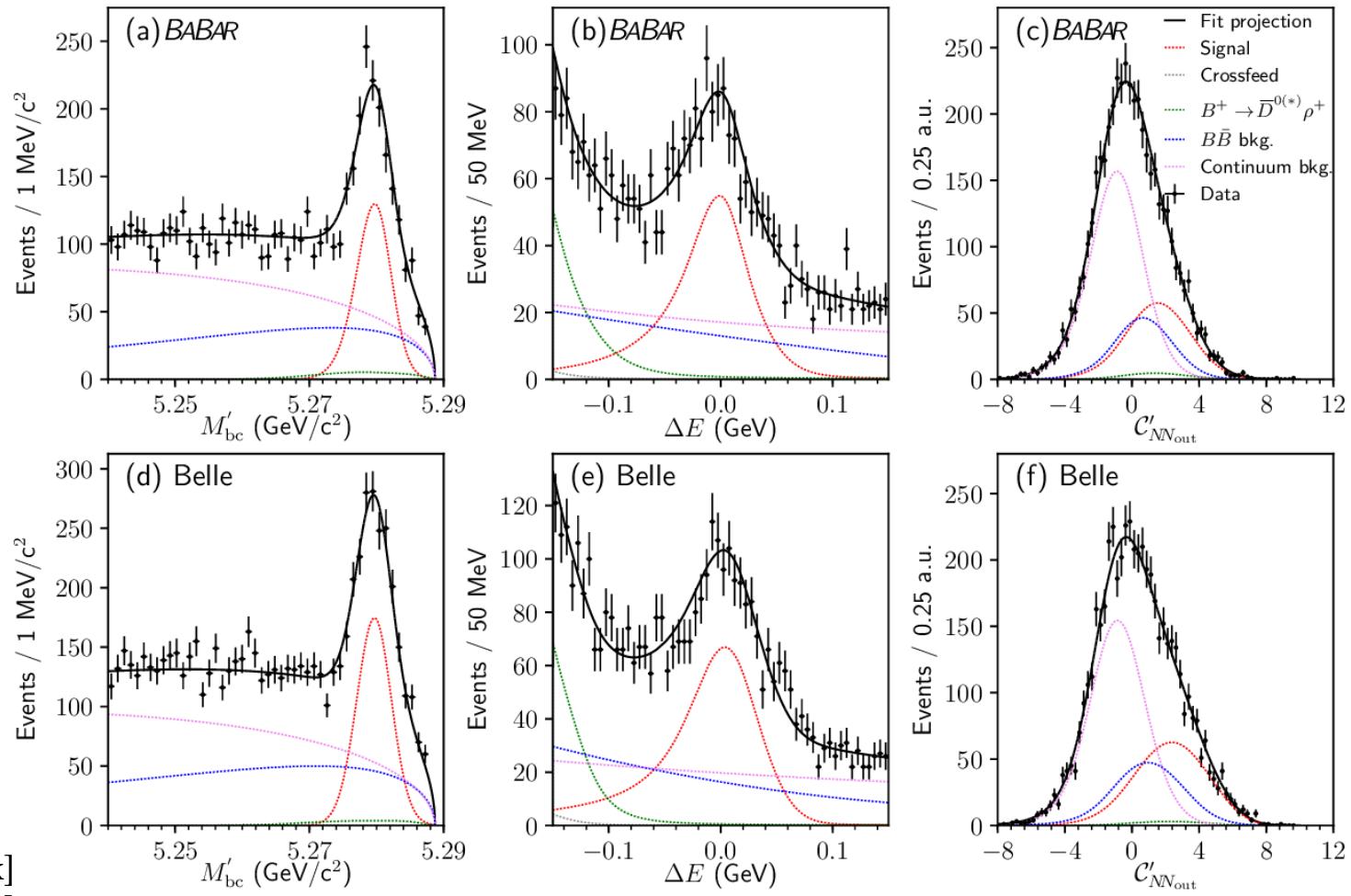
Signal yield

- 3D unbinned ML fit
- 1129 ± 48 events for BaBar
- 1567 ± 56 events for Belle

Background components

- Partially reconstructed $B^+ \rightarrow \bar{D}^{0(*)}\rho^+$ (only for $B^0 \rightarrow \bar{D}^{0(*)}\pi^0$)
- Combinatorial background from $B\bar{B}$
- Combinatorial background from continuum $e^+e^- \rightarrow q\bar{q}$,
 $q \in \{u, d, s, c\}$

[arXiv:1804.06152](https://arxiv.org/abs/1804.06152) [hep-ex]
[arXiv:1804.06153](https://arxiv.org/abs/1804.06153) [hep-ex]



Time-dependent Dalitz plot fit

- The log-likelihood function

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\text{BaBar}} + \sum_j \ln \mathcal{P}_j^{\text{Belle}}$$

$$\mathcal{P}(\Delta t, M_{K_S^0\pi^+}^2, M_{K_S^0\pi^-}^2) = \sum_k f_k \int [P_k(\Delta t') R_k(\Delta t - \Delta t')] d(\Delta t')$$

time and Dalitz plot PDF time resolution function

- k runs over signal and background components
- The fractions f_k are evaluated on an event-by-event basis from the $(M'_{bc}, \Delta E, C'_{NNout})$ distributions
- The only free parameters are $\sin 2\beta$ and $\cos 2\beta$
- An alternative fit with the single free parameter β

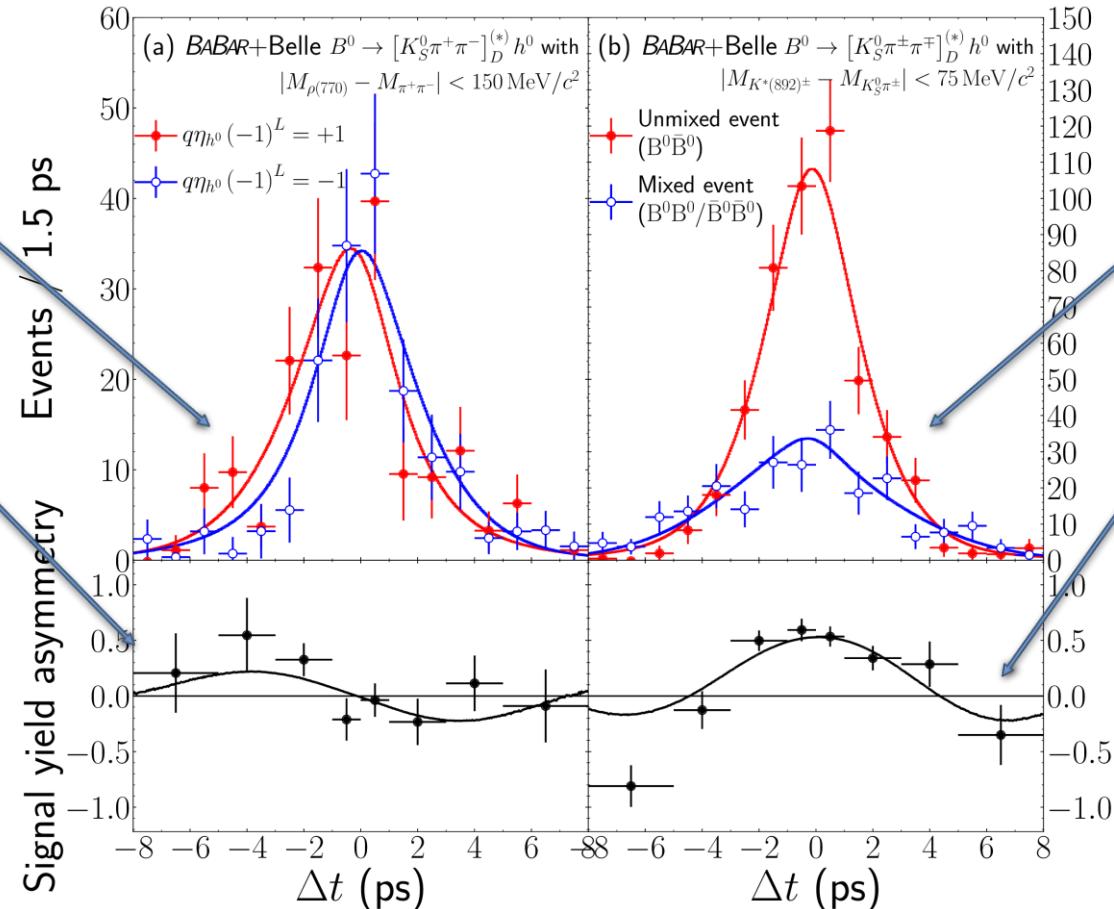
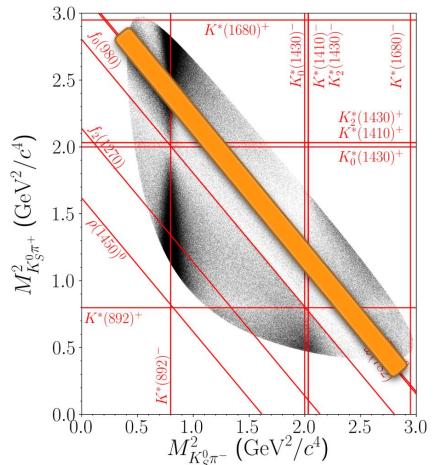
- Experiment-specific (Babar and Belle) techniques for
 - ❖ description of proper time resolution
 - ❖ flavor tagging
- Independent Dalitz plot reconstruction efficiency maps for $D^* \rightarrow D\pi$ and $B^0 \rightarrow Dh^0$ events
- The background Δt parameters are determined from M'_{bc} sideband

Proper time interval distributions

Dalitz plot region
predominantly populated
by \mathcal{CP} eigenstates

$$B^0 \rightarrow [K_S^0 \rho(770)^0]_D^{(*)} h^0$$

Asymmetry \approx proportional
to $\sin(\Delta m_d \Delta t)$

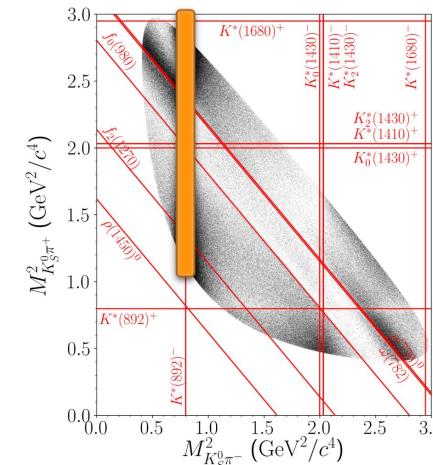


- Candidates with high quality flavor tags
- Background subtracted

Dalitz plot region
predominantly populated
by flavor-specific decays

$$B^0 \rightarrow [K^*(892)^\pm \pi^\mp]_D^{(*)} h^0$$

Asymmetry \approx proportional
to $\cos(\Delta m_d \Delta t)$



$B^0 \rightarrow Dh^0$, $D^0 \rightarrow K_S^0\pi^+\pi^-$: results

Unbinned ML fit of time-dependent DP distribution

$$\sin(2\beta) = 0.80 \pm 0.14 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \pm 0.03 \text{ (model)}$$

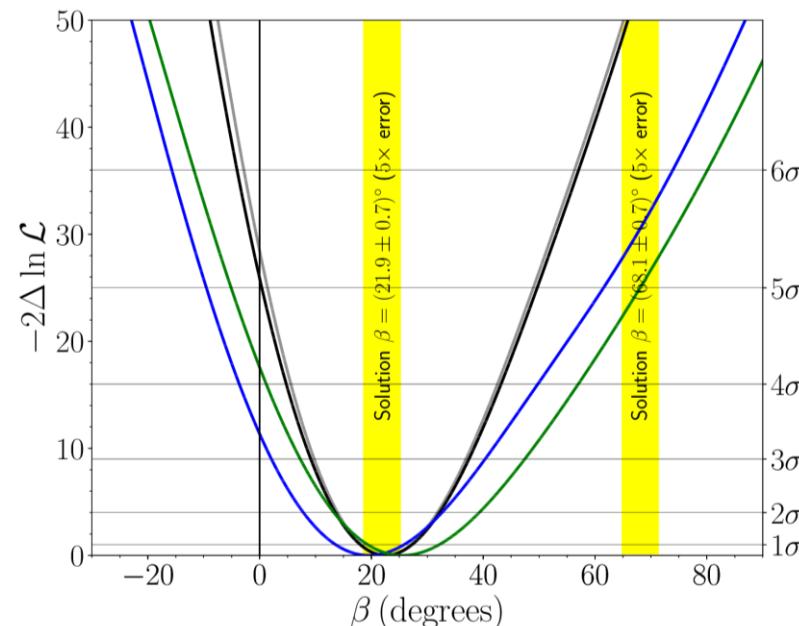
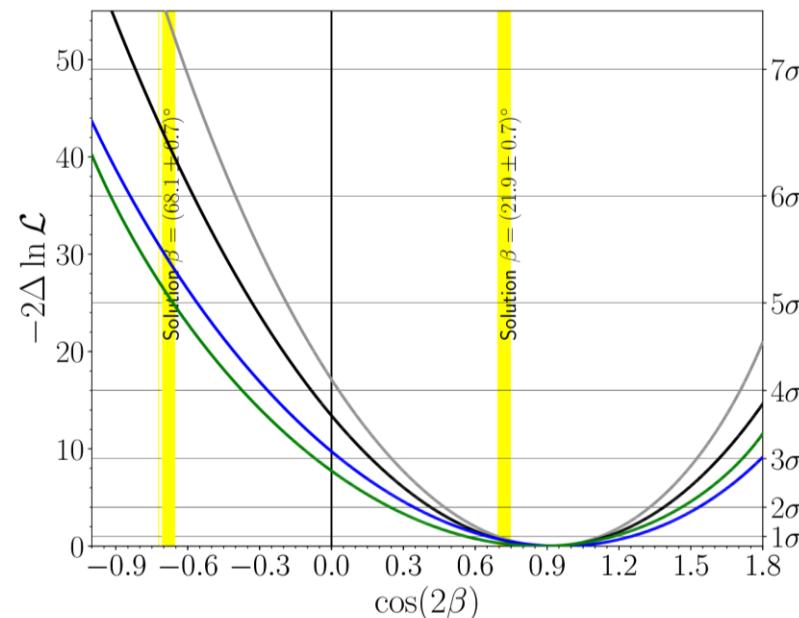
$$\cos(2\beta) = 0.91 \pm 0.22 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.07 \text{ (model)}$$

$$\beta = (22.5 \pm 4.4 \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.6 \text{ (model)})^0$$

Main systematics sources

- Possible fit bias
 - Vertex reconstruction
 - Δt resolution function
 - Signal purity
 - Background Δt PDFs
- ✓ First evidence for $\cos(2\beta) > 0$ @ 3.7σ
- ✓ Direct exclusion of the 2nd solution @ 7.3σ
- ✓ Observation of \mathcal{CP} violation @ 5.1σ

[arXiv:1804.06152](https://arxiv.org/abs/1804.06152) [hep-ex]
[arXiv:1804.06153](https://arxiv.org/abs/1804.06153) [hep-ex]



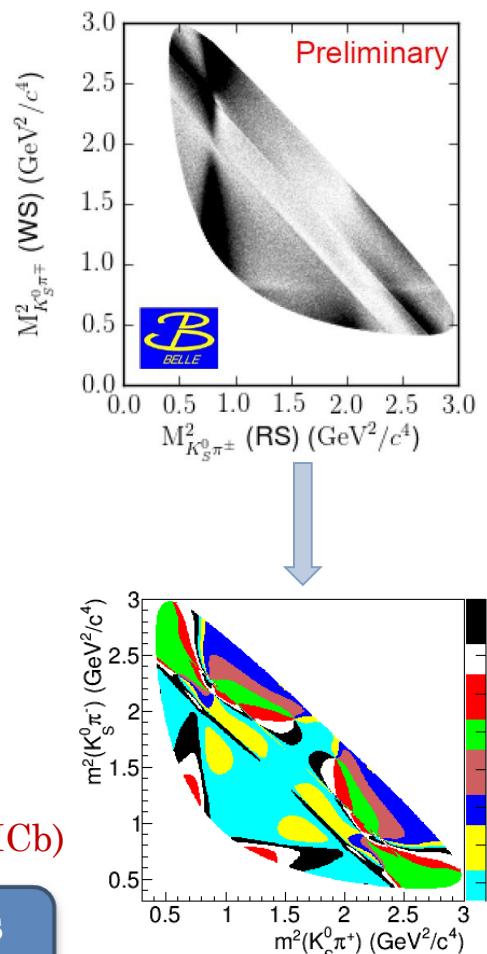
Future prospects

- ❖ New approaches
- ❖ New data

Future challenges and new ideas

- Dalitz plot analysis of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay is a powerful tool in flavor physics
 - ✓ The UT angle γ measurement with $B^\pm \rightarrow D K^\pm$, $D \rightarrow K_S^0 \pi^+ \pi^-$
 - ✓ The UT angle β measurement with $B^0 \rightarrow D h^0$, $D \rightarrow K_S^0 \pi^+ \pi^-$
 - ✓ Charm mixing parameters with $D^{*\pm} \rightarrow D \pi_S^\pm$, $D \rightarrow K_S^0 \pi^+ \pi^-$
- Model uncertainty can limit measurements precision with large future data sets from Belle II and LHCb
- The binned Dalitz plot technique
 - ✓ The ground idea by Giri et al. [PRD 68, 054018 (2003)]
 - ✓ The “equal-phase” and “optimal” partitioning techniques by Bondar and Poluektov [Eur. Phys. J. C47 (2006) 347; C55 (2008) 51]
 - ✓ New ideas
 - ✓ Double binned DP [JHEP 03 (2018) 195, PRD 97 (2018) 056002]
 - ✓ Unbinned model-independent approach [A. Poluektov, Eur. Phys. J. C78, 121 (2018)]

See the A. Poluektov's
talk this afternoon

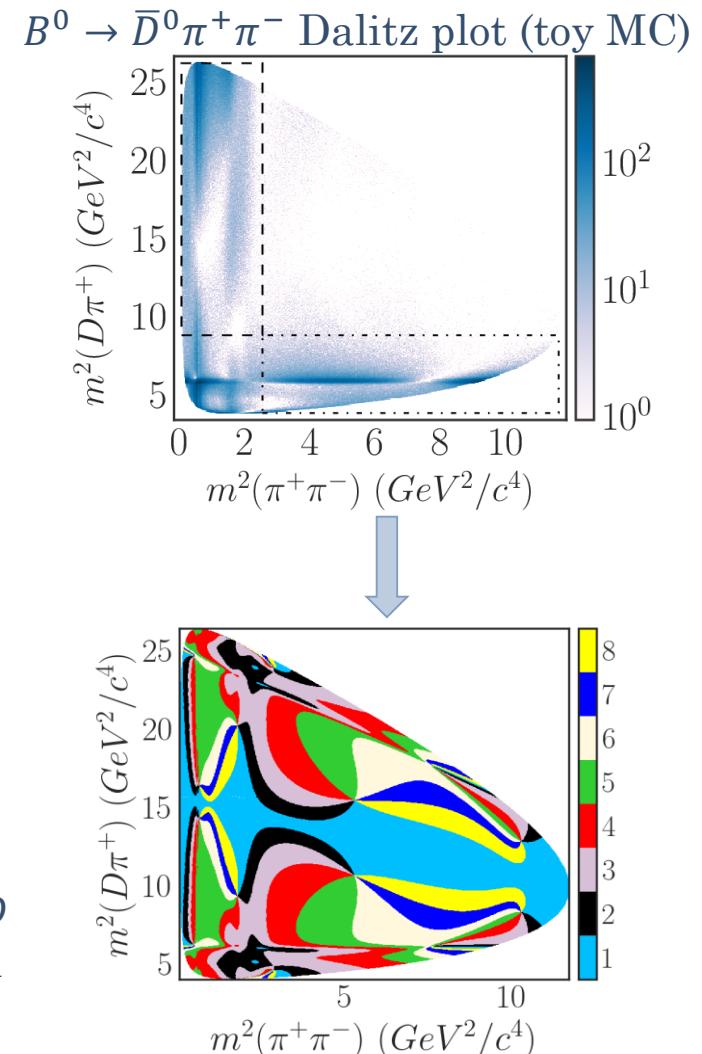


\mathcal{CP} violation with $b \rightarrow c\bar{u}d$ at Belle II and LHCb

- $B^0 \rightarrow D\pi^+\pi^-$, $D \rightarrow K_S^0\pi^+\pi^-$ JHEP 03 (2018) 195
- Time-dependent analysis of double binned Dalitz plot
- Only charged final-state particles (LHCb friendly)

Expected signal yields			
Decay	Belle (1 ab ⁻¹)	Belle II (50 ab ⁻¹)	LHCb (50 fb ⁻¹)
$B^0 \rightarrow D_{\mathcal{CP}}\pi^+\pi^-$	$1.0 \cdot 10^3$	$50 \cdot 10^3$	$140 \cdot 10^3$
$B^0 \rightarrow [K_S^0\pi^+\pi^-]_D\pi^+\pi^-$	$1.3 \cdot 10^3$	$65 \cdot 10^3$	$84 \cdot 10^3$
$B^0 \rightarrow D_{\mathcal{CP}}h^0$	$0.8 \cdot 10^3$	$40 \cdot 10^3$	—
$B^0 \rightarrow [K_S^0\pi^+\pi^-]_D h^0$	$1.0 \cdot 10^3$	$50 \cdot 10^3$	—
Decay	Belle II (50 ab ⁻¹)	LHCb (50 fb ⁻¹)	
$B^0 \rightarrow D\pi^+\pi^-$	$\delta\beta = 1.5^\circ$	$\delta\beta = 1.5^\circ$	
$B^0 \rightarrow Dh^0$	$\delta\beta = 0.7^\circ$	—	

Expected angle β uncertainty in combined analysis of D decays in $K_S^0\pi^+\pi^-$ and \mathcal{CP} eigenstates



Conclusions

- ✓ The B -factories potential to measure \mathcal{CP} violation in the $b \rightarrow c\bar{u}d$ transition is now revealed completely
 - ❖ The $2\beta \rightarrow (\pi - 2\beta)$ ambiguity is resolved at the confidence level of 7.3σ
 - ❖ The \mathcal{CP} violation is observed in $B^0 \rightarrow \bar{D}^0 h^0$ with \bar{D}^0 decaying into $K_S^0 \pi^+ \pi^-$ and \mathcal{CP} eigenstates (see PRL 115 (2015) 121604)
- ✓ With the future Belle II and LHCb data, the angle β can be measured in $b \rightarrow c\bar{u}d$ transitions with precision below one degree
- ✓ Model-independent techniques for measurements with the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay will become more in demand with large data sets

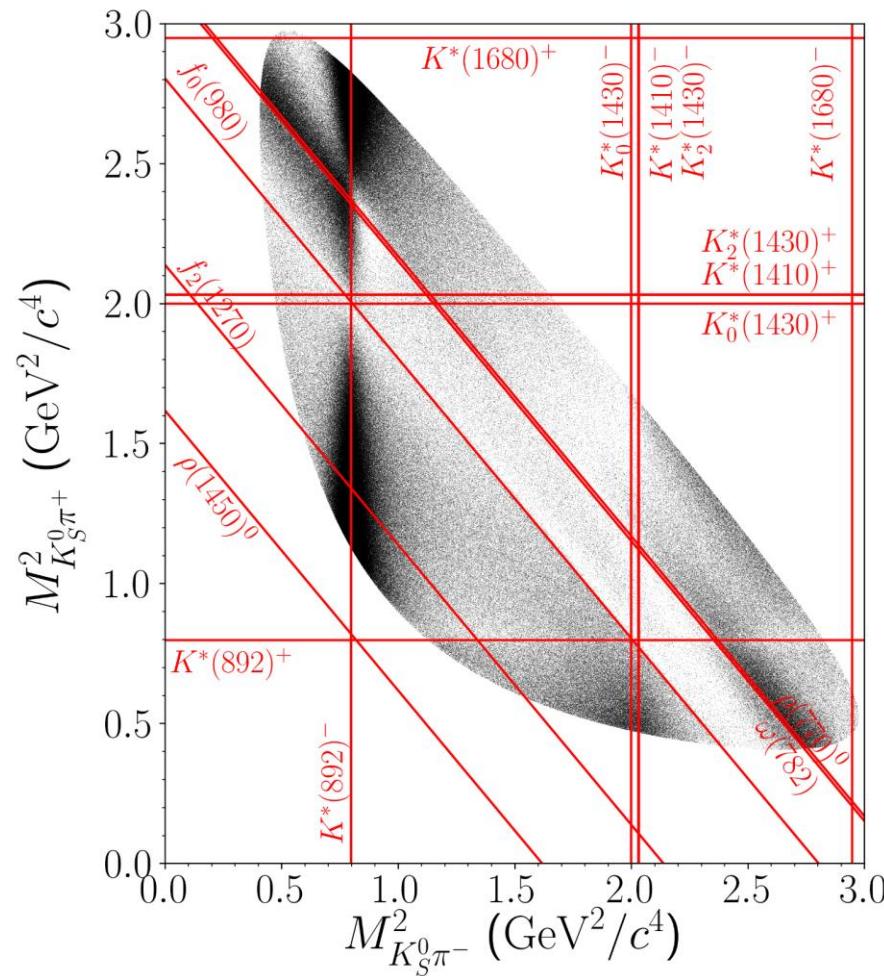
Thank you!

Backup





The $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay model parameters



Resonance	Amplitude	Phase (deg)	Fit Fraction (%)
$K_S^0 \rho(770)^0$	1 (fixed)	0 (fixed)	20.4
$K_S^0 \omega(782)$	0.0388 ± 0.0005	120.7 ± 0.7	0.5
$K_S^0 f_2(1270)$	1.43 ± 0.03	-36.3 ± 1.1	0.8
$K_S^0 \rho(1450)^0$	2.85 ± 0.10	102.1 ± 1.9	0.6
$K^*(892)^- \pi^+$	1.720 ± 0.006	136.8 ± 0.2	59.9
$K_2^*(1430)^- \pi^+$	1.27 ± 0.02	-44.1 ± 0.8	1.3
$K^*(1680)^- \pi^+$	3.31 ± 0.20	-118.2 ± 3.1	0.5
$K^*(1410)^- \pi^+$	0.29 ± 0.03	99.4 ± 5.5	0.1
$K^*(892)^+ \pi^-$	0.164 ± 0.003	-42.2 ± 0.9	0.6
$K_2^*(1430)^+ \pi^-$	0.10 ± 0.01	-89.6 ± 7.6	< 0.1
$K^*(1410)^+ \pi^-$	0.21 ± 0.02	150.2 ± 5.3	< 0.1
$\pi^+ \pi^-$ S-wave Parameters			10.0
β_1	8.5 ± 0.5	68.5 ± 3.4	
β_2	12.2 ± 0.3	24.0 ± 1.4	
β_3	29.2 ± 1.6	-0.1 ± 2.5	
β_4	10.8 ± 0.5	-51.9 ± 2.4	
f_{11}^{prod}	8.0 ± 0.4	-126.0 ± 2.5	
f_{12}^{prod}	26.3 ± 1.6	-152.3 ± 3.0	
f_{13}^{prod}	33.0 ± 1.8	-93.2 ± 3.1	
f_{14}^{prod}	26.2 ± 1.3	-121.4 ± 2.7	
s_0^{prod}	-0.07 (fixed)		
$K\pi$ S-wave Parameters			
$K_0^*(1430)^- \pi^+$	2.36 ± 0.06	99.4 ± 1.7	
$K_0^*(1430)^+ \pi^-$	0.11 ± 0.01	162.3 ± 6.6	< 0.1
$M_{K_0^*(1430)\pm}$ (GeV/ c^2)	1.441 ± 0.002		
$\Gamma_{K_0^*(1430)\pm}$ (GeV/ c^2)	0.193 ± 0.004		
F	$+0.96 \pm 0.07$		
R	1 (fixed)		
a	$+0.113 \pm 0.006$		
r	-33.8 ± 1.8		
ϕ_F (deg)	0.1 ± 0.3		
ϕ_R (deg)	-109.7 ± 2.6		
$K^*(892)^\pm$ Parameters			
$M_{K^*(892)\pm}$ (GeV/ c^2)	0.8937 ± 0.0001		
$\Gamma_{K^*(892)\pm}$ (GeV/ c^2)	0.0472 ± 0.0001		

Signal yields

Decay mode	BaBar yield	Belle yield
$B^0 \rightarrow D\pi^0$	469 ± 31	768 ± 37
$B^0 \rightarrow D\eta$	220 ± 31	238 ± 23
$B^0 \rightarrow D\omega$	219 ± 21	285 ± 26
$B^0 \rightarrow D^*\pi^0$	147 ± 18	182 ± 19
$B^0 \rightarrow D^*\eta$	74 ± 11	94 ± 13
Total	1129 ± 48	1567 ± 56

Systematic uncertainty

TABLE V. Experimental systematic uncertainties on the CP violation parameters.

Source	$\delta \sin 2\beta (\times 10^2)$	$\delta \cos 2\beta (\times 10^2)$	$\delta\beta (^{\circ})$
Vertex reconstruction	3.2	4.8	0.53
Δt resolution functions	2.8	5.8	0.41
Background Δt p.d.f.s	1.2	1.8	0.16
Signal purity	2.1	3.4	0.53
Flavor-tagging	0.3	0.4	0.07
Physics parameters	0.1	0.1	0.02
Possible fit bias	3.7	3.9	0.79
Dalitz plot reconstruction efficiency correction	< 0.1	0.2	0.02
Total	6.1	9.3	1.18

Model uncertainty

TABLE VI. Uncertainties on the CP violation parameters due to the Dalitz plot amplitude model.

Source	$\delta \sin 2\beta (\times 10^2)$	$\delta \cos 2\beta (\times 10^2)$	$\delta\beta (^\circ)$
Masses and widths of resonances	0.7	1.7	0.13
$\pi^+ \pi^-$ S -wave parametrization	1.1	1.9	0.11
$K\pi$ S -wave parametrization	1.0	1.6	0.38
Blatt-Weisskopf barrier factors	1.2	1.7	0.19
D meson mistag fraction	0.2	< 0.1	0.04
Dalitz plot reconstruction efficiency	0.9	0.9	0.06
Dalitz plot background shape	< 0.1	0.2	0.01
Effect of finite experimental mass resolution	0.1	0.2	< 0.01
Signal purity	< 0.1	< 0.1	0.01
Statistical uncertainties on resonance parameters	1.6	5.0	0.37
Removal of resonances	0.6	1.3	0.09
Alternative isobar Dalitz plot model	0.7	2.8	0.08
Total	2.9	6.9	0.61

\mathcal{CP} transformation for $B^0 \rightarrow \bar{D}^{(*)0} h^0$

Mode	\mathcal{CP} parity
$B^0 \rightarrow \bar{D}^0 \pi^0$	$(-1)^l \xi_{\pi^0} \mathcal{CP}(D) = -\mathcal{CP}(D)$
$B^0 \rightarrow \bar{D}^0 \eta^{(\prime)0}$	$(-1)^l \xi_{\eta^{(\prime)0}} \mathcal{CP}(D) = -\mathcal{CP}(D)$
$B^0 \rightarrow \bar{D}^0 \omega$	$(-1)^l \xi_\omega \mathcal{CP}(D) = -\mathcal{CP}(D)$
$B^0 \rightarrow \bar{D}^{*0} \pi^0, \quad \bar{D}^{*0} \rightarrow \bar{D}^0 \pi^0$	$(-1)^l (-1)^{l'} \xi_{\pi^0} \xi_{\pi^0} \mathcal{CP}(D) = \mathcal{CP}(D)$

Combined BaBar + Belle analysis of $\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$

PRL 115, 121604 (2015)

Time-dependent B decay rate

$$g(\Delta t) \propto 1 + q[A \sin(\Delta m \Delta t) + B \cos(\Delta m \Delta t)]$$

$A = -\eta_f \sin(2\varphi_1)$ and $B = 0$ for a CP -specific final state

Maximum likelihood fit of the Δt distributions

$$\sin(2\varphi_1) = 0.66 \pm 0.10 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$$

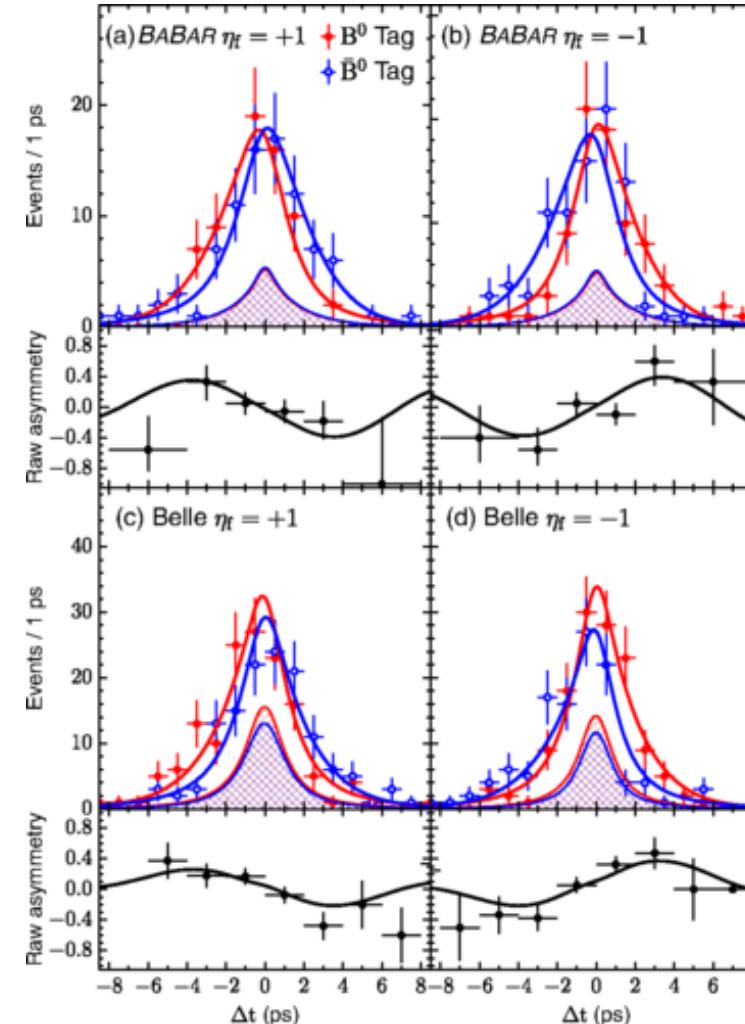
➢ No significant direct CP violation found:

$$B = -0.02 \pm 0.07 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$$

Main systematics sources

- Peaking background (0.049)
- Δt resolution functions (0.020)
- Vertex resolution (0.015)

✓ Observation of CP violation at 5.4σ confidence level



$B^0 \rightarrow D h^0$ with $D \rightarrow K_S^0 \pi^+ \pi^-$ (model-independent)

PRD 94, 052004 (2016)

Maximum likelihood fit of the Δt distributions

$$\sin(2\beta) = 0.43 \pm 0.27 \text{ (stat)} \pm 0.08 \text{ (syst)}$$

$$\cos(2\beta) = 1.06 \pm 0.33 \text{ (stat)} {}^{+0.21}_{-0.15} \text{ (syst)}$$

$$\beta = (11.7 \pm 7.8 \text{ (stat)} \pm 2.1 \text{ (syst)})^0$$



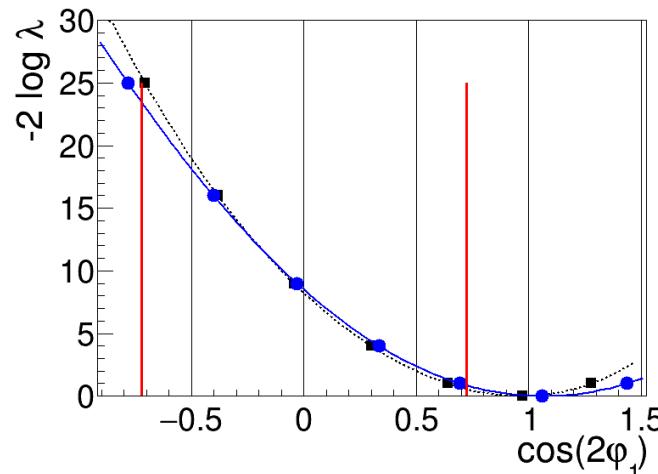
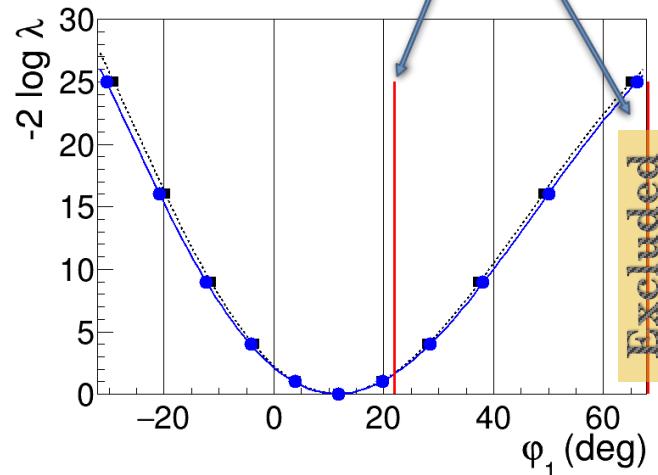
Main systematics sources

- Uncertainties of C_i and S_i : 1.1° (dominant)
- Δt resolution function
- Signal purity
- Background Δt PDFs
- Uncertainties of K_i

Stat. origin

- ✓ Direct exclusion of the 2nd solution @ 5.1σ
- ✓ The first model-independent measurement of $\cos(2\beta)$

The solutions corresponding to $\sin(2\beta) = 0.69$



The CKM mechanism of \mathcal{CP} violation

$$\mathcal{L} \propto -\frac{g}{\sqrt{2}} (\bar{u}_L, \bar{c}_L, \bar{t}_L) \gamma^\mu W_\mu^+ V_{CKM} (d_L, s_L, b_L)^T + h.c.$$

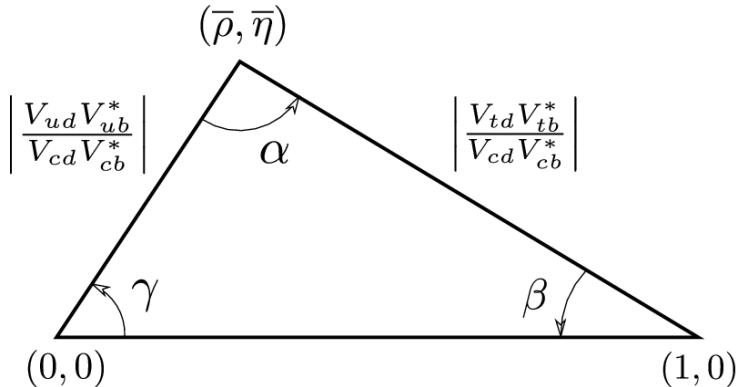
The CKM matrix

- The unitary matrix of quark mixing for weak charged currents (Cabibbo, Kobayashi and Maskawa, CKM)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Four independent parameters
- Can be parametrized with three Euler angles and **single phase**.

The Unitarity Triangle



$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + 1 = 0$$

The binned Dalitz plot approach

Motivation

- The phase difference $\Delta\delta_D$ between the $D^0 \rightarrow K_S^0\pi^+\pi^-$ and $\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-$ decay amplitudes is needed to measure the CKM angle γ in $B^\pm \rightarrow DK^\pm$ with $D \rightarrow K_S^0\pi^+\pi^-$ decays
- $\Delta\delta_D$ cannot be measured in each point of the phase space. Phenomenological models are used to **predict** $\Delta\delta_D$.
- A model cannot provide reliable information about the phase. **Even the uncertainty scale is not evident**
- The model uncertainty can limit future precise measurements

* The $D^0 \rightarrow K_S^0\pi^+\pi^-$ decay is considered here, but the binned approach can be applied to any multibody decay

Binned $D^0 \rightarrow K_S^0\pi^+\pi^-$ DP in a nutshell*

- The phase space is divided into $2\mathcal{N}$ regions
- The parameters K_i , C_i and S_i are defined for the i^{th} region:
 - ❖ K_i – probability of D^0 meson decay into the i^{th} region
 - ❖ C_i and S_i – cos and sin of the decay amplitude phase difference between \bar{D}^0 and D^0 averaged over the i^{th} region
- A decay probability (density) is expressed through C_i and S_i instead of $\Delta\delta_D$
- The parameters C_i and S_i can be measured in coherent decays of $D^0\bar{D}^0$ pairs

